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ORIGINAL ARTICLE

A preliminary analysis of economic fluctuations and climate changes in China from BC 220 to AD 1910

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Abstract Understanding the socioeconomic effects of past climate change is valuable for sustainable social development. However, quantitative analyses of the long-term relationships between climate change and human society have been limited by a lack of long-term high-resolution data that indicate socioeconomic processes. Here, based on 1,091 records extracted from 25 books on Chinese history and economic history written by leading contemporary scholars, an economic proxy series for China with decadal resolution is presented that encompasses the period from BC 220 to AD 1910. A method for semantic differential and integrating descriptions with multi-time resolution is developed. The statistical results show that warm and wet periods were associated with above-average economic performance, while cold and dry climatic scenarios greatly increased the possibility of economic crisis. Temperature was more influential than precipitation in explaining the long-term economic fluctuations, whereas precipitation displayed more significant effects on the short-term macro-economic cycle. It is proposed that the climatic effects on agrarian economic development were highly dependent on the social vulnerability, which is determined by particular social, economic and political backgrounds. From a deep time perspective, our study may provide new insight into the current intense arguments regarding the economic effects of global warming.

Keywords Climatic change · Macro-economic fluctuation · Proxy reconstruction · Impact · Agrarian China

Introduction

Investigating climate–society relationships has long been a hot topic, which is partially fueled by the recent development of high-resolution paleoclimatic reconstructions in many parts of the world (IPCC 2013). Many studies have demonstrated the important roles of climate change in facilitating the rise or fall of ancient communities. Prolonged droughts can undermine the water supply and agricultural productivity; droughts have been repeatedly cited as a main driver for many cases of abrupt social/civilization collapse (Haug et al. 2003; deMenocal 2001; Kennett et al. 2012; Weiss and Bradley 2001; Buckley et al. 2010). Climate deterioration-induced socioeconomic crisis was notably observed in Europe (Büntgen et al. 2011). During the Little Ice Age, food storage could not compensate for the loss caused by poor annual harvests; famine and plague caused large-scale depopulation, out-migration and farmland abandonment (Lamb 1995). Under this situation, serious demographic, economic and social crises became inevitable. For example, the cold–wet summers at the end of the sixteenth century caused far-reaching

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effects on the wine economy in southern Austria and substantially reduced local government revenues (Messerli et al. 2000). Quantitative results have revealed that macro-economic cycles in pre-industrial Europe were affected by the long-term temperature changes over a large spatial scale (Pei et al. 2014; Zhang et al. 2011). However, most of the economic effects of climate change were Eurocentric. Quantitative investigations of the economic effects of long-term climatic perturbations are still limited by the dearth of long-term and high-resolution data that indicate the dynamics of socioeconomic processes. Quantitative surveys based on multi-proxy comparisons not only have been pursued by PAGES (2009) but are also essential to help reduce uncertainty and avoid environmental determinism that is related to climate–society research, specifically when considering that some statements are growingly criticized as too simplistic and mono-causal (Butzer and Endfield 2012; Turner 2010; Butzer 2012; Yancheva et al. 2007; Zhang and Lu 2007; Zhang et al. 2008; Zhang et al. 2010b; Cheng et al. 2010).

Using long-term historical records to reconstruct a socioeconomic proxy and to quantitatively study the relationship between climate change and historical rhythms has been an advantage in China for climate sociology research (Fang et al. 2013; Ye et al. 2012; Su et al. 2014; Zhang et al. 2006; Lee et al. 2008). Previous studies paid more attention to the climatic effects on historical cyclical rhythms based on population (Lee et al. 2008), the frequency of revolts and wars (Zhang et al. 2010c; Zhang et al. 2006) and dynastic collapse events (Zhang et al. 2006). In comparison, climatic effects on the macro-economy have received little attention due to a lack of continuous and comparable statistical economic data.

Fortunately, the literature maintains rich qualitative descriptions, and different semantics conveyed by words and phrases can indicate certain intensities, scopes and directions (Osgood 1957). The semantic differential (SD) technique was first developed by Osgood (1957) to identify the emotional meaning of words. He believed that humans shared common emotional feelings to concepts or vocabulary, which varied little with changes in culture and language. Asch (1946) proposed that subjects were able to use a limited amount of information to form a unified and undifferentiated “general impression” on an object. Semantic analysis is most widely used in linguistics and psychology due to its effectiveness at indexing qualitative word descriptions, such as attitude measurements. This analysis is typically performed in terms of ratings on bipolar scales that are defined with contrasting adjectives at each end (Osgood 1957). Three basic dimensions, which have been labeled evaluation (e.g., good and bad), potency (e.g., large and small) and activity (e.g., fast and slow), have been identified in several early studies to account for most of the co-variation in the ratings (Snider and Osgood 1969). Semantic analysis has been used successfully to reconstruct long-time series of dryness/wetness indices (CMA 1981; Zheng et al. 2006), grain harvests (Su et al. 2014; Yin et al. 2014) and fiscal balance (Wei et al. 2014) in China and has been proven to be a suitable approach for converting qualitative descriptions found in literary sources into quantitative data.

In this study, we attempted to reconstruct a 2130-year-long agrarian economic sequence by focusing on the relative phase transition of macro-economic fluctuations in imperial China using the method of semantic differential. Based on the reconstructed sequence, a preliminary analysis was performed on the associations between climatic effects and the macro-economy in China over the past 2000 years for different temporal scales.

Data and methodology

Economic series

We chose the imperial era from the unified Qin Dynasty to the end of the Qing Dynasty (BC 221–AD 1911) as the reconstructed period in this study. Because these periods shared similar basic forms of economic organization and a highly agrarian-based economic system, they experienced cycle-like ups and downs in economic development that accompanied the so-called dynastic cycle (Fu 1981; Skinner 1985). We analyzed the general performance of the economic system by considering the empire as the analysis unit as suggested by Skinner (1985). This was because the materials used primarily addressed the empire-wide economic performance. Spatially, the dynastic economy was dominantly built on the development of key economic areas beginning in earlier periods in the middle and lower Yellow River. Thereafter, the economy expanded to the middle and lower Yangtze River (Fu 1981; Elvin 1973). Contributions to the empire’s total economy from other marginal areas in China, e.g., the Tibetan Plateau and Northwest China, were very small and sometimes negligible. The evidence of the historical economy in China is largely from eastern China (25–40 °N, 100–125 °E), which is a traditional and very stable crop-producing region that is substantially influenced by the East Asian monsoon. Therefore, the developed economic series has an empire-wide spatial representativeness.

In total, 1,091 records were extracted from passages of text in 25 books. All of these books address the history or economic history of China. Most of these books were written by leading Chinese scholars and published over the last thirty years (see Online Resource). These books not only contain rich and raw economic materials but also

Table 1 Differentiation of imperial macro-economic phases in China based on the semantic analysis of words used in books

Level	MS	RMP		LFS	
		Upward	Downward	Livelihoods	Finance
Collapse (1)	Totally collapsed, vanished; in ruins, a dead end; extremely desolate; cannibalism; unbearably languished	Collapse continued without any improvement	Quickly plummeted; sudden interruption; dropped to the lowest	Fail to survive; hunger to the point of cannibalism; unprecedented heavy corvée	Extreme lack of wealth; financial exhaustion and collapse
Depression (2)	On the verge of collapse; economic crisis; brokenness; depressed; destitute	Recovered up to a limit; little improvement; slightly better than the economic collapse	Large reduction in production; rapidly deteriorating	Shortage of food and clothing; extreme poverty; widespread bankruptcy; small-scale armed struggle	Extremely deficient; financial deterioration; constraints
Average (3)	Adequately fed; normal economic production; lived and worked in peace; slack; mild economic chaos	Began to improve; production had been restored; developing recovery	Stagnated; wandering and backward; increasingly depressed; recession; no longer prosperous	Reluctantly ensuring basic needs; slight improvement; heavy burden; moderate bankruptcy; displaced	On the right track; nearly balance; financially worse than sufficiency
Prosperity (4)	Thriving; preliminary prosperity; well-off situation; stable economic situation	Rapidly developed; fundamental improvement; full recovery; continually moving forward	Began to decline; no longer at the peak, somewhat retreating	Better at ensuring basic needs; recuperating; alleviated tax burden; beginning of bankruptcy before more serious issues	Accumulating wealth; sufficient food reserves to relieve taxes; plenitude before excess
Climax (5)	Strong economic strength; considerable wealth; unprecedented prosperity; affluence; peak; heyday	A great leap forward; increased nearly vertically; lasting prosperity	Maintained prosperity but failed to develop further	Basic needs could be met for the majority; lived in happiness and health	Excess wealth; sufficient treasury; strong finance; food was accumulated until it became moldy

provide objective and the authoritative assessments of historical experts on the relative phase change in the macro-economic development of China. The authors can form a more general impression of the macro-scale economic performance based on the systematic and comprehensive analysis of a variety of economic variables. Thus, the records extracted from these books are appropriate for our semantic analysis. The 1,091 records were divided into three groups (in descending order) according to their semantic characteristics and reliability in reflecting the macro-economy variations. Group 1 conveyed the macro-economic state (MS) and could directly determine the economic grade. Group 2 indicated directional relative change in macro-economic processes (RMP) and helped rank records based on before-and-after economic condition comparisons. Lastly, Group 3 indicated both state and directional changes of certain indices (primarily the peasants' livelihoods and state fiscal situations (LFS)) and played a supplementary role given the lack records in the previous two groups during certain periods. Groups 1–3 contained 458 (42 %), 576 (52.8 %) and 57 (5.2 %) records, respectively.

In our analysis, an odd 5-point scale was adopted to assign each record a grade ranked from 5 to 1 to express the relative phase of economic performance changing from an economic climax (5) to an economic collapse (1). Table 1 shows examples of using semantic differentiation to index qualitative descriptions. Different scales/grades represented different phases of the economic cycle. The common characteristics of economic performance at a similar developmental stage were summarized in each phase according to semantic similarity.

Different records exhibited multi-time resolutions (see Table 2); a downscaling approach was applied to integrate the various temporal resolution records. The detailed methods and steps for reconstructing the decadal time series were as follows:

(1) Macro-economic performance was evaluated using approximately 21 representative Chinese dynasties. Two major confrontation periods (i.e., AD 317–589 and AD 1127–1279) between the northern dynasties and the southern dynasties were identified in the present study. For other dividing periods, the averaging was based on the conditions of regional-regime economic activities.

Table 2 Historical economic descriptions with multi-time resolutions

No.	Interval (AD)	Records and their source	Group
1	17–25	The economy collapsed after the red-browed and Lulin peasant uprising (Fu 1984)	MS
2	25–220	The economy of the Eastern Han Dynasty had not been as prosperous as that of the Western Han Dynasty (Zhou 2007)	RMP
3	25–88	Economic situation gradually improved during the reigns of Emperors Guangwu, Ming, and Zhang (Shi and Hu 1994)	RMP
4	25–57	During the generation of Emperor Guangwu, the social economy was unbearably destitute, devastated everywhere, and extremely desolated (Fu 1984)	MS
5	25–36	In the early years of Guangwu, the social economy was dilapidated and production had not been restored; "people survive on wild millet and flax" (Tian and Qi 1998)	MS
6	37–88	The first 50 years of the Eastern Han Dynasty (after the unification wars around AD 36) were periods of economic recovery (Zhu and Shi 1995)	RMP
7	37–57	After the reunification, Liu Xiu adopted a respite policy, and social production was restored rapidly; people could engage in production peacefully (Tian and Qi 1998)	RMP
8	58–105	Beginning in the Yongping Age (AD 58–75) of Emperor Ming, the economy began to show some degree of prosperity, but this prosperity did not last long before declining after Emperor Zhang and He (Fu 1984)	MS
9	58–75	The national economy displayed prosperity during the reign of Emperor Ming (Shi and Hu 1994)	MS
10	58–75	During the 18-year reign of Emperor Ming, the Eastern Han Dynasty entered a period of social stability and economic development (Zhu and Shi 1995)	RMP
11	58–68	The positive measures of developing production began to reap benefits in the middle of Emperor Ming's reign: "a bumper harvest in agriculture in the 9th year of Yongping (AD 66)" (Zhu and Shi 1995)	MS
12	69–69	In the 12th year of the Yongping Age, economy displayed a scene of prosperity and peace (Tian and Qi 1998)	MS
13	69–75	At the end of Emperor Ming's reign, the social economy of the Eastern Han Dynasty peaked prosperously, but the economic rally did not return to its peak level in the Western Han Dynasty (Zhu and Shi 1995)	MS
14	76–88	The national economy during Emperor Zhang displayed prosperity but failed to reach the height of the Western Han Dynasty (Shi and Hu 1994)	MS
15	89–106	The economy of Emperor He was still reluctantly maintaining prosperity and peace (Zhu and Shi 1995)	MS

(2) Each record's resolution was decided according to the year provided by the individual record or according to Mao (2002) for the starting and ending years of an emperor's reign. In addition, several records had no concrete dating (e.g., the earlier periods of the Wu emperor's reign, the later stage of the Tang Dynasty, and prior to/since 1840). In this case, the resolutions were decided by the dating of other records that had a substantial temporal overlap with these records, or based on some important turning times that were closely connected with economic activity, such as the year of large-scale taxation reform. To facilitate comparison, records with nearly identical time-scales and substantial temporal overlap in each group were incorporated together into a total of 274 intervals (43 intervals for the southern dynasties during the periods AD 317–589 and AD 1127–1279 and 231 intervals for the other dynasties during the period BC 221–AD 1911). Notably, these intervals were summarized according to the resolution of the majority of the records, which was feasible because the temporal resolution of each record was applied to a certain interval or to a certain emperor's reign instead of one year in most cases. The length of the intervals ranged from several years to hundreds of years. Periods <10, <30 and <50 years accounted for 29.6 % (81 out of the 274), 65.7 % (180) and 80.7 % (221), respectively, of the entire dataset. Accordingly, the number of records in intervals with lengths <10, <30 and <50 years accounted for 20.2 % (220 out of the 1091), 54.8 % (598) and 80 % (864), respectively, of the total number of records. A total of 130 intervals (398 records) had shorter durations (higher-resolution data) compared with the other 144 (693 records) longer intervals (lower resolution data). The Mean

number of records for each interval in the sets of 130 and 144 intervals was ∼3 and 5, respectively.

(3) A trend-controlling series was constructed based on the grade judgment of important turning-point years (i.e., at each end of the bipolar scales defined using contrasting adjectives, e.g., collapse and climax; Table 1). A total of 109 turning points (20 during the periods AD 317–589 and AD 1127–1279 and 89 during the period BC 221–AD 1911) were ultimately determined according to the higher-resolution records in the 130 intervals. Their connections reflected macro-economic directional changes that were conveyed by the lower-resolution records in the 144 intervals. The turning-point year was determined by choosing the definite year or the end/midpoint year provided by the majority of the records or using a compromising principle. Besides, records in group MS (highest priority) were used as the basis for evaluating the grade. When MS data were unavailable or insufficient to grade a level, the RMP data (middle priority) were used to determine the point's level.

For each point's grade judgment, conflicts among multiple records in the same interval might occur due to truly different views by the authors or to different writing styles/habits. To handle this problem, we proposed several principles. If all of the records in one interval indicated the same economic grade, the grade was ranked according to the criterion in Table 1. If different records indicated the same type of either depression (1–3) or prosperity (3–5) but with different grades, then the level was graded based on the grade of the majority of the records. In the cases with equal frequency, comparison records in the RMP group were given priority for the grade rating, i.e., grade 5 was given priority over grade 4, while grade 4 was given priority over grade 3; similarly, grade 1 was given priority over grade 2, while grade 2 was given priority over grade 3. If different records indicated different economic phases (e.g., collapse and prosperity), then the grade was rated according to the predominant level of the majority of the records or a compromising grade was selected.

(4) Initial economic series without fixed time resolutions were constructed by refining the trend-controlling series through integrating multi-time resolution records in the aforementioned three groups. The principles for grade judgment complied with those provided in step (3).

Taking the grade evaluation of the early Eastern Han Dynasty (AD 25–106) as an example, the trend-controlling series showed a directional change of economic phase from grade 1 (AD 36) to grade 4 (AD 106) (Fig. 1a, indicated by No. 1, 2, 3, 6, 8 and 15 in Table 2). As shown in Table 2, the 30-year MS records for No. 4, 10, 14 and 15 divided the economic development of the early Eastern Han Dynasty into two sections: the period before Emperor Guangwu (AD 25–57), with economic grades ≤2, and the reigns of Emperors Zhang and Ming (AD 58–88), with economic grades of at least 3. If higher-resolution records were unavailable in all of the three groups, the economic grade of the early Eastern Han Dynasty could have only been determined with a time-scale of 30 years: suggesting an economic grade of 1 for the period AD 25–57 and 4 for the period AD 58–88. Fortunately, both periods had records with a resolution higher than 30 years. According to the MS records of No. 5, the economic grade during the period AD 25–36 was 1. For the period AD 37–57, only RMP entries could be

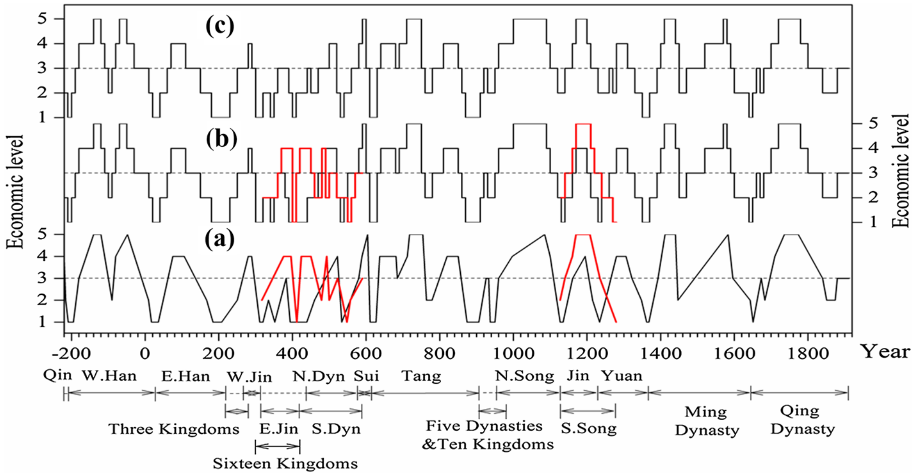

Fig. 1 Reconstruction of the economic series for the period BC 220–AD 1910. **a** Trend-controlling series; **b** 10-year-resolution series before being spatially weighted; **c** 10-year-resolution series after being spatially weighted between the north and south. The *black line* represents the economic levels of representative dynasties during the period BC 221–AD 1911. Where there are *red lines*, the *black lines* indicate the economic levels of dynasties in northern China, while the *red lines* indicate the economic levels of dynasties in southern China during the periods AD 317–589 and AD 1127–1279. Dynastic periods were defined following Mao (2002) (color figure online)

used to classify this decade as grade 2 (No. 7). Likewise, there were two 20-year MS and RMP records (No. 9 and 10, respectively) during the reign of Emperor Ming (AD 58–75), which was divided into two periods with approximately 10-year MS records by No. 11 and 13 in Table 2 based on the dividing year of AD 69 (No. 12). Therefore, it was easier to determine that the economic level for the period AD 69–75 was 4, while the economic level was 3 for the period AD 58–68.

According to the previous analysis, the grades of 148 intervals (24 during the periods AD 317–589 and AD 1127–1279 and 124 during the period BC 221–AD 1911) could be determined. The proportions of interval grades that were primarily ranked according to evidence from the MS, RMP and LFS groups accounted for 68.2 % (101), 18.2 % (27) and 13.6 % (20), respectively, of the data. The number of grades with interval lengths of 1–10, 21–30, 31–40, 41–50 and 51–60 years were 43 (29.1 % of the total 148), 57 (38.5 %), 34 (23 %), 7 (4.7 %), 6 (4.1 %) and 1 (0.6 %), respectively.

(5) The economic grades of the aforementioned 148 intervals were resampled by calculating the weighted Mean (the temporal proportion of each economic level within a decade was used as the weighting coefficient) as the final economic level for a given decade (i.e., AD 1–10). When a decade was only represented by a single grade, this grade was used as the decadal economic level. Two 10-year-resolution sequences were established (Fig. 1b). Unless there was only one economic level (not including the situation where two adjacent decadal grades were identical) for one decade, there were sufficient data during the decade. Therefore, a 10-year resolution was considered reliable and appropriate. A total of 95 decades contained reliable data (37.3 % of all 255 decades); the number of decades with no data in one, two, three, four and five consecutive decadal periods accounted for 41 (16.1 %), 52 (20.4), 36 (14.1 %), 16 (6.3 %) and 15 decades (5.8 %), respectively. Therefore, the series was reliable to reflect 30-year-scale variations.

(6) To obtain a statewide macro-economic sequence, the two aforementioned sequences were further spatially weighted into one sequence; the south–north population ratio was used as the weighting coefficient. The first period (AD 321–590) used a south–north population ratio of 1:2 (4,816,685 people in the south and 10,367,032 people in the north in AD 280 (Liang 2008)), whereas the second period (AD 1131–1280) used a compromising south–north population ratio of 1:1 based on statements of related studies (Liang 2008; Zheng 2003). The weighted calculations were rounded to an integer to generate the decadal empire-wide macro-economic series for the period BC 220–AD 1910 (Fig. 2c).

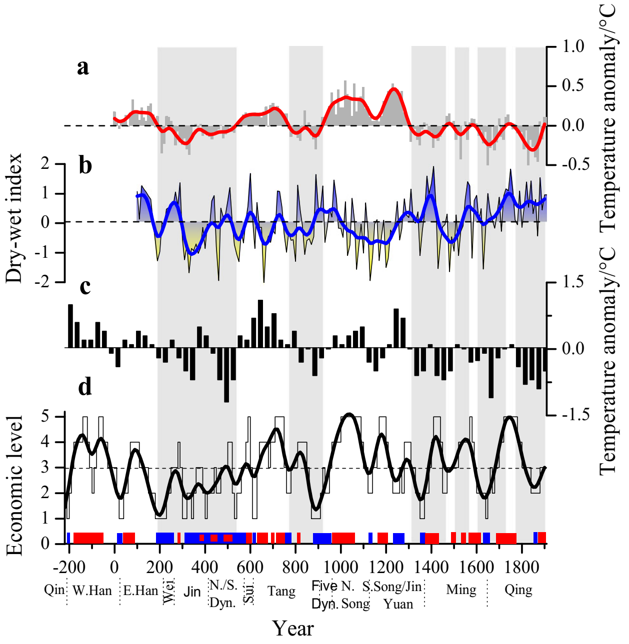

Fig. 2 Series comparison between economic fluctuations and climate changes in China from BC 220 to AD 1910. **a** Decadal temperature anomaly for all of China during the period AD 1–1910 (Ge et al. 2013); the *red curve* is the low-pass filtered series. **b** Decadal precipitation over eastern China during the period 101–1910 (Zheng et al. 2006); the *blue curve* is the low-pass filtered series. **c** Winter half-year temperature anomaly series for eastern China during the period BC 210–AD 1920 with a 30-year resolution (Ge 2011). **d** Decadal macro-economic series during the period BC 220–AD 1910 in China; the *black curve* is the low-pass filtered series. The *red and blue bars* indicate typical episodes of prosperity and crisis periods for the major dynasties identified according to Fan and Cai (1994). The *gray and white areas* delineate cold and warm phases, respectively (color figure online)

Climate data

To analyze the climatic effects on macro-economic fluctuations, temperature and precipitation reconstructions were adopted in the study. There are two representative decadal temperature anomaly series that cover all of China during the period AD 1–2000 (Yang et al. 2002; Ge et al. 2013). However, we only adopted the more recent series in this study. Ge et al. (2013) reconstructed the temperature anomaly series using principal component regression (PCR) by combining five regions of weighted paleoclimate proxy (28 proxies) records obtained from historical records, tree rings, stalagmite, ice cores and lake sediments. This decadal-scale series reflects the annual climate change over the past 2000 year relative to the 1851–1950 Mean. Particularly, the wintertime half-year temperature anomaly series in eastern China (Ge et al. 2003; Ge 2011) explains 71 % of the variance of the entire series (Ge et al. 2013). Because eastern China has long been the center of historical agricultural practices and economic activities, the temperature anomaly series from this region of China should be ideal for this study. Moreover, the wintertime half-year temperature anomaly series spans the entire period from BC 210 to AD 1910. This series was reconstructed from document-recorded phonological cold/warm events (i.e., phenology of plants, duration of frost and snow, distribution of subtropical crops and economic crops and sowing and harvest times) that were closely related to agricultural production. However, considering that this time series has a 30-year resolution, it was only used for visual comparisons.

The only available 2000-year-long decadal precipitation series that encompasses all of eastern China (25–40 °N, 105–121 °E) was reconstructed by Zheng et al. (2006). The series was derived by combining dry–wet indices reconstructed from historical documents in three sub-regions in eastern China (the Northern China Plain, the Jiang–Huai area and the Jiang–Nan area) (Ge 2011; Zheng et al. 2006). The data were provided as moving averages for each year from BC 105 to AD 2000. There were 93 missing data points (primarily during the period AD 101–260). We included the missing years by first calculating the Arithmetic Mean for a decade when <5 missing values in a given decade; the missing decades were determined via linear interpolation.

Statistics

We attempted to compare the macro-economic characteristics during different climatic phases and the economy–climate association at different temporal scales, given that the patterns are critically scale dependent (Gibson et al. 2000). To do so, a filter technique was necessary to obtain the short-term cyclical components and long-term trends in the time series of both climate change and the economic cycle. The Hodrick–Prescott (HP) filter (Hodrick and Prescott 1997) has been widely used in business-cycle research despite having several shortcomings (Cogley and Nason 1995). The smoothing level depends on the smoothing parameter λ. For larger values of λ, the solution series becomes smoother (Hodrick and Prescott 1997). For annual data, different λ values (6–400) have been proposed in many studies (Cooley and Ohanian 1991; Ravn and Uhlig 2002; Hodrick and Prescott 1997). We applied $\lambda = 10$ (which is consistent with the results obtained from a 100-year FFT low-/high-passing filter but can better capture the cyclical component) for the HP filter to investigate the economic, temperature and precipitation series; both low-pass filtered data and high-pass filtered data were obtained. These two types of data characterize macro-trends and short-term variations, respectively. Moreover, the original climatic and economic data include the complete long-term trends and short-term variations.

The cold/warm climatic phases were subsequently defined for periods with temperature anomalies <0 °C and at least 0 °C, respectively, based on the low-passing filtered temperature series for China. Six major warm and cold phase cycles were identified for the period AD 1–1910. The aggregated durations of the cold and warm phases were 980 and 950 years, respectively (Table 4). These phases were nearly consistent with the centennial-scale cold/warm periods identified by Ge et al. (2013) with respect to both temperature over all of China and the winter half-year temperature over eastern China (Ge 2011; Ge et al. 2003) except for the Little Ice Age (AD 1311–1920), which corresponded to centennial-scale cold periods. We maintained the three multi-decadal warm phases during the period AD 1311–1910 to ensure that the cold and warm phases had nearly the same length. For comparison purposes, we included the centennial-scale warm periods of BC 220–AD 200, AD 541–780 and AD 921–1310, and the centennial-scale cold periods of AD 201–540, 781–920 and AD 1311–1910 when necessary to perform the analysis (i.e., Table 5). Similarly, the relatively dry and wet phases were defined for precipitation index values <0 and at least 0, respectively, based on the low-pass-filtered precipitation series.

Pearson's correlation coefficients were calculated to quantitatively investigate the potential association between economy and climate at different frequency bands. The granger causality test (GCT) was previously used to test causal linkages from climate change to human socioeconomic crises (Zhang et al. 2011; Pei et al. 2014). Several related principles and the theoretical basis of GCT applications have been previously discussed (Zhang et al. 2011). A two-variable causal model with two stationary time series X_t and Y_t with zero means can be expressed in the following equation (Granger 1969):

$$X_t = \sum_{j=1}^{m} a_j X_{t-j} + \sum_{j=1}^{m} b_j Y_{t-j} + residual_t$$

where, a and b are the coefficients of the time series, j is the data of the time series at time point j, m is the length of the time series set based on time lag and residual_t is the residue at the time step of t.

GCT was adopted in this study to test the causal relationships between two pairs of data series at different frequency bands (Table 3). Given that GCA was preconditioned with both variables with zero Mean and being stationary temporally, the variables of different frequency bands were standardized first and an Augmented Dickey–Fuller (ADF) test was also essential prior to the GCA. The maximum lag in ADF test was determined according to the following formula (Hayashi 2000):

$$\mathrm{Lag}_{\mathrm{Max}} = \mathrm{int}\left[12 \times \left(\frac{T}{100}\right)^{0.25}\right]$$

where *T* is sample size and *int* means integer.

The results of the ADF test (Table 3) indicated that both the climatic and economic series in this study were stationary time series. Because the GCT test is very sensitive to the time lag, we adopted the statistical criteria of Akaike's information criterion (AIC) to determine the optimal lag length (Akaike 1974) for GCT:

$$\mathrm{AIC} = 2k - 2\ln L$$

where k is the number of independently adjusted parameters of the model, and L is the maximum likelihood function for the estimated model. The likelihood function L is expressed as follows:

$$L = \prod_{i=1}^{n} \left(\frac{1}{2\pi\delta^2}\right)^{1/2} \exp\left(-\sum_{i=1}^{n} \frac{\left(x_t - \sum_{j=1}^{m} a_j X_{t-j} - \sum_{j=1}^{m} b_j Y_{t-j}\right)^2}{2\delta^2}\right)$$

where n is the sample size and δ is the variance.

Results and discussion

Macro-economic characteristics during different climatic phases

Figure 1c outlines the macro-economic rise and fall from BC 220 to AD 1910, primarily at the multi-decadal scale. However, the semantic differential technique produces certain biases (Osgood 1957); the economic level with an upper or lower deviation of no more than one grade was considered to be acceptable margins of error in our analysis. To validate the reliability of our results, we compared our economic reconstruction with a traditional classification of prosperity/crisis periods according to historians (Fig. 2). These periods are usually labeled as the most typical episodes with relatively stronger comprehensive state power (i.e., Kong and Qian golden eras during the period AD 1684–1795) or as periods of being inversely trapped in considerable disorder (i.e., the "Yongjia Disturbance" around AD 311 and the "Anshi Disturbance" during AD 755–763) for one dynasty. Most of the good episodes coincided well with the rapidly rising phases or prosperity phases of reconstructed economy (and vice versa). The five longest dynasties (i.e., Han, Tang, Song, Ming and Qing) have long been accepted as the most glorious and economically prosperous eras in Chinese history (Fan and Cai 1994; Fu 1981); economic grades exceeding 4 dominated these intervals. The proportion of each grade (Table 5) shows a nearly normal distribution and partially verifies the reasonableness of the reconstruction.

Table 3 Augmented Dickey–Fuller (ADF) unit root test for indexes

Group	Variables	AIC lag	t	Prob.
Full composite	Economy	1	−6.324	0.000
	Temperature	4	−3.869	0.000
	Precipitation	0	−8.994	0.000
Long-term trend	Economy	4	−3.630	0.000
	Temperature	7	−2.636	0.009
	Precipitation	3	−3.386	0.001
Short-term variation	Economy	13	−8.794	0.000
	Temperature	13	−8.427	0.000
	Precipitation	13	−8.351	0.000

Economic fluctuations were closely related to temperature change at the centennial scale, particularly before the Ming Dynasty (Fig. 2). The three long periods of relatively better economic performance coincided with a warm climate, which is a stark contrast to the period AD 180–540 when long-term economic downturn was accompanied by persistent low temperatures (average of −0.1 °C lower relative to the 1851–1950 Mean (Ge et al. 2013)). In comparison, the economy seemed to display a closer relationship with precipitation at the decadal to multi-decadal scales.

Macro-economic characteristics during different climate phases are summarized in Tables 4 and 5. The statistics show that the warm phases had an above-average Mean economic level; the difference between the Mean economic levels during cold and warm phases is statistically significant (Table 4). It is estimated that the proportion of prosperity (levels 4 and 5) that occurred in the warm phases is 80 % higher than in the cold phases (Table 4). Approximately 64 % of the total prosperity (67 decades) during the period AD 1–1910 coincided with warm phases. In contrast, the proportion of economic depression (levels 1 and 2) in the cold phases is nearly two times higher than in the warm phases (Table 4). This result is consistent with the ideas of some previous studies in which higher ratios of poor harvests (Su et al. 2014; Yin et al. 2014) and wars (Zhang et al. 2006) were found in cold phases. The significant difference is also demonstrated by comparing the economic characteristics between each pair of centennial-scale climatic periods during the period BC 220–AD 1910 in China (Table 5). In warm periods, grades 3–5 exhibited a relatively higher percentage compared with the Means for the entire period (BC 220–AD 1910), which skews the distribution to the left (skewness <0; Table 5) in the frequency histogram. The relatively higher values of the coefficient of variation indicated that economic developments were much more unstable during the cold periods.

Table 4 Macro-economic characteristics comparison at the phase scale during AD 1–1910 in China

Items	Mean	t	*p*	Prosperity (grade 4–5)		Depression (grade 1–2)	
				No./ decade	Percentage/ %	No./ decade	Percentage/ %
Cold phases (980 years)	2.69	3.97	0.00	24	24.49	45	45.92
Warm phases (930 years)	3.37			43	46.24	24	25.81
Ratio (Cold/Warm phases)	0.8			0.56	0.53	1.88	1.78
Dry phases (950 years)	2.91	1.45	0.15	27	28.42	34	35.79
Wet phases (950 years)	3.17			37	38.95	30	31.58
Ratio (Dry/Warm phases)	0.92			0.73	0.93	1.13	1.13

See data and methodology for the definition for climatic phases

Table 5 Macro-economic characteristics in each centennial-scale climatic period during BC 220–AD 1910 in China

Periods	Sample	Mean	SD	CV (SD/Mean)	Percentage of each grade/%					Skewness
					1	2	3	4	5	
Whole period	213	3.07	1.21	0.39	10.3	23.9	28.7	22.5	14.6	0.01
W1	42	3.02	1.18	0.39	11.9	21.4	28.6	28.6	9.5	−0.14
W2	24	3.38^{***}	1.24	0.37	8.3	16.7	25	29.2	20.8	−0.35
W3	39	3.67^{***}	1.13	0.31	0	20.5	23.1	25.6	30.8	−0.21
C1	34	2.26^{***}	0.93	0.41	23.5	35.3	32.4	8.8	0	1.50
C2	14	2.57^{**}	1.22	0.48	28.6	14.2	28.6	28.6	0	−0.19
C3	60	3.17	1.15	0.36	5.0	26.7	31.7	20.0	16.6	0.14

W1-W3: Centennial warm periods spanning BC 220–AD 200, AD 541–780 and AD 921–1310, respectively; C1–C3: centennial cold periods spanning AD 201–540, AD 781–920 and AD 1311–1910 respectively

SD standard deviation, *CV* coefficient of variation

* indicates significance for the Mean-comparison test in relative to the Mean 3.07 of the whole period, * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$

The economic difference between dry and wet phases is not as significant as the temperature phases. However, better economic performance was found in wetter climates. Su et al. (2014) demonstrated that a combination of cold and dry conditions could cause extremely detrimental effects on agricultural harvests. This result may be applied to the climate–economic relationship. The statistics show that for the combination of cold and dry phases, the Mean economic grade for 41 decades was only 2.36; grades 1–2 accounted for as much as 56 % of the entire period. This suggests a substantial increase in the possibility of economic crisis for cold–dry climatic scenarios.

Short- and long-term effects of climate change on macro-economic fluctuations

The results of the correlation analysis provide more quantitative support concerning the aforementioned statements. Correlations based on the original data indicated that the economy was positively correlated with both temperature changes and precipitation changes at the 1 % significance level (Table 6). Moreover, no time lag was found for the economy to respond to both temperature and precipitation changes at the decadal scale. However, temperature changes (e.g., cooling) exhibited at least a 30-year effect on economy, whereas precipitation changes (e.g., drought) exhibited only a 10-year effect based on the rapid decrease in the coefficient. This result was also confirmed by the results based on the low-pass and high-pass filtered data (Table 6). The macro-economic trends exhibited a stronger relationship with the long-term temperature changes; however, the short-term economic variations had no significant correlation with short-term temperature changes. On the contrary, precipitation exhibited more evident short-term effects on macro-economic fluctuations. This finding implies that differences (e.g., timescale) exist in the impact mechanisms of temperature and precipitation on macro-economic fluctuations.

Scale has been increasing to be an important methodological issue, particularly for interdisciplinary studies such as investigating complex interactions within and among social and natural processes (Sayre 2005). The consideration of scale problems is fundamental to the identification of patterns and their explanation, since one pattern that appears at one level of extent may be lost at lower or higher levels (Gibson et al. 2000). Several studies have

Table 6 Correlation analysis of the short-term variation and long-term trend between economic series and temperature/precipitation indexes

Group	Variables	Lag/years			
		0	10	20	30
Full composite	Economy-temperature	0.32^{***}	0.28^{***}	0.24^{***}	0.19^{***}
	Economy-precipitation	0.2^{***}	0.15^{*}	0.08	0.03
Long-term trend	Economy-temperature	0.45^{***}	0.42^{***}	0.39^{***}	0.34^{***}
	Economy-precipitation	0.12	0.11	0.09	0.04
Short-term variation	Economy-temperature	0.04	0.02	−0.02	−0.07
	Economy-precipitation	0.25^{***}	0.10	0.01	0.05

* $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$

demonstrated that the effects of short-term and long-term changes in different climatic elements on different social factors are highly variable. Long-term temperature changes are typically considered as being much more influential than short-term changes in temperature, aridity threshold or precipitation for explaining fluctuations in population size and shifts in the population distribution (Lee et al. 2009), macro-economic cycles in Europe (Pei et al. 2014) and large-scale human socioeconomic crises (Zhang et al. 2011). Short-term climate variations merely raised prices, while longer climate changes resulted in economic crises (Pei et al. 2013). In our analysis, short-term reductions in precipitation may also induce a macro-economic crisis in the historical agrarian society in China.

However, the correlation results cannot indicate causality between climate change and economic fluctuations. A few studies have suggested that climate change, particularly with respect to long-term cooling, was the primary cause of economic crisis on a continental scale (Pei et al. 2014). Our GCT results in Table 7 suggest no direct and significant causal linkages between temperature/precipitation changes and economic variations in China, either for the long-term trends or short-term variations. This implies that a strict statistical causality might not be applied to the relationship between climate and macro-economic cycles in China, at least not be applied for the past 2000 years. However, the short-term GCA results may be substantially affected by high-frequency noise, particularly for the economic and temperature series in which the variance in the low-frequency signal is more evident.

Table 7 Granger causality tests for data of different frequency

Null hypothesis	Group	AIC lag	F	Prob.
Temperature does not granger cause economy	Full composite	2	0.852	0.428
	Long-term trend	5	0.852	0.515
	Short-term variation	14	0.544	0.903
Precipitation does not granger cause economy	Full composite	2	0.213	0.808
	Long-term trend	5	0.385	0.859
	Short-term variation	12	1.061	0.398

Potential mechanism for climatic effects

A reduction in ecological and agricultural resources led by climatic deterioration was previously thought to be the primary mechanism linking climate change and social crises around the world (Zhang et al. 2006; Zhang et al. 2011). For a heavily agrarian-based society in historical China, this mechanism is also the most direct and primary pathway through which past climate changes affected the rise and fall of macro-economic development. Long cool periods shorten the length of the growing seasons and reduce the elevation and latitude at which crops can be grown, which decreases the amount of land available for cultivation and leads to either a decline in total output or more intensive cultivation with lower yields, particularly in higher latitude regions (Galloway 1986; Lee et al. 2009). Higher ratios for poor harvests were found during the cold periods (Su et al. 2014; Yin et al. 2014). In the cold period of AD 1840–1890, agricultural yields in China were reduced by 10–25 % compared with the relatively warm period of AD 1730–1770 (Gong et al. 1996). Poor harvests during long-term cold periods had contributed to the large migration, great famine and Black Death, and 30 years' wars over the past two millennia in Europe (Büntgen et al. 2011; Lamb 1995). Moreover, previous work has shown that low temperatures are also correlated with below-average population growth in China over the past millennia (Lee et al. 2008). Decreasing food yields induced by a deteriorating climate was unable to support surplus population growth during the warm periods (Lee et al. 2008; Zhang et al. 2006). Moreover, sustainable economic development became more susceptible to disturbances from social unrest and war (Zhang et al. 2006), particularly considering that regional climate changes would produce different effects on the Sino society and nomadic society

(Fang and Liu 1992). These situations can easily break the state of macro-economic equilibrium due to limited social buffering mechanisms in the presence of recurrent long-term cooling perturbations, which helps explain why economic development was more unstable during the long-term cold periods.

Variability in short-term weather patterns also leads to lower yields due to the biological inability produced by cooler temperatures and the direct damage caused by associated climatic disasters (Galloway 1986). In relative to the long-term effects of climate change, it is thought that the short-term effects are more easily relieved by social adaptation and self-adjustment mechanisms (Pei et al. 2014). For instance, short-term reduction in temperature might only cause crop failure in some ecological-sensitive regions, and its effect is limited to regional scale. This is possibly another reason for the insignificant relationship between temperature and economy in the short term. In contrast, those short-term extreme drought/flood events would abruptly cause adverse effects on a larger scale beyond the threshold that society can adapt. It has long been noted that large-scale peasant uprisings in Chinese history were usually accompanied by extreme drought events and induced famines due to short-term anomalous reductions in precipitation (Deng 1937). It is estimated that a shift from a relatively warm phase to a cold phase at the turn of the nineteenth century caused the social vulnerability to reach a critical level approximately 20 years earlier on the North China Plain during the late Qing Dynasty (Fang et al. 2013). Therefore, short-term climatic effects are highly dependent on the particular social, economic and political backgrounds. An increasing number of studies have concluded that climatic or environmental social impacts are preconditioned by increasing socioeconomic vulnerability (Butzer 2012; Rosen 2007). We did not find a robust causal relationship between climate and economy possibly because the effects of climate are not a simple causality, but nonlinear and more complicated driving response processes may exist in multiple-factor interactions (Fang et al. 2013; Butzer 2012). Social phenomena (and its causes and consequences) has less clear hierarchical systems and usually operates at scales different from that of the natural or climatic phenomena (Gibson et al. 2000). Cross-scale interactions may always occur. For example, annual-scale social unrests may result in a rapid shift from an economic climax to collapse before a cooling period. Population growth during the earlier stages of a dynasty typically has a positive role in stimulating economic development; however, this same factor can have a negative effect and accelerate socioeconomic crises during the later periods (Lee and Zhang 2013). Xiao et al. (2014) demonstrated that climatic negative effects gradually intensify along with an increasingly intense contradiction between regional population and food balance and weaker governmental relief capability. Therefore, environmental determinism does not work in our analysis.

Compared with temperature, the relatively weaker relationship between the economic level and precipitation, particularly over long periods, may be primarily related to the strong historical variations in regional precipitation over China (Zheng et al. 2006; Zhang et al. 2010a). Even in eastern China, the spatial patterns of precipitation changes were very complicated. Wang et al. (1993) found that precipitation decreased in North China and increased south of the Yangtze River during the MWP (Medieval Warm Period); however, they also found that precipitation increased in the North China Plain and decreased in southern China during the LIA (Little Ice Age). Hao et al. (2012) also found that the North China Plain was dry during four warm periods and wet condition prevailed over most of China during the period 1741–1770, which corresponds to a relatively warm period that occurred during the LIA (approximately 1650–1850). The Grand Canal system has played an important role in maintaining the health of the imperial economic system since the Tang Dynasty (Elvin 1973). Grain and economic materials in southern China can be shipped to the northern areas where drought and famine are more common. This transportation of necessities helped delay the total collapse of the Tang Dynasty's economy by approximately 100 years (Zhao 2002). Our series-based long-term statistical results do not support the idea that prolonged drought led to the fall of the Tang Dynasty (Yancheva et al. 2007; Zhang et al. 2008), but support the conclusion of Zhang et al. (2010a). However, there are some limitations of the precipitation reconstruction used in this paper because it does not cover the whole China like the economic series. Therefore, the relationship between precipitation and economic state should be investigated more carefully over different temporal and spatial scales.

Conclusions

Based on words extracted from books, we reconstructed a 2130-year-long macro-economic phase shift series for China using a semantic differential method. The cyclical patterns of empire-wide macro-economic fluctuations were first quantitatively presented for the entire duration of imperial Chinese history. We also presented results regarding the relationships between climate change and the economic state at different temporal scales.

We found that warm climate periods coincided with better economic phases (above-average Mean economic level, higher ratio of economic prosperity, and less intense variations), whereas the opposite economic situation occurred during cold periods. For the combination of cold and dry periods, the possibility of economic crisis was as high as 56 %. Economic fluctuations were found to be positively correlated with both temperature and precipitation changes. However, temperature changes exhibited a more significant long-term effect on macro-economic fluctuations. In comparison, precipitation variations exhibited more significant short-term effects on the macro-economic cycle. Thus, these two patterns conveyed on different timescales suggest a difference in the impact mechanism between temperature and precipitation. Long-term cooling had negative effects on agricultural harvests, which made agrarian economic systems more susceptible to disturbances from famines, depopulation, social unrest and wars. For short-term periods, we propose that the climatic effects on agrarian economic development are highly depended on the social vulnerability, which is determined according to particular social, economic and political backgrounds. From a deep time perspective, our study may provide new insight into the current intense arguments regarding the economic effects of global warming.

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