Temporal and Spatial Distribution of Multi-scale Drought in North China

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Abstract. The North China is located in the East Asian monsoon region. The uneven spatial and temporal distribution of water resources leads to frequent drought disasters, and drought has increasingly become a limiting factor for regional development. In this paper, the intrinsic evolution characteristics of multi-scale spatial and temporal distribution of meteorological drought in the past 57 years in North China are analyzed by using standardized precipitation evapotranspiration index and ensemble empirical mode decomposition with multi-time scale features. The results show that the North China region was generally humid in the 1960s and 1970s. Drought in the 1980s and 1990s increased relatively. The interannual SPEI of North China changed in 1991, and entered a relatively dry period in the late 1990s and 2000s. From the SPEI index sequence, the scale characteristics of each scale were extracted. It was found that the SPEI sequence of the three-month time scale in North China mainly existed in the three scale ranges of monthly, interannual and intergenerational. At the same time, through the comparison of the temporal and spatial distribution characteristics of the summer drought in June and August 2002 in North China, it was found that the severe drought in August 2002 was caused by the temporal and spatial overlap of short-term scale and long-term drought events.

1. Introduction
Drought is the most common and widespread natural disaster in the world. It has a wide impact and has a profound impact on social and economic development [1]. Nearly $8 billion in global losses are caused by drought, far exceeding other meteorological disasters [2]. In recent years, the spatial and temporal distribution non-uniformity of precipitation caused by global warming has intensified, making the occurrence of drought events more frequent [3]. Under the background of global warming, the trend of aridification in North China is increasingly obvious [4]. From the end of the 20th century to the beginning of the 21st century, more than half of the years have experienced droughts and even extreme droughts [5]. In particular, the continuous drought process of 1999-2002 [6] has a great impact on social and economic development. Therefore, the government has to urgently implement the emergency water diversion project of the Yellow River and Tianjin to ease the impact of drought.

In recent years, scholars have conducted a lot of research on the frequent drought in North China [7-9]. Ma Zhuguo et al. [10] used the monthly precipitation and average temperature of China for nearly 50 years to construct a surface wet index, and conducted deeply research on the distribution characteristics of extreme drought in northern China. The results show that in the north China, the frequency of extreme drought is significantly increased, the frequency of extreme humidification is relatively reduced, and the frequent occurrence of extreme drought often corresponds to the area with obvious temperature increase; Yang Shuai et al [11] is based on the summer of 1951-2013 regional precipitation data, and temporal and spatial analysis of summer average precipitation and a circulation analysis of 500, 700 and 850hPa. The results show that the summer precipitation in North China
changed suddenly in the 1980s, and the aridification trend in North China was obvious. Lu Hongjian et al. [12] studied the temporal and spatial variation characteristics of meteorological drought in North China in the past 50 years based on the daily weather data of 60 stations from 1960 to 2009 using the modified Palmer drought index and M-K method and EOF analysis method. The results show that the PDSI (Palmer Drought Severity Index, PDSI) can better characterize the spatial and temporal evolution of drought in the North China Plain. The drought mainly has a spatial distribution pattern of increasing from south to north and southeast to northwest. The seasonal drought is obvious, and the interannual and interdecadal variations are significant. Yang et al.[13] used the monthly precipitation data of 614 meteorological stations in China to calculate the precipitation anomaly percentage and its drought grade sequence at each station, and used the REOF method to divide climatic zone. The time evolution characteristics of drought levels around 50a in each region were analyzed. The results showed that the drought in North China was significantly increase in the past 50 years.

In summary, most of the previous research results tend to analyze the overall variation characteristics of the spatial and temporal distribution of drought, and lack the intrinsic multi-scale variation characteristics of the spatial and temporal distribution of drought caused by climate change. Therefore, the precipitation data of each month in the North China region from 1960 to 2016 is used to calculate the standardized precipitation evapotranspiration index with multiple time scales, and then to characterize the drought changes in North China. Secondly, the Mann-Kendall method and the ensemble empirical mode decomposition method are used to research the multi-time-scale oscillation characteristics inherent in the drought index sequence under climate change. Ultimately, the comparison of drought events in different periods to reflect the spatial structural changes of drought.

2. Material
The study area is located at 110°E-123°E, 31°N-43°N, including 6 provinces and municipalities in Hebei, Henan, Shanxi, Shandong, Beijing and Tianjin. The study area is shown in Figure 1.

This paper uses monthly precipitation data and 57 years of drought disaster data from 65 weather stations in North China from 1960 to 2016. It is derived from the National Meteorological Science Data Sharing Platform.

Figure 1. Distribution of Research Area and Meteorological Site

3. Method

3.1. Standardized Precipitation Evapotranspiration Index
The standardized precipitation evapotranspiration index (SPEI) [14] describes drought from the perspective of water deficit and its accumulation. It has the advantages of multi-time scale, less input data and simple calculation. The three-parameter log-logistic probability distribution function is used to fit the difference between precipitation and potential evaporation, and then the normalized
probability density function is normalized. The potential evaporation is calculated using the thornthwaite method [15].

3.2. Ensemble Empirical Mode Decomposition
Ensemble empirical mode decomposition (EEMD) is a complex time series analysis method based on the evolution of empirical mode decomposition (EMD). It is suitable for analyzing nonlinear and non-stationary time series. It is mostly used to analyze time series climate elements and extract information on climate change such as drought disasters [16]. EEMD adds some white noise to the original signal, uses the combination of signal and noise as the signal to be decomposed, and then uses EMD to decompose the original sequence into different scales of intrinsic mode function (IMF). The calculation steps are as follows:

1. An overall sequence \( X(t) \) is obtained by adding a set of finite amplitude white noise \( w(t) \) to the target signal sequence \( x(t) \):
\[
X(t) = x(t) + w(t)
\]

2. EMD of \( X(t) \) yields the first IMF component \( c_1 \), representing the most high frequency component of the original sequence. Subtracting \( c_1 \) from \( X(t) \), the residual sequence \( r_1 \) of the high frequency component is removed, and then the EMD decomposition is continued for the residual sequence, and \( c_2, c_3, \ldots, c_n \) are obtained by loop until the residual sequence \( r_n \) satisfies the predetermined stopping principle, and the decomposition is terminated get \( X(t) \):
\[
X(t) = \sum_{j=1}^{n} c_j + r_n
\]

3. Add different white noises \( c_i(t) \) to the target signal, and repeat the above steps to decompose to obtain the respective IMF component groups.
\[
X_i(t) = \sum_{j=1}^{n} c_{ij} + r_{in}
\]

4. Take the average of the corresponding IMF as the final IMF group [17]
\[
c_j = \frac{1}{N} \sum_{i=1}^{N} c_{ij}
\]

In general, the parameters that are more important for EEMD are the average number of times and the signal-to-noise ratio. If the signal-to-noise ratio is too small, the decomposition effect of EEMD will not be obvious, and if the signal-to-noise ratio is too large, it will interfere with the final decomposition result. In addition, by increasing the average number of sets, the interference of the added white noise on the result can be reduced, but the more the number of integrations, the more the program runs. In this paper, the EEMD decomposition method is used to decompose the SPEI drought index sequence. When the multi-scale features of the drought signal are obtained, after several experiments, the signal-to-noise ratio parameter is set to 0.2, and the average number of sets is set to 150.

4. Results

4.1. Multi-time Scale Variation Characteristics of Meteorological Drought
In order to explore the multi-time scale variation characteristics of meteorological drought in North China, the monthly average precipitation and monthly average temperature data of 65 meteorological stations in North China from 1960 to 2016 were used to calculate the standardized precipitation evapotranspiration index for 57 years. A total of five time scale indices were obtained, and the results are shown in figure 2. The standardized precipitation evapotranspiration index of different time scales
reflects different regional meteorological drought conditions. The index of short time scale (1, 3, 6) can quantify the meteorological drought caused by short-term surface water unbalance. This phenomenon significantly responds to the changes that this difference between precipitation and potential evaporation. The long-term scale index (12, 48) can quantify the drought caused by the persistent imbalance of surface water accumulation, reflecting the inter-annual or intergenerational scale to explore the regional drought law.

The trend components of the SPEI index sequences of five time scales were tested by Kendall rank correlation test. It was found that the SPEI sequences of five time scales in North China showed a significant decrease trend (all passed the 0.01 significant test). In the past 57 years, it has been showing a trend of drought, which is basically consistent with Ma’s research [18]. At the same time, the variation of sequence on different time scales is also prominent: the dry- wet changes in the short-time scale are frequent, and the positive and negative fluctuations of the SPEI index occur, reflecting the characteristics of the season-to-year oscillation, which indicates the frequency of drought in the short-term in North China. The long-term dry and wet changes slowed down, reflecting the characteristics of interannual to intergenerational oscillations. Although there were dry and wet transitions in the 1960s and 1970s, they generally belonged to the relatively humid climate in North China. It increased from the dry period of the 1980s and 1990s, and entered a relatively dry period in the late 1990s and 2000s.

The Mann-Kendall trend and mutation test were performed on the interannual SPEI index in North China. It can be seen from figure 3 that the UF curve in North China was positive and negative before 1980. Since 1980, there has been a continuous negative value, and then it exceeded the significance level of 0.05 in 2004. Until 2012, it exceeded the significance level of 0.01, indicating that the characteristics of aridification began in 1980 in North China, and the trend of regional aridification became more and more obvious. The UB and UF curves intersected in 1991 at the criticality level of 0.05. This is the beginning of the interannual SPEI index mutation in North China.

Figure 2. Sequence Variation of SPEI Indices at Five Time Scales from 1960 to 2016 in North China
4.2. Characteristics of Intrinsic Structural Changes in Arid Multi-scale Space

This paper uses the comparison of drought events in different periods to reflect the spatial structural changes of the drought. The duration of drought events and drought intensity at different time scales were calculated according to the definition of drought events given by McKee [19]. The beginning of the drought event is that the SPEI continues to be negative and reaches -1, the end of the drought event is the positive value of the SPEI value, and the duration of the drought event is the time lag from the beginning to the end. This article uses the definition of Lin Wang’s research [20]. Drought intensity is defined as the minimum of SPEI in a drought event. According to statistics, there are 29 drought events in the three-month time scale in North China in the past 57 years, 17 drought events in the 6-month time scale, and 11 drought events in the 12-month time scale. The 48-month time scale there are only two drought events. The average duration of drought events at the 3-month time scale was 6.4 months, the average duration of drought events at the 6-month time scale was 10.7 months, and the average duration of drought events at the 12-month time scale was 16.4 months, while 48 The average duration of drought events on a monthly time scale can be as long as 81 months. Therefore, most of the drought events with short time scales are characterized by changes from season to year, and long-term drought events can even last for many years.

SPEI sequences of different time scales can reflect different types of drought, at some time, the types of drought at different time scales may overlap each other to cause serious drought events, affecting all aspects of social and economic development. According to Figure 2, the SPEI value of the 48-month time scale fluctuated from 1996, reaching the lowest point in August 2002, the lowest point was -2.75, and it returned to normal climate after 37 months. This reflects that when the SPEI value of the long-term scale decreases gradually, it is very likely that serious hydrological drought events will occur, resulting in a significant reduction in rivers, lakes, and groundwater, while long-term drought events are likely to last for several years. It is easy to cause a superposition with a short-time scale drought.

According to the research by Yanshu Rong [21], a persistent high temperature and drought process occurred in North China from 1997 to 2002, resulting in a severe drought in the North China region with three consecutive droughts. Figure 2 reflects that the SPEI index of the 48-month time scale is between 1960 to 1995. The overall climate is biased to be humid. Although there is some fluctuation, it is relatively stable, and the minimum index is not lower than -1.2. However, since 1996, the SPEI value of the 48-month time scale has been in a state of fluctuating decline, and reached the lowest value of -1.75 since 1960 in August 2002. In August 2002, North China was also in high temperature and low rainfall, developed to the most serious period. The spatial evolution characteristics of five time-scale droughts in June and August 2002 were further analyzed, as shown in figures 4 and 5.

According to Figure 4 and Figure 5 showing that the spatial distribution of SPEI values in the one-month time scale in June shows that except for some regions, the whole of North China is in a normal and humid state. However, due to the low temperature and high temperature, the drought of August developed rapidly. As a result, the North China region is rapidly in a wide range of drought conditions, 80% of the regions are affected by drought, and nearly 60% of the SPEI values are less
than -1. The distribution of SPEI at 3 and 6 months showed that most parts of North China were in normal condition except for parts of the Sea of Bohai in June, but the drought developed rapidly in August, except for the northwestern part of the mountain and southern Henan. In addition, more than 70% of the North China region is affected by drought, and nearly half of the areas have SPEI values less than -1. Extreme drought is distributed in northern Hebei and Shandong Peninsula. In June, the spatial distribution of SPEI at 12-month time scale showed that drought had affected Hebei, Shandong, eastern Shanxi and northern Henan. The drought continued to develop in August, Jiucheng was covered by drought, and 60% of the area was SPEI less than 1. The SPEI value of the 48-month time scale also reached the extreme value. The spatial distribution indicates that the North China region is in a wide range of extreme droughts in the whole region. More than half of the SPEI values are less than -2, and the extreme drought is widely distributed in the south-central Shanxi, Hebei provinces and western of Shandong. By the end of 2002, the average depth of groundwater in Beijing was 17 meters, which was nearly 10 meters lower than that at the end of 1995. The reserves decreased by 5.1 billion cubic meters. The Miyun Reservoir has been operating at low water levels for many years. Therefore, the superposition of drought events at different time scales will have a serious impact on all aspects of social and economic development such as industrial and agricultural production and urban water use.

**Figure 4.** Spatial Distribution of SPEI Indices at Five Time Scales in June 2002

**Figure 5.** Spatial Distribution of SPEI Indices at Five Time Scales in August 2002
4.3. Multi-scale Oscillation Characteristics of Dry and Wet Fluctuations

In order to analyze the characteristics of meteorological drought fluctuations in North China, Ensemble empirical mode decomposition (EEMD) was used to gradually decompose the SPEI sequence of the 1960-2016 three-month time scale in North China to understand the oscillations inside the sequence. Figure 6 contains intrinsic mode function (IMF1-8) and one trend component. According to figure 6, it can be seen that the amplitude and frequent fluctuations of IMF1 are the largest among the eight components. As the order increases, the amplitude of the IMF component gradually decreases, the wavelength gradually increases, and finally tends to be stable. The trend component represents the overall trend of the original SPEI sequence. The IMF8 shows the characteristics of intergenerational oscillations, showing the basic trend of intergenerational changes in dry and wet alternating in the past 57 years in North China.

In order to describe the degree of influence of the fluctuation period and amplitude of each scale signal on the overall characteristics of the SPEI sequence, the composition and correlation of each component with the original sequence can be analyzed. The average fluctuation period, variance contribution rate and Pearson correlation coefficient can be calculated by calculating the average fluctuation of each component. It can be seen from Table 1 that after multiple decompositions, the SPEI at the 3-month time scale exhibits the following changes. Firstly, there are cyclical changes in the annual period of 0.34 years (IMF1) and 0.73 years (IMF2). In terms of the variance contribution rate, the IMF1 variance contribution rate is 21.7%, and its oscillation signal is more obvious. The period of greater magnitude has a certain correlation with the monthly drought shown by the one-month time scale. The variance contribution rate of IMF2 is the largest of the 8 components, which is 23.2%. The period of large vibration amplitude has a good correspondence with the drought events shown on the 3-month time scale, such as 1990-1991, 1999-2001. Two periods with large amplitudes correspond to two three-month time scale drought events. At the same time, the correlation coefficients between IMF1 and IMF2 and the original sequence are 0.52 and 0.65, respectively, and both of them pass the significance level test of 0.01. Therefore, the variation characteristics of the IMF1 and IMF2 are significantly higher than those of the SPEI sequence of the original 3 month time scale. consistency.

Secondly, there are cyclical changes in the fluctuation period of 1.43 years (IMF3), 2.85 years (IMF4), and 5.7 years (IMF5) on the interannual scale. From the perspective of variance contribution rate, the variance contribution rate of IMF3 is the largest among the IMF components on the interannual scale, which is 13.4%. The oscillation signal has a good correspondence with the drought event at the 6-month time scale, such as the amplitude in IMF3. The two larger 1968, 1997-1999 years corresponded to two six-month time-scale drought events. As the other components increase with the period, the variance contribution rate decreases accordingly, and the correlation coefficient between the IMF component and the original sequence also decreases. It may be because these component periods are longer and the trend fluctuation is slower. When changes occur, these components will continue to follow the original trend for a period of time and then change accordingly.

Figure 6. IMF Component after EEMD of Monthly SPEI Sequence in North China in 1960-2016
### Table 1. Characteristics of IMF Components after Monthly EEMD of SPEI in North China

| IMF  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | RES |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Fluctuation cycle/year | 0.34 | 0.73 | 1.43 | 2.85 | 5.70 | 11.40 | 21.11 | 28.50 |
| Variance contribution rate % | 21.7 | 23.2 | 13.4 | 6.5 | 4.6 | 1.4 | 0.9 | 0.5 | 2.6 |
| Correlation coefficient | 0.52* | 0.65* | 0.57* | 0.41* | 0.28* | 0.15* | 0.12* | 0.17* | 0.17 |

*significantly correlated at the 0.01 level

The IMF component obtained for decomposition is either pure noise or a component of physical significance in the original sequence, which can be judged by a significance test [22]. The 90% and 95% confidence intervals were taken for testing. If the IMF component is above the confidence curve, it can be considered to pass the significance test, and it can be considered to contain information with actual physical meaning within the confidence level range in which it is located. Conversely, if it is below the confidence curve, it is considered that it contains is likely to be a white noise component. The calculation results are shown from figure 7.

According to figure 7, the horizontal axis represents the component period, and if the IMF component is closer to the left, the higher the frequency, the smaller the period. The vertical axis represents the energy spectral density of each IMF component, and the closer the IMF component is to the upper side, the higher the energy it has and the larger the amplitude. It can be seen from figure 7 that the eight IMF components are all above the 95% confidence curve, indicating that the eight IMF components have passed the significance test, and it can be considered that the physical meaning information is included in the range above the 95% confidence interval. At the same time, it is proved that the selection of the decomposed parameters is reliable. Among them, IMF1 is closest to the left, indicating that it has the highest frequency and the smallest period, which is basically consistent with the results in Table 1. IMF2 is the component closest to the top, indicating that it has the highest energy and the largest amplitude. IMF8 is the component closest to the bottom and closest to the right, indicating that it has the lowest energy, the smallest amplitude, the lowest frequency, and the largest period, which is also consistent with the results shown from figure 6 and table 1.

**Figure 7.** Significance test of each IMF component signal after SPEI sequence decomposition in North China (E is the average normalized energy, T is the average period, and the point represents each IMF component)

### 5. Conclusion

This paper uses the monthly precipitation and temperature data of 1960-2016 in 65 meteorological stations in North China to calculate the multi-time scale SPEI data, and studies the intrinsic multi-scale characteristics of drought spatial-temporal distribution in North China. The results show that:
(1) In order to explore the multi-time scale variation characteristics of meteorological drought in North China, the Kendall rank correlation test was used to test the SPEI sequences of five time scales. It was found that the SPEI of five time scales in North China were significantly reduced. The North China region generally belonged to a relatively humid period in the 1960s and 1970s, and increased in the 1980s and 1990s. The interannual SPEI in North China was changed in 1991, and the characteristics of aridification became more and more obvious.

(2) In order to analyze the multi-scale intrinsic characteristics of drought in North China, it is found that the severe drought in August 2002 is a short time scale and long time by comparing the temporal and spatial distribution characteristics of the multiple time scales of drought in June and August 2002 in North China. The scale drought is superimposed on each other.

(3) In order to research the multi-scale characteristics of dry-wet changes in North China, the empirical model decomposition method is used to extract the scale variation characteristics from SPEI sequences. It is found that there are three kinds of period ranges in the SPEI sequence in North China. The eight IMF components are significant periodic components, all of which have practical physical meaning.

6. References

[1] Zhang Q, Yao Y, et al. (2015). Research progress and prospects of monitoring and early warning and disaster mitigation techniques for arid meteorological disasters in Northwest China. Advances in Earth Science, 30(02), 196-213.

[2] Wang W G, Zheng G G, et al. (2014). Green Paper on Climate Change: Report on Climate Change Report. Progress in Climate Change Research (06), 470-470.

[3] An X L, Wang Q F, et al. (2016). Characteristics of agricultural drought disasters in North China. Journal of Beijing Normal University (Natural Science Edition), 52(05), 591-596.

[4] Fu Y B, & Wen G. (2002). Several issues of aridification in northern China. Climate and Environmental Research (01) 22-29.

[5] Rong Y S, Yu J H, et al. (2007). Characteristics and causes of drought in North China in the 1980s and 1990s. Plateau Meteorology, 26(02), 319-325.

[6] Rong Y S, Duan L Y, & Xu Ming. (2008). Diagnostic analysis of persistent arid climate in North China from 1997 to 2002. Arid area research (6) 842-850.

[7] Wei J, Tao S Y, et al. (2003). Application of Palmer Drought Index in Drought Analysis in North China. Journal of Geographical Sciences (01) 91-99.

[8] Sun A J, Gao B. (2000). Diagnostic analysis of severe drought and flood in summer in North China Plain. Atmospheric Sciences, 24(03), 393-402.

[9] Xu X D. (1999). Progress in drought research in North China. Meteorological Press.

[10] Ma Z G, H J, et al. (2003). The evolution of extreme wet and dry events in modern North China. Acta Geographica Sinica, 58(01), 69-74.

[11] Yang S. (2017). Temporal and Spatial Distribution Characteristics and Circulation Analysis of Summer Drought and Flood in North China. Modern Agricultural Science and Technology, No.710(24), 181-185.

[12] Yang W, Li D L. (2008). Characteristics of arid climate zones and their precipitation changes in China. Arid Meteorology, 26(02), 17-24.

[13] Lu H J, Mo X G, et al. (2012). Temporal and spatial variation characteristics of meteorological drought in the North China Plain from 1960 to 2009. Journal of Natural Disasters (06), 072-82.

[14] Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. Journal of climate, 23(07), 1696-1718.

[15] Zhang Y J, Wang C Y, et al. (2015). Analysis of the spatial and temporal distribution characteristics of drought in winter wheat area of North China based on spei index. Acta Ecologica Sinica, 35(21), 7097-7107.

[16] Li Y P, Chen C C, et al. (2014). Analysis of drought disaster characteristics in Beijing in the Ming Dynasty based on eemd. China Desert, 34(03), 835-840.

[17] Hu Y. (2017). Temporal and spatial variation characteristics of drought information in the arid
zone of central Ningxia based on multi-source data.

[18] Ma Z G, Fu Y B. (2006). Basic facts of aridification in northern China from 1951 to 2004. Science Bulletin, 51(20), 2429-2439.

[19] McKee, T. B, Doesken, N. J., & Kleist, J. (1993, January). The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179-183). Boston, MA: American Meteorological Society.

[20] Wang L, Chen W. (2012). Multi-time scale evolution characteristics of drought in Southwest China in the past 100 years. Progress in Meteorological Science and Technology, 02(4), 21-26.

[21] Rong Y S, Duan L, et al. (2008). Diagnostic analysis of persistent arid climate in North China from 1997 to 2002. Arid area research (06), 842-850.

[22] Wu Z, Huang N. E. (2009). Ensemble empirical mode decomposition: a noise-assisted data analysis method. Advances in adaptive data analysis, 1(01), 1-41.