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Periodic climate cooling enhanced natural disasters and wars in China during AD 10–1900

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Recent studies have linked climatic and social instabilities in ancient China; the underlying causal mechanisms have, however, often not been quantitatively assessed. Here, using historical records and palaeoclimatic reconstructions during AD 10–1900, we demonstrate that war frequency, price of rice, locust plague, drought frequency, flood frequency and temperature in China show two predominant periodic bands around 160 and 320 years where they interact significantly with each other. Temperature cooling shows direct positive association with the frequency of external aggression war to the Chinese dynasties mostly from the northern pastoral nomadic societies, and indirect positive association with the frequency of internal war within the Chinese dynasties through drought and locust plagues. The collapses of the agricultural dynasties of the Han, Tang, Song and Ming are more closely associated with low temperature. Our study suggests that food production during the last two millennia has been more unstable during cooler periods, resulting in more social conflicts owing to rebellions within the dynasties or/and southward aggressions from northern pastoral nomadic societies in ancient China.

Keywords: global warming; war cycle; drought/flood; locust plague; southward migration; human ecology

1. INTRODUCTION

Historians commonly attribute dynastic transitions or cycles to the quality of government and class struggles (Zhang *et al.* 2005). However, climatic fluctuation may be a significant factor interacting with social structures in affecting the rise and fall of cultures and dynasties (Cowie 1998; Hsu 1998). When the climate worsens beyond what the available technology and economic system can compensate for, people are forced to move or starve. Some authors suggest that climate cooling has had a huge impact on the production of crops and herds in pre-industrial Europe and China (Hinsch 1998; Atwell 2002; Zhang *et al.* 2007a), even triggering mass southward migration of northern nomadic societies (Fang & Liu 1992; Wang 1996; Hsu 1998). This ecological and agricultural stress is likely to result in wars and social unrest, often followed by dynastic transitions (Zhang *et al.* 2005). A few recent studies have demonstrated that wars and social unrests in the past often

were associated with cold climate phases (Zhang *et al.* 2005, 2007a,b). Climate cooling may have increased locust plagues through temperature-driven droughts or floods in ancient China (Stige *et al.* 2007; Zhang *et al.* 2009). Therefore, cool temperatures may directly or indirectly be detrimental to agriculture, and thus stimulate wars of rebellion within a dynasty (defined here as the 'internal war hypothesis'; see Zhang *et al.* 2005, 2007a,b). Alternatively, climate fluctuations may force nomads of the north during cold periods, through affecting livestock production (Fang & Liu 1992; Wang 1996; Hsu 1998), to migrate southwards, and thereby increase the frequency of conflicts between these northern pastoral nomadic societies and the agricultural societies (defined here as the 'southward aggression hypothesis'). However, both hypotheses have not yet been quantitatively assessed.

The purpose of this study aims to reveal the periodic cycles of war frequency in ancient China, and the associations of external aggression war or internal war with climatic or agricultural disasters. Our emphasis is on testing the internal war hypothesis and the southward aggression hypothesis. We use historical data on war frequency, drought frequency and flood frequency, all of

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which having been compiled by Chen (1939). In addition we use a multi-proxy temperature reconstruction for the whole of China reported by Yang *et al.* (2002), air temperature data for the Northern Hemisphere (Mann & Jones 2003), proxy temperature data for Beijing (Tan *et al.* 2003), and a historical locust dataset reported by Stige *et al.* (2007) and extracted from Ma (1958). Finally, we use historical data of rice price variations reported by Peng (2007). Chen (1939) distinguished wars into internal wars within the Chinese dynasties (including peasant uprisings and battles among warring states) and external aggression wars where the Chinese dynasties fought aggression from external societies (predominantly southward aggressions by northern nomads). These data on war frequencies provide us with the unique opportunity to test the temperature-associated internal war hypothesis and the external southward aggression hypothesis separately. The available data of rice price, drought/flood and locust plague occurrence enable us to assess the proposed potential causal mechanisms of how temperature variations affect war frequency. Cross-correlation function (CCF) and wavelet analysis were used to conduct statistical analysis on associations between war frequency and the influential factors.

2. MATERIAL AND METHODS

(a) War frequency data

The decadal data of war frequency from 246 BC to AD 1913 was compiled by Chen (1939) by referring to a large number of historical books. By following the traditional view of Chinese historians, wars were classified into three categories by Chen (1939): internal wars (Nei Huan), external aggression wars (Wai Huan) and other wars. The internal wars were defined as the battles within the Chinese dynasties ruled by either Han or non-Han descendants. The internal wars include peasant uprisings and battles among warring states within the Chinese dynasties. The external aggression wars were defined as battles between the Chinese dynasties and surrounding external societies (e.g. Northern Zhou, Northern Qi, Former Qin, Liao, Jin, Xi Xia, Huigu, Xiongnu, Mongolian, Qiang, Tibetan) that tried to raid or invade the territory of the Chinese dynasties. During AD 10–1900, the external aggression wars to the Chinese dynasties were mostly owing to southward aggressions from northern pastoral nomadic societies (e.g. Xiongnu, Mongolian, Manchurian, Nuzhen, Xianbei, Qidan). Wars that could not be clearly defined, or wars when the Chinese dynasties were invading the surrounding societies for expansion or as demonstrations of force, were defined as other wars. Chen (1939) compiled the data in decadal scale. However, in some periods, his decadal resolution does not match the calendrical decadal scale but is shifted for several years. Thus, if applicable, war frequency was recalculated from the original data of Chen (1939) by averaging the war frequencies of the neighbouring two decades to produce the best match to the calendrical decadal scale of the temperature time series. The book by Chen (1939) documents a higher number of wars than the two-volume book entitled *Tabulation of wars in Ancient China* (ECCMH 2002). The war data in the book edited by ECCMH (2002) was not classified into internal wars or external aggression wars, and are therefore not suitable for our study purposes.

(b) Temperature data

Decadal mean temperature for the whole of China (T) during AD 10–1990 was reconstructed by Yang *et al.* (2002) by combining multiple area weighted palaeoclimate proxy records obtained from ice cores, tree rings, lake sediments and historical records. The Northern Hemisphere air temperatures (T_N) from AD 200 to present were downloaded from the IGBP PAGES/World Data Center for Paleoclimatology (Data Contribution Series #2003-051) at the ftp site ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/mann2003b/mann2003b.txt. The original data are from a reference by Mann & Jones (2003). The air temperature in the warm season (May, June, July and August) near Beijing (T_B) during 665 BC–AD 1985 is reconstructed by Tan *et al.* (2003) based on a correlation between thickness variations in annual layers of a stalagmite from Shihua Cave (Beijing, China) and instrumental meteorological records. This record represents the only site close to northern pastoral nomadic regions having the long-term temperature data.

(c) Flood/drought data

Chen (1939) also compiled data of decadal frequencies of flood and drought events from 246 BC to AD 1913 covering the whole of China. The frequency of flood/drought events was calculated as the number of flood/drought records for each decade within the dynastic periods during AD 10–1900. As for the war frequency data, if applicable, the flood/drought data were also recalculated to produce the best calendrical decadal time series of flood/drought.

(d) Locust data

The decadal locust abundance data for AD 950–1950 was taken from Stige *et al.* (2007). Decadal means of locust abundance for the period AD 957–1956 were extracted from annual locust abundance (fig. 9a in Ma 1958). Ma (1958) derived the series by referring to the reported intensity and spatial extent of locust outbreaks mentioned in various sources of the older Chinese literature (e.g. Chen 1936, 1939).

(e) Rice price data

The decadal average of rice price is an indicator of grain or food shortage in ancient China (also see Zhang *et al.* 2007a). We used the annual data of rice price for the whole of China compiled by Peng (2007; a reprint copy of Peng 1965) for AD 961–1900, with 12 missing values during AD 1250–1360 and AD 1410. The missing data were reconstructed by interpolation. The prices of rice are different in currency unit for the periods AD 961–1250 (unit: silver) and AD 1361–1900 (unit: cent). The exchange rate of silver : cent was about 37 : 1. To achieve a smooth time series, the data of rice price for the period AD 961–1250 were adjusted to the same average as in the period AD 1361–1900 (the ratio of the averages of the two periods is 30, quite close to the silver : cent ratio).

(f) Statistics

All data except for temperature and locust data were first naturally log-transformed to stabilize variance. Frequencies of wars, drought/flood and locust plagues showed increasing trends with time, which are probably caused by better recording with progress of the societies. All data were then detrended by removing low-frequency components (more than 640 years) using low-pass filtering (Shumway & Stoffer

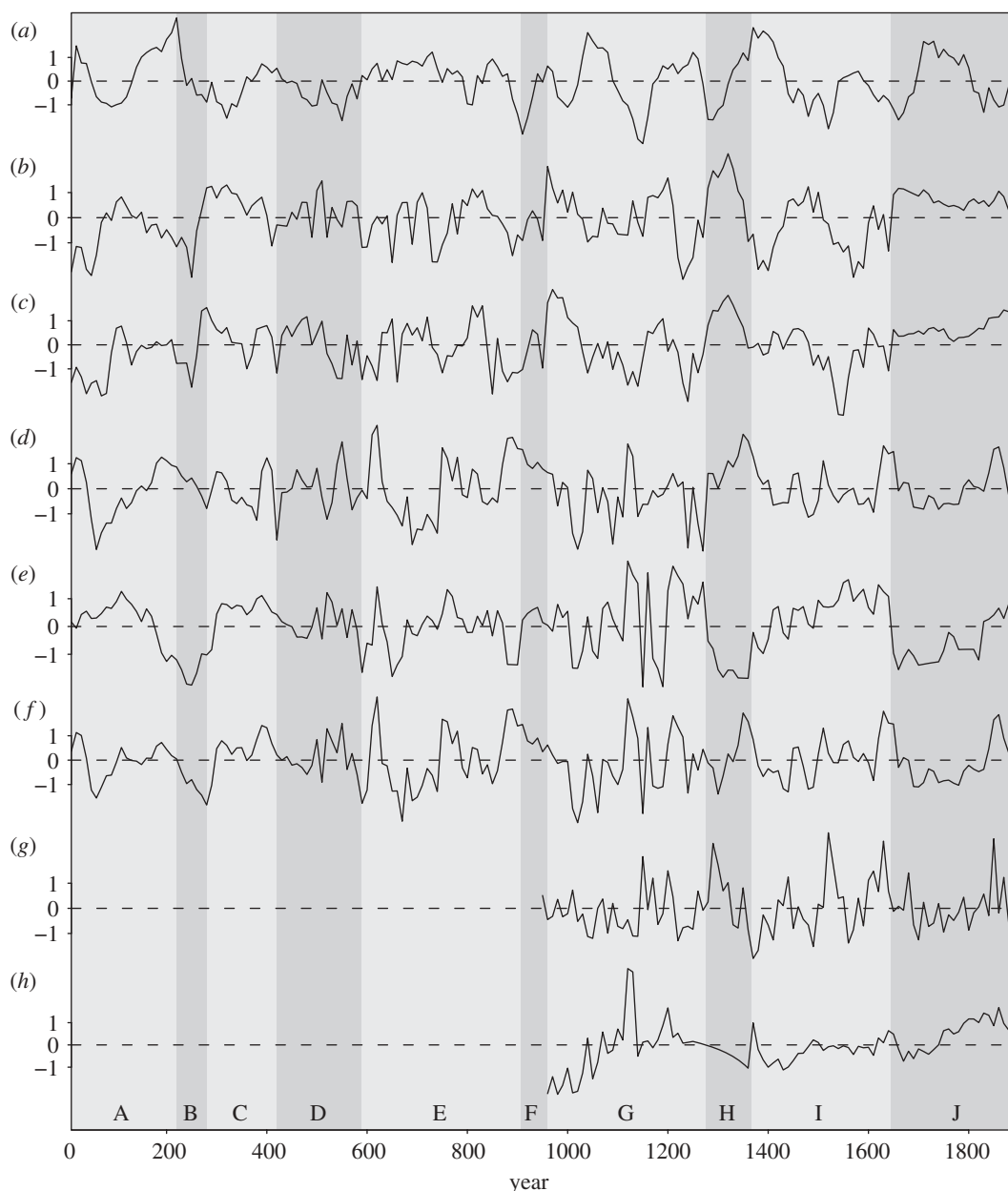


Figure 1. Decadal means of temperature of (a) the whole of China, (b) frequencies of droughts, (c) floods, (d) internal wars, (e) external aggression wars, (f) all wars, (g) locust plagues and (h) rice price in China during AD 10–1990. Dynastic periods are defined by following Chen (1939) as: A, Han (206 BC–AD 220); B, Three Kingdoms (AD 220–280); C, Jin (AD 280–420); D, Southern and Northern Dynasties (AD 420–589); E, Sui & Tang (AD 589–906); F, Five Dynasties and Ten Kingdoms (AD 907–959); G, Song (AD 960–1279); H, Yuan (AD 1276–1367); I, Ming (AD 1368–1643); J, Qing (AD 1644–1911).

2000) to adjust for possible errors caused by recording bias in later times. For the final comparison, all data were standardized to zero mean and one unit standard deviation. The detrended and standardized time series of frequencies of wars, droughts, floods, locust plagues, temperature and rice price are shown in figure 1.

CCFs and classic bootstrap methods are appropriate for analysing associations between two time series in time domain (Shumway & Stoffer 2000; Bloom *et al.* 2007), while the wavelet coherency method is suitable for analysing the associations at both time and frequency domains (Cazelles *et al.* 2008). In this study, using CCF and bootstrap methods, we analysed the associations between the frequencies of all wars (AW), internal wars (IW), external aggression wars (EW), variations of rice price (RP), droughts (D), floods (F), locust plagues (L) and temperature of the whole of China reconstructed by Yang *et al.* (2002) (T) in China

during AD 10–1900. The CCF and p -values of the current decade (lag 0), previous decade (lag -1) and before previous decade (lag -2) are shown in the electronic supplementary material, table S1. We identified potential causal paths or links by assuming that war frequency is positively associated with high-level climatic, agricultural or biological disasters. High levels of D, F, L and RP, and extreme temperature, can be potential indirect indicators of food shortage. They are potential causative factors in triggering and accelerating wars as natural disasters. We focus on identifying associations of high levels of AW, EW or IW with these natural disasters. We have also used wavelet analysis (Cazelles *et al.* 2008; see the electronic supplementary material) that appears suitable for investigating possible causal links of multiple variables within the overlapped coherency in frequency and time domains (Zhang *et al.* 2009). Wavelet coherency analysis was used to identify the time period and the frequency of

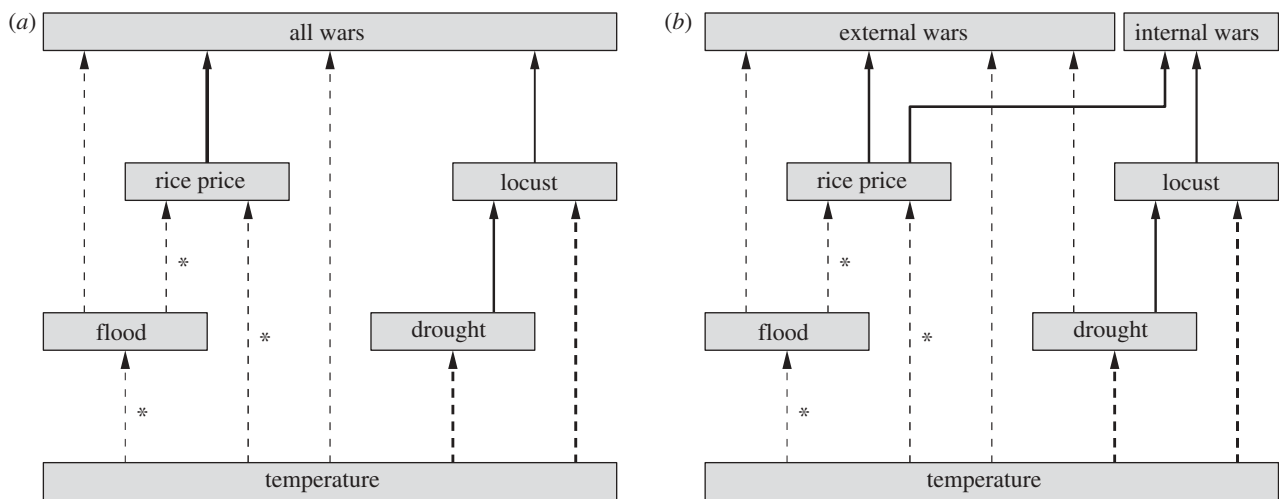


Figure 2. Possible causal links of temperature and temperature-associated rice price, locust plagues, droughts and flood with frequencies of (a) all wars and (b) external aggression wars or internal wars. Solid (positive effect) or dashed (negative effect) lines denote the maxima of CCF values with significant ($p < 0.05$) or near-significant ($p < 0.1$) levels in the electronic supplementary material, table S1s. Asterisks denote near-significant associations ($p < 0.1$). Line width denotes significant maxima of CCF values.

the causal paths identified by CCF analysis. The periods without data are taken as missing data. Thus, results of association of war frequency related to rice price or locust plague are only applicable for the period of AD 950 (or 960) to the 1900s. Results of associations of war frequency with temperature, drought and flood are derived from data during AD 10–1900.

3. RESULTS

Figure 2 summarizes our results and shows the maxima of significant ($p < 0.05$) or near-significant ($p < 0.1$) CCFs between decadal values of war frequency and possible influencing variables in phase and with time lags of one and two decades (see the electronic supplementary material, table S1). As shown in figure 2a, there are in total six paths through which temperature may affect frequencies of all wars (AW, sum of internal wars, external aggression wars and other wars), but only three paths are reasonable if we assume that wars are caused by climatic, agricultural or biological disasters. First, low temperatures (T) may directly increase AW through the path of low T → high AW. Second, low temperature may indirectly increase AW through the path of low T → high D (drought) → high L (locust) → high AW. Third, low temperature may indirectly increase AW through the path of low T → high RP (rice price) → high AW. These results suggest that climate cooling may have increased the frequency of all wars (AW) directly as well as indirectly through its associated increases of rice price level or drought and locust occurrence. The other paths (i.e. low T → high F → low AW; low T → high F → low RP → low AW) are not reasonable; in other words, flood disasters seem not to be key factors in causing high RP and high AW.

As shown in figure 2b, there are two possible paths through which low temperature may increase the frequency of external aggression wars (EW): low T → high EW; low T → high RP → high EW. Similarly, the other paths (i.e. low T → high F or high D → low EW; low T → high F → low RP → low EW) are not reasonable;

in other words, flood or drought disasters seem not to be key factors in causing high EW. There are also two possible paths through which low temperature may increase the frequency of internal wars (IW): low T → high D → high L → high IW; low T → high RP → high IW. These results suggest that climate cooling may have increased directly the frequency of external aggression wars. Besides, climate cooling may have increased indirectly the frequencies of both external aggression wars and internal wars through its associated increase of rice price; it may have increased indirectly the frequencies of internal wars through its associated increase of drought and locust plague. It is notable that we did not detect significant or near-significant direct effect of temperature on frequencies of internal wars.

As shown in the electronic supplementary material, table S2, using proxy data of air temperature of the Northern Hemisphere (T_N) and temperature of Beijing (T_B), we find AW shows significant out-of-phase associations with T_N of the previous decade (CCF = -0.2209 , $p = 0.003$) and the current decade (CCF = -0.2039 , $p = 0.003$). EW shows significant out-of-phase associations with T_N of the previous decade (CCF = -0.1273 , $p = 0.0494$) and the current decade (CCF = -0.1422 , $p = 0.0326$), and with T_B of previous decade (CCF = -0.1227 , $p = 0.0432$). IW shows significant out-of-phase associations with T_N of the previous decade (CCF = -0.1242 , $p = 0.0482$). Besides, EW shows near-significant out-of-phase associations with T_B of the current decade (CCF = -0.1015 , $p = 0.0828$) and previous two decades (CCF = -0.1033 , $p = 0.0724$); IW shows near-significant out-of-phase associations with T_N of the current decade (CCF = -0.1209 , $p = 0.06$). These results support the above observations of the out-of-phase associations between AW or EW and T. Besides, these results also reveal the out-of-phase association between IW and T_N .

Wavelet analysis shows all time series of EW, IW, T, T_N , T_B , D, F and RP variables have one or two predominant and consistent periodic bands around 160 years or/and 320 years (figure 3), suggesting that these variables may interact with each other around these two periodic

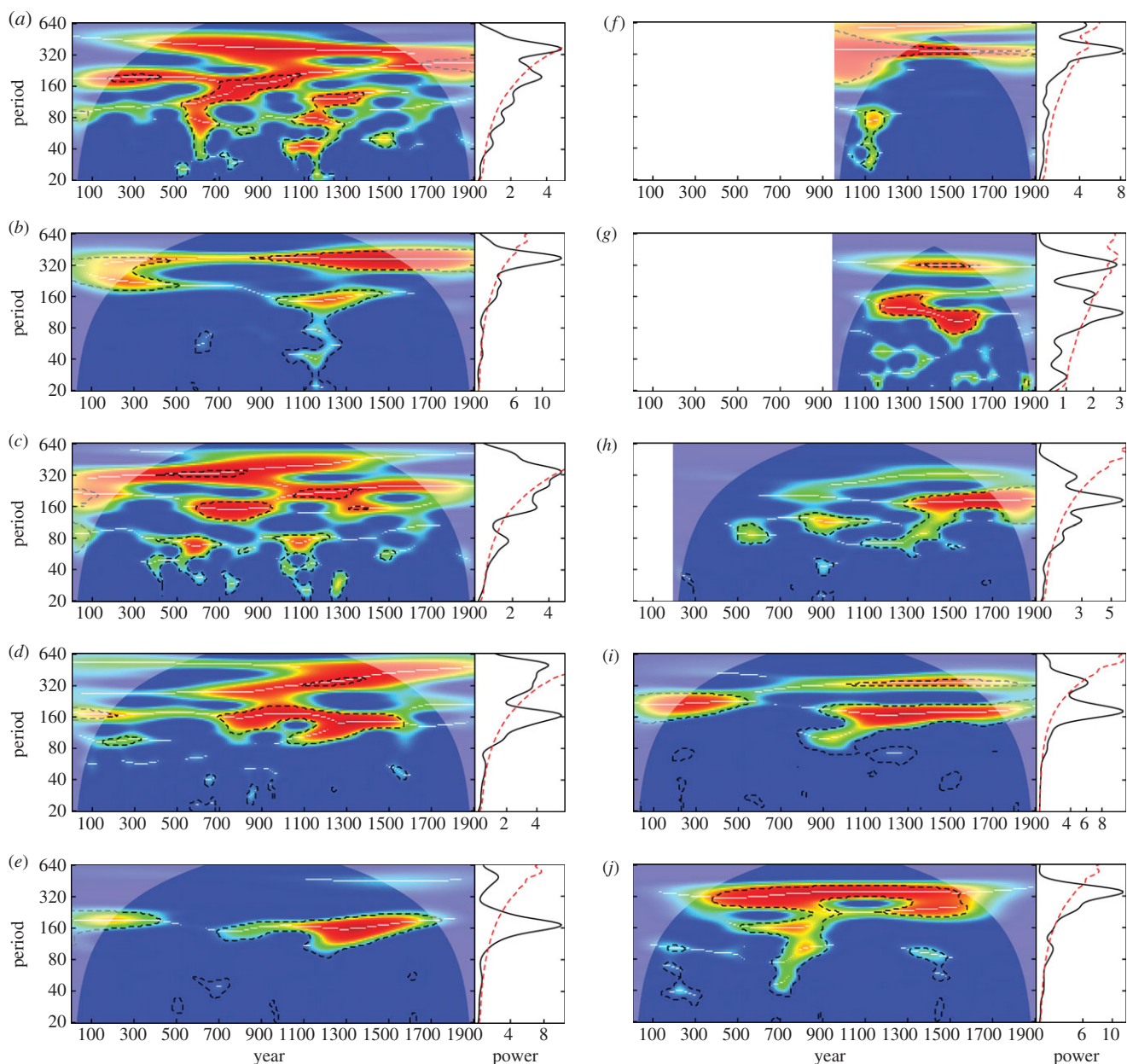


Figure 3. The continuous wavelet power spectra of (a) all wars, (b) external aggression wars, (c) internal wars, (d) flood, (e) drought, (f) rice price, (g) locust, (h) temperature in the Northern Hemisphere, (i) temperature in the whole of China and (j) temperature in Beijing in China during AD 10–1990. The colour codes for power values vary from dark blue (low values) to dark red (high values). The dotted white lines show the maxima of the undulations of the wavelet power spectrum. The cone of influence where edge effects might distort the picture is shown in a lighter shade. The graphs on the right of each panel represent the average wavelet power spectrum computed based on the corresponding left graphs. On the left and right graphs, the thick dashed lines show the $\alpha = 5\%$ significance levels computed based on 1000 ‘beta-surrogate’ series.

bands. T has one period initially around 240 years, then two bands around 160 and 320 years (the 160 year band is more predominant; figure 3*i*). T_N has a predominant period around the 160 year band and an obvious band of 320 years (figure 3*h*). T_B has a predominant period around the 320 year band and a weak band of 160 years (figure 3*j*). D has one period around 160 years (figure 3*e*). F has two periods around 160 and 320 years (the 320 year period shows somewhat steady increase; figure 3*d*). IW has three periods around 160, 240 and 320 years (figure 3*c*). EW has one period around 240 year initially, and then two periods around 320 and 160 years (figure 3*b*). AW has periods around 320 and 160 years (figure 3*a*). L has periods of 320 and 160 years (figure 3*g*). RP has a period of 320

years (figure 3*f*). There are also obvious periods around 80 or 40 year bands for some time series (e.g. AW , IW , L , RP , T_N , T_B , F). There are good overlaps among these variables around the predominant or obvious periodic bands. For example, EW has a very good match with T at the three periodic bands of 240, 160 and 320 years (figure 3*b,i*), supporting the significant out-of-phase associations between EW and T (figure 2*b*).

Overlapped coherency analysis confirms that they are indeed closely associated with each other around these two periodic bands (see figure 4; see the electronic supplementary material, figures S1–S3). EW shows predominant out-of-phase associations (all arrows point to left) with all of the three time series of temperature (T , T_N , T_B ; figure 4), supporting the significant CCF

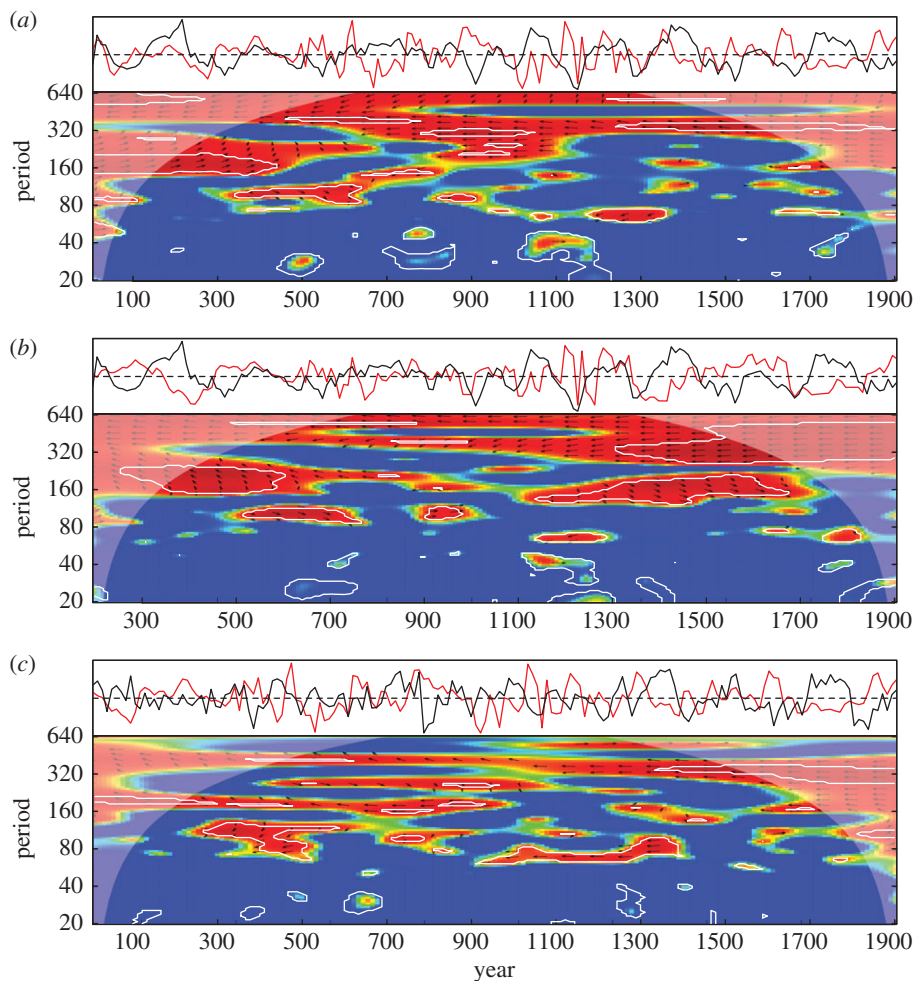


Figure 4. Wavelet coherences between the frequency of external aggression wars and temperature of (a) the whole of China, (b) the Northern Hemisphere and (c) Beijing in China during AD 10–1900. The colour codes for coherence values vary from dark blue (low values) to dark red (high values). The 5% and 10% significance levels computed based on 1000 ‘beta-surrogate’ series are shown as thick white dashed contour lines. The cone of influence where edge effects may distort the picture is shown in a lighter shade. The arrows indicate the relative phase relationship (with in-phase pointing to the right, out-of-phase pointing to the left). The graphs show the detrended and standardized time series of frequencies of external aggression wars (red lines) and temperature (black lines) during AD 10–1900.

estimations in the electronic supplementary material, tables S1 and S2. All T , T_N and T_B show predominant and consistent out-of-phase associations with EW around the 320 year periodic band, but there are a few short periods showing in-phase associations (all arrows point to right) around the 160 year band (figure 4). T and T_N also show predominant out-of-phase associations with AW (see the electronic supplementary material, figure S1); however, there are no predominant in-phase or out-of-phase associations between IW and all three temperature time series. T shows about equal out-of-phase and in-phase associations with IW, resulting in a non-significant CCF between them (see the electronic supplementary material, table S1 and figure S2a).

As shown in the electronic supplementary material, figures S1–S3, L shows obvious consistent in-phase associations with AW or EW around the 320 year band, with AW or IW around the 160 year band. RP shows predominant in-phase associations with AW and IW around the 320 and 80 year bands. These results suggest that low T , high RP and high L are potential

factors causing high AW, EW or IW at the specific periodic bands. F and D show obvious consistent out-of-phase associations with AW and EW around the 320 year band (see the electronic supplementary material, figures S1 and S3), suggesting that high F or D are less important key factors causing high AW or EW, or owing to a time-delayed effect caused by the covarying effect of IW on EW (see §4). In general, the observed associations by using wavelet analysis (see figure 4; see also the electronic supplementary material, figure S1–S3) are in good agreement with those observed by using CCF analysis (see figure 2). It is also notable that associations between variables are not always consistent around specific periods though they are strong or obvious. These inconsistencies often occur around the 160 year band, such as the associations between IW and D (see the electronic supplementary material, figure S2c) and between EW and D (see the electronic supplementary material, figure S3c), or they may occur between 160 and 320 year bands (e.g. figure 3d, for association between EW and L). This may be caused by several factors (see §4).

4. DISCUSSION

Our results demonstrate that periodic climate cooling may have increased the frequency of external aggression wars during AD 10–1900, supporting the southward aggression hypothesis. All three temperature time series show significant out-of-phase associations with the frequency of external aggression war (figure 4; see also the electronic supplementary material, tables S1 and S2), and these associations are predominant and consistent around the 320 year periodic band (figure 4). Because no causal links between high EW and high F or high D are established (figure 2), the negative effect of temperature on EW may be direct. External aggression wars as defined by Chen (1939) have mostly occurred between Chinese dynasties and the pastoral nomadic societies to their north. The northern part of the Chinese dynasties are more vulnerable to temperature cooling; it is estimated that a 2°C drop of annual air temperature can shorten the growing season of grass by 40 days (Zhang *et al.* 2005), adversely affecting grasslands and resulting in huge losses of domestic livestock owing to forage shortage (Fang & Liu 1992). Accordingly, previous studies have shown that cooling has had a negative impact on agricultural or livestock production in ancient China (Gong *et al.* 1996; Zhang *et al.* 2005). According to Ren (2004), pastoral nomadic regions experienced serious droughts and then southward immigration owing to collapses of livestock production in cold periods. There are reports on large-scale southward immigrations of northern pastoral nomadic societies in ancient China during the cold periods (e.g. Chen 1939; Wang 1996; Ding 2007; see also the electronic supplementary material). The collapses of the agricultural dynasties of the Han, Tang, Northern Song, Southern Song and Ming are closely associated with low temperature or rapid decline of temperature, and immediately replaced by dynasties ruled by the northern pastoral nomadic societies (see the electronic supplementary material, figure S4). We did not find significant links between high EW and high F or high D (figure 2), suggesting that the collapses of the agricultural dynasties were not caused by drought and flood events. Our results do not support the view that the collapses of the Tang and the Ming dynasties are caused by drier climate owing to weaker Asian summer monsoon (Yancheva *et al.* 2007; Zhang *et al.* 2008), but support the view of Zhang & Lu (2007; see the electronic supplementary material).

Our results also suggest that periodic low temperatures may have increased the frequency of internal wars mainly indirectly through increasing drought and locust plague frequencies during AD 950–1900, supporting the internal war hypothesis. Drought, flood and locust plague have been regarded as the three major natural disasters affecting crop production in ancient China (Zhang *et al.* 2009), suggesting that their detrimental effects on agricultural production may trigger internal uprisings. In the cold period of AD 1840–1890, agricultural yields in China were reduced by 10 to 25 per cent compared with the relatively warm period of AD 1730–1770 (Gong *et al.* 1996). Our findings provide quantitative evidence about climate-driven agricultural breakdown owing to droughts and locusts increasing the frequency of internal wars. Droughts have been well recognized as the positive effect on locust plagues in China because

they produce favourable wet bank or lake beach environments for locusts to lay eggs (Stige *et al.* 2007; Zhang *et al.* 2009). The positive effect of low temperature on locust plague is obviously indirect through increase of temperature-induced droughts. Because IW is positively associated with the locust plague around the 160 year periodic band, the indirect effect of temperature on IW might be dominant around this periodic band. We did not find significant direct effect of temperature on IW and T (figure 2*b*). However, we found a significant out-of-phase association between IW and T_N (figure 4*e*). This is in agreement with findings by Zhang *et al.* (2005). These results suggest that direct negative effect of temperature on IW may also exist. Thus, low temperature may destroy agriculture directly or/and indirectly through its induced high level of drought, flood and locust plagues. Our study also reveals that there are more droughts and floods in cold periods in China (figure 2; see also Zhang *et al.* 2009). This is in agreement with some previous studies that found there were fewer floods in the warm 9th to 11th centuries and more floods in the cold 14th to 17th centuries (Singer & Avery 2007). In the Little Ice Age, Europe suffered the most serious floods and hunger in its history, and both Roman and Mayan empires collapsed in cold periods (Singer & Avery 2007).

Our results demonstrate that frequencies of both internal wars and external aggression wars were strongly and positively associated with the price of rice. Rice price may be a good criterion reflecting food availability, suggesting that food shortage indicated by high rice price may have played a key role in social conflicts in ancient China. Surprisingly, the negative association between temperature and rice price only attains a near-significance level ($p < 0.1$), suggesting that the close positive association between frequencies of wars and rice price may be caused more by intrinsic factors of the society such as misgovernance, corruption and population growth, and that this strong association may mask the weaker associations of rice price with climatic disasters such as droughts and floods. Cool temperature causes high price of rice directly, while cool temperature also causes high floods, which cause low rice price (figure 2). These results suggest that cool temperature may cause food shortage (reflected by price of rice). Floods may benefit rice growth by increasing area of wetlands, resulting in a near-significant out-of-phase association between RP and F (figure 2).

It is very probable that cool temperature may be the driving force in causing high frequencies of meteorological, agricultural disasters and then man-made disasters (wars) in ancient China. In our previous study we found cool temperature significantly increased frequencies of drought and flood, and then locust plagues (Zhang *et al.* 2009). The larger the difference of temperature between Arctic and tropical equatorial regions, the greater the strength of wind, ocean waves, ocean circulation and cyclones; thus a cold climate would bring more climatic disasters than a warm climate (Singer & Avery 2007). Such effect of climate cooling works similarly on precipitation in China (see Zhang *et al.* 2009; see also the electronic supplementary material). Therefore, cool temperature could not only reduce agricultural and livestock production directly, but also reduce agricultural

production by producing more droughts, floods and locust plagues in ancient China indirectly. The collapses of agricultural and livestock production would cause wars within or among different societies.

We found three temperature time series (Yang *et al.* 2002; Mann & Jones 2003; Tan *et al.* 2003) had one or two predominant periodic bands of around 160 and/or 320 years during last two millennia (figure 3). These periods may be related to cyclic variations of solar activity, or cyclic changes of orbit position of the Earth (Singer & Avery 2007). Friis-Christensen & Lassen (1999) reported that solar activity can contribute 75 to 85 per cent of the climatic variation of the Earth. There are 87 and 210 year cycles of solar activity based on observations of sunspots (Braun *et al.* 2005). The two predominant periods of temperature are relatively wide owing to smooth variation of low-frequency temperature. The initial period of T is 240 years, and then divided into 160 and 320 year band. These may be related to the 210 year solar cycle. In some periods, the 80 year periodical band of temperature is also observed in our study, which may be related to the 87 year solar cycle. Using power spectral analysis, Tan *et al.* (2003) find the cycles of about 206 and 325 years of Beijing temperature are significant, and these cycles could be connected to solar variation cycles of about 208 and 350 years (Lean 2002). It is notable that the periods we discovered (e.g. 40, 80, 160, 320 years) are well linked to the solar cycle as predicted by the model $T = 11 \times 2^n$ ($n = 2, 3, 4, 5$; see Perry & Hsu 2000; Hsu 1998). The periodic associations between frequencies of external aggression wars and temperature (figure 4), or between drought/flood and temperature (Zhang *et al.* 2009), are predominant and consistent in phase shift, suggesting that the periodic variations of temperature may be the direct driving forces behind these variables. With the increase of the levels in figure 2, the periodic associations of temperature-driven drought/flood or locust plagues on war frequency may become less clear, probably owing to many reasons (e.g. time delay, frequency dependency; see the electronic supplementary material), which need to be investigated further in future studies.

It is generally believed that global warming is a threat to human societies in many ways (IPCC 2007). However, some countries or regions might also benefit from increasing temperatures in some ways (Nemani *et al.* 2003; Stige *et al.* 2007; Zhang *et al.* 2009). Our study suggests that during the last two millennia, food production in ancient China was more stable during warm periods owing to fewer agricultural disasters, resulting in fewer social conflicts. However, the present ongoing global warming may produce different effects on our industrialized societies, which have a much higher capacity for dealing with natural disasters than pre-industrial societies. Its potential consequence on our societies and ecosystems needs to be carefully monitored and investigated. Data quality is influenced by many factors, including data coverage and time–space density of reports. Thus, it is necessary to recover more data from additional sources for gaining the utmost insight from such comparisons.

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REFERENCES

- Atwell, W. S. 2002 Time, money and the weather: Ming China and the great depression of the mid-fifteenth century. *J. Asia Stud.* **61**, 83–113. (doi:10.2307/2700190)
- Bloom, R. M., Buckeridge, D. L. & Cheng, K. E. 2007 Finding leading indicators for disease outbreaks: filtering, cross-correlation, and caveats. *J. Am. Med. Informatics Assoc.* **14**, 76–85. (doi:10.1197/jamia.M2178)
- Braun, H., Christl, M., Rahmstorf, S., Ganopolski, A., Mangini, A., Kubatzki, C., Roth, K. & Kromer, B. 2005 Possible solar origin of the 1470-year glacial climate cycle demonstrated in a coupled model. *Nature* **438**, 208–211. (doi:10.1038/nature04121)
- Cazelles, B., Chavez, M., Bertheaux, D., Ménard, F., Vik, J. O., Jenouvrier, S. & Stenseth, N. C. 2008 Wavelet analysis of ecological time series. *Oecologia* **156**, 287–304. (doi:10.1007/s00442-008-0993-2)
- Chen, J. 1936 Outbreaks of locusts recorded in Chinese literatures. *Bull. Zhejiang Entomol. Bureau* **5**, 188–241.
- Chen, G. Y. 1939 *China successive natural and manmade disasters table*. Guangzhou, China: Jinan University Book Series.
- Cowie, J. 1998 *Climate and human change: disaster or opportunity?* New York, NY: Parthenon Pub. Group.
- Ding, H. 2007 *Large-scale immigration in history*. Beijing, China: China Development Press.
- ECCMH 2002 *Tabulation of wars in ancient China*. Beijing, China: People's Liberation Army.
- Fang, J. & Liu, G. 1992 Relationship between climatic change and the nomadic southward migrations in eastern Asia during historical times. *Clim. Change* **22**, 151–168. (doi:10.1007/BF00142964)
- Friis-Christensen, E. & Lassen, K. 1999 Length of the solar cycle: an indicator of solar activity closely associated with climate. *Science* **254**, 698–700. (doi:10.1126/science.254.5032.698)
- Gong, G., Ge, Q. & Xu, K. 1996 Influence of climatic changes on agriculture. In *Historical climatic changes in China* (ed. P. Zhang), pp. 406–425. Jinan, China: Shandong Science and Technology Press.
- Hinsch, B. 1998 Climate change and history in China. *J. Asia History* **22**, 131–159.
- Hsu, K. J. 1998 Sun, climate, hunger, and mass migration. *Sci. China Ser. D-Earth Sciences* **41**, 449–472. (doi:10.1007/BF02877737)
- IPCC 2007 Fourth assessment report on climate change 2007: synthesis report. Geneva, Switzerland: Intergovernmental Panel on Climate Change.
- Lean, J. 2002 Solar forcing of climate change in recent millennia. In *Climate development and history of the North Atlantic realm* (eds G. Wefer, W. H. Berger, K.-E. Behre & E. Jansen), pp. 75–88. Berlin, Germany: Springer.
- Ma, S. J. 1958 The population dynamics of the oriental migratory locust (*Locusta migratoria manilensis* Meyen) in China. *Acta Entomologica Sinica* **8**, 1–40.
- Mann, M. E. & Jones, P. D. 2003 Global surface temperatures over the past two millennia. *Geophys. Res. Lett.* **30**, 1820. (doi:10.1029/2003GL017814)
- Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B. & Running, S. W. 2003 Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **300**, 1560–1563. (doi:10.1126/science.1082750)
- Peng, X. W. 1965 *History of Chinese currency*. Shanghai, China: Shanghai People's Press.

- Peng, X. W. 2007 *History of Chinese currency*. Shanghai, China: Shanghai People's Press.
- Perry, C. A. & Hsu, K. J. 2000 Geophysical, archaeological, and historical evidence support a solar-output model for climate change. *Proc. Natl Acad. Sci. USA* **97**, 12 433–12 438. (doi:10.1073/pnas.230423297)
- Ren, M. E. 2004 The effect of climate changes on political, economic and social development in east China since holocene. *Adv. Earth Sci.* **19**, 695–698.
- Shumway, R. H. & Stoffer, D. S. 2000 *Time series analysis and its applications*. New York, NY: Springer.
- Singer, S. F. & Avery, D. T. 2007 *Unstoppable global warming: every 1,500 years*. Lanham, MD: Rowman and Littlefield Publishing Group.
- Stige, L. C., Chan, K. S., Zhang, Z. B., Frank, D. & Stenseth, N. C. 2007 Thousand-year-long Chinese time series reveals climatic forcing of decadal locust dynamics. *Proc. Natl Acad. Sci. USA* **104**, 16 188–16 193. (doi:10.1073/pnas.0706813104)
- Tan, M., Liu, T., Hou, J., Qin, X., Zhang, H. & Li, T. 2003 Cyclic rapid warming on centennial scale revealed by a 2650-year stalagmite record of warm season temperature. *Geophys. Res. Lett.* **30**, 1617. (doi:10.1029/2003gl017352)
- Wang, H. C. 1996 The relationship between the southern migrations of north nomadic tribes and climate change in China. *Scient. Geogr. Sinica* **16**, 274–279.
- Yancheva, G. *et al.* 2007 Influence of the intertropical convergence zone on the East Asian monsoon. *Nature* **445**, 74–77. (doi:10.1038/nature05431)
- Yang, B., Braeuning, A., Johnson, K. R. & Shi, Y. F. 2002 General characteristics of temperature variation in China during the last two millennia. *Geophys. Res. Lett.* **29**, 38–42.
- Zhang, D. & Lu, L. H. 2007 Anti-correlation of summer/winter monsoons? *Nature* **450**, E7–E8. (doi:10.1038/nature06338)
- Zhang, D., Jim, C. Y., Lin, C. S., He, Y. Q. & Lee, F. 2005 Climate change, social unrest and dynastic transition in ancient China. *Chinese Sci. Bull.* **50**, 137–144.
- Zhang, D. D., Brecke, P., Lee, H. F., He, Y. Q. & Zhang, J. 2007a Global climate change, war, and population decline in recent human history. *Proc. Natl Acad. Sci. USA* **104**, 19 214–19 219. (doi:10.1073/pnas.0703073104)
- Zhang, D. D., Zhang, J., Lee, H. F. & He, Y. 2007b Climate change and war frequency in eastern China over last millennium. *Hum. Ecol.* **35**, 403–414. (doi:10.1007/s10745-007-9115-8)
- Zhang, P. Z. *et al.* 2008 A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science* **322**, 940–942. (doi:10.1126/science.1163965)
- Zhang, Z. B., Cazelles, B., Tian, H. D., Stige, L. C., Brauning, A. & Stenseth, N. C. 2009 Periodic temperature-associated drought/flood drives locust plagues in China. *Proc. R. Soc. B* **276**, 823–831. (doi:10.1098/rspb.2008.1284)