atmosphere

Article

# Relationship between Drought and Precipitation Heterogeneity: An Analysis across Rain-Fed Agricultural Regions in Eastern Gansu, China

**Suping Wang [1,2,*], Qiang Zhang [2,3], Jinsong Wang [1,*], Yuanpu Liu [1] and Yu Zhang [1]**

[1] Key Laboratory of Arid Climatic Change and Reducing Disaster of Gansu Province/Key Laboratory of Arid Climatic Change and Disaster Reduction, Institute of Arid Meteorology, China Meteorological Administration, No. 2070 Donggang East Road, Chengguan District, Lanzhou 730020, China; liuyp@iamcma.cn (Y.L.); zhangy@iamcma.cn (Y.Z.)

[2] College of Atmospheric Sciences, Lanzhou University, No. 222 Tianshui South Road, Chengguan District, Lanzhou 730000, China; zhangqiang@cma.gov.cn

[3] Meteorological Bureau of Gansu Province, No. 2070 Donggang East Road, Chengguan District, Lanzhou 730020, China

* Correspondence: wangsp@iamcma.cn (S.W.); wangjs@iamcma.cn (J.W.)

**Abstract:** Based on daily meteorological data from 55 meteorological stations in eastern Gansu from 1960 to 2017, the characteristics of the drought process and precipitation heterogeneity were analyzed, and the relationship between drought and precipitation heterogeneity was evaluated. Results showed that there were 1–3 drought processes in the study area every year. Drought processes in the eastern and north-central regions were more frequent than those in other regions. Droughts were mainly manifested as intra-seasonal droughts, especially across the spring and summer. PCD (Precipitation Concentration Degree, the concentration degree of the precipitation at a certain time) ranged from 0.2 to 0.7 in the area. PCD increased in spring and autumn but decreased in summer and winter for most regions from 1960 to 2017. PCP (Precipitation Concentration Period, the shortest time which the precipitation was concentrated in) was from late April to early May in spring, mid-to-late July in summer, mid-September in autumn, and late January in winter. In the last 58 years, PCP has remained consistent in most regions, varying by approximately 10 days. In addition to insignificant changes in winter, the days with light and moderate rain presented a declining trend, especially in summer and autumn. The larger the PCD, the fewer the days with light and moderate rain, and the stronger the drought intensity. However, in the east-central region, the larger the PCD in autumn, the weaker was the drought intensity. This difference is related to the PCP and the evapotranspiration. Additionally, the later the PCP, the stronger was the drought intensity, particularly in summer and autumn. When PCD was $\geq$0.5 in spring and $\geq$0.4 in summer, the PCP was after May and August in spring and summer, respectively. Droughts appeared in 28–56% of periods when seasonal precipitation was above normal. When PCD was $\geq$0.5 in autumn and PCP was in early and middle September, droughts appeared in 7% of periods when precipitation was above normal. Our results show that although less precipitation is the leading influencing factor of drought in the dry rain-fed agricultural areas, the influence of precipitation heterogeneity should be also considered for the prediction and diagnosis of seasonal drought.

**Keywords:** drought; precipitation heterogeneity; rain-fed agricultural region; eastern Gansu

check for updates

**Citation:** Wang, S.; Zhang, Q.; Wang, J.; Liu, Y.; Zhang, Y. Relationship between Drought and Precipitation Heterogeneity: An Analysis across Rain-Fed Agricultural Regions in Eastern Gansu, China. *Atmosphere* **2021**, *12*, 1274. https://doi.org/10.3390/atmos12101274

Academic Editor: Peter Domonkos

Received: 24 August 2021
Accepted: 27 September 2021
Published: 29 September 2021



## 1. Introduction

Drought is the most common and serious meteorological disaster in China and globally [1–4]. Drought disaster loss accounts for over 15% of total natural disasters every year in China [5]. Furthermore, drought areas can be as high as 57% of the total natural disaster area [6]. Under global warming, the drought situation is worsening. In China, the response is more sensitive, as droughts show a trend of increasingly larger affected areas, greater frequency, and aggravated disasters in the recent half-century [7,8]. The rate of comprehensive losses caused by agricultural drought has increased by 0.5% every decade, with an overall growth of nearly 10% [9]. In the next 30 years, drought in China is predicted to become more frequent and serious [10].

Eastern Gansu is in the northwest inland region of China. Water resources are relatively deficient, and the ecological environment is vulnerable. Drought disasters are most likely to occur in this region, which is also the driest among regions with the same latitude globally [11]. The economic losses due to drought reach 4–6% of GDP every year, which is much higher than that of other regions in China. Meanwhile, eastern Gansu is also a climate-change-sensitive region. In recent decades, the tendency for increased aridity has been significant in this region, especially with increasing temperatures since the 1990s. Drought is especially severe throughout the region [7,8,12], and there appear to be a series of outstanding problems affecting sustainable development, such as water shortages in agriculture, industry, ecology, and residential living. These challenges include grain reduction, vegetation degeneration, land desertification, and the increasing scarcity of safe drinking water for humans and animals. In addition, compared to the notably dry Northeast and North China over the past half-century, this region has become increasingly drier [13,14]. Drought has been a critical natural factor that has restricted agricultural production, economic and social development, and ecological growth in these areas. It is important for disaster prevention and reduction, and sustainable economic and social development to recognize more fully the occurrence and development mechanisms of drought in the region.

Drought is an abnormal water shortage caused by an imbalance in the water budget. Both positive temperature and negative precipitation anomalies can contribute to drought developments. Increasing temperature increases evapotranspiration and accelerates water expenditure, while decreasing precipitation reduces water income. The amount of precipitation is the most crucial factor affecting drought. Drought readily occurs with low precipitation. However, precipitation variables include both the amount and its distribution. For a certain period, whether an area experiences drought is not only related to the amount of precipitation, but also to the concentration, intensity, and frequency of that precipitation [15,16]. If the PCD is greater and precipitation in the PCP is greater, flood disasters more readily occur, while droughts may occur in the other periods. Thus, even in humid regions with abundant precipitation or rainy seasons with more precipitation, serious droughts can occur. For example, the humid regions of southern China have experienced frequent droughts in recent years [17]. Moreover, even in the same region, under the same precipitation amount or precipitation anomaly percentage, the distribution of that precipitation may result in different degrees of drought and flooding [18]. Thus, the spatial and temporal changes in PCD and PCP are also worth considering. With an increase in concentration degree and heterogeneity of precipitation distribution, the probability of droughts and floods will also increase. Meanwhile, the delay and advance of the PCP and the change in precipitation intensity also have important effects on regional droughts and floods [19]. Some research suggests that weak precipitation events are closely associated with droughts [20]. Drought is more closely related to a reduction in the frequency and intensity of precipitation than it is to receiving less than moderate rainfall [21,22]. The decrease in weak precipitation is a cause of frequent drought disasters in the Changjiang-Huaihe River Valley and in southern China. Other researchers have confirmed the relationships between notably arid regions and the regions with reduced seasonal and annual moderate and light rainfall [23–25].

Previous research on the relationship between precipitation and drought also focused on the amount of precipitation and the development of droughts [26–28]. They mostly discussed the relationship from the perspectives of total precipitation, variation in precipitation amounts, and the tendency of drought occurrence. Few studies have examined the relationship between precipitation heterogeneity and meteorological droughts and floods. The effects of precipitation concentration and rainfall intensity on droughts have not been considered.

The eastern part of Gansu Province is a typical rain-fed farming region that relies on precipitation. Natural precipitation is the only source of water for agricultural production and life. Since the late 20th century, regional precipitation has declined significantly. Precipitation heterogeneity has changed dramatically and PCD has increased [29,30]. The reduction in light to moderate rain is significantly greater than that in the arid regions of Northeast, North, and Southwest China [22]. In addition, there are regional and temporal differences in the variation in regional precipitation heterogeneity [22,29,30]. The complexity and uniqueness of precipitation amounts, PCD, and precipitation intensity changes will inevitably influence the development of regional droughts. Other climatic factors needing further study include: the relationships between drought and precipitation intensity, variation of PCD, and delay or advance of the PCP within specific periods of time; the regional and temporal differences in these relationships; and determining the regions or periods of time most affected by precipitation heterogeneity.

This paper aims to focus on the effects of PCD, PCP, and precipitation intensity on drought in eastern Gansu within an overall warming climate trend. The relationships between precipitation amount and intensity, as well as the heterogeneity of precipitation with drought are discussed. Additionally, the response of regional drought to variations in precipitation heterogeneity was also investigated. The study is conducive to a deeper understanding of the relationship between climate change and drought-influencing factors. It can also provide scientific guidance for the composition and quantitative evaluation of regional-drought-influencing factors. This has an important scientific guiding significance for regionally accurate drought monitoring, prediction, and warning, and disaster prevention and reduction.

## 2. Data and Methods

### *2.1. Data*

The climate in the study area is characterized as Dw (snow climate with dry winter) according to the Köppen–Geiger classification [31]. Annual precipitation is between 200 and 700 mm, and the precipitation in the north is less than that in the south. Daily meteorological data including air temperature, precipitation, wind velocity, sunshine hours, and relative humidity of 55 meteorological stations in eastern Gansu province from 1960 to 2017 were used in this study. The data were derived from the meteorological data sharing network of the China Meteorological Administration, and homogenization and quality control checks, such as the time consistency, space consistency, extreme value check, climate limit value, or allowable value check, were performed [32–34]. Figure 1 shows the distribution of the study area, meteorological stations, and annual average precipitation in the region.

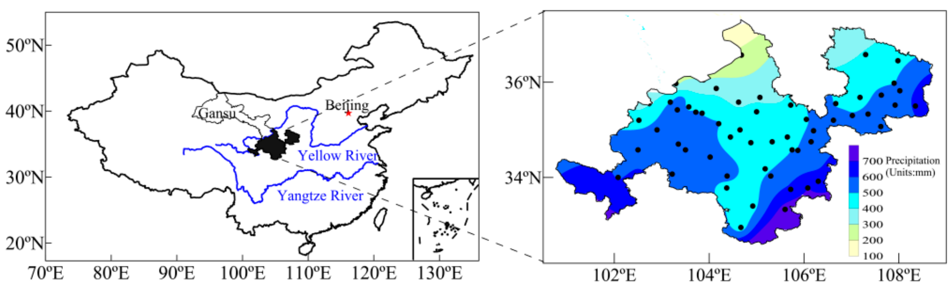


**Figure 1.** Distribution of annual average precipitation (mm) and the location of the study area, meteorological stations (black spots).

### *2.2. Methods*

#### 2.2.1. Recognition of Drought and Drought Processes

The comprehensive meteorological drought index (MCI) [35] was used as the criterion to judge drought. Precipitation and evapotranspiration at different time scales at earlier stages are comprehensively considered in MCI. It has been widely applied in drought monitoring and research in different regions of China [36,37]. The equation for MCI is shown as [35]:

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

where $SPIW_{60}$ is the standardized weighted precipitation index over the previous 60 days; $MI_{30}$ is the relative moisture index over 30 days; $SPI_{90}$ and $SPI_{150}$ are the standardized precipitation indices for the previous 90 and 150 days, respectively; and a, b, c, and d are the weight coefficients and are 0.3, 0.5, 0.3, and 0.2, respectively.

SPIW can be calculated as follows [35,38]:

$$WAP = \sum_{n=0}^{N} a^n P_n \quad (2)$$

where WAP is the weighted cumulative precipitation (mm), $P_n$ is the precipitation on the Nth day before the current day, N is the length of a certain period (days), and $\alpha$ is the contribution parameter. When N is 60 days, $\alpha$ is 0.85. The SPIW index is obtained by standardizing WAP:

$$SPIW = SPI(WAP) \quad (3)$$

MI can be calculated as follows [35]:

$$MI = \frac{P - ET_0}{ET_0} \quad (4)$$

where P is the precipitation during the period (mm), and $ET_0$ is the potential evapotranspiration during the period (mm), which is calculated by FAO Penman–Monteith [39]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (5)$$

where Rn is the net radiation at the crop surface ($MJ \cdot m^{-2} \cdot d^{-1}$); G is the soil heat flux density ($MJ \cdot m^{-2} \cdot d^{-1}$), which is the energy utilized in heating the soil (for day periods, it may be ignored, i.e., $G \approx 0$); $\gamma$ is the psychrometric constant ($kPa \cdot {}^\circ C^{-1}$); $\Delta$ is the slope of the vapor pressure curve versus temperature ($kPa \cdot {}^\circ C^{-1}$); $e_s$ is the saturation vapor pressure (kPa); $e_a$ is the actual vapor pressure (kPa); and $U_2$ is the wind speed at 2 m height ($m \cdot s^{-1}$), which is converted from the wind speed at 10 m height.

The SPI is developed by fitting precipitation to a Gamma distribution, which is then transformed to a normal distribution with the mean of zero and variance of one. The detailed computation procedure can be found in reference [40].

The categorization of drought by MCI is shown in Table 1.

**Table 1.** Categorization of drought by MCI.

| Grade | Drought Category | MCI |
|---|---|---|
| 1 | No drought | $-0.5 < MCI$ |
| 2 | Light drought | $-1.0 < MCI \leq -0.5$ |
| 3 | Moderate drought | $-1.5 < MCI \leq -1.0$ |
| 4 | Severe drought | $-2.0 < MCI \leq -1.5$ |
| 5 | Extreme drought | $MCI \leq -2.0$ |

A drought process is a drought that lasts for a certain period of time at a single station or over an area. According to the national standard Classification of Meteorological Drought [41], when the MCI exceeds the light drought threshold for 10 consecutive days, a drought process is determined. The beginning day is the first day the MCI reached the light drought category. If the MCI falls within the no drought category for 10 consecutive days, the drought is considered to be relieved and the drought process over. The process end day is the last day the MCI remains in the no drought category. The period from the beginning of light drought to the end of no drought is the duration of the drought process. Drought intensity (DS) is the sum of MCI values at and above the light drought threshold during the entire drought process. The equation is shown as:

$$\begin{gathered} \mathrm{DS} = \sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{MCI_i} \\ \text{when } \mathrm{MCI_i} \leq -0.5 \end{gathered} \tag{6}$$

where n is the duration of the drought process.

When evaluating whether a drought event occurs in a certain period (year, season, month), there must be at least one drought process in the evaluation period. Furthermore, the cumulative drought duration should exceed 1/4 of the evaluation period. The drought intensity is determined by the sum of the MCI index above mild drought during this period [41].

Seasons are classified as: spring (March to May), summer (June to August), autumn (September to November), and winter (December to February). For the extra-seasonal drought process, if the pre-season or post-season stride does not exceed 5 days, the season encompassing those 5 days will not be counted. If the span is longer than 5 days, the season should be included.

### 2.2.2. PCD and PCP

Precipitation Concentration Degree (PCD) and Precipitation Concentration Period (PCP) could quantificationally represent the spatial-temporal heterogeneity of the precipitation. PCD reflect the precipitation concentration level during a certain time, and PCP is defined as the shortest time in which the precipitation was concentrated. Zhang et al. [17] regarded the precipitation amount as the length of the vector, while the corresponding period of 10 days is seen as the direction of the vector. Thus, parameters characterizing the time distribution features of the precipitation amount at a station are defined as PCD and PCP:

$$\mathrm{PCD} = \frac{\sqrt{\mathrm{R_{xi}^2} + \mathrm{R_{yi}^2}}}{\mathrm{R_i}} \tag{7}$$

$$\mathrm{PCP} = \arctan\frac{\mathrm{R_{xi}^2}}{\mathrm{R_{yi}^2}} \tag{8}$$

$$\mathrm{R_{xi}} = \sum\nolimits_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{r_{i,j}}\ .\ \sin\theta_{\mathrm{j}}\right),\ \mathrm{R_{yi}} = \sum\nolimits_{\mathrm{j}=1}^{\mathrm{n}} \left(\mathrm{r_{i,j}}\ .\ \cos\theta_{\mathrm{j}}\right) \tag{9}$$

where n is the total precipitation amount at a station during the research period, $\mathrm{r_{i,j}}$ is the precipitation amount at a station over 10 days during the research period (precipitation amount in the jth period of the ith year), $\theta_j$ is the azimuth corresponding to each period of 10 days, i is the year (i = 1960, 1961, ... 2017), and j is the sequence of a period of 10 days during the research period (j = 1, 2, ... 36).

PCD ranges from 0 to approximately 1. The closer PCD is to 1, the higher the concentration degree, while the closer it is to 0, the more homogeneous the distribution of precipitation during the research period. Taking an extreme example, if the annual precipitation occurs only in a certain 10 days of a year, the ratio of the synthetic component with respect to the annual precipitation would be 1, the maximum value the PCD can approach. On the contrary, if the total precipitation of each 10 days within a year is evenly distributed, the PCD will reach the minimum 0. The PCP is the direction angle of the total synthetic component, pointing out the total effect of the synthesized 10 days' precipitation and also representing the mean angle of the total synthesizing vector. For the calculation of PCP, the azimuth was set to 360° during the research period (one season in this study). In a season, the interval was 40° between each period of 10 days. For example, in March of spring, the first period of 10 days corresponds to 0–40°, the second corresponds to 40–80°, and so on, and the third period of 10 days in May corresponds to 320–360°. In the other three seasons, the azimuths corresponding to each period of 10 days were determined similarly.

#### 2.2.3. Statistics of the Number of Precipitation Days in Different Drought Grades

According to the definition of the China Meteorological Administration, light rain days are identified as those with daily precipitation greater than or equal to 0.1 mm but less than 10.0 mm, moderate rain days are those with precipitation of 10.0 to 24.9 mm, heavy rain days have precipitation of 25.0 to 49.9 mm, and torrential rain days have more than 50.0 mm of precipitation. Rainy days are defined as the number of days with precipitation greater than or equal to 0.1 mm. The departure of the days with light and moderate rain (PD) was calculated based on the average days from 1981 to 2010, that is, $PD = D - D_{1981–2010}$, where D is the days with light and moderate rain in a certain period and $D_{1981–2010}$ is the average days in that period from 1981 to 2010.

## 3. Results and Discussions

### *3.1. Characteristics of Drought*

#### 3.1.1. Characteristics of the Drought Process

Figure 2 shows the average number of annual drought processes in the study region from 1960 to 2017. The results show that there were 1–3 drought processes per year in the study region, and drought processes in the eastern and central regions were higher than in the other regions.

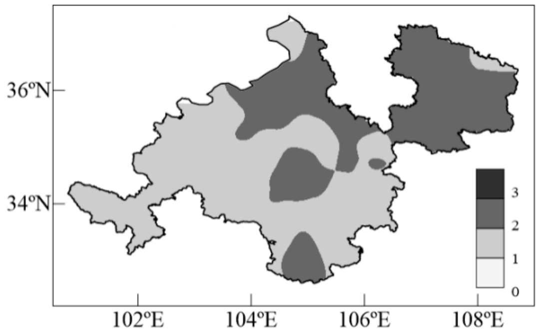


**Figure 2.** Average number of drought processes from 1960 to 2017 (numbers/per year).

The average drought duration was approximately 2 months in the period from 1960 to 2017 (Figure 3a). Average duration was less than 50 days in most southwestern regions, while the persistent period lasted 50–60 days in other regions. The longest drought process lasted for 180–270 days (Figure 3b), that is, continuous drought for 2 to 3 seasons. The longest drought process that occurred in the northern and southern regions lasted for 389 days. The droughts occurred from November 1979 to December 1980 and from January 1996 to February 1997, respectively, and began in autumn or winter and continued over a year.

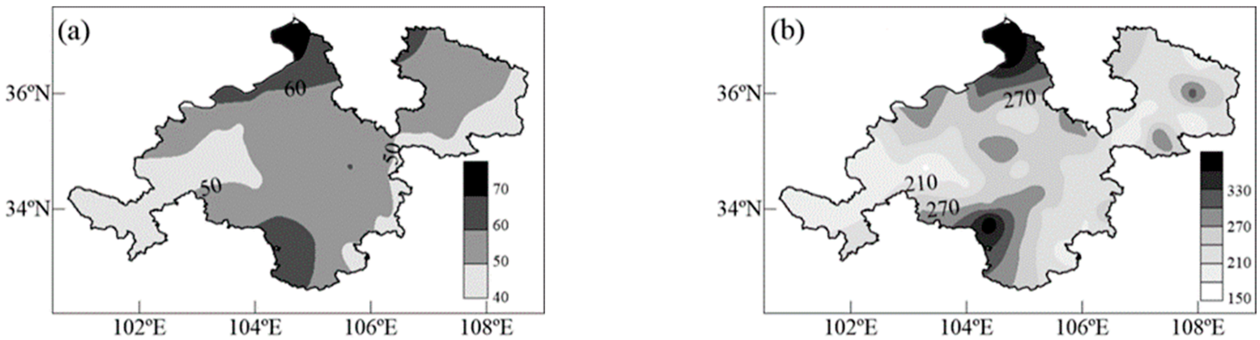


**Figure 3.** Average (**a**) and longest duration (**b**) of drought processes from 1960 to 2017 (days).

As shown in Figure 4a, average drought intensity in 1960 to 2017 was high in the north-central regions (−75.8), followed by the southwestern and some south-central regions (approximately −68). The maximum intensity of drought processes in the study area occurred in the central and eastern regions (Figure 4b). In the eastern areas, the most serious drought process occurred from 10 March 1995 to 11 January 1996. The cumulative intensity of the drought process reached up to −482.9 and lasted for 273 days. The second most serious drought occurred in the south-central region, from 1 June 1997 to 10 March 1998. The cumulative intensity was −464.4, and the drought lasted for 280 days. Additionally, in some of the middle regions, a stronger drought with a cumulative intensity of −430 to approximately −440 also occurred.

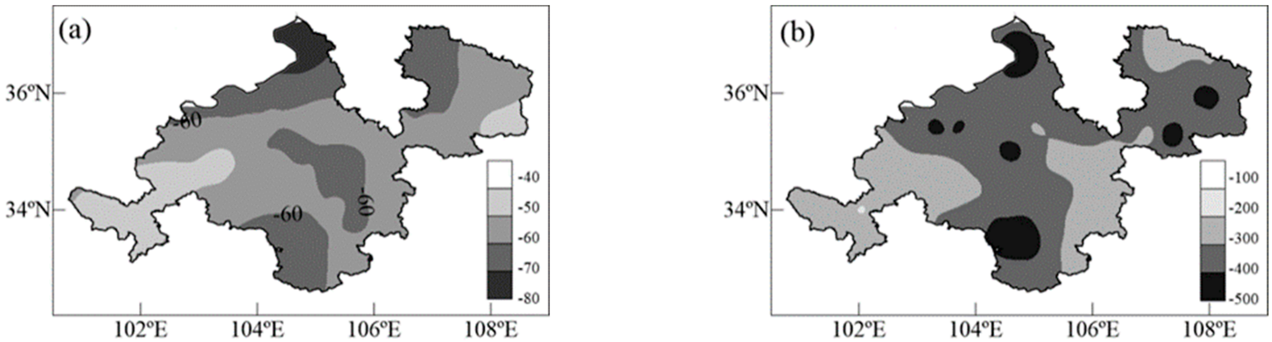


**Figure 4.** Average (**a**) and maximum intensity (**b**) of drought processes during 1960–2017.

3.1.2. Frequency of Different Types of Drought Processes

To further understand the main periods and regions of the drought process, the occurrence frequencies of different drought processes were determined. Spring drought refers to droughts confined to the months from March to May, while the spring-to-summer droughts are bounded by the months from March to August. The summer-to-autumn-to-winter drought spans two seasons from June of one year to February in the following year. Other drought types are similarly described. As shown in Figure 5, spring and summer droughts were the main types in the study area. The frequency of spring droughts was 24–58%, and they occurred approximately once every 3 years in most regions. In some of the north-central regions, the frequency was over 45%, and they occurred approximately once every 2 years (Figure 5a). The frequency of summer drought was 20–35%, and these occurred approximately once every 3–4 years. In the southeast and some of the middle regions, the frequency was slightly higher at once every 3 years (Figure 5b). Autumn droughts occurred with the least frequency among the four seasons (20.4% on average). Droughts occurred in the north-central and south-east regions slightly more often than in the other regions (25% to 30%, or approximately once every 4 years, Figure 5c). Winter droughts occurred with a frequency of 10–30%. The high-frequency region was located in the east-central region. There, the frequency was more than 25% and approximately once every 4 years (Figure 5d). The frequency of a continuous drought occurring during two seasons was 10–20%, or once every 5–10 years. The high-frequency region for spring-summer continuous droughts was the north-central and some of the eastern regions, where the frequency was above 20% and they occurred once every 5 years. There was a minimum frequency in the southwestern regions, which was 10–15% and approximately once every 7–10 years (Figure 5e). For summer-autumn continuous droughts, the high-frequency region was in the eastern and some of the south-central regions, and the frequency was 20–25% (Figure 5f). The north-central parts were the high-frequency regions for autumn-to-winter continuous droughts. The frequency ranged from 20% to 25% and occurred approximately once every 5 years (Figure 5g). The winter-spring continuous droughts occurred the least. However, the frequency in the south-central region was the highest and was 15–20%, or once every 5–7 years (Figure 5h). On average, continuous drought spanning three seasons had a frequency of approximately 6%. Continuous drought from summer to winter occurred most frequently. The frequency was approximately 5–10%, or once every 10–20 years. The north-central region had a high frequency of 10–15% (Figure 5i).

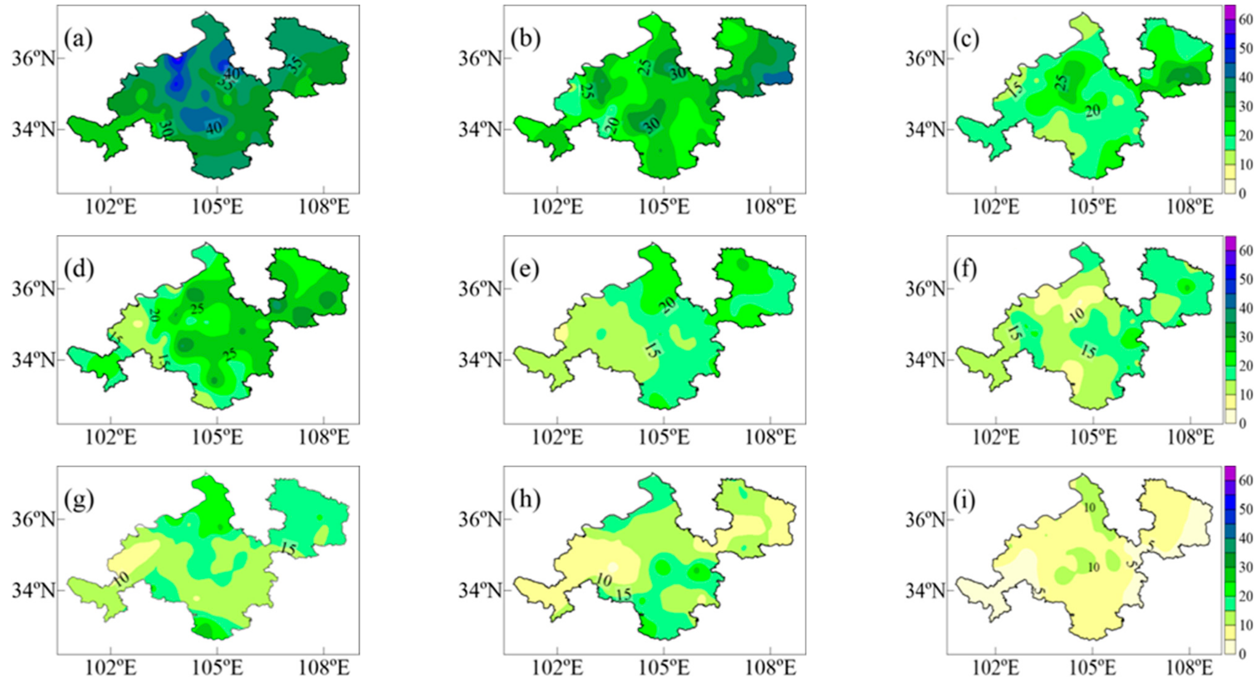


**Figure 5.** Frequency of different types of drought processes from 1960 to 2017 (%) ((**a**–**d**) are intra-seasonal droughts in the following order: spring drought, summer drought, autumn drought, and winter drought; (**e**–**h**) are extra-seasonal droughts in the following order: spring-summer, summer-autumn, autumn-winter, and winter-spring continuous drought; and (**i**) is the drought from summer to winter).

Figure 6 shows the percentage and cumulative percentage of different types of drought processes in the study area. Spring droughts accounted for a higher percentage than the other types. The average percentage was 7% for continuous drought during two seasons, and only 1–4% for continuous drought spanning three seasons. Continuous drought from summer to winter was slightly higher. Considering cumulative drought percentages, seasonal drought in the study area accounted for 61.4% of the total drought processes, and continuous droughts spanning two and three seasons accounted for 30.6% and 8%, respectively. The intra-seasonal drought process was the main regional drought process.

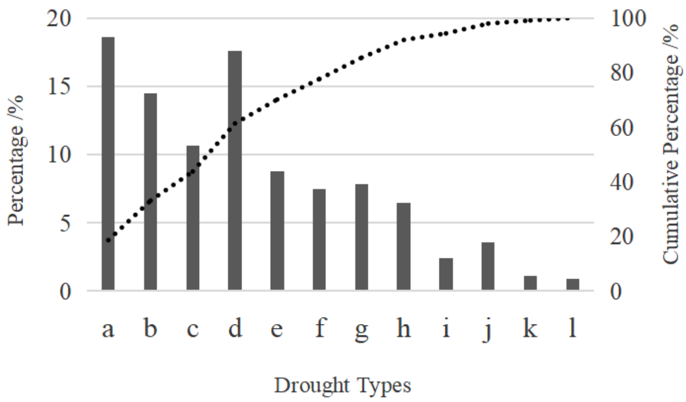


**Figure 6.** Percentage distribution and cumulative percentage distribution of different types of drought processes (a–d are intra-seasonal droughts in the following order: spring drought, summer drought, autumn drought, and winter drought; e–h are extra-seasonal droughts in the following order: spring-summer, summer-autumn, autumn-winter, and winter-spring continuous drought; and i–l are the drought processes that lasted for 3 seasons from spring, summer, autumn, and winter, respectively).

### 3.1.3. Distribution Characteristics of Seasonal Drought Processes

The annual distribution and average duration of drought in the study area are shown in Figure 7. The results show that in the study area, spring and summer droughts were more frequent than droughts in other seasons. Furthermore, most of the drought processes began in early spring (March–April) and mid-summer (July–August). The average duration was 60 days. Most autumn and winter droughts started at the end of autumn (middle and late November) and in the middle of winter (middle January). The drought processes lasted for approximately 40 days. The early spring (March–April) and middle summer (July–August) were critical periods for the growth of winter wheat and spring corn in the study area. Drought in these periods was unfavorable for agricultural production [42].

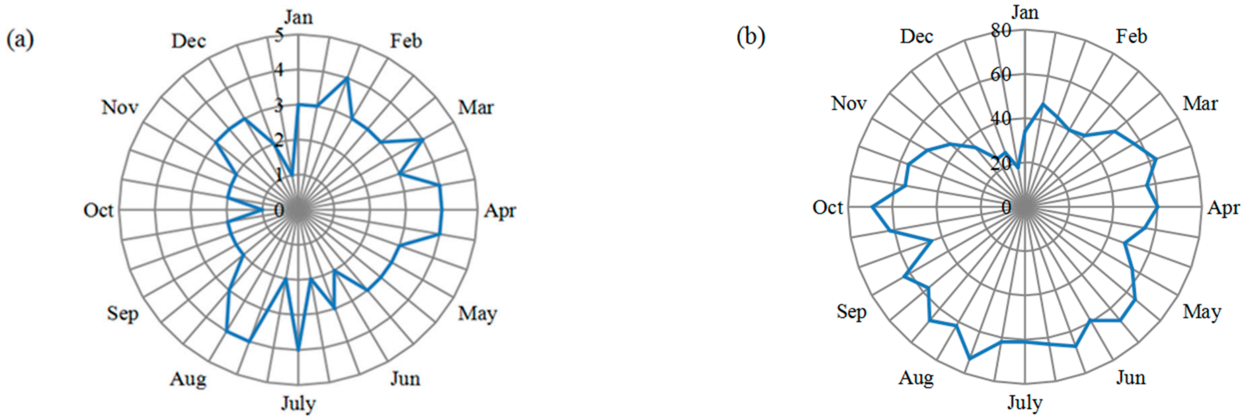


**Figure 7.** Beginning of drought process (**a**: stations/year) and multi-year mean of average duration (**b**: days).

## 3.2. Analysis of Precipitation Heterogeneity Characteristics

Figure 8 shows the PCD, PCP, and their trends in each season. The distribution and variation of PCD are shown in Figure 8a–d. PCD in the study area varied from 0.2 to 0.7. In the middle and southeastern regions, it was slightly smaller than in the other regions. Among the four seasons, the regional difference in PCD was relatively small, and precipitation was more homogeneous in summer. In the other three seasons, PCD was higher, and the regional differences were clear. Over the past 58 years, PCD in the middle and eastern areas has increased in the spring. Precipitation heterogeneity became evident, thereby causing drought and flood events more readily. In summer, except for the southwest, PCD generally declined in the remaining areas, and the precipitation tended to be homogeneous. However, the precipitation in the southwestern regions grew more concentrated, and the heterogeneity increased. In summer, owing to high temperatures and intense evaporation, if the precipitation tends to concentrate, precipitation will decrease and evaporation will increase during the non-concentrated period, while the likelihood of drought will also increase. In autumn, PCD showed an increasing trend, and heterogeneity also increased. However, in winter, PCD decreased, and the precipitation was distributed homogeneously. Precipitation was less in the study area during winter. Limited precipitation was distributed homogeneously in each period. Cumulative droughts occurred because of insufficient water.

The distribution and trend of the PCP (Figure 8e–h) showed that the PCP in spring was from late April to early May, and the rainy season in the east was approximately 10 days earlier than that in the other regions. In summer, the PCP was in middle and late July, and the rainy season in the easterly and northerly regions was 10 days later than in the other regions. The PCP occurred in mid-September in autumn and late January in winter. In the last 58 years, the PCP has not changed significantly in most of the study area (less than 15°). This indicates that PCP changes were limited to 10 days. However, there was also a significant delay in the PCP in local regions, such as the middle and southwestern regions in spring and middle regions in winter.

Drought is strongly related to the reduction in the frequency in light and moderate rain [2,20]. Figure 9a–d shows the distribution and the trend of the days with light and moderate rain during 1960 to 2017. Except for winter, most of the days with light and moderate rain were approximately 20–40 days per season. The southwest had more days with light and moderate rain than easterly and northerly regions. In the last 58 years, in addition to the insignificant change in winter, days with light and moderate rain showed a declining trend in the other seasons, especially in summer and autumn. Precipitation amount and the days with light and moderate rain in summer and autumn decreased significantly (figure not shown), but the number of heavy rain days increased in the study area over the last 58 years. Precipitation heterogeneity was enhanced, and both drought and flood risks increased.

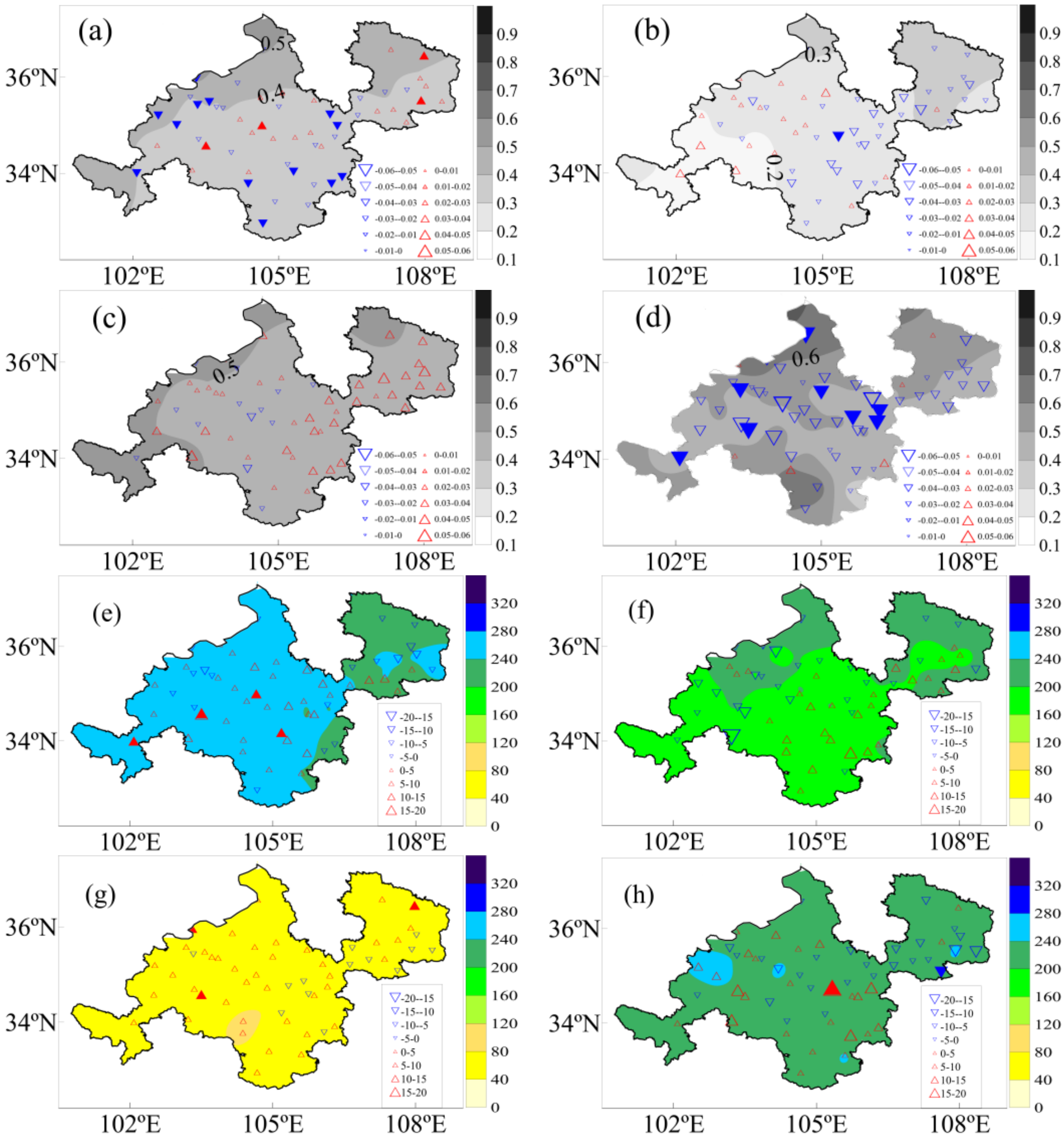


**Figure 8.** Average precipitation heterogeneity and its trend in each season. ((**a**–**d**) are PCD in spring, summer, autumn, and winter, respectively; (**e**–**h**) are PCP in spring, summer, autumn, and winter, respectively; solid indicates the trend is significant at the 0.05 level based on the Student's *t*-test).

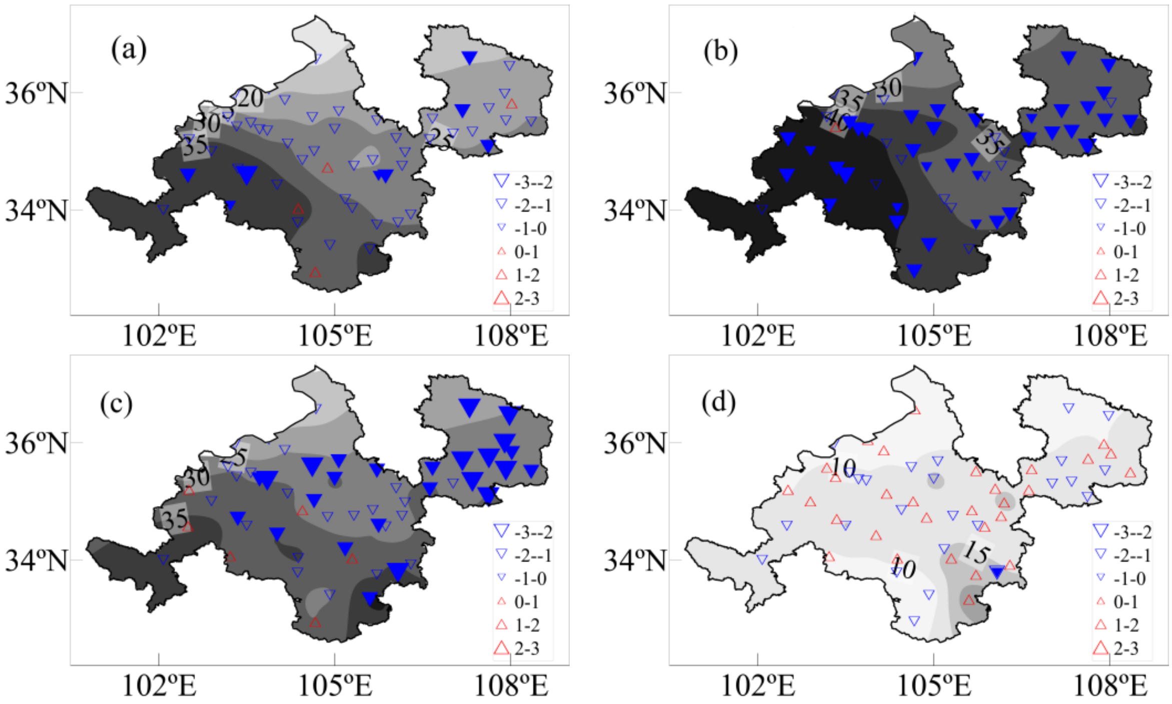


**Figure 9.** Average days with light and moderate rain and its trend in each season ((**a**–**d**) are spring, summer, autumn, and winter, respectively; solid indicates the trend is significant at the 0.05 level based on the Student's *t*-test).

Much of China has experienced a decline in the days with light and moderate rain in recent decades [25], which may be related to warming and a decrease in cloud cover. Fu et al. [13] suggested that higher temperatures could increase the condensation height of precipitable clouds and reduce cloud cover so that light rainfall days are in turn reduced. The study area has experienced a warming climate in recent decades [28]. Therefore, the influence of the decrease in cloud cover and days with light and moderate rain caused by warming on regional dry-wet cycles should not be ignored.

### 3.3. *Connection of Drought Intensity with Precipitation Amount and Heterogeneity*

There are two possible scenarios to explain the relationship between precipitation heterogeneity and drought. One scenario involves less precipitation. When precipitation frequency is irregular, cumulative drought may occur due to the long-term water deficiency. When precipitation is concentrated, drought may also occur during the non-centralized stage. This is more common in the arid and semi-arid regions of northern China. In the second scenario, when the total amounts of precipitation are sufficient, but events are concentrated, drought occurs in the non-concentrated periods because of the strong demand for evapotranspiration. This kind of drought readily occurs in regions with abundant precipitation in the south or in the warm season with large evapotranspiration. Questions remain concerning the relationship between drought intensity and precipitation and precipitation heterogeneity in the study area, and the existence of seasonal and regional differences.

#### 3.3.1. Correlation of Drought Intensity with Precipitation Heterogeneity in Each Season

Figure 10 shows the correlation between seasonal drought intensity and precipitation heterogeneity. The smaller the intensity value, the greater is the drought intensity. Because of this, negative correlations of drought intensity with PCD and PCP suggest that as PCD increases, the PCP is delayed, and the drought intensity increases. Figure 10a–d shows the correlation between drought intensity and PCD. In most periods, drought intensity was negatively correlated with PCD. That is, the more concentrated the precipitation, the stronger was the drought intensity. In spring and winter, the effects of PCD on drought intensity were the highest. In autumn, the more concentrated the precipitation, the weaker was the drought intensity in some of the east-central regions. As shown by the correlation of drought intensity with the PCP (Figure 10e–h), the later the PCP, the stronger was the drought. These effects manifested primarily in the summer and autumn. The correlation of drought intensity with days with light and moderate rain (Figure 10i–l) suggests that, except for summer, drought intensity was closely correlated with the days with light and moderate rain in most regions. The fewer the days, the stronger was the seasonal drought intensity, especially in regions with relatively few days with light and moderate rain in spring and autumn. In the east-central regions with fewer days with light and moderate rain, the drought intensity also had a greater correlation with the number of days with light and moderate rain in summer. However, the correlation was weaker than that in the other seasons. This is possibly related to a greater number of heavy rain days and a significant reduction in the total amount of precipitation in summer over the past decades. Overall, precipitation heterogeneity significantly influenced the middle and eastern study areas.

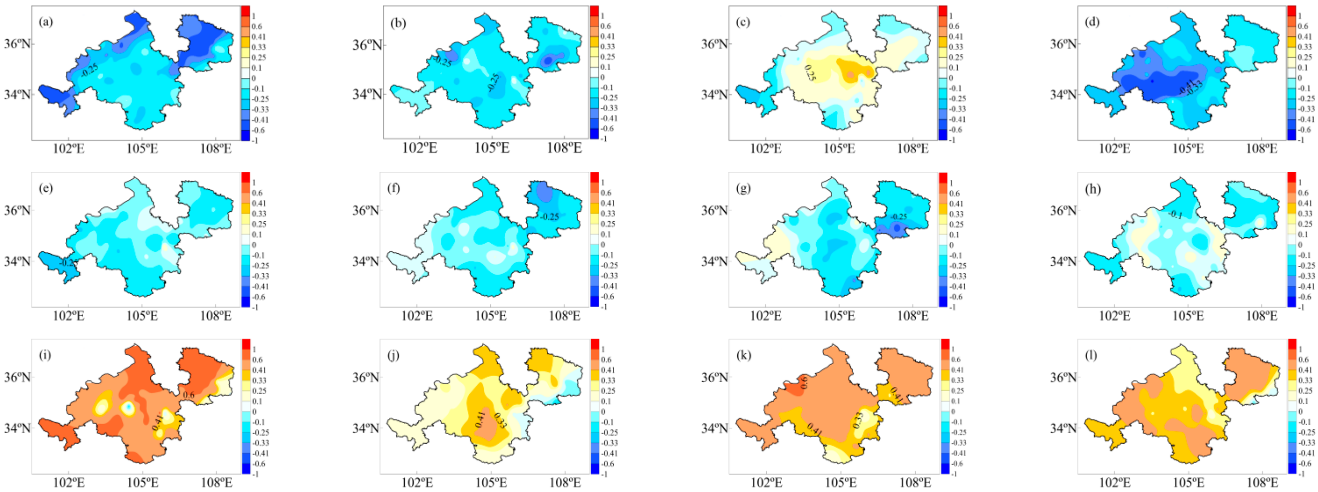

**Figure 10.** Correlation between drought intensity and precipitation heterogeneity in each season (columns 1–4 are spring, summer, autumn, and winter, respectively; (**a**–**d**) is PCD, (**e**–**h**) is PCP, (**i**–**l**) is the number of days with weak precipitation; r > 0.25 represent those significant at the 0.05 level based on the Student's *t*-test).

The relationship between PCD, PCP, and drought intensity is closely related to the distribution of seasonal evapotranspiration and the PCP. If the rain and high evapotranspiration were in the same period, the drought intensity was weaker. If the precipitation was more concentrated, and more distinct from the evapotranspiration period, the drought intensity was stronger. In spring and summer, evapotranspiration in each period was relatively strong. Furthermore, the more concentrated the precipitation, the longer was the non-concentrated period. With increased water deficit in the non-concentrated periods, droughts occurred with more frequency and greater intensity. In the northern and eastern regions with high evapotranspiration and southern regions with earlier PCPs, the effects were more pronounced. However, in autumn, the precipitation was concentrated in September, when evapotranspiration was higher than in October and November. Evapotranspiration in the middle region in mid-September was stronger than in the other regions (figure not shown), and the rain and high evapotranspiration occurred in the same period. Thus, in that period, the more concentrated the precipitation, the more the water output was compensated, and the drought was weaker. If it was increasingly concentrated in the late period, the drought was more severe. In winter, evapotranspiration rates were comparable across all regions of the study area. Precipitation was mainly concentrated in late January. The more concentrated the precipitation was, the later the PCP fell during the season. If the cumulative water deficit was greater in the early stage, droughts occurred more readily. Moreover, the south-central regions, with their higher evapotranspiration, had a greater influence on drought intensity.

3.3.2. Correspondence of Drought Intensity with Precipitation and Precipitation Heterogeneity

To quantitatively demonstrate the relationship between drought and precipitation heterogeneity, we compared drought intensity with precipitation and precipitation heterogeneity. The results suggest that in the eastern and middle study areas, the effects of precipitation heterogeneity on drought were the most significant, especially in spring and summer. When there was a large PCD and late PCP in spring and summer in the east, there was a greater than 75% probability of drought. Furthermore, 28–56% of those droughts occurred in conjunction with periods of excessive precipitation. In the middle areas, the probability of drought was over 27–90%, including 28–56% associated with excessive precipitation.

Because of the space limitations, only the correspondence of DS with precipitation and its heterogeneity in the eastern regions (east of 106° E) are shown in Figure 11. The horizontal and vertical axes represent the DS and precipitation anomaly percentages (Pa), respectively. The dots represent PCD, PCP, and the departure of the days with light and moderate rain (PD) in different drought grades. Across all seasons, droughts mainly occurred when there was less precipitation and a negative PD. Moreover, the smaller the PD, the stronger was the DS. The relationships between DS, PCD, and PCP were slightly more complicated. When the precipitation was low, the PCD and DS were larger. This was most prominent in the spring. In summer, the later the PCP, the stronger was the drought. When the precipitation was concentrated abnormally, even in the case of more precipitation, drought followed. At this time, PCD was ≥0.5 in spring and autumn, and ≥0.4 in summer. PCP was ≥240 in spring and summer; that is, after May and August, respectively. PCP was ≤80 in autumn (early and mid-September). In spring, the effects of PCD and PCP on drought were particularly significant. If PCD ≥ 0.5 and PCP ≥ 240 were defined as drought thresholds, drought occurred in 75% of the springs in the eastern regions, including 28% when associated with abundant precipitation. At that time, the average PCD and PCP were 0.6 and 290, respectively. In summer, PCD ≥ 0.4 and PCP ≥ 240 were regarded as the thresholds. In the eastern regions, drought occurred in 75% of periods, with 56% of periods having abundant precipitation. In autumn, PCD ≥ 0.5 and PCP ≤ 80 were the thresholds, and drought occurred in 34% of the periods, including 7% with abundant precipitation.

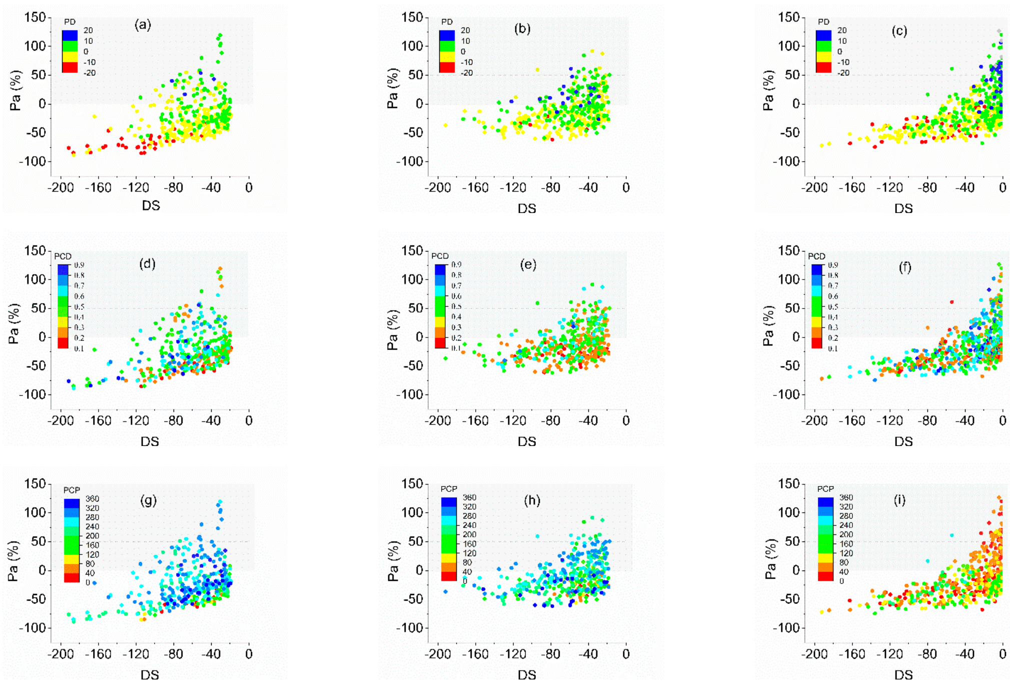


**Figure 11.** Correlation between drought intensity and precipitation and its heterogeneity in the eastern region (east of 106° E) (columns 1–3 are spring, summer, and autumn; (**a**–**c**) is PD, (**d**–**f**) is PCD, (**g**–**i**) is the PCP).

Current drought monitoring and prediction focus mainly on the precipitation amount within a period, such as the percentage of precipitation anomaly (Pa), the standardized precipitation index (SPI), and even the standardized precipitation evapotranspiration index (SPEI) [35]. In arid regions, it is generally believed that less precipitation is the direct cause of the drought. However, basing drought prediction solely on precipitation amounts can lead to incorrect conclusions [15]. For instance, if a prolonged dry period is followed by heavy precipitation events, the period may be concluded to be wet on average [16]. Our results show that although less precipitation is the leading factor of drought in the dry rain-fed agricultural areas of northern China, the impacts of precipitation heterogeneity are significant. In the study area, approximately 30–50% of droughts in seasons with abundant precipitation were caused by heterogeneous distribution. Therefore, when diagnosing seasonal drought, the total precipitation and the precipitation heterogeneity should be considered. In this way, drought monitoring can be performed accurately, and early warning can be given.

## 4. Conclusions

1. There were 1–3 drought processes per year during the study period in eastern Gansu province. There were more drought processes in the eastern and central northern regions than in other regions. The drought processes were mainly intra-seasonal droughts, accounting for 61.4% of the total drought processes. They occurred once every 2 to 4 years, with spring and summer droughts being the most prevalent. Most droughts began in the early spring and middle summer and lasted approximately 60 days.
2. PCD in the study area was between 0.2 and 0.7. PCD in summer was small and regional differences were small. In the last 58 years, PCD increased in spring in the central and eastern regions, decreased in summer in most regions except the southwest, increased in autumn, and decreased significantly in winter. In spring, the PCP was between late April and early May, and it was slightly earlier in the east. In summer, the PCP was in middle and late July and occurred 10 days later in the northern and eastern regions than in other regions. The autumn PCP occurred in mid-September, and the winter PCP was in late January. In the past 58 years, the PCP in most areas did not change significantly. Most changes lasted less than 10 days and were local. The days with light and moderate rain showed a decreasing trend in the spring through autumn seasons, especially in summer and autumn.
3. The larger the PCD, the stronger was the drought intensity. In spring and winter, PCD had the greatest effect on drought. In autumn, the larger the PCD, the weaker was the drought intensity. The later the PCP was delayed, the more severe the drought, especially in summer and autumn. Drought intensity was significantly correlated with the days with light and moderate rain in most regions; the fewer the days, the stronger was the drought, especially in regions with relatively fewer days with light and moderate rain in spring and autumn. The regions significantly affected by heterogeneous precipitation were mainly located in the central and eastern regions of the study area.
4. In spring and summer, when precipitation was insufficient, the days with light and moderate rain were fewer. As the PCD increased, the PCP was delayed, and the drought was more intense. In autumn, during times of abundant precipitation, the earlier the PCP, the stronger was the drought. When the PCD was $\geq$0.5 in the spring, the PCP was after May, and droughts occurred 28% of the time. When the PCD was $\geq$0.4 in summer, the PCP was after August, and droughts occurred in 56% of the periods. When the PCD was $\geq$0.5 in autumn, the PCP was in the middle and early September, and droughts occurred in 7% of the periods.

**Author Contributions:** Conceptualization, S.W., Q.Z. and J.W.; data curation, S.W.; formal analysis, S.W.; funding acquisition, S.W. and J.W.; investigation, S.W. and J.W.; methodology, S.W. and Y.L.; software, Y.Z.; writing—original draft preparation, S.W.; writing—review and editing, S.W.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Natural Science Foundation of Gansu Province (Grant No. 21JR7RA698),the National Natural Science Foundation of China (Grant No. 41705067),the innovation team project of the institute of arid meteorology (Grant No. GHSCXTD-2020-2),the Gansu Basic Research Innovation Group (Grant No. 20JR5RA121) and the Research project of Gansu Meteorological Bure.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

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

## References

1. Wilhite, D.A. Drought as a natural hazard: Concepts and definitions. In *Drought: A Global Assessment*; Wilhite, D.A., Ed.; Routledge: Abingdon, UK, 2000; pp. 3–18.
2. Dai, A.G. Increasing drought under global warming in observations and models. *Nat. Clim. Chang.* **2013**, *3*, 52–58. [CrossRef]
3. Trenberth, K.E.; Dai, A.G.; Schrier, G.V.D.; Jones, P.D.; Barichivich, J.; Briffa, K.R.; Sheffield, J. Global warming and changes in drought. *Nat. Clim. Chang.* **2013**, *4*, 17–22. [CrossRef]
4. Zhang, Q.; Han, L.Y.; Jia, J.Y.; Song, L.L.; Wang, J.S. Management of drought risk under global warming. *Theor. Appl. Climatol.* **2016**, *125*, 187–196. [CrossRef]
5. Li, M.S.; Li, S.; Li, Y.H. Studies on drought in the past 50 years in China. *Chin. J. Agrometeorol.* **2003**, *24*, 7–10. (In Chinese)
6. Huang, R.H.; Du, Z.C. Evolution characteristics and trend of droughts and floods in China under the background of global warming. *Chin. J. Nat.* **2010**, *32*, 187–195. (In Chinese)
7. Zhai, J.Q.; Huang, J.L.; Su, B.D.; Cao, L.G.; Wang, Y.J.; Jiang, T.; Fischer, T. Intensity-area-duration analysis of droughts in china 1960–2013. *Clim. Dyn.* **2017**, *48*, 151–168. [CrossRef]
8. Chen, H.P.; Sun, J.Q. Changes in Drought Characteristics over China Using the Standardized Precipitation Evapotranspiration Index. *J. Clim.* **2015**, *28*, 5430–5447. [CrossRef]
9. Zhang, Q.; Han, L.Y.; Hao, X.C.; Han, T.; Jia, J.Y.; Lin, J.J. On the impact of the climate change on the agricultural disaster loss caused by drought in China and the regional differences between the North and the South. *Acta Meteor. Sinca* **2015**, *73*, 1092–1103. (In Chinese)
10. Leng, G.; Tang, Q.; Rayburg, S. Climate change impacts on meteorological, agricultural and hydrological droughts in China. *Glob. Planet. Chang.* **2015**, *126*, 23–34. [CrossRef]
11. Zhao, G.; Jiang, X.; Ma, L. Control Action of Low-level Wind Shear to Rain Days and Its Precipitation Efficiency in Different Seasons over East of Northwest China during 1960–2009. *J. Desert Res.* **2015**, *35*, 1275–1282. (In Chinese)
12. Zhang, D.; Zhang, L.; Yang, J.; Feng, G.L. The impact of temperature and precipitation variation on drought in China in last 50 years. *Acta Phys. Sinca* **2010**, *59*, 655–663. (In Chinese)
13. Fu, C.B.; Ma, Z.G. Global change and regional aridification. *Chin. J. Atmos. Sci.* **2008**, *32*, 752–760. (In Chinese)
14. Jiang, J.; Jiang, D.B.; Lin, Y.H. Changes and Projection of Dry/Wet Areas over China. *Chin. J. Atmos. Sci.* **2017**, *41*, 43–56. (In Chinese)
15. Cindric, K.; Pasaric, Z.; Gajic-Capka, M. Spatial and temporal analysis of dry spells in Croatia. *Theor. Appl. Climatol.* **2010**, *102*, 171–184. [CrossRef]
16. She, D.X.; Xia, J. The spatial and temporal analysis of dry spells in the Yellow River basin, China. *Stoch. Environ. Res. Risk A* **2013**, *27*, 29–42. [CrossRef]
17. Zhang, L.J.; Qian, Y.F. Annual distribution features of precipitation in china and their interannual variations. *Acta Meteorol. Sin.* **2003**, *17*, 146–163.
18. Hou, W.; Yang, J.; Zhao, J.H. Staged Meteorological Drought Index Based on Boltzmann Function. *J. Appl. Meteor. Sci.* **2013**, *24*, 695–703. (In Chinese)
19. Goswami, B.N.; Venugopal, V.; Sengupta, D.; Madhusoodanan, M.M.S.; Xavier, P.K. Increasing trend of extreme rain events over India in a warming environment. *Science* **2006**, *314*, 1442–1445. [CrossRef]
20. Anoop, M.; Chen, L.S. Changes in precipitation pattern and risk of drought over india in the context of global warming. *J. Geophys. Res. Atmos.* **2014**, *119*, 7833–7841.
21. Fang, S.D.; Jiang, Z.H. Analysis of the Change in the Precipitation Intensity Distribution in the Yangze-Huaihe River Basin under Global Warming. *Clim. Environ. Res.* **2013**, *18*, 757–766. (In Chinese)
22. Ma, S.M.; Zhou, T.J.; Dai, A.G.; Han, Z.Y. Observed changes in the distributions of daily precipitation frequency and amount over China from 1960 to 2013. *J. Clim.* **2015**, *28*, 6960–6978. [CrossRef]

23. Qian, W.H.; Fu, J.L.; Yan, Z.W. Decrease of light rain events in summer associated with a warming environment in china during 1961–2005. *Geophys. Res. Lett.* **2007**, *341*, 224–238. [CrossRef]
24. Wu, F.T.; Fu, C.B. Change of precipitation intensity spectra at different spatial scales under warming conditions. *Chin. Sci. Bull.* **2013**, *58*, 664–673. (In Chinese) [CrossRef]
25. Huang, G.; Wen, G.H. Spatial and temporal variations of light rain events over china and the mid-high latitudes of the northern hemisphere. *Chin. Sci. Bull.* **2013**, *58*, 1402–1411. (In Chinese) [CrossRef]
26. Cook, B.I.; Smerdon, J.E.; Seager, R.; Coats, S. Global warming and 21st century drying. *Clim. Dyn.* **2014**, *43*, 2607–2627. [CrossRef]
27. Wang, L.; Chen, W.A. CMIP5 multi-model projection of future temperature, precipitation, and climatology drought in china. *Int. J. Climatol.* **2014**, *34*, 2059–2078. [CrossRef]
28. Huang, J.P.; Yu, H.P.; Guan, X.D.; Wang, G.Y.; Guo, R.X. Accelerated dryland expansion under climate change. *Nat. Clim. Chang.* **2016**, *6*, 166–171. [CrossRef]
29. Yang, J.H.; Wang, P.X.; Bai, H.Z.; Yang, Q.G.; Han, S.L. Intra-annual Inhomogeneity Characteristics of Precipitation over Northwest China. *Adv. Clim. Chang. Res.* **2007**, *3*, 276–281. (In Chinese)
30. Ma, S.M.; Zhou, T.J. Observed trends in the timing of wet and dry season in china and the associated changes in frequency and duration of daily precipitation. *Int. J. Climatol.* **2016**, *35*, 4631–4641. [CrossRef]
31. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
32. Li, Z.; Yan, Z.W. Homogenized China daily mean/maximum/mini-mum temperature series 1960–2008. *Atmos. Ocean. Sci. Lett.* **2009**, *2*, 237–243.
33. Xu, W.H.; Li, Q.X.; Wang, X.L.; Yang, S.; Cao, L.J.; Yang, F. Homogenization of Chinese daily surface air temperatures and analysis of trends in the extreme temperature indices. *J. Geophys. Res. Atmos.* **2013**, *118*, 9708–9720. [CrossRef]
34. Yang, S.; Li, Q.X. Improvement in homogeneity analysis method and update of china precipitation data. *Adv. Clim. Chang. Res.* **2014**, *10*, 276–281. (In Chinese)
35. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. *Standardization Administration of China, National standard GB/T20481-2017 Grades of Meteorological Drought*; Standards Press of China: Beijing, China, 2017; pp. 1–24. (In Chinese)
36. Wang, S.P.; Wang, J.S.; Zhang, Q.; Li, Y.P.; Wang, Z.L. Applicability Evaluation of Drought Indices in Monthly Scale Drought Monitoring in Southwestern and Southern China. *Plateau Meteor.* **2015**, *34*, 1616–1624. (In Chinese)
37. Wang, S.P.; Wang, J.S.; Zhang, Q.; Li, Y.P. Applicability Evaluation of Drought Indices in Northern China and the Reasons for Their Differences. *Plateau Meteor.* **2020**, *39*, 186–198. (In Chinese)
38. Lu, E. Determining the start, duration, and strength of flood and drought with daily precipitation: Rationale. *Geophys. Res. Lett.* **2009**, *36*, L12707. [CrossRef]
39. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements, Irrigation and Drainage Paper*; No. 56, Tech. Rep.; Food and Agriculture Organization of the United Nations: Rome, Italy, 1998.
40. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; American Meteorological Society: Boston, MA, USA, 1993; pp. 179–183.
41. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. *Standardization Administration of China, National standard GB/T20481-2006 Classification of Meteorological Drought*; Standards Press of China: Beijing, China, 2006; pp. 1–24. (In Chinese)
42. Zhang, T.F.; Zhang, B.; Liu, X.L.; Li, X.Y.; Zhao, Y.F.; Jin, S.L. Trend Analysis of the Variation of Meteorological Drought in Loess Plateau of Gansu Province Based on Comprehensive Meteorological Drought Index. *J. Glaciol. Geocryol.* **2012**, *34*, 1076–1083. (In Chinese)