

Drought variability in Inner Mongolia of northern China during 1960–2013 based on standardized precipitation evapotranspiration index

Shulin Liu^{1,2} · Wenping Kang^{1,2} · Tao Wang^{1,2}

Received: 1 June 2015 / Accepted: 28 September 2015 / Published online: 6 January 2016
© Springer-Verlag Berlin Heidelberg 2015

Abstract The standardized precipitation evapotranspiration index (SPEI) was widely used in climatology and hydrology studies, because its combination the sensitivity of the PDSI to the changes in ET (caused by air temperature fluctuations and trends) with the simplicity of calculation, but also has the robustness of the multitemporal nature of the SPI. In this article, the temporal and spatial pattern of drought based on SPEI was explored in the Inner Mongolia during 1960–2013. The results showed that SPEI can effectively reveal the multiscale feature of drought, and the effect of air temperature rising on drought severity and cumulative effect of drought itself. SPEI is suitable for those longer time scales such as 6-month or longer, and better in semi-humid and semi-arid areas than in arid area, due to much zero values or extreme maximum values at shorter time scale or in arid area. Generally, there is a drying trend in the whole Inner Mongolia, and a very severe drought was revealed at multi-time scales during the 2000s. Annual SPEI change at 6-month scale from APR to SEP indicated that drought in plant-growth season is very frequent and increasingly serious, and it should be given more attention. The severities of drought vary in different sub-regions. A significant abrupt change point of drought change trend in the whole Inner Mongolia at 12-month time scale was diagnosed in late 1990s, while this abrupt point in the middle-west subarea is a little earlier than those

in the northeast subarea and the southeast subarea. This lasting severe drought should be the result of joint action of increasing air temperature and obviously decreasing precipitation since 2000s. At the same time, the most severe and frequent drought mainly occurred along the Sino-Mongolia border and the Horqin Sandy Land, while the continuous belt along the Da Hinggan Ling Mountains, the Yinshan Mountains, the Hetao Plain and the Mu Us Sandy Land is the area with relative slight drying trend during the last decades. Drought spatial pattern indicated by SPEI was supported by spatial distribution of temperature vegetation drought index based on remote sensing.

Keywords Drought variability · Abrupt change · Standardized precipitation evapotranspiration index (SPEI) · Inner Mongolia

Introduction

Drought is a major natural hazard that can have devastating impacts on regional agriculture, water resources, the environment and land desertification, with far-reaching impacts in an increasingly globalized world (Keyantash and Dracup 2002; Svoboda et al. 2002; Romm 2011; Sternberg 2011), causing tens of billions of dollars in global damages, and collectively affecting more people than any other form of devastating climate-related hazards (Wilhite 2000). With the increasing global warming, drought became more frequent and showed an obvious increasing trend (Giorgi 2006; Lehner et al. 2006; Giannakopoulos et al. 2009). Widespread drying has occurred over Africa, East and South Asia, and other areas from 1950 to 2008, and most of this drying is due to recent warming (Dai 2011). Although global drought might be

✉ Shulin Liu
liusl@lzb.ac.cn

¹ Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, Lanzhou 730000, China

² Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

overestimated (Sheffield et al. 2012), the role of warming-induced drought stress is evident in recent studies that have analyzed drought impacts on net primary production and tree mortality (Martínez-Villalta et al. 2008; Williams et al. 2011; Linares and Camarero 2011; Diro et al. 2014). Droughts directly influences local agriculture and pasture production in the Mongolian Steppe (Goudie and Middleton 1992; Shinoda et al. 2010), and accelerate desertification process and even induce severe dust storms (Schubert et al. 2004). It is very important to monitor and assess drought for decreasing loss and ensuring human lives and property safe.

Drought has been studied based on its frequency, duration and severity, and spatial extent in terms of a region or application-specific index. A number of drought indices such as palmer drought severity index, PDSI (Palmer 1965; Mishra and Singh 2010), surface water supply index, SWSI (Shafer and Dezman 1982), standardized precipitation index, SPI (McKee et al. 1993), and effective drought index, EDI (Byun and Wilhite 1999), have been developed and widely used in various parts of the world (Wilhite et al. 2000). Of these, SPI has received much attention since its introduction by McKee et al. (1993). Known as a simple and objective measurement of meteorological drought, it has been applied effectively to dry regions (Hayes et al. 1999; Wu et al. 2001; Morid et al. 2006; Sternberg et al. 2011). In the recent years, the standardized precipitation evapotranspiration index (SPEI) combines the sensitivity of PDSI to changes in evaporation demand (caused by temperature fluctuations and trends) with the simplicity of calculation and the multitemporal nature of the SPI. The SPEI index is particularly suited to detecting, monitoring, and exploring the consequences of global warming on drought conditions (Vicente-Serrano et al. 2010). The SPEI was developed in 2010 and has been widely used in an increasing number of climatology and hydrology studies (Li et al. 2012; Zhuang et al. 2013; Yu et al. 2014; Wang and Chen 2014; Begueria et al. 2014; Jeong et al. 2014), and drought monitoring systems (e.g. Fuchs et al. 2012). Wang and Chen (2014) indicated that SPEI has good performance in measuring drought as well as flood through the comparison between spatial distribution of SPEI and China Historical Drought Dataset in typical years. Moreover, an updated global gridded database had been finished (Begueria et al. 2014). A crucial advantage of the SPEI over other widely used drought indices that consider the effect of potential evapotranspiration (PET) on drought severity is that its multi-scalar characteristics enable identification of different drought types and impacts in the context of global warming.

In this article, the Inner Mongolia of northern China as a typical study area was explored with the SPEI index, due to

severe desertification problem there (Wang et al. 2004). The main objective of this article is to explore practicality of SPEI in the desert zone of northern China, and to provide more reliable natural context for local agriculture and pasture activities, desertification control and ecosystem reconstruction.

Data and methods

Study area and data

The Inner Mongolia Autonomous Region of northern China covers an area of 1.18 million km². It located between 37°–54°N and 97°–127°E with a mean elevation about 1000 m. Inner Mongolia, with a temperate continental monsoonal climate, has a cold and long winter and a warm and short summer. Except for the relatively humid Da Hinggan Ling Mountains area, the most part of Inner Mongolia is arid, semi-arid or semi-humid from west to east. It has an average annual temperature of –5 to 10 °C and an annual average precipitation of 30–500 mm. This study area include Hulun Buir Sandy Land, Horqin Sandy Land, Onqin Daga Sandy Land, Mu Us Sandy Land, as well as Hobq Desert, Ulan Buh Desert, Tengger Desert and Badain Jaran Desert, which is the important grazing base and national ecological protection shelter.

Considering data availability and the length of records, monthly mean air temperature, total monthly precipitation, monthly mean relative humidity, and monthly mean wind speed dataset in all the shared meteorological stations of Inner Mongolia during 1960–2013 were obtained from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/>). According to the completeness and quality of data series, the total 46 stations with better quality control were selected to calculate SPEI and using for drought analysis in the whole Inner Mongolia. Fewer missing data in specific stations were replaced by linear regression estimate according to the closest series. SRTM DEM data with the 5° × 5° were downloaded from (<http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp>). The location of the study area and distribution of weather stations selected and several deserts and sandy lands in this study are plotted in Fig. 1.

Calculation of ET₀ and SPEI

Calculation of ET₀

Here, we followed the simplest modified approach to calculate ET₀ (Thornthwaite 1948), which has the advantage of only requiring data on monthly mean temperature and latitude of the site. Following this method (Ma and Fu 2001), the monthly ET₀ (mm) is obtained by

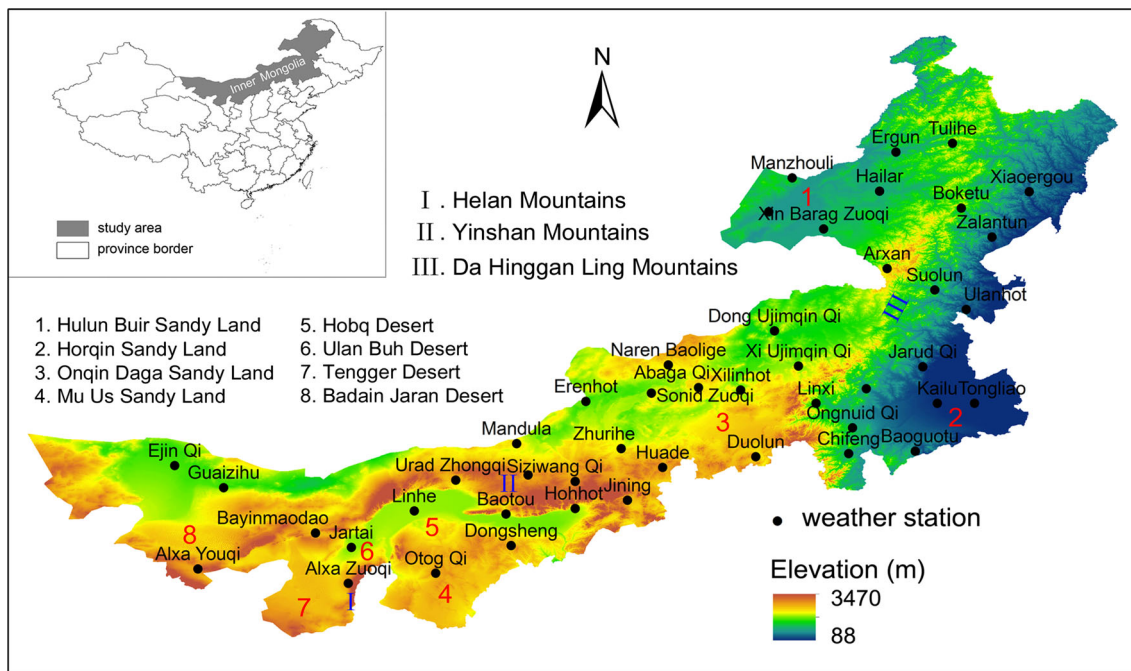


Fig. 1 Location of the study area and the meteorological stations

$$ET_0^i = \begin{cases} 0 & T_i \leq 0^\circ\text{C} \\ 16K(10T_i/I)^m & 0 < T_i \leq 26.5^\circ\text{C} \\ a_1 + a_2T_i + a_3T_i^2 & T_i > 26.5^\circ\text{C} \end{cases}$$

where T_i is the monthly mean temperature ($^\circ\text{C}$); m is a coefficient depending on I : $m = 0.49239 + 1.792 \times 10^{-2} I - 7.71 \times 10^{-5} I^2 + 6.75 \times 10^{-7} I^3$; constant $a_1 = -415.8547$; $a_2 = 32.2441$; $a_3 = -0.4325$. I is a heat index, which is calculated as the sum of 12 months index values I_i (when T_i is positive value, I_i will have a positive value, otherwise I_i take zero), the latter being derived from mean monthly temperature using the formula

$$I_i = \left(\frac{T_i}{5}\right)^{1.514}$$

and K is a correction coefficient computed as a function of the latitude and month,

$$K = \left(\frac{N}{12}\right) \left(\frac{\text{NDM}}{30}\right).$$

Here NDM is the real number of days of the month and N is the maximum number of sunshine hours, which is calculated using

$$N = \left(\frac{24}{\pi}\right) \varpi_s$$

where ϖ_s is the hourly angle of sun rising, which is calculated using

$$\varpi_s = \arccos(-\tan \varphi \tan \delta)$$

where φ is the latitude in radians and δ is the solar declination in radians, calculated using

$$\delta = 0.4093 \sin\left(\frac{2\pi J}{365} - 1.405\right)$$

where J is the average Julian day of the month.

There are lots of methods to calculate ET_0 . Some studies indicated that the $ET_0\text{-Th}$ (calculated with the Thornthwaite algorithm) is biased, and it underestimated ET_0 in arid and semiarid regions (Jensen et al. 1990), and overestimated ET_0 in humid equatorial and tropical regions (van der Schrier et al. 2011). Mavromatis (2007) showed that the use of simple or complex methods to calculate the ET_0 provides similar results when a drought index, such as the PDSI, is calculated. A sensitivity analysis of the PDSI using long-term data with both the Thornthwaite and the Penman–Monteith parameterizations revealed minor differences in PDSI (van der Schrier et al. 2011), indicating that choice of PET parameterization in drought indices that use a simple water balance such as the PDSI and SPEI may not greatly affect the resultant values. So we still use the modified $ET_0\text{-Th}$, i.e. adopting N (the maximum number of sunshine hours mentioned above), to calculate SPEI and the following analysis section in this article.

Table 1 Categorization of dryness/wetness grade by the SPEI

Categories	SPEI values
Extremely dryness	Less than -2
Severe dryness	-1.99 to -1.5
Moderate dryness	-1.49 to -1.0
Near normal	-1.0 to 1.0
Moderate wetness	1.0 to 1.49
Severe wetness	1.50 to 1.99
Extremely wetness	More than 2

Calculation of SPEI

The three-parameter log-logistic distribution has also been used to compute SPEI (Vicente-Serrano et al. 2010; Begueria et al. 2014). The average value of SPEI is 0, and the standard deviation is 1. The SPEI is a standardized variable multi-scalar, and it can therefore be compared with other SPEI values over time and space. An SPEI of 0 indicates a value corresponding to 50 % of the cumulative probability of D_i (the difference between the precipitation P_i and ET_0 i for the month i), according to a log-logistic distribution. Table 1 is the Categorization of dryness/wetness grade by the SPEI (Yu et al. 2014). For this study, SPEI was calculated at time scales of 1, 3, 6, 12, 24, 36 and 48 months.

Sequential Mann–Kendall test

The non-parametric Mann–Kendall–Sneyers test is a sequential version of the Mann–Kendall rank statistic proposed by Sneyers (1975). The test is based on the fact that, under the hypothesis of a stable climate, the succession of climatological values must be independent and the probability distribution must remain always the same (simple random series). The efficiency of this test has been demonstrated using a Monte Carlo technique by Goossens and Berger (1987). For the time series x_i ($1 \leq i \leq n$), the numbers of elements $x_i > x_j$ ($j < i$, $i = 1, \dots, n$) are counted and denoted by r_i . Under the null hypothesis (no trend), the rank series

$$s_k = \sum_{i=1}^k r_i$$

is normally distributed with mean and variance given by

$$E(s_k) = \frac{k \times (k + 1)}{4}$$

$$\text{Var}(s_k) = \frac{k \times (k - 1) \times (2k + 5)}{72}$$

Let

$$UF_k = \frac{s_k - E(s_k)}{\sqrt{\text{Var}(s_k)}}, k = 1, 2, \dots, n$$

be the normalized variable that has zero mean and unit standard deviation, which is the forward statistic sequence. The backward sequence UB_k is estimated using the same equation but with a reversed series of data. Their probability or significance level α can be obtained from calculation or using a look-up table. If the null hypothesis has been rejected, i.e. a change does exist somewhere in the time series, the detection of an increasing ($UF_k > 0$) or a decreasing ($UF_k < 0$) trend is indicated (Zhao et al. 2008). Similarly, the values of UB'_k are computed backward, starting from the end of series. Then $UB_k = -UB'_k$ ($k = n + 1 - k$, $k = 1, 2, \dots, n$). The sequential version of the test used here enables detection of the approximate time of occurrence of the trend by locating the intersection of the forward and backward curves of the test statistic. If the intersection occurs within the confidence interval, then it indicates a jump change point (Demaree and Nicolis 1990; Moraes et al. 1998). Critical value for 95 % confidence level is ± 1.96 .

Spatial interpolation analysis

ANUSPLIN is a software widely using in spatial interpolation analysis of climate elements (Hutchinson 2004; Hijmans et al. 2005; Liu et al. 2008). This software was used in this paper for spatial interpolation of SPEI. Two important data files were required in using this software. One is the file including SPEI data at each weather station with accurate longitude, latitude and elevation, and longitude and latitude were taken as input of independent SPLINE variables. The other one is ASCII file of the digital elevation model (DEM) data transformed from DEM raster data with 1 km \times 1 km spatial resolution, and it was taken as input of independent covariate. Thus, influence of the elevation on the SPEI can be considered during interpolation. The order of SPLINE is 2. According to statistics result in the log file, the signal to noise ratio (SNR) is 0.2202 and 0.2234 which both are smaller than 1; and the mean square for error (MSE) is 0.0006 and 0.0037 which are smaller than the generalized cross validation (GCV) that are 0.0037 and 0.0246, separately in the periods of 1960–1998 and 1999–2013. These assessment indicators showed that simulated surface is very good for SPEI interpolation.

Temperature vegetation drought index (TVDI)

For further test SPEI reliability in drought detection, another important product of TVDI was adopted in this paper. TVDI had been widely used in surface moisture status (Sandholt et al. 2002; Sha et al. 2014). TVDI with 1 km \times 1 km spatial resolution was calculated to study

drought conditions of August and September during 2000–2013 in Inner Mongolia, based on MODIS (moderate-resolution imaging spectroradiometer) products and part field tests, including MOD11 A2 (T_s) and MOD13A2 ($NDVI$) (Ftp://ladsweb.nascom.nasa.gov). Multi-year average TVDI in August and September was used to reflect regional drought characteristics.

Results and discussion

Change trend of SPEI at typical sites in different climate zones

SPEI at five typical weather stations with different annual total precipitation range from 35 to 470 mm showed that an obvious drought period can be found since about 2000 at these five stations, especially a lasting drought at Tongliao, Sonid Zuoqi and Ejin Qi at longer time scale of 48 months, although SPEI strongly fluctuate during the last 50 years (Fig. 2).

Change trend of drought in the whole Inner Mongolia and different subareas

Cluster analysis showed that 46 stations can be divided into three big groups which have very particular geographic features, based on similarity of SPEI time series of 46 stations during 1960–2013 (Fig. 3). They are the north-east subarea mainly including Hulun Buir Sandy Land and the northern part of the Da Hinggan Ling Mountains, the southeast subarea mainly including Horqin Sandy Land and the southern part of the Da Hinggan Ling Mountains, and the middle-west subarea with more arid climate mainly located to the west of the Da Hinggan Ling Mountains. There are different dry or wet periods in these three subareas. Before 1999, there is almost opposite dry or wet patterns between the two east subareas and the middle-west subarea. However, a significant drought abrupt occurred at the end of 1990s. Mann–Kendall test revealed that an abrupt change point is detected about 1997 in the middle-west subarea, and 1999 in the northeast subarea and in the southeast subarea of Inner Mongolia, as well as 1999 in the whole Inner Mongolia, with the confidence level of 0.05 (Fig. 4). Forty-three out of 46 stations exhibited negative slopes in the time series of humid index, which indicates that Inner Mongolia has become drier in the past 52 years (Hu et al. 2015). Severe and extreme droughts have become more serious since late 1990s for all of China (with dry area increasing by $\sim 3.72\%$ per decade) (Yu et al. 2014). The drought patterns in different subareas and their abrupt change might be highly related to intensities of Eastern Asia monsoon and the westerlies and their changes

under global warming (Wang 2001; Wang et al. 2006; Qian and Qin 2008).

Temporal-spatial patterns of drought in Inner Mongolia

Spatial difference of drought is huge among different weather stations. Ejin, Guaizihu, Erenhot, Manzhouli, Xin Barag Youqi are the stations with the most severe drought, while Bayinmaodao, Siziwang Qi and Huade are those weather stations with the slightest drought which are also showed in the spatial interpolation map of SPEI (Figs. 5, 6).

The whole Inner Mongolia has a drying trend during the last several decades. The most severe drought area mainly located along the Sino-Mongolia border including the Hulun Buir Sandy Land, the Xilingol grassland, the Alxa Plateau, and the Horqin Sandy Land. The continuous belt along the Da Hinggan Ling Mountains, the Yinshan Mountains, the Hetao Plain and the Mu Us Sandy Land is the area with relative slight drought (Fig. 6). This drought pattern derived from SPEI also got the support from spatial distribution of multi-year average TVDI based on remote sensing in August and September during 2000–2013, especially obvious in Hulun Buir Sandy Land, Horqin Sandy Land, Xilingol grassland and the whole Alxa Plateau (Fig. 7). Zou et al. (2005) found that the successive large increase in dry areas from the late 1990s to 2003 in Northeast, North and Eastern Northwest China were unprecedented during 1951–2003. Li et al. (2012) indicated drying trends across the whole of China, and the most significant drought was in the west, north and northeast of China. Nandintsetseg and Shinoda (2013) indicated a significant ($p < 0.05$) increase in the frequency and severity of growing-season droughts during the 2000s across the four vegetation zones (except high mountain) in Mongolia, and pointed out that droughts have driven a reduction in pasture production in Mongolia. Thus, it can be seen, a common drying trend exists in the whole Mongolian Plateau especially during the 2000s.

Multi-scalar characteristics of drought in Inner Mongolia

It is found that, at 1- and 3-month scale, there is a higher probability of zero values within the D_i water surplus or deficit series. And no solution of SPEI is still exist in some small number of cases (Begueria et al. 2014), although no solution only occupied by 0.49 and 0.14 % at 1- and 3-month time scales respectively, due to much zero values or part extreme maximum values (Jin 2006) in the accumulated difference $X_{i,j}^k$ series at shorter time scale, as commonly resulted from extreme low precipitation and

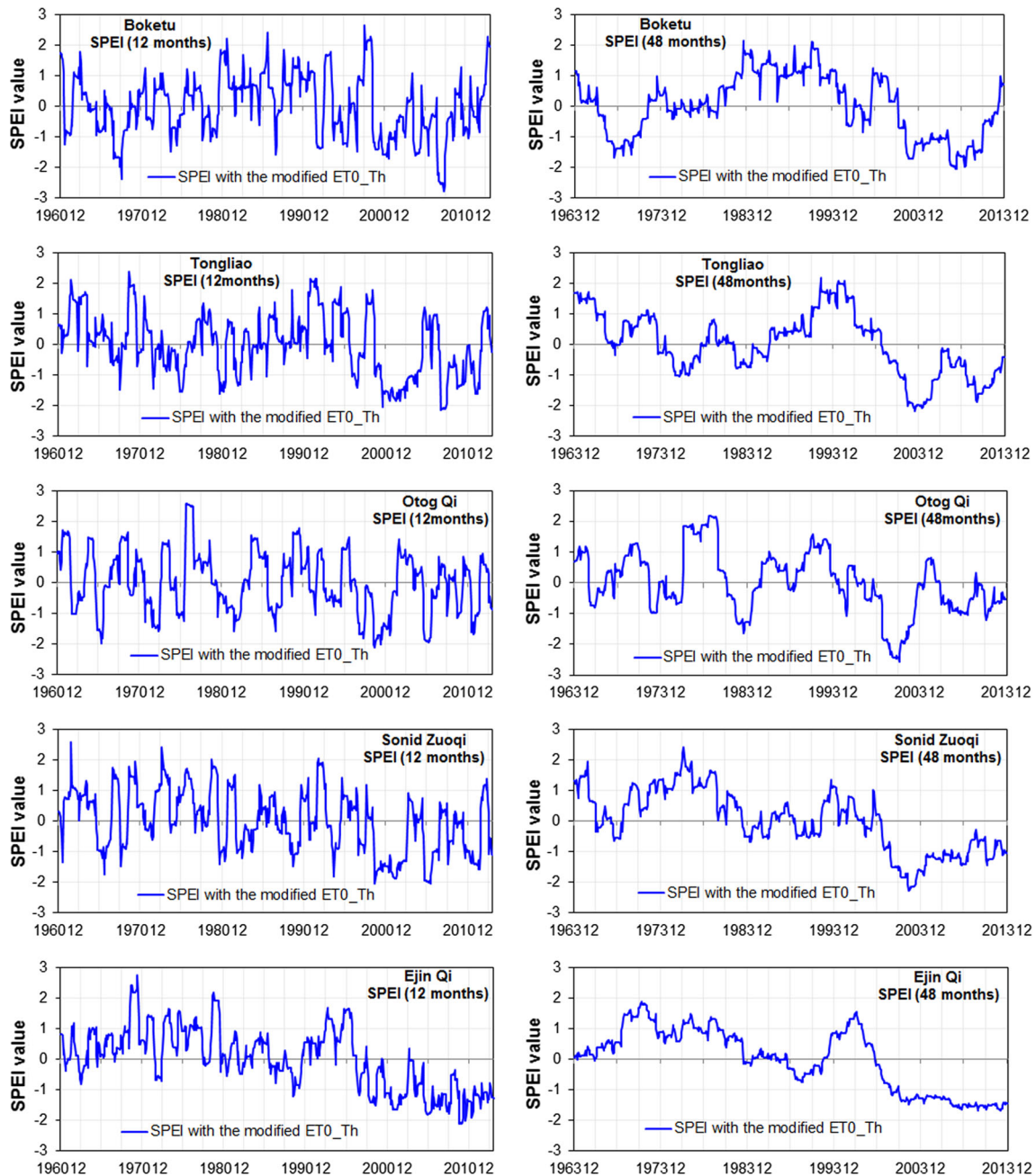
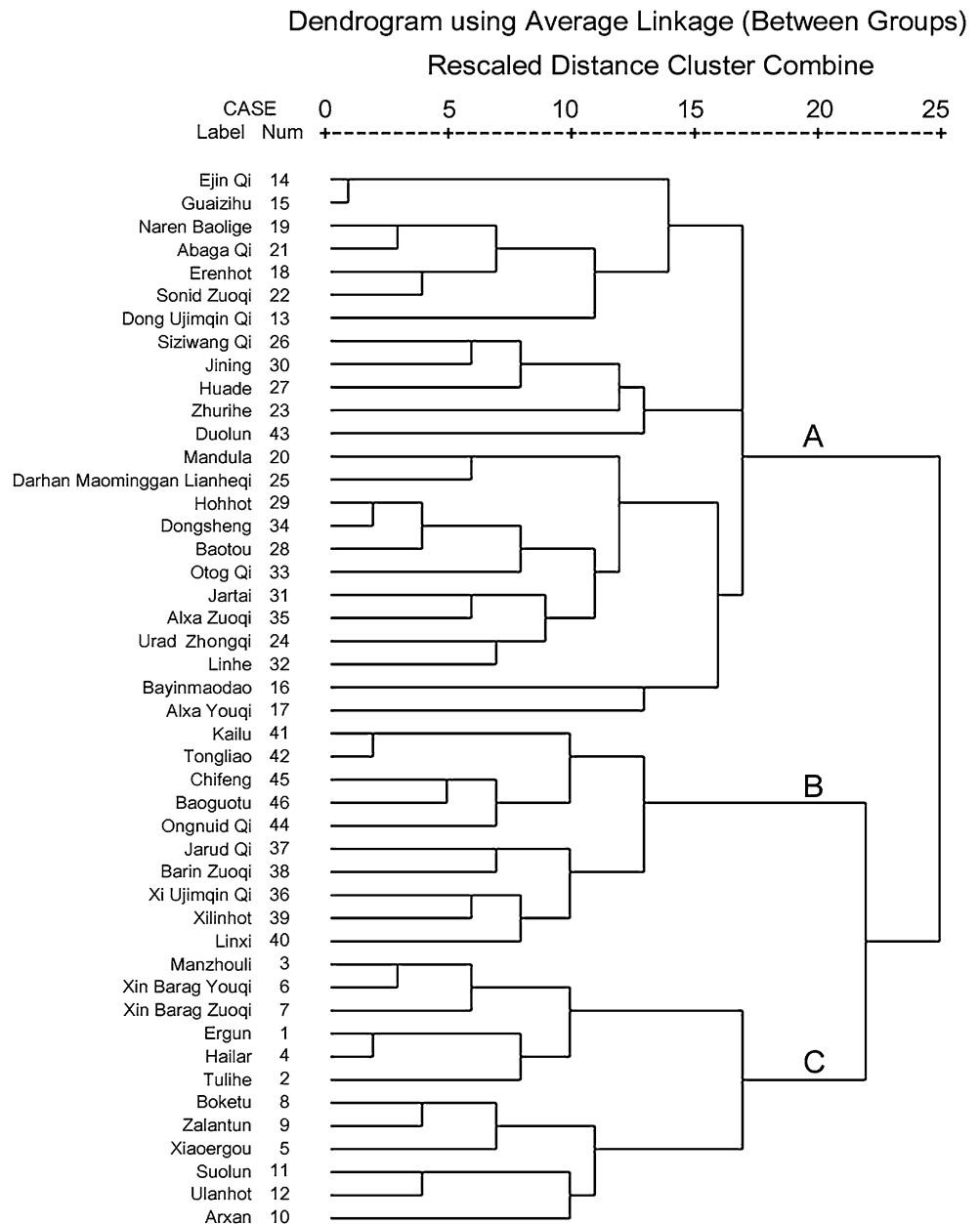


Fig. 2 Comparison of SPEI change trend at the 12- and 48-month time scales at five typical stations (the annual average total precipitation, 470 mm at Boketu; 369 mm at Tongliao; 270 mm at Otog Qi; 185 mm at Sonid Zuoqi; 35 mm at Ejin Qi)

evapotranspiration in winter. Statistics showed that the cases without solution relatively concentrated from August to September of 1998, and from July to October of 2013, they occupied about 33 and 17 % of total cases without solution at 3-month scale, separately. This is highly related to abnormal rich precipitation in 1998 (positive anomaly percentage, +49.8 %) and 2013 (positive anomaly percentage, +29.7 %). Zhuang et al. (2013) indicated that lack of precipitation and evapotranspiration during winter

months reduced confidence of SPEI values when applying 1-, 3-, and 6-month SPEIs in arid climatic regimes with annual precipitation less than 200 mm. Edwards and McKee (1997) indicated that, conceptually, although the SPI has a standard normal distribution with an expected value of zero and a variance of one, this is not always the case for the SPI at short time scales because of the skewed precipitation distribution. Wu et al. (2007) had pointed out that short periods without rain would not make a drought

Fig. 3 Cluster of 46 stations
a The middle-west subarea;
b the south-east subarea; **c** the north-east subarea



for regions with dry climates or low-precipitation seasons. From a mathematical point of view, the SPI values are lower bounded when a high frequency of zero values (no precipitation cases) occurs, leading to a non-normally distributed SPI. Therefore, SPEI values at 6-, 12-, 24-, 36- and 48-month scales were given in this paper (Fig. 8).

Very obvious multi-scalar droughts were indicated in the study area (Fig. 8). At 6-month scale, there is obvious and asymmetric a dry period and a wet period alternating cyclical phenomenon in most cases but that continuous two wet periods in 1998. Before 1999, those SPEI values fluctuate generally between -1 and 1, and the most dry

6 months is in 1965. After 1999, those SPEI values fluctuate generally between -2 and 1, most of those dryer 6-month SPEI values are obvious smaller than -1 but those in 2012 and 2013. At 12-month scale, there is an obvious alternating phenomenon between a longer wet period from 1960 to 1999 and a longer dry period from 2000 to 2012. Before 1999, there are only fewer several short slight drought events, such as the late 1960s, early 1970s, early 1980s. After 2000, there are continuous longer and more stronger drought events except for 2013. Long-term moderate dryness and even severe dryness can easily be found at 24-, 36-, 48-month scales.

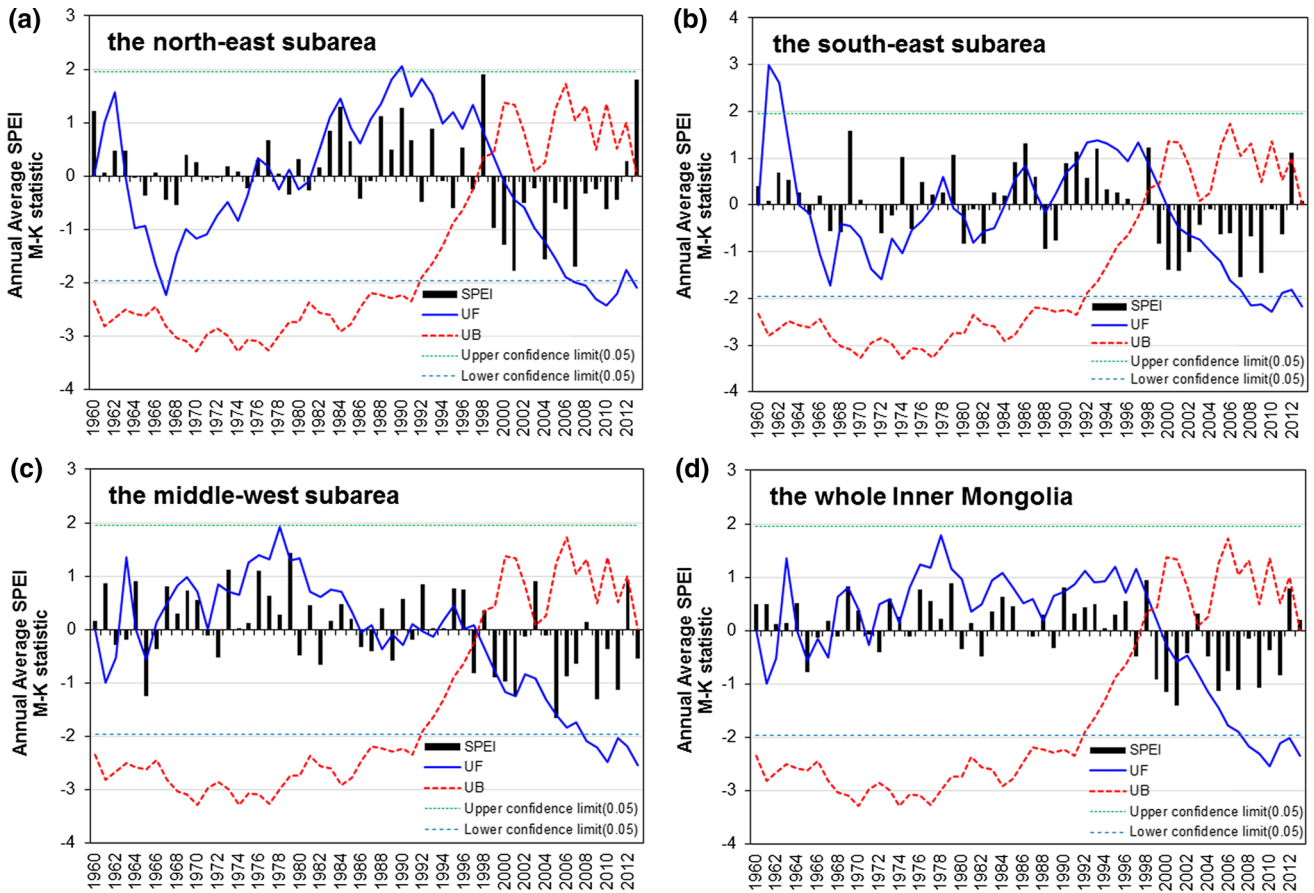
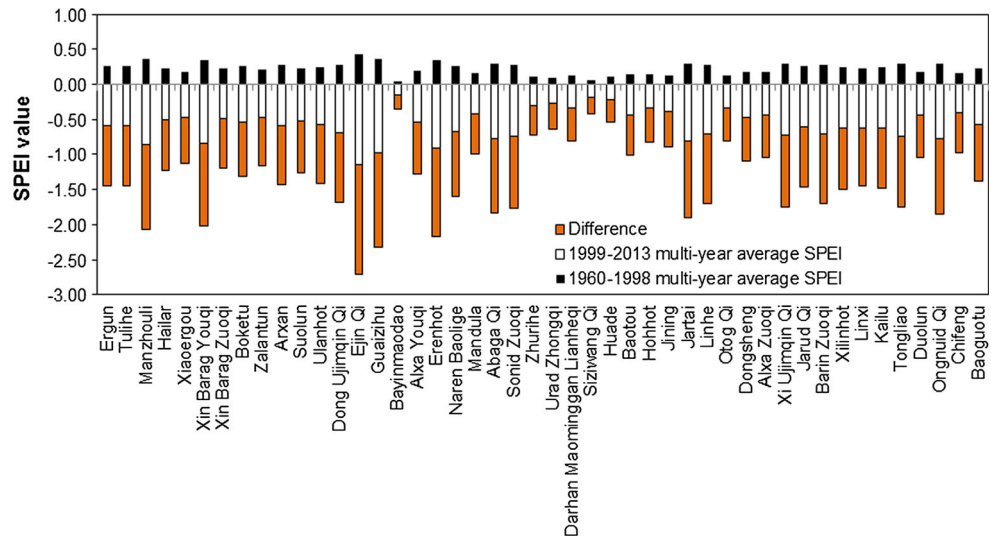


Fig. 4 Abrupt changes detected in SPEI using the Mann–Kendall method in the whole Inner Mongolia and three different sunareas (confidence level $\alpha = 0.05$)

Fig. 5 Contrast of multi-year average SPEI of several typical weather stations between 1960–1998 and 1999–2013, and the difference between the latter and the former in Inner Mongolia



Moreover, change trends of annual SPEI at 6-month scale from APR to SEP and from former OCT to MAR further showed that there are huge fluctuation of SPEI and

drying trend from moderate dryness to severe dryness in the plant-growth period from APR to OCT during 1960–2013 (Fig. 9a), while moderate wetness and little

Fig. 6 Spatial pattern of multi-year average SPEI before (a) and after the abrupt change (b), and the differences between the latter and the former (c) in Inner Mongolia

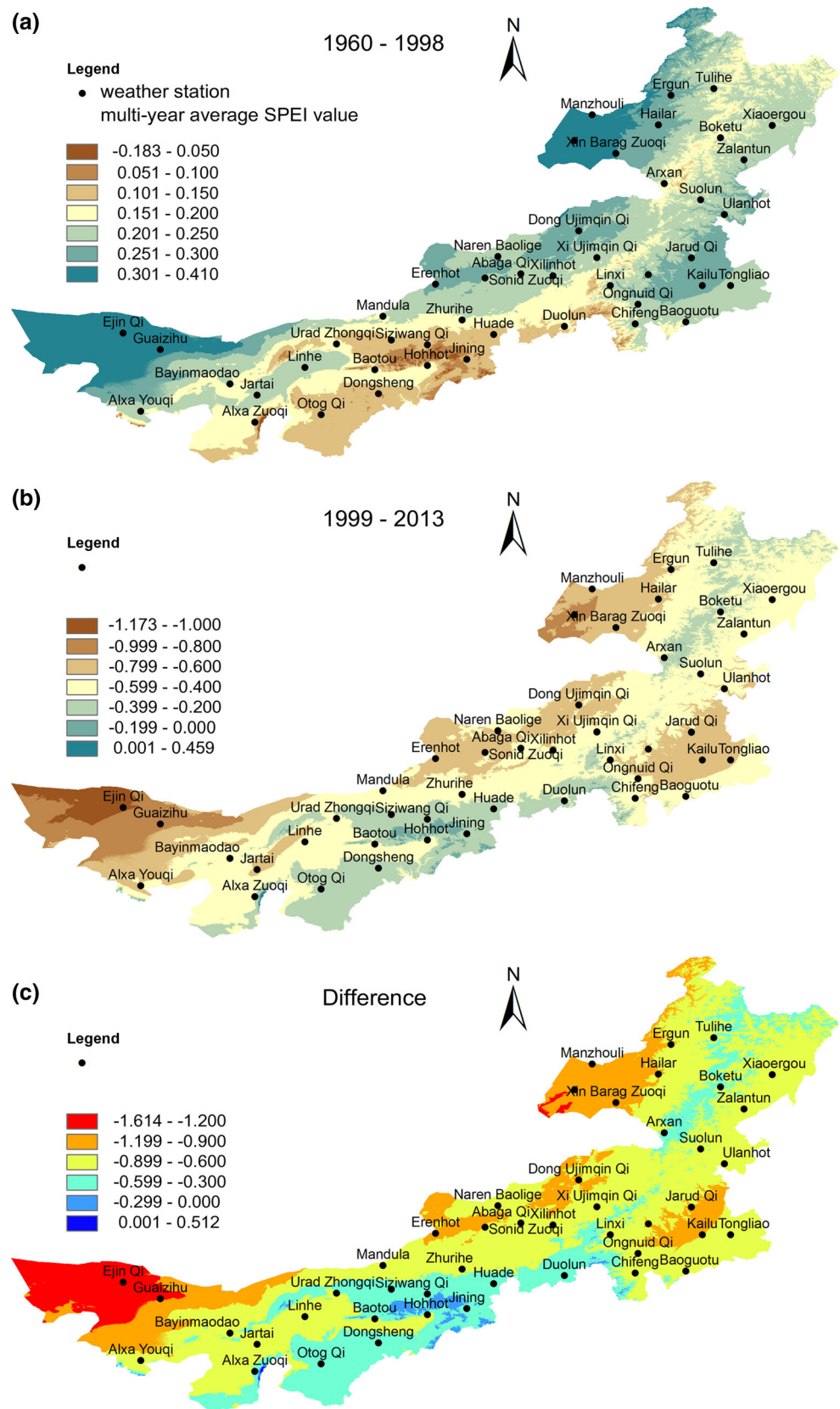


Fig. 7 Multi-year average TVDI of August and September during 2000–2013 in Inner Mongolia

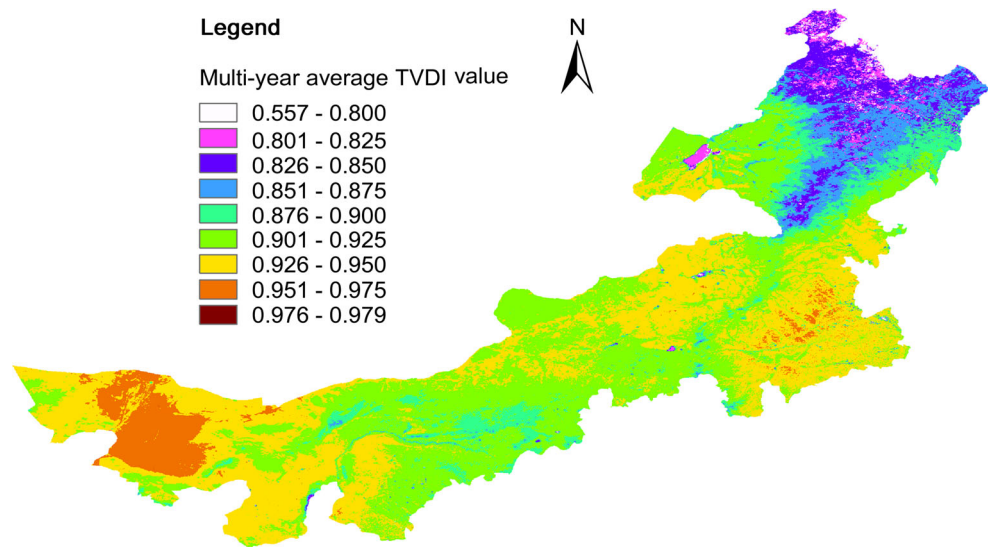


Fig. 8 Time series of SPEI at 6-, 12-, 24-, 36- and 48-month scales in the whole Inner Mongolia (1960–2013)

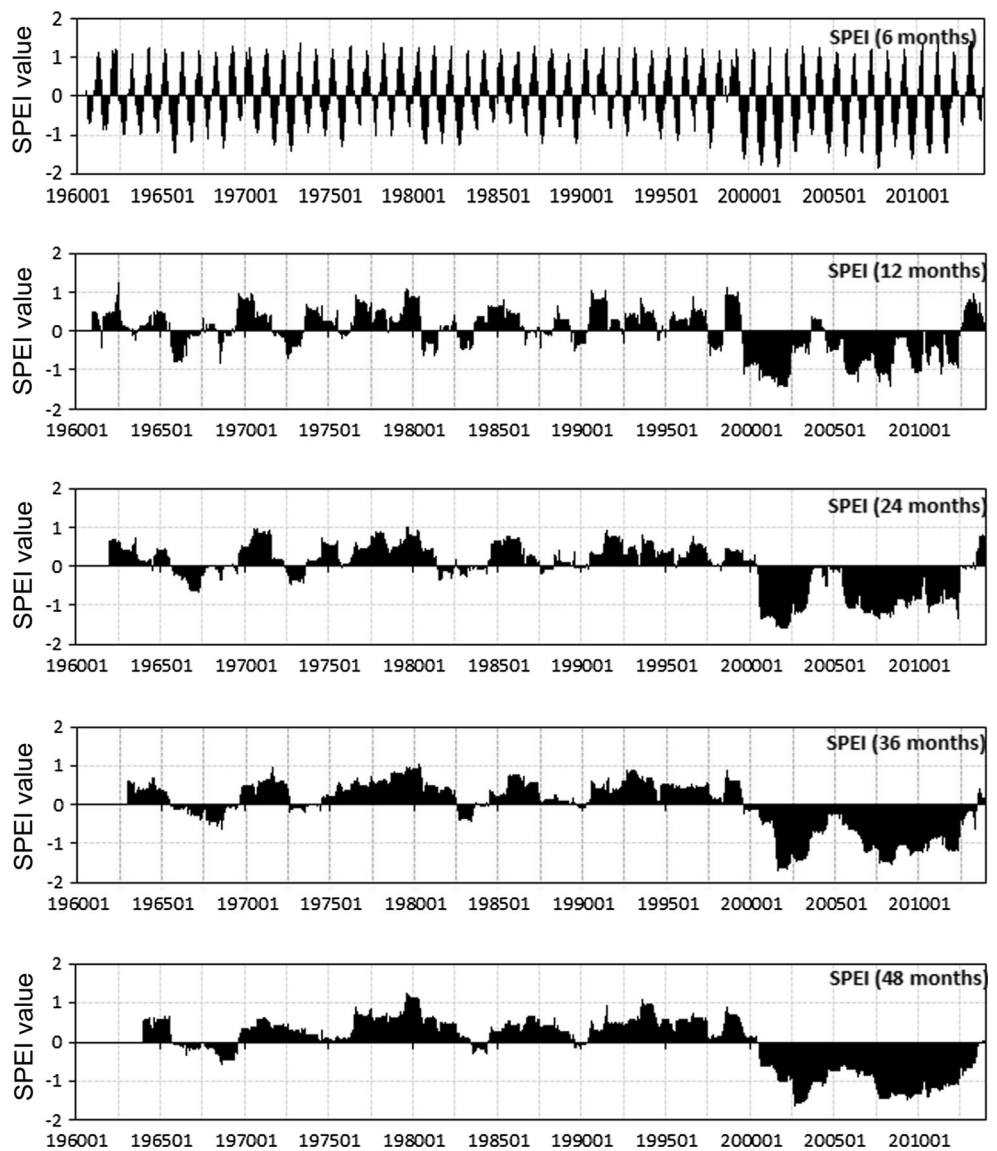
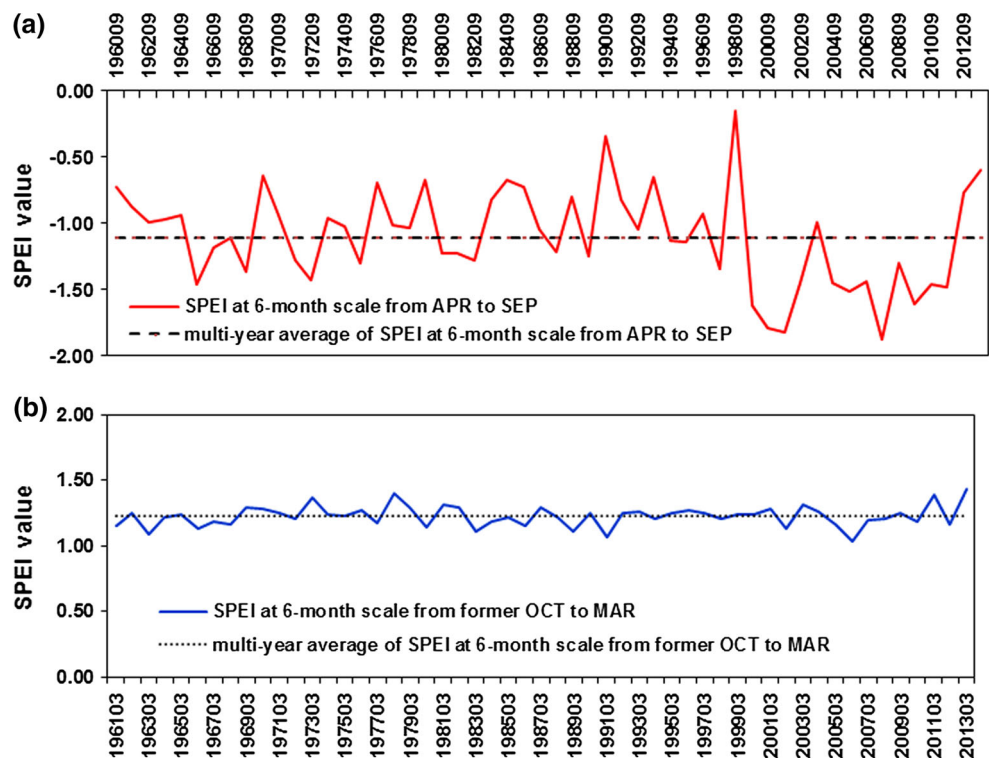


Fig. 9 Change trends of annual SPEI at 6-month scale from APR to SEP (a) and from former Oct to Mar (b) during 1960–2013 in the whole Inner Mongolia region



change in the non-growth period from former Oct to Mar (Fig. 9b). Thus, drought events in plant-growth season are the bigger contributor of annual drought event, and they should be given more attention, because they directly determine annual vegetation production and ecosystem services. Precipitation indices analysis also showed that Inner Mongolia is dominated by decreasing precipitation, and precipitation deficit may further deteriorate the shortage of water resources, and a higher risk of droughts can be expected in summer (Huang et al. 2015).

This drought feature during 1960–2013 in the Inner Mongolia is also showed by the percentage of total precipitation anomalies (Fig. 10a) and the percentage of average relative humidity anomalies (Fig. 10b). After 2000, those smaller SPEI values (more severe drought) obviously reflect the effect of significant rising air temperature (Fig. 10c) (p value <0.0001 , Sen's slope is 0.036) on drought, otherwise drought should be most severe in 1965 (Figs. 8, 10a) if no considering the contribution of higher temperature and ET_0 to drought. It is noticeable that this feature from wet to dry during 1960–2013 is more obvious with increasing time scales from 24-, 36- to 48-month. The drought events are the strongest and the longest during the last decade from 2000 to 2011. This lasting severe drought is the result of joint action of increasing air temperature and obviously decreasing precipitation since 2000s. Our results agreed with that conclusion that frequency of drought tend to decrease with the

increasing time scale (Mckee et al. 1993), but those drought duration and severities are not always decreased, and sometimes they are increased. Begueria et al. (2014) pointed out that the magnitude of the trend increased with the time scale of the SPEI. This is due to the cumulative character of the SPEI, which reinforces changes as D values accumulate at long time scales. Wu et al. (2007) pointed out that in dry climates, the analyst should focus on the duration of drought rather than on just its severity. The cumulative effect of drought itself and self-aggravative feature was clearly showed in the Fig. 8.

A recent study verified that the previously reported increase in global drought was overestimated because of the biased ET_0 calculation in PDSI, and little change in drought over the past 60 years was found when underlying physical principles (changes in available energy, humidity and wind speed) were considered (Sheffield et al. 2012). Wind speed actually had a significant decline trend (p value <0.0001 , Sen's slope is -0.02) in the Inner Mongolia since 1970s (Fig. 10d). This might also weaken the effect of rising temperature on drought at some degree, due to SPEI without considering the effect of wind speed on drought through accelerating evaporation (McVicar et al. 2012). In addition, despite air temperature rising faster due to urbanization effects (Hao et al. 2010), air temperature increasing can be certainly supported by records at most stations, including those in remote and thinly populated area (Chun et al. 2013). Feng et al. (2014) also showed a

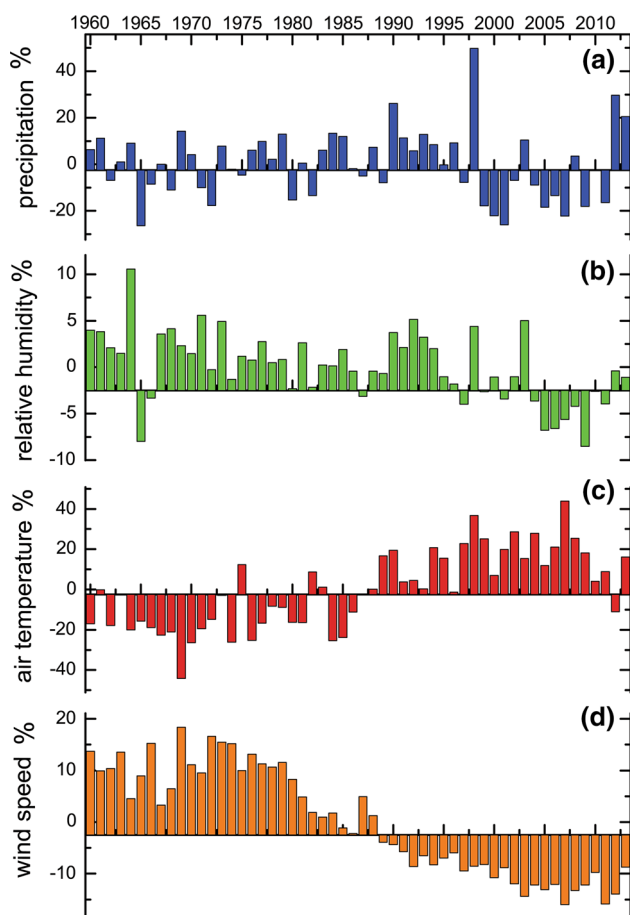


Fig. 10 Percentages of annual total precipitation anomalies (a), annual average relative humidity (b), annual average air temperature (c) and annual average wind speed anomalies (d) in the whole Inner Mongolia region during 1960–2013

significant increasing trend of ET_0 with the aggravation of drought in North China. Thus, our results still support the hypothesis that there is a general increase in drought severity under the context of global warming (Dai 2011; Begueria et al. 2014).

Conclusions

SPEI is able to reflect intrinsic multi-scale nature of drought and easy to calculate. SPEI is more suitable for those longer time scales including 6-month, due to much zero values or extreme maximum values at shorter time scale, although those small cases with no solution only occupied by 0.49 and 0.14 % at 1- and 3-month time scales, respectively. SPEI is a robust and reliable index which is more suitable for semi-humid, semi-arid areas than arid areas. Wind as an important factor affecting ET_0 was neglected in this article, but SPEI can effectively reveal the multi-scalar feature of drought, and the effect of

air temperature rising on drought severity and cumulative effect of drought itself. Frequency of drought tends to decrease with the increasing time scale, but that drought duration and severities do not always decrease and sometimes they also increase.

According to SPEI series features at each weather station in the Inner Mongolia, the study area can be divided into three subareas by cluster analysis. Generally, there is a drying trend in the whole Inner Mongolia, and a very heavy and lasting drought was revealed at multi-time scales during the 2000s. The severities of drought vary in different sub-regions. An abrupt change point of drought variability in the whole Inner Mongolia at 12-month time scale was diagnosed in 1999 at the confidence level $\alpha = 0.05$, while this abrupt point in the middle-west subarea is 1997 when is a little bit earlier than 1999 in the northeast subarea and the southeast subarea. This lasting severe drought should be the result of joint action of increasing air temperature and obviously decreasing precipitation since 2000s.

At the same time, the most severe drought area mainly located along the Sino-Mongolia border including the Hulun Buir Sandy Land, the Xilingol grassland, the Alxa Plateau, and the Horqin Sandy Land, while the continuous belt along the Da Hinggan Ling Mountains, the Yinshan Mountains, the Hetao Plain and the Mu Us Sandy Land is the area with relative slight drought during the last decades. Drought spatial pattern indicated by SPEI was supported by spatial distribution of TVDI based on remote sensing better.

Acknowledgments This research is supported by the Western Light Talents Training Program of Chinese Academy of Sciences, the National Natural Science Foundation of China (40801003), the National Basic Research Program of China (2009CB421308), and the Science and Technology Program of Gansu Province (1308RJZA314). The authors are grateful to several reviewers for their valuable comments and advices to improve the manuscript.

References

- Begueria S, Vicente-Serrano SM, Reig F, Latorre B (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *Int J Climatol* 34:3001–3023. doi:10.1002/joc.3887
- Byun HR, Wilhite DA (1999) Objective quantification of drought severity and duration. *J Clim* 12:2747–2756
- Chun X, Dan D, Bi LG, Liu MP, Liu Y, Hu HDL (2013) Climate change in Alxa Plateau over recent 60 years. *J China Hydrol* 33(2):43–50
- Dai AG (2011) Drought under global warming: a review. *Wiley Interdiscip Rev Clim Change* 2:45–65. doi:10.1002/wcc.81
- Demaree GR, Nicolis C (1990) Onset of sahelian drought viewed as a fluctuation-induced transition. *Quart J R Meteorol Soc* 116(491):221–238

- Diro GT, Sushama L, Martynov A, Jeong DI, Verseghy D, Winger K (2014) Land-atmosphere coupling over North America in the CRCM5. *J Geophys Res*. doi:10.1002/2014JD021677
- Edwards DC, McKee TB (1997) Characteristics of 20th century drought in the United States at Multiple Scales. *Atmos Sci Paper No. 634, Climatology Report 97-2*, Colorado State University, Fort Collins, pp 1–30
- Feng J, Yan DH, Li CZ, Yu FL, Zhan C (2014) Assessing the impact of climatic factors on potential evapotranspiration in droughts in North China. *Quat Int* 336:6–12. doi:10.1016/j.quaint.2013.06.011
- Fuchs B, Svoboda M, Nothwehr J, Poulsen C, Sorensen W, Guttman N (2012) A new national drought risk Atlas for the US from the National Drought Mitigation Center. <http://www.clivar.org/sites/default/files/Fuchs.pdf>
- Giannakopoulos C, Sager PL, Bindi M, Moriondo M, Kostopoulou E, Goodess CM (2009) Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming. *Global Planet Change* 68(3):209–224
- Giorgi F (2006) Climate change hot-spots. *Geophys Res Lett* 33(4):L08707. doi:08710.01029/02006GL025734
- Goossens C, Berger A (1987) How to recognize an abrupt climatic change? In: Berger WH, Labeyrie LD (eds) *Abrupt climatic change, evidence and implications*, NATO ASI series C: mathematical and physical sciences 216. D. Reidel publishing company Dordrecht, Holland, pp 31–45
- Goudie AS, Middleton NJ (1992) The changing frequency of dust storms through time. *Clim Change* 20(3):197–225. doi:10.1007/BF00139839
- Hao YX, Han FL, Xu J, Dong CY, Huang FR (2010) The influence of urban heat island on climatic change of Xilinhot. *Meteorol J Inner Mongolia* 6:34–37
- Hayes M, Wilhite DA, Svoboda M, Vanyarkho O (1999) Monitoring the 1996 drought using the standardized precipitation index. *Bull Am Meteorol Soc* 80:429–438
- Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *Int J Climatol* 25:1965–1978
- Hu Q, Pan FF, Pan XB, Zhang D, Li QY, Pan ZH, Wei YR (2015) Spatial analysis of climate change in Inner Mongolia during 1961–2012, China. *Appl Geogr* 60(SI):254–260
- Huang J, Sun SL, Xue Y, Zhang JC (2015) Changing characteristics of precipitation during 1960–2012 in Inner Mongolia, northern China. *Meteorol Atmos Phys* 127(3):257–271. doi:10.1007/s00703-014-0363-z
- Hutchinson MF (2004) ANUSPLIN Version 4.3 User Guide. Canberra: the Australia National University, Center for Resource and Environment Studies 2004. <http://cres.anu.edu.au/outputs/anusplin.Php>
- Jensen ME, Burman RD, Allen RG (eds) (1990) *Evapotranspiration and irrigation water requirements*. ASCE Manuals and Reports on Engineering Practices No. 70. Am Soc Civil Eng New York, p 360
- Jeong DI, Sushama L, Khaliq MN (2014) The role of temperature in drought projections over North America. *Clim Change* 127:289–303. doi:10.1007/s10584-014-1248-3
- Jin GY (2006) New thinking: how to process extraordinary flood data in frequency analysis. *J China Hydrol* 26(3):27–32
- Keyantash J, Dracup JA (2002) The quantification of drought: an evaluation of drought indices. *Bull Am Meteorol Soc* 83:1167–1180
- Lehner B, Doll P, Alcamo J, Henrichs T, Kaspar F (2006) Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis. *Clim Change* 75:273–299
- Li WG, Yi X, Hou MT, Chen HL, Chen ZL (2012) Standardized precipitation evapotranspiration index shows drought trends in China. *Chin J Eco Agric* 20(5):643–649. doi:10.3724/SP.J.1011.2012.00643
- Linares JC, Camarero JJ (2011) From pattern to process: linking intrinsic water-use efficiency to drought-induced forest decline. *Glob Change Biol* 18:1000–1015
- Liu ZH, Li LT, McVicar TR, Van Niel TG, Yang QK, Li R (2008) Introduction of the professional interpolation software for meteorology data: ANU SPLINN. *Meteorol Monogr* 34(2):92–100
- Ma ZG, Fu CB (2001) Trend of surface humid index in the arid area of northern China. *Acta Meteorol Sin* 59(6):737–746
- Martínez-Villalta J, López BC, Adell N, Badiella L, Ninyerola M (2008) Twentieth century increase of Scots pine radial growth in NE Spain shows strong climate interactions. *Glob Chang Biol* 14:2868–2881
- Mavromatis T (2007) Drought index evaluation for assessing future wheat production in Greece. *Int J Climatol* 27(7):911–924. doi:10.1002/joc.1444
- McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. *Proceeding of the Ninth Conference on Applied Climatology*. American Meteorological Society, Boston, pp 179–184
- McVicar TR, Roderick ML, Donohue RJ, Li LT, Van Niel TG, Thomas A, Grieser J, Jhajharia D, Himri Y, Mahowald NM, Mescherskaya AV, Kruger AC, Rehman S, Dinpashoh Y (2012) Global review and synthesis of trends in observed terrestrial near-surface wind speeds: implications for evaporation. *J Hydrol* 416–417:182–205. doi:10.1016/j.jhydrol.2011.10.024
- Mishra AK, Singh VP (2010) A review of drought concepts. *J Hydrol* 391(1):202–216. doi:10.1016/j.jhydrol.2010.07.012
- Moraes JM, Pellegrino HQ, Ballester MV, Martinelli LA, Victoria R, Krusche AV (1998) Trends in hydrological parameters of a southern Brazilian watershed and its relation to human induced changes. *Water Resour Manag* 12:295–311. doi:10.1023/A:1008048212420
- Morid S, Smakhtin V, Moghaddasi M (2006) Comparison of seven meteorological indices for drought monitoring in Iran. *Int J Climatol* 26:971–985
- Nandintsetseg B, Shinoda M (2013) Assessment of drought frequency, duration, and severity and its impact on pasture production in Mongolia. *Nat Hazards* 66:995–1008. doi:10.1007/s11069-012-0527-4
- Palmer WC (1965) *Meteorological droughts*. US Department of Commerce Weather Bureau Research Paper 45, 58
- Qian WH, Qin A (2008) Precipitation division and climate shift in China from 1960 to 2000. *Theor Appl Climatol* 93(1–2):1–17
- Romm J (2011) The next dust bowl. *Nature* 478:450–451. doi:10.1038/478450a
- Sandholt I, Rasmussen K, Andersen J (2002) A simple interpretation of the surface temperature—vegetation index space for assessment of surface moisture status. *Remote Sens Environ* 79(2):213–224
- Schubert SD, Suarez MJ, Pegion PJ, Koster RD, Bacmeister JT (2004) On the cause of the 1930s Dust Bowl. *Science* 303(5665):1855–1859. doi:10.1126/science.1095048
- Sha S, Guo N, Li YH, Han T, Zhao YX (2014) Introduction of application of temperature vegetation dryness index in China. *J Arid Meteorol* 32(1):128–134. doi:10.11755/j.issn.1006-7639(2014)-01-0128
- Shafer BA, Dezman LE (1982) Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. *Proceedings of the Western snow conference*. Colorado State University, Fort Collins, pp 164–175

- Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. *Nature* 491:435–440. doi:[10.1038/nature11575](https://doi.org/10.1038/nature11575)
- Shinoda M, Nachinshonhor GU, Nemoto M (2010) Impact of drought on vegetation dynamics of the Mongolian steppe: a field experiment. *J Arid Environ* 74(1):63–69. doi:[10.1016/j.jaridenv.2009.07.004](https://doi.org/10.1016/j.jaridenv.2009.07.004)
- Sneyers R (1975) Sur l'analyse statistique des séries d'observations. Technical Note 143, WMO, Geneva
- Sternberg T (2011) Regional drought has a global impact. *Nature* 472:169
- Sternberg T, Thomas D, Middleton N (2011) Drought dynamics on the Mongolian steppe 1970–2006. *Int J Climatol*. doi:[10.1002/joc.2195](https://doi.org/10.1002/joc.2195)
- Svoboda M, LeCompte D, Hayes M, Heim R, Gleason K, Angel J, Rippey B, Tinker R, Palecki M, Stooksbury D, Miskus D, Stephens S (2002) The drought monitor. *Bull Am Meteorol Soc* 83:1181–1192
- Thornthwaite CW (1948) An approach toward a rational classification of climate. *Geogr Rev* 38:55–94
- van der Schrier G, Jones PD, Briffa KR (2011) The sensitivity of the PDSI to the Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration. *J Geophys Res* 116:D03106. doi:[10.1029/2010JD015001](https://doi.org/10.1029/2010JD015001)
- Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J Clim* 23:1696–1718. doi:[10.1175/2009JCLI2909.1](https://doi.org/10.1175/2009JCLI2909.1)
- Wang HJ (2001) The weakening of the Asian monsoon circulation after the end of 1970s. *Adv Atmos Sci* 18:376–386
- Wang L, Chen W (2014) Applicability analysis of standardized precipitation evapotranspiration index in drought monitoring in China. *Plateau Meteorol* 33(2):423–431. doi:[10.7522/j.issn.1000-0534.2013.00048](https://doi.org/10.7522/j.issn.1000-0534.2013.00048)
- Wang BJ, Huang YX, Tao JH, Li DL, Wang PX (2006) Regional features and variations of water vapor in northwest China. *J Glaciol Geocryol* 28(1):15–21
- Wang T, Wu W, Xue X, Han ZW, Zhang WM, Sun QW (2004) Spatial-temporal changes of sandy desertified land during last 5 decades in northern China. *Acta Geogr Sin* 59(2):203–212
- Wilhite D (2000) Drought as a natural hazard: concepts and definitions. In: Wilhite DA (ed) *Drought: a global assessment*. Routledge, London, pp 3–18
- Wilhite DA, Sivakumar MVK, Wood DA (2000) Early warning systems for drought preparedness and drought management. In: *Proceedings of an expert group meeting Lisbon, Portugal*. World Meteorological Organization, Geneva
- Williams AP, Xu Ch, McDowell NG (2011) Who is the new sheriff in town regulating boreal forest growth? *Environ Res Lett*. doi:[10.1088/1748-9326/6/4/041004](https://doi.org/10.1088/1748-9326/6/4/041004)
- Wu H, Hayes MJ, Welss A, Hu Q (2001) An evaluation the standardized precipitation index, the china-z index and the statistical z-score. *Int J Climatol* 21:745–758
- Wu H, Svoboda MD, Hayes MJ, Wilhite DA, Wen FJ (2007) Appropriate application of the standardized precipitation index in arid locations and dry seasons. *Int J Climatol* 27:65–79. doi:[10.1002/joc.1371](https://doi.org/10.1002/joc.1371)
- Yu MX, Li QF, Hayes MJ, Svoboda MD, Heime RR (2014) Are droughts becoming more frequent or severe in China based on the standardized precipitation evapotranspiration index: 1951–2010? *Int J Climatol* 34:545–558. doi:[10.1002/joc.3701](https://doi.org/10.1002/joc.3701)
- Zhao FF, Xu ZX, Huang JX, Li JY (2008) Monotonic trend and abrupt changes for major climate variables in the headwater catchment of the Yellow River basin. *Hydrol Process* 22:4587–4599. doi:[10.1002/hyp.7063](https://doi.org/10.1002/hyp.7063)
- Zhuang SW, Zuo HC, Ren PC, Xiong GJ, Li BD, Dong WC, Wang LY (2013) Application of standardized precipitation evapotranspiration index in China. *Clim Environ Res* 18(5):617–625. doi:[10.3878/j.issn.1006-9585.2012](https://doi.org/10.3878/j.issn.1006-9585.2012)
- Zou X, Zhai P, Zhang Q (2005) Variations in droughts over China: 1951–2003. *Geophys Res Lett* 32(4):L04707. doi:[10.1029/2004GL021853](https://doi.org/10.1029/2004GL021853)