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Macro-economic cycles related to climate change in dynastic China

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ABSTRACT

Investigations of the relationships between climate and human history often place more emphasis on the science of climate change than on understanding human socio-economic processes, and therefore suffer from superficial results and an unbalanced perspective. This is partly due to the lack of high-resolution data concerning long-term socio-economic processes. Here, we base our study of climate and society on a series of 2130-yr-long economic proxy data from China with decadal resolution. The economy was associated significantly with temperature and precipitation at the two predominant bands of 100 and 320 yr. The phase transition of economic states was influenced positively by long-term temperature change combined with triggering effects of short-term changes in precipitation. However, climatic impact on economy should not be recognized as simple causality but some driving–response relation coupled with meditation by human agency at multiple scales. A model of 'adaptive cycles' implies, in relative to the developing phases, climate–economy relationship during the declining phases was more easily moderated by slower processes like rigidity and faster processes like unrest. From a more-macro perspective, climatic driving for the macro-economic cycles was moderated by larger and slower processes like social memory, spatial shifting of key economic areas, and social–technical advance.

Introduction

After extensive travels in Turkmenistan, Central Asia at the turn of the 20th century, Ellsworth Huntington proposed the idea that major cultural changes were strongly influenced by climatic change in his book *The Pulse of Asia* (Huntington, 1907; Wright, 1993). More recently, the idea of climatic determinism is being revived, fueled to some extent by the recent development of high-resolution paleo-climatic reconstructions in many parts of the world. Numerous studies have tried to link climate change with various social aspects ranging from water supply and agricultural productivity (Lucero, 2002; Buckley et al., 2010), human health (McMichael, 2012), population migration (Zhang et al., 2011; Zielhofer et al., 2012; Han et al., 2014), social conflict (Zhang et al., 2007; Tol and Wagner, 2010), and particularly political or civilization collapse (Binford et al., 1997; deMenocal, 2001; Weiss and Bradley, 2001; Haug et al., 2003; Büntgen et al., 2011; Kennett et al., 2012; Walsh et al., 2014). Many studies convey the concept that climate change or extreme droughts constitute the main driver for a large number of cases of abrupt social/civilization collapse.

However, the role of climate and environmental change in the rise or fall of societies is still a matter of intense debate. Many other scholars strongly object to these dogmatic statements as a simplistic, mono-causal approach to the study of climatic impacts on the fortunes of historical societies (Rosen, 2007; Butzer and Endfield, 2012). A typical example is the Classic Maya collapse. Persistent drought has been highlighted as the main reason for the abrupt collapse of Maya society (Hodell et al., 1995; deMenocal, 2001; Weiss and Bradley, 2001). However, some critics note that Maya civilization did not collapse as quickly as supposed by some of these studies and the process of multisite and regional abandonment in the Terminal Classic played out over at least 125 yr (Turner, 2010; Dunning et al., 2012). These disagreements partly stem from differing views of the nature of collapse (McAnany and Yoffee, 2009; Butzer, 2012; Butzer and Endfield, 2012).

Another similar example concerns climate-forcing leading to the origins of agriculture in the Near East. Many studies based their environmental determinism on the major restructuring of vegetation resulting from climatic fluctuation, and proposed that the shift to wild-cereal cultivation was a response of hunter-gatherers to the Terminal Pleistocene Younger Dryas (YD) climatic deterioration (Wright, 1993; Bar-Yosef and Belfer-Cohen, 2002; Rosen and Rivera-Collazo, 2012). Some works even refer to this as a collapse of Natufian foraging systems (Weiss and Bradley, 2001; Burroughs, 2005). Rosen and Rivera-Collazo (2012) proposed that the hunter-gatherer subsistence systems in the Near East were highly adaptable, and a shift in resource focus did not necessarily result in a major change in social and economic organization. The long-term social memory of past experience helped them

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initiate a series of subsistence procurement responses that allowed them to avoid an eventual shift from foraging systems, which simultaneously delayed the transition from foraging and low-level cereal cultivation to a major commitment to agricultural village farming in the southern Levant (Rosen and Rivera-Collazo, 2012).

A common feature of these studies is simply that they base their conclusions on the temporal correlation between climatic reconstruction and major social/cultural events. The climatic reconstructions can provide detailed background information of environment and ecology, but cannot give more information on the development of human society which often occurs at temporal resolutions different from the climatic events (IHOPE, 2010). Admittedly, many studies mistake the seeming-temporal coincidence between climate change and social fluctuation as a causal link. They fail to incorporate many other important factors that interact with climatic components on different temporal-spatial tiers, as well as the different role played by variable factors in specific spatial and temporal scales (Catto and Catto, 2004; Butzer, 2012). In particular, many socio-economic phenomena operated at different temporal scales from climate change. It is also dangerous to impose a presumed pattern from one geographic region upon another without considering the background environmental and historical contexts. An example of this is the explanation for the collapse of the Tang Dynasty for which a simple correlation was made between climate change and the breakdown of a social system (Yancheva et al., 2007; Zhang and Lu, 2007; Zhang et al., 2008, 2010a,b). Thus it is important to understand the role of climate change in a resilient and complex interlocking system of environment and society.

China can provide a good case study for relationships between climate and society, due to its unique historical rhythms (or "dynastic cycle") (Elvin, 1973; Fu, 1981; Skinner, 1985) and long-term historical records. Many recent studies have quantitatively demonstrated the statistical relationship between climate change and social phenomena, such as agricultural harvests (Su et al., 2014; Yin et al., 2014), population fluctuation (Lee et al., 2008), and frequency of social unrest and warfare (Zhang et al., 2006). However, most of these studies are still limited by the dearth of long-term socio-economic data and cannot give more quantitative support to the causal mechanisms. The present paper cannot deal with all the problems mentioned above, but we try to provide an important and unique perspective by using historical data, based on a well-understood socio-economic system. These types of data are essential in order to test the relationships between historical rhythms and climatic oscillations, by combining knowledge both from paleoclimatology and history (PAGES, 2009). Besides this, we also propose that the complex relationships between climate change and cyclical patterns can be best illustrated and predicted by a concept of 'adaptive cycles' (Gunderson and Holling, 2001).

In this paper we aim to reveal long cycles of macro-economic processes in ancient China, and examine their associations with temperature and precipitation. The wave-like fluctuations of economic development during the Chinese imperial era (221 BC–AD 1911) have been described and recorded in abundant Chinese historical documents. These have been further compiled and studied by contemporary historians in the form of academic books. The books on economic history (see Supplementary Appendix) provide a unique opportunity to reconstruct economic sequences conveying the phase transition of economic states over the past two millennia. In this paper, we first present a 2130-yr long macro-economic series using the method of 'semantic analysis' (Osgood, 1957). Then, in order to analyze economic relationships with climate change, we use an existing reconstruction of precipitation, and multi-proxy temperature data at different geographic scales ranging from the region of eastern China at the finest scale to the coarser scale of a range of latitudes in the northern hemisphere. Multi-statistical analyses, including wavelet, correlation, cross-wavelet correlation and regression, are used for the investigation of associations between economic level and climatic indices. Additionally, a 'Resilience Theory' model (Gunderson and Holling, 2001) is introduced to explore the role of climate change as one of the factors driving the secular macro-economic cycles in dynastic China.

Materials and methodology

Economic series

The decadal time series of a 2130-yr-long economic state index is constructed on the basis of 1091 records extracted from 25 books. All of these books deal with the history or economic history of China, and most of them are written by leading Chinese scholars and published in the last thirty years (such as the "The Feudal Social and Economic History of China" written by Fu, Zhufu during 1981–1989, see list of books in Supplementary Appendix). We chose the Imperial Era from the unified Qin to the end of the Qing Dynasty (221 BC–AD 1911), as the reconstructed period of study. This was a period with frequent alternation between state establishment and breakdown, but shared similar basic forms of economic organization and symbols and beliefs that justified the distribution of power, status, and wealth for most periods (Goldstone, 1991). The relatively homogeneous agrarian-economic system experienced cycle-like ups and downs of economic development, from a macro-historic perspective.

We analyzed the general performance of the economic system by taking the empire as the unit of analysis, as suggested by Skinner (1985). This was because the materials used primarily addressed the empire-wide or empire-scale economic performance. Spatially, the dynastic economy was built on the development of key economic areas beginning in earlier periods in the region of the middle and lower Yellow River, then expanding to the middle and lower Yangtze River in later periods (Elvin, 1973; Fu, 1981).

Semantic analysis is a concept most widely used in Linguistics and Psychology. The Semantic Differential (SD) technique was first developed by Osgood (1957) in order to identify emotional meaning of words, and has been proven to be a useful and effective tool in indexing qualitative word description such as attitude measurement. It is usually operated in terms of ratings on bipolar scales defined with contrasting adjectives at each end (Osgood, 1957). Three basic dimensions, which have been labeled Evaluation (like good and bad), Potency (like large and small), and Activity (like fast and slow), have been identified in a number of early studies to account for most of the co-variation in ratings (Snider and Osgood, 1969). Semantic analysis has been used successfully to reconstruct long time series' of dryness/wetness (or precipitation) indices (CMA, 1981; Zheng et al., 2006), grain harvests (Su et al., 2014; Yin et al., 2014), and fiscal balance (Wei et al., 2014), and has been proven to be a suitable approach for converting qualitative descriptions found in literary sources into quantitative data.

In this study we assigned each record a grade ranked 5–1 (according to the word's semantics) to express the economic performance changing from economic climax (5) to economic collapse (1). These grades represent the relative phase transitions of economic performance which can be measured as the general level of dynastic economic soundness. Here, we tend to define economic collapse as a dysfunction of an empire-level economic system (mainly characterized by major loss of population, large-scale land abandonment, and serious fiscal crisis, usually accompanied by the imperial breakdown). In our analysis we divided the qualitative descriptions into three-level groups according to semantic characteristics and their reliability in reflecting the fluctuation of the macro-economy as a whole. Firstly we used the group with a relatively higher reliability for economic level determination. There are two other reasons for this treatment. First, records from different books, representing opinions of single or a certain number of authors, demonstrate multi-time resolution; second, the economic records of short-term time intervals are not as numerous as those of long-term intervals and therefore they do not yield a continuous high-resolution series. Additionally, to integrate those descriptions from the historical records, we first formulated a sequence of economic trends using records with relatively lower resolution, and then refined it to be a decadal series using records with higher resolution.

We avoided the problem of conflicting views and non-comparable writing styles by selecting the opinions of the majority of authors. For the two major periods of AD 317–589 and AD 1127–1279, the empire-wide economic levels were spatially weighted against the levels between the northern and the southern dynasty with corresponding north-south population ratios, respectively, to generate a 2130-yr-long reconstruction of macroeconomic fluctuations in China from 220 BC to AD 1910 (Fig. 1). See Supplementary material Part A for more detailed descriptions of the materials and reconstruction method.

Climate series

Both temperature (Table 1, TempE.G, TempC.G, TempNH.M and TempNH.CL) and precipitation (Table 1, Prec.Z) sequences were used in this study (most of the data can be accessed at http://www.ncdc.noaa.gov/paleo/recons.html). TempE.G (Ge et al., 2003; Ge, 2011) has the closest spatial coverage to that of the economic series implemented in this analysis. Moreover, temperature could be reconstructed from document-recorded phonological cold/warm events which were closely connected to agricultural production (Ge et al., 2003). TempE.G should be very suitable for the study of climatic impacts on the agrarian economy in eastern China. However, the resolution of data for TempE.G during the study period is only 30 yr, and TempE.G can explain 71% of the variance of TempC.G (with a resolution of 10 yr) (Ge et al., 2013). In contrast, TempC.G covers the entire region of China. Therefore TempC.G is an ideal series to use in this study. Also, TempNH.M (Moberg et al., 2005) and TempNH.CL (Christiansen and Charpentier Ljungqvist, 2012) are two long representative (IPCC, 2013) temperature proxies of the northern hemisphere. Each annual temperature series was averaged to a decadal sequence.

Prec.Z (Zheng et al., 2006; Ge, 2011) is a decadal moving average of each year for AD 105–2000. There were 86 missing data points for AD 105–262. Removal of these years would reduce the length of the series data. Moreover, wavelet decomposition does not allow inclusion of missing values. Since this series was built to reveal the long-term pattern of precipitation change (Zheng et al., 2006), we included the missing years by first calculating the arithmetic mean of years when the missing values were less than 5 yr for each decade as the decadal value, and then those missing decades were ascribed by linear interpolation.

Statistics

Correlation analysis was used to analyze both the short term (original 10/30-yr series) and long term (3-point FFT low-pass filter series with cutoff frequency of 0.017 Hz for decadal series and 0.0056 Hz for TempE.G) climate–economy relationship. The moving correlation shows the continual change of the coefficient throughout the study period, and thus provides a more detailed dynamic relationship between economic fluctuation and climate change.

Wavelet analysis is a powerful tool for acquiring periodicity of time series' and has gained popularity in many fields of research. Particularly, unlike Fourier transform, wavelet analysis performs locally in both time and frequency domains and thus can track the change of its periodicity over time (nonstationary periodicity) (Cazelles et al., 2008; Rouyer et al., 2008). Cross-wavelet transform and wavelet coherence are suitable for examining relationships in time-frequency space between two time series' (Grinsted et al., 2004). The wavelet decomposition has been used to study climatic impacts on the rhythm of locust infestations and war periodicity in China (Zhang et al., 2010c). In this study, we first used the continuous wavelet in Matlab to decompose the extended economic series to produce contour graphs of the real part of a Morlet wavelet spectrum (Supplementary Fig. 3). It can be compared with the results by using the wavelet package provided by Torrence and Compo (1998) which enabled us to analyze the statistical significance at 95% (P = 0.05) level for each periodicity calculated against red noise based on 1000 surrogate data set pairs. Then cross wavelet analysis was applied to reveal the phase association of different periodicities between two time series' as well as their changing pattern over time. The widely used “Morlet” wavelet was adopted as the mother wavelet in all above analyses.

The regression model was used to identify each independent variable and their combined contributions to the dependent variables. Because all the variables used in the study are time series', in order to avoid spurious regression produced by the unsteady time series, a Unit Root Test was used first. The test of Augmented Dickey–Fuller (ADF) showed all the index series were stable time series' (Supplementary Table 3), so we could use the Ordinary Least Square (OLS) method to build a regression model. Considering the autocorrelation for most of the economic time series', the model formula we used for this study was as follows:

$$\text{Economy}_t = \alpha_1 + \alpha_{2^*}\text{Economy}_{t\text{-}1} + \alpha_{3^*}T_t + \alpha_{4^*}P_t + \varepsilon_t \quad (1)$$

where Economy_t, T_t, and P_t are reconstructed indexes of economy, temperature, and precipitation for decade t, respectively; α is a regressive coefficient, ε_t represents an error term.

Results

Economic periodicity

The reconstructed decadal macro-economic series is shown in Figure 1. As seen from Figure 1, macro-economic fluctuation on the decadal to multi-centennial scale was apparent. The up and down swings obviously constituted long-wave cycles, as easily indicated by the smoothing series (Fig. 1).

Periodicity analysis shows that the decadal series displayed 60-yr cycles around 220 BC–AD 0 and AD 450–800, and 100-yr cycles intermittently across the whole period (Fig. 2A). Whereas the predominant cycle of 160 yr appeared around AD 100 and AD 1500, around AD 1500 the cycle extended to 200–250 yr (Fig. 2A, Supplementary Fig. 3). Additionally, the high values of wavelet spectra during AD 600–1400 also indicated a potential 320-yr cycle. These cycles were more consistent temporally and statistically significant on the 3-point FFT smoothing series with the influence of high-frequency signals

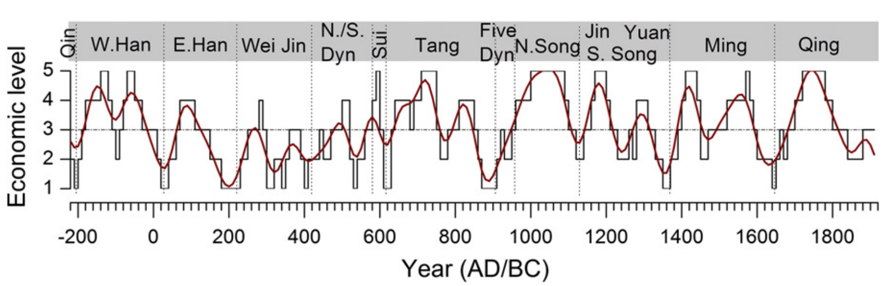

Figure 1. Reconstructed decadal macro-economic series and its 3-point FFT smoothing curve (red) from 220 BC–AD 1910 in China. Economic level 5–1 represent the relative phases of economic state identified from the word's semantics. 5: climax; 4: prosperity; 3: average condition; 2: depression; and 1: collapse.

Table 1
Climate indexes used in this study.

Name	Site	Proxy type	Resolution	Seasonality	Period (BC/AD)	Reference
TempE.G	Eastern China (25°–40°N, 105°–121°E)	Historical documents, regional mean	Three decades	October–April	210 (BC) –1990	Ge (2011)
TempC.G	China (23°–42°N, 80°–127°E)	Multi-proxies (28)	Decadal	Annual	1–1990	Ge et al. (2013)
TempNH.M	Northern Hemisphere (18°–90°N)	Multi-proxies (18)	Annual	Annual	1–1979	Moberg et al. (2005)
TempNH.CL	Northern Hemisphere (30°–90°N)	Multi-proxies (91)	Annual	Annual	1–1999	Christiansen and Charpentier Ljungqvist (2012)
Prec.Z	Eastern China (25°–40°N, 105°–121°E)	Historical documents, mean of 48 stations	Decadal	Spring–autumn	105–2000	Zheng et al. (2006), Ge (2011)

excluded. This was particularly evident for the predominant 100-yr cycle, followed by the cycles of 160–200 and 320 yr (Fig. 2D). Results based on the extended decadal series further finds a predominant 800-yr cycle (Supplementary Fig. 3).

Climate–economy correlations

Correlations between economy and climatic indexes are summarized in Table 2. The results show positive associations between economic states and temperature reconstructions with different units of spatial coverage, from the regional (Table 2, "TempE.G": eastern China), the whole of China (Table 2, "TempC.G"), to the whole northern hemisphere (Table 2, "TempNH.M", TempNH.CL) at the 10/30-yr scales for the past 2000 yr. All of these were significant statistically except for TempNH.CL. There was also a significant positive relationship between decadal economy and precipitation in eastern China.

By comparing the correlations of the periods before and after AD 960, we found that all climatic indexes apparently displayed more significant relationships ($P < 0.05$) before AD 960, except the TempNH.CL (Table 2) which showed a weak negative relationship before AD 960, but stronger positive association with economy after AD 960, significantly at $P < 0.001$. This contradiction might be due to the higher latitudes represented by the TempNH.CL. The positive associations between economy and temperature/precipitation were particularly stronger statistically for the first millennium AD when climatic indexes with a weighting representative of eastern China (Table 2, "TempE.G", TempC.G, and Prec.Z) were used. That means a warm and wet climate favored the agrarian economic development in Chinese history.

The moving correlation shows more detailed information on the consistency of the economy–climate correlations through the 2130-yr period. We find that the correlation between economy and climate indexes in China was generally positive, but often interrupted by several negative or weaker positive periods. For instance, the negative associations mainly distributed temporally around AD 1130–1550 with the maximum centered on AD 1210 and AD 1470 for TempC.G (Fig. 3C). These periods also witnessed the only weaker relationship between economy and TempE.G (Fig. 3B). Furthermore, the several negative correlations between economy and two larger-scale temperature indexes (Figs. 3D and E) partly correlate well with each other through time but they are less in parallel with TempE.G and TempC.G (Figs. 3B and C), suggesting that this variation is much more dependent on the spatial scale of the series rather than the temperature reconstruction method. However, a paralleling negative correlation centered on AD 430, AD 800, and AD 1300 appeared on TempNH.M and TempNH.CL; the latter two periods also witnessed a relatively reduced coefficient of TempC.G. All of the three major periods (approximately AD 300–600, AD 700–1000, and AD 1200–1400, respectively) were characterized by social-disorder accompanied by the invasion of northern nomads according to Chinese history (Fu, 1981), indicating that unrests and wars, among other things, might be some of the important factors moderating the climatic effects on agrarian economy.

The above associations are amplified on the longer time scale. Results based on 3-point FFT smoothing series' indicate that long-term fluctuation of economy was more significantly driven by long-term temperature change (Table 2). This was consistent with the impact of temperature on the fluctuation of population in central China (Lee et al., 2008), and macro-economic cycles in pre-industrial Europe (Pei

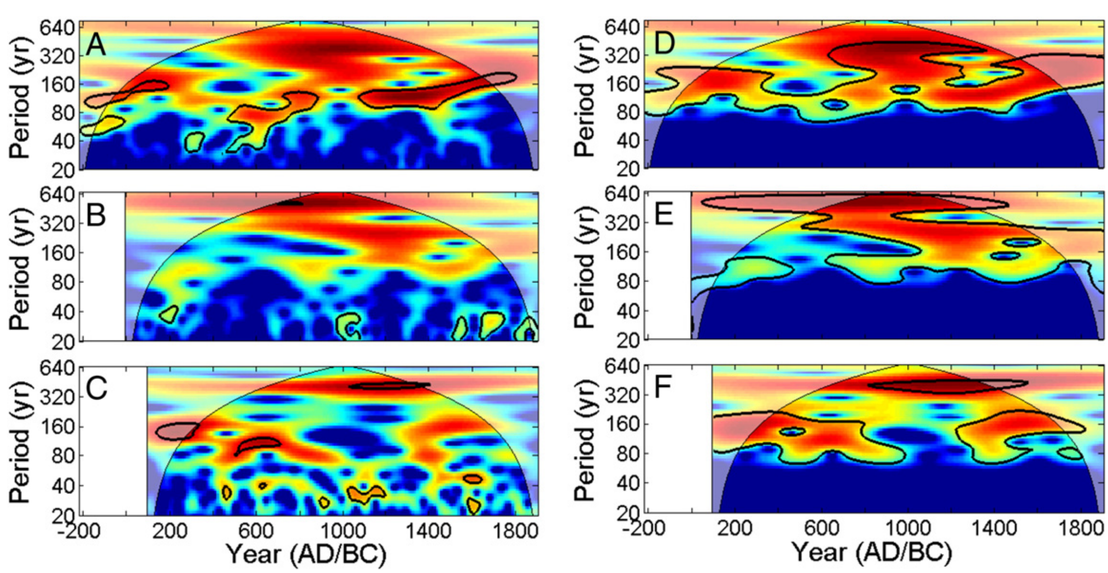

Figure 2. The continuous wavelet power spectra for decadal series (left: (A) economy, (B) TempC.G, (C) Prec.Z) and 3-point FFT smoothing series (right: (D) economy, (E) TempC.G, (F) Prec.Z) in China during 220 BC–AD 1910. The color codes for power values vary from dark blue (low values) to dark red (high values). The thick black contour lines designate the 5% significance level against red noise based on 1000 surrogate data set pairs. Semitransparent cones indicate the regions influenced by edge effects.

Table 2
Correlations between climatic indexes and economic short-term/long-term fluctuation.

Climatic index	Sample length	Pearson correlations of original series			Pearson correlations of 3-point FFT smoothing series		
		Sample length	Before AD 960	After AD 960	Sample length	Before AD 960	After AD 960
TempE.G	210 BC–AD 1890	0.322***	0.441***	0.353*	0.416****	0.864****	0.404**
TempC.G	AD 1–1910	0.315****	0.448****	0.241**	0.409****	0.558****	0.352****
TempNH.M	AD 1–1910	0.202***	0.274***	0.222**	0.222***	0.390****	0.239**
TempNH.CL	AD 1–1910	0.091	−0.074	0.438****	−0.034	−0.261***	0.49****
Prec.Z	AD 101–1910	0.200***	0.304***	0.067	0.145*	0.164	−0.031

* $P < 0.10$.
** $P < 0.05$.
*** $P < 0.01$.
**** $P < 0.001$.

et al., 2014). By contrast, there were weaker associations between long-term changes of economy and precipitation (Table 2). This may imply that the economy was more responsive to short-term precipitation oscillations.

To test this hypothesis, we made a correlation based on the high-frequency series of economy and precipitation (FFT high-pass filter series with cutoff frequency of 0.0125 Hz). The results confirmed our speculation, because economy became stronger and more significantly correlated with precipitation ($r = 0.283$, $P < 0.001$). However, the long-term precipitation trend showed a good positive correlation with economic trends when the climate tended to be drier. This situation happened around AD 1000–1600 when precipitation decreased significantly and extreme drought events occurred frequently (Zheng et al., 2006). The relative increase of precipitation coincided well with the rising trend of economy (Supplementary Fig. 4).

Cycle coherences

The wavelet analysis shows there are great overlaps between economic and climatic variables around the predominant or periodic bands. Economy had a very good match with temperature at the four periodic bands of 100, 160, 250, and 320 yr (Figs. 2D and E), and with precipitation at the three periodic bands of 100, 160, and 320–350 yr (Figs. 2D and F), as confirmed by the results based on the 3-point smoothing series. It is not as statistically significant for the common predominant bands displayed by the original decadal series, which is mainly influenced by the high-frequency signals (Figs. 2A–C). However, the decadal precipitation still demonstrated significant common bands of 100, 160, and 320–350 yr, only in comparison with the relatively higher power of wavelet spectra for temperature around these periods.

Cross-wavelet coherency confirms that climate and economy were indeed closely associated with each other around these periodic bands (Fig. 4, Supplementary Fig. 5). Temperature showed predominant and consistent in-phase associations with economy around the three periodic bands of 100, 320, and 600 yr (all arrows point to the right) (Fig. 4A), whereas precipitation showed predominant in-phase associations around the 100-yr and 160-yr bands, but out-of-phase associations were evident around the 320–350-yr bands during AD 650–1200 (Fig. 4B). For the periods shorter than 60 yr, we found both temperature and precipitation are relatively more predominant as in-phase

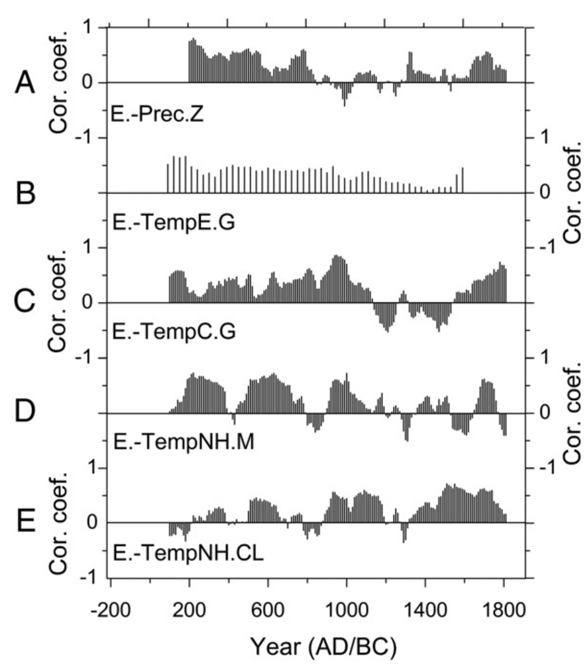

Figure 3. (A–E) Correlations between the reconstructed economic index (E.) and climate reconstructions (Table 1) using a 20-point (200 yr for decadal series and 600 yr for TempE.G) moving window centered at the x-axis values. "Cor. coef." on the y axis means correlation coefficient.

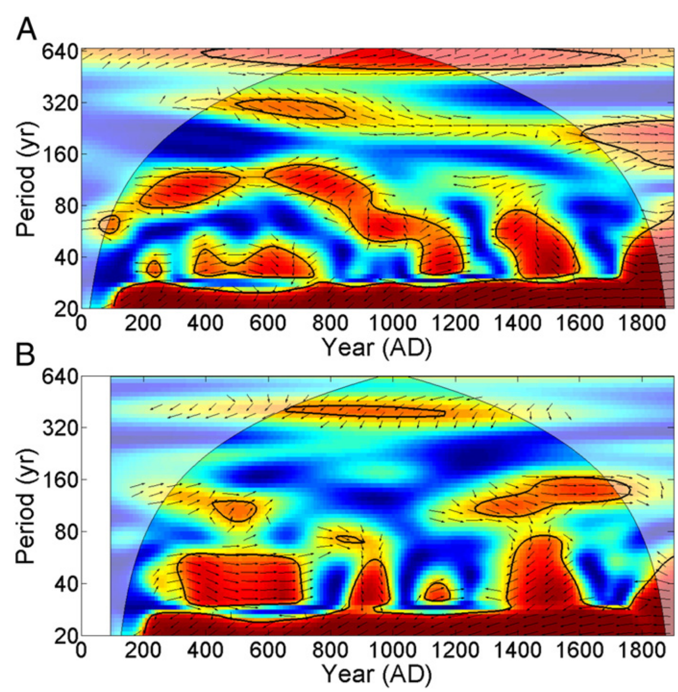

Figure 4. Wavelet coherences between the 3-point FFT smoothing series. (A) Economic level and temperature from the whole of China (Table 1, TempC.G) during AD 1–1910; (B) economic level and precipitation of eastern China (Table 1, Prec.Z) during AD 101–1910. The color codes for power values vary from dark blue (low values) to dark red (high values). The 5% significance level against red noise based on 1000 surrogate data set pairs is shown as a thick contour. Semitransparent cones indicate the regions influenced by edge effects. The arrows indicate the relative phase relationship (right: in-phase; left: out-of-phase).

associations before approximately AD 1000, compared with the out-of-phase associations for the subsequent years (Fig. 4, Supplementary Fig. 5).

Combined effects of temperature and precipitation changes

Regression models can study the effect of each variable and their combined effects in different combinations. The combined effects of the previous decadal economic state, temperature, and precipitation on the current decadal economic state are summarized in Table 3. Model 7a can explain 65% of the variance in the economic series. This value is much larger compared with less than 10% for models 1a and 2a (with temperature and precipitation as the only independent variable, respectively), and 14% for model 3a (with both temperature and precipitation included) (Table 3). However, models 4a–7a (Table 3) seem very stable regardless of whether a single climatic variable or both of them are added or not, and can explain at least 64% of the variance in the decadal economic series. The effects of climate were somehow covered by the strong autocorrelation of economic series on the decadal scale (the ACF indicates a 30-yr lagging autocorrelation). Residual diagnostics (Figs. 5A–C, model 7a) show that residuals are nearly normally distributed, but not independent and display periodically significant autocorrelation, which confirms that the functional forms of models 4a–7a still rely on the previous two or more decadal economic performance. This is partly influenced by the inhomogeneous variation of the reconstructed decadal economic series.

For comparison, we use the 30-yr-resolution TempC.G and Prec.Z (by calculating the 30-yr arithmetic average) to build the same regression model (Table 4, 1b–7b). The results change significantly for the models with the variable of $Economy_{t-1}$ added. The model with no climate predictor variable (only the previous three decadal economic state) can only explain 14% of the variance in the three-decadal economic series (Table 4, 4b). A model with temperature or precipitation as the only climate variable both explained 17% (Table 4, 5b–6b) but was not statistically significant for either temperature or precipitation. However, with both of them added, both the temperature and precipitation become statistically significant and the combined effects of the three components (Table 4, 7b) can explain 23% of the variance. This implies the economic state responded more significantly to the joint effects of temperature and precipitation changes, and their impacts on the economy were closely connected with the previous multi-decadal economic performance at the three-decadal scale. In comparison, the models (Table 4, 1b–3b) excluding the variable of $Economy_{t-1}$ show little difference from the results of the decadal series, except that precipitation as the only predictor variable in model 2b does not reach the significance level of $P < 0.1$, which further confirms that the long-term change of precipitation is not suitable for explaining the variance of the economy. Residual diagnostics (Figs. 5D–F, model 7b) show that the residuals are approximately normally distributed and independent. Besides this, all variables demonstrate a significantly positive linear effect in model 7b.

Discussion

One of the advantages of studying past climatic impacts on society in China, is the availability of well-preserved historical documents covering at least the past two millennia. In this study we used vocabulary descriptions dealing with phase shifts of macro-economic states of the dynasties, compiled in books written by currently leading scholars. We were able to reconstruct a 2130-yr long economic time series in China from these sources. In spite of some uncertainty, this series quantitatively outlined the contours and patterns of secular long-wave fluctuations for empire-wide economies through the whole duration of imperial Chinese history.

The discussion of the long economic cycle for capitalist economy since the late 18th century has been a popular topic (Groot and Franses, 2011), but a greater agrarian economic wave around 150–300 yr in the preindustrial era has received relatively little quantitative attention (Le Roi Ladurie, 1977; Skinner, 1985), with the exception of population (Lee, 1993; Turchin, 2009) and price (Fischer, 1996). Most social scientists were also reluctant to examine some possible links behind the cyclical pattern of history from a climatic change perspective. In this paper, our reconstructed economic series confirmed multiple predominant periodicities, from 60 to 800 yr. Our study reveals a similar historical rhythm of 160-yr and 320-yr periods as concluded by Zhang et al. (2010c), as well as a strong linear relationship between economic fluctuation and temperature/precipitation, similar to many other studies related to population, social unrest, and wars in China (Zhang et al., 2006; Lee et al., 2008). We not only confirm the association between climate and rice price around the predominant 320-yr cycle (Zhang et al., 2010c) from a macro-economic perspective, but also identify a significant association at the 100-yr periodicity.

Macro mechanism for climatic effects

As mentioned above, a number of previous studies have identified climatic forcing as the main cause of the decline in ecological and agricultural resources, and climatic deterioration as the primary mechanism to link climate change and social crisis (deMenocal, 2001; Zhang et al., 2006; Büntgen et al., 2011; Zhang et al., 2011). With a macro perspective, this can explain the mechanisms driving the impact of climate change on the macro economy in the present study, because the performance of economy was heavily dependent upon agricultural development in the agrarian-based empire.

Table 3
Regression models of economic fluctuation on the decadal scale.

Model	1a	2a	3a	4a	5a	6a	7a
Constant	2.966**** (0.084)	3.033**** (0.089)	2.982**** (0.084)	0.63**** (0.137)	0.655**** (0.146)	0.642**** (0.145)	0.711**** (0.150)
$Economy_{t-1}$				0.797**** (0.042)	0.780**** (0.046)	0.786**** (0.044)	0.76**** (0.047)
T_t	1.844**** (0.404)		1.948**** (0.4)		0.367 (0.269)		0.454* (0.270)
P_t		0.281*** (0.103)	0.325**** (0.097)			0.173*** (0.062)	0.187*** (0.062)
Adj R^2	0.095****	0.035***	0.144****	0.635****	0.64****	0.65****	0.653****

$Economy_{t-1}$ is the previous decadal economic level relative to that of the decade t; T_t and P_t are TempC.G (Table 1) and Prec.Z (Table 1) at the decade t, respectively.
* $P < 0.10$.
** $P < 0.05$.
*** $P < 0.01$.
**** $P < 0.001$.

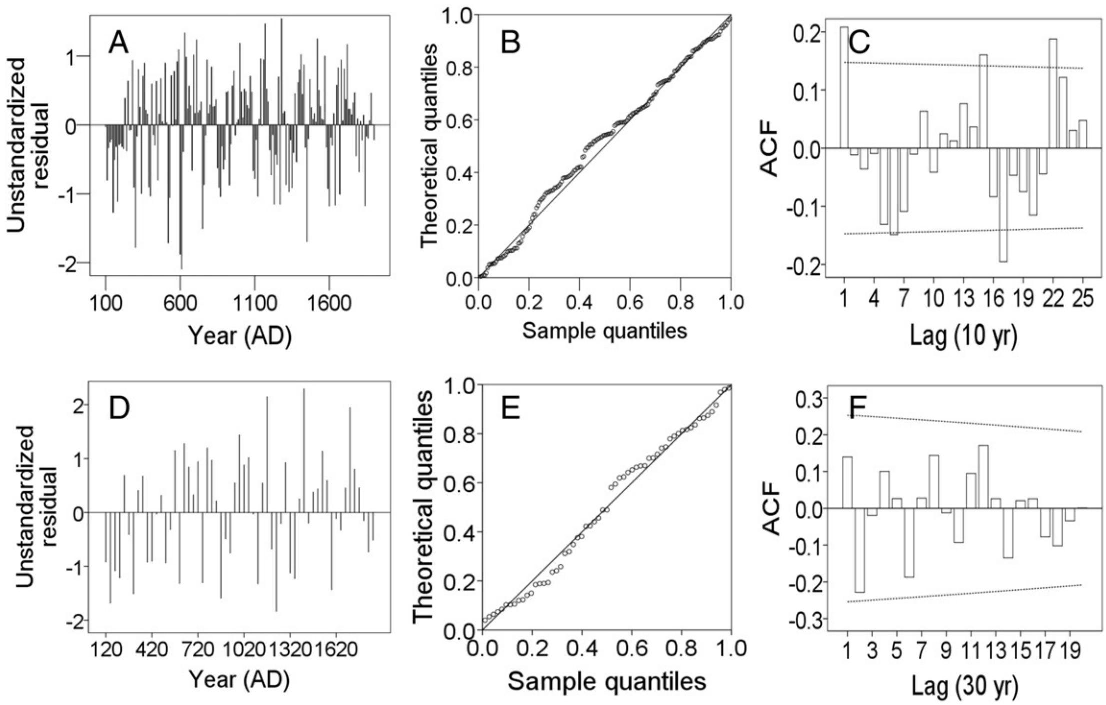

Figure 5. Residual diagnostics for regression analysis of effects of climate (TempC.G and Prec.Z) on economy based on the decadal series (A–C) and their three-decadal series (D–F), respectively. A and D: Time series of residuals reveal no residual trend; B and E: residuals were approximately normally distributed; C: autocorrelation function of residuals (ACF) reveals periodically significant autocorrelation; F: there is no significant autocorrelation function (ACF) of residuals.

However, we prefer to refine these concepts by equating them with food security. This can be measured by using the three variables of 'food availability' (agricultural production), 'food access' (food distribution) and 'food utilization' (food per capita) (Ericksen, 2008; Fang et al., 2013). Long-term climate change has significant direct effects on regional agricultural production (Galloway, 1986; Su et al., 2014; Yin et al., 2014), which in turn affects regional land carrying-capacity. At an empire-wide scale, government-led regulation of food constituted the main aspects of economic life in ancient China. The health of the economic system relied largely on how fairly wealth in the form of arable land and taxation of the individual was distributed by the state. A major abrupt climate change could lead to a profound decrease of food availability and would have exceeded the level at which society could compensate (Alley et al., 2003). While smaller and slower changes might cause undetectable fluctuations of food availability, a negative social response to the process of food access would likely augment the problem of food security (Rosen, 2007). When food supply per capita was barely adequate for the majority of a population, and the society was trapped in its inability to respond positively, famine and epidemics would become difficult to avoid, and ultimately lead to depression in a rural economy (Fang et al., 2013). A more "advanced" (Butzer, 2012) nationwide economic depression and collapse would follow armed conflicts, wars and invasions which would bring large depopulation, migration, damage and abandonment of land and irrigation facilities, and fiscal crises.

Periodic climate change also correlated with frequent invasions from the northern pastoral nomadic societies in China (Zhang et al., 2010c). The invasions from the north were some of the most important factors shaping the patterns of Chinese history (Elvin, 1973). This was particularly true for the period before the Yuan dynasty. Several large invasion events throughout history had brought destructive damage to the agrarian economy in the central plains, at least for the economy in northern China (Fu, 1981; Fang and Liu, 1992). From a macro-historic perspective, it may be one of the most important reasons contributing to stronger positive correlations between economic fluctuations and climatic indexes during the first millennium AD. However, the

Table 4
Regression models of economic fluctuation on the three decadal scales.

Model	1b	2b	3b	4b	5b	6b	7b
Constant	2.933****	2.958****	2.939****	1.868****	1.937****	1.717****	1.98****
	(0.143)	(0.154)	(0.143)	(0.367)	(0.387)	(0.386)	(0.391)
$Economy_{t-1}$				0.386****	0.338***	0.413****	0.323**
				(0.113)	(0.123)	(0.12)	(0.123)
T_t	1.747**		2.307***		1.136		1.653**
	(0.708)		(0.739)		(0.708)		(0.746)
P_t		0.326	0.501**			0.368	0.484**
		(0.241)	(0.232)			(0.22)	(0.22)
Adj R^2	0.076**	0.014	0.145***	0.137****	0.166***	0.173***	0.227****

$Economy_{t-1}$ is the previous three-decadal economic level relative to that of the three-decade t; T_t and P_t are TempC.G (Table 1) and Prec.Z (Table 1) at the three-decade t, respectively.
* $P < 0.10$.
** $P < 0.05$.
*** $P < 0.01$.
**** $P < 0.001$.

relationship between the southern invasion of nomadic societies and climate change is still controversial.

Temperature and precipitation employ a different mechanism in influencing economic fluctuations. Many studies emphasized the vital role of the aridity threshold in agricultural production and in the development of civilizations, cultural shifts and evolution (Lamb, 1995; Polyak and Asmerom, 2001; Lee et al., 2009). Extreme prolonged drought had been cited repeatedly for explaining the collapse of some civilizations that were sensitive to the change of water availability (deMenocal, 2001; Haug et al., 2003). However, our series-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). The short-term effects of precipitation events were much more evident. Therefore, researchers should be cautious when talking about the impacts of aridity on historical social change in China, due to a considerable regional variation of precipitation across China (Zhang et al., 2010a).

Climate change and social processes

Given the above discussion, it might be easy to assume the impact of climate change on social and economic processes was unidirectional and deterministic in a macro perspective, which conflicts with evidence for periods that were out of sync in the relationship between economy and temperature/precipitation (the most evident periods were from around the late 12th century to the late 16th century) (Supplementary Fig. 4). Moreover, climatic impact on the economy was closely connected with the economic performance of previous decades (Tables 3, 4). Climate change alone does not drive macro-economic cycles without the mediation of human action at multiple scales. We tend to accept the climate–economy linkage as a driving–response relationship under particular social conditions instead of simple causality. Therefore, the buffering mechanism of social institutions and their complicated interplay with climate change should never be underestimated (Rosen, 2007; Butzer, 2012). Economic collapse in Chinese history should be considered as a response to climatic pressure to avoid a total collapse, by population and agricultural resource redistribution and social reorganization. The cyclical nature of these alterations between increasing complexity and disintegration in the agrarian economy of China displayed a configuration that can be described using the model of the 'adaptive cycle' from the concept of Resilience Theory. This approach highlights the enduring nature of these trends.

The Resilience Theory model is widely used in Ecology and to some extent in Archeology, and has proved to be a useful tool for analyzing the interlinked social-ecological systems that are adaptive and enduring in a deep-time perspective (Gunderson and Holling, 2001; Holling, 2001; Redman, 2005; Dearing, 2008; Rosen and Rivera-Collazo, 2012). At the core of Resilience Theory are the adaptive cycles, which move dynamically through four phases, described as α-, r-, K-, and Ω-phases. These represent 'reorganization/renewal' (α-) with high capacity for resilience and change, 'growth/exploitation' (r-), 'conservation' (K) with low capacity for rapid change, and finally 'release' Ω- and disorganization (Fig. 6). Adaptive cycles can occur at different orders of magnitude and represent both fast and slow temporal scales. Interlinked sets of these cycles join together to form a multiscalar system known as Panarchy (Gunderson and Holling, 2001).

In this paper, we analyze the adaptive cycles at the scales of emperor and dynasty. As is displayed in Figure 6, the adaptive cycle is similar to the configuration of the reconstructed economic cycle, but the adaptive cycles enable us to take both large-slow and small-fast social and climatic processes into account. The phase of each Emperor or dynasty in the adaptive cycle is identified according to a basic knowledge of Chinese history, for instance, the traditional classification on prosperity/crisis periods by historians. Thus, the phase's identification might merit further explorations. However, the current diagram (Fig. 6) can still convey a new and instructive perspective in illustrating the role of climate in the socio-economic processes. The economic performance of several long dynasties all experienced α-, r-, K-, and Ω-phases of empire-scale adaptive cycles, interplaying with periodic climate change (Fig. 6). The α-phase (reorganization) was influenced by a larger macro-scale cycle of social memory (Gunderson and Holling, 2001), but reinstituted in different dynasties due to the highest potential for innovation and adaptability, such as the adjustment of the tax system (Elvin, 1973). Its low connectivity and weak internal regulation allowed regional economic development (economic fragmentation), making it flexible under the influence of disturbance from social disorder and unfavorable climate and thus able to avoid a total economic collapse after the disintegration in the Ω-phases. This illustrates the resilience of the overall system.

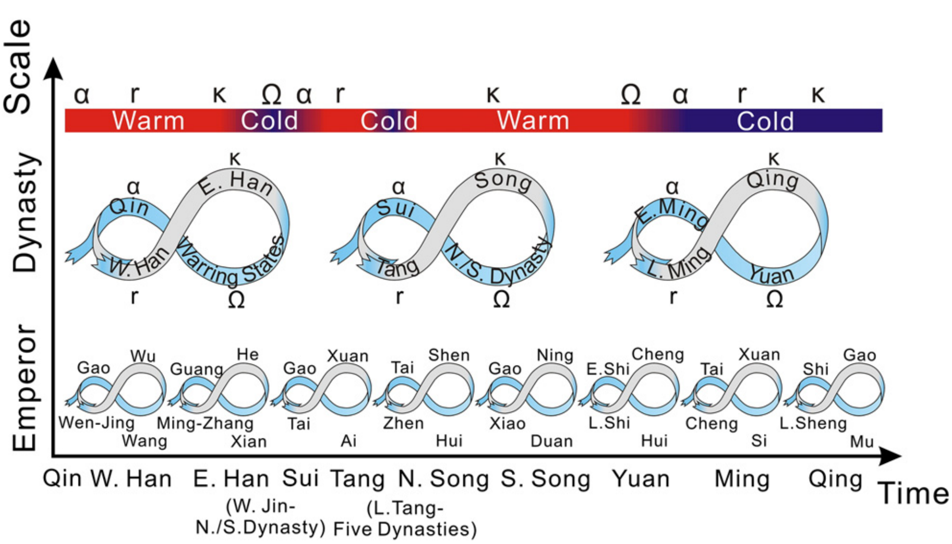

Figure 6. The adaptive cycle model used to analyze the role of climate in the macro-economic and dynastic cycles in China over the past 2000 yr. From top to bottom: (1) α, r, K, and Ω represent four phases of the adaptive cycle, respectively (Gunderson and Holling, 2001); here, they also refer to the dynasties identified in the second row of the figure; (2) the colored bar indicates centennial-scale warm/cold periods in China (Ge et al., 2013); (3) the phase of each major dynasty in the adaptive cycle; (4) the phase of Emperor in each dynasty in the adaptive cycle; the eight loops represent eight long dynasties: the Western Han (W. Han, 206 BC–AD 25), Eastern Han (E. Han, AD 25–220); Tang (AD 618–907); Northern Song (N. Song, AD 960–1127); Southern Song (S. Song, AD 1127–1279); Yuan (AD 1234–1368); Ming (E.: early; L.: late, AD 1368–1644); and Qing (AD 1644–1911).

The r-phase (exploitation) represented a slow accumulation of wealth, and the uptrend of economic development. Stimulus from short-term climate deterioration might trigger a relatively positive response in human agency under a situation of functional institution and fiscal surplus (Wei et al., 2014). For instance, the policy of encouraging migration to Northeast China for cultivation during the earlier Qing Dynasty effectively relieved people from the drought/flood disasters in the Northern China Plain (Fang et al., 2007; Xiao et al., 2014). In fact, this phase was often accompanied by a steadily rising temperature. This is indicated by a stronger positive association between economic fluctuation and temperature for upswing phases than that of the downswing phases (Table 5). This indicates that a positive feedback usually dominated the rising phases of economy.

Growing social and economic rigidity accompanying the r-phase reached a maximum in the K phase, when the over-connected socio-economic system exhibited the least flexibility and the lowest resilience or potential for change. Population growth during the warm periods, without proportionally increasing food supplies (Zhang et al., 2007) brought subsistence stress, and more economically marginalized people (or farmers), thus posing a challenge to social institutions. For instance, mass migration placed a massive burden on the environment (land erosion) of northern China. This erosion, exacerbated by aridity, was considered to be an important cause of economic failure in the later Qing Dynasty (Pomeranz, 1993). At the same time, these institutions were suffering from fiscal stress brought on by gradual privatization of land, population migration and the huge cost of the bureaucratic system. Such stress and taxation reform was the situation continually faced by the middle dynasties (Elvin, 1973; Fu, 1981). Some of the dynasties' reforms succeeded and regained prosperity after an initial depression. But for the most part, the slow processes of accumulating stresses and rigidities were either invisible or too complex for organizations and institutions to overcome (Gunderson and Holling, 2001). That is, this phase was usually characterized by being in a critical state and had high social vulnerability due to population-food imbalances and weakened response capacities. Under these conditions, recurrent climatic perturbations, particularly for the abruptly occurring droughts following decreasing temperature (Supplementary Fig. 4), would significantly increase the risk of economic decline or accelerate deteriorating socio-economic processes, as exemplified by the situation in the early 17th century and the early 19th century in China (Fang et al., 2013; Lee and Zhang, 2013; Xiao et al., 2014; Zheng et al., 2014).

The subsequent Ω-phases corresponded to the rapid collapse of economic networks, which usually was brought on by the eruption of social uprisings or wars in Chinese history (Fu, 1981; Fan and Cai, 1994). The outbreak of social uprisings had very complicated economic-political reasons, including dynastic feuding, the economic claims on resources made by various elite families, famine and political corruption. Although some scholars have demonstrated some correlations between social conflicts and temperature (Zhang et al., 2006), the role of climate shifts in the conflicts remains unclear and ambiguous. Climate change seemed to play an exacerbating role in economic and political instability or functioned as a short-term triggering effect through extreme drought/flood events (Fang et al., 2013; Wei et al., 2014). So a depression of decadal precipitation displayed much better correlation with that of economy compared with that of temperature (Supplementary Fig. 4). This mechanism led to the depression of the economy to a somewhat higher degree than that of temperature on the 3-point FFT smoothing series (Supplementary Fig. 4). For different dynasties, the duration of each phase may have varied. Particularly for the short dynasties, the economy might not have gone through all the four phases (Redman, 2005), and the collapse came quickly and unexpectedly during the peak of the K phase (such as the Qin, Northern and Southern dynasties, Sui), mostly because of the nonlinear effect brought on by social conflicts.

Table 5
Correlations between the rising/declining trends of economy and corresponding temperature and precipitation changes.

Items	Pearson correlation coefficient	Sample
T3r	0.486****	100
T3d	0.343***	91
T5r	0.520****	99
T5d	0.423****	92
P3r	0.109	94
P3d	0.203*	87
P5r	0.102	93
P5d	−0.038	88

T3r/T3d (or P3r/P3d) is the correlation between the rising/declining trends of 3-point FFT economic series and corresponding temperature series (TempC.G, Table 1) (or precipitation, Prec.Z, Table 1); T5r/T5d (or P5r/P5d) is the correlation between the rising/declining trends of 5-point FFT economic series and corresponding temperature (TempC.G) (or precipitation, Prec.Z).

* $P < 0.10$.
** $P < 0.05$.
*** $P < 0.01$.
**** $P < 0.001$.

The Adaptive Cycle model at the dynastic scale provides more support for the buffering effect of larger-slower processes such as technical advance, movement of key economic areas, and adjustment of the socio-economic system with the long-term influence of temperature changes. Before the Tang Dynasty, two centennial cooling episodes (the first was around 460–250 BC (Ge, 2011); the second was around AD 201–530 (Ge et al., 2013)) each coincided well with a downturn of economy lasting several centuries during the Warring States Period (approximately 476–220 BC) (Fu, 1981), and the period from the end of the Eastern Han to the Northern/Southern Dynasties (approximately AD 180–580). Both of these were followed by a short resilient α-phase consisting of a short-duration dynasty. A centennial cold period (Ge et al., 2003) also appeared around the middle Tang Dynasty, but did not induce a long-term depression as in the previous examples, partly due to the benefits from the economic exploitation in the south. The south-to-north transformation of economic resources together with reform of the tax system (Fan and Cai, 1994) helped delay the total collapse for approximately 100 yr for the Tang Dynasty.

Population redistribution as a direct result of social disorders also eased the regional population pressure and reduced its sensitivity to climatic stress. These examples illustrate the mitigating effect of particularistic nuances of individual social systems and their unique responses. Compared with the north, the south had more flexible adaptive options (more alternative choices of food, flexible farming systems, higher yields, and more developed commercial components), and was less sensitive due to the more mild climate, as is reflected in the studies of population change in southern China (Lee et al., 2008). This may help to explain the weak association between climate change and economic fluctuation during some periods such as the Southern Song Dynasty. However, when the southern economy gradually merged more closely with that of the north from the Southern Song to the earlier Yuan periods, the imperial economy was inevitably returning to the K-Phase of the adaptive cycle as in the case of the Eastern Han. The southern invasion of the Yuan, together with the less sophisticated social management system and frequent foreign military, already caused great historical retrogression (Fu, 1981). A large cooling shift from the end of the Medieval Warm Period to the Little Ice Age occurred around the 14th century AD (Ge et al., 2013), when nationwide agricultural depression accompanied the rise of drought/flood disasters across the country after the reign of Kublai Khan (AD 1260–1294) (Fan and Cai, 1994). This major climatic shift, among other things like fiscal crisis, brought the imperial economy from a K-phase during the Song period into a rapid releasing phase (Ω) during the late Yuan period. But the economic performance was still much better than that of similar previous phases.

The subsequent phases all happened in the cold Little Ice Age (AD 1320–1920) (Ge et al., 2003), indicating that climate is not the only factor driving the adaptive cycles. For example, during the Ming

Dynasty, the introduction of higher-yield crops stimulated a rapid population growth (Lee and Zhang, 2013), and a looser feudal dependency relationship encouraged migration which broadened the regional economic development. All of those factors contributed to the reduced climate dependence of economic development during the second millennium AD, as indicated by a weaker or even negative relationship between climate and economy. There was even a 30 to 60-yr lag of economy to temperature during the early Ming Period based on the 3-point FFT series (Supplementary Fig. 4). However, when population growth reached its upper limit with respect to the food supplies (Lee and Zhang, 2013), and economic development tended to be saturated since the late Ming, climate regained its measurable impacts on economic fluctuations as indicated by the higher coincidence and rising coefficient between temperature/precipitation and economy (Fig. 2, Supplementary Fig. 4). These negative processes had been amplified by the minor cycle of individual behavior, notably the three instances of large-scale military actions to the northwest, southwest and Korea during the reign of Emperor Wanli, and its resulting heavy taxation on farmers (Fan and Cai, 1994). A recent study confirmed that climate change indeed impacted the key processes (military farm production, food and fiscal crises, peasant uprising, etc.) involved in the collapse of the Ming Dynasty, through its interactions with social vulnerability (Zheng et al., 2014).

Implications for the future

The mechanisms driving the climatic impact on the macro-economic cycles behind the statistical results would be very complicated. The exact role of climate and how climate interacts with human agency at multiple scales merit further empirical explorations. The present study is only a very preliminary attempt to link the adaptive cycles with the climatic impact on macro-economic cycles, from a macro-historic perspective.

Present societies are facing the threat of global warming in many ways (Parry et al., 2007). Although our study suggests that economic performance during the past two millennia was better during periods of warm, wet and stable climate owing to more stable food production in ancient China. The unprecedented modern warming may cause increased variability in climate with more extreme events, resulting in unpredictable effects on different countries or regions. Food security, which heavily depends on regional agricultural production remains as vulnerable to climatic fluctuations as before, and may bring many human societies into a period of economic depression, and even conflict and unrest again. Positive social mitigation and rapid adaptation mechanisms are still the most important way to meet the challenges of the future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2014.11.001.

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