

Spatial characteristics analysis of drought disasters in North China during the Ming and Qing Dynasties

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Abstract. The grade sequence of drought disasters at 21 sites in the Ming and Qing dynasties (1470–1912) in North China is studied herein. Two aspects are explored to study the spatial distribution and characteristics of drought disasters in North China. The reconstruction of the sequence of drought disasters in North China during the Ming and Qing dynasties is based on the Empirical Orthogonal Function (EOF) and Rotated Empiric Orthogonal Function (REOF). The drought disaster has been divided into several space modes and several sensitive areas. This provides an important basis for a better understanding of the spatial distribution of drought disasters in North China during historical periods. The results show that the frequency of droughts is high in the northern area and low in the southern area of North China. The frequency of the drought intensity is high in Southeast China and low in West China. North China can be divided into six sensitive regions: middle–east, western, southern, eastern, northeastern, and northwestern North China.

1. Introduction

The regional drought problem is becoming increasingly serious because of global warming. Yet, North China belongs to an arid and semi-arid region. The drought is more notable in North China, especially in recent decades, and has attracted extensive attention from experts and scholars. The "China Science and Technology of the Blue Book No. 5" has classified the drought as main climate disaster of China. The North China drought frequency degree is the highest in the whole country (Li J. et al. 2013). In recent years, the shortage of water in arid and semi-arid regions became very serious due to the persisting drought. Geographically, North China presents a significant difference with respect to meteorology. The integrity of the available data is analyzed in this paper to study regional units. Considering the location of North China, research purpose, and administrative boundaries as main criteria for the classification, we selected the Hebei, Shanxi, Shandong, Henan provinces, and Beijing and Tianjin as study area. The four provinces and two municipalities were used to extend the research and discussion. The study region is located in the area between 31°N–43°N and 110°E–123°E. It is important to study the characteristic change of the drought region in a historical period to understand future occurrences of drought disasters in the region and prevent and control current droughts (Huang Q. et al. 2009).

Various scholars have conducted research on drought disasters in North China. Zhou L. (2009) analyzed the interannual summer variation of rainfall using modern platform precipitation data and explained the relation between the precipitation in North China and Northwest China and the Middle Yangtze River region. Ma Z. (2007) analyzed the characteristics of dry and wet change in North China

from 1951 to 2005. He identified that nearly 55 years experienced wet to dry processes, in this transition was found in 20th century around and after 1970, and explored the relationship between the change over the years and the Pacific Decadal Oscillation Index (PDOI). Rong Y. et al. (2008) used statistics on the distribution rate of droughts from 1997 to 2002 and found that the persistent drought in North China is the result of the interaction between the sub-members of the scale circulation system in the Eurasian region. Li Q. et al. (2002) proposed a new calculation model scheme for the dry and wet index, analyzed the characteristics of the linear index variation of the drought in North China in the last half century, indicated a very intense change in the drought potential in North China, and used singular spectrum analysis to test the periodicity of the time series. Zhou D. et al. (2014) used the standardized precipitation index of evapotranspiration and analyzed the spatiotemporal distribution of the drought intensity in North China. Gao C. et al. (2013) identified the collation and analyzed the history of the Ming Fen River Basin drought using the county as a drought grade division standard. They used the linear trend estimation method to estimate the spatiotemporal changes of the drought of the Fen River Basin, two aspects of frequency and intensity to study the spatial distribution of the drought, and the t-test to determine if there is a change in the drought dynamics depending on time. However, although there is a large amount of research and measuring data on droughts in North China are for nearly a half century, there is less research on periodic drought disasters in North China and the studies focused on the time evolution of drought and floods. Only a few studies use the spatial distribution of drought disasters in climate statistical methods to analyze the spatial characteristics of drought disasters. This paper focuses on previous studies with respect to the time and evolution of drought disasters, historical records of drought disasters in North China during the Ming and Qing dynasties, and the spatial distribution of drought disasters in North China during the historic period.

2. Data and Methods

The important resources in this paper are mainly obtained from "The chronology of drought in North China in the recent five hundred years" (Zhang W., 2009; referred to as "Drought chronology"), "North China, northeast drought and flood historical data of the recent five hundred years" (Central Weather Bureau of North China, 1975; referred to as "Historical drought and flood data"), and the collection compiled by Zhang D. (2004) based on the "China meteorological records collections of three thousand years" (referred to as "General collection"). The historical data in this paper covers a total of 443 years, from 1470 to 1912, from the mid-Ming Dynasty to the late Qing Dynasty. The historical data from 1470 (early Ming Dynasty) was relatively scattered, which hindered the separation of serial data; hence, it could not be put in sequence. To make study on "Drought chronology" and "Historical drought and flood data" in the current administrative division as unit, 21 representative stations have been selected: Beijing–Tianjin–Hebei Province (Tangshan, Cangzhou, Baoding, Shijiazhuang, and Handan), Shandong Province (Jinan, Dezhou, Yantai, Heze, and Linyi), Henan Province (Anyang, Zhengzhou, Luoyang, Nanyang, and Xinyang), and Shanxi Province (Datong, Taiyuan, Linfen, and Changzhi). In contrast to the "General collection" and "Historical drought and flood data", one year of disaster records is missing in the "Drought Chronology". If the data were not recorded in all three reports, the drought was considered as not having occurred in the region. This paper used the data with respect to three sources of information to determine the rank sequence of the droughts at 21 sites during 443 years in the Ming and Qing dynasties from 1470 to 1912. The criteria for the classification of the disaster grades are listed

in Table 1. Level 1 is set as “general disaster”, level 2 represents “high drought”, level 3 reflects “heavy drought”, and “no drought” is set as level 0.

Table 1. Repartition of the standard grade classification of drought disasters.

| Description of historical data disaster | Drought disaster grade |
|--|------------------------|
| "Spring drought", "summer drought", "winter and spring without rain" | 1 |
| "Summer and autumn high drought", "spring and summer high drought," "since the last year's winter solstice high drought, this year it started raining in July", for several months without rain as dry grain | 2 |
| "Scene of utter desolation," "people's food", "even the drought years, the particular age" etc. | 3 |

The Empirical Orthogonal Function (EOF; Wu H., 2005), also known as principal Component Analysis (PCA), is used to structurally characterize the matrix data. It is also a main method used to extract data features. Pearson (1902) first proposed this method. In the 20th century (1950), Lorenz applied this method to atmospheric science (Han R. et al 2014). It has been widely used thereafter. It can process irregular meteorological elements of the field and decomposed them into time coefficient and space vector features. The spatial modes must reflect the spatial distribution of the meteorological elements to a certain degree. The transformation of the Rotated Empirical Orthogonal Function (REOF) is based on the EOF decomposition, orthogonal rotation of the original matrix (maximum variance rotation), and high load vectors concentrated in a few variables. The remaining region is close to 0, so that the characteristics of the field in the rotation are more stable over time, the spatial distribution structure is clearer, and the local features of the abnormal distribution of the elements are more prominent (Chen Y. et al. 2010). Domestic and foreign scholars have successfully applied the EOF and REOF methods to climatic zoning and obtained good results (Han R. et al 2014; Liu L. et al. 2014; Wang Y. et al. 2014; Liu H. et al. 2014).

3. Results and Analysis

3.1 Drought frequency and spatial distribution intensity

Statistics were obtained for 21 sites in the Ming and Qing dynasties in North China and 443 years of droughts. A map showing the drought disaster frequency distribution has been created (Fig. 1A). The round size represents the frequency and occurrence of drought disasters. The greater the radius is, the higher is the frequency of the droughts. The drought frequency of the 21 study sites is the highest in Linfen (up to 181). This means 181 drought disasters occurred during the period of 443 years. The occurrence rate is 40.9% (1 drought every 2.4 years). The drought frequency is the smallest in Nanyang, where 69 droughts were recorded, accounting for 15.6%; a drought disaster occurred every 6.4 years. In

addition, the rest of the droughts occurred more than 100 times when removing the Nanyang data. Therefore, the drought disasters are more frequent in North China and the droughts are more serious.

Because the frequency of drought disasters only reflects the regional data and not the drought intensity and size, the weighted average method was used in this paper to calculate the drought intensity and the average grade of each site based on the following equation (Gao C. et al. 2013):

$$I = (a + 2b + 3c) / (a + b + c), \quad (1)$$

where I represents the drought intensity and average grade for each county and a , b , and c are 1, 2, and 3 occurrences of drought, respectively.

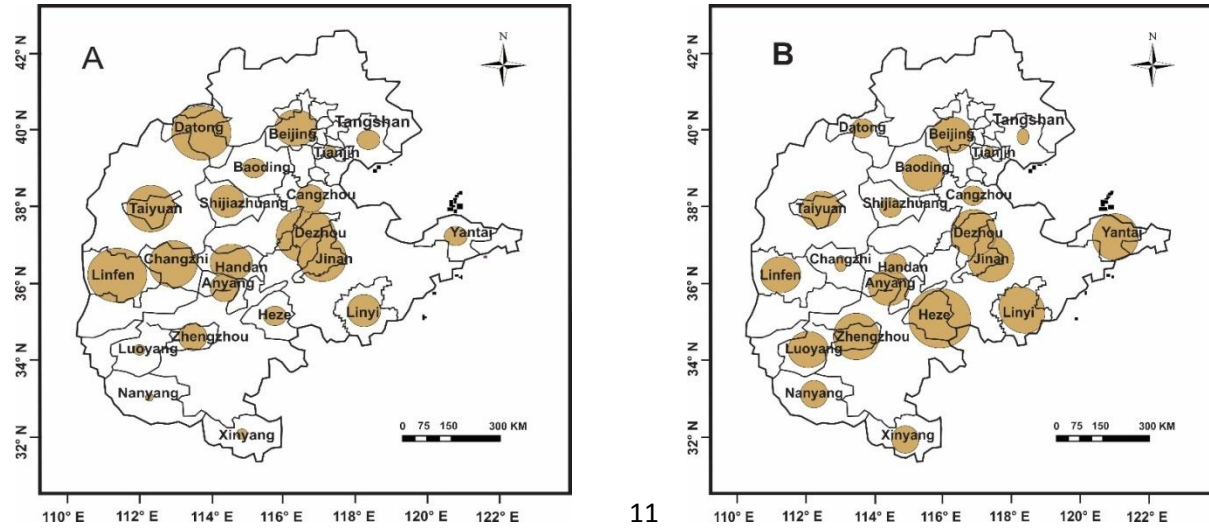


Figure 1. Frequency of drought disasters in North China during the Ming and Qing dynasties (1470–1912). (A) Frequency distribution map, (B) Intensity distribution map.

Figure 1B shows the distribution of the drought intensity at 21 sites in North China during the Ming and Qing dynasties. The circles represent the intensity of the drought disasters. The greater the radius of the circle is, the greater is the drought intensity. The figure shows the highest drought disaster intensities in Eastern North China in the Shandong Dezhou, Jinan, Heze, Linyi, and Yantai districts. In addition, the drought intensity in North China is the lowest in the northeast of Tianjin and Tangshan and in Hebei, Handan, Cangzhou, and Shijiazhuang. There is no correlation between the drought disaster degree and intensity. The frequency of the drought disasters is higher in the Shanxi District; however, the intensity is relatively low, which means that the drought is not serious, although there is more drought in the area. The frequency of the drought disasters is smaller in the Shandong Province (Heze, Yantai, and Linyi), but the intensity of the drought disasters is larger. This means less but more serious droughts occurred in these areas. In addition, not only the frequency of drought disasters is high in the Shandong Province (e.g., Dezhou, Jinan), but also the drought disaster intensity is high, indicating that the region is not only prone to drought disasters but also more serious ones.

An L. et al. (2014) found that in the past 50 years of drought disasters in North China, the zone of high frequency is mainly located in middle–southern North China and the frequency center appears in the southeast of Hebei. A large value of cumulative intensity value was observed in middle–southern North China, including Hebei, Henan and Shandong. The results of this paper indicate different frequency and intensity distributions for the droughts in North China during the historical periods. The center of frequency occurred moving east and the center of intensity was observed moving north. Figure 1 shows the drought intensity is relatively high in Hebei, Henan, and Shandong, the three provinces of the border area near Heze, Jinan, and other regions. The study of An L. et al. (2014) has certain similarities, indicating that although there has been a historical drought in recent years, the drought differs from other historical droughts. However, there is a general consistency in the variation. The study of drought disasters in the historic period is therefore still of great significance to current and future drought research.

Table 2. Variance contribution rate and cumulative variance contribution rate of EOF and REOF of the first 14 drought disasters in North China during the Ming and Qing dynasties.

| Model number | EOF | | REOF | |
|--------------|-------------------------------|--|-------------------------------|--|
| | Variance contribution rate /% | Cumulative variance contribution rate /% | Variance contribution rate /% | Cumulative variance contribution rate /% |
| 1 | 29.37 | 29.37 | 9.93 | 9.93 |
| 2 | 7.91 | 37.28 | 4.70 | 14.63 |
| 3 | 7.57 | 44.85 | 7.50 | 22.13 |
| 4 | 6.14 | 50.99 | 5.84 | 27.97 |
| 5 | 4.75 | 55.74 | 10.57 | 38.54 |
| 6 | 4.26 | 60.00 | 6.50 | 45.04 |
| 7 | 3.99 | 63.99 | 4.88 | 49.92 |
| 8 | 3.59 | 67.58 | 5.54 | 55.46 |
| 9 | 3.46 | 71.04 | 5.02 | 60.48 |
| 10 | 3.41 | 74.45 | 5.00 | 65.48 |
| 11 | 3.05 | 77.50 | 4.68 | 70.16 |
| 12 | 2.97 | 80.47 | 5.39 | 75.55 |
| 13 | 2.74 | 83.21 | 4.95 | 80.50 |
| 14 | 2.69 | 85.90 | 5.40 | 85.90 |

3.2 Spatial modal distribution of drought characteristics

The EOF and REOF are especially useful for the extraction of meteorological data; they can reflect the spatial distribution of meteorological data (Li Y., et al. 2000). Therefore, EOF and REOF are used in this paper to explore the degree of spatiotemporal evolution of the drought disasters during the Ming and

Qing dynasties in North China. We focus on the analysis of the spatial distribution and provide the distribution level of drought disasters in North China and a basic partition prediction.

The EOF method is used for the classification of the drought disaster rate to resolve the standard anomalies of 21 sites in North China during 443 years in the Ming and Qing dynasties and obtain space load vectors. The first “i” vector features for the “x” field contribution rate are:

$$\rho_i = \lambda_i / \sum_{i=1}^m \lambda_i \quad (2)$$

The “p” vector features for the “x” field cumulative contribution rate are:

$$P_i = \sum_{i=1}^p \lambda_i / \sum_{i=1}^m \lambda_i, \quad (3)$$

where “m” represents the number of sites.

The cumulative variance of contribution rate of the 14 droughts reached 85%. The convergence speed of the load vector is slow because of the extension of the North China region, complex topography, differences of drought disaster spatial distributions, and a significantly larger variability, but each load vector still retains the information about the main characteristics of the North China regional drought disasters. North et al. (1982) succeeded to calculate the error range of the features for a significant test. The error range of the characteristic value λ_j is:

$$e_j = \lambda_j \left(\frac{2}{n} \right)^{\frac{1}{2}}, \quad (4)$$

where “n” is the sample size. When the adjacent value is $\lambda_j + 1$, then:

$$\lambda_j - \lambda_{j+1} \geq e_j \quad (5)$$

It is considered that these two characteristic values corresponding to the Empirical Orthogonal Function are valuable signals. In the first five modes through the test, the cumulative variance contribution rate was 55.74% (Table 2). Hence this article analyzes the given five modes of spatial distribution. The first model of the maximum contribution rate of the variance is the highest and reflects the spatial distribution of the droughts best.

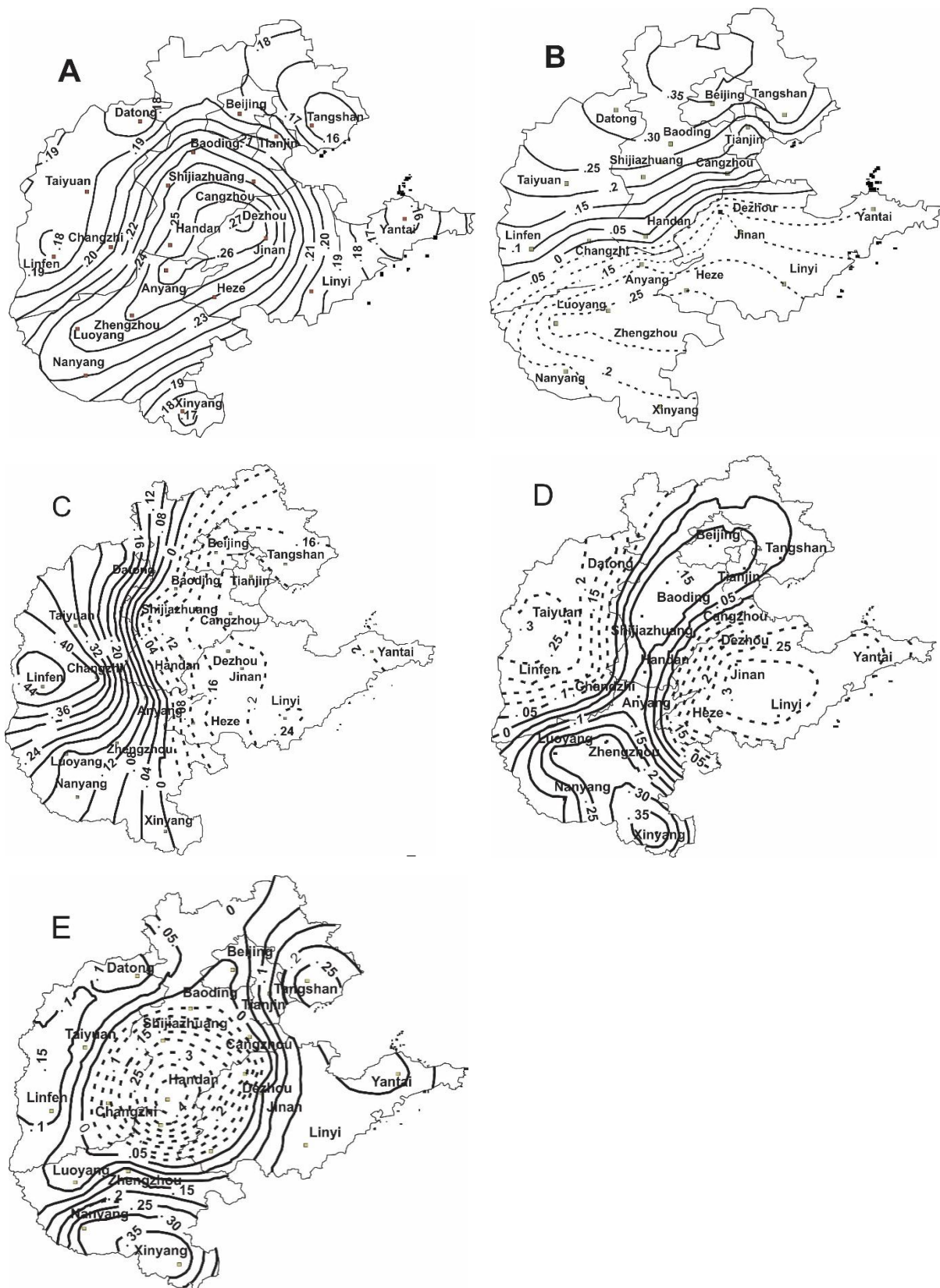


Figure 2. The EOF decomposition of the drought grade sequence in North China during the Ming and Qing dynasties (A. first model; B. second model; C. third model; D. fourth model; and E. fifth model).

The spatial distribution of the first model shows that the drought disasters in North China during the Ming and Qing dynasties are consistent in the whole region (Fig. 2A). This means that the changes of the droughts in the region are basically identical, showing more or less slight characteristics. The large load value area is located in Dezhou in the Shandong Province, which means that this region has the most variable drought disaster rate. The variance contribution of the first model is 29.37%, reflecting a more important contribution rate of drought disasters in North China. The changes of the time series and grade sequence are almost identical in North China. The correlation coefficient is 0.904 and the significance test value is 0.01. This shows that the first model reflects the distribution of drought disasters in North China well. The second model is a spatial distribution field model (Fig. 2B). The first and second feature fields differ significantly. The N-S spatial structural features are opposite. The drought is very serious in the southern part; the drought is rather slight in the northern part. The drought in the southern part is relatively slight, while the drought in the northern part is more severe. The zero line is located between 36°N–38°N and crosses the Changzhi, Handan, and Dezhou districts. The center of the maximum value is located in the center of the northern part of the Beijing District in North China. The center of the maximum negative value is located in the south of the Henan Province in the Zhengzhou and Luoyang districts. The third spatial distribution field model (Fig. 2C) shows that the drought spatial structure features of North China are reversed during the Ming and Qing dynasties. The zero line is located between 114°E–115°E, connecting the Xinyang and Handan districts. Its maximum center value is located in the Shanxi and Linfen districts in the western region of North China; the maximum negative center is located in the eastern Shandong Linyi districts in northeastern North China. The fourth spatial distribution field model (Fig. 2D) indicates that the spatial structure drought features are reversed in northern/south-southeast North China during the Ming and Qing dynasties. There are two positive and two negative centers. The center of the maximum of the two positive values in northern North China is in Hebei and Shijiazhuang, Baoding, and the southern part of the Henan and Xinyang districts. The two maximum negative centers are in the Shanxi and Taiyuan districts in the western part of North China as well as in Shandong, Jinan, and Linfen in the eastern part. The fifth model spatial distribution field (Fig. 2E) implies opposite characteristics for the drought in the northcentral region compared with the surrounding area, the middle – around reverse type. The center of the maximum negative value is located in Hebei and Handan in the northcentral region. The center of the maximum value is located in the Tangshan, Hebei, Shandong Laiyang, Shanxi Linfen, Xinyang, and Henan districts.

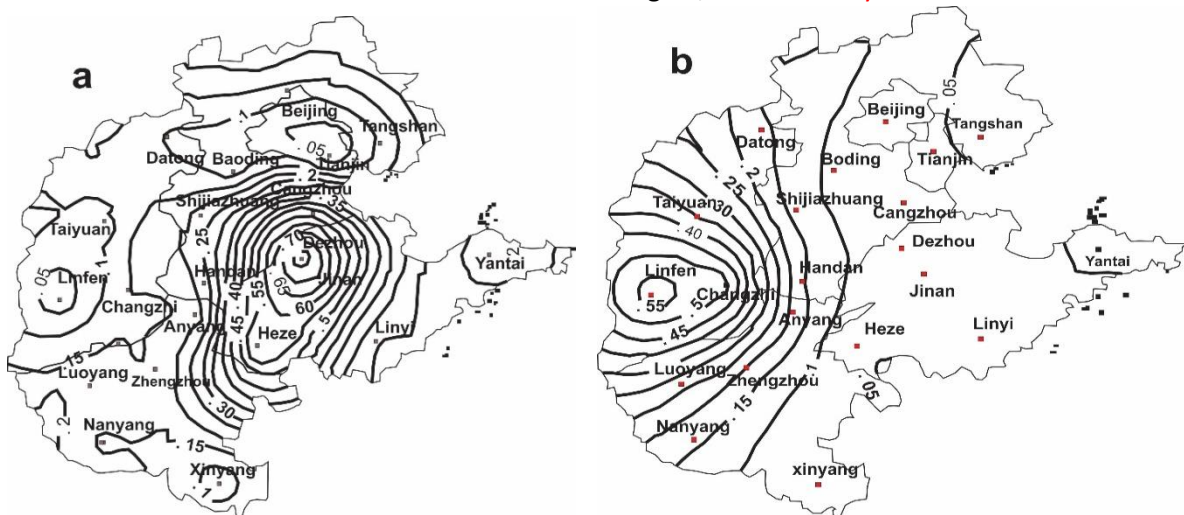
3.3 Space sensitive areas

Because of the spatiotemporal changes of drought disasters in North China during the Ming and Qing dynasties, the model composition of the EOF variance contribution rate is low, the convergence speed is low, and abnormal subregional features are complex. To further discuss regional features, this section will be based on the EOF decomposition of the REOF analysis.

There are three methods to determine the value “p” of EOF (Wei F., 1999). The cumulative variance contribution rate of 85% is used in this paper as the standard to determine “p”. In this paper, the first 14 features of the vector rotation are used. The characteristics of the vector variance distribution after rotation are relatively uniform (Table 2). According to the principle of rotation of factor analysis, the main factor of the geographical distribution of high loads is an important basis for the partition. Using

the significance test, the results show that the first six modes have passed significant test. The distribution of the first six main factors is shown in Figure 3.

The variance contribution rate of the 1st rotation vector (RLV1) is 9.93%. Large values are mainly observed in the eastern part of North China; the maximum value of the rotational load vector is observed in Shandong and Dezhou in eastern North China. This model is called eastern North China model (Fig. 3a). The variance contribution rate of the 2nd rotation vector (RLV2) is 4.70%. Large values are mainly observed in the western part of North China; the maximum rotational load vector is located in Shanxi and Linfen in the western region of North China. This model is called western North China model (Fig. 3b). The variance contribution rate of the 3rd rotation vector (RLV3) is 7.50%. Large values are mainly observed in southern North China; the center of the maximum rotational load vector is located in the Henan and Xinyang areas in southern North China. This model is called southern North China model (Fig. 3c). The variance contribution rate of the 4th rotation vector (RLV4) is 5.84%, with large values in the eastern part of North China and the center of the maximum rotational load vector in Shandong and Laiyang in eastern North China. This model is called eastern North China model (Fig. 3d). Shandong is located close to the Bohai and Yellow seas in the Yellow River Delta. It is characterized by abundant rainfall and less drought areas. The variance contribution rate of the 5th rotation vector (RLV5) is 10.57%, with large values in northeastern North China and the center of the maximum rotational load vector in Tangshan of northeastern North China. This model is called the northeastern North China model (Fig. 3e). The variance contribution rate of the 6th rotation vector (RLV6) is 6.50%, with large values in the northern part of North China and the center of the maximum rotational load vector in Shanxi and Datong in northwestern North China. This is called the northwestern North China model (Fig. 3.f). This area comprises more mountains. The Great Wall is located in the north, which is a dry area and the drought is more serious. The drought in North China can therefore be divided into six regions: middle–east North China, western North China, southern North China, eastern North China, northeastern North China, and northwestern North China. Because the REOF method can reflect the local characteristics of droughts in North China well, the absolute value of the high load area in the space of each model is higher. The regional characteristics of North China are intuitively reflected. Figure 4 is a schematic diagram of the six modes of REOF decomposition of the drought in North China. Northeastern North China is the most sensitive region, followed by middle–east North China.



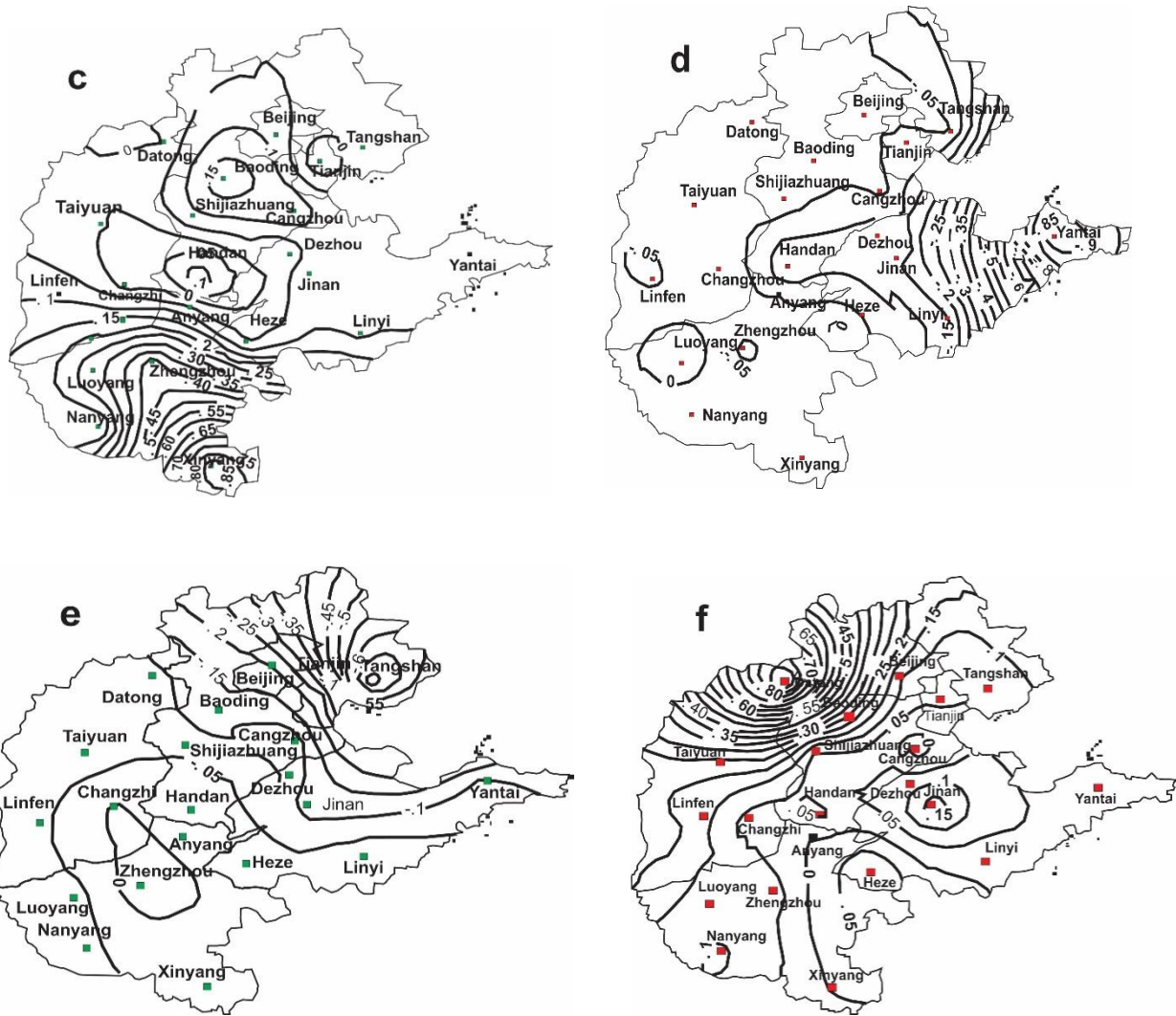


Figure 3. REOF drought rank sequence decomposition of North China during the Ming and Qing dynasties (a. The 1st rotation vector; b. the 2nd rotation vector; c. the 3rd rotation vector; d. the 4th rotation vector; e. the 5th rotation vector; and f. the 6th rotation vector).

Rong Y. (2004) considered the climate of North China based on different angular divisions and studied the precipitation from 1957 to 2002. He used a similar method to determine the rainfall in North China and divided it into five regions, northern North China, northeastern North China, middle North China, southern North China, and eastern North China (Fig. 5). Because of the differences of the study area in North China, Rong Y. (2004) removed the northern North China region and discussed the remaining four regions (northeastern North China, middle North China, southern North China, and eastern North China). In our article, the middle North China is divided into middle-east North China, western North China, and northwestern North China.

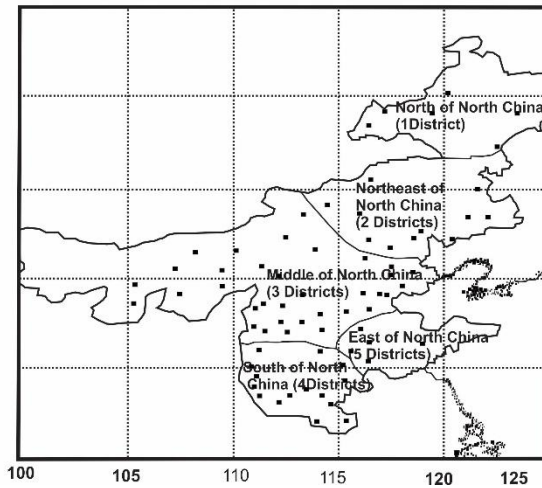
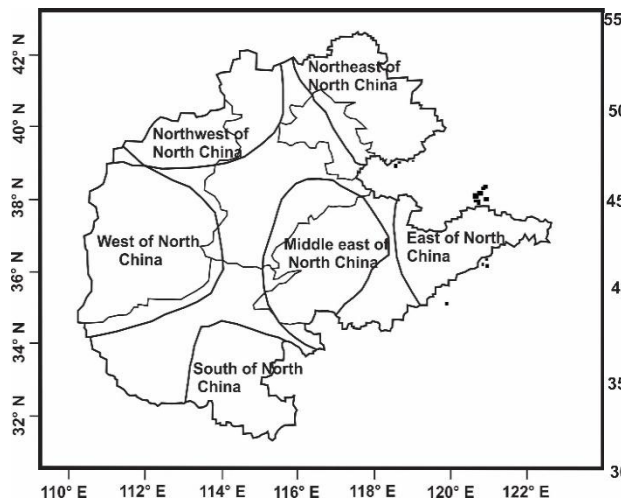


Figure 4. Schematic partition of the REOF analysis of droughts in the Ming and Qing dynasties in North China.

Figure 5. Partitions of five regions of rainfall in North China according to Rong Y. (2004).

4. Conclusions

Drought and floods are different. They do not occur suddenly but involve formation, occurrence, and development stages. The cause of drought is very complex including the existing precipitation, influence of geographical conditions, and other natural factors and the impact of economic, social, and human factors. North China is located in the humid and semi-humid climate zone. The annual average temperature differs significantly, the precipitation is concentrated, and the variation rate is high. The evaporation is fast and the precipitation is little. The global climate change has a big impact on North China. The precipitation in North China mainly depends on the precipitation of water vapor from the East Monsoon carried by the Pacific Ocean. The lack of water vapor transport and atmospheric circulation anomalies in North China induce drought. In addition, the solar activity and El Niño Southern Oscillation (ENSO) also have an effect on the drought in North China. The ENSO effect in different positions of development in China on drought and floods varies. When the ENSO is strong, drought emerges in North China; when the ENSO is weak, North China receives more precipitation (Ye D. et al. 1996).

Drought disasters occurred more frequently in North China during the Ming and Qing dynasties and the occurrence degree was more serious. The most frequent occurrence of drought disasters in western North China were observed in the Datong, Taiyuan, Linfen, and Changzhi districts of the Shanxi Province and in eastern North China in the Dezhou and Jinan districts of the Shandong Province. The smallest frequency of drought disaster occurrences was observed in southern North China in the Henan, Luoyang, and Xinyang districts. In general, the frequency of drought disasters in North China is high in the northern part and low the southern part. The highest intensity of drought disasters in North China is in the eastern part in the Dezhou, Jinan, Heze, Linyi, and Laiyang districts of the Shandong Province. The drought intensity is the lowest in the northeastern part of North China in Tianjin and in the middle part of the Hebei province in the Handan, Cangzhou, and Shijiazhuang districts. In general, the drought

intensity distribution is high in the southeastern part of North China and low in the northwestern part. The degree of drought potential and the drought disaster intensity are not consistent.

The drought disasters in North China are mainly consistent in the whole region; the change of drought disasters is basically the same. The characteristics show that the consistency of the features is high or low. Other typical fields mainly display local differences of the whole region such as South–North reversal, East–West reversal, Northsouth–Eastwest reversal, the middle–around reversal. North China can be divided into six spatial sensitive regions: middle–east, western, southern, eastern, northeastern, and northwestern North China. The northeastern and middle–eastern parts of North China are the areas most sensitive to drought disasters.

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Author Contributions

Shuoben Bi, Changchun Chen, and Yanping Li conceived and designed the experiments; Yanping Li and Weiting Wu performed the experiments; Shuoben Bi, Yanping Li, and Weiting Wu wrote the Chinese paper; and Shengjie Bi and Athanase Nkuzimana translated the paper.

Conflicts of Interest

The authors declare that they do not have any commercial or associative interest that represents a conflict of interest in connection with the paper they submitted.

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