Characteristics of spatio-temporal distribution of frost/snow disasters in North China during 1644–1911

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\section*{ABSTRACT}
This paper presents an analysis based on the use of historical data of frost/snow disasters in North China in combination with ArcGIS and other technical applications. Specifically, the frequency and intensity of frost/snow disasters in North China during the study period, 1644–1911 from the perspective of time and space, were analyzed. We applied the moving average, polynomial fitting, and CEEMD methods. The study yielded the following results: Frost/snow disasters occurred 1982 times during this period. Season wise classification revealed that fall recorded the highest frequency. Based on their annual frequency, the study period was divided into four stages. The CEEMD decomposition of annual frequency sequence revealed a cycle of 2.8 years and 5.3 years on the inter-annual time scale, and 119.4 years on the century-scale. Furthermore, an analysis of spatial distribution of the disasters depicted an uneven frequency distribution; however, an absolute degree of spatial consistency was observed between their grade and the frequency distribution. In Hebei and Henan areas, disasters were lower in frequency and were mainly classified under as mild or moderate grades; however, in Shanxi area, disasters were higher in frequency and corresponded mainly to the severe grade.

\section*{1. Introduction}
In recent years, climate change has attracted widespread attention, globally. The study of historical climate change has proven to be useful in creating a better understanding of climate change related events in future. Evidence of change based on pre-historic events, scientific data, environmental, socio-economic and political setting settings requires a historical approach to understand and model prevailing (present)

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conditions and the future, respectively. China has a long history that dates back to ancient times. It possesses a vast collection of historical records, which is unparalleled in the world. The data contains large amount of weather information that could potentially serve as the main resource for rebuilding the historical climate change database (Zheng et al. 2007). Considering the wide range of historical documents and the complexity of their contents, the task of extracting useful information from the massive data and scientifically using it for carrying out the reconstruction work of the cold/warm change in the historical periods, becomes highly significant.

Early researchers have conducted studies on some key themes related to frost/snow disasters (Choubin et al. 2019a, 2020; Mosavi et al. 2020). Among these entail a study conducted by Choubin et al. (2019a). In their study entitled: ‘Snow avalanche hazard prediction using machine learning methods’, they highlighted snow avalanche among the major destructive natural hazards in mountainous regions. Snow avalanche modelling in their study was carried out based on incident locations, meteorological factors and terrain characteristics which the current study partly adapts to a large extent to suit its scope. They reported high snow avalanche hazard zone was mostly near the streams and aligned with hillsides around the water pathways. Similarly, Choubin et al. (2019b) in a study in Haraz watershed, Iran, delved into the dynamics and variations of snow cover (SC) particularly in relief zones. They further assessed the dynamics of SC through investigating the monthly-normalized difference snow index (NDSI) during 2001 to 2018. Their results indicated a significant decline in SC is highest on the slope aspects of southeast (66.81%), south (62.35%), and southwest (62.35%). Thus, snowline elevation SLE increases faster on these slope aspects. Variations of SC frequency showed that 32% of the study area has a moderate to very high snow existence probability. According to Mosavi et al. (2020), snow avalanche has devastating impacts on geomorphic processes and socio-economic activities. They introduced machine learning models to ascertain snow avalanche susceptibility mapping at Karaj watershed in Iran. They reported high susceptibility avalanche regions were situated in the north and northeastern parts of the study area which had high elevation with more precipitation and lower temperatures.

Quite often, low temperatures lead to climate disasters—frost, snow, and the likes, resulting in undesirable consequences on the growth of crops, productivity of people and life in general (Li et al. 2005). Local as well as foreign scholars have conducted studies on the frost/snow disasters for several years now. Among the foreign scholars, Zinoni et al. (2002) used the frost observation data from 161 meteorological stations of Emilia-Romagna area for the year 1986 to design and synthesize the frost risk index; further, the findings were combined with the digital topographic map to create the frost risk map for the area. Tachiiri et al. (2008) studied the risk of snowstorm in Mongolia by means of an analysis of the vegetation index and snow weight index; they analyzed the mechanism of disaster-forming environment. Tolvanen (1997) studied the impact of frost disaster on soil and cranberry crops. Van Es et al. (1998) simulated the soil freezing at several sites in the northeastern part of the United States based on a 40-day climate and soil data; there was reference to the agricultural activities during the frost stage.

In recent years, studies related to snow and freezing disasters have gained tremendous weight in China due to its devastating risks and damages to human life and
properties, economy, society, resources, and the environment at large. The frequent catastrophic disasters have caused great losses of human lives and properties. High exposure industries are most vulnerable to climate disasters, including agriculture, transportation, construction, tourism, water conservancy, mining, power supply, among others. This is particularly true for those regions with rapid economic development and urbanization. In China, agriculture plays a critical role in the economic sector of the country. Snow and freezing disasters have severe consequences on crop production in spring and winter (Gao 2016).

There are many researches on frost/snow disasters in North China, but mainly on Shanxi Province and Hebei Province, with only one case in Henan Province.

Meng et al. (2012a) analyzed the distribution characteristics of Shanxi frost disaster over the last 100 years. He reported that frost disasters in Shanxi had a variation period of 2–3 years, 5–8 years, and 25–35 years, respectively for the three grades. Based on the collection and statistical analysis of historical documents of the Ming Dynasty in Shanxi Province, Meng et al. (2012b) study the level, stage, cycle and causes of frost, snow and low temperature disasters in the area. Based on historical documents from 1368 to 1948 in Shanxi Province, Meng and Liu (2012) study the grade, stage, cycle and causes of frost/snow disasters in the area. It was pointed out that the main cause of frost/snow disaster in Shanxi was the sudden drop of temperature below 0°C, caused by snowfall or cold current. Based on historical documents of Qing Dynasty in Shanxi Province, Meng et al. (2012c) studied the level, cycle and causes of frost and snow disaster in the area.

By collecting the historical literature on the occurrence of frost, snow and low temperature disasters in Hebei during the Ming Dynasty, coupled with using the methods of mathematical analysis, cumulative anomaly and wavelet analysis, Hao et al. (2017) analyzed the occurrence frequency, temporal and spatial characteristics, periodic law of frost, snow and low temperature disasters. The study revealed frost, snow and low temperature disasters have obvious spatial differences, and the spatial distribution characteristics of frost, snow and low temperature disasters in Hebei during the Ming Dynasty tend to be consistent with the activity path of winter monsoon. By combing and analyzing the geographical and geomorphological situation of Hebei region, the classification of frost/snow disasters, the review of major cold weather events in Hebei in Qing Dynasty, the temporal and spatial variation characteristics of frost/snow disasters, and the causes of frost/snow low temperature disasters, Zhou and Meng (2017) concluded that Hebei was a province susceptible to frequent frost/snow low temperature disasters during the Qing Dynasty.

Zhang et al. (2009) worked on the EOF (Empirical Orthogonal Function) analysis and wavelet analysis of frost disasters and interestingly, discovered frost damage. They studied the spatial and temporal distribution, along with its resultant changes in the Henan region over the last 50 years in the 20th century.

There are also some researches on frost/snow disasters in China. The main research results are briefly introduced as follows.

Based on the collection and wavelet analysis of historical documents of Qing Dynasty in Guanzhong Plain, Zhao et al. (2012a) studied the level, cycle and causes of frost/snow disasters in Qing Dynasty, and restore the minimum temperature when
the frost/snow disasters occurred during the Qing Dynasty. Based on the historical documents of the Ming Dynasty in Guanzhong Plain, Zhao et al. (2012b) studied the level, stage and occurrence cycle of frost/snow disasters during the Ming Dynasty.

During 1644–1911, when the Ming and Qing Dynasties ruled in China, several cold climate phases were recorded. There are a few studies conducted on the low temperature disasters during the reign of the Qing Dynasty. Xing and Zhao (2012) gave a historical description of the southern Shaanxi frost disaster during the Qing Dynasty. In the study, the frost disasters were divided into three levels—mild, moderate, and severe. The frequency of occurrences showed a variation period of 16–18 years, 7–8 years, and 46 years, respectively.

Luo et al. (2016) focused on the Erdos region during the Qing Dynasty. He used the literature and applied statistical analysis, specifically the least squares and wavelet analysis methods. The variation periods of the frost disaster cycle in the study area were 40–45 years which marks a lengthy period, 16–18 years and 11–15 years medium period, and 5–8 years for the short period.

Qin et al. (2008) used the objective analysis of grid data related to low temperature, rain, snowy weather, and other meteorological elements for the comparative analysis for the Guangxi region. The results showed a low-temperature, cold damage process of the internal causes.

Annual cold wave events in each station were calculated based on daily air-temperature data of 86 weather stations in recent 52 years (1961–2012) in Guangdong Province, South China. The spatiotemporal characteristics of cold wave over Guangdong Province were thoroughly analyzed by wavelet transformation and other statistical analysis method (Liu et al. 2015).

Hu et al. (2018) creatively used the time-series data from 1 A.D. to 1910 A.D. to analyze the historical case with the Ordinary Least Square (OLS) method. Their study provided practical implications for policymakers and governments.

Frost/snow disasters do not only cause serious losses to crops, people’s lives, property and social economy, but also caused crises to food, transportation, water resources and energy security. As human beings are unable to control the occurrence of frost/snow disasters at present, it is of great practical significance to further study and master the law of frost/snow disasters, making rational use of climate resources, adjust agricultural layout, and avoid or reduce the losses caused by disasters (Meng and Liu 2012).

In order to explore the evolution of frost disasters on a long-term, this paper analyzes their frequency and strength in the study area (described in the next section) over the study period (1644–1911) in terms of time and space from the historical data. This analysis will not only help us in getting a better understanding of frost disasters in the historical period from both the spatial and temporal perspectives, it can also provide a technical basis for corresponding relief work. The present study draws on the tenets of Sustainable Development Goal (SDG) 13, which dwells on a collective and urgent action to combat climate change and its impacts. Basically, SDG 13 is linked to the other sixteen goals of the 2030 Agenda for sustainable development. Therefore, conducting regional and historical studies that establish logical conclusions at the local, regional, national, continental and global levels require proactive,
strategic and feasible mechanisms to tackle the complex and encompassing nature of climate change. Our findings would explicitly enrich basic datasets that inform the decisions of global communities, especially in humid/arid regions, coupled with driving country-level or continental studies to ascertain what is known and unknown, but important and needs to be studied.

The innovations of this paper are as follows: (1) In spring and autumn, it is most vulnerable to frost/snow disasters caused by cold air coming early or late. (2) The frequency of disasters in North China during 1644–1911 was periodic. (3) An absolute degree of consistency between the spatial distribution of frost/snow disaster grade and the frequency distribution. (4) The disaster grade in highland areas is significantly higher than that of the lowlands and plain areas, which is mainly due to the joint action of monsoon and topographic conditions.

2. Data and methodology

2.1. Overview of the study area

North China falls in the semi-arid and semi-humid monsoon climate zone (Figure 1). Since a large stretch of land exists between the north and south of the country, there
is an obvious climate difference (Rong 2004). Taking into account the availability of data, the integrity and consistency of the study area in context, the four cities and provinces in Beijing, Tianjin, Shandong, Shanxi, Henan and Hebei provinces are selected for the analysis. As shown in Figure 1, the study area is located between 31°N–43°N and 110°E–123°E. It is located westward to the Taihang Mountains and the mountainous areas of western Henan, eastward to the Yellow Sea and Bohai Sea, northward and near to the Inner Mongolia plateau region, and southward to the Huaihe River basin area.

### 2.2. Geomorphological and climatic features of North China

The land area of North China is dominated mostly by North China Plain and Shanxi Province. Shanxi Province is covered predominantly by mountains and hills, along with seven basins, the North China Plain is mainly low and flat, with most parts being less than 50 meters above sea level. Therefore, except for Shanxi Province, most of North China is covered by lowlands, lakes, and marshes. Generally, this area of China has a terraced terrain, which slopes from west to east, and most of it belongs to the huge depressions formed in the Cenozoic era.

With regard to the main climatic characteristics, the majority of North China Plain is situated in the north temperate zone and has a humid and semi-humid climate, with dry and cold winters, hot and rainy summers, as well as dry springs (i.e. little rain, strong evaporation, and heavy droughts). The average annual temperature and annual precipitation decrease from south to north with increasing latitude. By contrast, Shanxi Province is located in two climatic zones—the middle temperate zone and the warm temperate zone—and has a continental monsoon climate that can vary both latitudinally and vertically. A number of provinces are characterized by semi-arid climatic conditions with long and cold dry winters, hot and concentrated rainfall in summer, a variable climate and sandy winds in spring, and a short autumn with large temperature differences. Temperatures differ widely between different parts of the province, decreasing from south to north and from the flat rivers to the mountains. The frost-free period is long in the south while being short in the north and long in the flat rivers. However, in mountainous areas, they remain short.

Therefore, the study area has complex and diverse landforms, with plateaus, mountains, plains, basins, and lakes. Such complex topographic and geomorphological features and the latitudinal differences between the north and the south lead to a changeable climate in the area. Hence, although research on the spatial and temporal characteristics of frost and snow disasters in the study area is complex, the results have scientific significance and good application value.

### 2.3. Data sources

The historical documentary sources for this study are mainly from *General Collection of Three-Thousand-Year Meteorological Records of China* (Zhang 2004), edited by Zhang Deer (hereinafter referred to as *General Collection*), which recorded the
meteorology of China from 23rd century B.C. to 1911 A.D. Following a systematic review of documentary materials collected from many libraries across China, 7,335 historical documents with information about ancient climates were extracted, including 7,713 local chronicles and 28 biographies presenting history. In total, over 220,000 relevant records were collected, and the time, place, and origin of meteorological disaster events were examined in detail. Wherever same historical facts were encountered, the earliest record was taken with the exact source indicated.

The specific contents of this collection include (1) various weather and climate conditions, atmospheric physical phenomena, and meteorological text descriptions in Chinese history, such as drought, water, rain, snow, frost, freeze, warmth, wind, hail, thunder, haze, etc.; (2) descriptions of the occurrence time, place, scope, and extent of meteorological disasters, disaster relief efforts, among others; and (3) climate-related famines, agricultural abundances and failures, epidemics, pest and disease disasters and so on. General Collection is of high research value because it systematically outlines the meteorological history of China (Zhang 2005).

In addition to General Collection, we also consulted China Meteorological Disasters Canon (Beijing Volume (Xie 2005), Tianjin Volume (Wang 2008), Hebei Volume (Zhang 2008), Henan Volume (Pang 2005), Shandong Volume (Wang 2006), and Shanxi Volume (Liu 2005) and General Collection of Major Natural Disasters and Anomalies Chronology of Ancient China (Song 1992); certain local chronicles of the four provinces and two cities were added as supplements.

The maps and other spatial data were derived from the Qing Dynasty section of Historical Atlas of China, edited by Tan Qichang (Tan 1992). This atlas illustrates the boundaries of the various dynasties and regimes within China during the historical period, as well as the administrative divisions and various place names within the boundaries. It also depicts some major physical geographical elements, such as rivers, islands, mountains, and lakes.

2.4. Normalization of frost and snow disaster data

The historical sources in this paper are the compiled historical materials and the original local chronicles. The information collected from the compiled materials was derived from the original materials and comprised selective and incomplete historical information and their spatial scope. Given this, when screening the descriptions of frost and snow disaster records in the historical materials, we first compared the information collected from the compiled materials with the original local chronicles to check whether the collected records were complete and whether the descriptions were consistent. If a record was cited by multiple sets of materials, they were filtered and compared to other variables selected against the long-run. If different records recorded the same warm and cold processes in the same area, then either the more detailed one was selected or the merged set was taken. In cases where the contents of the records were inconsistent, the records were processed on the basis of the principle of ‘originality first, calibration first, value first, and cross-reference’ (Zhang et al. 1999) and on the reliability, accuracy, completeness, resolution, and relevance of the sources to ensure the accuracy of the screened record information.
After the screening, comparison, proofreading, and coding of the frost and snow disaster historical data, the Access Database of Qing Dynasty Frost and Snow Disasters in North China was finally built.

2.4.1. Logical structure of the frost and snow disaster attribute database

In this study, we collected the following attribute data of frost and snow disasters in North China during the Qing Dynasty: The Gregorian calendar year, sexagenary cycle (as known as Ganzhi), dynastic year, province, city/county, month/day, season, disaster type, disaster extent, meteorological disaster details, ancient source, page number, and frost and snow disaster level. These attribute data were summarized, organized, and coded for storage in the access database, and the original record database of frost and snow disasters was established through classification and coding. The logical structure of this database is shown in Table 1.

2.4.2. Quality control of frost and snow disaster data

Individual errors in the records were identified when coding the data. Records with errors and inherent ambiguities in the language were verified, revised, corrected, and then coded correctly. Records that could not be verified and corrected and were more doubtful were discarded to ensure the quality of the snow and frost disaster data.

In general, the coding of historical materials should be based on their characteristics, and the coding format should be simple, practical, and easy to understand.

| Field name                  | Type                   | Whether the value is null (Y) or not (N) | Field description                                                                 |
|-----------------------------|------------------------|-----------------------------------------|-----------------------------------------------------------------------------------|
| Serial number               | int                    | N                                       | Primary key                                                                        |
| Gregorian calendar year     | int                    | Y                                       | Time recorded in the meteorological records                                        |
| Sexagenary cycle            | nvarchar (255)         | Y                                       | Time recorded in the meteorological records                                        |
| Dynastic year               | nvarchar (255)         | Y                                       | Dynasty and year recorded in the meteorological records                             |
| Province                    | nvarchar (255)         | Y                                       | Provincial units recorded in the meteorological records                             |
| City/County                 | nvarchar (255)         | Y                                       | City or county unit recorded in the meteorological records                          |
| Month/Day                   | nvarchar (255)         | Y                                       | Specific month and day recorded in the meteorological records                      |
| Season                      | nvarchar (255)         | Y                                       | Seasons recorded in the meteorological records                                     |
| Disaster type               | nvarchar (255)         | Y                                       | Specific types of meteorological disasters recorded in the meteorological records   |
| Disaster extent             | nvarchar (255)         | Y                                       | Extent of the meteorological disaster damage and casualties recorded in the meteorological records |
| Meteorological disaster details | nvarchar (255)     | Y                                       | Detailed description of the meteorological disasters recorded in the meteorological records |
| Ancient sources             | nvarchar (255)         | Y                                       | Books recording the meteorological records originally                              |
| Page number                 | int                    | Y                                       | Page numbers of meteorological records in General Collection                       |
| Frost and snow disaster level | int                    | Y                                       | Frost and snow disaster level values                                              |
Additionally, the coding format needs to save memory space as much as possible and fully accommodate the rich content of historical materials. Most of the historical materials of ‘disaster records’ in various places were extracted from different periods, prefectural records, county records, and official histories, which are rich in content and detail. These historical materials provide records on important details, such as the massive human response activities and government measures taken. According to this feature, each historical material was divided into 14 fields with independent content, expressed by 14 numerical codes. The historical materials were then entered into the computer one at a time. In this way, the database of frost and snow disaster attributes in North China during the Qing Dynasty was built.

2.4.3. Establishment of the frost and snow disaster spatial database
The spatial database maintains spatial information on the provinces, prefectures, counties, and frost and snow disasters in North China during the Qing Dynasty period, a time that mainly included the administrative area of four provinces and two cities. All the ancient names of counties in the area during that dynasty, the boundaries of the first- and second-level political districts, major rivers and lakes, etc., are also included. This database serves as a basis for the spatial analysis and research of frost and snow disasters. The specific procedures used for the establishment of this spatial database were as follows:

(1) The 1:2,450,000 administrative map of the four provinces and two cities of North China during the Qing Emperor Guangxu’s 34th year (1908) amid the Qing Dynasty period, as recorded in the Historical Atlas of China, was chosen as the base map.
(2) The map of each province in the Historical Atlas of China software was exported and saved as a PDF document.
(3) The scanned raster data were collated using ArcGIS software and aligned to maps of each province.
(4) Layered vectorization was performed to obtain vector layers of the provinces, prefectures, districts, and rivers and lakes.
(5) The WGS-84 spatial coordinate system was assigned to the vector layers.
(6) Attribute information was added to each layer, and the spatial data were finally entered into the database.

Figure 2 shows a flowchart of the technical process used to build the spatial database of frost and snow disasters.
2.4.4. Frost/snow disaster classification

Frost/snow disasters occurred 1982 times in North China during the study period. Taking into consideration their season, intensity, and duration, the frost/snow disasters have been classified into the following three grades: level-1, mild; level-2, moderate; level-3, heavy (Zhou et al. 2008). Among them, 1132 level-1 frost and snow disasters occurred, 708 level-2 frost and snow disasters occurred, and 142 level-3 frost and snow disasters occurred. Table 2 presents the grading basis for the frost/snow disasters.

2.5. Data analysis and methods

In this paper, the CEEMD (Complete Ensemble Empirical Mode Decomposition) method was used to decompose the time series in order to analyze its inherent periodicity (Yeh et al. 2010). The CEEMD method is based on EMD (Empirical Mode Decomposition), and EEMD (Ensemble Empirical Mode Decomposition); it is an improvement over the EEMD method. The method has additional auxiliary and negative auxiliary noise components; this addition does not only overcome the model aliasing phenomenon in EMD method, but can also eliminate the reconstruction residual noise in the signal (Wang et al. 2014).

For noise signals and intermittent signals, the mode aliasing phenomenon exists in EMD method, which seriously affects the accuracy of signal decomposition (Si et al. 2019). EEMD (Wu and Huang 2009) optimizes the existing problems of EMD reasonably. By adding Gaussian white noise in the whole time-frequency space, multiple mean IMF components are decomposed. As the final result, the mode aliasing phenomenon is effectively suppressed. Complementary ensemble empirical mode decomposition (CEEMD) (Yeh et al. 2010) adds \( N \) pairs of positive and negative auxiliary white noise to the original signal, and obtains \( 2N \) signals, and performs EMD for each signal. Finally, the calculation results are combined.
In CEEMD method, the decomposed modal function is denoted as $\text{IMF}_k$. The first mode, $\text{IMF}_1(n)$ is derived as:

$$
\text{IMF}_1(n) = \frac{1}{I} \sum_{i=1}^{I} \text{IMF}_i(n) = \text{IMF}_1(n)
$$

(1)

The first residual, $r_1[n]$ is calculated as:

$$
r_1[n] = x[n] - \text{IMF}_1[n]
$$

(2)

where $(\text{IMF}_k)$ is the same as the modal function obtained by EMD decomposition. The operator $E_j(\cdot)$ is defined. For the given signal generated by the EMD decomposition corresponding to the $j$-mode, $w^i$ for the N $(0, 1)$ distribution of white noise, and $r_1[n] + \epsilon_1 E_1(\omega^i[n])$, with $i = 1, \ldots, I$, $\text{IMF}_2[n]$ can be obtained by superimposing the given noise with the set of $r_1[n]$:

$$
\text{IMF}_2(n) = \frac{1}{I} \sum_{i=1}^{I} E_1(r_1[n] + \epsilon_1 E_1(\omega^i[n]))
$$

(3)

Similarly, for $k = 2, \ldots, K$, the residual is calculated as:

$$
r_k[n] = r_{(k-1)}[n] - \text{IMF}_k[n]
$$

(4)

Thereafter, the $k + 1$ modal is defined as:

$$
\text{IMF}_{k+1}[n] = \frac{1}{I} \sum_{k=1}^{K} E_1(r_k[n] + \epsilon_k E_k(\omega^i[n]))
$$

(5)

The final residuals are:

$$
R[n] = x[n] - \sum_{k=1}^{K} \text{IMF}_k
$$

(6)

The signal $x[n]$ is expressed as follows:

$$
x[n] = R[n] + \sum_{k=1}^{K} \text{IMF}_k
$$

(7)

3. Results

3.1. Concept and types of frost/snow disasters

The definition of frost, snow and low temperature disaster is that the disaster caused by the sharp drop of ground temperature, or the ground temperature reaching a
certain low level, or the snow cover on the ground belongs to frost, snow and low temperature disaster (Meng et al. 2012b). Frost, snow and low temperature disasters include frost and snow disasters. Such disasters are caused by low temperature. Low temperature can influence people’s health, and the functioning or productivity of plants and animals. The frost disaster is the phenomenon of frost fall in frost free period. Frost disaster, low temperature and snow disaster are mainly caused by cold air intrusion (Zhou and Meng 2017). The frost and snow disasters mentioned in this paper include frost, low temperature and heavy snow. They are all caused by cold air activities, but their manifestations and intensities are different in different seasons. Therefore, studying these three types of disasters together can enhance the understanding of their occurrence and development laws, reveal the trend and variability of cold air activities, and provide scientific basis for effectively predicting and preventing the occurrence of such disasters (Meng and Liu 2012).

### 3.2. Frost/snow disaster’s time series characteristics

#### 3.2.1. Frost/snow frequency changes

In order to sort the frost/snow disasters recorded in the historical literature, firstly, we estimated and discovered that the total occurrences of frost/snow disasters in North China over the study period averaged 7.4 times per year. Further, the trend of frequency was analyzed in terms of its average values, as shown in Figure 3. As can be seen, the frequency of frost/snow disasters occurring in the period 1700–1800 was relatively low, and the moving average value is lower than the multi-year average value. However, the frequency for the remaining period shows an alternating increasing and decreasing trend. In 1831, the frequency of disasters reached its peak, and a total of 71 frost/snow disasters occurred in that year.

![Figure 3. Annual frequency change of frost and snow disasters in North China during 1644–1911.](image-url)
Taking 20 years as a unit, the frequency values from the data and the corresponding results of fitting of the quadratic polynomial and the sixth order polynomial, are depicted in Figure 4. The black dashed line is the fitting result of the quadratic polynomial; it shows that the frequency displayed a decreasing trend followed by an increasing one in the period. The black solid line corresponds to the sixth-degree polynomial fitting; based on this result, the study period was divided into four stages. The first stage is the period, 1644–1703, which has a relatively high frequency of 571. In the second stage during the period 1704–1803, the frost/snow disaster occurred 336 times, which implies a relatively low frequency. The third stage, corresponding to period 1804–1903 recorded 998 occurrences, which means the frequency is relatively high. The occurrences recorded during 1904–1911, i.e. the fourth stage is 77, which means the frequency is relatively low. Therefore, it is evident that the frequency is unevenly distributed on dates; further, marked variations can be observed in the frequency of occurrence at each stage.

The frequency of occurrence of frost/snow disaster every 20 years is 148 times; this frequency needs to be subtracted from the average frequency of occurrence; then the frequency of frost/snow disasters is calculated and depicted in Figure 5. It can be seen that the second and fourth stages are negative anomalies since the frequency of occurrence of disasters is relatively low. The first and third stages are positive anomalies and the frequency of disasters is relatively high.

### 3.3. Frost/snow disaster season and grade classification

In order to analyze the seasonal differences in frost/snow disasters in North China, these events recorded in the study area for the study period were classified based on
the season of their occurrence. Of a total of 1833 occurrences, the spring frequency was 574, accounting for 31% of the total occurrences; the summer frequency was 223, accounting for 13% of the occurrences; the fall frequency was 645, making a 35% proportion of the total frequency; finally, the winter frequency and its proportion in the total frequency was 391 and 21%, respectively. The season wise distribution has been depicted in Figure 6. The fall has the highest frequency, followed by spring and winter. Summer has the lowest frequency among seasons. This pattern is attributed to the changes in the fall and winter season or in the beginning of the summer season. When the winter monsoon is very strong, or it goes too early or too late, it may result in climate anomalies. Consequently, the surface temperature might drop resulting in frost/snow disaster in serious cases and an impact on crops. If the winter monsoon comes too early, it will lead to autumn frost/snow disaster; if the winter monsoon goes too late, it will lead to spring frost/snow disaster. Therefore, spring and fall register the highest frequency of frost/snow disasters among the seasons.

The severity of the frost/snow disaster varies, and so does its impact on the production of crops and the life of people. The frost/snow disasters described in the historical records are classified into three grades: mild, moderate, and severe. According to the frequency statistics for the study period, North China recorded 1132 mild frost/snow disasters, accounting for 57% of the total frequency; 708 moderate frost/snow disasters, accounting for 36% of the total frequency; and 142 severe frost/snow disasters, accounting for 7% of the total frequency. Two facts can be pointed out: firstly, the highest frequency is mild frost/snow disasters, followed by moderate and severe disasters; and secondly, the frequency of mild and moderate frost/snow disasters account for more than 90% of the total frequency.

Figure 5. Change in frequency anomaly values of frost and snow disasters in North China during 1644–1911.
4. Discussions

4.1. CEEMD method

As the algorithm use all the local extrema to construct the envelopes, EMD contains some theoretical problems, such as mode mixing and boundary effect, decreasing the accuracy of denoising (Zhang et al. 2019). The EEMD was developed by Wu and Huang (2009) to essentially resolve the shortcoming through the help of added noises. Chen et al. (2012) combined EEMD and wavelet threshold filtering to improve the processing effect. There is residual noise in the signal reconstruction using EEMD, which causes EEMD not to be the best denoising method (Zhang et al. 2019). CEEMD is thus emerged and applied to improve the efficiency of EEMD by adding white noise in pairs to the original signal (Yeh et al. 2010; Chen et al. 2016).

The CEEMD data decomposition technique addresses the non-stationarity and non-linearity of input data (Torres et al. 2011). In the decomposition process, Gaussian white noise is added to the original data to construct a uniform reference frame, which is eventually removed by averaging of the respective IMFs and residue (Ali et al., 2020). The CEEMD process is the same as EEMD, only adding noise with opposite sign after adding a kind of noise. Consequently, this can offset the noise impact of the processed signal, reduce the number of iterations, and greatly improve the operational efficiency (Wang et al. 2020). The CEEMD method does not only solve the mode aliasing problem, but can accurately reconstruct the original signal (Si et al. 2019). According to EMD decomposition, two sets of IMF components are obtained, and then the two groups of components are averaged to obtain the final result (Wang et al. 2020). Comparing the existing signal decomposition methods, we can see that CEEMD has the best denoising performance and adaptability (Zhang et al. 2019).

Figure 6. Seasonal distribution of frost and snow disasters in North China during the period 1644–1911.
4.2. Characteristics of frost/snow disaster cycles

Climate change events have a certain time scale and periodicity (Zhou and Zhao 2008; Qian et al. 2009; Zhao et al. 2009). In order to analyze the periodicity of frost/snow disasters in North China, IMF (Intrinsic Mode Function) with different fluctuation periods and the RES (trend) were calculated for the study period by means of a gradually decomposing CEEMD sequence of frost/snow disasters. The results are demonstrated in Figure 8. From IMF1 to IMF7, a wide range of frequencies is observed. The annual frequency sequence has different periodic characteristics; further, the sequence of each component reflects the characteristics of the original sequence localization. The last term is the trend term RES, which represents the trend of the original sequence as a whole, i.e. the frequency of frost/snow disaster in North China across the overall time trend. Each IMF component in the graph has its corresponding quasi-periodic period; further, the quasi-periodic time on different time scales exhibits a strong or weak change of heterogeneity over time in the same period.

Figure 7 demonstrates that IMF1 has the maximum amplitude and fluctuation range among the seven natural modal functions; further, the amplitude decreases with the increase of the modal order, while the corresponding wavelength increases. The fluctuation range tends to be stable with an increasing order during the entire time span. The trend term RES displays a tendency to decrease firstly, and then increase on the total time scale; however, there is no obvious periodic change, which may be a part of the longer period.

Figure 8 shows the results of the significance test of the IMF signal component for the annual frequency sequence of frost/snow disasters in North China. Based on the
above, the period corresponding to each signal is obtained. The results are listed in Table 3. The observed annual frequency is cyclic on different time scales. The following are the cyclical fluctuations: 2.8 years (IMF1), and 5.3 years (IMF2) on the inter-annual scale; 11.3 years (IMF3), 22.6 years (IMF4), 45.2 years (IMF5), and 52.0 years (IMF6) on the inter-decadal scale; and 119.4 years (IMF7) on the century-scale. Furthermore, the decomposition of the IMF components is pure noise, and the original sequence of the physical meaning of the component (Xue et al. 2013). The vertical coordinates of the IMF component are the logarithmic square of the energy spectral density. The blue and red solid lines indicate the significance levels pertaining to $\alpha = 0.05$ and $\alpha = 0.10$, respectively. If the points lie above the lines (referring to the significance level test), it indicates the component contains actual or significant physical information. If the component does not pass the significance level test, it indicates the presence of white noise (Li et al. 2014). The vertical axis of the graph represents the energy spectral density of the IMF component. The larger the ordinate value, the higher the energy contained by the IMF component, and the larger is the amplitude. IMF1, IMF4, and IMF7 lie above the 95% significance level, indicating these components are highly significant. However, IMF5 shows the least significance, indicating this component contains maximum white noise. This implies that the actual physical significance is less, the corresponding oscillation period is not significant.

4.3. Spatial distribution characteristics of the frost/snow disasters

In order to analyze the spatial distribution characteristics of the frost/snow disasters in North China over the given period, their frequency as well as the grade are
evaluated, and plotted using the ArcGIS software. The corresponding results are shown in Figures 9 and 10, respectively. Figure 9 shows that the spatial distribution of frequency is uneven. In general, the frequency of occurrence in the Hebei and Henan provinces is relatively less, while that in the Shandong and Shanxi provinces, which include the Shandong Linqu County, Changle County, Shouguang County, Anqiu County, Gaomi County and other areas, is relatively high. In Shanxi, in the Xiangyuan County, Wuxiang County, Yangcheng County, Yueyang County, Linxian, and other areas, the frost/snow disasters occurred more frequently. The Shanxi province has a slightly higher frequency as compared to the Shandong province. This pattern has a certain relationship with the terrain—the terrain conditions in Shanxi are more complex; Luliang, Taihang, Zhouxi, Taiyue, Hengshan, Wutai, Yunzhong, and other high mountains lift the air, and also affect heat and other parameters, generating conditions favorable for frost/snow disasters in the windward slope.

Figure 10 shows the spatial distribution of the levels of frost/snow disaster. On comparing Figures 9 and 10, there is an absolute degree of spatial consistency between the spatial distribution in relation to frost/snow disasters grades and frequency distribution of frost/snow disasters in North China during 1644–1911, and the terrain conditions have an obvious influence on the occurrence of a frost/snow disaster. Figure 10 depicts that the Shandong, Henan, and Hebei provinces predominantly witnessed the mild and moderate disasters. Shanxi primarily witnessed severe disasters; a concentrated distribution of patches was observed in Linxian County, Yongning County, Fenyang County, Xiaoyi County, Jixiu County, Pingyao County, from the Qinyuan County area to the Tunliu County, Changzhi County, Huguan County, and Pingshun County area. These areas witness the severe frost/snow disasters. From Mengxian County, Shouyang County, and the Yushe County area to Yueyang County, Linfen County and Wanrong County also witnessed severe frost/snow disasters. The disaster levels in prone areas with leeward slopes, the high terrain mountains and the highland zones are significantly higher than the disaster levels in the lowlands and hirakawa area.

Shanxi Province and Hebei Province in the study area are selected as typical areas to make a brief description. Shanxi Province is located in the middle latitude. The invasion of cold air will inevitably bring frost, snow, low temperature and other weather phenomena. The higher altitude and the terrain of ‘two mountains and one basin’ strengthen the capacity and influence scope of cold air, and produce serious ‘frost damage’ while forming frost, snow and low temperature (Meng and Liu 2012). The frost, snow and low temperature disasters in Hebei Province are affected by the regional topography and climate, showing obvious regional characteristics. However, on the whole, the distribution of frost, snow and low temperature disasters tends to be consistent with the path of winter monsoon (Hao et al. 2017).

The occurrence of frost/snow disasters is affected by the winter monsoon, topography, and geomorphological conditions. In the case of monsoon’s origin, intensity,
altitude and other factors, the frequency and grade of frost/snow disasters in North China are in uniform distribution. The spatial distribution of the disaster grade has obvious flaky characteristics, but the zonal aspect has no obvious impact.

4.4. Analysis on the mechanism of frost/snow disasters

Causes of frost/snow disasters are that the sudden drop of ground temperature is caused by cold current or snowfall, or by snow (Zhou and Meng 2017).

The formation of frost/snow disaster is not only related to the weather conditions at that time, but also closely related to the geographical location and topography. The influence of latitudes and altitudes supersedes that of longitudes. At the turn of autumn, winter and early summer, if the influence of winter monsoon is too strong, or it comes too early and goes too late, climate anomalies may occur. When the surface temperature of the earth’s surface and plants drops enough to cause damage or even death to the plants, disasters are prone to occur, which makes the probability of disasters occurring in autumn and spring the highest (Meng and Liu 2012).

Topography and monsoon activity are important factors affecting the spatial difference of frost/snow disasters (Hao et al. 2017). Frost/snow disasters are generally caused by cold air intrusion and subsidence. The cold air is easy to deposit in the low depression area, so the low depression basin is more vulnerable to frost/snow disaster. Such disasters are often severe with devastating impacts. In terms of aspect, the windward slope of cold air is more severely affected than the leeward slope, which is
due to the low temperature of the northern slope, the direct invasion of cold air, and the temperature usually falling below 0 °C (Meng and Liu 2012).

The snow and freezing spatio-temporal patterns show relatively stable characteristics with a zonal differentiation due to stepped topography, different climate and bodies or systems affected by the disaster.

5. Conclusions

Snow and freezing disaster are one of the most dominant disasters, which does not only threaten human lives and properties, but adversely impact the economy, resources, and the environment at large. Snow and freezing disasters at the regional level can serve as a guide, thereby facilitating risk reduction and disaster management.

Results indicated in a particular climatic zone, key elements or bodies susceptible or involved in risk and disaster management can pertinently develop reactive and anticipatory mechanisms. These mechanisms are at adapting or mitigating disturbances or stressors linked to certain and uncertain climate hazards. The research on the temporal and spatial distribution of frost, snow and low temperature disasters during the Ming and Qing dynasties does not only solely provide some reference for today’s disaster prevention, but also explore underlying issues and characteristics of disasters through the discussion of their causes. This eventually facilitates the systematization and sustainability of modernized agricultural practices.
We collected and compiled the records of frost/snow disasters in North China for the period 1644 to 1911, and classified them into three levels: mild, moderate, and severe, according to the severity of the disaster and the corresponding influence range. Using several temporal and spatial analysis methods, we analyzed the spatio-temporal distribution and characteristics of frost/snow disasters in North China. Based on the study findings, we drew the following conclusions:

1. Based on the frequency of frost/snow disasters, the study period was divided into four stages. The second and fourth stages marked a period of low frequency disaster, while the first and third stages are high frequency disaster stages. Findings proved there was dynamic ebb in the occurrence (frequency) of frost/snow disasters over the given study period. The season’s wise count of occurrences in spring, summer, fall, and winter, shows fall registered the maximum occurrences, followed by spring. In spring and autumn, it is most vulnerable to frost/snow disasters caused by cold air coming early or late.

2. EEMD method has many iterations and slow operational efficiency. CEEMD has made further improvement on the basis of EEMD method. CEEMD adds auxiliary noise in the form of positive and negative pairs on the basis of the original method. Interestingly, this can offset the noise impact of the processed signal, reduce the number of iterations, and greatly improve the operational efficiency. The CEEMD method does not only solve the mode aliasing problem, but can accurately reconstruct the original signal.

In order to explore the periodicity of frequency of the frost/snow disasters in North China from 1644 to 1911, the CEEMD decomposition of annual frequency sequence was performed. It was observed that the frequency of disasters in North China during this period was periodic. The period was 2.8 years, and 5.3 years on the inter-annual scale, 11.3 years, 22.6 years, 45.2 years, and 52.0 years on the inter-decadal scale, and 119.4 years on the century-scale. Among them, 2.8 years, 22.6 years, and 119.4 years cycles were more significant than others. Reasons for the periodic occurrence of these disasters are partly as a result of the formation of snowstorms emanating from low-pressure systems that heave moist-air into the atmosphere. In addition, change in global and prevailing microclimatic conditions amplifies the frequency and magnitude of frost/snow disasters. Here, high moisture content in the atmosphere drive massive than normal precipitation, constituting heavier snowfall in suitable conditions.

- Over the 1644 to 1911 period, the frequency distribution of frost/snow disasters in North China was observed to be uneven in space. The frequency in the Hebei and Henan provinces was relatively low. In contrast, the frequency in the Shandong and Shanxi provinces was relatively high. The frequency of occurrence was slightly higher in the Shanxi Province, as compared to Shandong province. The disaster level based spatial distribution map revealed there is an absolute degree of spatial consistency between the spatial distribution in relation to frost/snow disasters grades and frequency distribution of frost/snow disasters in North China during
1644–1911. Shandong, Henan, and Hebei are mainly classified as mild and moderate disaster areas. The Shanxi area is primarily classified as a severe disaster area showing concentrated distribution of flakes, as it has leeward slopes and high terrain constituting mountains. The disaster grade in the highland areas was significantly higher than in the lowlands and hirakawa area, which is mainly due to the combined effect of the monsoon and terrain conditions.

The physical causes of terrain effects on the spatial distribution of frost/snow disasters could be further examined in future studies. Again, the need to combine statistical analysis with the cold historical data offers a peculiar opportunity to enrich basic datasets that enhances frost/snow related studies in the study domain, as well as other areas. In addition, contrasting and comparison of different periods or time-scales, geographic locations and key events could be of scientific interest to the international research community.

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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.

Authors’ contribution

Shuoben Bi, Xiuhua Xu, and Jiwei Sun conceived and designed the experiments; Ying Qu, Xiuhua Xu, and Feng Zhao performed the experiments; Shuoben Bi and Ying Qu wrote the Chinese paper; Isaac Sarfo, Feng Zhao, Xiuhua Xu, and Jiwei Sun translated the paper.

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Data availability statement

The data that support the findings of this study are available from the first author, Shuoben Bi, upon reasonable request.
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