Does Drought Show a Significant Decreasing Trend From 1961 to 2017 in Northern China?

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Abstract

Understanding the variation of drought is essentially important in climate change and risk assessment. Based on the monthly meteorological data at 321 stations, this study computed the Standardized Precipitation Evapotranspiration Index (SPEI), which was estimated using the potential evapotranspiration (PET) with the Penman–Monteith equation. The trends, affected-area, duration, and frequency of drought was determined using the piecewise linear regression method (LRM) for 1961–2017 over northern China. The results found that (1) drought displayed a wetting trend in 1961–2017 at a rate of 0.05/10a ($p > 0.05$), which generally occurred in winter and in most study areas, particularly in the Xinjiang Uygur Autonomous Region. In contrast, an apparent drying trend occurred on the Loess Plateau. (2) The LRM identified that the turning point (TP) for trends occurred in 1990; the annual SPEI had been increasing pre-1990 and decreasing post-1990. This was especially the case in the Xinjiang Uygur Autonomous Region, Tibet, Gansu, and Inner Mongolia, consistent with patterns of seasonal drought at their respective TP apart from autumn. (3) From 1961 to 2017, the drought-affected area decreased at a rate of $-1.69\%/10a$ ($p < 0.05$). This area decreased before the TP and increased after the TP at different drought levels. The seasonal drought also showed decreasing trend, particularly in winter. (4) The highest frequency and duration of drought occurred in the Loess Plateau and Xinjiang Uygur Autonomous Region, respectively, although it decreased post-1990. These findings suggest that long-term trends in drought were not significant in northern China during 1961–2017. Although the severity, frequency, and duration of drought decreased post-1990, the recent drying trend and increase in the drought-affected area should not be dismissed.

1. Introduction

Drought is one of the most widespread natural hazards with substantial effects on environment and society, including natural ecosystems, hydrology, agriculture, and the economy (Sternberg 2011; Wilhite 1985; Wang et al. 2018). Drought is identified as a spatiotemporal change with a unique complexity and slowness distinct from other disasters, such as earthquakes, floods, volcanic eruptions, and typhoons (Wang et al. 2015; Vogt and Safriel 2011; Wang et al. 2020). Under global climate change, over half of the land area on Earth is susceptible to drought, which is likely to increase in severity (Kogan 2012). For example, the devastating drought in the Sahel region of West Africa caused land degradation in the early 1970s, whilst a severe drought in 2006 resulted in crop failures and livestock deaths in East Africa (Ning 2003; Mainyu 2012; Charney 2010; Ntale and Gan 2003). China is characterized by a vast territory and diverse ecological systems, which are highly vulnerable to extreme events such as drought. This is particularly the case for northern China, where drought is more pronounced (Wei et al. 2003; Chen and Yang 2013; Ma et al. 2003). Therefore, drought assessment is the starting point for addressing extreme weather; it is crucial to mitigating global climate change, drought risk management, disaster mitigation, economic growth, and ecological protection.

In general, there are four types of drought: meteorological drought (precipitation shortage relative to climatological average), agricultural drought (a lack of water supply to crops caused by a soil moisture

deficit), hydrological drought (low water levels caused by stream-flow deficits), and socioeconomic drought (where water supply cannot satisfy water demand to meet a quality of life) (Ali et al. 2015; Boken et al. 2005; Loon and Anne 2015; Zhang and Jia 2013). Researchers have recently introduced the concept of ecological drought, which constitutes an intermittent deficit of water availability prompting ecosystems to exceed vulnerability thresholds and affecting ecosystem services (Shelley et al. 2017; Zhang et al. 2016). Each type of drought may be assessed using different indices that have been used in studies of global droughts. Such indices includes the standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010), Palmer drought severity index (PDSI) (Palmer 1965), standardized precipitation index (SPI) (McKee et al. 1993), surface water supply index (SWSI) (Shafer and Dezman 1982), and reconnaissance drought index (RDI) (Tsakiris and Vangelis 2005). Sheffield and Wood (2007) used the Variable Infiltration Capacity (VIC) model to derive a hydrologically based drought index. They reported that there was a slight wetting trend in the global soil moisture, whereas trends in drought duration, intensity, and severity for most regions were negative during 1950–2000. They also indicated that there had been a change in the drying trend from the 1970s, and the use of the PDSI may overestimate the occurrence of drought due to the use of the Thornthwaite potential evapotranspiration (PET) equation. In contrast, there has been little change in drought over the past 60 years according to the Penman–Monteith PET equation (Sheffield et al. 2012).

In China, research results on drought have varied with the use of different indices; among these research, northern China is an important study area. Some studies have shown that drought has increased in terms of the improved meteorological comprehensive drought index and SPEI, whereas its severity and frequency were higher in northern China than southern China (Han et al. 2019; Wu et al. 2020). Based on the revised PDSI for drought and wetness, Yu et al. (2014) observed a distinct drought trend, where seasonal and periodical drought characteristics could be identified in North China. Wang et al. (2020) evaluated the five drought indices in northern China during 1960–2014, indicating that the monitoring capacity of each drought index was closely related to drought impact factors and their time scales. Several studies have also published contradictory statements; for example, the use of SPI and SPEI showed that drought did not increase throughout China from 1961 to 2012 (Xu et al. 2015). The application of various drought indices may generate different conclusions for a specific study area (Mahmoudi et al. 2019; Wang et al. 2020; Chen et al. 2018). Moreover, droughts have seasonal and regional characteristics. As such, multidimensional drought analysis, typically characterized by analysis of the affected area, intensity, frequency, and duration of drought, offers a better understanding of the drought mechanisms at play (Xu et al. 2015; Han et al. 2019; Yu et al. 2014).

This study sought to investigate long-term changes in drought in northern China over the past 50 years. The SPEI was selected as the drought indicator, estimated by PET based on the Penman–Monteith equation. As a widely used drought index, the SPEI combines the sensitivity of the PDSI to changes in evapotranspiration effects, whilst possessing the multitemporal robustness of the SPI (Wang et al. 2020; Potop 2011; Ayantobo et al. 2017; Wang et al. 2017). The main objectives of this study are as follows: (1) to monitor the spatiotemporal variation in annual and seasonal drought during 1961–2017 using the piecewise linear regression method (LRM); and (2) to evaluate the affected area, duration, and frequency

of drought in northern China. The investigation of changes to the characteristics of drought provides insight into drought risk management under climate change.

2. Materials And Methods

2.1 Study area and dataset

China is divided into northern and southern regions along the Qinling Mountains-Huaihe River line, according to its geographical location and climatic conditions (Han et al. 2019). The study area is northern China, which includes the I Xinjiang Uygur Autonomous Region, II Gansu, III Inner Mongolia, IV Heilongjiang, V Jilin, VI Liaoning, VII Beijing, VIII Tianjin, IX Hebei, X Shanxi, XI Shaanxi, XII Ningxia Hui Autonomous Region, XIII Qinghai, XIV Tibet, XV Sichuan, XVI Henan, XVII Shandong provinces. Of the 756 meteorological stations in China, 321 meteorological stations were screened and selected as they met specific requirements by removing missing data (Fig. 1). Meteorological data were collected from the National Climate Center of China Meteorological Administration to compute the SPEI. The data collected included monthly precipitation, temperature data, maximum and minimum temperatures, wind speed, relative humidity, and sunshine hours over the 1961–2017 period.

2.2 Methods

2.2.1 Calculation of SPEI

Based on previous studies, SPEI was determined by following a series of steps. First, the Penman–Monteith equation was used to calculate PET; this equation has been successfully applied in humid and arid climates around the world. Second, based on the climatic water balance, SPEI was determined by standardizing the difference between precipitation and PET for a given month. Third, the log-logistic probability distribution was selected to generate the SPEI time series. The classification of droughts is presented in Table 1. Based on the initial precipitation and PET in each season, the SPEI was calculated for 1-, 3-, and 12-month time scales to represent monthly, seasonal, and annual drought conditions, respectively. Further information on this computation is available in the supporting materials and references (Vicente-Serrano et al. 2010; Wang et al. 2020; Wu et al. 2020; Beguería et al. 2014).

Table 1 Drought classification of SPEI

	Normal	Mild drought	Moderate drought	Severe drought	Extreme drought
SPEI	≥ -0.5	-0.5~ -0.99	-1.0 ~ -1.49	-1.5 ~ -1.99	≤ -2.0

2.2.2 Area–frequency–duration of drought

This study analyzed drought at the annual and seasonal scales; the latter was divided into spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). McKee et al. (1993) defined drought events as beginning when the 1-month SPEI falls below -1

and ending when the SPEI returns to above -1, in this analysis for at least two consecutive months. Based on the spatial variability, the kriging interpolation method interpolates northern China into 8 km grids, where the drought-affected area was computed as the ratio of the grid where the SPEI was below -1, to the total grid cells. Drought frequency was defined as the number of drought occurrences over a given period in the study area (Spinoni et al. 2014; Wu et al. 2020; Zhai et al. 2017). Drought duration was defined as the sum of months in drought events during different periods (Fig. S1). Additional information is available in the supporting materials.

2.2.3 Trend analysis

The turning point (TP) year of SPEI from 1961 to 2017 was identified using the piecewise linear regression method (LRM) for northern China (Toms and Lesperance, 2003).

$$Y = \begin{cases} \beta_0 + \beta_1 t + \varepsilon, & t \leq \alpha \\ \beta_0 + \beta_1 t + \beta_2(t - \alpha) + \varepsilon, & t > \alpha \end{cases} \quad (1)$$

where Y is SPEI, t is year, α is the TP of SPEI trend, $\beta_0, \beta_1, \beta_2$ are regression coefficients, ε is the residual of the fit. Before the TP, the linear trend of SPEI is β_1 , whereas after the TP, this trend is $\beta_1 + \beta_2$; α is determined by the least square error methods. The t-test was used to test the null hypothesis “ β_2 is not different from zero,” for evaluating the need to introduce the TP.

3. Results

3.1 Spatiotemporal characteristics of drought trends

3.1.1 Annual variation

The annual SPEI over northern China was increasing, with a rate of change for 1961–2017 at 0.05/10a ($p = 0.133$), indicating a trend towards wetter conditions (Fig. 2a). Moreover, the annual SPEI had significantly reduced within a year; the maximum and minimum SPEI occurred in 1964 and 1965, respectively. The LRM identified that the TP of the SPEI occurred in 1990 for the 1961 to 2017 period. Before 1990, the annual SPEI had been increasing at a rate of 0.11/10a ($p = 0.206$); however, this trend had commenced slightly decreasing after 1993, with a rate of change of -0.03/10a ($p = 0.785$) for 1990–2017 (Fig. 2b).

The spatial distribution of trends in annual SPEI over northern China showed clear differences for the 1961–2017 period. The map in the bottom right corner of Fig. 3 shows a significant wetting trend (red) or a significant drying trend (green) at a 5 % significance level. Prior to the TP, most of the study area was experiencing a wet period (i.e., Xinjiang Uygur Autonomous Region, Gansu, Qinghai, Shaanxi, Henan provinces, and Inner Mongolia), whereby 57.32% of northern China was experiencing an increasing wetting trend (Fig. 3d). In contrast, the Tibet and Shandong provinces were experiencing a drying trend, although this trend was not significant in the former (Fig. 3b). After 1990, a clear difference between the

east and west regions had become apparent in the study area. For example, the Xinjiang Uygur Autonomous Region, Gansu, Inner Mongolia, Beijing, and Tianjin had become significantly dry, and Liaoning exhibited a wetting trend unique to that of the 1961–TP period (Fig. 3c). Compared to the early stage, the significant drying trend had increased to 12.15 % of the study area. Overall, the distribution of the wetting trend was widespread throughout northern China during 1961–2017, particularly in the Xinjiang Uygur Autonomous Region, whereas the drying trend was evident in Gansu (Fig. 3a).

3.1.2 Seasonal variation

The seasonal SPEI was observed to increase over 1961–2017, where the TPs were 1990, 1993, 2006, 1989 in spring, summer, autumn and winter, respectively (Fig. 4). In spring, the rates of change for 1961–2017, 1961–TP, and TP–2017 were 0.07/10a ($p = 0.069$), 0.18/10a ($p = 0.052$), and -0.05/10a ($p = 0.611$), respectively (Fig. 4a). Notably, the drying trend was concentrated in the central region, such as the Gansu, Shaanxi, Ningxia Hui Autonomous Region, and Shanxi provinces, which experienced a significant decrease in SPEI during 1961–2017 (Fig. 5). Instead, the region experiencing a wetting trend was scattered, and the significantly increased region accounted for 28.04% of northern China, where it was more distinctly in the Xinjiang Uygur Autonomous Region and Jilin (Fig. 6). The wetting trend during spring was clear in most of northern China (i.e., Xinjiang Uygur Autonomous Region, Gansu, Qinghai, Hebei, Henan, Liaoning, and Inner Mongolia) prior to the TP and then significantly decreased following the TP (11.53% of the study area). In summer, the SPEI rates of change for 1961–2017 were 0.02/10a ($p = 0.497$), which was slightly lower than that in spring. However, the dry and wet trends over these two seasons exhibited similar spatial distributions, in addition to some eastern regions. During 1961–TP, the wetting trend was distributed in the northwest and central regions; SPEI significantly decreased in the Xinjiang Uygur Autonomous Region, Gansu, and Inner Mongolia following the TP, which spanned 5.92 % of the study area (Fig. 6).

The SPEI rates of change for 1961–2017, 1961–TP, and TP–2017 in autumn were 0.03/10a ($p = 0.189$), -0.02/10a ($p = 0.607$), and 0.47/10a ($p = 0.079$), respectively. Before the TP, a drying trend was prominent whilst a wetting trend dominated after the TP (Fig. 4). The Xinjiang Uygur Autonomous Region, Beijing, Tianjin, Hebei, and Inner Mongolia also displayed a significant wetting trend. Prior to the TP, a drying trend appeared in the central region; however, most regions of northern China exhibited a wetting trend in the last ten years (74.76% of the study area). The wetting trend was most pronounced in winter, where the rates of change for 1961–2017, 1961–TP, and TP–2017 were 0.09/10a ($p = 0.015$), 0.10/10a ($p = 0.282$), and -0.01/10a ($p = 0.952$), respectively (Fig. 4). The dry and wet changes were significant in the middle region (i.e., Gansu, Qinghai, Shaanxi, Shanxi, Hebei, Henan, Beijing, Tianjin provinces, and central Inner Mongolia). Following the TP, these provinces experienced a significant drying trend, in which the SPEI decrease substantially to 16.51% (Fig. 5). The wetting trend of the annual SPEI could largely be attributed to trends in winter, spring, and summer (Fig. 6).

3.2 Variations in drought-affected area for northern China

The overall trend in the drought-affected area had fallen over the past 57 years, whereby the rate of change was $-1.69/10a$ ($p < 0.05$) (Fig. 7a). According to the TP, the percentage of drought-affected area was highest in 1965 (34.79 % of the study area) pre-1990, where a decreasing trend was evident at a rate of $-2.63/10a$ ($p > 0.05$). The percentage of drought-affected area was less than that in 1961–TP post-1990, in which the highest percentage occurred in 1997 (31.90 % of the study area). However, the percentage of the drought-affected area increased at a rate of $0.50/10a$ ($p > 0.05$), and different levels of drought exhibited the same trend, with the abatement of more severe droughts (Fig. 7b). The drought-affected areas with $SPEI \leq -1$, $SPEI \leq -1.5$, and $SPEI \leq -2$ were 7.98 %, 1.37 %, and 0.11 % during 1961–2017, respectively. The maximum drought-affected area was recorded in the mid-1960s for the 1961 to 2017 period (Table 2).

Table 2 Percentage (%) of areas affected by different drought severities over the 1961–2017 period

Level	Annual	Spring	Summer	Autumn	Winter
$SPEI \leq -1$	7.98 (1965)	9.24 (1962)	7.05 (1997)	7.80 (2001)	9.24 (1963)
$SPEI \leq -1.5$	1.37 (1965)	1.88 (1962)	1.13 (1974)	1.62 (1998)	1.79 (1963)
$SPEI \leq -2$	0.11 (1966)	0.19 (1962)	0.07 (1974)	0.20 (1998)	0.18 (1963)

Note: The value in parentheses is the year when the maximum drought-affected area was recorded.

Similar to the annual trend in drought-affected areas, the seasonal trend also decreased from 1961 to 2017 at rates of $-1.71/10a$ ($p \neq 0.05$), $-0.19/10a$ ($p \neq 0.05$), $-0.86/10a$ ($p \neq 0.05$), $-2.20/10a$ ($p \neq 0.05$) in spring, summer, autumn, and winter, respectively (Fig. 8a). The drought-affected areas in the four seasons had different degrees of reduction, particularly for winter. The percentage of drought-affected areas in spring was higher than other seasons (Fig. 8b). Similar to patterns in the annual drought-affected areas, the moderate drought-affected areas in spring, summer, autumn, and winter were 9.24 %, 7.05 %, 7.80 %, and 9.24 %, respectively. The severe drought-affected areas were 1.88 %, 1.13 %, 1.62 %, and 1.79 % in spring, summer, autumn, and winter over 1961–2017, respectively. Extreme droughts tended to occur in autumn (0.20 %) and spring (0.19 %), and drought areas mainly occurred in the late 1990s and early 1960s (Table 2).

3.3 Variations in drought frequency and duration for northern China

The LRM identified that 1990 was the TP for drought over the past 57 years. The 1961–2017 period was roughly divided into two of the same subperiods (i.e., 1961–1989 and 1990–2017) to explore variation in drought frequency patterns over northern China. Drought frequency was between 25 and 30 times during 1961–2017, where only some stations in the Xinjiang Uygur Autonomous Region and Qinghai experienced a lower drought frequency (Fig. 9). Prior to the TP, the drought frequency of these provinces was in excess of 15 times, although the mid regions, such as Gansu, Ningxia Hui Autonomous Region, Shaanxi, and eastern Inner Mongolia experienced lower frequencies. Drought frequency had greatly

reduced after the TP, showing an opposite spatial distribution compared with the previous period. Stations in Xinjiang Uygur Autonomous Region, Beijing, Tianjin, and Heilongjiang recorded drought frequencies of less than 10 times, whereas Inner Mongolia, Qinghai, Gansu, Ningxia Hui Autonomous Region, Shaanxi, and Shanxi provinces recorded frequencies greater than 10 times. Drought frequencies of more than 15 times were observed based on 49.22 % (158) and 19.94 % (64) of meteorological stations over northern China during 1961–1989 and 1990–2017, respectively.

To further analyze drought in northern China, the corresponding periods of total drought duration were investigated (Fig. 9). The total drought duration in most of the study area lasted less than 110 months over the 1961–2017 period. In contrast, the Xinjiang Uygur Autonomous Region experienced longer drought durations, exceeding 100 months. Drought duration also exhibited the same spatial distributions during the subperiods as observed in drought frequency. In 1961–1989, the drought duration of the study area was mainly between 30 and 50 months (136 meteorological stations), followed by 50–70 months (123 meteorological stations). The maximum drought duration occurred in the Xinjiang Uygur Autonomous Region and Qinghai, exceeding 90 months. Post-1990, the duration of drought had decreased significantly in northern China. Most regions experienced droughts that lasted less than 50 months (252 meteorological stations). Drought durations of 50–70 months mainly occurred in the middle regions, including Qinghai, Gansu, Shaanxi, Shanxi, and Inner Mongolia. Durations of 70–90 months of drought were mainly concentrated in the Gansu, Ningxia Hui Autonomous Region, and Inner Mongolia provinces.

4. Discussion

The results indicate that a wetting trend occurred over northern China during 1961–2017 when using the SPEI to monitor drought. The wetting trend mainly occurred in the west, east, and northeast of the study area, whereas the drying trend was concentrated on the Loess Plateau. These results are consistent with those of previous studies (Wu et al. 2017; Zhai et al. 2015; Wang 2017). For example, Zeng et al. (2020) used the SPEI to observe that China had experienced a significant wetting trend observed in the western region, the Tibetan Plateau, and eastern China from 1965 to 2017. Xu et al. (2015) showed that the western part of the North China Plain and Loess Plateau experienced a significant drying trend using three months of SPI, RDI, and SPEI indices; this trend was mainly attributed to a significant decrease in precipitation. Conversely, different studies have reported on the evidence of a drying trend in northern China. Due to decreased precipitation coupled with a general increase in temperature, they reported on the occurrence of significant drying trends over North China and the central and eastern regions of Northwest China using SPEI based on PET determined by the Thornthwaite equation (Yu et al. 2014). Previous studies have shown that the use of the Thornthwaite equation may overwhelm significant increases in PET (Sheffield et al., 2012; Li et al., 2015; Wang et al., 2015). The TP determined using the LRM was 1990; most regions, such as the Xinjiang Uygur Autonomous Region and Inner Mongolia, experienced a wetting trend pre-1990, and a drying trend post-1990. Some papers reported that drought events frequently occurred in China in the 1990s; for instance, Zou et al. (2015) concluded that since the late 1990s, most of northern China (except western Northwest China) had experienced severe and prolonged drought. Liu

et al. (2013) analyzed changes in the Penman–Monteith evapotranspiration series, indicating that the TP occurred around 1993 based on Pettitt's test.

A seasonal wetting trend was evident throughout the investigated period, where the increase in the trend was prominent in winter, potentially as a result of winter precipitation; this finding was consistent with other studies (Li et al. 2005; Wang et al. 2017; Yu et al. 2014). Regionally, the wetting trend in winter, distributed in the Xinjiang Uygur Autonomous Region and Gansu, was mainly related to increasing westerly precipitation and decreasing blocking activities (Wu et al. 2020). Ma et al. (2003) found that the drought tendency from May to September was evident in most regions within northeast China regions. Ma et al. (2012) indicated that drought was likely to occur in all seasons, particularly in summer and spring; the former is the most common in northeast China. However, several studies identified that spring drought over the 1961–2010 period in the northeast was the severest, followed by winter. This was particularly the case in Heilongjiang Province, which presented contradictory comments (Han et al. 2014). Based on self-calibrating PDSI, a significant wetting trend in China occurred in spring and autumn from 1961 to 2009; however, the results from this study indicate that this trend was not significant in northern China (Wang et al. 2017). Differences in these results were related to drought type, drought indicator, data source, calculation method, study period, and study area that feature differing natural and climatic conditions (Sheffield et al. 2012; Wang et al. 2020; Wang et al. 2015; Xu et al. 2015). SPEI is an appropriate indicator for short or long-term drought trends and is reflective of the climatic water balance (Zhao and Gao 2015).

In general, the drought-affected area was decreasing for 1961–2017 at both annual and seasonal scales. Although the percentage of these areas had decreased from 1990 compared with pre-1990, there was an increasing trend at a rate of 0.50/10a from 1990 to 2017. The percentage of drought-affected area was decreasing at the seasonal scale from 1961–2017. This decrease in drought area may be related to changes in precipitation in different regions under atmospheric–ocean interactions (Zhai et al. 2017). However, research has revealed significant increases in drought areas based on PDSI in north China from 1951 to 2003. Since the late 1990s, most of northern China has also experienced severe and prolonged dry periods (Zou et al. 2005). Drought has become more severe, extensive, frequent, and enduring since 1960 (Ma et al. 2019). The maximum drought-affected area was recorded in the 1960s and late 1990s, where drought frequency in most of northern China was between 25 and 30 times, and its duration was below 100 months. These results highlight that in addition to global climate change, the rapid development of human society will also affect the vegetation, land, atmosphere and other ecosystem elements, and then trigger the occurrence of drought. When drought occurred in the Xinjiang Uygur Autonomous Region, its duration extended over a long period of time. On the other hand, a high frequency of drought occurred in the Loess Plateau and north China, where sustainable water resources were limited.

These drought events may be attributed to decreased precipitation and increased temperature under global warming. Increased precipitation can mitigate the drying trend, especially in the Xinjiang Uygur Autonomous Region and Heilongjiang (Fig. 10a). For example, precipitation was increasing in the

Xinjiang Uygur Autonomous Region and northwest China, where SPEI showed a wetting trend on annual and seasonal scales for 1961–2017 (Sui et al. 2013). Rainfall less than the threshold through the four seasons can lead to seasonal drought. The mean precipitation during the crop-growing season (from May to September) and summer (from June to August) decreased from 1960 to 2009, which could increase the occurrence of summer and autumn droughts (Yu et al. 2014). Meanwhile, temperature had risen under the influence of global warming, accelerating soil water evaporation. Almost all of northern China experienced an upward trend in temperature from 1961 to 2017 (Fig. 10b). In addition, several knock-on effects such as El Niño from the strong anomalous cyclones of the Northwest Pacific also reduced precipitation in affected areas (Zhang et al. 2013; Sutanto et al. 2013). Although precipitation is the main factor influencing the occurrence of drought, the mechanism of drought events is complicated by the many factors involved, e.g., soil water storage, vegetation self-protection mechanism, human activities, topography etc., which still need to be further explored in different ways.

Based on the drought indicator–SPEI, which estimated by the Penman–Monteith potential evapotranspiration equation, this study investigated piecewise variations of annual and seasonal drought in northern China over the past 50 years. Multidimensional evaluation of the affected area, duration, and frequency of drought provided insight into drought risk management under climate change. The difference between the results and other studies relate to the research period, research scope, and drought index. There are limitations to the data acquisition in this study, such as the few stations in the Qinghai-Tibet Plateau. With the exception of drought trend–area–frequency–duration, the drought severity (integral area) should also be analyzed in future. Additionally, other drought indices and new methods, such as the empirical orthogonal function and process-based model with experimental data may also be used in future.

5. Conclusions

This study observed that drought events were not significant over northern China over the past 57 years. The annual SPEI increased before the TP and decreased after the TP, consistent with seasonal drought trends apart from autumn. The wetting trend tended to arrive in winter and occurred in most of the study area, particularly in the Xinjiang Uygur Autonomous Region. The area–frequency–duration of drought analysis demonstrated that the frequency and duration of drought decreased in northern China post-1990. However, the influence of drought could not be ignored as the trend in the affected area has been increasing in recent years, particularly in the Loess Plateau. This indicates that most of northern China is relatively dry and easily plagued by drought stress. In addition to the complex climate and topography conditions in northern China, other factors that influence drought using different drought indices and methods should also be considered to better understand the mechanisms underpinning drought occurrence.

Declarations

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Author contributions

Conceptualization, Lu Yu; Data curation, Lu Yu and Zhitao Wu; Formal analysis, Lu Yu; Funding acquisition, Zhitao Wu, Yong Liu, Ziqiang Du, Hong Zhang and Lu Yu; Investigation, Ziqiang Du; Methodology, Zhitao Wu; Project administration, Yong Liu; Resources, Zhitao Wu and Hong Zhang; Software, Lu Yu; Supervision, Yong Liu and Hong Zhang; Validation, Zhitao Wu and Yong Liu; Visualization, Ziqiang Du; Writing – original draft, Lu Yu; Writing – review & editing, Lu Yu and Zhitao Wu.

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Figures

Figure 1

Terrain, meteorological station, provinces within the study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Trends of annual SPEI over northern China for (a) 1961-2017, 1961-TP, TP-2017; and (b) detecting the turning point of SPEI from 1961 to 2017

Figure 3

Spatial distribution of annual SPEI trends over northern China for (a) 1961-2017; (b) 1961-TP; (c) TP-2017; and (d) percentages of SPEI that increased/decreased at the 5% significance levels. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Trends of seasonal SPEI in (a) spring; (b) summer; (c) autumn; and (d) winter over northern China during 1961–2017, 1961-TP and TP-2017

Figure 5

Spatial distribution of seasonal SPEI trends and significance that increased/decreased at the 5% significance levels over northern China during 1961-2017, 1961-TP, TP-2017. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or

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Figure 6

Percentages of seasonal SPEI that increased/decreased at the 5% significance levels in different period

Figure 7

Percentages of drought-affected areas (a) with $SPEI \leq -1$; and (b) at different levels of drought

Figure 8

Percentages of drought-affected areas in seasonal (a) trends ($SPEI \leq -1$); and (b) drought levels during 1961–2017

Figure 9

Spatial distribution of drought frequency and duration in northern China during 1961–2017, 1961–1989, 1990–2017. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 10

Spatial distribution of precipitation and temperature in trends from 1961 to 2017. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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