

Spatio-temporal variations in extreme drought in China during 1961–2015

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Abstract: Understanding the past variations in extreme drought is especially beneficial to the improvement of drought resistance planning and drought risk management in China. Based on the monitoring data of meteorological stations from 1961 to 2015 and a meteorological drought index, the Standardized Precipitation Evapotranspiration Index (SPEI), the spatio-temporal variations in extreme drought at inter-decadal, inter-annual and seasonal scales in China were analyzed. The results revealed that 12 months cumulative precipitation with 1/2 to 5/8 of average annual precipitation will trigger extreme drought. From the period 1961–1987 to the period 1988–2015, the mean annual frequency of extreme drought (FED) increased along a strip extending from southwest China (SWC) to the western part of north-east China (NEC). The increased FED showed the highest value in spring, followed by winter, autumn and summer. There was a continuous increase in the decadal-FED from the 1990s to the 2010s on the Tibetan Plateau (TP), the southeast China (SEC) and the SW. During the period 1961–2015, the number of continuous drought stations was almost the same among 4 to 6 months and among 10 to 12 months of continuous drought, respectively. It can be inferred that drought lasting 6 or 12 months may lead to more severe drought disasters due to longer duration. The range of the longest continuous drought occurred in the 21st century had widely increased compared with that in the 1980s and the 1990s. Our findings may be helpful for water resources management and reducing the risk of drought disasters in China.

Keywords: extreme drought; China; standardized precipitation evapotranspiration index; climate change

1 Introduction

Extreme weather and climate events are one of the most significant and increasingly attractive topics under the global climate warming background over the past few years (Easterling

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et al., 2000; Cook *et al.*, 2014). Drought, especially extreme drought, can cause considerable damage to crop yield, human economies, people's livelihood and property, and even influence the social stability of nations (Cook *et al.*, 2014; Kelley *et al.*, 2015; Lesk *et al.*, 2016). According to the hydro-meteorological disaster reports, the global drought-induced grain output dropped by an average of 10.1% from 1964 to 2007 (Lesk *et al.*, 2016). A significant change in extreme droughts in the second half of the 20th century had affected many parts of the world (Frich *et al.*, 2002). The southern U.S., northern Mexico and the Central Great Plains experienced extreme drought in the summers of 2011 and 2012 (Wang *et al.*, 2014a). The crop yield of the U.S. in 2012 fell 26% below the expected yield, which was the largest crop failure since 1866 (Hoerling *et al.*, 2014). The drought in Syria between 2007 and 2010 was the most serious drought in history, resulting in a large crop failure and a large-scale migration of farmers into urban centers (Kelley *et al.*, 2015). Moreover, previous studies predicted the risk of drought could increase in the 21st century by using climate model simulations on soil moisture (Sheffield, 2008) and drought indices (Dai, 2013).

China is one of the countries that experience the most frequent and serious drought in the world. Extreme drought often causes serious natural disasters, imposing a great threat on agricultural production and people's livelihood in China (Li *et al.*, 2012). Drought caused direct economic losses accounting for 21.2% of the total losses caused by all types of weather and climate disasters, which is only second to floods losses (Qin, 2015). About 17% of the grain total output (70–80 billion kg) was lost caused by drought per year on average in China (Liu *et al.*, 2013a). During 1991 to 2009, the frequency of drought was about 79.21% recorded by national wheat meteorological stations of China, which was higher than other nine types of agro-meteorological disasters (Zhang *et al.*, 2014). The winter drought in 2008–2009 led to a loss of nearly 16 billion Chinese yuan in northeast China and more than 10 million people faced water shortages (Wang *et al.*, 2011). In recent decades, drought has also occurred in southern China, especially in southwest China (Qiu, 2010; Xu *et al.*, 2015). Extreme drought is getting more and more attention given that the pressures on resources, environment and ecology increase along with the global climate change and the rapid economic development of China. Moreover, the inter-decadal variations in the frequency of extreme drought (FED) events are more uneven than that of moderate drought events in China (Li *et al.*, 2012). However, few studies have focused on quantifying and explicitly analyzing the spatio-temporal variations and trends of extreme drought, which are prerequisites for drought risk management and China's planning of drought disaster resistance. Extreme drought is a small probability event that occurs when water deficit is severe. Compared to all levels of droughts, extreme drought often suffers severe drought disasters. Moreover, all levels of droughts do not necessarily result in disasters, which affect the accuracy of drought assessment. Therefore, analysis of the variations in extreme droughts can improve understanding of major drought events and drought management.

Various drought indices have been developed for drought monitoring and drought assessment. However, there is as yet no unique and universally accepted droughts indicator that we can identify its impacts on different systems, such as agriculture, water resources and ecosystems (Heim, 2002). Some studies compared the differences between the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI), which are commonly used for analyzing the spatio-temporal patterns and variations in meteorological droughts (Jain *et al.*, 2014; Ren *et al.*, 2014). To some extent, the SPI is better and more

sensitive than the PDSI in reflecting meteorological droughts, soil moisture variations and extreme droughts events (Keyantash and Dracup, 2002; Lloyd-Hughes and Saunders, 2002). The Standardized Precipitation Evapotranspiration Index (SPEI), which is based on precipitation and evaporation demand, combines the multi-scalar characteristic and simple calculation of the SPI with the sensitivity of the PDSI to temperature changes (Vicente-Serrano *et al.*, 2010; Yu *et al.*, 2014). Moreover, the SPEI is more sensitive to potential evapotranspiration (PET), especially in arid regions (Cook, 2014). Based on the hypothesis of log-logistic distribution of samples, Wang and Chen (2014) confirmed the reliability of the SPEI with Thornthwaite equation (Thornthwaite, 1948) in most of China, except in western and boreal China of less than 3-month time scale in winter. Moreover, by comparing the distribution of the SPEI with the Historical Dataset in China (MICMB, 1981) in typical years, the SPEI can accurately describes the geographic center, extent and intensity of several major drought events in China (Wang and Chen, 2014). As the Thornthwaite potential evapotranspiration method is mainly applicable to wetland limitations, Zhao *et al.* (2015) used the calculation of evaporation from the Penman-Monteith equation proposed by the Food and Agriculture Organization (FAO) (Allen *et al.*, 1998) to assess the applicability of SPEI in China. The modified method was also presented in the modified SPEI proposed by Beguería *et al.* (2014). The SPEI based on Penman-Monteith equation applied to national drought assessment performed well at both yearly and monthly time scales, making up the shortcomings in the applicability of the original SPEI in winter at a short time scale level in arid region (Liu and Jiang, 2015; Zhao *et al.*, 2015). In addition to reflecting the meteorological droughts, the SPEI is also a reasonable index for assessing droughts conditions in agriculture, water resources and vegetation etc. (Potop *et al.*, 2012; Stagge *et al.*, 2015).

Numerous studies have pointed out changes in the frequency and intensity of extreme climate events, but most of these studies have been focused on extreme precipitation or temperature. Variations in extreme drought in China have received less attention, and most studies on extreme drought have concentrated on the regional analysis (Lu *et al.*, 1962; Yang *et al.*, 2013; Zhang *et al.*, 2015). From the autumn of 2009 to the spring of 2010, extreme drought was encountered in southwest China due to abnormally low precipitation and high temperature anomalies (Lu *et al.*, 1962). The inter-annual and inter-decadal trend of extreme drought events had gradually decreased from 1960–2013 in the Huaihe River Basin (Zhang *et al.*, 2015). Yang (2013) detected that the extreme severe drought events had a tendency of gradual increase in China, mainly due to the obvious aridity in northern China in the second half of the 20th century. Since almost all severe drought disasters are associated with long-term continuous or extreme drought, the evolutionary process of extreme drought in space and time is an important aspect in the field of drought research. With global warming, increased attention to the hydrological cycle raises the question as to whether extreme drought is truly increasing in China and how extreme drought has changed in different regions.

In this study, we analyzed the spatio-temporal patterns and variations in extreme drought at inter-decadal, inter-annual and seasonal scales in China by using the monitoring data of meteorological stations from the period of 1961–2015 with the SPEI based on Penman–Monteith equation. The objectives of the study are: 1) to understand the spatial distribution of critical annual precipitation when extreme drought happened as well as the spatial differences of average annual and seasonal variations in the FED between the period of

1988–2015 and 1961–1987; 2) to exhibit temporal variations in the inter-decadal and inter-annual changes in the FED for different subareas during 1961–2015; 3) to explore the annual changes in the number of meteorological stations under different duration of extreme drought from 2 to 12 months respectively, and the decade of each station when the longest extreme drought duration occurred during 1961–2015. The conclusions of the study will help to further understand the evolution of extreme drought in China. It can also provide scientific basis for the research of extreme drought mechanism and the risk management of extreme climate events.

2 Data and methods

2.1 Study areas and data sources

Due to the impact of the East Asian monsoon climate and vast territory with complicated terrain, the climate in China varies from region to region significantly. Therefore, it is relatively difficult to estimate the characteristics of climatic hazards for such a wide territory as a whole unit. In this study, considering the climate division and administrative zones, the Chinese mainland was partitioned to six subareas (Figure 1): northeast China (NEC), northwest China (NWC), northern China (NC), southeast China (SEC), southwest China (SWC) and the Tibetan Plateau (the TP). We first divided China into the NWC, the TP and eastern monsoon region according to the 400 mm contour line of mean annual precipitation which is an important climate demarcation line between semi-arid and semi-humid areas. The boundary of the Tibetan Plateau was adopted from the scope in Zhang *et al.* (2002). The other four eastern monsoon regions were divided in terms of the Qinling Mountains–Huaihe River line and administrative boundaries.

This study used the quality-proven data on daily sunshine hours, temperature (maximum and minimum temperature), wind speed, relative humidity from 824 meteorological stations, and monthly precipitation data from 756 meteorological stations from the National Meteorological Information Center of the China Meteorological Administration (CMA) (<http://cdc.nmic.cn/home.do>) over China during 1961–2015. Many meteorological stations in China have observational records going back to the early 1950s. However, most data from the 1950s contains large amounts of gaps due to instrument malfunctions. Considering the length, quality, continuity, homogeneity of the records and the applicability of the assumed distribution of the SPEI, 547 stations were chosen for further calculations, as shown in Figure 1. Missing data of the selected meteorological stations is inevitable for long-term monitoring. The missing data from several stations is replaced by the average of the same date or same month in other years without missing data. The fill charts were drawn with the method of kriging interpolation by using the software of ArcGIS10.

2.2 Calculation of Standardized Precipitation Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) based on the SPI (McKee *et al.*, 1993) is a standardized meteorological drought index to quantify the severity of droughts conditions with consideration of water balance and spatial comparison at different time scales (Vicente-Serrano *et al.*, 2010). The difference D_i between precipitation P_i and PET_i for the month i is calculated using:

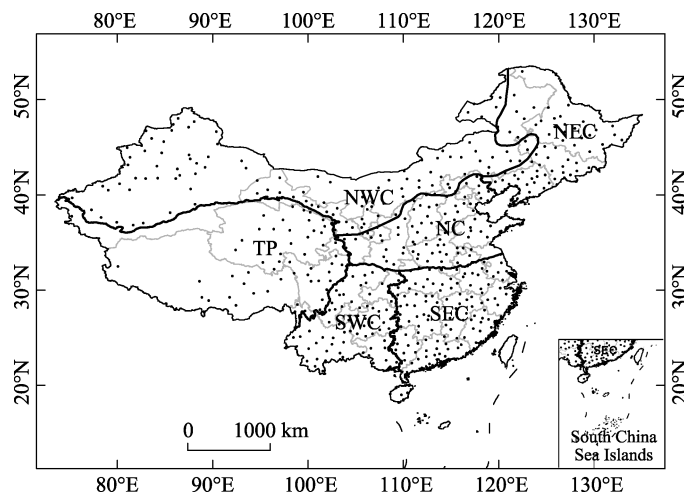


Figure 1 Locations of the 547 stations and different subareas in China: northeast China (NEC), northern China (NC), southeast China (SEC), southwest China (SWC), northwest China (NWC) and the Tibetan Plateau (the TP). The first four subareas are often regarded as the eastern monsoon regions of China.

$$D_i = P_i - PET_i \quad (1)$$

The calculated D_i is aggregated at different time scales. It is recommended to use a three-parameter log-logistic distribution for standardizing the accumulative series D_i to obtain the SPEI at a given time scale. It calculates drought indices by standardizing the series D_i at different time scales. The SPEI can characterize the degree of dryness/wetness deviation from normal conditions. To capture the spatio-temporal variations in drought more typically, we defined extreme drought as $SPEI \leq -2$ (Table 1) which is more closely related to drought disaster (Kelley *et al.*, 2015). Drought duration (in months) was defined as a continuous period that SPEI is less than -1.0 . By comparing the average annual SPEI and the areas of China's crops affected by drought disasters from 1961 to 2015, the correlation coefficient of the SPEI at the 6-month time scale was higher than at other time scales. So, we selected 6-month time scale in all parts of the study except the analysis of critical precipitation as annual precipitation with 12 months scales of SPEI.

Table 1 Dryness/wetness categories according to the SPEI and the corresponding cumulative probabilities relative to the reference period (McKee *et al.*, 1993; Zhao *et al.*, 2015)

Categories	SPEI classifications	Cumulative probability (%)
Extremely dry	≤ -2.0	2.28
Severely dry	-1.99 to -1.5	6.68
Moderately dry	-1.49 to -1.0	15.87
Near normal	-0.99 to 0.99	50.00
Moderately wet	1.0 to 1.49	84.13
Severely wet	1.5 to 1.99	93.32
Extremely wet	≥ 2.0	97.72

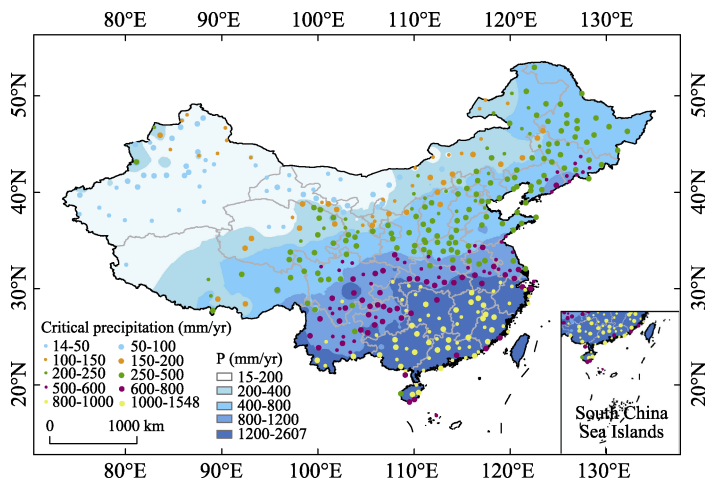
Not only PDSI with different parameters (e.g. the Thornthwaite and Penman-Monteith equations) leads to discrepant results in assessing droughts (Zhang *et al.*, 2016), the SPEI

also faces the similar outcomes. In this study, we used the SPEI index with PET recommended by FAO, which was considered to be better monitored for the observed variations in soil moisture and stream flow in China than the SPEI based on Thornthwaite equation (Chen and Sun, 2015; Thornthwaite, 1948; Zhao *et al.*, 2015). Considering the capability of the selected distribution over China (Wang and Chen, 2014; Zhao *et al.*, 2015), the log-logistic distribution was tested by Kolmogorov-Smirnov test, and all the data of D series passed the significance level test of 0.05. The reference period was the whole analysis period (1961–2015). The specific program on the website (<http://digital.csic.es/handle/10261/10002>) was used in this study. The critical precipitation of each station is the maximum 12 months cumulative precipitation when extreme drought (the $\text{SPEI} \leq -2$) occurs at time scales of 12 months during 1961–2015. The frequency of extreme drought (FED) in this study is defined as the ratio of the number of extreme drought months with $\text{SPEI} \leq -2$ to the total number of samples.

3 Results

3.1 Spatial patterns of critical precipitation

We first analyzed the spatial distribution of critical annual precipitation when extreme drought happened at 12-month time scale in the period 1961 to 2015 for 547 stations (Figure 2). It reflected the spatial differences of 12 months cumulative precipitation when extreme drought occurred under the background of local climate. The spatial distribution of critical annual precipitation presents an obvious zonal distribution. It is very similar to the spatial pattern of annual precipitation which is decreasing from southeast to northwest China. By comparing with average annual precipitation, extreme drought often happened when the cumulative precipitation was around half of local mean annual precipitation in the areas where the mean annual precipitation is less than 800 mm. The critical precipitation is 15 to 100 mm in northwest China where the average annual precipitation is less than 200 mm. Similarly, the critical precipitation is 100–200 mm and 200–500 mm respectively in the regions



where the mean annual precipitation is 200–400 mm and 400–800 mm. In areas with annual precipitation over 800 mm (the SWC and the SEC), the critical precipitation is above half (around 5/8) of the average annual precipitation due to the relatively high temperature. Zhang *et al.* (2010) discovered that decreased precipitation was the key factor in drought formation in eastern China. Our results further suggest that when water and heat are both considered, precipitation plays a major role in the occurrence of extreme drought over China. The spatial distribution of critical precipitation can be used as reference information for early warning and drought mitigation measures.

3.2 Spatial variations in the FED

3.2.1 Spatial variations in extreme drought frequency

To investigate the changes of extreme drought frequency in different areas during 1961 to 2015, the differences of extreme drought frequency between the two periods of 1988–2015 and 1961–1987 were shown in Figure 3. The time segmentation method referred to the idea of Zou *et al.* (2005), and there was a turning point in the FED around 1987 in China as shown in Figure 5g. The regions with the increased FED by more than 2.0% were mainly in the northwest of the NEC, the northern agriculture-pasture transitional zone, the western part of the NC, the SWC and the western SEC. Yan and Yang (2000) reasoned that the aridification in northern China may come down to a decrease in the frequency of drizzles during 1951–1997. Most of the western part of China (the TP and the western part of the NWC), the eastern NEC, the NC and the SEC experienced the decreased FED. The FED had decreased by 4.0% – 8.2% in the mid-western NWC, the northern TP and the eastern NC.

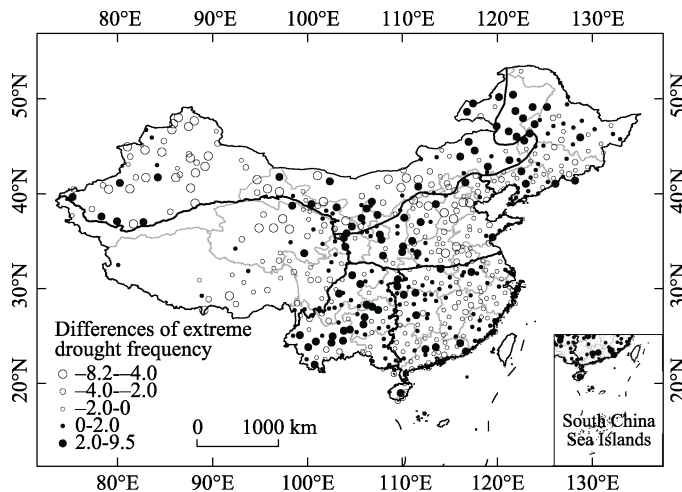


Figure 3 The differences in FED between two periods: 1988–2015 minus 1961–1987 (%)

The increased FED mainly occurred in a strip oriented from the SWC to the western NEC, whereas a large regional decrease in FED occurred in western China (most parts of the TP and the NWC) and eastern China (eastern part of the NEC, the NC and the SEC) from 1961 to 2015. This might be related to the changes in the sea surface temperature of the tropical Pacific and the tropical Indian Ocean, leading to frequent serious drought events in the central and southwest China (Zhai *et al.*, 2017). Zhang *et al.* (2015) also found that extreme drought events had gradually decreased in the Huaihe River Basin by using the Surface Hu-

mid Index. The increase in precipitation and relative humidity significantly reduced the FED in the North China Plain (the eastern NC) from 1962 to 2011 (Liu *et al.*, 2013b). In conclusion, areas with the increased FED were mainly concentrated in central China and the western part of northeast China. The extent of the decreased FED was larger than that of the increased FED.

3.2.2 Spatial variations in the seasonal FED

Figure 4 shows the average annual FED during 1961–2015 and the drought frequency variations in each station from 1961–1987 to 1988–2015 in four seasons. Generally, the FED occurred most frequently in spring. Nearly half of China suffered from spring droughts with an average annual FED of more than 2.5%. There are obvious differences in the spatial distribution of the FED between 1988–2015 and 1961–1987. Extreme drought frequency decreased by more than 6.0% in most parts of the NWC and the TP, the southeast part of the NEC and the SEC. Meanwhile, the FED increased by more than 2.0% mainly in the northern NEC, the central part of the NWC, the Huaihe River Basin (the southern NC and the northern SEC) and the southwestern and central parts of the SWC.

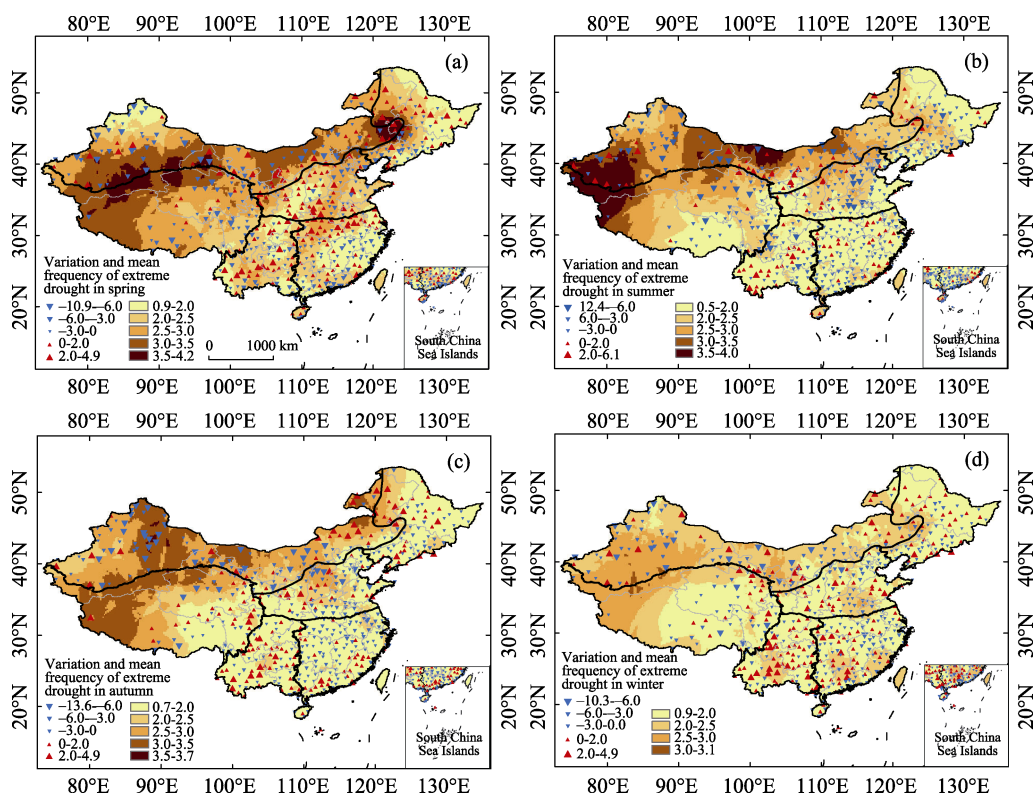


Figure 4 The average annual FED during 1961 to 2015 (shading) and the differences of extreme drought frequency between 1988–2015 and 1961–1987 (triangles) in spring (a), summer (b), autumn (c) and winter (d) (%)

The FED in summer was generally lower than that in spring. However, the scope and severity of extreme drought frequency showed little reduction in the western NWC and the TP. It may be due to the barrier effect of the Tibetan Plateau to the warm and humid air from the southeast monsoon and southwest monsoon, leading to little precipitation in the northwest of

China. Moreover, the high temperature of summer increased the evapotranspiration, which increased extreme drought frequency in NWC. The decreased FED appeared in most parts of China, especially in the TP, the western NWC and the eastern NC. The regions where the FED increased by more than 2.0% were mainly located in the middle of NWC and the southwestern SWC.

A gradually increased FED was presented obviously from southeast to northwest in both summer and autumn over China. Located in the mid-latitude and the east coast of Eurasia, the East Asian monsoon brings more precipitation to the eastern regions of China in summer and autumn. The regions of decreased frequency with more than 6.0% in autumn mainly occurred in the central-western NWC, the northern TP and most parts of eastern China for the period of 1988–2015 relative to 1961–1987. The intensity and extent of the extreme drought frequency had increased obviously in autumn, including the eastern NWC, the western NEC and NC, the eastern TP and the southwestern SWC.

The FED in winter was generally the lowest in most parts of China, within 2.5%, from 1961 to 2015. A significant reduction in evapotranspiration for the lowest temperature might be the major reason for the lower FED. The general decreased FED occurred in most parts of the NWC, the western TP and eastern China. The increased frequency mainly appeared in central China from the central NWC, the western NC, the SWC to the western SEC. Generally, the seasonal order of the increased FED from more to less was spring, winter, autumn and summer.

3.3 Temporal variations in the FED

3.3.1 Inter-annual variations in the FED

The average annual FED among different subareas presented commonality as well as differences from 1961 to 2015 in China (Figure 5). Most subareas and the whole of China experienced the lowest FED from the mid-1980s to the mid-1990s. Most of China had experienced a widespread extreme drought from the mid-1960s to the early 1970s. An increase in the FED occurred in the NWC, the TP, the NC, the SEC and the whole of China in the 1960s and the early 1970s. An obvious increase of the FED has occurred in the NWC, the NEC and the NC since the late 1990s and the SWC since the late 2010s. Although the highest FEDs appeared in the early 1960s in the SEC, the drought of a single year did not seem to have had serious impact. In contrast, the relatively high FED in the 1960s had a strong impact in the NC, where serious drought disasters were recorded in 1962, 1965, 1966 and 1968 in Haihe River Basin (HPFFR, 1985).

Although there has not been a substantial change in the FED in recent decades, most subareas of China experienced a decrease before around 1997. Then, a wide range of extreme drought occurred in most parts of China since the 21st century. Compared to 17 extreme drought events in China, it is consistent with the extreme drought frequency above 6% in the corresponding subareas (Ren *et al.*, 2015). The decrease and concentration of precipitation in recent years contributed to a significant increase in the incidence of extreme drought events (Li *et al.*, 2012).

3.3.2 Inter-decadal variations in frequency of extreme drought

The inter-decadal variations in severe drought disasters are closely related to the summer Asian

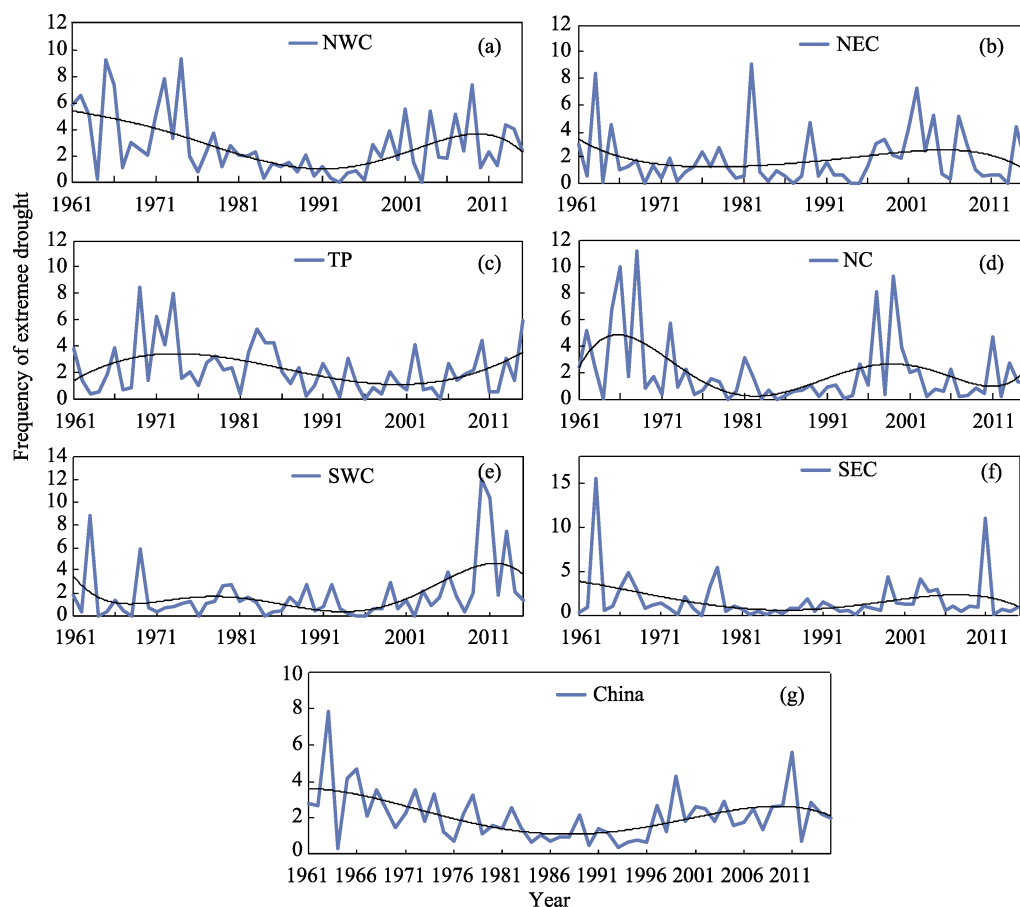


Figure 5 Time series of the average annual FED (broken lines) and 5-order polynomial fitting curves (curves) in different subareas (a–f) and China (g) during 1961–2015 (%)

Monsoon, which caused significant changes in summer precipitation patterns in both East and South Asia (Ding *et al.*, 2013). Table 2 illustrates that the highest FED for the NWC, the NC and the SEC are concentrated in the 1960s. This was probably due to the two weakened summer monsoon in the middle of 1960s and the late of 1970s (Huang *et al.*, 2004). There was a continuous increase in the decadal FED from the 1990s to 2015 in the TP, the SEC, the SWC and the whole of China. This might be related to the significant decrease of winter and spring snow over the TP since the late 1990s (Si and Ding, 2013), which led to the high summer precipitation region shifting northward from the Yangtze River Basin to the Huaihe River Basin. The maximum variations between the maximal and minimal FED is more than five times in the NC, SEC and SWC, where there is a risk of high droughts and floods. The increased frequency of droughts since 2000 affecting agricultural production and frequency of drought-related disasters have been increasing and have led to growing economic losses in China (Qin *et al.*, 2015).

3.4 Variations in drought duration

3.4.1 Variations in inter-annual scope of different drought duration

Different duration of continuous drought may result in different degrees of influence on

various departments and industries. The analysis of the characteristics of different continuous periods is beneficial for the research of the laws, causes and mechanisms of extreme drought. The temporal variations in the number of meteorological stations under different duration of continuous drought from 2 months to 12 months are shown in Figure 6. There was an obvious

Table 2 Inter-decadal FED in different subareas during 1961–2015 (The upward arrow indicates changes in frequency relative to the past decade.)

Regions	Frequency of extreme drought (%)					
	1960s	1970s	1980s	1990s	2000s	2010–2015
NEC	2.2	1.3	1.8	1.5	3.0↑	1.3
NWC	4.3	3.8	1.4	1.3	3.2↑	2.6
TP	2.4	3.4	2.5	1.3	1.9↑	2.7↑
NC	4.3	1.4	0.8	2.8	1.0	1.8↑
SEC	3.2	1.5	0.6	1.2	1.7↑	2.4↑
SWC	2.0	1.2	1.1	0.9	2.6↑	5.9↑
China	3.2	2.1	1.2	1.5	2.2↑	2.7↑

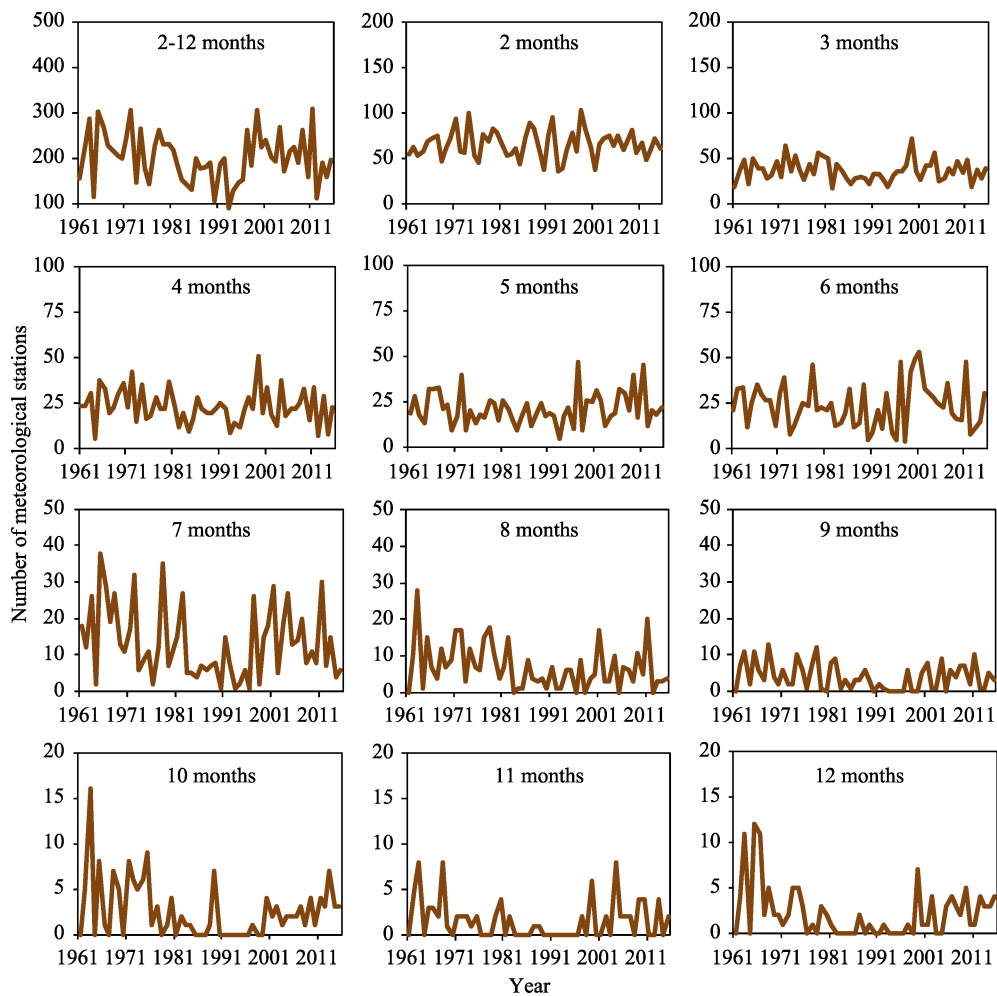


Figure 6 Time series of annual number of meteorological stations under the specific drought duration (consecutive months with $SPEI \leq -1.0$) in China during 1961–2015

decrease of meteorological stations from the early 1980s to the mid-1990s under the total cumulative continuous periods of 2 to 12 months. The similar characteristics of continuous drought also appeared in 3 and 7 to 12 months, respectively. There were 50 to 100 stations for 2 months of continuous drought and 25 to 50 stations for 3 months of continuous drought during 1961 to 2015. From 2 months to 3 months of continuous drought, the number of stations of continuous drought had reduced by half. The double decreasing also occurred from 7 to 9 months. However, the differences in the station number of continuous drought were relatively small among 4 to 6 months with 0 to 50 stations. A similar situation also occurred from 10 to 12 months with 0 to 5 stations. It can be inferred that continuous drought of 6 or 12 months may probably lead to more severe drought disasters due to longer duration.

3.4.2 The decades of the longest continuous drought

In Figure 7, 385 stations were detected the sole decade of the longest continuous drought during 1961–2015 over China. The number of meteorological stations in each decade was 112, 80, 35, 31, 84 and 43 from the 1960s to 2010s, respectively. The most extensive continuous drought in China occurred in the 1960s. There was no obvious regional distribution of the longest continuous drought in both the 1960s and the 1970s. The longest continuous drought in the 1980s and 1990s mainly appeared in the southern and central parts of the NEC, the Hetao area (the junction of the southern part of the NWC and the northwest NC) and the western SEC. There was a significant increase in the scope of the longest continuous drought in the 2000s, which mainly occurred in the NEC, the SWC and the eastern SEC. It is noteworthy that more than 30% of stations detected the longest continuous drought since the 2000s, and about 50% of them occurred from 2011 to 2015, which far exceeded the number in the 1980s or the 1990s. Compared with the extent in the 1980s and the 1990s, the areas of the longest continuous drought showed a national increase except the TP and the NC since the 21st century.

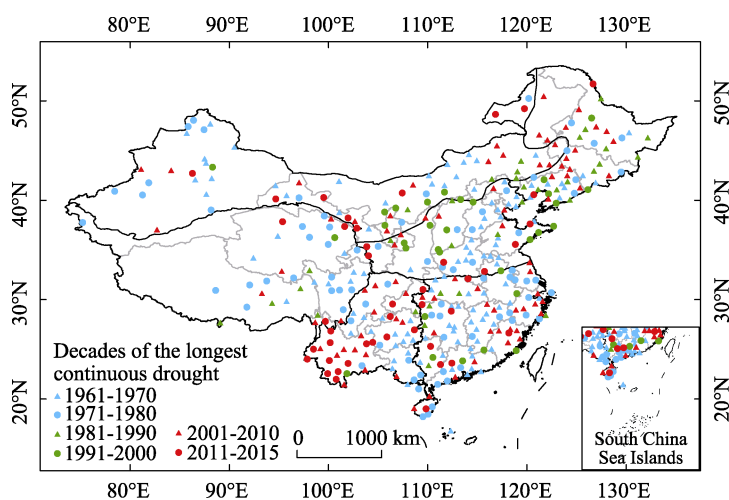


Figure 7 Decades when the longest continuous drought ($\text{SPEI} \leq -1$) occurred during 1961–2015

4 Discussion

Under the background of global climate warming, the frequency and intensity of drought events may probably increase in the 21st century. Drought disasters caused by different intensity of drought events varied greatly. Droughts that caused severe drought disasters often occurred in droughts with long duration and high drought intensity (i.e. the level of extreme drought). The analysis of the spatio-temporal variations in extreme droughts will be conducive to improve the understanding of the occurrence, development, and possible causes of extreme droughts. It will also provide an important prerequisite for effective drought prevention and drought resistance. However, the existing studies had less research on the variations in extreme drought in China. This paper focuses on the occurrence and variations in extreme drought based on meteorological observation data in China.

It is worth mentioning that different conclusions are likely to be reached using different drought definitions, methods, datasets and application areas (Potop *et al.*, 2012; Sheffield *et al.*, 2012; Yu *et al.*, 2014; Chen and Sun, 2015). The drying trends using the drought indices based on temperature or potential evapotranspiration calculated by Thornthwait's formula were more severe than those of methods based on FAO Penman–Monteith equation, especially in northern China (Ma and Fu, 2006; Zhang *et al.*, 2015). Vicente-Serrano *et al.* (2012) also found that drought indices based on temperature data (such as the PDSI) were preferable for identifying drought impact on vegetation activity and growth. Drought responses were more sensitive to elevated temperature in northern China, especially in the arid regions, while relatively large responses to precipitation were found mainly in southern China (Chen and Sun, 2015). Changes in extreme climate events are often more sensitive to various climate change monitoring activities, making it more difficult to assess changes in extreme climate events than to assess changes in the mean (Cook *et al.*, 2014). Therefore, it is a more difficult and more important problem to estimate the long-term climate change of the low probability of extreme drought than the mean state of the climate (Katz and Brown 1992; Plummer *et al.*, 1999). An accurate method and higher-quality homogenized temperature data are important pre-conditions to detect the change and trend of extreme events accurately. By contrasting records (NBSPRC, 1995; HPFFR, 1985) of drought disaster with the FED in this study, the latter is consistent with severe drought disaster events, especially in Haihe Basin and northern China in 1962, 1965, 1966, 1968, 1972 and 1978, with extreme drought in the SPEI occurring more than 3–6 times per decade per station.

The frequency of extreme drought had changed obviously in most parts of China during the period 1961–2015. The regions where the FED increased were mainly distributed in a strip from the western part of northeast China to southwest China. The increase in the FED occurred in the western part of northeast China mainly in spring and autumn, and the increase in the northern agricultural and pastoral areas was mainly in spring. In most parts of the SWC, the FED increased significantly in spring, autumn and winter. In all, the FED of China has been the most widely distributed in spring since 1961. The FED of the NC mainly increased in the 1990s, while the FED of other subareas increased significantly since the 2000s. Moreover, it showed persistent increase in the FED in the TP, the SWC and the SEC in the 21st century. Although the widest range of the longest continuous drought occurred in the 1960s, the fact that the markedly increase in the 21st century are also worth noting, es-

pecially since 2011 in most parts of the SWC and the SEC.

In this paper, the analysis of spatial and temporal changes of the extreme drought was based on the changes of the occurrence probability (2.28%) of cumulative water deficit anomaly. The direct causes of extreme drought are the exceptionally low precipitation and the increase in potential evapotranspiration caused by a significant increase in temperature. Although drought disasters are a regional phenomenon, their occurrence is often affected by continuous large-scale circulation anomalies. The weakened trend of summer monsoons may probably lead to a long-term and widespread drought in the Yellow River basin and northern China (Zhang and Zhou, 2015). The western Pacific subtropical high to the north often leads to drought in the Yangtze River basin. In addition, the Yangtze River basin often experienced dry years when the position of the Tibetan Plateau high pressure is more easterly than the Tibetan Plateau. The FED in the TP, the SWC and the SEC exhibited a consistent persistent trend of increase in the 21st century. It is speculated that there are certain links on droughts and floods in the three regions. The development stage of ENSO has a significant impact on the low rainfall and drought in the middle and upper reaches of the Yangtze River basin and in northern China (Ye *et al.*, 1996). For example, the ENSO development year in 1963, 1965, 1968, 1972 and 1982 showed a high FED of extreme drought in Figure 5g. The results of this study will enhance our understanding of the variations in extreme drought in China, and the mechanism and reasons of extreme drought as well as the applicability of different time scales to various types of drought should be studied further.

5 Conclusions

Spatio-temporal distributions and variations in frequency of extreme drought (FED) and the longest continuous drought in China were examined during the period of 1961–2015 from inter-decadal, inter-annual and seasonal time scales in China and its six subareas. The conclusions showed that:

(1) The critical precipitation of extreme drought decreased from southeast China (more than 1500 mm) to northwest China (less than 50 mm) during 1961–2015. The extreme drought began to occur when the 12 months cumulative precipitation in the NWC, the NEC and the NC was around 1/2 of the annual average precipitation, and extreme drought in the SWC and the SEC usually occurred when the cumulative precipitation was less than 5/8 of the mean annual precipitation. Therefore, the annual precipitation was considered to be the main determinant of extreme drought occurrence in China.

(2) A drying strip stretching from the SWC to the western NEC had experienced significantly increased FED from 1961–1987 to 1988–2015. The decreased FED mainly occurred in eastern China (most areas of the TP and the NWC) and western China (western regions of the NEC, the NC and the SEC). The extent of the decreased frequency in western and eastern China was larger than that of the increased frequency which was mainly concentrated in central China and the western part of northeast China. The seasons of the increased FED from more to less were spring, winter, autumn and summer.

(3) The FED experienced a decrease before 1997, followed by a wide range of droughts since the 21st century. The maximum frequency mainly occurred from the 1960s to the early 1970s in the NWC, the NC, the TPC and the SEC. There was a continuous increase in the

decadal FED from the 1990s to 2015 in the TP, the SEC, the SWC and the whole of China.

(4) The differences in the station number that documented continuous drought were relatively small between 4 and 6 months and from 10 to 12 months of continuous drought. The number of stations that documented the longest continuous drought in each decade was 114, 78, 33, 29, 83 and 42 from the 1960s to the 2010s. Compared with the 1980s and 1990s, the number of meteorological stations of the longest continuous drought had an increased distribution since the 21st century.

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