Characteristics of Clustering Extreme Drought Events in China During 1961–2010

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ABSTRACT

Based on the Multi-Scale Standardized Precipitation Index (MSPI), extreme severe drought events in China during 1961–2010 were identified, and the seasonal, annual, and interdecadal variations of the clustering extreme drought events were investigated by using the spatial point process theory. It is found that severe droughts present a trend of gradual increase as a result of the significant increase and clustering tendency of severe droughts in autumn. The periodicity analysis of the clustering extreme droughts in different seasons suggests that there is a remarkable interdecadal change in the occurrence of clustering extreme droughts in winter. Meanwhile, it is revealed that the clustering extreme drought events exhibit greatly different annual mean spatial distributions during 1961–2010, with scattered and concentrated clustering zones alternating on the decadal timescale. Furthermore, it is found that the decadal-mean spatial distributions of extreme drought events in summer are correlated out of phase with those of the rainy bands over China in the past 50 years, and a good decadal persistence exists between the autumn and winter extreme droughts, implying a salient feature of consecutive autumn-winter droughts in this 50-yr period. Compared with other regions of China, Southwest China bears the most prominent characteristic of clustering extreme droughts.

Key words: extreme drought events, clustering, interdecadal, seasonal

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1. Introduction

As one of the most damaging meteorological disasters, drought has been one of the major topics for climate research in the past several decades in China (Zhang and Chen, 1991; Ma and Ren, 2007). Many previous studies have focused on the influence and mechanisms of drought events. It is revealed from a large number of facts that aridification in China, especially in northern China, is getting increasingly serious. Recent investigations indicate that extreme drought events have shown an ascending trend under the background of global warming in the past decades (Ma and Fu, 2003; Dai et al., 2004; Lian et al., 2005; Fu and Zeng, 2005; Fu et al., 2005; Huang, 2006; Huang et al., 2008; Hou et al., 2009).

Clustering is considered as a new important feature of extreme climatic events. Strong impact and serious damage of such events have attracted close attention and intense research interests of scientists worldwide (Min et al., 2003; Dai et al., 2003; Sun et al., 2009; Ren et al., 2010). Generally, clustering may be reflected temporally or/and spatially. Temporal clustering refers to extreme climate events lasting for a long period of time. For example, the extreme drought in Yunnan Province in 2009/2010 that lasted for more than 100 days is categorized as a temporally clustering extreme event. If an extreme climate event observed frequently is concentrated in a certain region, it is called a spatial clustering event. For example, the unusual freezing rain, frost, and snowstorm disasters that attacked southern China at the beginning of 2008

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are taken as a spatial clustering event.

So far, various studies have been carried out to understand the clustering characteristics of meteorological disasters such as torrential rains, droughts, and other extreme events (Liu et al., 2003; Wang et al., 2008; Sun et al., 2009; Yu et al., 2012; Wu et al., 2012; Liu et al., 2012; Huang et al., 2012). For example, Wu et al. (2012) diagnosed and analyzed the lasting drought and waterlogging processes in mid summer across the drainage areas of the Dongting and Boyang lakes of China, and found that the East Asian summer monsoon stayed in its strong phase when persistent drought events happened, accompanied with a weak tropical convergent system and a strong subtropical convergent system. Zhao et al. (2012) analyzed the clustering properties of droughts in Xinjiang Region and pointed out that the clustering droughts occur most frequently in May and June in Northwest Xinjiang. Wang et al. (2008) analyzed the Tibetan Plateau low vortices and found that the plateau low vortices demonstrate obvious intermittent clustering properties with an interannual variation. Sun et al. (2009) illustrated the relationship between the clustering tropical cyclone activities over Northwest Pacific and the intraseasonal oscillations of atmosphere in summer 1991, and indicated that favorable vertical shear conditions are satisfied for the development of tropical cyclones, leading to the clustering of tropical cyclones. Liu et al. (2003) found that the interdecadal change of clustering sandstorms in Beijing, Tianjin, and Hebei Province decreased and the frequency and influencing area of clustering sandstorms were the lowest in the 1990s.

In terms of spatial clustering, results from numerical experiments with the kth nearest-neighbour (k-NN) algorithm based on the point process theory in space indicate that the k-NN method is applicable to the study of clustering extreme climatic events (Yang et al., 2010a). The greatest advantage of the method is that single extreme climatic events can be interrelated and the clustering features can be described objectively and quantitatively. By using this method, the clustering extreme temperature and precipitation events in China are discussed and demonstrated (Yang et al., 2010a, b, 2012).

With the same tool, the current study aims to investigate and uncover the clustering features of severe drought events in China in the past 50 years, which have not been extensively documented previously. Meanwhile, the seasonal and decadal variations of the clustering extreme drought events in China in the 50-yr period will also be examined.

2. Data and establishment of drought index

To reduce the influence of uneven distribution of stations on the cluster mining results, the observation stations in West China (to the west of 95°E) are excluded. The present study focuses on the clustering features of extreme droughts occurring in areas of China where the East Asian monsoon dominates.

The Multi-Scale Standardized Precipitation Index (MSPI) is used to define extreme drought events in China during 1961–2010. MSPI is a meteorological drought index. It reflects overlapping multi-scale information of the regional climate system. This index was established based on daily precipitation data at 2415 base stations of China during 1981–2011, among which 2211 stations were chosen, with total no-observation days less than 300 days, and the absent record was replaced with the multi-year average at each station (Ren et al., 2005). Two intrinsic scales (mean and anomaly) of regional precipitation from the rainfall observation data are derived by using the Information Entropy Method. The MSPI grading standards for various degrees of droughts are set up based on the standard computational methods of Standardized Precipitation Index (SPI). The MSPI is then finally established as in Hou et al. (2013). A number of cases were tested and the index's ability to capture droughts and floods has been verified and affirmed (Hou et al., 2012). For instance, this index well described the processes of occurring, developing, maintaining, and decaying of the severe drought disaster along the mid-lower reaches of the Yangtze River in 2011. In addition, MSPI is capable to reveal and characterize droughts in various severity degrees. In a word, this index can be used for daily monitoring and detection of drought events (Hou et al., 2013).

On the basis of the MSPI indices at 1409 stations located east of 95°E in China during 1961–2010, the extreme drought events were identified according to the grading standards of the MSPI, and the features of clustering extreme drought events and their seasonal and decadal variations were examined in detail in this paper.

3. Clustering extraction methods

3.1 Algorithm of the k-NN distance cluster mining

The algorithm of the k-NN cluster mining is based on the concept of k-NN out of the spatial point process theory. It converts the two-dimensional (2-D) data that contain clustering points and scattering points in certain spatial extension into the one-dimensional (1-D) distribution function of mixed density, uses the expectation-maximization (EM) algorithm to decompose the mixed density, and then achieves the goal of identifying the clustering points (Pei et al., 2004, 2006, 2007). The W_k distribution of the two overlapped 2-D spatial point processes keeps to the following mixing distribution:

$$W_k \sim p g_{W_k}(k, \lambda_1) + (1-p) g_{W_k}(k, \lambda_2), \tag{1}$$

where k is the order of distance, p is the proportional coefficient, W_k is the k-NN distance of any point, and λ_1 and λ_2 are the distribution parameters of clustering areas and background areas, respectively. In Eq. (1), probability density function is given as:

$$g_{W_k}(k, \lambda) = \frac{\mathrm{e}^{-\lambda \pi x^2} 2(\lambda \pi)^k x^{2k-1}}{(k-1)!},$$

where λ_1 and λ_2 are calculated with the EM algorithm put forward by Byers and Raftery (1998).

The value of k and its influence on the method have been discussed in previous research, and it was found that k is a key parameter to estimate the clusters (Pei et al., 2004, 2006; Yang et al., 2009). A moderate value of k can reduce the error rate in the algorithm. Much research work has been done on the value settings for different datasets to extend its applicability and it is presented that the algorithm is applicable to the clustering weather and climate extreme events, especially the momentous extreme events (Yang et al., 2010a, b). Using the previous theoretic research results and taking those weather stations as random points in space, the frequency of extreme drought events every year can be converted into the number of occurrences, and the clusters of extreme drought events can be evaluated reasonably (Yang et al., 2012).

3.2 Decadal cluster index

Based on the above algorithm, the decadal cluster index (DCI) P_{DCI} is defined through mathematical operations. The definition of P_{DCI} standardizes the strong and weak clusters on different timescales and describes the decadal cluster events quantitatively. This index contributes to the analysis on the decadal spatial variation features of the clusters of extreme climatic events (Yang et al., 2012). The P_{DCI} is presented as follows:

$$P_{\mathrm{DCI}} = \frac{n_M/M}{n_L/L} \times \frac{n_M}{n_{\mathrm{sum}}/N}, \tag{2}$$

where L is the overall length of time series, n_L represents the frequency of the total clustering events during this period, M is the decadal length, n_M is the frequency in the M period, N is the total number of stations, n_{sum} is the total times of all stations around the country during this decade. According to the definition of Yang et al. (2012), a high value area with an accumulated probability above 85% is considered as the 1st-grade area, while above 70% is the 2nd-grade high value area. In the following discussion about interdecadal variation features of P_{DCI}, we are mainly concerned about the areas of the 1st- and 2nd-grade high-value clustering.

4. Annual and seasonal variation trend of the clustering extreme droughts

4.1 Annual variation trend

Figure 1a shows the interannual variation of clustering extreme drought events during 1961–2010. The dotted line represents the linear trend. It is demonstrated that the clustering feature experiences significant annual variability. The smallest number of stations experiencing extreme droughts is 163 in 1975, while in the high value year (1996), the number of stations reaches 664. This means that the clustering degree of severe droughts in the year with the biggest station number is about four times of that in the year

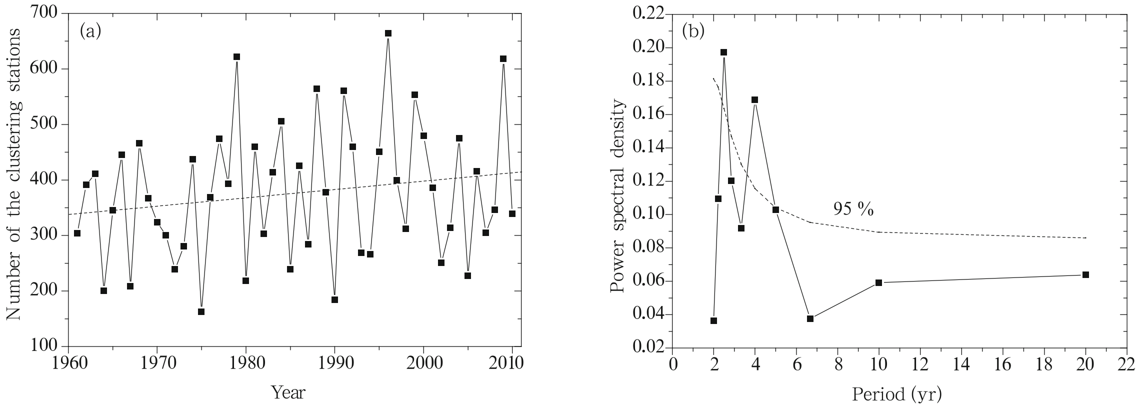

Fig. 1. Clustering characteristics of extreme drought events. (a) Annual variation trend of the number of clustering stations and (b) spectral analysis.

with the smallest station number. Then, an increasing trend is found for the clustering extreme drought events in the last 50 years (see also Ma and Fu, 2005; Ma and Ren, 2007). Besides, the severe droughts not only have a remarkable interannual variation but also keep decadal variation features during different periods. For example, during 1996–2008, clustering severe drought presents a clearly descending trend, but in 2009 it increases suddenly, getting to the 3rd peak value in the 50-yr period, only next to that in 1996 and 1979. The period analysis (Fig. 1b) shows a 2–5-yr cycle in the annual variation curve of the extreme drought clusters. The period is roughly the same as the period cycle of ENSO, which may illustrate a close impact of ENSO events on the droughts in China (Huang and Wu, 1989). It is noticed that the 2-yr cycle is the most outstanding, which is consistent with the result that drought events take place approximately every 2–3 years in most parts of China (Huang et al., 1998).

4.2 Seasonal variation trend

Drought events occur all year round in China, but with different characteristics in different seasons. The temporal trend of clustering extreme droughts in each season is given in Fig. 2. Figure 1a reveals that extreme droughts in the recent 50 years exhibit an increasing trend, which is mainly caused by the more frequent occurrence of severe droughts in the 1990s. However, if decomposed into the seasonal scale, the increasing trend of clustering droughts is noticed obviously only in autumn with a trend growth rate of 2.54 yr^{-1} passing the significance test. On the contrary, the clustering droughts present a slight decreasing trend with different levels in the other three seasons. The downward trends in spring and winter are slightly weak with the decreasing rates being less than 1.0 yr^{-1}, while the decreasing trend in summer is a little strong, passing the significance test. In addition, comparing the intensities in each season finds that the strongest clustering droughts among the four seasons occur respectively in 1963 (spring), 2001 (summer), 1979 (autumn), and 1988 (winter), followed by the second strongest clustering droughts respectively in 1999 (spring), 1965 (summer), 1991 (autumn), and 1974 (winter). It can be seen that the strongest clustering droughts occur in different years but they never happen in the same season, suggesting that seasonal difference in extreme clustering droughts exist commonly over China. Furthermore, it is demonstrated that the seasonal difference of the droughts is more distinct after 2001. During spring and summer, the frequency values of clustering droughts fluctuate within a small range around low values, but with an obvious 2-yr oscillation in summer. They present a descending trend in autumn but a clear up-going trend in winter with the number of the clustering stations growing from 100 to more than 400 within 10 yr. The spectral analysis reveals clear seasonal differences as well. There is a 5-yr outstanding cycle in spring, which is

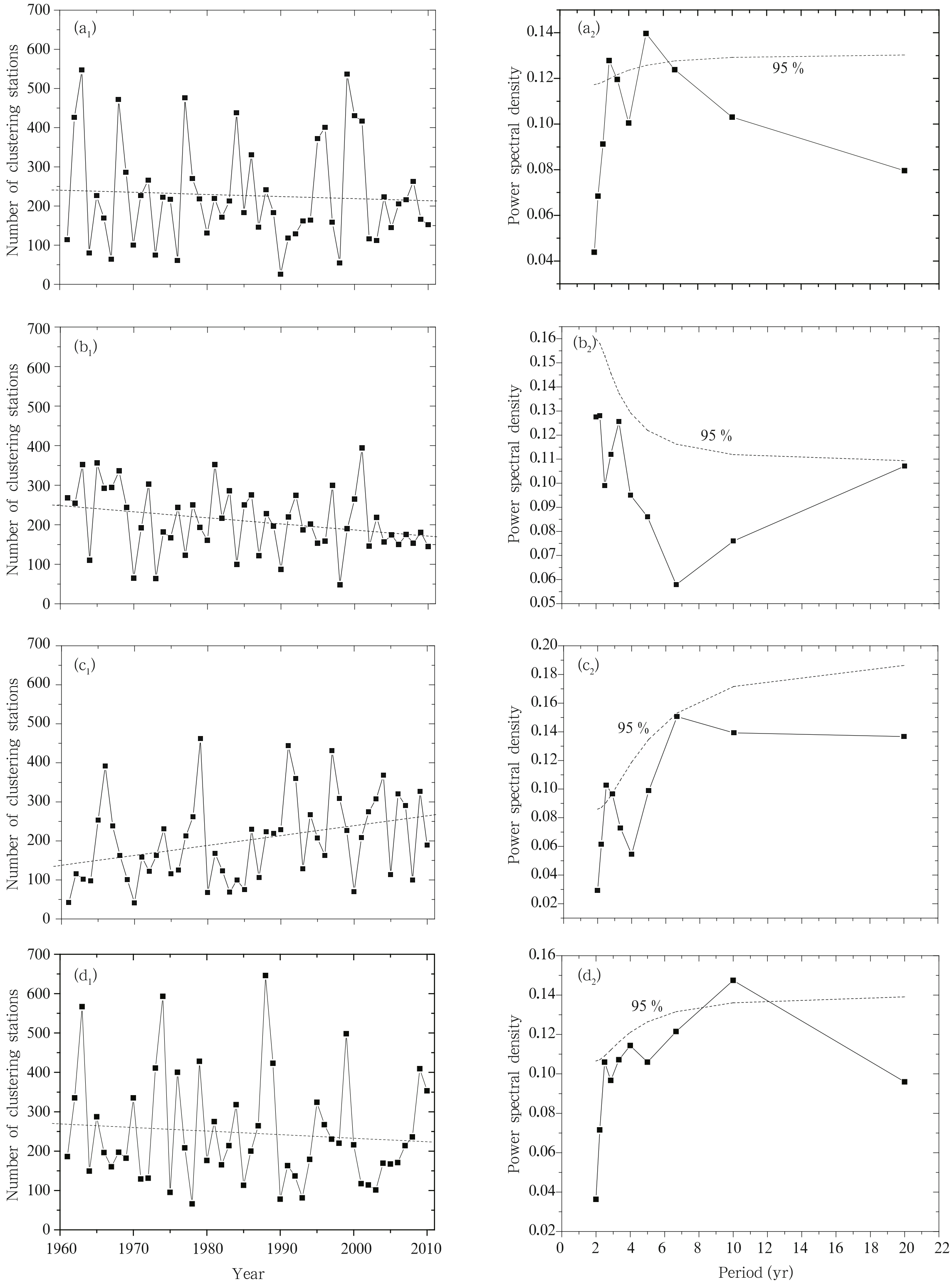

Fig. 2. Seasonal variation trends of the number of clustering stations of the extreme drought events and each corresponding spectral analysis. The left/right panels show the seasonal variation/spectral analysis in (a_1, a_2) spring, (b_1, b_2) summer, (c_1, c_2) autumn, and (d_1, d_2) winter, respectively.

consistent with the conclusion of Yao et al. (2007) who reported a cycle of 5–8 yr in spring droughts. There is an obvious 3-yr cycle in autumn droughts but no clear cycles for summer droughts. The interdecadal cycle of the 10-yr period is clearly noticed in winter droughts, which has passed the periodicity testing.

5. Decadal variation features of the spatial distribution of extreme droughts

5.1 Clustering characteristics of severe droughts

The spatial distribution of P_{DCI} of severe droughts deduced by Eq. (2) over China is given in Fig. 3. It can be seen that North China, Yellow and Huaihe River basins, Sichuan Province, etc., are the most vulnerable areas to be attacked by clustering extreme droughts. Zhang and Chen (1991) revealed that the arid trend in North China is similar to that in the Saharan areas in North Africa, suggesting that the interdecadal variation of the drought events in North China is not an isolated phenomenon but related to global climate change. This may be caused by the significant increase of SST in the central and eastern equatorial Pacific during the mid 1960s and from the 1980s to early 1990s (Huang et al., 1999). Yan and Yang (2000) also pointed out that the decrease of drizzles in northern China is one of the facts that reflect the aridity trend of the atmospheric environment.

Figure 4 displays spatial variations of P_{DCI} of extreme droughts in China in the past 50 years. It is noticed that the location and scope of the high P_{DCI} values are obviously different in different decades. High values of P_{DCI} appear scattered and cover two separate regions, i.e., northwestern Northeast China and the mid-lower reaches of the Yangtze River, with the total high value area being the smallest in the 1960s. Scattered high values of P_{DCI} are also found in the 1980s and 2000s, but their total area seems larger than that in the 1960s. Specifically, in the 1980s, the high-value clustering zone shifts southwestward, appearing mainly over Southwest China, South China, and western South China, with a little over the eastern part of the Yellow and Huaihe River reaches; while during the 2000s, the clustering zones mainly distribute in western North China, southeastern Northeast China, Southwest China, and South China. In contrast, highly concentrated high values of clustering droughts occur in the 1970s and 1990s. In the 1970s, obvious clustering droughts occur mainly in the Jianghuai area and the mid-lower reaches of the Yangtze River. In the 1990s, the clustering droughts cover the largest total area, compared to situations in other decadal periods, and they occur mainly in the region between the Yellow River and Yangtze River, and extend southwest to Sichuan Province.

The area coverage and concentration degree of clustering extreme droughts seem to demonstrate a 20-yr variation period. The clustering droughts in the 1960s, 1980s, and 2000s are scattered while those in the 1970s and 1990s are more centralized. Meanwhile, the area of clustering droughts exhibits an increasing trend in general. For example, the clustering extreme droughts in North China show a continuous growing trend after the 1970s and reach the maximum coverage by the 1990s. Furthermore, it is revealed that the position of major clustering extreme droughts shows an oscillation between north and south of China, with

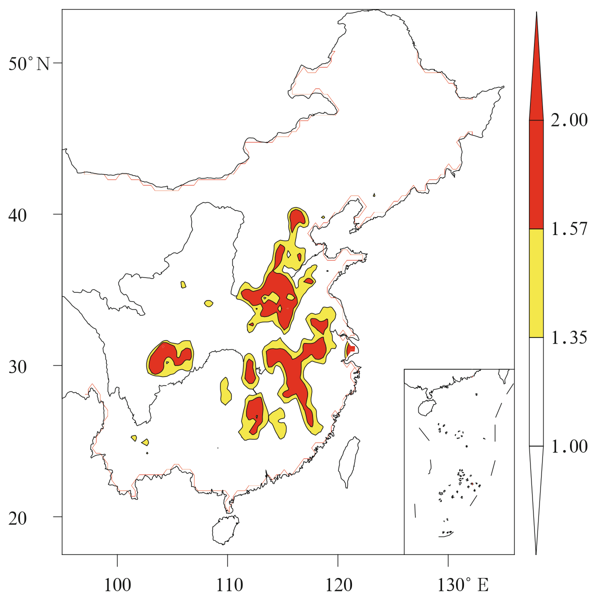

Fig. 3. Distribution of the extreme drought clusters with high values of decadal cluster index (P_{DCI}) in China during 1961–2010.

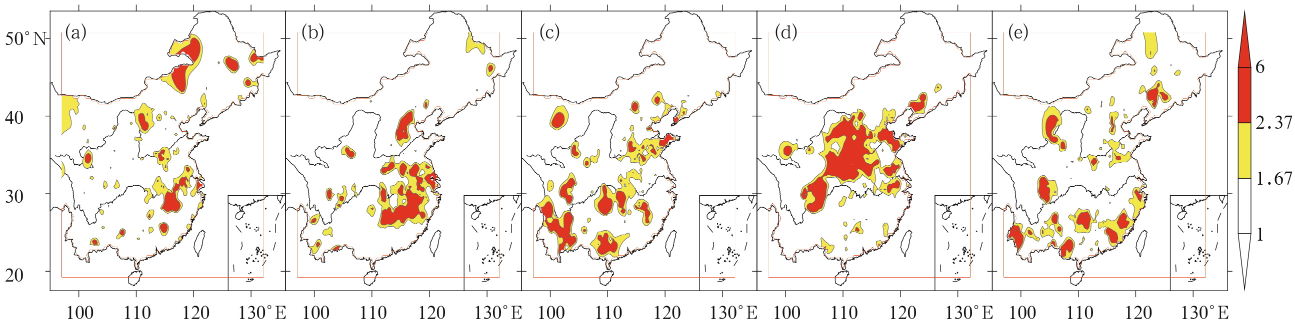

Fig. 4. Spatial distributions of cluster indices of extreme droughts in different decades. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, and (e) 2001–2010.

a quasi-20-yr period. The clustering extreme droughts appear in the north in the 1960s, gradually migrate southward to the mid-lower reaches of the Yangtze River in the 1970s, and then step south further into most parts of South China in the 1980s. However, in the 1990s, the centers of clustering extreme droughts return to North China and the Yellow and Huaihe River reaches, and in the 2000s, the main coverage goes back to South China again.

Ma and Shao (2006) reported that Northeast and North China experienced high frequency of severe droughts during the 1980s and 1990s, with the most severe droughts occurring frequently in northern China during 1991–2000. It is revealed in Fig. 4 by either the concentration degree of clustering or the intensity of clusters that 1990s is the most remarkable 10-yr period that witnessed the most severe clustering of extreme droughts in the last 50 years over North China. Combined with previous results (Lu, 2002; Ma et al., 2005; Ma and Ren, 2007), it is deduced that clustering character is an important feature of the drought events in North China.

Comparatively, the clustering of droughts is weak in Northeast China. Comparing the distribution patterns between the extreme drought clusters and extreme precipitation clusters, Yang et al. (2012) found a good out-of-phase correlation between the two types of clustering events, namely, large-scale severe precipitation episodes occur where there is no extreme drought. The weak clustering of droughts in Northeast China is probably because both the extreme dry and rainy events show increasing tendencies in Northeast China (Ma et al., 2003), which have suppressed the clustering feature in this region, reflecting the interaction and restriction between different severe weather events.

Further analysis exhibits that intensities of clustering extreme events show some opposite patterns in North and South China in different decades, following the regularity of "strong in south and weak in north" or "strong in north and weak in south". This is similar to the reversed distribution features of droughts and floods in South China and North China (Yan et al., 2004).

5.2 Variation features of the clustered extreme droughts in different seasons

Droughts take place all through the year in China (Wang et al., 2005). To analyze the interdecadal variation features of the clustering drought events in different seasons, Figs. 5a–5d respectively show spatial distributions of $P_{\rm DCI}$ of extreme droughts in spring, summer, autumn, and winter in different decades in the last 50 years. Significant seasonal differences can be seen from these figures.

In spring (Fig. 5a), the clustering extreme droughts present two distinct high-value zones, separately located in the south and north in the 1960s. The south zone stays over Southwest China while the north zone lies in Northeast China. During the 1970s, the two high-value zones move southward and eastward, respectively, i.e., the northeast high-value zone moves to North China while the southwest one to South China. During the 1980s, the high-value zones

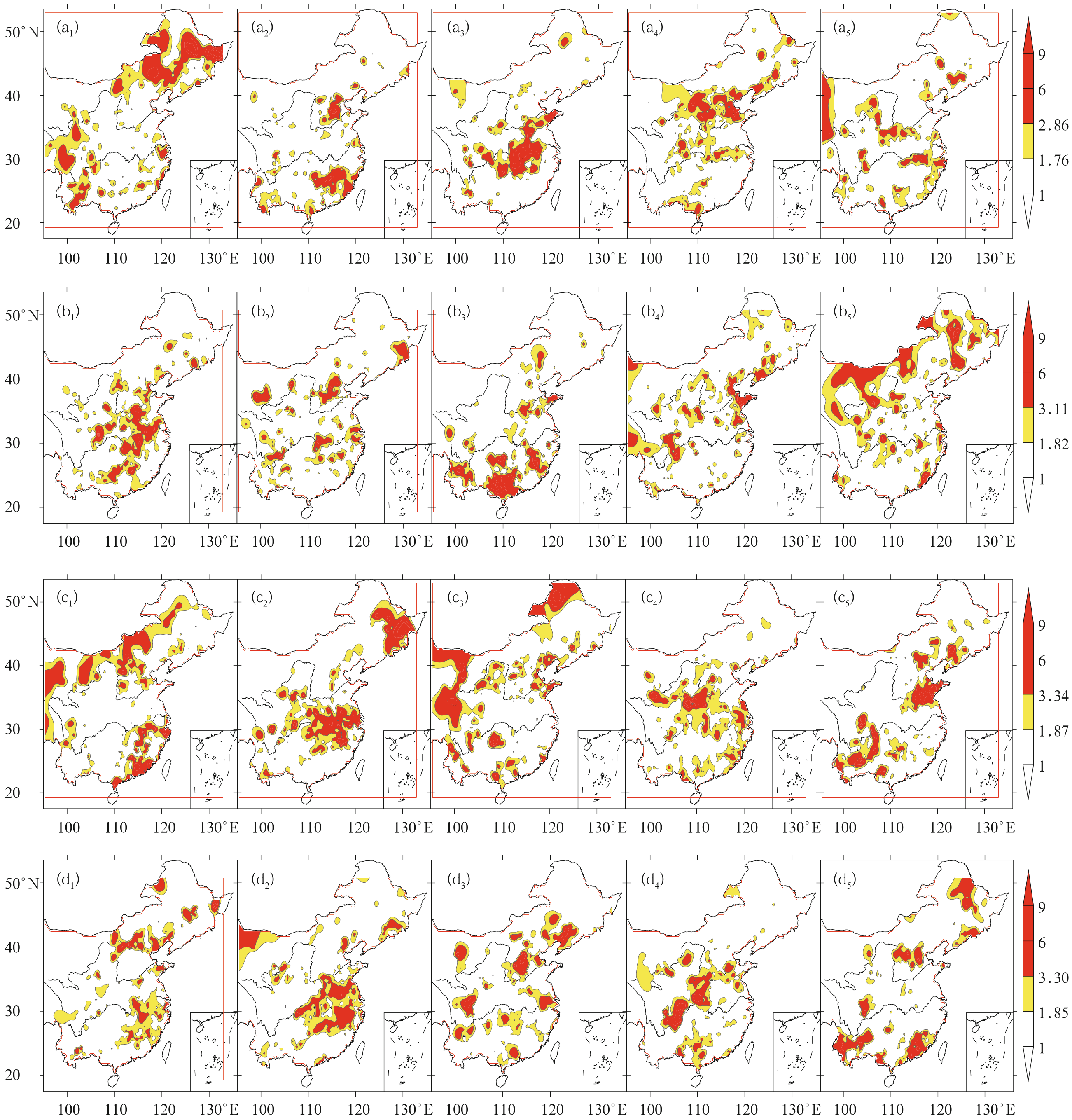

Fig. 5. Spatial distributions of cluster indices of extreme droughts in different decades in spring (a_1–a_5), summer (b_1–b_5), autumn (c_1–c_5), and winter (d_1–d_5) during 1961–1970 (a_1–d_1), 1971–1980 (a_2–d_2), 1981–1990 (a_3–d_3), 1991–2000 (a_4–d_4), and 2001–2010 (a_5–d_5).

are in the mid-lower reaches of the Yangtze and Yellow River, especially concentrated over central China. In the 1990s, large areas of clustering droughts move northward to North China and southern Northeast China. But in the 2000s, the drought situation in the north relieves a little and the high-value zones of clustering droughts become scattered and more southward, primarily staying over the reaches of the Yellow and Huaihe River, south of the Huaihe River, and Northwest China. Moreover, it is found that the highly clustering droughts in the north move gradually southward and eastward from the 1960s to 1980s, but again to the north after the 1990s; while the highly clustering droughts in the south keep a trend of moving eastward and northward. Guo and Zhi (2009) pointed out that central China and southeast coastal areas of China are the areas where spring drought is more likely to occur. Ma et al. (2003) indicated that moist springs over North China mainly appeared in the 1960s and 1980s. The consensus between their study and the present study is that there is essentially no clustering extreme drought over North China during these two periods, as shown in Fig. 5a.

By contrast, the spatial distribution of $P_{\rm DCI}$ of extreme droughts in summer (Fig. 5b) is greatly different from that in spring. During the 1960s, the high-value regions mainly cover the mid reaches of the Yellow River and most parts of the mid-lower reaches of the Yangtze River. In the 1970s, however, the clustering drought coverage turns more scattered and obviously smaller and the whole clustering drought zone becomes weakened, distributed over the south to the Yangtze River and the northern part of North China. In the 1980s, the droughts are more concentrated again but located southward, spreading over South and Southwest China as well as the narrow part of the lower reaches of the Yellow River. During the 1990s, the drought zones turn scattered once again and the main distribution moves northward to North China and the southwestern part of Northeast China. At the beginning of the 2000s, the clustering of droughts enlarges again and continuously moves northward, covering most parts of northern China. Analysis of the interdecadal variation features of clustering droughts in summer reveals that the major cluster zones of the extreme drought events occur in the 1960s, 1980s, and 2000s, with concentrated distributions, but with more scattered coverage in the 1970s and 1990s. This presents a consistent feature reverse to the distribution of rainy bands documented by Wang et al. (2005). Li et al. (2003) suggested that summer precipitation pattern over China is with a characteristic of "less in the north and more in the south" after the 1970s. This is somewhat opposite to the clustering features of the summer extreme droughts found in this study.

The spatial distribution of $P_{\rm DCI}$ of extreme droughts in autumn exhibits an obvious interdecadal variation. The high-value zones of $P_{\rm DCI}$ are divided into two areas in the 1960s, separately located in the southeast coastal region and the region from North China to Inner Mongolia. But in the 1970s, clustering droughts stay in the mid-lower reaches of the Yangtze River and eastern Northeast China. In the 1980s, the high-value zones become separated again primarily over North China, Northwest China, northern Northeast China, and Southwest China. Then, in the 1990s, the high-value zones link together over the areas between the Yangtze and Yellow Rivers. During the 2000s, the high-value zones of $P_{\rm DCI}$ show a distribution with isolated south and north parts, appearing in eastern North, southern Northeast, and Southwest China. Based on the above analysis, the high-value zones of $P_{\rm DCI}$ in autumn are featured with an alternating pattern of "separated south and north" and "joined middle", which shows up in turn in different decadal periods. Yan et al. (2004) stated that autumn is one of the most serious drought seasons in North China. It can be seen in Fig. 5c that the area of the clustering extreme droughts in North China increases while the clustering droughts become more intensified after the 1980s. During the 1990s, highly clustering droughts appear over the Huaihe River, which is possibly caused by the control of the northwesterly airflows (Wang et al., 2002). For Southwest China, many areas such as Sichuan and Chongqing are vulnerable to abnormal less rainfall, which easily leads to the occurrence of droughts (Guo and Zhi, 2009). In addition, it is also found that clustering extreme droughts occur in almost every decade over Southwest China except the 1970s.

The decadal variation of clustering extreme droughts in winter has some similarities to that in autumn. In the 1960s, the high-value zones of $P_{\rm DCI}$ are located in the mid-lower reaches of the Yangtze River and the areas to its south, with weak clustering strength. In addition, some strong clustering of droughts occurs over the northern part of North China and Northeast China. During the 1970s, clustering droughts concentrate over the Jianghuai area, the mid-lower reaches of the Yangtze River, and South China, with high intensity and large coverage. In the 1980s, the highly clustering droughts distribute scattered with high clustering values found in the north, especially in North and Northeast China. The high-value zones of P_{DCI} become concentrated again in the 1990s, staying in western central China and eastern Southwest China. But in the 2000s, the high-value zones return to the scattered state, dispersed over Southwest and South China, northern North China, and eastern Northeast China. The aridity in North China is always a focused topic in meteorological research. Ma and Fu (2001) revealed that winter precipitation in North China presents interdecadal variation features with alternation of less and more in different decades within the period 1961–2000. In the 1980s and 1990s, precipitation decreases significantly over northeastern Northeast China and the middle reaches of the Yellow River (Ma et al., 2005). The highly clustering droughts over North China are coincident well with the above-mentioned facts in Fig. 5d. The distinct more and less decadal alternation characteristic for the drought events over North China can also be noticed in Fig. 5d. Furthermore, the drought cluster in North China appears stronger in the 1960s, 1980s, and 2000s, but weaker in the 1970s and 1990s, so the variation of spatial distribution has a 20-yr period in North China. In contrast, the above decadal variation is not so visible in the areas south of the Yangtze River. Considering the 10-yr periodic characteristic of droughts in winter from Fig. 2d, it is deduced that in general, the decadal characteristics in North China have played a dominant role in the interdecadal variation of severe droughts in China in winter.

Comparing the spatial variation features of the clustering severe droughts among the four seasons, an interesting phenomenon is noticed: in the last 50 years, the summer droughts have a south-north oscillation, while the spring, autumn, and winter droughts all share the characteristics of alternating appearance of a scattered distribution in North and South China but a concentrated distribution in central China. This is possibly because summer precipitation is related to the progress of the East Asian monsoon while most of the spring, autumn, and winter precipitation is respectively brought about by low-latitude systems and mid–high-latitude systems. Hence, in some years, the effects of the south and the north systems are independent in comparison, while in some other years the interaction of the two systems is more notable. It is interesting that the clustering extreme droughts present the variations of scattered and concentrated patterns in spring, autumn, and winter with a quasi-20-yr period, but their phases are not consistent, of which the phase evolution of autumn and winter droughts is more alike. Therefore, it is inferred that continuous droughts spanning across autumn to winter is an important characteristic during the last 50 years. For example, consecutive extreme droughts across autumn and winter occur over South China, the mid-lower reaches of the Yangtze River, eastern Northwest and Central China, and Southwest China in the 1960s, 1970s, 1990s, and after the 2000s, respectively.

6. Conclusions

Clustering is a new characteristic of extreme climate events noticed in recent years and becomes a hot topic in the latest investigations of extreme climate events. Based on the theory of spatial point process and its initial applications in temperature and precipitation events, this paper analyzed and revealed the variation trends, seasonal differences, and interdecadal spatial variation features of the clustering extreme droughts over China. The detailed results are as follows.

(1) Extreme drought clusters in the last 50 years exhibit a tendency of gradual increase, and obvious aridity in North China may be a great contributor for such a trend. Analysis of seasonal variations of clustering extreme droughts indicates that the increasing of such events for the whole year may result mainly from the significant increase of clustering droughts in autumn.

(2) The interannual variation of clustering extreme droughts has a notable period of 2–5 yr. By the power spectrum analysis, it is found that the

periodicities of the severe drought clusters in different seasons have obvious discrepancies. More specifically, the periodicity in summer is not so outstanding, but a remarkable 5-yr period can be found in spring and a 3-yr period in autumn. Comparatively, winter is associated with a significant 10-yr period.

(3) The spatial distribution of decadal variation of the extreme drought events has notable interdecadal differences. The highly clustering droughts follow a decadal variation regulation with scattering and concentrating patterns taking place by turn during the last 50 years. In addition, the 1990s witnessed the most serious clustering extreme droughts. Comparatively, the clustering feature in Northeast China is weaker all the time. This is probably because the combined occurrences of dry and wet events make the highly clustering droughts in this region not so distinguishable in Northeast China.

(4) The interdecadal variation patterns of extreme droughts exhibit significant seasonal differences. In spring, there are almost no highly clustering extreme droughts in North China during the 1960s and 1980s. In summer, the spatial patterns of highly clustering droughts have a strong reverse relationship with the distribution of rainfall band during the last 50 years in China. In autumn, the most remarkable drought trends are found in North China and secondly in Southwest China. The interdecadal variation of extreme droughts in winter is similar to that in autumn. It is deduced that the continuous droughts across autumn and winter is an important characteristic of droughts over China during the past 50 years. In addition, the highly clustering zones of winter severe droughts demonstrate a strong and a weak alternating occurrence on the decadal timescale, especially over the northern part of China.

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