

Article

Identification and Spatial-Temporal Variation Characteristics of Regional Drought Processes in China

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Abstract: Based on the daily temperature and precipitation data from 1961 to 2021 obtained from 2019 national meteorological stations of China, and by means of Meteorological Drought Comprehensive Index (MCI) and some improved identification methods, we identified all drought event processes in all the seven regions of China in this paper. We also carefully analyzed these regional droughts and made following conclusions: drought was spreading towards southern China with an increasing frequency; consecutive drought year group occurred in all the seven regions of China with an increasing frequency under the background of global warming; both drought duration and comprehensive intensity consistently changed with the area affected by drought, with a correlation coefficient of 0.52–0.67 and 0.88–0.99 respectively, and passed the significance test of 0.05. The method used in this paper could be employed to effectively monitor and evaluate drought processes from multiple dimensions including duration, comprehensive intensity and area affected by drought. Thus, it actually provided a helpful decision-making basis for governments to prevent the risk of drought.

Keywords: regional drought identification; comprehensive drought intensity; consecutive drought year group; China



Citation: Cai, X.; Zhang, W.; Zhang, C.; Zhang, Q.; Sun, J.; Cheng, C.; Fan, W.; Yu, Y.; Liu, X. Identification and Spatial-Temporal Variation Characteristics of Regional Drought Processes in China. *Land* **2022**, *11*, 849. <https://doi.org/10.3390/land11060849>

Academic Editor: Adrianos Retalis

Received: 2 May 2022

Accepted: 1 June 2022

Published: 5 June 2022

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1. Introduction

Drought refers to a natural phenomenon occurring when precipitation is significantly lower than the historical average. Usually, drought can cause serious hydrological imbalances and adversely affect land resource production systems [1]. Under the influence of global warming and rapid social and economic development, frequent drought has currently become one of the most serious environmental problems in the world [2–6], and attracted great attention from the international community and many studies by scholars from various countries [7–16]. Carrão et al. observed that drought risk was increasing globally and the major challenge for risk management was not to adapt human populations or their activities to drought hazard changes, but to progress on global initiatives that mitigated their impacts in the whole carbon cycle in the late 21st century [17]. The study by Rajsekhar et al. also confirmed that the climate of southwestern North America is becoming drier, and the frequency of droughts has greatly increased. They believed that this phenomenon indicates that under the influence of global warming, the climate of global subtropical arid regions tends to involve droughts and expand to higher latitudes [18]. Nicholls and Kiem et al. believed that the consecutive climate warming in the middle of 20th century and the El Niño–Southern Oscillation phenomenon have caused frequent

extreme droughts in Australia in the past decade [19,20]. Touchan et al. also found that climate change exacerbated droughts in mid-latitude Africa, leading to the worst drought since the mid-15th century during the period of 1999–2002 [21,22]. Similar to the global drought situations, China's arid area and drought intensity have shown an increasing trend. In recent years, China has frequently experienced record-breaking extreme drought events. For example, from the autumn of 2009 to the spring of 2010, an autumn-winter-spring consecutive drought rare in history occurred in Southwest China, in terms of the duration, the area influenced and the intensity of drought [23]. According to the climate warming trends, Zhao et al. divided the study period by drought characteristics in North China into three stages, that is, 1951–1984 (stage I), 1985–1997 (stage II), and 1998–2019 (stage III). The comprehensive analysis results showed that the drought intensity in North China had significant stage characteristics [24]. Zhou Guoyi et al. pointed out that the increase in global average temperature leads to an increase respectively in the magnitude, frequency and duration of drought events, which brings more negative impacts on forest ecosystems [25]. Ren Guoyu et al. comprehensively studied the main characteristics of precipitation changes in the Haihe River Basin since 1736, and believed that the period from the late 1940s to the early 1960s had been the wettest period since 1736, but there were several persistent climate droughts since the beginning of the 20th century, including the severe drought from 1997 to 2003, which were not uncommon in the climate history since 1736, especially the longest drought occurred from 1826 to 1843 [12]. Yao N. et al. found that the recent meteorological droughts in both southern China and northern China had good correlation with agricultural drought and hydrological drought [26]. In short, under the influence of global warming, the meteorological factors around the world are undergoing significant changes and resulting in a significant increase in the frequency of drought events and a worsening trend in both duration and severity. Drought has expanded from affecting agriculture mainly to affecting other sectors, including the development of the entire economy and society, and even caused ecological and environmental degradation.

Due to the complex mechanism and slow and consecutive process of droughts, single analysis of precipitation changes is not enough to fully characterize the range and intensity of drought and aridification. Especially under the climate background of decreasing precipitation and increasing temperature, climate warming has become one of the important factors aggravating the drought process. Therefore, the objective characterization of aridification needs to integrate the common influence of changes in meteorological elements, such as precipitation and temperature. As an important indicator and means to quantitatively assess drought, drought indices play an important role in drought monitoring and prediction. The meteorological drought indices that are widely used and studied in China mainly include the following: percentage of precipitation anomaly (Pa) [27,28], Palmer Drought Severity Index (PDSI) [29,30], Standardized Precipitation Index (SPI) [31,32], Precipitation Z index [33], Relative Moisture Index (MI) [34,35], Compound Index of meteorological drought (CI) and the Standardized Precipitation Evapotranspiration Index (SPEI) [36]. These studies have laid the foundation for theoretical reference and practical reference. However, each of the above methods has limitations. MCI (Meteorological Comprehensive drought Index) comprehensively considers factors such as longer time scales and precipitation weights in different periods, and its drought monitoring and evaluation effect is significantly higher than that of the CI index [37]. Liao et al. [38] studied the temporal and spatial distribution of drought in China and the characteristics of disaster changes based on the MCI index, which improved the ability to identify drought disasters. As we all know, drought events are regional extreme weather and climate events, which not only have certain intensities, but also have the characteristics of duration and influence range. How to use the above drought index to comprehensively identify or characterize regional drought events from three dimensions of intensity, time and scope is of great significance to the monitoring and evaluation of the regional drought process [39]. Ren et al. (2012) [40] proposed an objective identification technique for regional extreme events (OITREE), which could better identify regional meteorological drought events, and has

achieved many results [41–43]. The research results have promoted the development of identification and assessment techniques for regional meteorological drought events in China. However, there are many difficulties to objectively determine parameters such as setting the distance between adjacent monitoring sites, the drought coincidence rate, and the component weight of the comprehensive intensity when applied in practical application. Jing et al. (2016) [44] established an extreme event identification method based on intensity, area of influence and duration by using interpolated grid data, but the practical application of this method was limited due to the determination of the extreme threshold and the complicated calculation.

Zhang et al. (2020) [45] recently systematically summarized the important achievements of drought researches since the 1950s in China in view of the characteristics of drought events, the spatial and temporal distribution of droughts, the change rules of droughts, the causes of droughts, the influencing mechanisms of droughts, the formation process of drought risks and the response of droughts to climate warming. Combined with the international cutting-edge studies and hotspot issues and development trend of drought research, they scientifically analyzed the weaknesses and problems of drought researches in China, and suggested that future drought research in China needs to make breakthroughs in the identification, monitoring and prediction of drought events, the transition between different types of drought, the response of drought to global warming, and the risk assessment of drought disasters.

Previous studies on drought in major regions of China have received a lot of attention, and a series of meaningful results have been obtained, but different studies use different drought indices in different regions, and the results were inconsistent. Most of the studies were limited in a small area, and did not comprehensively identify and study the changes in the whole drought event from the three dimensions of intensity, affected area and duration. In this paper, the regional drought event processes in China are identified by using the MCI index, which was used in meteorological drought operational monitoring in China, and by combining the improved identification technology and the comprehensive intensity analysis method of the regional drought process based on the theory of extreme intensity, with both the duration and the region (EIDR) proposed by Lu et al. (2017) [46], and the improved method of OITREE. On this basis, the drought event processes were analyzed from drought event duration, frequency, comprehensive intensification, the groups of consecutive drought years, temperature and precipitation on the contribution of drought and so on. The ultimate goals of this paper were to reveal the new regulations of spatial and temporal evolution characteristics of regional drought events under the background of global warming in recent decades in China. The research results will provide the scientific basis for government departments to formulate regional drought risk prevention and control strategy planning.

The contents of this paper are as follows: the data and methods used in this study are introduced in Section 2, Section 3 provides the results, Sections 4 and 5 give summaries and discussions, respectively.

2. Materials and Methods

2.1. Data Description and Regional Division

A total of 31 provinces (municipalities directly under the Central Government) in China were selected as the study area (excluding Taiwan, Hong Kong and Macau). From 1961 to 2021, the daily precipitation, average temperature, maximum temperature, minimum temperature and other data of 2019 national ground observation stations with a long sequence of more than 60 years in China were selected (data from the National Meteorological Information Center of China Meteorological Administration, <http://data.cma.cn/> (accessed on 20 April 2022)). The data were quality controlled to meet the research needs. The data on drought-affected areas from 1971 to 2019 are from the National Bureau of Statistics of China (<http://www.stats.gov.cn/tjsj/>) (accessed on 20 April 2022). According to the characteristics of China's administrative regions and climatic and geographical

conditions, it is divided into the following seven regions to analyze the distribution of drought in China (Figure 1): Northeast China: Liaoning, Jilin, and Heilongjiang provinces; North China including Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia 5 provinces (cities); Northwest China including Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang 5 provinces (cities and autonomous regions); Central China including Henan, Hunan and Hubei 3 provinces; East China including Shanghai, Jiangsu, Zhejiang, Fujian, Anhui, Shandong, Jiangxi 7 provinces (cities); Southwest China including Chongqing, Sichuan, Guizhou, Yunnan, Tibet 5 provinces (cities); South China including Guangdong, Guangxi and Hainan 3 provinces (regions).

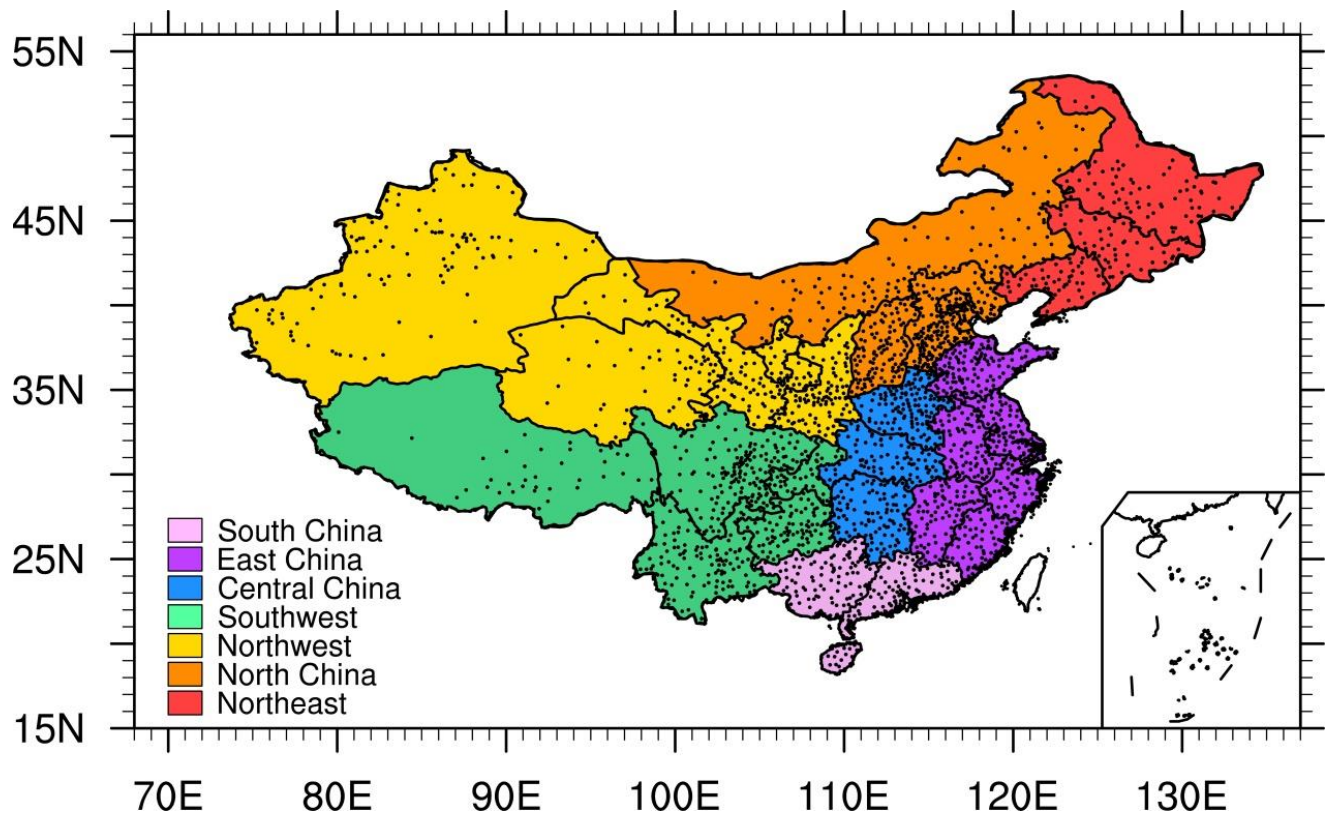


Figure 1. Distribution of national-level surface weather stations in China.

2.2. Analysis Procedure of Regional Drought Process

2.2.1. Method Steps to Follow

Firstly, the precipitation and temperature data from 1961 to 2021 were selected. Secondly, the Standardized Precipitation Index (SPI) of different scales was calculated according to the precipitation data, and the 30-day evapotranspiration was calculated by using the temperature data. At the same time, the relative wettability was calculated by using precipitation data and 30-day evapotranspiration. Then, the MCI was generated by the SPI value and relative wettability. Next, the MCI was used to identify the regional drought process; the number of days and frequency of drought were counted. Finally, the days of drought process, the comprehensive intensity of drought process, annual frequency of drought process and consecutive drought year groups were analyzed by using the regional drought process (Figure 2).

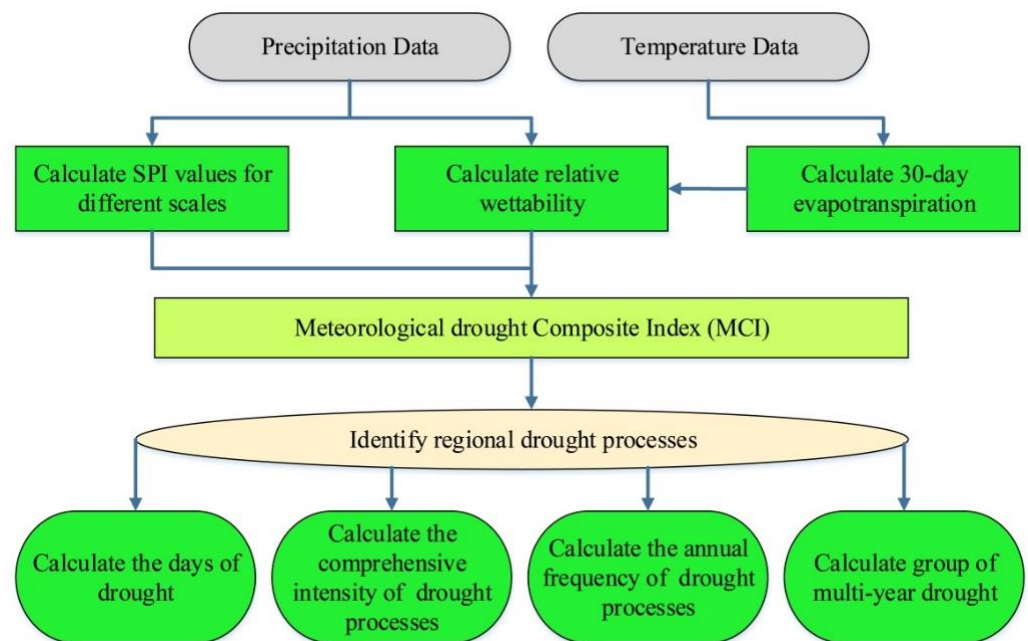


Figure 2. Flow chart for calculating the drought index and the intensity of the drought process.

2.2.2. Regional Drought Processes

The identification and evaluation methods of regional drought processes mainly refer to the meteorological standard ‘Methods for Monitoring and Assessment of Regional Drought Processes’ [47]. The MCI currently used in China’s real-time meteorological drought monitoring business was adopted as the drought index. The index considers the comprehensive effects of effective precipitation within 60 days, evapotranspiration within 30 days and precipitation within 90 and 150 days. According to the Chinese national standard ‘Meteorological Drought Grade’ [48], the daily Meteorological Drought Comprehensive Index (MCI) of China meteorological observation stations from 1960 to 2019 was calculated, and the formula is as follows [48]:

$$MCI = K_a \times (a \times SPIW_{60} + b \times MI_{30} + c \times SPI_{90} + d \times SPI_{150}) \quad (1)$$

where $SPIW_{60}$ is the standardized weighted precipitation index in the past 60 days; MI_{30} is the relative wettability index in the past 30 days; SPI_{90} and SPI_{150} are the standardized precipitation index in the last 90 days and nearly 150 days, respectively; K_a is the seasonal adjustment coefficient, which is determined according to the sensitivity of main crops to soil moisture in different seasons; a , b , c , and d are the weight coefficients, respectively, and the values in northern China are 0.3, 0.5, 0.3 and 0.2 and the values in the southern region are 0.5, 0.6, 0.2 and 0.1. The weight coefficients are not fixed, it must be adjusted as the local environment, climate, research object and time period changes. The seasons division was as follows: winter (December to February of the next year), spring (March to May), summer (June to August), and autumn (September to November).

2.2.3. Regional Daily Drought Intensity

When the average drought intensity of a monitoring station in a fixed area on a certain day is mild drought or above and at least one station has a drought intensity level of moderate drought or above, it is considered that a regional drought has occurred on that day. The regional daily drought intensity I_d is calculated according to Equation (2), which is as follows [47]:

$$I_d = \frac{1}{L} \sum_{i=1}^j I_i \quad (2)$$

where L is the number of total stations in the region; j is the number of stations with drought grade of mild drought or above in the region and I_i is the drought index MCI_i of the station in the i -th region with a drought grade of mild drought or above.

2.2.4. Determination of Drought Process

When the regional daily drought intensity I_d reached the grade of mild drought or above, lasted for 15 days or more and the maximum daily drought intensity reached the grade of moderate drought or above, a regional drought process was considered to have occurred.

The date when the first mild drought occurred in the regional drought process was the first day of the drought. After the occurrence of the drought process, when the drought grade was confirmed as no drought for 5 consecutive days, the regional drought process was considered finished, and the last day before the end of the drought process when the meteorological drought grade reached mild drought or above was the end date.

The total number of days from the beginning date to the end date (including the end date) of a regional drought process is the number of drought process days.

2.2.5. Regional Cumulative Drought Intensity

Regional cumulative drought intensity is the combination of regional daily drought intensity and duration, calculated according to Equation (3), which is as follows [47]:

$$D(n) = n^{\alpha-1} \sum_{\varepsilon=1}^n I_d(\varepsilon) \quad (3)$$

where $D(n)$ is the regional cumulative drought intensity in the n days; n is days of drought process duration; $I_d(\varepsilon)$ is the absolute value of the regional daily drought intensity on the ε -th day in the drought process, it is calculated according to Equation (2); α is the weight coefficient between 0.5 and 1.0, in general, 0.5 is more appropriate [49].

2.2.6. Intensity of Regional Drought Process

The regional cumulative drought intensity was calculated by the consecutive drought days in the sliding regional drought process, and the strongest cumulative drought intensity in the regional drought process was taken as the regional drought process intensity (z). Equation (4) was used for calculation, which is as follows [47]:

$$Z = \max_{k=1, m; n=1, k} (D(n)) \quad (4)$$

where $\max_{k=1, m; n=1, k} ()$ determines the drought day k ($1 \leq k \leq m$) in a certain period through consecutive sliding comparison. For n ($1 \leq n \leq k$), m is the total number of days in the regional drought process; n is the duration of drought in the regional drought process, $1 \leq n \leq m$ and $D(n)$ is the regional cumulative drought intensity, which is calculated according to Equation (3).

2.3. Frequency of Drought and Consecutive Drought Years Group

In the last 60 years, the years in which the drought process of mild drought or above occurred at least once in each region of China was counted, and the frequency of drought occurrence was calculated by formula (5), which is as follows [47]:

$$P = \frac{y}{Y} \times 100\% \quad (5)$$

where y is the actual number of years in which the drought process occurs and Y is the number of data chronological series. We define a drought process that has consecutively occurred for 2 years or more as a "group of multi-year drought (GMYD)".

3. Result

Based on the method of drought process determination, all meteorological drought processes occurred in all seven regions of China, including Northeast, North China, Northwest, Central China, East China, Southwest and South China, from 1961 to 2021 have been identified.

3.1. Spatial Distribution of the Annual Average Drought Process Days in China

According to the start and end times of the drought process in various regions of China from 1961 to 2021, the annual drought days of each station have been counted, and the spatial distribution of the annual average drought process days in China has been obtained (Figure 3).

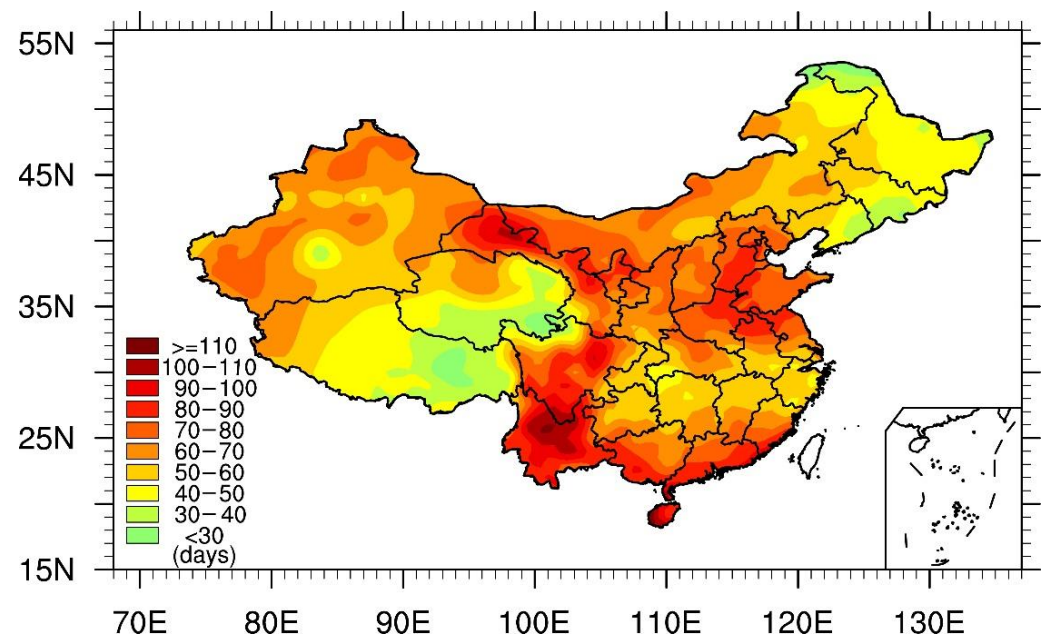


Figure 3. Spatial distribution of annual average drought days in China (unit: day/year).

The regions with severe drought include southern Beijing, western Tianjin, and southeastern Hebei in North China; and Hainan, southeastern Guangdong, and southern Guangxi in South China; and most of Yunnan, central and southern Sichuan in Southwest; and the northern Gansu and the central Ningxia in Northwest; the annual average number of drought process days in these regions are more than 80 days. Among them, the annual average number of drought process days of southwestern Hainan and part of northern Guangxi are more than 110 days. The regions with less than 40 days of drought process are mainly located in parts of eastern Tibet, parts of eastern Qinghai, eastern Liaoning bordering on Jilin, and northwest of Heilongjiang. The annual average drought process days in other regions are between 40 and 80 days. This is consistent with the results of Zhang et al. [50].

3.2. Annual Frequency of Drought Processes (AFDP) in All Seven Regions of China

According to the study results of Zou et al. [51] that most drought events occurred after 1980, the entire 61 year study period is, therefore, divided into the following two phases: 1961–1979 (Phase 1) and 1980–2021 (Phase 2). Figure 4 respectively shows the annual frequency of drought processes (AFDP) that occurred in all seven regions of China during the whole period, Phase 1 and Phase 2.

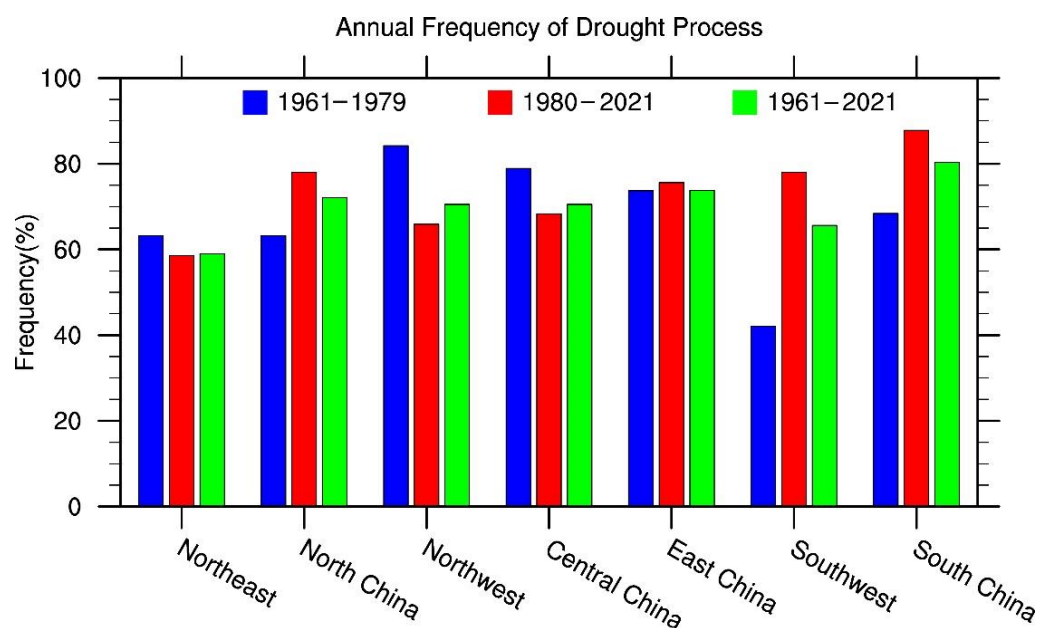


Figure 4. Annual Frequency of Drought Process in Different Periods in Seven Regions of China.

There were 36 years of drought processes in Northeast China; the AFDP was 59% for the whole period, and 63.2% for Phase 1 and 58.5% for Phase 2. There were 44 years of drought processes in North China; the AFDP was 72.1% for the whole period, and 63.2% for Phase 1, 78.0% for Phase 2. There were 43 years of drought process in Northwest China; the AFDP was 70.5% for the whole period, and 84.2% for Phase 1, 65.9% for Phase 2. There were 43 years of drought process in Central China; the AFDP was 70.5% for the whole period, and 78.9% for Phase 1, and 68.3% for Phase 2. There were 45 years drought process in East China and the AFDP was 73.8% for the whole period, and 73.7% for Phase 1, 75.6% for Phase 2. There were 40 years of drought process in Southwest China; the AFDP was 65.6% for the whole period, and 42.1% for Phase 1, 78.0% for Phase 2. There were 49 years of drought process in South China; the AFDP was 80.3% for the whole period, and 68.4% for Phase 1, 87.8% for Phase 2. In terms of the AFDPs of the seven regions of China, South China ranks first, followed by Central China, and North China ranks third. Further analysis of the AFDP in the two phases since 1980 shows that the AFDP in Northeast, Northwest and Central China all demonstrated a downward trend, namely, the AFDP in Phase 2 was lower than in Phase 1, and the biggest drop, 18%, occurred in Northwest China. In contrast, the AFDP in Southwest, South China, East China and North China all showed an upward trend. Ranking the first, the AFDP in Southwest China increased by 35.9%; secondly, the AFDP of South China increased by 19.4%. Overall, the regions with increasing AFDP since 1980 are mainly in the south. This indicates that, in the context of global warming, the scope of droughts in China is constantly expanding. In the past, the regions with frequent droughts were mainly in those semi-arid and semi-humid regions in the north. However, in recent years, the scope of drought has expanded into the humid and sub-humid regions of Southwest and South China.

3.3. Variation Characteristics of the Year-Group of Consecutive Droughts

A multi-year drought is far more harmful than consecutive single-year droughts. During a multi-year drought, not only agricultural production and food security would be severely threatened, but also water resources, ecological environment and sustainable social and economic development would be seriously influenced. In this paper, we define a drought process that has consecutively occurred for 2 years or more as a “group of multi-year drought (GMYD)”.

Table 1 presents the variation characteristics of the GMYDs of all seven regions in China from 1961 to 2021. There were 10, 11, 9, 12, 7, 8 and 7 GMYDs, respectively, in Northeast, North China, Northwest, Central China, East China, Southwest and South China. Their year-frequencies of drought process for the whole study period are 27.8%, 25.0%, 20.9%, 27.9%, 15.6%, 20.0% and 14.3%, respectively. There were 36 drought process years and 10 GMYDs in Northeast China from 1961 to 2021. The frequency of GMYD was 27.8%. A total of 7 out of the 10 GMYDs were the 2-year type; its frequency was 19.4%. Furthermore, of the seven two-year GMYDs, two occurred in Phase 1, and five occurred in Phase 2. This means that the occurrence probability of 2-year GMYD in this region has greatly increased since 1980. At the same time, only one 3-year GMYD occurred from 1992 to 1994; its frequency was 2.8%. The 6-year GMYD occurred twice, respectively, from 1961 to 1966 and from 1999 to 2004; its frequency was 5.6 %. There were 44 of drought process years and 11 GMYDs in North China from 1961 to 2021. The frequency of GMYD was 25.0%. Three GMYDs occurred in Phase 1, including two two-year GMYDs from 1961 to 1962 and from 1965 to 1966, one seven-year GMYD from 1972 to 1978. Eight GMYDs occurred in Phase 2, including one nine-year GMYD from 1999 to 2007, one seven-year GMYD from 1991 to 1997, three three-year GMYDs from 1980 to 1982, from 1984 to 1986, and from 2013 to 2015, three two-year GMYDs from 1985 to 1986, from 2010 to 2011, and from 2019 to 2020. There were 43 drought process years and 9 GMYDs in the Northwest from 1961 to 2021. The frequency of GMYD was 20.9%. The nine GMYDs included one fifteen-year GMYD from 1968 to 1982, one six-year GMYD from 2004 to 2009, one five-year GMYD from 2011 to 2015, one four-year GMYD from 1999 to 2002 (the four frequencies of GMYDs above were equal to 2.3%), and five two-year GMYDs from 1961 to 1962, from 1965 to 1966, from 1985 to 1986, from 1994 to 1995, and from 2020 to 2021, with the frequency of 11.6%. Thus, it could be concluded that multi-year droughts in the northwest region are significantly longer than in other regions. There were 43 drought process years and 12 GMYDs in Central China from 1961 to 2021. The frequency of GMYD was 27.9%. The 12 GMYDs included three five-year GMYDs from 1971 to 1975, from 1988 to 1992, and from 1997 to 2021, with a frequency of 7.0%; and two four-year GMYDs from 1965 to 1968, and from 2011 to 2014, with a frequency of 4.7%; and four three-year GMYDs from 1963 to 1965, from 1977 to 1979, from 1984 to 1986 and from 2019 to 2021, with a frequency of 14.3%; and three two-year GMYDs from 1981 to 1982, from 2003 to 2004 and from 2006 to 2007, with a frequency of 7.0%. It could be concluded that although the multi-year drought in Central China occurred more often, their durations were usually less than 6 years. There were forty-five drought process years and seven GMYDs in East China from 1961 to 2021. The frequency of GMYD was 15.6%. The seven GMYDs included one sixteen-year GMYD from 1994 to 2009, one six-year GMYD from 1963 to 1968, one five-year GMYD from 1988 to 1992, one four-year GMYD from 1976 to 1979, two three-year GMYDs from 1971 to 1973 and from 2014 to 2015, and one two-year GMYD from 1984 to 1986. Although the multi-year droughts in East China were less frequent than in other regions of China, usually they were longer. There were forty drought process years and eight GMYDs in Southwest China from 1961 to 2021. The frequency of GMYD was 20.0%. The eight GMYDs included one ten-year GMYD from 2006 to 2015, and one seven-year GMYD from 1986 to 1992, and one four-year GMYD from 2018 to 2021 (the frequencies of the three GMYDs above are equal to 2.5%); and three three-year GMYDs from 1978 to 1980, from 1982 to 1984, and from 1997 to 1999, with a frequency of 7.5%; and two two-year GMYDs from 1974 to 1975 and from 1994 to 1995, with a frequency of 5.0%. There were forty-nine drought process years and seven GMYDs in South China from 1961 to 2021. The frequency of GMYD was 14.3%. The seven GMYDs included one fourteen-year GMYD from 2002 to 2015, with a frequency of 2.0%; and one ten-year GMYD from 1983 to 1992, with a frequency of 2.0%; and two seven-year GMYDs from 1963 to 1969, and from 1994 to 2000, with a frequency of 4.1%; and one five-year GMYD from 1976 to 1980; one four-year GMYD from 2018 to 2021, and one three-year GMYD from 1971 to 1973. The frequency of these three GMYDs above was

2.0%; although there were less GMYDs in South China than in other regions, they lasted longer (Table 1).

Table 1. Statistics of GMYDs in all seven regions of China from 1961 to 2021.

Region	Amount of GMYD																Total Amount of GMYD
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
Northeast	7	1			2											10	
North China	5	3				2		1								11	
Northwest	5		1	1	1									1		9	
Central China	3	4	2	3												12	
East China	2	1		1											1	7	
Southwest	2	3	1			1			1							8	
South China		1	1	1		2			1				1			7	
Total	24	13	5	6	3	5		1	2				1	1	1	64	

From the analysis above, we may conclude that all the seven regions in China have experienced multi-year droughts during the study period from 1961 to 2021. Although the frequencies of GMYD in East China, South China and Southwest were low, their multi-year droughts lasted longer than in other regions. In addition, the occurrence probability of multi-year droughts in East China has greatly increased since 1980. It brought serious threats to agricultural production and the ecological environment. For example, China experienced a severe 6-year drought from 1978 to 1983. Among the nearly 133.3 million hectares of farmland affected by the drought, 62.1 million hectares were seriously damaged and this caused a heavy loss.

3.4. Variation Characteristics between Duration and Frequency of Drought Process

Figure 5 shows the interrelation between the duration and the frequency of drought processes from 1961 to 2021. The occurrence frequency of droughts in all seven regions of China, North, Northwest, Central, East, Southwest and South were 48, 74, 60, 62, 72, 63 and 95, respectively.

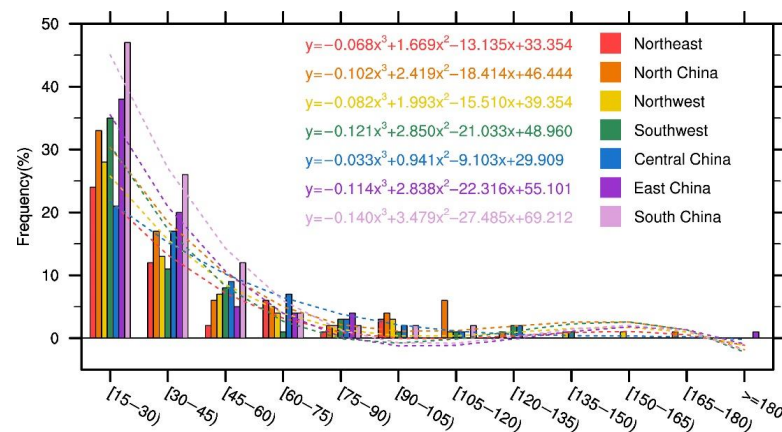


Figure 5. Frequency distribution of regional drought processes in China from 1961 to 2021.

The frequencies of the regional droughts with a duration of less than 1 month (15–30 days) in all seven regions of China, North, Northwest, Central, East, Southwest, and South were 24, 33, 28, 21, 38, 35 and 47, respectively, and accounted for 50.0%, 44.6%, 46.7%, 33.9%, 52.8%, 55.6 and 49.5% of all droughts in its region, respectively. The frequencies of the regional droughts with a duration of 1–2 months (30–60 days) in all seven regions of China, Northeast, North, Northwest, Central, East, Southwest, and South were 14, 23, 20, 26, 25, 19 and 38, respectively, accounting for 29.2%, 30.7%, 33.3%, 41.9%, 34.7%, 30.26% and 40.0% of all droughts in its region, respectively. The frequencies of the regional droughts with a duration

of 2–3 months (60–90 days) in all seven regions of China, Northeast, North, Northwest, Central, East, Southwest, and South were 7, 7, 6, 10, 8, 4 and 6, respectively, and accounted for 14.6%, 9.3%, 10.0%, 16.1%, 11.1%, 6.3% and 6.3% of all the droughts in its region, respectively. There was no regional drought process with a duration of 3–4 months (90–120 days) in East China, while the frequencies of drought processes in Northeast, North China, Northwest, Central China, Southwest and South China during the study period were 3, 10, 4, accounting for 6.3%, 13.3%, 6.7%, 4.8%, 3.2%, and 4.2% of all the droughts in its region, respectively. There was no regional drought process with a duration of 4–5 months (120–150 days) in Northeast, East China and South China. While the frequencies of drought process in North China, Northwest, Central China and Southwest during the study period were 1, 1, 2 and 3, respectively, accounting for 1.3% and 1.7%, 3.2% and 4.8% of all droughts in its region, the regional drought process with a duration of 5–6 months (150–180 days) only occurred once in North China and Northwest, accounting for 1.3% and 1.7% of all the droughts in its region, respectively. While this type of drought did not appear in other several regions during this period, the regional drought process with a duration more than 6 months (180 days) only occurred once in East China, accounting for 1.4% of all droughts in its region, while other regions did not experience this type of drought process during the study period. The analysis above illustrates the rule that for a regional drought process, the longer the duration, the lower the frequency. The determination coefficient (R^2) is between 0.91 and 0.98 (passed the 99% significance test).

3.5. Seasonal Distribution of Regional Drought Processes in China

In Northeast China, summer drought occurred 15 times, ranked first, and accounted for 35.7% of all seasonal drought in this region; a spring-to-summer consecutive drought occurred 13 times, ranked second, and accounted for 31.0% of all seasonal droughts in this region. Both spring droughts and autumn droughts occurred 5 times, and accounted for 11.9% of all seasonal droughts in this region; a summer-to-autumn consecutive drought occurred 4 times, and accounted for 9.5% of all seasonal droughts in this region (Figure 6).

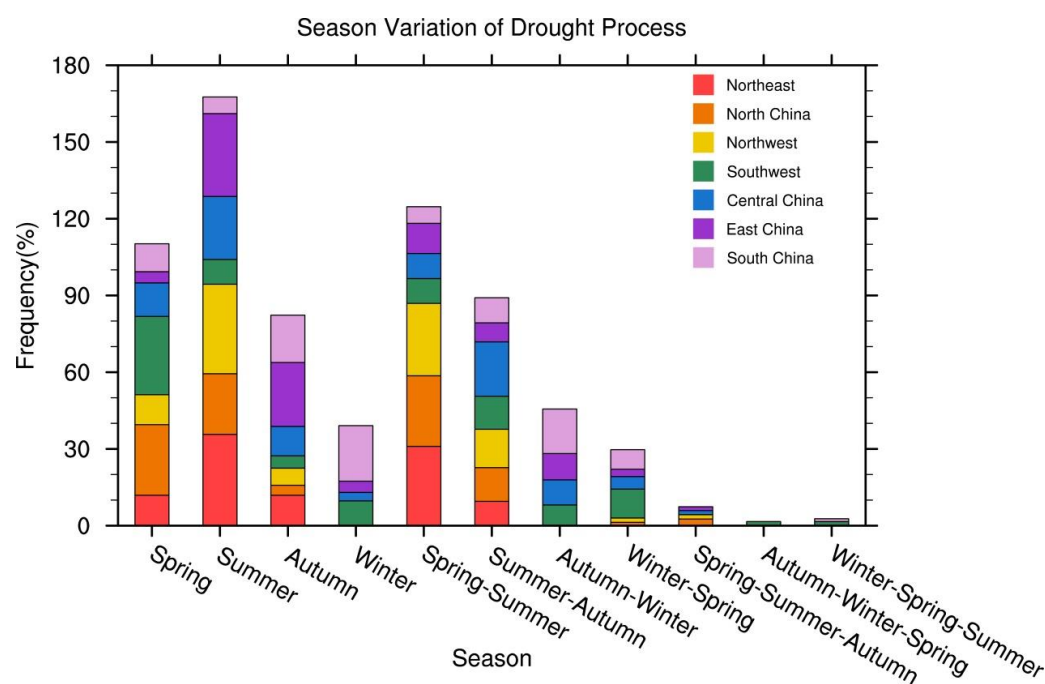


Figure 6. Seasonal distribution of regional drought processes in China from 1961 to 2021.

In North China, both spring droughts and a spring-to-summer consecutive drought occurred 21 times, tied first place, and accounted for 27.6% of all seasonal droughts in this region. Summer droughts occurred 18 times and accounted for 23.7% of all seasonal

droughts in this region; a summer-to-autumn consecutive drought occurred 10 times and accounted for 13.2% of all seasonal droughts in this region. Autumn droughts occurred 3 times, accounted for 3.9% of all seasonal droughts in this region; a winter-to-spring consecutive drought occurred once and accounted for 1.3% of all seasonal droughts in this region. A spring-to-summer-to-autumn consecutive drought, the longest drought process in this region, occurred twice and accounted for 2.6% of all seasonal droughts in this region. In Northwest China, summer droughts occurred 21 times, ranked first, and accounted for 35.0% of all seasonal droughts in this region. Secondly, spring-to-summer consecutive droughts occurred 17 times and accounted for 28.3% of all seasonal droughts in this region. Summer-to-autumn consecutive droughts, spring droughts, and autumn droughts, respectively, occurred 9 times, 7 times, and 4 times, and accounted for 28.3%, 15%, 11.7% and 6.7% of all seasonal droughts in this region, respectively. Both spring-to-summer-to-autumn consecutive droughts and winter-to-spring consecutive droughts occurred once, and each accounted for 1.7% of all seasonal droughts in this region. In Central China, summer droughts occurred 15 times, ranked first, accounted for 24.6% of all seasonal droughts in this region. Secondly, summer-to-autumn consecutive droughts occurred 13 times, and accounted for 21.3% of all seasonal droughts in this region. Spring drought and autumn droughts occurred 8 times and 7 times, respectively, and accounted for 13.1% and 11.5% of all seasonal droughts in this region, respectively. Both spring-to-summer and winter-to-spring consecutive droughts occurred 6 times and accounted for 9.8% of all seasonal droughts in this region. Winter-to-spring consecutive droughts, winter droughts and spring-to-summer-to-autumn consecutive droughts occurred 3, 2 and 1 times, respectively, and accounted for 4.9%, 3.3% and 1.6% of all seasonal droughts in this region, respectively. In East China, summer drought occurred 22 times, ranked first, and accounted for 32.4% of all seasonal droughts in this region. Autumn droughts occurred 17 times, ranked second, and accounted for 25.0% of all seasonal droughts in this region. Spring-to-summer, autumn-to-winter and summer-to-autumn consecutive droughts occurred 8, 7 and 5 times, respectively, and accounted for 11.8%, 10.3% and 7.4% of all seasonal droughts in this region, respectively. Both spring drought and winter drought occurred 3 times and accounted for 4.4% of all seasonal droughts in this region. Winter-to-spring and spring-to-summer-to-autumn consecutive droughts occurred 2 and 1 times, respectively, and accounted for 2.9% and 1.5% of all seasonal droughts in this region, respectively. In Southwest China, spring droughts occurred 19 times, its frequency ranked first, and accounted for 30.6% of all seasonal droughts in this region. Secondly, summer-to-autumn consecutive droughts occurred 8 times and accounted for 12.9% of all seasonal droughts in this region; summer droughts, winter droughts and spring-to-summer consecutive droughts all occurred 6 times and accounted for 9.7% of all seasonal droughts in this region. Both autumn-to-winter consecutive droughts and autumn droughts occurred 5 and 3 times, and accounted for 8.1% and 4.8% of all seasonal droughts in this region, respectively. Both autumn-to-winter-to-spring and winter-to-spring-to-summer consecutive droughts occurred only once; accounted for 1.6% of all seasonal droughts in this region. In South China, winter droughts occurred 20 times, its frequency ranked first, and accounted for 21.7% of all seasonal droughts in this region. Secondly, both autumn droughts and autumn-to-winter consecutive droughts occurred 17 and 16 times; accounted for 18.5% and 17.4% of all seasonal droughts in this region, respectively. Spring drought occurred 10 times, and accounted for 10.9% of all seasonal droughts in this region; summer-to-autumn and winter-to-spring consecutive droughts occurred 9 and 7 times, accounted for 9.8% and 7.6% of all seasonal droughts in this region, respectively. Summer drought occurred 6 times, and accounted for 6.5% of all seasonal droughts in this region. Winter-to-spring-to-summer consecutive droughts occurred only once; accounted for 1.1% of all seasonal droughts in this region. Evidently, this result is consistent with the research conclusion of Zhao et al. [49]. Generally, there are more summer droughts and spring-to-summer consecutive droughts in Northeast China. The droughts in Northwest and North China looked similar, with more spring droughts, more summer and more spring-to-

summer consecutive droughts. There were more summer droughts and summer-to-autumn consecutive droughts in Central China. There were more summer and autumn droughts in East China. There were more spring droughts in Southwest China. There were more autumn droughts, winter droughts and autumn-to-winter consecutive droughts in South China. There were more spring-to-summer consecutive droughts in Northern China than that in Southern China, while there were more winter droughts in Southern China than in Northern China. This is directly related to the geographical environment and climate difference of the regions.

3.6. Variation in the Duration and Comprehensive Intensity of the Drought Processes

Figure 7a–g shows large fluctuations in both duration and comprehensive intensity of the regional drought processes in all seven regions of China.

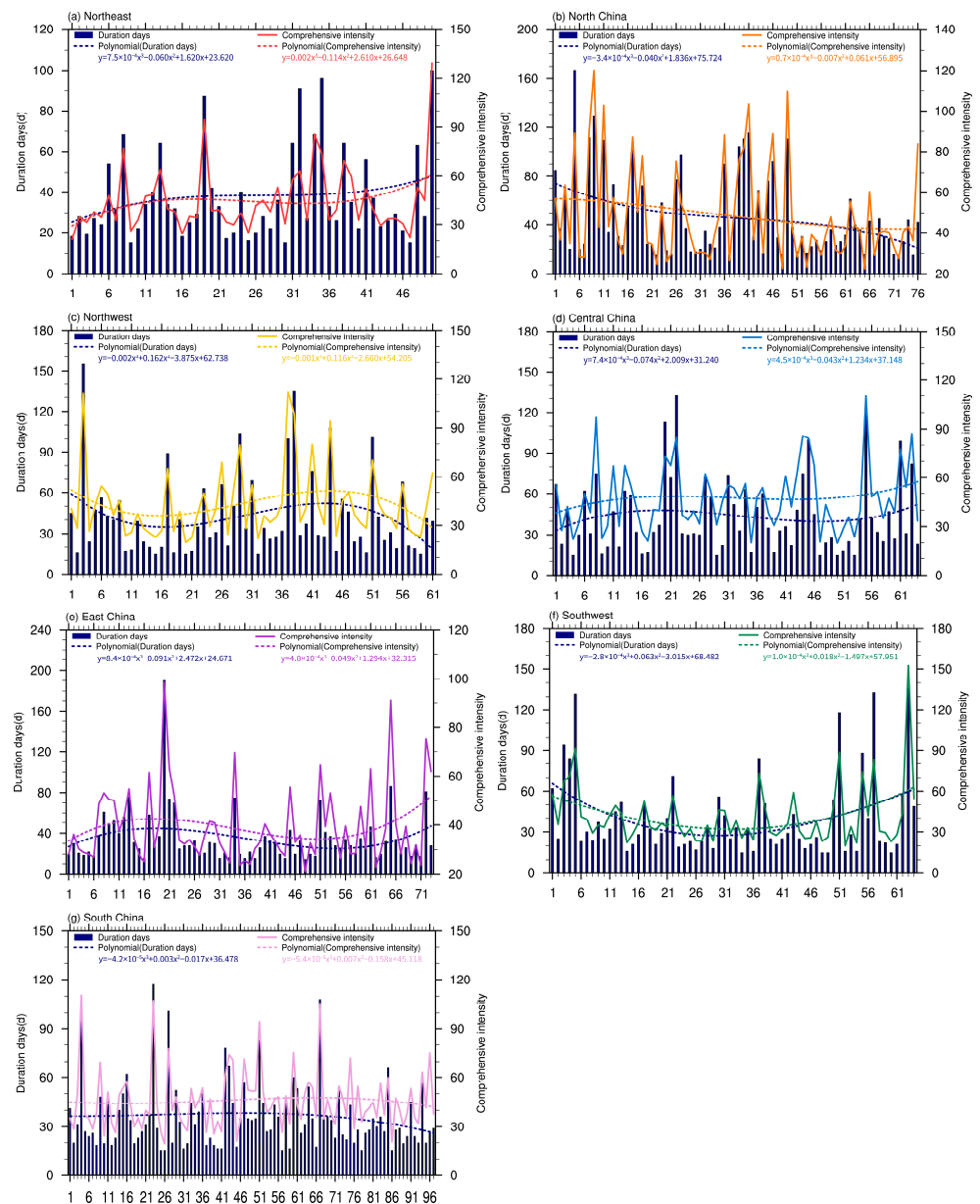


Figure 7. (a–g) Variation of duration and comprehensive intensity of regional drought processes in China 1961 to 2021.

In Northeast China, the mean and maximum durations were 38.0 days and 100 days, respectively, and the mean comprehensive intensity was 45.2 (maximum 129.4). Both the trendlines of duration and comprehensive intensity were cubic functions with positive cubic coefficients, thus in an upward spiral pattern. The correlation coefficient of duration with comprehensive intensity was 0.88914 (passed the 99% significance test). In North China, the mean and maximum durations were 45.6 days and 167 days, respectively. Its trendline was a cubic function with negative cubic coefficient, thus in a downward spiral type. Its determination coefficient (R^2) was 0.9159 (passed 95% significance test); the mean of comprehensive intensity was 48.4 (maximum 120.2). Its trendline was a cubic function with a positive cubic coefficient, the comprehensive intensity was in a trend of a forward-wave pattern, the determination coefficient (R^2) was 0.049 (passed 95% significant test) and the correlation coefficient of duration with comprehensive intensity was 0.9159 (passed 99% significance test). In Northwest China, the mean and maximum durations were 43.5 days and 155 days, and the mean and maximum comprehensive intensities were 43.1, and 111.9. All of their trendlines were cubic functions with negative cubic coefficients. The duration was in a downward spiral pattern, and the correlation coefficient of duration with comprehensive intensity was 0.9473 (passed the 99% significance test). In Central China, the mean and maximum durations were 43.5 days and 132 days and the mean and maximum comprehensive intensities were 47.6 and 109.9. All of their trendlines were cubic functions with positive cubic coefficients. The duration had an upward spiral trend and the correlation coefficient of duration with comprehensive intensity was 0.877 (passed 99% significance test). In East China, the mean and maximum durations were 35.4 and 190 days, and the mean and maximum comprehensive intensities were 39.4 and 98.5. Both of their trendlines of the two were cubic functions with positive cubic coefficients, and the duration trend was in an upward spiral pattern. The correlation coefficient of duration with comprehensive intensity was 0.877 (passed 99% significance test). In Southwest China, the mean and maximum durations were 43.5 days and 136 days, and its trendline was a cubic function with negative cubic coefficient, and presented an M pattern (large on two ends and small in the middle). Its determination coefficient (R^2) was 0.1386 (passed 95% significance test). The mean and maximum comprehensive intensities were 41.2 and 152.4, its trendline was a cubic function with positive cubic coefficient and also presented an M pattern, its determination coefficient of (R^2) was 0.0275 (passed 95% significance test) and the correlation coefficient of duration with comprehensive intensity was 0.932 (passed 99% significance test). In South China, the mean and maximum durations were 36.0 days and 117 days, the mean and maximum comprehensive intensities were 45.9 and 110.6, and their trendlines were all cubic functions with negative cubic coefficients, thus in a downward spiral pattern. The correlation coefficient of duration with comprehensive intensity was 0.8858 (passed 99% significance test). It could be observed that there was a strong correlation between the duration and the comprehensive intensity of the drought process in all seven regions of China. In addition all of them had passed the 99% significance test.

3.7. Variations in Annual Average Durations and Drought Affected Areas

The drought actual affected area data of each province in China during 1978–2020 come from China Statistical Yearbook, then the regional annual drought-affected areas were obtained. By combining this with the annual regional drought days calculated before, the variation characteristics of the drought-affected areas in each of the seven regions from 1978 to 2020 were obtained (Figure 8).

Evidently, the annual drought days in all of the seven regions of China had an inter-decadal variation. The annual drought days in Northeast China, North China and Northwest China peaked in the late 20th and early 21st centuries (129 days in 2001, 171 days in 1999 and 164 days in 1997, respectively). All their trendlines were quadratic polynomials with positive coefficients of quadratic terms, and presented the same pattern of being low at the two ends and high in the middle. Although the trend line in South China was similar, there were two peaks, one was in 2005 (215 days), and the other was in 1991 (178 days). In

Central China, however, the trendline was high at the ends, but low in the middle, and the highest value appeared in 1978 (150 days). The annual drought days in East China showed a downward trend, and the highest value appeared in 1978 (190 days). The annual drought days in Southwest China fluctuated little in the early stage, and the peak occurred in 2009 (228 days). The annual average drought days in seven regions were consistent with the change trend of the annual drought affected area. The correlation coefficients of the annual drought days with the annual drought affected area in Northeast China, North China, Central China, Northwest China and South China were 0.52, 0.54, 0.67, 0.65, 0.57 and 0.53, respectively. All of them passed the 99% significance test. The correlation coefficient of the annual drought days with the annual drought affected area in Southwest China was 0.27 (passed the 95% significance test). The analysis above revealed that all the regional drought process identified had strong correlation with the drought affected area, but not a strict one-to-one pattern. In some years, the difference was quite large (Figure 8). For example, in 2019, the annual drought days in East China reached 127 days, but the affected area was only 1667 km². As another example, in 2020, the annual drought days in Central China reached 113 days, but the affected area was only 216 km². The main reason is that the meteorological drought index only represents the lack of atmospheric moisture, rather than considers the status of the underlying crops. If the drought days in these years were mainly distributed in autumn and winter, during which the crops required less water, then the actual drought effected areas could be much smaller than the meteorologically calculated drought-affected areas. On the contrary, if a drought occurred in spring or summer during which the crops required more water, the actual drought affected area would increase significantly.

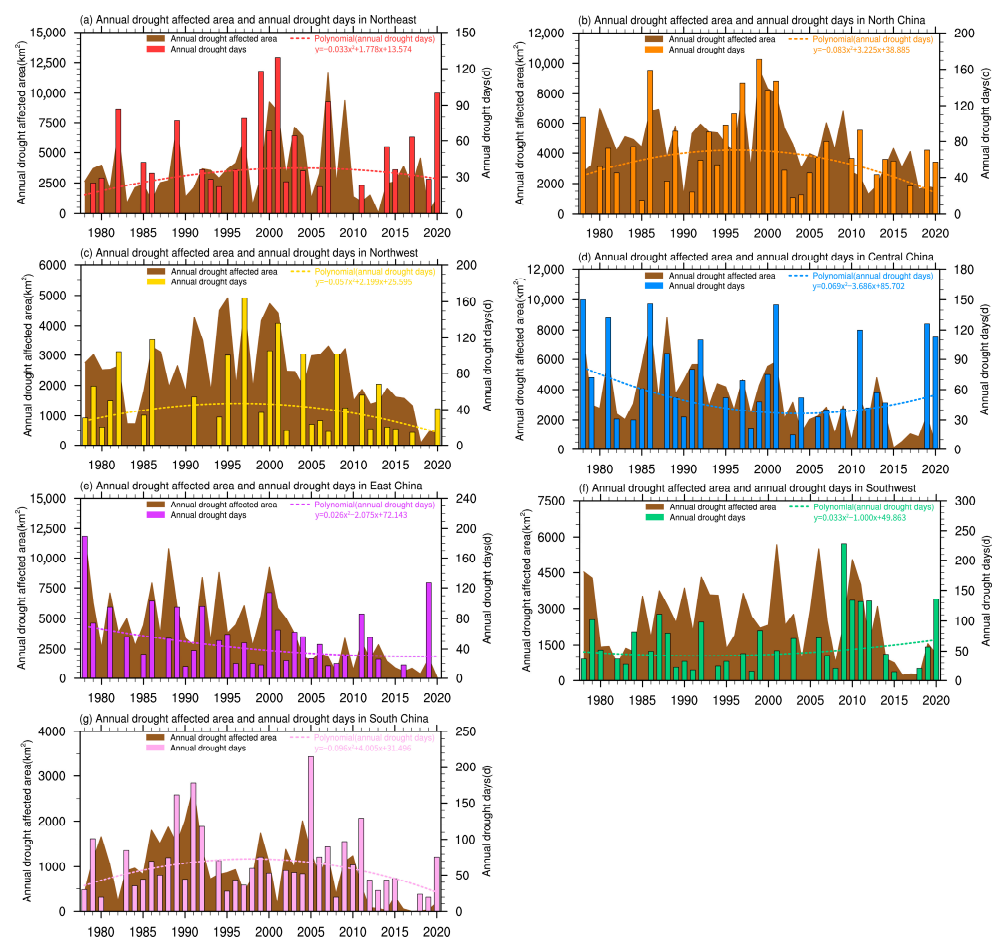


Figure 8. (a–g) Variation of annual average drought days and annual drought affected areas in all seven regions of China from 1978 to 2020.

3.8. The Relation of Drought Days with Regional Warming and Precipitation

In the past 60 years, the trend of aridity was significantly related to regional warming and precipitation changes (Figure 9).

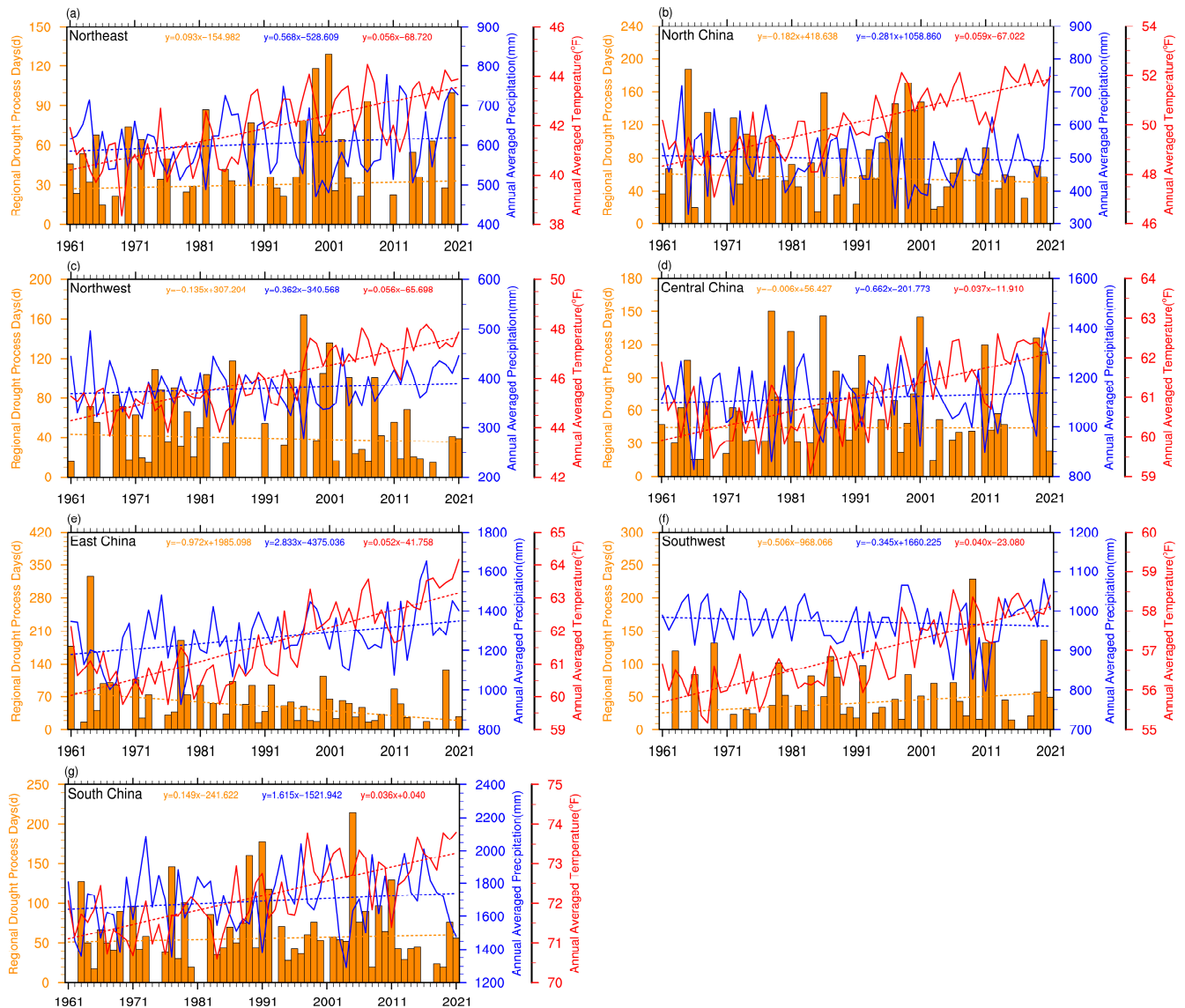


Figure 9. (a–g) Annual average precipitation and annual average temperature combined with drought days in the seven region of China from 1961 to 2021.

The multi-year average temperature in the seven regions of China falls in between 41.9°F and 72.2°F , and the maximum regional multi-year average temperature was between 44.4°F and 73.8°F . The annual averaged temperatures in all seven regions showed an upward trend and the linear slopes were 0.588 in North China, 0.588 in Northeast China, 0.561 in Northwest China, 0.519 in East China, 0.402 in Southwest China, 0.365 in Central China and 0.365 in South China. Generally, the temperature showed an upward trend, and most of the northern regions showed a significant warming trend. Most of North China, most of Northeast China and parts of Northwest China were the three regions with maximum temperature increments in the past 60 years, which increased about $32.72\text{--}33.44^{\circ}\text{F}/10\text{a}$. There was no significant warming or cooling trend in most of the areas of southern China. This is consistent with the research results of Zou et al. and Zhai et al. [51,52]. The inter-annual variations in annual precipitation in all seven regions of China were

significant. Before the 1980s and at the beginning of the 21st century, the average annual precipitation in China had a decreasing trend, while in the 1990s and from 2010 to 2021, the annual average precipitation in most regions had an increasing trend. The annual average precipitation of the regions was 379.3–1693.4 mm, and the maximum annual precipitation was 495.9–2089.0 mm. The linear slopes with positive coefficients for linear polynomials were 28.327 in East China, 16.149 in South China, 6.624 in Central China, 5.684 in Northeast China and 3.615 in Northwest China. The linear slopes for linear polynomials were -3.45 in Southwest China and -2.809 in North China. In general, from 1961 to 2021, for the annual average precipitation, all the regions of China presented weak increasing trends. The absolute value of correlation coefficients between the annual average precipitation and the annual drought days in all regions were in the range of 0.44–0.67, including -0.67 in Northwest China, -0.63 in Central China, -0.56 in North China, -0.54 in East China, -0.52 in South China, -0.49 in Northeast China, and -0.44 in Southwest China, and they all passed the 99% significance test. The drought days in all seven regions of China correspondingly changed with the increase or decrease in temperature and precipitation. For example, in 1982 in Northeast China, 1999 in North China, 1998 in Northwest China, and 1978 in Central China, the higher temperature was associated with less precipitation and more drought days. On the contrary, in 1968 in Southwest China and 1964 in East China, the lower temperature corresponded to more precipitation and less drought days. A deeper analysis showed that the regions with the most significant aridification trend were highly consistent with the regions that the temperature increase and precipitation decrease obviously, indicating that regional warming and precipitation reduction played an important role in the drought trend. Although northern China has tended to be more humid in recent years, due to the severe multi-year consecutive drought occurred in the end of the 20th century and beginning of the 21st century, the threats of drought are still serious in China [51]. Meanwhile, the drought area in southern China has tended to expand due to regional warming and decrease in precipitation. For example, in 2021, the precipitation levels in Guangxi, Guangdong, Fujian, and even southern Hunan and southern Jiangxi were unusually low, but the annual average temperature in these areas broke the highest record since 1961. Correspondingly, widespread and severe meteorological droughts occurred. For example, a moderate drought occurred in most areas of South China; meanwhile, a severe drought occurred in Guangxi, central and northern Guangdong, Hunan and southern Jiangxi.

4. Discussion

China is located in the Asian monsoon climate region, coupled with the complex terrain and landform, which means that China is one of the countries with the most serious drought disaster losses in the world [53]. This paper took seven regions of Northeast China, North China, Northwest China, Central China, East China, Southwest China and South China as the study areas. A new method was proposed that used the maximum cumulative weight intensity to represent the comprehensive intensity of the drought event process. We found this method can better identified the regional drought process in China than others. Compared with the methods of drought days or drought index accumulative amount and OITREE method, this method is simple and objective, and the results are more consistent with the actual situation of each regions. The regional drought process identification method and comprehensive drought intensity assessment technique presented in this paper has further application potential in drought event monitoring, assessment and early warning.

According to ‘the extreme intensity with both the duration and the region (EIDR)’ proposed by Lu et al. (2017) [46], the calculation method of the comprehensive intensity index was improved. However, the value of weight coefficient A in Formula (3) should be determined based on the analysis of drought affected objects, ecological environment and the drought disasters throughout history in different regions.

It is worth noting that there is no strict one-to-one correspondence between the monitoring results of the meteorological drought index and drought losses. Although drought disasters were mainly caused by meteorological drought, they are also related to many

factors, such as season, soil type, surface conditions and human activities, so not every meteorological drought event will eventually lead to disasters. However, the duration and comprehensive intensity of the regional drought processes obtained in this paper had a high correlation with the drought affected area. The results obtained in this paper are similar to those obtained by previous analyses based on precipitation and other drought indices [54–60] that indicated that the methods and results in this paper have higher credibility. However, in the application of drought real-time monitoring and drought intensity assessment, it is necessary to combine soil types and surface conditions for a comprehensive analysis. The causes of meteorological drought and formation mechanism of drought-induced disasters need to be further studied.

The evapotranspiration in the MCI index used in this paper is calculated by the Thornthwaite method, without considering the influence of factors such as sunshine and wind speed, which makes the evapotranspiration more affected by temperature and this needs to be further improved in the future studies.

Due to different time scales and different climatic factors in the different drought indices, there are uncertainties in the research results about the spatial and temporal distribution characteristics of drought. The north of China is dominated by the temperate monsoon climate, and the south is dominated by the subtropical monsoon climate, so the climate in southern China is evidently different from that in northern China, and the uncertainty of the assessment results is more obvious. The identification and assessment methods of regional drought processes, the selection of drought indices, the construction of comprehensive intensity indices, etc., still need to be optimized and improved in practical application.

5. Conclusions

In this study, a regional drought comprehensive intensity index was constructed based on MCI to calculate the regional drought days and was used to identify the drought process, and the EIDR method was used to calculate the comprehensive intensity of the drought event process. Using this technique, the spatial and temporal distribution characteristics and occurrence frequency of the drought event processes in China and seven regions were analyzed. The main conclusions are as follows:

The frequency of drought event processes in different regions of China was different, including 59% in Northeast China, 72.1% in North China, 70.5% in Northwest, 70.5% in Central China, 73.8% in East China, 65.6% in Southwest, and 80.3% in South China, respectively. South China ranked first, followed by Central China, and North China ranked third. By comparing the drought frequency of two periods (1961–1979 and 1980–2021) in each region, the results show that the annual frequency of drought processes in Northeast, Northwest and Central China have shown a decreasing trend and the decline was greatest in the northwest, about 18%. The frequency of drought processes in Southwest, South China, East China and North China all showed an increasing trend, especially in Southwest China, which increased by 35.9%, followed by South China, which increased by 19.4%.

From the frequency analysis of the consecutive drought year group from 1961 to 2021, it occurred in every region of China. Although the frequency of the consecutive drought year group in East China, South China and Southwest was lower, the consecutive years of drought were longer than other regions. It shows that against the background of global climate change, the scope of drought in China is constantly expanding. In the last century, drought disasters mainly occurred in the northern regions of China, but in recent years, the scope of drought disasters in China have expanded to Southwest and South China.

Through the study of the seasonal characteristics of drought processes in different regions, the results are as follows: Northeast China had more summer droughts and spring-to-summer consecutive droughts; North China and Northwest had more spring droughts, summer droughts, and spring-to-summer consecutive droughts; Central China had more summer droughts, and summer-to-autumn consecutive droughts. There were more summer droughts and summer-to-autumn droughts in East China; more spring

droughts in Southwest China; more autumn droughts, winter droughts, and autumn-winter droughts in South China; there are more winter drought in the south China than north China.

Through the analysis of drought duration in different regions, the results show that the droughts with a duration of more than 3 months in China were located in North China, Northwest, East China and Southwest, and the longest duration was more than 6 months. The trends of the average number of drought days and the areas affected by drought in each region of China were consistent with the actual drought disaster area; the more drought days, the greater the area affected by drought. The correlation coefficients were 0.52, 0.54, 0.67, 0.65, 0.57 and 0.53 in Northeast, North, central, northwest and South China, respectively and they all passed the 0.01 significance test. The correlation coefficient was 0.27 in southwest China, and passed the 0.05 significance test.

The results show the regions with the most significant aridification trends in China were highly consistent with the regions with the largest warming and precipitation reductions. Especially in areas with less precipitation, the number of days in the drought process was greater, and the absolute values of the correlation coefficients arranged in descending order were as follows: Northwest (−0.67), Central China (−0.63), North China (−0.56), East China (−0.54), South China (−0.52), Northeast (−0.49), and Southwest (−0.44). They all passed the 0.01 significance test. This indicated a strong correlation between the regional drought event processes obtained in this paper and the mean annual precipitation.

Author Contributions: Conceptualization, methodology and validation, X.C., C.Z. and Q.Z.; Software and data curation, Q.Z., C.Z. and W.Z.; Formal analysis, X.C., Q.Z., C.Z. and W.Z.; Investigation, J.S., C.C., W.F., Y.Y. and X.L.; Resources, Q.Z. and C.Z.; Writing—original draft preparation, X.C., Q.Z., C.Z., W.Z. and J.S.; Writing—review and editing, X.C., C.Z., Q.Z., W.Z., J.S., C.C., W.F. and Y.Y.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2020YFA0608203) and the Basic Research Fund (2021Z001) of Chinese Academy of Meteorological Sciences.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data analyzed in this study are subject to the following licenses/restrictions: the dataset can only be accessed from inside China Meteorological Administration. Requests to access these datasets should be directed to Xiuhua Cai, caixha@126.com.

Acknowledgments: We would like to thank Ren Guoyu, a researcher at the National Climate Center of the China Meteorological Administration, for his great guidance in the revision process of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CI	Compound Index of meteorological drought
EIDR	The extreme intensity with both the duration and the region
MI	Relative Moisture Index
MCI	Meteorological drought Composite Index
OITREE	Objective identification technique for regional extreme vents
Pa	Percentage of precipitation anomaly
PDSI	Palmer Drought Severity Index
SPI	Standardized Precipitation Index
SPEI	Standardized Precipitation Evapotranspiration Index
Z	Precipitation Z index
AFDP	Annual frequency of drought processes
GMVD	Group of multi-year drought

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