



Spatiotemporal shifts of population and war under climate change in imperial China

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Received: 12 July 2020 / Accepted: 16 February 2021 / Published online: 6 March 2021
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Abstract

Studies on the spatiotemporal relationship between historical climate change and the patterns of population and war are rare. In this research, statistical methods (such as correlation test and Granger causality analysis) and visualization technique are applied to demonstrate how temperature, in terms of long-term trend and cyclic mode, fundamentally affects the temporal-spatial variations of population center and war center during imperial China (5–1911 CE). Results show that (1) the consistent southward migration of population center and war center overall accords with the macro-trend of temperature cooling over the last two millennia. (2) The extent of the outward expansion of the Chinese Empire is measured by the population center–war center distance that lengthens during warm periods but shortens in cold phases, which correspond to the north/west/northwestward advancement and south/east/eastward retreatment of war center, respectively, while population center moves within a small range. (3) The shift of population latitude precedes that of war latitude, indicating the change from ecological-demographic to social-political sphere in space. We suggest that similar to population center, the temperature-influenced ancient Hu Line, which symbolizes the disparity of population density in different regions of China, may shift by several hundred kilometers; latitudinal rather than longitudinal variations of population center and war center are more robust in history. We also find that precipitation controls war center and population center on the multicentennial scale, but not the scale focused upon in this study. These findings provide new insights and theoretical implications into the in-depth understanding of the nature–human nexus.

Keywords Climate change · Temporal-spatial pattern · Population center · War center · Imperial China

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1 Introduction

The nexus of climate change and human society in historical China has attracted considerable attention in academia over the past decade. Among the related research, topics about climate change and demographic dynamics (Zhang et al. 2007a; Lee et al. 2008, 2009, 2016; Lee and Zhang 2010, 2013; Lee 2014) as well as warfare have been widely investigated (Zhang et al. 2005, 2006, 2007a, b, 2015; Zhang and Lee 2010; Zhang et al. 2010; Bai and Kung 2011; Zheng et al. 2014; Chen 2015; Fang et al. 2015; Xiao et al. 2015; Zhang and Pei 2015; Liu et al. 2016; Liu et al. 2018). With sophisticated conceptual framework, robust logical system, and/or well-validated causality in these studies, climate cooling and economic downturn were deemed as the ultimate and direct cause of large-scale human crises in pre-industrial societies, respectively (Zhang et al. 2011a). However, such studies are predominantly carried out by time-series approaches, whereas the spatial patterns of population and war are seldom involved (Zhang 2000; Pan et al. 2013; Xu et al. 2015).

Until recent years have the spatial phenomena of population and war and their connections with climate change been partly explored. Specifically, Lee et al. (2009) looked into climate change and population distribution in China over the last millennium by adopting spatial statistics such as population ratio between North and South China, mean population center, and standard distance of population. Temperature rather than aridity thresholds was proved to be more influential. By calculating and depicting the moving track of the national population center of China from 2 to 1910 CE, Zhang and Zhang (2019) confirmed that the distributions of natural disasters (flood and drought) and their social impacts (famine, cannibalism, and war) were influenced by population on the provincial and decadal scales. As for climate change and the spatiality of war in ancient China, Zhang et al. (2015) and Zhang and Pei (2015) corroborated that geopolitical variables, such as the boundary between agricultural and nomadic regimes, size of agricultural empire, battle location, and the direction of war, were affected by multicentennial precipitation fluctuation. With the aid of spatial statistics such as standard deviational ellipse and emerging hot spot analysis, Zhang et al. (2020a, b) substantiated that the spatial disparities of war were fundamentally regulated by secular temperature variation via agricultural and pastoral productivity, and the war hot spots were preponderantly located in northern China (e.g., the Loess Plateau and the North China Plain) under warm and wet climate yet altered southeastward (e.g., the Jianghuai region and the lower reaches of the Yangtze River/Yangtze River Delta) in cold and dry conditions. Nonetheless, so far there is no publication regarding the spatial linkage of population and war, and the mechanism of climate change and the temporal-spatial pattern of them is still vague.

In order to relate population to war, we determine the centroids of population (commonly referred to as “population center” below) in China over the imperial age and the same for war (ibid, “war center”), and evaluate how these centroids move in relation to each other. However, except a few scholars who have attempted to quantify the long-term variation of population center on the national scale (Lee et al. 2009; Pan et al. 2013; Zhang and Zhang 2019), others have either literally described, or not focused on the nationwide pattern, or merely fixed the study period in modern times (Li 1983; Yuan and Guo 1998; Zhao and Fu 2001; Ma and Niu 2016; Yang et al. 2016). With respect to war center, only the related battle coordinates (i.e., battle longitude and battle latitude) have been investigated (Zhang et al. 2015; Zhang and Pei 2015; Pei et al. 2019). Therefore, looking from a spatiotemporally quantitative perspective, this study aims to fill the aforementioned research gaps by delving into the synchronous/asynchronous evolution of population center and war center, as well as their connections to

climatic variation in imperial China. Its significance is to better understand the spatiotemporal distribution and regularity of social phenomena and help figure out the mechanism between climatic impact and social response. Here we raise three research questions: (1) How are population center and war center governed by temperature/precipitation change in the long run and warm–cold/wet–dry cycles? (2) Whether the dynamic movement of population center (i.e., demographic change) precedes that of war center (i.e., social-political change), or vice versa? (3) Can the extent of the expansion of the Chinese Empire be quantified by the center feature of population and war? For facilitating these research questions, we hypothesize that on a long-term scale, climate change controls the spatial variation of population (proxy: population center) in vast land area of China, and the changed spatial distribution of population leads to the shift of human conflict locations (proxy: war center); additionally, warm and/or wet (cold and/or dry) climate triggers a north/west/northwestward (south/east/southeastward) migration of population center and war center, and the distance between population center and war center, which represents the outward expansion (inward contraction) of the Chinese Empire, becomes lengthened (shortened).

In the following contents, the centroids of population and war will be divided into two components: longitude and latitude, and the temperature series is divided into seven cycles for comparison (Section 2). For checking whether precipitation could have an effect, a nationwide sequence is referenced and divided into three cycles. Statistical methods, such as correlation and Granger causality analysis (GCA), and visualization technique, as well as the software used in this study are also introduced in this section. Results are shown in Section 3, which includes the temporal analysis of the relationship between climate change and population/war coordinates on the annual scale, and the spatiotemporal investigation between population center and war center during seven warm–cold cycles on the multidecadal–centennial scales and three wet–dry cycles on the multicentennial scale. Section 4 provides some discussions about the mechanism of temperature variation and the spatial pattern of population and war, supplemented by precipitation and other possible non-climatic factors, comprising the power balance between agriculturalists and pastoralists, the shift of political center, and government policy. Finally, according to the research findings, we make a few conclusions in Section 5.

2 Materials and methods

2.1 Geographical distribution of population in China

The distribution of population density could reflect the physical geographical conditions (mainly climate and landform) and human ecological settings (Fig. 1). The Heihe–Tengchong Line (also known as the “Hu Line”), proposed by the well-known Chinese geographer, Hu Huanyong, is connected by Heihe of Heilongjiang Province and Tengchong of Yunnan Province and divides China into two areas with contrasting population densities (Hu 1935). Decades later, based on 2010 national census data, a research carried out by Yang et al. (2016) showed that the distribution of population density in China is still unchanged. Although the southeastern part (warm and/or wet) remained populous most of the time in comparison with the ecological restriction and lower land carrying capacity of the northwest (cold and/or dry), this line was actually formed in recent hundreds of years after the abrupt climate change during the thirteenth century (Wang et al. 1995). Hence, the effect of climate on the spatial pattern of population should be crucial in ancient agrarian society.

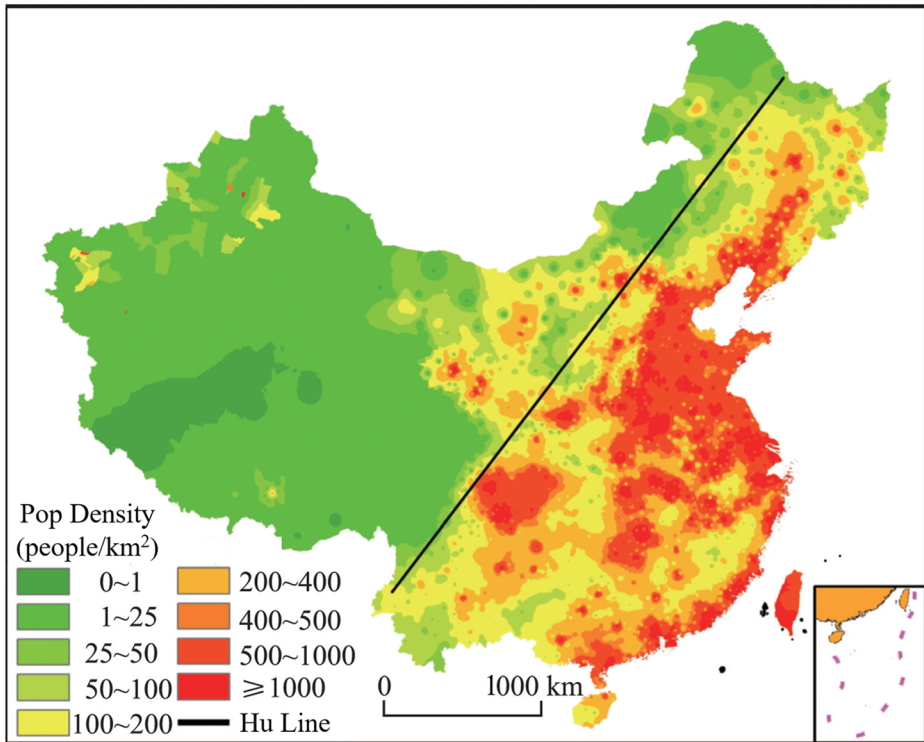


Fig. 1 Distribution of population density in China in 2010 (revised from Yang et al. 2016). The Hu Line is drawn in black

2.2 Data

Paleotemperature anomaly data, derived from Ge et al. (2013), were reconstructed by a partial least squares regression method based on multi-proxies (lake sediments, stalagmites, historical documents, tree rings, and ice cores) from five regions (northeast, central east, southeast, northwest, and the Tibetan Plateau) of China during 5–1995 CE. It was downloaded from the paleoclimatology dataset in National Oceanic and Atmospheric Administration’s National Centers for Environmental Information (<https://www.ncdc.noaa.gov/paleo/study/14548>). Due to the relatively coarse temporal resolution, the original data (decadal unit) were linearly interpolated into an annual sequence; then a 50-point fast Fourier transform (FFT) filter representing the 50-year variation was employed to obtain the same low-frequency signal as in Ge et al. (2013). Based on the long-term series, seven warm (W)–cold (C) cycles were divided according to the criteria introduced in Zhang et al. (2020b), and their spans are presented in Table S2a (Online Resource). The annual series of precipitation of China during 300 BCE–2000 CE, reconstructed by Zhang et al. (2015), was synthesized from 38 document-based single-proxy hydroclimatic datasets using the composite plus scale method (Mann et al. 2008). This is the first-published long precipitation sequence that spans the past 2300 years on the national scale. However, this nationwide precipitation reconstruction only illustrates three major wet/dry cycles (multicentennial scale) in history as precipitation varies asynchronously in China. Therefore, according to Zhang et al. (2015) and Zhang et al. (2020b), a 300-year

Butterworth low-pass filter was used to retrieve the low-frequency signal, and the average of this sequence was calculated to facilitate comparisons, based on which three wet (WP, to avoid confusion with the abbreviation of “warm”)–dry (D) cycles were divided (also, please see Table S2b in Online Resource for details). The imperial era from 5 to 1911 CE was thus considered as the study period for consistency.

War data were gathered from *Tabulation of Wars in Ancient China*, an appendix that belongs to the *Military History of China*, which was summarized by the Editorial Committee of Chinese Military History (1985) and extensively employed in previous research (Zhang et al. 2005, 2006, 2007a, b, 2015; Lee and Zhang 2010, 2013; Zhang and Lee 2010; Lee 2014; Pei and Zhang 2014; Zhang and Pei 2015; Lee et al. 2016, 2017; Liu et al. 2016; Pei et al. 2017; Zhang and Zhang 2019; Zhang et al. 2020a, b). In this study, battle is considered as the basic unit of war. The criterion is that if two sides engaging in a war have a fight in reality, then such a fight is regarded as a battle. All the ancient battlefields in this compendium were verified with *Historical Atlas of China* (Tan 1982), counted within the present territory of China, and converted into currently used place names, from which the geographical locations (i.e., coordinates) of these battlefields were retrieved. In other words, battlefields beyond the national boundary were excluded even though they were in the areas that historically belonged to the Chinese Empire. The exclusion of such battlefields may affect the spatial pattern of war, yet these “outliers” only account for a small proportion of all records. Also, they are usually difficult to locate owing to extreme remoteness and the lack of enough documents. It is well-known that a battle impossibly happens at an exact point. Nevertheless, the spatial scale of this study was set to the national scale rather than the regional or local one, because we would probe into the battle points/coordinates and their derivatives—war centers throughout the country, based on the territory of China at present.

Population data were sorted out from *Examination of Historical Chinese Population in Various Provinces and Districts* written by Lu and Teng (2006), in which population number, population density, and population percentage in each province of China were compiled. Unfortunately, Lu and Teng’s data are discontinuous since only 18 time-slices are contained. As in previous studies, the common logarithm of data points was taken, linearly interpolated, and anti-logged back to create an annual series (Lee et al. 2008, 2009, 2016, 2017; Lee and Zhang 2010, 2013; Lee 2014; Pei and Zhang 2014; Pei et al. 2016; Zhang and Zhang 2019). Given that population grows exponentially in the long run, this method could avoid any distortions in data interpolation.

2.3 Method

From the battle data, the mean location of the battles in China for each year was calculated to serve as the center point for them, linearly interpolated into annual series, and then smoothed by a 50-point FFT filter as temperature anomaly data. Meanwhile, the weighted mean population center was calculated to serve as the centroid of the Chinese population. The calculation procedure of population center follows the same formula in Lee et al. (2009):

$$\left(\bar{x}_{wmc}, \bar{y}_{wmc} \right) = \left(\frac{\sum_{i=1}^n w_i X_i}{\sum_{i=1}^n w_i}, \frac{\sum_{i=1}^n w_i Y_i}{\sum_{i=1}^n w_i} \right) \quad (1)$$

where \bar{x}_{wmc} and \bar{y}_{wmc} denote the weighted mean population center, x_i and y_i are the coordinates of a provincial centroid, and w_i is the weight of the provincial centroid (i.e., the population size of this province at a certain year i). The provincial centroids can be retrieved by ArcMap 10.3 in this study. Using the “Mean Center” tool of this software after uploading a base map with current provincial boundaries, the centroids were generated; then they were substituted into the above formula to obtain the calculation results, from which the variation of national population center over time was visualized. The spatial patterns characterized by battle and population centers were compared with temperature/precipitation series and cycles to determine whether war center and population center (a) synchronously evolve, and how they are influenced by climate change. Also, to further examine their connection, the center distance for each interval was measured in ArcMap. Meanwhile, Pearson’s correlation analysis and GCA were performed in SPSS 22 and EVIEWS 9, respectively. GCA is a statistical method developed by Granger (1969, 1988) and has been increasingly applied to the climate–society research since Zhang et al. (2011a). It could validate the causal linkages of time sequences on the premise that the cause must precede the effect. For details about GCA, please read the contents in [Online Supplementary Material](#).

3 Results

3.1 Temporal analysis of temperature, precipitation and population–war coordinates

The long-term trends and cyclic fluctuations of temperature anomaly, precipitation, battle coordinates, and population coordinates in ancient China are presented in Fig. 2. First, the temperature anomaly generally declines over the last 2000 years, especially from C5 (1331–1490 CE) to C7 (1791–1911 CE) when the trough (i.e., the lowest value) of the 50-year smoothed temperature anomaly series becomes deeper and deeper (Fig. 2a). Second, the 50-year battle longitude has no obvious trend, but it basically shifts westward (eastward) during warm (cold) intervals except for the little difference in cycle 5 (Fig. 2b). The annual battle longitude primarily ranges between 100° E and 120° E and marches to the far west in three periods, namely W1 (5–125 CE), W3 (596–765 CE), and W7 (1706–1790 CE), which correspond to the Eastern Han, Sui–Tang, and Qing dynasties, respectively. Third, the temporal alteration of battle latitude is quite complex (Fig. 2c). On the one hand, overall, the extent of annual battle latitude is expanding through time, and the total trend goes southward. In early stages, battle latitude prevails in 30–42° N, yet it gradually occupies 22–42° N until the end of the study period; that is to say, the northernmost edge is almost unchanged, whereas the southernmost margin extends southward more and more. On the other hand, except cycle 5, warm (cold) phase corresponds to the northward (southward) migration of the 50-year filtered battle latitude, which actually follows a two-step process that fluctuates around 35° N from W1 to W4 (951–1120 CE) and sharply drops to the south of 32° N afterward (except the crest in W6, i.e., 1491–1615 CE). The turning “point” in between coincides with the transition from the Medieval Warm Period (MWP) to the Little Ice Age (LIA), which may partly explain why the hypothesized spatial regularities of battle coordinates are inapparent during cycle 5. Fourth, owing to coarser resolution, the trends for population coordinates appear more pronounced than their cyclic fluctuations (Fig. 2d and e). Also, the eastward and southward shifts of population longitude and latitude, respectively, are more remarkable and stable than the counterparts of battle coordinates, in which the slope of

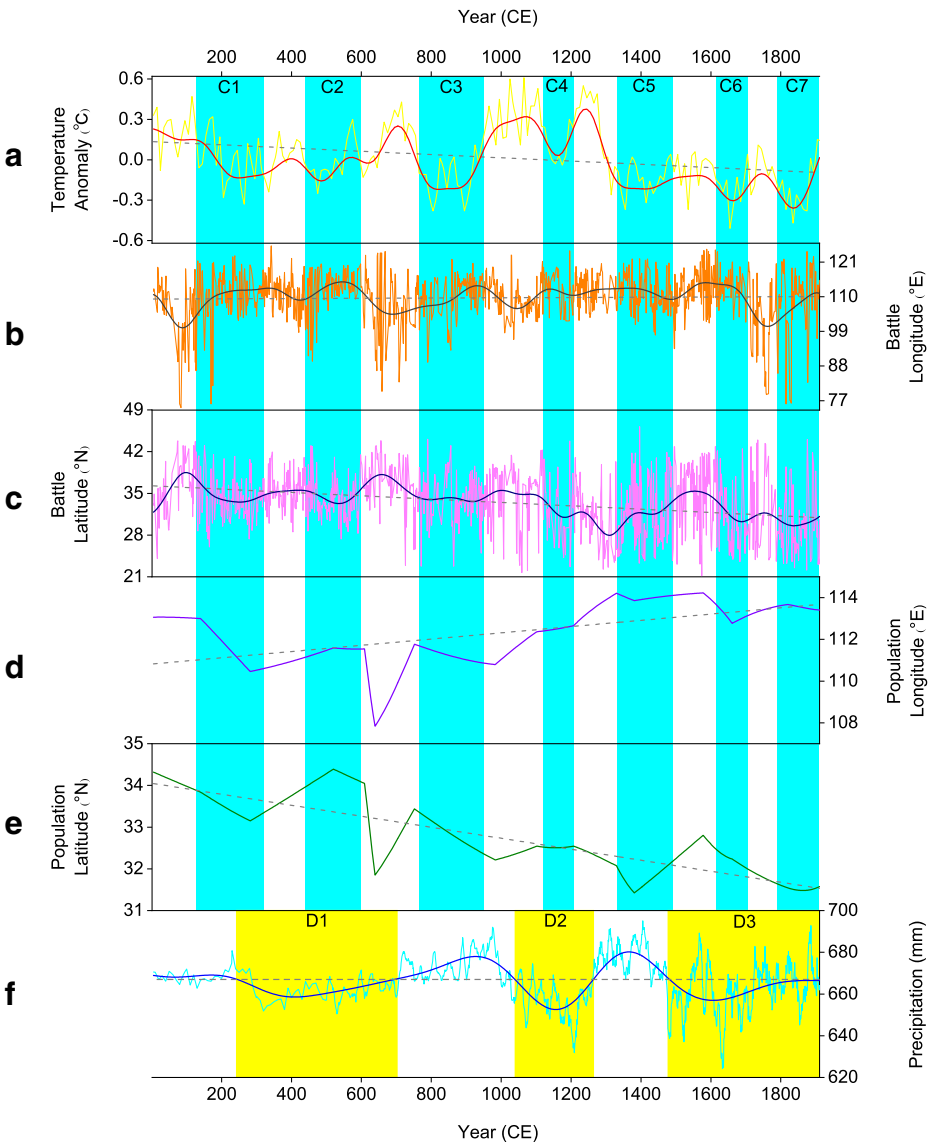


Fig. 2 Composite series of climate change and battle–population coordinates in China, 5–1911 CE. (a) Annual temperature anomaly (yellow) and the 50-year filtered sequence (red) under seven cycles (cold phases are labeled and highlighted in cyan bars); (b) battle longitude (orange) and the 50-year filtered data (dark gray); (c) battle latitude (light magenta) and the 50-year filtered curve (navy); (d) population longitude (purple); (e) population latitude (green); (f) annual precipitation (cyan) and the 300-year smoothed series (blue) under three cycles (dry periods are labeled and colored in yellow bars). Gray dash lines and dotted line denote the overall trends and the average of precipitation sequence, respectively

population latitude, rather than that of population longitude, looks steeper. In summary, the better consistency of cooling vs. the southward migrations of battle and population latitudes instead of the eastward movements of battle and population longitudes implies that

temperature change may play an important role in the latitudinal variation of population center and war center.

Compared with temperature, the annual and multicentennial variations of precipitation series both show three large cycles (Fig. 2f), in which D1 (250–685 CE) and D2 (1042–1262 CE) roughly coincide with C1–C2 and C4, respectively, while D3 (1484–1911 CE) falls within the LIA (i.e., after C5 to C7). Except the first wet stage, the other two manifestly correspond to long cold intervals (C3 and C5), i.e., the temporal patterns of temperature and precipitation in ancient China may be sometimes out-of-phase (warm–dry vs. cold–wet). As the annual battle coordinates fluctuate drastically but their multidecadal variabilities (50-year FFT filtered curves) and temperature anomaly have similar regularities, and population coordinates overall follow the long-term trends, they cannot be directly compared with either the annual or 300-year precipitation change from this figure. In the next subsections, correlation and GCA could further examine the relationship between precipitation and the coordinates of population and war.

Table 1 shows Pearson's correlation matrix among temperature, precipitation, and the coordinates of population and war in historical China on the annual scale. First, the time variable "year" is positively correlated with population longitude ($r = 0.592$, $p < 0.01$, the same below) and negatively correlated with temperature anomaly ($r = -0.305$), population latitude (with the smallest correlation coefficient among all values, $r = -0.859$), and battle latitude ($r = -0.325$), which means population longitude turns to the east, while population latitude and battle latitude shift southward through time. However, precipitation and battle longitude have no trends as the correlation coefficients cannot pass the significance test, which statistically verifies the variation characteristics of the annual series in Fig. 2b and f. Second, correlations between temperature anomaly and the longitudinal (latitudinal) components of population–war centers are significantly negative (positive); in other words, as temperature generally drops over the past two millennia, population longitude and battle longitude become larger and larger (farther eastward), while population latitude and battle latitude become smaller and smaller (farther southward). The correlation between temperature and population coordinates in this table is consistent with the result in Lee et al. (2009). However, temperature and precipitation is negatively correlated, which does not conform to our hypothesis and the climatic feature of China that warm and wet (cold and dry) conditions usually join hand in hand. Nonetheless, the confidence level only gets 95% (i.e., $p < 0.05$) and the correlation coefficient is very small ($r = -0.057$). Third, precipitation has no correlation with the longitudinal components of population–battle coordinates but negatively correlates with population latitude and battle latitude, which means higher (lower) precipitation corresponds to southward (northward) migration of population and war. Fourth, population longitude and battle longitude have no correlation, whereas population latitude and battle latitude are positively correlated ($r = 0.272$). This implies that the changes in the latitudes of population center and war center are more consistent than their longitudinal variations.

Based on the correlation results in Table 1, GCA was conducted to further figure out the causal relationship between temperature/precipitation change, population coordinates, and battle coordinates (Table 2). Since there are no correlations between precipitation and population/battle longitude, as well as population longitude and battle longitude, they were excluded in GCA. The results clearly indicate that (1) temperature is the Granger-cause of population coordinates ($p < 0.01$) and battle latitude ($p < 0.05$) but not battle longitude ($p = 0.499$); (2) precipitation is the Granger-cause of population latitude ($p < 0.01$) instead of battle latitude ($p = 0.084$); (3) the movement of population latitude precedes that of battle

Table 1 Correlation matrix of annual climatic variation and population–battle coordinates in ancient China

	Temperature anomaly	Precipitation	Population longitude	Population latitude	Battle longitude	Battle latitude
Year	−0.305**	−0.022	0.592**	−0.859**	0.029	−0.325**
Temperature anomaly		−0.057*	−0.208**	0.208**	−0.111**	0.195**
Precipitation			0.028	−0.154**	−0.030	−0.083**
Population longitude				−0.370**	0.030	−0.301**
Population latitude					0.039	0.272**
Battle longitude						−0.180**

** $p < 0.01$; $N = 1907$

latitude ($p < 0.01$, with a 19-year lag, see Table S4 in Online Resource), yet the null hypothesis of the opposite causal link cannot be rejected ($p = 0.906$), and such causation is invalid. Thus, the causal chain of “temperature/precipitation → population latitude → battle latitude” can be preliminarily built. Nevertheless, since the effects of temperature and precipitation on population latitude are opposite, caution should be kept and the related explanations will be given in Section 4.

3.2 Spatiotemporal evolution of population center and war center during seven temperature cycles

The evolutions of war centers and population centers during each warm and cold interval of seven temperature cycles (i.e., on the multidecadal–centennial scales) are visualized in Fig. 3. Evidently, the spatial extent of war center is much larger than that of population center. The former varies within 30–37° N and 101–113° E, whereas the latter changes within 31–34° N and 110–114° E. Population centers are mostly located in (accurately speaking, along the border between) present-day Henan and Hubei, with two in Shaanxi, while war centers extend outward during warm stages, such as in central Gansu (W1), southwestern Shanxi (W2), southern Ningxia (W3), central Shaanxi (W4), and even as far as western Sichuan (W7). Among them, it is interesting to observe that the three farthest war centers in W1, W3, and W7 cross beyond the modern Hu Line (to avoid confusion it is not shown in this figure), which symbolizes the powerful military strength and frontier expansion of the Eastern Han, Sui–Tang, and Qing Empires. Despite the limited size of population data, the contrast of the motion

Table 2 Granger causality analysis between temperature, precipitation, and population–battle coordinates

Hypothesized causal link (null hypothesis)	<i>F</i>	<i>P</i>	<i>N</i>
TEMPERATURE does not Granger Cause POPULATION LONGITUDE	171.528	0.000**	1906
TEMPERATURE does not Granger Cause POPULATION LATITUDE	32.353	0.000**	1906
TEMPERATURE does not Granger Cause BATTLE LONGITUDE	0.908	0.499	1900
TEMPERATURE does not Granger Cause BATTLE LATITUDE	1.605	0.047*	1888
PRECIPITATION does not Granger Cause POPULATION LATITUDE	7.867	0.005**	1906
PRECIPITATION does not Granger Cause BATTLE LATITUDE	1.477	0.084	1888
POPULATION LATITUDE does not Granger Cause BATTLE LATITUDE	2.276	0.001**	1888
BATTLE LATITUDE does not Granger Cause POPULATION LATITUDE	0.605	0.906	1888

** $p < 0.01$; * $p < 0.05$

tracks between population center and war center in magnitude implies that the movement of war center may be amplified by that of population center.

To reveal more details about these centers in each warm and cold phase, scatter plots are depicted as Fig. 4. Population center longitude generally shifts eastward over time (Fig. 4a). The westernmost and easternmost longitudes are located in 110° E (W3) and 114.1° E (W6), respectively. With the exceptions of cycles 1 and 6, the longitude in warm period is situated farther westward than that in cold period. In comparison, population center latitude exhibits a downward trend from W1 to C7 (Fig. 4b); hence, the latitude has the smallest value in C7 (31.5° N). However, the latitude in W1 (34.1° N) is not the highest because the one in C2 (34.2° N) goes slightly more northward. Except for cycles 2 and 4, the latitude in warm phase shifts more northward than that in cold interval. According to these two components together with the motion track in Fig. 3, the overall southeastward movement of population center from the Yellow River basin to the Yangtze River basin pinpoints the major direction of migration in China over the past 2000 years.

The general trend of the longitudinal component of war center is unclear (Fig. 4a). With the exception of cycle 5, the mean longitudes are located farther westward during warm stages. The westernmost and easternmost positions lie in 101.37° E (W7) and 113.13° E (C2), respectively. For the latitudinal component, however, the trend declines through time (Fig. 4b), which is in line with the downward trend for population center latitude. In particular, the mean war latitude fluctuates between 34° N and 37° N from W1 to W4, and then dramatically decreases to the south of 31° N in W5 via C4. Although it returns to the north during W6 (35° N), it ultimately shifts to the south of 32° N in the remaining intervals. Similar to war center longitude, except cycle 5, the war center latitude in warm phase is higher than that in cold stage

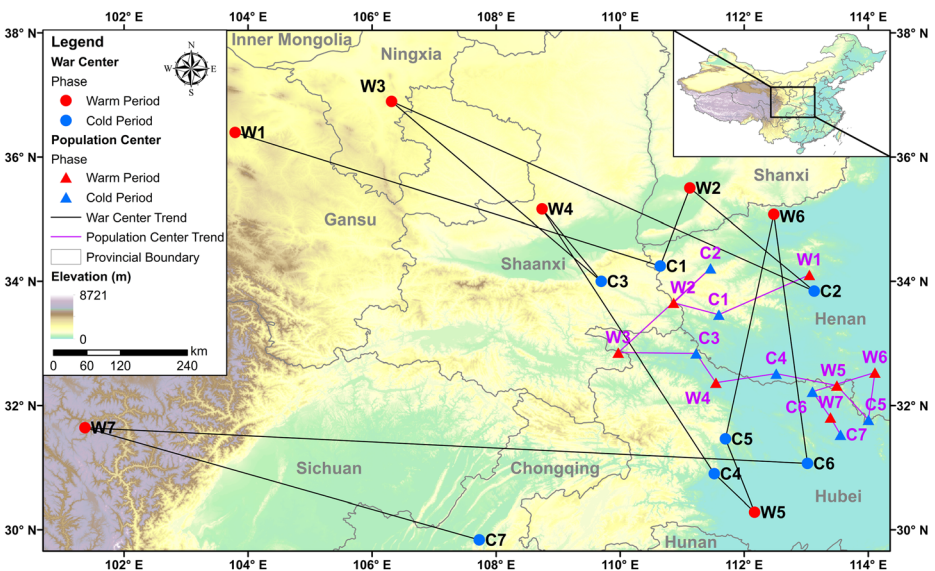


Fig. 3 Evolutions of war center and population center in different warm and cold intervals. Note: circles connected by black lines represent war centers (with black labels); triangles linked by purple lines denote population centers (with purple labels). Warm and cold intervals are colored in red and blue, respectively. The rectangle in the inserted map in the top right corner shows the variation ranges of war centers and population centers in China

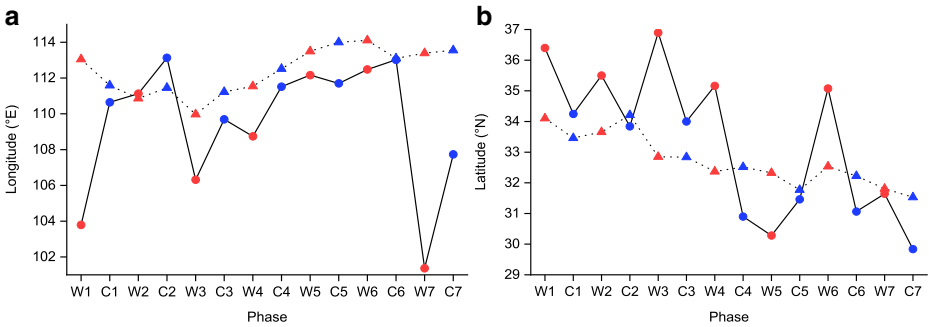


Fig. 4 Longitudinal (a) and latitudinal (b) components of population centers and war centers throughout seven temperature cycles. Note: circles (connected by solid line) and triangles (linked by dotted line) represent war center and population center, respectively; red and blue colors denote warm and cold phase, respectively

within the same cycle. The northernmost and southernmost locations reside in 36.9° N (W3) and 29.8° N (C7), respectively.

The distance between war center and population center does not display any distinct trend (Fig. 5). Except a few stages in which the distances exceed 500 km, such as in W1 (880 km), W3 (560 km), W7 (the longest one, up to 1139 km), and C7 (589 km), other distances remain relatively short. The distance is longer in every warm interval, which implies the outward expansion of the Chinese Empire (including those dynasties ruled by nomads) that the central government grows strong enough to initiate military campaigns and maintain frontier control. Thus, the territorial area and the theater of war become larger, and more wars spread toward North/West/Northwest China, thereby lengthening the war center–population center distance (given that population center just changes within a small range). W1, W3, and W7 correspond to three typical eras in history, namely, the Eastern Han, Sui–Tang, and Qing dynasty, respectively, and the outward movement of war center is striking (Fig. 3). By contrast, such an expansion ceases and even retreats in cold stages, and the empire loses the control of much of its territory, because the power of the central government is severely undermined by cooling-induced economic downturn and it fails to manage remote regions. Consequently, war center contracts southeastward, and the distance between war center and population center shortens.

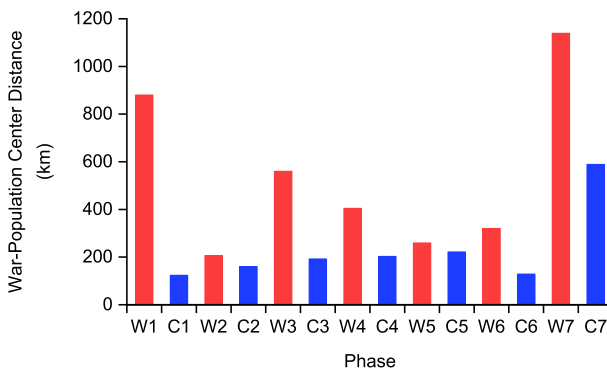


Fig. 5 Distance of war center and population center during each warm (red bar) and cold (blue bar) phase

3.3 Spatiotemporal evolution of population center and war center during three precipitation cycles

The temporal-spatial patterns of population center and war center in three wet–dry cycles are portrayed in Fig. 6. Similar to seven warm–cold cycles, war centers and population centers as a whole shift southeastward during the past two thousand years; also, the range of war center (around 30–36° N and 106–112° E) is much larger than that of population center (approximately between 32–34° N and 110–114° E). Unlike the statistical results on the annual scale in Section 3.1, in this figure, the multicentennial-scale movements of war center and population center for cycles 1 and 2 (except cycle 3) have the regularity similar to the centers on the multidecadal–centennial scales in seven temperature cycles (Fig. 3). In another word, war center and population center move more northward/northwestward under better (warm and/or wet) climatic condition, whereas migrate to the south/southeast in cold and/or dry period. For precipitation, this is only valid on the multicentennial scale, which is in accordance with the conclusion about the association between the 400- to 800-year precipitation fluctuations and the pastoralist-agriculturalist conflicts in Zhang et al. (2015); the disagreement of the results between annual and multicentennial scales reveals the complexity of precipitation change. The motion directions of war center and population center from WP1 (5–249 CE) to WP2 (686–1041 CE) are opposite; afterwards, they alter in the same way. Interestingly, both war and population centers reach to the most southeastward position in WP3 (1263–1483 CE), yet turn northwestward in different extents during D3. The reason of such anomalous centers over this cycle will be interpreted in Section 4. As the components of war center and population center, as well as their distances in each precipitation interval do not present a relatively regular and consistent pattern as those between warm and cold phases (Figs. 4 and 5), the related results are not shown here.

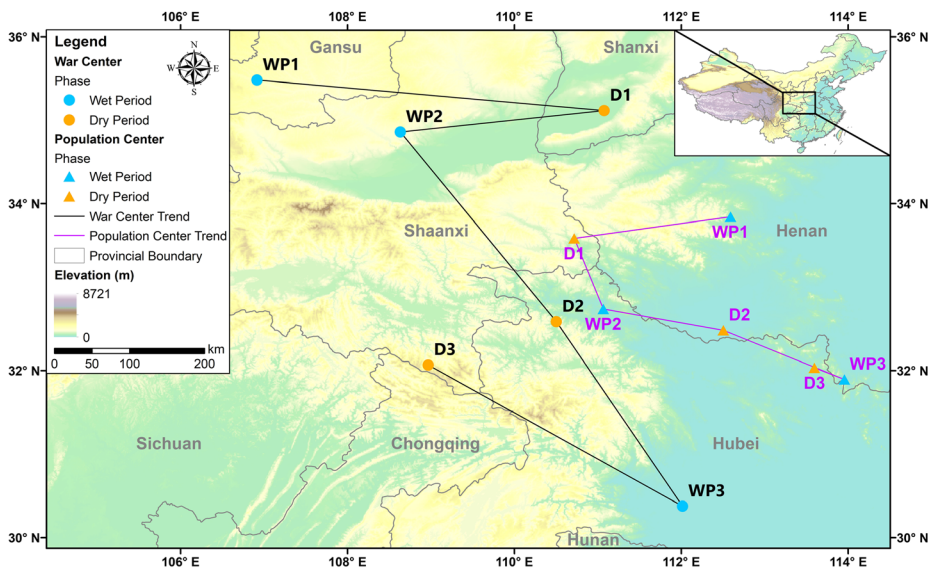


Fig. 6 Evolutions of war center and population center in different wet and dry phases. Note: wet and dry intervals are colored in blue and orange, respectively; other elements are the same as the counterparts in Fig. 3

4 Discussion

4.1 Possible mechanism from temperature variation to the temporal-spatial pattern of population and war

The decreases in battle latitude with larger magnitude and population latitude with smaller extent may result from temperature cooling throughout the past two thousand years, as battle latitude and population latitude follow the latitudinal zonality of temperature that is spatially consistent (i.e., “south–warm vs. north–cold”). Yet battle longitude and population longitude change unstably, and perhaps precipitation contributes more. However, due to the complex topography in such a vast territory of China and the stochastic rainfall process, the spatial distribution of precipitation is uneven and even opposite in different regions, e.g., “south–flood vs. north–drought” or vice versa; or “Yangtze River basin–flood vs. North and South China–drought” or vice versa (Wang and Zhao 1979). In addition, because of the huge variability in monsoon climate, precipitation oscillates frequently from year to year, which means the nationwide precipitation in history is extremely difficult to reconstruct and may not well-reflect any regular spatial pattern as paleotemperature even if it is reconstructed (Hao et al. 2016; this study). Also, it is worth to note that intermediate social-economic factors should play a part in the mechanism of temperature change and the movements of population–war centers, whereas these variables are often unavailable and hard to spatially quantify. Hence, in this study we have to simplify the whole association, with the spatial linkages among climate (temperature variation), demography (population center), and society (war center) presented and discussed only. Temperature change is still regarded as the ultimate factor as in Zhang et al. (2011a); also, supported by the results in Tables 2 and S4, temperature is the Granger-cause of population coordinates, followed by the order of “population latitude → battle latitude” with a 19-year lag. Such validated causation of latitudinal components therefore contributes to the alteration from population center to war center.

Here, two achievements of this study can be drawn from these causal links. First, the Hu Line (also a symbol of the spatial pattern of population as population coordinates/centers) may not be stationary all the time. As mentioned in Section 2.1, in fact, the line was formed since the LIA (Wang et al. 1995), which means the historical one may situate more northwestward during warmer conditions. Recent studies have calculated the change in population centers in contemporary China, and the most recent centers are located in either southern Henan or northern Hubei, depending on different calculation methods (Pan et al. 2013; Ma and Niu 2016; Yang et al. 2016). If the current positions of population center and the Hu Line are taken as an analogy, the latter in the early imperial China may be crudely estimated by the movement of population center in Fig. 3. For example, the population centers in W2 or W3 come relatively close to the modern Hu Line. As the distances between the population center in W3 and those in recent years are approximately 300–400 km, it can be estimated that during W3 the Hu Line may migrate northwestward with similar magnitude. Furthermore, the longitudinal components of population centers between W1 and C7 have a tiny difference (merely about 0.5° , please see the [Online Supplementary Material](#) for details); in comparison, throughout the study period population center totally moves southward for 2.7° , with a corresponding ~ 300 -km latitudinal decline for the Hu Line. To sum up, by connecting the variation of the Hu Line with climate change in longer-term history, our study broadens the horizon of demographic studies in China.

Second, spatially the change of war center is caused by the variation in population center, which indicates that the climate-induced demographic change results in the locational shift of social conflict. Researchers have found that intermediated by other socioeconomic factors, overpopulation (i.e., population pressure on resources) and climate cooling (which lowers the land carrying capacity and creates population pressure as well) synergistically operate to drive the population growth dynamics and demographic cycles in the long run (Galloway 1985, 1986; Scott et al. 1998; Lee et al. 2008, 2009; Lee and Zhang 2010, 2013; Zhang et al. 2011b; Lee 2014; Wu and Ge 2014). The effect of overpopulation on social conflict has also been addressed (Ho 1959; Webster 1975; Zhao and Xie 1988; Carneiro 2000; Lee et al. 2008). The findings of this research exhibit more details of the changes in population centers and war centers during different historical stages. In Figs. 3 and 4b, notably, population center is usually located farther southward than war center during early stages; however, such a pattern largely reverses in later cycles. That is to say, population in the early imperial era is concentrated in the north, so that engaging in battles in remote areas (e.g., the far north or the Western Regions) is feasible. As temperature drops, the land carrying capacity in North China declines and people continually migrate southward, where the land carrying capacity is much higher. Over time, the increasingly high population density (i.e., overpopulation/population stress) in southern China represented by the southernly situated population center may intensify the competition for resources (particularly land) among Han Chinese and between the Han people and ethnic minorities. As a result, more and more conflicts take place in the far south, which draws war center toward the south.

4.2 Other factors beyond temperature

According to the 50-year smoothed curve of temperature anomaly in Fig. 2a, the climate during the thirteenth century was the warmest (with the highest value, 0.4 °C) in the MWP. Soon the MWP ended with plummeting temperature, and the climatic pattern gradually developed into a long, frigid one, i.e., the LIA. However, war center in W5 (1206–1330 CE) continues moving southward and reaches to its second lowest position all over the seven cycles, and the counterpart in C5 does not shift further southward but northwestward. Such “outliers” of war centers during cycle 5 (1206–1490 CE) may not be attributed to temperature change. In fact, as the national precipitation series reconstructed by Zhang et al. (2015) and the related wet–dry cycles divided by Zhang et al. (2020b) show, the stage D2 (1042–1262 CE) is basically dry; besides, the period around 1150–1250 CE is the driest century during the last 2000 years (Zhang et al. 2015). Since W5 partly overlaps with this dry interval (1206–1262 CE), and Fang (1989) and Pei and Zhang (2014) have indicated that precipitation rather than temperature is more influential in determining southward nomadic migration and the subsequent conflicts between pastoralists and agriculturalists, the anomalous southward shift of war center in W5 could be explained to some extent. Looking from this exception, precipitation can interrupt the mechanism between temperature and population/war center at times, and can only display the nationwide pattern with large cycles of population center and war center shifts. If we only look at war frequencies, boundary shifts between pastoralists and agriculturalists and nomadic migrations in historical China, they were controlled by precipitation variations on the multicentennial scale (Zhang et al. 2015; Zhang and Pei 2015).

However, something different is also found in this study. As aforementioned, the annual series has a negative correlation with population–battle coordinates (Table 1), yet

multicentennial war center and population center shift synchronously (except cycle 3, Fig. 6) as the centers on the multidecadal–centennial scales in seven temperature cycles (Fig. 3). This implies that the short-term effect of precipitation fluctuation (with high variability), e.g., population is attracted to the south (possibly for better development opportunities) during wetter conditions, can be totally different from the long-term effect of wet–dry mode that gets closer to the counterpart of warm–cold stages. It is understandable that people (especially peasants) were unable to migrate in a very long distance on the annual scale given the poor transportation in the past, so that such a short-term perturbation of migration may be temporary. The discovery of the short-term effect of precipitation on population center may be another potential contribution of this study, whereas more evidence should be collected and more analyses should be done to further distinguish between the short- and long-term effects of precipitation change. The basic condition for this research purpose needs the regional precipitation reconstructions of the whole of China as precipitation in a short term is unsynchronized in different regions. In short, although there are correlation and causation between precipitation and population latitude (Tables 1 and 2), precipitation is just correlated with battle latitude, not the Granger-cause of it. Therefore, in this study whether precipitation could be deemed as one of the fundamental causes of social phenomena like temperature is questionable.

Non-climatic factors will be elucidated below. First, the balance of power between pastoralists and agriculturalists should be taken into account. In most warm stages, the agricultural region in eastern China is controlled by a unified empire, which is more powerful than nomadic regimes. That is why war center usually moves northwestward. But in W5, eastern China was divided into two regimes, i.e., Jin in the north, and Southern Song in the south. Meanwhile, the vast steppe belt in North and Central Asia was controlled by the unprecedentedly powerful Mongol Empire, which had the overwhelming superiority in military compared with either Jin or Southern Song. Hence, the intermittent Song–Jin War and the Mongol conquest of the Jin (by 1234 CE) and Southern Song dynasties (by 1279 CE) in the thirteenth century further push war center to the south (Fig. 3). This also explains the anomalous positions of war center and population center in WP3 (Fig. 6). During the Mongol invasions (WP3 in the beginning) when the entire of China was conquered by nomads for the first time, refugees fled to the south or southeast, such that the proportion of population in southern China increases. Meanwhile, during the Yuan–Ming transition rebellion wars were concentrated in South/Southeast China.

Political center may also play a role in the anomalous position of war center. For instance, after the demise of the Northern Song dynasty in 1127 CE, the capital of the Song Empire relocated from present-day Kaifeng to Hangzhou along with massive agriculturalists' migration toward Southeast China. The proportion of population in the south continually increases, which may lead to the southward movement of war center in W5 through the mechanism mentioned above (Section 4.1). During C5 (1331–1490 CE), Zhu Yuanzhang, the first emperor of the Ming dynasty, overturned the Yuan Empire and established the capital in Nanjing in 1368 CE. However, his son, Zhu Di, also known as the Emperor of Yongle, relocated the capital to Beijing after usurping the throne from his nephew, Zhu Yunwen. The capital Nanjing only lasted for 54 years (1368–1421 CE), but the duration of Beijing as a capital was longer in the remaining years of C5, since it was also the capital of the Yuan dynasty. Therefore, accompanied with the northward relocation of the national political center and the persistent war against the Mongols (or the Northern Yuan regime) along the northern border, war center shifts northward as well.

Population/migration is not only determined by climate but also intervened by government policy (Ye et al. 2004; Fang et al. 2007; Xiao et al. 2013, 2015; Lee et al. 2016), which sometime can be the fuse of war. Take governmentally encouraged/forced migration as an example. In D3, which covers temperature cycles 6 and 7 (see Fig. 2), the distribution of population becomes not so extreme, because the government initiated several large-scale migration movements to West China, followed by many military campaigns toward there. Specifically, after the westward migration from Jiangxi to Huguang in the Ming dynasty, the more massive one in the early Qing dynasty (also known as “Huguang fills Sichuan”) greatly increased the population of the entire southwest, as migrants also flooded into Guizhou and Yunnan (Yang 2017). After by the mass migration launched and organized by the government, which makes population center in C6 (1616–1705 CE) move a bit southwestward (Fig. 3), Southwest China was intensively exploited during the late imperial era. Overpopulation in such a mountainous area with an ecologically fragile karst landform soon exhausted the land carrying capacity and aggravated the tension between the Han Chinese and ethnic minorities. Meanwhile, the rule of the central government was strengthened by the measure of bureaucratization of native officers, which is aimed at cancelling the hereditary local chieftain (or “Tusi”) system and directly assigning officials. Such a frontier management policy undoubtedly ignited numerous revolts in that region. Thus, the southwestward extension of war center in cycle 7 (1706–1911 CE) becomes highly appreciable (Fig. 3).

5 Conclusion

In this study, war–population coordinates and their associations with temperature and precipitation variation in China (5–1911 CE) are examined via correlation analysis and Granger causality analysis on the annual scale. The mean centers of population and war and/or their distances during seven warm–cold cycles and three wet–dry cycles are visualized on the multidecadal–multicentennial scales. It highlights the importance of holding a spatiotemporal view, and the discoveries, which theoretically contribute to the related academic fields and lay a foundation for more in-depth research on the climate–human nexus, supplement the previous work using time-series approaches only. We conclude that:

1. The spatiotemporal dynamics of population and war are fundamentally controlled by temperature change because of the consistent temporal-spatial patterns on the annual and multidecadal–centennial scales. On the whole, temperature drops throughout the last two thousand years, and population center and war center as well as the ancient Hu Line correspondingly migrate southeastward for hundreds of kilometers, which implies a huge change in human geographical conditions during historical China.
2. The extent of the external expansion of the Chinese Empire is successfully quantified by the distance between population center and war center. When the empire expands outward (contracts inward) during warm (cold) phases, war center chiefly shifts north/west/northwestward (south/east/southeastward), and the population center–war center distance increases (decreases).
3. The movement of population latitude is prior to that of battle latitude, i.e., spatially the long-term change of ecological-demographic sphere precedes political-societal change in ancient China. However, the longitudinal components of population center and war center have no relationship, which indicates that the effect of temperature on the latitudinal

variation in the spatial pattern of population and war is larger, more stable, and more regular.

4. Precipitation change, the power balance between nomads and agriculturalists, national capital movement, migration, and government policy may interrupt the above general trend and regularity on occasion during the Chinese imperial era. Among them, the short-term precipitation fluctuation does affect population latitude, but has no causal effect on battle latitude (with negative correlation only). The shifts of war center and population center during multicentennial precipitation cycles show a pattern similar to those in temperature cycles.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10584-021-03042-y>.

Acknowledgements The authors thank the anonymous reviewers for their valuable comments on this manuscript.

Code availability Not applicable.

Author contribution D.D.Z. conceptualized and supervised this study; S.Z., D.D.Z., and Q.P. designed the methodology; S.Z. performed data analysis and wrote the original draft; S.Z., D.D.Z., and Q.P. reviewed and revised this paper.

Funding This research was supported by the Fund for Key Platform Construction Project–Special Project of High Level University Construction at Guangzhou University (grant number 290020363) and the China Postdoctoral Science Foundation (grant number 2020M680117).

Data availability The data on population centers and war centers and their distances during seven warm–cold cycles and three wet–dry cycles are listed in Table S2 (Online Resource).

Declarations

Conflict of interest The authors declare no competing interests.

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