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Beyond climate and conflict relationships: New evidence from a Copula-based analysis on an historical perspective ☆

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ABSTRACT

This paper contributes to the new climate-society literature (Carleton and Hsiang, 2016) by analyzing the role of climate in conflicts over the pre-industrial period in Europe, in the vein of the recent literature initiated by Tol and Wagner (2010) and Burke and Hsiang (2014). As far as we know, this study is the first to apply a (time-varying) copula analysis to climate-economics literature and to investigate the dependence between climate and conflicts in a historical time series context. Both social disturbances and wars are considered and their interrelationships are taken into account. The main contributions of the paper are: (1) the use of copula analysis compared to previous correlational approaches; (2) the analysis of the temporal heterogeneity of climatic effects via a time varying approach; (3) the introduction of agricultural and fiscal pressure channels to investigate the interrelationships between climate, social disorders and warfare; (4) the investigation of El Niño Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO) Teleconnections effects whereas previous long-term historical studies have only focused on precipitation and temperature data. Time varying Copula analysis enabled us to identify a positive dependence between temperatures and conflicts, and negative or positive dependences between anomalous precipitation and conflicts, by explicitly focusing on the joint distribution of our variables. We were also able to precisely identify the periods/regimes during which the link between climate and conflict was genuinely active and then stress on the agricultural and fiscal revenues channels.

1. Introduction

A new multi-disciplinary literature referred to as climate-society literature has emerged recently to investigate how climate is likely to affect society (Carleton and Hsiang, 2016). This literature constitutes a multidisciplinary renaissance of quantitative empirical research highlighting important linkages in the coupled climate-human system.[1]

The motivation of this work consists in better understanding the links between climate and conflicts by adding a new piece in this literature. The positive association between climate and conflicts has been empirically highlighted in a recent literature (Hsiang et al., 2011, 2013; Burke et al., 2015b,a): for example, Hsiang et al. (2013) identified an empirical connection between climate

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[1] See especially Dell et al. (2014) for a survey of macroeconomy-climate change literature.

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change and conflicts across 12,000 years of human history. The conflict terminology is a proxy of intergroup violence and social interactions, as classified by Burke and Hsiang (2016). Then, climate variations may influence relationships between different groups in society and can lead to social disturbances, for instance civil unrest, including riots or insurrections. In this respect, climate change is likely to increase civil conflicts and protests inside a country. Land invasion in Brazil (Hidalgo et al., 2010) or civil war induced by droughts in Somalia (Maystadt and Ecker, 2014) are examples of such cases. More generally, climate can generate interpersonal violence (Hsiang et al., 2013; Burke et al., 2015a), from low-level aggression to violent crimes (see Ranson, 2014 for example) through physiological and cognitive mechanisms and even suicides (Burke et al., 2018).

However, the link between climate and violence remains a controversial topic despite the existence of a very huge literature. Adams et al. (2018) considered that the connections between climate change and conflicts were overstated by sample biases, since the countries that were mentioned most were also the most violent ones recently. In the same vein, some researchers moderate the previous positive correlation's results between climate and violence and find weak or no consistent correlation between climate and conflict: not only Buhaug (2010a,b),[2] stressing on the lack of control variables, but also Buhaug et al. (2014), Koubi et al. (2012), Raleigh et al. (2014) or O'Loughlin et al. (2014). Similarly, recent studies find that the climate-conflict relationship is strongly context dependent: Von Uexkull et al. (2016) underlines the effects of local droughts on violence for agriculturally dependent groups as well as politically excluded groups in very poor countries whereas Ide et al. (2020) highlight that the relationship between disasters and conflict is highly conditional, occurring almost exclusively in countries with ethnic exclusion, low levels of human development and large populations. Böhmelt et al. (2014) show that demand-side drivers, such as population pressure, agricultural productivity, and economic development are likely to have a stronger impact on water conflict risk than supply-side factors, represented by climate variability. More broadly, some researchers such as Ide (2017) have pointed to the limits of current quantitative approaches and the need of a complementary qualitative approach to well understand the exact mechanisms through which climate change affects violent conflict.

In this paper, we add a new piece in this literature by adopting a long-term historical perspective to empirically understand the links between climate and violence with long time series, in the vein of Tol and Wagner (2010) and Burke and Hsiang (2014). Indeed, Zhang et al. (2007, 2006 and, to a lesser extent, 2011) suggested that the link between climate and conflicts is not recent and already existed in pre-industrial societies. We focus on the pre-industrial Europe to naturally experiment the effect of extreme weather and climate change on conflicts. Indeed, our sample period (1300–1900 and more especially 1500–1800) falls within the period of lowest temperatures at any time in the past millennium, the so-called Little Ice Age (see for instance Osborn and Briffa, 2006).[3] Cooling periods in feudal Europe are also likely to have been a major cause of economic and human crisis via social disturbances (Zhang et al., 2011 or Parker, 2013).

As previously explained by Zhang et al. (2007, 2011) and Pei et al. (2013), a large geographic scale can help us to understand the complex interactions between nature and human society, while focusing on a specific socioeconomic period (pre-industrial Europe in this case) can help us to interpret the relationship between climate and socioeconomic variables. Our study thus brings an interesting contribution to the literature on the long-term impact of climate change. Only a limited number of studies have quantitatively detected the short- and long-term impacts of climate variations on society during the pre-industrial era (Pei et al., 2013, 2014; Kaniewski and Marriner, 2020), especially in the economic literature.[4]

For the first time, we used a new time-varying copula methodology to re-investigate the empirical association between climate and conflicts. By the way, this paper tries to take into account several potential issues in the previous literature. At least, this paper provides an alternative view to analyze the dependence between climate and conflicts. In addition, conflicts were defined very generally as encompassing both social disturbances or riots, and wars. Although previous papers have generally been more interested in wars, we expected to find positive correlations between social troubles and wars, and therefore investigated them simultaneously. Copula methodology was interesting in that it enables us to investigate the dependence of two variables in a complex way, while time-varying analysis enables us to classify periods with zero, negative or positive dependence and study temporal heterogeneities. Contrary to a correlation, the copula approach can highlight extreme dependencies for very high or low values of the studied series and is particularly suitable to quantitatively investigate climate series characterized by rare and strong event (droughts, floods, hurricanes, hot wave). In addition, Copula-based methodology enables us to highlight the possible asymmetry of the dependencies between climate and conflicts. Nevertheless, note that the copula methodology is not a per se causality method and do not give information about which one of the two series drives or leads the other one.

In our context, the time varying copula methodology provides a way of making a distinction between periods of close association between climate and violence or social disorders and periods without any correlation. Using historical records, we can explain whether the periods identified by our empirical methodology can be explained by any particular events. Finally, this methodology is interesting to identify whether the relationship between climate and conflict is a mean relationship or stems from extreme events, and whether it is stable over time and gradual or, on the contrary, whether particular sub-periods are driving the negative

[2] See some controversial exchanges in the PNAS journal between Burke et al. (2010a,b) and Buhaug (2010a,b).

[3] The Little Ice Age is a controversial topic: see for example White (2014) as opposed to Kelly and Gráda (2014, 2013).

[4] Some rare cases are Waldinger (2015), Tol and Wagner (2010) and Iyigun et al. (2017a,b). Waldinger (2015) used European city panel data to assess the economic effects of long-term, gradual climate change over the 1500–1750 period when people have time to adapt. However, she focused on panel data about major European cities with a very low time-series dimension to explore the city dimension of the data. The evidence indicates that decreased temperatures led to shortened growing periods and more frequent harvest failure in this period. Iyigun et al. (2017a,b) and Tol and Wagner (2010) were more similar to our contribution. The former used panel data with a new conflict dataset over 1400–1900, finding that climate change increased conflict. The latter used time series and are closely related to our paper.

correlation found in the previous literature. Finally, as also stressed by De Juan and Wegenast (2019), temporal variability has received substantially less attention than spatial variability. However, it is particularly important if we want to assess the potential impact of climate change on violence in the future.

From a climatology point of view, taking into account the Little Ice Age enables us to proxy important climate (cold) changes and infer some results about climate change. From a society/policy point of view, working on pre-industrial Europe is interesting to show how economic or social vulnerability might lead to, or reinforce effects of climate on conflicts. Considering (Tol and Wagner, 2010), the economies in the 1600's were very similar (in income comparisons) to some vulnerable developing countries today. Since the developing countries are particularly concerned by probable future climate change (Burke et al., 2015b), our cliometric investigation can help policy makers warn populations and implement suitable climate change mitigation policies. From a methodology point of view, focusing on the 1500–1800 period leads us to compare our results with some benchmark studies and check their robustness (especially Tol and Wagner, 2010; Zhang et al., 2011). In addition, focusing on a long-run period enables us to use relatively rich data, considering the abundance of detailed records during this particular period and thus to conduct time series causal identification. In addition, large-scale data and historical analysis enable us to avoid some potential sampling bias, especially in panel studies, as pointed out by Adams et al. (2018), since we focus on a relatively homogeneous subset of European countries. From a history point of view, the period covers the macroeconomic and general human crisis of the seventeenth century (Fischer, 1996; Parker, 2013) already studied by Zhang et al. (2011) or Pei et al. (2014, 2015).

Contributions. The contribution of our paper is not only to revisit the climate/violence link using historical long-run data but also to apply a new empirical methodology to this literature. Unlike previous literature that used correlation and Granger causality in time series with filtered data (Zhang et al., 2007, 2011) or regression analysis (Tol and Wagner, 2010), we applied a time varying copula methodology to non-transformed data. (1) Using non-transformed data enables us to avoid the so-called 'Slutsky effect' outlined by Kelly and Gráda (2014). (2) The copula methodology, usually computed in finance and/or in risk management enables us to investigate the co-movements between two series by capturing a myriad of complex and nonlinear dependence relationships, especially tail and asymmetric dependencies; indeed, the copula methodology is able to model all the joint distribution between the variables and capture the influence of extreme events in tails – like extreme weather and climate events that are rare events by definition – on other variables such as proxies of violence in this paper. Thus, the copula approach provides a specific assessment of changes in the tails of the joint distribution. (3) We use a time-varying copula approach to take into account the fact that the association might be limited to only specific time periods and takes into account temporal heterogeneity (as outlined for example by Van Baalen and Mobjörk (2018) of the association between climatic conditions and violent conflict. Identifying the sub-periods enables us to better identify the causal channels at work between climate and conflicts and some potential co-founders such as agricultural productivity and fiscal pressure.

As far as we know, this study was the first to use copulas and time-varying copula analysis in the climate-economics literature and therefore in the analysis of climate and conflicts in a time-series historical context. Copula analysis identified a positive dependence between temperatures and conflicts, and negative or positive dependence between precipitation anomalies and conflicts, by focusing explicitly on the joint distribution of our variables. Moreover, using the time-varying approach, we were able to precisely identify the periods/regimes during which the link between climate and conflict was genuinely active. In addition, we tried to link these dependence regimes to historical information to identify a causal pattern between climate and the so-called "general crisis" including macroeconomic crisis, revolts, social and political conflicts. The impact of climate on bioproductivity and cereal yield leading to famines and poor macroeconomic indicators has been suggested previously in the literature (Zhang et al., 2007, 2011; Pei et al., 2014). We checked the robustness of this causal pattern and added new mechanisms to investigate the ex-post link between economic crisis, famine and the likelihood of protests and wars linked to a variation in climate.

Finally, a last original contribution of this paper is related to the empirical data selected to capture weather extremes and climate variations. In order to test the potential climate origins (see for example Parker (2013)) of the cooling period induced by the Little Ice Age on human behaviors, we investigate the effects of ENSO (El Nino Southern Oscillation) and NAO (North Atlantic Oscillation) Teleconnections whereas previous long-term historical studies have only focused on precipitation and temperature data. Indeed, the origin of the Little Ice Age period studied in this paper might be linked to significant variations in NAO or ENSO. Studying these Teleconnections is a mean to better feature the climate/conflicts links and capture ex ante effects of the climate on conflicts and not only ex post effects via temperatures and precipitations. It could be interesting to forecast climate variations and potential increased violence episodes and to earlier alert governments and local authorities.

Copula methods face climate/conflict relationship. Although the Copula are not a new concept (Sklar, 1959), their application is very recent (Patton, 2012) and for the first time, we applied this method to the climate/conflict literature. This method has several merits to address the relationship between climatic factors and conflicts. Previous results are based on very simple mean correlations coefficients leading to some doubts about the existence of a true causal relationship. The effects of climate on conflicts are likely to be nonlinear and be the result from complex relationships between rare and extreme climatic events (droughts or floods, very cold or heat waves) rather mean temperatures or precipitations, and also extreme outcomes consisting in surge in agricultural yields and prices, social disturbances or wars. Copula method is a powerful statistical method taking into account this complexity by considering the entire joint distribution between two series and able to highlight the links behind the "simple" picture. In addition, the time varying process enables us to identify the specific active time periods when some . Contrary to previous literature, it enables to detect the most reliable sub-periods when climatic variation has led to violence and to identify the main specific co-founders at work for these specific historical sub-periods. Weakness: The method consists in a pair dependence? need to test enough potential distributions to fit the most plausible dependence form?

The rest of our paper is structured as follows. Section 2 presents the related literature, followed by the hypotheses in Section 3. Methodology and data are presented in Section 4. Section 5 present and discusses the results of the baseline Copula analysis. Section 6 extends the baseline analysis to a large set of robustness checks. Concluding remarks are presented in Section 7.

2. Related literature

Climate and conflicts after 1900. There is an abundant empirical literature about the potential effect of climate on conflicts (Burke et al., 2015a,b). A large part of the literature is related to the violence in African countries since the 1980's: among others, see Miguel et al. (2004) on the link between rainfall and civil conflict in Sub-Saharan countries, Burke et al. (2009) on adding temperatures to control previous causality between climate and civil wars in Africa, or Couttenier and Soubeyran (2013) employing the Palmer Drought Severity Index and water availability, which all point to an increasing violence effect of climate anomalies. On a more global level and using modern data, Melissa et al. (2012), Bergholt and Lujala (2012) and Hsiang et al. (2011).[5] The previous works have been challenged by Buhaug et al. (2014), Koubi et al. (2012), Raleigh et al. (2014), O'Loughlin et al. (2014), Von Uexkull et al. (2016), Ide (2017) and Ide et al. (2020), among others (see the introduction).

Climate and conflicts on an historical perspective. Our paper is more related to historical perspective papers. However, historical studies using quantitative analysis with very long-run data are scarcer. Hsiang and Burke (2014) adopted an interesting point of view by classifying empirical studies based on whether the data began before or after 1900. They argued that this cutoff was relevant to the characteristics of each kind of study: pre-1900 studies examine long historical time series, while the others examine shorter and more recent panel data where spatial heterogeneity is more pronounced. In the context of this study, we focused on the Little Ice Age period between 1500 and 1800 (1300–1900 as a robustness check) and were therefore in line with pre-1900 studies. In many pre-1900 studies, the value added lies in examining low-frequency climate changes that are absent per se or difficult to analyze in recent data. Thus, we are looking at historical studies here, especially concerning Europe zone, the geographical scope of our study.

Basically, as summarized by Scheffran et al. (2012), long-term historical empirical studies consist in investigating a potential coincidence between climate variability and armed conflict in line with some narratives about the evolution of societies and, for instance, the collapse of civilizations. Zhang and other researchers from Hong-Kong are sometimes considered the pioneers of quantitative investigation of this link (Tol and Wagner, 2010). Relying on correlation, linear regression and bivariate Granger causality tests, Zhang et al. (2006, 2007)) found evidence that cooler periods were correlated to periods of violence in eastern China (see also Yancheva et al. (2007) and Bai and Kung (2010)). Haug et al. (2003), Kennett et al. (2012) for the Americas and Zhang et al. (2011) also conducted similar investigations for Europe afterwards. More generally, they hypothetized that climatic change was associated to a large-scale human crisis, especially over the 1500–1800 Little Ice Age period.

Climate and conflicts on an historical perspective: the European case. Tol and Wagner (2010) also focused on European countries, but over a longer period (the last millennium, 1000–1980), computing Pearson correlations and regressions (with a deterministic trend or autoregressive specifications) on non-filtered and filtered data with Hamming window series. They found evidence of a negative correlation between temperature reconstructions (especially Luterbacher et al., 2004b,a) and the annual number of violent conflicts (fromwww.warscholar.com) and a positive correlation between precipitations (Pauling et al., 2006) and conflicts proxied on the same basis as previously Using different subsamples, they found that the largest mean negative effect was concentrated in the 1250–1775 period; the effect during the Little Ice Age period (1500–1700) seems to disappear over the 1700–1900 sample. This last period is interpreted as a transition period from a cold/violent to a warmer/peaceful period (Zhang et al., 2011; Hsiang and Burke, 2014). These results also suggest that temporary cooling episodes during moderate or warm periods have little effect on conflict in comparison to considerable cooling from cold baseline conditions. Büntgen et al. (2011), looking over a more extended period, found an association between times of cooling and turmoil in Europe, especially during the 30-Year War in the 1600's, in line with the present study.

Alongside this literature about climate and conflicts defined as civil conflicts or wars, there are some articles focusing on food riots, social unrest and social disturbances more generally. De Juan and Wegenast (2019) assessed the impact of temperatures on social unrest over 300 years (1500–1817) in England and confirmed the negative association between temperatures and food riots. However, they found that this association was inconsistent and largely confined to the 18th century, using time-varying correlations with a 20-year window. Moreover, computing 50 km*50 km gridded data, they found that past exposure of a region to adverse weather conditions dampened the effect of current exposure. Almer et al. (2017) looked at how deviations of the current drought situation from the long-run average affected the level of rioting in a cell via water scarcity. They relied on Tollefsen et al. (2012) for data on the number of distinct ethnic groups in a cell.

3. Stylised facts and hypotheses

3.1. Some stylised facts

Zhang et al. (2011) have suggested, using visual inspection and correlations, that cold periods, especially 1600–1650 during the Little Ice Age are associated with an increasing number of conflicts (wars and social disturbances). The Fig. 1 seems to confirm the association between temperatures (EUR_TEMP), the number of wars and the number of social troubles events, notably over 1600–1650 which is the coldest period covering the considered sample. The co-movement between climate and conflicts seem to be

[5] This paper is slightly different in the sense that they evaluate the impact of ENSO (El Nino Southern Oscillation) teleconnection, which is to say a global climate change and not a local climate change (temperature, rainfall, storms etc…) on the probability of conflict measured by an ACR (Annual Conflict Risk) proxy. are often cited.

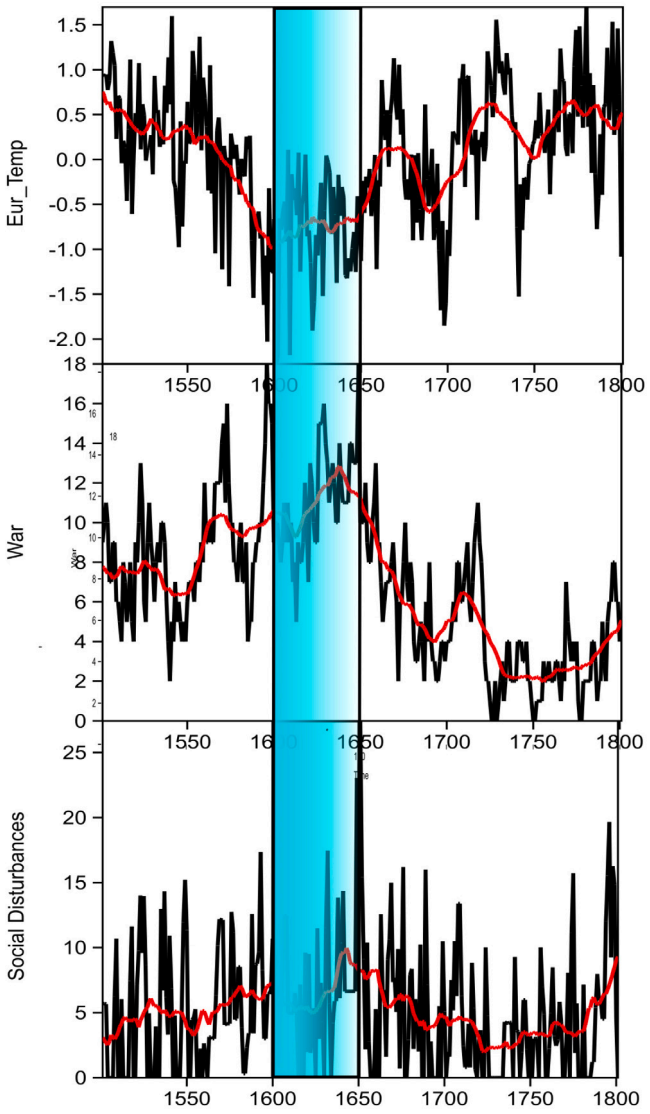

Fig. 1. Cold periods and conflicts: visual inspection.

at work for both kinds of conflicts. Previous literature has highlighted the impact of the cold period (very low annual temperatures) on the decreasing agricultural yields and on the inflation of grain and food prices. The economic difficulties are likely to be the cause of social disturbances and increasing inter-countries conflicts in a more general way. The Fig. 2 clearly highlights a negative association between the annual temperatures and the grain prices, especially over 1600–1650 period corresponding to a peak in such prices. The growth rate of fiscal revenues is also reported—for England only due to availability long time series data. The statistical link between climate, grain prices inflation and fiscal revenues is not completely clear.

3.2. Hypotheses about the climate-conflict relationship

In this paper, we consider different kinds of conflicts in the same analysis as war and civil unrest. Although they have very different drivers and dynamics, they can be linked each other by interrelationships.[6]

[6] For instance, if weather changes generate lot of social disturbances (due to a decline in agricultural yields generating inflation of food prices and thus famines and inequalities), declaring war could be a way for the national authority of uniting the people around a common – or at least another – objective. Although this argument is disputable in an age characterized by rudimentary nationalism, the wars were a mean in the formation of the states (see for example Charles (1975) about states formations and war relationships) and it is an example highlighting the interrelationships between social troubles and wars.

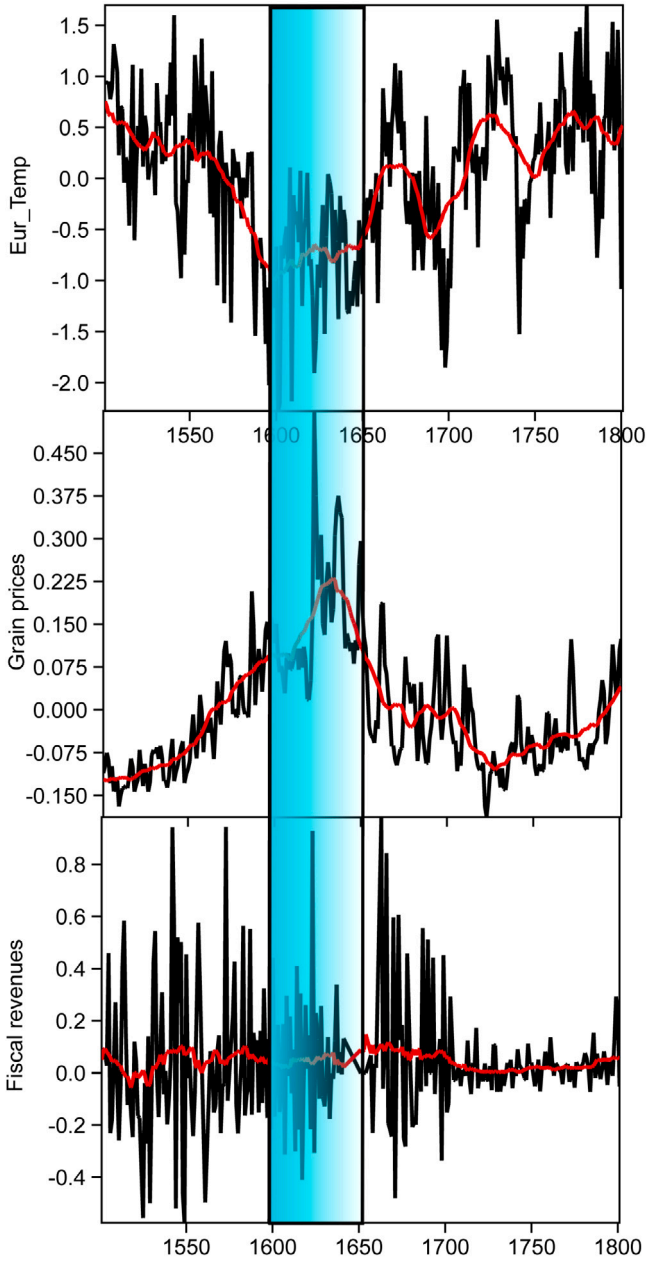

Fig. 2. Cold periods, grain prices and fiscal revenues: visual inspection.

Limited natural resources, famines and riots. In line with previous literature, we hypothesized that human populations are not very different from animal populations regarding the behavior they adopt in times of resource limitations (Zhang et al., 2011). When climate variations reduce agricultural crop yields (Schlenker and Roberts, 2009) and limit natural resource exploitation and therefore food, warfare can be viewed as an adaptation process to equalize the supply and demand of natural resources.[7]

In this respect, climate change can lead to social disturbances by directly generating food riots The magnitude of protests is viewed as a main outcome of famine generated by the negative climate variation impact on agricultural productivity[8] and the occurrence of recurrent subsistence crises during spells of strong cooling. In addition, climate also impacts social conflicts

[7] It is a bit different in the modern world considering the valuable insights on cooperative adaptation to environmental stress gained by research on governance of the commons, climate change adaptation and environmental peacebuilding in the last 2–3 decades.

[8] See the seminal paper from Deschenes and Greenstone (2007), on this relationship.

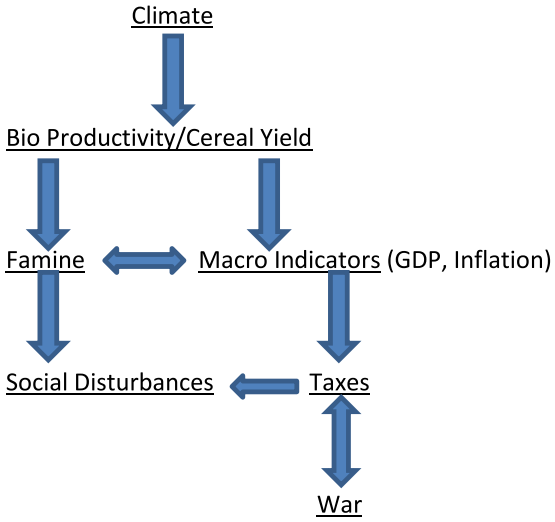

Fig. 3. Theoretical hypotheses and causal scheme.

indirectly by potentially intensifying social disequilibrium or ideological divides. When famines occur in times of bad crops with poor macroeconomic indicators (strong inflation, especially for cereal products, lower agricultural production), the opportunity cost of rioting for very poor populations tends to decrease; then, episodes of famine are therefore likely to increase social disturbances. This channel is reinforced by heavy and growing taxes levels during the studied period (Karman and Pamuk, 2010) and by the occurrence of a high number of external wars (Gennaioli and Voth, 2015) and fears of famine and conflicts (Antoine and Michon, 2006). In one sense, the system is a somewhat self-sustaining vicious circle, since bad macroeconomic indicators, famines and conflicts are potentially reinforced by each other.

Economic crisis, fiscal pressure and wars. Generally, in times of macroeconomic crisis, political leaders choose to conduct wars to get external resources, turn attention away from internal problems and bring people together by fighting common enemies. Incidentally, they increase taxes that may already be very high for farmers and craftspeople, exacerbating the economic and food subsistence riots. As a consequence, climate-induced economic crises can lead to social crises with riots and social unrest at the same time as wars, with each type of "conflict" reinforcing each other. Indeed, as stressed by Antoine and Michon (2006), riots in the 17th century were a model of public demonstration not only to protest about high grain prices but also again fiscal pressure and military occupations. Several historical sources about the 17th century reveal the revolts of people traumatized by the fiscal explosion and the paroxysm of the war effort. Finally, climate variations, by reducing bioproductivity and hence increasing food prices (Zhang et al., 2007, 2011 or Waldinger, 2015), can trigger social unrest directly or reinforce social and political unrest and instability due to social inequalities, increasing taxes and broadly social protests. In other words, climate vulnerability can translate into economic and social vulnerability, leading to more violence and conflicts both inside (social disturbances and civil wars) and outside (inter-State wars and conflicts) the countries. The Fig. 3 is an attempt to summarize the potential causal linkages at work.

4. Empirical methodology: a copula approach

4.1. Why a copula approach ?

In order to investigate the possible interdependence between climate and conflicts, we used Copulas to model average and tail dependence and examine transmission and contagion in a quantitative manner. Working with copulas is, in simple terms, to work with the joint distribution of two variables (see for example Cherubini et al. (2011), McNeil et al. (2015) and Ibragimov and Prokhorov (2017)). Thus a positive dependence or positive correlation (change in climate is positively related to conflict number and/or intensity) or a negative dependence with negative correlation coefficients (climate and conflicts are going in opposite directions). Copulas can be viewed as a co-movement of different variables.

The main interest of this analysis is to work on the whole distribution i.e. not only on the mean dependence, but also on the tail dependence. Dependence between climate and conflicts might exist in the tails only.

Indeed, copulas have enjoyed great popularity in different applied sciences when the usual normality assumption is called into question. This approach allows us the study of dependence structures. Copula modeling makes possible the release of the normality assumption which appears as a big and an unrealistic constraint in real world where extreme and unpredictable events could occur; specially in climate or conflicts studies.

It also allows us to consider more realistic models of asymmetric marginal distributions with heavy tails and more adequate models of nonlinear dependence between the multivariate distribution components.

The concept of tail dependence provides information on the "amount" of dependence at the tails of the distribution (so the extreme and unpredictable events). It is so a relevant tool for the study of the simultaneous occurrence of extreme values. A crucial argument in favor of Copula methodology is that it is a local measure unlike Kendall's tau and Spearman's rho which measures dependence over the entire distribution. This copula allows us to study dependence over time. It is in fact very restrictive and unrealistic to think that everything is constant over time. And moreover that extreme and non-standard events could not occur.

Dependence between climate and conflicts might exist in the tails only. Using different copulas and so different distributions, it is also possible to take asymmetric effects into account: for example, only the negative temperature or precipitation anomalies could be correlated with conflicts.

For all these reasons and possibilities of investigations, Copula approach appears to be relevant and the good one to study the relationship between climate and conflict in a long time history.

4.2. How does it work ?

A copula is a function which links univariate marginal distribution to the multivariate distribution for which the marginal distribution of each variable is uniform. Let X and Y be continuous random variables following a distribution function $F(X,Y)$ and $F_X(X), F_Y(Y)$ their marginal distributions respectively. Therefore, $U = F_X(X) \in [0,1]$ and $V = F_Y(Y) \in [0,1]$. Thus the copula C is the distribution function of (U,V) as below:

$$C(u1,u2) = P(U \leq u_1, V \leq u_2) = P(X \leq F_X^{-1}(u_1), Y \leq F_Y^{-1}(u_2)) \tag{1}$$

Let F be a bivariate distribution function with F_X and F_Y the margins. There is therefore a copula C such that:

$$F(X,Y) = C(F_X(X),\ F_Y(Y)) \tag{2}$$

Furthermore, C is unique if the margins F_X and F_Y are continuous. Likewise, if C is a copula, then for any $u_1 \epsilon [0,1]$, the partial derivative $\frac{\partial C}{\partial u_i}$, $i \in \{0,1\}$ exists for all $u_2\ \epsilon [0,1]$. For such u_1 and u_2 there are:

$$0 \leq \frac{\partial C(u_1,u_2)}{\partial u_1} \leq 1 \quad \text{and} \quad 0 \leq \frac{C(u_1,u_2)}{\partial u_2} \leq 1 \tag{3}$$

Moreover, if the copula is sufficiently differentiated, then the copula density may be as follows:

$$c(u_1,u_2) = \frac{\partial \mathrm{C}\ (u_1,u_2)}{\partial u_1 \partial u_2} \tag{4}$$

In case of an absolute continuity of bivariate distribution, copula density can be represented as follows:

$$c(u_1,u_2) = \frac{f(F_X^{-1}(u_1),\ \ F_Y^{-1}(u_2))}{f_X\left(F_X^{-1}(u_1)\right) \times f_Y(F_Y^{-1}(u_2))} \tag{5}$$

where f_X and f_Y denote the marginal densities of variables X and Y, respectively.

An appealing feature of the copula is tail dependence, which measures the probability that two variables are in the lower or upper joint tails of their bivariate distribution. The coefficient of upper (right) and lower (left) tail dependence for two random variables X and Y is obtained from the copula as:

$$\tau_U = Lim_{u\to 1} Pr(Y > F_Y^{-1}(u)/X > F_X^{-1}(u)) = Lim_{u\to 1} \frac{1-2u+C(u,u)}{1-u} \tag{6}$$

$$\tau_L = Lim_{u\to 0} Pr(Y \leq F_Y^{-1}(u)/X \leq F_X^{-1}(u)) = Lim_{u\to 0} \frac{C(u,u)}{u} \tag{7}$$

where $\tau_U, \tau_L \in [0,1]$. Lower (upper) tail dependence means that $\tau_L > 0$ ($\tau_U > 0$) indicates a non-zero probability of observing a high number of small (large) values for one series together with a high number of small (large) values for another series.

1. The Gaussian (Normal) copula is given by:

$$C_G(u_1,u_2,\ \rho) = \Phi_N(\Phi^{-1}(u_1), \Phi^{-1}(u_2)) \tag{8}$$

With Φ the cumulative distribution function (cdf) of the standard normal random variable $N(0,1)$ ($\Phi^{-}1$ its inverse cdf) and $/rho$ is the correlation coefficient for the copula.

2. The Student copula is a copula associated with the bivariate t-distribution. It is defined as follows:

$$C_t(u_1,u_2,\rho,\vartheta) = t_{\rho,\vartheta}(t_\vartheta^{-1}(u_1), t_\vartheta^{-1}(u_2)) \tag{9}$$

where $t_{\rho,\vartheta}^{-1}$ is the t-distribution with ϑ degrees of freedom; ρ is the correlation coefficient and t_ϑ^{-1} is the inverse of the univariate Student t-distribution function. However, when $\vartheta \to \infty$: the Student copula tends to the Normal copula which does not authorize tail dependence.

3. The Gumbel copula was proposed by Gumbel (1960) and is also called the Gumbel–Hougaard copula. Its expression is defined by:

$$C_\theta(u_1,u_2) = exp((-\ln(u_1))^\theta + (-\ln(u_1))^\theta)^{1/\theta}, 1 \leq \theta < \infty \tag{10}$$

where the copula parameter $\theta \geq 1$. It is asymmetric with upper tail dependence: $\tau_U = 2 - 2^{1/\theta}$ and lower tail independence ($\tau_L = 0$).

4. The Clayton copula was introduced by Clayton (1978) and takes the following copula form:

$$C_\theta(u_1,u_2) = ({u_1}^{-\theta} + {u_2}^{-\theta} - 1)^{-1/\theta}, \theta \in]0,\infty] \tag{11}$$

It is asymmetric with lower tail dependence: $\tau_L = 2^{-1/\theta}$ and upper tail independence ($\tau_U = 0$).

The study used the Canonical Maximum likelihood (CML) to estimate the parameter of the copula. We followed the methodology set out in Bedoui et al. (2018). Firstly, we estimated the margins using an empirical distribution of X and Y:

$$\widehat{F_X}(x) = \frac{1}{T}\sum_{t=1}^{T} 1I_{\{X<x\}} \quad and \quad \widehat{F_Y}(y) = \frac{1}{T}\sum_{t=1}^{T} 1I_{\{Y<y\}}$$

where I is the indicator function. Then we applied the CML method. The procedure of this was in two steps:

1. Transformation of the initial sample set into uniform variables, using the empirical marginal distribution:

$$\hat{u}_t = (\hat{u_1},\hat{u_2}) = (\widehat{F_X}(x_1^t), \widehat{F_Y}(x_2^t)) \tag{12}$$

2. Estimation of the copula parameters via the following relation:

$$\hat{\alpha}_{CLM} = argmax \sum_{t=1}^{T} LnC(\hat{u_1},\hat{u_2},\alpha) \tag{13}$$

To investigate the dynamic effect of dependencies, we employed the time varying approach of Patton (2006a, 2012, 2006b).[9] This methodology allows to evaluate the variation of dependencies during time and highlights some possible extreme events which can bring higher relationship between our variables.

Thus, our approach is a time-varying coefficients approach but differs from 'regime copula' that captures only some persistent break in the dependencies. Indeed, for the case of punctual extreme event, the regime switching approach will not catch it since it will be not enough time persistent to be highlighted as a change of state. But, our approach with a global time varying approach can reach both case: punctual and persistent as a regime state since if the estimated parameter of the dependency stay a long period of time in a high level it means that we are in a regime state.

Finally, we employ two goodness-of-fit tests (Fermanian et al., 2005; Genest and Rémillard, 2008) of the selected copula models to ensure the best possible decision and future investigations: the bootstrap based Cramér–von Mises statistic (CvM) and the Vuong and Clarke test. This latter computes a goodness-of-fit score for each bivariate copula family under consideration. For each possible pair of copula families this test decides which of the two families fits the given data best and assigns a score – pro or contra a copula family – according to this decision.

4.3. Data

Temperature and precipitation data. There are different sources of climate reconstructions for the last 500 years in Europe and the northern Hemisphere, and even for the last 2000 years (earlier data is referred to as Paleo data). We chose to work from 1500 onwards and not before in order to use the most relevant data series starting in 1500. In addition, we focused on the Little Ice Age period and on pre-industrial Europe, as in Zhang et al. (2011). For robustness purposes, we used several well-recognized, high-quality sources focusing mainly on annual mean temperatures and precipitations for Europe as a whole, in line with the previous literature (see Zhang et al. in 2007 and 2011 or Tol and Wagner, 2010 for example). The climatic data for 1500–1900 came from the gridded datasets of Luterbacher et al. (2004b,a) for temperature and Pauling et al. (2006) for precipitation; see also Xoplaki et al. (2005).

Our climatic dataset consisted of temperature and precipitation anomalies and was chosen among those most often taken into consideration in a vast multidisciplinary literature: in the vein of Zhang et al. (2007, 2011), EUR_TEMP was constructed as a combination of annual mean temperature reconstruction series for European land areas (25°W to 40°E and 35°N to 70°N) from the well-known Luterbacher et al. source and of the reconstruction associated with Osborn and Briffa (2006); the combination was normalized to homogenize the original variability of the two different series and preserve the amplitude of temperature change (see Zhang et al., 2011, appendix).

NH temperatures (hereafter $Mann_NH$) from Mann and Jones (2003), total temperatures (Temp2006) from Büntgen et al. (2004), precipitation anomalies from Büntgen et al. (2011) (we used AMJ proxy as the most relevant proxy to identify periods of drought

[9] In this paper we follow Patton (2006a,b) and use the same parameterizing time variation in the conditional copula dynamic. The parameters evolve over time according to the same dynamic equation as in these references.

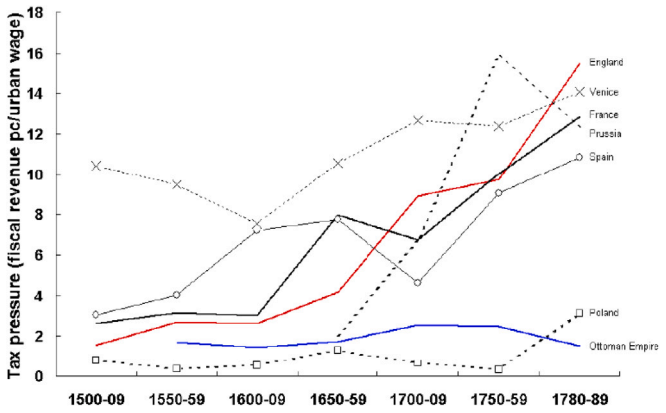

Fig. 4. Tax pressure dynamics over 1500–1800. Note: Data from Kivanc and Pamuk (2010).
Source: Data from Kivanc and Pamuk (2010); reproduced from Gennaioli and Voth (2015).

or extra rain) were also used for robustness checks and comparison purposes (for example, data for temperatures from Luterbacher et al. (2004b,a) had previously been used by Tol and Wagner (2010)).

ENSO and NAO Teleconnection data. We also tested the effects of ENSO and NAO teleconnections. For example, Parker (2013) explained that strong positive ENSO is likely to be behind the years of considerable cooling in the 17th century during the Little Ice Age period. We supplemented the previous climate database by collecting ENSO and NAO series. The North Atlantic Oscillation (NAO) is a climate phenomenon at work in the North Atlantic region, which could drive summer and winter climate in northern and southern areas of Europe. Existing literature has shown that the NAO is considered to be one of the major modes of variability of the Northern Hemisphere atmosphere (see Hurrell, 1995; see also Visbeck et al. (2001) and Kim and Mc Carl (2005)) and is likely to explain approximately 30% of climate variability over the Euro-Atlantic region (Pavan, 2000). The NAO is traditionally defined as the normalized pressure difference between a station on the Azores and one in Iceland. It is computed each winter since it is particularly at work between November and April. The NAO index Reconstruction is based on three academic works, multi-proxies by Cook et al. (2002), tree-ring records by Glueck and Stockton (2001), and speleothem records by Trouet et al. (2009) covering 1500–1800 AD. To increase the reliability of the NAO index, these three curves were standardized first. Then, these three curves were calculated to get the mean value. A negative NAO value is associated with cold and dry climate regimes whereas positive NAO value is associated to warm and wet climate regimes.

The El Nino Southern Oscillation (ENSO) is considered to be the dominant mode of interannual climate variability on Earth, alternating between anomalously warm (El Nino) and cold (La Nina) conditions in the tropical Pacific at intervals of 2–7 years. The amplitude of ENSO variability affects the occurrence and predictability of climate extremes around the world and could have important social and economic effects (see for instance Cashin et al. (2017) and D. (2017). We used the 1100 Year ENSO Index Reconstruction from Li et al. (2011) based on the North American Drought Atlas (a database of drought reconstructions based on tree-ring records) to produce a continuous, annually-resolved record of ENSO variability over the past 1100 years. A negative ENSO value refers to a La Nina episode (abnormally cold temperatures) whereas a positive ENSO value refers to a El Nino episode (abnormally warm temperatures). The magnitude of the values lead to a classification: significant ENSO events and/or weak, moderate, strong or very strong ENSO events.

Conflicts data. Regarding the conflict data, we used three different variables: social disturbances, war and war fatalities. The number of wars was obtained from the Conflict catalogue developed by Brecke (1999) who constructed a long-time-scale dataset to discern patterns in the nature of violent conflict that were not feasible before. The initial sample start date is 1400 but Brecke extends the Conflict Catalog back for regions 3 and 4 (West and East Europe) to the 900–1399 period. As already explained by Zhang et al. (2011), the catalogue documents a total of 582 wars fought over 1500–1800, including all violent conflicts of Richardson's magnitude (32 or more deaths) or higher. As a corollary, the war fatality index composed by Zhang et al. (2011) is an annual units index; so they developed a ratio from fatalities (when records exist) of each war divided by its duration (number of wars) and finally scaled on a yearly basis.

Social disturbances data were obtained from Sorokin's book (1937), volume III entitled "Social and Cultural Dynamics" that recorded the most important internal troubles in both Central and Eastern Europe for an aggregate total of 205 disturbances over our studied period. Political (modifications of political regime), socioeconomic (modification of existing economic or social order), national and separatist disturbances, and religious disturbances were recorded. Since each disturbance is provided in great detail by Sorokin, by duration, location, masses involved etc…, the magnitude has been divided by its duration (number of years) to get a magnitude/year ratio and then the annual magnitude is summed up on a yearly basis and finally divided by the number of countries in Europe (Zhang et al., 2011). Finally, the reliability[10] of this data set previously used by Zhang et al. (2011) is high.

[10] Severe reporting biases on social disturbances have been revealed in the modern world (see for example Böhmelt et al. (2014) or Ide and Scheffran (2014)).

Table 1
Sub-periods identification of copula dependence: Social disturbances.

	EUR_TEMP	Mann NH	Temp2006	Precipitation	Precipitation AMJ	ENSO	NAO
	Around 1560 (–) Around 1590–1610 (–) Around 1650 and 1675 (–) Around 1730–40 (–)	1593–1600 (–) 1650–1655 (–)	1595–1600 (–) 1650–1655 (–)	1735–1740 (–)		1675 (1660–1680) (+)	1650 (1640–1660) (+)
Goodness-of-Fit	Clayton	Clayton	Clayton	Gaussian	Clayton	Gaussian	Clayton
CvM statistic	3.29	4.68	4.07	3.06	2.03	2.50	2.30
Scoring-Fit	Clayton	Clayton	Clayton	Gaussian	Clayton	Gaussian	Clayton

Note: Each cell corresponds to an episode of dependence between a climatic proxy and the social disturbances variable: for example, all cells in the column 1 refer to the dependence between EUR_TEMP and the social disturbances over four time episodes: around 1560, 1600, 1650 and 1740. Each cell refers to the dates of a potential active sub-period (dependence is particularly high in this particular regime) identified by our methodology and visual inspection of all distributions via the Figs. 5 to 22 . For example, the value corresponding to the second line in the first column noted "Around 1600" reveals a negative dependence between EUR_TEMP and social disturbances over the 1590–1610 period. The result comes from the visual inspection of all 4 Copula distributions (Gaussian, Student, Clayton, Gumbel). The sign of the dependence for Gaussian and Student distributions (positive + or negative –) is denoted in parentheses; when no sign is added, the dependence for Gaussian and T distributions is considered as near zero. By definition, the sign associated to Clayton and Gumbel distributions is always positive (or zero if no dependence). Previous information is supplemented by Goodness-of-fit tests to indicate what kind of distribution better fits the data. However, these tests need to be cautiously interpreted: indeed, they hold for a static copula modeling but here we computed time-varying copulas to capture change of dependencies during time. Nevertheless, these tests allow us to confirm the potential existence of tails and asymmetric dependencies of the bi-variate series.

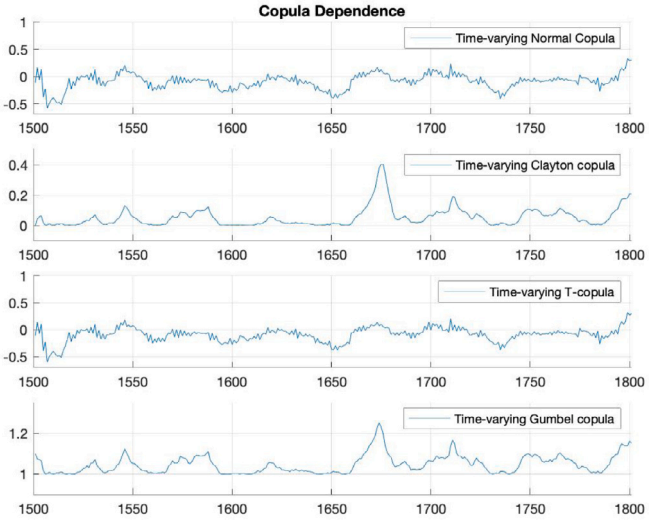

Fig. 5. Temperatures from Zhang et al. EUR_TEMP (2011) social disturbances.

5. Results and discussion

We now discuss the results of our copula computations. For each pair of variables – for example temperature anomalies and war – the dependence coefficients over 1500–1800 has been computed considering four different distributions: Gaussian, Clayton, Student and Gumbel. The maximum likelihood estimates of the parameters of the different copula models (Normal, Clayton, Student, Gumbel) are reported in Table 5 for full details. Moreover, to investigate the possible asymmetric dependence in either direction, we specify and estimate the alternative "symmetrized Joe–Clayton" copula (SJC) (see Patton (2006a,b)). The main reason for our interest in the symmetrized Joe–Clayton specification is that although it nests symmetry as a special case and does not impose symmetric dependence like the Normal copula (the Normal can be considered as a benchmark copula). This copula enables us to test the presence or absence of asymmetry in the tails (see Appendix A.6 and Table 5 that reports the Symmetrized Joe–Clayton with associated lower and upper tails coefficients).

We prioritized the Normal and Student distributions as benchmarks to investigate mean (symmetric) relationships, but Gumbel and Clayton copula distributions are more suitable to analyze extreme shocks in the tails. The Gumbel distribution enables us to focus on positive extreme shocks, while Clayton distribution enables us to exclusively consider negative shocks. Goodness-of-fit tests are computed and enable us to confirm or not the visual inspection and global analysis.

Social Disturbances. We identified several sub-periods of copula dependence between climate proxies and social disturbances as highlighted by Figs. 5, 8, 11 and 14 in Appendix. All results are summarized in Table 1. To make the reading of the results

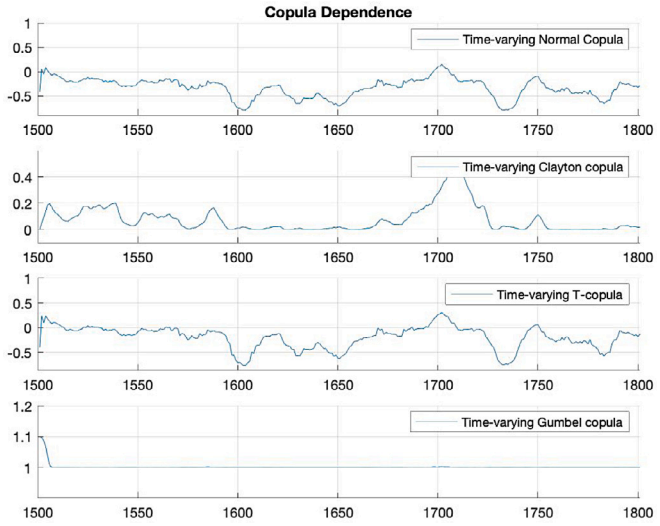

Fig. 6. Temperatures from Zhang et al. EUR_TEMP (2011) War.

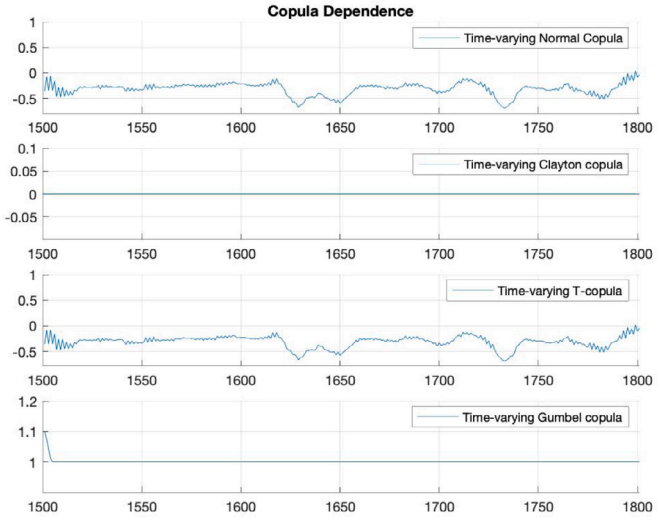

Fig. 7. Temperatures from Zhang et al. EUR_TEMP (2011) War fatality.

easier, each line of Table 1 corresponds to an "active" dependence between climate and social troubles during a sub-period of the sample. For the three temperature proxies (EUR_TEMP, $Mann_NH$, Temp2006), all the dates in the table correspond to a period with a strong negative coefficient: in other words, lower temperatures are associated with a higher number of social disturbances (and conversely) for both symmetric Gaussian and Student distributions. For the three proxies, we found a negative dependence around 1595–1600 and 1650–1655. These two dates seem to be particularly remarkable.

Goodness-of-fit tests indicate that the relationship is particularly well fitted by the asymmetric negative Clayton distribution. In other words, it means that an extremely negative climate shock is related to an increasing number of social disturbances in Europe during the studied period. The same result holds with the precipitations (AMJ proxy). It means that a negative shock of precipitations (droughts or extreme reduction of rainfalls) is associated to an increasing number of protests, especially during the 1735–1740 period (see also the Clayton distribution plot, Fig. 14 in Appendix A.2).

As previously explained, the symmetrized Joe–Clayton" copula (SJC) enables us to detect the presence or absence of asymmetry in the tails. We can see in Table 5 (Appendix A.6) that the dependency shape between $EurTemp$ and Social Disturbance clearly validates the asymmetry property of extreme dependencies between lower and upper tails. Indeed the lower tail dependence equals $\tau_{SJCLower} = 8.1643$ against a positive one $\tau_{SJCUpper} = 0.0314$. This result is a supplementary proof of the superiority of the Clayton copula fitting. It means that the relationship is concentrated on the negative extreme values of temperatures and social disturbance.

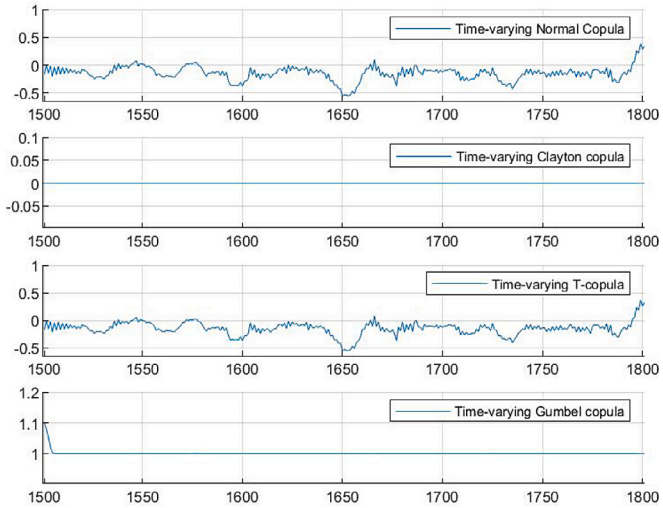

Fig. 8. Temperatures from Mann et al. (2006) Social Disturbances.

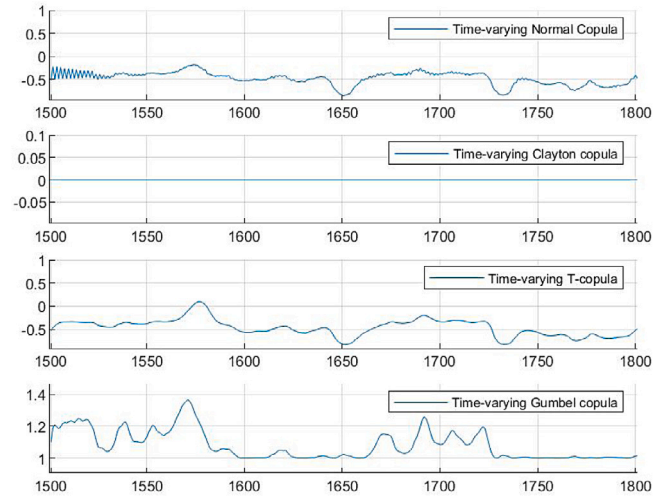

Fig. 9. Temperatures from Mann et al. (2006) War.

More broadly, the results from Table 1 reveal three main periods of negative dependence between temperatures and the number of social disturbances. Since potential causality from disturbances to climate is implausible, our results suggest that cold periods are likely to increase the number of riots. Our assumption is that cooling temperatures negatively impact agricultural yield leading to low production and high prices (especially grain prices). The scarcity of agricultural goods and the related inflation is likely to trigger large economic crises (Parker, 2013). Thus, during an economic crisis period provoked by strong cooling temperatures, the probability of food riots increases. When economic crisis occurred, centralized European states were likely to further increase taxes to collect new sources of revenue and maybe aggravates the economic and social crisis.

Our results suggest that the negative link between temperatures and social troubles is mainly active in the first-half of the 17th century. Tax pressure also considerably increased between 1600–1609 and 1650–59, as demonstrated by Fig. 2 from Kivanc and Pamuk (2010), Karman and Pamuk (2013) and restricted to a few number of countries by Gennaioli and Voth (2015). This tax pressure shift fits with the increase in the negative dependence between climate and protests around the first-half of the 17th century for countries with a high number of social problems. Though we suggest that high tax pressure reinforced the revolts due to food availability problems, we nonetheless did not formally prove the causality here (see Fig. 4).

We also analyzed precipitations and so potential effects of droughts and floods on conflicts. Gaussian distributions can capture a smooth/structural reduction or increasing of the rainfall. However, the precipitations changes are often characterized by extreme events or shocks: in this case, Copula methodology is particularly suitable to detect them by considering the entire bi-variate distribution throughout negative tails (Clayton distribution, droughts events here) and positive tails (Gumbel distribution, floods events). When we look at the link between precipitations and social troubles, the picture is a bit less clear-cut than for temperatures.

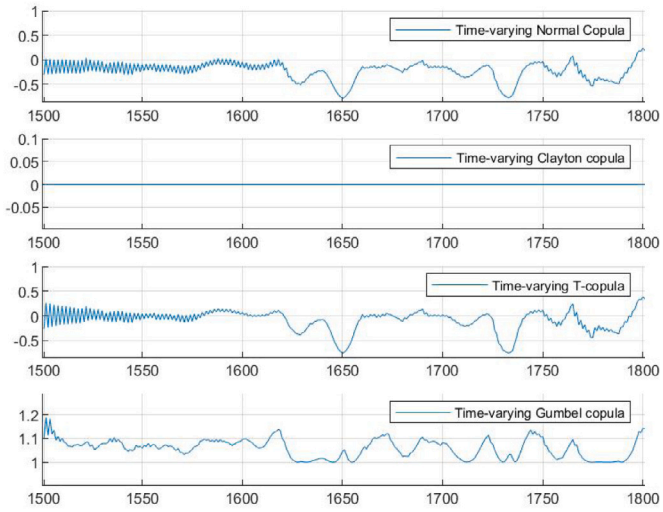

Fig. 10. Temperatures from Mann et al. (2006) War fatality.

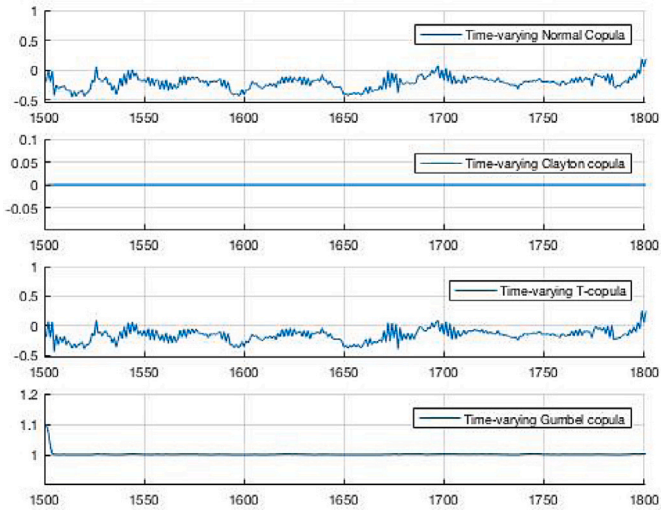

Fig. 11. Temperatures from Büntgen et al. (2006) Social Disturbances.

Table 2
Sub-periods identification of copula dependence: War.

	EURTEMP	Mann NH	Temp2006	Precipitations	Precipitations AMJ	ENSO	NAO
	Around 1600 (–)		1600–1605 (–)		1580–1600 (+)	1605 (–)	
	Around 1650 (–)	1650 (–)	1630–1650 (–)	1630–1640 (–)		1630–35 (–)	1625–1660 (+)
	Around 1730–1740 (–)	1729–1735 (–)	1755 and 1765 (–)	1730 (–)	1730 (–)		1735 (+)
Goodness-of-Fit	Clayton	Gumbel	Gumbel	Gumbel	Clayton	Student	Student
CvM statistic	3.19	7.67	2.77	3.13	1.47	1.59	2.30
Scoring-Fit	Clayton	Gumbel	Gumbel	Gumbel	Student-Clayton	Student	Student

The only stand-out case is a positive dependence identified regarding the Clayton distribution around 1735–1740. In other words, negative extreme precipitations shocks (that could correspond to droughts over the period) were associated with a high number of social disturbances. This result seems to be plausible when looking at the historical archives and studies: for example, Fragoso et al. (2018) reported a severe and long-lasting 1737–38 in Portugal whereas Murphy et al. (2020) identified that UK likely suffered from clusters of dry seasons during 1740–1744.

Finally, we tested for the first time the impact of ENSO and NAO teleconnections on conflicts to capture the potential origins of temperature variation effects on violence. The periods 1660–1680 with a peak around 1675 for ENSO and 1640–1660 with a peak

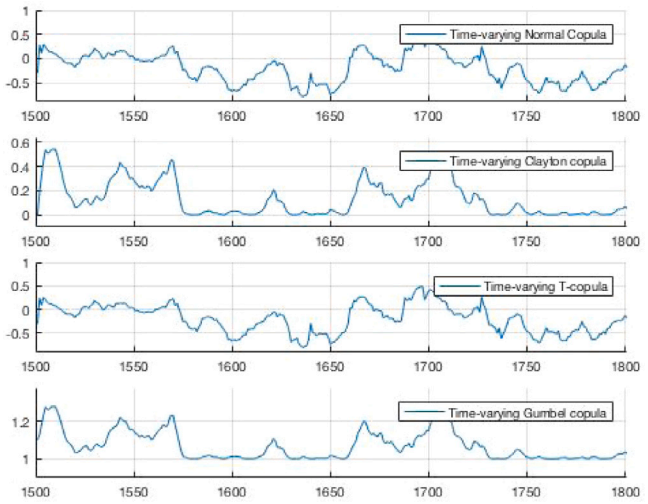

Fig. 12. Temperatures from Büntgen et al. (2006) War.

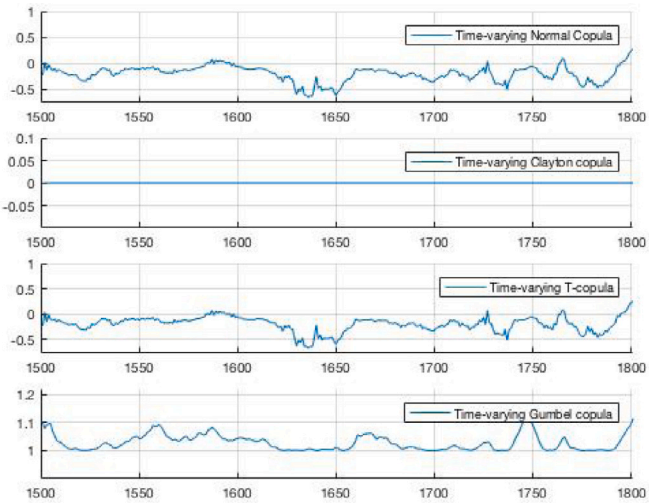

Fig. 13. Temperatures from Büntgen et al. (2006) War fatality.

Table 3
Sub-periods identification of copula dependence: War fatality.

	EUR TEMP	Mann NH	Temp2006	Precipitations	Precipitations AMJ	ENSO	NAO
	Around 1630 and 1650 (–) Around 1730 (–)	1650 (–) 1729–1735 (–)	1630–1650 (–) 1732–33 and 1740 (–)	1620–1640 (–) 1730 (–)	1630 (+) 1730–35 (–)	1635 (–)	1630–1660 (+)
Goodness-of-Fit	Clayton	Gumbel	Gumbel	Gumbel	Clayton	Clayton	Clayton
CvM statistic	2.12	1.78	1.24	0.97	0.30	1.32	2.30
Scoring-Fit	Clayton	Gumbel	Gumbel	Gumbel	Clayton	Clayton	Clayton

around 1650 for NAO were clearly remarkable periods with a positive dependence. Concerning NAO that is most relevant indicator for European countries, this peak is rationale since it is well synchronized with the 1650–1655 sub-period for negative temperature anomalies. The fitting tests confirm that Clayton distribution is very relevant for the NAO-Social disturbances bivariate distribution, indicating the influence of negative extreme shocks and so strong negative NAO values on the number of social troubles. In other words, NAO probably lead (negative) temperatures anomalies that generated more social problems around 1650–1655. Indeed, a negative phase of NAO generally brings lower air pressure and stronger cold-air outbreaks and was associated with a high number of social riots. Our result is in line with Lee et al. (2013) that gave the first demonstration that the NAO affected social stability in preindustrial societies. Concerning ENSO, the result is less clear-cut. It is again logical since ENSO firstly impacts Pacific and Latin

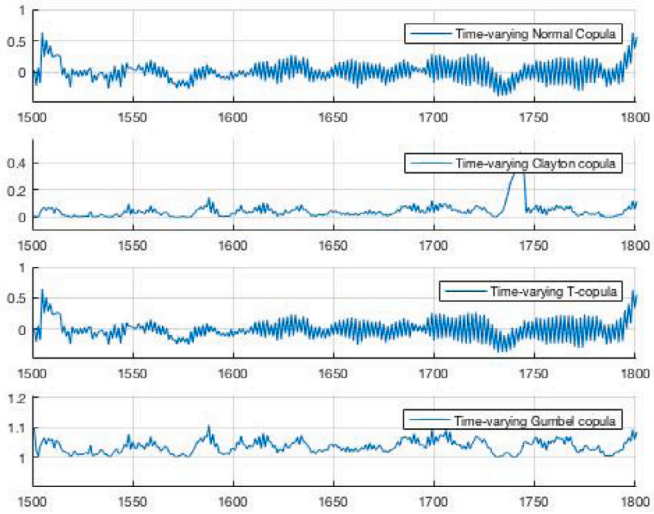

Fig. 14. Precipitations social disturbances.

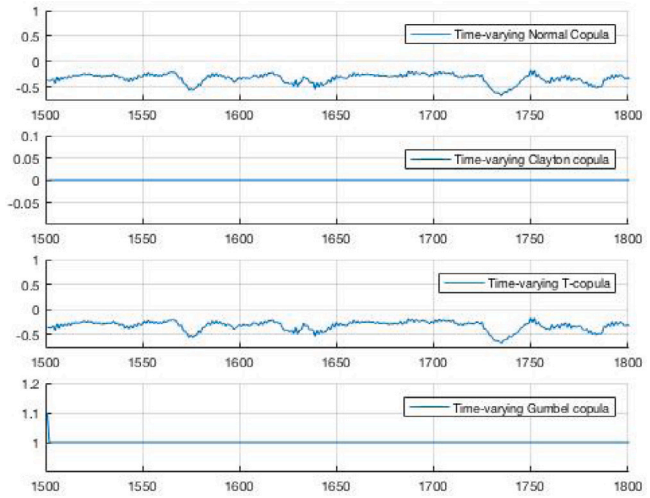

Fig. 15. Precipitations War.

America countries before European ones. Nonetheless, our result – positive ENSO values corresponding to La Nino episodes with abnormal warm temperatures associated with more disturbances – is in line with Hsiang et al. (2011) for the recent 1950–2014 period.

War and War fatalities. Our assumption is that general crisis (both on economic and social aspects) is likely to generate more external conflicts, as a given country is more likely to declare war on a foreign country to collect some new external revenues. At the same time, money is important for military success and the ruler risks losing fiscal revenues in a war (Gennaioli and Voth, 2015), to shield the economies better against wars (Kivanc and Pamuk, 2010) and so tax pressure is likely to increase in the short run. In addition, declaring war is a means of uniting the people around a common objective and creating a diversion from the food crisis and social disturbances. As a consequence, climate shocks can affect both social disturbances inside the country and external (inter-State) conflicts with an increasing number of wars. Between 1500 and 1700, there was a war between major powers underway in 95% of all years (Gennaioli and Voth, 2015).

Overall, our results, summarized in Tables 2 and 3, suggest a negative dependence between temperature anomalies and war episodes, especially in the first-half of the 17th century. The dependence is particularly concentrated on three main sub-periods: around 1600 i.e. in the beginning of the 17th century, around the 1630–1650 period with a strong negative peak around 1650, and around 1730. Thus, during these periods, low levels of temperatures associated with cooling episodes were associated with increasing war events. Clayton and Gumbel distributions have particularly high scoring-fit scores indicating that extreme weather shocks (cold and warm temperatures) are associated to increasing conflicts. In addition, as shown by Table 5, the dependency

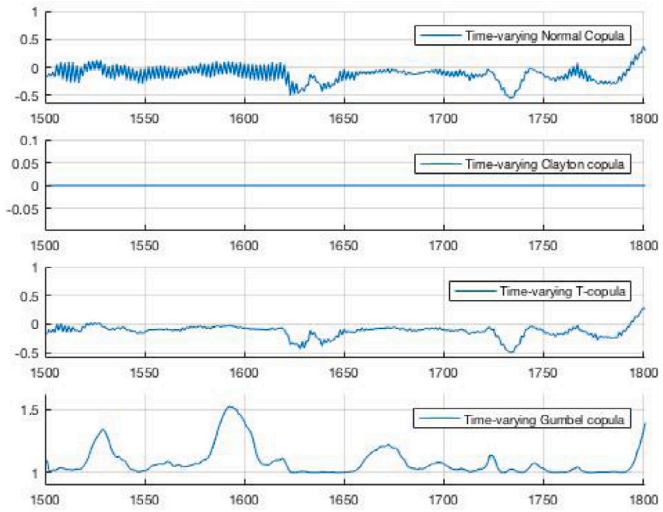

Fig. 16. Precipitations War fatalities.

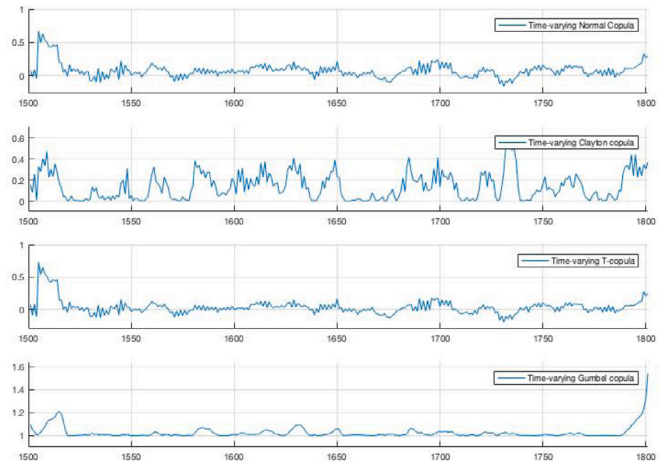

Fig. 17. Precipitations AMJ social disturbances.

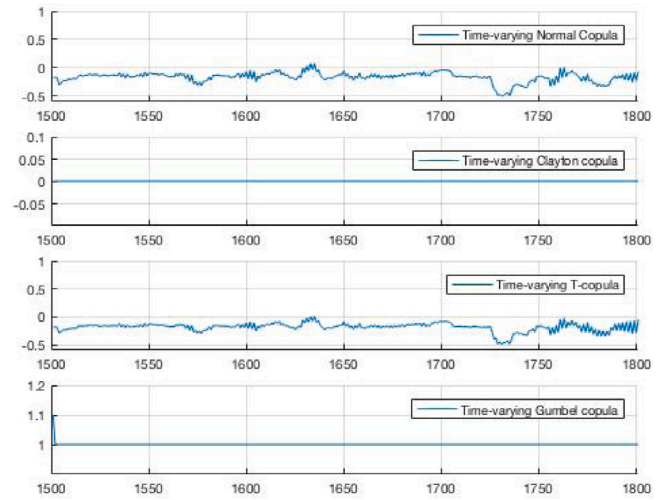

Fig. 18. Precipitations AMJ War.

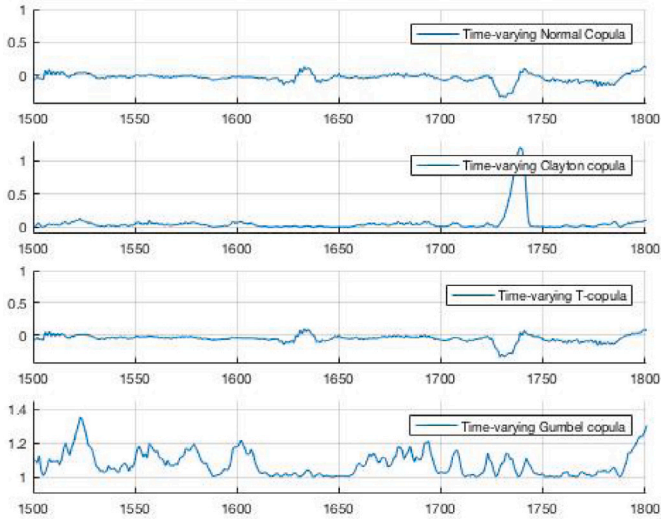

Fig. 19. Precipitations AMJ War fatalities.

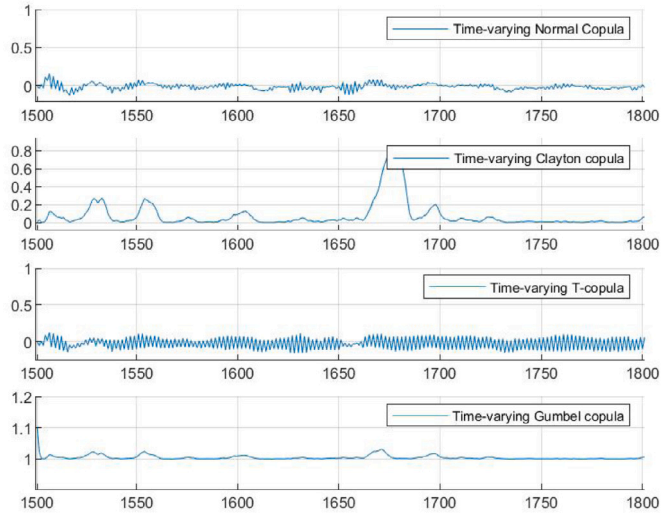

Fig. 20. ENSO and social disturbances.

between the temperatures and Warfare, especially for the War Fatality Index, clearly validates the asymmetry property of extreme dependencies between lower and upper tails. Indeed the lower tail dependence equals $\tau_{SJCLower} = 1.4192$ against $\tau_{SJCUpper} = 0.003$ for EUR_TEMP temperatures and $\tau_{SJCLower} = 3.865$ against $\tau_{SJCUpper} = 0.003$ concerning $Mann\_NH$ temperatures.

When we used global annual precipitations, we again found a negative dependence around 1630 and 1730 as already identified previously and around 1730 when we used AMJ precipitations to focus on droughts episodes. We only found a negative dependence around 1730 but a slight positive episode (corresponding to a floods period) in the end of the 16th century.

Results for war and war fatalities considering "Mann temperatures" were along the same lines. The copula time varying analysis led us to detect two main negative peaks with Normal and Student-copula distributions. Thus, the average correlation between temperatures and war episodes tended to be near zero, but turned negative in some periods. Results using Luterbacher et al. (temp2006) and Zhang et al. (EUR_TEMP) temperature proxies led to the detection of three main sub-periods and so seem robust to the climate proxy used: around 1600, around 1630–1650 and in the mid 1700's (1750–1760 for the first or 1730–1740 for the second temperature proxy respectively).

When we substituted the war index by the war fatalities index, we also found two main episodes characterized by an increasing negative dependence between temperatures and war fatalities around 1630–1650 and 1740. Nonetheless, the first episode around 1600 that was identified previously now completely disappeared. Anyway, the relationship between cooling and war is robust. In addition, the precipitation results in relation to the war fatality index confirmed the previous results for the war index.

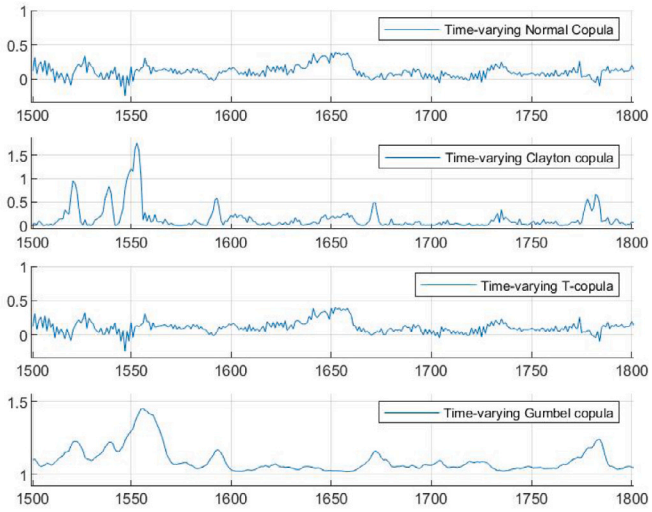

Fig. 21. NAO and social disturbances.

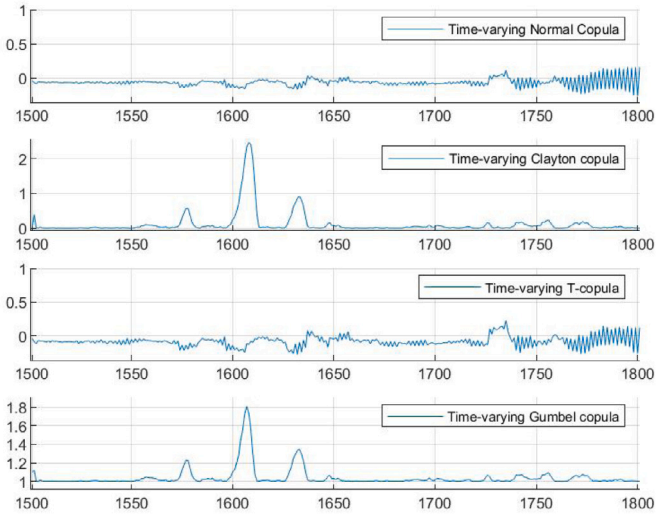

Fig. 22. ENSO and War.

Regarding precipitation, we found two main periods with an active link between climate and the war fatalities index: around 1630 and around 1730. These periods are very similar to the periods identified for the temperatures. Thus, the dependence between climate and wars covers both temperature and precipitation anomalies. More precisely, we show evidence of "negative" links between precipitation and the war fatality index. A negative link implies that low precipitation and thus drought episodes are associated with a high number of conflicts around 1630 and 1730.

Finally, ENSO seems to be negatively related to warfare around 1630–1635. It means that negative ENSO anomalies i.e. La Nina episodes during this sub-period (abnormal cold sea surface temperatures) have been associated with a high level of warfare. Again, it converges with the effect of cold temperatures on conflicts identified by investigating directly our three temperature proxies. Concerning NAO, positive dependence were at work around 1630–1660: cold atmospheres were positively linked to high levels of warfare.

When we computed copula-based dependence between ENSO (NAO) and the grain prices, we highlighted a strong peak corresponding to a positive dependence between NAO and the grain prices (Gaussian and Student distributions) around 1640–1660 (see Fig. 27 in Appendix A.4) and two peaks (Clayton and Gumbel distributions, see Fig. 28) for ENSO. Again, the relationship is less clear-cut for ENSO. Anyway, this complementary analysis is in favor of the existence of an agricultural channel explaining the effect of weather changes (ENSO/NAO) on conflicts.

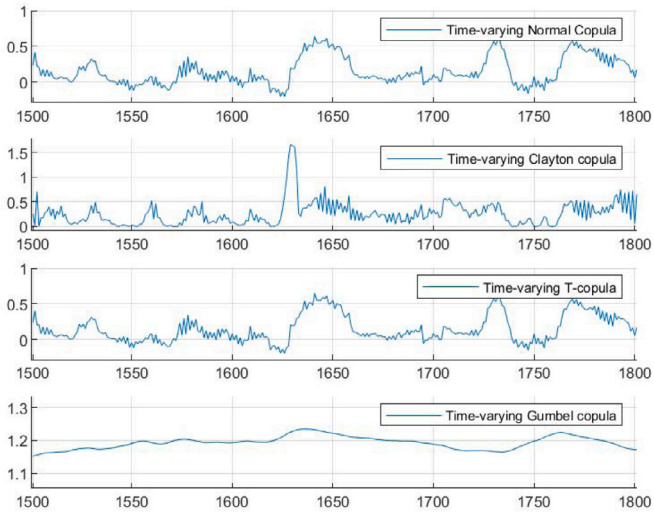

Fig. 23. NAO and War.

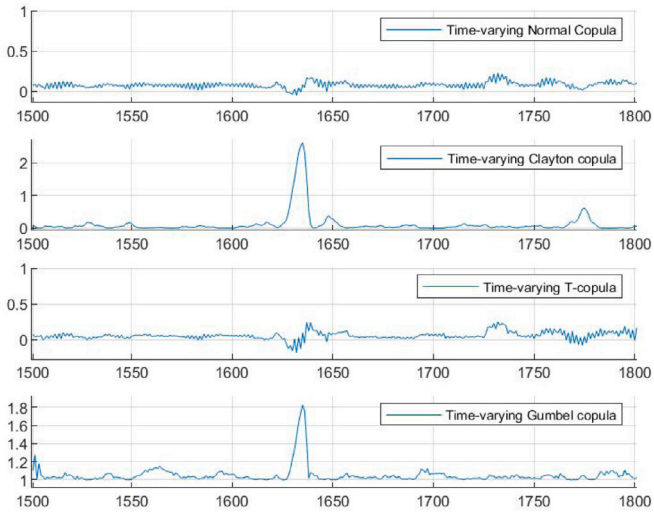

Fig. 24. ENSO and War fatalities.

Historical perspective and causal scheme

To go further, we wanted to investigate whether the main periods of dependence identified by the copula analysis could be easily explained by narrative historical sources. We also wanted to explain whether the agricultural channels and especially the link between climate, agricultural yield and food prices was likely to explain the correlation and possible causality from climate to conflicts.

The figures presented in Appendix A.4 highlight negative dependence between temperatures (EUR_TEMP) and grain prices, around 1630 and 1730. The picture is again clearer with the NAO index, with a sharply increasing dependence between NAO and grain prices over the 1625–1650 period. Cooling periods characterize by negative NAO values are therefore associated with increasing grain prices. As a consequence, the period for which there is a strong link between NAO, temperature anomalies and grain prices coincides with the period for which climate and conflicts are strongly related. There are a number of clues suggesting the existence of a link between climate and conflicts around 1630 and, more largely, over 1630–1650. So the following causal scheme NAO → temperature → grain price → conflicts seems to be a plausible scheme over the 1630–1650 period. In contrast, the dependence between ENSO and grain prices is less relevant concerning a potential direct link, since it is concentrated around 1610. Again, although ENSO has been evoked in the historical literature as a potential origin of the Little Ice Age (Parker, 2013), its influence in European countries was probably too weak to be detected.

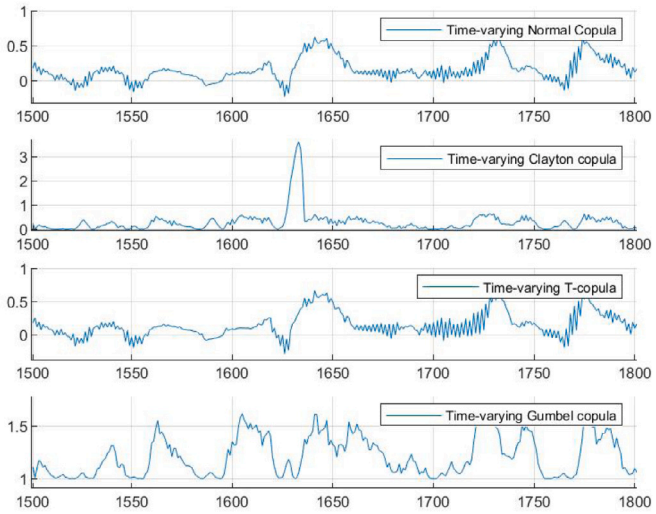

Fig. 25. NAO and War fatalities.

From an historical point of view, the 1630–1650 period identified by our quantitative analysis coincides perfectly with the occurrence of a lot of social disturbances and war events in Europe. In Britain, there was the English Civil War (1642–1651) and more generally the Wars of the Three Kingdoms between 1639 and 1651, with several civil conflicts in England, Ireland and Scotland. In France, the so-called Fronde (1648–1653) is perfectly coincident with our quantitative analysis. Antoine and Michon (2006) explained that the food riots were an important model of violence and public demonstration. France experienced a lot of temporary (or short-term) riots (Bordeaux, Agen but also Troyes, Amiens, Aix-en-Provence or Dijon were quasi permanently turbulent cities) that were linked to years with high grain and bread prices (for example 1630 and 1661–1662, according to them). Sometimes, fears of a price hike or the dealings of grain merchants were enough to provoke social demonstrations. Based on the studies of Nicolas (2008) on the French Revolution or "disorder", some historians mentioned the occurrence of 200 local revolts in France during the "Ancien Régime". In Spain, according to the same authors, a lot of social troubles occurred in Andalucia (Granada, Seville, Cordoba) over the period 1645–1652, in Zaragoza (1643) and in Jerez (1664). Some historians have talked about the Spanish Price Revolution linked to the high rate of inflation that occurred in the first half of the 17th century across Western Europe, and fears of famine among the population, but also the occurrence of new wars and battles, the working conditions of the little people and craftspeople or the implementation of supplementary taxes as previously evoked.

The role of climate can be viewed as an initial shock leading to an economic and then a social crisis with social disturbances and conflicts throughout a decrease in agricultural productivity, cereal prices inflation and famines. The decline in agricultural productivity seems to have been an important channel, as outlined by Iyigun et al. (2017b) throughout the introduction of potatoes that dramatically reduced conflict over 1400–1900 by increasing real wages and the opportunity cost of arming. On contrary, when the agricultural productivity declined and problems of food availability emerged, the opportunity cost of arming and then violence is weak.

In addition, this agricultural effect has been probably reinforced by the increasing fiscal pressure, for instance over 1600–1650, and by fears of troubles associated to wars (the weariness of the military presence and the atrocities associated with it) and external conflicts.[11] Several historical sources about the 17th century reveal the revolts of people traumatized by the fiscal explosion and the paroxysm of the war effort. Antoine and Michon (2006) highlighted the link between riots and fiscal pressure in France by different examples such as the troubles associated to a part of Gascony regularly and violently opposed the pruning levies from 1638 to 1645 or the "Croquants" opposing the tax changes that herald Cardinal Richelieu's fiscal screwdriver.

6. Robustness checks

Political developments and causality. A first limitation of our work might be the lack of exogeneity. For example, the period for which temperature/precipitation-conflict links are found to be strongest (1630–1650) was the heyday of political conflicts in Europe, including the final stage of the French–Spanish rivalry, the visible rise of Sweden as a major power and a large part of the 30 Years War. These turbulence caused major famines as well: as a consequence, we have to question whether political developments are not the actual drivers of the conflict (and food prices) signal. Though we should be cautious with this kind of methodology and

[11] Antoine and Michon (2006) underlined that "Bad harvests, epidemics and the start of the war in 1635 made these years a particularly difficult period which explains the sudden increase in revolts". See also Voigtlander and Voth (2013) and Kaniewski and Marriner (2020) about the links between war and epidemics

Table 4
Granger causality tests.

	F-Statistic	Prob.	Lags
SOCIAL_DISTURB does not Granger Cause EUR_TEMP	0.30901	0.8716	4
EUR_TEMP does not Granger Cause SOCIAL_DISTURB	2.55326	0.0416	4
WAR does not Granger Cause EUR_TEMP	0.54263	0.5824	2
EUR_TEMP does not Granger Cause WAR	0.29643	0.7439	2
WAR_FATALITY_IDX does not Granger Cause EUR_TEMP	1.23442	0.2940	2
EUR_TEMP does not Granger Cause WAR_FATALITY_IDX	0.11612	0.8904	2
GRAIN_PRICE does not Granger Cause EUR_TEMP	0.21696	0.8845	3
EUR_TEMP does not Granger Cause GRAIN_PRICE	2.50092	0.0618	3
SOCIAL_DISTURB does not Granger Cause GRAIN_PRICE	0.24847	0.8623	3
GRAIN_PRICE does not Granger Cause SOCIAL_DISTURB	2.40823	0.0696	3
WAR does not Granger Cause GRAIN_PRICE	1.61578	0.1883	3
GRAIN_PRICE does not Granger Cause WAR	3.06604	0.0300	3
SOCIAL_DISTURB does not Granger Cause FISCAL	2.14972	0.1210	2
FISCAL does not Granger Cause SOCIAL_DISTURB	0.79747	0.4529	2
WAR does not Granger Cause FISCAL	3.17032	0.0456	2
FISCAL does not Granger Cause WAR	0.06592	0.9362	2
FISCAL does not Granger Cause EUR_TEMP	1.12150	0.3435	3
EUR_TEMP does not Granger Cause FISCAL	0.87582	0.4560	3
SOCIAL_DISTURB does not Granger Cause WAR	1.43030	0.2426	2
WAR does not Granger Cause SOCIAL_DISTURB	4.96176	0.0000	2

Note: The table reports the value of the F-Statistic corresponding to the null hypothesis, its associated *p*-value and the number of lags considered on the basis of AIC criteria.

the existence of causality, especially when applied to historical time series, we proceed to linear Granger causality tests to check the robustness of our previous results in line with Zhang et al. (2011). The results of Table 4 reveal interesting findings: (1) there is direct causality between European temperatures and social problems but not for the wars; however this direct causality assessment could be biased by the absence of omitted variables (see Triacca (1998) for example) such as agricultural and economic variables; (2) they confirm the (potential) causal scheme introduced in previous Fig. 3 since climate variables (European temperatures here) seem to cause agricultural outcomes that seem to cause economic crisis that seems to exacerbate conflicts; (3) the role of fiscal pressure (*via* the total fiscal revenues from England here) suggests a causality from conflicts to fiscal revenues rather than the other way (fiscal pressure to conflicts [12]): social disturbances slightly (at 12% significance level) cause fiscal revenues and more wars lead to more fiscal revenues; (4) the results suggest that war cause protests and not the contrary, thus the emergence of conflicts with other countries is likely to weaken the population and might exacerbate the riots and turbulence.

Extended period and other historical datasets. To check the robustness of our results mainly based on the Zhang et al. (2011) dataset during the 1500–1800 period, we apply our methodology on a recent data set built by Kaniewski and Marriner (2020) to investigate the link between conflict and plague pandemics. The main interest of this dataset is to check our baseline findings both on another dataset and on an extended period (1347–1840) covering the "pre" Little Ice Age (AD 1300–1550).

Again, our copula methodology reveals the role of cooler temperatures (summer and NH temperatures anomalies from Neukom et al., 2014; Luterbacher et al., 2016 and also Mann and Jones, 2003) on conflicts (number of conflicts per year computed from Brecke data), see Figs. 29 and 30 (Appendix A.5). We also find that positive precipitation anomalies ie. extra rainfalls and potential floods (data from Cook et al. (2015)) are associated with conflicts (see the Gumbel distribution, see Fig. 31 (Appendix A.5)).

7. Conclusion

The relationship between climate and conflict is a controversial topic that has attracted considerable attention in recent years. In this paper, we used a time-varying copula-based analysis, for the first time in a climate study, to quantitatively investigate the extent to which climate can be considered as a major driver of conflict. We are focusing our analysis on the pre-industrial Europe which has so far been underexplored in the literature and enables us to work on a long-run perspective. We can reaffirm the existence of a link between climate and wars in the spirit of Zhang et al. (2006, 2007), Tol and Wagner (2010) and Burke and Hsiang (2014) and also, in a more original manner, between climate and social disturbances in the vein of Zhang et al. (2011).

However, contrary to previous literature, our results highlight that the climate/conflict relationship is not a uniform one. Here, we are able to show which sub-periods over the Little Ice Age are particularly concerned by this relationship: around 1600, 1630–1650 and 1730. Providing information about sub-periods enables us to better analyze the patterns between climate and conflicts. The first two periods – especially the second one – seem to be very reliable considering historical textbooks and historians' studies to explain a potential link between climate, protests and civil conflicts in some European countries in the first-half of the 17th century.

[12] Note that these results need to be cautiously interpreted considering the fragility of the fiscal revenues historical data.

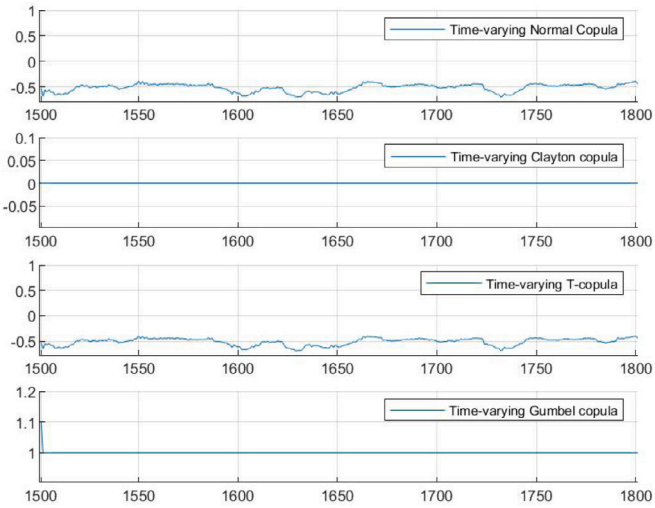

Fig. 26. Temperatures EUR_TEMP and grain prices.

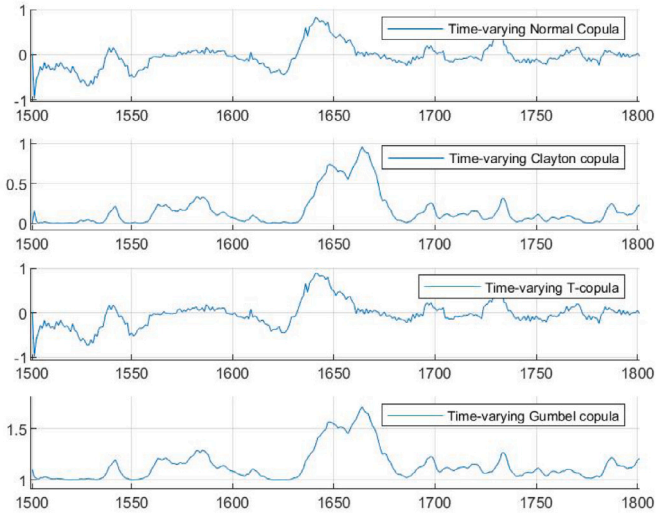

Fig. 27. NAO and grain prices.

The timing of the shift in copula coefficients coincides with a decrease in cereals yield, an increase in inflation and food prices, an increase in tax pressure and finally a global (economic and social) crisis, as yet indicated in Parker (2013).

On a more general methodological point of view, this paper highlights the interest of using time-varying Copula analysis as a suitable tool to investigate the climate/conflict nexus and the impact of extremes weather and climate change over time. This approach do not suffer from limitations in panel data studies (sample bias, omitted variables or over-controlling) are is more prone to capture extreme events and asymmetries in the distribution of both climate and conflict variables. However, a large time dimension data set is needed to perform this method.

We have also tried to look behind the direct correlation between climate and conflict by outlining a global causal scheme from climate to social disturbances and war. A decline in agricultural productivity generates a macroeconomic crisis with inflation (especially grain prices) leading to famines. People's fears about food availability generate food riots directly. These social troubles are then reinforced by heavy and increasing taxes. As a consequence, general crisis (economic, social) with increasing social disturbances is likely to generate more external conflicts. A given country is more likely to declare war on a foreign country to collect some new external revenues. At the same time, money is important for military success and the ruler risks losing fiscal revenues in a war, and so tax pressure is likely to increase in the short run. In addition, declaring war is a way of uniting the people around a common objective and creating a diversion from the food crisis and protests. As a consequence, climate shocks can affect both social disturbances inside the country and external (inter-state) conflicts with an increasing number of wars. A self-sustaining vicious circle is likely to be at work.

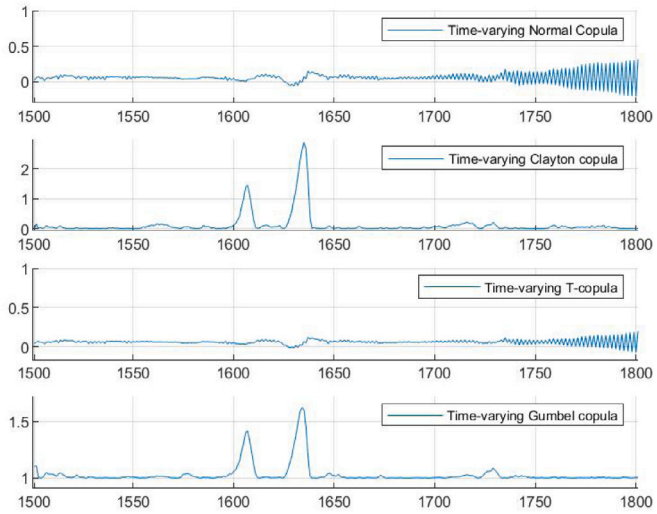

Fig. 28. ENSO and grain prices.

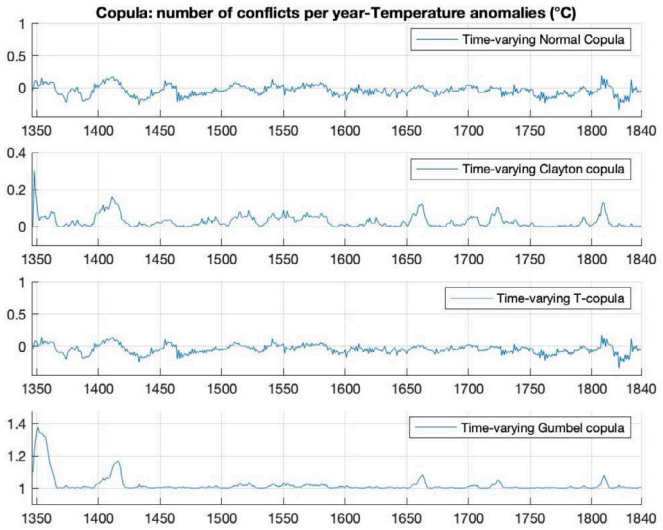

Fig. 29. Temperatures anomalies (Kaniewski and Marriner, 2020) and conflicts.

Furthermore, we have tried to explain whether ENSO and NAO teleconnections are likely to explain the observed climate variations in temperatures and precipitations and thus the likelihood of conflicts. It is clear that the climate teleconnections are associated with increasing conflicts for the 1630–1660 period for wars and a little later (around 1660) for social disturbance events. Hence, ENSO and above all NAO, have probably modified the temperature and precipitation dynamics in the European countries and then activated the causal scheme described previously. This result has interesting policy implications for the future by encouraging the governments to better and earlier forecast the likelihood of conflicts emergence in a given region by monitoring the changes in climate teleconnections such as ENSO and NAO but also PDO (Pacific Decadal Oscillation) and other indexes according to the regional area of the given country.

Finally, our study is a novel piece in the scarce literature about long-term climate change impact on society, which is one of the most topical questions for policymakers nowadays. In terms of policy implications in a modern context, this study is important for countries suffering from the climate – not cooling, but warming – in developing countries with pre-industrial economies that are heavily reliant on agriculture like a high number of developing countries (Tol and Wagner (2010) and Iyigun et al. (2017a)). Excess cooling or excess warming, drought or floods, are likely to reduce agricultural yield, increase grain prices and fiscal revenues and generate economic and social crisis. Agricultural and foods safety issues combined with increasingly heavy taxes are likely to lead to social disturbances and armed conflicts by reducing the opportunity cost of the violence. In this paper, we have shown that the significant links between climate and conflicts were concentrated only in certain sub-periods, probably due to some self-sustained vicious circles between agricultural production, tax burden, people's fears, revolts and inter-State conflicts. The relationship

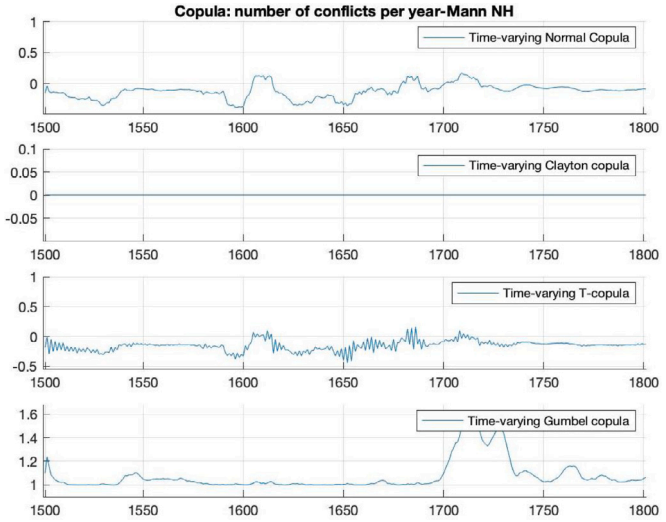

Fig. 30. Temperatures anomalies (Mann and Jones, 2003) and conflicts.

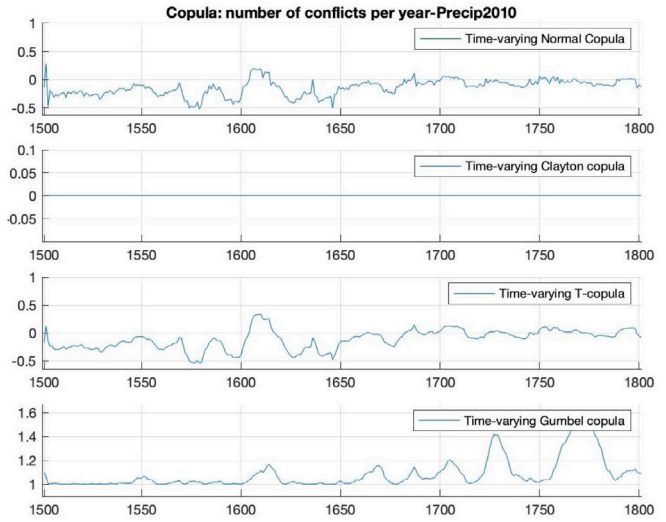

Fig. 31. Precipitations anomalies and conflicts.

between climate and conflict is not uniform and is dependent on some other underlying factors. The introduction of the time varying Copula methodology is an original mean to revisit the climate-conflicts relationships. This methodology might be applied to contemporaneous conflict data in a further work to better understand the drivers of violence and its links with climate change in a near future.

Appendix

In this appendix, we report all copula plots for the social disturbances, war and war fatalities indices respectively. Time is on the X-axis (1500 to 1800) and the coefficient of dependence is reported on the Y-axis.

A.1. Temperature impact on social disturbances, war and war fatalities

See Figs. 5–13.

A.2. Precipitations impact on social disturbances, war and war fatality

See Figs. 14–19.

Table 5
Static estimation of copulas.

	τ_{Normal}	$\tau_{Clayton}$	$\tau_{Student}$	τ_{Gumbel}	$\tau_{SJCLower}$	$\tau_{SJCUpper}$
Eur_temp - Social disturb	−0,1146	0,0001	−0,1183	1,1000	8,1643	0,0314
	(0,0093)	(0,0016)	(0,2806)	(0,1058)	(0,0674)	(0,0064)
Eur_temp - War	−0,4016	0,0001	−0,4098	1,1000	0,0003	0,8847
	(0,0315)	(0,0011)	(0,1365)	(0,0715)	(0,0022)	(0,0160)
Eur_temp - War fatality idx	−0,3503	0,0001	−0,3590	1,1000	1,4192	0,0003
	(0,0266)	(0,0011)	(0,4854)	(0,0780)	(0,0208)	(0,0024)
Mann NH - Social disturb	−0,1654	0,0001	−0,1710	1,1000	2,7433	0,0625
	(0,0165)	(0,0014)	(0,5885)	(0,0881)	(0,0337)	(0,0052)
Mann NH - War	−0,5194	0,0001	−0,5281	1,1000	0,6085	0,0003
	(0,0428)	(0,0009)	(0,1125)	(0,0658)	(0,0123)	(0,0020)
Mann NH - War fatality idx	−0,3040	0,0001	−0,2642	1,1000	3,8665	0,0003
	(0,0191)	(0,0011)	(0,6771)	(0,0873)	(0,0353)	(0,0024)
Temp2006 - Social disturb	−0,1888	0,0001	−0,1982	1,1000	0,0337	0,0042
	(0,0164)	(0,0014)	(0,8145)	(0,0949)	(0,0076)	(0,0038)
Temp2006 - War	−0,2961	0,0001	−0,3064	1,1000	0,0003	1,2482
	(0,0254)	(0,0013)	(0,5510)	(0,0778)	(0,0025)	(0,0208)
Temp2006 - War fatality idx	−0,2284	0,0001	−0,2351	1,1000	3,2975	0,0003
	(0,0192)	(0,0013)	(0,0010)	(0,0859)	(0,0343)	(0,0027)
Precip2010 - Social disturb	0,0208	0,0103	0,0181	1,1000	0,0732	0,0000
	(0,0018)	(0,0152)	(0,0010)	(0,1272)	(0,0010)	(0,0075)
Precip2010 - War	−0,3467	0,0001	−0,3557	1,1000	0,0003	0,1330
	(0,0303)	(0,0011)	(1,3252)	(0,0723)	(0,0024)	(0,0074)
Precip2010 - War fatality idx	−0,1760	0,0001	−0,1755	1,1000	7,4548	0,0003
	(0,0131)	(0,0013)	(1,3181)	(0,0975)	(0,0597)	(0,0028)
PrecipAMJ - Social disturb	0,0784	0,1570	0,0773	1,1000	0,0000	392,6085
	(0,0024)	(0,0280)	(0,1492)	(0,1434)	(0,0042)	(12,8233)
PrecipAMJ - War	−0,1794	0,0001	−0,1853	1,1000	0,4907	0,0635
	(0,0151)	(0,0015)	(0,0010)	(0,0893)	(0,0172)	(0,0057)
PrecipAMJ - War fatality idx	−0,0748	0,0001	−0,0721	1,1000	12,9245	0,0625
	(0,0051)	(0,0017)	(0,0010)	(0,1156)	(0,1066)	(0,0059)
ENSO - Social disturb	−0,0108	0,0050	−0,0114	1,1000	0,0313	0,0002
	(0,0014)	(0,0245)	(0,3951)	(0,1165)	(0,0098)	(0,0080)
NAO - Social disturb	0,1151	0,0295	0,1199	1,1000	649,7285	0,0000
	(0,0110)	(0,0268)	(0,4051)	(0,2997)	(4,6367)	(0,0049)
ENSO - War	−0,0314	0,0471	−0,0404	1,1000	0,0440	33,0999
	(0,0038)	(0,0152)	(1,8942)	(0,1171)	(0,0088)	(0,2322)
NAO - War	0,2340	0,2580	0,2408	1,1518	741,7325	504,1013
	(0,0191)	(0,0365)	(0,0012)	(0,0160)	(4,3078)	(6,6441)
ENSO - War fatality idx	0,0703	0,0988	0,0724	1,1000	1,1170	233,2730
	(0,0052)	(0,0222)	(0,0001)	0,1780	(0,0737)	(0,7373)
NAO - War fatality idx	0,1774	0,2310	0,1788	1,1118	88,4954	890,0174
	(0,0130)	(0,0348)	(0,0001)	(0,0684)	(6,6743)	(22,3703)
EUR_TEMP - Grain price	−0,5259	0,0001	−0,5354	1,1000	0,3560	0,0003
	(0,0463)	(0,0009)	(0,1101)	(0,0638)	(0,0097)	(0,0020)
NAO - Grain price	0,0095	0,0001	0,0053	1,1000	525,5689	0,0000
	(0,0002)	(0,0021)	(0,0001)	(0,1817)	(10,0896)	(0,0025)
ENSO - Grain price	0,0178	0,0099	0,0400	1,1000	3,7313	0,0003
	(0,0036)	(0,0070)	(0,0001)	(0,1604)	(0,3495)	(0,0076)
Nber of conflicts - Temperature anomalies (° C)	−0,0465	0,0001	−0,0473	1,1000	4,5518	0,0625
	(0,0039)	(0,0017)	(0,0001)	0,0860	(0,0472)	(0,0055)
Nber of conflicts - Mann NH	−0,1542	0,0001	−0,1828	1,1000	13,2290	0,0314
	(0,0035)	(0,0015)	(0,8278)	(0,1251)	(0,9933)	(0,0029)
Nber of conflicts - Precip2010	−0,1384	0,0001	−0,1713	1,1000	14,1746	0,0314
	(0,0025)	(0,0017)	(1,0604)	(0,1305)	(0,9295)	(0,0030)

Note: The Table refers to the maximum likelihood estimates of the parameters of the different copula models Normal, Clayton, Student, Gumbel and Symmetrized Joe–Clayton with associated lower and upper tails coefficients. The columns refer to each copula tested considering the previous ordering. Standard errors are in (.).

A.3. ENSO and NAO impact on social disturbances, war and war fatalities

See Figs. 20–25.

A.4. Temperatures, ENSO and NAO impact on grain prices

See Figs. 26–28.

A.5. Robustness check

See Figs. 29–31.

A.6. Static estimation of copulas and symmetrized clayton copulas

It is quite clear that the knowledge of the marginal distributions and linear correlation coefficients is not sufficient to fully describe a joint distribution: Clayton's copula, for example, has contours that are quite peaked in the negative quadrant, implying greater dependence for joint negative events than for joint positive events. Gumbel's copula refers to the opposite.

It should allow for asymmetric dependence in either direction and should nest symmetric dependence as a special case. We specify and estimate an alternative copulas, the "symmetrized Joe–Clayton" copula (SJC) (see Patton (2006a,b) for full details). The main reason for our interest in the symmetrized Joe–Clayton specification is that although it nests symmetry as a special case, it does not impose symmetric dependence on the variables like the normal copula (the normal copula may be considered as a benchmark copula).

The classical Joe–Clayton copula has two parameters, τ_u and τ_L, which are measures of dependence known as tail dependence (see Patton (2006a,b)). The normal copula has $\tau_u = \tau_L = 0$ for correlation less than one, meaning that in the extreme tails of the distribution the variables are independent. The Joe– Clayton copula allows both upper and lower tail dependence to range anywhere from zero to one freely of each other. As mentioned in Patton (2006a,b), one major drawback of the Joe–Clayton copula is that even when the two tail dependence measures are equal, there is still some (slight) asymmetry in the Joe–Clayton copula, due to simply the functional form of this copula. A more desirable model would have the tail dependence measures completely determining the presence or absence of asymmetry. To this end, we investigate the symmetrized Joe–Clayton (SJC) copula. It is clearly only a slight modification of the original Joe–Clayton copula, but by construction it is symmetric when $\tau_u = \tau_L$. From an empirical perspective, the fact that the SJC copula nests symmetry as a special case makes it a more interesting specification than the Joe–Clayton copula.

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