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RESEARCH PAPER

The pulse of imperial China: a quantitative analysis of long-term geopolitical and climatic cycles

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ABSTRACT

Aim The long-term cyclical patterns of China's geopolitical shifts are of great interest to scholars and the public, but to date there has been no satisfactory explanation for the alternating occupancy patterns of the country's pastoral and agrarian polities. We fill this gap by differentiating the agroecological settings of these polities over time and quantitatively analysing the relationships between climate change and historical geopolitical variations.

Location China.

Methods Our dataset comprised 38 palaeohydroclimate reconstructions, the historical boundaries of China's empire and the changes in its size, and 1028 wars and 2737 battle locations over the past 2300 years. China-wide precipitation during the period was reconstructed using the 'weighted composite plus scale' method. Time-series analyses were performed to identify the strength of the associations between climate change and the geopolitical variables. Granger causality analysis and wavelet analysis were performed to verify the hypothesized causal links. Wavelet analysis was also used to identify the possible interactions (i.e. frequencies, significance, consistency and synchrony) between the signal components of the climatic and geopolitical variables at different temporal scales.

Results China's mean precipitation fell into three multicentennial cycles. The geopolitical variables corresponded to those cycles in the imperial era. The spatial–temporal frequencies of the boundaries and size of the agriculturalist empires and its frontiers with pastoralist empires were regulated by the long-term (low-frequency) precipitation fluctuations at the multicentennial scale. Wars of aggression were an important explanatory factor driving the land-occupancy patterns of the two ecoempires under climate change, and caused most of the territorial shifts. Short-term (high-frequency) geopolitical changes were not associated with climate change.

Main conclusions Precipitation-induced ecological change was an important factor governing the macrogeopolitical cycles in imperial China. Long-term territorial expansion favoured the polity (agriculturalist or pastoralist) that was better adapted to the changing ecological conditions in the country's heartland.

Keywords

Agroecology, climate change, geopolitical boundary, granger causality analysis, empire size, imperial China, precipitation, war, wavelet analysis.

INTRODUCTION

There are different schools of thought within the Western social sciences, especially political science, concerning the causes of the territorial changes and shifts in political power throughout human history (Huntington, 1996; Kearns, 2009). The topic has, however, rarely been analysed quantitatively and the relationship between ecological change and geopolitical shifts has never been examined. The long-term geopolitical cycles in China have attracted considerable attention from academia and the general public, but their cause remains unknown. For centuries after China's first emperor took the throne in 221 BC, nomadic tribes in the country's northern marginal areas launched regular large-scale attacks on its agricultural heartland and established empires that lasted hundreds of years ('*Yin* periods'). The agriculturalists (primarily the Han people) in China's heartland usually overthrew those empires after 200 to 300 years, replacing them with their own agriculturalist empires ('*Yang* periods'; Ledyard, 1983). Lee (1933) identified three multicentennial geopolitical cycles in imperial China, all of which were characterized by similar patterns of warfare, national development and cultural change.

Temperature and precipitation generally decrease from the south to the north of China. During the imperial period, pastoralists and agriculturalists were nurtured by two ecosystems separated by the Great Wall, which the agriculturalists built along a natural divide between the two ecosystems. The Great Wall served as the political boundary between the pastoral and agrarian polities during the Qin–Han (221–207 BC and 202 BC – AD 220), Sui (AD 581–619) and Ming (AD 1368–1644) dynasties, when the *Yang* periods started. Under 'normal' climatic conditions, the agriculturalists planted wheat and millet in the semi-wet, cool northern China ('wheat/millet China') and rice in the wet, warm southern China ('rice China'). Under the same conditions, the pastoralists reared animals in the semi-arid and arid areas further north ('pastoral China') (Fig. 1). In pastoral and wheat/millet China, bioproductivity was primarily governed by precipitation (Begzsuren *et al.*, 2004; Sternberg, 2008), whereas the multicropping system in rice China was sustained by temperature (Zhang *et al.*, 2007). Historical records indicate that, when the level of humidity declined (through a reduction in rainfall of up to 30%–40%), the pastoral area north of the Great Wall underwent desertification. The large farming area south of it degraded into a pastoral area, allowing the pastoralists to move south. When the humidity increased, a substantial portion of the pastoral area north of the Great Wall became arable land again (Fang & Liu, 1992). The south–north shift in the pastoral–agricultural boundary covered 7.5° (from 41.5° to 34° N) under climate change (Ge *et al.*, 2013). The observed long-term agroecological changes reflect variations in precipitation and temperature during China's long history.

Chang (1946) posited that the Chinese climate has expressed itself explicitly in the landscape, modes of human occupancy and livelihoods, and has had far-reaching and persistent historical consequences. It has also been shown theoretically that conflicts over land occupancy between pastoralists and agriculturalists constitute a struggle between two ecosystems (Hinsch, 1988) and that these conflicts are more likely to occur during dry periods (Bai & Kung, 2011). We hypothesized that change in climate (precipitation and temperature) altered the agroecological landscape and people's livelihoods in imperial China and led to geographical shifts and changes in human occupancy modes that were represented by the shrinking and expansion of two ecology-based polities: pastoralist and

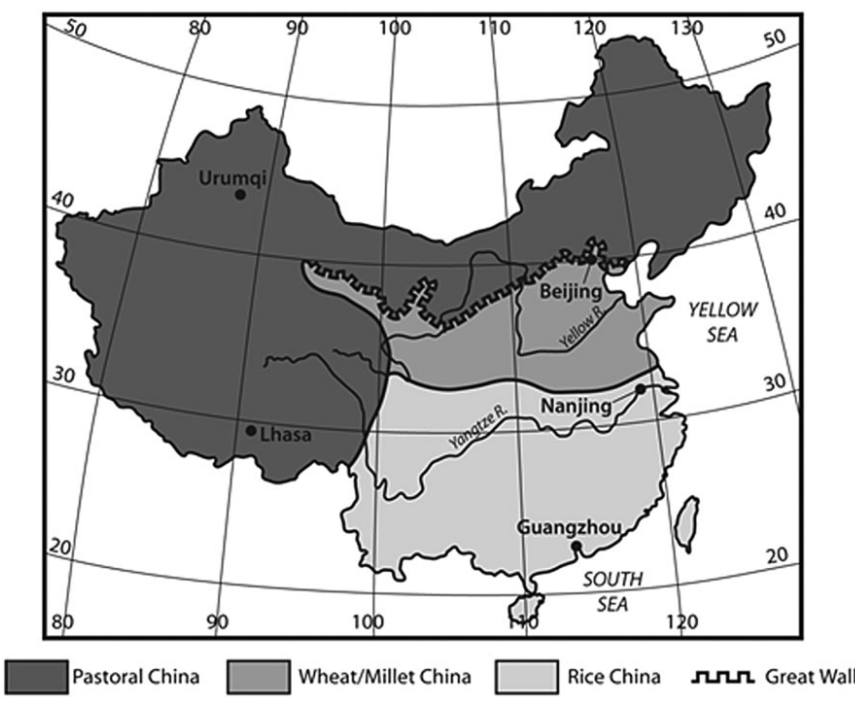

Figure 1 The three agro-ecological zones in imperial China. The boundaries between the zones shifted north and south under climate change (Zhao, 1986).

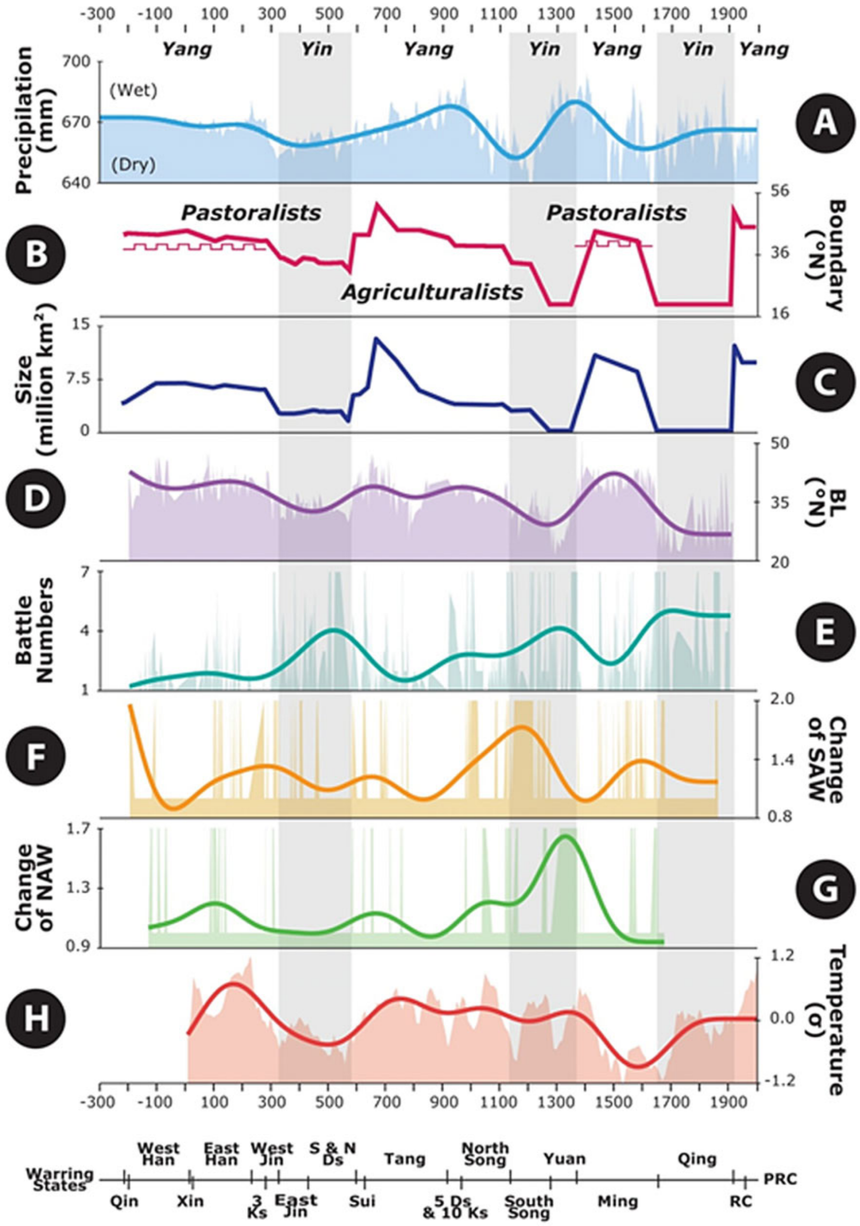

Figure 2 Climate and the geopolitical cycles of imperial China. (A) Reconstructed PRECIPITATION index of China, 300 BC – AD 2000; (B) BOUDARY, 220 BC – AD 2000; (C) SIZE, 220 BC – AD 2000; (D) BL, 200 BC – AD 1911; (E) BN, 200 BC – AD 1911; (F) change in SAW, 200 BC – AD 1867; G. Change in NAW, 133 BC – AD 1675; (H) TEMPERATURE, AD 1–1990. The bold lines in panels (A) and (D–H) represent the 300-yr low-pass filtered results. *Yin* periods mean the time when nomadic tribes established empires on the agricultural heartland; *Yang* periods represent the time that agriculturalists (primarily the Han people) occupied the agricultural heartland. Grey shading marks the *Yin* periods. The wall symbol indicates the average latitude of the Qin–Han and Ming Great Wall.

agriculturalist. Because humidity change played an important role in the agroecological changes in the northern part of China (pastoral and wheat/millet China), the country's geopolitical shifts should exhibit a cyclical pattern: the agriculturalist empires expanding northwards in wetter periods and the pastoralist empires extending their territories to the south during dry periods, in line with the adaptive capacities of the two polities to different climates.

To quantitatively explore the relationship between climate change and geopolitical shifts, it was necessary to explore the connection between the climate and the spatial extent of the pastoralist and agriculturalist polities at different temporal and spatial scales. As the alternating dominance of the pastoralist and agriculturalist empires during the imperial period was often manifested in political actions such as wars of aggression, the interactions between climate, political action (war) and geopolitical change throughout Chinese history were expected to reveal the relative importance of the two hypothesized key factors, ecological change and political action, in determining the country's geopolitical shifts.

METHODS AND MATERIALS

Datasets

Geopolitical change was represented by the mean latitudinal shift in the political boundary between the agriculturalist and pastoralist polities at 110–120° E (BOUNDARY, Fig. 2B) and by the size of the agriculturalist polity's territory from 221 BC to AD 2000 (SIZE, Fig. 2C), obtained from three major atlases of historical geography. The resolutions for the BOUNDARY and SIZE time series were at the centennial scale. We used the battlefield latitudes of 2737 battles (BL, Fig. 2D) that took place between the agriculturalists and pastoralists between 200 BC and AD 1911 (Editorial Committee of Chinese Military History, 1985) to illustrate the annual variations in the geopolitical boundary. The time series of the number of battles (BN, Fig. 2E) between the two polities was included to reflect the magnitude of change in armed conflict in the study period. The wars were further divided into southward wars of aggression by the pastoralists (SAW, Fig. 2F) and northward wars of aggression by the agriculturalists (NAW, Fig. 2G).

Climate datasets and palaeoprecipitation reconstruction

Owing to the absence of China-wide palaeoprecipitation data, 38 documentary-based single-proxy hydroclimate reconstructions at annual resolution were synthesized. The 'composite plus scale' method (Mann *et al.*, 2008) was used to reconstruct a multiproxy precipitation series for China from 300 BC onwards (PRECIPITATION, Fig. 2A). Temperature changes were obtained from a recent reconstruction (Yang *et al.*, 2002) and presented in a China-wide, multiproxy temperature series spanning AD 1–1990 (TEMPERATURE, Fig. 2H).

Verification of the hypothesized links

All of the above time series and their associations were tested using correlation and regression analyses. A higher level of quantitative association was explored using Granger causality and wavelet analyses, giving explicit, precise results. Granger causality analysis is based on the principle that a cause happens prior to an effect and that a cause makes unique changes to the effect (Granger, 1980). Wavelet analysis uncovers the characteristics of a data series with joint time and frequency domains. The coherence between two time series has been used to provide confidence in causal relationships in complex systems (Cazelles *et al.*, 2008). All of the results gleaned from these quantitative tests were combined to estimate the strength of the proposed associations between climate change and the geopolitical cycles. (See Supporting Information for more detailed explanations of the methods used.)

RESULTS

Association between climate and geopolitical change

The reconstructed PRECIPITATION was significantly correlated with the time series of solar insolation (Steinhilber *et al.*, 2012), Asian monsoon (Wang *et al.*, 2005; Cosford *et al.*, 2009; Dong *et al.*, 2010) and Chinese historical lake reclamation (Fang, 1993; see Supporting Information). The correlations varied at different time-scales covering the past 2300 years (Fig. 2A). Although the decadal change was irregular and obscure, three multicentennial wet–dry cycles were easily identified. Dry periods, defined as precipitation below the average value recorded over the period AD 1800–2000, occurred in AD 250–600, AD 1050–1250 and AD 1500–1700. The reconstruction was compared with instrumental records from the Climate Research Unit. The two time series were found to be significantly correlated at annual resolution ($r^2 = 0.440$; $P < 0.01$) and at decadal resolution ($r^2 = 0.617$; $P < 0.01$) from AD 1951 to AD 2000, the period covered by both time series (see Fig. S2). This reconstruction represented low-frequency changes in precipitation and was similar to the previous frequency estimation of 600–800 years (Lu, 1991). The long cycles can be attributed to shifts in large-scale atmospheric circulation (Pauling *et al.*, 2006; Neukom *et al.*, 2010).

BOUNDARY, SIZE, BL, BN and SAW corresponded very closely to the fluctuations in PRECIPITATION, but with different time-lags. They all exhibited similar frequencies at the multicentennial scale and exhibited the three *Yin–Yang* cycles (Fig. 2). All of the cross-correlation coefficients were significant, except between TEMPERATURE and NAW (Table S1a). The regression results also indicated that the geographical (BOUNDARY, SIZE and BL) and political variables (BN and SAW) were significantly dependent on PRECIPITATION, and that the geographical variables (SIZE and BL) were significantly dependent on the political variables SAW and NAW (Table S1b,d,e). Changes in PRECIPITATION were followed by latitudinal shifts in BOUNDARY, agriculturalist empire size (SIZE) and latitudinal shifts in BL (Fig. 2B–D). Although the TEMPERATURE frequency differed from the frequencies of the geographical and political variables, the associations between TEMPERATURE and BOUNDARY, SIZE, BL, BN and SAW were found to be statistically significant in the correlation and regression analyses (Fig. 2H; Table S1a,c). TEMPERATURE thus also played a role in triggering geopolitical shifts and warfare. NAW was significantly correlated with PRECIPITATION, but not with TEMPERATURE (Table S1a–c).

Granger causality analysis was performed to verify whether climate change occurred prior to the geopolitical shifts and caused unique changes in the geopolitical variables (Granger, 2001). Null hypotheses were rejected at the 90% significance level for the effect of PRECIPITATION on BOUNDARY, SIZE, BL, SAW and NAW, and of each of SAW and NAW on SIZE and BL (Table 1). We concluded that PRECIPITATION Granger-caused the southward and northward shifts in the geopolitical boundary of the agriculturist empire, the changes in the size of its territory, and the southward and northward wars of both polities in imperial China. The southward and northward aggressions of both polities also Granger-caused SIZE and BL. However, none of the null hypotheses involving TEMPERATURE could be rejected. Thus, TEMPERATURE did not Granger-cause the geopolitical and precipitation changes, although the corresponding paired correlations and regressions were established.

Despite the established statistical causal links between the climatic and geopolitical variables, the r^2 values in the regression tests were low for the paired variables (Table S2b–e), indicating that the linear regression models explained less of the variability in the response data around their means during the long history. The details of the frequency and time-domains of the variables

Table 1 Granger causality analysis of the relationships between the climate, geographical, and political variables.

Hypothesized causal links (null hypothesis)	*F*	*P*	*n*
PRECIPITATION does not Granger-cause BOUNDARY†	4.180	0.000**	2221
PRECIPITATION does not Granger-cause SIZE†	6.114	0.000**	2221
PRECIPITATION does not Granger-cause BL†	1.627	0.033*	2112
PRECIPITATION does not Granger-cause BN†	2.211	0.001**	2112
PRECIPITATION does not Granger-cause SAW†	2.457	0.017*	2068
PRECIPITATION does not Granger-cause NAW†	2.629	0.007**	1809
TEMPERATURE does not Granger-cause PRECIPITATION†	0.880	0.631	1991
TEMPERATURE does not Granger-cause BOUNDARY‡	1.187	0.239	1991
TEMPERATURE does not Granger-cause SIZE†	0.811	0.732	1991
TEMPERATURE does not Granger-cause BL†	0.917	0.544	1912
TEMPERATURE does not Granger-cause BN†	0.964	0.485	1912
TEMPERATURE does not Granger-cause SAW†	0.577	0.775	1868
TEMPERATURE does not Granger-cause NAW†	0.332	0.954	1676
SAW does not Granger-cause SIZE†	1.706	0.029*	2068
SAW does not Granger-cause BL†	2.754	0.000**	2068
NAW does not Granger-cause SIZE†	1.830	0.016*	1809
NAW does not Granger-cause BL†	2.852	0.000**	1809

$^{**}P < 0.01$; $^{*}P < 0.05$.
†No differencing.
‡First-level differencing.
The shaded rows indicate pairs that did not pass the Granger causality test. The differencing was used to transform the time series into stationary series (Ahmad & Harnhirun, 1996), using $DY_t = Y_t - Y_{t-1}$.

and their coherence were examined to identify when and at what time-scale climate change exerted an effect on the geopolitical variables.

Frequency bands and coherence of the climate and geopolitical variables

The interactions between the features of the variables (including their frequencies, significances, consistencies and synchronies) at different temporal scales were explored. They were decomposed into time and frequency domains using wavelet analysis. A testing frequency band of 20–1000 yr was used for the continuous wavelet power spectrum. The spectrum analysis results revealed a consistent and significant frequency band for PRECIPITATION, BOUNDARY, SIZE, BL, BN and SAW at approximately 800 yr throughout the tested period (Fig. 3A–F). A second common frequency band at approximately 400 yr appeared over AD 560–2000 for PRECIPITATION, AD 900–2000 for BOUNDARY, AD 700–2000 for SIZE, 200 BC – AD 2000 for BL, 200 BC – AD 700 and AD 1400–2000 for BN, and AD 400–1800 for SAW. There was also a significant 200-yr band over AD 500–2000 for BL and over AD 800–1400 for SAW. There was some high-frequency noise around the 100-yr and 300-yr bands for BN and SAW and the 150-yr and 250-yr bands for PRECIPITATION, in various periods. NAW and TEMPERATURE differed from the other variables: NAW's dominant band was around 300 yr (Fig. 3G) and TEMPERATURE's dominant bands were around 200 yr and 1000 yr (Fig. 3H).

BL displayed a very high degree of data resolution at the annual scale and was the most precise variable for measuring the political boundary changes. The lack of any significant spectrum in the high-frequency bands (< 200 yr) across the whole period (Fig. 3D) for BL implies a consistent, long-term/low-frequency, and large rhythmic process behind the geopolitical movements observed in the imperial era. It also implies that the short-term/high-frequency variations in the geopolitical movements were random, irregular (as the frequency bands below 200 yr were neither strong nor continuous for certain periods of time) and over short distances. BL, BN and SAW had 200-yr bands and some noise at higher frequencies, indicating that TEMPERATURE (with a 200-yr band) and other processes were involved.

Five of the variables (BOUNDARY, SIZE, BL, BN and SAW) had the same major periodic bands as PRECIPITATION, indicating very strong links between them. These links also passed the Granger causality test (Table 1). We used wavelet coherence analysis to examine their frequency-band coherence with PRECIPITATION and the statistical causal relationships in the frequency domain (Fig. 4). The analysis was also used to test the rest of the links between the variables (Fig. S1). Because PRECIPITATION was negatively associated with BN and SAW, BN and SAW were reversed before the coherence analysis. The decomposed rhythmic associations between PRECIPITATION and all of the geopolitical variables were extremely strong in the *c.* 800-yr band over the entire period (Fig. 4: A1, B1, C1, D1 and E1). Their coherences in the *c.* 400-yr band were also strong in some periods: AD 800–1700 for PRECIPITATION/BOUNDARY; AD 900–1800 for PRECIPITATION/SIZE; AD 800–1910 for PRECIPITATION/BL; AD 900–1500 for PRECIPITATION/BN; and AD 800–1600 for PRECIPITATION/SAW. These results indicate that changes in the political territory and armed battles were highly sensitive to precipitation changes in the long-term. The phases of BOUNDARY, SIZE, BL and BN, which can be treated as cycles, followed the changes in PRECIPITATION precisely in the 780–820-yr bands throughout the imperial era (Fig. 4: A2, B2, C2 and D2; Table 2) at the 90% significance level. The phase synchronicity of PRECIPITATION/SAW, however, was not significant (Fig. 4: E2; Table 2). The phase synchronicities of PRECIPITATION/NAW, SAW/BL and SAW/SIZE in the 780–820-yr bands were not significant (Table 2, Fig. S1), demonstrating that the movements of SAW and NAW were only slightly affected by other factors and did not fully govern

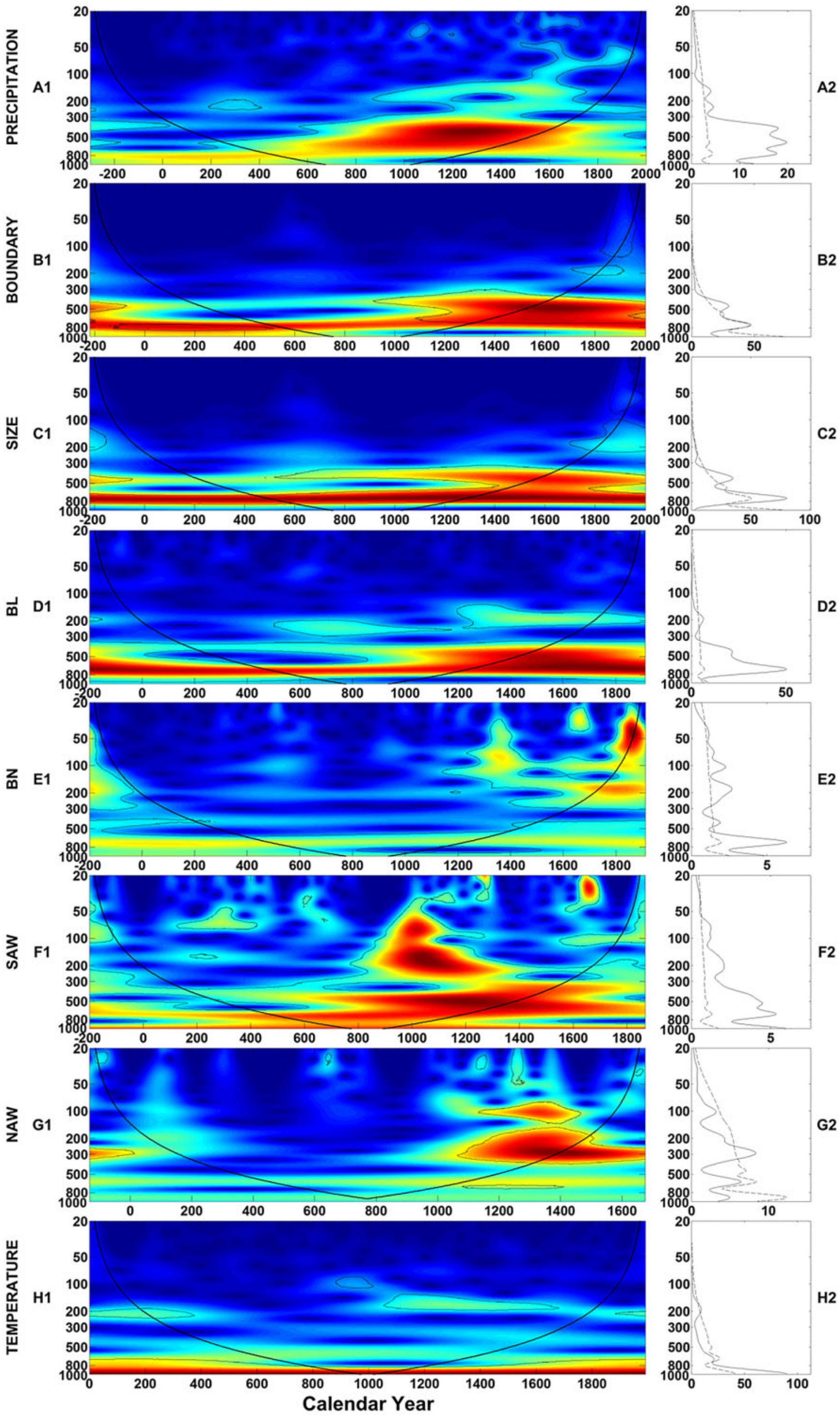

Figure 3 The continuous wavelet power spectra of environmental and political variables in China over various periods: (A1, A2) PRECIPITATION, 300 BC – AD 2000; (B1, B2) BOUNDARY, 220 BC – AD 2000; (C1, C2) SIZE, 220 BC – AD 2000; (D1, D2) BL, 200 BC – AD 1911; (E1, E2) BN, 200 BC – AD 1911; (F1, F2) SAW, 200 BC – AD 1867; (G1, G2) NAW, 133 BC – AD 1675; and (H1, H2) TEMPERATURE, AD 1–1990. The left-hand panels indicate the 20–1000-yr frequency bands on the vertical axis and the frequency distribution in the study period (calendar year) on the horizontal axis. In the left-hand panels, the spectra values vary from dark blue, indicating low values, to dark red, indicating high values. The cone of influence, which indicates the region affected by edge effects, is shown with a black line. The right panels indicate the average strengths of the wavelet power spectra. The solid lines show the power strength of each variable in the 20–1000-yr frequency bands. The horizontal axis implies the degree of power strength. The dashed lines represent the computed 95% (0.05) significance level.

the geopolitical changes. The significant 200-yr band of TEMPERATURE was only associated with BN, BL and SAW in the scattering of the short time duration (Fig. S1), implying that the conflicts between the two polities were associated with temperature change to some extent. The lack of continuous coherence in the high-frequency bands (< 200 yr) between the climate and geopolitical variables implied that climate change was not an important driving force of the short-term geopolitical shifts and that the shifts may have been controlled by other forces. This also explained why the r^2 values in the precipitation/geopolitical variables regression tests were low (Table S1b–e).

DISCUSSION

The results of all quantitative tests were combined to illustrate the strength of the suggested links between the variables (Table 3).

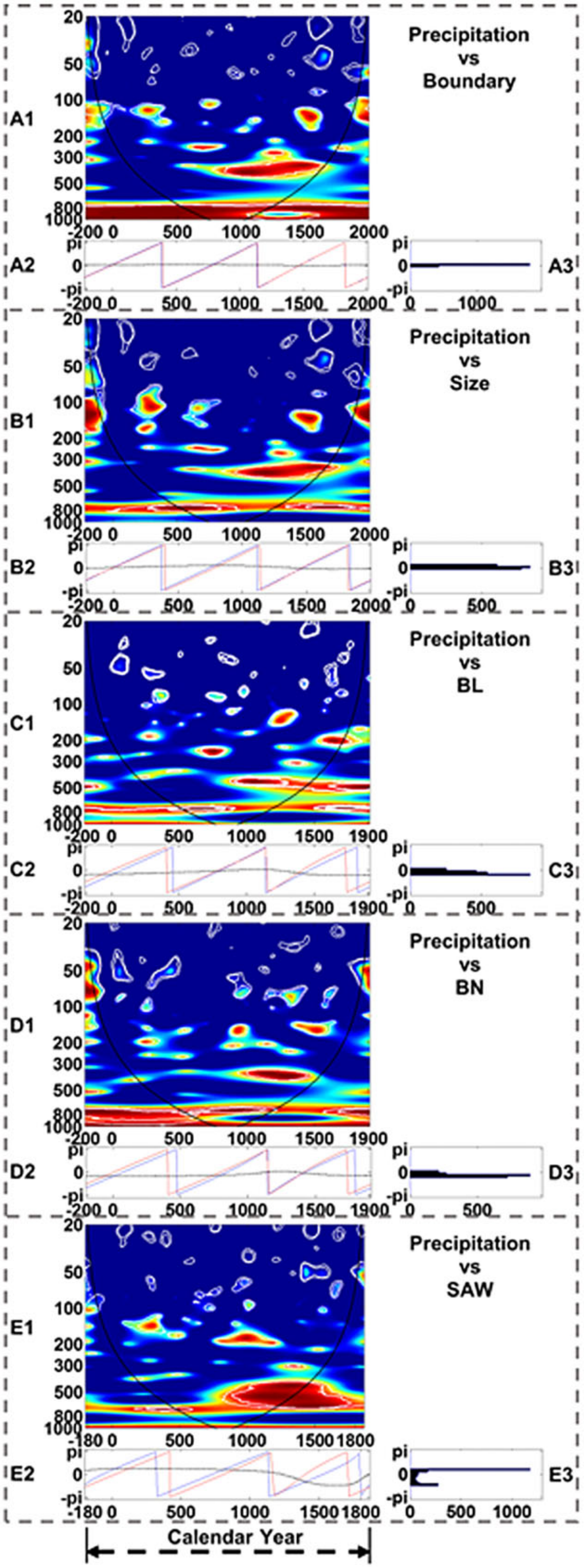

Figure 4 Wavelet coherence between variables in imperial China: (A1–A3) PRECIPITATION and BOUNDARY; (B1–B3) PRECIPITATION and SIZE; (C1–C3) PRECIPITATION and BL; (D1–D3) PRECIPITATION and BN; and (E1–E3) PRECIPITATION and SAW. A1, B1, C1, D1 and E1 were computed in 20–1000-yr frequency bands, shown on the vertical axis, and the coherency distribution in the study period (calendar year) shown on the horizontal axis. The coherence values are colour-coded from dark blue (low values) to dark red (high values). The cone of influence, which indicates the region affected by edge effects, is shown with a black line. The solid contour line in white represents the 90% (0.1) significance level. The phase relationships between PRECIPITATION and the corresponding geopolitical variables were computed in 780–820-yr frequency bands, as shown in A2, B2, C2, D2 and E2. The red line represents the phase of PRECIPITATION and the blue lines represent the phase of the corresponding geopolitical variables. The horizontal black lines represent the phase differences (cycle differences) in 780–820-yr frequency bands. The smaller the phase (cycle) difference, the closer the black line is to zero. The distribution of the phase differences between PRECIPITATION and the corresponding geopolitical variables in the 780–820-yr frequency bands are shown in A3, B3, C3, D3 and E3. The phase differences in A3, B3, C3 and D3 are significant at the 90% (0.1) level (Table 2).

Table 2 Phase difference for the coherency of the 780–820-yr bands.

Variables	Coherency
PRECIPITATION and BOUNDARY	0.016***
PRECIPITATION and SIZE	0.098*
PRECIPITATION and BL	0.096*
PRECIPITATION and BN	0.090*
PRECIPITATION and SAW	0.146
PRECIPITATION and NAW	0.936
SAW and BL	0.394
SAW and SIZE	0.398

***$P < 0.01$; *$P < 0.1$.

Climate change and the territorial shifts of the two polities

The statistical results of the multicentennial relationship between precipitation change and the geographical variables (Table 3) suggest a new explanation for the macrohistory of imperial China. Gradual drying triggered more armed conflicts between the pastoral and agrarian polities, and the number of battles and level of southward nomadic aggression both peaked in the driest periods (Table 3: 'very strong' and 'strong' links). The nomadic tribes moved south and conquered China's heartland (*Yin* period). In the first *Yin* period, pastoralists (known as the Five Barbarians) moved south and conquered all of wheat/millet China, down to the northern banks of the Yangtze River (35° N), forcing the agriculturalist emperor to move to rice China. In the second and third *Yin* periods, the later pastoralists

Table 3 Strength of the hypothesized links between paired variables in the climate and geopolitical system. See Table 1 for sample sizes.

First variable	Second variable	Strength of link*
PRECIPITATION	BOUNDARY	very strong
PRECIPITATION	SIZE	very strong
PRECIPITATION	BL	very strong
PRECIPITATION	BN	very strong
PRECIPITATION	SAW	strong
SAW	SIZE	strong
SAW	BL	strong
PRECIPITATION	NAW	moderate
TEMPERATURE	BL	moderate
TEMPERATURE	BN	moderate
TEMPERATURE	SAW	moderate
NAW	SIZE	moderate
NAW	BL	moderate
TEMPERATURE	BOUNDARY	weak
TEMPERATURE	SIZE	weak
TEMPERATURE	NAW	unlikely

*Very strong, passed all of the quantitative tests; strong, significant in the correlation and regression analyses, passed the Granger causality test or has similar major frequency bands, significant in the band coherency; moderate, significant in the correlation and regression analyses, passed the Granger causality test or has similar major frequency bands; weak, only significant in the correlation and regression analyses; unlikely, failed all tests.

(the Jin, Mongol and Manchu) moved further south, taking over all of rice China. When the humidity levels increased, the agriculturalists moved north and occupied a substantial portion of the former pastoral lands at higher latitudes.

The very strongly linked multicentennial changes in the precipitation and the geographical variables of the two polities, (BOUNDARY, SIZE and BL; Table 3) reveal that precipitation-induced ecological change was the major driving force behind the macrogeopolitical shifts in imperial China. The directions of these shifts imply that the changes in the two polities' territories favoured whichever polity could better adapt to the ecological conditions of the time. Thus, the geopolitical shifts were actually ecopolitical changes. The results also indicate that the long-term changes (> 200 yr) in the frontier (BL) between the two polities were primarily controlled by precipitation-induced ecological change, rather than an artificial political boundary (i.e. the Great Wall). Temperature changes also exerted some influence on the geopolitical shifts and struggles between the two polities, although that influence was apparent only in the higher frequencies (e.g. the 200-yr band) of BN, BL and SAW in some periods. Temperature was only weakly or moderately linked with the territorial changes and armed conflicts (Table 3).

Adaptive choices, war and geopolitical change in the face of ecological change

There were two ways in which the pastoralist and agriculturalist polities could adapt to climate-induced ecological stress, cultural adaptation *in situ* or migration. Their choices for cultural adaptation were to improve their social institutions and technology and/or transform their economy. Cultural adaptation is a painful and time-consuming process for any society and takes several decades to even thousands of years to accomplish (Burton *et al*., 1993). Migration, in contrast, is an instant way of adapting to ecological stress, although mass migration to an occupied territory usually involves warfare. War is a means for states to acquire (or maintain) better areas for settlement (Reiter, 2003). The victorious side in a war is not required to make significant cultural changes. Armed conflicts between the two polities (BN and SAW) were strongly or very strongly linked with PRECIPIATION. As the results demonstrate, war was a common means of expanding territory for both polities in the face of climate change, particularly for the pastoralists in dry periods.

The links between PRECIPITATION and the war variables (BN, SAW and NAW) were weaker than the links between PRECIPITATION and the geographical variables (BOUNDARY, SIZE and BL) (Table 3). There was some noise in the high-frequency (< 200 yr) bands for the war variables, implying that factors other than PRECIPITATION were also responsible for the outbreaks of armed conflict between the polities. The strength of the links between the geographical and war variables were weaker than those between PRECIPITATION and the geographical variables, in particular the links between NAW and the geographical variables (Table 3). This comparison suggests that a proportion of the geopolitical shifts were not the result of war, but were the result of the peaceful retreat and advance of both polities when the ecological conditions improved (i.e. became wetter).

Different responses to climate change by the two polities

The strong link between PRECIPITATION and SAW (Table 3) demonstrates that SAW was a major adaptive choice for the pastoralist polity in a drying climate. With more SAW, BL moved south and SIZE shrank (strongly linked). SAW, therefore, was a major force that directly changed the macrogeopolitical distribution in the Chinese imperial era. NAW was less frequent than SAW (46.6% of SAW) and often occurred in the wetter periods. NAW was only weakly linked with PRECIPITATION and moderately linked with the geopolitical variables (Table 3). The dissimilarity in the polities' responses to climate change may be attributable to the differences in their ecological vulnerability, cultures and geographical locations. A pastoral ecosystem is more vulnerable to climate change than an agricultural ecosystem because pastoral products cannot be stored and the limited biodiversity of pastoral areas confines their inhabitants to a life of following water and grasses.

In response to the climate-induced ecological deterioration of their land, the pastoralists in the dry, cold north had much a greater incentive to migrate south, because they were subject to both 'push' and 'pull' forces. The agriculturalists, in contrast, were subject only to 'push' forces, as the dry, cold north was not ideal for farming and the southern, western and eastern boundaries of the agriculturalist polity were blocked by the mountains and sea. In the wetter periods, some of the pastoral lands became suitable for farming and some of the deserts in the northern pastoral areas became grassland. The pastoral people could move north without any great loss in their livelihood, resulting in less conflict (NAW) for the agriculturalists' expansion.

Could the geopolitical changes have been driven by other internal factors? The aggressiveness of the imperial political system, low adaptive capacity of the preindustrial society, economic power and population in China may have been common necessary conditions responsible for the adaptive choices and consequent geopolitical shifts. However, the first two of these were not generally considered as variables in the imperial era. Furthermore, population changes and economic power have irregular cycles, ranging from multidecadal to multicentennial scales (Lee & Zhang, 2010; Su *et al.*, 2014). These factors, therefore, could not generate the macrogeopolitical cycles at the frequencies found here.

Statistical laws are considered important in interpreting historical laws based on many cases, but may not apply to every single case (Bunge, 2009). For example, in studying a single event of geopolitical change, many factors may be necessary but insufficient conditions of that change in a complex geopolitical system. This study differs from its predecessors in terms of both the temporal scale investigated and the hierarchies of reasoning or levels of quantitative association used. By decomposing China's imperial history into different time domains, we found that multicentennial geopolitical changes were associated with climate change, although short-term changes (< 200 yr) exhibited no rhythmic patterns. Short-term geopolitical changes may be associated with non-linear, irregular social and political changes (no continuous frequency). The results indicate that a geopolitical system, just like a complex ecological system (O'Neill *et al.*, 1989; Norton & Ulanowicz, 1992), can be governed by different factors at different spatial and temporal scales. When a selected factor has a characteristic time-scale that is adequate to the scale of the considered process and all of the other factors have significantly different time-scales, we can consider the selected factor the most likely one to be controlling the process (Korotayev *et al.*, 2006). The findings of this study, therefore, do not refute earlier theories about geopolitical shifts and the complexity of political change in history. The links established between climate change and geopolitical shifts are only the first step in the quantitative study of geopolitics. Finally, we must emphasize that the characteristics of this large-unit variation are not simple combinations of the attributes of small units, but demonstrate long-term common behaviour by the pastoral and agrarian polities under changing ecological conditions and thus represent a new theory of geopolitical change.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Appendix S1 Correlation and regression analysis.
Appendix S2 Additional wavelet coherence results.
Appendix S3 Further materials and methods.
Appendix S4 References

BIOSKETCH

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