The Economic Effects of Long-Term Climate Change: Evidence from the Little Ice Age

Maria Waldinger (ifo Institute Munich)*

January 12, 2022

Abstract

Recent studies have consistently found important economic effects of year-to-year weather fluctuations. I study the economic effects of long-term and gradual climate change over a 250-year period in the Little Ice Age (1600-1850), during which people and economies had time to adapt. Results show significant negative economic effects of long-term climate change. In further results, I examine mechanisms through which climate affected the economy. Results show that temperature impacted the economy through its effect on agricultural productivity, mortality, and migration. I also explore adaptation to climate change and find that economies increased trade and changed land use in response to the Little Ice Age. Cities with good access to trade were significantly less affected. I discuss the relevance of these results for understanding the impact of today's climate change, especially in developing countries.

Keywords: Climate Change, Adaptation, Little Ice Age, Long-Run Economic Growth, Urban Growth, Early Modern Europe, Agricultural Productivity

*Contact: waldinger@ifo.de I especially thank Jürg Luterbacher, Nico Voigtlander and Joachim Voth for generously sharing data. I thank Daniel Sturm, Joerg Baten, Ethan Butler, Melissa Dell, Sam Fankhauser, James Fenske, Roger Fouquet, Claudia Goldin, Elliott Green, Solomon Hsiang, Nathan Nunn, Kevin O'Rourke, Helmut Rainer, Max-Stephan Schulze, Claudia Steinwender, Martin Tingley, Fabian Waldinger, and Diana Weinhold for very helpful comments and suggestions. I thank seminar participants at Harvard University, LSE, University of Oxford, University of Warwick, University of Tuebingen, University of Sussex, University of Essex, Queen Mary University of London, University of Heidelberg, and the ifo Institute for Economic Research, the EEA 2014 and AEA 2015, the BETA Workshop in Historical Economics, AK Klima Basel, and the 2015 EHS Conference. I gratefully acknowledge financial support from Cusanuswerk.

The reality of human-induced climate change and the urgency to respond have become increasingly clear among researchers, policymakers and the wider population.[1] Heat waves, storms, and other weather events have become more frequent and more extreme, and temperatures rise even faster than predicted only a few years ago (EASAC, 2018; Cheng et al., 2019). Producing reliable estimates of the economic effects of climate change is a central and challenging task in the quest for tackling climate change. Empirical evidence, however, is scarce. A prominent approach to estimating economic impacts of climate change scenarios is the use of Integrated Assessment Models (IAMs).[2] These have been widely used and have informed important policy choices (e.g. Stern, 2007). They have been criticized, however, for building assumptions on insufficient empirical evidence (e.g. Dell, 2012, p. 92; Pindyck, 2013; Carleton et al., 2018, p. 862). Indeed, many elements of the climate-economy relationship remain little understood.

More recently, Deschenes et al. (2007; 2012), Dell (2012), Burgess et al. (2013), Barreca et al. (2015), Carleton et al. (2018), and Barreca et al. (2016) have pioneered an empirical approach to studying the economic effects of climate change. They use year-to-year temperature fluctuations, and they consistently find important economic effects. Understanding climate change, however, also entails understanding the effects of *long-term* temperature change. Do long-term temperature changes also have economic effects, even when people have time to adapt? Or, do countries mitigate short-run effects through adaptation? In this paper, I study a historical episode of climate change, the Little Ice Age, to examine the economic effects of long-run temperature change over a period of 250 years, when people have time to adapt.[3]

[1] Nobel price laureates at the 2015 Lake Constance reunion of Nobel prize winners called for action on climate change. Pope Francis I issued an encyclical on climate change. President Obama released America's Clean Power Plan to reduce greenhouse gas emissions. In the US, two-thirds of respondents said they believed that global warming is caused by humans (Ming Lee et al., 2015). 90 percent of Europeans think climate change is a serious problem (European Commission, 2014: 5).

[2] Integrated Assessment Models model the relationships between greenhouse gas emissions, resulting climate change, and the effects on human welfare. They are used to calculate the social costs of carbon, and to evaluate specific climate policies.

[3] The Little Ice Age spanned the time period 1400 to 1900. The temperature data for this study starts in 1500; I use city size data beginning in 1600. The study period includes periods of cooling (1500 to 1700) and periods when cities experience temperature increases as they come out of the Little Ice Age (1700 to 1850).

The Little Ice Age brought significantly colder climate to large parts of Europe.[4] It is the most recent climatic episode preceding the current human-induced period of climate change. It represents the largest temperature change since the beginning of recorded history (Aguado and Burt, 2007, p. 483). Historical evidence suggests that the Little Ice Age affected numerous outcomes in various parts of Europe. Harvest failure in the Czech Republic and in Switzerland in the 1770s has been linked to adverse weather (Pfister and Brázdil, 2006); the heights of military recruits in Bavaria in the 18th century were affected by lower temperatures (Baten, 2002); and witch hunts increased in Switzerland and Germany during periods of particularly adverse weather conditions between the 16th and 18th centuries. (Behringer, 1999; Oster, 2004).

To estimate the economic effects of the Little Ice Age, I construct a panel data set for 2,120 European cities. These data measure annual temperatures between 1500 and 1850, and city size for several points in time. During this period, Europe first experienced temperature decreases (1500 to 1700), then temperature reverted back to pre-Little Ice Age temperatures (1700 to 1850). The temperature data for each city come from temperature reconstructions that were undertaken by climatologists (Luterbacher et al., 2004). As a proxy for economic growth, I use data on historical city sizes from Bairoch (1988).[5] The data's panel structure allows me to include city fixed effects and time-period fixed effects in all specifications.

The main results indicate a significant negative effect of relatively cool temperatures on city size. This finding is consistent with anecdotal historical evidence on the negative economic effects of low temperatures during the Little Ice Age. To address omitted variable bias, I control for a host of relevant geographic and historical control variables that impacted urban growth in Early Modern Europe.[6] Results are also robust to including country-specific time trends and country $\times$ time-period fixed effects, and to the omission

[4]In the study period, cities first experienced on average decreasing temperatures. Later they experienced on average increasing temperatures as Europe came out of the Little Ice Age.

[5]City size has been used in other papers on historical economic outcomes (De Long and Shleifer, 1993, Stasavage, 2012). Sutton et al. (2007) use current total urban population as a proxy for national GDP.

[6]Early Modern Europe is the historical period spanning the 15th to 18th centuries, roughly from the end of the Middle Ages to the beginning of the Industrial Revolution. It is well established that city growth in Early Modern Europe was unevenly distributed across space with centers of growth in northwestern Europe (Broadberry, 2013; Van Zanden, 2009; Koot, 2013).

of potential outliers.

Finally, I study non-linear temperature effects. I show that the relationship between temperature and city size is driven by the negative effect of especially cold years, and that a linear functional form fits the temperature-city size relationship very well for the largest part of the temperature distribution.

In Section 4, I study three mechanisms through which temperature may have affected city size: the effect of temperature on agricultural productivity, on mortality, and on migration. To investigate the Little Ice Age's effect on agricultural productivity, I estimate the effect of temperature on yield ratios and wheat prices.[7] The cooler temperatures during the Little Ice Age decreased yield ratios,[8] and increased wheat prices.[9]

Then, I investigate temperature's effect on mortality using data on mortality for 404 English parishes between the years 1538 and 1838 (Wrigley and Schofield, 1989) and show that cooler temperatures increased mortality. The timing of the effect suggests that increases in mortality mostly occurred through temperature's effect on agricultural productivity rather than through a health effect of temperature. Finally, I investigate temperature's effect on migration based on the location of birth and marriage for 6,350 couples in England between the years 1538 and 1871 (Wrigley et al., 2018). I find that the share of marriages with at least one migrant is on average higher following time periods with cooler temperatures, but the result is not significant.

Another important question in the climate-change debate is to understand how economies adapt to climate change. Following Costinot et al. (2016), I examine two important adaptation strategies: adaptation through trade, and adaptation through changes in land use.[10] To examine whether economies adjusted trade in response to the Little Ice Age, I collect data from the Sound Toll Registers on 900,000 million ship passages to 750 European destinations between 1591 and 1857 (Sound Toll Registers, 2018). I show that trade volumes increased in response to cooler temperatures. These results are driven by cooler

[7]The yield ratio is the ratio of grains harvested to grains sown.

[8]This means that less grain was harvested per grain sown

[9]Because city-level demand changes only gradually, yearly fluctuations in wheat prices offer a plausible reflection of changes in supply.

[10]Besides adjusting trade and land use, economies may have adapted to the Little Ice Age in innumerable other measurable and non-measurable ways which I do not observe.

temperatures during the growing season. I then examine heterogeneity in the economic effects of temperature change on city size and show that the effects of temperature change were significantly smaller for cities that participated in long-distance maritime trade compared to those that did not. This effect is driven by cities with a relatively high number of trading partners.

To explore the role that inland trade opportunities may have played in adjusting to adverse temperature change, I construct a measure of potential trade opportunities guided by the gravity model of trade. Potential trade opportunities are measured as the number and sizes of cities within a particular distance of each city. Results show that cities with larger trade opportunities are less affected by temperature change. Then, I use variation in the model's distance parameter induced by natural barriers to transportation and find that cities both with large and small trade opportunities are less affected by temperature changes if they are surrounded by relatively flat terrain compared to cities in the same sub-sample surrounded by relatively rugged terrain.

Then, I examine whether the Little Ice Age led economies to adjust land use, either through expansion of cropland and pasture or by converting cropland to pasture (Klein Goldewijk, 2015a,b). I find evidence that economies with relatively warm temperature changes had greater increases in the area of agricultural land than countries with cooler temperatures.

In the conclusion, I discuss the paper's relevance for understanding the impact of today's climate change. The results highlight the particular vulnerability of economies that depend heavily on agriculture, and have restricted access to trade - such as in the case of many developing countries.

This paper contributes to studies examining the economic impacts of climate change using historical data (Baten, 2002; Kelly and OGrada, 2010[11]; Pfister and Brázdil, 2006; Turner et al., 2012; Behringer, 1999; Oster, 2004; Anderson et al., 2017; Berger and Spoerer, 2001; Olmstead and Rhode (2011)) and using modern data.[12] Deschenes and

[11]The existence of the Little Ice Age has been questioned, for example in Kelly and OGrada (2014). For a reply, see Buntgen and Hellmann (2013).

[12]A number of papers in urban economics estimate the effect of temperatures on city size (Rappaport and Sachs, 2003; Rappaport, 2007; Glaeser et al., 2001). While this literature analyzes the effect of

Greenstone (2007), Deschenes and Greenstone (2012), Dell et al. (2012), Burgess et al. (2017), Burke et al. (2018), and Diffenbaugh and Burke (2019) find negative effects of year-to-year changes in temperature on economic and non-economic outcomes. My results contribute to this literature by showing that long-term and gradual temperature changes may also have an economic impact.

This study also contributes to work on adaptation to climate change using modern data. Barecca et al. (2015; 2016) show that the effect of an additional very hot day in US regions with hot climate is substantially smaller compared to the effect of an additional very hot day in a US region with cooler climate. The difference in effect sizes has shrunk over the course of the 20th century, but has not disappeared. Hsiang (2010) show that cyclones cause less damage per cyclone in countries that have historically been more often exposed to cyclones, but that adaptation to changes in cyclone risk is minimal. (Burke and Emerick, 2016) find little adaptation to climate change in U.S. agriculture, and there is slow adoption of energy efficiency programs (Fowlie et al., 2015) and patterns of migration poorly adapted to increased flooding (Boustan et al., 2012). Carleton et al. (2018) show that higher income reduces climate impacts indicating that economies with higher incomes are better at adapting to climate change. Since the studies use modern data results are likely to be informative of effect sizes and of future impacts. Overall, these papers show that economies are adjusted to long-term climatic conditions, but respond slowly to change in these conditions. My study contributes to this literature by documenting that adaptation through trade took place in the long-run and that it effectively shielded cities from the negative impacts of adverse climatic change. These results chimes with work by Burgess and Donaldson (2010) that explores trade and resilience to adverse weather and climate. A general drawback of empirical studies is the limited ability to extrapolate to other time periods or world regions. Based on an extensive data collection effort, Carleton et al. (2018) produce estimates and predictions of current and future climate impacts on mortality at a global scale while also taking into account costs and benefits of adaptation. The paper thereby unites the virtues of IAMs (global coverage and predictions of future

temperature as an amenity, this paper analyzes the effect of temperature as a factor in the economy's production function.

impacts) and of empirical approaches (estimates based on econometric measurement).

The remainder of the paper is organized as follows: Section 1 provides historical background on the Little Ice Age and on urban growth in Early Modern Europe. Section 2 describes the data. Section 3 introduces the estimation strategy, and presents main results. Section 4 examines mechanisms through which temperature's effect on city size have operated by focusing on temperature's effects on agricultural productivity, mortality, and migration. Section 5 investigates evidence on adaptation to temperature change by examining whether economies adjust trade and land-use patterns in response to temperature changes and whether the effect of temperature on city size varies with a city's access to trade. Section 6 concludes.

1 The Little Ice Age

The Little Ice Age was a climatic period from about 1400 to 1900 that brought colder climate to Europe (Cronin, 2009: 298).[13] It is the most recent period of climatic change prior to the current period of human-induced warming. In Europe, average annual temperatures fell by about 0.5 to 1º C.[14] Figure 1 shows the Little Ice Age in the context of temperatures over the past 2000 years (adapted from Moberg et al., 2005). Temperature started decreasing at around 1400 marking the beginning of the Little Ice Age.[15] At 1500, when my temperature data start, the Little Ice Age had begun. 1600 and 1700 both mark temperature lows. For cities in my sample, temperatures during the 17th century were lower compared to temperatures during the 16th century (see Figure 2 and Figure A.2 in the appendix). After 1700, temperatures reverted and reached the pre-Little Ice Age mean over the course of the 19th century.

Other world regions, besides Europe, were also affected, e.g. China, Japan, India, and West Africa (e.g., Zhang et al., 2007; Fan, 2010, for China; Cronin, 2009: 300; Parker, 2013; Grove, 2004: 560). The Little Ice Age has been linked to decreases in agricultural

[13]The earth's climate has always undergone changes due to natural forcing agents. Climatic change has been documented, e.g., for the period of the Roman Empire (McCormick et al., 2012), the Mayan civilization (DeMenocal, 2001), and Carolingian Europe (McCormick et al., 2007).

[14]This is the equivalent of a fall in temperature of 1 degree to 2 degrees Fahrenheit.

[15]The Little Ice Age was preceded by the Medieval Climate Optimum that brought relatively warm temperatures to parts of Europe and is associated with increased agricultural productivity.

productivity (Baten, 2002; Pfister and Brázdil, 2006) and to social unrest. Witch hunts reappeared in parts of Europe, especially during the coolest periods of the Little Ice Age (Behringer, 1999; Oster, 2004).

There is debate among climatologists about the causes of the Little Ice Age, but reduced levels of energy emitted by the sun and increases in volcanic activity mattered.[16]

Historical evidence shows that many people noticed signs not only of year-to-year temperature change, but of long-term temperature change. Glaciers expanded; tree lines in the high Alps fell; high mountain pastures had to be abandoned. Peasants everywhere noticed delays in fruit blossoming, delays in the beginning of growing periods, haymaking seasons, or of the grape ripening period (Behringer et al., 2005: 93f.). Larger land estates kept meticulous records of such key dates; smaller estates and peasants used reference points during the ecclesiastical calendar to keep track of them. Even small changes in these key dates had potentially large effects on living standards, for example, when shorter growing periods reduced the harvest.[17]

2 Data

The main data set for this paper is a balanced panel of 2,120 European cities. Its two key components are data on annual temperature for Europe for each year since 1500 from Luterbacher et al. (2004) and data on city size in 1600, 1700, 1750, 1800, and 1850 from Bairoch (1988).

I use the size of European cities as a proxy for economic growth. The data include European cities that had more than 5,000 inhabitants at least once between 800 and 1850. The final data set includes 2,120 cities.[18]

[16]Low levels of solar energy were caused by a reduced number of sun spots (Eddy, 1976: 1189). High volcanic eruptions cool the surface of the earth by sending large quantities of sulfate gases into the atmosphere. These scatter solar radiation back to space (Cronin, 2009: 300ff.).

[17]Even if people had considered all the cool years of the Little Ice Age as exceptions to an otherwise warmer climate, the mere experience of these cool temperatures must have made people aware of the possibility that such temperatures *can* occur and that they *can* have detrimental effects on the harvest. Most kinds of adaptation measures that researchers think about, e.g., expanding agriculturally productive land or extending trade networks, would not have turned the economy into a "cool-climate economy," but would have made the economy more resilient and better able to cope with all kinds of weather shocks, including but not exclusively limited to cool temperatures.

[18]The original data set includes 2,191 cities. I drop 71 because temperature data are not available: nine cities are located outside of Europe and 62 cities are located east of 40 degree E longitude. I use a

The temperature data are reconstructed temperatures taken from Luterbacher et al. (2004).[19] The data contain annual gridded seasonal temperatures for European land areas. Each grid cell measures 0.5 by 0.5 degrees, which corresponds to an area of about 50 by 50 kilometers (ca. 30 by 30 miles) in Europe. I assign temperature data to each city based on the temperature grid cell in which the city is located. The temperatures in this data set have been reconstructed based on temperature proxies (tree ring series, ice cores, ocean and lake sediments), historical records, and directly measured temperature for later years (Luterbacher et al., 2004: 1500). I assign temperature data to each city based on the temperature grid cell in which the city is located.

I combine the two data sets as follows: City size is available in 1600, 1700, 1750, 1800, and 1850. For each time period, I calculate local mean temperature over the preceding 100 or 50 years.[20]

If $t = 1600$ or $t = 1700$: $MeanTemperature_{it} = \frac{\Sigma_{n=1}^{100} Temperature_{it-n}}{100}$

If $t = 1750$ or $t = 1800$ or $t = 1850$: $MeanTemperature_{it} = \frac{\Sigma_{n=1}^{50} Temperature_{it-n}}{50}$

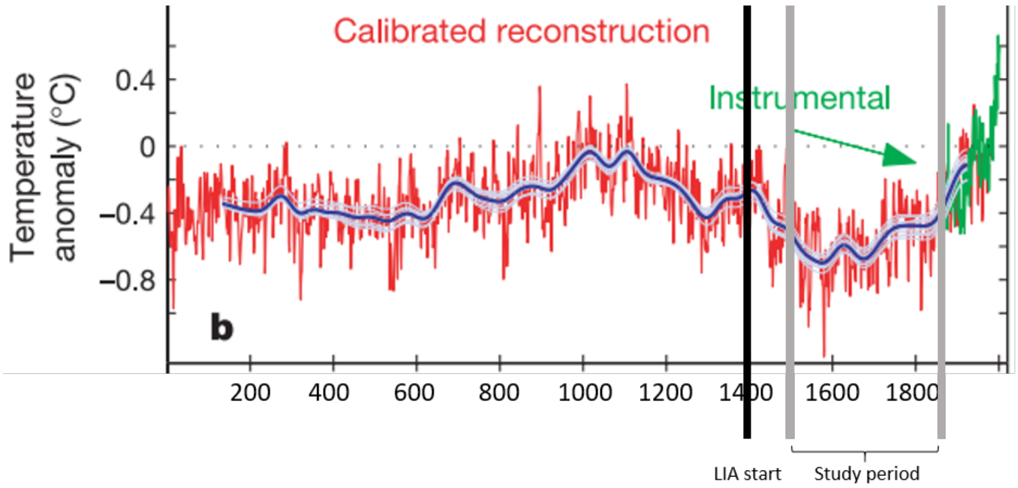
Panel 1 in Figure 2 depicts average temperature over the course of the study period. The data spans the period 1500 to 1850, hence the period when temperature decreased (ca. 1500 to 1700) and started going up again (ca. 1700 to 1850) reaching pre-Little Ice Age mean temperature over the course of the 19th century. Panel 2 in Figure 2 depicts the average temperature changes for three groups of cities, those experiencing strong, moderate, and weak cooling during the 17th century. Figure A.1 in the appendix shows

version of the data set by Voigtländer and Voth (2012). They use linear interpolation to fill missing values for time periods between non-zero values. Furthermore, Bairoch records city size of cities below 1,000 inhabitants as having zero inhabitants. When using the natural log of city size as the outcome variable, I assume that cities below 1,000 inhabitants have 500 inhabitants. This is a realistic assumption as the large majority of European cities were founded in Antiquity, the High or Late Middle Ages. Alternative specifications with cities below 1,000 inhabitants assumed to have one inhabitant or when using absolute numbers of inhabitants instead of the log of city size yield similar results (Table 14).

[19] Temperature changes during the Little Ice Age have been detected based on historical variation in glacial advances in European mountain areas, data from ocean sediments, ice-cores and continental climate proxies (Grove, 2004: 560). The relationship between climate proxies and instrumentally-measured temperatures is estimated for the recent past. Based on this relationship, measures of climate proxies are used to reconstruct earlier temperatures. For locations without climate proxies, temperatures are interpolated based on a climate model describing the European climate system.

[20] The time periods are of different lengths due to the structure of the city size data. I examine whether results may be affected by differences in time periods, and show main results weighted by time period lengths in Appendix Table A.2. The coefficient sizes and significance levels of results remain very similar.

Figure 1: Temperature over the past 2000 years



Notes: Temperature graph "Estimations of northern hemisphere mean temperature variations" from Moberg et al. 2005. Modifications: vertical black bar and grey bars, "LIA start", "study period" (this is the time period for which I have temperature data) and years on the x-axis have been added. In the original article, the graph is part of a larger graphic. The region between the two grey bars indicates the period for which temperature data is available.

city-level temperature curves for 12 major European cities. The graphs show that cities were differently affected by cooling.[21]

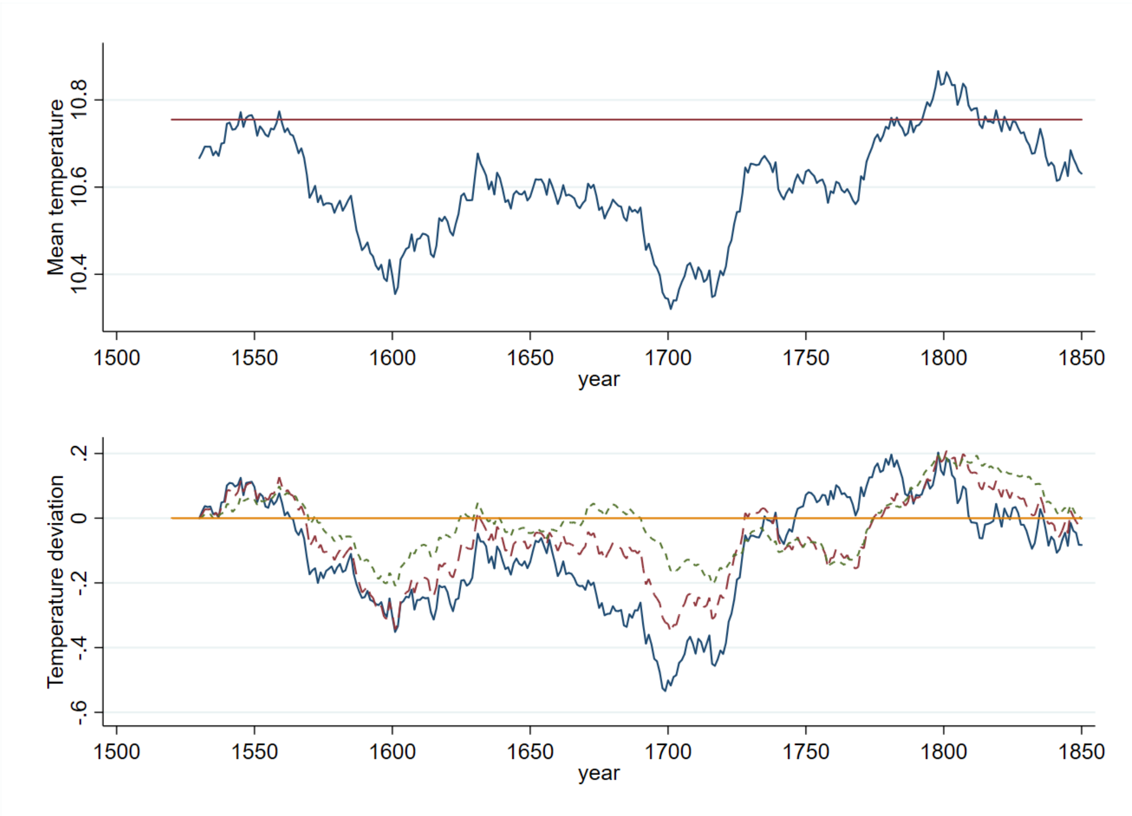
Data on control variables are obtained as follows: Data on local potato suitability, wheat suitability, and altitude are taken from the Food and Agriculture Organization (FAO)'s Global Agro-Ecological Zones (GAEZ) database FAO/IIASA/ISRIC/ISS-CAS/JRC (2012). Data on ruggedness are taken from Nunn and Puga (2012). Location of the Roman road network is taken from the Digital Atlas of Roman and Medieval Civilizations (McCormick et al., 2014). Data on country borders in Early Modern Europe, on the extent of the Roman Empire in year 1 CE, and information on the location of rivers in pre-modern Europe are taken from Nüssli (2016). Information on the spread of the Protestant Reformation in 1600 has been collected from Haywood et al. (2000).

In Section 4 and section 5, I introduce five more data sets for which I will provide details in the respective section.

Summary statistics in Table 1 show characteristics for all cities (column 1), for those that experienced above average (smaller) temperature decreases (column 2), and for those

[21] Differences in reconstructed temperature between the data I am using and the data in Figure 1 by Moberg et al. (2005) could be because Moberg et al. (2005) draw on climate proxies from around the Northern Hemisphere and do not focus their analysis on surface temperature in Europe.

Figure 2: Temperature variation over the study period



Notes: Panel 1 shows mean temperature (30-year moving average) over the course of the study period (blue line). The red line is the temperature mean from 1900 to 1950, after the end of the Little Ice Age and before the onset of global warming. Panel 2 shows changes in the long-term mean in temperature for three groups of cities: cities with strong cooling (below 25the percentile in temperature change) and with weak cooling (above 75th percentile in temperature change) and cities with moderate cooling (between the 25th and 75th percentile in temperature change) in the 17th century. The yellow line is the temperature mean from 1500 to 1530 from which temperature deviations are measured.

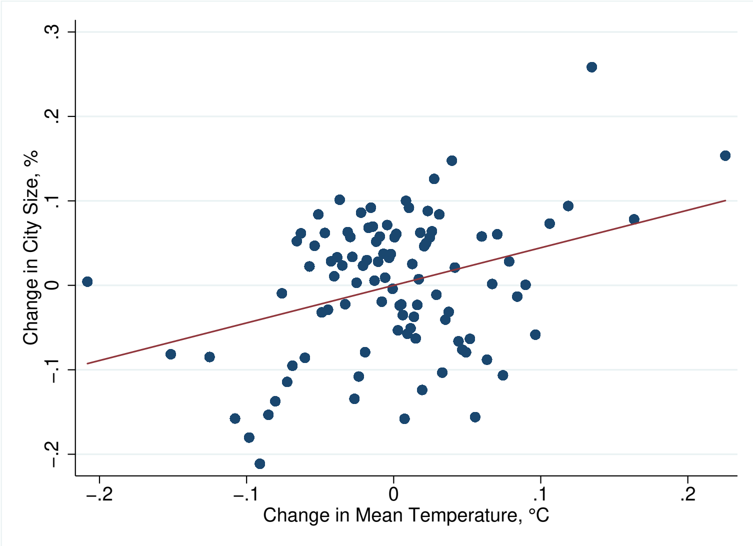
that experienced below average temperature decreases (column 3). Roughly 80 percent of cities experienced temperature decreases during the 17th century. For the remaining cities, average temperature change remained close to zero (<0.016º C, see Figure A.2). The table indicates that cities that experienced below average temperature decreases were in 1600 larger by about 1600 inhabitants, and were located in regions with initially warmer climates. City growth was higher in areas with greater decreases in temperature. Geographic variables indicate relatively long distances to the ocean, higher potato and wheat suitability and more cities are of Protestant denomination (see Table in the appendix). If one found a positive effect of relatively large temperature decreases, one might be concerned that this effect could be due to these initial differences. The main results, however, indicate the opposite, that city growth was slowed down by relatively cold temperatures.

Table 1: Summary Statistics

	(1)	(2)	(3)
	All	**Above average fall in temperature**	**Below average fall in temperature**
City size in 1600	5.680	4.898	6.471
	14.617	*13.977*	*15.195*
Mean Temperature in 1600	9.255	6.658	11.850
	3.589	*1.635*	*3.098*
City Growth, 1600 to 1850	13.051	17.589	8.514
	55.198	*74.928*	*21.001*
Geographic Control Variables			
Altitude	238.804	142.622	335.351
	262.043	*143.435*	*313.607*
Ruggedness	0.126	0.069	0.183
	0.161	*0.081*	*0.197*
Potato Suitability	29.724	35.344	24.083
	16.509	*18.028*	*12.508*
Wheat Suitability	43.273	49.189	37.334
	22.018	*22.880*	*19.383*
Historical Control Variables			
Protestant Reformation			
Catholic	0.638	0.414	0.863
	0.481	*0.493*	*0.344*
Lutheran	0.126	0.252	0.000
	0.332	*0.434*	*0.000*
Calvinist/Huguenots	0.121	0.110	0.132
	0.326	*0.313*	*0.339*

Notes: Data on city size, temperature and control variables were collected from various sources as described in section 2. Cities that experienced above/below average fall in temperature are cities that experienced above/below average decrease in long-term mean temperature from the 16th to the 17th century.

Figure 3: Change in Mean Temperature vs. Change in City Size



Notes: The figure displays a binned scatter plot corresponding to the estimates from column 2 of Table 2. I residualize Log City Size and mean temperature with respect to city fixed effects, time-period fixed effects, historical, and geographic control variables using an OLS regression. I then divide the sample into 100 equally sized groups, and plot the mean of the y-residuals against the mean of the x-residuals in each bin.

3 The Effect of Climate Change on Economic Outcomes - Empirical Strategy and Main Results

To examine whether temperature changes during the Little Ice Age (between 1600 and 1850[22]) affected city size I use the panel data set for 2,120 European cities described in the previous section.[23] First, I examine the relationship between temperature and city size graphically including all cities of the sample and conditional on city and time-period fixed effects and geographic control variables. Figure 3 shows a positive relationship between temperature and city size. In the context of the Little Ice Age, this implies that a temperature decrease within a city is associated with decreases in city size.

In the baseline regression specification, I include city fixed effects, time-period fixed effects, and an array of geographical and historical control variables. Each control variable is interacted with a full set of time-period indicator variables.

[22]The temperature data used in the analysis starts in 1500. The first period for which city size data is available is 1600.

[23]While current climate change is concerned about increases above the optimum temperature, temperatures in most areas decreased, or were below the optimal temperature for European agriculture. For the current episode of climate change, climate researchers have predicted that Northern European agriculture might benefit from small temperature increases due to its relatively cold climate (EEA, 2012: 158).

$$(1) \qquad Log\,City\,Size_{it} = \beta + \gamma Mean\,Temperature_{it} + Time\,FE_t + City\,FE_i + \delta X_{it} + \epsilon_{it}$$

$Log\ City\ Size_{it}$ is the natural logarithm of size of city i in time period t. $Mean\ Temperature_{it}$ is mean year temperature in city i, and time period t over the past 100 years and past 50 years. $Time\ FE_t$ represents time-period fixed effects that control for variation in temperature and in city size over time that is common to all cities. $City\ FE_i$ represents city fixed effects. The city fixed effects control for time-invariant city characteristics, e.g., distance to the ocean and to waterways, permanent climatic or soil characteristics that may affect a city's access to trade or its agricultural productivity. X_{it} represents a number of control variables, each interacted with time-period indicator variables. They are described in more detail when introduced into the analysis. ϵ_{it} is the error term.

3.1 Standard Errors

I report three types of standard errors for the main results in table 2: 1) standard errors assuming both spatial and serial correlation (following Conley, 2008), 2) two-way clustered standard errors at the temperature grid level and the region times time-period level, and 3) standard errors clustered at the temperature grid level of the underlying temperature data. The Conley spatial-serial standard errors assume standard errors to be spatially correlated within a radius of 400 kilometers from each city and serially correlated across all time periods. The correlation is assumed to be linearly decreasing with distance and to be zero beyond the cutoff.[24] The two-way clustered standard errors are clustered at the temperature grid level and the region times time-period level. Regions are 10 European regions. The two-way clustered standard errors account for both spatial and serial correlation. Finally, I report standard errors clustered at the grid level of the underlying temperature data as is commonly done in related papers using historical panel temperature data (e.g. Anderson et al., 2017).

The advantage of the Conley spatial-serial standard errors is that they assume spatial

[24] Results are robust to choosing larger or smaller cutoffs (see Table A.1 in the Appendix).

correlation within 400 kilometers of each city.[25] This may be preferable to assuming spatial correlation within a region, particularly for cities close to a region's border. The city of Strasbourg, for example, has been a major European crossroads since the 13th century and has been closely connected to the urban centers in nearby Belgium, Luxembourg, and the Germanic Holy Roman Empire. In addition, political borders change a lot over the course of my study period. Strasbourg, for example, has been part of both the German Holy Roman Empire and France at different points in time.[26]

3.2 Controlling for Historical Determinants of City Size

It is well established that economic and urban growth has been highly uneven across Europe with especially high growth in northwestern Europe. I therefore include a number of historical control variables into the specification controlling for factors that have been identified as drivers of urban growth within Early Modern Europe, for example, the overseas trade expansion of the Atlantic powers, human capital accumulation, the spread of Protestantism, and legacies of the Roman Empire (see section A.2 for more information on historical control variables). If temperature changes were correlated with these historical factors, the estimated effect of temperature and city size would be biased unless these are included as control variables.

Table 2 reports results. The coefficient of interest is γ. It is the estimated effect of a one-degree increase in long-run mean temperature on city size conditional on control variables. The identification relies on the assumption that temperature changes are not correlated with other determinants of city size besides those that are controlled for.

[25] Table A.1 in the appendix shows results for various cut-offs.

[26] The two-way clustered standard errors, on the other hand, have an advantage in that they allow for arbitrary spatial auto-correlation of all cities - as long as these are located within one region - and do not impose a functional form on the decay of the autocorrelation. On the other hand, while there might be exceptions, the Conley assumption that cities that are further apart are less correlated is plausible.

Table 2: Temperature and City Size

	Log City Size					
	(1)	(2)	(3)	(4)	(5)	(6)
Mean Temperature	0.505	0.696	0.721	0.918	0.808	1.163
Standard Errors Clusters						
Assuming Spatial and Serial AC	(0.255)**	(0.260)***	(0.262)***	(0.324)***	(0.259)***	(0.431)***
Two Way (City and Region x Time Period	(0.273)*	(0.277)**	(0.278)**	(0.325)***	(0.271)***	(0.467)**
Temperature Grid	(0.190)***	(0.210)***	(0.211)***	(0.274)***	(0.209)***	(0.386)***
Control Variables						
City Fixed Effects	yes	yes	yes	yes	yes	yes
Time-Period Fixed Effects	yes	yes	yes	yes	yes	yes
Country in 1600 Linear Time Trend					yes	
Country in 1600 × Time-Period FE						yes
Historical Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes
Geographic Controls (× Time-Period Fixed Effects)		yes	yes	yes	yes	yes
Sample	ALL	ALL	Excluding Capital Cities	Excluding Ocean Cities	ALL	ALL
Observations	10,600	10,600	10,510	8,395	10,600	10,600
R-Squared	0.767	0.768	0.758	0.766	0.779	0.783

Notes: Observations are at the city-time-period level. Regressions in columns 1, 2, 5, and 6 use a baseline sample of 2,120 cities. Capital cities are excluded in column 3, cities located less than 10 kilometers from an ocean are excluded in column 4. The time periods are 1600, 1700, 1750, 1800, and 1850. The dependent variable is the natural log of number of city inhabitants. "Mean temperature" is year temperature averaged over the periods 1500 to 1600, 1600 to 1700, 1700 to 1750, 1750 to 1800, and 1800 to 1850. Information on three types of standard errors are provided: 1) standard errors assuming both serial and spatial correlation (following Conley, 2008), 2) two-way clustered standard errors at the temperature grid level and the region times time-period level, and 3) standard errors clustered at the temperature grid level of the underlying temperature data. All specifications include city and time-period fixed effects. Column 5 in addition includes country linear time trends, and column 6 country times time period fixed effects. Historical control variables are a city's religious denomination in 1600 (Catholic, Catholic but only after the Counter Reformation, Lutheran, Anglican, Calvinist/Huguenots, or Calvinist/Lutheran), whether a city was a university town in 1500, whether it was part of a country engaged in Atlantic trade, and whether it was part of the Roman Empire in year 1 CE, a city's distance to the nearest Roman road, and its distance to the ocean. Five geographic control variables control for the city's altitude, its soil suitability for wheat cultivation and for potato cultivation, ruggedness and precipitation. All control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for p<0.01, ** for p<0.05, and * for p<0.1.

The coefficient in column 1 is .505. The positive sign of the coefficient shows a positive relationship between mean temperature and city size. In other words, the finding indicates that relatively cool temperatures during the Little Ice Age had a negative effect on city size. This is the effect of experiencing cooler temperatures during periods of overall cooling (1500 to 1700) and during the period when cities came out of the Little Ice Age (1700 to 1850), hence the effect of experiencing cooler temperatures for longer.

The coefficient indicates that a one-degree decrease in long-term mean temperature decreased city size by around 65 percent. To interpret the size of the coefficient it is important to note that this coefficient is estimated based on *long-term* changes in temperature which are substantially smaller than the difference in temperature between the warmest and the coldest year. The city with the largest decrease in long-term temperature from the 16th to the 17th century experienced a decrease of 0.28º C. Hence, this city would experience a decrease in city size due to temperature by 18.2 percent over a one-hundred-year period. A decrease in temperature of one standard deviation[27] decreased city size by 4.7 percent over a one-hundred-year period.

City size is used here as a proxy for economic growth. While the exact relationship between city size and economic growth in the Early Modern period is not known, Glaeser (1993) shows a correlation between city size and economic growth (measured as income growth) of 0.39 for American cities between 1960 and 1990. If the relationship was of a similar size in Early Modern Europe, then the result that a 1-degree temperature change changes city size by around 65 percent translates into the result that a 1-degree temperature change changes economic growth by 25 percent. This is roughly similar to Burke et al. (2015) who find a percentage change of 25 percent in global GDP per capita for a temperature change between 1 and 2 degree Celsius (Pooled response, long-run effect) and decreases of around 80 percent in GDP per capita after 100 years for the poorest 20 percent of countries if temperatures increase by 4 to 5 degrees Celsius by 2100 (under the "business as usual", RCP8.5, SSP5, scenario).

3.3 Controlling for Geographic Determinants of City Size

To further test the robustness of results, I include several geographic control variables in column 2 of Table 2: altitude, soil suitability for potato cultivation, soil suitability for wheat cultivation, and terrain ruggedness. These may have affected city size through their effects on agricultural productivity.[28] Each variable is interacted with time-period indicator variables to allow for time-varying effects of these variables. The coefficient increases with the inclusion of these controls indicating that a one standard deviation decrease in temperature decreased city size by 7.3 percent over a one-hundred-year period.

In columns 3 and 4, I systematically exclude cities from the sample cities that may

[27]This is the standard deviation of the decrease in temperature from the 16th to the 17th centuries which was the time period of the starkest temperature decreases during the Little Ice Age.

[28]Local vegetation, for example, changes with higher altitudes and increased ruggedness (Beniston et al., 1997). Nunn and Qian (2011) show the importance of soil suitability for potato cultivation.

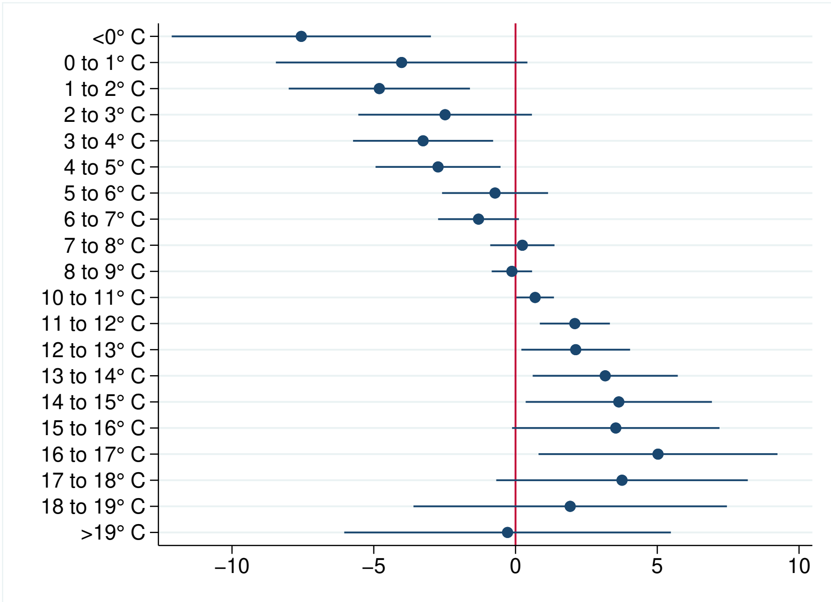
have been especially fast growing, namely capital cities and cities located on the coast. The results remain robust to including these additional controls and to excluding capital and port cities from the sample. In columns 5 and 6, I show that the results are robust to the inclusion of country-level time trends and to including country times time-period fixed effects in the model. Countries are defined as countries in 1600 according to Nüssli (2016). The country-level linear time trends control for linear trends in city growth that are specific to a country, e.g., because a country's institutional setup led to larger or lower city growth over time. The country times time-period fixed effects control for factors at the country level that change over time, and could affect the outcome variable, for example, a country's openness to trade.[29]

3.4 Alternative Functional Forms of the Temperature Variable

In the preceding section, I estimate a linear effect of temperature on city size. A number of papers show that a temperature change toward the extremes of the temperature distribution can have especially harmful effects (Burgess et al., 2017). In this section, I estimate non-linear temperature effects. Specifically, I measure the fraction of years over the past time period (50 or 100 years) during which the mean temperature fell within a specific temperature bin (e.g. below zero degree, zero to one degree, one to two degree, and so on; all degree in Celsius). London, for example, experienced one year with temperatures below eight degree, 21 years with temperatures between eight and nine degree, 61 years with temperatures between nine and 10 degree, and 17 years with temperatures between 10 and 11 degree between 1600 and 1700. Figure 4 plots coefficients on these temperature variables. Temperature bin nine to 10 degree is omitted as reference category. The results indicate that a larger fraction of cooler years is correlated with smaller city sizes. Cities with a high fraction of very cold years experienced the smallest growth and the effect on city size increases almost linearly with temperature until about 17 degree. Above 17 degree the effect of temperature on city size declines with the estimated effect of temperatures above 19 degree being negative but not significant, suggesting that a high fraction of

[29]Results in section A.4 in the appendix also show that estimates change little when weighing by city population or by time period length.

Figure 4: Estimated impact of the fraction of years per time period with mean temperature in a certain temperature bin



Notes: The figure plots coefficient sizes and confidence intervals of a regression of log city size on 20 temperature variables. Each variable measures the fraction of years over the past time period (50 or 100 years) during which the mean temperature in city i fell within a specific temperature bin (e.g. below zero degree Celsius, zero to one degree Celsius, one to two degree Celsius, and so on). Temperature bin nine to 10 degree is omitted as reference category.

very hot years was not positive for city growth. These results show that the relationship between temperature and city size is indeed driven by the negative effect of especially cold years. Figure 4 also indicates that a linear functional form fits the temperature-city size relationship very well for the largest part of the temperature distribution.

4 Why does a Change in Temperature Affect City Size?

I now investigate mechanisms through which the Little Ice Age may have affected city size. In particular, I test whether the effect of the Little Ice Age on city size may have operated through its effect on agricultural productivity, on mortality, and on migration.

4.1 The Role of Agricultural Productivity - The Effect of Temperature on Yield Ratios and Wheat Prices

In European climate, temperature is the most important determinant of the duration of the yearly growing period (Olesen and Bindi, 2002: 243). During the Little Ice Age, temperature levels needed for plant growth were reached later in the year, which shortened growing seasons in Europe (Aguado and Burt, 2007: 483). In England, for example, growing seasons were five weeks shorter in the 17th century compared to the 13th century (Grove, 2004: 629).

In this section, I test whether the Little Ice Age affected agricultural productivity. I use historical yield ratios and wheat prices as measures of agricultural productivity. I start by examining the relationship between yield ratio and different temperature variables.

The data on yield ratios are taken from Slicher et al. (1963). The author provides a panel of crop yield data by year and location from the 16th to the 19th centuries for locations[30] in 12 European countries. Yield ratio is the ratio of harvested crop grains to crop grains used for sowing. A higher yield ratio indicates higher agricultural productivity. I define three temperature variables based on the temperature data from Luterbacher et al. (2004): yearly mean temperature, growing-season temperature, and non-growing-season temperature. I also include *Access to Ocean* and *Atlantic Trader* (interacted with time-period indicator variables) as control variables.[31]

I first regress $Yield\ Ratio$ in location l and year τ on mean temperature in location l and year τ. I include location fixed effects for each location l and decade fixed effects for each decade d, and control variables interacted with decade fixed effects d.[32]

$$(2) \qquad Yield\ Ratio_{l\tau} = \beta + \gamma Temperature_{l\tau} + Location\ FE_l + \delta X_{ld} + Decade\ FE_d + \epsilon_{l\tau}$$

Results in column 1 of Table 3 show that higher temperatures in one year are associated with higher yield ratios in the same year. A one-standard-deviation increase in mean temperature increases yield ratio by 0.8 (up from 5.57, an increase of 14 percent).

In columns 2, I introduce wheat prices as an alternative measure of agricultural productivity. I combine annual data on wheat prices for 10 European cities from Allen (2001)

[30] Locations include different types of settlements, such as cities, land estates, and land-holding monasteries.

[31] *Access to Ocean* is an indicator variable which is one for all cities located less than 10 kilometers from the ocean. *Atlantic Trader* is an indicator variable which is one for all locations in countries engaging in Atlantic trade. Both variables are.

[32] The limited data availability for many years does not allow for the inclusion of year fixed effects, but decade fixed effects are likely to be able to capture long-term trends in yield ratios over time, for example due to technological innovation. While yield data are provided for between one and 200 years, the panel is unbalanced. For the majority of locations (346 out of 551) yield data are provided for one year only. In some cases, where yield ratios are provided for longer time periods, average yield ratios are provided covering between two and 50 years. I include only locations with a least 10 independent observations.

with yearly temperature data from Luterbacher et al. (2004). Wheat price data are available for Amsterdam, London, Leipzig, Antwerp, Paris, Strasbourg, Munich, Florence, Naples, and Madrid. As city-level demand changes only gradually, yearly fluctuations in wheat prices mostly reflect changes in supply. Determinants of agricultural productivity, other than temperature, such as certain institutions or technologies, are unlikely to change immediately from year to year in response to temperature changes. The immediate effect of temperature on wheat prices therefore depends primarily on temperature's effect on agricultural productivity. I estimate the following specification to assess the effect of temperature on wheat prices:

$$(3) \qquad Log\,Wheat\,Price_{i\tau} = \beta + \gamma Temperature_{i\tau} + City\ FE_i + Year\ FE_\tau + \delta X_{i\tau} + \epsilon_{i\tau}$$

I regress *Log Wheat Price* in city i and year τ on temperature in city i, and year τ. I also include city fixed effects and time-period fixed effects. $X_{i\tau}$ denotes additional control variables. The coefficient of interest is γ. It describes the relationship between changes in temperature and changes in wheat prices. Results in columns 3 and 4 show that higher temperature in one year is associated with lower wheat prices in the same year.

In columns 3 and 4, I test whether temperatures during the growing and non-growing seasons had different effects on yield ratios and wheat prices (see Figure A.5 for an overview of the different temperature variables). In column 3, I regress $Yield\ Ratio_{l\tau}$ on temperature during the growing season in year τ (spanning spring and summer) and the preceding non-growing season (spanning winter in year τ and fall in year $\tau - 1$). Results show that warmer temperature during the growing season significantly increases yield ratios, whereas temperature during the non-growing season does not have an effect. A one-standard-deviation increase in growing season temperature increases yield ratio by 0.58 (up from 5.57, an increase of 10.5 percent).

Wheat prices in year τ are the average wheat price over the calendar year τ. Hence, wheat prices in the *later* part of year τ - after the harvest - are determined by temperature in the growing season of year τ and temperature in the preceding non-growing season of year τ. Wheat prices in the *earlier* part of year τ are determined by temperature in the growing season year $\tau - 1$ and temperature in the preceding non-growing season in

Table 3: Temperature, Yearly Yield Ratios and Wheat Prices

VARIABLES	(1) **Yield Ratio**	(2) **Wheat Prices**	(3) **Yield Ratio**	(4) **Wheat Prices**
Mean Temperature	0.430***	-0.111***		
	(0.115)	(0.0283)		
Growing season temperature			0.364***	-0.115***
Season τ			(0.116)	(0.0221)
Non-growing season temperature			-0.148	0.0303*
Season τ			(0.0952)	(0.0171)
Growing season temperature				-0.0993***
Season τ-1				(0.0191)
Non-growing season temperature				-0.0151
Season τ-1				(0.0166)
City Fixed Effects	yes	yes	yes	yes
Decade Fixed Effects	yes		yes	
Year Fixed Effects		yes		yes
Control Variables	yes	yes	yes	yes
(×Year Fixed Effects)				
Observations	205	2,731	205	2,714
R-Squared	0.231	0.684	0.217	0.682
Number of bootstrap units	12	10	12	10
Number of repetitions	999	999	999	999

Notes: The outcome variable yield ratio is defined as the ratio of harvested crop grains to the crops used for sowing. The outcome variable wheat prices is the natural log of wheat prices. "Mean temperature" is temperature averaged over the same year. "Growing-Season Temperature" is temperature during spring and summer of year tau. "Non-Growing-Season Temperature" is temperature during fall of year tau-1 and winter of year tau. I omit all locations from the yield data sample with less than 10 independent data points. The final yield data sample includes 12 cities in four European countries: France, Germany, Poland, and Sweden. Wheat price data are for Amsterdam (282 years), Antwerp (133 years), Leipzig (215 years), London (351 years), Madrid (274 years), Munich (253 years), Naples (248 years), Florence (305 years), Paris (334 years), and Strasbourg (336 years). Bootstrapped standard errors are clustered at the city level. The control variable "Access to Ocean" is an indicator variable that is one for all cities located less than 10 kilometers from the ocean. The control variable "Atlantic Trader" is an indicator variable which is one for all locations in countries engaging in Atlantic trade. These control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

year $\tau - 2$. In column 4, I therefore regress wheat prices in year τ on growing-season temperature in year τ and in year $\tau - 1$ as well as on the corresponding non-growing season temperatures in years $\tau - 1$ and $\tau - 2$. Results in column 4 show that warmer temperature during growing seasons significantly decreased wheat prices, but temperature during non-growing seasons did not have an effect. These results show that temperature during the growing season was particularly important for agricultural productivity during the Little Ice Age. This is consistent with the evidence on the importance of growing-season temperatures on present-day agricultural output (e.g. Burgess et al., 2017: 32; Schlenker and Roberts, 2009; Guiteras, 2009). Results in Table A.5 in the appendix show that results on the effect of *long-term* temperature changes on wheat prices are consistent with results estimated for the effect of year-to-year temperature changes.

4.2 The Effect of Temperature on Mortality

Another channel through which temperature may have affected city size is temperature's effect on mortality. To examine this channel, I construct a data set that records mortality for 404 English parishes at the yearly level for the years 1538 to 1838 using data from Wrigley and Schofield (1989). The underlying primary sources of the mortality data are parish registers (for more details see Wrigley et al., 1989: 15-62). I geocode the parishes and combine them with the temperature data from Luterbacher et al. (2004). For this analysis, I aggregate both mortality and temperature at the level of the agricultural year. The agricultural year t starts with the beginning of the non-growing season in fall of year $t - 1$ and ends with the end of the growing season in year t (see Figure A.5 for an overview of the different temperature variables). Temperature may have affected mortality through its effect on agricultural productivity (lower temperatures decrease food production leading to malnutrition). I estimate the effect of temperature on mortality with the following regression.

$$
\begin{aligned}
(4) \qquad Crisis\ Mortality_{pt} &= \beta + \gamma Temperature_{pt-1} \\
&+ Parish\ FE_p + County_c \times TimePeriod\ FE_t + \delta X_{pt} + \epsilon_{pt}
\end{aligned}
$$

The dependent variable is an indicator variable *Crisis Mortality*. The variable is one if mortality in at least one month during a year reached a crisis level as defined by Wrigley and Schofield (1989). Wrigley and Schofield (1989) define crisis mortality months as months in which the death rate in parish p were more than 10 percent above a 25-year moving average of mortality for this month and parish.

I regress $Crisis\ Mortality_{pt}$ on temperature during the past agricultural year, and on temperature during the past growing season and non-growing. The specification also includes all geographic and historical control variables (interacted with year indicator variables) as used in the main specifications for which there was variation within England: distance to Roman roads, distance to the ocean, altitude, soil suitability for potatoes, and ruggedness.[33] The specification further includes parish fixed effects and county times time-period fixed effects.

Results in Table 4 show the estimated effect of temperature in the agricultural year $t-1$. Results in column 1 show a negative relationship between agricultural year temperature and crisis mortality for the entire sample (significant at the 10 percent level); hence warmer years were followed by lower mortality. Then, I investigate whether growing and non-growing seasons may have had different effects on mortality. Results in column 4 show that growing-season temperature had a negative significant effect on crisis mortality for the entire sample (significant at the 10 percent level) whereas the coefficient on non-growing-season temperature, while also negative, is smaller and not significant. These results indicate that lower temperature during the growing season, not during the non-growing season, lead to increases in mortality in England during the Little Ice Age. The coefficients indicate that a one-standard-deviation decrease in growing season temperature increased the probability that mortality reached crisis level by 4.7 percent (compared to a mean of 5 percent).

Then, I investigate whether access to markets mitigated the effects of temperature on crisis mortality. If markets allowed people to purchase products that had become costlier

[33] The variables Protestant and Atlantic trader are omitted as they do not vary within England. All of England became Anglican and England as a whole was an Atlantic trader. The variables university and Roman Empire were left out because none of the parishes in the Wrigley and Schofield (1989) data were home to a university, and because England was not part of the Roman Empire in year 1 CE.

to produce and to sell products which were not affected, then markets could have helped people to mitigate the adverse effects of temperature. The data by Wrigley and Schofield (1989) provide information on the distance between a parish and the nearest market town. In columns 2 and 3 and columns 5 and 6 of Table 4, I test whether a parish's distance to the closest market may have had an impact on the effect of adverse temperatures on crisis mortality[34] For parishes far from a market (columns 2 and 5), agricultural-year temperature and growing-season temperatures had significant effects on crisis mortality, indicating that parishes farther away from markets experienced higher crisis mortality when temperatures fell. In parishes close to a market (columns 3 and 6), the effect of temperature had the same sign but was smaller and insignificant. The coefficients indicate that a one standard deviation decrease in agricultural year temperature in t-1 increases crisis mortality by 8 percent in places far from markets, and by 4.6 percent in places close to markets though the latter effect is not significant. These results show that places far from markets were significantly less resilient to temperature changes compared to places close to markets.

[34] I define parishes as far from a market if they are more than four kilometers away from a market, which corresponds to the median distance between a parish and the nearest market town in the sample. Results are similar for other cutoffs.

Table 4: Temperature and Mortality

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	Mortality Crisis in Year t			Mortality Crisis in Year t		
	All Parishes	**Parishes far from Market**	**Parishes close to Market**	**All Parishes**	**Parishes far from Market**	**Parishes close to Market**
Agricultural-Year Mean Temperature in Year t-1	-0.0721*	-0.105**	-0.0617			
	(0.0371)	(0.0466)	(0.0502)			
Growing-Season Temperature in Year t-1				-0.0626*	-0.0829**	-0.0449
				(0.0322)	(0.0330)	(0.0514)
Non-Growing-Season Temperature in Year t-1				-0.00936	-0.0216	-0.0168
				(0.0231)	(0.0229)	(0.0359)
Observations	118,500	118,500	56,400	118,500	56,400	59,700
R-squared	0.173	0.173	0.243	0.173	0.243	0.227
Agricultural-Year Mean Temperature in Years t-1 to t-5	-0.106	-0.240***	-0.0949			
	(0.0731)	(0.0876)	(0.106)			
Growing-Season Temperature in Years t-1 to t-5				-0.124**	-0.160***	-0.137
				(0.0606)	(0.0576)	(0.0922)
Non-Growing-Season Temperature in Years t-1 to t-5				0.0426	-0.0660	0.0709
				(0.0585)	(0.0758)	(0.0795)
	118,500	56,400	59,700	118,500	56,400	59,700
	0.173	0.243	0.227	0.173	0.243	0.227
Parish Fixed Effects	yes	yes	yes	yes	yes	yes
County x Year Fixed Effects	yes	yes	yes	yes	yes	yes
Control Variables (×Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes

Notes: Observations are at the parish-year level. Regressions in columns 1 and 4 use a sample of 404 English parishes with data for the years 1538 to 1840. In columns 2, 3, 5, and 6, the sample is split between parishes less than four kilometers and more than four kilometers from the nearest market town. The dependent variable "Mortality Crisis" is an indicator variable that is one for parish i in year t if mortality in year t is more than 10 percent above a 25-year moving average of mortality in parish i. "Agricultural-Year Mean Temperature" is mean temperature over the agricultural year starting with the beginning of the non-growing season in fall of the preceding year and ending with the end of the growing season in summer of the same year. "Growing-Season Temperature" in year t is temperature during spring and summer of year t. "Non-growing-season temperature" in year t is temperature in fall of year t-1 and winter of year t. Standard errors are clustered at the temperature grid level of the underlying temperature data. Control variables include all control variables from the main specification (see Table 2) that vary within England: distance to the nearest Roman road, distance to the ocean, altitude, soil suitability for wheat cultivation, soil suitability for potato cultivation, and ruggedness. All control variables are interacted with year indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

So far, I have studied the effect of temperature during the past agricultural year on mortality. It is plausible, however, that temperature over *several* years may also have affected mortality. Food reserves may delay the effect of temperature on mortality and more than one year with adverse temperatures may be especially harmful after food reserves have been depleted. In the second part of Table 4, I show that cooler temperature over the past five years increased mortality. Again, it is the growing season period that affected mortality, rather than the non-growing season, and the estimated effect of growing-season temperature on mortality for the whole sample (column 4) is mainly driven by the effect estimated for parishes relatively far from market towns (column 5). Coefficient sizes indicate that a one-standard-deviation decrease in temperature over five past agricultural years increased crisis mortality by 9.3 percent in parishes far from markets and by 7.9 percent in parishes close to markets (though the latter effect is not significant). These results indicate larger temperature effects when temperature stays low over more than one agricultural year.

Temperature may also affect mortality through a direct health effect because cooler temperatures weaken the immune system (Foxman, 2016). Results in section A.5 show no evidence of a temperature effect on mortality through this channel.

4.3 The Effect of Temperature on Migration

Another channel through which temperature may have affected city size is through temperature's effect on migration. Historical evidence indicates that economic crises, in particular agricultural crises, increased migration in Early Modern Europe, for example after the Great Irish Famine (Gráda and O'Rourke, 1997) and after times of agricultural crises in Sweden (Martenius, 2014). The relationship between economic crises and migration, however, can be ambiguous. Poor people may have been entrapped in times of economic crisis as they were unable to pay the costs of migration (Hatton and Williamson, 1994). During the Great Irish Famine, for example, overseas migration increased more in richer parts of Ireland compared to poorer parts (Gráda and O'Rourke, 1997). Landless people in 19th century Sweden did not move because of the prohibitively high costs of long-distance migration (Dribe, 2003).

To examine the relationship between temperature changes and migration in Early Modern Europe, I use data on the location of birth and marriage of 6,350 couples in 7 English parishes between 1571 and 1871 from Wrigley et al. (2018).[35] These parishes had certain urban characteristics, in particular market rights, that make it plausible that

[35] These data shed light on short-distance, rural-to-urban migration, the most important type of immigration for cities in early modern England, with London being the only exception. A study by Clark (1979: 68) on the migration history of 7,000 people in Early Modern England shows that "roughly half of all the migrants had traveled no more than ten miles, while only about one in ten had moved over forty miles, and less than one in twenty over one hundred miles" Other types of migration (e.g., international migration) mattered for larger cities, but took up a much smaller share of the migrant population. I only include data which the data source classifies as reliable.

inhabitants of the surrounding rural areas would have sought these out in times of crisis. Migrants were attracted by economic sectors “unaffected by the same conditions which are producing economic stress in the place of origin,” (Dribe, 2003: 295).[36]

The data comprise information on the location of birth and marriage of one or both partners. Based on this information, I compute the number of marriages in which at least one partner was born outside the parish in which the ceremony takes place; I call these marriages "migrant marriages." I link this information to information on temperature from Luterbacher et al. (2004) and to geographic and historical control variables. To investigate whether the share of migrant marriages responds to temperature changes, I divide the data in 50-year periods and calculate the average share of migrant marriages and average temperature during each time period. Then, I examine the relationship between changes in migrant shares and changes in temperature. In Figure A.6, I plot the relationship between changes in migrant marriages and changes in temperature conditional on control variables and time-period indicator variables. The relationship is positive. This indicates that parishes with relatively benign climatic conditions attracted on average more migrants than parishes with relatively adverse climatic conditions during the same time period. This result should be interpreted with caution as it is not statistically significant and relies on information from only seven English parishes. Data covering a larger geographic space would surely be preferable.

5 Adaptation to the Little Ice Age

The previous part of the paper has shown that the Little Ice Age decreased city size through its effect on agricultural productivity, mortality, and migration. In the following, I investigate adaptation to the Little Ice Age. As Costinot et al. (2016), I study two adaptation strategies: 1) adaptation in trade and 2) adaptation in agricultural land use.

[36]Ideally, I would examine both the effect of temperature on emigration and on immigration - that is, whether parishes with lower temperature experienced more emigration and whether parishes with more benign temperatures attracted more migrants (compared to the other parishes). As these data only provide information on migrant shares in destination locations, I only examine the immigration effect.

5.1 Adaptation in Trade

To examine whether economies increased trade in response to the cooler temperatures of the Little Ice Age, I obtain information on 900,000 ship journeys to 750 destination ports in Europe representing 3,700 trade relationships between the years 1591 and 1857. The data include the exact date of the passage and tax levied on the cargo. I access these data from the Sound Toll Registers (STR, 2018), a unique data source on European trade in the Early Modern period. The Sound Toll was a historical toll collected by the Danish state from all ships passing the Oeresund strait (in English: the Sound) at the city of Helsingoer. The toll was proportionate to the ship's cargo value (Gøbel, 2010).[37] In its time, the Sound, a narrow strait separating Sweden and Denmark, was one of Europe's most important shipping routes. It connected the Baltic region and the rest of Europe. The Baltic region was the main supplier of grain in the "European Grain Trade" of the Early Modern period. Virtually all ships supplying grain from the Baltic region to the rest of Europe had to pass through the Sound, as it was the only practical way in and out of the Baltic.

Based on this information, I create a data set at the destination port-year level. I create two measures of trade volume: the number of ship arrivals at destination port i in year t and the total amount of Sound Toll levied per destination port and year. As port names are often misspelled in the original data (e.g. Copenhaatat instead of Copenhagen) I manually standardize the port names and then geo-reference the standardized port names and link them to temperature data (Luterbacher et al., 2004) and the usual geographic and historical control variables.

I define temperature variables measuring temperature over the past five, 25, 50, and 100 agricultural years. The final data set is a balanced panel with information on 760 destination ports for the years 1591 to 1857.

To assess whether these port cities increased trade as a response to the cooler temperatures of the Little Ice Age, I estimate the following specification:

[37] The toll was determined as one to 2 percent of the cargo value. To discourage ships to understate the value of their cargo the right was reserved to purchase the cargo at the total value as in the customs forms. (Gøbel, 2010).

$$(6) \qquad Ln(Nr\ of\ Ship\ Arrivals)_{it} =$$

$$\beta + \gamma Temperature_{it} + \delta MarketAccess + Time\ FE_t + Destination\ Port\ FE_i + \theta X_{it} + \epsilon_{it}$$

The specification estimates the relationship between the number of ships arriving at destination port i in year t and temperature at destination port i in year t. The specification also includes destination-port fixed effects, time-period fixed effects and geographic and historical control variables interacted with decade indicator variables. To control for each port city's market access, I control for distance to all other cities and (for a subsample) for city size both in each port city and in the other cities in the data set. Results in

Table 5: Temperature and Trade (Number of Ship Arrivals)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES				**Ln Number of Ships**				
Growing-Season Temperature	-0.101				-0.159			
in t-1 to t-5	(0.0774)				(0.163)			
Non-Growing-Season Temperature	0.0516				0.182*			
in t-1 to t-5	(0.0505)				(0.108)			
Growing-Season Temperature		-0.758***				-1.754***		
in t-1 to t-25		(0.277)				(0.569)		
Non-Growing-Season Temperature		0.00971				0.537		
in t-1 to t-25		(0.187)				(0.406)		
Growing-Season Temperature			-1.362***				-2.734***	
in t-1 to t-50			(0.422)				(0.843)	
Non-Growing-Season Temperature			-0.230				0.497	
in t-1 to t-50			(0.281)				(0.586)	
Growing-Season Temperature				-1.984**				-5.500***
in t-1 to t-100				(0.776)				(1.457)
Non-Growing-Season Temperature				-0.715				-0.0791
in t-1 to t-100				(0.576)				(1.228)
Destination Port Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Distance to other cities	yes	yes	yes	yes	yes	yes	yes	yes
City size					yes	yes	yes	yes
Control Variables (×50 year period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes
Observations	202,920	202,920	202,920	202,920	58,740	58,740	58,740	58,740
R-squared	0.267	0.268	0.268	0.268	0.442	0.442	0.443	0.444
Number of destination ports	760	760	760	760	220	220	220	220

Notes: Observations are at the destination port-year level with data for 758 destination ports and the years 1591 to 1857. The dependent variable is the natural log of the number of ship passages arriving at port i in year t. "Agricultural-Year Mean Temperature" in year t is the mean temperature over the agricultural year starting with the beginning of the non-growing season in fall t-1 and ending with the end of the growing season in summer of year t. All specifications include destination-port fixed effects, year fixed effects, and geographic and historical control variables interacted with decade fixed effects. Historical controls include information on a country's religious denomination in 1600 (s. Table 2 for details), whether a country had a university town in 1500, whether it was engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, and its distance to the ocean. Five geographic control variables control for the country's mean altitude, its mean soil suitability for wheat cultivation, its mean soil suitability for potato cultivation, and mean ruggedness. Standard errors are clustered at the level of the temperature grid cell of the underlying temperature data. Significance levels are indicated as *** for p<0.01, ** for p<0.05, and * for p<0.1.

Table 5 show a negative relationship between the number of ships arriving at a destination port and growing-season and non-growing season temperatures over the past five, 25, 50, and 100 years (columns one to four). This relationship is not significant for growing season temperatures over the previous five years. The relationship is significant at the 1 percent or 5 percent level for temperatures over the previous 25, 50, and 100 years. Hence, more ships arrived at ports that had experienced cooler temperatures. The coefficients indicate that a one-standard-deviation decrease in growing season temperature over the past 25 years increases the number of incoming ships by three percent. When considering the subset of the sample for which city size data is available (columns 5 to 8) the same temperature change increases the number of ship passages by 6.7 percent. Since the port cities with city size data are on average bigger, possibly more developed port cities, this might indicate that these react more strongly to changes in temperature than smaller port cities.

Theoretically, an increase in the number of incoming ships does not necessarily indicate an increase in imports if, for some reason, the ships carried on average less cargo. In table A.8, I therefore estimate temperature's effect on an alternative outcome variable, total taxes paid at the Sound on goods arriving in each port per year. These taxes were 1 to 2 percent of the cargo value. Results show that cooler temperatures during the growing season lead to increases in the value of imported goods.

5.2 Heterogeneity in the Effect of Temperature on City Size - Access to Trade

If economies responded to the Little Ice Age by increasing trade, then the effect of temperature on city size may have been mitigated for cities with better access to trade. In this section, I test this hypothesis by estimating the following specification:

$$\text{(7)} \qquad Ln\ City\ Size_{it} = \beta\ + \gamma Mean\ Temperature_{it} + \alpha Mean\ Temperature_{it}\ \times\ Trade_i$$
$$+City\ FE_i + Time\ FE_t + \delta X_{it} + \epsilon_{it}$$

First, I identify cities in the main data set which participated in long-distance trade. To do so, I first identify all cities that participated in Sound Toll trade. One might be concerned that the decision to participate in Sound Toll trade was endogenous to the temperature patterns during the Little Ice Age. As an alternative measure of participation in long-distance trade, I therefore identify all cities that were members of the Hanseatic League in 1400*, prior* to the period I am studying.

As in the main specification, I regress *Ln City Size* of city i in time period t on *Mean Temperature*, city fixed effects, time-period fixed effects, and the usual geographic and historical control variables. In addition, I include a variable interacting a city's mean temperature with an indicator variable that is one if the city participated in Sound Toll trade. Column 1 of Table 6 shows the estimated effect of temperature for all cities. In column 2, I add an interaction term of temperature and an indicator variable that is one for all cities in the main data set that are part of the Sound Toll trade. Results show that Sound Toll traders are significantly less affected by temperature changes compared to non-traders. The corresponding specification when treating only members of the Hanseatic League as traders shows that cities that were these were also significantly less affected by temperature changes, their coefficient turning even slightly negative (Column 4).

If trade helped cities to overcome adverse effects of temperature change, then better access to trade may have helped more. In column 3, I explore whether differences in trade intensity mattered. I use each city's number of trading partners as a measure of trade intensity. The first interaction term is one for cities that engage in Sound Toll trade but have relatively few trading partners (below the 25th percentile, trading with up to four different cities). The second interaction term is one for cities that engage in Sound Toll trade and have a higher number of trading partners (above the 25th percentile). Results in column 3 show that, while both interaction terms are negative, only the coefficient on the interaction term for cities with a relatively high number of trading partners is significant and it is twice as large as the coefficient on the interaction term for cities with relatively few trading partners. The mitigating effect of trade is larger for cities that trade more. The estimated effect of a one standard deviation decrease in temperature is estimated to reduce city size by 0.3 percent. For cities in the Sound Toll trade, but with few trading partners, a one-standard-deviation decrease in temperature is estimated to reduce city size

Table 6: Heterogeneity in the Effect of Temperature

	(1)	(2)	(3)	(4)	(5)
Trade Measure:		Sound Toll Trade		Hanseatic Trade	
Mean Temperature	0.696***	0.851***	0.857***	0.716***	0.839***
	(0.188)	(0.209)	(0.209)	(0.188)	(0.208)
Mean Temperature x Trade		-0.727***		-0.980***	
		(0.187)		(0.174)	
Mean temperature x Nr Trade Partner<25 pctile			-0.438		-0.626*
			(0.328)		(0.324)
Mean temperature x Nr Trade Partner>25 pctile			-0.818***		-0.723***
			(0.187)		(0.189)
Observations	10,600	10,600	10,600	10,600	10,600
R-squared	0.485	0.485	0.485	0.485	0.485
Number of cityid	2,120	2,120	2,120	2,120	2,120

Notes: Column 1 of this table reports OLS estimates of the main specification (identical to column 2 in Table 2) for comparison. Column 2 shows results when including an interaction term between "Mean Temperature" and "Sound Toll Trade",an indicator variable that is one for all cities that were destination cities in the Sound Toll trade. Column 3 shows results when including two interaction terms: one interaction term between "Mean Temperature" and the indicator variable NrTradePartner<25pctile which is one for all cities whose number of trading partner was below or equal to the 25th percentile, another interaction term between "Mean Temperature" and the indicator variable NrTradePartner>25pctile which is one for all cities whose number of trading partner exceeded the 25th percentile. Standard errors are clustered at the temperature grid level of the underlying temperature data. All specifications include city and time-period fixed effects. Historical and geographical controls are as defined in Table 2. All control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for p<0.01, ** for p<0.05, and * for p<0.1.

by 3.7 percent (compared to 9.8 percent for cities that do not participate in the Sound Toll trade). This distinction can also be seen for Hanseatic traders, but less strong. Cities with many Hanseatic trade partners are significantly less affected by temperature than cities without Hanseatic trade partners. Cities with few Hanseatic trade partners are less affected than cities without Hanseatic trade partners (significant at the ten percent level) but the estimated effect of temperature on them is still larger than for cities with many Hanseatic trade partners.[38]

These results show that trade was an effective way of shielding an economy from the negative effects of temperature changes, especially for cities that had a higher number of trading partners and that had trading partners in locations with relatively warm temperatures. The findings are also consistent with work examining modern developing countries

[38]This could reflect that - within those engaged in Hanseatic trade - even those with relatively few trading partners are still relatively well connected because they had well-established trade connections by the time that the Little Ice Age occurred.

- such as, for example, findings showing that trade openness has mitigated the adverse effects of weather shocks in India (Burgess and Donaldson, 2010). On the other hand, it is important to note that the decision to join the Hanseatic League in 1400 - while not related to the temperature patterns I am studying - is also not random. Members of the Hanseatic League are likely to have been different from other cities on other dimensions than trade, for example a higher level of human capital or a more diversified economy. These may have helped overcome climate-related shocks irrespective of trading relations.

These results provide an opportunity to calculate how expensive (in terms of city population levels) the Little Ice Age would have been for cities within the Sound Toll trade network had they not been part of this group. To do so, I compute the temperature effect for Sound Toll cities and compare it to the effect if they had not been Sound Toll cities.[39] A loss of 1,186,000 inhabitants, representing 3 percent of the total population of Sound Toll cities over the study period, would have been the cost of not being part of the Sound Toll trade network. This is almost four times as high as the temperature effect that these trading cities actually experienced.

5.3 Trade Opportunities and the Effect of Temperature

The Sound Toll Registers represent one of the most comprehensive sources on trade in Early Modern Europe, but they do not capture inland trade. In this section, I construct a measure of potential inland trade opportunities for all cities in the data set. I then estimate whether cities with larger trade opportunities are differently affected by temperature changes compared to cities with smaller trade opportunities. This measure is guided by the gravity model for trade (Isard, 1954). The size of trade flows in the gravity model depends on the respective economies' sizes and distance between these economies. To construct the

[39]The estimated temperature effect for Sound Toll cities equals 0.161 (by adding main temperature effect and temperature effect for Sound Toll cities). I multiply this by the actual temperature change that Sound Toll cities experienced, and calculate the change in city size that is due to change in temperature. This is the estimated change in city size due to temperature for Sound Toll cities. The calculated temperature effect for Sound Toll cities lies at a loss of 307,000 inhabitants or 1.6 percent of the total population over the study period.

I then add these changes to the actual city sizes to calculate city size in Sound Toll cities that would have occurred if they had not experienced any temperature change-related effect. Then, I use the main temperature effect for non-Sound Toll cities (0.844) to calculate the change in city size that Sound Toll cities would have experienced if they had not been Sound Toll cities.

measure, I identify the number and sizes of cities located up to 50 kilometers from each city in the data set and add up their total size.[40] Then, I estimate the main specification, but for two separate groups of cities: cities with relatively large trade opportunities and cities with relatively small trade opportunities. Cities with relatively large trade opportunities are defined as cities with an above median number of cities within 50 kilometers that are of above median total size. Cities with relatively small trade opportunities are defined as cities with a below median number of cities within 50 kilometers that are of below median total size. Results in columns 2 and 5 of Table 7 show that the estimated effect of temperature on city size for cities with high trade opportunities is close to zero (column 2), whereas the estimated effect of temperature on city size for cities with low trade opportunities is large and significant at 1 percent (column 5).

It is possible, however, that cities in similarly dense regions shared many characteristics, not just their ability to trade. In a second step in the analysis, I therefore use exogenous variation in travel costs due to the presence of natural barriers. I focus on the degree of ruggedness around each city. The data on ruggedness stem from Nunn and Puga (2012). Ruggedness is a natural barrier that increases trade costs. Roads or canals are much costlier to install on rugged terrain. Even after construction, transportation on roads or via canals through rugged terrain is still slower compared to following a road or a canal through flat terrain. In the gravity model, natural barriers to trade, such as ruggedness, increase transportation costs, and increase the distance parameter. Then, I estimate whether cities with a similar number of potential trading partners of similar size were differently affected by temperature changes if exposed to different degrees of ruggedness.

In columns 3, 4, 6, and 7, I estimate the effect of temperature for cities with large trade opportunities and low or high ruggedness (columns 3 and 4) and small trade opportunities and low or high ruggedness (columns 6 and 7). For each subgroup of cities, cities exposed to a low degree of ruggedness are less affected by temperature changes compared

[40] Results are very similar when using alternative distances, and when using city size of only the three, five or 10 largest cities within that distance. Fifty kilometers is a plausible distance for trade relationships between cities in Early Modern Europe. It is about the distance from London to the port city of Brighton (straight south from London to the southern shore of Great Britain).

Table 7: Trade Opportunities, Natural Barriers, and the Effect of Temperature

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	All Cities	Cities with High Trade Opportunities			Cities with Low Trade Opportunities		
		All	Low Ruggedness	High Ruggedness	All	Low Ruggedness	High Ruggedness
Mean Temperature	0.696***	0.02	-0.83	1.10	0.75***	0.58*	0.99**
	(0.190)	(0.61)	(0.73)	(1.00)	(0.25)	(0.33)	(0.40)
Control Variables							
City Fixed Effects	yes	yes	yes	yes	yes	yes	yes
Time-Period Fixed Effects	yes	yes	yes	yes	yes	yes	yes
Historical Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes
Geographic Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes
Observations	10,600	4,595	2,290	2,305	4,755	2,375	2,380
R-squared	0.767	0.78	0.80	0.76	0.77	0.82	0.73

Notes: Observations are at the city-year level. The regression in column 1 shows the baseline specification and the whole sample (identical to column 2 in Table 2) The dependent variable is the natural log of number of city inhabitants. "Mean temperature" is year temperature averaged over the periods 1500 to 1600, 1600 to 1700, 1700 to 1750, 1750 to 1800, and 1800 to 1850. "Cities with High Trade Opportunities" are cities with an above median number of trading partners that are of above median size within a radius of 50 kilometers around the city. "Cities with Low Trade Opportunities" are cities with a below median number of trading partners that are of below median size within a radius of 50 kilometers around the city. "Low (High) Ruggedness" is below (above) median ruggedness in a radius of 5 kilometers around the city. All specifications include city and time-period fixed effects. Control variables are as defined in table 2 and are interacted with time-period indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

to cities in the same subgroup but exposed to a high degree of ruggedness. The coefficient for cities with large trade opportunities but a high degree of ruggedness is large and positive (not significant), indicating that these cities were on average negatively affected by temperature decreases. The rugged terrain may have prevented them from taking advantage of trade opportunities in their surroundings. The coefficient for cities with large trade opportunities and a low degree of ruggedness is small and negative (not significant), indicating that these cities were on average not negatively affected by temperature decreases, and that they may have even benefited. In the subgroup of cities with low trade opportunities, the estimates show that all cities are affected by temperature changes, but that the estimated effect for cities with a high degree of ruggedness is substantially larger.

These results show the different temperature change-related effects on cities with a similar number of potential trading partners of similar sizes but for whom transportation costs varied due to natural barriers.

5.4 Adaptation in Land Use

Another way of adapting to climate change in Costinot et al. (2016) is to adjust land use according to an economy's comparative advantage. In the Early Modern period, the expansion of cropland and pasture was one strategy to increase agricultural output[41]

The relationship between temperature change and land use is ambiguous. Countries that were especially affected by the Little Ice Age may have expanded pasture and cropland to compensate for decreased agricultural productivity. Alternatively, countries that were not as affected by the Little Ice Age may have expanded pasture and cropland to benefit from their relatively high agricultural productivity. They could have then entered into trade relationships with those whose agricultural productivity had decreased.

In this section, I examine the relationship between temperature changes during the Little Ice Age and three outcome variables: the natural log of a country's total pasture, and the natural log of a country's total cropland. For this purpose, I use information on a country's total pasture, total cropland, and the ratio of a country's pasture to cropland from the History database of the Global Environment (Goldewijk, 2010; Klein Goldewijk et al., 2010, 2011). It is important to keep in mind that these data are calculated based on current-day and historical population, cropland, and pasture data, that are also estimates. The calculation depends on a number of assumptions that are hard to verify, such as agricultural technology, or the amount of land that a farmer could handle. Other processes that are likely to have influenced national cropland and pasture area, such as trade, across country boundaries are not taken into account. On the other hand, the database is unique in providing internally consistent information on historical land use patterns for 42 European countries (within constant boundaries of 2012) for each decade since 1500.[42] Mindful of the limitations of the data, I use information on for each decade between 1500 and 1850, and combine them with temperature variables at the country and decade level. To estimate whether changes in land use were related to changes in temperature during the Little Ice Age, I estimate the following regression.

$$Land\,Use_{id} = \beta + \gamma Temperature_{id} + DecadeFE_d + CountryFE_i + \delta X_{id} + \epsilon_{id} \tag{8}$$

The temperature variables measure temperature over the past 10, 25, 50, and 100 agri-

[41] It is well documented, for example, that agricultural land in England was expanded by clearing forests (Merriman, 2009: 167). Similarly, the Dutch expanded farm land by draining marshes (Tol and Langen, 2000).

[42] Uncertainty in the data works against me finding any patterns, especially as temperature changes *over time* are not part of the data generation process.

cultural years. I include decade and country fixed effects as well as the usual geographical and historical control variables interacted with decade indicator variables.

Results in Table 8 show a positive relationship between the outcome variables and temperature. This indicates that countries which were less affected by cooler temperatures of the Little Ice Age expanded areas for pasture and crops, possibly to benefit from their relatively higher agricultural productivity. While the coefficients are positive throughout, they are not significantly different from zero until considering up to 50 years of agricultural-year temperatures. This is consistent with the high economic and political costs that accompany processes of land reclamation. Results in Table A.9 show that the results in Table 8 are mainly driven by temperatures during the growing seasons. As countries less affected by temperature changes increase their agriculturally productive land countries more affected by temperature changes may have benefited from increases in supply if they are in trade relations with these economies.

6 Conclusion

My study shows that long-term temperature changes have important effects on economies. It also shows that economies are affected differently depending on certain characteristics. Access to trade appears as a key tool in overcoming the negative effects of long-term temperature changes. My results show that economies that participate in long-distance trade are able to respond to temperature changes by increasing trade. In addition, temperature's effect on mortality are much reduced in parishes that are located relatively close to a market. Thus, trade comes out as a key tool for adapting successfully to the effects of long-term temperature changes.

My results also underline the importance of the agricultural sector as a channel through which temperature affect the economy. On the one hand, access to trade and the role of the agricultural sector for an economy have undergone fundamental change since the Early Modern period. On the other hand, it is true that many developing countries' economies have less advantageous trade relationships and a larger share of the population work in agriculture. The findings highlight the vulnerability to climate change that agriculture-

Table 8: Temperature and Land Use

VARIABLES	(1)	(2) lnTotalPasture	(3)	(4)	(5)	(6) lnTotalCropland	(7)	(8)
Agricultural Year Mean Temperature, years t-1 to t-10	0.03 (0.08)				0.01 (0.06)			
Agricultural Year Mean Temperature, years t-1 to t-25		0.11 (0.16)				0.05 (0.13)		
Agricultural Year Mean Temperature, years t-1 to t-50			0.50** (0.24)				0.40** (0.17)	
Agricultural Year Mean Temperature, years t-1 to t-100				2.38*** (0.85)				2.12*** (0.52)
Country Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Decade Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Control Variables (×Decade Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes
Observations	570	570	570	570	570	570	570	570
R-squared	0.994	0.994	0.994	0.995	0.997	0.997	0.997	0.998

Notes: Observations are at the country-decade level. The sample contains data for 48 European countries (treated as constant over time in the boundaries of 2012) for every ten years between 1500 and 1850. The dependent variables are the natural log of the area of pasture, the natural log of the area of cropland, and the ratio of the area dedicated to pasture to the area dedicated to cropland. "Agricultural-Year Mean Temperature" is the mean temperature over the agricultural year starting with the beginning of the non-growing season in fall and ending with the end of the growing season in summer. All specifications include country fixed effects, decade fixed effects, and historical and geographic control variables as in the main specification. Historical controls include information on a country's religious denomination in 1600 (s. Table 2 for details), whether a country had a university town in 1500, whether it was engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, and its distance to the ocean. Five geographic control variables control for the country's mean altitude, its mean soil suitability for wheat cultivation, its mean soil suitability for potato cultivation, and mean ruggedness. All control variables are interacted with decade indicator variables. Standard errors are clustered at the country level. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

dependent economies with limited access to trade may face.

References

Acemoglu, D., Johnson, S., and Robinson, J. (2005). The rise of europe: Atlantic trade, institutional change, and economic growth. *American Economic Review*, 95(3):546–579.

Aguado, E. and Burt, J. (2007). *Understanding Weather and Climate*. Pearson.

Allen, R. C. (2001). The great divergence in european wages and prices from the middle ages to the first world war. *Explorations in Economic History*, 38:411–447.

Anderson, R. W., Johnson, N. D., and Koyama, M. (2017). Jewish persecutions and weather shocks: 1100–1800. *The Economic Journal*, 127(602):924–958.

Bairoch, P. (1988). *The population of European cities, 800-1850: data bank and short summary of results*. Geneva: Droz.

Barreca, A., Clay, K., Deschênes, O., Greenstone, M., and Shapiro, J. S. (2015). Convergence in adaptation to climate change: Evidence from high temperatures and mortality, 1900-2004. *American Economic Review*, 105(5):247–51.

Barreca, A., Clay, K., Deschenes, O., Greenstone, M., and Shapiro, J. S. (2016). Adapting to climate change: The remarkable decline in the us temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, 124(1):105–159.

Baten, J. (2002). Climate climate, grain production and nutritional status in southern germany during the 18th century. *Journal of European Economic History*, 30(1):9–47.

Becker, S. O. and Woessmann, L. (2009). Was weber wrong? a human capital theory of protestant economic history*. *The Quarterly Journal of Economics*, 124(2):531.

Behringer, W. (1999). Climatic change and witch-hunting: the impact of the little ice age on mentalities. *Climatic Change*, 43(1):335–351.

Beniston, M., Diaz, H. F., and Bradley, R. S. (1997). Climate change at high elevation sites: An overview. *Climatic Change*, 36(3):233–251.

Berger, H. and Spoerer, M. (2001). Economic crises and the european revolutions of 1848. *The Journal of Economic History*, 61(2):293–326.

Boustan, L. P., Kahn, M. E., and Rhode, P. W. (2012). Moving to higher ground: Migration response to natural disasters in the early twentieth century. *American Economic Review*, 102(3):238–44.

Broadberry, S. (2013). Accounting for the great divergence. *London School of Economics and Political Science Economic History Working Papers*, 184(13).

Buntgen, U. and Hellmann, L. (2013). The little ice age in scientific perspective: cold spells and caveats. *Journal of Interdisciplinary History*, 44(3):353–368.

Burgess, R., Deschenes, O., Donaldson, D., and Greenstone, M. (2013). The unequal effects of weather and climate change: Evidence from mortality in india. *Unpublished working paper.*

Burgess, R., Deschenes, O., Donaldson, D., and Greenstone, M. (2017). Weather, climate change and death in india. *Cambridge, United States: Massachusetts Institute of Technology, Department of Economics. Manuscript.*

Burgess, R. and Donaldson, D. (2010). Can openness mitigate the effects of weather shocks? evidence from india's famine era. *The American Economic Review Papers and Preceedings*, pages 449–453.

Burke, M. and Emerick, K. (2016). Adaptation to climate change: Evidence from us agriculture. *American Economic Journal: Economic Policy*, 8(3):106–40.

Burke, M., González, F., Baylis, P., Heft-Neal, S., Baysan, C., Basu, S., and Hsiang, S. (2018). Higher temperatures increase suicide rates in the united states and mexico. *Nature climate change*, 8(8):723.

Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239.

Cantoni, D. and Yuchtman, N. (2014). Medieval universities, legal institutions, and the commercial revolution*. *The Quarterly Journal of Economics*, 129(2):823.

Carleton, T., Delgado, M., Greenstone, M., Houser, T., Hsiang, S., Hultgren, A., Jina, A., Kopp, R. E., McCusker, K., Nath, I., et al. (2018). Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits.

Cheng, L., Abraham, J., Hausfather, Z., and Trenberth, K. E. (2019). How fast are the oceans warming? *Science*, 363(6423):128–129.

Clark, P. (1979). Migration in england during the late seventeenth and early eighteenth centuries. *Past and Present*, 83:57–90.

Clodfelter, M. (2002). *Warfare and Armed Conflicts: A Statistical Reference to Casualty and Other Figures, 1500-2000.* McFarland.

Conley, T. (2008). *Spatial Econometrics.* Palgrave Macmillan.

Costinot, A., Donaldson, D., and Smith, C. (2016). Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy*, 124(1):205–248.

Cronin, T. M. (2009). *Paleoclimates Unterstanding Climate Past and Present.* Columbia University Press.

De Long, J. B. and Shleifer, A. (1993). Princes and merchants: European city growth before the industrial revolution. *The Journal of Law and Economics*, 36(2):671–702.

Dell, M. (2012). Path dependence in development: Evidence from the mexican revolution. *Mimeo Harvard University.*

Dell, M., Jones, B, F., and Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95.

DeMenocal, P. B. (2001). Cultural responses to climate change during the late holocene. *Science (New York, NY)*, 292(5517):667–673.

Deschenes, O. and Greenstone, M. (2007). The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *American Economic Review*, 97(1):354–385.

Deschenes, O. and Greenstone, M. (2012). The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather: Reply. *American Economic Review*, 102(7):3761–3773.

Diffenbaugh, N. S. and Burke, M. (2019). Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences.*

Dincecco, M. and Onorato, M. G. (2016). Military conflict and the rise of urban europe. *Journal of Economic Growth*, 21:259–282.

Dribe, M. (2003). Dealing with economic stress through migration: Lessons from nineteenth century rural sweden. *European Review of Economic History*, 7(3):271–299.

EASAC, E. A. S. A. C. (2018). Extreme weather events in europe. *EASAC Statement.*

Eddy, J. A. (1976). The maunder minimum. *Science*, 192(4245):1189–1202.

EEA, E. E. A. (2012). Climate change, impacts and vulnerability in europe. *EEA Report*, 12.

Fan, K. (2010). Climatic change and dynastic cycles in chinese history: a review essay. *Climatic Change*, 101:565–573.

FAO/IIASA/ISRIC/ISS-CAS/JRC (2012). Harmonized World Soil Database (version 1.2).

Fowlie, M., Greenstone, M., and Wolfram, C. (2015). Are the non-monetary costs of energy efficiency investments large? understanding low take-up of a free energy efficiency program. *Energy Institute at Haas working papers*, 256.

Foxman, E. (2016). Two interferon-independent double-stranded rna-induced host defense strategies suppress the common cold virus at warm temperature. *Proc Natl Acad Sci U S A*, 113(30):8496–501.

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., Rocklöv, J., Forsberg, B., et al. (2015). Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet*, 386(9991):369–375.

Glaeser, E. L. (1993). Cities, information, and economic growth. *Cityscape Proceedings of the Regional Growth and Community Development Conference*, 1:9–47.

Glaeser, E. L., Kolko, J., and Saiz, A. (2001). Consumer city. *Journal of economic geography*, 1(1):27–50.

Gøbel, E. (2010). The sound toll registers online project, 1497–1857. *International Journal of Maritime History*, 22(2):305–324.

Goldewijk, K. k. (2010). History database of the global environment.

Gráda, C. Ó. and O'Rourke, K. H. (1997). Migration as disaster relief: Lessons from the great irish famine. *European Review of Economic History*, 1(1):3–25.

Grove, J. M. (2004). *Little Ice Ages: Ancient and Modern.* Routledge.

Guiteras, R. (2009). The impact of climate change on indian agriculture. *Manuscript, Department of Economics, University of Maryland, College Park, Maryland.*

Hatton, T. J. and Williamson, J. G. (1994). International migration and world development: a historical perspective. In *Economic aspects of international migration*, pages 3–56. Springer.

Haywood, J., Hall, S., Jotischky, A., McGlynn, S., and Swift, J. (2000). *The Cassell Atlas of World History: The Medieval and Early Modern Worlds.* Andromeda and Cassell and Co.

Hsiang, S. M. (2010). Temperatures and cyclones strongly associated with economic production in the caribbean and central america. *Proceedings of the National Academy of Sciences*, 107(35):15367–15372.

Isard, W. (1954). Location theory and trade theory: Short-run analysis. *The Quarterly Journal of Economics*, 68(2):305–320.

Kelly, M. and OGrada, C. (2010). The economic impact of the little ice age.

Kelly, M. and OGrada, C. (2014). Debating the little ice age. *Journal of Interdisciplinary History*, 45(1):57–68.

Klein Goldewijk, K. (2015a). Total cropland.

Klein Goldewijk, K. (2015b). Total pasture.

Klein Goldewijk, K., Beusen, A., and Janssen, P. (2010). Long-term dynamic modeling of global population and built-up area in a spatially explicit way: Hyde 3.1. *The Holocene*, 20(4):565–573.

Klein Goldewijk, K., Beusen, A., Van Drecht, G., and De Vos, M. (2011). The hyde 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography*, 20(1):73–86.

Kohn, G. (2007). *Encyclopedia of Plague and Pestilence: From Ancient Times to the Present*. Facts on File Library of World History. Facts On File, Incorporated.

Koot, G. (2013). The little divergence and the birth of the first modern economy, or when and why did northwestern europe become much richer than southern and eastern europe. *Mimeo University of Massachusetts Dartmouth*.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M., and Wanner, H. (2004). European seasonal and annual temperature variability, trends, and extremes since 1500. *Science*, 303(5663):1499–1503.

Martenius, I. (2014). The swedish emigration to america.

McCormick, M., Büntgen, U., Cane, M. A., Cook, E. R., Harper, K., Huybers, P., Litt, T., Manning, S. W., Mayewski, P. A., More, A. F., and s (2012). Climate change during and after the roman empire: reconstructing the past from scientific and historical evidence. *The Journal of Interdisciplinary History*, 43(2):169–220.

McCormick, M., Dutton, P. E., and Mayewski, P. A. (2007). Volcanoes and the climate forcing of carolingian europe, ad 750-950. *Speculum*, 82(4):865–895.

McCormick, M., Maione-Downing, B., Grigoli, L., and Zambotti, G. (2014). *Digital Atlas of Roman and Medieval Civiliations*. President and Fellows Harvard University.

Merriman, J. (2009). *A history of modern Europe: from the Renaissance to the present*, volume 1. WW Norton & Company.

Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M., and KarlÃ©n, W. (2005). Highly variable northern hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature*, 433(7026):613–617.

Nunn, N. and Puga, D. (2012). Ruggedness: The blessing of bad geography in africa. *Review of Economics and Statistics*, 94(1):20–36.

Nunn, N. and Qian, N. (2011). The potato's contribution to population and urbanization: evidence from a historical experiment. *The Quarterly Journal of Economics*, 126(2):593–650.

Nüssli, C. (2016). Euratlas Periodis Historical Atlas of Europe. https://www.euratlas.net/.

Olesen, J. E. and Bindi, M. (2002). Consequences of climate change for european agricultural productivity, land use and policy. *European journal of agronomy*, 16(4):239–262.

Olmstead, A. L. and Rhode, P. W. (2011). Adapting north american wheat production to climatic challenges, 1839–2009. *Proceedings of the National Academy of sciences*, 108(2):480–485.

Oster, E. (2004). Witchcraft, weather and economic growth in renaissance europe. *The Journal of Economic Perspectives*, 18(1):215–228.

Parker, G. (2013). *Global crisis: war, climate change and catastrophe in the seventeenth century*. Yale University Press.

Pfister, C. and Brázdil, R. (2006). Social vulnerability to climate in the" little ice age": an example from central europe in the early 1770s. *Climate of the Past*, 2(2):115–129.

Pindyck, R. S. (2013). Climate change policy: What do the models tell us? *Journal of Economic Literature*, 51(3):860–872.

Rappaport, J. (2007). Moving to nice weather. *Regional Science and Urban Economics*, 37(3):375–398.

Rappaport, J. and Sachs, J. D. (2003). The united states as a coastal nation. *Journal of Economic growth*, 8(1):5–46.

Schlenker, W. and Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to us crop yields under climate change. *Proceedings of the National Academy of sciences*, 106(37):15594–15598.

Slicher, v. B. et al. (1963). The agrarian history of western europe, ad 500-1850. *The agrarian history of Western Europe, AD 500-1850.*

Stasavage, D. (2012). Oligarchy and growth lessons from europe's autonomous cities.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review, Part II: The Impacts of Climate Change on Growth and Development.* Cambridge University Press.

STR (2018). Sound Toll Registers Online. http://www.soundtoll.nl/index.php/en/welkom.

Sutton, P. C., Elvidge, C. D., Ghosh, T., et al. (2007). Estimation of gross domestic product at sub-national scales using nighttime satellite imagery. *International Journal of Ecological Economics & Statistics*, 8(S07):5–21.

Tol, R. S. and Langen, A. (2000). A concise history of dutch river floods. *Climatic change*, 46(3):357–369.

Turner, M. A., Rosenthal, J. S., Chen, J., and Hao, C. (2012). Adaptation to climate change in preindustrial iceland. *American Economic Review*, 102(3):250–55.

Van Zanden, J. L. (2009). *The long road to the industrial revolution: the European economy in a global perspective, 1000-1800*, volume 1. Brill.

Voigtländer, N. and Voth, H.-J. (2012). The three horsemen of riches: Plague, war, and urbanization in early modern europe. *Review of Economic Studies*, 80(2):774–811.

Weber, M., Parsons, T., and Tawney, R. (1930). *The protestant ethic and the spirit of capitalism.* G. Allen & Unwin.

Wrigley, E., Davies, R., Oeppen, J., and Schofield, R. (2018). 26 English parish family reconstitutions [Data Collection]. http://doi.org/10.5255/UKDA-SN-853082.

Wrigley, E. and Schofield, R. (1989). *The Population History of England 1541-1871.* Cambridge Studies in Populatio. Cambridge University Press.

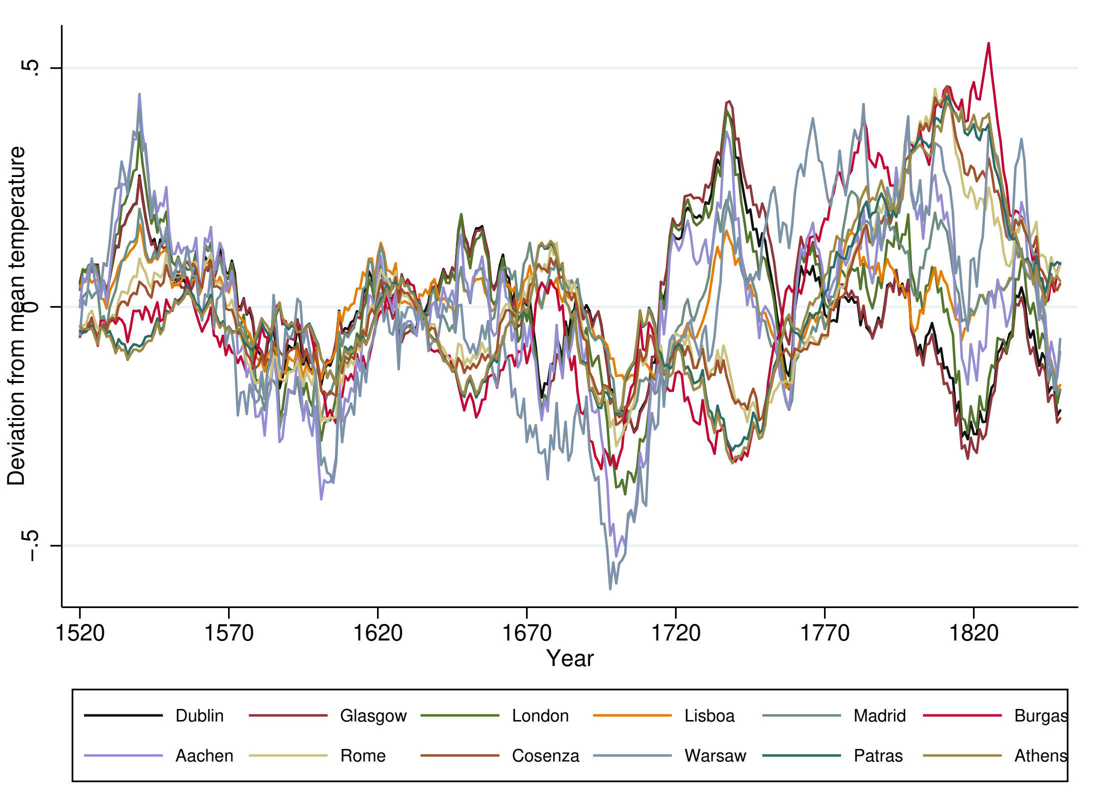
Zhang, D. D., Zhang, J., Lee, H. F., and He, Y.-q. (2007). Climate change and war frequency in eastern china over the last millennium. *Human Ecology*, 35(4):403–414.

A Appendix

A.1 Temperature variation and city locations

Figure A.1 shows city-level temperature deviations from average temperature (20-year moving average) for 12 European capitals or regional capitals between 1520 and 1850. The graph shows that cities were affected differently by the Little Ice Age. Temperature decreases in certain cities coincide with temperature increases or relatively stable temperature in others. When cities experience temperature increase or decrease at the same time (such as around 1600 and around 1700) the extent of the increase or decrease differs

Figure A.1: Temperature in 12 European cities



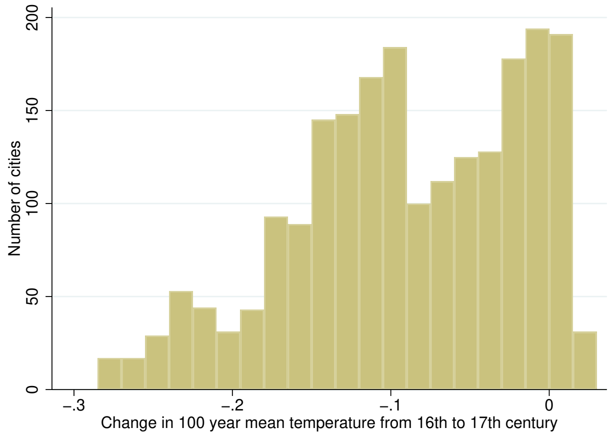
Notes: The figure displays temperature graphs for 12 European capitals or regional capitals for the years 1520 to 1850. Temperature is a 20-year moving average and depicted as deviations from city-level mean temperature.

by cities. The histogram in Figure A.2 shows the temperature change from the 16th to the 17th century, the height of the Little Ice Age, for all cities in the sample. The large majority of cities experienced temperature decline.

A.2 Historical control variables

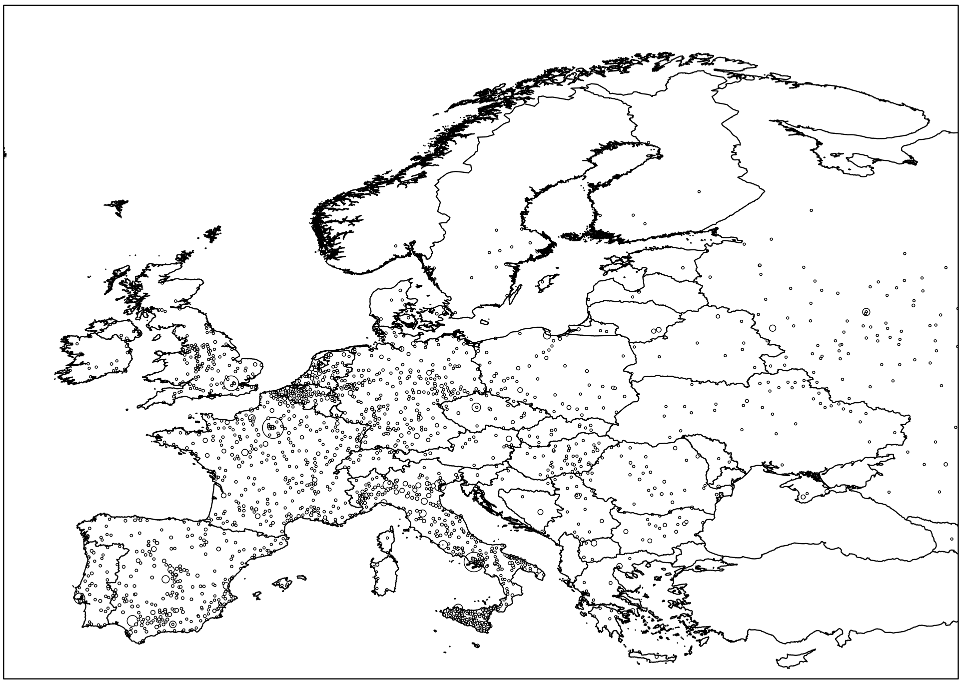
Weber et al. (1930) famously argued that Protestantism introduced a stricter work ethic, making Protestant countries better off. Becker and Woessmann (2009) show that Protestantism had a positive effect on human capital accumulation due to its emphasis on people's ability to read the Bible. I include indicator variables that are one if a city was majority Lutheran, Calvinist, Anglican, or Catholic in 1600. Cantoni and Yuchtman (2014) and Van Zanden (2009: 12) emphasize the importance of universities and of human capital accumulation for economic growth in Early Modern Europe. I include an indicator variable for cities that were university cities in 1500. Acemoglu et al. (2005) show that the overseas trade expansion of western European countries had a positive effect on economic

Figure A.2: Histogram



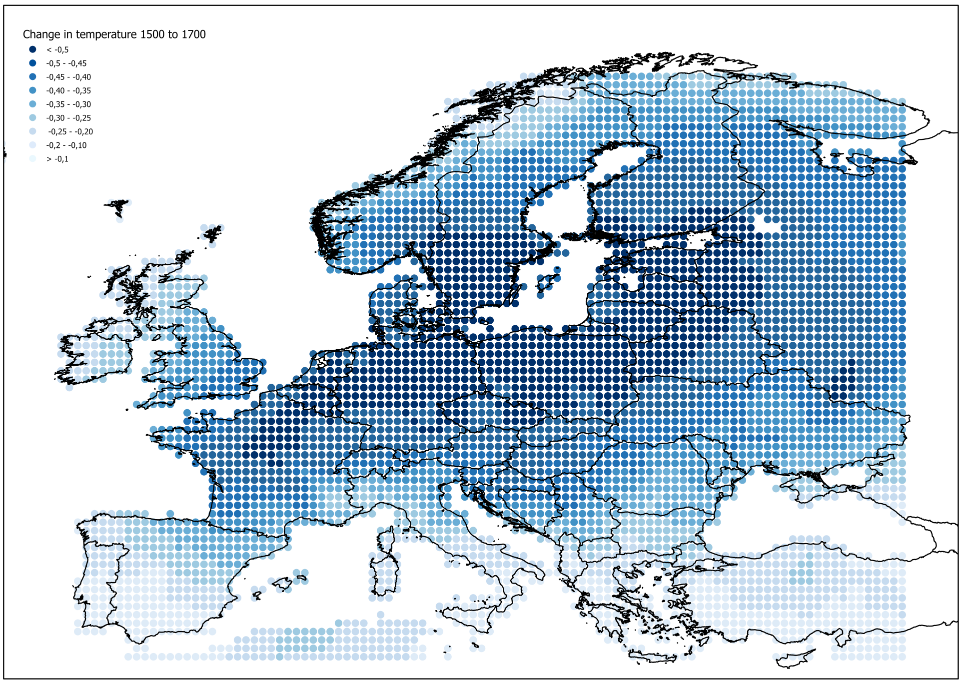
Notes: The figure shows a histogram of the change in city-level mean temperature between the 16th and 17th centuries.

Figure A.3: Locations of cities in the sample



Notes: The figure shows the locations of the 2120 cities in the main sample. Circles are proportionate to city size in 1600.

Figure A.4: Temperature variation in the study region



Notes: The figure shows the grid cells of the temperature data and changes in temperature between the beginning of the study period (1500-1520) and the height of the Little Ice Age (1680-1700).

Figure A.5: Mean Temperature, Agricultural Year Temperature, Growing- and Non-Growing Season Temperatures

Mean Temperature		Meteorological Year t-2				Meteorological Year t-1				Meteorological Year t			
Months	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Seasons	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Growing- and Non-Growing Season Temperatures	Non-Growing Season		Growing Season		Non-Growing Season		Growing Season		Non-Growing Season		Growing Season		
Agricultural-Year Temperature	Agricultural Year t-2				Agricultural Year t-1				Agricultural Year t				

Notes: The figure serves to clarify the relation between the three temperature variables Mean Temperature, Growing- and Non-Growing-Season Temperatures, and Agricultural-Year Temperature on the one hand and seasons and months on the other hand. Mean Temperature is the main dependent variable and is mean temperature over the meteorological year that runs from December to November. Growing seasons run from the beginning of spring to the end of summer (March to August), and non-growing seasons from the beginning of fall to the end of winter (September to February). The agricultural year runs from the beginning of the non-growing season to the end of the growing season (September to August).

Table A.1: Assuming Spatial Correlation Within Different Distances

	Log City Size	
	(1)	(2)
Mean Temperature	0.505	0.696
SE assuming Spatial and Serial AC		
within 300 km radius	(0.251)**	(0.248)***
within 400 km radius	(0.255)**	(0.260)***
within 500 km radius	(0.264)*	(0.270)***
within 600 km radius	(0.268)*	(0.268)***
Control Variables		
City Fixed Effects	yes	yes
Time-Period Fixed Effects	yes	yes
Historical Controls (× Time-Period Fixed Effects)	yes	yes
Geographic Controls (× Time-Period Fixed Effects)		yes
Observations	10,600	10,600
R-Squared	0.767	0.768

Notes: The specifications are identical to specifications in column 1 and 2 of Table 2, except that standard errors assuming both serial and spatial correlation (following Conley, 2008) are calculated assuming autocorrelation within a 300, 400, 500, and 600 kilometers radius around a city. Observations are at the city-year level. Regressions use a baseline sample of 2,120 cities. "Mean temperature" is year temperature averaged over the periods 1500 to 1600, 1600 to 1700, 1700 to 1750, 1750 to 1800, and 1800 to 1850. The specifications include city and time-period fixed effects. Historical controls include information on a city's religious denomination in 1600 (see Table 2 for details), whether it was a university town in 1500, whether it was part of a country engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, its distance to the nearest Roman road, and its distance to the ocean. Five geographic control variables control for the city's altitude, its soil suitability for wheat cultivation, its soil suitability for potato cultivation, ruggedness and precipitation. All control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

growth. I add an indicator variable for Atlantic traders, i.e., Great Britain, the Netherlands, Belgium, France, Spain, and Portugal. I also create an indicator variable that is one for all cities that were part of the Roman Empire, and an indicator variable for all cities that were located within one kilometer of a Roman road. As an additional measure for a country's natural openness for overseas trade, I include an indicator variable for all cities located within 10 kilometers of the coast.

Table A.2: Main Estimates Weighted by Period Length

	Log City Size							
	Unweighted Estimates				Estimates Weighted by Time Period Length			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Mean Temperature	0.505	0.696	0.721	0.918	0.449	0.711	0.738	0.893
Standard Errors Clusters								
Two Way (City and Region x Year)	(0.276)*	(0.285)**	(0.286)**	(0.344)**	(0.329)	(0.324)**	(0.324)**	(0.366)**
Temperature Grid	(0.19)***	(0.210)***	(0.211)***	(0.274)***	(0.185)**	(0.206)***	(0.208)***	(0.269)***
Control Variables								
City Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Time-Period Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Historical Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes
Geographic Controls (× Time-Period Fixed Effects)		yes	yes	yes		yes	yes	yes
Sample	ALL	ALL	Excluding Capital Cities	Excluding Ocean Cities	ALL	ALL	Excluding Capital Cities	Excluding Ocean Cities
Observations	10,600	10,600	10,510	8,395	10,600	10,600	10,510	8,395
R-Squared	0.767	0.768	0.758	0.766	0.768	0.770	0.756	0.766

Notes: Results in columns 1 to 4 are identical to baseline results in Table 2 and are reported to facilitate comparison. The specifications used in columns 5 to 8 are the same as in the main specification, except that estimates are weighted by period length in years: 100 years for the first two periods (1500 to 1600, 1600 to 1700), and 50 years for the last three periods (1700 to 1750, 1750 to 1800, and 1800 to 1850) Observations are at the city-year level. Regressions in columns 1, 2, 5, and 6 use a sample of 2,120 cities. Capital cities are excluded in columns 3 and 7; cities located less than 10 kilometers from an ocean are excluded in columns 4 and 8. The time periods are 1600, 1700, 1750, 1800, and 1850. The dependent variable is the natural log of number of city inhabitants. "Mean temperature" is year temperature averaged over the periods 1500 to 1600, 1600 to 1700, 1700 to 1750, 1750 to 1800, and 1800 to 1850. Information on two types of standard errors are provided: 1) two-way clustered standard errors at the temperature grid level and the region times year level and 2) standard errors clustered at the temperature grid level of the underlying temperature data. All specifications include city and time-period fixed effects. Historical controls include information on a city's religious denomination in 1600 (see Table 2 for details), whether it was a university town in 1500, whether it was part of a country engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, its distance to the nearest Roman road, and its distance to the ocean. Five geographic control variables control for the city's altitude, its soil suitability for wheat cultivation, its soil suitability for potato cultivation, ruggedness and precipitation. All control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for p<0.01, ** for p<0.05, and * for p<0.1.

A.3 Spatial correlation within different distances

A.4 Estimates weighted by period length and by population

A.5 Health and Mortality

Results in section 4.2 showed temperature's effect on mortality through its effect on agricultural productivity. Alternatively, temperature may have had a direct health effect because colder temperatures in winter weaken the immune system (Foxman, 2016). Such effects of cold temperature should be particularly prevalent during the winter months. During the Early Modern period, heating was expensive and mostly limited to the kitchen and possibly a living room. Farmers spending a lot of their work time outside the home were especially exposed to cold temperatures. To investigate this direct effect of tempera-

Table A.3: Main Estimates Weighted by Population

	Log City Size							
	Unweighted Estimates				**Population-Weighted Estimates**			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Mean Temperature	0.505***	0.696***	0.721***	0.918***	0.428**	0.629***	0.660***	0.845***
	(0.19)	(0.210)	(0.211)	(0.274)	(0.186)	(0.202)	(0.204)	(0.267)
Control Variables								
City Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Time-Period Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Historical Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes
Geographic Controls (× Time-Period Fixed Effects)		yes	yes	yes		yes	yes	yes
Sample	ALL	ALL	Excluding Capital Cities	Excluding Ocean Cities	ALL	ALL	Excluding Capital Cities	Excluding Ocean Cities
Observations	10,600	10,600	10,510	8,395	10,600	10,600	10,510	8,395
R-Squared	0.767	0.768	0.758	0.766	0.768	0.770	0.756	0.766

Notes: Results in columns 1 to 4 are identical to baseline results in Table 2 and are reported to facilitate comparison. The specifications used in column 5 to 8 are the same as in the main specification, except that estimates are weighted by Log City Size. Observations are at the city-year level. Regressions in columns 1, 2, 5, and 6 use a sample of 2,120 cities. Capital cities are excluded in columns 3 and 7, cities located less than 10 kilometers from an ocean are excluded in columns 4 and 8. The time periods are 1600, 1700, 1750, 1800, and 1850. The dependent variable is the natural log of number of city inhabitants. "Mean temperature" is year temperature averaged over the periods 1500 to 1600, 1600 to 1700, 1700 to 1750, 1750 to 1800, and 1800 to 1850. Standard errors are clustered at the temperature grid level of the underlying temperature data. All specifications include city and time-period fixed effects. Historical controls include information on a city's religious denomination in 1600 (s. Table 2 for more detail), whether it was a university town in 1500, whether it was part of a country engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, its distance to the nearest Roman road, and its distance to the ocean. Five geographic control variables control for the city's altitude, its soil suitability for wheat cultivation, its soil suitability for potato cultivation, ruggedness and precipitation. All control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

ture on health I estimate equation A.5 where crisis mortality in season j, parish p and year t is regressed on temperature in season j, parish p and year t. Parish FE_{p} is a full set of parish fixed effects and county by year fixed effects are a full set of county by year fixed effects. δX_{pt} are the full set of control variables for parish p interacted with year fixed effects. $County_c \times YearFE_t$ are a full set of county by year fixed effects. The equation is estimated separately for each season, hence each one estimates the effect of seasonal temperature on mortality in the same season: I regress 1) winter mortality on winter temperature (column 1 in Table A.4), 2) spring mortality on spring temperature (column 4), 3) summer mortality on summer temperature (column 7), and 4) fall mortality on fall temperature (column 10).

$$
\begin{aligned}
(5) \qquad & Crisis\ Mortality^{j}_{pt} = \\
+ \qquad & \gamma Temperature^{j}_{pt} \\
+ \quad & Parish\ FE_p + County_c\ \times\ Year\ FE_t + \delta X_{pt} + \epsilon_{pt}
\end{aligned}
$$

Results do not show a relationship between temperature and mortality in any season, indicating that temperature's effect on mortality operated mainly through its effect on agricultural production rather than through its direct effect on health. These results are estimated for English parishes, where temperatures, for example during winter, are more moderate than in other European countries. Direct health effects of cold temperatures have been well-documented in many other settings (Gasparrini et al., 2015). The direct health effect of temperature on mortality is more important in countries with cooler winter temperatures.

A.6 Temperature changes and migration

A.7 Temperature and changes in wheat prices in the long-term

A.8 Correlation between Temperature Source Density with Characteristics of Economic Heterogeneity

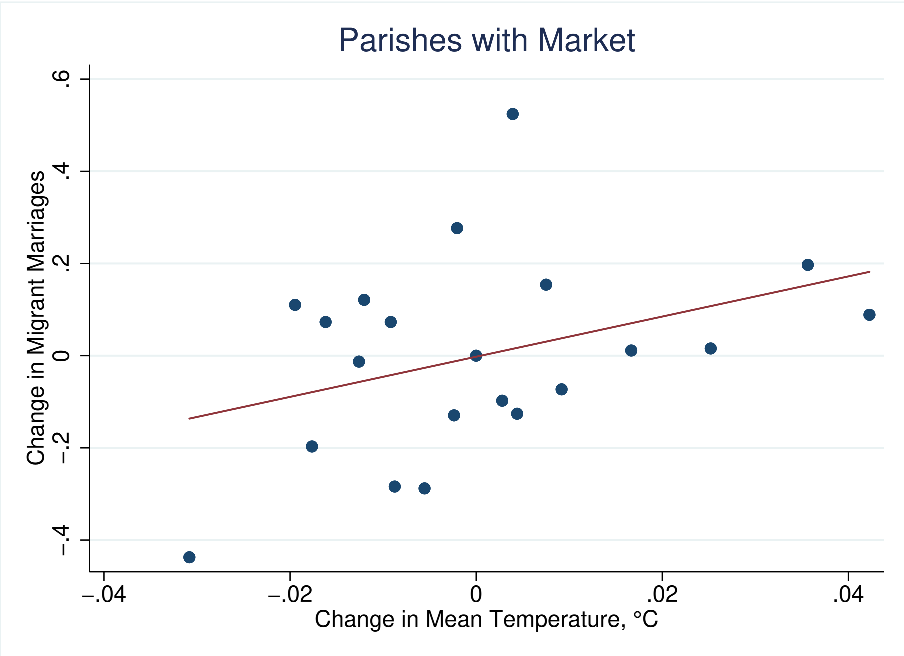
Table A.6 explores the concern that the smaller coefficients for trading cities might be due to the reconstructed temperature data which relies on 102 temperature sources. If

Table A.4: Temperature, Mortality and Health

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	Mortality Crisis											
VARIABLES	**In Winter**			**In Spring**			**In Summer**			**In Fall**		
Sample	**All**	**Far from Market**	**Close to Market**	**All**	**Far from Market**	**Close to Market**	**All**	**Far from Market**	**Close to Market**	**All**	**Far from Market**	**Close to Market**
Winter Temperature	0.003	0.008	-0.001									
	(0.009)	(0.011)	(0.013)									
Spring Temperature				0.013	-0.020	0.026						
				(0.012)	(0.015)	(0.020)						
Summer Temperature							-0.012	0.003	-0.038**			
							(0.012)	(0.015)	(0.018)			
Fall Temperature										0.001	0.010	-0.029
										(0.022)	(0.029)	(0.035)
Parish Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
County x Year Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Control Variables (×Time-Period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Observations	103,738	48,686	52,122	103,738	48,686	52,122	103,738	48,686	52,122	103,738	48,686	52,122
R-squared	0.153	0.229	0.209	0.145	0.235	0.195	0.155	0.234	0.211	0.175	0.244	0.229

Notes: Observations are at the parish-season level. Regressions in columns 1, 4, 7, and 10 use a sample of 404 English parishes with data for the years 1538 to 1840. In the remaining columns, the sample is split between parishes which are located less than four kilometers (columns 2, 5, 8, 11) and more than four kilometers (columns 3, 6, 9, 12) from the nearest market town. The dependent variable "Mortality Crisis" is an indicator variable that is one for parish i in season t if mortality in season t is more than 10 percent above a 25-year moving average of mortality in parish i. "Winter Temperature" is mean temperature over the the winter period (December, January, February). Temperatures in spring (March, April, May), summer (June, July, August), and fall (September, October, November) are defined accordingly. Standard errors are clustered at the parish level. Control variables include all control variables from the main specification (s. Table 2) that vary within England: distance to the nearest Roman road, distance to the ocean, altitude, soil suitability for wheat cultivation, soil suitability for potato cultivation, and ruggedness. All control variables are interacted with year indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

Figure A.6: Change in Temperature and Changes in the Share of Migrant Marriages



Notes: The figure displays the relationship between changes in the share of migrant marriages and changes in mean temperature over 50-year periods between 1584 and 1809. The specification includes time-period fixed effects but not parish fixed effects. Thereby, it estimates whether parishes with relatively higher (or lower) temperature change attracted more (or fewer) migrants in a given time period. Control variables include all control variables from the main specification (s. Table 2) that vary within England: distance to the nearest Roman road, distance to the ocean, altitude, soil suitability for wheat cultivation, soil suitability for potato cultivation, and ruggedness. All control variables are interacted with time-period indicator variables.

Table A.5: Long-term Temperature Changes and Wheat Prices

	(1)	(2)	(3)	(4)
VARIABLES		**Ln Wheat Price**		
Mean Temperature	-0.327	-0.0577		
	(0.290)	(0.210)		
Growing-Season Temperature in Year t			-0.372*	-0.347*
			(0.214)	(0.191)
Non-Growing-Season Temperature in Year t			-0.00678	0.224
			(0.298)	(0.208)
City Fixed Effects	yes	yes	yes	yes
50-Year-Period Fixed Effects	yes	yes	yes	yes
Control Variables (× Time-Period Fixed Effects)		*yes*		*yes*
Observations	66	66	66	66
R-Squared	0.862	0.875	0.863	0.878
Number of bootstrap units	10	10	10	10
Number of repetitions	999	999	999	999

Notes: The results are at the city-50-year-period level. The outcome variable wheat prices is the natural log of wheat prices averaged over 50-year periods between 1550 and 1850. "Mean Temperature" is temperature averaged over 50-year periods. Growing-Season temperature is temperature from March to August averaged over 50-year periods. Non-growing-season temperature is temperature from September to February averaged over 50-year periods. Wheat price data are available for Amsterdam, Antwerp, Leipzig, London, Madrid, Munich, Naples, Florence, Paris, and Strasbourg. Bootstrapped standard errors are clustered at the city level. The control variable "Access to Ocean" is an indicator variable which is one for all cities located less than 10 kilometers from the ocean. The control variable "Atlantic Trader" is an indicator variable which is one for all locations in countries engaging in Atlantic trade. These control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for p<0.01, ** for p<0.05, and * for p<0.1.

Table A.6: Correlation between Temperature Source Density with Characteristics of Economic Heterogeneity

	50 km	**100 km**	**200 km**	**300 km**
	(1)	(2)	(3)	(3)
City Participating in Sound Toll Trade	0.0909	0.211**	0.330*	0.149
	(0.0606)	(0.0873)	(0.169)	(0.311)
Control Variables				
Historical Controls	yes	yes	yes	yes
Geographic Controls	yes	yes	yes	yes
Observations	2,120	2,120	2,120	2,120
R-Squared	0.100	0.170	0.319	0.335

Notes: This Table estimates the correlation between the indicator variable "City participating in Sound Toll trade" and the number of temperature sources within a certain radius. "Number of temperature sources within..." is obtained from tables S1 and S2 of "Supporting Online Material: European seasonal and annual temperature variability, trends, and extremes since 1500" (Luterbacher et al., 2004). Observations are at the city level. Historical controls include information on a city's religious denomination in 1600 (see Table 2 for detail), whether it was a university town in 1500, whether it was part of a country engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, its distance to the nearest Roman road, and its distance to the ocean. Five geographic control variables control for the city's altitude, its soil suitability for wheat cultivation, its soil suitability for potato cultivation, ruggedness and precipitation. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

trading cities were located further away from temperature sources, then temperature data for these cities would have been reconstructed based on fewer temperature sources. As a result, measurement error in the temperature data would be higher for these cities compared to the rest of the sample. This would bias results downwards explaining the smaller coefficients. Table A.6 explores the correlation between temperature source density and cities participated in Sound Toll Trade. It shows that being a city participating in Sound Toll trade is positively correlated with measures of temperature source density. Hence, there is no concern that density of temperature sources explains the smaller temperature effects for trading cities.

A.9 The Effect of Temperature on Plague and War

In this section, I examine the relationship between temperature changes and two variables, plague and war and whether this relationship may contribute to our understanding of the relationship between temperature and city size. Plague outbreaks and wars have had very large human costs at multiple times during the study period. The plague outbreak of 1665/1666 in London killed around 100,000 people or one quarter of the city's population. Vienna was hit by plague in 1679 and lost around 76,000 inhabitants until the early 1680s. The 30 Years' War alone decimated the population of the German lands by more than a third.

If the cooler temperatures of the Little Ice Age affected the outbreak or severity of plague then a negative effect of lower temperature on city size could be in part explained by temperature's effect on plague. The historical evidence on the relationship is ambiguous. On the one hand, there are cases where years of harvest failure have been followed by plague outbreaks. On the other hand, fleas, the main vector of the disease from rats to humans, thrive in warm and humid conditions and stop reproducing below a certain temperature threshold. As a result, plague mortality in typically peaked in the summer[...] the lowest rate of spread occurred between January and April," (Campbell, 2017: 289). In this case, cooler temperatures should have had a dampening effect on plague outbreaks.

A growing literature describes a link between adverse temperatures depressing economic production and conflict. Since the cooler temperature of the Little Ice Age depressed agricultural productivity they could have contributed to warfare and thereby had a negative effect on city population. First, I examine whether temperature changes have had a direct effect on plague and war and whether temperature's effect on city size may have operated through its effect on plague and war by estimating the specification below.

$$(7) \qquad Plague/War_{it} = \beta + \gamma Mean\ Temperature_{it} + City\ FE_i + Time\ FE_t + X_{it} + \epsilon_{it}$$

The variable Plague is measured as the number of years in which a town or country were affected by plague. The information is taken from Kohn (2007) which provides a list of plague years and the town or country affected covering the whole study period. To obtain a measure of the prevalence of war I collect data on major battles between 1500 and 1850 from Clodfelter (2002). The author compiles information on all wars taking place over the entire study period and area. To obtain a measure of how much a city has been affected by war I measure the distance between each city and the closest battle over the past time period. Clodfelter (2002) lists all major battles separately.

To examine whether plague and war are possible mechanisms through which temperature's effect on city size operated, I test whether temperature changes have had a direct effect on plague and war. Results in columns 1 and 2 of Table A.7 show insignificant relationships between mean temperature and each outcome variable. The signs of the coefficients are opposite to the one that one would expect if plague and war had been mechanisms transmitting the effect of temperature on city size. Warmer - not cooler - temperatures are associated with more plague years and smaller distance to the nearest battle.

Because of the importance of both plague and war in the Early Modern period it seems necessary to also examine whether these variables could be biasing results in the main specification. Columns 3 and 4 of Table A.7 show results when including Distance to the nearest battle and plague years as control variables. In both cases, the main coefficients on mean temperature increases slightly. The coefficient on plague comes out negative and significant indicating that an additional plague year had a negative effect on city size. The coefficient on Distance to the nearest battle comes out insignificant and negative. Even though the relationship is not significant it indicates that on average cities closer to battles were growing more than cities further away from battles. This could be reflecting a mechanism of urban growth documented by Dincecco and Onorato (2016). The paper shows evidence that cities have grown in the face of battles because the population of the surrounding area would flee to the city for protection thereby leading to city growth.

A.10 Temperature and trade value

A.11 Temperature and changes in land use

Table A.7: Plague and War as Dependent and Control Variables

	(1)	(2)	(3)	(4)
	Dependent Variable =		Dependent Variable =	
	Plague	Distance to	Ln City Size	Ln City Size
VARIABLES		Nearest Battle		
Mean Temperature	2.628	-0.217	0.716***	0.695***
	(1.744)	(0.578)	(0.210)	(0.210)
Plague			-0.007***	
			(0.001)	
Distance to Nearest Battle				-0.005
				(0.006)
Control Variables				
City Fixed Effects	yes	yes	yes	yes
Time-Period Fixed Effects	yes	yes	yes	yes
Historical Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes
Geographic Controls (× Time-Period Fixed Effects)	yes	yes	yes	yes
Observations	10,600	10,600	10,600	10,600
R-squared	0.701	0.812	0.770	0.768

Notes: Observations are at the city-year level. All regressions use a baseline sample of 2,120 cities. The time periods are 1600, 1700, 1750, 1800, and 1850. The dependent variable is the natural log of number of city inhabitants. "Mean temperature" is year temperature averaged over the periods 1500 to 1600, 1600 to 1700, 1700 to 1750, 1750 to 1800, and 1800 to 1850. The variable "Plague" is the number of plague years over the past time period. "Distance to Nearest Battle" is a city's distance to the closest battle taking place during the past time period. Standard errors are clustered at the temperature grid level of the underlying temperature data. All specifications include city and time-period fixed effects, historical and geographic control variables. Historical controls include information on a city's religious denomination in 1600 (see Table 2 for more detail), whether it was a university town in 1500, whether it was part of a country engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, its distance to the nearest Roman road, and its distance to the ocean. Five geographic control variables control for the city's altitude, its soil suitability for wheat cultivation, its soil suitability for potato cultivation, ruggedness and precipitation. All control variables are interacted with time-period indicator variables. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$

Table A.8: Temperature and Trade (Cargo Tax Value)

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				Ln Cargo Tax Value				
Growing-Season Temperature	-0.212				-0.405			
in t-1 to t-5	(0.139)				(0.295)			
Non-Growing-Season Temperature	0.0780				0.286			
in t-1 to t-5	(0.0881)				(0.192)			
Growing-Season Temperature		-1.241**				-3.000***		
in t-1 to t-25		(0.498)				(1.015)		
Non-Growing-Season Temperature		-0.0855				0.735		
in t-1 to t-25		(0.330)				(0.723)		
Growing-Season Temperature			-2.182***				-4.566***	
in t-1 to t-50			(0.752)				(1.490)	
Non-Growing-Season Temperature			-0.534				0.602	
in t-1 to t-50			(0.499)				(1.024)	
Growing-Season Temperature				-3.436**				-9.240***
in t-1 to t-100				(1.367)				(2.557)
Non-Growing-Season Temperature				-1.206				-0.532
in t-1 to t-100				(1.013)				(2.118)
Destination Port Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes
Distance to other cities	yes	yes	yes	yes	yes	yes	yes	yes
City size					yes	yes	yes	yes
Control Variables (×50 year period Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes
Observations	202,920	202,920	202,920	202,920	58,740	58,740	58,740	58,740
R-squared	0.260	0.261	0.261	0.261	0.426	0.427	0.428	0.428
Number of destination ports	760	760	760	760	220	220	220	220

Notes: Observations are at the destination port-year level with data for 758 destination ports and the years 1591 to 1857. The dependent variable is the natural log of the total tax that all ships heading for destination port i in year t paid at the Sound Toll. "Agricultural-Year Mean Temperature" in year t is the mean temperature over the agricultural year starting with the beginning of the non-growing season in fall t-1 and ending with the end of the growing season in summer of year t. All specifications include destination-port fixed effects, year fixed effects, and geographic and historical control variables (s. Table 2 for more details) interacted with decade fixed effects. Standard errors are clustered at the level of the temperature grid cell of the underlying temperature data. Significance levels are indicated as *** for $p<0.01$, ** for $p<0.05$, and * for $p<0.1$.

Table A.9: Growing-Season Temperature and Land Use

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	**Ln Total Pasture**				**ln Total Cropland**				**Ratio Pasture To Cropland**			
Growing-Season Temperature	0.135				0.157**				2.815			
Years t-1 to t-10	(0.101)				(0.0766)				(2.606)			
Non-Growing-Season Temperature	-0.0993				-0.142*				0.134			
Years t-1 to t-10	(0.0923)				(0.0769)				(1.711)			
Growing-Season Temperature		0.219				0.240**				4.469		
Years t-1 to t-25		(0.148)				(0.112)				(3.984)		
Non-Growing-Season Temperature		-0.129				-0.215				1.057		
Years t-1 to t-25		(0.188)				(0.159)				(3.261)		
Growing-Season Temperature			0.513**				0.517***				9.017	
Years t-1 to t-50			(0.233)				(0.180)				(7.632)	
			0.00908									
Non-Growing-Season Temperature			(0.176)				-0.0858				4.836	
Years t-1 to t-50							(0.147)				(5.879)	
Growing-Season Temperature				0.740				0.774**				8.614
Years t-1 to t-100				(0.441)				(0.328)				(7.517)
Non-Growing-Season Temperature				1.661**				1.361***				39.39
Years t-1 to t-100				(0.628)				(0.366)				(35.58)
Country Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Control Variables (×Decade Fixed Effects)	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Observations	570	570	570	570	570	570	570	570	570	570	570	570
R-squared	0.994	0.994	0.994	0.995	0.997	0.997	0.997	0.998	0.939	0.939	0.940	0.943

Notes: Observations are at the country-decade level. The sample contains data for 48 European countries (treated as constant over time in the boundaries of 2012) for every 10 years beween 1500 and 1850. The dependent variables are the natural log of the area of pasture, the natural log of the area of cropland, and the ratio of the area dedicated to pasture to the area dedicated to cropland. "Growing-Season Temperature" is temperature during spring and summer of year t. "Non-Growing-Season Temperature" is temperature during fall of year t-1 and winter of year t. Standard errors are clustered at the country level. All specifications include country fixed effects, year fixed effects, and historical and geographic control variables as in the main specification. Historical controls include information on a country's religious denomination in 1600 (s. Table 2 for detail), whether a country had a university town in 1500, whether it was engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, and its distance to the ocean. Five geographic control variables control for the country's mean altitude, its mean soil suitability for wheat cultivation, its mean soil suitability for potato cultivation, and mean ruggedness. All control variables are interacted with decade indicator variables. Standard errors are clustered at the country level. Significance levels are indicated as *** for p<0.01, ** for p<0.05, and * for p<0.1.