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Document de Travail n° 2020 – 20

Avril 2020

Bureau d'Économie Théorique et Appliquée BETA

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Cliometrics of Climate Change: A Natural Experiment on the Little Ice Age

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April 16, 2020

Abstract

This paper presents the findings of climate change impact on a widespread human crisis due to a natural occurrence, focusing on the so-called Little Ice Age period. The study is based on new non-linear econometrics tools. First, we reassessed the existence of a significant cooling period using outliers and structural break tests and a nonlinear Markov Switching with Levy process (MS Levy) methodology. We found evidence of the existence of such a period between 1560-1660 and 1675-1700. In addition, we showed that NAO teleconnection was probably one of the causes of this climate change. We then performed nonlinear econometrics and causality tests to reassess the links between climate shock and macroeconomic indicators. While the causal relationship between temperature and agricultural output (yields, production, price) is strongly robust, the association between climate and GDP identified by the MS Levy model does not reveal a clear causality link. Although the MS Levy approach is not relevant in this case, the causality tests indicate that social disturbance might also have been triggered by climate change, confirming the view of Parker (2013). These findings should inform current public policies, especially with regard to the strong capacity of climate to disrupt social and economic stability.

Keywords: Little Ice Age, climate change, non-linear econometrics, Markov Switching Levy, Causality, Economic cycles, Social crisis
JEL classification: C22, C53, E32, E33, F00, Q00

1 Introduction

In a recent paper, Hsiang and Kopp (2018) stressed the important role of economists to complement climatologists in order to gain a better understanding of global climate change. Since we can expect a growing impact of global warming in the near future (see the latest IPCC reports for example), it is important to investigate the vulnerability of both developing and developed economies to such changes in climate conditions. One way to approach this would be to analyze how economies have historically been affected by strong climate shocks through an assessment of the links between climatic shocks and macroeconomic indicators (both economic and social variables) and how pre-industrial economies adapted to climate change shocks in the past. In a recent book, the historian Geoffrey Parker (2013) suggests examining the potential links between climate and major disruptions or calamities in human activity (wars, social disturbances, famines, invasions) over the course of the seventeenth century.

However, studies assessing the impact of climate on macroeconomic and social events are very scarce, especially by econometricians who have not been particularly interested in the topic. The purpose of our paper is thus to reinvestigate the link between climate and macroeconomic and social indicators using advanced time series econometrics.

Very broadly, our paper relates to the emerging literature on climate econometrics (see for instance Deschenes and Greenstone (2007), Dell et al. (2012, 2014), Hsiang (2016)) that empirically explores the effects of year-to-year fluctuations in temperatures or precipitations on economic or social outcomes like agriculture production, conflict, health and economic growth among other indicators. More recently Burke et al. (2015) and Kahn et al. (2019) outlined climate growth causality in both developing and developed countries; Colacito et al. (2019) stressed the special case of the USA.

However, empirical evidence of long-term and dynamic effects of climate on economic outcomes remains very limited. It is a crucial question regarding the global warming issue since long-run, historical investigations can give us some insights into the potential adaptation of the population and the economy to climate shocks. Recently, Behrer and Park (2017) found evidence that US regions with a hotter climate were better adapted to heat. Understanding long-term adaptation is crucial if we are to adapt policies in response to ongoing climate change (Bastin et al., 2019).

The economics literature focusing on historical analysis with long horizon data appears to be very scarce. Waldinger (2015) conducted panel econometrics to assess the economic impact of long-term and gradual climate change over the period 1500-1750 when people had time to adapt. However, she focused on panel data of 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 shorter growing periods and more frequent harvest failure in this period. Using historical wheat prices, the author shows that temperatures affected economic growth through its effect on agricultural productivity.

Auray et al. (2016) built a growth model to assess the impact of temperatures and precipitation in pre-industrial England over the period 1669-1800. Using historical data on real wages and real rents, they extracted the productivity variations that could be due to the reallocation of labor and land and climatic factors as a residual. They show that a 2-degree rise in temperature would reduce the TFP by 11% and so wages would follow the same pattern. Furthermore, they noted that temperature might have a non-linear effect on productivity and thus on growth: low variations have a positive effect, while wide temperature variations have a negative impact.

Other scholars, such as geographers, have been more interested in the link between climate and socio-economic outcomes from a historical perspective. The closest papers to our study are those of Zhang et al. (2007, 2011, 2015) and Pei et al. (2014) which found evidence that climate change exerted causal effects on social and economic fluctuations in China and European pre-industrial societies using correlations and bivariate Granger causality tests. Zhang et al. (2011) tried to identify potential links between temperature anomalies and wars/social disturbances during the pre-industrial era in Europe and show that cooling from 1560 to 1660 caused successive agro-ecological, socioeconomic and demographic catastrophes, leading to the General Crisis of the Seventeenth Century. Pei et al. (2014) and Zhang et al. (2015) focused on the links between climate and macroeconomic cycles in the agrarian society of pre-industrial Europe through a temporal-scale analysis. Their main conclusion is that climate change can only impact the macroeconomic cycle in the long-term and that short-term effects are less significant due to possible social adaptation methods and self-adjustment mechanisms.

In these studies, they conducted statistical analysis using Butterworth filters (30 or 40 years) to get low-pass and high-pass filtering series and to find evidence of a positive significant correlation between temperatures, grain prices and wages, but only for high-pass filtering data (long-run). These results are confirmed by bivariate Granger causality tests to identify a set of causal linkages.

However, after examining the statistical chronology of the little ice age period thanks to a battery of temperature and precipitation datasets over the 1300-1800 period, Kelly and OGrada (2014) argued they were skeptical of the existence of a Little Ice Age period. In a more general way, they questioned the frequent statistical use of filtered climatic series in some disciplines. For instance, common evidence in the climatology literature about the existence of a Little Ice Age and climate-economics relationship probably finds its origin in a so-called Slutsky effect stemming from the use of smoothed instead of unsmoothed data when correlation and causality were performed:

"contrary to the existing consensus of a European Little Ice Age, we can find little evidence for change points or temporal dependence in the weather series (...) may reflect the fact that our analysis is based on unsmoothed data. This is in contrast to the common practice in climatology of smoothing data using a moving average or other filter to extract long run climate signals from noisy local weather observations. When data are uncorrelated, as the annual European weather series we examine appear to be, such smoothing can introduce

the appearance of irregular oscillations: a Slutsky effect". In addition, the use of filtered series could lead to spurious stationarity.

this paper, we propose computing a new nonlinear econometric methodology to reassess 1) the potential existence of a Little Ice Age period regarding long- run temperature dynamics 2) the causal importance of this potential climate change on macroeconomic activity and social disturbance over the period 1500-1800. To this end, we use a novel Markov Switching (MS hereafter) with Levy process to take a variety of nonlinear patterns in the time dynamics of our series into account. One advantage of the MS Levy method performed in this paper is that it avoids the Slutsky effect described by Kelly and Ograda (2014) since we only focus on the exploitation of raw/untransformed data. The second advantage is that we can investigate nonlinear effects in the time series and closely identify different, more or less long, regimes with different levels of causality between climate and macroeconomic conditions. Finally, we use two different types of Granger causality methods to assess the causal linkages between climate change and economic cycles on the one hand and climate change and social outcomes like social disturbances on the other.

Our MS Levy results clearly detect some regime changes in 1550-1700 and note evidence of a Little Ice Age period with a strong cooling period. Focusing on the NAO (North Atlantic Oscillation) teleconnection, we show that a change in NAO is likely to be at the origin of this climate change. However, our data also show that this period is not uniform. Indeed, we identified some specific sub-regimes with strong changes in both temperature and grain prices, and even societal outcomes within this period. Using historical sources, we noted the relevance of the sub-regimes identified by our methodology. During the Little Ice Age period, we also show that some changes in grain prices, wages, GDP and social disturbances are partially coincident with climate changes. Some causal linkages between climate and grain prices, and thus climate and societal disturbances in the sub-periods identified by our econometric methodology, are plausible. Nonetheless, our results nuance the previous literature by finding strong evidence for only a subset of variables. Most of the series we used do not appear to be stationary and exhibit nonlinear patterns in contrast to what has been assumed in the earlier literature. Omitting non-linearity and unit roots may be the cause of some overestimations in previous papers.

Section 2 presents the data and the econometric methodology, especially the MS Levy model. Section 3 attempts to answer the following question: Did the Little Ice Age exist? In section 4, we discuss whether climate cooling during the plausible Little Ice Age period is likely to have impacted economic and societal cycles. Section 5 concludes.

2 Data and econometric framework

2.1 Data

We collected different types of historical data over the potential Little Ice Age period but for comparative purposes, decided to focus on data between 1500-1800 in similar vein to the previous literature. In particular, we followed Zhang et al. (2011) in collecting a large part of our dataset series (for more detailed information, please read the appendix on Zhang et al. (2011)).

We first collected two anomaly series of temperatures for the whole of pre-industrial Europe and several series concerning macroeconomic and social indicators on long-run temperature data reconstructions stemming especially, but not only, from the celebrated work of Luterbacher et al. (2004).

The *Eurtemp* climatic variable denotes the European anomaly temperature series calculated by Zhang et al. (2011). This variable was derived from two authoritative annual scale temperature reconstructions by Luterbacher et al. (2004) for European land areas (25oW to 40oE and 35oN to 70oN) over the period 1500-2003 and part of the series from Osborn and Briffas (2006) over the 800-1995 that are most relevant for the European region. Since the two temperature reconstruction series were derived from different proxies and reconstructed using different methods, each of them was normalized to homogenize the original variability of all the series. Note that the series are detrended to better focus on the stochastic dynamics.

The second climatic variable called *winter_europe_lut* consists of Luterbacher et al.s (2004) winter temperature data to better capture the potential Little Ice Age period by focusing on cooling anomalies in winter periods.

We completed our climatic variables set by adding the NAO (North Atlantic Oscillation) teleconnection variable. As we will explain later, NAO (North Atlantic Oscillation) is the most active climatic teleconnection in the North Hemisphere and is likely to explain European winter temperatures to a large degree. Here, we use reconstruction data from The North Atlantic Oscillation Index based on three academic studies, multi-proxies by Cook et al (2002), tree-ring records by Glueck et al (2001), and speleothem records by Trouet et al (2009). These three curves cover the study period of 1500-1800 AD. To increase reliability of the NAO index, the three curves were first standardized. They were then calculated to get the mean value.

We also used agricultural data to investigate the link between temperature and agricultural yields identified for instance by Waldinger (2015): grain yields and grain prices series come from Zhang et al. (2011) and Pei et al. (2014). Grain yield is based on the old Dutch Van Bath dataset (also used by Waldinger (2015)) and is calculated as a ratio of grain harvest to seed amount using data from 18 countries: wheat, rye, barley and oat yields are arithmetically averaged to give a synthetized aggregate for pre-industrial Europe.

Additionally, we used several economic variables from Pei et al. (2014): real wages as a proxy of income and purchasing power that used two seminal sources: the first is an annual dataset of real day wages for laborers in England and the second source of data is from Allen (2001).

For the first time, we also used GDP data reconstructions by Fouquet and Broadberry (2015) to proxy global production and wealth of nations. Only Holland, UK and Italy were considered as good candidates to represent the economic situation in pre-industrial Europe and we left Spain, Portugal and Sweden out of the dataset.

Finally, we collected conflict and violence data and constructed three different variables in the vein of Zhang et al. (2011): social disturbances, war and war fatality. War denotes the number of wars and is obtained from the Conflict catalogue drawn up by Brecke (1999, 2001). As explained by Zhang et al. (2011), the catalogue documents a total of 582 wars fought between 1500-1800. Social disturbance data were obtained from Sorokins book (1937), volume III, entitled Social and Cultural Dynamics that recorded the most significant internal disturbances in both Central and Eastern Europe for an aggregate total of 205 social disturbances during our study period. Political disturbances (change to political regimes), socioeconomic disturbances (change to existing economic or social order), national and separatist disturbances, religious disturbances are all recorded. Since Sorokin gives the magnitude of each disturbance considerable detail including duration, location, masses involved, etc., the magnitude has been divided by its duration (number of years) to get a magnitude/year ratio and the annual magnitude is then calculated on a yearly basis and finally divided by the number of countries in Europe (Zhang et al., 2001).

Raw time series are presented in Appendix in figures 1 to 4. Taking a quick look at all the series, it is possible to identify some clear and interesting trends. - The first two series, though from different sources, display some similar patterns: a decreasing trend from 1500 to 1600 with a peak around 1600-1650 followed by an increasing trend. The last two raw series from Luterbacher et al. (2004), especially the winter temperatures series, display more noisy dynamics. It is interesting to compare the ability of MS Levy to detect regimes in all the different temperature series and in heterogeneous dynamics. - The green yield series exhibit three distinct sub-periods: a decreasing trend between 1500 and 1600, a stable period with very low yield levels between 1600 and 1700 and an increasing trend from 1700. The grain price series exhibits the exact opposite, except that the stable period with high price levels is concentrated in the 1620-1650 period. So, graphically, there is simultaneity between part of the low yields period and the high grain prices period. - The wage and famine series show a peak for the 1600-1660 period corresponding to a low wages period in the same sub-period (after and maybe consecutive to a decreasing trend between 1500 and 1600). - Trends for GDP growth rates series are less clear-cut. Some facts are particularly notable: there is a more volatile period in the 1600-1650 period for Hollands GDP growth rate and, in contrast, a less volatile period in 1570-1670. Finally, the 1550-1700 period seems to be more volatile for the UK. In contrast, between 1500 and 1560, volatility is highest in Italy and the rest of the period appears to be a more stable period.

In the Table 1 below, we calculated some simple correlation coefficients to get a brief idea of the potential correlations between our variables. We can see that

European temperatures are positively associated with grain yield, agricultural production, wages but negatively with grain prices and number of famines or plagues, in line with the studies by Zhang et al. (2007, 2011). In addition, European temperatures are negatively associated with wars, in line with the literature on climate and conflicts (e.g., Tol and Wagner, 2010, on the same period). However, the link between European temperatures and GDP (UK, Italy, Holland) is not clear-cut. In similar vein, the link between temperatures and social disturbances do not seem significant. When winter temperatures are used instead of aggregate European temperatures, the level of significance tends to decrease quite strongly. All in all, the causal link between cooling temperatures and social and economic crises do not appear totally evident.

Table 1: Correlation coefficients matrix

	EUR_TEMP	WINTER_TEMP	GRAIN_YIELD	GRAIN_PRICE	AGRI_PROD	WAGE	FAMINE	PLAGUE	DISTURB	WAR	UK	HOLLAND	ITALY
EUR_TEMP	1.000000 ——												
WINTER_TEMP	0.547125 11.28346	1.000000 ——											
GRAIN_YIELD	0.446746 8.620073	0.144629 2.523216	1.000000 ——										
GRAIN_PRICE	-0.530140 -10.79317	-0.124771 -2.170842	-0.495335 -9.843212	1.000000 ——									
AGRI_PROD	0.496411 9.871567	0.104670 1.816866	0.503182 10.05146	-0.805460 -23.46137	1.000000 ——								
WAGE	0.467655 9.133235	0.110529 1.919790	0.532325 10.85520	-0.750121 -19.58126	0.649069 14.72886	1.000000 ——							
FAMINE	-0.463500 -9.029758	-0.019816 -0.342152	-0.450234 -8.704395	0.639696 14.36700	-0.466263 -9.098501	-0.524999 -10.64842	1.000000 ——						
PLAGUE	-0.461925 -8.990747	-0.098895 -1.715610	-0.361973 -6.703167	0.583495 12.40299	-0.307445 -5.577462	-0.545917 -11.24796	0.516459 10.41146	1.000000 ——					
DISTURB	-0.088272 -1.529783	0.023696 0.409179	-0.088978 -1.542124	0.270143 4.843472	-0.222901 -3.947167	-0.156502 -2.735341	0.156583 2.736805	0.180979 3.176638	1.000000 ——				
WAR	-0.273324 -4.905078	0.017186 0.296717	-0.260654 -4.660686	0.572519 12.05428	-0.412866 -7.825249	-0.304122 -5.510998	0.569202 11.95085	0.269891 4.838593	0.223303 3.954674	1.000000 ——			
UK	0.030084 0.519573	-0.004094 -0.070678	-0.031122 -0.537506	0.076080 1.317161	-0.091060 -1.578495	-0.106188 -1.843507	-0.034190 -0.590559	-0.011208 -0.193490	0.015829 0.273287	-0.032062 -0.553755	1.000000 ——		
HOLLAND	0.025913 0.447480	0.030076 0.519432	0.054643 0.944697	-0.004623 -0.079808	-0.042380 -0.732242	0.002805 0.048418	-0.011027 -0.190369	-0.021112 -0.364538	-0.012531 -0.216327	-0.032261 -0.557194	-0.110665 -1.922188	1.000000 ——	
ITALY	0.067848 1.173942	0.071724 1.241340	-0.001949 -0.033645	0.010331 0.178346	-0.059035 -1.020887	-0.044706 -0.772524	-0.032558 -0.562332	-0.014040 -0.242394	0.008513 0.146967	-0.021992 -0.379726	0.057699 0.997696	-0.026357 -0.455157	1.000000 ——

Note: Numbers below coefficients are p-values of the F-test for statistical significance

Finally, temperatures and economic time series tend to move hand in hand to some extent. In the rest of the paper, we compute MS Levy regressions to take this stylized fact further. Indeed, nonlinear phenomena may play an important role in the climate-economics relationship due to complex reallocations of resources by agents in good (normal temperatures) or bad (very cold during this period, but also very hot temperatures more generally) economic conditions. This implies dynamic relationships that cannot be captured by the contemporaneous correlations displayed in Table 1 and need to be investigated through more complex approaches.

2.2 The MS Levy methodology

As previously mentioned, the MS Levy methodology has several advantages. First, it is a suitable method to describe many nonlinear patterns in certain time series. Second, the MS Levy model uses the data without transformation and so avoids the Slutsky effect. This methodology allows both identification of dynamics' break or change and capture of pure jumps and spikes in the series.

Let $(\omega, \mathcal{F}, P)$ be a filtered probability space and T be a fixed terminal time horizon. We model the dynamic of a sequence of historical values of time series - both climate and economic or societal outcomes - using a regime-switching stochastic jump-diffusion. This model is defined using the class of pure jump processes such as Lévy processes.

Definition 1 *A Lévy process L_t is a stochastic process such that*

1. $L_0 = 0$.
2. *For all $s > 0$ and $t > 0$, we have that the property of stationary increments is satisfied. i.e. $L_{t+s} - L_t$ as the same distribution as L_s.*
3. *The property of independent increments is satisfied i.e. for all $0 \leq t_0 < t_1 < \cdots < t_n$, we have $L_{t_i} - L_{t_{i-1}}$ independent for all $i = 1, \ldots, n$.*
4. *L has a Cadlag path. This means that the sample paths of a Lévy process are right continuous and admit a left limits.*

Remark 2 *In a Lévy process, discontinuities occur at random times.*

Definition 3 *Let $(Z_t)_{t\in[0,T]}$ be a continuous time Markov chain on finite space $\mathcal{S} := \{1, 2, \ldots, K\}$. Denote $\mathcal{F}_t^Z := \{\sigma(Z_s); 0 \leq s \leq t\}$, as the natural filtration generated by the continuous time Markov chain Z. The generator matrix of Z, denoted by Π^Z, is given by*

$$\Pi_{ij}^Z \geq 0 \quad \text{if } i \neq j \text{ for all } i, j \in \mathcal{S} \quad \text{and} \quad \Pi_{ii}^Z = -\sum_{j \neq i} \Pi_{ij}^Z \quad \text{otherwise.} \tag{1}$$

Remark 4 *The quantity Π_{ij}^Z represents the switch from state i to state j.*

Let us define the regime-switching Lévy Model:

Definition 5 *For all $t \in [0,T]$, let Z_t be a continuous time Markov chain on finite space $\mathcal{S} := \{1,\ldots,K\}$ defined as in Definition 3. A regime-switching model is a stochastic process (X_t) which is solution of the stochastic differential equation given by*

$$dX_t = \kappa(Z_t)\left(\theta(Z_t) - X_t\right)dt + \sigma(Z_t)dY_t \tag{2}$$

where $\kappa(Z_t)$, $\theta(Z_t)$ and $\sigma(Z_t)$ are functions of the Markov chain Z. Hence, they are constants which take values in $\kappa(\mathcal{S})$, $\theta(\mathcal{S})$ and $\sigma(\mathcal{S})$

$$\kappa(\mathcal{S}) := \{\kappa(1),\ldots,\kappa(K)\} \in^{K^*}, \quad \theta(\mathcal{S}) := \{\theta(1),\ldots,\theta(K)\},$$
$$\sigma(\mathcal{S}) := \{\sigma(1),\ldots,\sigma(K)\} \in^{K^+}.$$

where Y is a stochastic process which could be a Brownian motion or a Lévy process.

Remark 6 *The following classic notations apply:*

- *κ denotes the mean-reverting rate;*
- *θ denotes the long-run mean;*
- *$\sigma_.$ denotes the volatility of X.*

Remark 7

- *In this model, there are two sources of randomness: the stochastic process Y appears in the dynamics of X, and the Markov chain Z. There is one randomness due to the market information which is the initial continuous filtration $\mathcal{F}$ generated by the stochastic process Y; and another randomness due to the Markov chain Z, $\mathcal{F}^Z$.*
- *In our model, the Markov chain Z infers the unobservable state of the economy, i.e. expansion or recession. The processes Y^i estimated in each state, where $i \in$, capture: a different level of volatility in the case of Brownian motion (i.e. $Y^i \equiv W^i$), or a different jump intensity level of the distribution (and a possible skewness) in the case of the Lévy process (i.e. $Y^i \equiv L^i$).*

We recall the main properties of the Normal Inverse Gaussian (NIG) distribution. Indeed, we assume that a Lévy process L follows a Normal Inverse Gaussian (NIG) distribution. The NIG family of distribution was introduced by Barndorff-Nielsen and Halgreen (1977). The NIG density belongs to the family of normal variance-mean mixtures, i.e. one of the most commonly used parametric densities in financial economics.

Taking $\delta > 0$, $\alpha \geq 0$, the density function of a NIG variable $NIG(\alpha,\beta,\delta,\mu)$ is given by

$$f_{NIG}(x;\alpha,\beta,\delta,\mu) = \frac{\alpha}{\pi}\exp\left(\delta\sqrt{\alpha^2-\beta^2}+\beta(x-\mu)\right)\frac{K_1\left(\alpha\delta\sqrt{1+(x-\mu)^2/\delta^2}\right)}{\sqrt{1+(x-\mu)^2/\delta^2}}. \tag{3}$$

where K_ν is the Bessel function of the third kind with index ν. It can be represented by the following integral

$$K_\nu(z) = \frac{1}{2}\int_0^\infty y^{\nu-1}\exp\big(-\frac{1}{2}z(y+y^{-1})\big)dy \ .$$

For a given real ν, the function K_ν satisfies the differential equation given by

$$x^2 y^{''} + xy^{'} - (x^2+\nu^2)y = 0 \ .$$

This class of distribution is stable by convolution as the classic normal distribution. i.e.

$$NIG(\alpha,\beta,\delta_1,\mu_1) * NIG(\alpha,\beta,\delta_2,\mu_2) = NIG(\alpha,\beta,\delta_1+\delta_2,\mu_1+\mu_2) \ .$$

Lemma 8 *If $X \sim NIG(\alpha,\beta,\delta,\mu)$ then for any $a \in^+$ and $b \in$, we have that*

$$Y = aX + b \sim \left(\frac{\alpha}{a},\frac{\beta}{a},a\delta,a\mu+b\right).$$

The log cumulative function of a NIG variable is given by

$$\phi^{NIG}(z) = \mu z + \delta\left(\sqrt{\alpha^2-\beta^2} - \sqrt{\alpha^2-(\beta+z)^2}\right), \quad \text{for all } |\beta+z| < \alpha \ , \quad (4)$$

The first moments are given by

$$[X] = \mu + \frac{\delta\beta}{\gamma} \ , \quad \mathrm{Var}[X] = \frac{\delta\alpha^2}{\gamma^3} \ . \quad (5)$$

with $\gamma = \sqrt{\alpha^2-\beta^2}$. And finally the Lévy measure of a NIG$(\alpha,\beta,\delta,\mu)$ law is

$$F_{NIG}(dx) = e^{\beta x}\frac{\delta\alpha}{\pi|x|}K_1(\alpha|x|)\,dx \ . \quad (6)$$

Remark 9 *An interesting point of the NIG distributions is that each parameter in $NIG(\alpha,\beta,\delta,\mu)$ distributions can be interpreted as having a different impact on the shape of the distribution: α - tail heaviness of steepness; β - skewness; δ - scale and μ - location.*

We apply the statistical estimation process initiated by Chevallier and Goutte (2017a) and developed by Chevallier and Goutte (2017b) in the application to modeling of CO2 and fuel-switching prices.

This methodology is a two-step approach by estimating in (2) *(i)* the model parameters in a regime-switching Brownian process, and *(ii)* the distribution parameters. We fit a regime-switching Lévy model such as (2) where the stochastic process Y is a Lévy process that follows a Normal Inverse Gaussian (NIG) distribution. Thus the optimal set of parameters to estimate is $\hat{\Theta} := \left(\hat{\kappa}_i,\hat{\theta}_i,\hat{\sigma}_i,\hat{\alpha}_i,\hat{\beta}_i,\hat{\delta}_i,\hat{\mu}_i,\hat{\Pi}\right)$, for $i \in \mathcal{S}$. So we have the three parameters of the dynamics of X, the four parameters of the density of the Lévy process L, and the transition matrix of the Markov chain Z. The results and their interpretations are stated in Section 5.4.

Table 2: Breaks tests results

Variables	Dates	Type	Delta	Size	t-stat
Average European Temperatures (Zhang et al., 2011) Eur_Temp	No outliers detected				
Average European Temperatures $Annual\_Temp$ (Luterbacher et al., 2004)	No outliers detected				
Winter European Temperatures $Winter\_Temp$ (Luterbacher et al., 2004)	No outliers detected				
Grain Price	1622	TC		0,30906	8,11
Wage	1534	AO		1,1978	4,76
Wage	1537	TC		1,4153	4,34
Wage	1547	TC		0,32606	4,23
Social Disturbances	1648	TC	-0,37		-6,97
War	1648	AO		6,57	4,61
Holland GDP	1568	AO		-862,42	-5,8
Holland GDP	1617	AO		1008,8	6,25
Holland GDP	1576	AO		622,26	4,19
Holland GDP	1619	AO		-643,7	-3,99
UK GDP	1628	AO		-243,89	-3,67
Italy GDP	1533	AO	88,134	192,47	4,13
Italy GDP	1504	TC	-80,252	-153,21	3,7
Italy GDP	1546	AO			-3,34
Italy GDP	1525	TC			-3,33

3 Did little ice age exist?

In line with Kelly and OGrada (2014), we first applied some outliers and tests for breaks to our temperature variables to help us detect a potential Little Ice Age period. Though descriptive and graphical analyses seem to show a period of strong cooling between 1600 and 1660, the question of the existence of a Little Ice Age period is still debateable and needs further investigation.

We first computed the Chen and Liu (1993) outliers test using the TRAMO Seats software. Chen and Liu (1993) developed a break detection from AutoRegressive Moving-Average (ARMA) models, and considered three types of breaks (see for example Charles et al. (2018) for a formal description): an additive outlier (AO), a level shift (LS) and temporary change (TC). As Charles et al. (2018) explained, AOs are outliers related to an exogenous change in the series with no permanent effects, whereas TCs and LSs are more in the nature of structural change. TCs represent short-lived shifts in a series with a return to previous levels while LSs are more the reflection of permanent shocks.

We then applied the Bai and Perron (1998, 2003) procedure to detect potential outliers: this method is useful as it captures structural changes in both mean and variance.

Table 2 shows that it is impossible to detect some breaks (both in mean and in variance) in the three temperature anomaly variables we used. Thus, in line with Kelly and OGrada (2014), we did not find evidence of a Little Ice Age from this statistical methodology. However, this is not enough to definitively conclude that there was no major cooling period in the 1500-1800 period. The conclusion of the outlier tests only implies that special warming or cooling did not emerge as a strong exogenous shock. However, other forms of statistical patterns such as smooth and persistent ones might be at work.

We thus went further than the outlier tests and applied the MS Levy methodology for the first time to identify the potential existence of a Little Ice Age era and some coinciding regimes between our climatic, social and economic variables.

We began by using the reconstruction of winter temperatures for Europe drawn up by Luterbacher et al. (2004) over the 1500-2004 period (winter luterbacher in appendix). This series exhibited the best statistical score according to our MS Levy model to identify different clear-cut regimes (hotter and cooler) over the period studied. Based on this variable, we outlined the existence of two clear different regimes (see detailed results displayed in Table 2): a cold (negative temperature mean value of -0.87) regime and a hot regime or at least a less colder one (positive mean: 0.3055). Regime 1, which is represented by negative values, is three times more volatile than regime 2, which suggests the existence of extreme winters with probably highly negative temperature values in contrast to normal winter temperatures.

We also computed the proportion of cold observations described by regime 1 in the total number of observations for each century and obtained the following results. They are clearly in favor of the existence of an over-representation of cooler winter observations (regime 1) during the 1500-1700 period:

- 33% of regime 1 over the 1900-2000 period
- 74% of regime 1 over the 1800-1900 period
- 42% of regime 1 over the 1700-1800 period
- 77% of regime 1 over the 1600-1700 period
- 61% of regime 1 over the 1500-1600 period

We next turned to the reconstruction of average temperatures across all of Europe using Annual Europe temperatures (for autumn, winter, spring and summer as a whole) from Luterbacher et al. (2004), called annual europe lut in our appendix. The global temperatures are less clear-cut regarding the existence of the Little Ice Age and it is more difficult to identify different regimes, probably due to compensation effects between positive temperature variations in summers and negative variations in winters. However, the MS Levy was able to identify the 1500-1772 period as a colder period, while the 1773-1830 period was identified as a less cold one, which seems to confirm the existence of a Little Ice Age period between 1500 and 1772 as a very broad view.

To keep the sample consistent with other series (1500-1800) and for comparative purposes, we used the European Temperature anomaly computed by Zhang et al. (2011, 2014), called Eur Temp anomaly in the appendix as the benchmark temperature anomaly series. The results from the MS Levy estimates applied to the temperature series are presented in the first four lines of Table 3. They clearly show the existence of two different regimes in the European temperature dynamics with a colder regime prevailing in the 1563-1659 and the 1674-1701 periods.

Overall, the MS Levy approach globally appears in favor of the existence of significant cooling episodes during the period under study and hint at the existence of a Little Ice Age. More interestingly, the MS Levy model appears to indicate that the global cooling period was not entirely uniform: the end of the 16th century to 1660 and then 1674-1700 seem to be marked by the coldest periods. We go further by applying and discussing the regimes identified by the MS Levy method for all the variables in our dataset in the following section.

4 Did climate negatively impact economic and social environment during the Little Ice age?

If climate affected pre-industrial European societies, we would expect some correspondence between the regimes identified in the temperature series (section 3) and the potential regimes the MS Levy model identified in the social and macroeconomic series. Therefore, we apply the same methodology as previously for a set of different series (see again Table 3): grain yield, grain price, wages, social disturbances and war, in line with Zhang et al. (2011). Like Pei et al. (2014), we also wanted to measure the potential correspondence and causality between climate, grain yield, grain price, wages and economic activity/production. Instead of using population growth, however, we preferred to use the GDP series recently drawn up by Fouquet and Broadberry (2015).

At first glance and before analyzing the MS Levy results, we tried to find some consistence in the results of the outliers tests for all the macroeconomic and social series. As previously noted, Table 2 did not reveal the presence of outliers in the temperatures series. However, some outliers appear to be present for the other series. Table 2 did not reveal clear links between the outliers or breaks detected by our tests. The only remarkable result was that a temporary change was detected in 1622 for grain price which could be linked to additional outliers in Holland and UK GDP in 1617 and 1628 respectively.

To get a more precise picture, we then applied the MS Levy methodology for all the social and macroeconomic series in our database. Hereafter, we separately comment (in detail) on the results for each series regarding the presence and nature of the different regimes. Table 3 synthesizes all the estimated results and Table 4 outlines the main historical regimes identified by the MS Levy estimates and is used as an overall picture for our general discussion.

Table 3: MS Levy estimates

Variables	Regime	Mean	q_ii	P(R)=i	Theta	Kappa	Sigma	Alpha	Beta	Delta	Mu
Eur_Temp	State 1	-0,61	0,96	0,48	-0,61	0,77	0,35	25,14	-22,52	1,37	2,75
	State 2	0,51	0,96	0,52	0,51	0,71	0,23	25,53	0,26	14,88	-0,15
Winter_Temp	State 1	-0,88	-0,74	0,57	-0,88	1,20	1,10	23,13	-17,78	1,91	2,30
	State 2	0,31	0,66	0,43	0,31	0,96	0,52	22,91	20,09	1,75	-3,21
Grain Yield	State 1	3,76	0,99	0,35	3,76	0,64	0,09	10,07	-0,21	0,22	0,00
	State 2	5,65	0,99	0,65	5,65	0,22	0,18	3,94	-1,01	0,39	0,10
Grain price	State 1	-0,09	0,92	0,47	-0,09	0,31	0,00	40,32	24,82	0,02	-0,01
	State 2	0,11	0,93	0,53	0,11	0,20	0,00	10,81	1,78	0,04	-0,01
Agricultural Prod	State 1	-25,44	0,75	0,78	-25,44	0,19	3802,07	0,01	0,00	68,05	0,98
	State 2	89,18	0,11	0,22	89,18	0,20	13203,26	0,01	0,00	250,64	33,69
Wage	State 1	0,04	0,93	0,56	0,04	0,09	0,05	0,96	-0,25	0,82	0,22
	State 2	-0,06	0,91	0,44	-0,06	0,21	0,25	14,01	10,25	4,49	-4,82
Famine	State 1	9,27	0,95	0,44	9,27	0,01	0,00	0,07	0,02	0,08	-0,03
	State 2	-0,97	0,96	0,56	-0,97	0,01	0,14	21,20	19,74	1,04	-2,67
War	State 1	2,19	0,95	0,27	2,19	0,44	0,99	19,29	11,33	5,64	-4,09
	State 2	8,68	0,98	0,73	8,68	0,23	4,01	2,89	0,23	1,50	-0,12
Social Disturbances	State 1	1,63	0,65	0,60	1,63	0,73	5,05	98,93	97,62	0,31	-1,91
	State 2	12,31	0,48	0,40	12,31	0,52	17,15	42,56	39,01	0,60	-1,37
UK GDP	State 1	0,41	0,64	0,73	0,41	1,52	5286,16	0,02	0,00	77,57	10,26
	State 2	25,52	0,00	0,27	25,52	0,72	6625,12	0,04	0,02	200,40	145,30
Holland GDP	State 1	4,40	0,97	0,78	4,40	1,33	21795,74	0,01	0,00	252,10	9,50
	State 2	1,32	0,90	0,22	1,32	1,26	136935,27	0,00	0,00	611,64	-81,84
Italy GDP	State 1	-1,04	0,99	0,80	-1,04	0,89	1477,96	0,06	0,01	81,48	7,55
	State 2	0,85	0,98	0,20	0,85	0,98	7066,17	0,02	0,00	165,12	1,73
NAO	State 1	0,22	0,97	0,75	0,22	0,49	0,20	2,37	0,92	1,80	0,76
	State 2	0,59	0,91	0,25	0,59	0,92	0,29	21,21	-15,08	2,94	2,98

4.1 Grain yield dynamics :

The observation distinctions between the two regimes is clear with an alternation of relatively long periods containing at least a dozen observations in each regime. This is reinforced by the value of the jump parameter which is above one. In other words, a major stochastic shock is needed to switch from state 1 to state 2 since the q_{ii} probability (probability to remain in the current regime) is high (0.99 in each regime). Regime 1 exhibits the lowest mean value at 3.76 (versus 5.65 in regime 2). However, regime 2 is the most volatile. This tendency is confirmed when we look at the $Sigma$ volatility parameter: its value is twofold in the second regime (0.18 versus 0.09). In addition, the mean reverting speed ($Kappa$) is higher in the first regime (probably "normal"/"fundamental" regime).

4.2 Grain price :

Again, the classification is good and a major shock is needed to switch from one given regime to another. The first regime has a negative price value (-0.09) and the second regime has a positive price value (0.11). The mean reverting speed ($Kappa$) is virtually the same in each regime but slightly higher in the first regime (associated to a fundamental regime). Observed volatility is however weak in both regimes.

Both dynamics are clearly Gaussian with a NIG parameter superior to 1 in compliance with the apparent dynamics of the series. If we look at the correspondence/match between the temperature anomalies and grain price (see Table 4), regime 2 with the highest grain prices is related to the periods of cooler temperatures. We can thus suggest that grain prices increased in periods of cooling temperatures. Historically and with regard to our datation: 1555-1649, 1674-1700 (especially 1674-1685) and 1787-1800 appear to be periods that correspond to lower temperatures and increasing prices (regime 2).

4.3 Wage :

In comparison with the previous series, identifying significantly distinct regimes is less clear-cut (52% of in sample forecasting?). However, the probability of staying in one regime is important (over 91%). Again, an important shock was needed to generate a switch of the series from one regime to another. Regime 1 denotes the regime with the highest wages and the second denotes the regime with the lowest payroll values. The first state is highly volatile and clearly exhibits some jumps (alpha=0,96) that probably explain why the identification rate is only 52% . The asymmetry is important in the regime 2 with lowest wages.

4.4 Holland economic growth :

Good classification (rate 78%) and the probability of remaining in the same regime is over 90%. Regime 1 denotes a relatively significant growth rate (mean

Table 4: Identification of historical regimes

	Regime 1	**Regime 2**
European Temperatures	Low 1541-1546 1563-1659 1674-1701 1739-1745	High 1500-1540 1547-1562 1660-1673 1702-1738 1746-1798
Grain Yield	Low 1600-1706	High 1500-1599 1707-1800
Grain Price	High 1555-1649 1674-1699 1787-1800	Low 1500-1554 1650-1657 1700-1786
Wage	Low 1597-1651 1667-1690 1712-1794 1795-1800	High 1500-1562 1568-1576 1585-1596 1652-1666 1691-1710**
Social Disturbances	Too much volatility to identify clear periods	
War	High 1500-1689 1701-1719 1789-1800	Low 1690-1700 1720-1688
Holland GDP	Low 1565-1580 1601-1632** 1701-1706	High 1500-1564 1581-1600 1633-1699 1707-1800
UK GDP	Distinction between regimes not significant	
Italy GDP	Low 1564-1579 1588-1670 1694-1800	High 1500-1563 1580-1587 1671-1693
Famine	High 1576-1605 1626-1655 1676-1685 1716-1745	Low 1500-1505 1516-1575 1606-1625 1686-1715 1746-1765 1776-1795

Note: the most coincident sub-periods identified among the series are reported in red color.

4.40) in comparison with regime 2 (1.32), The speed of adjustment is almost the same in each regime. Regime 2 clearly exhibits more volatility and thus, in times of relatively low economic growth, the Dutch economy was more unstable. This variable is more volatile than the other series and exhibits a lot of jumps.

If we correlate this with the temperature dynamics (please refer to Table 2), the following mechanism holds: when the climate is cooler and especially during the coldest phases of the Little Ice Age period, the Dutch economy seemed to switch from a normal economic growth regime to a more volatile regime with lower growth. The GDP growth results confirm the previous results of Zhang et al. (2011), Pei et al. (2014) and Waldinger (2015) that used population growth rates concerning a potential negative impact of temperatures on agricultural yield and so on the entire economic production. This is not altogether surprising since the share of the agricultural sector in pre-industrial economies was very high.

We also performed the same exercise for Italy and the UK but the results are less evident or not significant. We nonetheless noted some interesting facts: in the first part of the sample there was strong synchronization of GDP cycles in Holland and in Italy, which progressively disappeared over time.

4.5 Social Disturbances :

The quality of in-sample forecasting was moderate (only 54%) with probabilities remaining in the same regime at around 50%, making is a relatively unstable variable. The model switched more frequently from one regime to another one and it was difficult to clearly identify different regimes. However, the values in regime 1 are relatively low and seem to correspond to a normal regime. They are lower than the values of regime 2 (1.63 versus 12.31) which consists of periods of increasing social disturbance. Both regimes exhibit Gaussian distributions.

4.6 War :

Regarding the War variable regimes, we noted that in regime 2 (i.e. the regime in which Social Disturbance is ten times more than in the normal regime), the war variable value was four times more than normal (8.68 against 2.19). A link between climate, war and social disturbance is thus plausible in some regimes. Moreover, the intensity of jumps is much higher in the unstable regime state corresponding to economic crises periods since the parameter *Alpha* equals 2.89 against 19.29. All these results indicate that regime 2 exhibits an unstable crisis period where both Social Disturbance and War values increase. It is not surprised since 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. From a statistical point of view, the jumps have much greater intensity than in standard normal time periods.

5 General discussion

Given the detailed results in Tables 2 and 3, we find evidence that the MS Levy approach is able to detect coinciding regimes for both climatic and socio-economic series. Thus, it offers a new way to investigate the impact of the cooler Little Ice Age period on the economy and society of pre-industrial Europe, complementing previous correlations and bivariate Granger causality tests by taking nonlinearity patterns into account. The different regimes and sub-periods identified by the MS Levy model during the 1500-1800 period are an informative complement to previous graphic and outlier analyses. Though the1600-1660 period graphically appears as a singular cooling period with a potential impact on society, the MS Levy model gives us further information about regime switching and identifies some sub-periods within the periods under study. In contrast to Zhang et al. (2011) who only take 1560-1660 as the central cooling period, but consider 1661-1800 as a homogeneous mild phase, our MS Levy model identified different sub-regimes. Our method probably identifies more complex and lasting/diffuse effects of climate on macroeconomics that a simple graphic and correlation analysis is unable to detect. Indeed, a climate shock in period t may generate economic and social consequences in the contemporaneous period t but also during $t+k$ periods since the dynamic effects of climate on economics should also be taken into consideration (Dell et al., 2014). Hence, potentially declining European temperature between 1563-1659 (Eur_temp temperatures) might be viewed as the main kernel of the Little Ice Age period which, in that sense, is in line with Zhang et al. (2011). Moreover, this cooling regime seems to more or less coincide with lower grain yields (1600-1706), higher grain prices (1555-1649), lower wages (1597-1651) and lower GDP growth rates in Holland (1565-1632 and, above all 1601-1632), in Italy (1588-1670). In this way, the emergence of episodes of famine (1576-1605 and 1626-1655) may potentially be a consequence of climate shock and its contagion on the macroeconomic cycle.

Furthermore, and this result is maybe more surprising, several variables also seem to have aligned at the end of the 17th century: average European temperatures once again declined over the 1674-1701 period, while grain prices rose and were more volatile in 1674-1699 and probably led to lower wages (1667-1690), generating a new episode of famine detected by the model in virtually the same time interval (1676-1685).

Investigating these regimes in greater depth, we can see that all the high volatility regimes - whatever the variables (climatic or socio-economic) considered began at the end of the 16th century and mainly covered the seventeenth century, with a stronger significant impact on the first half of the 17th century in line with the narrative writings of Parker (2013). If we look at the first set of synchronized periods for both weather and socio-economic variables, we find that 1650 appears to correspond to a higher volatility (both climate and economic variables) peak. The MS Levy model appears to detect a change in the dynamics of the series around 1650 for temperatures (1659), wages (1651) and famine (1655), even though the model seems to identify a new turbulent period between 1670 and the beginning of the 18th century.

Regarding our methodology, the second sub-period 1670-1700 appears, as in seismic dynamics, to be an aftershock. Going further, we try to explain the climatic origins of this regime switching. Parker (2013) stressed the potential causal role of higher volcanic activity (in 1640 for instance) and of the ENSO (El Nino Southern Oscillation) teleconnetion that occurred twice as often in the mid-seventeenth century (1638, 1639, 1641, 1642-46, 1648-50, 1651-52, 1659, 1660, 1661). Admittedly, historians cannot blame El Nino for everything. Some regional climates are El Nino sensitive, while others, even though contiguous, are not. As a consequence, ENSO is probably not at the origin of all weather disturbances, especially in Europe. Indeed, ENSO is mainly active in the Pacific Ocean, even though it is a teleconnection that impacts the weather and socio-outcomes everywhere. Moreover, the effect of ENSO teleconnection on local weather conditions is strongly spatially and temporally heterogeneous. Consequently, we decided to apply the MS Levy method to identify regimes in NAO teleconnection. Indeed, NAO (North Atlantic Oscillation) is the most active climatic teleconnection in the North Hemisphere, and can explain 30% of the variability of local weather conditions such as precipitation, but especially European winter temperatures (see Pozo-Vasquez et al., 2001 or Hurrell, 1995).

The MS Levy results show an alternation between the different regimes during the 1571-1650 period. The model detects two episodes of negative NAO values in 1571-1591 and 1628-1650 that cover an episode of positive values (1628-1650). We once again find the previous break around 1650 in the dynamics of NAO. We know that positive phases of NAO lead to cooler and drier winters in Western Europe (see for example Hurrell, 1995). Some recent papers (Heino et al., 2018 and Kim and Carl, 2005) using contemporaneous data have emphasized the role of large-scale climate oscillations, especially NAO, on crop productivity, agricultural value added and the whole economic performance. There is very strong synchronization between the regimes detected for NAO and the regimes detected for European temperatures and the other series. As a consequence, these results seem to confirm the substantial role of NAO oscillations and thus provide another example that North Atlantic Oscillations are among the potential origins of the emergence of a Little Ice Age period and a global crisis during the seventeenth century.

In a more general manner, our results on NAO and average temperatures seem to be consistent with historical records. When we look at the historical analysis of Parker (2013) regarding the global crisis in the seventeenth century, our detected regimes over the same period appear to be in line with many of the historical records. If we only focus on European countries, some remarks by Parker (2013, p.5) are very enlightening as the whole of Europe experienced an unusually cold winter in 1620-1: many rivers froze so hard that for three months they could bear the weight of loaded carts (...) and people could walk across the ice between Europe and Asia"; "English men and women noted the extraordinary distemperature of the season in August 1640, when the land seemed to be threatened with the extraordinary violence of the winds and unaccustomed abundance of wet", "October 1641 began what contemporaries considered a more bitter winter than was of some years before or since seen in

Ireland (...) Hungary experienced uncommonly wet and cold weather between 1638 and 1641. (...) In the Alps, unusually narrow tree rings reflect poor growing seasons throughout the 1640's (...) In eastern France, each grape harvest between 1640 and 1643 began a full month later than usual and grain prices surged, indicating poor cereal harvests (...) Central Germany recorded in his diary in August 1640 (...) while 1641 remains the coldest year ever recorded in Scandinavia". Parker (2013) noted that the decade ended with another bout of extreme weather around the globe", by giving some historical records in England, in France or in Dutch Republic: "226 days of rain or snow according to a meticulous set of records from Fulda in Germany (compared with an upper limit of 180 days in the twentieth century) followed by 'a winter that lasted 6 months'. In France, appalling weather delayed the grape harvest into October in 1648, 1649, 1650, and drove bread prices to the highest levels in almost a century (...) In the Dutch Republic, so much snow fell early in 1651 that the state funeral of Stadholder William II had to be postponed".

All in all, the period between 1620-1650 seems to have experienced dramatic temperatures and weather conditions. It is very interesting to note that the period of famine between 1626-1655 detected by our MS Levy model corresponds almost exactly to this period. Thus, the global crisis in the 17th century is likely to be strongly correlated with climatic variations.

From an historical point of view, the period around 1630 (1630-1650) identified by our quantitative analysis coincides perfectly with 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 one significant period identified by 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 that were linked to years with high grain and bread prices (for example 1630 and 1661-1662, according to Antoine and Michon). Sometimes, fears of a price hike or the dealings of grain merchants were enough to provoke social demonstrations. Based on the studies of Jean Nicolas studies (2002) on the French Revolution or "disorder", some historians mention the occurrence of 200 local revolts in France during the "Ancien Rgime".

Finally, our climatic study suggests that the dramatic climate changes around the globe in the seventeenth century underpinned the global crises and the high grain and bread prices crises (for example in 1630 and in 1661-1662 in France). It is likely that food riots or some important wars (the Wars of the Three Kingdoms between 1639 and 1651 or the so-called Fronde in France over 1648-1653) are coincident with one significant period identified by our quantitative analysis. However, our quantitative framework is not clear-cut on these aspects. Linking climate in the Little Ice Age to social disturbance and frequency of wars in the same way as Zhang et al. (2011) is more delicate, and the synchronization between social disturbances and climate variables is less clear-cut. While our model detects an increasing regime of wars in the seventeenth century, it does not distinguish clear social disturbance sub-periods; the model continuously jumps from one insignificant regime to another. The MS Levy model thus leads to a more cautious conclusion compared to Zhang et al. (2011) who established correlation and causality tests on filtered data between climate on the one hand and social riots and wars on the other. Several explanations may be considered: the quality of social disturbances and war data and, notably, the lower frequency that reduces the number of observations and the accuracy of the MS tool and the presence of delayed effects, that is the possibility that the causal links emerge only a few decades after a climatic shock.

6 Causality analysis

Going beyond the detection of some potential coincident regimes between climatic and economic variables, we performed Granger causality tests to identify causal linkages between climate, economic and social variables. We focused on the sub-samples corresponding to the regimes identified by the MS Levy model. We thus choose the 1550-1700 sub-period, which yielded 151 observations exhibiting reasonable statistical properties. The investigation was designed to confirm or infirm the causal and theoretical framework outlined by Pei et al. (2014, see figure 1): $climatevariations \rightarrow grainyield \rightarrow grainprice \rightarrow inflation \rightarrow realwage \rightarrow population$. However, contrary to Pei et al. (2014), we prefer to substitute population by Uk and Holland GDP data obtained from Fouquet and Broadberry and we only focus on the precise Little Ice Age detected by the MS Levy model around 1550-1700. In addition, in line with Zhang et al. (2011), we wanted to investigate if temperature changes during the Little Ice Age period were likely to beat the origin of large human crisis.

Prior literature (Zhang et al. (2011), Pei et al. (2014)) applied Granger causality to scrutinize the link between climate and macro cycles and climate and social outcomes. Their analysis showed that temperatures Granger cause grain prices and that grain prices may have impacted the number and intensity of social disturbance events such as war, nutritional status, famine, epidemics and migration dueing the period in question. In this paper, we reinvestigate the link between climate and social disturbances. However, in contrast to Zhang et al. (2011), we believe that it is not useful to conduct similar analysis on famine, epidemics or migration given the low frequency of these series and the low statistical power of Granger causality analysis when series with a low number of observations are used. As a consequence, we only investigated social disturbances and war variables in the present paper.

We first computed ADF and ADF-GLS unit root tests and found that not all series are stationary in levels (presence of a unit root). This result is in contrast with Zhang et al. (2011) that found stationarity for most of the series. Though the period under study was slightly different, the statistical filtering they used was probably the cause of these diverging results. This point is very important however since conventional Granger causality analysis should be computed on stationary series.

We first computed bivariate Granger causality with first-difference variables. The results, using 2 and 4 lags respectively (Table 5), suggest the existence of a strong causal relationship from temperatures to Grain Price, and from temperatures to Agricultural Production and wages over the Little Ice Age period selected. As a consequence, the coinciding regimes previously identified also show some causal relationships, with climate change affecting agricultural prices and production during the period under study. However, the results are less clear-cut regarding the climate impact on social disturbances and are not conclusive with respect to a direct impact of climate on the war index and GDP. Our results nuance previous conclusions in the literature.

Nonetheless, despite the fact that temperature does not seem to directly Granger cause GDP and social disturbances, it is possible that temperature Granger causes GDP through a third, omitted variable (see Triacca (2001)). For instance, if $Temp \nrightarrow GDP|I_{Temp,GDP}(t)$ and $Temp \rightarrow GDP|I_{Temp,AgriYield,GDP}(t)$ so $AgriculturalProduction \rightarrow GDP$ and so agricultural GDP would be a third omitted variable that establishes a causal bridge between temperatures and GDP. As a consequence, we also test (Table 6) whether grain prices, agricultural production and wages can cause GDP and social disturbance by modifying the set of information (and variables) from two to three variables and then run the bivariate Granger causality tests again. The results reveal clear causality from temperature to UK GDP through grain prices, wages and agricultural production, but not for Holland GDP and social disturbance.

Finally, given the potential drawbacks and limitations of the Granger analysis, we performed an alternative causality analysis using the Toda Yamamoto (1995) methodology (TY hereafter). The conventional Granger causality tests consist of an unrestricted VAR framework and are conditional on the assumption that the underlying variables are stationary; otherwise, the Wald test statistic has a nonstandard asymptotic distribution. In particular, He and Maekawa (2001) pointed out that the use of the F statistic to test Granger causality often leads to spurious causality between two independent and irrelative processes where one of or both of them is or are non-stationary. In the case of non-stationary time series, we should investigate cointegration and, if it exists, should proceed with a vector error correction model instead of unrestricted VAR with variables in level. The TY procedure avoids the bias associated with cointegration tests as it does not require the pre-testing of cointegrating properties of the system (see Zapata and Rambaldi (1997) and Clark and Mizra (2006)).

It is important to note that the TY procedure also has some weaknesses. The approach suffers from loss of power since the VAR model is intentionally over-fitted (Toda and Yamamoto (1995)). However, according to the Monte Carlo experiments on bivariate and trivariate models performed by Zapata and Rambaldi (1997), despite the intentional over-fitting, the TY procedure also performs similar but more complex test procedures in samples of at least fifty (in our case the sample size is 151).

The TY results confirm that temperature probably impacted on agricultural production and grain prices during the Little Ice Age period. Moreover, climate change is likely to have led to some social disturbance and reduced GDP but to a lesser extent. The results are robust to third variable omitted bias: both grain price and grain yield have been used as a third variable. As a consequence, our results confirm the link between climate and grain prices suggested by the earlier literature; the link between climate and grain prices or agricultural production is entirely robust. However, our findings understate previous results concerning the existence of a strong link between climate and social disturbance or conflict and other social outcomes as suggested by the climate-conflict literature (Tol and Wagner, 2010, Hsiang and Carleton, 2016). Finally, our analysis fails to demonstrate the existence of a causal relationship between climate and GDP over the period under study.

Table 5: Unit Root tests

	LEVEL		**1st DIFF**	
	ADF	**ADF-GLS**	**ADF**	**ADF-GLS**
EUR_TEMP	0.3738	0.6020	0.0000	0.0000
GRAIN YIELD	0.4185	0.2621	0.0000	0.0000
GRAIN PRICE	0.3801	0.5073	0.0671	0.0000
AGRI PROD	0.3131	0.7365	0.0003	0.0000
WAGE	0.0001	0.4452	0.0000	0.0000
SOCIAL DISTURBANCES	0.0000	0.0094	0.0000	0.0000
WAR	0.0046	0.0000	0.0012	0.0000
UK GDP	0.9759	0.5007	0.0000	0.0000
HOLLAND GDP	0.0021	0.5146	0.0000	0.0000
ITALY GDP	0.1610	0.0385	0.0068	0.0000

Table 6: Bivariate Granger Causality tests with a two variables information set

	F Stat	**Prob**	**F Stat**	**Prob**
GRAIN PRICE does not Granger Cause EUR_TEMP	0.91333	0.4035	0.26773	0.8983
EUR_TEMP does not Granger Cause GRAIN PRICE	**4.79535**	**0.0096**	**2.09181**	**0.0850**
AGRI PROD does not Granger Cause EUR_TEMP	0.73250	0.4825	0.33330	0.8552
EUR_TEMP does not Granger Cause AGRI_PROD	**4.36337**	**0.0144**	**2.52844**	**0.0432**
WAGE does not Granger Cause EUR_TEMP	1.00285	0.3693	0.62516	0.6453
EUR_TEMP does not Granger Cause WAGE	**3.30467**	**0.0395**	1.93026	0.1086
SOCIAL DISTURBANCES does not Granger Cause EUR_TEMP	0.40641	0.6668	0.30901	0.8716
EUR_TEMP does not Granger Cause SOCIAL DISTURBANCES	0.21163	0.8095	**2.55326**	**0.0416**
WAR does not Granger Cause EUR_TEMP	1.23442	0.2940	1.57975	0.1829
EUR_TEMP does not Granger Cause WAR	0.11612	0.8904	0.67234	0.6122
UK GDP does not Granger Cause EUR_TEMP	0.89635	0.4103	0.98389	0.4184
EUR_TEMP does not Granger Cause UK GDP	1.35012	0.2624	1.07304	0.3722
HOLLAND GDP does not Granger Cause EUR_TEMP	0.00491	0.9951	0.21718	0.9285
EUR_TEMP does not Granger Cause HOLLAND GDP	0.30726	0.7359	0.91946	0.4545
ITALY GDP does not Granger Cause EUR_TEMP	0.45381	0.6361	0.31635	0.8667
EUR_TEMP does not Granger Cause ITALY GDP	0.14977	0.8610	0.17505	0.9509

Table 7: Bivariate Granger Causality tests with a three variables information set (2)

	Prob	**F Stat**
AGRI PROD does not Granger Cause HOLLAND GDP	**2.92374**	**0.0569**
HOLLAND GDP does not Granger Cause AGRI PROD	0.45735	0.6339
GRAIN PRICE does not Granger Cause HOLLAND GDP	1.22245	0.2975
HOLLAND GDP does not Granger Cause GRAIN PRICE	0.77952	0.4605
WAGE does not Granger Cause HOLLAND GDP	0.40514	0.6676
HOLLAND GDP does not Granger Cause WAGE	1.53075	0.2198
AGRI PROD does not Granger Cause UK GDP	**2.68357**	**0.0717**
UK GDP does not Granger Cause AGRI PROD	**3.25840**	**0.0413**
GRAIN PRICE does not Granger Cause UK GDP	**2.28501**	**0.1054**
UK GDP does not Granger Cause GRAIN PRICE	6.06442	0.0030
DE_WAGE_IDX does not Granger Cause UK	**5.78500**	**0.0038**
UK does not Granger Cause DE_WAGE_IDX	19.0358	5.E-08
DE_AGRI_PROD_IDX does not Granger Cause SOCIAL_DISTURB	1.76935	0.1741
SOCIAL_DISTURB does not Granger Cause DE_AGRI_PROD_IDX	0.03110	0.9694
GRAIN PRICE does not Granger Cause SOCIAL DISTURBANCES	**3.62265**	**0.0291**
SOCIAL DISTURBANCES does not Granger Cause GRAIN PRICE	0.10190	0.9032
WAGE does not Granger Cause SOCIAL DISTURBANCES	1.80287	0.1685
SOCIAL DISTURBANCES does not Granger Cause WAGE	1.44242	0.2397

Table 8: Bivariate Toda Yamamoto causality procedure

	F Stat	**P-value**	**Order VAR**
EUR_TEMP does not Granger Cause GRAIN PRICE	**2.571**	**0.056**	3
EUR_TEMP does not Granger Cause AGRI PROD	**3.123**	**0.027**	3
EUR_TEMP does not Granger Cause WAGE	1.272	0.283	2
EUR_TEMP does not Granger Cause SOCIAL DISTURBANCES	**2.045**	**0.091**	4
EUR_TEMP does not Granger Cause WAR	0.174	0.840	2
EUR_TEMP does not Granger Cause UK GDP	0.933	0.426	3
EUR_TEMP does not Granger Cause HOLLAND GDP	0.309	0.818	3
EUR_TEMP does not Granger Cause ITALY GDP	0.979	0.404	3

Table 9: Trivariate Toda Yamamoto causality procedure

	Conditional to	**F Stat**	**P-value**
EUR_TEMP does not Granger Cause GRAIN PRICE	AGRI PROD	**3.024**	**0.031**
EUR_TEMP does not Granger Cause DE_AGRI PROD	GRAIN PRICE	**2.634**	**0.0052**
EUR_TEMP does not Granger Cause WAGE	AGRI PROD	1.680	0.189
EUR_TEMP does not Granger Cause WAGE	GRAIN PRICE	1.587	0.195
EUR_TEMP does not Granger Cause SOCIAL DISTURBANCES	AGRI PROD	0.986	0.375
EUR_TEMP does not Granger Cause SOCIAL DISTURBANCES	GRAIN PRICE	**2.097**	**0.103**
EUR_TEMP does not Granger Cause WAR	AGRI PROD	0.270	0.763
EUR_TEMP does not Granger Cause WAR	GRAIN PRICE	0.134	0.939
EUR_TEMP does not Granger Cause UK GDP	AGRI PROD	2.159	0.119
EUR_TEMP does not Granger Cause UK GDP	GRAIN PRICE	0.975	0.400
EUR_TEMP does not Granger Cause HOLLAND GDP	AGRI PROD	0.548	0.579
EUR_TEMP does not Granger Cause HOLLAND GDP	GRAIN PRICE	0.235	0.871
EUR_TEMP does not Granger Cause ITALY GDP	AGRI PROD	1.311	0.272
EUR_TEMP does not Granger Cause ITALY GDP	GRAIN PRICE	1.826	0.145

7 Conclusion

The impact of climate change on economic performance in the future is likely to increase, affecting not only the agricultural sector but all aspects of economic growth. Indirect effects on social disturbance, war and violence as well as epidemics, and thus on the way society overall works, could be significant.

In this paper, we assess the impact of major climate shocks on several societal and economic outcomes by considering the historic Little Ice Age period, and thus the pre-industrial economy, as a case study. We used nonlinear econometrics, especially MS Levy estimates, to identify potential common regimes for climate, economic and societal outcomes. Finally, we performed both conventional and TY Granger causality analysis over the periods identified by the MS Levy model.

More specifically, our paper contributes to the literature on the existence of a Little Ice Age period and the effects of climate change on social and economic outcomes during this period in the vein of Zhang et al. (2011) and Pei et al. (2014). In contrast to these studies conducted by geographers, we did not use statistical filters to avoid the so-called Slutsky effect outlined by Kelly and OGrada (2014). We instead computed a non-linear time series methodology with raw data to detect potential links between climate and socio-economic variables using Markov regime-switching with a Levy process, reinvestigating the causal linkages between climate and socio-economic variables.

Our findings point to the existence of a strong cooling period and thus a Little Ice Age between 1560 and 1700 through two major episodes: 1563-1659 and 1674-1701. The Little Ice Age period was thus shown to be non uniform. Using historical sources, we discussed the relevance of the sub-regimes identified by our methodology. Since ENSO is a potential driver of the Little Ice Age, we also found that some changes in North Atlantic Oscillation (NAO) dynamics coul have been one of the causes of this climate change. In this way, our analysis demonstrated the likely existence of a Little Ice Age. This finding appears robust since the so-called Slutsky effect is explicitly taken into consideration. In addition, non-stationarity, nonlinearity and causality issues were also addressed.

Our estimates show that the grain markets, wages, the famine index and GDP of some major European countries such as Holland appear to share common statistical trends and coincident regimes. These coinciding regimes and the association between climate and other variables could indicate some causality links. We derived a robust strong causality between temperature, grain prices and agricultural production over several decades; thus, climate could have lasting effects, while the adaptation of countries might be relatively slow.

The impact of climate on agricultural production is very clear, but the impact of climate on GDP is less robust. The effect of climate on social disturbance is plausible, but again needs more investigation to be entirely robust. However, the possible association between climate and social disturbance is in line with the recent climate-conflict literature although we did not find a significant link between climate and wars.

More generally, our findings suggest that climate can have a certain impact on macroeconomics. With todays trends expected to increase in the near future, agricultural yields and production are liable to decline in vulnerable countries, at least in the short-run. Considerable time (several decades) is likely to be needed to adapt without other mitigation policies. From a methodological point of view, simple linear correlation and bivariate Granger Causality tests used in the previous literature might have over-estimated the impact of climate as the main driver of large-scale human crisis. We used new econometric tools to further examine and check the robustness of previous results, but a more general causality analysis, including nonlinear causality patterns with a broad set of variables, might be a further way to extend this analysis in the future.

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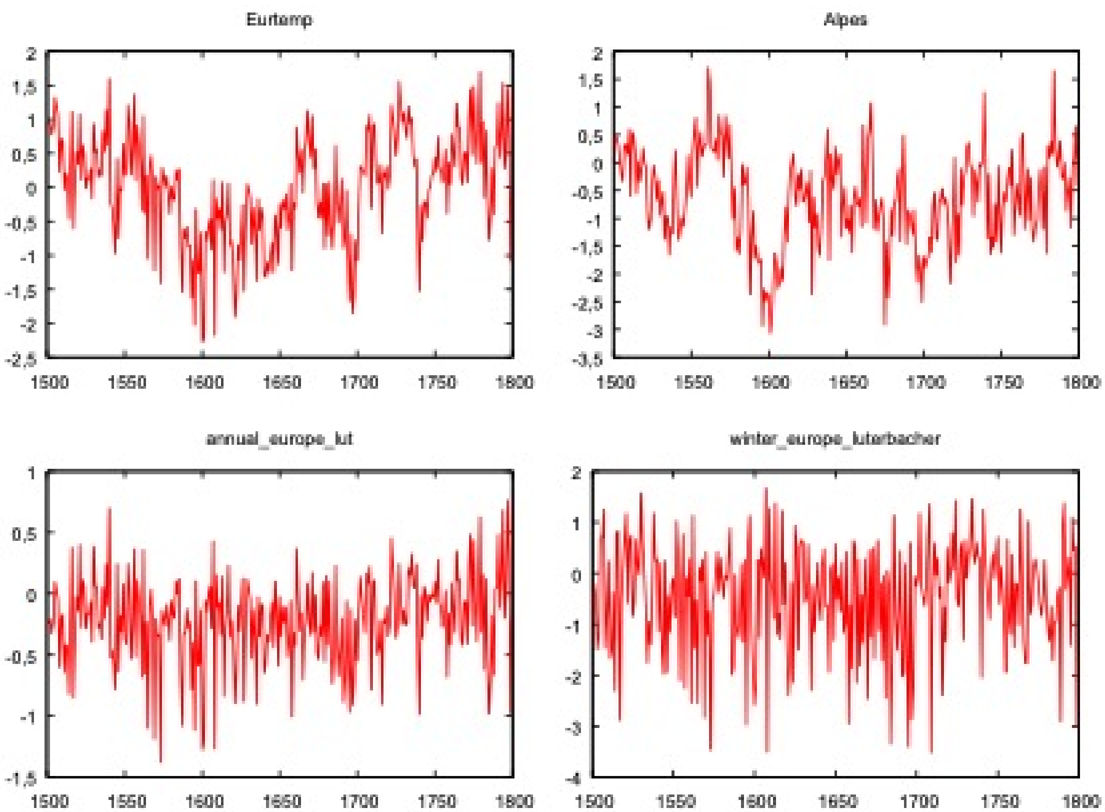

Figure 1: Temperatures variables dynamics

Appendix

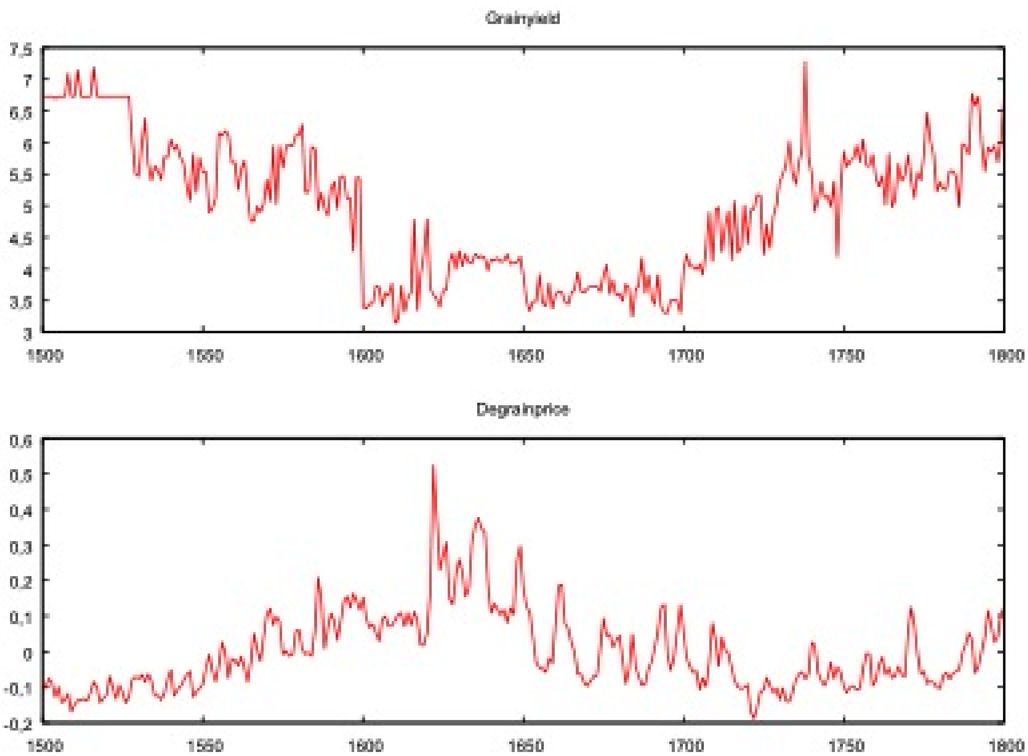

Figure 2: Grain yield and price dynamics

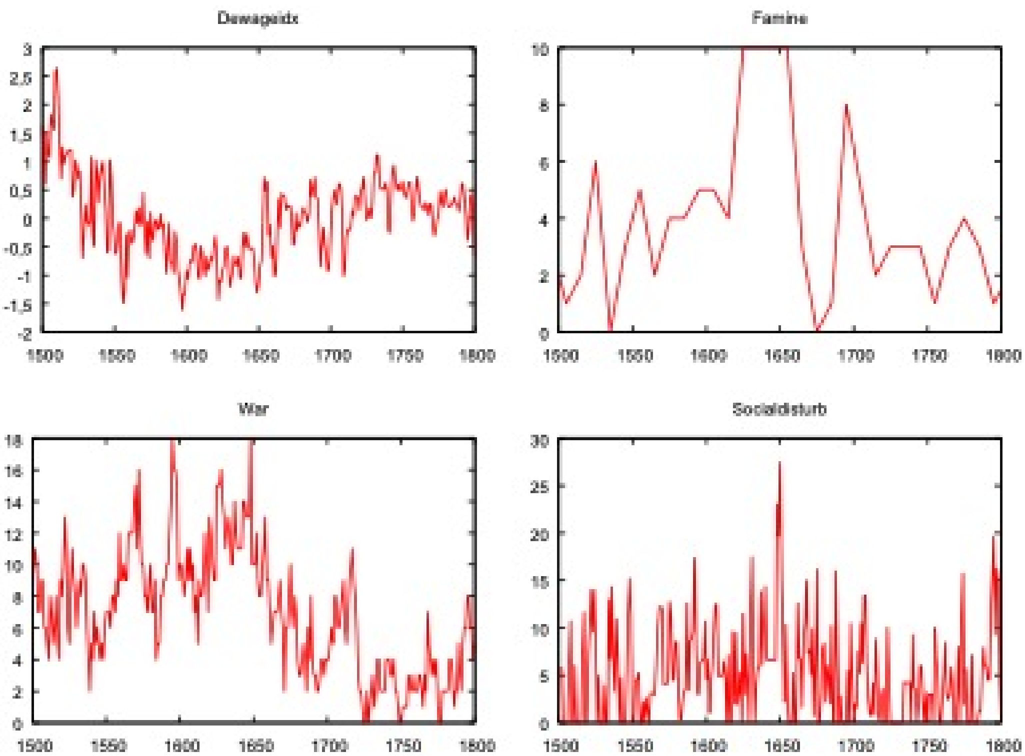

Figure 3: Wage, Famine, War, Social disturbances dynamics

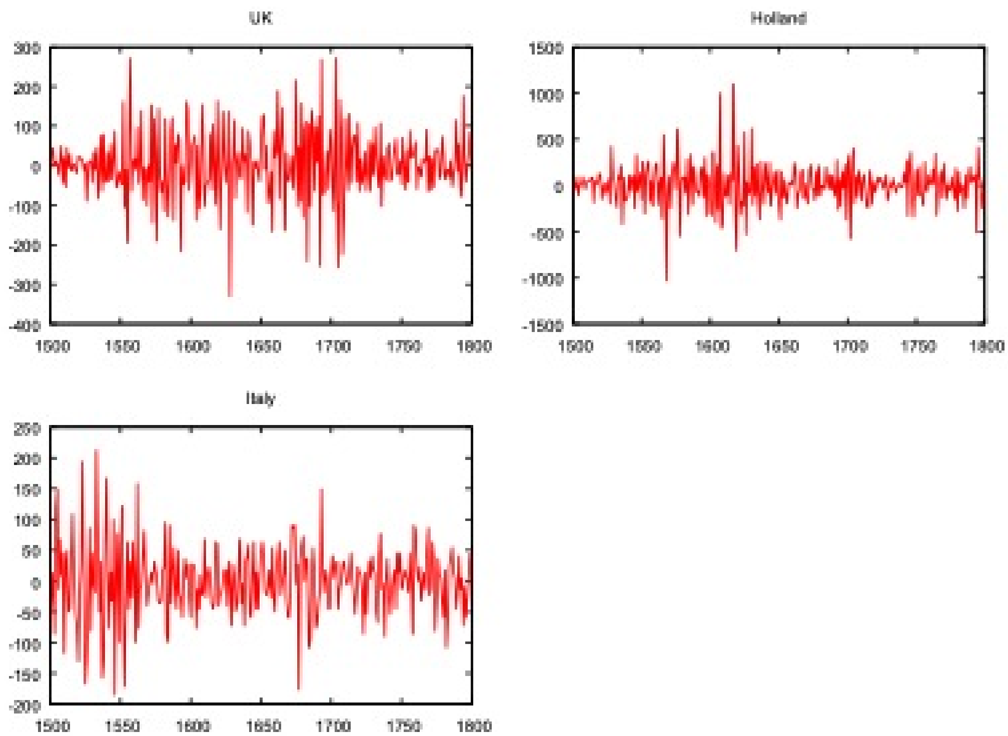

Figure 4: GDP growth dynamics for UK, Holland, Italy