Concurrent droughts and hot extremes in northwest China from 1961 to 2017

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Northwest China forms the main part of the arid and semi-arid areas in China, and even includes some extremely arid areas. This zone of interaction is affected by the westerlies and monsoons making it sensitive to global climate change. Drought is the main type of natural disaster affecting northwest China. Global warming has caused a gradual strengthening of the frequency and intensity of hot extremes, when dry conditions and heatwaves occur simultaneously or successively; as a result, that socio-economic risks can increase considerably. The present study examined changes in concurrent droughts and hot extremes in northwest China during 1961–2017 based on data from 119 meteorological stations. The result shows that the frequency of concurrent droughts and hot extremes exhibited an increasing trend over most parts of northwest China, while a negative trend occurred in western Xinjiang and at some sites in Qinghai. Concurrent droughts and hot extremes appeared more often in May in western Xinjiang, and in summer in other parts of northwest China. Overall, the trends of such concurrent events, regardless of different definitions, increased from 1961–2017 over northwest China. In particular, from 1981–2017, the trend rose more significantly than in other decades, and reached an abrupt point of change in 1996. Although the trend changed from a positive significant signal to a negative one from 2001–2017, the trend grew 2–3 times from 1997–2017. Changes in large-scale atmospheric circulation show that an anticyclonic circulation strengthened, increasing in geopotential height over the mid-high latitudes of Eurasia and was centred on Mongolia and Lake Baikal. This enhanced relative humidity in western Xinjiang and eastern Qinghai, and weakened it elsewhere from 1997–2017. These changes have contributed to the changes in the spatial distribution and trends in concurrent droughts and hot extremes in northwest China.

KEYWORDS
concurrent droughts and hot extremes, northwest China, SPEI, threshold

1 | INTRODUCTION

Extreme climatic events, such as hot extremes and droughts both lead to serious environmental and economic problems. Droughts are considered among the most costly type of natural disasters because of their effects on crop yield, infrastructure, industry, and tourism (Mishra and Singh, 2010). Droughts develop more slowly than other types of extreme weather and climate phenomena, such as floods, hurricanes, and tornadoes (Nasrollahi et al., 2015). Droughts are projected to increase in frequency and severity in the future as a result of climate change, mainly as a consequence of decreases in regional...
precipitation but also because of increasing evaporation driven by global warming (Dai, 2011; Trenberth, 2011; Sheffield et al., 2012; Greve et al., 2018; Samaniego et al., 2018). The relationship between droughts and hot extremes is widely acknowledged (Vautard et al., 2007; Zampieri et al., 2009; Mueller and Seneviratne, 2012). High temperatures lead to accelerated soil evaporation, reduced soil moisture, and plant water loss. A lack of soil moisture strongly reduces latent cooling and thereby has a crucial effect on the spatial extent and amplitude of hot extremes. The occurrence probability of hot extremes is increasing under global warming (Perkins et al., 2012; Donat et al., 2013; Seneviratne et al., 2014; Chen and Zhai, 2017). Soil moisture deficits are likely to enhance the frequency and duration of hot extremes (Hirschi et al., 2010). In some regions, hot extremes have been shown to be induced by surface moisture deficits (Seneviratne et al., 2010; Mueller and Seneviratne, 2012).

Northwest China lies in the centre of the innermost part (31°–50°N, 73°–111°E) of the Eurasian continent, where isolation from any nearby oceans results in a dry climate (Shi et al., 2006) (Figure 1). This region forms the main part of the arid and semiarid areas in China, and even includes some extremely arid areas. Droughts are the main type of natural disasters occurring in this region, although observations show that precipitation rates have experienced an increasing trend over the past 50 years in the western part of northwest China (Shi et al., 2006; Li et al., 2016; Ren et al., 2016; Peng and Zhou, 2017). The frequency and intensity of hot extremes are increasing in a warming climate, trend that is predicted to increase in the future as a result of climate change in northwest China (Ding et al., 2010; Li et al., 2012; Chen et al., 2018; Chen and Sun, 2018; Xu et al., 2018; Zhu et al., 2018). As one of the most sensitive areas in the world in terms of responding to global climate change, when dry conditions and heatwaves occur simultaneously or successively, the combined effects often have severe additional impacts while socioeconomic risks increase (Mishra and Singh, 2010; AghaKouchak et al., 2014; Leonard et al., 2014; Mazdiyasni and AghaKouchak, 2015; Zhang et al., 2018). In this study, we focused on changes in events involving concurrent droughts and hot extremes in northwest China using the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010; Beguería et al., 2014; Yu et al., 2014). Moreover, we investigate the change of climate extremes caused by both individual and joint occurrence of droughts and hot extremes while focusing on additional information related to an analysis of how concurrent extreme events differ from the variables individually.

2 | METHODS

2.1 | Data

The monthly precipitation (mm), air temperature (°C), and daily maximum temperature data (°C) acquired during 1961–2017 from 119 meteorological stations in northwest China were collected from the National Meteorological Information Centre of the China Meteorological Administration, available from http://data.cma.cn/ (Figure 1). Daily maximum temperatures have been adjusted for homogeneity and abrupt discontinuities have been corrected. Missing data of one or 2 days were filled in by average values of day −1 and day +1. Monthly data have been verified by quality control and homogeneity assessment, and availability of various weather elements is generally above 99%. Monthly average data were used to compute the SPEI to represent meteorological drought. Daily maximum temperature data were used to compute the hot extremes as described in Section 2.3 below.

In addition to observational data, monthly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 dataset with a grid resolution of 2.5° × 2.5° from 1961 to 2017 are used to investigate the atmospheric circulation changes controlling concurrent of droughts and hot extremes in northwest China, including geopotential height at 500 hPa and relative humidity at 700 hPa.

2.2 | Droughts

In this work, the SPEI was employed for defining drought events. The SPEI was developed by combining the sensitivity of the Palmer Drought Severity Index (Palmer, 1965) to the changes in evaporative demand (caused by air temperature fluctuations and trends) with fairly simple calculation methods; however, the SPEI also has the robustness of the multitemporal nature of evaporative demand, such as the Standardized Precipitation Index (McKee et al., 1993). The multiscalar characteristics of the main formula are as follows (Vicente-Serrano et al., 2010; Yang et al., 2017):

\[
D^k_n = \sum_{i=0}^{k-1} (P_{n-i} - PET_{n-i}),
\]

where \(D^k_n\) is the aggregate of the difference between the precipitation \(P\) and potential evapotranspiration \(PET\) from month \(n - k + 1\) to month \(n\) on a timescale \(k\). For example, when
where $T$ is the monthly-mean temperature ($^\circ$C); $I$ is a heat index, which is calculated as the sum of 12 monthly index values $i$, the latter being derived from mean-monthly temperature using Equation (3):

$$i = \left(\frac{T}{5}\right)^{1.514},$$

where $a$ is a coefficient depending on $I$:

$$a = 6.75 \times 10^{-7}T^3 - 7.71 \times 10^{-5}T^2 + 1.79 \times 10^{-2}T + 0.492,$$

where $d$ is a correction coefficient that depends on the latitude and month. Next, the water balance is normalized into a log-logistic probability distribution to obtain the SPEI index series. The log-logistic distribution was selected for standardizing the D series to obtain the SPEI. The probability density function of log-logistic distributed variable is expressed as (Yu et al., 2014):

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x - \gamma}{\alpha}\right)^{\beta - 1} \left[1 + \left(\frac{x - \gamma}{\alpha}\right)^{1-\beta}\right],$$

where $\alpha, \beta,$ and $\gamma$ are the scale, shape, and origin parameters, respectively, for $D$ values in the range of $(\gamma > D < \infty)$. The three parameters of the Pearson III distribution can be obtained following Singh et al., 1993.

Thus, the probability distribution function of the $D$ series is given by Equation (6):

$$F(x) = \left[1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right]^{-1}.$$  

Then with $F(x)$, the SPEI can easily be obtained as the standardized values of $F(x)$ (Abramowitz and Stegun, 1964):

$$\text{SPEI} = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3},$$

where $W = \sqrt{-2\ln(P)}$ for $P \leq 0.5$ and $P$ is the probability of exceeding a determination $D$ value, $P = 1 - F(x)$. If $p > 0.05$, then $P$ is replaced by $1-P$ and the sign of the resultant SPEI is reversed. The constants are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

In the present study, the SPEI was calculated over 12-month (for drought trends and analysis) and 3-month (for concurrent droughts and hot extremes analysis) time scales using monthly air temperature and precipitation data for the period of 1961–2017 from 119 stations covering northwest China. A drought is defined as an event that has an SPEI of $<-1.0$.

### 2.3 Hot extremes

A hot extreme event was defined as a period of $\geq 3$ consecutive days with maximum temperatures above the daily threshold for each month of the period 1961–2017. The threshold is defined as the 85th and 90th percentile levels of daily maxima for a given location (Meehl and Tebaldi, 2004; Perkins and Alexander, 2013; Russo et al., 2014), to capture a relatively large number of events. There is a consensus that the 85th and 90th percentiles can be defined as extreme (Easterling et al., 2000; Perkins and Alexander, 2013).

We only considered events that occurred during a 6-month warm season (May–October) for hot extremes using the following two conditions: the daily maximum temperature above the 85th or 90th percentile for at least three consecutive days for $H_{85}$ or $H_{90}$, respectively.

### 2.4 Concurrent droughts and hot extremes

We derived concurrent droughts and hot extremes in northwest China by summing the number of concurrent events occurring during May–October for each year. When a month 3-month SPEI $<-1.0$, we respectively summed the number of different conditions of hot extremes for each month (Mazdiyasni and AghaKouchak, 2015). Here, the number of concurrent droughts and hot extremes was defined as follows: simultaneous a month 3-month SPEI $<-1.0$ and hot extremes for a fixed $H_{85} (D_{H85})$ or $H_{90} (D_{H90})$.

### 2.5 Trend analysis methods

The linear trend over time was assessed using Pearson’s Correlation Tests (Pearson, 1895). The statistical significance of the linear trend was assessed at the 95% level.

A Mann–Kendall (MK) test for abrupt change of time series was employed (Mann, 1945; Kendall, 1975). The MK test for monotonic trends is a nonparametric method that can reveal the changing trend in a time series, and has been widely applied in climatology. It calculates two standardized statistic series, UF and UB as defined below, for a data series and plots them with confidence lines. The null hypothesis is rejected and a significant abrupt change occurred if the UF curve and the UB curve intersect within the confidence zone. The present study used the confidence level of 95% (1.96 and $-1.96$) as the boundary lines of the confidence zone (Du et al., 2015).
Given a time series of $X = (x_1, x_2, x_3, \ldots, x_n)$, the statistical parameter $f_k$ was given using Equation (8):

$$f_k = \sum_{i=1}^{k} \sum_{j=1}^{n} \text{logistic}(x_i > x_j), \ k = 2, 3, \ldots, n,$$

(8)

when $x_i > x_j$, logistic $(x_i > x_j)$ is 1, and 0 otherwise. The mean and variance of $f_k$ were defined using Equations (9) and (10):

$$E[f_k] = \frac{k(k-1)}{4} \quad \text{and} \quad \text{var}(f_k) = (k-1)(2k+5)/72$$

(9)

$$UF(k) = \frac{f_k - E(f_k)}{\sqrt{\text{var}(f_k)}}, \ (k = 2, 3, \ldots, n).$$

(10)

A reversed data series $X' = (x'_1, x'_2, x'_3, \ldots, x'_n) = (x_n, x_{n-1}, x_{n-2}, \ldots, x_1)$ was used in the calculation for UB.

$$UB(k) = -\frac{f_k - E(f_k)}{\sqrt{\text{var}(f_k)}}, \ (k = 2, 3, \ldots, n).$$

(11)

where $f_k$, $E(f_k)$, and var($f_k$) were calculated using the same equations used for UF($k$).

3 | RESULTS

3.1 | Characteristics of drought in northwest China

In general, from 1961 to 2017, the frequency of annual droughts over northwest China has been between 0.30 and 0.40 year$^{-1}$ (Figure 2a), where a drought is defined as a 12-month period during which the SPEI $< -1.0$ in December. The annual drought frequency in western northwest China, Ningxia, and in some parts of Gansu and Shaanxi Provinces was higher than other areas of northwest China. In particular, droughts in the Tarim and Turpan basins occurred most often because the regions experience a warm temperate continental climate in this area of extremely arid desert (Yang and Scuderi, 2017).

Annual SPEI trends in northwest China for the period 1961–2017 showed a strongly different pattern of distribution. Droughts occurred with increasing frequency mainly in eastern Xinjiang, the northern area of Golmud in the Qinghai Province, the Hexi Corridor, Ningxia to Longnan, and north Shaanxi; the trends of the annual SPEI in these areas were less than $-0.20$ decade$^{-1}$. In western Xinjiang and some areas of Qinghai, a decrease in drought occurrence was detected (Figure 2b). The spatial changes in the water vapor flux in northwest China were similar to the spatial distribution of SPEI (Wei et al., 2010; Ren et al., 2016).

The surface-sensible heat flux in northwest China was the strongest on the Eurasian continent; however, the corresponding surface latent heat flux in the present study area was very weak (Bueh et al., 2002). Conversely, the heat flux reflected the lack of a water source in this region, leading to the deficiency in annual precipitation.

Although previous research has shown that northwest China has generally become wetter (Zou et al., 2005), the decadal probability of a monthly drought event (3-month SPEI $< -1.0$) between May and October shows other and different characteristics. The probability of a monthly drought in the southwest of Xinjiang, the Hexi Corridor, and Ningxia was below 10%; meanwhile, in northwest Xinjiang and east Qinghai, it was between 20 and 40%, and in other parts of the region fell between 10 and 20% in the 1960s and 1970s (Figure 3a,b). The area with a less than 10% probability of a monthly drought in the 1980s increased when compared with that of the 1960s and 1970 (Figure 3c). However, from 1990 through to 2017, this probability increased to greater than 20% in most parts of northwest China while the area with the probability of drought at below 10% shrunk in spatial extent. The probability of a monthly drought in southwest Xinjiang, the Hexi Corridor, and in Northern Ningxia increased to greater than 30%, and even to as much as 50%, but decreased in east Qinghai and Shaanxi (Figure 3d,e,f)). Our result shows that although the frequency of droughts declined in the 1980s, the threat of drought in the above area continued to exist.

![FIGURE 2](https://www.wileyonlinelibrary.com) (a) Spatial distribution of drought, which is defined as a 12-month standardized precipitation evapotranspiration index (SPEI) $< -1.0$ between 1961–2017 over northwest China (unit: Year$^{-1}$) and (b) trend in the variation of the 12-month SPEI over northwest China for 1961–2017 (unit: Decade$^{-1}$); + indicates statistical significance at the 95% confidence level) [Colour figure can be viewed at wileyonlinelibrary.com]
3.2 Characteristics of hot extremes in northwest China

Clear increasing trends were observed for hot extreme events in most parts of northwest China for the period of 1961–2017 (Figure 4). Regardless of the thresholds and duration, the trends of hot extreme events showed a similar spatial distribution across the study area. An increasing trend was mainly observed in southern Xinjiang, the Hexi Corridor, and Ningxia; the trends of \( H_{85} \) included increases of greater than 0.60 decade\(^{-1} \). The trends of \( H_{90} \) in the above areas were initially smaller, but also showed significant increasing trends at the 95% confidence level.

3.3 Characteristics of concurrent droughts and hot extremes in northwest China

The time series of annual concurrent droughts and hot extremes over northwest China were calculated based on the average of 119 stations from 1961–2017. The number of concurrent droughts and hot extremes increased sharply in the 1990s and the rate of change remained stable in other years, regardless of different definitions (Figure 5). Figure 6 shows the result of the MK abrupt change test for the number of concurrent droughts and hot extremes and was used to detect potential abrupt changes over the period of 1961–2017. An intersection point between UF and UB curves was detected in 1996 and was significant at the confidence level of 95%. Before the abrupt change point, the number of concurrent droughts and hot extremes did not increase significantly at the confidence level of 95% (UF statistic < 1.96); since 1996, however, the UF statistic exceeded 1.96, which marks the 95% confidence level for a significant increasing trend. The mean annual numbers of \( DH_{85} \) and \( DH_{90} \) from 1961–1996 were 0.6 and 0.4; later, the numbers increased to 1.7 and 1.2 during 1997–2017 by growing by 2.8 and 3.2 times, respectively.
We applied a running trend analysis to determine whether the trend signal was persistent in concurrent droughts and hot extremes, which entailed estimating trends over time windows of variable width starting in 1961 for the five selected stations; the running annual averages for each decade were calculated to the end of the time series (Table 1). For the entire period, the value of DH85 showed increasing rates of 0.24 decade$^{-1}$, while the trend of DH90 was 0.18 decade$^{-1}$. Significant trends were observed during 1961–2017. From the 1970s to 1980s, the trend of concurrent droughts and hot extremes increased more quickly than during the other periods. Even the trends of DH85 and DH90
rose to 0.42 decade$^{-1}$ and 0.31 decade$^{-1}$, and it was mainly significant from 1981 to 2017. The trend changed from a positive significant signal to a negative signal from 2001 to 2017, then, the trends changed again to a positive signal.

Although the regional average number of concurrent droughts and hot extremes increased between 1961 and 2017 over northwest China, the spatial distributions of the trend of the number of concurrent droughts and hot extremes varied with different thresholds and durations over time.

In fact, the number of DH85 events exhibited an increasing trend over most parts of northwest China, especially in eastern Xinjiang, north of Golmud in the Qinghai Province, and in the Hexi Corridor, Ningxia to Longnan, and north Shaanxi where the rates were greater than 0.30 decade$^{-1}$ and were significant at the 95% confidence level (Figure 7a). Even in eastern Xinjiang and in north of Golmud in Qinghai, the trends exceeded 0.60 decade$^{-1}$. This spatial distribution was similar to the annual SPEI trends in northwest China for the period 1961–2017 (Figure 2b). In western Xinjiang and at some individual sites, the trends were negative.

The trend and distribution of the number of DH90 events was similar to the trends for DH85 events. The DH90 events exhibited increasing trends in most parts of the region; in particular, the trends were greater than 0.30 decade$^{-1}$ in eastern Xinjiang, north of Golmud in the Qinghai Province, and in the Hexi Corridor, Ningxia to Longnan, and north Shaanxi. Moreover, the trends in the southern Taklamakan Desert and a small part of northern Qinghai were above 0.50–0.60 decade$^{-1}$ (Figure 7b). Here, we also found that the area with a downward trend for DH90 events in western Xinjiang was larger than those for DH85; the same area had a downward trend for the incidence of drought. This means the occurrence of DH90 events in this area was determined by the existence of drought. However, the trends of DH90 events in north Qinghai were different, with the incidence of drought decreasing, and the incidence of both H90 and DH90 increasing. These findings indicate that the characteristics of concurrent droughts and hot extreme events can be distinguished from the incidence of droughts or extreme hot events when considered alone.

Western Xinjiang and southern Qinghai experienced their greatest number of DH85 events in May (Figure 8a). The greatest number of DH85 events in the Tarim basin and Hexi Corridor appeared in June, and these occurred most frequently in July in Ningxia, eastern Xinjiang, western Gansu, and northern Shaanxi. The areas with the greatest number of DH85 events occurring in August–October were smaller than that in May–July, and the stations with this pattern were scattered. Areas with the greatest number of DH85 events occurring in October only included part of the transition area between southern Ningxia and Gansu. Months when the greatest number of DH90 events occurred in most areas of northwest China and were different areas than those with DH85 events (Figure 8b). The areas of western Xinjiang and south Qinghai had the greatest number of DH90 that occurred in May, and it decreased over time as well as the greatest number that occurred in June–August and the number of these increased over time. The month of greatest number of DH90 events was July in part of the Hexi Corridor and in northern Qinghai. In part of the transition area between south Ningxia and Gansu, the greatest number of DH85

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<td>1961–2017</td>
<td>0.24a</td>
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<td>1971–2017</td>
<td>0.31a</td>
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<td>1981–2017</td>
<td>0.42a</td>
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<td>1991–2017</td>
<td>0.26</td>
<td>0.21</td>
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<td>2001–2017</td>
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<td>2011–2017</td>
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* Indicates statistical significance at the 95% confidence level. DH85 and DH90 indicate simultaneous month 3-month SPEI < −1.0 and hot extremes during which the daily maximum temperature exceeded the 85th and 90th percentiles for at least three consecutive days, respectively.

![FIGURE 7](https://wileyonlinelibrary.com)  
**FIGURE 7** Trend variations of the number of concurrent droughts and hot extremes for the period of 1961–2017 in northwest China (unit: Decade$^{-1}$). (a) DH85, (b) DH90 (+ represents statistical significance at the 95% confidence level). DH85 and DH90 indicate simultaneous month 3-month SPEI < −1.0 and hot extremes during which the daily maximum temperature exceeded the 85th and 90th percentiles for at least three consecutive days, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
events occurred from October to July. In much of the eastern part of northwest China, the greatest number of DH90 events occurred in August. By comparing the months with the greatest number of DH85 and DH90 events that occurred in northwest China, we found that in Xinjiang, DH85 events are more likely to appear in May, and in eastern Xinjiang, extreme DH85 events occurred more frequently in summer.

3.4 | Changes in large scale atmospheric circulation (geopotential height, relative humidity)

Anomalies in large-scale circulation should play a role in change in trends of concurrent droughts and hot extremes in northwest China. Therefore, we created composite circulation maps from the National Centres for Environmental Prediction and the National Centre for Atmospheric Research reanalysis data in May–October for the two halves of the data period (1961–1996 and 1997–2017), and subtract one from the other. Opposite distributions of the 500 hPa geopotential height and the 700 hPa relative humidity are obvious between the means found in 1997–2017 and 1961–1996 (Figure 9). This distribution suggests that positive anomalies of the 500 hPa height were centred over the midhigh latitudes of Eurasia, centred on Mongolia and Lake Baikal. At the 500 hPa geopotential height, the largest differences (more than 25 m) occur near Lake Baikal; this causes cold air from high latitudes in the west less likely to spread south; therefore, the frequency and intensity of hot extremes are increasing in northwest China (Figure 9a). The enhanced relative humidity at 700 hPa in western Xinjiang and eastern Qinghai, and weakened in other regions during 1997–2017 may explain the decreasing trend in drought in western Xinjiang and eastern Qinghai with a concurrent increasing trend in other areas (Figure 9b). This finding indicated that most of northwest China is under warm-dry conditions, but conditions across western Xinjiang and eastern Qinghai were relatively warm-wet from 1997 to 2017.

4 | CONCLUSIONS

The combined analysis of different types of climate extremes may reveal information that is not apparent from the analysis of individual extremes (Hao et al., 2013). In this study, we have examined the spatial and temporal distribution of droughts and hot extremes based on individual and joint

The frequency of drought appeared to be higher in western northwest China, Ningxia, and in some parts of Gansu and Shaanxi Provinces than in other parts of northwest China. In western Xinjiang and some areas of Qinghai, decreases in drought trends were detected. Most areas in eastern Xinjiang experienced their highest probability of a monthly drought from 1990–2017. The minimum probability of a monthly drought was in northwest China in the 1980s. This may be caused by an increase in annual precipitation in western northwest China over the past 50 years (Ren et al., 2016).

Hot extreme events in most parts of northwest China are clearly increasing regardless of the threshold applied and drought duration, even in the areas where the trend of drought occurrence decreased, such as western Xinjiang and some areas of Qinghai. The frequency of concurrent droughts and hot extremes exhibited an increasing trend over most parts of northwest China, especially in eastern Xinjiang, north of Golmud in the Qinghai Province, the Hexi Corridor, Ningxia to Longnan, and north Shaanxi, but negative trend in western Xinjiang and at some individual sites in Qinghai. Concurrent droughts and hot extremes appeared more often in May in western Xinjiang, and in summer in other parts of northwest China. Overall, the trends of concurrent droughts and hot extremes, regardless of different definitions, increased from 1961–2017 over northwest China, especially from 1981–2017. The trend rose more significantly at this time than in other decades, and reached an abrupt point of change in 1996, which is similar to time points of abrupt change for spring and summer temperature in most of northwest China (Ding and Zhang, 2008). Although the trend changed from a positive significant signal to a negative one from 2001–2017, the trend grew 2–3 times from 1997–2017. However, longer-term changes in concurrent droughts and hot extremes should be related to changes in large-scale atmospheric circulation. In the Northern Hemisphere, positive anomalies of the 500 hPa height centred over the midhigh latitudes of Eurasia, centred on Mongolia and Lake Baikal; simultaneously, the relative humidity increased at 700 hPa in western Xinjiang and eastern Qinghai, and weakened elsewhere from 1997–2017. This pattern may explain the changes in spatial distribution and trends in concurrent droughts and hot extremes in northwest China.

5 | DISCUSSION

The contributions of droughts and hot extremes individually in concurrent droughts and hot extremes varied in diverse areas. Our analysis shows that concurrent droughts and hot extremes appeared more often in May in western Xinjiang, and in summer in other parts of northwest China. This is consistent with the most frequent occurrence of seasonal drought and hot extremes in the region (Qian et al., 2011), leading to the occurrence of concurrent droughts and hot extremes more easily during this season. The water deficit serves as the dominant driver for most droughts, because the supply of terrestrial moisture is limited and sparse vegetation occurs in most parts of northwest China. As a result, evapotranspiration decreases with the decrease in soil moisture (Wang and Yuan, 2018), coupled with the appearance of extreme temperatures, leading to the concurrent occurrence of droughts and hot extremes. In addition, observations indicate that during the last 20 years, most of the increase in the number of drought events happened under warm-dry conditions that coincided with relatively high temperature anomalies but without large anomalies in annual precipitation, implying the number of hot drought events increased (Chen and Sun, 2017). However, in areas such as western Xinjiang and some areas of Qinghai where individual areas experienced increased precipitation with a concurrent warming trend, the trends of concurrent droughts and hot extremes decreased in western Xinjiang, while increasing in Qinghai. This would explain why the change of concurrent droughts and hot extremes was mainly affected by the occurrence of drought in western Xinjiang, and affected by hot extremes in north Qinghai. Changes in the relationship between precipitation and temperature may be more important than changes in one or the other individually (Nicholls, 2004). This indicates that the characteristics of concurrent droughts and hot extreme events can be distinguished from individual drought or hot extreme events when these are considered alone.

The trends of concurrent droughts and hot extremes reached an abrupt point of change in 1996 that may be associated with changes in atmospheric circulation patterns, but are also caused by other changes in natural variability. The snow cover of the Tibetan Plateau can affect regional (eastern Asia in particular) climate change (Zhang et al., 2004; Wu and Kirtman, 2007; Wang et al., 2008; Lin and Wu, 2011). Previous studies have found that snow cover in the Tibetan Plateau declined significantly after 1995, passing the 99% significance test (Wu et al., 2012b). A reduced snow anomaly in the Tibetan Plateau can enhance the climatological high-pressure ridge over Mongolia and the adjacent regions. The subsidence associated with the high-pressure anomalies tends to suppress local cloud formation, which increases the net radiation budget, heats the surface, and favours the occurrence of more frequent heatwaves (Wu et al., 2012a). Moreover, reduced sea ice coverage in the Arctic Ocean, phase change of the Pacific Decadal Oscillation, and other external forcing factors will cause changes of synoptic systems and circulation anomalies associated with droughts and hot extremes (Zhang et al., 2005; Wang et al., 2014; You et al., 2016). Anthropogenic warming has increased the occurrence of hot droughts, and the impact will be amplified in the future (Samaniego et al., 2018). Further
studies of mechanism are needed to explain these “discrepancies” between individual and combinations of extreme climate events.

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