RESEARCH ARTICLE

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REGIONAL GEOGRAPHIC FACTORS MEDIATE THE CLIMATE-WAR RELATIONSHIP IN EUROPE

[a]Harry F. Lee, PhD, [b]David D. Zhang, PhD, [c]Peter Brecke, PhD,
[d]Qing Pei, PhD

[a,b,d]Department of Geography and International Center for China Development Studies, University of Hong Kong, Pokfulam Road, Hong Kong

[c]Sam Nunn School of International Affairs, Georgia Institute of Technology, Atlanta, Georgia 30332-0610, U.S.A.

[a]harrylee@hku.hk, [b]zhangd@hku.hk, [c]peter.brecke@inta.gatech.edu,
[d]peiqing@hku.hk

Abstract

It has been demonstrated in recent studies by that wars occurred with greater frequency in Europe in periods of cold climate over the past millennium, and food scarcity is the explanation. However, the issue of whether the climate-war relationship holds consistently across the European continent has been insufficiently explored. In the present study, we seek to advance the macroscopic understanding of the climate-war association in Europe via the statistical analysis of fine-grained paleo-climate and historical warfare data covering the period 1400–1999, with a specific focus on how regional geographic factors mediate the association. Our statistical results show that the climate-war correlation varied across Europe. At multi-centennial time-scale, temperature-war correlation was stronger in Eastern Europe, in part because of the region's greater dependence on agriculture and in part due to the region's prevailing continental climate. At multi-decadal to centennial time-scale, the temperature-war correlation in Europe was periodically distorted when population pressure was unleashed via a significant decline in the rate of population growth or through

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industrialization. Furthermore, the regional disparity in terms of population growth rate and pace of industrialization might be responsible for the diverse trends and trajectories of the temperature-war correlation in Eastern Europe and Western Europe. Our results may help to resolve some major controversies about the climate-conflict link.

Keywords: climate change, land carrying capacity, population pressure, wars, violent conflicts, Europe

1 INTRODUCTION

Throughout history, Europe has been the scene of many great and destructive wars that have ravaged both rural and urban areas, imposing enormous cost in human, economic and environmental terms [43, 58]. Scholars in various disciplines have sought to theorize the causes of wars. Historians cite government mismanagement and concomitant social turmoil; military scientists and politicians emphasize power imbalances among competing groups or entities; psychologists and biologists relate warfare to innate human aggressiveness; while Marxist theorists hold that warfare is the unavoidable consequence of class struggle [69, 70]. Under the paradigm of historical particularism, many scholars tend to deduce the fundamental causes of warfare to the interplay of economic, social, political, cultural, or ethnic factors [20, 64].

Within the academic research of historical European warfare, however, a new theoretical paradigm has been developed in the past decades to show how deteriorating climate profoundly affects the entire social fabric owing to reduced agricultural productivity and the consequent subsistence crises, triggering widespread popular unrest [3, 8, 12, 13, 18, 28, 32, 33, 53]. That paradigm is described in full in the following passage [28]:

> “The changing climate had [an] impact on the political developments in Europe. The Vikings were no longer the all powerful. The cities of the German Hanseatic League suffered economic declines. There was the Thirty-Year War, and Germany was devastated. Soldiers robbed and pillaged during the first half of the 17th century, and the people were on the move again. But they had no place to go, and roamed aimlessly as depicted by Bertolt Brecht’s play Mother Courage. Historians, as usual, blamed the war and warriors, but the warriors joined Wallenstein’s or Gustov Adof’s army because they could no longer farm at home. Not very many people were killed, but many died of starvation or epidemics after they were weakened by hunger. The culprit was obviously not so much the war, but the cold and wet climate of the Little Ice Age; a global cooling had devastating effects on the agricultural production in many parts of central and northern Europe.”

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The premise of climate-war correlation is that when climatic conditions deteriorate over long time periods, it not only reduces agricultural and livestock production directly, but also reduces agricultural production indirectly by creating more extreme events (e.g., droughts, floods, insect infestations). So long as the economy of human society was dependent upon agricultural production, scarcity manifested itself in two causal pathways: a direct path, in which resource-oriented wars erupted as most of the world's population struggled to satisfy the lower levels of Maslow's Hierarchy of Needs [45]; and an indirect path, as constrained food resources and economic difficulties stemming from that scarcity intensified social pressures and increased the likelihood of war outbreaks [69]. In fact, the above insight can be traced to Huntington's work the Pulse of Asia [29] a century ago. He suggests that in historical China, the Mongol conquests in the 13th century and Manchu conquests in the 17th century were primarily triggered by climate change. However, linking climate change to human history fell from favour because of the smack of environmental determinism and also due to the absence of quantitative evidence. In extreme cases during the early 20th century, some historians actually ruled out investigating natural phenomena altogether, regarding them as purely accidental facts unrelated to human history [55].

With the advances in high-resolution paleo-climate reconstructions made in the past decade, scholars can now re-examine the correlation between climate change and social stability using quantitative methods. For historical China, it has been demonstrated by large-N quantitative studies that more wars occurred in periods of cold climate, and food scarcity is the reason [15, 35, 36, 37, 67, 68, 70, 71, 72]. In addition, the climate-war association was stronger in some regions than in others, a disparity attributable to regional geographic factors [67, 68, 70]. The above findings set a scientific benchmark that reinforces the climate-war correlation paradigm. For Europe, Tol and Wagner [65] replicated those research findings. As in the case of historical China, they found that wars were more prevalent during colder periods in the past millennium, while this relationship weakened in the industrialized era. Zhang et al. [73] further evidenced that climate change was the ultimate cause, and climate-driven economic downturn was the direct cause, of large-scale human crises in pre-industrial Europe. Nevertheless, a focus on the climate-war association in Europe leaves one important issue insufficiently-explored: is the climate-war relationship found consistently across the European continent? If the answer is 'No,' is the disparity attributable to regional geographic factors as in the case of historical China? In the present study, we sought to answer the above questions by using quantitative means in order to expedite the macroscopic understanding of the climate-war association in Europe.

2 MATERIAL AND METHODS

For the purposes of this study, the most important factor is the comprehensiveness of data sources (time span, spatial coverage, and the number of incidents recorded). Use of less comprehensive datasets may bias the associated conclusions. The data employed in this research are detailed as follows: warfare data, temperature data, precipitation data.

2.1 Warfare data

A number of publications contains the warfare data of Europe over extended periods [31, 41, 62]. Still, the *Conflict Catalogue* [6] is believed to be the most comprehensive dataset for armed conflicts in Europe. The author has attempted to compile a dataset of all recorded violent conflicts that meet Richardson's magnitude 1.5 or higher criterion (32+ deaths) in 1400–1999[1]. The *Conflict Catalogue* is a superset of all other conflict compilations and is the product of the distillation of conflicts found in over 100 different books, articles, and on-line datasets that contain listings of wars. The books include encyclopaedias or handbooks of military history, compilations of major military battles, academic treatises, historical atlases, and historical chronologies for particular countries or regions. The *Conflict Catalogue* makes use of data sources in a number of languages other than English, including French, German, Russian, Turkish, Arabic, Chinese, and Japanese. Significant effort has gone into resolving inconsistencies between different sources with respect to wars where they overlap. This is a much higher number of wars than has been recorded in any other publication.

In Brecke's *Conflict Catalogue* [6], the geographic breakdown of armed conflicts was made as follows: armed conflicts which occurred west of 15°E in Europe (plus Sweden and Italy) were coded in the 'Western Europe' category, while armed conflicts which occurred east of 15°E in Europe (including the Caucasus region) were coded in the 'Eastern Europe' category (Figure 1). The above zonation was based on the regional variation of physiographic condition and socio-economic context, as well as a tradeoff between precision in location, concordance with regional studies breakdowns, and comprehensibility in graphics. In the present study, the exploration of the regional variation of climate-war correlation across Europe was conducted in line with the above criteria.

We followed the practice adopted in Tol and Wagner's study [65] to compile our annual war time-series for the whole of Europe (Figure 2(b)), Eastern Europe (Figure 2(c)), and Western Europe (Figure 2(d)), in each case that the violent conflict lasted >1yr, we counted a conflict in every year that it raged. For instance, the Thirty Years War is recorded as a conflict for each year from 1618–1648. This method of compilation is believed to capture the frequency, duration, and to a degree, the scale of the conflicts more accurately.

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[1] The dataset can be downloaded at http://www.int-res.com/articles/suppl/c056p001_supp.pdf.

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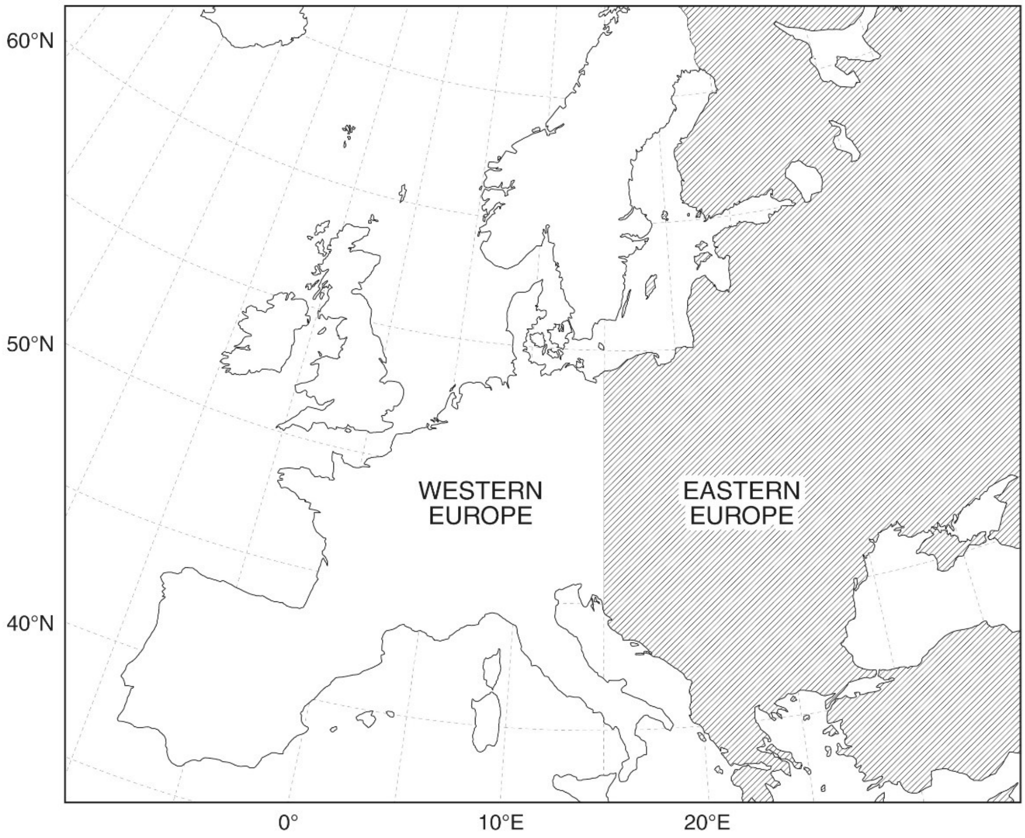

Figure 1 Map of Europe and the delineation of Eastern Europe and Western Europe made according to Brecke's Conflict Catalogue [6].

2.2 Temperature data

Paleo-climatologists have employed ingenious methods to reconstruct the annual temperature of Europe. Some temperature reconstructions span >1,000yrs, but their spatial coverage is limited to only parts of Europe [12, 13, 24, 34]. On the other hand, there are also temperature reconstructions covering the whole of the European continent. However, their time span is relatively short [42]. Recently, Guiot et al. [25] utilized 117 proxy records, including tree-rings, documentaries, pollen assemblages, and ice cores (the majority of proxy series have an annual resolution) to produce a gridded reconstruction of growing season (spring and summer) temperatures in Europe between 600–2007. The spatial area extends from 27.5°N to 72.5°N and from 7.5°W to 57.5°E and is demarcated into 125 grids (5° in latitude and longitude). Data are in °C anomalies relative to the 1961–1990 average. As Guiot et al.'s reconstruction [25] is the latest temperature series which covers the entire European continent and spans the past millennium, it was employed in this study. We arithmetically averaged the temperature data of the 125 spatial grids to generate the European temperature time-series (Figure 2(a)).

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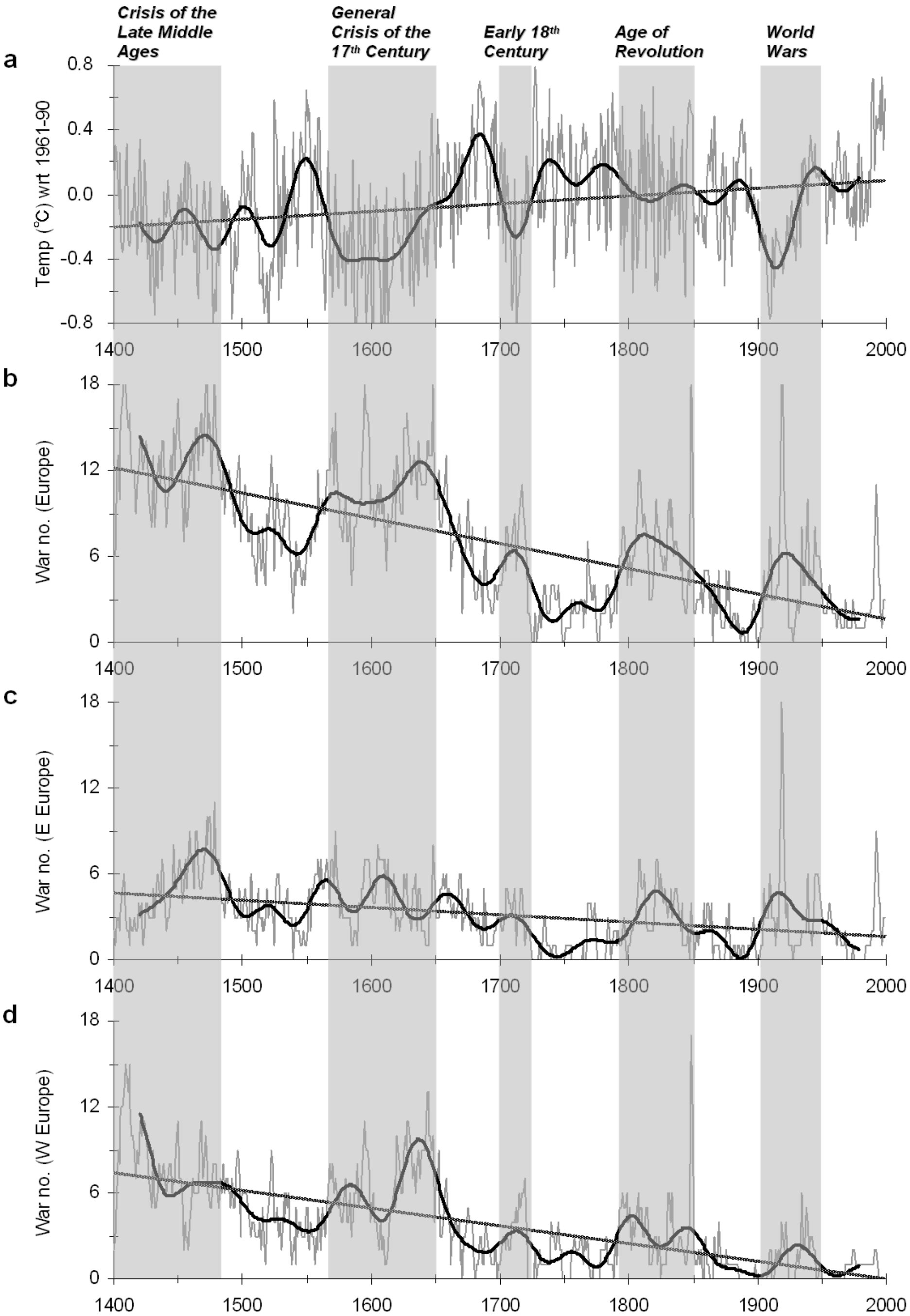

Figure 2 Annual temperature and number of violent conflicts in Europe. (a) Mean annual temperature anomaly (°C) from the 1961–1990 mean [25]. (b) Annual number of violent conflicts in the whole of Europe [6]. (c) Annual number of violent conflicts in Eastern Europe [6]. (d) Annual number of violent conflicts in Western Europe [6]. In all panels, grey lines represent original data, grey-shaded lines represent the long-term (linear) trend of the original data, and solid black lines represent the 40-yr cycle of the original data (elicited via Butterworth low-pass filter). Clusters of peaks of violent conflicts are shaded as grey stripes.

2.3 Precipitation data

The number of precipitation reconstructions for the entire European continent is relatively small. We employed Pauling et al.'s seasonal precipitation reconstructions for European land areas (30–40°E and 30–71°W; given on a 0.5° x 0.5° resolved grid) for the years between 1500–1983 [54]. For the precipitation reconstructions, a large variety of long instrumental precipitation series, precipitation indices based on documentary evidence and natural proxies that are sensitive to precipitation signals (tree-ring chronologies, ice cores, corals and a speleothem) were used as predictors. The precipitation reconstruction done by Pauling et al. [54] contains data for each of the seasons. Because the reconstruction by Guiot et al. [25] is for growing season temperature alone, only growing season (spring and summer) precipitation was considered in this research, in order to make the assessment of their respective effects on wars possible.

Our study period is delimited to 1400–1999, which maximizes the use of our available data. As the precipitation data is confined to 1500–1983, in the analysis in which the precipitation data is employed, the period covered was limited to 1500–1983 accordingly. Correlation, multiple regression, and moving correlation analyses were employed to quantitatively examine the climate-war relationship. Autoregressive disturbances in time-series were corrected by using the Prais-Winsten estimation method. The minimum level of significance was chosen as 0.05.

3 ANALYSIS OF CLIMATE-WAR ASSOCIATION IN EUROPE

Examination of climate-war association for the whole of Europe and the comparison of climate-war association between Eastern Europe and Western Europe were made in the following aspects: descriptive statistics of wars; temperature-war association in various lengths of cycle; temperature, precipitation, and wars; and temporal consistency of temperature-war association.

3.1 Descriptive statistics of wars

As shown in Table 1, there were 1,166 violent conflicts in Europe in 1400–1999; 52.5% of them occurred in Western Europe, while the remaining 47.5% of them occurred in Eastern Europe. Armed conflicts in Europe were often short in duration. Whether in the whole of Europe, Eastern Europe, or Western Europe, >70% of armed conflicts were concluded within ≤ 3yrs, while >90% of armed conflicts ended within ≤ 8yrs. Nevertheless, there were some exceptional events of extended duration. In Eastern Europe, the Russo-Crimean war in 1540–1572 spanned 33yrs; in Western Europe, warfare between the Netherlands and Spain in 1566–1609 spanned 44yrs. On average, armed conflicts in Western Europe lasted slightly longer than those in Eastern Europe. Moreover, the duration of armed conflicts in Western Europe spread out over a larger range of values.

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Table 1. Frequency table of the duration of violent conflicts in the whole of Europe, Eastern Europe, and Western Europe.

Duration	Whole of Europe	Eastern Europe	Western Europe
1	447	205	242
2	246	131	115
3	140	67	73
4	83	36	47
5	61	25	36
6	31	15	16
7	29	15	14
8	22	10	12
9	20	10	10
10	16	10	6
11	6	2	4
12	17	11	6
13	5	1	4
14	6	1	5
15	4	1	3
16	6	4	2
17	3	2	1
18	1	0	1
19	4	2	2
20	2	1	1
21	3	0	3
22	1	1	0
25	2	2	0
26	1	0	1
27	2	0	2
28	1	0	1
30	2	1	1
31	2	0	2
32	1	0	1
33	1	1	0
44	1	0	1
Total	1,166	554	612
Mean	3.546	3.410	3.670
Std. dev.	4.429	3.962	4.814

As shown in Figure 2, the number of armed conflicts in the whole of Europe, Eastern Europe, and Western Europe exhibited a long-term downward trend. Furthermore, the downward trend in Western Europe was very obvious, which significantly pulled down the trend for the whole of Europe. In terms of the number of armed conflicts, Europe (Western Europe in particular) grew more peaceful. In the whole of Europe, there were five clusters of peaks of violent conflicts, which corresponded to the four major chaotic periods in European history: the Crisis of the Late Middle Ages, the

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General Crisis of the 17th Century, the Age of Revolution, and the World Wars. Those clusters also coincided with periods characterized by either consistently low temperature (i.e., the Crisis of the Late Middle Ages), multi-decadal temperature drop (i.e., the General Crisis of the 17th Century, Early 18th century, and the World Wars), or exceptional inter-annual temperature variability (i.e., the Age of Revolution). The good match between temperature change, clusters of peaks of armed conflicts, and chaotic periods in European history at the continental scale confirms the notion that the complex interactions within and among natural and social processes are more readily disentangled at a large spatial scale [11, 48].

3.2 Temperature-war association in various lengths of cycle

In order to address whether the climate-war relationship held consistently in various cycles at multi-centennial time-scale, both of the temperature and war time-series were smoothed by different Butterworth low-pass filters, ranging from 10-yr to 40-yr.[2] Correlation analysis was then employed to measure the association between the two time-series. Results are shown in Table 2.

Throughout the period 1400–1999, we found no significant correlation for the original annual temperature and war time-series for the whole of Europe, Eastern Europe, and Western Europe. Human beings are not inanimate objects of climatic forcing. Annual climatic stress upon land carrying capacity[3] can be largely buffered by social mechanisms such as grain storage and trade. There might also be threshold effects triggering certain events. A decline in natural resource availability may only cause conflicts after a threshold is crossed [57]. Hence, the climate-war relationship might not be apparent in the very short-term. Nevertheless, if the climate deterioration is a multi-decadal one, its stress upon land carrying capacity could be too big for the social buffering mechanisms to deal with. Therefore, the negative association between temperature and wars could be envisaged when both the temperature and war series were smoothed by a 10-yr filter. The correlations became strongly significant when the series were smoothed by 30-yr and larger filters. Briefly, the climate-war relationship in Europe is revealed to be more apparent in multi-decadal cycles, a finding that concurs with previous research findings [69]. Although the social buffering mechanisms are supposed to be more effective over time, rather than removing the association between climate change and war, they simply made the relationship evident over longer cycles.

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[2] Further increase in the length of filters will result in unnecessary reduction of the degrees of freedom because the first half-cycle and last half-cycle of the smoothed data cannot be taken into subsequent statistical analysis.

[3] Land carrying capacity is not a fixed value due to technological improvement, but that this improvement does not operate on a time-scale sufficient to mitigate climate deterioration.

Table 2. Correlation between temperature and violent conflicts in Europe using different cycle lengths.

Region	Cycle length	1400–1999	1400–1699	1700–1999
Whole of Europe	0-yr	0.020	–0.028	0.058
	10-yr	–0.076	–0.122*	–0.056
	20-yr	–0.110**	–0.096	–0.078
	30-yr	–0.500***	–0.414***	–0.586***
	40-yr	–0.534***	–0.420***	–0.694***
Eastern Europe	0-yr	0.002	–0.041	0.044
	10-yr	–0.056	–0.091	–0.047
	20-yr	–0.016	–0.044	0.035
	30-yr	–0.448***	–0.406***	–0.477***
	40-yr	–0.501***	–0.278***	–0.711***
Western Europe	0-yr	0.020	–0.004	0.041
	10-yr	–0.057	–0.083	–0.030
	20-yr	–0.145***	–0.078	–0.190**
	30-yr	–0.262***	–0.209***	–0.346***
	40-yr	–0.193***	–0.236***	–0.252***

The cycles are elicited via Butterworth low-pass filter. Autoregressive disturbances in time-series were corrected by using the Prais-Winsten estimation method. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

We further divided the period into two equal portions, each spanning 300yrs, for comparison. When the same statistical procedure was applied to the periods 1400–1699 and 1700–1999, respectively, some interesting results were found (Table 2). First, correlation coefficients in the 1400–1699 column were generally weaker than those in the 1700–1999 column (temporal disparity). Second, correlation coefficients for Eastern Europe were generally stronger than those for Western Europe (spatial disparity).

One clue to the temporal disparity may be found in the effectiveness of mass migration in dissipating climatic forcing in different periods. Migration is an important outlet for societies faced with livelihood systems that are becoming unviable because of climate change and resource depletion [16, 52]. In the early centuries of the past millennium, population density was low, while uninhabited or sparsely populated lands (without political boundaries) were still abundant in Europe. The supply of land far exceeded the demand [38]. When a region is characterized by low population density and a large amount of fertile land, the correlation between temperature and wars will be weak or of low significance, and vice versa [69]. During the time when cooling shrank the land carrying capacity, people could move to those unoccupied lands for subsistence. This was a mechanism of utmost importance in dissipating climatic forcing upon the European continent in the early centuries of the past millennium. This might explain why the climate-war relationship was generally weak in the earlier period. In the later centuries of the past

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millennium, Europe became much more densely populated (Figure 3). As shown in Table 3, population grew dramatically between 1400–1699 and 1700–1999. Established political boundaries in populated areas often limited mass migration [38, 47].[4] Climatic forcing could no longer be dissipated by mass migration. The result of such mass migration, when it occurred, often was war [69, 73]. The absence of this important social buffering mechanism may explain why the climate-war relationship was strong in the later period.

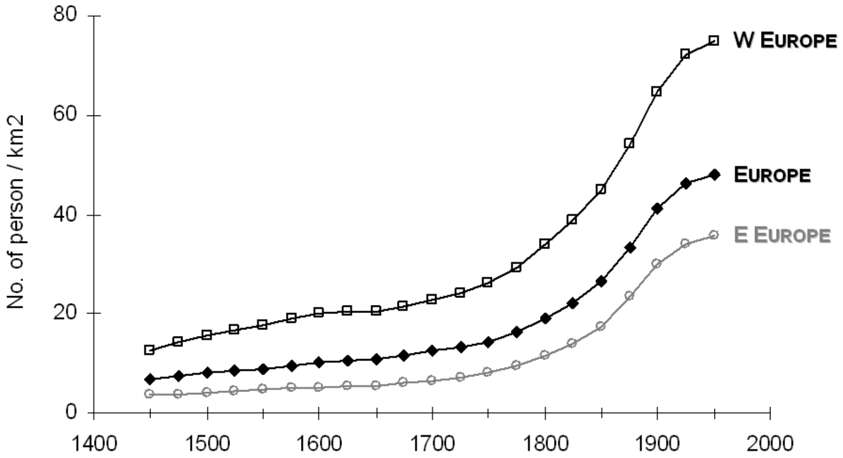

Figure 3 Population density in Europe. It is derived from McEvedy and Jones [46] and the unit is expressed in the number of people per km^2. Data are smoothed by the 100-yr Butterworth low-pass filter and then sampled at every 25th pt (i.e., 1pt = 1yr) along the temporal dataset.

The spatial disparity can be attributable to the dependency of agriculture in the two regions. Most pre-industrial economies had standards of living not much above subsistence, among that the majority of the population were focused on producing their means of survival. In medieval Europe, 80% of the labour force was employed in subsistence agriculture. However, prior to the Industrial Revolution (c. 1800), the economy of the nations of Western Europe such as Spain, France, Britain, and Holland was somehow based upon colonization and trade policies, rather than agriculture. Germany could join the western powers in the 19th century when the European economy had an industrial base; dependence upon climate is no longer total when trade and industry take the place of agriculture [28]. The gap between Eastern Europe

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[4] Someone may argue that improvement in transportation since the mid-19th century has cheapened ocean travel and made it far safer than before, resulting in vast exodus overseas in 1840–1920 (~46 million persons). Nevertheless, when measured against the circumstances of the deeper past, the conditions that permitted such an intercontinental outpouring were exceptional. It is not reasonable to suppose the above migration pattern to recur [47].

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and Western Europe in terms of the level of industrial production has further widened since the Industrial Revolution [4].

Table 3. Comparison of the change of population density in Europe between 1400–1699 and 1700–1999.

Region	Start yr	End yr	% of change
	1400	***1700***	
Whole of Europe	6.17	12.35	+100.2%
Eastern Europe	3.21	6.39	+99.1%
Western Europe	11.56	23.14	+100.2%
	1550	***1850***	
Whole of Europe	9.05	27.26	+201.2%
Eastern Europe	4.79	17.70	+269.5%
Western Europe	17.74	46.06	+159.6%
	1699	***1999***	
Whole of Europe	12.31	72.74	+490.9%
Eastern Europe	6.37	52.49	+724.0%
Western Europe	23.09	112.23	+386.1%
	1400	***1999***	
Whole of Europe	6.17	72.74	+1,078.9%
Eastern Europe	3.21	52.49	+1,535.2%
Western Europe	11.56	112.23	+870.8%

The data is derived from McEvedy and Jones [46] and the unit is expressed in the number of people per km^2. The percentage of change is calculated from the lower limit (1400 to 1700) to upper limit (1400 to 1999).

One point, however, is worth mentioning: the negative correlation between temperature and wars (smoothed by 40-yr filter) in Eastern Europe sprung from –0.278 (in 1400–1699) to –0.711 (in 1700–1999). This point should be kept in mind, and will be further explained in a later section.

3.3 Temperature, precipitation, and wars

Temperature and precipitation are both important climatic variables in determining agricultural production and, ultimately, land carrying capacity. We identified their respective effect upon the risk of wars in Europe via multiple regression analysis. Our data were each smoothed with the Butterworth low-pass filter to remove variations on time-scales <40yrs[5]. The numbers of violent conflicts were entered as dependent variables, while temperature and

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[5] In reference to the data processing methods of our previous work [69, 71, 73], our temperature and war data were also smoothed by a 40-yr Butterworth low-pass filter. This could make our associated findings more appropriate within the context of climate-war studies.

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precipitation were entered as independent variables. Three regression models were run, including (1) Temperature; (2) Precipitation; and (3) Temperature + Precipitation. We assume that the progression of calendar years gives a rough approximation of societal development, given the social buffering mechanisms mentioned earlier. To isolate the effect of time on the number of wars, in each model, three de-trending methods were used to eliminate the trend from the violent conflicts, using parabolic (yr and yr^2), squared (yr^2), and cubic (yr^3) terms (see [23]). Nine multiple regressions were run in total for each of the regions.

For the whole of Europe (Table 4), when the time effect was controlled, temperature was negatively correlated with the number of violent conflicts in the Temperature Model. A 10% decrease in temperature resulted in a 6.4% increase in violent conflicts. In the Precipitation Model, however, precipitation failed to exhibit a significant and substantive effect on violent conflicts. In the Temperature + Precipitation Model, when temperature and precipitation were entered into the regressions together, both variables were significantly correlated with the number of violent conflicts, although the influence of temperature was revealed to be much stronger. A 10% decrease in temperature resulted in a 7.1% increase in violent conflicts, while a 10% decrease in precipitation only resulted in a 2.3% increase in violent conflicts.

For Eastern Europe (Table 5), a 10% decrease in temperature resulted in a 5.4% increase in violent conflicts in the Temperature Model. On the other hand, a 10% increase in precipitation results in a 1.2% increase in violent conflicts in the Precipitation Model. Yet, in the Temperature + Precipitation Model, only temperature was significantly correlated with the number of violent conflicts. A 10% decrease in temperature resulted in a 5.6% increase in violent conflicts.

For Western Europe (Table 6), a 10% decrease in temperature resulted in a 2.5% increase in violent conflicts in the Temperature Model. In addition, a 10% decrease in precipitation results in a 1.3% increase in violent conflicts in the Precipitation Model. In the Temperature + Precipitation Model, both variables were significantly correlated with the number of violent conflicts. A 10% decrease in temperature resulted in a 3.1% increase in violent conflicts, while a 10% decrease in precipitation resulted in a 2.2% increase in violent conflicts.

As it was found by Tol and Wagner [65], our study shows that precipitation exerted a weaker influence in triggering wars than temperature did for the whole of Europe. However, down to the regional level, the situation was a bit different. Our findings indicate that in Eastern Europe, temperature was much more important than precipitation in triggering warfare. In Western Europe, however, temperature and precipitation were somehow equally important in triggering warfare. The above disparity might be attributable to the varying regional climatic conditions in Eastern Europe and Western Europe.

Table 4. Regressions of violent conflicts on calendar year, temperature, and precipitation in the whole of Europe.

Model	Constant	Independent variables					n	R^2_{adj}	β (temp)	β (prec)
		Yr	Yr^2	Yr^3	Temp	Prec				
Temperature	–0.011 (0.527)	5.905** (2.228)	–6.150** (2.224)		–0.478*** (0.027)		444	0.603	–0.642	---
Temperature	–0.304 (0.556)		–0.269 (0.151)		–0.473*** (0.027)		444	0.603	–0.636	---
Temperature	–0.284 (0.530)			–0.290 (0.149)	–0.473*** (0.027)		444	0.602	–0.636	---
Precipitation	0.003 (0.570)	3.232 (2.889)	–3.657 (2.885)			–0.031 (0.060)	444	0.420	---	–0.024
Precipitation	–0.142 (0.546)		–0.437* (0.186)			–0.033 (0.060)	444	0.399	---	–0.026
Precipitation	–0.122 (0.541)			–0.445* (0.184)		–0.032 (0.060)	444	0.392	---	–0.026
Temperature + Precipitation	–0.013 (0.533)	5.721** (2.136)	–5.933** (2.132)		–0.529*** (0.027)	–0.291*** (0.046)	444	0.622	–0.710	–0.231
Temperature + Precipitation	–0.303 (0.568)		–0.236 (0.146)		–0.524*** (0.027)	–0.292*** (0.046)	444	0.622	–0.704	–0.233
Temperature + Precipitation	–0.285 (0.541)			–0.256 (0.144)	–0.524*** (0.027)	–0.292*** (0.046)	444	0.622	–0.704	–0.233

All data have been smoothed by 40-yr Butterworth low-pass filter and then normalized prior to the regression analysis. The regressions are corrected for autoregressive disturbances using the Prais-Winsten estimation method. Standard errors are in parentheses. R^2_{adj} = adjusted R^2; β = standardized coefficients; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

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Table 5. Regressions of violent conflicts on calendar year, temperature, and precipitation in Eastern Europe.

Model	Constant	Independent variables					n	R^2_{adj}	β (temp)	β (prec)
		Yr	Yr^2	Yr^3	Temp	Prec				
Temperature	0.008 (0.443)	2.878 (3.271)	–2.910 (3.267)		–0.557*** (0.041)		444	0.436	–0.545	---
Temperature	–0.094 (0.408)		–0.043 (0.191)		–0.555*** (0.041)		444	0.409	–0.542	---
Temperature	–0.091 (0.405)			–0.051 (0.190)	–0.555*** (0.041)		444	0.406	–0.542	---
Precipitation	0.024 (0.482)	0.114 (3.826)	–0.359 (3.822)			0.199* (0.082)	444	0.244	---	0.115
Precipitation	0.021 (0.461)		–0.245 (0.222)			0.199* (0.082)	444	0.144	---	0.115
Precipitation	0.029 (0.464)			–0.244 (0.221)		0.199* (0.082)	444	0.136	---	0.115
Temperature + Precipitation	0.007 (0.441)	2.827 (3.269)	–2.852 (3.265)		–0.572*** (0.043)	–0.082 (0.072)	444	0.451	–0.559	–0.048
Temperature + Precipitation	–0.092 (0.407)		–0.035 (0.191)		–0.569*** (0.043)	–0.083 (0.072)	444	0.438	–0.557	–0.048
Temperature + Precipitation	–0.090 (0.404)			–0.043 (0.190)	–0.569*** (0.043)	–0.083 (0.072)	444	0.435	–0.557	–0.048

All data have been smoothed by 40-yr Butterworth low-pass filter and then normalized prior to the regression analysis. The regressions are corrected for autoregressive disturbances using the Prais-Winsten estimation method. Standard errors are in parentheses. R^2_{adj} = adjusted R^2; β = standardized coefficients; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

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Table 6. Regressions of violent conflicts on calendar year, temperature, and precipitation in Western Europe.

Model	Constant	Independent variables					n	R^2_{adj}	β (temp)	β (prec)
		Yr	Yr^2	Yr^3	Temp	Prec				
Temperature	–0.028 (0.501)	6.212 (3.585)	–6.564 (3.580)		–0.247*** (0.045)		444	0.534	–0.253	---
Temperature	–0.268 (0.513)		–0.371 (0.219)		–0.241*** (0.045)		444	0.526	–0.248	---
Temperature	–0.248 (0.497)			–0.389 (0.216)	–0.241*** (0.045)		444	0.529	–0.248	---
Precipitation	–0.021 (0.540)	4.552 (3.685)	–4.985 (3.681)			–0.211** (0.077)	444	0.429	---	–0.128
Precipitation	–0.198 (0.532)		–0.447* (0.224)			–0.214** (0.077)	444	0.430	---	–0.130
Precipitation	–0.178 (0.522)			–0.459* (0.222)		–0.214** (0.077)	444	0.429	---	–0.130
Temperature + Precipitation	–0.030 (0.515)	6.003 (3.518)	–6.316 (3.513)		–0.310*** (0.046)	–0.363*** (0.077)	444	0.548	–0.318	–0.221
Temperature + Precipitation	–0.271 (0.538)		–0.331 (0.219)		–0.305*** (0.046)	–0.365*** (0.077)	444	0.532	–0.313	–0.222
Temperature + Precipitation	–0.252 (0.519)			–0.350 (0.215)	–0.305*** (0.046)	–0.365*** (0.077)	444	0.536	–0.313	–0.222

All data have been smoothed by 40-yr Butterworth low-pass filter and then normalized prior to the regression analysis. The regressions are corrected for autoregressive disturbances using the Prais-Winsten estimation method. Standard errors are in parentheses. R^2_{adj} = adjusted R^2; β = standardized coefficients; * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

The climate of Europe varies from sub-tropical to polar. Prevailing westerlies (conditioned by the Azores High) bring rain from the Atlantic Ocean to the west, while the Siberian High brings colder, drier weather from the east. Subject to the above geographic settings, Eastern Europe is characterized by a continental climate with large annual variation in temperature due to the lack of significant bodies of water nearby. Relatively moderate precipitation occurs mostly in summer. Precipitation reaches only between 250 and 500mm annually [17]. Given that variability of temperature is much more profound than that of precipitation in Eastern Europe, the agricultural production there is primarily determined by temperature instead of precipitation. On the other hand, Western Europe is characterized by a maritime climate with moderately cool summers and comparatively warm winters and a narrow annual temperature range. It typically lacks a dry season, as precipitation is both adequate and reliable throughout the year [17]. Since both temperature variability and precipitation variability are not extreme in Western Europe, they play equally important roles in determining the agricultural production there. The above relationship is ultimately translated into the regional disparity regarding the influence of temperature and precipitation changes upon war outbreak.

3.4 Temporal consistency of temperature-war association

The disparity of the strength of the climate-war association between 1400–1699 and 1700–1999 reveals that the climate-war relationship did not hold consistently at multi-centennial time-scale. Such inconsistency may be applied to a shorter time-scale. Therefore, we employed moving correlation analysis to further inspect the possible non-stationary relationship at multi-decadal to centennial time-scale, in which climate variability is usually discussed [50]. The moving correlation window was set at a 101-pt (i.e., 1pt = 1yr) width and moved to every 10th pt along the temporal dataset. The moving correlation curves (MC curves) of the whole of Europe, Eastern Europe, and Western Europe are shown in Figure 4.

For the whole of Europe, all of the moving correlation coefficients were negative, which exceeded 99% significance ($p < 0.01$) (Figure 4(a)). The long-term trend of the MC curve was headed slightly downward, which implies in general that the negative association between climate change and war was getting stronger with time. Despite the long-term downward trend, the climate-war correlation was periodically distorted in the 1470s–1500s, 1580s–1670s, and 1810s–1850s. The distorted correlations were clustered in three periods, as opposed to being randomly scattered throughout the data.

We proceeded to compare the MC curves of Eastern Europe and Western Europe. For Eastern Europe, the long-term trend of the MC curve was downward, while for Western Europe, the long-term trend of the MC curve was upward (Figure 4(b)). The long-term downward trend of the MC curve for the whole of Europe might be attributable to the strengthening of a negative climate-war correlation in Eastern Europe. The MC curves of Eastern Europe and Western Europe were further compared in three phases (Figure 4(b)). In

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Phase I (before the 1670s), we found that no matter in Eastern Europe or Western Europe, the majority of the moving correlation coefficients were negatively significant at the 99% level. In addition, the association between temperature and war was distorted in some periods. However, the MC curve of Western Europe lagged behind the one of Eastern Europe by ~50yrs. In Phase II (1670s–1810s), all of the moving correlation coefficients for Eastern Europe and Western Europe were negatively significant at the 99% level. The MC curves of both regions basically moved in a synchronous manner. In Phase III (1810s afterwards), a great divergence was envisaged in which the MC curves of Western Europe and Eastern Europe went in opposite direction. In Western Europe, moving correlation coefficients ranged between weakly positively significant or not statistically significant. In Eastern Europe, the moving correlation coefficients were all negative and getting stronger with time.

Given that cooler climate resulted in human catastrophes only if the population system had already pushed against its Malthusian constraints [35, 36, 37, 63, 66], the disparity of MC curves between Eastern Europe and Western Europe might be attributable to periodic differences of population pressure in the two regions. To test the above hypothesis, we correlated those MC curves with the associated population growth rate within the periods of decreasing population growth rate. Statistical results show that during population decline, MC curves and population growth rate were in negative association (Table 7). This implies that the impact of cooling upon social stability was weakened when population pressure within societies had been reduced. Such a phenomenon was especially true for Eastern Europe. The time lag between the MC curves of Eastern Europe and Western Europe in Phase I could be attributable to the different timing of population decline in the two regions. On the other hand, the synchronous movement of MC curves happened in Phase II because the period was marked by steady population growth in both Eastern Europe and Western Europe.

Regarding the disparity of MC curves in Phase III, another factor pertinent to population pressure played a part – industrialization[6]. Industrialization not only decreases human dependency on agricultural production, but also increases land carrying capacity. Population growth in Eastern Europe has surpassed that in Western Europe since the early 17th century [46], while the level of industrial production in Eastern Europe was lower than that in Western Europe in the pre-industrial period [4]. This historical regional setting made Eastern Europe particularly vulnerable to climate deterioration. The industrial take-off which resulted from the Industrial Revolution (c. 1800) has served as

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[6] Industrialization is the process of social and economic change that transforms a human group from an agrarian society into an industrial one. It is part of a wider modernization process, where social change and economic development are closely related with technological innovation, particularly with the development of large-scale energy and metallurgy production. It is the extensive organization of an economy for the purpose of manufacturing.

a catalyst which further magnifies the disparity of the two regions. Although industrial production grew rapidly from the period 1840–1850, the rate of industrial growth in Eastern Europe was far below than that in Western Europe (Figure 5). Such an ever-widening gap between their respective levels of industrialization, together with the significant gap between their respective rates of population growth, explain not only the disparity of MC curves for Eastern Europe and Western Europe in Phase III, but also the significant increase of the negative temperature-war correlation in Eastern Europe from 1400–1699 to 1700–1999.

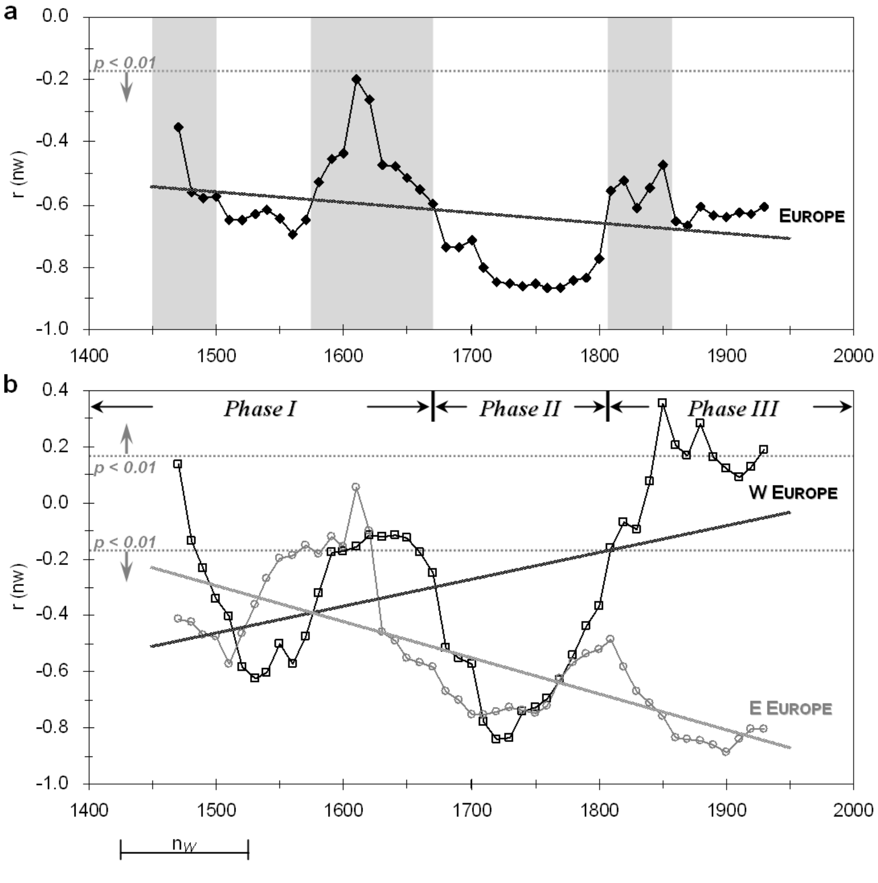

Figure 4 Moving correlation curve (MC curve) between temperature and violent conflicts in Europe. (a) The whole of Europe. The periods in which the climate-war relationship is distorted are shaded as grey stripes. (b) Eastern Europe and Western Europe. Correlation window, nw, is equal to 101-pt (yr). The width of the window is indicated in the lower left-hand corner. All data have been smoothed by 40-yr Butterworth low-pass filter prior to the moving correlation analysis. In all panels, correlation is calculated at every 10th pt along the time series. The corresponding values are plotted at the centres of the window periods. Shaded lines represent the long-term (linear) trend of the MC curves. The thin dashed horizontal lines indicate the 99% confidence limit after correcting the degrees for autocorrelation of the time series.

Table 7. Correlation analysis between moving correlation curve (MC curve) and population growth rate within the period of decreasing population growth rate.

	Periods of decreasing population growth rate			
Region	Whole of Europe	Eastern Europe	Western Europe	All regions
Whole of Europe	−0.276	−0.623**	0.055	−0.428
Eastern Europe	−0.678**	−0.770***	0.103	−0.824**
Western Europe	−0.262	−0.569*	0.070	0.105

The periods of decreasing population growth rate for various European regions are listed as follows: Whole of Europe: 1480s–1530s, 1610s–1640s, 1830s–1850s and 1900s –1930s; Eastern Europe: 1480s–1620s, 1830s–1840s and 1910s–1930s; Western Europe: 1480s–1540s, 1570s–1630s, 1830s–1850s and 1900s–1920s; all regions: 1480s–1530s, 1610s–1620s, 1830s–1840s and 1910s–1920s.

In order to match with the time-scale of the MC curve, population growth rate data (derived from McEvedy and Jones [46]) are smoothed by the 100-yr Butterworth low-pass filter and then sampled at every 10th pt (i.e., 1pt = 1yr) along the temporal dataset. Autoregressive disturbances in time-series were corrected by using the Prais-Winsten estimation method.

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

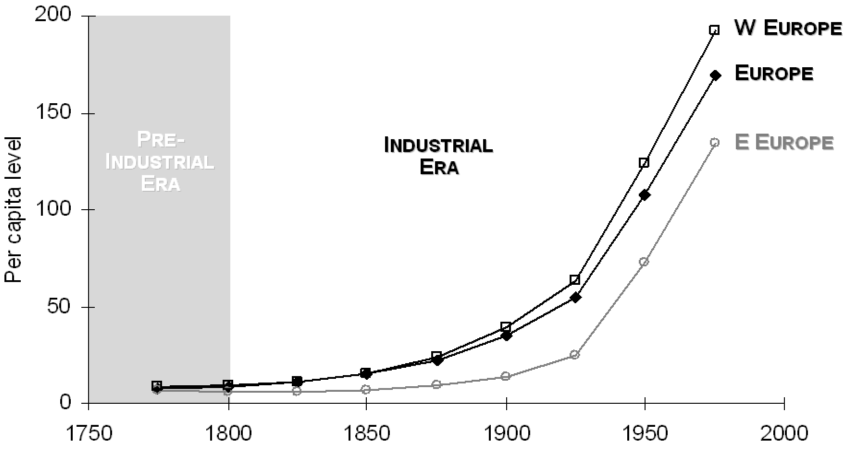

Figure 5 Level of industrialization in Europe. It is derived from Bairoch's study [4] and defined in terms of volume of industrial production per capita relative to the U.K. (in 1899–1901 = 100). Data points represent the 50-yr averaged value. Pre-industrial era is shaded as a grey strip.

4 DISCUSSION

4.1 Comparing our research findings with those of other studies

Despite the difference in culture, resource endowment, and socio-political structure, those large-N studies consistently show that periodic cooling is a significant factor in triggering wars and social unrests in China [15, 35, 36, 37,

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67, 68, 70, 71, 72], Europe [1, 65, 73], and various regions in the Northern Hemisphere [69, 74] over extended periods. Although the findings in the present study concur with those of previous studies about Europe [1, 65, 73], we further accentuate that the climate-war correlation varied across the European continent, just like the case of China. At multi-centennial time-scale, temperature-war correlation was stronger in Eastern Europe partly because of the region's higher dependency on agriculture and partly because of the region's prevalence of continental climate. At multi-decadal to centennial time-scale, the temperature-war correlation in Europe was not stationary. It was periodically distorted when population pressure was released through a considerable decline in the rate of population growth or through industrialization. Furthermore, the regional disparity in terms of population growth rate and pace of industrialization might be responsible for the diverse trends and trajectories of the temperature-war correlation in Eastern Europe and Western Europe.

Tol and Wagner [65] find that the climate-war relationship in Europe weakens in the industrialized era. Owing to social and technological advancement, human societies have become less dependent on agriculture and agricultural production has been less affected by the weather in general. However, our findings show that their observation is only relevant to Western Europe, not to Eastern Europe. In fact, because of the strengthening of the climate-war correlation in Eastern Europe over time, the climate-war relationship in the whole of Europe was also getting stronger in the long run.

4.2 Addressing the controversies about climate-war association

Despite the fact that the physical history of climate in Europe is presently known in considerable detail, climatic change is rarely integrated in grand historical syntheses [55]. The reluctance to discuss the issue of climatic change may be rooted in the prevalent view that events in the natural environment are not relevant to human history. Here we base on our research findings to address some major controversies about the climate-war link: a) if climate-war link can be broken by human adaptation; b) if climate-war link is too environmentally deterministic in a sense.

4.2.1 Can climate-war link be broken by human adaptation?

When facing environmental changes, humans can respond with various strategies such as importing foodstuffs, reducing taxes in affected area, planting crops that are highly resistant to cold and dry weather, improving cultivation skills, and so on. The above measures could help maintain social stability during protracted periods of cold [20]. Briefly, warfare is unlikely cause by deteriorating climate because of the adaptive capacity of humans. However, from the case of Europe, even though human societies could adapt to climate deterioration via social buffering mechanisms in the short run, they failed in the long run if the climate variability was a multi-decadal and continental-wide one. Hence, it may be inappropriate to focus on the short-term success of human adaptive responses to refute the impact of climatic change on human societies. In addition, the term 'adaptation' (and the consequent reduction in vulnerability to climate change) seems as if it could easily be extended to human collectivities. However, human history is filled with examples of groups that have proposed models of societal progress that turn out only to benefit a fraction of the population [22, 52], just like the case of industrialization in Europe. Our empirical results show that it only helped Western Europe disconnect the link from climate change to violent conflicts after the 1810s.

Human agencies are always presumed to have choices in adapting to a wide variety of environmental conditions. Too often, adaptation is assumed to take place as a spontaneous, readily available, and cost-free activity. In the real world, the so-called 'choices' may be constrained by a bundle of socio-economic and cultural factors [5]. Indeed, the capability of human societies to cope, adapt, or recover from the effects of climate change is shaped by the interaction of environmental and social forces [21]. Moreover, population pressure may gradually reduce the societies' coping ability and narrow their coping range [22, 61]. For instance, mass migration may be a possible adaptive choice to risks associated with climate change. But, it is constrained by an increasingly populated world. Hence, human adaptations are not always the outcome of a selection process over which human agency has control [7, 60]. Therefore, the complacent view that adaptation will surely solve the problem is a dangerous delusion.

4.2.2 Is climate-war link too environmentally deterministic in a sense?

Emphasizing the effect of climate change upon war is seemingly smack of environmental determinism. Here we emphasize that not every individual cases of war can be attributed to cooling. Every incident is unique and has its local, social, and political contexts if it is viewed in a micro-historic perspective. Clearly, wars can be induced by factors other than climatic change. Sometimes, they may simply happen at random. Nevertheless, we should distinguish individual cases of wars from cycles of wars. They are different analytical units representing different hierarchies of a problem, which should be addressed by different research approaches. Such a distinction in the scale of analysis should not be overlooked, because a sparse attention to the scale of analysis may result in a comparison between apples and oranges.

In this research, the climate-war relationship is investigated in a macro-historic perspective. We found that the correlation between climate change and violent conflicts was valid in terms of their multi-decadal cycles. In a broader perspective, as noted by Fagan [18, 19], ever since the beginnings of farming some 12,000yrs ago, humans' survival depended on crop yields and on storing enough seed to plant for the next year. The sufficiency or insufficiency of food was a powerful motivator of human action. Even as late as the 19th century, millions of peasants lived at the subsistence level; in fact, the description is still applied to millions of people living in less developed parts of the world. Climate is, and always has been, a powerful catalyst in human history [18, 19].

On balance, a cooling climate means shorter growing seasons, and implies some abandonment of marginally arable land, retreat in certain areas

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from double cropping, and reduced yields of certain crops [23]. Given that social stability is a function of economy in terms of agricultural production, and that agricultural production was significantly determined by long-term climate change in the past (cf. Introduction), deteriorating climate was an influential factor driving the multi-decadal war cycles in European history. This conclusion is further substantiated with empirical historical data and statistical analyses.

5 CONCLUSIONS

Since human societies exist in the context of certain environmental conditions, a changing climate that significantly alters these conditions is expected to have an impact on human life and society. At the heart of the debate over the role of climate in warfare lies the desire to provide scenarios of future conflict patterns under global warming [56]. The warmth after the late 20th century is an anomalous and unprecedented event in the last millennia [44, 49]. Since both natural and anthropogenic forcing has been engaged, global temperature is expected to rise faster and faster in the foreseeable future [2]. It is generally believed that the warmth is a threat to human societies in many ways [30], while the magnitude of temperature increase has the potential to undermine human security and overwhelm adaptive capacities of societies in many world regions [59].

There is an ongoing debate about increased temperature and violent conflicts in Africa [9, 10, 26, 51]. The present study shows that the social instability in Europe (Eastern Europe in particular) was triggered by a cold climate at long-term temporal time-scale, which seems to contradict with the case of Africa. People may even think that our results are a plea to welcome global warming. However, it is worth mentioning that cooling shortens the crop growing season and reduces farmland area in middle and high latitudes (Europe) [23], while warming shortens the duration between sowing and harvesting and increases evapotranspiration in equatorial regions (Africa) [39]. Both are detrimental to agricultural productivity and subsequently human societies. Concerning Africa – the region adversely affected by the warmth, most of the countries there are underdeveloped or developing. They are supported by weather-sensitive agro-pastoral production system and characterized by inadequate capacity, economic strength, and institutional capabilities, and most importantly, by rapid population growth [30]. Out of the 12 major food-insecure regions in the world, five of them locate in Africa [40][7]. Given the vulnerability of natural and social systems of African countries to

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[7] The 12 major food-insecure regions are: South Asia, China, Southeast Asia, East Africa, Central Africa, Southern Africa, West Africa, Central America and Caribbean, Sahel, West Asia, Andean region, and Brazil. Each of the regions comprises groups of countries with broadly similar diets and agricultural production systems and contains a notable share of the world's malnourished individuals as estimated by the Food and Agriculture Organization (FAO) [40].

climate change, the impact of climate change could prove extremely detrimental in the coming decades. The failure of African societies to cope with climate change may generate a range of security problems that will have dire global consequences. It can jeopardize the stability of the international system and rebound adversely to wealthy countries [14]. Therefore, it is imperative for both the academic and policy realms to understand better whether or not, and under what regional geographic conditions, climate change has contributed to violent conflicts in Africa at long-term temporal scale. Some scholars mention that the negative effects of inter-annual variability in climate may be mitigated if the relationship of direct dependence of African agriculturalists on climate is broken [27], just like the case of Western Europe presented in this study. When will it happen? Only time will tell.

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COMPETING INTERESTS STATEMENT

No competing interests.

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