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Spatiotemporal drought variability on the Mongolian Plateau from 1980–2014 based on the *SPE*I-PM, intensity analysis and Hurst exponent

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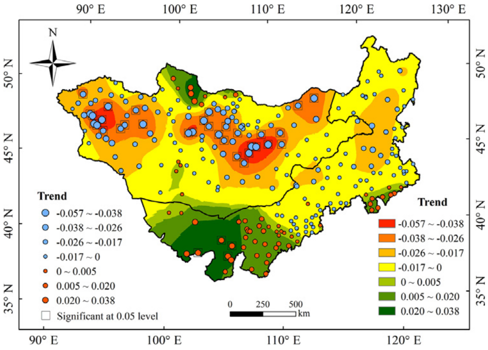
HIGHLIGHTS

- Variations of drought in Mongolian Plateau were investigated based on *SPE*I-PM.
- Annual *SPE*I obviously decreased in 1980–2014 and an abrupt change occurred in 1999.
- Changing rate in 1980s–1990s and 1990s–2000s were faster than that in 2000s–2010s.
- Drought in Mongolia was more serious than in Inner Mongolia since the 21st century.
- The Mongolian Plateau is still dry for some time in the future.

GRAPHICAL ABSTRACT



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ABSTRACT

Knowledge about variations of drought can provide a scientific basis for water resource planning and drought mitigation. In this study, the variations and patterns of drought identified by the Standardized Precipitation Evapotranspiration Index (*SPE*I) were investigated on the Mongolian Plateau for the period 1980–2014, based on intensity analysis, linear regression, the Mann-Kendall test, wavelet analysis, and Hurst exponent. The results show that: 1) the annual *SPE*I decreased at a rate of −0.0133/yr over the past 35 years, and a major abrupt change occurred in 1999; 2) drought on the Mongolian Plateau intensified from 1980 to 2014, and the drought in Mongolia has been more serious than in Inner Mongolia since the beginning of the 21st century; 3) the rate of drought/wet changes in 1980s–1990s and 1990s–2000s were faster than that in 2000s–2010s. In 1980s–1990s, the different drought levels were transformed into various wet levels. In 1990s–2000s, the wet levels were transformed into drought, and in 2000s–2010s, the losses of drought levels were larger than the gains in wet levels; 4) the Hurst exponent is a reliable way to predict drought tendency, with a predictive accuracy as high as 91.7%; 5) the mean H value of the *SPE*I time series during 1980–2014 was 0.533, indicating that the future drought trend is generally consistent with the current state. In the future, the proportion of area with increasingly severe drought (72.2%) will be larger than that with increasingly wetter conditions (27.8%) on the Mongolian Plateau.

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1. Introduction

Although the warming of the planet has been gradual, increasingly frequent and severe extreme weather events such as intense storms, heat waves, droughts, and floods have been abruptly and acutely felt. Among these events, drought is one of the most serious extreme weather events and refers to lower than normal precipitation over land for a period of time (Dai, 2011). Moreover, drought disasters are extremely complicated due to the high frequency, long duration, and large affected areas of these events (Li et al., 2009). Drought has great impact on agriculture, water resources, natural ecosystems, and society, resulting in numerous negative effects, such as huge economic loss, famine, epidemics, and land degradation (Beguería et al., 2010). According to statistics from the International Disaster Database (EM-DAT), global annual losses caused by drought reached about 221 billion dollars from 1960 to 2016. With the development of global warming, the frequency of drought has exhibited a significant upward trend (Giannakopoulos et al., 2009; Guo, 2012). Therefore, drought monitoring and assessment is of great theoretical and practical importance in protecting the eco-environment, improving human life, and avoiding or reducing the unnecessary loss of life and money.

Although numerous studies have focused on drought in the past, describing the drought intensity, magnitude, and spatiotemporal transition has remained difficult due to the uncertainty in defining the timing of initiation and termination of drought events. Therefore, many researchers have developed drought indicators to analyze and monitor droughts, causing the study of droughts to enter the stage of quantification and objectivity (Zhai et al., 2010; Belayneh et al., 2014; Zhang et al., 2013). This work has also greatly enhanced the spatial and temporal comparability of drought events (Heim, 2002). Vicente-Serrano et al. (2010) proposed the Standardized Precipitation Evapotranspiration Index (*SPE*I), which considers the two most important drought influencing factors—precipitation and evaporation—and can comprehensively reflect changes in the surface water balance. The *SPE*I is also a duration function and can, therefore, reflect the duration and accumulation of drought, making it an ideal index for evaluating, monitoring, and assessing drought within the background of global warming (Yu et al., 2014; Hernandez and Uddameri, 2014). Beguería et al. (2014) revisited the parameter fitting and evapotranspiration models of the *SPE*I and pointed out that the different physical meanings of different evapotranspiration formulas and different meteorological factors considered would lead to different calculations of the *SPE*I index. The Thornthwaite (TH) evapotranspiration model was widely used to calculate the *SPE*I (Yu et al., 2014). This model only considers the temperature and latitude of the station. However, temperature, high winds, sunlight, humidity, and soil moisture also have significant impact on drought variation (Trenberth et al., 2013). Moreover, the findings of Chen et al. (2005) showed that some errors may exist when using the TH method to compute the Chinese PET. Accordingly, a more comprehensive method should be introduced to calculate the potential evapotranspiration (PET). Thus, to address these problems, lots of researchers recommended the use of a more robust Penman-Monteith (PM) equation to compute the PET (Chen and Sun, 2015; Zhao et al., 2010). Liu and Jiang (2015) indicate that the *SPE*I based on the PM formula can describe the characteristics of dry and wet change more reasonably in northern China compared to the TH method; and the estimation of PET based on PM in arid and semi-arid areas is more applicable than the TH method.

The Inner Mongolia Autonomous Region and Mongolia constitute the main body of the Mongolian Plateau. As an important part of the East Asian ecosystem, the Mongolian Plateau not only represents an important ecological barrier in China but also plays an important prominent role in the global carbon cycle (Zhen et al., 2008; Leng, 2011). Due to the arid and semi-arid natural environment, the ecological environment of the Mongolian Plateau is very fragile and sensitive to climate change (John et al., 2013). In the context of continuous global warming, the warming rate in this region is higher than the global level (Wang et al., 2008), indicating that the Mongolian Plateau is a sensitive area in terms of global warming. A great deal of research has been conducted on drought in Inner Mongolia (Liu et al., 2016; Huang et al., 2015; Li et al., 2014); however, few studies have examined the drought in Mongolia or even the entire Mongolian Plateau. They have shown that, over the last 40 years, rising temperatures (Li and Qian, 2005) and decreasing precipitation (Yatagai and Yasunari, 1995) have aggravated drought (Li and Liu, 2012) on the Mongolian Plateau. The increased drought has directly affected the development of agriculture and animal husbandry, accelerated the desertification process, and caused serious dust storms on the plateau (Shinoda et al., 2010; Goudie and Middleton, 1992).

Mongolian Plateau is dominated by grassland ecosystem and animal husbandry is the major industry in the region. Drought will seriously weaken the productivity of grassland, decrease surface vegetation coverage, easily to induce the soil erosion and desertification, and cause a serious of secondary disasters and eventually lead to grassland degradation and it is difficult to recover. The meteorological drought is the prerequisite for hydrological, agricultural, and socioeconomic drought. Therefore, in this study, intensity analysis, linear trend analysis, and the Mann-Kendall test are used to analyze spatiotemporal changes in meteorological drought based on the examination of the Mongolian Plateau from 1980 to 2014 using *SPE*I-PM, Morlet wavelet analysis and the Hurst exponent to predict the spatiotemporal patterns of drought in the future. Intensity analysis can reveal the change process and conversion pattern of different grades of drought, thereby addressing some of the deficiencies of previously published quantitative research methods. This work will provide a scientific basis for the planning of water resource utilization and drought disaster prevention and mitigation on the Mongolian Plateau.

2. Data and methods

2.1. Study area

The Mongolian Plateau is located in the interior of the Eurasian continent and includes Mongolia, southern Russia, and northern China (Wei et al., 2009). In this paper, we focus on the central part of Mongolian Plateau (hereinafter referred to as the Mongolian Plateau) as the study area, which covers all of Mongolia and Inner Mongolia (Fig. 1). The plateau lies between 37°22′–53°20′ N and 87°43′–126°04′ E and covers a total area of 275×10^4 km^2. The terrain is generally mountainous in the northwest, with the Gobi Desert in the southwest and relatively flat grasslands with large hills in the central and eastern areas. The elevation decreases gradually from west to east, with an average elevation of approximately 1580 m. In the northern part of the Mongolian Plateau (Mongolia), the water vapor associated with precipitation is mainly from the Arctic Ocean, and the annual precipitation decreases from 300 to 400 mm in the north to 100 mm in the south. In the southern part of the plateau, the water vapor is from the Pacific Ocean, and the annual precipitation decreases from 300 to 400 mm in the south to 100–200 mm in the north. At the same time, the temperature is relatively low in the north and high in the southern plateau.

2.2. Data sources

The climate data were used to calculate *SPE*I indicator. They were provided by the Inner Mongolia Key Laboratory of Remote Sensing and Geographic Information Systems, which contains 264 meteorological stations (Inner Mongolia: 129, Mongolia: 135) across the plateau (Fig. 1). This data covers the period of 1980 to 2014 and includes the monthly precipitation, maximum temperature, minimum temperature, wind speed, sunshine hours, relative humidity, altitude, latitude, and longitude. Based on the locations of the meteorological stations, we

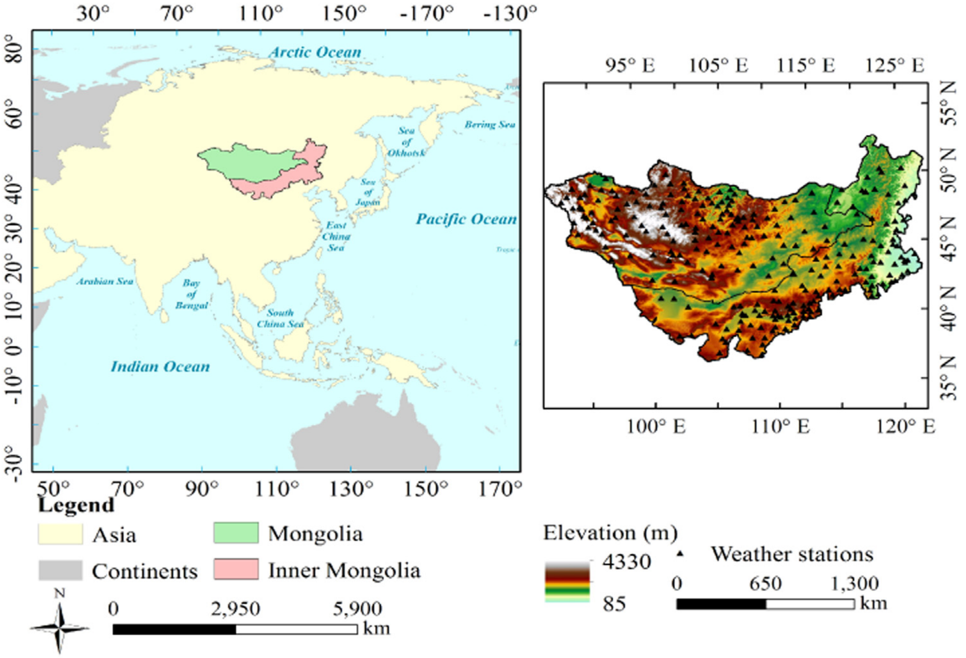

Fig. 1. Map of the geographical location, elevation, and the distribution of weather stations of the Mongolian Plateau.

interpolated the *SPEI* data at a resolution of 1 km by means of inverse distance weighted (IDW) interpolation to obtain the spatial distribution of drought (Ma et al., 2017).

2.3. Methods

2.3.1. Standardized precipitation evapotranspiration index (SPEI)

The *SPEI* index was used to analyze the spatial-temporal variation of drought on the Mongolian Plateau and its calculation procedures are shown in reference Beguería et al., 2010. The *SPEI* values for different time scales can reflect anomalous water states at different times in the past, and the 12-month *SPEI* can better reflect annual variations in drought (Xu et al., 2013). We focus on the decadal and annual variation characteristics of drought in this study; thus, the 12-month *SPEI* is calculated.

2.3.2. Intensity analysis

The intensity analysis, which was proposed by Aldwaik and R.G.P. (2012), is a method for quantitative analysis of land use and land cover change. It uses a transfer matrix to analyze the land type map at different time points in the same region and obtains different land cover change patterns at the interval level, category level, and transition level. A detailed description of this method can be found in Huang et al. (2012). Similarly, the distributions of different drought levels in a region change in different time periods. Intensity analysis can answer the following three questions about the patterns of changes in drought: 1) How fast is the total annual rate of change in drought for a certain time interval? 2) Are the different categories of drought change active or dormant? 3) Which level was dominant in the process of mutual transition among the different categories of drought? Based on the answers to these questions, we can explain the annual change trend, the changes among different categories, and the pattern of drought transitions on the Mongolian Plateau.

The calculation of the intensity analysis is described in the following Eqs. (1)–(8) (Aldwaik and R.G.P., 2012; Huang et al., 2012):

$$\mathrm{U} = \frac{\sum_{t=1}^{T-1}\left\{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]\right\} / \left[\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}\right]}{Y_T - Y_1} \times 100\% \quad (1)$$

where *U* is the value of a uniform line for time intensity analysis; C_{tij} is the number of pixels that transition from category *i* at time Y_t to category *j* at time Y_{t+1} (the same below); *J* is the number of drought categories (the same below); *T* is the number of time points; *t* is the index for a time point, which ranges from 1 to *T*−*1*; Y_t is the year at time point t (the same below); *i* is the index for a drought category at some initial time; and *j* is the index for a drought category at some final time.

$$S_t = \frac{\left\{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right]\right\} / \left[\sum_{j=1}^{J}\sum_{i=1}^{J} C_{tij}\right]}{Y_{t+1} - Y_t} \times 100\% \quad (2)$$

where S_t is the annual intensity of change for time interval $[Y_t, Y_{t+1}]$.

$$G_{tj} = \frac{\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tjj}\right] / (Y_{t+1} - Y_t)}{\sum_{i=1}^{J} C_{tij}} \times 100\% \quad (3)$$

where G_{tj} is the annual intensity of the gross gain of category *j* for time interval $[Y_t, Y_{t+1}]$.

$$L_{ti} = \frac{\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tii}\right] / (Y_{t+1} - Y_t)}{\sum_{j=1}^{J} C_{tij}} \times 100\% \quad (4)$$

where L_{ti} is the annual intensity of the gross loss of category *i* for time interval $[Y_t, Y_{t+1}]$.

$$W_{tn} = \frac{\left[\left(\sum_{i=1}^{J} C_{tin}\right) - C_{tnn}\right] / (Y_{t+1} - Y_t)}{\sum_{j=1}^{J}\left[\left(\sum_{i=1}^{J} C_{tij}\right) - C_{tnj}\right]} \times 100\% \quad (5)$$

where W_{tn} is the value of the uniform intensity of transition to category *n* from non-*n* categories at time Y_t during time interval $[Y_t, Y_{t+1}]$, and *n* is the drought category that other categories transitioned into ($i \neq n$).

$$R_{tin} = \frac{C_{tin} / (Y_{t+1} - Y_t)}{\sum_{j=1}^{J} C_{tij}} \times 100\% \quad (6)$$

where R_{tin} is the annual intensity of transition from category *i* to

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category n during time interval $[Y_t, Y_{t+1}]$.

$$V_{tm} = \frac{\left[\left(\sum_{j=1}^{J} C_{tmj}\right) - C_{tmm}\right] / (Y_{t+1} - Y_t)}{\sum_{i=1}^{J}\left[\left(\sum_{j=1}^{J} C_{tij}\right) - C_{tim}\right]} \times 100\% \tag{7}$$

where V_{tm} is the value of uniform intensity of transition from category m to all non-m categories at time Y_{t+1} during time interval $[Y_t, Y_{t+1}]$ and m is the drought category that transitioned into other categories.

$$Q_{tmj} = \frac{C_{tmj}/(Y_{t+1} - Y_t)}{\sum_{i=1}^{J} C_{tij}} \times 100\% \tag{8}$$

where Q_{tmj} is the annual intensity of transition from category m to category j during time interval $[Y_t, Y_{t+1}]$ $(j \neq m)$.

Intensity analysis is based on the distribution of categories at the time point and requires the classification criteria to be consistent at each time point. Therefore, according to the spatial distribution of *SPE*I values on the plateau during 1980–2014, we obtained the distribution of *SPE*I values for four time points (decades), i.e., the 1980s (1980–1989), 1990s (1990–1999), 2000s (2000–2009) and 2010s (2010–2014), to meet the premise of intensity analysis. First we needed to determine the classification criterion of drought, which was modified according to the local climate condition, and it is shown in Table 1 (Ming et al., 2015; Bao et al., 2015; Liu et al., 2016).

2.3.3. Hurst exponent and R/S analysis

The Hurst exponent is a useful statistical method for understanding the properties of a time series without making assumptions about statistical restrictions. It was proposed by Hurst in the analysis of hydrological data from the Nile River (Hurst, 1951) and is often used to analyze long-term time series correlations. There have been several analyses that have been used to calculate the H exponent (Granero et al., 2008; Lo, 1991; Kendziorski et al., 1999); among them, the R/S analysis, also called the Rescaled Range analysis is widely used to calculate the H exponent. The principle of R/S is briefly described as follows (Granero et al., 2008):

A time series x(t) is defined as

$$\langle x \rangle_t = \frac{1}{\tau} \sum_{t=1}^{\tau} x(t) \quad t = 1, 2, 3 \cdots. \tag{9}$$

The cumulative deviation is calculated by

$$\mathrm{x}(\mathrm{t}, \tau) = \sum_{u=1}^{\tau} \left(x(u) - \langle x \rangle_t\right) \quad 1 \le \mathrm{t} \le \tau. \tag{10}$$

The extreme deviation sequence is formulated by

$$\mathrm{R}(\tau) = \max_{1 \le t \le \tau} X(t, \tau) - \min_{1 \le t \le \tau} X(t, \tau) \quad \tau = 1, 2, 3 \cdots. \tag{11}$$

The standard deviation sequence is formulated by

$$\mathrm{S}(\tau) = \left[\frac{1}{\tau} \sum_{t=1}^{\tau} \left(x(t) - \langle x \rangle_\tau\right)^2\right]^{\frac{1}{2}} \tau = 1, 2, 3 \cdots. \tag{12}$$

Based on R(τ) and S(τ), we obtain the following:

$$R/S = \mathrm{R}(\tau)/\mathrm{S}(\tau), \tag{13}$$

Assuming

$$R/S \propto \left(\frac{\tau}{2}\right)^H. \tag{14}$$

Then, the Hurst phenomenon exists in the time series, and H is called the Hurst exponent, ranging from 0 to 1. When H = 0.5, there are no changes. A value of H > 0.5 indicates that the process has a continuous characteristic and that the future trend is consistent with the past trend, whereas a value of H < 0.5 indicates that the future trend is opposite that of the past.

2.3.4. Other methods

The linear regression method (Tong et al., 2017) was used to study the spatiotemporal variation trend of the *SPE*I, the Mann-Kendall statistical test (Smadi and Zghoul, 2006) was used to study abrupt changes in the *SPE*I time series, and Morlet wavelet analysis (Li et al., 2013) was used to calculate the periodicity of drought in this study.

3. Results

3.1. Spatiotemporal variations of drought in Mongolian Plateau

3.1.1. Spatial pattern of drought on the plateau

Fig. 2 shows the spatial distribution of drought/wet conditions for the four decades. In the 1980s, the plateau was dominated by light drought, moderate drought occurred in the western plateau, and the northeastern part was relatively wet. In the 1990s, besides the light drought occurring in western part of Inner Mongolia, the plateau exhibited near normal and moderate wet, and the climate of Mongolia was wetter than that of Inner Mongolia; the 1990s was the most humid period on the plateau. However, in the early 21st century, drought significantly intensified and the area of moderate drought and severe drought increased; most of the plateau was dominated by moderate drought, and severe drought mainly appeared in the middle of the plateau. During 2010–2014, the drought has been significantly alleviated compared to the previous stage, with the areas experiencing moderate and severe drought transitioning into areas of near normal and light drought, while the western plateau remained more arid than the east.

3.1.2. Temporal and spatial variation in drought during 1980–2014

As a meteorological drought index, the *SPE*I value corresponds to the severity of the drought, in which a smaller *SPE*I value signifies a more severe drought. The 12-month *SPE*I is useful for analyzing the annual variation in drought characteristics. The variation curve of annual *SPE*I values in Fig. 3a shows that the annual *SPE*I value of the entire plateau has exhibited a decreasing trend over the past 35 years at a rate of −0.0113/yr.

At the decadal scale, the 1980s was a relatively dry period during 1980–2014, with an average value of −0.172. In the 1990s *SPE*I values were >0, except for 1997 and 1999, with an average of 0.386. In contrast, with the exception of 2003, the 2000s had *SPE*I values <0, with

Table 1
Drought/wet grade categories based on the *SPE*I.

	Categories	Severe drought	Moderate drought	Light drought	Near normal	Moderate wet	Severe wet
	*SPE*I values	≤−1.00	(−1.0, −0.5]	(−0.5, 0]	(0, 0.5]	(0.5, 1]	>1
Probability (%)	1980–1989	24.28	14.85	16.59	14.77	13.11	16.40
	1990–1999	8.52	16.36	13.71	14.17	16.44	30.80
	2000–2009	40.08	19.51	12.46	11.02	7.27	9.66
	2010–2014	20.45	15.38	18.33	13.03	11.44	21.36

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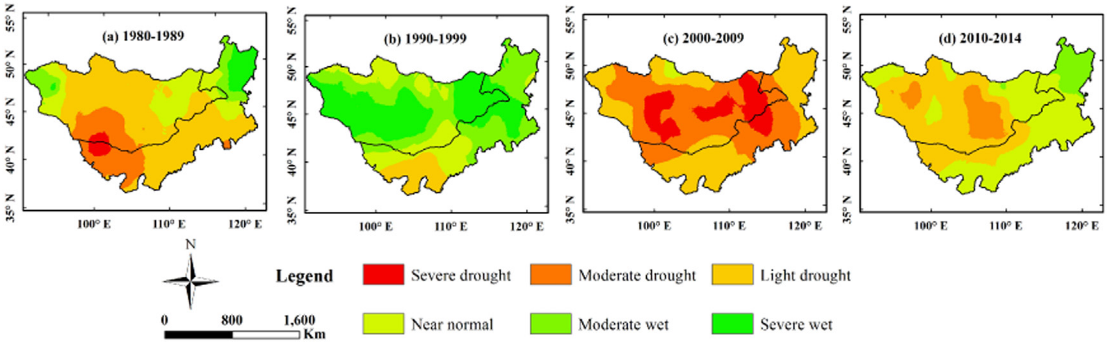

Fig. 2. Distribution maps of drought/wet classes on the Mongolian Plateau for each decade.

an average of −0.637. However, after 2010 the drought tendency had slowed noticeably, and the average value from 2010 to 2014 was −0.060. The 1990s was the wettest period, and the 2000s was the driest period on the Mongolian Plateau during 1980–2014.

The change trend in annual *SPE*I values featured obvious stages. Therefore, the Mann-Kendall test is used to detect the characteristics of these changes. Fig. 3b shows the Mann-Kendall statistical test of the annual *SPE*I on the plateau. UF is the time series statistical curve and UB is the inverse time series statistical curve. The intersection of the two curves within the confidence interval is determined as an abrupt change point (Smadi and Zghoul, 2006). At the significance level of 0.05 (correspondingly the threshold value of ±1.96 for the UF and UB curves), the two curves intersect in 1999. After 1999, the UF curve decreases significantly and crosses the threshold value. Therefore, the annual *SPE*I exhibits an obvious change, which occurred in 1999. After this major change, the *SPE*I value is <0 and the drought is evident.

Fig. 4 shows the spatial variations in the annual *SPE*I at each station and for the entire plateau during 1980–2014. The figure shows that, except for the 36 stations that exhibit a significant change trend, the annual *SPE*I values for the majority of the stations decreased insignificantly. The annual variations of *SPE*I showed an increasing trend (green in the figure), mainly distributed in the western region of Inner Mongolia and a small part in southern Mongolia. Central and western Mongolia has a relatively larger decreasing magnitude. The area where the change trend of the annual *SPE*I was <0 accounted for the 79.4% of the total area, while the trend was larger than 0 in 20.6% of the total area, which means that the drought intensified during 1980–2014. In addition, the magnitude of the *SPE*I decrease was greater in the north than in the southern plateau, and the drought in Mongolia was worse than in Inner Mongolia.

3.2. Results of the intensity analysis

The drought transition matrix for three time intervals (1980s–1990s, 1990s–2000s, and 2000s–2010s) is obtained to satisfy the premise of the intensity analysis (Table S1 in supplementary information), based on ArcGIS. The interval level intensity analysis can answer the first research question “In a given time interval, was the total annual rate of change in drought relatively fast or relatively slow?” The results of the interval level intensity analysis are shown in Fig. 5, in which the bars on the left represent the overall scale of drought variation for each time interval, while the bars on the right represent the time intensity obtained using Eq. (2). Additionally, the dashed line on the right is the uniform line obtained using Eq. (1). If the bar exceeds the uniform line, the change in the drought in that time interval was relatively fast; otherwise, it was relatively slow. Fig. 5 shows that the drought area decreased from 90% to 77% of the total area during 1980–2014, and the variation rates for the periods 1980s–1990s and 1990s–2000s were faster than those for 2000s–2010s.

The category intensity analysis can answer the question “Which categories of drought changes are relatively active and which categories are relatively dormant in a given time interval?” The results are shown in Fig. S1, Fig. S2 (in supplementary information) and Fig. 6. Each drought level is represented by a horizontal bar. The two panels in each figure, (a) and (b), represent the gross annual areas of gain and loss, respectively, in the study area, based on the pixel number. The bars extending to the left of zero show the gross annual area of gain/loss in the study area, calculated using Eqs. (3) and (4), while the bars extending to the right of zero show the intensity of the annual gain/loss (the numerators of Eqs. (3) and (4)) within each category. The dashed line is the uniform line: if a bar exceeds the uniform line, the change in drought category is relatively active in the given time interval; otherwise, it is relatively dormant.

Fig. S1 (in supplementary information) is the category intensity analysis for 1980s–1990s. The annual change area of severe wet and near normal gains (Fig. S1(a)) and losses (Fig. S1(b) in supplementary information) were both active and the change in area of gains was larger than losses. The annual change in area of moderate wet gain was much larger than loss but dormant; the losses for light, moderate, and severe drought were active. Because the area of moderate and severe drought was zero in the 1990s, their gains, losses and intensity in time interval 1980s–1990s were also zero (Table S1 in supplementary information). In general, the change in areas of gains for different wet levels were

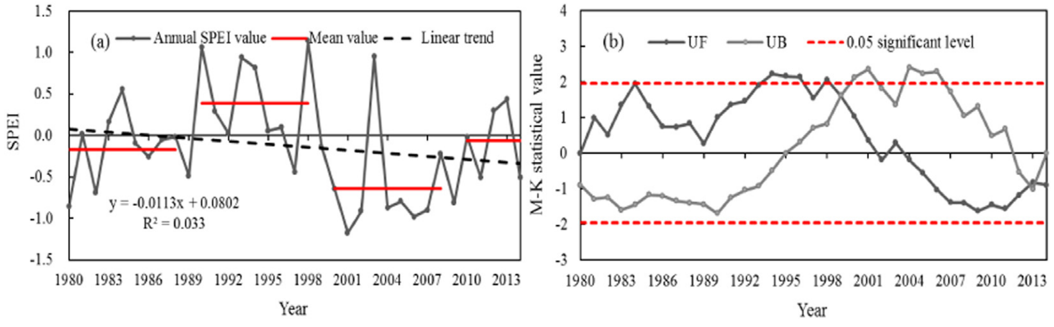

Fig. 3. Annual change trend (a) and Mann-Kendall statistical test (b) of the 12-month *SPE*I on the Mongolian Plateau during 1980–2014.

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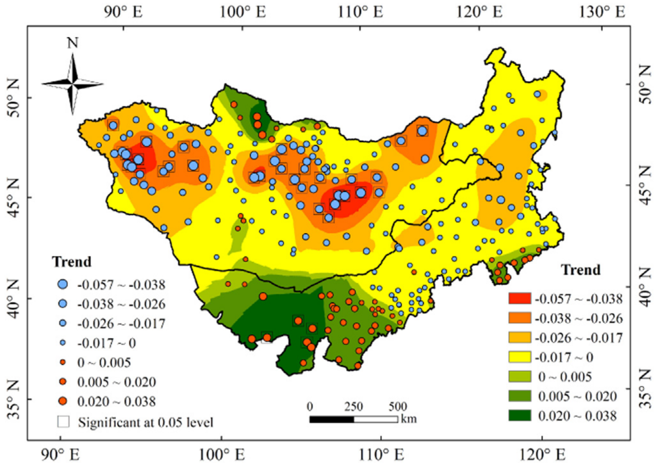

Fig. 4. Spatial variation trends in the annual *SPE*I on the Mongolian Plateau during 1980–2014. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

larger than the change in areas of losses and the change in areas of losses for different drought levels were active during 1980s–1990s, indicating that the plateau had entered a relatively wet period.

Fig. S2 (in supplementary information) is the category intensity analysis for the interval 1990s–2000s. Fig. S2(a) shows that gains mainly occurred in the different drought levels and that the intensities were active. In contrast, losses occurred in the different wet levels and the changes were active (Fig. S2(b)). Hence, the transition from 1990s to 2000s was associated with increasing drought.

Fig. 6 is the category intensity analysis for the interval 2000s–2010s. The gains of moderate wet and near normal were both active (Fig. 6(a)), while the moderate and severe drought losses were active (Fig. 6(b)), and the loss area was larger than the gain area, from which we can conclude that the 2010s was wetter than the 2000s. Because the areas of severe wet conditions in the 2000s and 2010s were zero, gain, loss, and intensity in the time interval 2000s–2010s were also zero (Table S1 in supplementary information).

Fig. S3 (in supplementary information) shows the results of the transition intensity analysis, addressing the question "Which level was dominant in the transition process among the different categories of drought?" Each category was represented by a vertical bar. The lower bar was obtained by Eq. (8), representing the annual intensity of transition from category *m* to category *j* ($j \neq m$) (transfer out) during the time intervals, and the dashed line was the uniform intensity (Eq. (7)). Similarly, the upper bar was calculated by Eq. (6), representing the annual intensity of transition from category *i* to category *n* ($i \neq n$) (transfer into) during the time intervals, and the dashed line was the uniform intensity (Eq. (5)). To show the transition pattern for each category, the dominant conversion forms are enumerated in Table S2 (in supplementary information). As shown in the table, the dominant drought transition categories in the three time intervals were identical. In the 1980s–1990s, drought/wet levels were transformed into different wet levels. In 1990s–2000s, the three wet levels were transformed into drought levels, and the severe drought level was converted into severe wet. In 2000s–2010s, the transformation occurred mainly from the drought categories; specifically, the light drought level transitioned into moderate wet, moderate drought into light drought, and severe drought into moderate drought and near normal. The transition level analysis not only confirms the results of the previous two analyses but also reveals the conversion between the dry and wet levels for each time interval. These results can provide a deeper analysis of the drought.

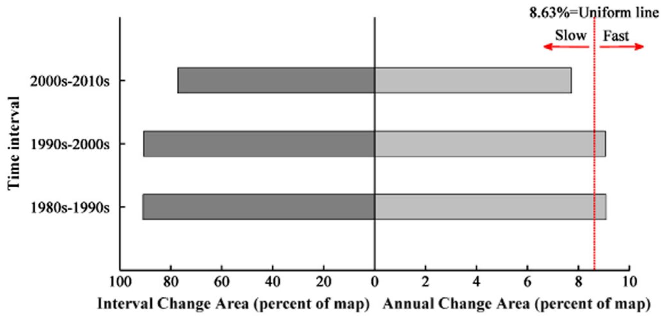

Fig. 5. Interval intensity analysis for three time intervals: 1980s–1990s, 1990s–2000s, and 2000s–2010s.

3.3. Future prediction of drought on the Mongolian Plateau

3.3.1. Morlet wavelet analysis

Morlet wavelet analysis was used to perform a period analysis of the annual *SPE*I values in this study, and the results are shown in Fig. S4 (in supplementary information). The midpoint of the contours is the dry/wet transition, with positive wavelets representing wet conditions and negative wavelets representing dry conditions. Fig. S4(a) contains several different periodic and oscillation centers associated with significant decadal and annual changes. Combine with Fig. S4(b), we conclude that there is a 10a oscillation center in the annual *SPE*I values for the Mongolian Plateau. The oscillation period 10a is very significant and continues from 1980 to 2014, with four alternating dry-wet cycles, including four dry periods and four wet periods. The plateau is in a dry period at present, and the contours of the oscillation periods have not closed. Therefore, a period of drought can be expected to continue on the Mongolian Plateau into the future after 2014.

3.3.2. Future drought trend based on the Hurst exponent

The R/S analysis method was used to calculate the H (Hurst) value of the *SPE*I values for the Mongolian Plateau during 1980–2014 to predict the trend in future drought/wet changes. The spatial distribution of the H values of the *SPE*I is shown in Fig. 7(a). According to the statistics, the mean H value of the annual *SPE*I values during 1980–2014 in the plateau was 0.533 (Table S3 in supplementary information). Therefore, the drought trend in the future is consistent with the current state, in general. Drought trend which opposite ($H < 0.5$) and consistent ($H > 0.5$) to the current state account for 26.8% and 73.2% of the total plateau, respectively. The linear trend has quantitatively revealed the trends in the *SPE*I time series over a given period, while the R/S analysis qualitatively shows whether the future drought will be consistent or opposite to the current status. However, neither of the two approaches described above shows a rising or falling trend in the future. Therefore, we can spatially overlay the results of the two analyses (Fig. 4 and Fig.7(a)) to predict the future trend of drought changes, and the results are shown in Fig. 7(b).

In the future, the area has decreasing drought trend will increase up to 72.2% of the plateau, where the drought trend for 62.4% of the area will be the same as the present stage and consistently decreasing; the area of increasing drought trend is expected to be 27.8% and mainly located in the Inner Mongolia.

3.3.3. Validation of future prediction based on the Hurst exponent

To validate the accuracy of using Hurst exponent to predict the drought trend in the future, we divided the study period into two periods, 1980–2009 and 2010–2014, and used the H values during 1980–2009 to predict the future annual *SPE*I change trend for 2010–2014. This analysis verifies the reliability of the Hurst method. Note that the H value of the annual *SPE*I time series on the plateau during 1980–2009 was 0.527 (Table S3 in supplementary information), which indicates that the future *SPE*I variation trend was consistent with that of the previous period, which is supported by the data presented in Fig. 3a and Table S3 (in supplementary information). Fig. 8 shows the spatial distribution of the H values for the annual *SPE*I time

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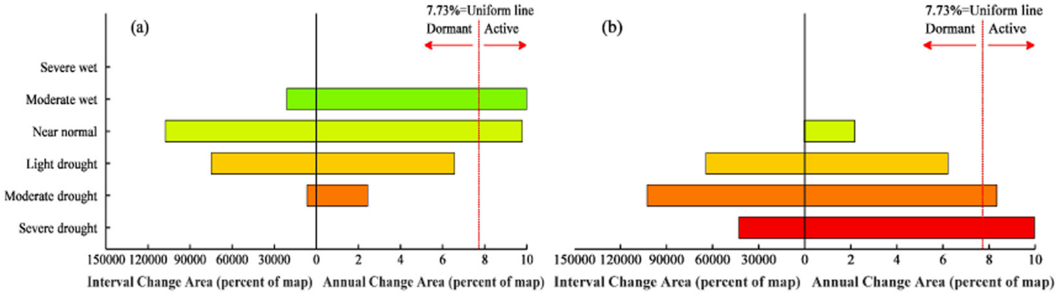

Fig. 6. Category intensity analysis for 2000s–2010s, (a) for gains and (b) for losses.

series on the Mongolian Plateau during 1980–2009. H values of <0.40 are distributed in the middle of the plateau and are shown in blue in the figure. In these regions, the future annual *SPE*I trends are contrary to the trend in 1980–2009. Fig. S5(a) shows that the annual *SPE*I variation trend in these regions was <0 during 1980–2009 and >0 during 2010–2014 (Fig. S5(b)). H values >0.70 distributed in the middle of the plateau, indicating that the future drought trend in this area is consistent with the trend in 1980–2009. It is evident from Fig. S5 (in supplementary information) that the *SPE*I trend in this area was >0 during the period 1980–2009 as well as 2010–2014.

Mongolian Plateau during 1980–2009. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

We also choose the four representative stations with relatively low H values (a and b) and relatively high values (c and d) to validate the reliability of the H-based forecasting. The stations are shown in Fig. 8. The H values for the annual *SPE*I time series from 1980 to 2009 for these stations were used to predict the *SPE*I trend during 2010–2014. These calculations yield values of $H_a = 0.442$, $H_b = 0.403$, $H_c = 0.705$, and $H_d = 0.790$. The annual *SPE*I trends in a and b are contrary to those in the past. Fig. S6(a) (in supplementary information) showed that the annual *SPE*I values decreased at a rate of −0.019/yr but increased at rate of 0.012/yr during 2010–2014 (Fig. S6(b)). For station b, it increased during 1980–2009 and decreased during 2010–2014. The H values were >0.5 at stations c and d during 1980–2009; thus, the annual *SPE*I trend after 2009 is consistent with the previous state. Fig. S6(c) and Fig. S6(d) show that the annual *SPE*I values of station c consistently increased at a rate of 0.175/yr, and the annual *SPE*I values of station d consistently decreased at a rate of −0.005/yr. The accuracy of the station-based prediction using H values was as high as 91.7% (among the 264 stations, only 22 stations had inaccurate predictions). Therefore, this study demonstrates that using Hurst exponent to predict the future drought tendency is reliable.

4. Discussion

Based on the *SPE*I-PM, we studied the spatial and temporal changes in the pattern of meteorological drought on the Mongolian Plateau during 1980–2014. Considerable research has been performed on the changes in meteorological drought on the Mongolian Plateau. Narisu et al. (2016) used the Palmer Drought Severity Index (PDSI) to study the spatiotemporal variation characteristics of drought on the Mongolian Plateau. They found that the arid area is increasing and that the drought became serious during 1980–2013. Cao et al. (2014) used the temperature vegetation dryness index (TVDI) method to assess the spatiotemporal changes in drought on the Mongolian Plateau and found that the aridification intensified in 1981–2012. The results of our study are consistent with these findings. Also, previous studies have shown that, over the last 40 years, the temperature has risen (Li and Qian, 2005), precipitation has decreased (Yatagai and Yasunari, 1995), and drought has intensified (Li and Liu, 2012) on the Mongolian Plateau and in Inner Mongolia (Liu et al., 2016). Fig. S7 (in supplementary information) shows the trends in the spatial changes in annual precipitation (a) and annual mean temperature (b) on the plateau during 1980–2014. The greater decrease in precipitation and the larger increase in temperature occurred in the north-central portion of Mongolia, leading to greater drought (Fig. 4). In contrast, the increase in precipitation and slight increase of temperature in the southwestern corner of plateau led to light drought (Fig. 4). Therefore, the decrease in precipitation and the increase in temperature are the main factors responsible for the drought intensification.

The intensity analysis provides an effective way to explore variations in drought conditions. Based on the rate (fast or slow), intensity (active or dormant), and direction (gain or loss) of change in the drought conditions for each period, the drought trends on the Mongolian Plateau were analyzed for the period from 1980 to 2014. Intensity analysis has the following advantages compared to previous studies. It is based on

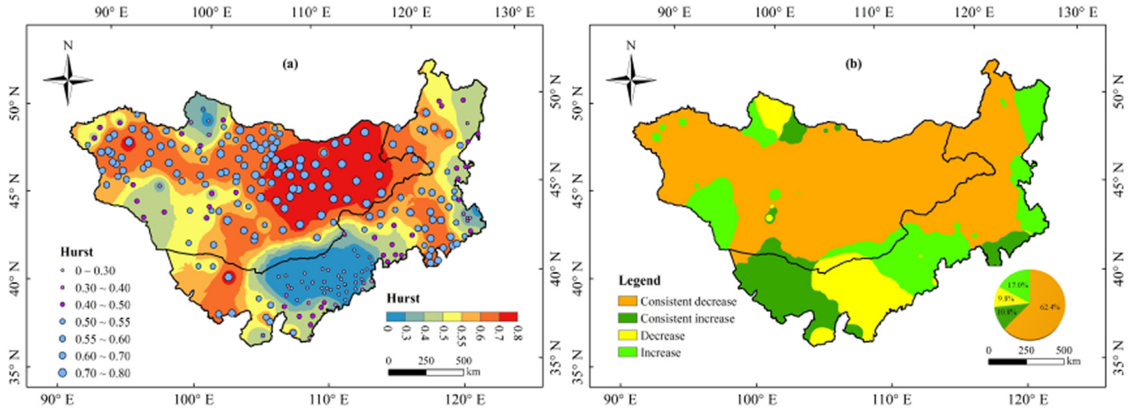

Fig. 7. Spatial distribution of the H values of the annual *SPE*I time series on the Mongolian Plateau during 1980–2014. Increase indicates that the trend of drought is decreasing at present, but will have an increasing trend in the future, and decrease means that the trend of drought is currently increasing but will alleviate in the future (H < 0.5). Consistent indicates that the future trend of drought changes will be the same as the present stage (H > 0.5).

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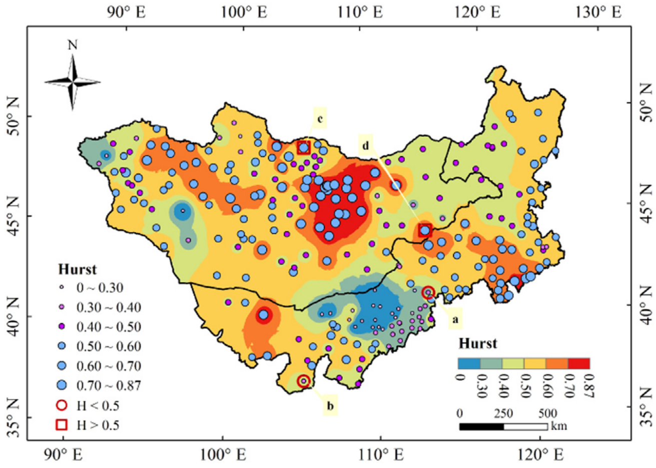

Fig. 8. Spatial distribution of H values of the annual *SPE*I time series on the.

raster data, unlike methods based on drought frequency (Touchan et al., 2011) or station-based drought frequency (Huang et al., 2010), and it can be applied to arid areas. In the analysis of drought trends, intensity analysis gives more attention to the process of change, and the subject in the study is the change in area. The analysis of the time interval level is used to refine the changing speed. The analysis of the drought category level is used to determine the increase and decrease in each drought level, which not only considers the changes in the drought area but also considers the changes in position. The analysis of the transition level provides a detailed description of the transitions between each drought category. The results of the analysis of these three levels describe the changes in drought from different perspectives and, in comparison with previous research methods on drought trends, provide a deeper understanding of drought (Potop et al., 2014; Huang et al., 2014). However, the intensity analysis cannot analyze the spatial distribution.

We used the Hurst exponent to predict the future drought trend of the plateau. However, this analysis cannot predict how long the anticipated drought trend will continue in the future and cannot predict the future drought trends in different categories. Moreover, H values have not previously been widely used to predict drought trends (Tatli, 2016), and only a few studies have used them to study vegetation trends and capital markets (Granero et al., 2008; Peng et al., 2012; Jiang et al., 2015). Therefore, it is proof, in this study, that the Hurst exponent is an effective method to predict future drought trends.

5. Conclusions

In this study, annual (12-month) *SPE*I time series from 1980 to 2014 were analyzed using intensity analysis, linear regression, the Mann-Kendall test, wavelet analysis, and the Hurst exponent method to investigate spatial and temporal variations in the drought characteristics of the Mongolian Plateau. This work led to the following main conclusions:

(1). The annual *SPE*I value exhibited a significant decreasing trend with a rate of −0.0113/yr, and an obvious change occurred in 1999, after which the drought were significant. On the Mongolian Plateau, during 1980–2014, the 1990s was the wettest period, and the 2000s was the driest period.

(2). The change trend of the annual *SPE*I was <0 for 79.4% of the total area, meaning that the drought intensified during 1980–2014. Additionally, the magnitude of the *SPE*I decrease was greater in the north than in the southern plateau, and the drought in Mongolia was worse than that in Inner Mongolia.

(3). The results of the intensity analysis show that the rate of changes in the interval 1980s–1990s and 1990s–2000s were faster than that in 2000s–2010s. The changing areas of gains in different wet levels were larger than the losses and the change of losses in different levels of drought were active during 1980s–1990s. In 1990s–2000s, the gains were in different drought levels, and the losses occurred in different wet levels. In 2000s–2010s, the gains of moderate wet and near normal were both active, while the moderate and severe drought losses were active. The 2010s was wetter than the 2000s.

(4). There is 10a oscillation center in the annual *SPE*I time series of the plateau. Moreover, the Hurst exponent analysis shows that the mean H value of the *SPE*I time series during 1980–2014 is 0.533, indicating that the future drought trend is consistent with the current state. Areas in which the drought is opposite that of the current state (H < 0.5, i.e., the climate is getting wetter) account for 26.8% of the total area of the plateau, while the areas with values of H > 0.5 account for 73.2% of the total area. The area with trend of decreasing drought and increasing drought was 72.2% and 27.8%, respectively. Furthermore, the accuracy of these predictions is as high as 91.7%.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.09.121.

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