

1 Historical droughts in the Qing dynasty (1644-1911) of China

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10 **Abstract.** This study presents a new epistemological analysis of drought chronology through a well-defined
11 methodology for reconstructing past drought series as well as series of other associated ecological and societal impact
12 variables. Instead of building grading system based on mixed criteria, this method facilitates transparency in
13 reconstruction process and enables statistical examination of all variables when building series. The data for the
14 present study is derived mainly from the REACHES database, however, other archival documentary and index data
15 from independent sources are also applied to understand drought narratives and to cross check and validate the
16 analysis derived from the REACHES. From time series analysis, six severe drought periods are identified in the Qing
17 dynasty, and then spatial analysis is performed to demonstrate spatial distribution of drought and other variables in
18 the six periods as well as social network analysis to reveal connections between drought and other ecological and
19 societal variables. Research results clearly illustrate the role of human intervention to influence the impacts of drought
20 on societal consequences. Particularly, the correlation between drought and socioeconomic is not strong; crop failure
21 and famine are important intermediate factors, meanwhile ecological factor such as locust and disaster relief measures
22 are all imperative to intervene between crop production and famine. Implications of the study on drought impact are
23 provided as well as its significance on historical climate reconstruction studies.

24 25 1. Introduction

26 Global warming is expected to influence the earth's hydrological cycle and put higher stress on water resources.
27 Climate simulations reveal a wide expansion of dry areas over land and an intensification of wet-dry contrast at lower
28 latitudes (Held and Soden, 2006; Schewe et al., 2014). There are some recent observations that hint agreement with
29 the projected enlarging wet-dry contrast pattern and intensified drought (Schewe et al., 2014) although substantial
30 uncertainties about specific patterns and trends remain. Even less understood is the interannual and decadal scale
31 change pattern of regional precipitation and the duration and magnitude of drought at finer spatial and temporal
32 resolution (IPCC 2013). Obviously, more high quality hydroclimate data are necessary if we wish to remove these
33 uncertainties. Such data are also necessary for assessing the performance of climate models, especially on their
34 capability in projecting reliably the climates of next few decades. The length of instrumental meteorological data series
35 is only a little more than a hundred years which is not long enough to assess the validity of climate models that make
36 predictions of many decades into the future (Cook et al., 2014; Ljungqvist et al., 2016).

38 The most direct manifestation of hydroclimate variability is the drought and flood of the environment (Routson et al.,
39 2016; Stevenson et al, 2018). Drought and flood are two extremes of the hydrological cycle and both can induce severe
40 environmental and socioeconomic consequences. Flood which generally represents sudden onset of excessive water
41 can lead to immediate loss of lives and material damages. The formation of drought, on the contrary, normally refers
42 to a slower and longer water deficiency process that can result in a more chronologically extended range of impacts
43 on agriculture and water scarcity contributing to catastrophic socioeconomic outcomes (Brázdil et al., 2019). Given
44 the intensified drought condition in the future scenarios as described above, there is an urgent need to study past
45 drought, especially the severe drought cases, to decipher their occurrence, duration, magnitude, and the associated
46 ecological and societal consequences for implications of future adaptation.

47

48 Studying past drought and humidity has been a long practiced subject in historical climatology and paleoclimatology
49 (Stahle et al., 2007; Tan and Liao, 2012; Yi et al., 2012; Cook et al., 2015; Ge et al., 2016; Hao et al., 2016; Brázdil
50 et al., 2018; Shi et al., 2018). In the instrumental era, drought is relatively easy to be defined based on the temperature
51 and precipitation measurements. The instrumental era can be tracked back to the mid or late 19th century when many
52 national weather services started (Broennimann et al., 2018). Some early instrumental meteorological data might be
53 acquired in some regions dated back to the late 17th and early 18th century. Prior to the instrumental era, there are
54 primarily two sources of data that can be used to build drought series of high temporal resolution: tree ring data and
55 [documentary records](#) (White, 2019). Tree rings provide abundant information about moisture, and sometimes
56 temperature, for reconstructing millennial long hydroclimate indices from which drought can be inferred. The most
57 well-known works include Old World Drought Atlas using tree ring data (Cook et al., 2015) calibrated with Palmer
58 Drought Severity Index (PDSI) (Palmer, 1965), Monsoon Asia Drought Atlas (Cook et al., 2010), and Megadroughts
59 over North America (Stahle et al., 2007). Yet, tree ring reconstruction often suffers from the uncertainty in growing
60 seasonality of trees and ambiguous interpretation of isotopes (Schofield et al., 2016). [Nonetheless, high quality](#)
61 [quantitative drought-indices series such as Standardized Precipitation Index \(SPI\) \(McKee et al., 1993\), Standardized](#)
62 [Precipitation-Evapotranspiration Index \(SPEI\) \(Vicente-Serrano et al., 2010\), PDSI, and Palmer Z Index can also be](#)
63 [reconstructed from documentary data. For example, Brázdil et al., \(2016\) and Možný et al. \(2016\) have built monthly,](#)
64 [seasonal, half-year and annual resolution SPI, SPEI, Z-index, and self-calibrated PDSI for the Czech Lands. Moreover,](#)
65 [some other special drought indices series were developed in Europe like Drought Rogation Index in Spain \(Barriendos,](#)
66 [1997\) or Drought Index in Italy \(Diodato and Belocchi, 2011\).](#)

67

68 Documentary records reflect direct human observations of weather condition and are less ambiguous when used for
69 reconstructing past climate. They contain weather, climate, phenological, and socioeconomic situations in specific
70 locations in various time resolution such as daily, monthly or seasonal, allowing comprehensive analysis on drought
71 events, scales, and contexts (Brázdil et al., 2019; Huang et al., 2019). To be sure, there are also some criticisms about
72 inferring drought from documented records, for example, it is sometimes hard to distinguish whether the drought
73 record refers to rainfall deficiency, hydrological process or crop irrigation need. Several studies tried to remedy this
74 by proposing four categories of drought: meteorological drought caused by significant reduction of precipitation for
75 weeks or months compared to normal precipitation; agricultural drought associated with lack of water for plant growth

76 for a period lasting from weeks to 6-9 months; hydrological drought characterized by a shortage or absence of water
 77 in water courses, reservoirs or aquifers; and socioeconomic drought caused by negative effect of drought on everyday
 78 life, social system and stability (Heim, 2002; Brázdil et al., 2018). There is yet another view suggesting drought as a
 79 complicated process of water shortage caused and modified by human processes (Van Loon et al., 2016). Despite of
 80 such shortages, documentary records are still one of the most important sources for reconstructing drought series, only
 81 that we have to be very careful in extracting proper information from them.

82

83 Brazdil et al. (2018) have described various types of documentary records that can be used for extracting drought
 84 information. Before the instrumental era, all historical climate records are essentially qualitative or narrative in nature,
 85 and it is necessary to transform them into numerical data series so that statistical analysis of them can be performed.
 86 The most common practice is to design a three-, five- or seven-grade system based on the duration and severity of
 87 drought (Zheng et al., 2014; Brazdil et al., 2018) so that every single quotation of drought record can be assigned a
 88 specific value according to the grading criteria. Arranging these grades as a sequence in time and we get a time series
 89 of drought grade, often called a drought index series. In reality, however, transformation process from qualitative
 90 narratives to digital series can be tricky because a wide spectrum of grade assignment strategy exists and different
 91 investigators can derive very different index series based on the same set of drought records. More detailed discussions
 92 on this matter have been given by Brázdil et al. (2005) and Pfister et al. (1999).

93

94 In China, a dryness-wetness (also referred to as drought/flood) index has been widely used in recent decades for
 95 reconstructing past climates (Tan and Liao, 2012; Yi et al., 2012; Zheng et al., 2014, Hao et al., 2016; Shi et al., 2018,
 96 for detailed review on historical climate records in China and reconstruction of past climates please refer to Zhang
 97 and Crowley 1989). The index series was initially built by the Academy of Chinese Meteorological Science (CMA,
 98 1981; Wang and Zhao, 1981) based on historical documentary records and was sequentially expanded by several
 99 Chinese scholars (see Zhang, 2003; also see Hao et al., 2019). The index system, based on Yi et al. (2012) with
 100 modifications from Zheng et al. (2014) and Tan et al. (2013), specifies a five-grade scheme as described in Table 1:

101

Table 1: Dryness-Wetness index in China

Grade	Severity	Examples of some descriptions
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)
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)
3	Normal	Favorable weather (e.g. good weather for crops, bumper harvest)
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 outbreak)

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. thousands of miles of barren land, severe drought throughout south of the Yangtze River lower reach), famine (e.g. tens of thousands starved to death on the street, hungry people consumed tree roots or fine soils)
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103 This scheme uses mixed meteorological/hydrological/socioeconomic criteria to determine the drought grade to form
104 China's dryness-wetness index series. This system has the advantage in evaluating drought severity, however, it is
105 difficult to identify specific drought categories in the records as mentioned earlier. Thus one cannot identify whether
106 or not a certain drought event was associated with meteorological deficiency of rainfall or had more to do with the
107 failure of the agricultural irrigation systems. This can lead to biased interpretation of drought records as representing
108 the atmospheric humidity condition. It also prevents proper statistical associations among different drought categories
109 (each as an independent variable) and could lead to erroneous conclusions about the nature of the drought and its
110 impact.

111

112 This study takes a new conceptual point in examining the drought records and proposes a new method to reconstruct
113 past drought series and that of other associated ecological and societal variables from Chinese historical documentary
114 records. Our objective is to make the interpretation of every drought and associated variables as literally clear and
115 operationally independent as possible. This method can facilitate statistical examinations of these variables and enable
116 transparency in the reconstruction process of historical drought series. Moreover, we will also perform contextual
117 analysis of severe drought events through analyzing the strength of relation among different variables and at the same
118 time examining their spatial characteristics. In order to assess more clearly the true nature of the drought event, we
119 acquired more archival information from historical documents so as to gauge governmental and societal responses to
120 severe drought events.

121

122 In the following sections, we will first briefly introduce the data used for analysis (Sect. 2). Then the methods will
123 be described (Sect. 3), followed by the presentation of the results of time series analysis of those variables. We will
124 then examine the six severe drought periods, their spatiotemporal patterns and the details of the narratives (Sect. 4).
125 Finally, the climate-society interaction will be explored, followed by an outlook into the future research work (Sect.
126 5).

127

128 2. Data

129 2.1 Drought and associated data from REACHES database

130

131 The main data source of this study is the REACHES database which is a digitized and category-coded climate records
132 in Chinese historical documents in the last three millennia (readers are referred to Wang et al., 2018 for detailed
133 descriptions about the database). The present study utilizes only the records in the last imperial dynasty of China, i.e.,
134 the Qing dynasty (1644-1911). There is a total of 93,415 records (database version VOL34-V3.1-04-E2) in this period
135 and we retrieved drought and related records including locust, dried waterbody (representing hydrological drought),
136 crop failure (representing agricultural drought), famine and socioeconomic turmoil (along with famine to represent
137 socioeconomic drought). Locust outbreak is an important ecological indicator closely related to drought and famine
138 as locust outbreak often occurs in drought climate and these insects consume great quantities of crops resulting in
139 wide spread famine and even cannibalism (Huang et al., 2019). Rigorous statistical study of locust outbreaks and their
140 relation with drought and societal aftermath they caused are rarely performed.

141

142 REACHES has a sophisticated code system to include as much information as conveyed in the historical records. It
143 uses a 9-digit code scheme: the first two digits describe the main category of the climate nature (for example,
144 precipitation, temperature, etc.). The next two digits describe the subcategory (for example, rainfall and snow are two
145 of many subcategories under precipitation category) and the next three digits describe special vocabularies (for
146 example, light rain and torrential downpour under rainfall subcategory). The last two digits denote the magnitude and
147 time information. As an example, a code of a record 300130156 can be deciphered as follows: the first two digits “30”
148 indicate that the record belongs to the main category of drought, the next two digits “01” indicates that it is in the
149 “drought” subcategory (i.e., the record says “drought” directly). There are other subcategories related to drought but
150 were described in different contexts, for example, “watercourse dried out” is assigned as subcategory 11. The next
151 three digits “301” indicate that its vocabulary is major drought (亢旱, *Kang Han*). The last two digits “56” denote
152 magnitude and time-duration information. In this case, 5 means the magnitude is “heavy and occurred many times”
153 and “6” indicates the event duration lasted between 60 and 90 days.

154

155 Famine is also a main category item with the code 35. On the other hand, locust outbreak is a subcategory (code 01)
156 item under the main category of pest/vermin category (code32). Thus the complete code representing a locust record
157 is 3201. Crop is a main category item (code 33) that comprises various degrees of harvest conditions and crop species,
158 and a vocabulary code system ranging from 100 to 499 is assigned to describe them individually. Similarly,
159 socioeconomic turmoil is a main category item with code 71 and the subcategory items most relevant to this study
160 include immigration/displacement (code 03, so the total retrieval code is 7103), battle/war (code 05), impoverishment
161 (09), death/severely injured (code 10), human trafficking (code 12), and abandoned settlements (code 16).

162

163 As the historical documents were written by a great variety of author types, not all of them were written in a fixed
164 standard style and special care must be taken to denote and encode these records. For example, some records
165 sometimes use a negative tense to describe the absence of a phenomenon which should take place around the time,
166 such as “no drought” (無旱, *Wu Hang*). In this case, it would be encoded under drought category with magnitude code
167 8 denoting “not occurring”. Since “no drought” items should not be taken into the drought series in this study, we
168 have carefully removed all those records with magnitude code 8 in the data series.

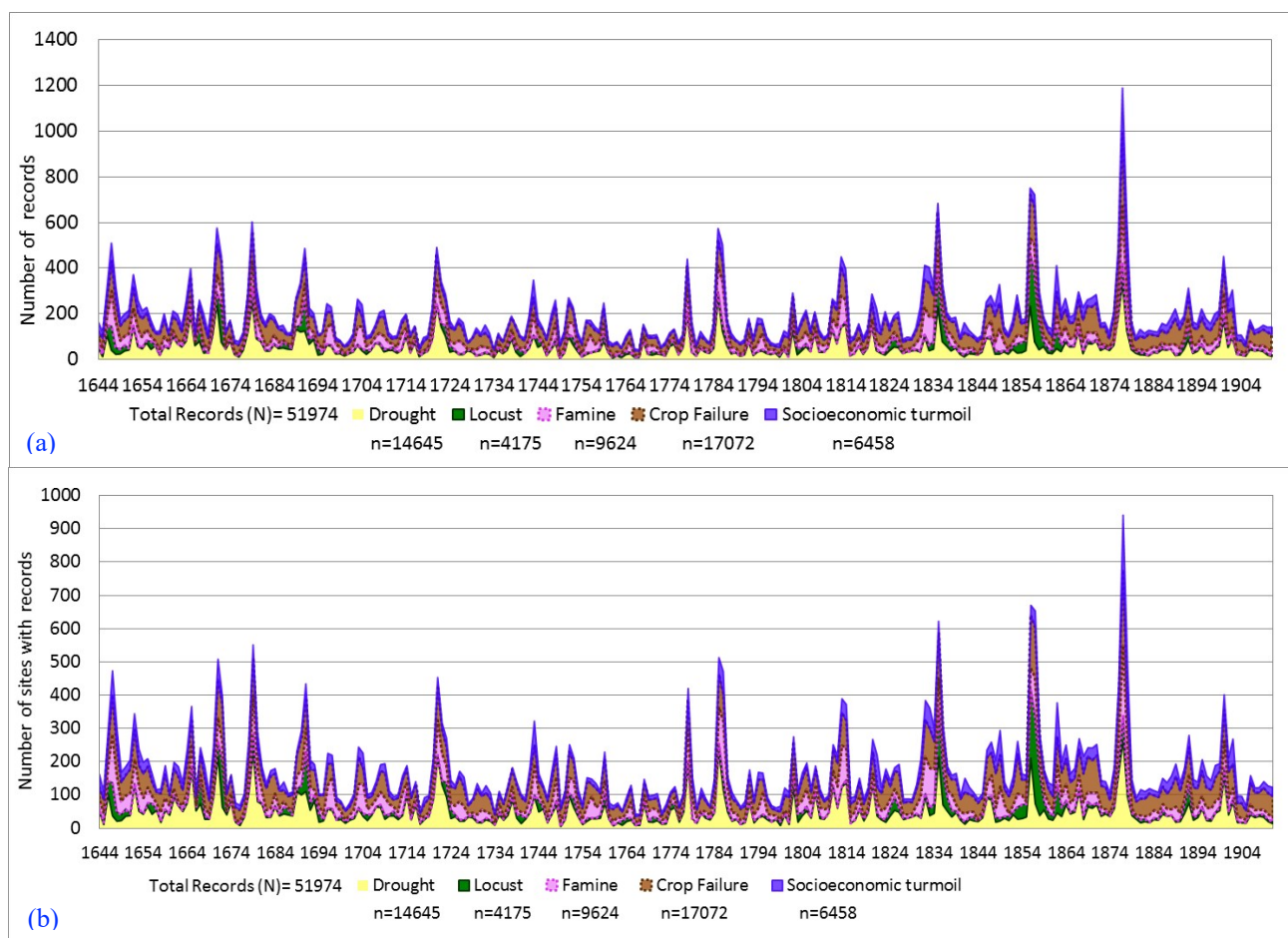
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170 Finally, and importantly, all records of the REACHES are taken from the *Compendium of Chinese Meteorological*
171 *Records of the Last 3,000 Years* (Zhang, 2013), which includes only records that have direct (or indirect) implications
172 or linkages with meteorological phenomena. Those not directly related to meteorological matter were not included in
173 the *Compendium*. In particular, some socioeconomic events that are not explicitly linked to climate conditions may
174 not be included in the *Compendium* but, as often happens in human society, they may be linked in some indirect way.
175 This means that care must be taken when using and analyzing the socioeconomic variables in the REACHES because
176 of the potentially biased sampling. Other sources of relevant socioeconomic data should be considered to cross check
177 and validate the analysis.

178

179 We retrieved 51,974 records related to drought and other related variables from the REACHES database (version
180 VOL34-V3.1-04-E2) for the period of 1644-1911. Figure 1a shows time evolution of records for the variables of
181 drought, locust, crop failure, famine and socioeconomic turmoil, and Fig. 1b shows number of sites (i.e. counties,
182 cities and prefectures, in REACHES. Total n of sites with drought records=1,404) that have the corresponding records
183 of the year. The two diagrams exhibit almost identical trends showing good general consistency of the data series of
184 these variables and it is also highly likely that the records are evenly or randomly distributed over the sites. All data
185 derived from the REACHES database pertinent to this study will be deposited at NOAA national center for
186 environmental information (<https://www.ncdc.noaa.gov/paleo-search/study/23410>).

187



188

189 **Figure 1: Time series plots of drought and associated series derived from the REACHES database. (a) shows**
 190 **number of records per year; (b) shows number of sites (counties, cities or prefectures) that have records of the**
 191 **year. Thus, one site may have more than one record for the year. Note that drought variable here includes**
 192 **meteorological and dried waterbody related hydrological drought, crop failure is interpreted as agricultural**
 193 **drought, famine and socioeconomic turmoil are taken to represent socioeconomic drought.**

194

195 2.2 Other archival and index data

196

197 As mentioned previously, the *Compendium* does not focus on and hence collect in a comprehensive manner
 198 socioeconomic events, therefore sampling bias may exist. To comprehensively compare and analyze drought and
 199 associated data series from the REACHES with socioeconomic variables, we have consulted with independent
 200 documentary sources aside from the *Compendium*. These include Draft History of the Qing Dynasty (清史稿, *Qingshi*
 201 *Gao*), Actual Veritable Records of Emperors of the Qing Dynasty (清實錄, *Qing Shilu*), Gazetteers of Xunzhou
 202 Prefecture (Tongzhi reign edition) ([同治]潯州府志, [*Tong Zhi*] *Xun Zhou Fu Zhi*), Gazetteers of Gui County
 203 (Guangxu reign edition) ([光緒]貴縣志, [*Guang Xu*] *Gui Xian Zhi*), Gazetteers of Pingnan County (Guangxu reign
 204 edition) ([光緒]平南縣志, [*Guang Xu*] *Ping Nan Xian Zhi*), and Gazetteers of Yongchun County (Chinese
 205 Republican Period edition) ([民國]永淳縣志, [*Min Guo*] *Yong Chun Xian Zhi*). Practically, it might be unavoidable
 206 that some of the contents in the historical books, if referred to climatic and weather conditions, were quoted in the

207 *Compendium*. For example, there are 5 quotations of records from Actual Veritable Records of Emperors of the Qing
208 Dynasty and 148 records from Draft History of the Qing Dynasty found in the REACHES among the overall of 93,415
209 records in the Qing dynasty. The coverage, however, is minimal in quantity among all, in the meantime, these
210 documents contain meticulous records of social, economic and institutional events of the time. Local gazetteers
211 particularly contain detailed information about social unrests such as the massive rebellion, Taiping Civil War (太平
212 天國 [Tai Ping Tian Guo]), in the mid-19th century.

213

214 Besides the above documents, we also collected records on grain price, civil war and population indices for further
215 analysis. Grain price data (1738-1911) was derived from Qing Dynasty Grain Price Database which compiles the
216 monthly grain price reports preserved in the First Historical Archives of China in Beijing and the National Palace
217 Museum in Taipei by Wang (2009). Civil war data that reveals the frequency of civil wars in Qing Dynasty was
218 derived from Chronology of China's Ancient Wars by Chinese Military History Writing Group (1985). Population
219 index data comes from several different sources: Provincial population statistics 1661-1776 CE from Encyclopedia of
220 Official Documents of the Qing Dynasty (清朝文獻通考, *Qingchao Wenxian Tongkao*); Provincial population
221 statistics 1780-1890 from Annual Registers of Quantities of Provincial Population and Grain Storage by the Ministry
222 of Revenue (戶部匯奏各省民數穀數清冊, *Gesheng Minshu Gushu Qingce*); and The History of Population in China,
223 Vol. 5: Qing Period (中國人口史第五卷清時期, *Zhongguo Renkoushi Diwujuan Qingshiqi*) by Cao (2001).

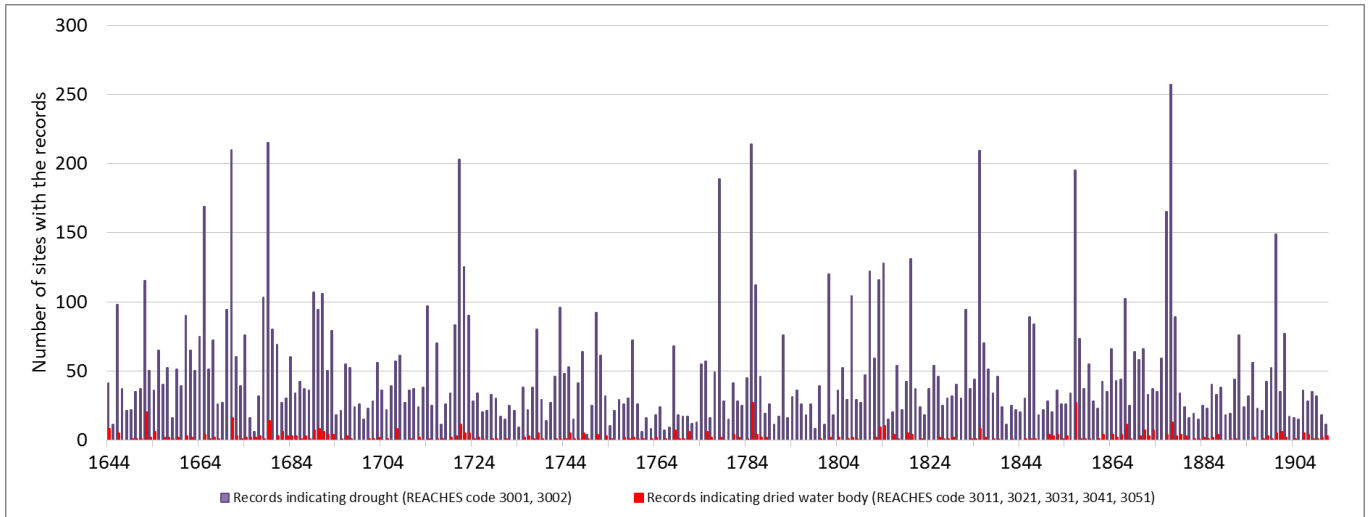
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225 **3. Methods**

226 **3.1 Time series and cross checking of the variables**

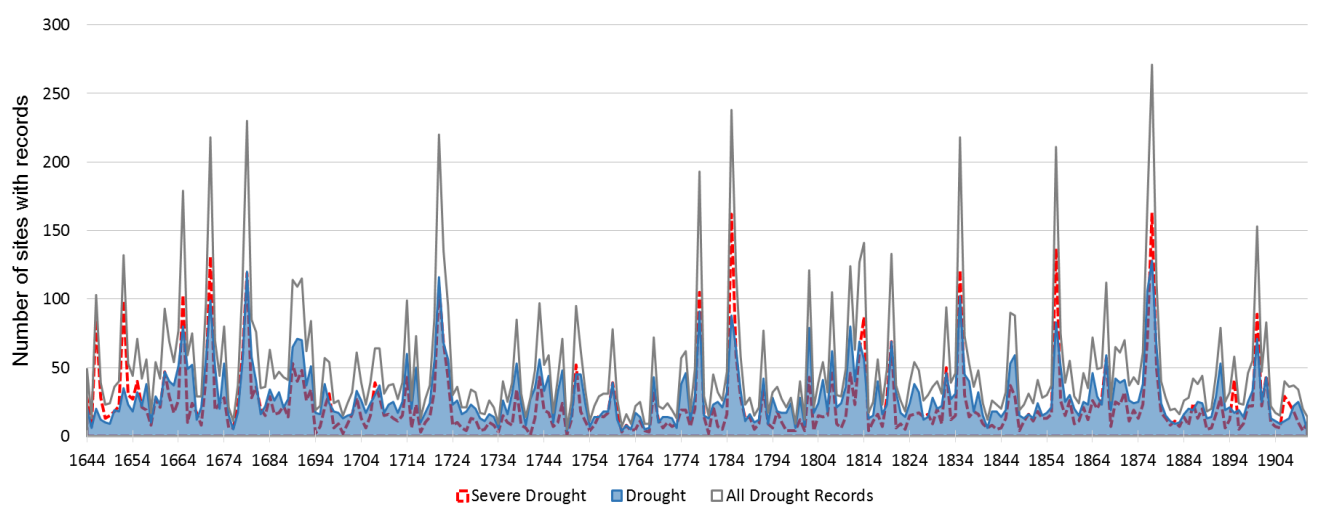
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228 We used the retrieved records to build several time series for different variables and performed tests to cross check
229 the reliability and robustness of the drought data. First of all, we gave strict definitions for drought variable. In this
230 analysis, the drought variable only corresponds to those records with the vocabulary category of drought (such as 天
231 旱 *Tien Han*、亢旱 *Kang Han*、苦旱 *Ku Han*, all with category code 3001), enduring scorching sun, sultry weather
232 (e.g. 恆陽 *Heng Yang*、恒暘 *Heng Yang*, all with code 3002), dried out of different types of water body that includes
233 dried watercourses (e.g. 水竭 *Shuei Jyue*, code 3011), dried tide/sea water, (e.g. 潮水涸 *Chao Shuei He*, code 3021),
234 dried lake/pond (e.g. 湖涸 *Hu He*, code 3031), dried underground water (e.g. 無泉 *Wu Quan*, code 3041) and dried
235 river/creek (e.g. 河水絕 *He Shuei Jyue*, code 3051). We further divide the drought records into two groups; one
236 group that consists of pure drought vocabularies (code 3001 and 3002) is interpreted as meteorological drought, and
237 the other that consists of dried water bodies (code 3011-3051) is interpreted as hydrological drought. Figure 2 shows
238 the comparison of the time series. We found that higher number of hydrological drought records often occurred in the
239 years having more meteorological drought records. Correlation coefficient of the two is 0.67, and the coefficient
240 increases to 0.77 when only severe drought (to be explained later) is considered. This finding indicates that the large
241 majority of hydrological drought in China can be caused by metrological drought albeit the relation is not perfect.



242 **Figure 2: Comparison of drought records that indicate pure drought vocabularies (interpreted as**
 243 **meteorological drought) and dried waterbody (interpreted as hydrological drought).**

244
 245 To further ramify the impact of different drought types, we divide drought events into normal drought and severe
 246 drought. The criteria of severity assignment are based on the attribute of the vocabulary used and the duration
 247 described in the record. Records that contain adjectives indicating extreme or severe drought (magnitude code 2 and
 248 5) or the event lasted for more than two months (time-duration code 6 and 7) are categorized as severe drought. In
 249 contrast, those records that do not have any adjectives indicating the severity or those with duration less than two
 250 months are categorized as normal drought. In this way we form the annual drought population and annual severe
 251 drought population series and Fig. 3 shows the time series plot of these two series. It is obvious that severe drought
 252 and drought series have good consistency and match very well especially for the peak years of the drought events.
 253 Remarkably, those peak drought years mostly appeared in the mid to late 17th century and after late 18th century. The
 254 top 3% of the drought years (those with more than 169 records of the year) are the years of 1665, 1671, 1679, 1721,
 255 1778, 1785, 1835, 1856 and 1876.



256 **Figure 3: Time series plot of annual normal drought, severe drought, and all drought populations in REACHES**
 257 **during the Qing dynasty.**

258

3.2 Spatial analysis of Kernel density estimation

Precise geographical information in REACHES makes it relatively easy to perform spatiotemporal analysis of the climate data series derived from it. There are in total 1,660 sites representing cities, counties, or prefectures in the REACHES database. We performed the spatial analysis of kernel density function for the drought data. We first determine the number of certain kinds of records each year and the numbers are summed over the time period defined for the analysis. For example, in the 1720-1740 severe drought, Baoshan district of Shanghai City had three drought records occurred separately in the years of 1720, 1723 and 1724. The frequency for the period of Baoshan district would therefore be three. We then use ArcGIS (version 10.4) to relate the data to 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 every data point, a kernel function K can be expressed as Eq. (1):

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

where $\hat{f}(x, y)$ is the estimated density value at location (x, y) , n is the value of the point of concern (for example in the case, n is the number of drought records 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 the point i and location (x, y) . Eq. (1) shows that 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 smoothed surface by considering point value of larger distance. In the environment of ArcGIS, the kernel density estimation is based on the quadratic kernel function (Silverman, 1986).

3.3 Social network analysis

To explore statistical characteristics of the relations between one variable and other variables in the drought data set, we performed social network analysis. This analysis affords us to understand more quantitatively 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.

296 Generally, social network analysis adopts a pairwise approach to calculate relations between variables (e.g. if agent A
297 is linked with agent B). Thus, to implement the analysis, data transformation is needed to display and inventory events
298 (with specific codes) under every single record. For example, a record says that ‘in 1833, Guangling county of Shanxi
299 Province, the misery [of the year] began with drought, followed by excessive rainfall, and ended with frost damages.
300 The rice costed a thousand per dou (tradition Chinese volume unit, equivalent to 10 Chinese liters). There hadn’t been
301 so extreme in the previous several decades.’ (1833 年。山西省廣靈縣。始苦於旱，繼潦於雨，終隕於霜，斗米
302 千錢，數十年來未有如是之極也)(record ID 2945-25). To perform the social network analysis, we decomposed the
303 record so that the drought, excessive rainfall and frost damages each is listed as a separate event, and then we calculated
304 the pairwise coefficients between different variable pairs, e.g., drought with rainfall, drought with frost, or drought
305 with rice price, etc. When all events of every record have been decomposed and restructured following the algorithm,
306 then the analysis could be performed to estimate the magnitude of every event (i.e. variable) and to calculate the
307 strength of connections among those variables during certain time period. The function of edge list was applied to
308 perform this analysis under Gephi software (<https://gephi.org/>, last access 15 March 2020).

309

310 **4. Results**

311 **4.1 Chronologies of drought and related variables**

312

313 Figure 4 shows the time series of all variables (in their annual values) reconstructed from the REACHES database.
314 There are two temperature time series in the lowest part of the figure for comparison purpose to be discussed later.
315 Naturally there are multidecadal and centennial variabilities which are more obvious in some periods amid regular
316 fluctuations in 1644 - 1911.

317

318 One of the unique features of Fig. 4 is the inclusion of the locust outbreak series. While there had been studies on
319 locust outbreak and climate, Wang (1985) was perhaps the first one to utilize Chinese historical records of locust
320 outbreaks to investigate their temporal and spatial behaviors. The analysis we present here will further reveal how
321 close this biological phenomenon is related to the climate factor.

322

323 We first observe that there appears to be a good synchronization of large amplitude events (high peaks in the curves)
324 for all variable in six periods highlighted by light brown columns. These periods are roughly: 1665-1680, ~1720,
325 1770-1790, 1830s, 1850s, and 1870s, and the periods are also correspondent to the top 3% drought years in the
326 previous analysis (Sect. 3.1). The most prominent of the synchronization is between the locust and drought series, that
327 is, locust outbreaks occurred most often during high drought occurrence periods. The close relation between locust
328 outbreak and drought has been known in China since ancient time. For example, the famous poet of Northern Song
329 dynasty (960-1127 AD) Su Shi (蘇軾, 1037-1101) wrote in his poem 《Rhymed after Zhang Chuandao’s poem Happy
330 for the Rain, made after I prayed for rain in Changshan Temple》: “As always locust and drought will occur together,
331 this is what I learned from old farmers”. Chen Fangsheng (陳芳生), a Qing dynasty scholar who authored a book *A*
332 *Study on Catching Locusts* 《Bu Huang Kao 捕蝗考》 published in 1776 in which he commented “when drought

333 becomes extreme, locust outbreak occurs”. The synchronization in the two series thus provides a statistical verification
334 of this ancient wisdom.

335

336 The synchronization is not limited to drought and locust. Other variables exhibit similar behavior. Thus Fig. 4 shows
337 that when drought occurs, it is very likely that locust outbreak will occur as well as crop failure, famine and
338 socioeconomic turmoil. We have not yet gone into detailed ramification on the cause and effect analysis of this
339 synchronization, but the order of events as described in the previous sentence seems to match “common sense” that
340 under the general background of drought climate, locust outbreak has a high chance to occur which, in turn, results in
341 crop failure causing famine. And finally, in the absence of effective intervention of the government, socioeconomic
342 disasters occurred. We are currently collecting more evidence to further study such links.

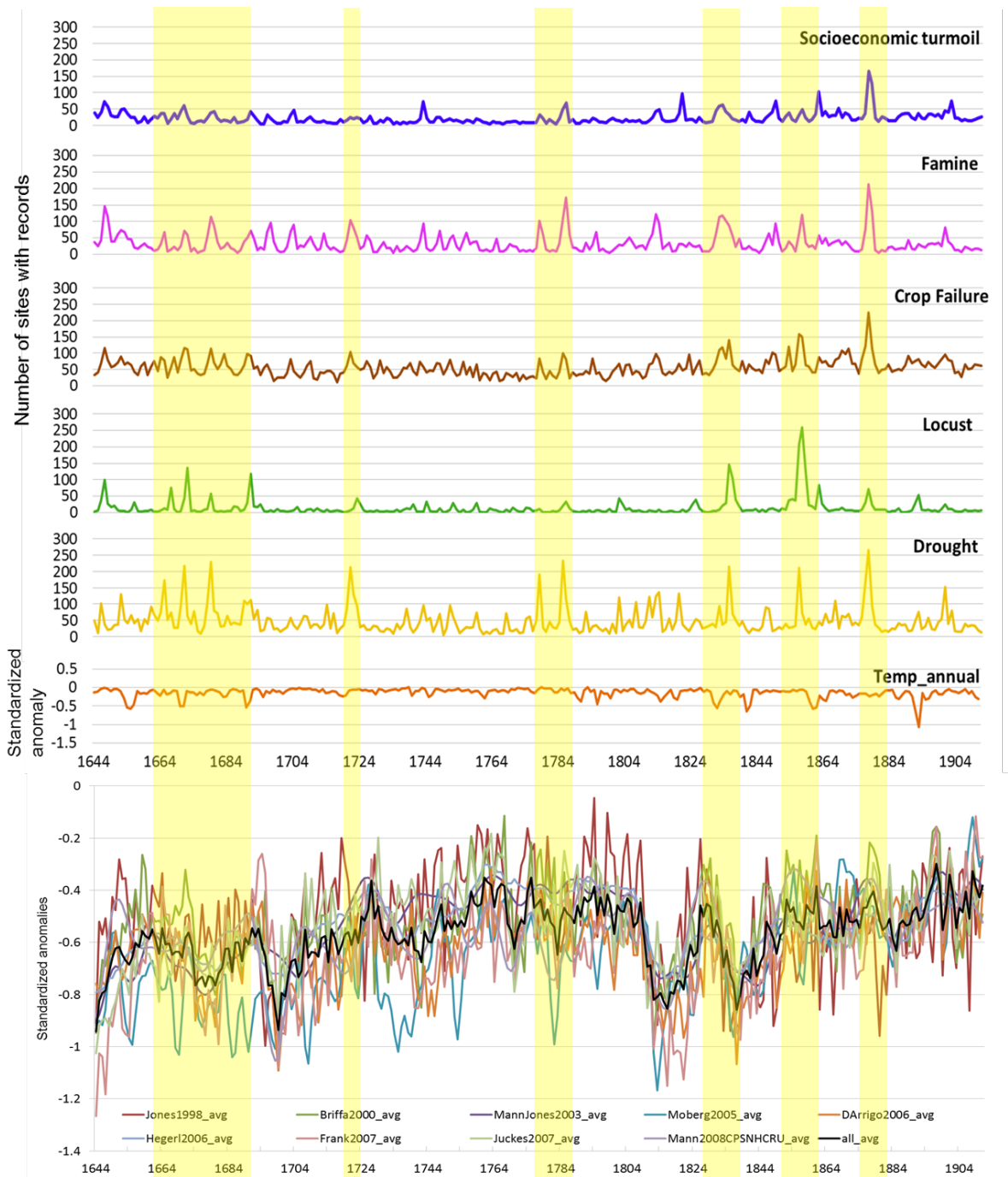
343

344 In order to further ramify this synchronization feature, we calculated the 9-years running variance for the time series
345 as shown in Fig. 5. The six periods identified previous now become even clearer. Notwithstanding of the
346 synchronization of high occurrence, however, the amplitudes of the variables are not related linearly. While the
347 amplitudes of drought are more or less even in the six periods, the amplitudes of other variables seem to vary
348 significantly. For example, locust outbreak was more numerous in 1660-1680, 1830s and 1850s (the highest peak). It
349 is fewer in the rest three periods. On the other hand, there are fewer famine in the 1600s but become more numerous
350 in the 1770-1790, 1850s and peaked in the 1870s. Socioeconomic turmoil has relatively low amplitude in the early
351 and mid-Qing dynasty until 1820s when it shows an increase and peaked in 1870s. This is just to say that the
352 correlations of these series are not perfect and their relations are nonlinear albeit they have a tendency to occur in the
353 same period. Table 2 shows correlation coefficients among all those variables. We see that drought is highly correlated
354 with crop failure and famine but is less correlated with locust and socioeconomic turmoil. This probably can be
355 interpreted as that drought resulted directly in the crop failure which very likely led to famine, but there were
356 circumstances that locust outbreak did not occur during the drought. The real reason needs to be investigated further.
357 It is possible that measures of locust prevention had been taken sometimes effectively and not so in other times.
358 Likewise, the socioeconomic situation is not that directly linked to drought if the government provided adequate relief
359 (e.g., provide food, tax waiver, etc.). We plan to look into more details about the relations among these variables in
360 the future.

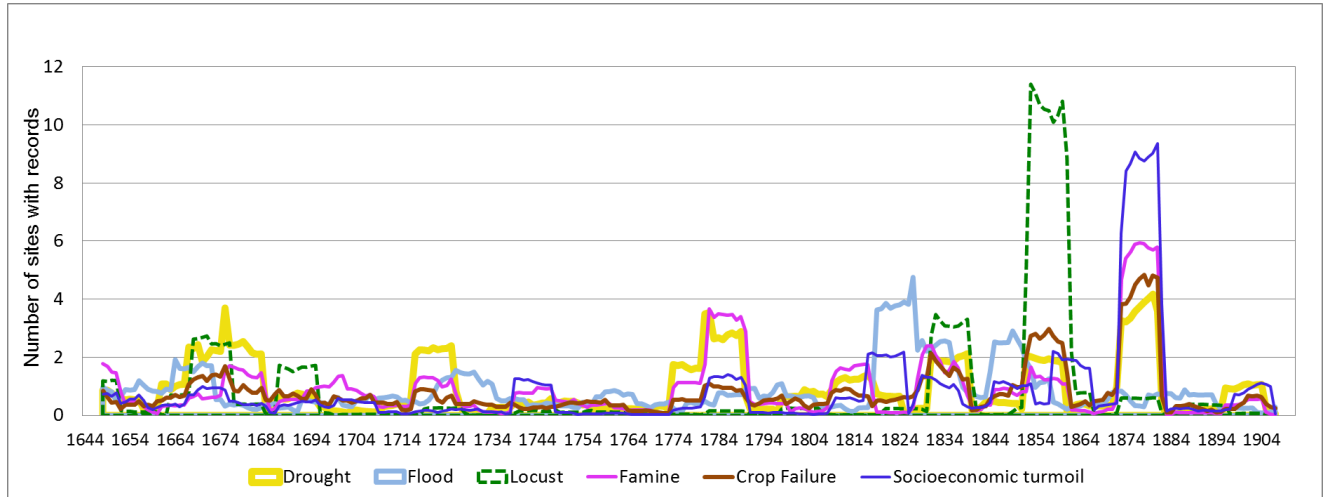
361

362 To further understand the multidecadal and centennial variabilities, we compare these series with two temperature
363 series: one reconstructed from REACHES (Lin et al., 2019) and the other North Hemisphere ensemble temperature
364 from Frank et al. (2010). The two temperature series show similar trends in anomaly which appears to augment the
365 reliability of data derived from REACHES. Figure 4 shows that higher frequency of all the drought-related variables
366 tend to occur more often when temperature is lower in the 17th century and after late 18th century. Thus colder periods
367 in historical time also tend to be periods of low agricultural yields and social instability, which is consistent with some
368 previous studies (Pei et al., 2019; Su et al., 2016; Wei et al., 2017)

369
370



371 **Figure 4: Time series plots of socioeconomic turmoil, famine, crop failure, locust, drought, and monsoonal**
372 **China annual temperature anomaly reconstructed from the REACHES. The bottom panel shows ensemble**
373 **North Hemisphere temperature anomalies from Frank et al. 2010. Periods with more frequent drought records**
374 **are highlighted in yellow bars.**



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

376

377 **Table 2: Correlation coefficients of REACHES multiple variables**

Drought Category	Variable	Drought	Locust	Socioeconomic Turmoil	Famine	Crop Failure
Meteorology & Hydrology	Drought	1.000				
Ecological-related	Locust	0.375	1.000			
Socioeconomics	Socioeconomic turmoil	0.442	0.287	1.000		
	Famine	0.618	0.379	0.718	1.000	
Agriculture	Crop Failure	0.626	0.511	0.685	0.675	1.000

378 All coefficients have P-value <0.001. High correlation coefficients are shaded with dark gray and medium correlation
 379 coefficients are shaded with light gray. Note that we have in Sect. 3.1 identified the correlation coefficient between
 380 meteorological drought and hydrological drought as 0.67 which increases to 0.77 when severe drought is considered.

381

382 **4.2 The spatial pattern of drought during the six high occurrence periods**

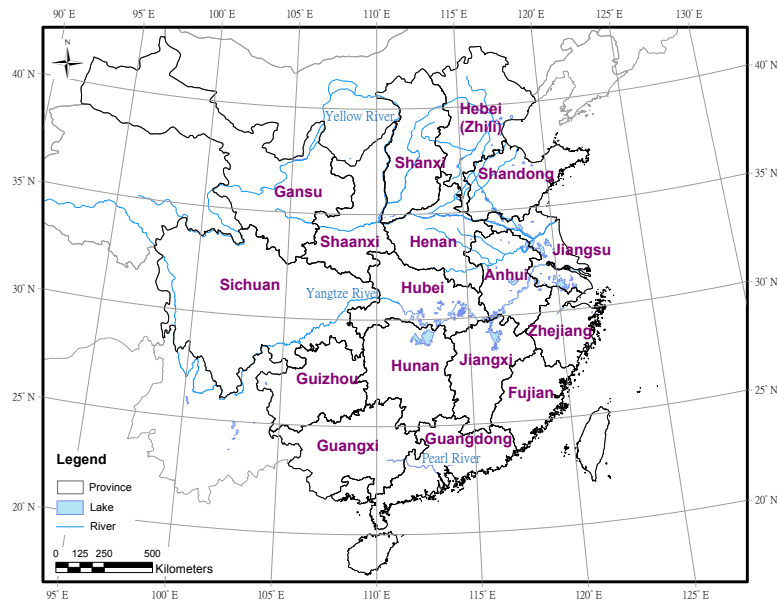
383

384 In the above analysis, we identified six periods in which the drought-related variables exhibit nearly synchronous
 385 fluctuations. We now would like to demarcate more precisely these periods based primarily on the drought series. In
 386 doing so, we also considered auxiliary information we found in the aforementioned historical documents such as Draft
 387 History of the Qing, Actual Veritable Records of Emperors of the Qing Dynasty and the Gazetteers. For example,
 388 during the period of 1720-1740, the severe drought mainly occurred around 1720 but the drought soon continued in
 389 1730s and 1740s, and their socioeconomic effects were closely linked, so it seems to be strategically prudent to
 390 consider the period 1720-1740 as a high severity period. On the other hand, the three severe drought periods in the
 391 1800s appear to be less closely linked in time (one peak every two decades) and the auxiliary information show that
 392 their socioeconomic consequences were not closely linked either. Thus we do not see the necessity of lumping the

393 three periods together. In this way, we demarcate the six severe drought periods in Qing dynasty as follows: 1665-
394 1691, 1720-1740, 1770-1790, 1830-1850, 1850-1870, and 1870-1890.

395

396 In the following, we will examine the spatial distributions of the drought and the corresponding distribution of locust
397 outbreaks and socioeconomic turmoil. We will also provide a summary of the population and war frequency and the
398 results of social network analysis in these six periods.



399

400 **Figure 6: Provincial boundaries and names in eastern part of China. The basic latitude and longitude grid map**
401 **is from ESRI data set, provincial and city/county boundary and river shapefiles are from China National**
402 **Bureau of Mapping and Surveying, Digital Map Database of China (1990 version).**

403

404 The following discussions will frequently mention the provincial names in China and hence may be confusing for
405 readers not familiar with Chinese geography. Figure 6 is a simplified map showing the locations of the provinces
406 mentioned in the discussion for reference.

407

408 4.2.1 Period 1665-1691

409 Figure 7 shows the overall situation of drought-related variables in the period 1665-1691 including the spatial
410 distribution of the kernel density function of drought (7(a)) and associated locust outbreaks and social turmoil (7(b)),
411 and the social network chart (7(c)). Figure 7(a) shows the drought kernel density distribution which is an indicator of
412 the severity of drought. It is seen that in this period drought was fairly wide spread in the eastern half of China from
413 as far north as Hebei province and as far south as Guangdong province. There appear to be two “epicenters” of drought,
414 one in the lower Yellow River flood plain (Hebei and Shandong) and the other in the middle and lower reaches of
415 Yangtze River (Anhui and northern Jiangsu). There are also secondary centers in Hubei, Jiangxi, and Zhejiang. The
416 drought in the south such as Fujian and Guangdong were relatively mild.

417

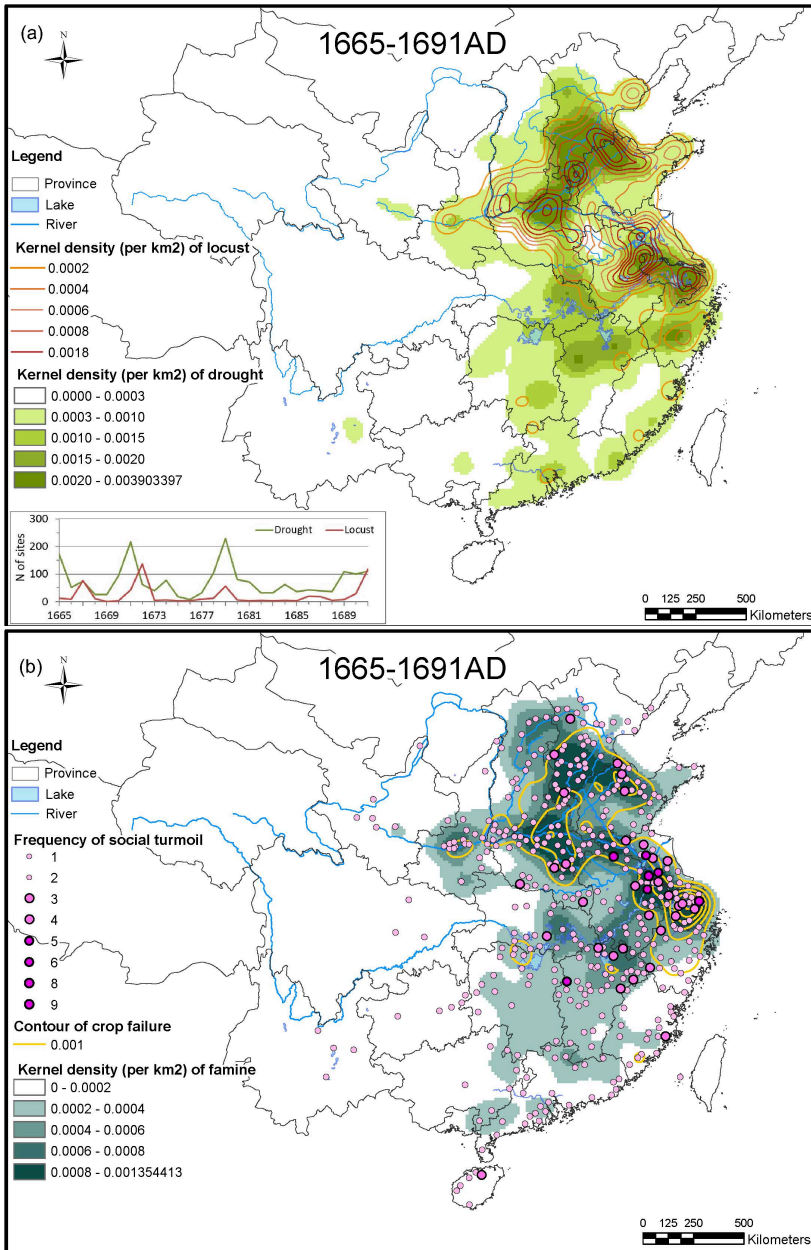
418 Here we would like to stress an important caution when reading the spatial patterns: this should be viewed as a *map*
419 *of anomaly* instead of a map of humidity. This is because the drought index (as well as other severity indices such as
420 temperature) derived here represents the *deviation from the local norm*, and the local norm can be quite different in
421 different locations in a country as large as China. Thus, a certain dry condition lasted for, say, a month may well be
422 considered a drought in the normally humid Southern China but could be regarded as a normal condition in the Loess
423 Plateau region in Northern China because their norms are quite different. There is a need of an algorithm that converts
424 the anomaly index to actual humidity which must consider this local norm factor. An investigation is being conducted
425 on this subject.

426

427 Figure 7(b) shows the corresponding spatial patterns of locust outbreaks and social turmoil in this period. We observe
428 that the patterns are both similar to that of drought and both are also centered around lower Yellow and mid- and lower
429 Yangtze, which again vindicates the ancient wisdom of the close relationship between drought and locust (and the
430 consequential social turmoil they might cause).

431

432 The period of 1665-1691 is about two decades after the collapse of Ming Empire in 1644 which was replaced by the
433 Manchurian Qing Empire after the bloody wars among different parties including Ming, Qing and the rebellious
434 farmers led by Li Zicheng (李自成). Population of China was substantially reduced due to the wars. But even at this
435 time, revolts in different parts of China were still going on. Severe drought and locust outbreaks occurred in 1670-
436 1672 and appeared again in 1679 and 1689-1691. Given the very similar patterns of drought, locust outbreak and
437 social turmoil distributions at the time, it is possible that many of these revolts were motivated by the food shortage
438 (thus climate-related) in addition to those motivated by political considerations (e.g., The Revolt of the Three
439 Feudatories in 1673-1681). This will require further studies to ramify.



440

441 **Figure 7: Spatial distribution of the kernel density function of drought (a) and locust outbreaks and social**
 442 **turmoil (b), and the social network chart (c) in the drought period 1665-1691.**

443

444 **4.2.2 Period 1720-1740**

445

446 The 1720-1740 drought as shown in Fig. 8(a) appears to be not as wide spread as that in 1665-1691. While there are
 447 still two centers: one in Lower Yellow and another in Lower Yangtze, the latter appears to be the more severe one.

448 The corresponding locust breakouts and social turmoil are also centered in these two regions although that in the
 449 Lower Yellow appears to be somewhat more extensive. There were locust outbreaks reported in Fujian, Guangdong
 450 and Guangxi provinces but there wasn't much corresponding drought reported in these areas. There was social turmoil

451 in areas not affected by drought or locust also. Were these disturbances not climate-related? The reason is unclear and
452 will requires further studies.

453

454 There is a term in Chinese historical community called High Qing era or the Kang-Yong-Qian Prosperity Period (康
455 雍乾盛世), referring to the period reigned by the Emperors Kangxi, Yongzheng and Qianlong when Chinese economy
456 was relatively prosperous and is often considered as the golden era of the whole Qing dynasty. The demarcations of
457 the period differ among scholars but a generally usable one is 1684-1799 (Guo, 2002). The period of 1720-1740 of
458 concern here falls in this golden era.

459

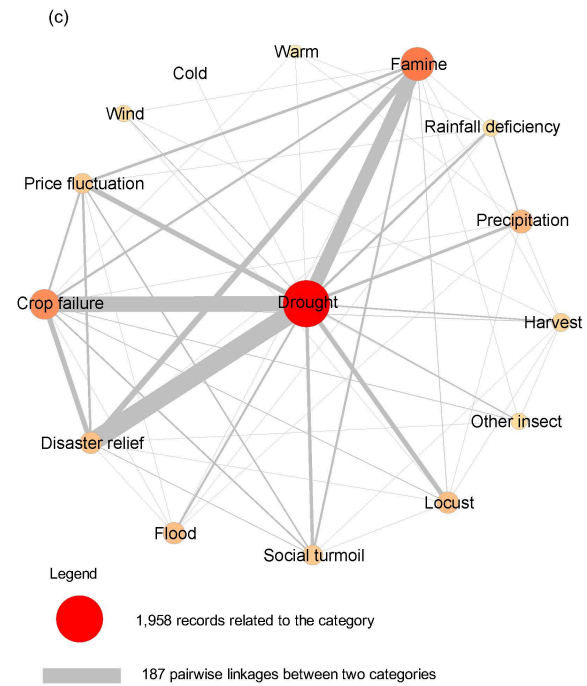
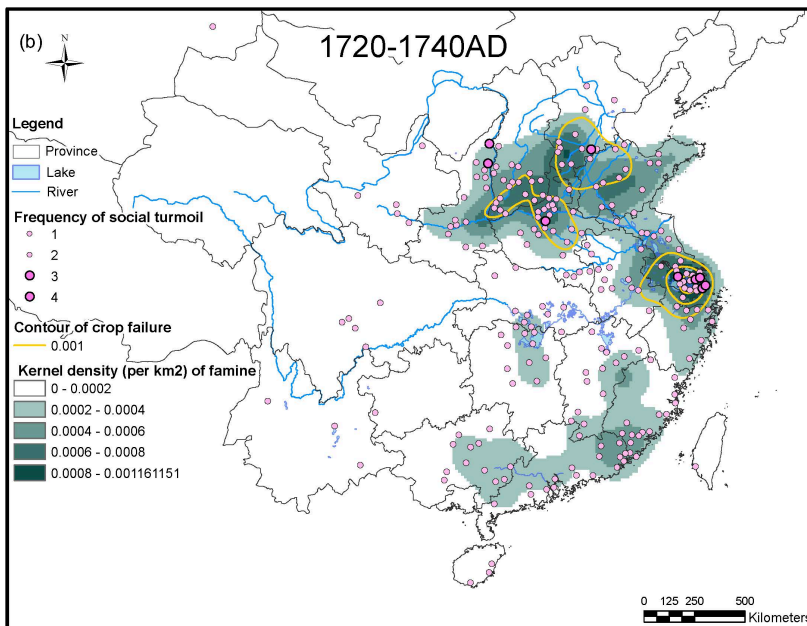
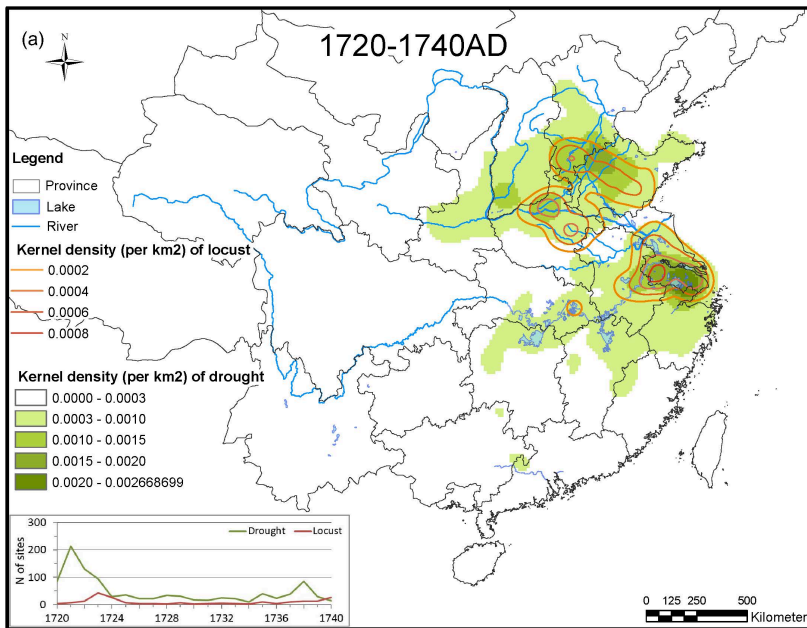
460 Emperor Kangxi died in 1721 and was succeeded by his son Emperor Yongzheng after a conspiratorial process. But
461 Yongzheng himself died in 1735 after another process also full of rumors and his heir was Emperor Qianlong who
462 died in 1799. Thus Emperor Yongzheng was the main ruler in the period 1720-1740. During this time, the whole
463 China empire was generally stable. There were some wars with minority tribes such as the one with the Mongolian
464 Goldan Tseren of Dzhungar Khanate but not extensive.

465

466 Population of China had grown general during this period, but the drought and locust outbreaks certainly left their
467 marks in the affected areas. According to a 1725 population record, Shandong's population grew slowly at this time
468 and the population of Jiangsu declined. Later famine occurred in the north of Huai River flood plain around 1738
469 which is drought-related and lasted for several years (Fig. 8(b)).

470

471 The social network analysis (Fig. 8(c)) showed some interesting feature, that is, the links between the pairs of drought-
472 locust, drought-crop failure, and drought-famine, though still significant compared to other pairs, were much weaker
473 than in the previous period. This seems to indicate that while drought occurred, the societal impact was relatively mild.
474 Although the real reasons still need to be researched carefully, there are documentary evidence showing that the
475 governmental policies, such as shipment of grains to and tax relief for the disaster-affected areas, and the
476 implementation of locust elimination, might have played a significant role here.



477

478 Fig. 8 Spatial distribution of the kernel density function of drought (a) and locust outbreaks and social turmoil (b),
 479 and the social network chart (c) in the drought period 1720-1740.

480

481 4.2.3 Period 1770-1790

482

483 This period was entirely under the reign of Emperor Qianlong. Five years later in 1795 he claimed to pass the throne
 484 to his son Emperor Jiaqing (嘉慶) although in reality he was still in control until he died in 1799. China was relatively
 485 stable politically in this period. It was reported that the national population had returned to that in Ming dynasty Only
 486 some minor revolts occurred in Western China in 1771-1776 by Jinchuan tribes (大小金川) who were related to
 487 Tibetan, and in Taiwan in 1786-1788 led by Lin Shuanwen (林爽文) of Tiandihui (天地會, literally Heaven and
 488 Earth Society, a secret society that still exists today). A British diplomatic mission led by George Macartney was

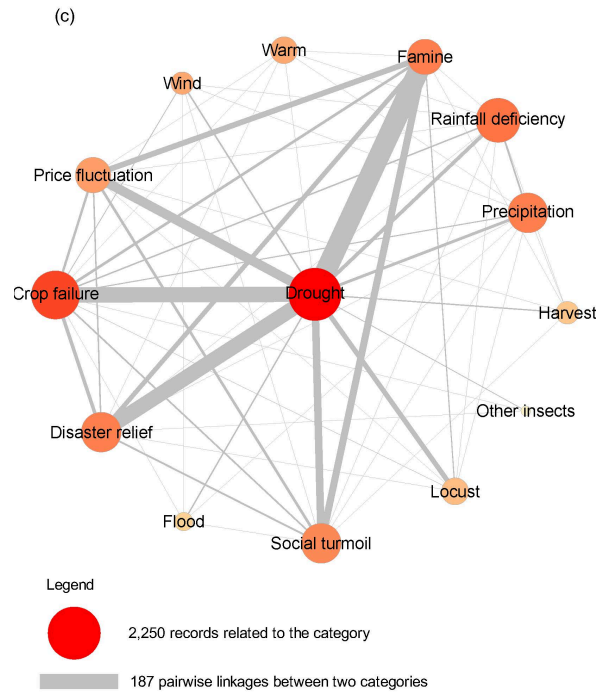
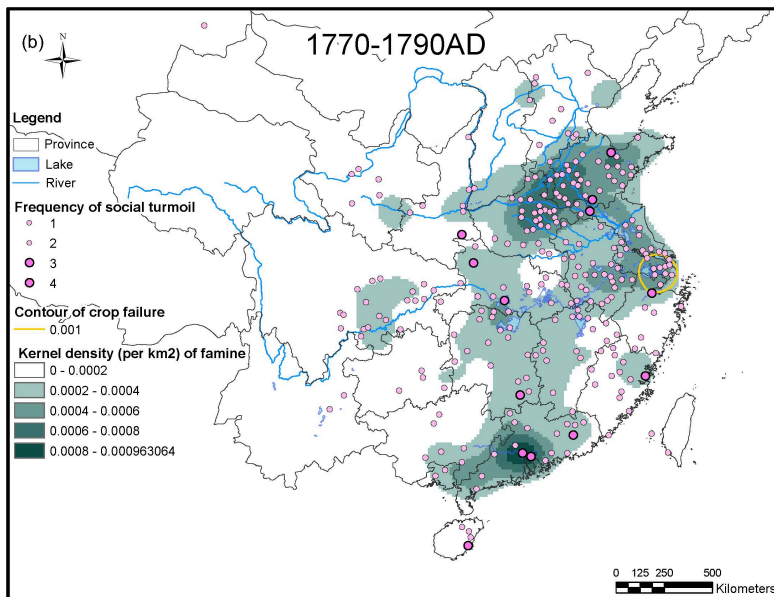
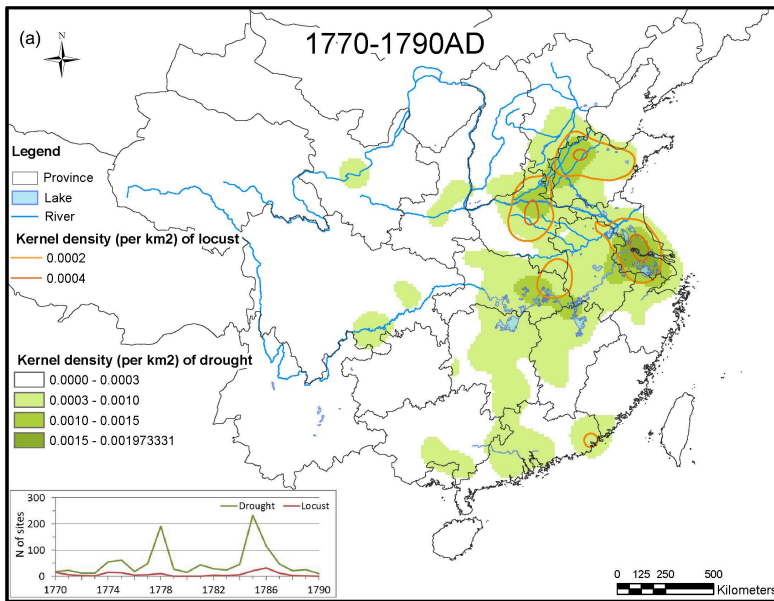
489 granted an audience with Emperor Qianlong in 1793, an event that became the prelude of wars between China and
490 Western Powers later.

491

492 The spatial distributions of drought and the corresponding locust outbreaks and social turmoil as shown in Fig. 9(a)
493 and (b) are both similar to that in 1720-1740, namely, both are still centered on Lower Yellow and Lower Yangtze
494 regions and a smaller center in Guangdong in the south. Drought appears to be more mild but affected areas appear to
495 be wider, but social turmoil appears to be somewhat worse than in 1720-1740.

496

497 The social turmoil was likely linked to social inequality due to the gap between the rich and poor. The wide spread of
498 locust outbreaks also prompted the government to pay more attention to the technology of locust eradication and the
499 previously mentioned *A Study on Catching Locusts* was published in this period. Drought in this period led to a
500 reduction in crop yield resulting in famine and sharp rise of grain price around 1779 and 1786. [Figure 9\(c\)](#) shows the
501 social network analysis of this period.



502

503 **Figure 9: Spatial distribution of the kernel density function of drought (a) and locust outbreaks and social**
 504 **505 turmoil (b), and the social network chart (c) in the drought period 1770-1790.**

506 **4.2.4 1830-1850 period**

507

508 The overall political and economic situation of China was going downhill after nearly 200 years of Qing rule. The
 509 middle age of Emperor Qianlong's rule was generally considered as the peak of heyday of Qing dynasty and by 1830
 510 China was facing increasing economic downturn after Emperor Daoguang (道光) assumed the throne in 1820 when
 511 his father Jiaqing died. Many Chinese historians consider that the overspending by Qianlong is to blame for the
 512 declining economy, especially from the discovery of the stunning corruption by his most favored minion, Heshen (和
 513 珅) who was believed to have amassed illegally a net wealth equal to fifteen years of total tax collection by the Qing
 514 government. But from today's point of view, the challenge from Western Powers at the time such as the British, French

515 and German was probably a more serious problem. Although there were some smaller riots occurring in this period,
516 the most well-known armed conflict was the Opium war occurred in 1840 between Qing and British Empires. After
517 the war, the inability of Qing government to cope with the international pressure in various aspects was completely
518 exposed and ushered in more serious challenges internally.

519

520 But perhaps part of the blame can be attributed to the climate factor. [Figure 10\(a\)](#) and (b) show the drought and the
521 corresponding locust outbreaks/social turmoil spatial patterns. The drought condition looks similar to that in [Fig. 8\(a\)](#)
522 but the locust/social turmoil looks much worse and more wide spread than in 1770-1790. Locust outbreaks reached as
523 west as Shaanxi province in Northern China and Sichuan province in Central China which were largely spared in the
524 previous period, and as far south as Guangdong and Guangxi provinces. Hubei province in Central China was plagued
525 badly by locusts and social unrest. Even the relatively wealthy province of Zhejiang had seen serious locust outbreaks
526 and social unrest. Such relations among drought-related factors can also be seen in the social network analysis in [Fig.](#)
527 [10 \(c\)](#). But overall, drought is mostly related to crop failure and famine. Drought in this period did not seem to link
528 strongly with precipitation and the reason is unclear at the moment.

529

530 An interesting feature worthy of note here is the spatial patterns of locust outbreaks and social turmoil which exhibit
531 an east-west (E-W) orientation. There are apparently two prominent E-W belts: the north one along Shandong,
532 southern Hebei and southern Shaanxi provinces; the south one along Jiangsu, southern Hubei and northern Hunan
533 provinces.

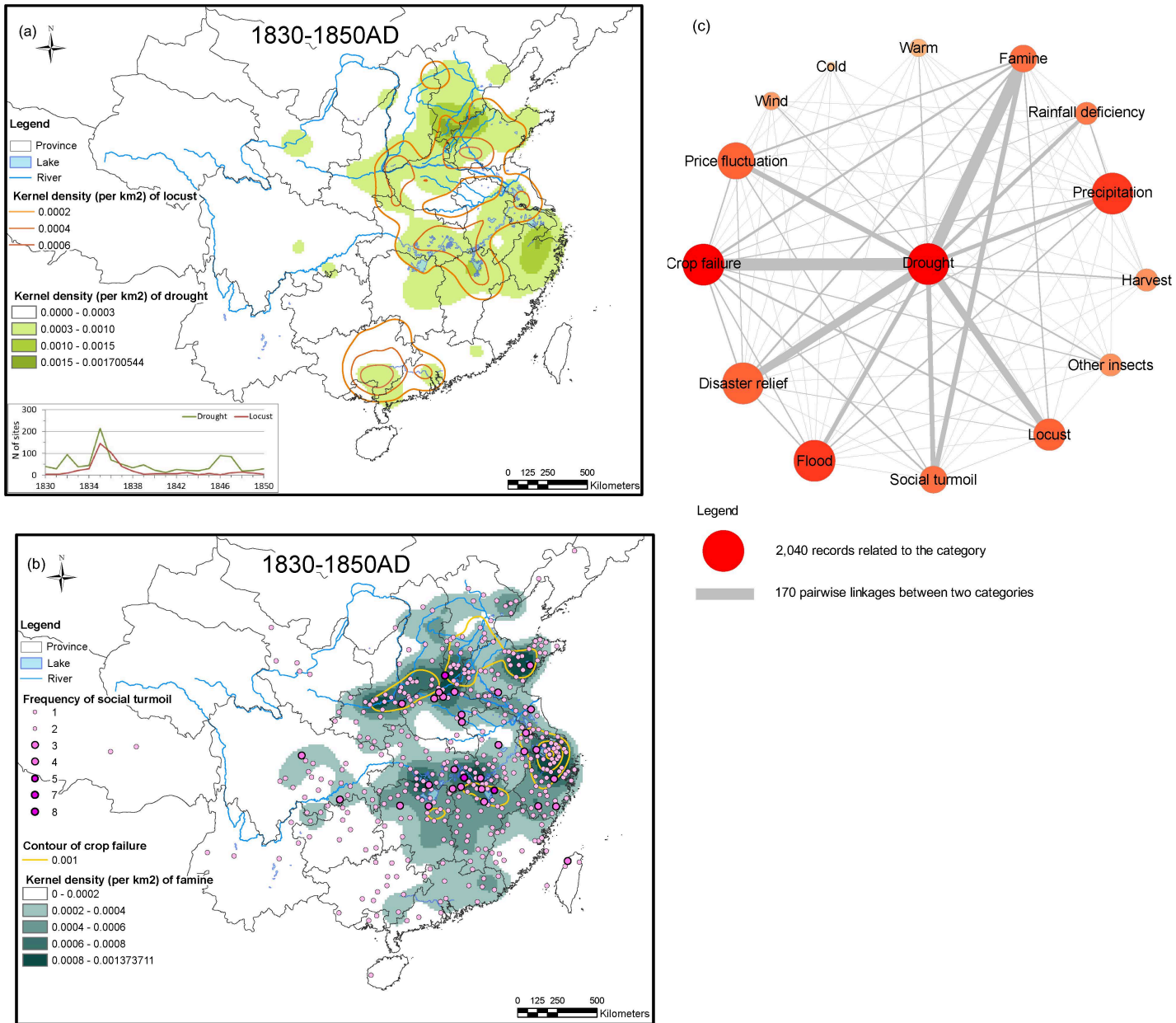
534

535 Documentary sources show that the national population continued to grow rapidly but per capital arable land declined
536 significantly. Whether or not the decrease in arable land was due to climate factor remains to be studied, but there is
537 little doubt that the society was under great stress of resource competition. This eventually led to numerous uprisings.

538

539 One would expect that many of the uprisings must be due to food shortage given the declining production of grains.
540 Curiously, the rice price information in 1825-1860 we obtained for several places including Suzhou (of Jiangsu
541 province), Hubei and Guangxi paints a fairly different scene. Suzhou's rice price fluctuated more wildly but appears
542 to be steady when averaged throughout the period. Guangxi's rice price was very steady and Hubei's price was even
543 declining during this period. Perhaps this phenomenon only pertains to these few cities as we have not studied the
544 situation of other locations. This will be left for future research.

545



546

547 **Figure 10: Spatial distribution of the kernel density function of drought (a) and locust outbreaks and social**
 548 **turmoil (b), and the social network chart (c) in the drought period 1830-1850.**

549

550 **4.2.5 Period 1850-1870**

551

552 In this period, drought condition in the Yellow plain in Hebei and Shandong in Northern China worsened and locust
 553 outbreaks were also wide spread similar to the 1830-1850 period. Fig. 4 shows that locust outbreak frequency in this
 554 period is the highest in the whole Qing dynasty. Famine occurred in locations where locust outbreaks were severe.
 555 The center of the worst condition – severe drought, heavy locust outbreaks and high famine density – was in the
 556 combined region of Hebei and Shandong provinces forming a northwest-southeast (NW-SE) belt as shown in Fig. 11
 557 (a) and (b). This is in contrast to the E-W orientation of the corresponding distributions in the previous period as

558 shown in Fig. 10. Could this difference in orientations be an indication of the regional atmospheric circulation pattern
559 change? We will conduct further studies on this subject in the future.

560

561 This was a time that political situation of Qing became increasingly unstable. Emperor Daoguang dies in 1850 and
562 was succeeded by his son Emperor Xianfeng (咸豐). Rebellions erupted all over China and the deadliest one was the
563 Taiping Rebellion (太平天國之亂) led by Hong Xiuquan (洪秀全), who was a self-proclaimed Christian and who
564 claimed himself to be the brother of Jesus Christ, that started in 1850 and ended in 1864. This is thought to be the
565 largest scale civil war in China in Qing dynasty and the bloodiest. Casualties was estimated in the range of 10-30
566 million and another 30 million fled to other and foreign settlements of China. This 14-year war impacted 18 provinces
567 but the region south of Yangtze River suffered the most casualties in this conflict.

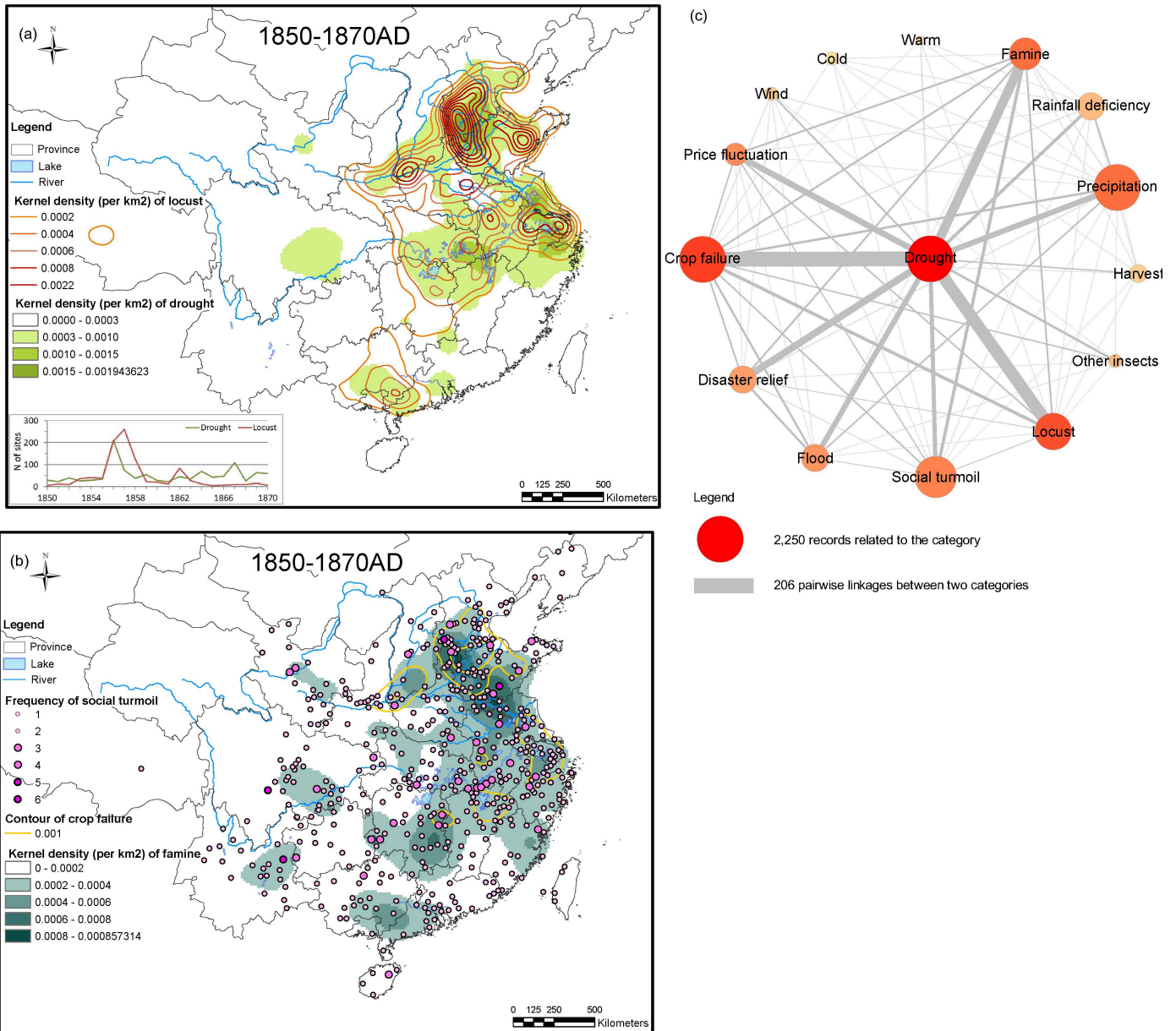
568

569 In the Central and Northern China, it was another bloody war, the Nian Rebellion (捻亂), that caused severe damages
570 to the country. “Nian” was one of the cult-like secret societies active in Central China especially along the region
571 between Anhui and Henan provinces after the disastrous Yellow River flood in 1851 that deluged hundreds of
572 thousands of square miles killing a large number of people. The scale of the societal turmoil was not as large as Taiping
573 but still caused serious social disruptions and loss of lives. The rebellion lasted from 1853 to 1868. There is no doubt
574 that this and Taiping Rebellions caused huge damages to Chinese economy and contributed to the many heavy turmoil
575 circles in Fig. 11 (b). Since these turmoil circles are unrelated to drought, they could appear in locations not affected
576 by drought. The social network analysis in Fig. 11(c) shows the strong links between drought-locust, drought-crop
577 failure and drought-famine.

578

579

580



581

582 **Fig. 11 Spatial distribution of the kernel density function of drought (a) and locust outbreaks and social turmoil**
 583 **(b), and the social network chart (c) in the drought period 1850-1870.**

584

585 4.2.6 Period 1870-1890

586

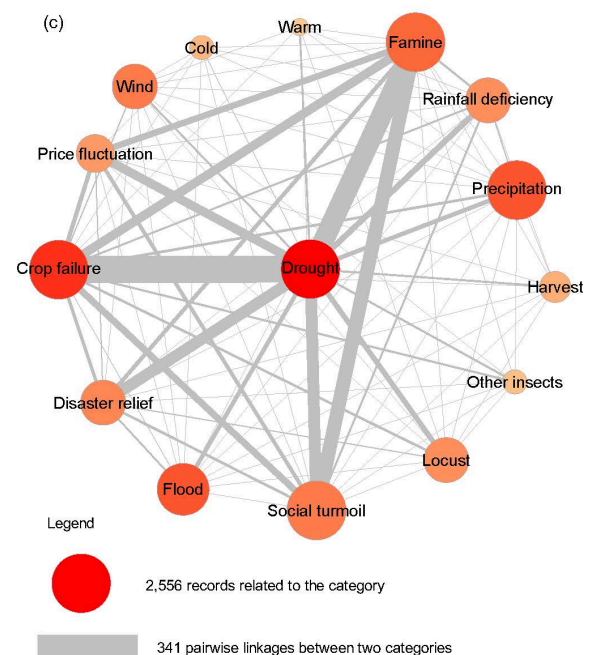
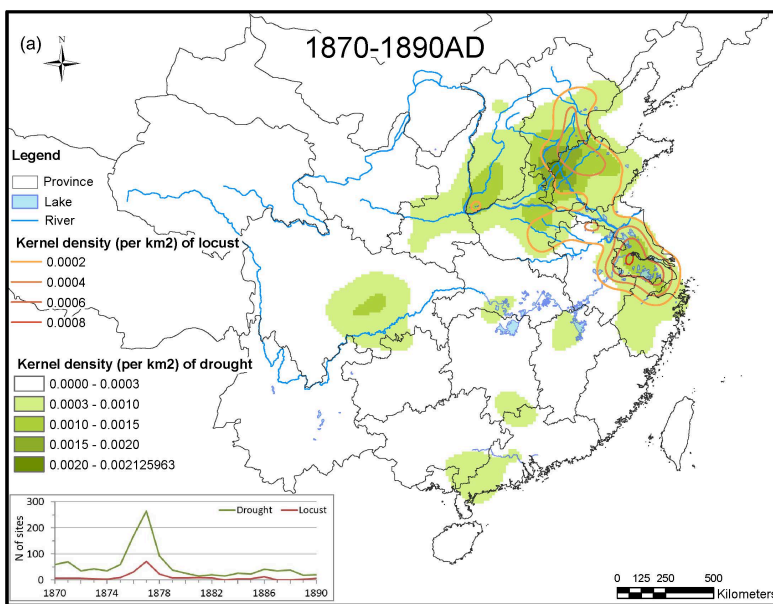
587 **Figure 12** (a) and (b) show the drought spatial distribution and the corresponding locust outbreaks/social turmoil
 588 distribution. In the Northern China, the two spatial patterns match quite well. The drought was centered on the region
 589 between Hebei and Shandong. The center of locust outbreaks/social turmoil was larger encompassing Shandong,
 590 Hebei, Shanxi, and Shaanxi. There was a small pocket of drought as well as locust/social turmoil in Sichuan province.
 591 The whole belt shows a NE-SW orientation. There was also a small center of drought and locust/social turmoil in
 592 northern Jiangsu. The rest of China, especially the south, appeared to be under no serious threat of drought although
 593 there were still sporadic social disturbances occurred in various places.

594

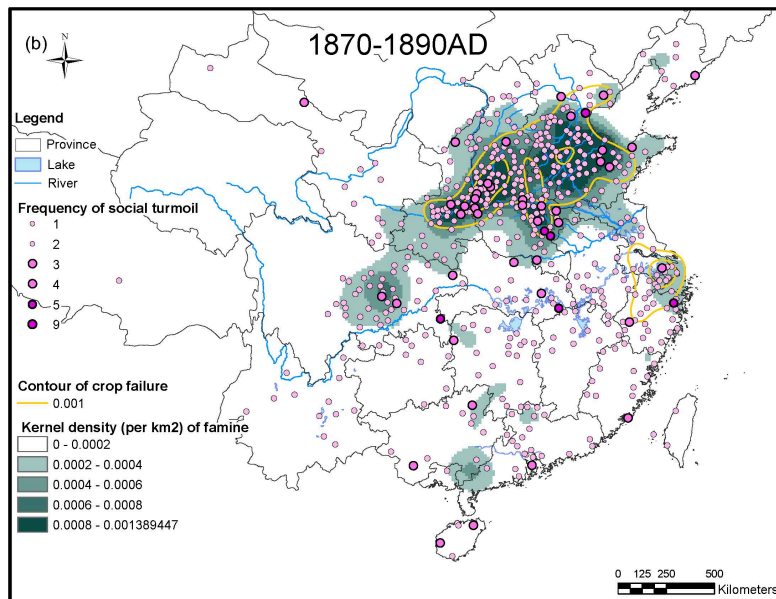
595 This period was near the end of Qing dynasty which lasted 21 more years and finally ended in 1911. China was
596 devastated by the Taiping Rebellion in the previous period and political situation was highly unstable as foreign
597 powers posed huge challenges to Qing government. Emperor Xianfeng died in 1874 and Emperor Guangxu (光緒), a
598 nephew of Xianfeng but adopted as a son later, succeeded the throne although the person in real power was the
599 Empress Dowager Cixi (慈禧太后) who declared war to all foreign powers after the Boxer Rebellion erupted in 1900
600 leading to the invasion of Beijing by the allied armies of eight countries.

601

602 The social network chart in Fig. 12 (c) shows a feature unique in this period that is not prominent in other periods: the
603 link between famine and social turmoil is very strong (the grey bar linking the two is very thick). This can also be
604 understood from Fig. 5 that the numbers of crop failure, socioeconomic turmoil and famine are all very high in this
605 period and they are highly correlated. This is also possibly an indicator that the government relief effort was not
606 effective in this period. This is not so in other earlier periods where the grey bars linking famine and socioeconomic
607 turmoil are rather thin. For example, the purple socioeconomic turmoil circles in the period 1665-1691 in Northern
608 China in Fig. 7(b) are fairly numerous, yet the grey bar linking famine and socioeconomic turmoil is relatively thin,
609 possibly indicating that the effectiveness of the relief programs by the government at this earlier period. Of course,
610 the socioeconomic interactions between various factors can be very complicated and nonlinear, and the above
611 statements should be regarded as temporary conjectures instead of definite conclusions. Further analyses need to be
612 performed to fully understand such relations.



613



614

615 **Fig. 12 Spatial distribution of the kernel density function of drought (a) and locust outbreaks and social**
 616 **turmoil (b), and the social network chart (c) in the drought period 1870-1890.**

617

618 5. Discussions

619

620 In the above, we proposed a new scheme to define the severity of drought reported in the Chinese historical documents
 621 and the relations between drought and other related ecological, agricultural, and socioeconomic variables. Instead of
 622 building mixed criteria to evaluate drought severity by artificial and often subjective judgment on the texts of the
 623 written records and assign them into different grades, this study adopts a more objective scheme to extract information
 624 from descriptive statements for reconstructing drought chronology. Drought and its associated variables are carefully
 625 categorized individually so as to build their distinctive chronologies. The advantage of this scheme is the
 626 straightforwardness of the approach without subjective guessing of the severity. It also allows cross check among
 627 variables and thorough statistical examinations on the relations.

628

629 In this study, we examined the literal meaning of drought mentioned in the written records by considering the four
 630 categories of drought as defined by Brázdil et al., (2018) and Heim (2002). We found that in the Chinese literature
 631 context, meteorological drought and hydrological drought are closely correlated with each other ($R=0.67$). The
 632 hydrological drought had even stronger correlation with severe meteorological drought ($R = 0.77$). This is easy to
 633 understand in that severe meteorological drought must necessarily result in hydrological drought unless the society
 634 has access of highly reliable non-precipitation water resource (such as underground water), which was nonexistent in
 635 historical China. Agricultural drought denoted by crop failure in this study is also highly correlated with
 636 meteorological and hydrological drought ($R = 0.63$). On the other hand, socioeconomic drought as represented by
 637 famine is also correlated fairly well with meteorological and hydrological drought ($R=0.62$). But the correlation
 638 between socioeconomic turmoil and meteorological and drought is weaker ($R=0.44$) possibly because there are other
 639 causes for the turmoil.

640

641 We found that in the period of 1644-1911 drought and related phenomena including locust outbreak, crop failure,
642 famine and socioeconomic turmoil tended to occur with lower temperature anomalies in the 17th century and 19th
643 century. The trend of temperature anomalies derived from REACHES database is generally consistent with other
644 studies (e.g., Frank et al., 2010; Ge et al., 2017). While some previous studies in China have pointed out that there
645 were more droughts in the 16th and 17th century than in the 18th and 19th centuries (Song, 2000; Zheng et al., 2006;
646 Shen et al., 2007; Yi et al., 2012; Ge et al., 2016), the resolution of their data did not allow them to identify intrinsic
647 drought events at interannual and decadal level. In contrast, the good time resolution of data series derived from
648 REACHES allows us to clearly identify the six severe drought periods as described in previous sections.

649

650 Another strength of data series derived from REACHES is the precise geographic information carried in them (Wang
651 et al., 2018). While some previous studies were able to show spatial patterns of the drought and flood (CMA, 1981),
652 they were not shown in precise locations and not carried fine resolutions. Our study facilitates the analysis of the
653 spatial patterns of drought and other related climate variables, as illustrated by the discussions in the previous section.
654 The spatial analysis reveals many features that cannot be easily shown by the series analysis alone. For example, one
655 can obtain an immediately appreciation of the similarity of the drought and locust spatial distributions in several
656 periods by simply inspecting the maps shown in the last section. It would be difficult to reach such a conclusion from
657 the time series shown in Fig. 4 or Fig. 5 because the series simply show the total counts nationally. One would need
658 to perform time series for each location to come to the same conclusion but that would be an extremely arduous effort.

659

660 To ensure the information shown on the maps are reliable, we delved into a great quantity of archival information and
661 index data from independent sources in the context of social and economic aspects related to the severe drought events
662 in these six periods. We found good consistency between the contents retrieved from the archival data and the analysis
663 derived from the REACHES. For example, heavily impacted regions shown on the maps are very consistent to those
664 provinces and cities or counties mentioned in the archival data.

665

666 We also performed the social network analysis to show the relative magnitudes of drought and related variables in the
667 six periods and the strength of connections among all variable pairs. In general, the features seen from these social
668 network charts are consistent with “common sense” at a qualitative level although the strength of the links between
669 different variable pairs can be quite different in different periods. We tried to interpret some of these links to
670 understand their implications, however, we stress that due to the complexity of human society it is not always easy to
671 make straightforward interpretations. In human events, a small perturbation can sometimes trigger a huge consequence
672 due to the high nonlinearity of social dynamics. We plan to conduct further studies to gain deeper insights on this
673 subject.

674

675 **6. Conclusions**

676 The strength of the study is the transparency of the method to extract information from descriptive statements of
677 drought records for reconstructing drought chronology. Our main purpose is to carry out such an objective scheme in

678 which different categories of drought and associated variables can be clearly defined and be carefully examined. All
679 the data series developed in the study is made publicly accessible and can be widely applied in future studies of
680 multidiscipline. The main conclusion of the study can be displayed in several ways: First, this study demonstrates the
681 richness of the historical documentary records to be used in space-time analysis for revealing extreme events and their
682 societal responses, as also revealed in previous studies such as Pfister (1992) and Brázdil et al. (2019). Careful
683 encoding and interpreting of the records into separate categories relating to drought phenomena, instead of pooling
684 them together for drought degree judgment, is substantial for further understanding drought contexts and estimating
685 their associations. Second, in the Qing dynasty (1644-1911), we identify six drought periods and importantly our
686 spatial and social network analysis reveal various spatial patterns and directionalities of the drought phenomena in the
687 periods (e.g. a NW-SE belt in 1850-1870 drought period, and a NE-SW orientation in 1870-1890 period) and the
688 societal impacts were also discrepant. The socioeconomic interactions can be very complicated and nonlinear, thus
689 further analyses need to be performed to fully understand such relations.

690

691 Finally, as we have emphasized before, the climate series presented here are anomaly series and extreme care must be
692 taken when interpret the characteristics of the series. For example, some researchers may interpret a period of high
693 drought frequency as a “dry climate” period while in reality the high frequency only indicates that many “dry weather
694 days” had occurred. This can be best understood by inspecting Fig. 5 where the flood time series is also included. We
695 see that the flood frequency could also be quite high during a high drought frequency period and many flood cases are
696 indeed due to excessive rainfall, and obviously one cannot interpret this as a “humid climate” period. A more
697 appropriate interpretation would be that this is a period of high precipitation variability. The interpretation of other
698 anomaly series should also consider the possibility of this type of bias. Lastly, it will be also imperative in future study
699 to compare drought and other climate time series across different continents such as the comparison between East
700 Asia and Europe, so that more insightful view can be acquired to better understand general circulation at the times.

701

702

703 **Data availability**

704 Data series reconstructed in this study will be deposited at NOAA national center for environmental information
705 (<https://www.ncdc.noaa.gov/paleo-search/study/23410>). Or users can also contact the authors for more information
706 on data series.

707

708 **Competing interests**

709 The authors declare that they have no conflict of interest.

710

711 **Author contribution**

712 KHE Lin set up the research topic, designed the research, performed the analysis and drafted the manuscript. PK
713 Wang motivated the research, and comprehensively edited the manuscript. PL Pai helped collecting archival data
714 and working on historical context. YS Lin helped retrieving and cleaning the data series, and implementing the
715 analysis.

716

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722 **References**

723 Barriendos, M.: Climatic variations in the Iberian Peninsula during the late Maunder Minimum (AD 1675–1715): an
724 analysis of data from rogation ceremonies, *Holocene*, 7, 105–111, <https://doi.org/10.1177/095968369700700110>,
725 1997.

726 Bicker, R., and Jackson, I. (ed.): *Treaty Ports in Modern China: Law, Land and Power*, Routledge, London, 2016.

727 Brázdil, R., Dobrovolný, P., Trnka, M., Büntgen, U., Řezníčková, L., Kotyza, O., Valášek, H., and Štěpánek, P.:
728 Documentary and instrumental-based drought indices for the Czech Lands back to AD 1501, *Clim. Res.*, 70, 103–
729 117, <https://doi.org/10.3354/cr01380>, 2016.

730 Brázdil, R., Dobrovolný, P., Trnka, M., Řezníčková, L., Dolák, L., and Kotyza, O.: Extreme droughts and human
731 responses to them: the Czech Lands in the pre-instrumental period, *Clim. Past*, 15, 1–24, [https://doi.org/10.5194/cp-](https://doi.org/10.5194/cp-15-1-2019)
732 [15-1-2019](https://doi.org/10.5194/cp-15-1-2019), 2019.

733 Brázdil, R., Kiss, A., Luterbacher, J., Nash, D. J., and Řezníčková, L.: Documentary data and the study of past
734 droughts: a global state of the art, *Clim. Past*, 14, 1915–1960, <https://doi.org/10.5194/cp-14-1915-2018>, 2018.

735 Brázdil, R., Pfister, C., Wanner, H., Storch, H. V., and Luterbacher J.: Historical climatology in Europe – the state of
736 the art, *Clim. Change*, 70, 363–430, <https://doi.org/10.1007/s10584-005-5924-1>, 2005.

737 Brönnimann, S., Martius, O., Rohr, C., Bresch, D., and Lin, K-HE.: Historical weather data for climate risk
738 assessment, *Ann. NY Acad. Sci.*, 1436, 121–137, <https://doi.org/10.1111/nyas.13966>, 2018.

739 Cao, S. J. (ed.): *History of Population in China, Vol. 5 Qing Dynasty*, Fudan University Press, Shanghai, China,
740 2001.

741 Chinese military history writing group: *Chronology of China's Ancient Wars* Chinese People's Liberation Army
742 Publishing House, Beijing, China, 1985.

743 CMA: *Yearly charts of dryness/wetness in China for the last 500-year period* in Administration CM (ed.),
744 Cartographic Publishing House, Beijing, China, 1981.

745 Cook, B. I., Smerdon J. E., Seager, R., and Coats, S.: Global warming and 21st century drying, *Climate Dynamics*,
746 43, 2607–2627, <https://doi.org/10.1007/s00382-014-2075-y>, 2014.

747 Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D'Arrigo, R. D., Jacoby, G. C., and Wright, W. E.: Asian Monsoon
748 Failure and Megadrought During the Last Millennium, *Science*, 328, 486–489,
749 <http://dx.doi.org/10.1126/science.1185188>, 2010.

750 Cook, E. R., Seager, R., Kushnir, Y., Briffa, K. R., Büntgen, U., Frank, D., Krusic, P. J., Tegel, W., van der Schrier,
751 G., Andreu-Hayles, L., Baillie, M., Baittinger, C., Bleicher, N., Bonde, N., Brown, D., Carrer, M., Cooper, R.,
752 Čufar, K., Dittmar, C., Esper, J., Griggs, C., Gunnarson, B., Günther, B., Gutierrez, E., Haneca, K., Helama, S.,
753 Herzig, F., Heussner, K-U., Hofmann, J., Janda, P., Kontic, R., Köse, N., Kyncl, T., Levanič, T., Linderholm, H.,

754 Manning, S., Melvin, T.M., Miles, D., Neuwirth, B., Nicolussi, K., Nola, P., Panayotov, M., Popa, I., Rothe, A.,
755 Seftigen, K., Seim, A., Svarva, H., Svoboda, M., Thun, T., Timonen, M., Touchan, R., Trotsiuk, V., Trouet, V.,
756 Walder, F., Ważny, T., Wilson, R., and Zang, C.: Old World megadroughts and pluvials during the Common Era,
757 *Sci. Adv.*, 1, 1:e1500561, <https://doi.org/10.1126/sciadv.1500561>, 2015.

758 Diodato, N. and Bellocchi, G.: Historical perspective of drought response in central-southern Italy, *Clim. Res.*, 49,
759 189–200, <https://doi.org/10.3354/cr01020>, 2011.

760 Frank, D. C., Esper, J., Raible, C. C., Büntgen, U., Trouet, V., Stocker, B., and Joos, F.: Ensemble reconstruction
761 constraints on the global carbon cycle sensitivity to climate, *Nature*, 463, 527–530,
762 <https://doi.org/10.1038/nature08769>, 2010.

763 Ge, Q., Liu, H., Ma, X., Zheng, J., and Hao, Z.: Characteristics of temperature change in China over the last 2000
764 years and spatial patterns of dryness/wetness during cold and warm periods, *Adv. Atmos. Sci.*, 34, 941–951,
765 <https://doi.org/10.1007/s00376-017-6238-8>, 2017.

766 Ge, Q., Zheng, J., Hao, Z., Liu, Y., and Li, M.: Recent advances on reconstruction of climate and extreme events in
767 China for the past 2000 years, *J. Geogr. Sci.*, 26, 827–854, <https://doi.org/10.1007/s11442-016-1301-4>, 2016.

768 Hao, Z., Wu, M., Zheng, J., Chen, J., Zhang, X., and Luo, S.: Patterns in data of extreme droughts/floods and harvest
769 grades derived from historical documents in eastern China during 801–1910, *Clim. Past*, 16, 101–116,
770 <https://doi.org/10.5194/cp-16-101-2020>, 2020.

771 Hao, Z., Zheng, J., Zhang, X., Liu, H., Li, M., and Ge, Q.: Spatial patterns of precipitation anomalies in eastern
772 China during centennial cold and warm periods of the past 2000 years, *Int. J. Climatol.*, 36, 467–475,
773 <https://doi.org/10.1002/joc.4367>, 2016.

774 Heim, R. R.: A review of twentieth-century drought indices used in the United States, *Bull. Am. Meteorol. Soc.*, 83,
775 1149–1166, <https://doi.org/10.1175/1520-0477-83.8.1149>, 2002.

776 Held, I. M., and Soden, B. J.: Robust responses of the hydrological cycle to global warming, *J. Clim.*, 19, 5686–
777 5699, <https://doi.org/10.1175/JCLI3990.1>, 2006.

778 Huang, B., Li, G., Li, F., Kong, D., and Wang, Y.: The 1855 to 1859 locust plague in China, *Nat. Hazards*, 95, 529–
779 545, <https://doi.org/10.1007/s11069-018-3498-2>, 2019.

780 IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment
781 Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United
782 Kingdom and New York, NY, USA, <https://doi.org/10.1017/CBO9781107415324>, 2014.

783 Kuo, C. K.: Historical Report on the Kang-Qian Prosperity Period, China Yan Shi Press, China, 2002.

784 Lin, K-HE, Wang, P. K., Lin, Y. H., and Wang, C. W.: Experiments on the reconstruction methods and calibration
785 of the climate series derived from REACHES historical database of China in 1644-1911, EGU General Assembly,
786 Vienna, Austria, 7–12 April 2019, EGU2019-12868, 2019.

787 Lin, N.: Social networks and status attainment, *Annu. Rev. Sociol.*, 25, 467–488,
788 <https://www.jstor.org/stable/223513>, 1999.

789 Ljungqvist, F. C., Krusic, P. J., Sundqvist, H. S., Zorita, E., Brattström, G., and Frank, D.: Northern Hemisphere
790 hydroclimate variability over the past twelve centuries, *Nature*, 532, 94–98, <https://doi.org/10.1038/nature17418>,
791 2016.

792 McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time steps, in:
793 Preprints, 8th Conference on Applied Climatology, 17–22 January 1993, Anaheim, CA, USA, 179–184, 1993.

794 Možný, M., Brázdil, R., Dobrovolný, P., Trnka, M., Potopová, V., Hlavinka, P., Bartošová, L., Zahradníček, P., and
795 Žalud, Z.: Drought reconstruction based on grape harvest dates for the Czech Lands, 1499–2012, *Clim. Res.*, 70,
796 119–132, <https://doi.org/10.3354/cr01423>, 2016.

797 Palmer, W. C.: *Meteorological Drought*, Office of Climatology Research Paper 45, U.S. Weather Bureau,
798 Washington, USA, 1965.

799 Pei, Q., Lee, H. F., Zhang, D. D., Fei, J.: Climate change, state capacity and nomad-agriculturalist conflicts in
800 Chinese history, *Quat. Int.* 508, 36–42, <https://doi.org/10.1016/j.quaint.2018.10.022>, 2019.

801 Pfister, C., Brázdil, R., Glaser, R., Barriendos, M., Camuffo, D., Deutsch, M., Dobrovolný, P., Enzi, S., Guidoboni,
802 E., Kotyza, O., Miltzer, S., Rácz, L., and Rodrigo, F. S.: Documentary evidence on climate in sixteenth-century
803 Europe, *Clim. Change*, 43, 55–110, <https://doi.org/10.1023/A:1005540707792>, 1999.

804 Pfister, C.: Monthly temperature and precipitation in central Europe 1525–1979: quantifying documentary evidence
805 on weather and its effects, in: *Climate Since A.D. 1500*, edited by: Bradley, R. S. and Jones, P. D., Routledge,
806 London, UK and New York, USA, 118–142, 1992.

807 Routson, C. C., Woodhouse, C. A., Overpeck, J. T., Betancourt, J. L., and McKay N. P.: Teleconnected ocean
808 forcing of western North American droughts and pluvials during the last millennium, *Quat. Sci. Rev.*, 146, 238–250,
809 <https://doi.org/10.1016/j.quascirev.2016.06.017>, 2016.

810 Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M.,
811 Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang,
812 Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., and Kabat, P.: Multimodel
813 assessment of water scarcity under climate change, *Proc. Natl. Acad. Sci. U.S.A.*, 111, 32458–3250,
814 <https://doi.org/10.1073/pnas.1222460110>, 2014.

815 Schofield, M., Barker, R. J., Gelman, A., Cook, E. R. and Briffa, K. R.: A Model-Based Approach to Climate
816 Reconstruction Using Tree-Ring Data, *J. Am. Stat. Assoc.*, 111:513, 93–
817 106, <https://doi.org/10.1080/01621459.2015.1110524>, 2016.

818 Scott, J.: *Social Network Analysis*, Sage Publications, London, United Kingdom, 2017.

819 Shen, C., Wang, W-C., Hao, Z., and Gong W.: Exceptional drought events over eastern China during the last five
820 centuries, *Clim. Change*, 85, 453–471, <https://doi.org/10.1007/s10584-007-9283-y>, 2007.

821 Shi, H., Wang, B., Cook, E. R., Liu, J., and Liu, F.: Asian Summer Precipitation over the Past 544 Years
822 Reconstructed by Merging Tree Rings and Historical Documentary Records, *J. Clim.*, 31, 7845–7861,
823 <https://doi.org/10.1175/JCLI-D-18-0003.1>, 2018.

824 Silverman, B. W.: *Density Estimation for Statistics and Data Analysis*, Chapman and Hall/CRC Publications, New
825 York, United States, 1986.

826 Song, J.: Changes in dryness/wetness in China during the last 529 years, *Int. J. Climatol.*, 20, 1003–1016,
827 [https://doi.org/10.1002/1097-0088\(200007\)20:9<1003::AID-JOC529>3.0.CO;2-S](https://doi.org/10.1002/1097-0088(200007)20:9<1003::AID-JOC529>3.0.CO;2-S), 2000.

828 Stahle, D. W., Fye, F. K., Cook, E. R., and Griffin, R. D.: Tree-ring reconstructed megadroughts over North
829 America since A.D. 1300, *Clim. Change*, 83, 133, <https://doi.org/10.1007/s10584-006-9171-x>, 2007.

830 Stevenson, S., Overpeck, J.T., Fasullo, J., Coats, S., Parsons, L., Otto-Bliesner, B., Ault, T., Loope, G., and Cole, J.:

831 Climate variability, volcanic forcing, and last millennium hydroclimate extremes. *J. Clim.*, 31, 4309–

832 4327, <https://doi.org/10.1175/JCLI-D-17-0407.1>, 2018.

833 Su, Y., Liu, L., Fang, X. Q., Ma, Y. N.: The relationship between climate change and wars waged between nomadic

834 and farming groups from the Western Han Dynasty to the Tang Dynasty period, *Clim. Past*, 12, 137–150,

835 <https://doi.org/10.5194/cp-12-137-2016>, 2016.

836 Tan, P. H., and Liao, H. M.: Reconstruction of temperature, precipitation and weather characteristics over the

837 Yangtze River Delta Area in Ming Dynasty, *J of Geog Research*, 57, 61–87,

838 <http://rportal.lib.ntnu.edu.tw:80/handle/20.500.12235/23617>, 2012.

839 Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling,

840 A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T.,

841 Rangelcroft, S., Wanders, N., and Van Lanen, H. A. J.: Drought in the Anthropocene, *Nat. Geosci.*, 9, 89–91,

842 <https://doi.org/10.1038/ngeo2646>, 2016.

843 Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A multi-scalar drought index sensitive to global

844 warming: The Standardized Precipitation Evapotranspiration Index – SPEI, *J. Climate*, 23, 1696–

845 1718, <https://doi.org/10.1175/2009JCLI2909.1>, 2010.

846 Wang, S.W., and Zhao, Z C.: Droughts and floods in China, 1470-1979. in "Climate and History" T.M.L.Wigley,

847 M.J.Ingram and G.Farmer (Eds.), Cambridge University Press, 271–288, 1981.

848 Wang, P. K.: Locust infestation and climate conditions of China in historical time, 17th Conference on Agriculture &

849 Forest Meteorology and 7th Conference on Biometeorology & aerobiology, Scottsdale, Arizona, 21–24 May 1985,

850 American Metrological Society, 1985.

851 Wang, P. K., Lin, K-HE, Liao, Y. C., Liao, H. M., Lin, Y. S., Hsu, C. T., Hsu, S. M., Wan, C. W., Lee, S. Y., Fan, I.

852 C., Tan, P. H., and Ting, T. T.: Construction of the REACHES climate database based on historical documents of

853 China, *Sci. Data*, 5,180288, <https://doi.org/10.1038/sdata.2018.288>, 2018.

854 Wang, Y. C.: The secular trend of prices during the Ch'ing period (1644-1911), *Journal of Chinese Studies*, 5, 347–

855 371, 1972.

856 Wang, Y. C.: Qing Dynasty Grain Price Database, Institute of Modern History, Academia Sinica, Taipei.

857 Wei, Z., Rosen, A. M., Fang, X., Su, Y., Zhang, X.: Macro-Economic Cycles Related to Climate change in Dynastic

858 China, *Quat. Res.*, 83, 13–23, <https://doi.org/10.1016/j.yqres.2014.11.001>, 2017.

859 White, S.: A Comparison of drought information in early North American colonial documentary records and a high-

860 resolution tree-ring-based reconstruction, *Clim. Past*, 15, 1809–1824, <https://doi.org/10.5194/cp-15-1809-2019>,

861 2019.

862 Yi, L., Yu, H., Ge, J., Lai, Z., Xu, X., Qin, L., and Peng, S.: Reconstructions of annual summer precipitation and

863 temperature in north-central China since 1470 AD based on drought/flood index and tree-ring records, *Clim.*

864 *Change*, 110, 469–498, <https://doi.org/10.1007/s10584-011-0052-6>, 2012.

865 Zhang, D.: Supplement for the yearly chart of dryness/wetness in China for the last 500 years, *J. Appl. Meteorol.*

866 *Sci.*, 14, 379–388, 2003.

867 Zhang, D.: A Compendium of Chinese Meteorological Records of the Last 3,000 Years, Phoenix House.Ltd. ,
868 Jiangsu, People's Republic of China, 2013 (First edition published in 2004).
869 Zhang, J., and Crowley, T. J.: Historical climate records in China and reconstruction of past climates, *J. Clim.*, 833–
870 849, 1989.
871 Zheng, J., Wang, W. C., Ge, Q., Man, Z., and Zhang, P.: Precipitation variability and extreme events in Eastern
872 China during the past 1500 years, *Terrestrial, Terr. Atmospheric Ocean. Sci.*, 17, 579–592,
873 [https://doi.org/10.3319/TAO.2006.17.3.579\(A\)](https://doi.org/10.3319/TAO.2006.17.3.579(A)), 2006.
874 Zheng, J. Y., Ge, Q. S., Hao, Z. X., Liu, H. L., Man, Z., Hou, Y. J., and Fang, X. Q.: Paleoclimatology proxy record
875 in historical documents and methods for reconstruction on climate change, *J. Quat. Sci.*, 34, 1186–1196,
876 <http://www.dsji.com.cn/EN/10.3969/j.issn.1001-7410.2014.06.07>, 2014.
877