Dry/Wet Changes and Their Standing Characteristics in China During the Past 531 Years*

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ABSTRACT

Time series of the dryness-wetness (DW) index of 531 yr (AD 1470–2000) at 42 stations in regions A (most of North China and the east of Northwest China) and B (the Yangtze-Huaihe River valley) in China are applied to investigating the historical DW characteristics over various periods of the series with a relatively stationary average value using Bernaola-Galvan (BG) algorithm. The results indicate that region A/B underwent three drought-intensive periods (DIP; 1471–1560, 1571–1640, and 1920–2000/1501–1540, 1631–1690, and 1911–1960) in the last 531 years. In the DIP of the last 130 years, the frequency of DW transition has increased in region A, but not obviously changed in region B in comparison with the other two historical DIPs. The dry period started in about 1920 in region A with severe drought events occurring from the late 1970s to the early 1980s. It lasted for about 50–70 yr in this century, and then a DW shift took place. The wet period in region B might maintain for the coming several decades. The variations of DW in region A are positively correlated with changes in temperature, but in region B, the correlation with temperature is weaker. It is found that the number of DW indices of various categories within a running window is an exponential function of the running window length. The dryness scale factor (DSF) is defined as the reciprocal of the characteristic value of the exponential distribution, and it has a band-like fluctuation distribution that is good for the detection of extreme drought (flood) clustering events. The results show that frequencies of the severe large-scale drought events that concurrently occurred in regions A and B were high in the late 12th century, the early 13th century, the early 17th century, and the late 20th century. This provides evidence for the existence of the time-clustering phenomena of droughts (floods).

Key words: dryness-wetness index, abrupt change, temperature, the dryness/wetness scale factor, consecutive

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1. Introduction

The complexity of the climate system stems from its complicated interactions with many natural and anthropogenic factors, which are hardly identified and quantitatively assessed (IPCC, 2007). Paleoclimatic proxy records mainly reflect natural climate changes (Overpeck and Trenberth, 2003), and may serve as the climate background of no or less anthropogenic impacts, and thus reveal the regularity and characteristics of natural climate changes in the past several hundred, thousand, or even ten thousand years. On the other hand, studies on grave historical climatic disasters caused only by natural factors are beneficial for investigation of the global warming and the frequent extreme climate events that currently occur under the joint effects of natural and anthropogenic forcings. Yang et al. (2000, 2002), Zhang (1983a), and Song (2000) made the success in studying paleoclimate changes in China using proxy data. Huang (1990) and Shi and Feng (2003) reported the progress in investigating the physical mechanisms and

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dynamical processes of drought/flood in South China and North China.

The climatic averages, trends, and correlation coefficients from previous studies on paleoclimate proxy data of ice cores, stalagmites, and historical writings provide climatic background for present climate projection (Yao and Thompson, 1992; Wang et al., 1998a; Wan et al., 2005; Gong and Feng, 2007). However, a climate system itself is a giant nonlinear system similar to the earth system and follows the most complicated principle of systems (maximum entropy principle). Therefore, dryness-wetness (DW) index and temperature series observed and reconstructed from proxy data and historical writings must comply with some universal principles. In recent years, there have been some reports on this issue (Liu et al., 2000; Bartos and Janosi, 2006). Kiraly and Janosi (2002) investigated the detrended daily temperature data from 1951 to 1989 at 16 stations in Hungary and found that the temperature fluctuations complied well with the scaling law. Peters et al. (2002) and Pelletier (1997) also found the characteristics of the scaling law from statistics of precipitation in different rainfall categories. These studies reveal the scale-free characteristics of climate systems and common attributes of nonlinear complex systems, which provide a theoretical basis for interannual and interdecadal climate projections. The understanding of the scale-free characteristics of climatic systems over a long period will be improved from researches on intrinsic laws of climate change in the historical periods with no or fewer anthropogenic activities. Therefore, using the paleoclimate data to explore these laws is benifical.

The impacts of global warming on variations of DW in China have been concerned in recent decades. Many researchers focus on possible relations between temperature and DW changes in present days (instrumental period) rather than those in several centuries ago due to lack of data. In this study, we investigate the changes in frequencies of the DW transition (among wetness, normal, and dryness) using the last 531-yr DW index (Zhang, 1980; Chinese Academy of Meteorological Sciences, 1981; Zhang, 1983a), and then discuss the possible relationship between DW and temperature changes in North China and the east of Northwest China (region A), and the Yangze-Huaihe River valley (region B). We also investigate climate change in the Northern Hemisphere (NH) utilizing the last 400-yr temperature series reconstructed from proxy data by Wang et al. (1998b) and the tree ring series in the NH (Briffa, 2000). Based on these investigations, we study the scale-free characteristics of DW index series in regions A and B using the 531-yr DW index and the last 1041-yr DW index, define drought scale factor from the point of view of clustering occurrence of droughts, and explore the characteristics of dryness persistence (DP) and its association with the climatic background.

2. Data

2.1 The last 531-yr DW index

Previous studies (Zhang, 1980; Chinese Academy of Meteorological Sciences, 1981; Zhang, 1983b) have reconstructed the 531-yr (AD 1470–2000) DW index series at 120 stations in China. A DW index is defined according to intensity as well as the temporal and spatial scales of dryness/wetness, which is divided into five categories: extremely wet (DW = 1), wet (DW = 2), normal (DW = 3), dry (DW = 4), and extremely dry (DW = 5). We select 42 DW series (Fig. 1), among which 20 series are complete and 22 series have missing data within 20%. The 42 complete DW index series of 531 yr at 42 stations are obtained by filling the missing data with interpolation. Because the missing data is less than 20%, the interpolation will not change the overall characteristics of the original series. Based on geographic locations of the 42 stations, we divide them into regions A and B (Fig. 1b) hereafter. Since only a few stations are located in South and Southeast China, we will not discuss the spatial and temporal characteristics of changes and persistence of DW over South and Southeast China here.

2.2 The last 1041-yr DW index in 6 regions of China

Based on the last 531-yr DW index series at 120 stations, Zhang et al. (1997) reconstructed 6 regional

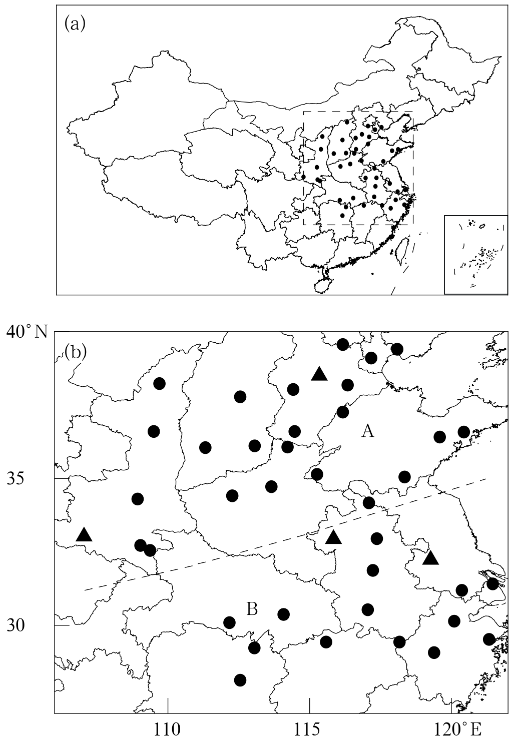

Fig. 1. (a) Distribution of the 42 stations in China, and (b) the enlarged box in (a) divided into regions A and B by a dashed line. Four representative stations denoted by solid triangles are selected in this study: Hanzhong (33.07°N, 107.03°E) and Baoding (38.51°N, 115.31°E) in region A; Fuyang (32.93°N,115.83°E) and Yangzhou (32.23°N, 119.26°E) in region B.

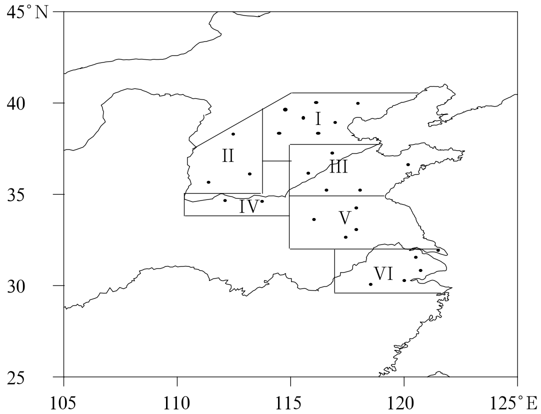

Fig. 2. Six regions for regional climatic DW index series in the last 1041 years (Zhang et al., 1997). I: Hebei, II: Shanxi, III: lower reaches of the Yellow River, IV: Henan, V: Jianghuai, and VI: Suhang regions.

DW index series of 1041 yr for Hebei, Shanxi, the lower reaches of the Yellow River, Henan (these regions belong to region A in Fig. 1), and Jianghuai and Suhang regions (belong to region B in Fig. 1) using the clustering analysis. The definition of the DW index is the same as that for the last 531-years (Fig. 2). The analysis of the spatial and temporal charactertics of drought/wet transition and persistence over regions A and B based on the 1041-yr DW index series will be used to verify and cross-check the reliability of conclusions derived from the 531-yr data. Since the method of using DW index series performs better for drought persistence analysis than for wetness, we will focus on the discussion of drought change and persistence over regions A and B.

3. Results

3.1 Abrupt changes of DW index and frequencies of DW transition

The 531-yr DW index series at 42 stations are analyzed using the power spectrum method. The results show that the significant 10–20-yr cycles exist at most of the 42 stations. The filtering of the 10-yr period is performed on the original index series, and then the Bernaola-Galran (BG) algorithm is applied to detecting the abrupt change in the low frequency series (Huang et al., 2006), because the high frequency components of the DW index series might contain some unwanted information such as noises and random fluctuations. Table 1 lists numbers of abrupt change points and their average intervals for each one-hundred-year period in regions A and B, respectively.

BG algorithm is used to detect abrupt change points of the low frequency series of the DW index, which is divided into relatively stationary sub-series (the mean value segments). To analyze the overall DW characteristics of those sub-series, a mean value segment, with sum of the numbers of DW= 5 and 4 (1 and 2) equal to and greater than 37.5% of the total length of the segment, is defined as a dry (wet) period, otherwise a normal period, considering the fact that ratios for categories 5, 4, 3, 2, and 1 in the 531-yr DW index series are 1/8, 1/4, 1/4, 1/4, and 1/8, respectively (Zhang, 1980).

For the purpose of determining the turning time between dryness and wetness for regions A and B,

Table 1. Numbers of abrupt change points (NACP) and their average intervals (AI) in each one-hundred-year period for regions A and B

No.	A		B	
	NACP	AI	NACP	AI
1	4.5	28.2	4.6	28.1
2	5.4	22.6	4.8	26.1
3	5.1	24.3	5.2	24.0
4	4.8	26.1	4.7	26.9
5	7.3	20.7	6.2	24.9

*Numbers 1–4 denote successively a period of 100 yr starting from AD 1470, and the number 5 indicates the last 130 years.

we successively count differences between wet and dry period numbers within each 10 yr for the 531-yr DW index series, and the results are plotted in Fig. 3. Figure 3a shows that region A underwent three drought-intensive periods (DIPs) in the last 531 years: 1471–1560, 1571–1640, and 1920–2000, with the DW turning points at about 1560, 1640, and 1920, respectively, and a relatively short dry period from 1770 to 1820. The third DIP had more abrupt change points, and shorter intervals between two successive abrupt change points than the other two periods (Table 1). In other words, the transition frequency for the third DIP is obviously higher than that for the other two DIPs. This is a significant feature of droughts occurring in North China in the last 100 years.

Region B also experienced three DIPs (Fig. 3b): 1501–1540, 1631–1690, and 1911–1960, with the turning points in about 1540, 1690, and 1960, respectively; while 1550–1620, 1700–1790, and 1800–1900 were three wetness-intensive periods (WIPS). In comparison with region A, region B has more wetness periods than dryness periods. Meanwhile, the DIPs and WIPs in region B are also different from those in region A. In addition, there is a WIP for region B in the recent 40 years. Obviously, dry climate dominated in the recent 100 years in the Yangtze-Huaihe River valley and in North China before 1951, and afterwards the climate is mainly dry in North China while wet in the Huaihe River valley. This result is similar to that from previous studies on precipitation features in the recent 100 years by Huang et al. (2006), Zhou and Huang (2006), and Bao and Huang (2006).

To analyze the abrupt change information in the 531-yr DW index series, we also calculate the abrupt change points per 10 yr for regions A and B. The results are plotted in Figs. 3c and 3d, respectively. Differences between wet and dry period numbers within each 10-yr period regions A and B display an anti-phase relation with the number of abrupt change points with a time lead or lag. For region A, the abrupt change points are relatively concentrated around turning points in about 1560, 1640, 1760, and 1920, but less concentrated within the DIPs and WIPs. For region B, the abrupt change points are also concentrated in about 1540, 1620, 1690, and 1960. This indicates that in the DW transition periods, the climate state is relatively unstable, and abrupt changes or various extreme climatic events are more likely to occur.

Figure 4 demonstrates the wavelet analysis of

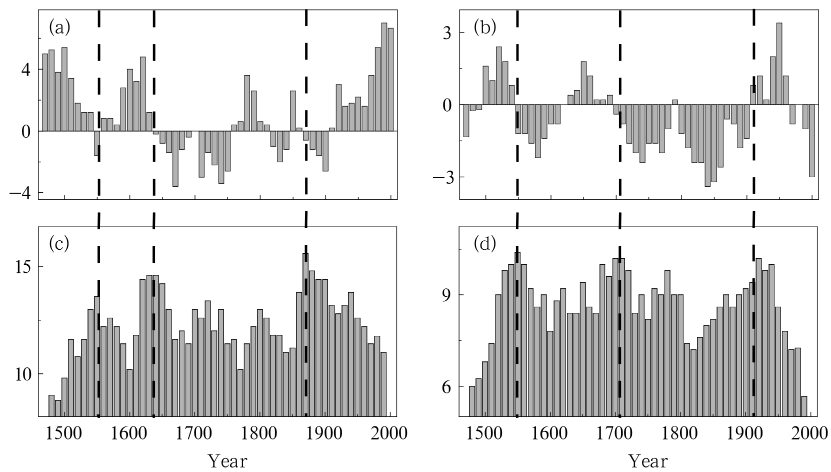

Fig. 3. (a, b) Differences of dry and wet period numbers and (c, d) 50-yr running means of abrupt change points per ten years for regions A and B, respectively. Vertical dashed lines denote the time periods when DW transitions and abrupt change points are relatively concentrated.

531-yr DW index series at four representative stations: Hanzhong, Baoding, Fuyang, and Yangzhou. It can be seen from Figs. 4a and 4b that quasi-periods of 150–200 yr exist in the DW index series at Hanzhong and Baoding stations, which basically accords with that of decadal running mean differences between dry and wet period numbers in Fig. 3a. Obviously, present climate is in a state similar to that in about 1470, when numbers of dry and wet years were anomalously great, and in peak positions. The climate state at present lies at a closed center of wavelet coefficients (i.e., the middle point of a quasi-cycle on a large scale). Therefore, we project that similar to the DIP in about 1470, the dry period in region A, which started from about 1920 with severe droughts from the late 1970s to the early 1980s, might last for another 50–70 yr into the future, and then shift to a wet period. Significant quasi-periods of 100–150 yr also appear in the DW index series at Fuyang and Yangzhou stations (Figs. 4c and 4d). The climate state in the recent 30 years is similar to that in about 1750 and 1850, and lies at the closed center of wavelet coefficients, Therefore, region B might be still in an overall WIP in subsequent several decades.

3.2 Relationship between DW characteristics and temperature changes in the last 531 years

Wang et al. (1998b) reconstructed the recent 400-yr temperature series for 10 regions in China using the ice core δ^{18}O and tree ring proxy data. To investigate the possible relations between temperature (Figs. $5a_2$ and $5b_2$) and DW changes in China, we select average temperature anomalies for North China and Central China in 1600–2000, and compare them with decadal running mean differences of dry and wet period numbers for regions A and B (Figs. $5a_1$ and $5b_1$). Meanwhile, we take the NH tree ring series (Figs. $5a_3$ and $5b_3$) as the background of NH temperature changes (Briffa, 2000), then explore the possible relations between DW transitions in the two regions and climate change in the NH. Moreover, we discuss the possible relations of the Pacific Decadal Oscillations (PDO; Figs. $5a_4$ and $5b_4$) with the transition of DW for regions A and B.

It is seen from Figs. $5a_1$ and $5a_2$ that in region A, the DW change is positively correlated to the temperature change, with high temperature corresponding to relatively dry, low temperature to relatively wet, and relatively stable temperature to normal conditions. A previous study (Yan, 1999) suggested that possible reasons for the recent 30-yr droughts might be the reduction of light rain occurrence and the increase of evaporation due to the temperature increase. Figures $5a_1$ and $5a_2$ further demonstrate that temperature change is one of the important factors affecting DW variations in northern China.

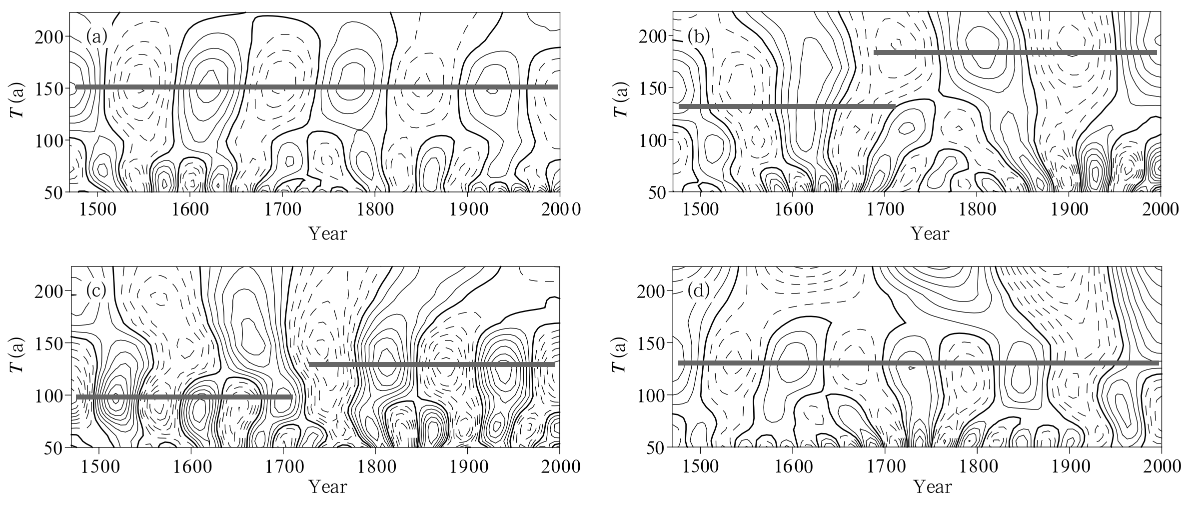

Fig. 4. Wavelet transforms of 531-yr DW index series at four representative stations: (a) Hanzhong (33.07°N, 107.03°E) and (b) Baoding (38.51°N, 115.31°E) in region A, and (c) Fuyang (32.93°N, 115.83°E) and (d) Yangzhou (32.23°N, 119.26°E) in region B. The horizontal thick line denotes the time when the principle period dominated.

In region B, DW changes and temperature variations in the last 531 years were negatively correlated in 1600–1780 and positively correlated in 1800–2000 (Figs. $5b_1$ and $5b_2$). However, the positive correlation in region B is weaker than that in region A, especially before 1700. The reason might be that the rainfall in region B is obviously higher than that in region A, and temperature changes do affect DW changes in regions A and B, but its influence on DW changes in region B is relatively weaker in comparison with that in region A. This also indicates that the major factors impacting DW changes in region B are likely multiple, such as rainfall, temperature, etc. It is difficult to discern which one is dominant.

Figures $5a_3$ and $5b_3$ display the NH tree ring series, which exhibit to some extent the characteristics of NH climate change. It can be seen from Figs. $5a_3$ and $5b_3$ that DW changes in region A (northern China) are in agreement with the NH climate change. In particular, since the 1970s, the DW change in region A has been significantly and positively correlated to the NH tree ring series change. This indicates that droughts in northern China occurred under the background of NH dry and warm climate. In region B, there also exists a certain association between DW changes and NH tree ring series, but the association in region B is not so good as in region A. This reveals the complexity of DW changes in region B. Figures $5a_4$ and $5b_4$ show the Pacific Decadal Oscillation (PDO) index series. On the decadal to centennial scales, the PDO exhibits different correlations with the transition of DW in the two regions, with positive PDO corresponding to dry periods, negative PDO to wet periods, and normal PDO to normal periods of DW.

3.3 Definition of dryness scale factor (DSF) and its spatial patterns

To analyze the extent and persistence of dryness at various stations in a certain period, we define categories of DP from the clustering occurrence of droughts in a certain length of time-period based on Zhang's DW category defined from the interannul variation. For windows of various lengths ranging from 2 to 15, the higher the ratio of the year number of DW= 4 and 5 over the length of the window, the more frequent the clustering occurrence of droughts and the higher the intensity of droughts. For example, if the window length (win) is 2 yr, and the year number of

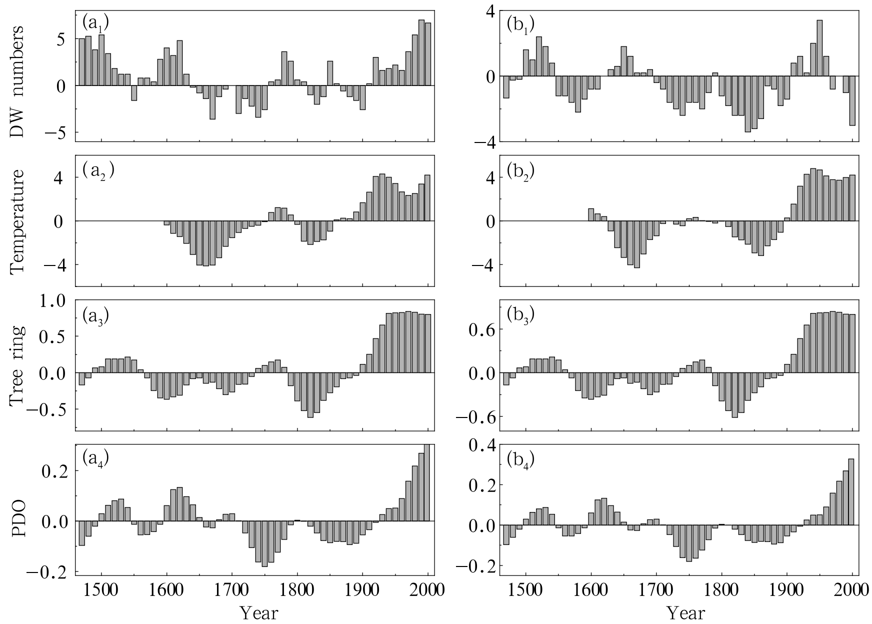

Fig. 5. Histograms for (a_1, b_1) decadal running mean differences between dry and wet period numbers, (a_2, b_2) temperature series in regions A and B, respectively, (a_3, b_3) NH tree ring series, and (a_4, b_4) PDO index series.

DW= 4 and 5 in the window is 1, then DP = 1; and if win = 3 yr, and the year number of DW= 4 and 5 is 2, then DP = 2; and so on. That is, the extent of DW for a certain time period is defined by the ratio of the year number of DW =4 and 5 over the win. Obviously, high DP categories mostly correspond to severe drought events, and thus, DP here could be used as a definition of extreme drought events, and is beneficial to analysis of the clustering occurrence, extreme events, and persistence of droughts.

Taking win successively from 2 to 15, moving the windows with various lengths at the step length of 1 yr along a DW index series for a station, and taking account of the year number of DW = 4 and 5 within the window, respectively, yield the quantitative evolution of DP category at the station. We performed such computational procedures to the 531-yr DW series at 42 selected stations using win = 2, 3,$\cdots$, 14, 15, and found that all the frequencies of various DP categories at various stations satisfy an exponential distribution (Fig. 6), i.e.,

$$P(x) = A\mathrm{e}^{-\gamma x}, \tag{1}$$

where $P(x)$ is the frequency of various DP categories, x is win, γ is the characteristic value of the exponential distribution, and A is a constant. This indicates that dry events of various DP categories occur with

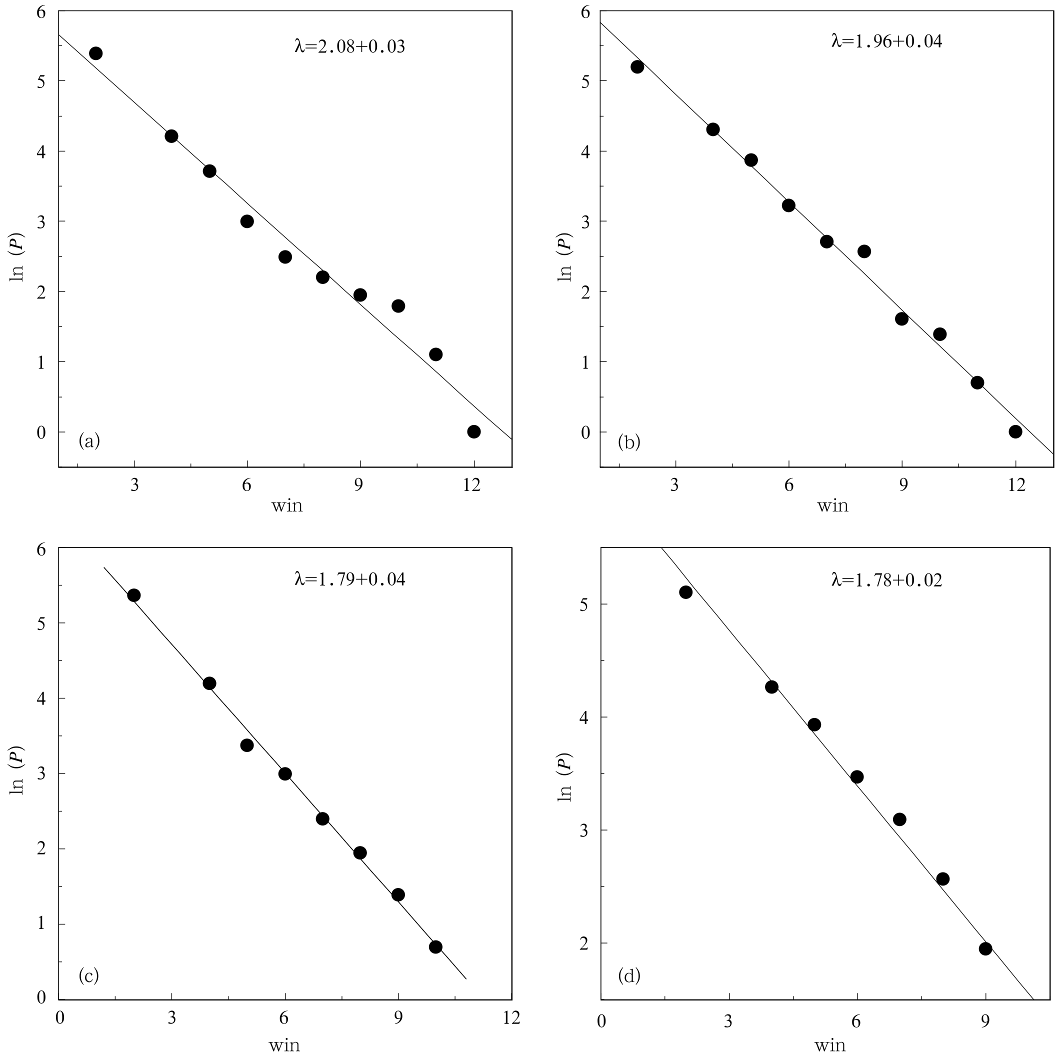

Fig. 6. Semi-log distributions of the frequency of various DP category droughts versus win for (a) Hanzhong, (b) Baoding, (c) Fuyang, and (d) Yangzhou stations.

certain probability that obeys a certain law. This law is similar to the exponential distribution that the earthquake occurrence probabilites at various scales comply with. The reason might be that all the complex systems such as the climate system and the earth system obey the most complicated principle (the maximum entropy principle) (Feng et al., 2006; Bak and Tang, 1989; Gutenberg and Richer, 1944; Frette et al., 1996).

Figure 6 displays the semi-log distributions of the frequency of droughts of various DP categories versus window length (win) at the four representative stations in regions A and B. The exponential distributions at other stations are similar, so they are omitted here. In consideration of the physical meaning of the exponential distribution, the larger the characteristic value γ, the less frequent the higher DP category events, and the more rapid the decay in the frequency of various DP category events from high to low; if γ is small, the opposite is true. Therefore, we define DSF as

$$\lambda = 1/\gamma, \tag{2}$$

and use λ to describe the characteristic of DP. Obviously, the larger the λ, the longer the duration of dryness.

Figure 7a exhibits the spatial distributions of DSFs at 42 stations, i.e., a band-like fluctuation distribution whose value generally increases northward; and the mean values of DSFs in regions A and B are 1.87 and 1.62, respectively. The large value zone of DSF starts from the west of North China, and extends southeastward to the north of Jiangsu and Anhui provinces with the major large value center at the west of North China. The values of DSF are relatively smaller in the north of Shandong and the south of Hebei, and small in the east of Sichuan, Hubei, Hunan, Guizhou, Zhejiang provinces, and the south of Jiangsu and Anhui provinces, with the major low value center in the south of Hubei Province and the north of Hunan Province. The values in Central China and the southeast coastal region are relatively larger, exhibiting a zonal pattern. DSF describes the duration of dryness, therefore, the duration of dryness is relatively longer in northern China than that in the Yangtze River valley, that is, the dryness in northern China is featured with stronger persistence or intensive occurrence of droughts, and the temporal clustering of drought events is significant. This agrees with the fact of frequent severe arid events in northern China in history (Ma et al., 2005; Ma and Fu, 2006). In addition, we calculate the spatial pattern of year numbers of DW = 4 and 5 at 42 stations in 1470–2000. The results are plotted in Fig. 7b. Obviously, the two spatial patterns (Figs. 7a and 7b) are similar, i.e., their band-like distributions are similar, and the centers of large value areas basically accord with each other.

3.4 Temporal evolution features of DSF

On the basis of the obtained spatial distribution of DSF, we further investigate which period of DW index series has the largest impact on DSF by setting win = 20 yr. The first 20 years of the DW index series are cut off from each 531-yr DW series in the first computation. Then the DSF, $\lambda(1)$, is calculated from the truncated DW series. Such a computation is performed for each of 24 (18) stations in region A (B). All DSFs calculated from the 24 (18) stations in region A (B) are added up, to enlarge the effect of the first 20-yr period of the DW index series on the DSF. In the second computation, the above procedures are repeated to obtain $\lambda(2)$. The 21st–40th DW indices instead of the 1st–20th DW indices are cut off from the 531-yr DW index series. Such a computational process goes on until the ends of the DW index series are encountered.

$$\begin{aligned}
&\lambda(i) = \sum_{j=1,24} \frac{1}{\gamma_j}, \quad (i = 1, 2, \cdots, n/\text{win}) \\
&\overline{\lambda} = \frac{\sum_{i=1,n/\text{win}} \lambda(i)}{n/\text{win}}, \\
&\Delta\lambda(i) = \lambda(i) - \overline{\lambda},
\end{aligned} \tag{3}$$

where win is the length of the window, n is the size of the series, and $\Delta\lambda(i)$ is the anomaly of DSF.

Figure 8 shows anomalies of the sum of DSFs for 24 stations (18 stations) in region A (B) when win = 20, 30, and 40 yr, respectively. We also set win = 30 and 40 yr in order to verify the reliability of the results for win = 20 yr (Fig. 8a), and the computational results are plotted in Figs. 8b and 8c, respectively.

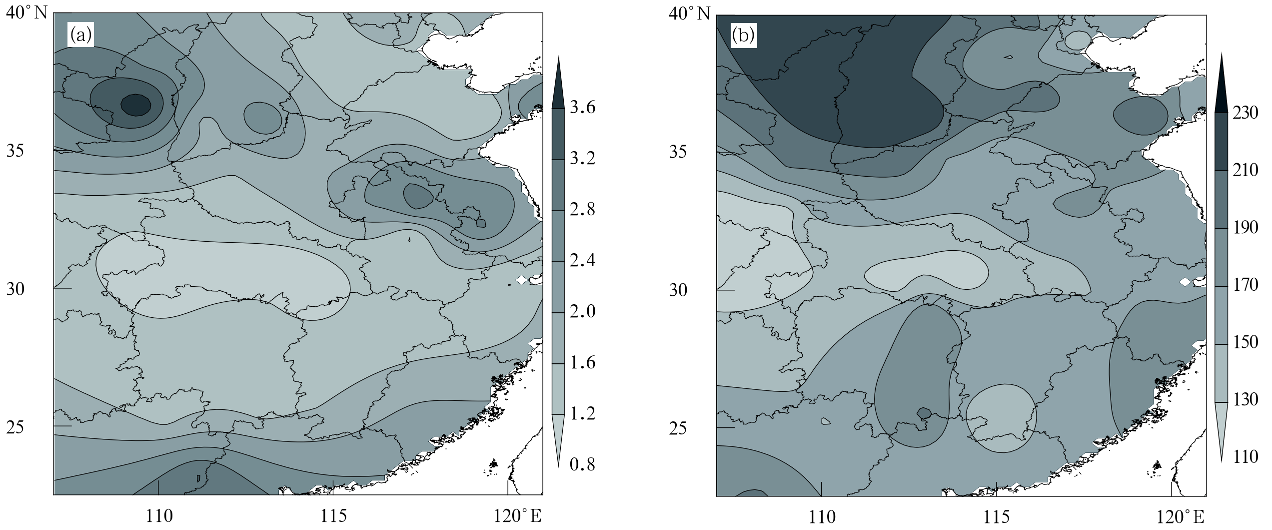

Fig. 7. Spatial distributions of (a) DSF and (b) dry-year number in 1470–2000. The study area consists of the selected 42 stations.

It can be seen from Fig. 8c that when the DW indices within 1470–1510, 1600–1680, and 1960–2000 are deleted, the calculated sum of DSFs is negative. Obviously, the DW indices in the above three window periods have great effects on the DSF for northern China (region A), and affect the DP in those periods. The above three periods correspond right to the periods of three concurrent large-scale droughts in region A, among which the period of 1960–2000 accords with that from the late 1970s to the early 1980s when severe drought events occurred in northern China. Therefore, temporally concurrent severe drought events with a large spatial scale play a critical role in persistent occurrences of droughts. In addition, the three drought periods have different climate backgrounds: 1470–1510 was the first stage of the Little Ice Age in China (Zhu, 1973; Wang et al., 1998a), 1600–1680 was the maximum stage of the Little Ice Age (Zhu, 1973; Wang et al., 1998a), while 1960–2000 corresponds to present global warming starting from 1920 (Wang, 2006).

Similarly, the DSFs (DP) in region B are also analyzed (Figs. 8d-f). When the DW indices of 1510–1550, 1630–1670, and 1870–1950 are deleted from the 531-yr DW index series at 18 stations in region B, the calculated DSFs are reduced. That is to say, these periods in the DW index series have larger impact on the DSF, among which the impact of 1870–1950 indices is the most significant with a climate background of the global warming since 1920 (Wang, 2006). In other words, the DPs in 1510–1550, 1630–1670, and 1910–1950 are significant, and the clustering phenomenon of droughts took place in these periods. When the last 30-yr DW indices are deleted from the 531-yr DW index series at 18 stations in region B, the sum of DSFs in region B is not obviously changed. Therefore, it can be inferred that in the recent 30 years, climate in the Yangtze River valley (represented here by region B) is generally wet.

3.5 DW persistence characters in North China and eastern China in the last 1041 years

Similar to the above analysis of the 531-yr DW index series, the 1041-yr DW index series in North China and the six regions in eastern China, reconstructed by Zhang et al. (1997), are also used to investigate the DW persistence characteristics in North China and the Jianghuai River valley under a longer climate scenario as well as to verify the reliability of the previous 531-yr DW analysis results. We found that numbers of various DW categories have an exponential relation in the form of Eq. (1) with a corresponding window length. This suggests that on the millennium time scale and in a local region, occurrence frequencies of various DW

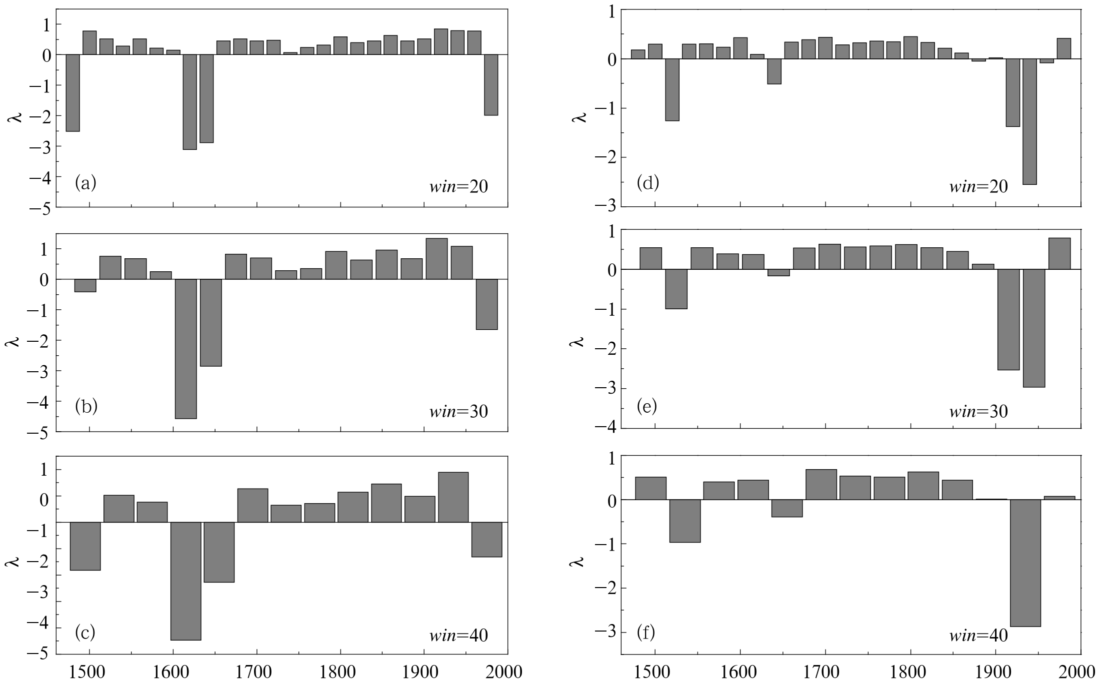

Fig. 8. Anomalies of the sum of DSFs for 24 stations in region A (left panels) and 18 stations in region B (right panels) when win = 20 yr (a, d), 30 yr (b, e), and 40 yr (c, f), respectively.

categories may also obey the exponential distribution, with more remarkable characteristics and smaller error range of calculated exponent value γ in comparison with the 531-yr DW index series. Table 2 shows that values of DSFs in regions I–IV are larger than 2.0. That is to say, on the millennium timescale, the persistence of droughts in the four regions are stronger; the probability for successive or multiple occurrences of DW = 4 and 5 in a certain period is higher; concurrent large-scale extreme drought events are more likely to occur. In particular, the DSFs for regions II (Shanxi) and III (the lower reaches of the Yellow River) are even larger, so is the probability for concurrent large-scale extreme drought events in these two regions. However, DSFs in regions V and VI are relatively small, and the probability for successive or multiple occurrences of drought events in a certain period is smaller. Meanwhile, we also take into account the year numbers of DW = 4 and 5 in each of the six regions in the 1041 years, and find that the year number is larger in regions I–IV, but smaller in regions V and VI. The values of DSFs in various regions are positively proportional to the numbers of corresponding drought years. This to some extent provides evidence for the reliability of the conclusion that the DSF in North China is larger and the DP is stronger. The spatial distributions of DSFs over the six regions are consistent with those in Fig. 7a (the case for 42 stations and the time scale of 31 yr). Therefore, the occurrence probabilities for drought events in various categories in the DW index series for a millennium or 531 years all obey a exponential distribution. This is an intrinsic attribute of DW changes, and the spatial distribution of DSFs is relatively stable.

Table 2. DSFs and dry-year numbers (DYN) for six regions in China

Region	I	II	III	IV	V	VI
DSF	2.17	2.91	2.77	2.30	1.52	1.37
DYN	376	444	388	369	351	329

*I–VI denote the same regions as in Fig. 2.

In regions I–IV, after 20-yr DW indices arbitrarily chosen in 1140–1280 are deleted from the 1041-yr DW index series, the calculated DSF changes greatly. Especially, after the deletion of the indices of 1260–1280, the DSF is dramatically reduced (Fig. 9a). In addition, after the deletion of the indices during

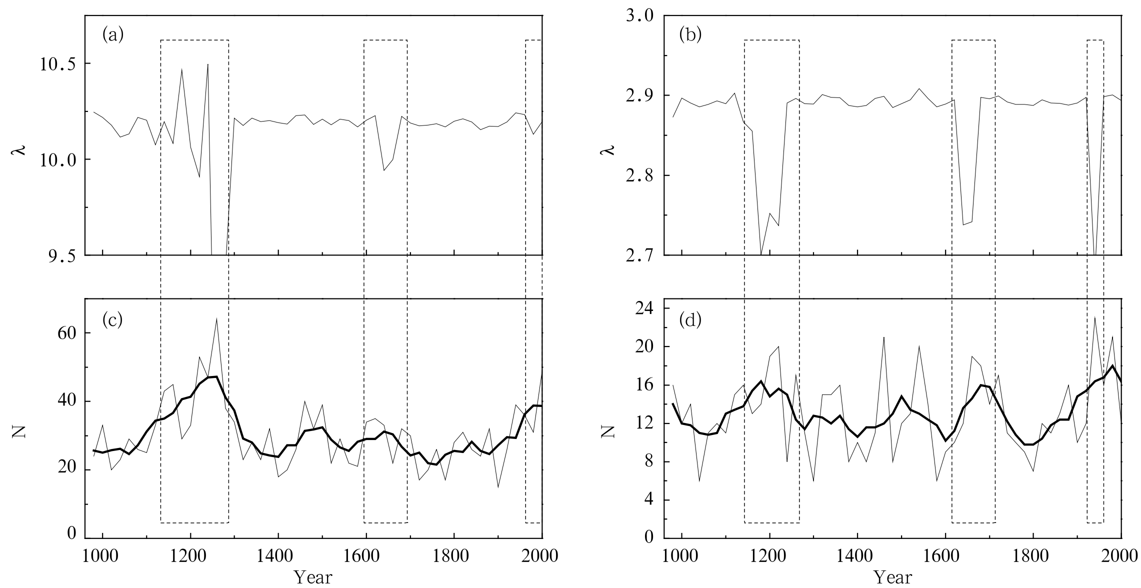

Fig. 9. Sum of DSFs (a, b) and the year numbers of DW = 4 and 5 (c, d) within the running window of 20 yr for North China (left pannels) and the Jianghuai River valley (right panels). The DSF is calculated from the 1041-yr DW index series, of which 20-yr indices are successively cut off from the left to right of the series, until the end of the series is encountered. Thick lines in (c) and (d) denote the 5-yr running means.

1620–1660 and 1980–2000, the DSFs are also significantly reduced. Based on the physical meaning of DSF, these indicate that the DP in North China in these periods was strong, and drought years (DW = 4, 5) frequently and successively occurred (temporally clustered), i.e., probability of extreme drought events was high (Fig. 9c). In the recent 30 years, the aridity phenomenon in northern China is discernible from changes of DSF. However, as far as changes in DSF are concerned, this drought period is not the severest one in the last 1041 years, because the reduction of DSF is much larger when the indices of 1260–1280 are deleted than when the indices of 1980–2000 are deleted. We successively calculated the year numbers of DW= 4, 5 within the running window of 20 yr in regions I–IV (Fig. 9c), and found that time periods with DSF obviously reduced often correspond to those when the year numbers of DW = 4, 5 are larger, and the year number is larger in 1260–1280 than that in 1980–2000, which to some extent verifies the reliability of the 531-yr DW analysis results. After the deletion of the indices of 1140–1260, 1620–1700, and 1920–1960, DSFs in regions V and IV are obviously reduced (Fig. 9b), and all these three periods correspond to larger year numbers of DW= 4, 5 within the running window of 20 yr (Fig. 9d). It can be seen that larger-scale extreme drought events concurrently occurred in both North China and the Yangtze-Huaihe River valley from the late 12th century to the early 13th century, in the early 17th century and the late 20th century. According to previous studies (Dai et al., 2005; Briffa et al., 1990), the period 1260–1280 corresponds to the late Medieval Warm Period, when the average temperature was higher, and the evaporation was larger. This led to the concurrent occurrence of large-scale droughts. The period 1980–2000 has a global warming climate background, and a reduction in the number of light rain and larger evaporation resulted in the droughts in this period (Wang, 2006; Zhi et al., 2006). The period 1620–1660 corresponds to the early Little Ice Age maximum in the 17th century, and droughts in this period might result from low temperature and less rainfall (Zhu, 1973; Gong et al., 2006).

4. Conclusions and discussion

The current study on the DW transition characteristics in the last 531 years at 42 stations suggests that region A underwent three DIPs in 1471–1560, 1571–1630, and 1920–2000, with DW turning points in about 1560, 1640, and 1920; the transition frequency among dry, normal, and wet periods is higher in the third DIP than in the first two periods. This is a distinctive feature for the recent 100-yr dryness in northern China. Region B also experienced three DIPs: 1501–1540, 1631–1690, and 1911–1960. Abrupt change points are mostly concentrated in the transition periods when climate states are unstable, and abrupt changes and various extreme climatic events are more likely to occur. In combination with the periodic analysis of wavelet coefficients, we found that in region A, the dryness started in about 1920, underwent a severe stage from the late 1970s to the early 1980s, and might last in the coming 50–70 years, before turning to a wet period. In region B, climate might still stay in an overall wet state in the coming several decades. The DW changes in region A are positively correlated with temperature variations. In general, when temperature is higher, the climate is relatively dry; when temperature is lower, the climate is relatively wet. Therefore, temperature changes are one of the important factors affecting the dryness in northern China. The association between DW change and temperature variation in region B is weaker in comparison with that in region A, indicating that major factors influencing DW changes might be multiple, such as rainfall and temperature, but it is difficult to discern which one dominates. In addition, the PDOs also have certain effects on DW changes in China.

Analysis of the DP of droughts from the 531-yr DW series at the 42 stations reveals that occurrence frequencies of drought events under different DW categories have an exponential relation with corresponding length of the running window, that is $P(x) = A\mathrm{e}^{-\gamma x}$. The reciprocal ($\lambda$) of exponential characteristic value (γ) is defined as the dryness scale factor (DSF), which is used to describe the drought duration. The spatial pattern of DSF is a band-like fluctuation distribution whose value increases northward. The DP in northern China is stronger than that in the Yangtze-Huaihe River valley, and the spatial pattern of DSF in North China and the Yangtze-Huaihe River valley basically accords with that of the drought-year number in the last 531 years. The DIPs in the DW index series impact significantly on DP, and Table 3 displays the time-periods during which DW indices contribute significantly to the DSFs for North China and the Yangtze-Huaihe River valley. In those periods, the probability of drought events of higher DW category was also higher, which verifies the existence of drought-clustering phenomenon from an other aspect. Meanwhile, those drought-clustering periods roughly correspond to the climate background of the Medieval Warm Period, the three stages of the Little Ice Age, and the present global warming period, respectively. Especially, intensities of drought events occurring in the historical periods with increasing temperatures are also higher.

Table 3. Time periods when DW indices significantly contribute to DSF

	Region	Dry periods
531-yr	A	1470–1510, 1600–1680, 1960–2000
series	B	1510–1550, 1630–1670, 1910–1950
1041-yr	I–IV	1140–1280, 1620–1660, 1980-2000
series	V–VI	1140–1260, 1620–1700, 1920–1960

The study on the 1041-yr DW index series in the six regions of China indicates that occurrence probabilities of various DW categories in the DW index series of 1041 or 531 yr all obey the exponential distribution. Meanwhile, the spatial pattern of DSFs in the six regions of China in the last 1041 years is consistent with that in the last 531 years at 42 stations. Therefore, the spatial pattern of DSFs is relatively stable. After the deletion of the indices of a certain window-length period, the DSFs in the six regions are all changed to a certain extent, and large-scale extreme drought events concurrently occurred in both North China and the Yangtze-Huaihe River valley from the late 12th century to the early 13th century, in the early 17th century and the late 20th century, which suggests that the DW background in North China and the Yangtze-Huaihe River valley in those periods are similar to each other (Table 3). The impact of the DW indices of 1260–1280 (corresponding to the climate background of the late Medieval Warm Period in higher latitudes) on DSF is more significant than that of 1980–2000 (corresponding to the climate background of the global warming in the 20th century), and the year number of DW= 4 and 5 in 1260–1280 is also higher than that in 1980–2000; therefore, strong and large-scale drought events are more likely to concurrently occur in warm climates, and the aridification in northern China in the recent 130 years might result from the joint effects of anthropogenic and natural changes under the latter dominance (Feng et al., 2005).

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