Changes of concurrent drought and heat extremes in the arid and semi-arid regions of China during 1961–2014

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Abstract
Arid and semi-arid regions of China (ASRC) are increasingly threatened by drought. Especially when drought and heat extremes coincide, the resultant impact would be even more harmful to human society and the natural environment. This study investigates the spatio-temporal changes in concurrent drought and heat extremes in ASRC during 1961–2014. Summer heat extremes quantified by hot day (HD), warm night (WN), daytime (DHW), and nighttime heatwave (NHW) are examined. On average, the concurrent nighttime events (concurrent drought-WN and drought-NHW) increases by 2.7 times faster than daytime ones (concurrent drought-HD and drought-DHW), and they appear more frequently in eastern than western ASRC. We also find that all four types of concurrent events have been significantly increased over the past decades. Compared to daytime (i.e., HD and DHW), the concurrent events at nighttime (i.e., WN and NHW) increased even more rapidly. During the study period, concurrent drought-DHW (drought-NHW) climbed up at the rate of 0.03 (0.08) events decade^{-1} and concurrent drought-HD (drought-WN) increased by 0.17 (0.45) days decade^{-1}. Geographically, eastern ASRC exhibited a more pronounced increasing trend than the west. Given the increasing threats of concurrent events, we suggest that more attention should be paid to these compound events in future climate change studies.

KEYWORDS
arid and semi-arid region, concurrent drought and heat, heat wave, long-term trend, Northwest China, standardized precipitation index

1 | INTRODUCTION

Under global warming, extreme climate events such as drought and heat waves (HWs) tend to become more frequent, stronger, and longer-lived in many parts of the world (Meehl and Tebaldi, 2004; Luo and Lau, 2017; Lin et al., 2018). As one of the most severe natural disasters, drought has profound impacts on crop productivity, infrastructure, industry, and tourism (Mishra and Singh, 2010; Sarker, 2019). Since the mid-1950s, widespread droughts frequently occurred in North Africa, North America, and East Europe (Dai et al., 2004; Dai, 2013; Spinoni et al., 2014). In China, frequent drought is also one of the most devastating natural disasters (Chen and Sun, 2019). For instance, the drought from autumn 2009 to spring 2010 in southwestern China destroyed more...
than 98.9 million hectares of crops (Yang et al., 2012). Besides these areas, drought is the main disaster type in arid and semi-arid regions of China (ASRC). From 1980 to 2007, the frequency of drought in Shaanxi Province of Northwest China increased by more than 36% (Gu et al., 2010). The spatial extent of the spring drought in Ningxia increased by about 14.4% decade\(^{-1}\) during 1972–2011 (Tan et al., 2015).

In addition to drought, HWs would have a serious impact on the social-economy and human health as well (Khan et al., 2019). For example, more than 70,000 people were killed by the European HW in 2003 (Robine et al., 2008). The HW in the summer of 2010 in Russia caused around 55,000 deaths and led to economic damage of 15 billion US dollars (Barriopedro et al., 2011; Rahmstorf and Coumou, 2011). The HWs in 1998 and 2003 elevated the mortality risk in Beijing (Dong et al., 2016; Yin and Wang, 2017).

Most existing studies of climate and weather extremes consider only single events and may underestimate the effects of concurrent extremes (Leonard et al., 2014). Compared with single HW events, HWs coinciding with drought (referred to concurrent drought-HWs) can pose even more profound influences on society and the environment (Mishra and Singh, 2010; Mazdiyasni and Aghakouchak, 2015; Sharma and Majumdar, 2017). For instance, a concurrent event with simultaneous drought and HW in May and June 2012 hit the Montana state in America, and destroyed more than half of wheat crops production, causing economic losses of over 1 billion US dollars (Mazdiyasni and Aghakouchak, 2015).

China has frequently been suffering from concurrent drought and heat extremes in history, and the likelihood of such events has dramatically increased in many regions (Wang et al., 2011a; Feng et al., 2014; Yuan et al., 2015; Li et al., 2019). The concurrent drought and heat extremes in Southwest China reduced the yield of winter wheat by more than 30% (Li et al., 2010). The number of concurrent drought events increased by 2.29% decade\(^{-1}\) from 1980 to 2010 in the Pearl River basin of China (Zhang et al., 2019).

These studies have deepened our understanding of simultaneous events in China. However, the changes of concurrent drought and heat extremes in ASRC, one of the largest arid/semi-arid regions of the globe, have not been fully understood. In the current paper, we aim to understand the spatio-temporal variations of concurrent heat extremes combined with drought (i.e., concurrent drought-heat) in ASRC during 1961–2014, and to try to explain the mechanism of the trend change. This paper is structured as follows: the dataset and methods are introduced in Section 2. Analysis results are discussed in Section 3 and Section 4 makes concluding remarks.

## DATA AND METHODOLOGY

### Data

Daily maximum temperature (\(T_{\text{max}}\)), minimum temperature (\(T_{\text{min}}\)), and rainfall observed at more than 300 weather stations in ASRC during the period of 1961–2014 are obtained from the China Meteorological Data Service Center (http://data.cma.cn). The raw datasets have been homogenized by the method as described in Xu et al. (2013), and the temporal inhomogeneity in the data has been evaluated by the Easterling–Peterson technique (Li et al., 2004; You et al., 2010). Following Xing and Wang (2017), ASRC is defined as the region where the climatological rainfall rate is smaller than 3 mm day\(^{-1}\) (Figure 1). We exclude the stations with more than three missing days in any summer (i.e., June–August), and 328 stations are remained for the following analyses. The locations of these stations are shown in Figure 1.

### Methods

Four types of summer heat extremes including hot day (HD), warm night (WN), daytime (DHW), and nighttime heat-wave (NHW) are studied in this paper. HD (WN) is defined when daily \(T_{\text{max}}\) (\(T_{\text{min}}\)) is larger than the 90th percentile value on the corresponding calendar day of the reference period 1961–1990. Here, the 90th percentile is computed from the set of all daily temperature values in a 31-day moving window centering that day over the reference period (i.e., \(31 \times 30 = 930\) days). A DHW (NHW) event is defined when \(T_{\text{max}}\) (\(T_{\text{min}}\)) is larger than the moving 90th percentile value of daily temperature for at least three consecutive days (Luo and Lau, 2017).

Drought is defined by the standardized precipitation index (SPI) (McKee et al., 1993). In the computation of SPI, the monthly precipitation series is first derived from daily observations for each station, and the probability density function (PDF) of the monthly series is fitted by Gamma function:

\[
g(P) = \frac{1}{\beta^n \Gamma(n)} P^{n-1} e^{-\frac{P}{\beta}},
\]

where \(\alpha\) is shape parameter, \(\beta\) is scale parameter, \(P\) is precipitation, and \(\Gamma(\alpha)\) is given by

\[
\Gamma(\alpha) = \int_0^\infty k^{\alpha-1} e^{-k} dk.
\]
\[ G(P) = \int_{0}^{P} g(P) dP = \frac{1}{\beta \Gamma(\alpha)} \int_{0}^{P} P^{\alpha-1} e^{-\frac{P}{\beta}} dP. \]  

(3)

Note that the Gamma function does not include the case with \( p = 0 \), thus \( G(P) \) is adjusted as:

\[ H(P) = q + (1-q)G(P), \]  

(4)

where \( q \) is the probability of \( p = 0 \).

The adjusted CDF can be transformed into a standard normal distribution function of \( t \):

\[ H(P) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{P} e^{-\frac{t^2}{2}} dt. \]  

(5)

And SPI can be calculated from this normal distribution function, more specifically,

where \( b_0 = 2.515517, b_1 = 0.802853, b_2 = 0.010328, c_1 = 1.432788, c_2 = 0.189269, c_3 = 0.001308. \)

SPI can be used to evaluate drought conditions at various time scales. In our study, we chose SPI at a timescale of 3 months, as suggested by Khalili et al. (2011). A concurrent event with compound drought and extreme heat (concurrent drought-heat) is defined when a heat event occurs in a month with SPI less than −0.5 (Mazdiyasni and Aghakouchak, 2015).

The secular trends of concurrent extremes are estimated by simple linear regression, and their significances are evaluated by the nonparametric modified Mann–Kendall (mMK) test that considers the autocorrelation in the time series (Hamed and Rao, 1998), and has been widely used in hydrological and climatological studies (Luo and Lau, 2018, 2019; Sa’adi et al., 2019).

In mMK method, the \( S \) statistic in the original Mann–Kendall method is first calculated by:

\[
SPI = \begin{cases} 
- \left( t - \frac{b_0 + b_1 t + b_2 t^2}{1 + c_1 t + c_2 t^2 + c_3 t^3} \right), & t = \sqrt{\ln \left( \frac{1}{(H(P))^2} \right)} , \text{when } 0 < H(P) \leq 0.5. \\
\left( t - \frac{b_0 + b_1 t + b_2 t^2}{1 + c_1 t + c_2 t^2 + c_3 t^3} \right), & t = \sqrt{\ln \left( \frac{1}{(1.0-H(P))^2} \right)} , \text{when } 0.5 < H(P) \leq 1.
\end{cases}
\]  

(6)

**FIGURE 1** Spatial distribution of the climatological mean of summer precipitation (unit: mm) in China during 1961–2014. Black thick contour indicates the arid and semi-arid regions of China (ASRC).
\[ S = \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \text{sgn}(x_j - x_i). \]  

(7)

where \( k \) is the number of observations, and \( x_j \) the \( j \)th observation. Then the \( S \) statistic is normalized by

\[ Z = \frac{S}{\sqrt{V(S)}}. \]  

(9)

\( V(S) \) is the variance of \( S \), and is calculated by

\[ V(S) = \frac{k(k-1)(2k+5)}{18} \cdot \text{COR}. \]  

(10)

Here, \( \text{COR} \) denotes correction owing to autocorrelation in the data:

\[ \text{COR} = 1 + \frac{2}{k(k-1)(k-2)} \sum_{i=1}^{k-1} (k-1)(k-i-1)(k-i-2) \cdot r_i, \]  

(11)

where \( r_i \) is the autocorrelation coefficients at lag-\( i \).

### 3 | RESULT

#### 3.1 | Changes in heat extremes

The yearly statistics of regional mean heat extremes in ASRC during 1961–2014 are first examined in Figure 2. As the figure shows, all four types of extreme heat events display dramatic intensifying tendency. The frequencies of HD and WN increase by 1.85 and 2.86 days decade\(^{-1}\),

![FIGURE 2](Image)
respectively (Figure 2a,b). Compared to daytime heat extremes, nighttime events bear much steeper increasing trends. As for consecutive events (Figure 2c,d), the occurrences of DHW and NHW are becoming more frequent, that is, respectively increasing at rates of 0.28 and 0.42 events decade\(^{-1}\). Similar to daily extremes, the consecutive HW events at nighttime in ASRC increase faster than the daytime ones.

Figure 3 shows the spatial distribution of the long-term trend of heat extremes. Discernable increasing trends are observed for all four heat indicators in nearly all parts of ASRC. These trends exhibit some noticeable regional disparities, with a stronger trend in eastern parts and weaker in the west. Again, in most areas of ASRC, nighttime extremes (i.e., WN and NHW) seem to have faster increases than daytime events (i.e., HD and DHW). An anomalous anticyclonic circulation has been observed over the Eurasian continent (centering Mongolia and Lake Baikal) in recent decades, and its associated increasing geopotential height might be responsible for the rapid warming in Northwest China (You et al., 2011).

3.2 | Changes of the droughts

The trends of summer mean SPI and drought months with SPI < \(-0.5\) during 1961–2014 are depicted in Figure 4. It is seen in Figure 4a that, SPI increases in most parts of ASRC, especially in Qinghai, Ningxia, and northern Xinjiang provinces, with only a few stations evidencing slight decreases. The number of summer droughts (months with SPI < \(-0.5\)) is reducing in 89.76% of the stations in ASRC. These results indicate that most areas of ASRC experience a wetting summer climate. On average, the mean trend of the stations in ASRC is 0.06 events decade\(^{-1}\). This finding agrees with the increasing trend in the convergence of water flux (the sum of

FIGURE 3  Spatial distribution of the trends of summer heat extremes in ASRC during 1961–2014. The cross symbol indicates significant trend at the .05 level

FIGURE 4  Spatial distribution of the trends of summer SPI and droughts in ASRC during 1961–2014. The cross symbol indicates significant trend at the .05 level
horizontal advection and wind convergence terms) over
Northwest China during the past decades (Peng and
Zhou, 2017). On the one hand, the increased downward
longwave radiation in this area favors the evaporation
and increases the atmospheric moisture; on the other
hand, central Asia is covered by an anomalous cyclone
and horizontal vorticity advection, thereby leading to a
wetting tendency (Peng and Zhou, 2017). This wetting
tendency can also be observed in Figure 4b.

3.3 | Changes in concurrent drought-heat extremes

We now proceed to examine the change in concurrent
drought-heat events. Figure 5 depicts the mean frequency
of these extreme in ASRC during 1961–2014. On average,
ASRC experiences 3.03 (2.59) days per year and 0.4 (0.3)
events per year concurrent drought-HDs (drought-WNs)
and concurrent drought-DHWs (drought-NHWs), respec-
tively. This result indicates that, compared with concur-
rent nighttime extremes, daytime events occur more
frequently. Geographically, more concurrent drought-
events are observed in eastern than western parts. In par-
ticular, the most frequent concurrent drought-HD
appears in Gansu province which experiences nearly
22 events per year.

Regional mean frequencies of the concurrent
drought-HWs are calculated by averaging all stations in
ASRC, and their yearly changes are shown in Figure 6.
Despite some interannual variations in the time series,
all four concurrent types exhibit significant increasing
trends during the past decades. Concurrent drought-WN
increases by 0.45 days decade\(^{-1}\), and this rate is faster
than that of concurrent drought-HD, that is, 0.17 days
decade\(^{-1}\) (Figure 6a,b). The trend of concurrent drought-
WN frequency is around 2.6 times higher than concur-
rent drought-HD. This result is consistent with the differ-
ent increasing rates in HD and WN (Figure 2a,b).

As shown in Figure 6c,d, concurrent drought-HWs at
daytime and nighttime also tend to occur more fre-
cently in recent years. The frequencies of concurrent
drought-DHW and concurrent drought-NHW occur-
rences increase by 0.08 and 0.03 events decade\(^{-1}\), respec-
tively. The trend of concurrent drought-NHW frequency
is around 2.7 times higher than concurrent drought-
HW. Similar to the stronger trend of WN than HD, con-
current drought-NHW also exhibits a larger increase than
concurrent drought-DHW. That is, the frequency of
nighttime HWs combined with drought climbs up faster
than those daytime ones.

The spatial distribution of the trends of concurrent
heat extremes in ASRC is shown in Figure 7. Evident
increases in concurrent events appear at most stations of
the region. 72.9%, 85.1%, 73.5%, and 89.3% of stations
have positive trends for concurrent drought-HD, -WN,
-DHW, and -NHW, respectively. Notably, the eastern
parts bear even more pronounced trends for all concur-
rent drought-heat extreme indicators, suggesting that
these areas are experiencing increasing threats exerted by
concurrent heat events. This may be related to the fact
that the trend of extreme heat events in the east is larger
than that in the west, as we mentioned earlier. The larg-
est increasing trends in concurrent drought-HD

![Figure 5](https://example.com/figure5.png)

**Figure 5** Spatial distribution of the climatological mean frequency of concurrent drought-heat extremes in ASRC during 1961–2014.
**FIGURE 6** Time series of the concurrent drought-heat extremes in ASRC during 1961–2014. Numbers in square bracket denote their corresponding trends, and all are significant at the .05 level.

**FIGURE 7** Spatial distribution of the trends of concurrent drought-heat extremes in ASRC during 1961–2014. The cross symbol indicates significant trend at the .05 level.
(drought-WN) and concurrent drought-DHW (drought-NWH) reach as high as 3.75 (6.25) days decade$^{-1}$ and 0.58 (0.92) events decade$^{-1}$, respectively. It is also noticed that, in most parts of ASRC, concurrent nighttime heat events display larger increasing trends than daytime types.

4 | CONCLUSION AND DISCUSSION

The risk of heat extremes is intensified under climate change, posing increasing threats to society and the environment. Heat events combined with drought (referred to concurrent drought-heat) can cause even more profound impacts. In this paper, we examine the changes in concurrent drought-heat extremes in ASRC during 1961–2014. In particular, the differences between daytime and nighttime concurrent drought events are compared, and regional disparities of these changes are discussed as well.

By examining the observations at 328 stations in ASRC, we observe increasing occurrences both daily (HD and WN) and consecutive extremes (DHW and NHW) in nearly all parts of the region, even though drought seems becoming less frequent in many parts in recent years. Most regions in ASRC appear a wetter summer climate. The number of summer droughts is reducing in most areas of ASRC, and the reduction in the frequency of drought events in the western region is faster than in the east. It is also observed that, on average, compared with nighttime concurrent drought-heat events, the ASRC region receives more frequent daytime concurrent extremes. In addition, we notice that the western parts of ASRC get rarer concurrent heat events than the east.

Moreover, we find that ASRC bears increasing occurrences of all concurrent events (including both daily and consecutive extremes), especially in eastern areas. The frequencies of concurrent nighttime events increase by approximately 2.7 times faster than the daytime. During 1961–2014, concurrent drought-WN (drought-HD) and concurrent drought-NHW (drought-DHW) increased by 0.45 (0.17) days decade$^{-1}$ and 0.08 (0.03) events decade$^{-1}$, respectively. Those increasing trends are even more prominent in eastern than western parts.

As suggested by previous studies (Peng and Zhou, 2017; Wang et al., 2018; Liu et al., 2019), Northwest China experienced a wetting trend during the past decades. Our analysis confirmed this trend by showing that most areas of ASRC experience a wetter summer climate. One possible reason is the increasing snowfall of Northwest China in previous winter and spring seasons (Sun et al., 2010; Li, 2013), which increases the runoff on the land surface, thus contributing to wetting soil moisture in the following summer (Wang et al., 2011b). Meanwhile, thermodynamics and dynamics changes in Northwest China may also lead to summer wetting in that area. First, the anomalous central Asian anomalous cyclone and Mongolia anticyclone result in precipitation increases in Northwest China (Peng and Zhou, 2017). Second, the southward displacement of the Asian subtropical westerly jet aggravates the convection of northwest vortex over the western parts of Northwest China, thus increasing precipitation there too (Peng and Zhou, 2017).

Previous studies suggested that the high pressure anomalies in Mongolia and the surrounding areas have been induced by anomalous reductions in summer snowfall on the Tibetan Plateau (Wu et al., 2012; Li et al., 2019). Sinking associated with high pressure anomalies can be detrimental to the formation of local clouds, which increases surface radiation and provides a suitable environment for frequent HW activities (Wu et al., 2012). Anthropogenic warming also leads to more serious HW events (Chen and Sun, 2017). Other possible contributing factors and underlying processes warrant further investigations.

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