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# Historical droughts in the Qing dynasty (1644-1911) of China and the role of human interventions

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## Abstract

This study presents a new epistemology to analyze drought chronology through a clear-cut methodology for reconstructing past drought series as well as series for other associated ecological and societal variables. Instead of building grading system based on mixed criteria, this method can facilitate transparency in the reconstruction process and can enable statistical examinations of all variables when building the series. The data used is from the REACHES database, however other archival documentary and index data from independent sources are also applied to understand drought narratives and to cross check and validate the analysis derived from the REACHES. From time series analysis, six severe drought periods are identified in the Qing dynasty, and then spatial analysis is performed to demonstrate spatial distribution of drought and other variables in the six periods as well as social network analysis to reveal connections between drought and other ecological and societal variables. Research results clearly illustrate the role of human intervention to influence the impacts of drought on societal consequences. Particularly, the correlation between drought and socioeconomic is not strong; crop failure and famine are important intermediate factors, meanwhile ecological factor such as locust and disaster relief measures are all imperative to intervene between crop production and famine. Implications of the study on drought impact are provided as well as its significance on historical climate reconstruction studies.

Keywords: drought, documentary records, human intervention, historical climatology, climate reconstruction

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## 1. Introduction

Global warming is expected to influence the earth's hydrological cycle and put higher stress on water resources. Climate simulations reveal a wide expansion of dry areas over land and an intensification of wet-dry contrast at lower latitudes (Held and Soden, 2006; Schewe et al., 2014). The projections of the enlarging wet-dry pattern and amplified drought have been subtly detected in the recent observations. However, less well understood is the interannual or decadal scale changing pattern of regional precipitation and duration and magnitude of drought at fine resolution. Moreover, large uncertainty of hydroclimate projections still resists due to limitation of instrumental meteorological data to assess climate models (Cook et al., 2014; Ljungqvist et al., 2016).

Drought and flood are two extremes of the hydrological cycle. Both of them can induce severe environmental and socioeconomic consequences. Flood which generally represents sudden onset of excessive water can lead to immediate loss of lives and material damages. The formation of drought, on the contrary, normally refers to a slower and longer water deficiency process that can result in a more chronologically extended range of impacts on agriculture and water scarcity contributing to catastrophic socioeconomic outcomes (Brázdil et al., 2019). Given the intensified drought condition in the future scenarios, there is a necessity to study past drought, especially the severe drought cases to decipher their occurrence, duration, magnitude, and the associated ecological and societal consequences for implications of future adaptation.

Studying past drought and humidity has been a long practiced subject in historical climatology and paleoclimatology. In the instrumental era, drought can be relatively easier to be defined based on the temperature and precipitation measurements. And the instrumental era can be tracked back to the mid or late 19$^{th}$ century when many national weather services started (Broennimann et al., 2018). Some early instrumental meteorological data might be acquired in some regions dated back to the late 17$^{th}$ or early 18$^{th}$ century. However, prior to the instrumental era, there are primarily two sources of data that can be used to build temporally highly resolved drought series data: tree rings and documented records (Brázdil et al., 2018). Tree rings provide abundant information about moisture, and sometimes temperature, for reconstructing millennial long hydroclimate indices to infer drought. The most well-known work include Old World Drought Atlas using tree ring data calibrated with Palmer Drought Severity Index (PDSI)(Cook et al., 2015), Monsoon Asia Drought Atlas (Cook et al.,

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2010), and megadroughts over North America (Stahle et al., 2007). Yet, tree ring reconstruction usually suffers from growing seasonality of trees and blurred interpretation of isotopes.

Documentary records reflect direct human observations of weather condition; it can be less ambiguous when used for reconstructing past climate. And some records can convey as detailed information as daily, monthly or seasonal weather, environmental, phonological, and socioeconomic situations in specific locations, allowing comprehensive analysis on drought events, scales, and contexts (Brázdil et al., 2019; Huang et al., 2019). There are also some critiques about inferring drought from documented records. For example, some argue that drought records are sometimes vague in the content, hard to distinguish if the drought refers to rainfall deficiency, hydrological process or cropping need. Several studies thus purpose four categories of drought: meteorological drought caused by significant reduction of precipitation for weeks or months compared to mean precipitation, agricultural drought associated with lack of water for plant growing for a period lasting from weeks to 6-9 months, hydrological drought characterized by a shortage or absence of water in water courses, reservoirs or aquifers, and socioeconomic drought amplified by negative effect of drought to influence everyday life, social system and stability (Brázdil et al., 2018; Heim, 2002). There exists also a progressive view suggesting drought as a complicated process of water shortage caused and modified by human processes (Van Loon et al., 2016).

Given the multifaceted nature of drought, reconstruction of past drought in the last millennium still heavily relies on the information that we can retrieve from tree rings and especially from the documentary records. Brazdil et al. (2018) have elaborately outlined a number of various types of documentary evidences that can be used for such an investigation. Notably, all records are qualitative or narrative in the nature; strategies are thus imperative to transform them into inferable numeric drought series. Three-, five- or seven-scaled grading system based on duration and severity of drought is the most commonly practiced method, so that every single quotation of drought record can be given a specific value according to the criteria. And a drought index system can be formed accordingly. However, in reality, the transformation process can be controversial and disputable because a wide spectrum of how different grades should be formed and for what purposes exists (detailed information see (Brázdil et al., 2005; Pfister et al., 1999). In China, a dryness-wetness (sometimes called drought/flood) index has been prevailingly used in recent decades for reconstructing past climate (Hao et al., 2016; Shi et al., 2018; Tan and Liao, 2012; Yi

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et al., 2012; Zheng et al., 2014). The index was initially built by the Academy of Chinese Meteorological Science (CMA, 1981) and was sequentially expanded by several Chinese scholars (Zhang, 2003)(more details see Hao et al., 2019). Yet, its five-scaled grade system ranging from 1=very wet, 2=wet, 3=normal, 4= dry to 5=very dry has been sustained and, importantly, presented plural acknowledge of grade judgment from climatic, ecological and societal phenomena. Below exemplifies some of the criteria and typical descriptions in the archives for the grades (mainly adopted from Yi et al. 2012, and modified from Zheng et al. 2014 and Tan et al. 2013).

Grade 1 (very wet): Prolonged heavy rain (e.g. excessive rain continued over a month in spring or summer), Extensive flood (e.g. heavy rain for several days, land flooded, boating on land), Unusually heavy typhoon rain (e.g. cropland and houses of several counties inundated by typhoon rainfall)

Grade 2 (wet): Spring or autumn prolonged rain with moderate damage (e.g. protracted rain in spring or autumn), Local flood (e.g. counties flooded for months, drought in spring but heavy rain in summer)

Grade 3 (normal): Favorable weather (e.g. good weather for crops, bumper harvest)

Grade 4 (dry): Light drought disaster in single season (e.g. drought in spring or autumn), Local light drought disaster (e.g. short rainfall in summer, drought in other months, drought and locust plague)

Grade 5 (very dry): Continued drought for more than one season or for several months (e.g. drought from spring to summer or from summer to autumn, no rain in four months and rivers dried out), Severe drought over extensive area (e.g. a thousand miles of barren land, severe drought throughout south of the Yangtze River lower reach), Famine (e.g. tens of thousands starved to die on the street, ate tree roots or soils)

The mixed identification of drought grade in China's dryness-wetness index system though likely efficient in evaluating drought severity illustrates a difficulty to identify specific drought categories in the records as mentioned earlier. Lacking explicit explanations to identify if a certain drought event was directly associated with meteorological deficiency of rainfall or had more implications on the agricultural needs can make interpretation of drought records inexplicit or biased. It also prevents from substantive statistical analyses on the examinations of the associations among those different drought categories (each as independent variable) and from building narratives for comprehensively understanding drought contexts and their impacts.

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This study thus aims to propose a new epistemology to analyze drought chronology through a clear-cut methodology for reconstructing past drought series as well as series for other associated ecological and societal variables. Our goal is not to stress on the drought grading method for building chronology and identifying severe events. Contrarily, our objective is to make every drought and associated variables as literally clear and operationally independent as possible. This method can facilitate statistical examinations of the variables and can enable transparency in the reconstruction process for building past drought series. Moreover, we are also able to perform contextual analysis for severe drought events through analyzing the strengths of the relations among variables and to identify their spatial characteristics. More archival data from historical documents are also applied to further explain the narratives of the governmental and societal responses to the severe events. In the following sections, we will briefly introduce the data used for analysis (section 2), methods (section 3), and the analytical results illustrating reconstructed time series of those variables, six severe drought periods and their spatiotemporal patterns and the narratives (section 4). Discussions on the climate-society interactions are provided, as well as limitation and future application of the proposed methodology and the analysis (section 5).

## 2. Data

### 2.1 Drought and associated data from REACHES database

The data source of this study mainly comes from the REACHES database, illustrating a wealth of Chinese historical documents in the dynasties of the last two millennia (Wang et al., 2018). In the total of the 93,415 records (database version VOL34-V3.1-04-E2) of the Qing dynasty (1644-1911 CE), the last dynasty of China, we used the database code system to systematically retrieve drought and other associated records including locust, famine, crop failure (presenting agriculture drought), and socioeconomic turmoil (along with famine presenting socioeconomic drought in the categories). Locust is traditionally viewed as an important ecological indicator, closely related to drought and famine since detailing locusts could consume great quantities of crops resulting in cannibalism (Huang et al., 2019). However, statistical examinations of it and drought are not adequate.

REACHES has a sophisticated code system to completely encode as much information as conveyed in the vocabularies of the historical records. In the 9-digits code series, first 2 digits describe main category, 2 following digits describe subcategory, 3 subsequent digits depict vocabularies, and the last 2 digits are designed for magnitude and time information. For example, a code series like 300130156 can

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be deciphered as follows: the first 30 illustrate the quotation belonging to the drought category, the following 01 reveal its subcategory as drought (others like watercourse dried out as 11), the remaining digits 301 indicates its vocabulary as major drought (亢旱, *Kang Hang*), and the last two digits denote magnitude and time-duration information. In this case, 5 means the magnitude as heavy and multiple times and 6 means the duration between 60 and 90 days.

As for mentioned, drought is encoded as a category with code digit 30 under hazard domain in the REACHES database. Famine is also a category under hazard domain with code 35. Locust is a subcategory (code 01) under pest/vermin category (code32), thus the complete code to retrieve locust records is 3201. Crop is a category (code 33) under hazard domain but the category comprises various degrees of harvest conditions and species. Thus we had to use vocabulary tracking codes to retrieve those codes ranging from 100 to 499. Socioeconomic turmoil is a category with code 71, and we specifically retrieved the most relevant subcategories including immigration/displacement (code 03, total retrieval code as 7103), battle/war (code 05), impoverishment (09), death/severe hurt (code 10), human trafficking (code 12), and abandoned settlements (code 16). Notably, Chinese writing sometimes uses negative tense to describe absence of some phenomenon which should take place around the time, such as no drought (無旱, *Wu Hang*). In this case, it would be encoded under drought category with magnitude code 8 denoting no happening. Since no drought should not be taken into drought variable in this study of question, we have carefully dealt with all those records with magnitude code 8 for all variables and removed them from the data sets.

Finally, and importantly, all records of the REACHES are from the Compendium of Chinese Meteorological Records of the Last 3,000 Years (Zhang, 2013), which means that only records that have direct (or indirect) implications or linkages with meteorological phenomena would be collected in the compendium. It points out that care should be extraordinarily taken when using and analyzing the socioeconomic variables in the REACHES since the potentially biased sampling. Other sources of relevant socioeconomic data are strongly recommended to cross check and validate the analysis.

In total, we retrieved 51,974 records from the REACHES database (version VOL34-V3.1-04-E2). Figure 1a shows time evolution of records for the drought, locust, famine, crop failure and socioeconomic turmoil variables, and 1b shows number of sites (i.e. counties, cities and prefectures, in REACHES total n of

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sites=1,660) that have the corresponding records of the year. The two diagrams are almost identical showing good consistency and the records likely evenly distributed over the sites. Notably, all data derived from the REACHES database and pertinent to this study will be deposited at a repository (DOI assigned later).

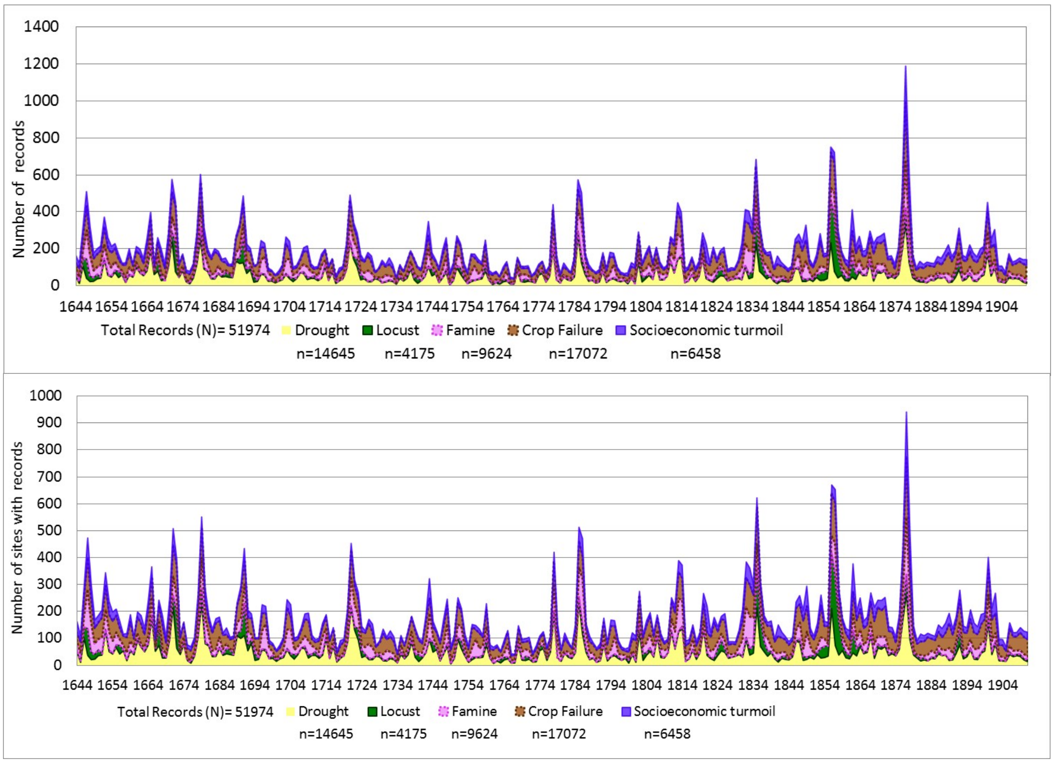


Figure 1 Statistics of drought and associated records from the REACHES database. 1a (upper panel) shows number of records per year; 1b (lower panel) shows number of sites (counties, cities or prefectures) that have records of the year. Thus one site may have more than one record of the year.

## 2.2 Other archival and index data

To comprehensively compare and analyze drought and associated data series from the REACHES with other socioeconomic variables from independent data sources, several archival and index data were also collected for analysis. The archival data include Draft History of the Qing Dynasty (清史稿, *Qingshi Gao*), Actual Veritable Records of Emperors of the Qing Dynasty (清實錄, *Qing Shilu*), Gazetteers of Xunzhou Prefecture (Tongzhi reign edition) ( [同治]潯州府志, [*Tong Zhi*] *Xun Zhou*

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*Fu Zhi*), Gazetteers of Gui County (Guangxu reign edition) ([光緒]貴縣志, [*Guang Xu*] *Gui Xian Zhi* ), Gazetteers of Pingnan County (Guangxu reign edition) ([光緒]平南縣志, [*Guang Xu*] *Ping Nan Xian Zhi* ), and Gazetteers of Yongchun County (Chinese Republican Period edition) ([民國]永淳縣志, [Min Guo] *Yong Chun Xian Zhi* ). These documents have recorded meticulously social, economic and institutional events of the times. Local gazetteers particularly recorded detailed information about social unrests such as the massive rebellion, Taiping Civil War (太平天國 [Tai Ping Tien Guo]), in the mid 19th century.

Additionally, we also collected grain price, civil war and population indices for further analysis. Grain price data (1738-1911) was gained from Qing Dynasty Grain Price Database, based on monthly grain price reports preserved at the First Historical Archives of China in Beijing and the National Palace Museum in Taipei, edited by Yeh-Chien Wang, Academia Sinica (Wang, 2009). Civil war data reveals frequency of civil wars in the Qing Dynasty, acquired from Chronology of China's Ancient Wars (Chinese military history writing group, 1985). And population data comprises several different sources. Provincial population statistics 1661-1776 CE are from Encyclopedia of Official Documents of the Qing Dynasty (清朝文獻通考, *Qingchao Wenxian Tongkao*). Provincial population statistics 1780-1890 are from Annual Registers of Quantities of Provincial Population and Grain Storage by the Ministry of Revenue (戶部匯奏各省民數穀數清冊, Gesheng Minshu Gushu Qingce) and from The History of Population in China, Vol. 5 Qing Period (中國人口史第五卷清時期, *Zhongguo Renkoushi Diwujuan Qingshiqi*)(Cao, 2001).

## 3. Methods

### 3. Time series and cross checking of the variables

We used the retrieved records to build several time series for different variables and performed tests to cross check reliability and robustness of the drought data. First of all, we gave strict definitions for drought variable. In our analysis, drought variable only contains records with the Chinese vocabularies of drought (e.g. 天旱 *Tien Han*、亢旱 *Kang Han*、苦旱 *Ku Han*)(category code 3001), enduring scorching sun, sultry weather (e.g. 恆陽 *Heng Yang*、恒暘 *Heng Yang*) (code 3002), and dried out of different types of water body including dried watercourses (e.g. 水竭 *Shuei Jyue*, code 3011), dried tide/sea water, (e.g. 潮水涸 *Chao Shuei He*, code 3021), dried lake/pond (e.g. 湖涸 *Hu He*, code 3031), dried underground water (e.g. 無泉 *Wu Cyuan*, code 3041) and dried river/creek (e.g. 河水絕 *He Shuei Jyue*, code 3051 ). And we further separated the drought variable into two groups; one group that only

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considers pure drought vocabularies (code 3001 and 3002) is interpreted as meteorological drought, and the other that stresses dried water body (code 3011-3051) is interpreted as hydrological drought. Figure 2 shows the comparison of the time series. It is found that the occurrence of higher number of hydrological drought records mostly appears in the years having more meteorological drought records. Correlation coefficient of the two is 0.67, and the coefficient increases to 0.77 when only severe drought (will be explained later) is considered rather than the drought records.

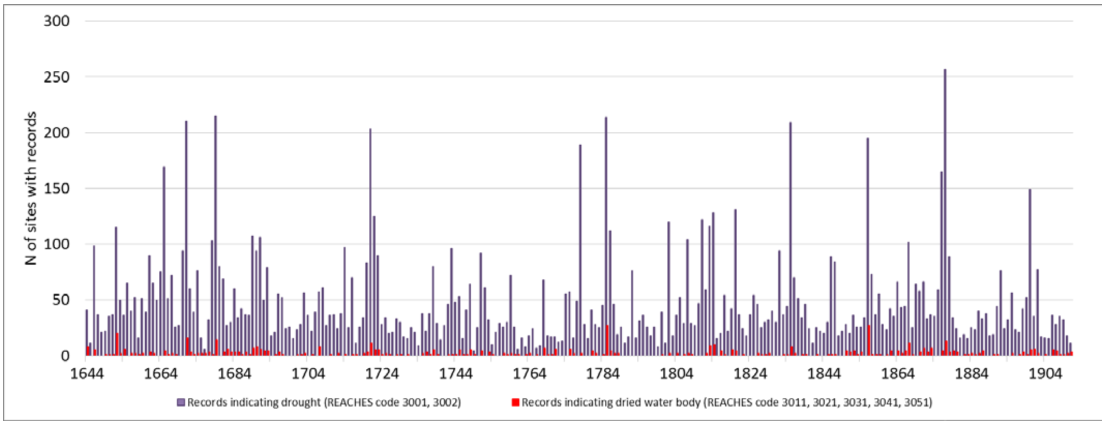


Figure 2 Comparison of drought records that indicate pure drought vocabularies (interpreted as meteorological drought) and dried water body (interpreted as hydrological drought).

To further investigate distributions of different drought types, we purposively distinguished drought and severe drought. The criteria are also based on the Chinese vocabulary attribution and the duration described in the records. Nominally, severe drought reflects Chinese vocabularies indicating extreme/severe drought (magnitude code 2 and 5) or the event last for more than two months (time-duration code 6 and 7, and we also used starting and ending date information to identify the length of every event). In contrast to severe drought, drought reflects those plainly described in the records with magnitude information falling into uncertain magnitude or light or the duration less than two months. Figure 3 shows the time series and it is obvious that severe drought and drought series have good consistency and match very well especially for the peak years of the drought events. Remarkably, those peak drought years mostly appeared in the mid to late 17$^{th}$ century and after late 18$^{th}$ century.

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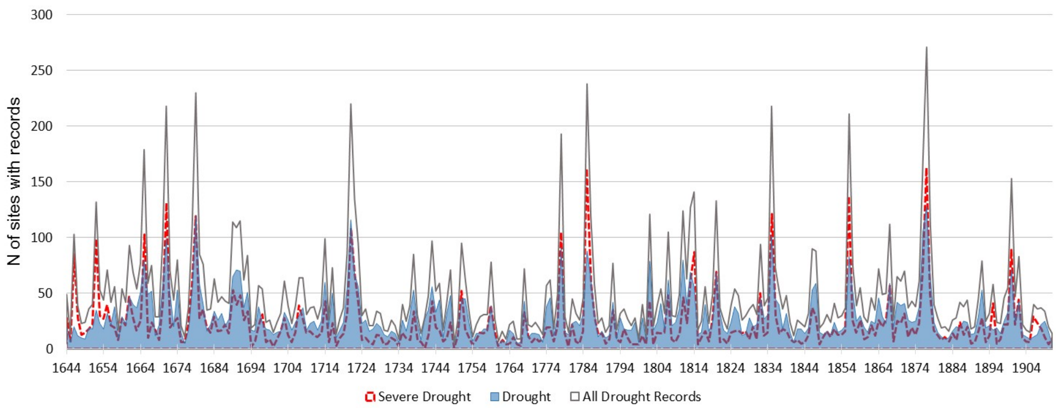


Figure 3 Time evolution of severe drought, drought, and all drought records in the REACHES.

### 3.2 Spatial analysis of Kernel density estimation

The integral information of when and where the records were recorded can assist comprehensive spatial analysis to analyze spatiotemporal patterns. To perform the analysis, statistics of the records were converted into site-based data format, and there are in total 1,660 sites representing cities, counties, or prefectures in the REACHES database. Every site was calculated number of certain records per year and the number was then summed according to the time period defined for the analysis. For example, in the 1720-1740 severe drought, Paoshan of Shanghai City had three drought records separately occurred in the years of 1720, 1723 and 1724. Then the frequency for the period of Paoshan would be three. We then used ArcGIS (version 10.4) to relate the data into the maps and implemented Kernel density function to conduct spatial analysis.

Kernel density estimation is a non-parametric method to estimate the probability density function of a random variable. In ArcGIS it is often used to calculate density of point features around each raster cell depending on the geographic distance and value of certain features. Namely, every cell value is the highest at the location of the point features and diminishes with increasing distance from the point and reaches zero at the search radius distance, called bandwidth, from the point. On very data point, a Kernel function K can be expressed as below:

$$\hat{f}(x,y) = \frac{1}{nh^2} \sum_{i=1}^{n} K\left(\frac{d_i(x,y)}{h}\right)$$

Where $\hat{f}(x,y)$ is the estimated density value at location $(x,y)$, $n$ is the value of the point under concern (for example in the case, $n$ is the number of drought records

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during the period), $h$ is a measure of bandwidth (for a circular Kernel it is the radius of the circle), $d_i(x, y)$ is the distance between event point *i* and location $(x, y)$, and $K$ is a density function characterizing how the contribution of point *i* varies as a function of $d_i(x, y)$.

Thus, the method estimates a smoothly curved Kernel surface fitted over each point depending on the point value and values of its neighboring points within desired bandwidth. The choice of bandwidth is therefore important since larger bandwidth would result in more smoothened surface by considering point value of larger distance. In the environment of ArcGIS, the Kernel density estimation is based on the quadratic (biweight) Kernel function (Silverman, 1986).

### 3.3 Social network analysis

To explore statistical characteristics of the relations between every variable and other associated variables, we used social network analysis to discover the underlying relations of all variables. Social network is a statistical method widely applied in sociology to explore how different agents are connected with each other so as to decide their distinctive network types and to analyze if and how various types of networks would influence individual behaviors and performances (Lin, 1999; Scott, 2017). In this study, we treated each variable as an independent agent and then calculated their statistical relations.

Generally, social network analysis adopts a pairwise approach to calculate relations between variables (e.g. if agent A is linked with agent B). Thus, to implement the analysis, data transformation is needed to display and inventory events (with specific codes) under every single record. For example, a record says that ‘in 1833, Quang Ling county of Shanxi Province, [the year] started in misery of drought, then inundated in rainfall, later damaged in frost, rice price up to thousands of dollars per dou (tradition unit, equivalently 10 kilograms modern unit), none of previous price in the last decades have reached the highest’ (1832 年。山西省廣靈縣。始苦於旱，繼潦於雨，終隕於霜，斗米千錢，數十年來未有如是之極也)(record ID 2945-25). For this specific record, since detailed time information is missing for every meteorological event, the events would be decomposed and then displayed in a way that drought linked with rainfall, drought linked with frost, drought linked with rice price, rainfall linked with rice price, frost linked with rice price and so on to further calculate their pairwise coefficients. When all events of every record have been decomposed and restructured following the algorithm, then the analysis could be

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performed to estimate the magnitude of every event (i.e. variable) and to calculate the strength of connections among those variables during certain time period. The function of edge list was applied to perform this analysis under Gephi software.

# 4. Results

## 4.1 Chronologies of drought and multiple variables

Figure 4a shows annual time series of all variables reconstructed from the REACHES database. It is obvious that while all variables have their natural fluctuations over the time period between 1644 and 1911, there are some observable multidecadal or centennial trend during the period. Mid to late 17$^{th}$ century and late 18$^{th}$ into 19$^{th}$ century present higher anomalies than the early half of the18$^{th}$ century. The trend is particularly remarkable for drought and locust variables. Although not so strong in signal, similar trend can also be observed for crop failure, famine and socioeconomic turmoil variables. If taken drought variable as a major concern, there is only one spike around 1720 in the earlier half of the 18$^{th}$ century and some increasing frequency around 1730-1750. To further understand the multidecadal and centennial trend, the series were compared with two temperature series, one reconstructed from REACHES (Lin et al., 2019) and the other North Hemisphere ensemble temperature from Frank et al. (2010) (Figure 4b). It is intriguingly found that higher frequency of drought and associated variables coincidently appeared with lower temperature anomalies in the 17$^{th}$ century and after late18$^{th}$ century. The two studies both show similar temperature anomaly trend in this time scale.

Figure 4a also indicates synchronization of high frequency events (peak numbers of variables, shaded in light brown color) appeared in the same time periods. We further conducted 9-years running variance for the time series. Figure 5 explicitly indicates significant overlay of the variables in several identifiable periods: 1660-1680, 1714-1724, 1770-1790, 1830s, 1850s, 1870s. It is notified that the intensities of drought in these six periods are all significant, however, other variables like locust, famine, crop failure and socioeconomic turmoil displayed heterogeneity over the periods. Locust plague was more significant in the 1660-1680 and 1830s and then reached a peak in the 1850s. Famine, while presenting increases in the 1600s, was relatively more significant in the 1770-1790 and 1800s and doubled in the 1870s. Socioeconomic turmoil presented a trend with sporadic increases in the early and mid Qing dynasty and a dramatic propagation in the late 1800s. Table 1 shows correlation coefficients among all those variables. Clearly, drought is highly correlated with crop failure and famine, and is less correlated with locust and socioeconomic turmoil.

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Locust is more related with crop failure. And socioeconomic turmoil is highly correlated with crop failure and famine. Crop failure is highly correlated with famine. This likely indicates that while drought can have a significant impact on crop failure and famine, its direct correlations with social turmoil and locust can be less evident. More analysis on the narratives of the severe drought events and the impacts is thus necessary.

4a

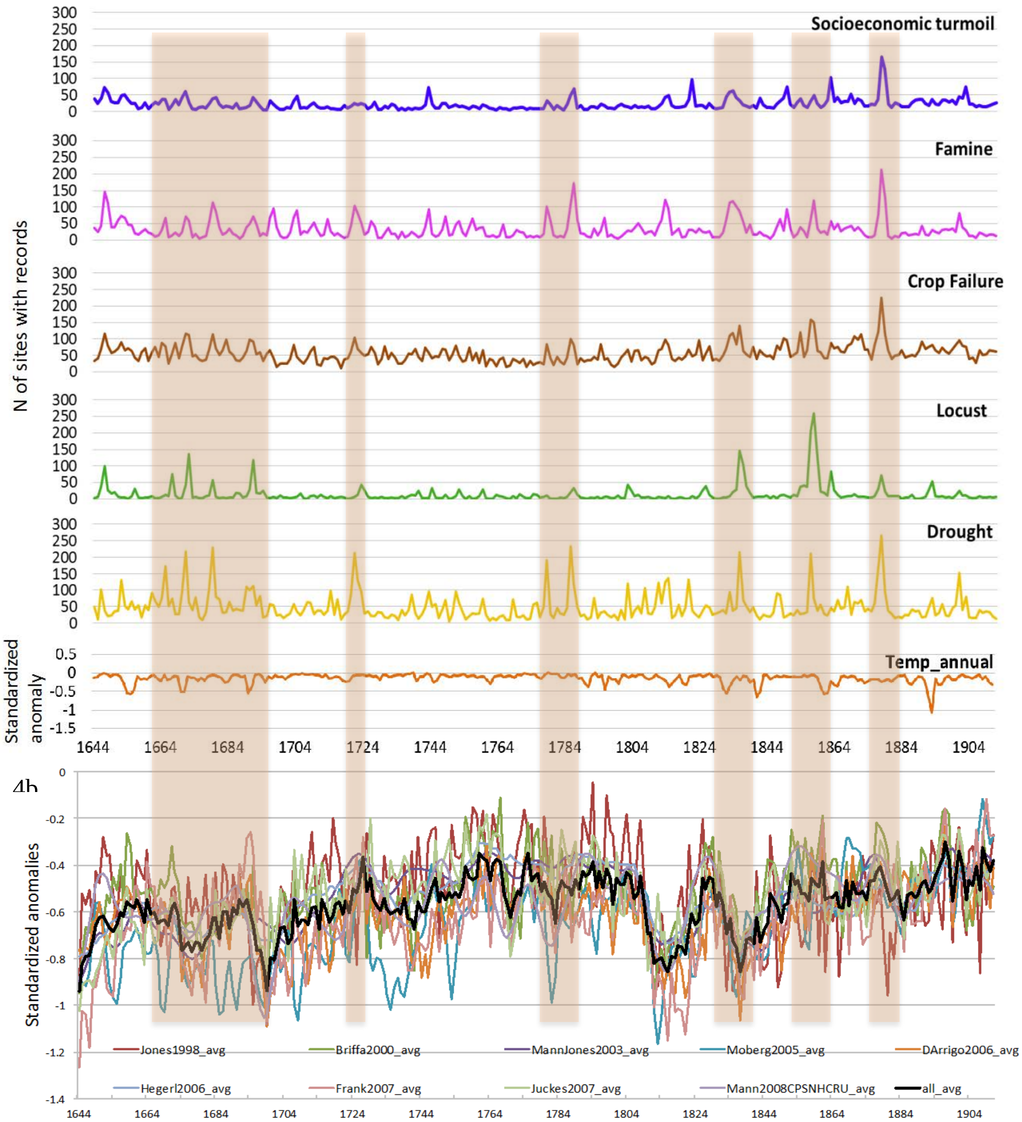

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Figure 4 Time series of multiple variables. 4a shows series of the variables reconstructed from the REACHES. Temp_annual denotes annual temperature anomalies reconstructed in Eastern China. 4b shows ensemble North Hemisphere temperature anomalies from Frank et al. 2010.

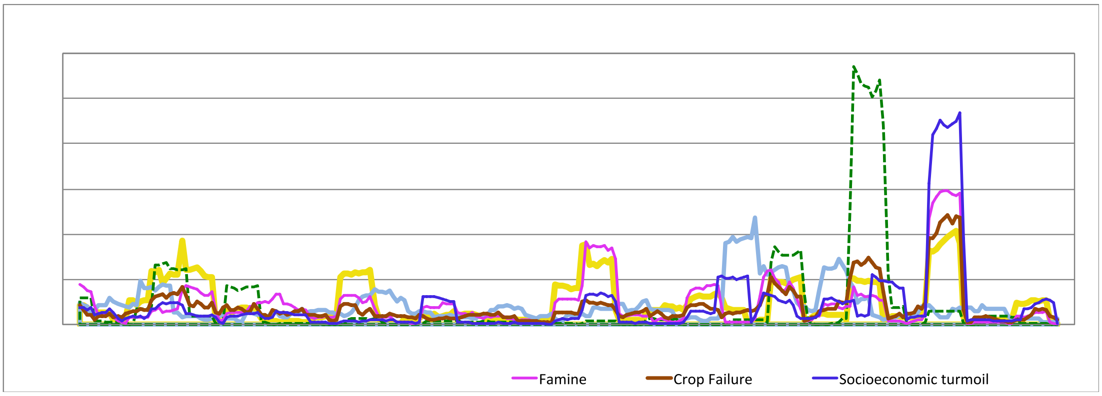


Figure 5 The 9-Years running variance for the multiple variables of the REACHES.

Table 1 Correlation coefficients of REACHES multiple variables

| | Drought | Locust | Socioeconomic turmoil | Crop Failure | Famine |
|---|---|---|---|---|---|
| Drought | 1.000 | | | | |
| Locust | 0.375 | 1.000 | | | |
| Socioeconomic turmoil | 0.442 | 0.287 | 1.000 | | |
| Crop Failure | 0.626 | 0.511 | 0.685 | 1.000 | |
| Famine | 0.618 | 0.379 | 0.718 | 0.675 | 1.000 |

*All coefficients have P-value <0.001. High correlation coefficients are shaded with dark gray and medium correlation coefficients are shaded with light gray.

## 4.2 Six severe drought periods and spatial patterns

According to the previous analysis, we identified six severe drought periods as follows: 1665-1691, 1720-1740, 1770-1790, 1830-1850, 1850-1870, and 1870-1890. Notably, those severe drought periods are defined primarily based on the drought frequency and severity, but the temporal definitions for every period are slightly modified according to the supporting narratives that we collected from other archival documents (will be explained later). For example, during 1720-1740, the severe drought mainly occurred around 1720 but we extended the period till 1740 due to

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continuous drought in the 1730s and 1740s and their socioeconomic effects were closely linked. For three severe drought periods in the 1800s, one may argue that three periods can be viewed as an enduring mega drought from 1830 to 1890. This view can be acceptable, however we separated them because three peaks in every two decades can be clearly identified and the spatial patterns as well as social contexts of them are heterogeneous.

For the spatial patterns (Figure 6), severe drought in the late 1600s had the most intensive and widest spread condition over the whole eastern China, from north of Hebei Province down to Guangdong Province. Drought especially clustered in the Yellow River plain and lower and middle reaches of the Yangtze River plain. In the meantime, severe locust plague extensively invaded in these regions where crop failure and famine coincidently happened. Socioeconomic turmoil occurred countrywide but had higher frequency agglomerating in the low reach of Yangtze River into Huai River.

The 1720-1740 drought was relatively much lighter than the 1600s one, mainly focusing on the lower reaches of the Yellow River and Yangtze River plains. From density distribution, drought in the lower reach of Yangtze River plain was more intensive than in the Yellow River plain, and so were locust plague, famine and socioeconomic turmoil. However, interpretation of the spatial pattern at regional and local scales should be very careful, because distribution of record is subject to the nature that the phenomena must be recorded by some persons in certain places. Thus places have higher population density such as big cities or capitals can have an amplified effect in recording than other villages or remote areas. Therefore, within regional scale, it might not be proper to interpret that drought in lower reach of Yangtze River plain (where Shanghai, Suzhou, and Hangzhou are located) was definitely severer than in the neighboring counties due to this amplification effect. However, for regional comparison, the spatial distribution can undoubtedly reveal overall density pattern across eastern China.

The 1770-1790 drought also presented a prevailing pattern but with less severity, spreading from Yellow River plain to Guangdong Province. Other variables such as locust plague and famine were also widely distributed but intriguingly crop failure was not as significant as others. Socioeconomic turmoil still sporadically appeared and with a tendency to occur more frequently in the south, central-west, and north parts of China. The 1830-1850 drought also manifested a big area distributing mainly in the Yellow River and Yangtze River plains, with a small area in the south of

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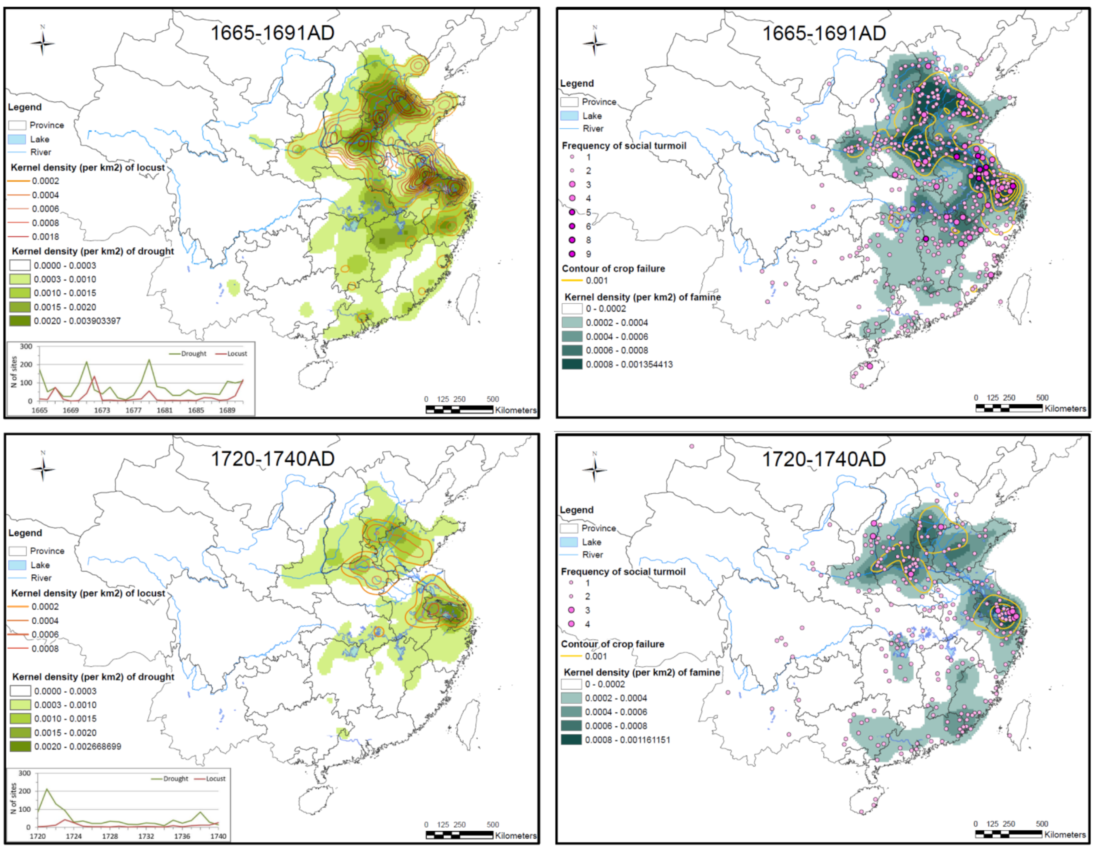
Guangdong and Guandxi Provinces. The most noted phenomenon of the period was the wide invasion of locust plague and famine that spread deeply into the central-west (e.g. Sichuan Province). Socioeconomic turmoil also developed substantively along the Yangtze River plain into its middle reach. Locust plague deteriorated and reached its peak in the 1850-1870 during which severe famine continued and socioeconomic turmoil spread across the whole country. In the 1870-1890 drought, lower mid-latitude seemed to have relieved from severe drought where famine and crop failure along with drought mostly appeared in the Yellow River plain, Yangtze River delta, Sichuan Province. Socioeconomic turmoil clustered also in the Yellow River plain.

6a



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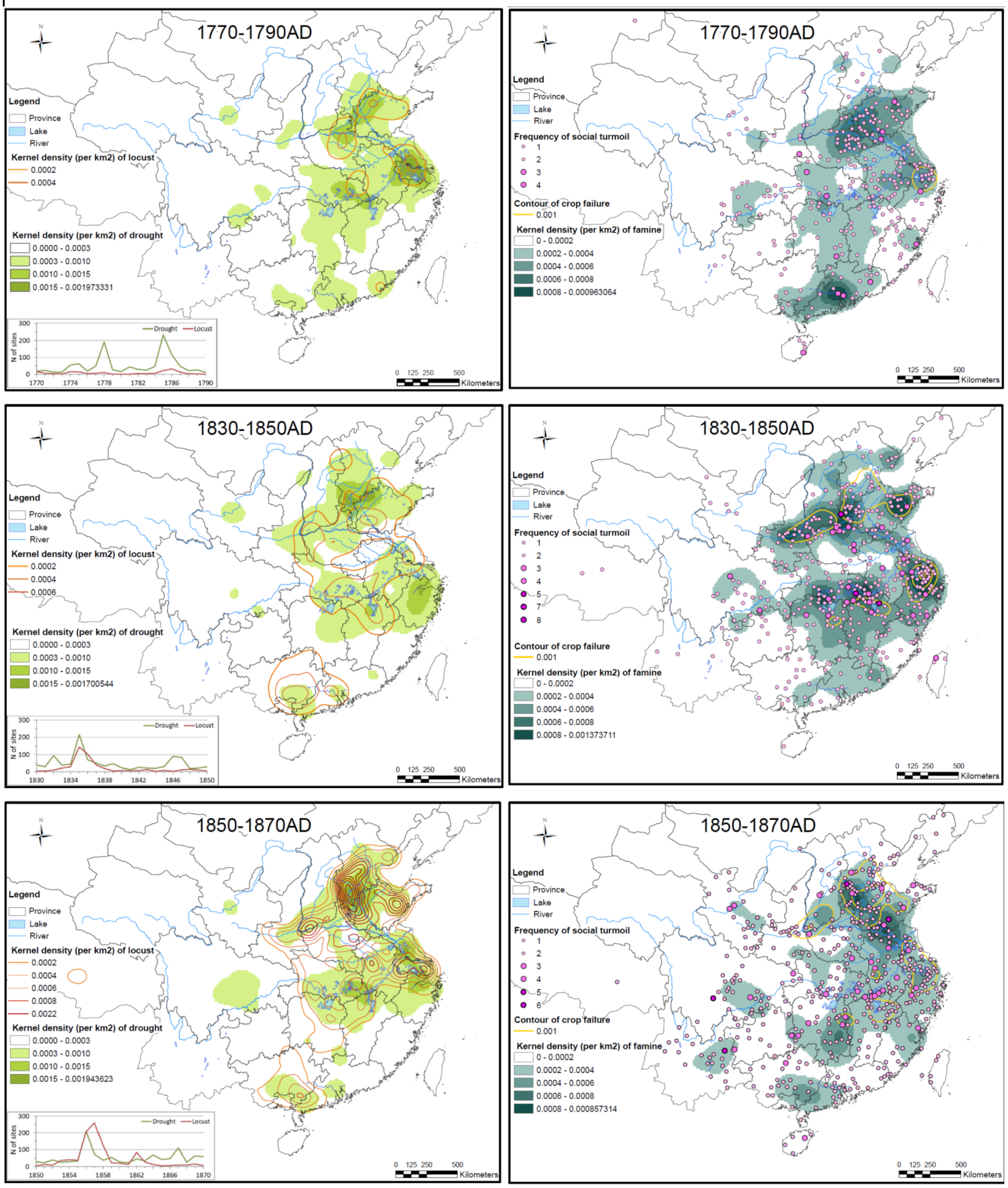

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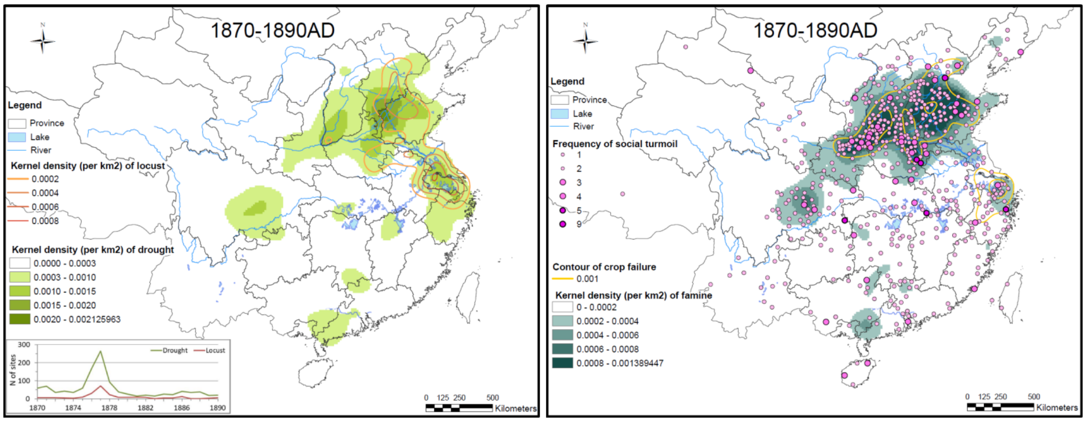


6b

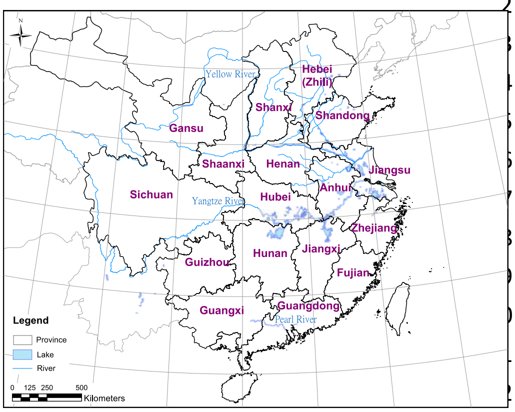


Figure 6 Kernel density distributions of drought & locust (6a left panels) and famine, crop failure, and social turmoil (6b right panels) records in the six severe drought periods. 6b shows provincial boundaries and names. Using Esri World latitude and longitude grids dataset and the provincial and city/county boundary and river shapfiles are from China National Bureau of Mapping and Surveying, Digital Map Database of China, Beijing, China, 1990.

## 4.3 Narratives of the six severe drought periods

To further investigate how drought was associated with locust, food production and social responses, we built up narratives of the six periods to reveal their contexts and important factors. The content of the narratives were from the archival documents mentioned in the data section. Since those are from independent sources, the built narratives can also be viewed as good material to cross check and validate the REACHES reconstructed series and analysis.

The first three of the six severe drought periods occurred during the golden era (1683-1839 CE) of the Qing dynasty, which represented the most prosperous era of the dynasty under ruling emperors of *Kang Xi*, *Yong Zheng*, and *Qian Long*

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sequentially. In the era, the society experienced fast population growth and stabilization of social order for the first time in the decades after numerous wars and battles in the dynastical transition from Ming to Qing in the 1644. Meanwhile, centralization of monarch power was greatly strengthened and governmental policies including disaster relief such as grain dispatching, tax exemption and procedures for locust mitigation were effectively implemented. By the end of the golden era, however, unfortunately the succeeding emperors were not as capable and the country also faced grand challenges of western force invasion especially after the first Opium War (1840-1842) when Qing was then forced to sign an unequal treaty with the United Kingdom. Prevailing civil rebellions blossomed across the country and the dynasty collapsed in the early 20th century.

#### 4.3.1 1665-1691 drought (Emperor *Kang Xi* reign)

After the wars of the Ming-Qing transition, population continued to reduce in the decades. Frequent civil wars still occurred in the1670-1680 and 1690 (Figure 7). Qing governments had to put great efforts to conquer various local revolts especially in the south and northwest of China, such as suppressing the revolts of the Three Feudatories and Chakhar Mongols. When severe drought and locust plagues occurred from 1670 to 1672, areas around Zhili (previous name of Hebei), Shandon, Henan, Anhui and Jiangsu were seriously affected. Amplified droughts and locust plagues appeared again in the 1679, and 1689-1691, expanding to wider regions including Hubei and Shanxi. Although droughts and locust plagues caused poor harvest and famine from time to time and could be associated with socioeconomic turmoil, the severity seemed not to cause significant population decline and social impacts. As shown in Figure 7b, population grew slowly during this period. And Figure 7a also shows that while the circle of socioeconomic turmoil is large, the connections between it and drought or famine or crop failure is not such strong. This might indicate that socioeconomic turmoil of the time could be linked to other social processes. In fact, in the reign of the Emperor *Kang X*i, governmental policies for disaster relief, such as food supply, stabilizing grain price and tax exemption were accurately implemented including a notified command to catch locusts for preventing from enhanced crop damage. Therefore, while having severe natural disasters, documents showed that governmental effectiveness seemed to contribute to mitigating further damages and avoiding people from displacement and amplified social unrests.

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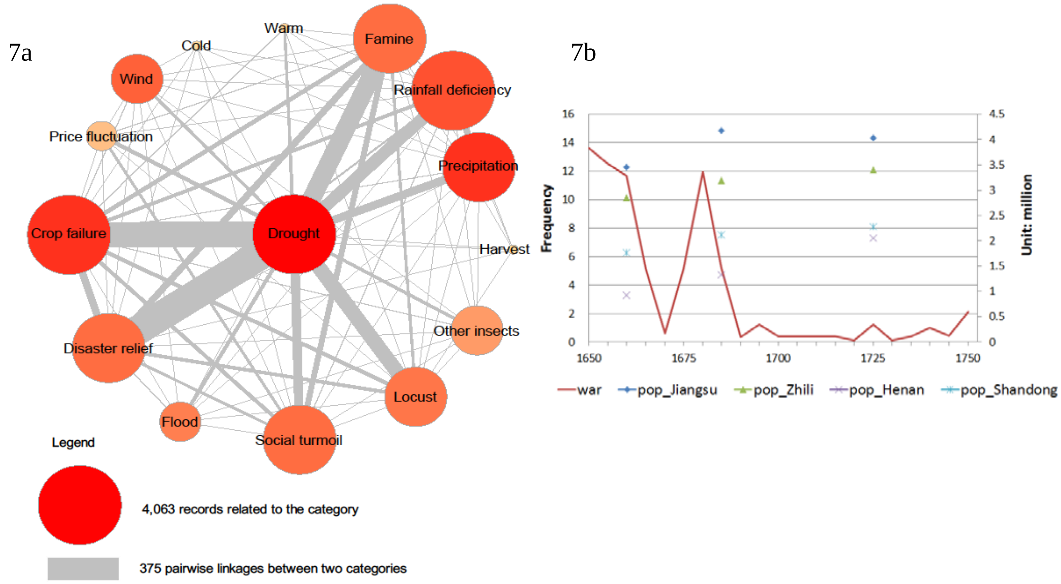


Figure 7 The 1665-1691 drought network analysis and socioeconomic context. 7a shows network analysis for variables retrieved from REACHES database. The size of circle represents the number of records in a category. The thickness of the line connecting two different circles represents how frequent they are mentioned together in the records. Social turmoil is shortened term for socioeconomic turmoil. 7b shows population and war frequency in 1650-1750.

4.3.2 1720-1740 drought (Late *Kang Xi* to *Yong Zheng* and early *Qian Long* reign)

In the late years of the *Kang Xi* reign, population continued to grow and land prices also increased. This had resulted in the increasing cost of the agricultural products and the gaps between rich and poor also substantially widened. In the meantime, drought and occasional locust plagues happened and significantly affected agricultural production. In 1723, drought and locust plagues occurred in Shandon, Anhui and Jiangsu, which was probably related to the continuation of the 1721 drought. Regional drought and locust plagues still had a certain influence on the affected areas. According to the 1725 population record, Shandong's population grew slowly at this time, and the population of Jiangsu showed a downward (Figure 8). After that, famine appeared in the north of the Huai River around 1738 lasting for several years, which was also related to drought. During this period, socioeconomic turmoil was only sporadic, individual, and small in scale (Figure 8), and was easy to suppress. Besides, governmental policies on disaster relief remained effective, including porridge

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releasing, grain dispatching and tax exemption, and more forceful commands to catch locusts were implemented.

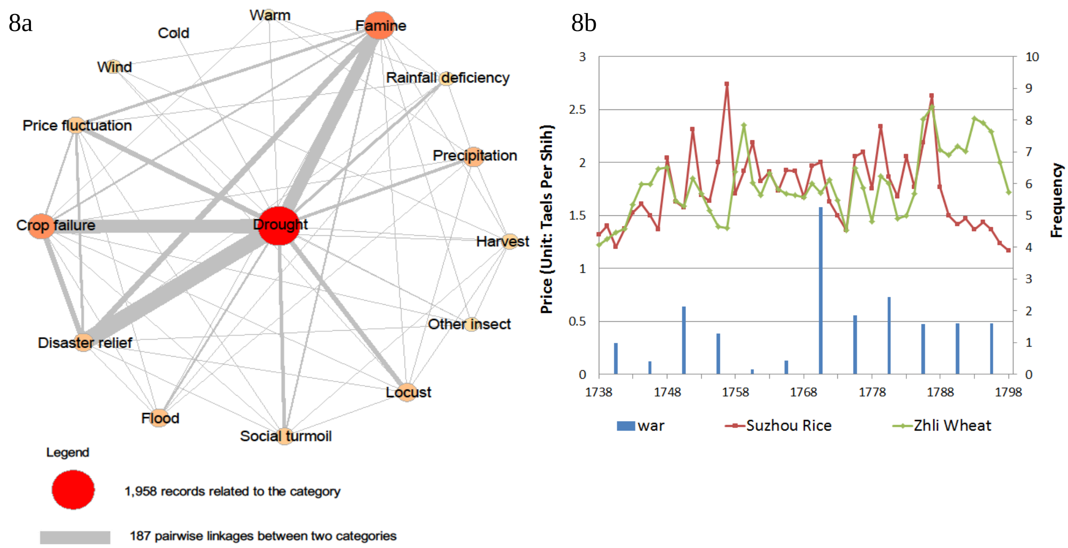


Figure 8 The 1720-1740 drought network analysis and socioeconomic context. 8a shows network analysis for variables retrieved from REACHES database. The size of circle represents the number of records in a category. The thickness of the line connecting two different circles represents how frequent they are mentioned together in the records. Social turmoil is shortened term for socioeconomic turmoil. 8b shows grain price in Suzhou (Jiangsu Province) and Zhili and and war frequency in 1738-1798.

### 4.3.3 1770-1790 drought (*Qian Long* reign)

In the middle of the *Qian Long* reign, population returned to the size of the Ming Dynasty (Figure 9). However, social inequality and gaps between poor and rich enlarged that sequentially resulted in frequent social unrests with longer and wider social impacts. Fortunately, during the *Qian Long* reign, the government's ruling power still maintained functional to stabilize society. According to the historical documents, locust plagues were once severe during the period. Then the government enforced strict locust catching command emphasizing eradication of locusts before the insects grew their wings. This policy was likely to be effectively implemented so that the threat of locust plagues was substantively mitigated. However, drought still led to a reduction in crop yields resulting in famine and rise of grain price around 1779 and 1786 (Figure 8b).

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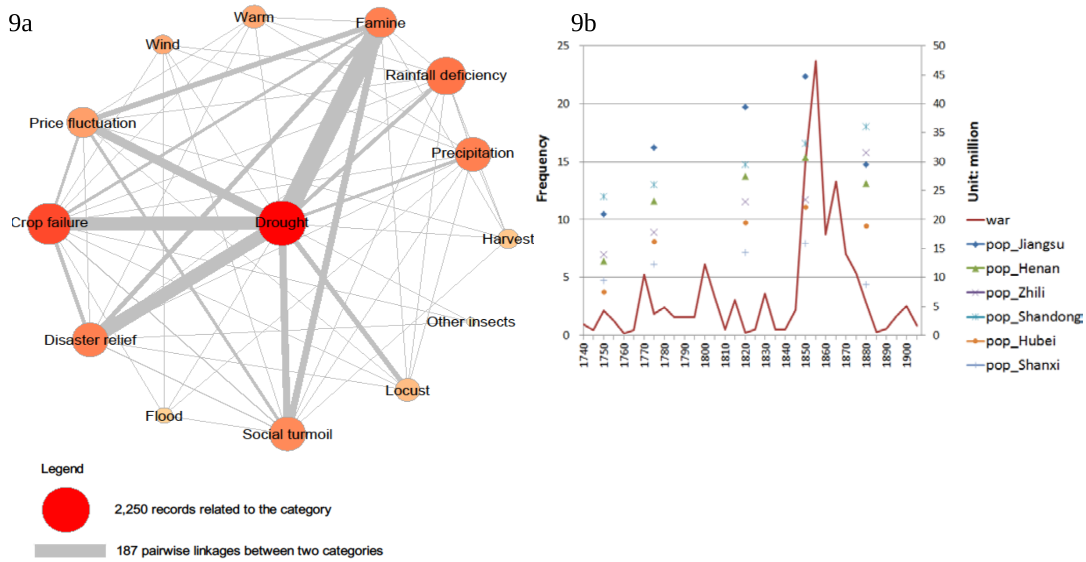


Figure 9 The 1770-1790 drought network analysis and socioeconomic context. 9a shows network analysis for variables retrieved from REACHES database. The size of circle represents the number of records in a category. The thickness of the line connecting two different circles represents how frequent they are mentioned together in the records. Social turmoil is shortened term for socioeconomic turmoil. 9b shows population and war frequency in 1740-1905.

4.3.4 1830-1850 drought (Emperor *Dao Guang* reign)

After the golden era, population continued to grow for several decades (Figure 9b) but per capital arable land presented a significant decline in the 19$^{th}$ century, therefore the society was under great stress of resource competition. When the Qing dynasty signed unequal financial treaty with the United Kingdom in 1842 and later more treaties with other foreign countries, the imperial power was also stuck in serious political corruption that had eventually led to massive uprisings across the country (Figure 10). The most well-known revolt was the Taiping civil war which was related to a construction of Taiping Heavenly Kingdom (1851-1864) founded in Guiping (Guangxi Province) and Guangxi in 1847, and gradually expended northward to Hunan and Hubei. As a matter of fact, historical documents revealed that the beginning of the Taiping rebellion could be associated with deteriorated locust plagues in the region. According to the Guangxi records, a large-scale locust plague occurred in 1833-1836; after that, the area around Guiping was noted with serious

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drought and locust plagues in 1845-1848, and by 1850, rice price rose and famine appeared. Besides, Hubei also had serious famine, drought and locust plagues in 1832 that continued in 1835.

However, the trajectory of rice price in different regions presented very different patterns (Figure 10b). Rice price did not fluctuate greatly in Guangxi over the period. In Hubei, rice price showed a slight increase in 1832 and then maintained a decline trend. In Suzhou, rice price firstly increased in 1834 and then drop till an increase in 1840-1851. The regional difference of price fluctuation is likely to indicate that food production and consumption of the time was restricted to local scale without much inter-regional interactions. This separation might also influence food supply and allocation during disaster relief.

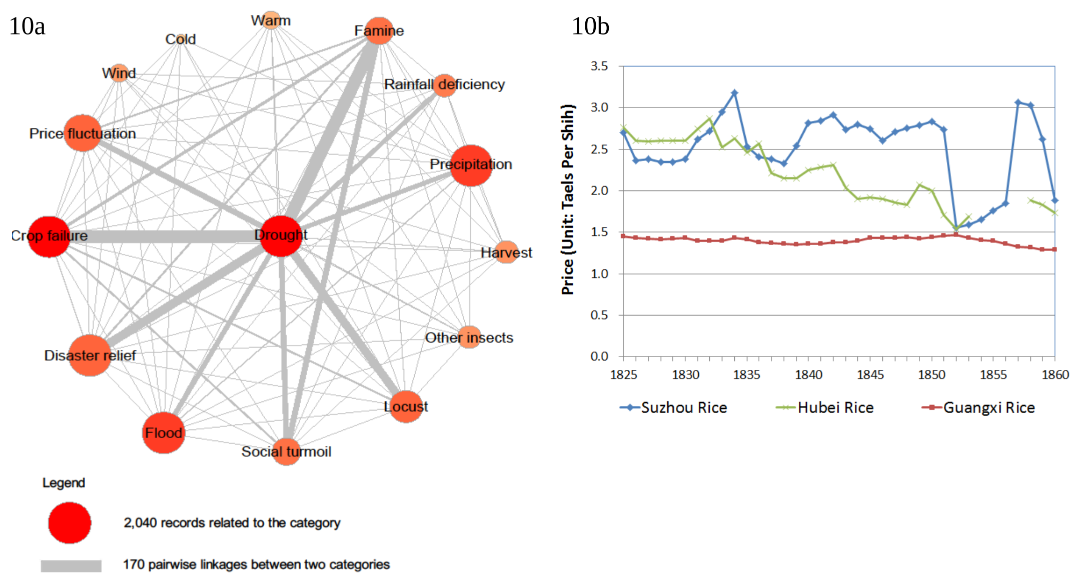


Figure 10 The 1830-1850 drought network analysis and socioeconomic context. 10a shows network analysis for variables retrieved from REACHES database. The size of circle represents the number of records in a category. The thickness of the line connecting two different circles represents how frequent they are mentioned together in the records. Social turmoil is shortened term for socioeconomic turmoil. 10b shows grain price of Suzhou, Hubei and Guangxi in 1825-1860.

4.3.5 1850-1870 drought (*Dao Guang* to *Tong Zhi* reign)

When the Taiping Army rose in the south, northern China was also tormented by the

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Nien Rebellion (1853-1868) that sequentially resulted in significant population decline especially in the Provinces of Jiangsu, Zhejiang, Anhui, Jiangxi, Zhili, Hubei, Shanxi, Shaanxi and Gansu (Figure 11). In 1856-1858 severe drought happened with amplified locust plague disasters. The most affected regions including Zhili, Hubei and Shandon were also where frequent battles occurred during the period. Socioeconomic unrests and drought cooperatively resulted in a dramatic food shortage and increase of grain price (Figure 11b). Jiangsu, the main rice market of China, had the most sudden increase of rice price. During this period, population continued to decrease, governmental policies for disaster relief mainly referred to limited food allocation to impacted regions and population immigration (and displacement).

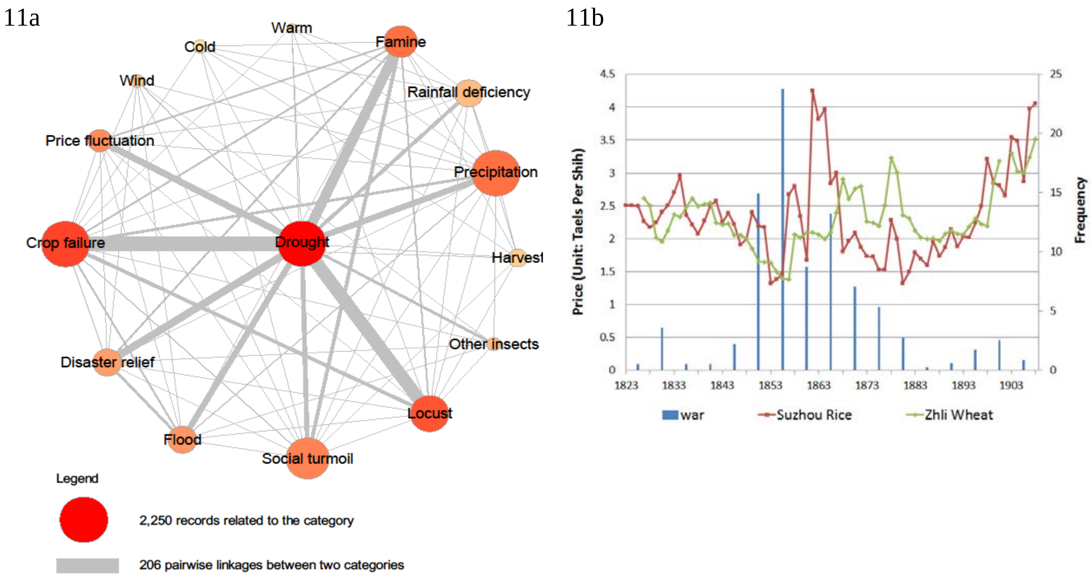


Figure 11 The 1850-1870 drought network analysis and socioeconomic context. 11a shows network analysis for variables retrieved from REACHES database. The size of circle represents the number of records in a category. The thickness of the line connecting two different circles represents how frequent they are mentioned together in the records. Social turmoil is shortened term for socioeconomic turmoil. 11b shows grain price and war frequency in 1823-1908.

4.3.6 1870-1890 drought (*Tong Zhi* to *Guang Xu* reign)

When severe drought occurred in northern China from 1876 to 1879, the affected regions mainly clustered in Shanxi, Henan, Shaanxi, Zhili, and Shandong. Grain prices in these provinces also rose sharply (Figure 12b) and population continued to

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decline (Figure 9b). Although drought did not cause significant civil wars, famine still caused serious social unrests as figure 12a shows that during this period socioeconomic turmoil had strong connections with drought and famine. And importantly the wars between Qing dynasty and the foreign powers continued to expand.

However, according to some historical research (Wang, 1972), disaster relief in the late 1800s could be more effective than in the earlier 1800s. The main reason was the integration of the grain market to link North China with Yangtze River plain that substantially strengthened inter-regional grain product movement and exchange. From the disaster relief perspective, efficient food interexchange and allocation could greatly alleviate food shortage problems in the affected regions avoiding further death and social impacts. And notably, spatial integration of grain market was benefited from transportation development due to military and financial needs of the time under threats of foreign country invasion.

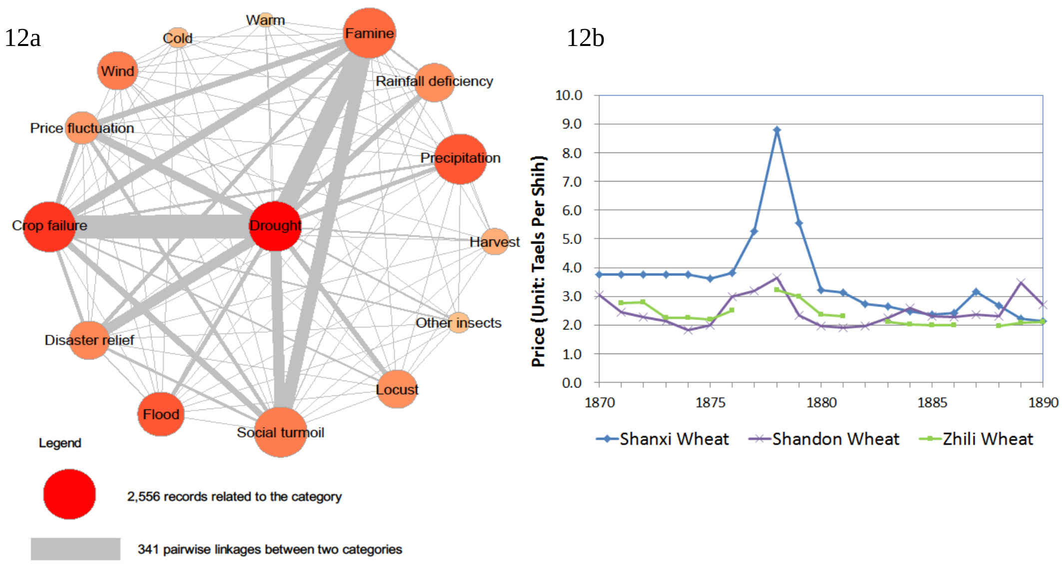


Figure 12 The 1870-1890 drought network analysis and socioeconomic context. 12a shows network analysis for variables retrieved from REACHES database. The size of circle represents the number of records in a category. The thickness of the line connecting two different circles represents how frequent they are mentioned together in the records. Social turmoil is shortened term for socioeconomic turmoil. 12b shows grain price of Shanxi, Shandong and Zhili in 1870-1890.

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## 5. Discussions and conclusions

This study presents a novelty in the methodology to analyze historical droughts and their relations with other associated ecological, agricultural, and socioeconomic variables. Instead of building mixed criteria to evaluate drought severity by artificial and often subjective judgment on the texts of the written records and assign them into different grades, this study adopts a clear-cut methodology to build a transparent procedure for studying and reconstructing drought chronology. Drought and its associated variables including locust, famine, crop failure and socioeconomic turmoil are carefully defined and separately dealt with to build their distinctive chronologies. The advantage of this method is the transparency of the approach, which also allows cross check among variables and thorough statistical examinations on the relations.

There are several important methodological innovations and new findings in this study. Firstly, we examined the literal meaning of drought mentioned in the written records by considering the four categories of drought as defined by the scholars (Brázdil et al., 2018; Heim, 2002). We found that, in the Chinese literature context, metrological drought and hydrological drought can be closely correlated with each other (R=0.67); especially hydrological drought had even stronger correlation coefficient (R=0.77) with severe drought. This can be easily understandable since hydrological drought needs more time to develop and dry after prolonged lack of rainfall or any type of water infusion. Agricultural drought denoted by crop failure in this study also presented high correlation (R=0.63) with meteorological drought. Socioeconomic drought estimated separately by famine (R=0.62) and socioeconomic turmoil (R=0.44) has relatively less correlations.

Secondly, by using the proposed method, we found a distinct multi-decadal to centennial scale hydroclimate fluctuations in the 1644-1911. Higher frequency of drought and associated events coincidently appeared with lower temperature anomalies in the 17$^{th}$ century and after the late18$^{th}$ century. The lower temperature anomalies are consistent in REACHES and other studies (Frank et al., 2010; Ge et al., 2017). Additionally, while several previous studies in China have clearly pointed out that 16$^{th}$ and 17$^{th}$ century had more frequent droughts than the later two centuries (Ge et al., 2016; Shen et al., 2007; Song, 2000; Yi et al., 2012; Zheng et al., 2006), seldom of them were able to identify intrinsic drought events at interannual and decadal resolutions. In this study, six severe drought events are identified including 1665-1691, 1720-1740, 1770-1790, 1830-1850, 1850-1870, and 1870-1890 drought periods.

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Thirdly, to explore spatial pattern of the variables, we performed Kernel density estimation, which explicitly uncovers spatial distribution of drought and all other variables in the six severe drought periods. The spatial distribution is very powerful to reveal spatial autocorrelations of drought and other variables and to compare their distribution and severity among these six periods. Moreover, social network analysis reveals the relative magnitude of those variables in the six periods and the strength of connections among them.

Fourthly, and importantly, to build narratives for the six severe drought periods, we applied a great quantity of archival and index data from independent sources to further investigate the social and economic contexts of the severe drought events. In addition to the empirical implications (which we will elaborate later), research results show a good consistency between the content retrieved from the archival data and the analysis derived from the REACHES. For example, heavily impacted regions shown on the maps are very consistent to those provinces and cities or counties mentioned in the archival data. Interpretation of social network analysis for the six periods can be a little controversial since the patterns do not always reflect the contexts as recorded in the archival data. For example, in the 1665-1691 drought period, socioeconomic turmoil presents a big circle however the historical documents recorded that drought disaster was though severe but was controlled under governmental effectiveness. In this regard, we could also interpret that socioeconomic turmoil while was frequently recorded in the REACHES database but the connections between it and drought or famine is relatively weaker than the later periods as shown in the network analysis. In other words, it suggests that the socioeconomic turmoil in this period could be more associated with other social process than direct connections with natural disasters. An opposite example is the socioeconomic turmoil in the 1870-1890 in which the variable was strongly connected with drought and famine. Nonetheless, the comparison between REACHES and other independent data validates the reliability of the REACHES database.

In addition to the methodological innovation, there are also two important implications from the analysis. One is from the disaster risk perspective, and the other is the highlight for historical climate reconstruction. Our analysis suggests that drought though can be connected with socioeconomic turmoil; the correlations between them are not direct, straightforward or inevitable. It is obvious that crop failure and famine are the most important and intermediate variables to influence if drought would develop to result in the amplified social impacts. This correlation is not

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only revealed in their coefficients as shown in Table 1 but also clearly demonstrated in the narratives of the six severe periods. Moreover, locust plague and disaster relief are two imperative factors to influence between the magnitudes of crop failure and famine. This clearly points out that human intervention is an important determinant in shaping the socioeconomic as well as environmental feedbacks to the drought and their impacts.

Comparing two severe drought periods in the 1700s and other three periods in the 1800s, apparently the magnitude of crop failure was quite different even if the severity and spatial distribution of drought were not dramatically discrepant. While there could be some other environmental and social factors to influence crop production, it is obvious that locust mitigation policy in the 1700s could play an important role to avoid enhanced crop failure during the period so as to alleviate severe famine due to food shortage. From the disaster relief perspective, governmental capabilities to implement disaster relief policies were also important factor to mediate severity of famine. Disaster relief policies such as grain dispatching, porridge relief and tax exemption when effectively implemented as in the gold era could greatly reduce death and stabilize grain prices, which were all important to maintain social order. After the golden era, governmental capabilities and social stabilities rapidly degraded and threats from foreign forces had worsened. When enduring drought occurred, the society had less capability to respond so that locust, crop failure, famine and socioeconomic turmoil had strongly linked together to form catastrophic disaster impacts.

It is also noted that while socioeconomic turmoil was frequently recorded in the REACHES database, estimate of statistical correlations based on the frequencies of drought and socioeconomic turmoil does not necessarily reflect the real situations. Namely, it is inappropriate, and even dangerous, to interpret the relations between the two simply based on the statistics. As mentioned earlier, large number of socioeconomic turmoil records in the 1665-1991 drought had more relations with post-Ming rebellions and social unrests. The two natural and social events coincidently happened at the same time. However, another case from Taiping civil war was clearly triggered by famine and locust plagues in Guangxi. Even Guangxi was not the most serious drought area at the time, ineffectiveness of the local government to motivate resources for mitigating disaster eventually led to social unrests. Similar context also applied to the 1856-1858 and 1876-1879 droughts. Therefore, caution should be taken beyond statistics to investigate any relationships between natural and social processes.

Some highlights for historical climate reconstruction include interpretation of drought chronology and the meaning of severe drought in the climate reconstruction. It is very often that when an analysis delivers a drought chronology then the periods (mostly decades or centuries) with higher frequency of drought would be easily interpreted as a dry weather. As a matter of fact, this interpretation could be inadequate and biased. As shown in figure 5 in which we purposively reserve flood series for demonstration, it is obvious that the fluctuation of flood series has good consistency with drought series especially in the mid-17$^{th}$ and early 19$^{th}$ centuries. It is thus likely that these two periods have more extreme hydroclimate events than other centuries and time periods. Moreover, this also illustrates the importance to separately deal with drought and flood events instead of integrating them into one single index as practiced in many previous studies. Future studies can also use spatial distribution of those extreme hydroclimate variables to reconstruct their spatial patterns so as to investigate the climatic factors and atmospheric conditions. More specific insights can also be derived from using the data to analyze atmospheric circulation and eastern Asian monsoon in these intervals of little ice age. Data series reconstructed in this study will be deposited at NOAA World Data Center.

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