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The Economic Effects of Long-Term Climate Change:

Evidence from the Little Ice Age

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Abstract

Recent studies have consistently found important economic effects of year-to-year weather fluctuations. This paper studies the economic effects of long-term and gradual climate change, over a period of 250 years, when people have time to adapt. In particular, I study the effects of the Little Ice Age, a historical episode of long-term climate change. Results show significant negative economic effects of long-term climate change. Cities with good access to trade were substantially less affected. Results from yearly historical wheat prices and yield ratios show that temperature change impacted economic growth through its effect on agricultural productivity. Further evidence shows a lack of adaptation. I show evidence of the relevance of these results to the context of contemporary developing countries and recommend ways in which these findings may improve Integrated Assessment Models.

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

1 Introduction

The reality of human-induced climate change and the urgency to respond have become increasingly clear among researchers, policymakers and the wider population.[1] Producing reliable estimates of the economic effects of climate change is one of the central, while also most challenging tasks in the quest for tackling climate change. Empirical evidence, however, is scarce.

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[1] Nobel price laureates at the 2015 reunion of Nobel prize winners at the Bodensee 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 by 32 percent from 2005 levels by 2030. A Yale/Gallup/Clearvision Poll found a significant increase in the numbers of Americans aware of climate change impacts between 2004 and 2014. More than two-thirds of respondents (69 percent) said they believed that global warming is mainly or partly caused by human activities (Ming Lee et al., 2015). Another survey has found that 90 percent of Europeans think climate change is a serious problem (European Commission, 2014: 5).

A prominent approach to estimating economic impacts of climate change scenarios is the Integrated Assessment Model (IAM).[2] IAMs 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 et al., 2012: 92; Pindyck, 2013: 862). Indeed, many elements of the climate-economy relationship remain little understood. Recently, Deschenes et al. (2007, 2012), Dell et al. (2012), Burgess et al. (2014), and Barreca et al. (2015a, 2015b) 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. Now, the question arises whether similar effects also result from long-term temperature changes, even when people have time to adapt, or whether countries mitigate short-run effects through adaptation (Dell et al., 2012: 68). In this paper, I study a historical episode of climate change, the Little Ice Age, to examine the economic effects of long-term temperature change over a period of 250 years, when people have time to adapt.

The Little Ice Age brought significantly colder climate to large parts of Europe. It is the most recent climatic episode preceding the current human-induced period of climate change, and it represents the largest temperature change since the beginning of recorded history (Aguado et al., 2007: 483). Historical evidence suggests that lower temperatures shortened growing seasons and decreased agricultural productivity. The Little Ice Age had a considerable effect on living conditions throughout Europe (Baten, 2002; Pfister et al., 2006; Behringer, 1999, 2010; Oster, 2004).

To estimate the economic effects of the Little Ice Age, I construct a panel data set for 2120 European cities. These data measure annual temperatures between 1500 and 1750, and city size for several points in time. The temperature data for each city come from temperature reconstructions that were undertaken by climatologists (Luterbacher et al., 2004a). As a proxy for economic growth, I use data on historical city sizes from Bairoch (1988).[3] The data's panel structure allows me to include city fixed effects and year fixed effects in all specifications.

The main results indicate a significant negative effect of Little Ice Age temperatures on city size. This finding is consistent with historical evidence on the negative economic effects of Little Ice Age temperatures. I also show that results are robust to a number of specification checks. If temperature changes were correlated with other variables that affect city size, estimation results would be biased. To address this concern, I control for a host of relevant geographic and historical control variables that have impacted urban growth in Early Modern Europe.[4] Each variable is

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

[3] City size has been used in other papers examining historical economic outcomes, e.g. De Long and Shleifer (1993), and Stasavage (2012). Sutton et al. (2007) use current total urban population as a proxy for national GDP. Nunn et al. (2011) use total population at the country level as a proxy for income per capita. I also show effects on country-level urbanization rates, an alternative proxy for economic growth. Urbanization rates have been used previously as a proxy for economic prosperity, e.g. Acemoglu, Johnson and Robinson (2002), Acemoglu, Johnson and Robinson (2005) and Nunn et al. (2011). Acemoglu, Johnson and Robinson (2005) document the strong correlation between urbanization and per capita income.

[4] 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).

interacted with a full set of time indicator variables to allow for flexible effects over time. I control for soil suitability for potato and wheat cultivation (Nunn et al., 2011) as well as for elevation and ruggedness (Beniston et al., 1997; Nunn et al., 2012). I also control for a number of historical determinants of city size in Early Modern Europe that have received particular attention in the literature: being part of an Atlantic trading nation (Acemoglu, Johnson, and Robinson, 2005); being majority Protestant in 1600 (Becker and Woessmann, 2009); having a history of Roman rule and access to Roman roads (Jones, 2003; Landes, 1999); the presence of a university (Cantoni et al,. 2014); distance to battlegrounds (Dincecco et al. 2015); and distance to the coast. Finally, I show that results are robust to using Conley (1999) standard errors that assume spatial autocorrelation between observations, to including country-specific and city-specific time trends, country-times-year fixed effects, and to the use of alternative city samples. I also show that density of historical temperature sources does not affect estimation results.

In further results, I investigate the effect of temperature on agricultural productivity as a channel through which temperature might have affected the economy of Early Modern Europe. In particular, I estimate the effect of temperature on yield ratios and on historical wheat prices.[5] Results indicate that colder temperatures during the Little Ice Age decreased yield ratios, that less grain was harvested per grain sown. Next, I estimate temperature's effect on European wheat prices as an alternative measure for agricultural productivity. I combine yearly temperature data with yearly wheat prices for 10 European cities for the years 1500 to 1750 (Allen, 2003). Because city-level demand changes only gradually, yearly fluctuations in wheat prices offer a plausible reflection of changes in supply. Results indicate that decreasing temperatures led to increases in wheat prices.

Another important concern in the climate-change debate is identifying characteristics that affect an economy's ability to adapt to climate change. I therefore examine heterogeneity in the economic effects of temperature changes. My results show that cities with good access to trade (in particular cities with access to an ocean or river, cities that were part of a long-distance trade network, and cities that were relatively large at the beginning of the study period) are significantly less affected by temperature changes.[6]

My results indicate that some economies were not able to sufficiently adapt their activities to fully compensate for the adverse effects of temperature change. The question arises whether adaptation was merely insufficient or altogether absent. In a final step of the analysis, I examine the relationship between severity of the Little Ice Age and timing of potato adoption in Early Modern Europe. Potato adoption was an effective way to adapt to the climatic conditions of the Little Ice Age. Unlike grain, potatoes thrive in cold and wet conditions and resist storm and hail (Deppe, 2010: 34). There is, however, no evidence of adaptation through potato adoption.

I then discuss the relevance of these results for understanding the impact of today's climate change. I show that today's developing world shares important characteristics with Early Modern Europe. For example, commonalities include the importance of the agricultural sector,

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

[6] This is also consistent with Dell et al. (2012)'s finding that climate change affects poor countries, but not rich countries.

non-participatory political institutions, and low levels of human capital. Finally, I recommend that Integrated Assessment Models could be improved by revising overly optimistic assumptions on adaptation. Evidence on strong heterogeneity in the economic effect of climate change underlines the importance that IAMs should be built on evidence from both developed and developing countries.

This paper contributes to research examining the economic effects of climate change and adaptation to climate change. Deschenes et al. (2007, 2012), Dell et al. (2012), and Burgess et al. (2014) find negative effects of year-to-year changes in temperature on economic and non-economic outcomes. This paper is also related to the strand of literature on adaptation to climate change. Studies find evidence of slow adaptation to climate change in U.S. agriculture (Burke and Emerick, 2015), slow uptake of air-conditioning in cold U.S. states (Barreca et al. 2015a, 2015b), slow adoption of energy efficiency programs (Fowlie et al., 2015) and patterns of migration maladapted to increased flooding (Boustan et al., 2012). It is also related to research examining the role of climate for socioeconomic and geopolitical outcomes in the past, e.g. nutritional status (Baten, 2002), population size (Pfister et al., 2006), witch hunts (Behringer, 1999, Oster, 2004), persecution of the Jewish population (Anderson et al., 2013), and the outbreak of the European revolution of 1848 (Berger and Spoerer, 2001).

The remainder of the paper is organized as follows: Section 2 provides historical background on the Little Ice Age and on the relationship between climate, agricultural productivity and urban growth in Early Modern Europe. Section 3 describes the construction of the data set. Section 4 introduces the estimation strategy, presents main results and robustness checks. Section 5 examines the role of agricultural productivity as a channel through which temperature changes affected economic outcomes. Section 6 investigates economic heterogeneity in the effect of temperature on city size. Section 7 shows evidence on adaptation. Section 8 discusses the results' relevance for developing countries today and how Integrated Assessment Models can be improved. Section 9 concludes.

2 The Impact of the Little Ice Age

2.1 The Little Ice Age

The Little Ice Age was a climatic period from about 1350 to 1750 that brought colder climate to Europe.[7] It is the most recent period of climatic change prior to the current period of human-induced climate change. In Europe, average annual temperatures fell by about 0.5 to 1 degree Celsius[8]. Other world regions were also affected, e.g. China, Japan, India, and West Africa. Historical evidence suggests that climatic conditions of the Little Ice Age had economic, political, and social effects around the world (see e.g. Zhang et al., 2007; Fan, 2010, for China; Cronin, 2010: 298, Parker, 2013; Grove, 2004: 560). The Little Ice Age has been linked to increases in warfare and disease outbreaks during the 17th century (Parker, 2013). Decreases in

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[7] The Earth's climate regularly changes. Since the beginning of recorded history, climatic change has been documented, for example, for the period of the Roman Empire (McCormick et al., 2012), for the late Mayan civilization (750-900 CE; DeMenocal, 2001), and for Carolingian Europe (750-900 CE; McCormick et al. 2007).

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

agricultural productivity (Baten, 2002; Pfister et al. 2006); increases incidences of witch hunts (Oster, 2004); and more frequent political uprisings and state breakdowns (Parker, 2013) have been documented during this period.

There is debate among climatologists about the causes of the Little Ice Age, but different contributing factors have been identified, in particular decreases in energy emitted by the sun and increases in volcanic activity.[9]

2.2 Impact on agricultural productivity and city growth and economic growth

In European climate, temperature is the most important determinant of the duration of the yearly growing period (Olesen et al. 2002: 243). As temperatures fell, temperature levels needed for plant growth were reached later in the year. This shortened growing seasons and reduced agricultural productivity in Europe (Aguado et al., 2007: 483). In England, for example, growing periods were reduced by five weeks in the 17th century compared to the 13th century (Grove, 2004: 629).

Agricultural productivity changes may affect city size through their effect on income per capita (Nunn et al., 2011: 607). When agricultural productivity decreases, workers in the rural economy have less to sell, and they earn less. Less income is available to purchase manufacturing goods. Hence, both demand for manufactured goods, and prices for manufactured products decrease. Manufacturing activities were typically concentrated in cities in Early Modern Europe.[10] With decreases in income from agriculture reducing manufacturing employment, living in cities became less profitable, and fewer rural workers moved to cities in search of work (Voigtlaender and Voth, 2013: 781). In that “cities emerge once peasants’ productivity is large enough to provide above-subsistence consumption, such that agents also demand manufacturing goods," (Voigtlaender and Voth, 2013: 788), decreases in peasants’ productivity similarly reduces city growth. In addition, a shock to agricultural productivity affects the relative prices of agricultural and manufactured products. If labor is mobile, and if demand for agricultural produce is inelastic, the number of workers migrating from the rural to the urban economy may be affected.[11]

Agricultural productivity may also alter urban growth and urbanization through its effect on the urban death rate. Lower agricultural yields typically led to higher susceptibility to diseases in Early Modern Europe.[12] Due to higher population density, fatal infectious diseases can spread

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[9] Among the causes of the Little Ice Age were low levels solar energy and high volcanic activity. Low levels of solar energy were caused by reduced number of sun spots during the period. Sun spots are dark spots on the surface of the sun caused by magnetic fields. The energy levels in the areas surrounding sun spots are especially high (Eddy, 1976: 1189). Volcanic eruptions were especially frequent during the Little Ice Age. They can cool the surface of the earth by sending large quantities of sulfate gases into the atmosphere. These scatter solar radiation back to space (Cronin 2010: 305f.).

[10] The most prominent manufacturing regions in Early Modern Europe were located in England, the Netherlands, and Belgium, but manufacturing was at the heart of urban economies all over Europe. In certain regions, such as some areas of England, even small towns and villages offered work in manufacturing ("proto-industrialization", Allen 2003).

[11] Labor mobility was high within most parts of Europe (de Vries, 1976: 157). In certain parts of Eastern Europe, serfdom restricted labor mobility (Nafziger, 2012). Empirical findings on the price elasticity of food show that demand for agricultural produce is inelastic (Andreyeva et al. 2010).

[12] Galloway (1985) shows that temperature changes - through their effect on food prices - affect death from

readily, and, thus, they represent a bigger threat in cities than in rural areas. “Infectious [...] diseases generally thrive in towns, where people live at relatively high densities and interact at comparatively high rates." (Dyson, 2011: 39). As a result, increased prevalence of infectious diseases will especially affect the urban population more than the rural population.

3 Data

The main data set for this paper is a balanced panel of 2120 European cities. Its two key components are data on annual mean temperature for Europe for each year since 1500 from Luterbacher et al. (2004a) and data on city size in 1600, 1700, and 1750 from Bairoch (1988).

I use the size of European cities as a proxy for economic growth. The data include 2191 European cities that had more than 5000 inhabitants at least once between 800 and 1850.[13] During the period under study, city size is available in 1500, 1600, 1700 and 1750. Of 2191 cities, I drop cities for which teperature data is not available: nine cities are located outside of Europe and 62 cities are located east of 40°E longitude. The final data set includes 2120 cities.

The temperature data are reconstructed temperatures taken from Luterbacher et al. (2004a).[14] 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 km or about 30 by 30 miles. The temperatures in this data set have been reconstructed based on temperature proxies (tree ring series, ice cores), historical records, and directly measured temperature for later years (Luterbacher et al., 2004a: 1500).

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

$$\begin{array}{ll} \text{If } t = 1600 \text{ and } t = 1700\text{:} & MeanTemperature_{it} = \Sigma_{n=1}^{100} Temperature_{it-n} \\ \text{If } t = 1750 & MeanTemperature_{it} = \Sigma_{n=1}^{50} Temperature_{it-n} \end{array}$$

Figure 1 to 4 (see below) show city-level temperature changes for four European cities: Moscow, Berlin, Paris and Lisbon. The figures illustrate that temperature changes during this period varied across cities. Temperature between the warmest and the coldest period changes

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diseases in London in the 17th and 18th centuries. “[...] few persons actually died of starvation during poor harvest years. The increase in deaths was rather a function of the increased susceptibility of the body to various diseases as a result of malnourishment" (Galloway, 1985: 488).

[13] I use a version of the data set by Voigtländer and Voth (2013). They use linear interpolation to fill missing values for time periods between non-zero values. Furthermore, Bairoch records city size of cities below 1000 inhabitants as having 0 inhabitants. When using natural log of city size as outcome variable, I assume that cities below 1000 inhabitants have 500 inhabitants. This is a realistic assumption as the large majority of European cities were founded in anitquity, in the High Middle Ages, or Late Middle Ages. I show in Table 14 that alternative specifications with cities below 1000 inhabitants assumed to have 1 inhabitant or when using absolute numbers of inhabitants instead of log of city size yield similar results.

[14] Temperature changes during the Little Ice Age were first measured through historical variation in glacial advances in European mountain areas. Later, data from ocean sediments, ice-cores and continental climate proxies also provided evidence for temperature changes during the Little Ice Age (Grove 2004: 560). To reconstruct past temperatures, the relationship between measures of climate proxies and actual temperatures is estimated for the recent past for which instrumental temperature data are available. Based on this relationship, measures of climate proxies are used to reconstruct earlier temperatures. Finally, for locations without climate proxies temperatures are interpolated based on a climate model describing the European climate system.

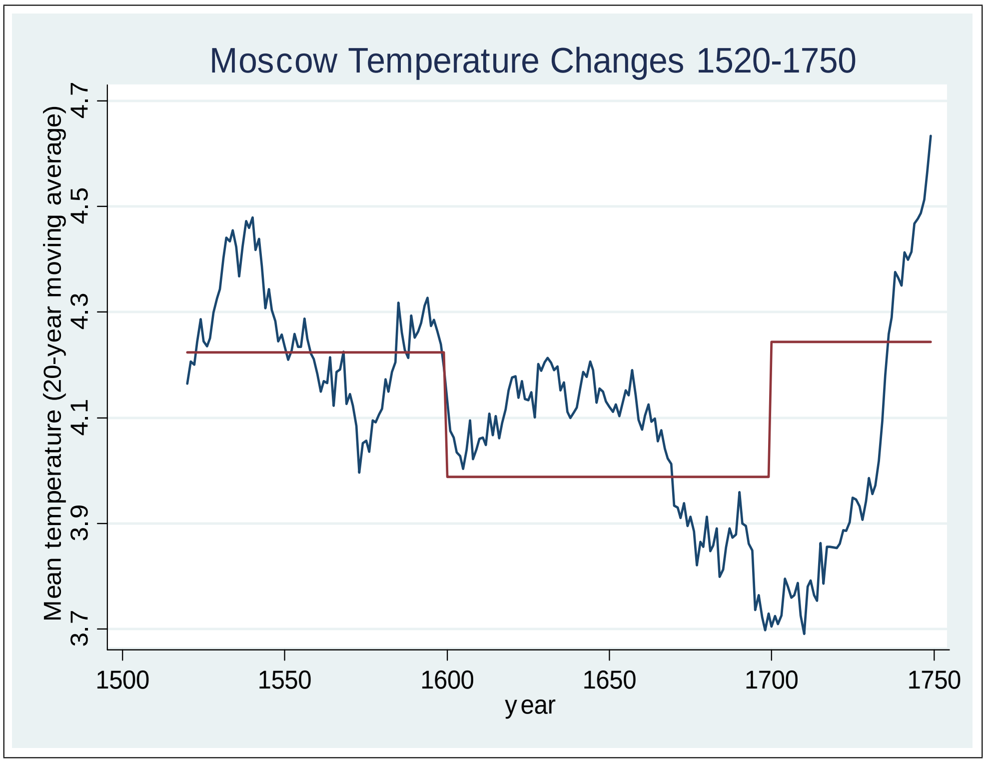

Figure 1: The graph plots yearly temperatures (20 years moving averages) for Moscow and the corresponding computed long-term averages (straight lines).

by about 0.8 degree Celsius for Moscow, Berlin, and Paris, while the temperature change for Lisbon lies only around 0.25.

I construct a second panel data set to explore the relationship between temperature changes and agricultural productivity. For this purpose, I combine yearly temperature data from Luterbacher et al. (2004a) with yearly wheat prices for 10 European cities from Allen (2001). Wheat prices are available for Amsterdam, London, Leipzig, Antwerp, Paris, Strasbourg, Munich, Florence, Naples, and Madrid. Yearly prices are available for these cities over a period of 200 to 250 years starting around 1500, and depending on the city.

A third data set explores the relationship between temperature changes and yield ratios[15] from 1500 to 1750. Data on yield ratios for 12 European countries are collected from Slicher van Bath (1963). Slicher van Bath (1963) provide yield ratios for 493 European locations in 14 European countries. For each location, yield ratios are available only for certain years, in some cases only for a single year, in others for each year over several decades. Because of the sporadic nature of the available data, I aggregate the yield ratio information at the country and year level and combine them with yearly country-level mean temperatures.

In section 4.5, I introduce urbanization as an alternative indicator of economic growth. Urbanization is defined at the country level as the number of inhabitants living in cities divided by the country's total population. Data on city population from Bairoch (1988) is combined with

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[15] Yield ratios are the ratio of grains harvested to grains sown.

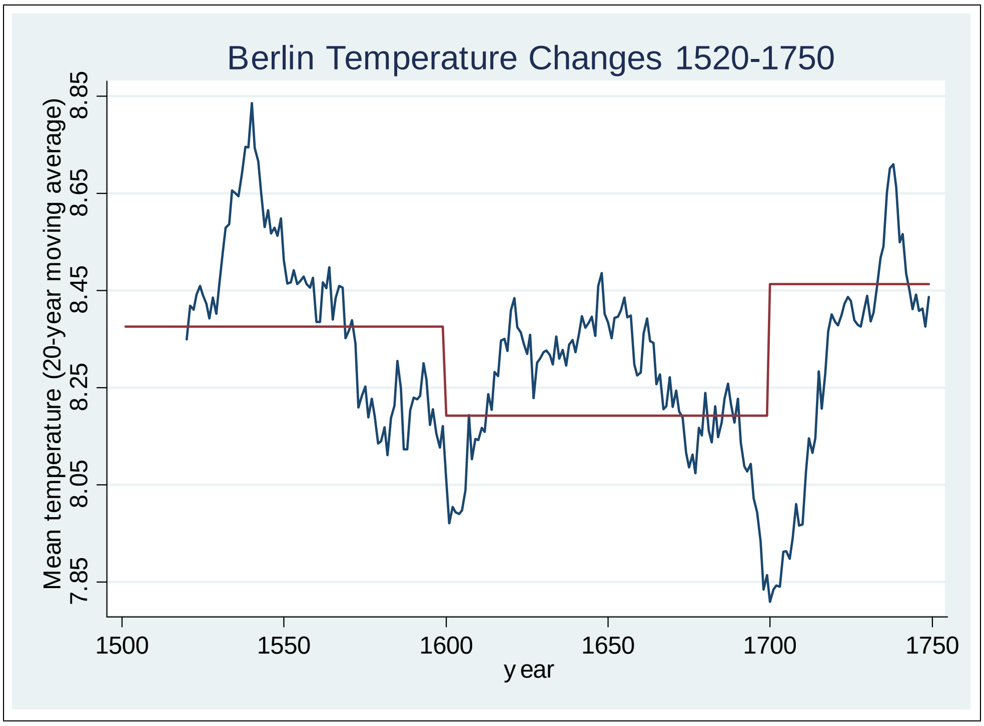

Figure 2: The graph plots yearly temperatures (20 years moving averages) for Berlin and the corresponding computed long-term averages (straight lines).

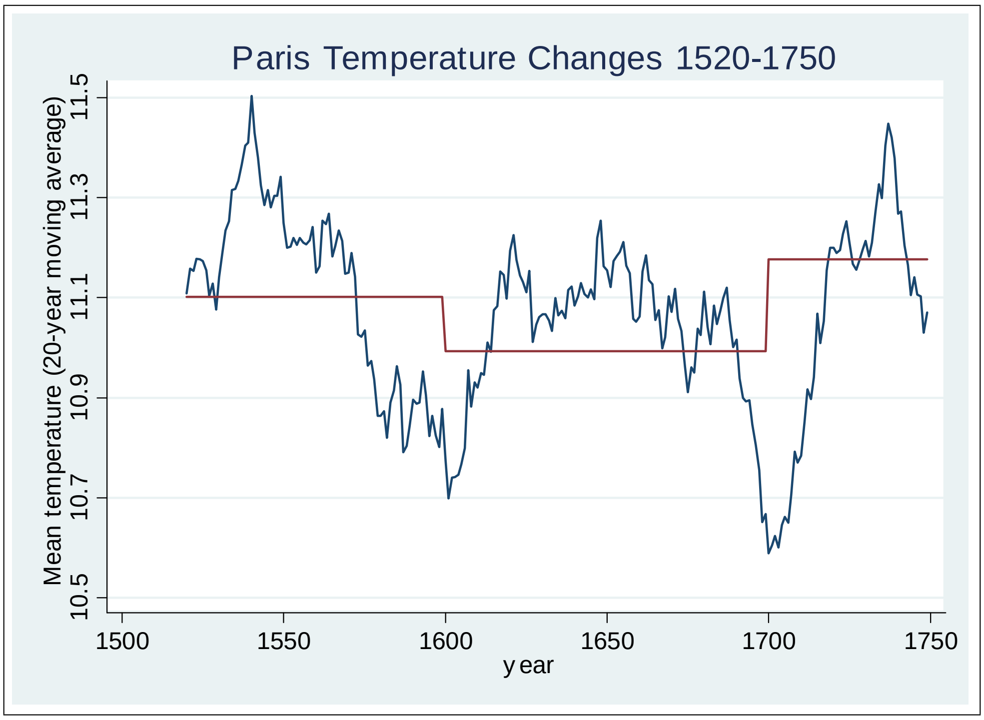

Figure 3: The graph plots yearly temperatures (20 years moving averages) for Paris and the corresponding computed long-term averages (straight lines).

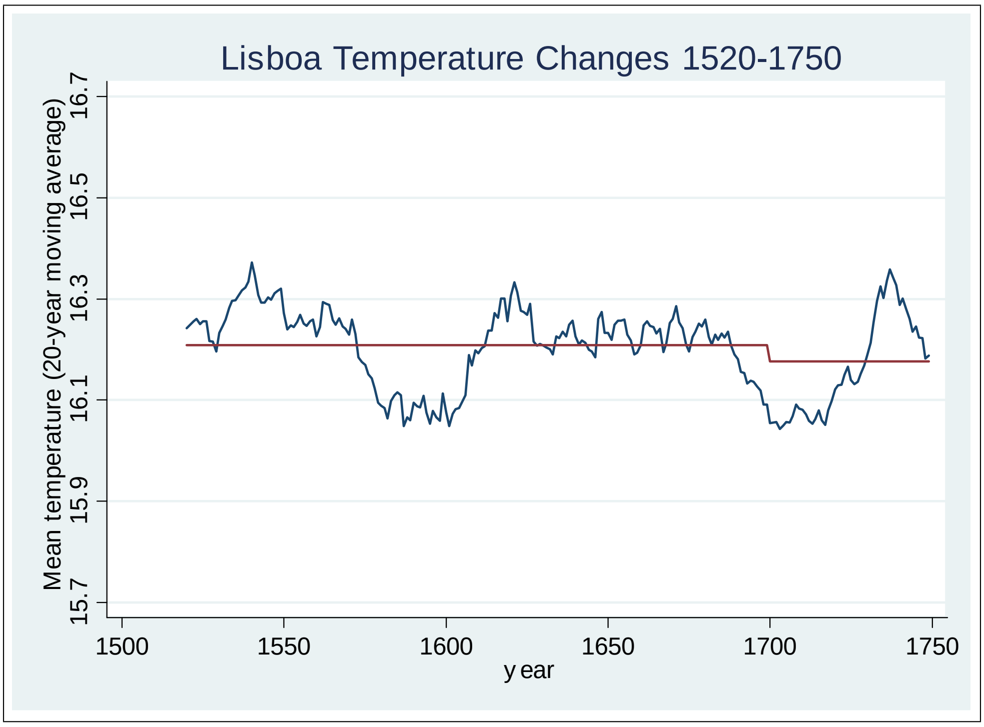

Figure 4: The graph plots yearly temperatures (20 years moving averages) for Lisbon and the corresponding computed long-term averages (straight lines).

data on total population from McEvedy and Jones (1978). Countries are defined as in McEvedy and Jones (1978).

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 (IIASA/FAO, 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 0, and information on the location of small and big rivers in pre-modern Europe are taken from NUssli (2012). Information on member cities of the Hanseatic League and on the spread of the Protestant Reformation in 1600 has been collected from Haywood (2000).

Finally, I construct a data set exploring barriers to climate change adaptation, in particular potato adoption. I obtain information on potato adoption from various sources (see Table 12). I combine country-level data on the year of potato adoption with data on the average potato suitability index, and a measure of institutional quality. Potato suitability data for European countries is taken from IIASA/FAO (2012). Information on institutional quality is taken from Stasavage (2012). The variable Representation measures how often a country's representative assembly met on average per year between 1250 and 1800. If a representative assembly did not exist during this time period the measure is 0. The highest value the measure can take is 1.

Summary statistics in Table 1 show main characteristics for all cities (column 1), those that experienced above average temperature decreases (column 2), and below average temperature decreases (column 3). Circa 80 percent of cities experienced temperature decreases during the 17th century. For the remaining cities average temperature change remained close to zero (<0.016 degree Celsius). The table indicates that cities that experienced below average temperature decreases were on average larger by about 800 inhabitants, and were located in regions with initially warmer climates. City growth, on the other hand, was higher in areas with higher decreases in temperature. Potato and wheat suitability was higher, and member cities of the Hanseatic League all experienced a relatively large fall in temperature. Geographic variables, on the other hand, indicate relatively long distance to the ocean, and there are relatively more Protestant denominations. If one found a positive effect of relatively large temperature decreases, one might be concerned that they are due to these initial and exogenous differences. The main results, however, indicate the opposite, that city growth was slowed down by relatively cold temperatures.

4 The Effect of Climate Change on Economic Outcomes

4.1 Empirical Strategy

I use the panel data set for 2120 European cities to test whether temperature changes during the Little Ice Age, between 1500 and 1750, affected city size. First, I examine the relationship between year temperature and city size, graphically including all cities of the sample and conditional on city and year fixed effects and geographic control variables. Figure 5 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 on average associated with decreases in city size. The graph must be interpreted with caution. As will be discussed later, other geographical or historical factors that may be correlated with temperature and city size could explain this relationship.

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

$$(1) \qquad LogCitySize_{it} = \beta + \gamma MeanTemperature_{it} + a_t + i_i + c_{it} + \epsilon_{it}$$

Log City Size is the natural logartihm of size of city i in time period t. $MeanTemperature_{it}$ is mean year temperature in city i, and time period t over the past 100 years (for the years 1600 and 1700) and past 50 years (for the year 1750, see also previous section for more detail). i_i are a full set of 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. a_t are a full set of year fixed effects that control for variation in temperature and in city size over time that is common to all cities in the data set. c_{it} are a number of control variables, each interacted with indicators for each

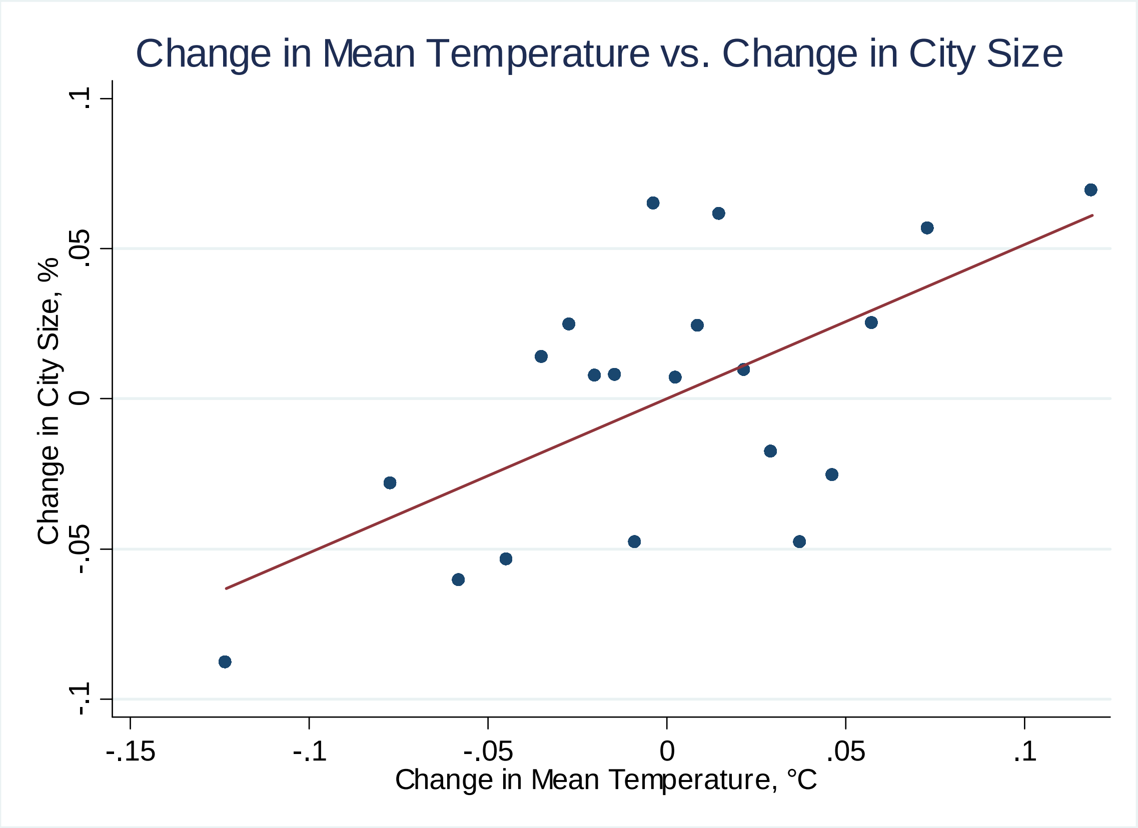

Figure 5: The figure displays a binned scatter plot corresponding to the estimates from column 6 of table 2. I residualize Log City Size and Mean Temperature with respect to city fixed effects, year fixed effects and geographic control variables using an OLS regression. I then divide the sample into 20 equally sized groups and plot the mean of the y-residuals against the mean of the x-residuals in each bin.

time period. They will be described in more detail when introduced into the equation. ϵ_{it} is the error term. Standard errors are clustered at the city level.

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.

4.2 Main Results

Table 2 shows baseline results. The table reports results for six different specifications. The first specification in column 1 estimates the effect of mean temperature on city size including city fixed effects and year fixed effects. The relationship is positive and significant at the 1 percent level. This indicates that temperature decreases during the Little Ice Age had a negative effect on city size, a finding that is consistent with historical evidence on the negative economic effects of the Little Ice Age.[16]

In columns 2 to 6, I include several geographic control variables that may have affected city size through their effects on agricultural productivity: altitude, soil suitability for potato cultivation, soil suitability for wheat cultivation, and terrain ruggedness. 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. If these variables were also correlated with temperature changes, omitting them may lead to bias. Each variable is interacted with time indicator variables for each time period to allow for time-varying effects of these variables. Results in Table 2 show that the point estimates remain stable with the introduction of these control variables.

The coefficient on *Mean Temperature* is the estimated effect of a one degree increase in *long-run* mean temperature on city size.[17] A one-standard-deviation decrease in temperature decreases city size by 7 percent.

4.3 Alternative Historical Determinants of Urban Growth

The previous estimates show a negative effect of temperature on city size during the Little Ice Age. This result is consistent with historical evidence on the negative effects of the Little Ice Age on economic conditions.

It is also well established that economic and urban growth has been highly uneven across Europe with especially high growth in Northwestern Europe. A number of factors have been held accountable for this "Little Divergence,"[18], for example the overseas trade expansion of the

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

[17] As can be seen from Figures 1a and 1b, even though the difference in temperature between the warmest and coldest period lies around 0.8 degree Celsius, e.g. in Berlin and Paris (see Figure 1), changes in long-term mean temperature are around 0.2 degrees Celsius.

[18] The term was coined in the context of Japan's relative growth compared to China during the Tokugawa Shogunate period (1600-1868). It was later applied to the surge of North Sea Area economies, first Holland in

Atlantic powers, human capital accumulation, the spread of Protestantism, warfare, and legacies of the Roman Empire. If temperature changes were correlated with these historical factors, the estimated effect of temperature and city size would be biased. In the following, I therefore control for historical factors that have been identified as drivers of urban growth within Early Modern Europe.

Becker and Woessmann (2009) show that Protestantism had a positive effect on human capital due to its emphasis on people's ability to read the Bible. Weber famously argued that Protestantism introduced a stricter work ethic, making Protestant countries better off. Besides, for most European rulers, choosing a Protestant denomination was a highly political act. Rulers distanced themselves from the influence of the Roman Catholic Church that rejected the newly developing ideas on scientific research (Merriman, 2010). Because Protestantism may have affected economic development and, hence, city growth in these various ways, I include indicator variables that are 1 if a city was majority Lutheran, Calvinist, Anglican, or Catholic in 1600.

Van Zanden (2009: 12) emphasizes the importance of human capital accumulation for economic growth in Early Modern Europe. In the same vein, Cantoni and Yuchtman (2014) show that the establishment of universities increased the number of people trained in law, a development that had a positive effect on economic activities in medieval Europe because it decreased the uncertainty of trade. I include an indicator variable for cities that were university cities in 1500.

Acemoglu, Johnson, and Robinson (2005) show that the overseas trade expansion of Western European countries had a positive effect on economic growth. I add an indicator variable for Atlantic traders, i.e. Great Britain, the Netherlands, Belgium, France, Spain, and Portugal.

Several studies identify war as an important factor in the development of Europe, e.g. through its effect on state-building (Tilly, 1990). Recently, Dincecco et al. (2015) argue that exposure to military conflict had a direct effect on urban growth because it induced people to seek protection from violence within city walls. I add a variable that measures the distance to the nearest battleground for each time period.

I also create an indicator variable that is 1 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 km of the coast.

Table 3 shows results. Column 1 of Table 3 shows the baseline estimates including the geographic control variables (identical to column 6 in Table 2). Columns 2 to 8 report estimates when including each historical determinant of city size separately. Column 9 reports estimates when including all alternative historical determinants. Results show that the coefficient on temperature remains stable across these different specifications. These results suggest that, while important in their own right, the alternative determinants of city growth do not drive the relationship between temperature and city size.

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the 16th and 17th centuries, later Britain during the Industrial Revolution (Broadberry, 2013: 6).

4.4 Robustness

4.4.1 Alternative Samples

An important concern remains the stark differences in urban growth within Early Modern Europe. If temperature decreases were especially small in areas of Europe with strong urban growth, then we might be concerned that the relationship we observe could be driven by differences in patterns of urban growth within Europe. In Table 4, I systematically exclude cities from the sample that historians have reported as especially fast growing, namely capital cities, cities located at the coast, and a group of cities that de Vries (1984) reports as having been especially fast growing in the Early Modern Period. Finally, I exclude all cities that were part of Atlantic traders, almost halving the sample. For all samples, the results remain robust.

4.4.2 Time Trends

Some of the historical factors discussed in section 4.3 were at the country level, reflecting the concern that country-level characteristics, such as institutions, could explain results. In this section, I explore this concern further, and test whether the estimated effect of mean temperature on city size is robust to the inclusion of country and city-level time trends and country-times-year fixed effects. Countries are defined as countries in 1600 according to Nussli (2012). 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 increases city growth rates over time. City-level linear time trends control for linear trends in city growth that are specific to a city, e.g. growth trends in port cities might have been especially affected by expansion of inter-Atlantic trade compared to other cities in the same country. The country-times-year fixed effects control for factors at the country level that change over time, and could affect the outcome variable, for example, a country's institutions. Characteristics that do not change over time are captured by the city fixed effects. Table 5 shows results for specifications including these different trends and fixed effects. Column 1 of Table 5 shows the baseline specification including city fixed effect and year fixed effects. In column 2, I introduce a linear time trend at the country level. In column 3, the country-level time trend is replaced by country-times-year fixed effects. Then, I add a city-level linear time trend. Estimates in Table 5 show a positive and important relationship between mean temperature and city size across all specifications, despite the fact that the additional fixed effects and time trends substantially reduce the degrees of freedom. The coefficient in column 4 including city fixed effects, country-times-year fixed effects, and city-level linear time trends is no longer significant, but similar in size to the previous estimations.

4.4.3 Using Conley Standard Errors Assuming Spatial Autocorrelation

Table 6 shows the baseline regression estimating different standard errors. Column 1 of Table 6 is the baseline specification with standard errors clustered at city level. Column 2 shows the same specification with standard errors clustered at the grid cell level of the underlying temperature data set. Each city is assigned temperature data of the grid cell in which the city is located. Different cities are assigned the same temperature data if they are located in the same grid cell. All cities whose temperature data have been informed by the same observation in the temperature reconstruction data set form a cluster. Column 3 shows the specification using Conley standard errors. Conley standard errors assume spatial autocorrelation for cities located within 100 km from each other. Spatial autocorrelation is assumed to decrease with distance between cities and complete independence is assumed for cities located further than 100 km apart. Finally, column 4 reports results when using two-way city and year clusters. Results are significant across these specifications.

4.4.4 Underlying Temperature Data Density

The temperature data by Luterbacher et al. (2004a) is reconstructed based on documentary historical evidence; on various climate proxies such as tree ring, ice core, coral data series; and instrumental temperature and pressure data for later years.[19] Each data source describes one location or region. For all other locations, temperature is interpolated based on temperature information of closest temperature data sources in combination with climate models for Europe. In comparison to original data, interpolated data might be subject to larger measurement error and bias results for cities located far from original temperature sources towards zero.

In Table 7, I investigate this concern econometrically. I define variables that count the number of original temperature sources within a given radius of each city, i.e. the number of original temperature sources located within 10, 20, 30, 40, 50, 100, 250, and 500 km of each city (for location of temperature sources, see Luterbacher et al. 2004b: 4).[20] In column 1 of Table 7, I estimate the main specification and include the entire sample. In column 2, I limit the sample to cities that are located within 500 km of at least one original data source. In column 3, I limit the sample to cities that are located within 250 km of at least one original data source. I do the same for 100, 50, 40, 30, 20, and 10 km in columns 4 to 9. Each time, I restrict the sample to cities that are located closer and closer to an original data source. Results show that coefficient sizes are largest for cities within relatively close distance to an original data source. They are smaller for cities within relatively large distance from an original data source. Variation in underlying temperature data density would therefore lead to underestimating the effect of temperature change for relatively less developed cities. Results in section 6 show larger effects for less developed cities compared to more advanced cities.

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[19] Documentary evidence include scientific writings, narratives, annals, and monastery records. These provide information, for example, on warm and cold spells, phenological phenomena, freezing of water bodies, droughts and floods, cloud movements, and wind direction. These data are calibrated against overlapping instrumental records for later years. Based on this relationship, documentary evidence prior to instrumental records are translated into quantitative climate data.

[20] The number of original temperature sources is positively correlated with variables explaining heterogeneity in the effect of climate change, such as whether a city is relatively large, close to a waterway, or was part of the long-distance trading network of the Hanseatic League. Again, if measurement error leads to attenuation bias this would bias coefficients towards zero for cities for which investigation of economic heterogeneity finds larger effects of temperature changes.

4.5 The Effect of Temperature on Urbanization

So far, city size has been used as an indicator of economic growth. In this section, I introduce urbanization as an alternative indicator of economic growth. This is a widely used measure of historical per capita GDP (DeLong and Shleifer, 1993; Acemoglu, Johnson, and Robinson, 2002, 2005). From a historical perspective, urbanization has been shown to have been strongly correlated with economic growth (Acemoglu, Johnson, and Robinson, 2002). To estimate the effect of mean temperature on urbanization I regress urbanization in country c in time period t on a country's mean temperature, year fixed effects, country fixed effects, and geographic and historical controls each of them interacted with time period indicator variables.

$$(2)\ Urbanization_{crt} = \beta + \gamma MeanTemperature_{crt} + a_t + c_c + gc_{ct} + hc_{ct} + \epsilon_{crt}$$

$Urbanization_{ct}$ is defined at the country level as the number of inhabitants living in cities divided by the country's total population. Data on city population from Bairoch (1988) is combined with data on total population from McEvedy and Jones (1978). Countries are defined as in McEvedy and Jones (1978). This measure of urbanization is available for 22 European countries and three time periods. The geographic and historical historical control variables, introduced in sections 4.2 and 4.3, are here defined at the country level: a country's average altitude, average potato suitability, and average wheat suitability. A country is assigned to the Roman Empire if at least part of it fell within the boundaries of the Roman Empire. A measure for Roman roads measures the length of Roman Roads within the boundaries of this country. The variable battle provides the number of battles that took place within its boundaries within each time period. The variable University provides a sum of the number of the universities located within a country's boundaries in a given time period. Dummy variables for each one of the Christian denominations (Catholic, Lutheran, Anglican, Calvinist) are 1 if at least part of the country's territory belonged in majority to one denomination in 1600.

Table 8 reports results. The first column includes only year fixed effects. Region fixed effects are included in column 2, region times year fixed effects in column 3, and country fixed effects in column 4.

Consistent with previous results, estimates show a robust and positive relationship between mean temperature and urbanization. With the introduction of controls the size of the coefficient on mean temperature increases. The last specification including country fixed effects is no longer statistically significant. This seems unsurprising given the sample size of 22 countries. As the estimates are based on within-country variation in temperature and urbanization, variation used for estimation is much reduced.

5 The Role of Agricultural Productivity

5.1 The Effect of Temperature on Yield Ratios

I now investigate potential channels through which the economic effects of the Little Ice Age may have operated. In particular, I test whether the Little Ice Age may have altered economic growth through its effect on agricultural productivity. In this section, I use historical yield ratios as measure of agricultural productivity. Yield ratio is defined as ratio of the amount of harvested crop grains to the amount of crop grains used for sowing. The data are taken from Slicher van Bath (1963). The author provides crop yields by year and city during the 16th, 17th, and 18th centuries for European countries. For each city, crop-yield data availability varies between one year and several hundred years. For certain years, information on crop yields is available from more than one city within one country. For other years, data are available from only one city or not at all. I aggregate the yield ratio data at the country and year level following Slicher van Bath (1963)'s classification of countries. For each year, I take the mean yield ratio of cities for which this information is available.

$$(3) \qquad YieldRatio_{ct} = \beta + \gamma MeanTemperature_{ct} + countryFE_c + c_i + \epsilon_{it}$$

Table 9 presents results. First, I estimate the effect of mean temperature on yield ratios including year fixed effects and country fixed effects. In columns 2 to 5, I add specific control variables that may have affected trade to clarify whether the estimated relationship could be explained by other variables, in particular the number of battles fought within one country during each year, whether a country has access to an ocean and whether it is an Atlantic Trader. The coefficient size is robust to the inclusion of these controls. As standard errors increase, the significance of the coefficient in the last specification lies at 10 percent.

5.2 The Effect of Temperature on Wheat Prices

In this section, 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) with yearly temperature data from Luterbacher et al. (2004a). 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 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. Because people typically reduce consumption when prices increase, the result may be seen as a lower bound estimate. I propose the following specifications to assess the effect of temperature on agricultural productivity:

$$(4) \qquad WheatPrice_{it} = \beta + \gamma MeanTemperature_{it} + i_i + c_i + \epsilon_{irt}$$

I regress the wheat price in city i and time period t on temperature in city i, and time period t. c denotes a number of additional control variables. I also include a full set of city fixed effects i. The coefficient on interest here is γ. It describes the relationship between changes in temperature and changes in wheat price in city i and time period t.

Table 10 reports results. Columns 1 to 5 contain estimates of the effect of temperature on wheat prices when including city fixed effects and year fixed effects. In columns 2 to 5 four additional control variables are introduced that may have affected wheat prices. I include reconstructed precipitation data. Then, I include a measure of the prevalence of warfare, the number of battles that were fought in a country in a given year. It is likely that wars in a country may have increased the costs of trading, which could have affected wheat prices. I also control for whether a country has access to the ocean and whether it is an Atlantic trader. These two variables are proxies for access to trade. Access to trade and lower transportation costs may have affected wheat prices. If these variables were also correlated with mean temperature, omitting them from the specification would bias results. The two variables, Access to Ocean and Atlantic Trader, are interacted with a full set of year fixed effects allowing for different effects at different points in time.

The coefficient on mean temperature in column 1 is negative and significant at the 1 percent level. This indicates that a one degree increase in temperature leads to an average decrease in wheat prices of 11 percent. A one standard deviation decrease in temperature of 0.6 degree Celsius would increase wheat prices by 6.6 percent. This indicates that decreases in temperature led on average to an increase in wheat yields and therefore to a decrease in prices. This result is consistent with the main results in Tables 2 and 3 showing that, overall, an increase in temperature had a positive effect on city size. This result is robust to the inclusion of the control variables described above (columns 2 to 5).

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

If temperature affects city size through its effect on agricultural productivity, we would expect cities that depend especially on agriculture to be more affected by temperature changes than cities whose economies are more advanced. De Vries (1976: 7f.) finds that grain-growing villages were more affected by harvest failure than places with more diverse economies. Burgess et al. (2014) find that short-term temperature shocks in India only affected rural, not urban, areas because the former depended on agriculture. Burgess and Donaldson (2010) show that trade openness mitigates the adverse effects of weather shocks. To test this hypothesis, I propose the specification below.

$$(5) \qquad CitySize_{it} = \beta + \gamma MeanTemperature_{it} + \theta MeanTemperature \times BigCity_{ict} + \delta MeanTemperature \times Waterways_{ict} + \alpha MeanTemperature \times Hanseatic\ League_{ict} + a_t + i_i + c_{it} + \epsilon_{it}$$

As in the main specification, I regress city size of city i in time period t on MeanTemperature, city fixed effects i, year fixed effects a, and a host of geographic control variables. In addition, I add three interaction terms to the specification. Each term interacts mean temperature with a proxy for a city's ability to trade, in particular a city's size, whether it has access to waterways, and whether it was part of the Hanseatic League, a long-distance trading network. The variable *BigCity* is an indicator variable that is 1 for all cities larger than the median city in the year 1500. Larger cities are more likely to specialize in non-agricultural goods, and to trade their goods. It is plausible that they are in a better position to compensate for the possibly adverse effects of temperature changes. The variable *Waterways* is an indicator variable that is 1 for all cities within 10 km of a river or ocean. In Early Modern Europe, using waterways was an important means of reducing transportation costs. Cities located near waterways were therefore likely to be better connected to trade. The variable *HanseaticLeague* is an indicator variable that is 1 for all cities that were part of the Hanseatic League, a network of independent trading towns in Medieval Europe.[21]

Column 1 of Table 11 includes the baseline results. In columns 2 to 4, I include each interaction term separately. Results show that the estimated main effect of mean temperature increases while the interaction terms have a negative sign. This indicates that the effect of mean temperature on cities that were relatively small, with less access to waterways, and without Hanseatic League affiliation, was significantly larger compared to bigger, better connected cities. In column 5, all interaction terms are included. The result confirms the previous findings. The estimated effect of a change in mean temperature is significantly lower for relatively big cities with better access to trade. The sizes of the coefficients on the interaction terms are slightly decreased. This is unsurprising because the interacted variables are correlated. The coefficients are negative and around half the size of the main effect of temperature changes, indicating that these characteristics on average halve the effect of changes in mean temperature.

7 Was Climate Change Adaptation insufficient or inexistent? The Example of Potato Adoption

In the previous sections, results have shown negative effects of long-term temperature changes during the Little Ice Age. It follows that adaptation was either insufficient to counteract this effect, even over a period of 250 years, or that it did not take place. In this section, I address this question and directly examine evidence on adaptation. In particular, I examine the case of potato adoption in Early Modern Europe. Unlike grains, potatoes thrive in cold and wet conditions. As they grow underground they are also better protected from storm and hail, that regularly destroyed grain harvests, sometimes within hours (Deppe, 2010: 34).[22] Switching from wheat or rye to potato cultivation would have granted protection against harvest failure and helped to adapt to the climatic conditions of the Little Ice Age (Pfister et al., 2006: 124).

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[21] The Hanseatic League was established as an alliance between two north German trading cities, Hamburg and Lubeck, that joined forces to fight piracy in the North and Baltic Sea (Merriman, 2010: 24). Later, more than 30 other cities joined as members or as kontor (branch) cities that had constant offices of the Hanseatic League. The League granted trading privileges, provided nautical charts and waged war. The Hanseatic cities were located in the German states or in North and Eastern Europe. Most member cities were directly located on the North or Baltic Seas, others, such as Cologne and Dortmund, were not. At its peak in the 14th century, the league controlled the sea routes of the North and Baltic Seas from London to Novgorod. In the period under study, the Hanseatic League was past its peak of influence. Yet, its members were still more likely than other European cities to be involved in trading activities.

[22] In addition, the potato's nutritional qualities were superior to the main alternative of the time, bread made from cereals. A diet of potatoes supplemented only by milk provided all nutrients necessary to the human body. Besides, growing potatoes was especially advantageous for small-scale farmers as potatoes require less crop land per calorie produced compared to grain. Hence, with potatoes, small-scale farmers who also owned a cow were able to provide for their families (McNeill, 1999: 5).

In this section, I examine whether severity of Little Ice Age conditions affected timing of potato adoption. I construct a country-level dataset with informatin on the year of potato adoption in a country (see Table 12), severity of the Little Ice Age (based on Luterbacher et al., 2004a), soil suitability for potato cultivation (IIASA/FAO, 2012), and quality of political institutions (Stasavage, 2012). Potato adoption is measured as the year in which potato adoption is documented for at least part of a country.[23] Severity of the Little Ice Age is measured as the change in mean temperature from the 16th to the 17th century.

Figure 6 presents the relationship between Little Ice Age severity and potato adoption graphically. If people started cultivating potatoes in order to adapt to the Little Ice Age we would expect a positive relationship, that lower temperature is associated with earlier year of potato adoption. Instead, the relationship is slightly negative and insignificant indicating that countries that experienced larger temperature decreases during the Little Ice Age adopted the potato on average slightly later. There is no evidence that potatoes were adopted as a means of adapting to the Little Ice Age. The graph, however, should be interpreted with caution because other factors affected timing of potato adoption. There is evidence that a region's climatic and soil characteristics (Nunn et al., 2011) and political institutions affected adoption. If soil suitability for potato cultivation was lower in areas that were more affected by the Little Ice Age, then not controlling for it could bias results.

In Figure 7, I depict the estimated effect of Little Ice Age severity on timing of potato adoption conditional on soil suitability for potato cultivation and an on quality of political institutions. Again, the estimated relationship between Little Ice Age severity and timing of potato adoption is slightly negative and insignificant. While more evidence is needed to come to conclusive estimates, this exploration does not show any evidence of adaptation to Little Ice Age climate through potato adoption.

8 Discussion

8.1 Relevance to developing countries today

In the previous sections, I show evidence on the negative long-term effects of climate change, and on lack of adaptation. To what extent can these findings from an episode of climate change in the past inform our understanding of the impact of climate change today? "There are two ways to consider the impact of climate change. We can predict the future based on current trends or we can study a well-documented episode of the past," (Parker, 2014). Numerous papers have done the former; this paper does the latter. The former approach has the advantage that it examines the impact of climate change in socioeconomic conditions as similar as possible to future socioeconomic conditions, but is limited in the time span that can be studied. The latter approach examines the impact of climate change over several centuries, but in socioeconomic conditions that are further removed from the future. Learning from climate change in history therefore requires awareness of historical socioeconomic conditions and cautious extrapolation.

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[23] This is different from the year of potato introduction, when the first potato plant reached a country, but remained otherwise obscure (see table 13 for the lag between the two years).

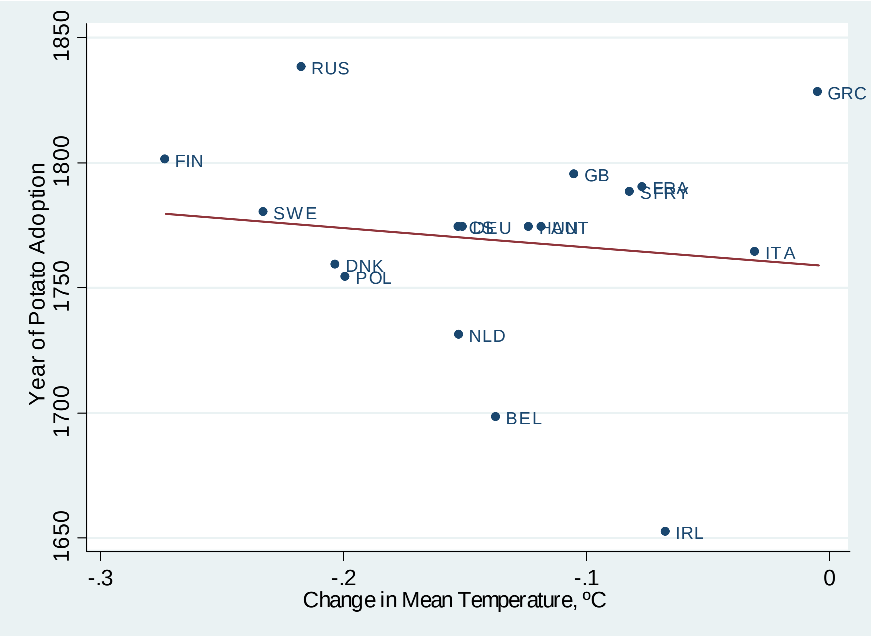

Figure 6: The figure displays the country-level relationship between change in mean temperature in the 17th century and the year of potato adoption.

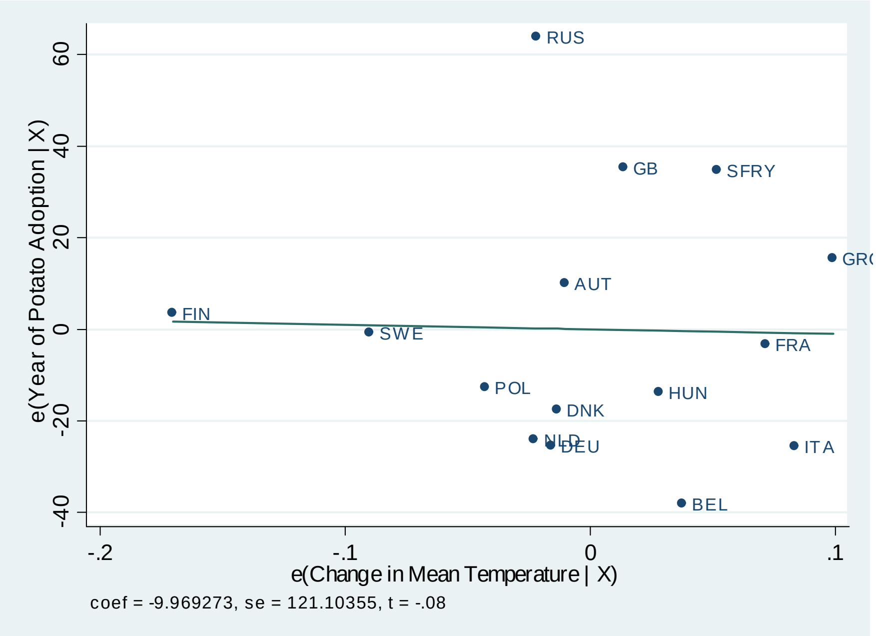

Figure 7: The figure displays the country-level relationship between change in mean temperature in the 17th century and the year of potato adoption conditional on soi suitability for potato cultivation and a measure of a country's institutional quality in 1700.

Socioeconomic and political conditions of Early Modern Europe were very different compared to current-day Europe.[24] In certain developing countries today, however, the share of GDP from agriculture is relatively similar to shares of GDP from agriculture in Early Modern Europe.[25] Though contemporary developing countries' economies are, of course, very different from Early Modern European economies in many respects, these numbers show that they still rely heavily on agriculture. Agricultural productivity has been identified as an important mechanism through which temperature affects economic outcomes in both historical and current-day contexts (historical: Baten, 2002; Pfister et al., 2006; current-day: Burgess et al., 2014; Schlenker et al., 2006, 2009; Deschenes and Greenstone, 2007). Therefore, the findings of my analysis of the Little Ice Age showing that long-term changes in temperature changes can have important economic effects may contribute to our understanding of the economic effects of contemporary climate change in developing countries. It is also consistent with findings from medium-term temperature changes showing the limited ability of developing countries to adapt to medium-term changes in temperature the last 50 years of the 20th century (e.g. Dell et al., 2012).

Likewise, barriers to adaptation in Early Modern Europe remain relevant in the context of developing countries today. Credit constraints (Fafchamps, 2009: 1) and uncertain or absent private property rights (Namara et al., 2011: 34) continue to hamper adaptation to climate change in developing countries.[26]

8.2 Integrated Assessment Models

Mindful of interpretative challenges, this paper's findings may help build better informed Integrated Assessment Models (IAMs).[27] IAMs assume that economies can substantially reduce economic losses from climate change through adaptation.[28] The PAGE model (Hope, 2006, 2008), for example, assumes that developed countries can reduce losses by 90 percent and developing countries by 50 percent (Greenstone et al., 2013: 4, 5, 20). The FUND damage function predicts that temperature increases up to about 3 °C are beneficial (Greenstone et al., 2013: 4). This paper's findings, however, suggest that adaptation to climate change is a slow process, especially in today's developing countries, where credit constraints and lack of private property

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[24] One indicator of these differences is the declining importance of the agricultural sector, a feature of the structural transformation of the contemporary European economy as a whole.

[25] While in 1600 and 1700 43.2 and 26.8 percent (respectively) of the United Kingdom's GDP came from agriculture, the share plummeted to 1 percent in 2012. However,the share of GDP from agriculture in certain developing countries today is relatively similar to shares of GDP from agriculture in Early Modern Europe. For example, the agricultural sector generates between 35 percent and 56 percent of GDP in contemporary Burkina Faso, Chad, and Mali. (Broadberry et al., 2011; World Bank, 2014).

[26] Besides, adoption of a new crop discussed above, alternative adaptation strategies today include switching planting dates, expanding cropped areas (e.g. through drainage or irrigation) or diversifying income (Burke and Lobell, 2010). These adaptation strategies are also similar to those documented for the Early Modern period. Farmers adjusted planting or harvesting dates to each year's weather, which is well documented for the time of the wine harvest (Pfister, 1980). Dutch farmers applied draining techniques to increase availability of arable land (Tol and Langen, 2000).

[27] Integrated Assessment Models consider social and economic factors driving greenhouse gas emissions, and the effects of these emissions on climate and human welfare.

[28] PAGE, for example, assumes that developed countries can reduce losses by 90 percent and developing countries by 50 percent (Greenstone et al., 2013: 5, 20).

rights pose important challenges to economic agents.[29] In the light of these results, the assumed adaptation rates seem overly optimistic.

Then, IAMs are calibrated "based on a sparse set of studies (some from the 1990s) done at particular geographic locations," (IPCC, 2014: 245), mostly developed countries. Results in this paper, however, indicate important heterogeneity in the long-term impact of climate change. The impact varies with an economy's dependency on agriculture and access to trade implying that today's developing countries are likely to experience more severe economic damage than most developed countries.[30] Hence, damage functions should be calibrated based on evidence from both developed and developing regions. Otherwise, the economic impact of climate change in developing countries could be systematically underestimated. IAMs could more clearly model disparities between developed and developing world regions for both the effects of long-term climate change and countries' ability to adapt.

9 Conclusion

This paper shows empirical evidence on the economic effects of long-term climate change in Early Modern Europe during a 250-year period (1500-1750) of the Little Ice Age. It estimates the economic impact of climate change by factoring in the potentially mitigating effects of adaptation. Results show the negative economic effects of long-term climate change. The findings further show that climate change operated through its effect on agricultural productivity and that more advanced economies that were well connected to trade networks were less affected. Adaptation waslacking and could not undo the negative economic effects of climate change. These results contribute to a recent strand of literature of empirical evidence on the effects of climate change and on the slow nature of adaptation processes. Based on these results, I suggest that IAMs could be improved by revising overly optimistic assumptions on adaptation and by calibrating damage functions based on evidence from both developed and developing regions. IAMs reconsidered in this way could more clearly model disparities between developed and developing world regions in the effects of long-term climate change.

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[29] This result is also consistent with recent empirical studies on the slow character of climate change adaptation (Barreca et al., 2015b; Burke and Emerick, 2015; Fowlie et al., 2015.)

[30] This result is also consistent with evidence from Dell et al., 2012).

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10 Tables

TABLE 1 - Summary Statistics

	(1) **All**	(2) **Above average fall in temperature**	(3) **Below average fall in temperature**
City size in 1500	3.712	3.308	4.118
	9.962	*9.660*	*10.242*
Mean Temperature in 1500	10.601	8.284	12.927
	3.296	*1.725*	*2.824*
City Growth, 1500 to 1750	4.368	4.947	3.788
	19.439	*24.589*	*12.233*
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*
Potatoe 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			
Atlantic Trader	0.450	0.400	0.501
	0.498	*0.490*	*0.500*
RomanEmpire	0.689	0.474	0.905
	0.463	*0.499*	*0.293*
University in 1500	0.031	0.024	0.037
	0.172	*0.155*	*0.188*
Hanseatic League	0.111	0.222	0.000
	0.315	*0.416*	*0.000*
Distance to...			
River	0.101	0.116	0.087
	0.302	*0.400*	*0.149*
Ocean	1.449	2.095	0.800
	1.641	*1.924*	*0.919*
Roman Road	1.248	2.312	0.181
	2.917	*3.793*	*0.580*
Battle	5.028	4.867	5.190
	5.066	*6.109*	*3.731*
Protestant Reformation			
Catholic	0.638	0.414	0.863
	0.481	*0.493*	*0.344*
Recovered Catholic	0.037	0.073	0.001
	0.188	*0.259*	*0.031*
Lutheran	0.126	0.252	0.000
	0.332	*0.434*	*0.000*
Anglican	0.073	0.141	0.004
	0.260	*0.348*	*0.061*
Calvinist/Hugenots	0.121	0.110	0.132
	0.326	*0.313*	*0.339*
Calvinist/Lutheran	0.057	0.113	0.001
	0.232	*0.317*	*0.031*

TABLE 2 - The Effect of Temperature on City Size - Baseline Estimates and Geographic Controls

	Ln City Size					
	(1)	(2)	(3)	(4)	(5)	(6)
Mean Temperature	0.567***	0.653***	0.624***	0.565***	0.490***	0.491***
	(0.127)	(0.142)	(0.143)	(0.139)	(0.144)	(0.144)
City Fixed Effects	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes
Geographic Controls (×Year Fixed Effects)						
ln Elevation		yes	yes	yes	yes	yes
ln Wheat Suitability			yes	yes	yes	yes
ln Potatoe Suitability				yes	yes	yes
ln Ruggedness					yes	yes
precipitation						yes
Observations	6,360	6,360	6,360	6,360	6,360	6,360
R-Squared	0.885	0.886	0.886	0.886	0.887	0.887

Robust standard errors in parentheses, clustered at city level
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750. 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, and 1700 to 1750. The variables ln Wheat Suitability and ln Potato Suitability are the natural log of a wheat and potato suitability index defined by IIASA/FAO (2012). The measure for ruggedness is defined as in Nunn and Puga (2012). For more detailed information, please see the Data section.

TABLE 3 - Robustness Additional Historical Control Variables

	Ln City Size								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Mean Temperature	0.491***	0.740***	0.500***	0.426***	0.548***	0.411**	0.445***	0.336**	0.489**
	(0.144)	(0.185)	(0.144)	(0.151)	(0.158)	(0.160)	(0.150)	(0.156)	(0.208)
City Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Geographic and Historical Controls (× Year Fixed Effects)									
Geographic Controls	yes	yes	yes	yes	yes	yes	yes	yes	yes
Protestant		yes							yes
University			yes						yes
Atlantic Traders				yes					yes
Battle					yes				yes
Part of Roman Empire						yes			yes
Access to Roman Roads							yes		yes
Distance to Ocean								yes	yes
Observations	6,360	6,360	6,360	6,360	6,360	6,360	6,360	6,360	6,360
R-Squared	0.887	0.893	0.887	0.887	0.887	0.887	0.887	0.888	0.894

Robust standard errors in parentheses, clustered at city level
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750.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, and 1700 to 1750. Geographic control variables are control variables of table 2, namely ln Wheat Suitability, ln Potato Suitability, ln Ruggedness and precipitation. Protestantrepresents seven indicator variables, each one representing one of seven post-Reformation religious groupings: Catholic, Recovered Catholic (= Catholic after the Counter-Reformation), Lutheran, Anglican, Calvinist/Hugenots, Calvinist/Lutheran. Each variable is 1 for a city if the city was majority of this grouping in 1600. University is an indicator variable that is 1 for all cities that had a university in 1500. Atlantic Traders are defined as cities in countries that have been identified as Atlantic Traders in Acemoglu, Johnson, and Robinson (2005), namely Great Britain, the Netherlands, Belgium, France, Spain and Portugal. Battle is a distance measure between a city and the closest battle site during the time period according to Clodfelter et al. (2002). Part of Roman Empire is an indicator variable that is 1 if a city was located within the Roman Empire in the year 0. Access to Roman Road is an indicator variable that is 1 for all cities located within 10 km of a historical Roman road. Distance to ocean is a distance measure between a city and the closest coast line. All geographic and historical control variables are interacted with a full set of time period indicator variables.

TABLE 4 - Robustness Different Samples

	Ln City Size				
		Baseline Sample Excluding...			
	Baseline Sample (1)	**Capital Cities** (2)	**Coastal Cities** (3)	**Successful Cities** (4)	**Atlantic Traders** (5)
Mean Temperature	0.491***	0.486***	0.534***	0.481***	0.423***
	(0.144)	(0.145)	(0.193)	(0.145)	(0.161)
City Fixed Effects	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes
Geographic Controls (× Year fixed effects)	yes	yes	yes	yes	yes
Observations	6,360	6,306	5,037	6,261	3,711
R-Squared	0.887	0.882	0.881	0.882	0.896

Robust standard errors in parentheses, clustered at city level
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750. 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, and 1700 to 1750. The sample in columns 3 and 4 is restricted to cities that were not capital cities between 1600 and 1750. Regression 3 excludes cities that are located less than 10 km from the sea. Regression 4 excludes cities that were listed by de Vries (1984:140) as especially successful, fast growing cities between 1600 and 1750. Regression 5 excludes cities that were located in one of the countries identified in Acemoglu et al. (2005) as Atlantic traders: Portugal, Spain, France, England, and the Netherlands.

TABLE 5 - Alternative Fixed Effects and Time Trends

	Ln City Size			
	(1)	(2)	(3)	(4)
Mean Temperature	0.564***	0.259**	0.526*	0.420
	(0.127)	(0.127)	(0.299)	(0.374)
Fixed Effects				
City FE	yes	yes	yes	yes
Year FE	yes	yes		
Country in 1600 × Year FE			yes	yes
Linear Time Trend				
Country in 1600		yes		
City				yes
Observations	6,360	6,360	6,360	6,360
R-Squared	0.885	0.895	0.899	0.974

Robust standard errors in parentheses, clustered at city level
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750. 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, and 1700 to 1750. Country in 1600 is defined as the sovereign state that a city was located in in 1600 according to Nussli (2012). Two-way cluster by city and year take into account serial correlation.

TABLE 6 - Robustness Using Alternative Standard Errors

	Ln City Size			
	Clustered at...			
	City Level	Grid Cell Level	Conley SE	Two-way Cluster City and Year
	(1)	(2)	(3)	(4)
Mean Temperature	0.487***	0.487***	0.487***	0.487*
	(0.144)	(0.172)	(0.173)	(0.276)
City Fixed Effects	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes
Geographic Controls (× Year fixed effects)	yes	yes	yes	yes
Observations	6,360	6,360	6,360	6,360
R-Squared	0.887	0.887	0.887	0.228

Robust standard errors in parentheses, clustered at different levels
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750. 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, and 1700 to 1750. Geographic and Historical Controls are interacted with a full set of year fixed effects and defined as in tables 2 and 3. The grid cell level refers to the grid cell of the underlying temperature data set (Luterbacher et al., 2004a) and measure about 50 by 50 km. Conley Standard Errors assume spatial autocorrelation (Conley, 1999). Here, they assume spatial autocorrelation for all cities that are located within 100 km of each other. Spatial autocorrelation decreases with distance. No spatial autocorrelation is assumed for cities located more than 100 km from each other.

TABLE 7 - Estimated Effect of Mean Temperature on Log City Size

	Cities with At Least 1 Original Temperature Source Within...								
	All Cities	**500 km**	**250 km**	**100 km**	**50 km**	**40 km**	**30 km**	**20 km**	**10 km**
					Log City Size				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Mean Temperature	0.489**	0.453**	0.391*	0.153	-0.0148	0.379	0.661	0.774	0.531
	(0.208)	(0.210)	(0.230)	(0.411)	(0.498)	(0.534)	(0.592)	(0.784)	(0.945)
City Fixed Effects	yes	yes	yes	yes	yes	yes	yes		
Year Fixed Effects	yes	yes	yes	yes	yes	yes	yes		
Geographic Controls (× Year fixed effects)	yes	yes	yes	yes	yes	yes	yes		
Historical Controls (× Year fixed effects)	yes	yes	yes	yes	yes	yes	yes		
Observations	6,360	6,342	5,433	2,724	1,149	888	582	351	120
R-Squared	0.894	0.885	0.880	0.884	0.898	0.906	0.922	0.934	0.959

Robust standard errors in parentheses, clustered at different levels
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750. The left-hand-side 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, and 1700 to 1750. Geographic and Historical Controls are interacted with a full set of year fixed effects and defined as in tables 2 and 3. A map of locationss of original temperature sources .is provided in Luterbacher et al. (2004b: 4, Maps A and B).

TABLE 8 - The Effect of Temperature on Urbanisation

	Urbanisation			
	(1)	(2)	(3)	(4)
Mean Temperature	0.134***	0.188**	0.187**	0.598
	(0.0441)	(0.0762)	(0.0823)	(0.474)
Year Fixed Effects	yes	yes		yes
Region Fixed Effects		yes		
Region×Year Fixed Effects			yes	
Country Fixed Effects				yes
Observations	66	66	66	66
R-squared	0.295	0.512	0.533	0.915

Robust standard errors in parentheses, clustered at country level
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the country-year level. Data on urbanisation is computed based on total urban population (sum of all city inhabitants per country as in Bairoch, 1988) divided by a country's total population (inhabitants per country, data collected from McEvedy and Jones [1978]). These data are available for the following countries: Austria, Belgium, Bulgaria, Czechoslovakia, Denmark, Finland, France, Germany, Great Britain, Greece, Hungary, Ireland, Italy, Luxembourg, Macedonia, Malta, Netherlands, Norway, Poland, Portugal, Rumania, Russia, Spain, Sweden, Switzerland, Yugoslavia. European regions are defined as follows. Northwestern Europe: Belgium, Denmark, Finland, Greatbritain, Ireland, Netherlands, Norway, Sweden. Southwestern Europe: France, Italy, Malta, Portugal, Spain. Central Europe: Austria, Germany, Luxembourg, Switzerland. Eastern Europe: Czechoslovakia, Hungary, Poland, Russia. Southeaster Europe: Bulgaria, Macedonia, Greece, Rumania, Yugoslavia.

TABLE 9 - The effect of yearly temperature on yearly yield ratios

	Yield Ratios				
	(1)	(2)	(3)	(4)	(5)
Mean Temperature	0.430***	0.459***	0.451***	0.434**	0.543*
	(0.111)	(0.112)	(0.112)	(0.142)	(0.259)
Year Fixed Effects	yes	yes	yes	yes	yes
Country Fixed Effects	yes	yes	yes	yes	yes
Control Variables (×Year Fixed Effects)					
Precipitation		yes	yes	yes	yes
Battle			yes	yes	yes
Access to Ocean				yes	yes
Atlantic Trader					yes
Observations	702	702	702	702	702
R-Squared	0.802	0.803	0.803	0.820	0.847

Robust standard errors in parentheses, clustered at country level
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the country-year level. Data on yield ratios are taken from Slicher van Bath (1963) and available for locations in 12 European countries: Belgium, Czechoslovakia, Denmark, France, Germany, Great Britain, Italy, Netherlands, Poland, Russia, Spain, and Switzerland for various years starting in 1504.

TABLE 10 - The effect of yearly temperature on yearly wheat prices

	Ln Wheat Prices (grams of silver per kg)				
	Year Fixed Effects				
	(1)	(2)	(3)	(4)	(5)
Mean Temperature	-0.110***	-0.104***	-0.106***	-0.106***	-0.103**
	(0.0215)	(0.0219)	(0.0217)	(0.0217)	(0.0351)
City Fixed Effects	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes
Region×Year fixed Effects					
Control Variables (× Year Fixed Effects)					
Precipitation		yes	yes	yes	yes
Battle			yes	yes	yes
Access to Ocean				yes	yes
Atlantic Trader					yes
Observations	2,111	2,111	2,111	2,111	2,111
R-Squared	0.663	0.666	0.666	0.666	0.736

Robust standard errors in parentheses, clustered at city level
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Note: Data are panel data for ten European cities. The dependent variable is the yearly wheat price in grams of silver according to Allen (2002). The data are available for Amsterdam (1500-1910), London (1500-1914), Leipzig (1564-1810), Antwerp (1500-1718), Paris (1500-1911), Strasbourg (1500-1875), Munich (1500-1913), Northern Italy (1500-1860), Naples (1514-1803), Madrid (1501-1800). Mean temperature is annual year temperature. Regressions includes the entire sample. Control variables are variables that could have had a direct effect on local grain trade and are defined as in table 2 and 3. Robust standard errors are in parentheses and clustered at city level.

TABLE 11 - Exploring Economic Heterogeneity

	Ln City Size				
	(1)	(2)	(3)	(4)	(5)
Mean Temperature	0.487***	0.746***	0.691***	0.602***	0.984***
	(0.144)	(0.190)	(0.177)	(0.157)	(0.209)
Mean Temperature Interacted with:					
Big City		-0.601***			-0.486**
		(0.191)			(0.197)
Access to Waterways			-0.464**		-0.429**
			(0.209)		(0.209)
			‘		
Hanseatic League				-0.568***	-0.495**
				(0.213)	(0.209)
City Fixed Effects	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes
Geographical Controls (× Year Fixed Effects)	yes	yes	yes	yes	yes
Observations	6,360	6,360	6,360	6,360	6,360
R-Squared	0.887	0.887	0.887	0.887	0.887

Robust standard errors in parentheses, clustered at city level
*** p<0.01, ** p<0.05, * p<0.1

Note: Observations are at the city-year level. All regressions use a baseline sample of 2120 cities. The time periods are 1600, 1700, and 1750. 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, and 1700 to 1750. Column 2 includes an interaction term between Mean Temperature and BigCity. BigCity is an indicator variable that is 1 for all cities larger than the median city in 1500. Column 3 includes an interaction term between Mean Temperature and Access to Waterways. Acess to Waterways is an indicator variable that is 1 for all cities within 10 km of a river or an ocean. Column 4 includes an interaction term between Mean Temperature and Hanseatic League. Hanseatic League is an indicator variable that is 1 for all cities that were part of the Hanseatic League. Column 5 includes all three interaction terms.

TABLE 12 -Year of First Introduction and Widespread Adoption of the Potato

Country	Potato Introduction	Potato Adoption	Source
Austria		1774	Langer (1963): 15
Belgium	1670	1698	Vandenbroeke (1971): 22
Denmark	1720	1759	Berdichevsky (2011): 99
France	1660	1790	Vandenbroeke (1971): 23
Germany	1601	1774	Langer (1963): 14; Nunn et al. (2011): 602
Great Britain	1596	1795	Chapman (2000)
Hungary		1774	Langer (1963): 15
Netherlands		1731	Vandenbroeke (1971): 22
Poland		1754	Langer (1963): 15
Russia	1754	1838	Langer (1963): 14, 16
Sweden	1725	1780	Laufer (1938): 68

Note: The table provides data on potato introduction and adoption for European countries. Introduction is the year in which the first potato plant is documented in a given country. Adoption is the year for which widespread adoption in the whole country or a significant region in the country is first documented. The last column provides references to the sources providing potato introduction and adoption years.

TABLE 13 - Economic characteristics of Countries in Early Modern Europe and Today

	Today			Early Modern Europe		
Indicator	Country	Year	Value	Country	Year	Value
Sectoral Shares in GDP, (%): Agriculture	United Kingdom	2012	1	England	1600	43.2
	France	2012	2	England	1700	26.8
	Burkina Faso	2012	35.0			
	Chad	2012	56.0			
	Mali	2012	42.0			
	Senegal	2012	17.0			
Sectoral Shares in GDP, (%): Industry	United Kingdom	2012	21	England	1600	32.5
	France	2012	19		1700	39.2
	Burkina Faso	2012	24			
	Chad	2012	13			
	Mali	2012	22			
	Senegal	2012	25			
Sectoral Shares in GDP, (%): Services	United Kingdom	2012	78	England	1600	24,3
	France	2012	79		1700	34.0
	Burkina Faso	2012	42.0			
	Chad	2012	34.0			
	Mali	2012	38.0			
	Senegal	2012	59.0			
Share of Workforce employed in Agriculture (%)	United Kingdom	2012	1.0	England	1705	35
	France	2012	3.0		1775	29
	Burkina Faso	2012	90.0	Prussia	1705	80
	Chad	2012	80.0		1775	70
	Mali	2012	80.0	Spain	1705	71
	Senegal	2012	77.5		1775	66
				France	1705	70
					1775	65
Farm Size (% of holdings of certain size)	England	1993	< 2 ha.: 5.6	Savoy	1600	<1 ha.: 45%
	France	1989	< 2 ha.: 27.4	Bohemia	1725	<1 ha.: 35.7%
	Burkina Faso	1993	< 2 ha.: 32.4	Hochberg Germany	1788	<1 ha.: 45%
	Senegal	1993	< 2 ha.: 37.5			
	Ethiopia	2001	< 2 ha.: 87.1			
	Uganda	1991	< 2 ha.: 73.4			
Literacy	United Kingdom	2014	99.0	England	1500	6
	France	2014	99.0	Netherlands	1500	10
	Burkina Faso	2007	28.7	France	1500	7
	Chad	2011	35.4	Spain	1500	9
	Mali	2011	33.4	England	1800	53
	Senegal	2009	49.7	Netherland	1800	68
				France	1800	37
				Spain	1800	20
Agricultural Productivity (crop yields in kg per hectar)	France	2012	6831	England	1550-59	1593.2
	United Kingdom	2012	6213		1600-10	2028.3
	Burkina Faso	2012	1230		1650-60	2411.8
	Chad	2012	1282		1700-10	2461.4
	Mali	2012	1667.0		1750-60	2890.7
	Senegal	2013	1310.0			

Note: Sources are as follows: For sectoral shares in GDP (%): Broadberry et al. (2011): 52; World Bank (2014): Data. For share of workforce employed in agriculture: Broadberry et al. (2010): 149; CIA World Factbook (2014); for farm size (% of holdings of certain size): Eastwood et al. (2010): 3328 (both historical and today). For literacy: Allen (2002): 415; CIA World Factbook (2014).

TABLE 14 - Robustness to different outcome variables

	Log city size (500)	**Log Citysize (1)**	**Log Citysize (1000)**	**Number of inhabitants (absolute numbers)**
	(1)	(2)	(3)	(3)
Mean Temperature	0.564***	1.936***	0.411***	3,482**
	(0.127)	(0.394)	(0.104)	(1,661)
Year Fixed Effects	yes	yes	yes	yes
Year fixed Effects	yes	yes	yes	yes
Observations	6,360	6,360	6,360	6,360
R-Squared	0.885	0.850	0.891	0.901

Robust standard errors in parentheses, clustered at country level
*** p<0.01, ** p<0.05, * p<0.1

Note: The table reports results for alternatively specified outcome variables. In Bairoch (1988) cities smaller than 1000 inhabitants are reported as having 0 inhabitants. In the main specifications cities with less than 1000 inhabitants are assumed to have 500 inhabitants. This table shows that the relationship is robust to alternative specification. In column 1, the baseline specification is reported. In column 2, cities with below 1000 inhabitants are assumed to have 1 inhabitant. In column 3, cities with below 1000 inhabitants are assumed to have 1000 inhabitants. Column 3 reports results when city size enters the specification as absolute number, including zero values.