The Economic Effects of Long-Term Climate Change:

Evidence from the Little Ice Age, 1500-1750

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Abstract

Understanding the economic effects of *long-term* and *gradual* climate change, when people have time to adapt, is a central question in the current debate on climate change. Empirical evidence, however, is scarce. I study the economic effects of climate change over a period of 250 years during the Little Ice Age, a historical episode of climate change, between 1500 and 1750. Historians have argued that relatively low temperatures during this period decreased agricultural productivity and economic growth. I test this hypothesis and provide econometric evidence of the economic effects of long-term adverse temperature changes during the Little Ice Age. Results indicate that, during this particularly cold period, further temperature decreases had an overall negative effect on city size in Europe. These results are robust to controlling for an array of geographical control variables and for alternative determinants of economic growth in Early Modern Europe. Further results indicate that cities with good access to trade were substantially less affected by temperature changes and that cities with relatively warm initial climate benefited from temperature decreases while cities in temperate and cold climates were negatively affected. Finally, I use yearly historical wheat prices and historical yield ratios to show that yearly temperature changes affected economic growth though its effect on agricultural productivity.

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

1 Introduction

One of the central and also most controversial questions in the current debate on climate change regards its economic impact: How large will the economic effects of climate change be and how will long-term effects, when people have time to adapt, compare to short-term effects? Which characteristics affect an economy's vulnerability to climate change? A prominent approach to estimate economic impacts of climate change scenarios have been Integrated Assessment Models (IAMs, e.g. Stern, 2007). They are used, among other things, to predict the effect of certain climate change scenarios on the economy. IAMs have been very influential and have informed important policy choices; their results, however, have been criticized for depending heavily on

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assumptions based on “little theoretical knowledge and no empirical evidence” (Pindyck 2013: 860). These models suffer from a high degree of uncertainty regarding the negative effects of climate change on economic output. “[...] when it comes to the damage function [the effect of a given temperature rise on economic output] we know almost nothing. [...] It is the most speculative element of the analysis, in part because of uncertainty over adaptation to climate change“, (Pindyck, 2013: 862, 867).

A recent strand of literature in economics has addressed this issue and pioneered a new, empirical approach to estimating the economic effects of temperature changes. Dell et al. (2012), Burgess et al. (2014), and Deschenes et al. (2007, 2012) use year-to-year temperature changes to estimates the economic effects of climate change. Yet, the authors point out that the effects of year-to-year temperature changes might be different from the effects of long-term temperature changes. “[...]in the long run, countries may adapt to a particular temperature, mitigating the short-run economic impacts that we observe,” (Dell et al. 2012: 68).

In this paper, I use a historical episode of climate change to estimate the economic effects of *long-term* climate change factoring in the potentially mitigating role of adaptation. To the best of my knowledge, it is the first paper to provide econometric evidence on the economic effects of long-term climate change. In particular, I study the economic effects of temperature changes during the Little Ice Age[1] on Europe over a period of 250 years, from 1500 to 1750. The Little Ice Age is the most recent climatic episode preceding human-induced (anthropogenic) climate change. It is characterized by temperatures decreases in large parts of Europe. Historical evidence indicates that lower temperatures lead to shorter growing seasons and decreased agricultural productivity, especially for crops that require relatively warm temperatures such as wheat. Historical research indicates that the Little Ice Age had a considerable effect on living conditions throughout Europe (e.g. Baten, 2002). It has been described as “the largest temperature change during historical times,” (Aguado et al., 2007: 483)[2].

To estimate the economic effects of these temperature changes I construct a panel data set for about 2100 European cities. These data measure annual temperature 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., 2004). The data contain gridded ‘temperature maps’ for each year since 1500 that cover all of Europe. As grid cells are relatively small (50 by 50 kilometers) the data allow for precise measurements of climate change at the local level. As a proxy for economic growth, I use data on historical city sizes from Bairoch (1988)[3].

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[1] The term Little Ice Age was first coined by Matthes (1939) to describe "an epoch of renewed but moderate glaciation" relative to the warmer climate of the Holocene climatic period that began ca. 11,000 years ago (Cronin, 2009: 218).

[2] "historical" refers to the time period since the end of the Ice Age, about 11,000 years ago. Climatologists refer to this time period as the Holocene (the "wholly recent" current climatic period, an interglacial period of relative warmth [Cronin, 2009: 216]). It witnessed the Neolithic Revolution and the evolution of the first trading civilisations, e.g. the Sumer in present-day Iraq .

[3] City size has been used before 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. In a robustness check, country-level urbanization rates are used as an alternative proxy in this paper. Urbanization rates have been used before as a proxy for economic prosperity, e.g. Acemoglu, Johnson and Robinson (2002),

The data's panel structure allows me to include city fixed effects and year fixed effects in all specifications. City fixed effects control for all city-specific and time-invariant factors that may affect city growth. Year fixed effects control for variation in temperature and city size over time that is shared by all cities. In particular, they control for growth trends that affected all cities in the same way.

The main results indicate a significant negative effect of Little Ice Age temperatures on city size which is consistent with the historical evidence on the negative economic effects of the Little Ice Age. Then, I show that this finding is robust to a number of specification checks. While it is safe to assume that temperature changes are exogenous to economic growth, they are not necessarily distributed randomly across space. It is also well established that city growth in Early Modern Europe has been unevenly distributed across space with centers of growth in Northwestern Europe (e.g. Broadberry, 2013; van Zanden, 2009; Koot, 2013). If temperature changes were correlated with a third factor that also affects city size estimation results would be biased. To address this concern I directly control for a host of relevant geographic and historical control variables. Each variable is 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, 2011) as well as elevation and ruggedness (Benniston et al., 1997; Nunn et al., 2012). Then, I 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), majority Protestant in 1600 (Becker and Woessmann, 2009), a history of Roman rule and access to Roman roads (Jones, 1981; Landes, 1998), having a university (Cantoni et al,. 2013), distance to battlegrounds (Dincecco et al. 2013), and distance to the coast. Finally, I show that the results are robust to using Conley (1999) standard errors that assume spatial autocorrelation between observations, when I include country specific time trends and when I use different sub-samples. The results corroborate historical and anecdotal evidence on the negative economic effects of Little Ice Age temperatures.

Historians have argued that the negative effects of the Little Ice Age were driven by agricultural productivity. I therefore directly investigate the effect of temperature on agricultural productivity as a plausible channel through which temperature might have affected the economy of Early Modern Europe. I estimate the effect of temperature on historical wheat prices and on yield ratios, the ratio of grains harvested to grains sown. I combine yearly temperature data with yearly wheat prices for ten European cities for the years 1500 to 1750 (Allen, 2003)[4]. As city level demand changes only gradually, yearly fluctuations in wheat prices are plausibly a reflection of changes in supply. Results indicate that decreasing temperatures lead to increases in wheat prices in northern cities while it led to falling prices in southern cities.[5] Next, I estimate temperature's effect on European country-level yield ratios as an additional measure for

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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] Wheat price data is available for since 1500 for Amsterdam, London, Antwerp, Paris, Strasbourg, Munich, Florence, since 1501, 1514, and 1564 for Madrid, Naples, and Leipzig respectively.

[5] This is consistent with evidence on heterogeneous effects of temperature changes: Depending on initial temperatures a temperature decrease have negative effects in areas with temperatures below the optimum while the same decrease has positive effects in areas where temperatures lie above the temperature optimum (Olesen, 2002).

agricultural productivity. Again, results indicate that colder temperatures during the Little Ice Age decreased yield ratios.

Another important concern in the climate change debate is to identify factors that affect vulnerability to climate change. In a second step of the analysis, 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.

A second potential source of heterogeneity in the effect of temperature changes is initial climate. Recent IPCC reports (Intergovernmental Panel on Climate Change) predict that temperature increases will affect regions within Europe (as well as world regions) differently depending on their initial climate (Parry et al., 2007; Kovats et al., 2014). I therefore test whether the Little Ice Age affected regions within Europe differently and find that temperature decreases benefited the relatively Southern European climate zone while having adverse effects in the rest of Europe. Finally, I discuss implications of my results for our understanding of the effects of the current climate change.

This paper contributes to various strands of literature, in particular to the empirical literature on the effects of climate on economic growth. As mentioned above, the use of year-to-year temperature data to estimate the economic effects of short-term temperature changes has been introduced in papers by Dell, Jones, and Olken (2012), Deschenes and Greenstone (2007, 2012) and Burgess et al. (2014). Dell, Jones, and Olken (2012) use worldwide temperature and precipitation data between 1950 and 2003 and find large, negative effects of higher temperature on growth in the short-term, but only in poor countries. Deschenes and Greenstone (2007, 2012) use year-to-year temperature and agricultural data to conclude that warming will significantly decrease US agricultural output. Burgess et al. (2014) find that rainfall shocks in India affects mortality in rural areas, but not in urban areas, through its effect on agricultural incomes. In these studies the authors emphasize that the effect of short-term temperature fluctuations are not the same as the effect of long term gradual temperature changes because it does not allow for adaptation. Deschenes and Greenstone (2008) find relatively modest effects of heat waves on health outcomes in the US, also because people are able to adapt their consumption of health-preserving goods such as air conditioning.

It is also related to research on the effects of climatic events on political outcome variables, such as insurgency (Dell, 2012), civil conflict (Miguel et al., 2004), and democratic institutions (Brückner and Ciccone, 2011) as well as labour productivity (Heal and Park, 2013). It further contributes to the literature in economic history that examines the role of climate for economic outcomes in the past (e.g. Baten, 2002; Pfister et al., 2006) and political and social outcomes (Behringer, 1999; Oster, 2004; Anderson et al., 2013; Berger and Spoerer, 2001).

The remainder of the paper is organized as follows. Section 2 provides climatological and historical background on the Little Ice Age and outlines the theoretical relationship between climate during the Little Ice Age, agricultural productivity and urban growth. Section 3 describes the data and the construction of the data set. Section 4 introduces the estimation strategy, presents main results and conducts a number of robustness checks. Section 5 examines the role of agricultural productivity as a channel through which temperature changes affected economic outcomes. Section 6 investigates economic and climatological heterogeneity in the effect of temperature on city size and discusses the results' contribution to our understanding of the potential economic effects of climate change. Section 7 concludes.

2 The Little Ice Age, Agricultural Productivity and Urban Growth

2.1 The Little Ice Age

The Little Ice Age was a climatic period that lasted from about 1350 to 1750[6]. It was preceded by the Medieval Warm Period, a climatic period of relatively warm and stable conditions (ca. 900-1250), and followed by the Anthropocene, the period of global warming affected by human activity (Cronin,2010: 298; Crutzen, 2002: 23). The Little Ice Age brought colder climate to large parts of Europe[7]. In Europe, average year temperatures fell by about 0.5 to 1 degree Celsius. This difference in average year temperatures was caused especially by temperature decreases during the winter season and long wintery periods (Matthews et al., 2005: 24). The temperature decrease during the Little Ice Age was not uniform over time and over space. Instead, especially cold and relatively warmer periods alternated. In most regions, temperatures fell below the pre-Little Ice Age mean. Especially cold waves have been identified for the periods from 1580 to 1610, and from 1690 to 1700 (Grove, 2004: 560). Temperature decline was not uniform across space. Within Europe, temperature changes were for example relatively large in Northern Europe compared to Southern Europe (Luterbacher, 2004).

2.2 Effect of temperature changes on agricultural productivity

Before plant growth sets in after European winters temperatures a certain temperature thresholds need to be passed. “The main effect of temperature is to control the duration of the period when growth is possible in each year,“ (Olesen et al. 2002: 243). During the Little Ice Age temperatures fell by about 0.5 to 1 degree Celsius. Winter seasons were especially cold and long (Matthews et al., 2005: 24). As temperature levels needed for plant growth were reached later in the year this shortened growing seasons which reduced agricultural productivity, especially in northern Europe,“ (Aguado et al., 2007: 483). In England, by the seventeenth century growing

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[6] 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. The energy that the sun emits is not constant over time. Sun spots are dark spots on the sun surface that indicate especially high solar activity (on the contours of the dark sunspots). The counted sun spots were especially few during the late 17th and early 18th century, the so-called Maunder Minimum, indicating low solar activity (Eddy, 1976: 1189). Volcanic eruptions affect temperatures by sending large quantities of sulphate gases into the atmosphere where they convert to particulate sulphate aerosols and influence radiative forcing. Volcanic eruptions were especially frequent during the Little Ice Age.Volcanic aerosols usually have a residence time in the atmosphere of only one to three years, depending on the size of the eruption. One primary effect is a general cooling of the surface of the earth by scattering radiation back to space (Cronin 2010: 305f.).

[7] The Little Ice Age was not solely a European phenomenon. Climate proxies from other world regions speak for a worldwide Little Ice Age (see e.g. Zhang et al., 2007; Fan, 2010, for China; Cronin, 2010: 298, Parker, 2013; Grove, 2004: 560).

periods were reduced by as much as five weeks compared to the 13th century (Grove, 2004: 629).

Decreasing temperatures affected agricultural productivity especially areas of marginal agricultural productivity such as in mountain areas or in areas of already cold climate in northern Europe (Engler et al., 2013). Even under normal conditions, food production there barely exceeded subsistence level. Holopainen et al. (2009) study the effects of the Little Ice Age on Finnish agriculture. They find that cold temperatures turned certain areas inhospitable and forced farmers to migrate to other areas. In mountain areas, snow persisting until late in spring or advancing glaciers reduced quantity and quality of mountain pastures or turned them altogether inhospitable for cattle. This reduced dairy production which depends on the cattle's nutritional intake (Grove, 2004: 631).

2.3 Effect of changes in agricultural productivity on city growth and economic growth

The first channel through which agricultural productivity changes may lead to changes in city size is the effect of agricultural productivity on income per capita (Nunn et al., 2011: 607). When agricultural productivity decreases workers in the rural economy have less to sell and earn less. The closer to subsistence level rural per capita income moves, the less income is available for manufacturing goods. Hence, demand for manufacturing goods and prices for manufacturing products decrease. Manufacturing activities were typically concentrated in cities in Early Modern Europe[8]. With decreases in income from agriculture working in manufacturing and living in cities therefore became less profitable. It discouraged rural workers to move to cities (Voigtlaender and Voth, 2013: 781). As „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 reduces city growth.

Second, a shock to agricultural productivity changes the relative prices of agricultural and manufacturing products. Prices for agricultural produce increase as agricultural productivity decreases. Less workers will migrate from the rural to the urban economy. This mechanism depends on the assumptions that labour is mobile. Labour mobility was high within most parts of Europe (e.g. de Vries, 1976: 157). In certain parts of Eastern Europe it was restricted where serfdom restricted labour mobility (e.g. Nafziger, 2011). This mechanism also assumes that demand for agricultural produce is inelastic (i.e. a one percent decrease in prices increases demand by less than one percent) which is consistent with empirical findings on the price elasticity of food (e.g. Andreyeva et al. 2010).

A third mechanism through which agricultural productivity affected urban growth and urbanization was its effect on the urban death rate through its effect on people's susceptibility to diseases. Galloway (1985) shows that temperature changes – through their effect on food prices – affect death from 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

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[8] 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 England, even small towns and villages offered work in manufacturing ("proto-industrialisation", Allen 2002: 4).

of the increased susceptibility of the body to various diseases as a result of malnourishment,“ (Galloway, 1985: 488). In addition, infectious diseases are a more important cause for death in cities compared to rural areas. „Infectious diseases dominate the causes of [urban] death. These diseases generally thrive in towns, where people live at relatively high densities and interact at comparatively high rates,“ (Dyson, 2011: 39). As a result, decreased prevalence of infectious diseases will benefit the urban population more compared to the rural population. Crop failure and food shortage also affected mortality from disease because it increased geographical mobility. In times of famine, the number of people journeying in search for food increased. If a certain region was known to still have food resources available, then people tried to reach this region to be safe from starvation there. At the same time, they brought with them infectious diseases (Appleby, 1980: 654).

In sum, agricultural productivity affected people's incentives to move from the rural to the urban economy and disease prevalence in Early Modern cities. Both factors were important determinants of city growth and urbanization. Due to the high disease prevalence urban death rates exceeded rural death rates and cities depended on rural-to-urban migration for their survival. „the urban sector is a demographic “sink”—that is, in the long run its population would not exist without rural-to-urban migration“, (Dyson 2011: 39) and „migration from the countryside has, in past societies, been the immediate cause of urbanization“, (Malanima, 2010: 250).

This paper uses city size as a proxy for economic growth[9]. How may the Little Ice Age have affected not only city size but economic growth in general? The section above describes how temperature decreases had adverse effects on agricultural productivity. The agricultural sector was by far the most important sector at the time. The majority of the labour force in early modern Europe worked in agriculture. Differences in agricultural productivity were the main determinant of differences in overall economic productivity (Dennison, 2010: 148f.). Changes in agricultural productivity were changes in productivity in the most important economic sector.

2.4 Interactions between the Effect of Climate and other Variables

Micro level studies, such as by Pfister et al. (2006), Baten (2002), and Galloway (1985), show that the effect of climate on economic outcomes does not take place in isolation, but that it may depend on other factors, e.g. an economy's structure and institutions. Pfister et al. (2006) identify local access to trade and responsiveness of political institutions as two factors

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[9] This paper estimates the effect of local temperature changes on local city size. Local temperature might have affected the local economy and city size because of high transaction costs.In many parts of Europe, food transportation was more costly. The physical costs of transportation, the institutional impediments, such as taxes or the need for official transport permits, or the prohibition of the movements of goods increased these costs (Dennison et al., 2010: 156). „The amplitude of grain prices mirrors this difference in the magnitude of climate impacts [...]. Rye prices in Bern did not even double [while] average prices for rye tripled in Brno (Moravia) [and were] even more dramatic in Bohemia", (Pfister et al. 2006: 122). In a similar vein, using London as a case study Galloway (1985) identifies a relationship between adverse weather conditions, reduced harvest, increases in prices and increases in mortality for London. „Among people living at or near subsistence level [...] variation in food prices were primary determinants of variation in the real wage." Similarly, Baten (2002) finds an effect of climate on grain production in 18th century Southern Germany: relatively mild winters from the 1730s to the early 1750s led to increases in production while relatively cold winters between 1750s and 1770s reduced agricultural productivity which affected the nutritional status of the local population.

that shape the economic effects of climatic change. The Bern authorities systematically traded with adjacent territories in response to the outcome of the grain harvest. „In the event of bumper crops, Bern used to sell grain to the adjacent territories. In the event of deficient harvests, grain was usually imported by order of the administration from the surrounding belt of grain-exporting territories such as the Alsace, Burgundy, Savoy and Swabia“, (Pfister et al., 2006: 124).In response to difficult climatic conditions the authorities of Bern had established a comprehensive network of grain stores from the late seventeenth century onwards. In addition, taxation was relatively low and was managed by a relatively efficient administration (Pfister et al., 2006: 124). Later, after around 1750, the authorities augmented these short-term measures by improving the legal framework such that would promote agricultural productivity, e.g. by privatization of communal land and introducing poor relief. At this time, potato cultivation became an attractive alternative to grain cultivation as the potato was less vulnerable to the impacts of the Little Ice Age (Pfister et al., 2006).

In contrast to the Swiss example, the authorities in Vienna reacted slowly to the onset of famine in the Czech Lands. Instead of importing grain from other regions, the authorities merely prohibited exports and grain distilling. Later, grain and flour were imported from Vienna and Hungary, but not in sufficient quantities. By the third year of famine, Bohemia had lost about 10% of its population (Pfister et al., 2006: 125f.). in addition to the limited responsiveness, the Czech population was subject to heavy taxes and feudal dues that limited the population's economic buffer.

These examples illustrate that the effect of climate is likely to depend on a city's ability to compensate for agricultural losses by trading or the responsiveness of political institutions.

3 Data

The basic data set for this paper is a balanced panel of 2120 European cities. Its two main components are data on annual mean temperature for Europe for each year since 1500 from Luterbacher (2004) and data on city size in 1600, 1700, and 1750 from Bairoch (1988). The dataset covers European land area between 25°W to 40°E longitude and 35°N to 70°N latitude. It covers all European cities in the data set, except for Russian cities east of 40°E longitude.

I use data on the size of European cities from Bairoch (1988) as a proxy for economic growth. The data set includes 2191 European cities that had more than 5000 inhabitants at least once between 800 and 1850[10]. I use a version of the data set that has been modified by and used in Voigtländer and Voth (2013). They use linear interpolation to fill missing values for time periods between non-zero values. During the period under study, city size is available in 1500, 1600, 1700 and 1750. Of these 2191 cities, I drop 62 because they are located east of 40°E longitude, an area for which temperature data is not available and nine cities because they are not located on the European continent. The final data set includes 2120 cities.

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[10] Bairoch records city size of cities below 1000 inhabitants as having 0 inhabitants. In my specifications, I assume that cities below 1000 inhabitants to have 500 inhabitants. I show 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 (see table A1 in the Appendix).

The temperature data is reconstructed temperature taken from Luterbacher et al. (2004)[11]. The data contain annual gridded seasonal temperature data 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. The temperature in this data set has been reconstructed based on temperature proxies (tree ring series, ice cores), historical records, and directly measured temperature for later years (Luterbacher et al., 2004: 1500).

I combine the two datasets 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.

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

If $t = 1750$ $MeanTemperature_{it} = \Sigma_{n=1}^{50} Temperature_{it-n}$

Figure 1 to 4 (see below) shows 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 change between the warmest and the coldest period lie around 0.8 degree Celsius for Moscow, Berlin, and Paris, while the temperature change for Lisbon lies only around 0.25. The temperature decrease between 1500 and 1700 is followed by an increase in temperature, this increase compensates the previous temperature decrease in Moscow. For Berlin and Paris, the subsequent increase in temperature more than compensates for the previous decrease. The graphs show that temperature changes within Europe varied across space.

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. (2004) with yearly wheat prices for ten 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.

A third data set explores the relationship between temperature changes and yield ratios, the ratio of grains harvested to grains sown. 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, some of them towns, others farm estates, in 14 European countries. I collected yield ratio information for the time period 1500 to 1750. For each location yield ratios are available only for certain years, in some cases only for a single year, in others for 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.

Data on control variables is obtained as follows: Data on local potato suitability, wheat suitability, and altitude are taken from the Food and Agriculture Organization (FAO)'s Global

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[11] 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).

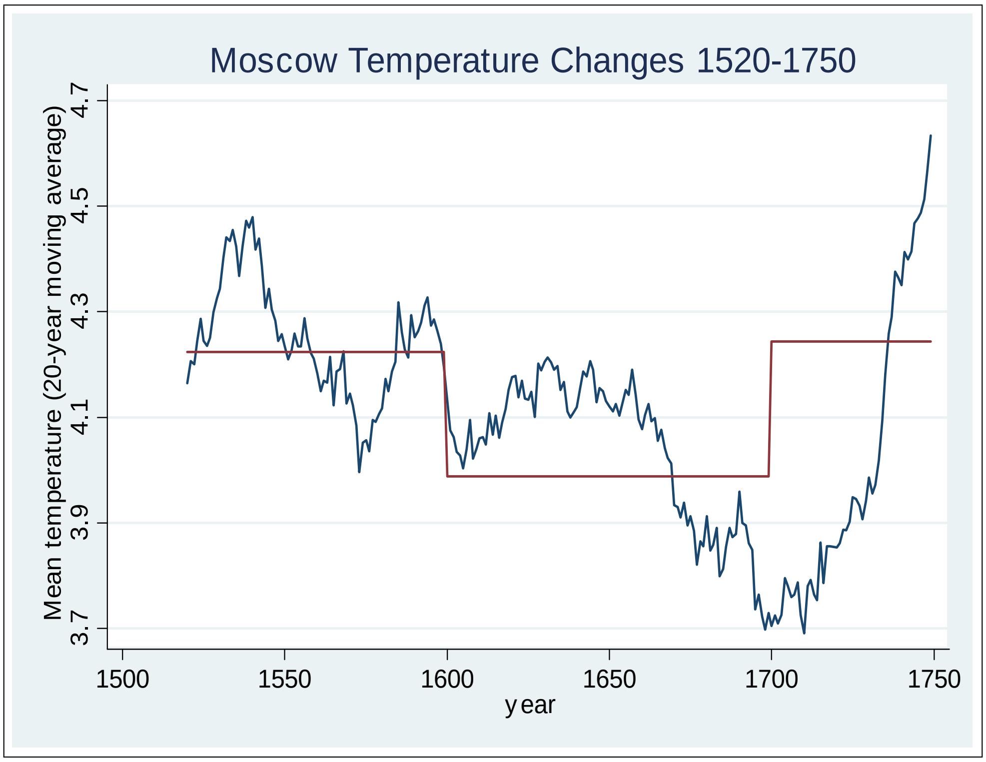

Figure 1: Note: The graph plots yearly temperatures (20 years moving averages) for Moscow and the corresponding computed long-term averages (straight lines).

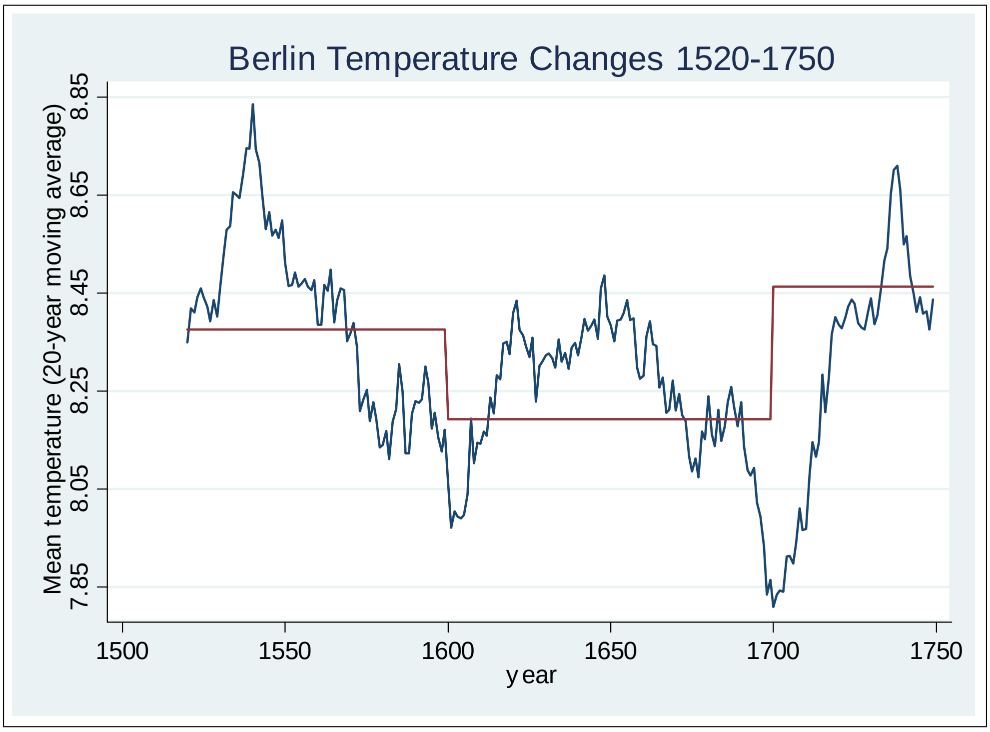

Figure 2: Note: The graph plots yearly temperatures (20 years moving averages) for Berlin and the corresponding computed long-term averages (straight lines).

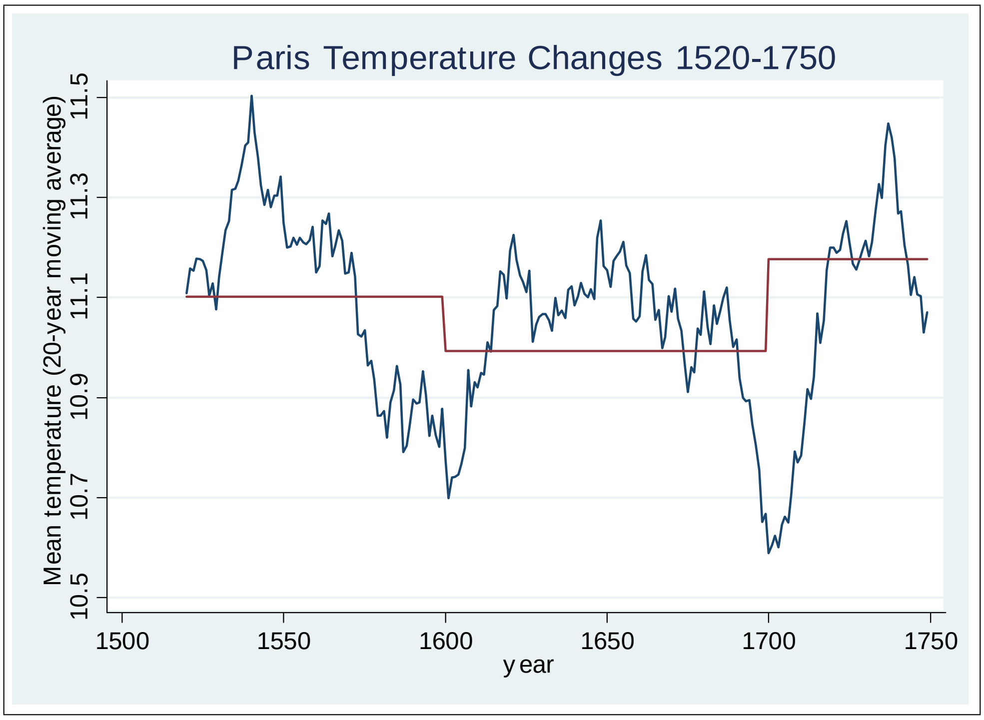

Figure 3: Note: The graph plots yearly temperatures (20 years moving averages) for Paris and the corresponding computed long-term averages (straight lines).

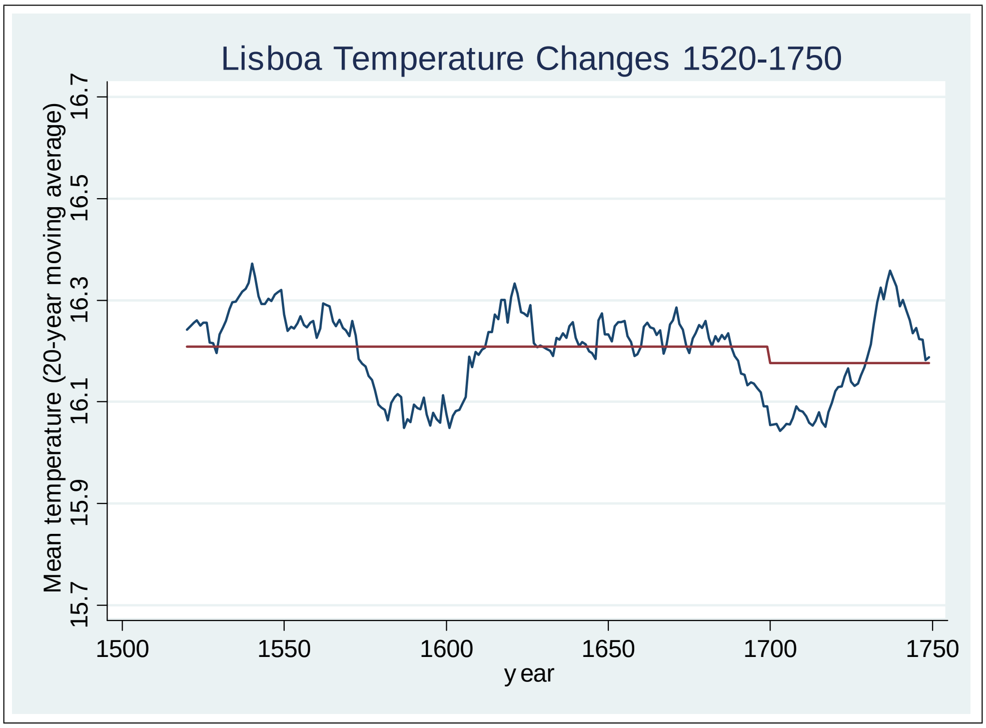

Figure 4: Note: The graph plots yearly temperatures (20 years moving averages) for Lisbon and the corresponding computed long-term averages (straight lines).

Agro-Ecological Zones (GAEZ) database (IIASA/FAO, 2012). Data on ruggedness is 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 Nüssli (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).

Summary statistics in table 1 summarize main characteristics of cities for all cities (column 1), those that experienced above average (column 2), and below average (column 3) temperature decreases. 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, has been higher in areas with higher decreases in temperature. Potato and wheat suitability has also been 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 Empirical Strategy and Main Results

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, have affected city size. To show the underlying microdata I plot city size and temperature for six cities: three capital cities and three cities from the respective country of median size in 1600. Figure 5 below plots within-city variation in temperature and city size for these six European cities: London and Dover, Paris and Bastia, Rome and Montepulciano. The solid line denotes changes in city population, the dashed line denotes changes in mean year temperature. City growth of the capital cities appears to be uninterrupted over the whole time period. Growth of the median sized cities appear to be relatively slow in the earlier time period. There appears to be no connection between temperature and city size for capital cities. For median sized cities relatively cold periods appear to be associated with periods of slower city growth.

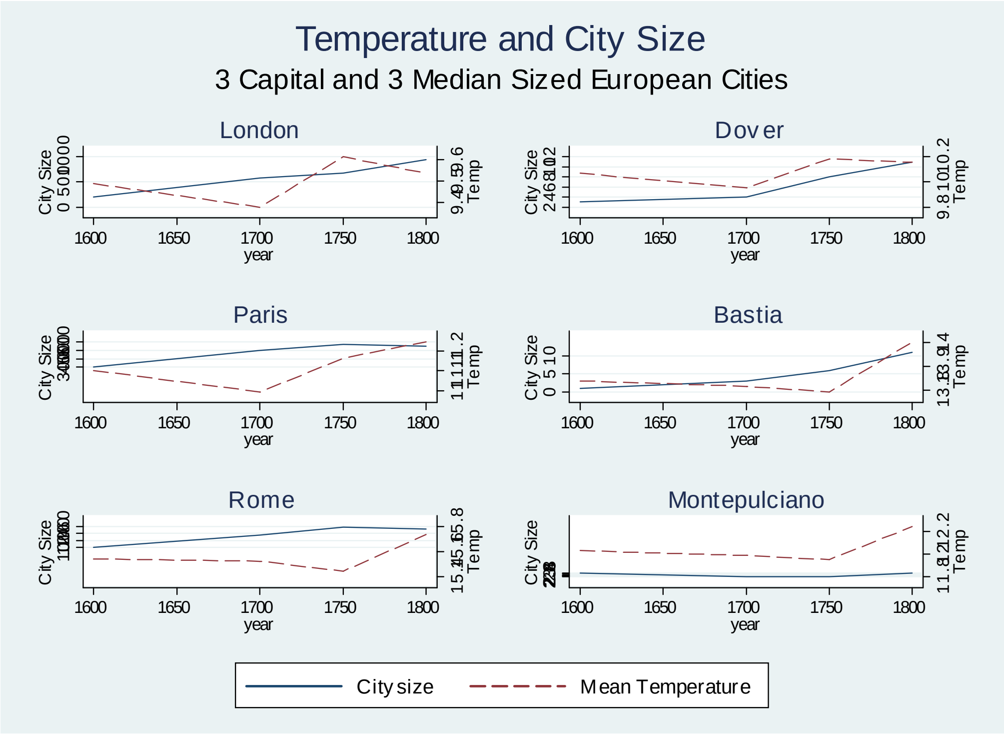

Figure 5: Variation in city size and mean year temperature between 1600 and 1800 for three European capital cities and three median sized cities in the same country: London and Dover, Paris and Bastia, Rome and Montepulciano.

Next, I examine graphically the relationship between year temperature and city size including *all* cities of the sample and conditional only on city fixed effects. The graph shows a positive relationship significant at the 1% level between temperature and city size. This implies that - on average - a temperature decrease within a city is associated with decreases in city size. The coefficient size of 0.62 implies that a one degree increase in the average temperature over 100 years is associated with a change in temperature of 62%. Note that a one degree increase in the average temperature over 100 years does not equal a one degree change in temperature. Figures 1a and 1b show that - while the difference in temperature between the warmest and coldest years lie at about 0.8 degree Celsius - the difference in average temperatures lie at around 0.2 degree Celsius. The estimated effect of the Little Ice Age for the four cities in Figures 1a and 1b (Moscow, Berlin, Paris, and Lisbon) hence lie at around a 5 to 12 percent decrease in city size due to adverse temperature changes. The graph should be interpreted with caution. As will be discussed later, other geographical or historical factors could be correlated with temperature and city size and could explain this result. In the following, I will therefore explore the relationship in greater detail.

In the baseline regression specification, I include city fixed effects and year fixed effects. I further include an array of geographical and historical control variables. Each control variable

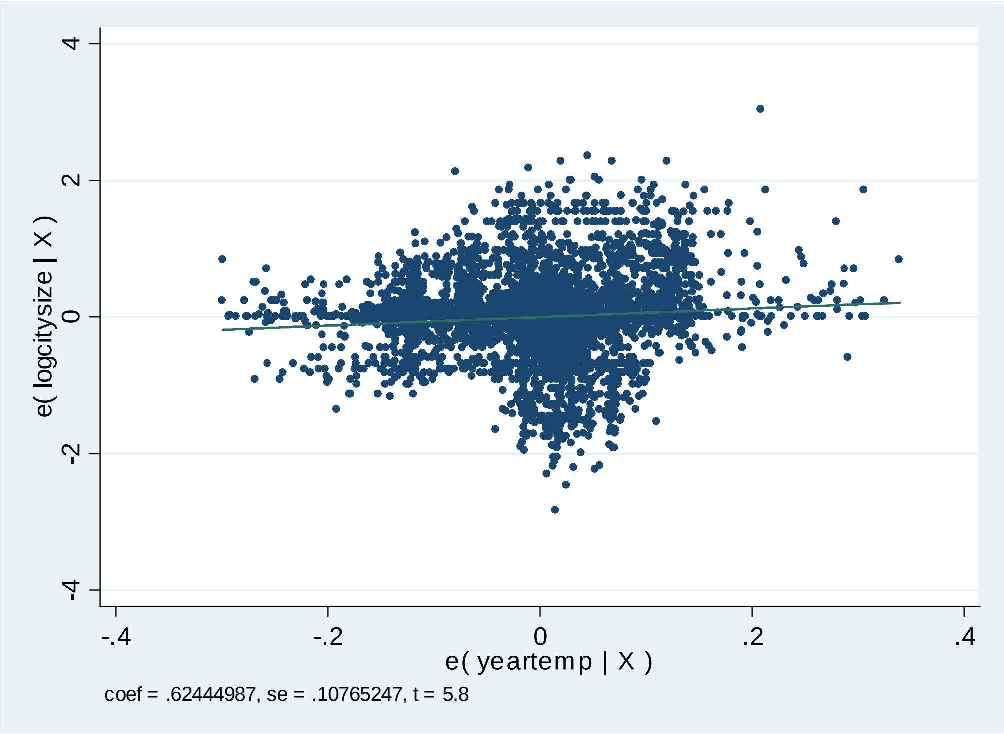

Figure 6: Note: The figure plots the relationship between city size and temperature conditional on city fixed effects.

is interacted with a full set of time period indicator variables.

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

City Size is the 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 sea 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 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. This specification estimates the effect of temperature on city size based on variation in both variables within each city conditional on year fixed effects and on control variables interacted with time period indicators. 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 five 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% level. This indicates that temperature *decreases* during the Little Ice Age had a *negative* effect on city size which is consistent with historical evidence on the negative economic effects of the Little Ice Age[12].

In columns (2) to (6), I include one-by-one several geographic control variables that may have affected city size, for example through their effects on agricultural productivity: altitude, soil suitability for potato cultivation, for wheat cultivation, as well as terrain ruggedness. Local vegetation, for example, changes with higher altitudes and increased ruggedness (e.g. Beniston et al., 1997). Nunn and Qian (2011) show the importance of (soil suitability for) potato cultivation for population growth. If these variables are 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, columns (2) to (6) show that the point estimates remain stable.

The coefficient on *Mean Temperature* is the estimated effect of a one degree increase in long-run mean temperature on city size. As can be seen from Figures 1a and 1b, even though the difference in temperature between the warmest and coldest period lie 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 on average. The estimated results indicate that temperature decreases during the Little Ice Age have decreased city size for half the cities in the sample by between 5 and 20 percent.

4.3 Controlling for Historical Determinants of Urban Growth

Results thus far show that temperature decreases of the Little Ice Age have had a negative effect on city size. This result is consistent with historical evidence on the negative effects of the Little Ice Age on economic conditions. In addition, I have controlled for a set of geographical variables that may have been correlated with both city size and temperature changes, each variable interacted with time indicator variables.

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"[13], for example the overseas trade expansion of the Atlantic powers and human capital accumulation. If temperature changes were correlated with

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[12] While current climate change is concerned about temperature increases above the temperature optimum, temperatures during the Little Ice Age dropped in most areas *below* the optimal temperature for European agriculture. For the current episode of climate change, climate researchers have also predicted that - however only in the short-term and only for very small increases - Northern European agricuture nmight benefit from mild temperature increases due to its relatively cold climate (EEA 2012: 158).

[13] 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 Noth Sea Area economies, first Holland in the 16tha nd 17th century, later Britain during the Industrial Revolution (Broadberry, 2013: 6).

these historical factors the estimated effect of temperature and city size would be biased. In the following, I therefore directly control for historical factors that have been identified as drivers of disparity in urban growth within Early Modern Europe.

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 for Atlantic traders, i.e. Great Britain, the Netherlands, Belgium, France, Spain, and Portugal.

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.

Van Zanden (2009: 12) emphasizes, among other factors, the importance of human capital accumulation for economic growth in Early Modern Europe. In the same vein, Cantoni and Yuchtman (2013) show that the establishment of universities increased the number of people trained in law which had a positive effect on economic activities in medieval Europe as it decreased the uncertainty of trade. I include an indicator variable for cities that were university cities in 1500.

Becker and Woessmann (2009) show that Protestantism had a positive effect on human capital due to its emphasis on people's ability of reading 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, among other things, the newly developing ideas on scientific research (e.g. Merriman, 2010). As 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.

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. (2013) argue that exposure to military conflict had a direct effect on urban growth as it induced people to seek protection from violence within city walls. I add a variable that measure the distance to the nearest battleground during the time period.

In column 6 of table 3, I add an indicator variable that is 1 for all cities that were part of the Roman empire. In column 7 of table 3, I add an indicator variable for all cities that were located within one kilometer of a Roman road.

Table 3 shows estimates. Column 1 of table 3 shows the baseline estimates including the geographic control variables. Columns 2 to 8 report estimates when including each alternative 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.

4.4 Robustness

4.4.1 Alternative Samples

Previous results have shown the robustness of the results to the inclusion of geographic and historical controls. An important concern, however, 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 might 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, a group of cities that de Vries (2006) 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 Alternative Time Trends

In the previous sections, I have systematically controlled for alternative factors that could explain the relationship between temperature and city size. Some of these factors 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 level time trends and country times year fixed effects. The country level linear time trends control for country level linear trends in city growth that is specific to a country, e.g. because a country's institutional setup increases city growth rates over time. The country times year fixed effects control for factors at the country level that change over time that could affect the outcome variable while being correlated with temperature changes. A country's institutions, for example, could affect its city growth. If these change over time then they are not captured by the city 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. Countries are defined as countries in 1600 according to Nussli (2012). Estimates in table 5 show that the size of the coefficient are affected by the use of different fixed effects and time trends. However, they also show a positive and important relationship between mean temperature and city size across all specifications.

4.5 Using Conley Standard Errors Assuming Spatial Autocorrelation

Table 6 shows the baseline regression estimating different standard errors. Column 1 and 2 of table 6 is the baseline specification when clustered at city level when including geographical controls (column 1) and when including geographic and historical controls (column 2). Column 3 and 4 show the same two specifications when clustering at the grid cell level of the underlying temperature data set. Temperature data is provided by grid cell (see section 3 for more detail). Each city is assigned temperature data of the grid cell that the city is located in. Different cities can have been assigned the same temperature data if they are located in the same grid cell. All cities whose temperature data has been informed by the same observation in the temperature reconstruction dataset form a cluster. Finally, column 5 and show the two specifications 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.

4.5.1 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. In the absence of a direct measure, it has been widely used as a measure of historical per capita GDP by a number of studies (e.g. DeLong and Shleifer, 1993; Acemoglu, Johnson, and Robinson, 2002, 2005) and it has been shown that urbanization has been strongly correlated with economic growth (e.g. 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 the previously introduced geographic and historical controls, each of them interacted with time period indicator variables.

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

Urbanization is defined at the country level as the number of inhabitants living in cities divided by the total population. Countries are defined as in McEvedy and Jones (1978). The measure of urbanization is available for 22 European countries and three time periods. The control variables are now defined at the country level: each country's average altitude, average potato suitability, 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 a sum of the 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 7 reports results. The first includes only year fixed effects, specification (2) adds region fixed effects. Region times year fixed effects are included in specification (3) and country fixed effects in specification (4).

Results show a robust and positive relationship between mean temperature and urbanization. With the introduction of new controls the size of the coefficient on mean temperature increases. These estimates confirm the earlier findings that showed a positive effect of mean temperature and city size. 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. One might be concerned that the insignificant results in column (4) signify that the country fixed effect, hence country-wide institutional, economic or political factors – had been driving results. In this case, however, we would also expect a drop in the size of the coefficient and not only reduced statistical significance. It is reassuring that the size of the coefficients remains positive and increases when introducing country fixed effects.

5 The Role of Agricultural Productivity

5.1 The Effect of Temperature on Wheat Prices

Historians have provided evidence that the Little Ice Age affected economic growth through its effect on agricultural productivity (e.g. Behringer, 2010: 93; Aguado, 2007: 483). The economic importance of the agricultural sector in European economies at the time also makes it plausible that temperature may have affected city size through its effect on agricultural productivity (Dennison, 2010: 148).

In this section, I test this hypothesis. I combine yearly temperature data from Luterbacher et al. (2004) with annual data on wheat prices for ten European cities from Allen (2001). Data is available for Amsterdam, London, Leipzig, Antwerp, Paris, Strasbourg, Munich, Florence, Naples, and Madrid. In this section, I use wheat prices as a proxy for agricultural productivity. As city level demand changes only gradually, yearly fluctuations in wheat prices are likely to be a reflection of 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 is therefore likely to depend primarily on temperature's effect on agricultural productivity. As people are likely to 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:

$$(3) \qquad WheatPrice_{it} = \beta + \gamma MeanTemperature_{it} + i_i + c_i + \epsilon_{irt}$$

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 8 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 as a measure of war a variable that counts 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 Sea 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 to account for the possibility that these characteristics may have had affected differently at different points in time.

The coefficient on mean temperature in column 1 is negative and significant at the 1% 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 therefore 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 results is consistent with results in table 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). The coefficient decreases only slightly and remains significant.

Then, in table 9, I estimate specification (2) for each of the ten cities separately. I regress Wheat Price in time period t on mean temperature in time period t. The ten cities in the data set are located in different climate zones within Europe it would be interesting to test whether the effect of temperature on wheat prices varies with initial climate. An increase in temperature might affect agricultural productivity differently in northern Europe, where it is relatively cold, than in southern Europe, where it is relatively warm (e.g. Olesen et al, 2002).

Column 1 contains the specification as estimated in column 1 of table 11. Columns 2 to 11 show results of regressions for each city separately. Results are shown according to latitude, showing the northernmost city, Amsterdam, first and the southernmost city, Madrid, last. For the seven northernmost cities results coefficients on temperature are negative indicating that an increase in temperature in these areas improves agricultural productivity and lowers wheat prices. For the three southernmost cities, Florence, Naples and Madrid, the coefficient on temperature is positive indicating that an increase in temperature reduced agricultural productivity and lead to an increase in wheat prices.

5.1.1 The Effect of Temperature on Yield Ratios

In this section, I introduce historical yield ratios as an alternative, more direct measure of agricultural productivity. Yield ratio is defined as ratio of the amount of harvested crop grains over the amount of crop grains used for sowing. The data is taken from Slicher van Bath (1963). The author provides crop yields by year and city during the 16th, 17th and 18th century for European countries. For each city, the number of years for which crop yield data is available varies between one and several hundred years. For certain years, information on crop yields is available from various cities within one country. For other years, data is 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. This has the advantage that cities for which crop yields are available for only one year are not omitted. The estimates are reported in table 10. In column 1, the relationship between yearly mean temperature and yield ratio is estimated with no further controls. Then, year fixed effects (column 2) and region fixed effects (column

3) are introduced into the specification. In column 4 country fixed effects are introduced into the specification following Silcher van Bath's information on the country in which each city is located. In columns 5 to 8, I add additional control variables to clarify whether it is really the link between yield ratios and weather that is of relevance here or whether other variables that were not included before could explain the estimated relationship. As described in the previous section, I control for precipitation, for the number of battles fought within one country during each year, and for a country's access to an ocean and its status as an Atlantic Trader.

$$(4) \qquad YieldRatio_{crt} = \beta + \gamma MeanTemperature_{crt} + countryFE_c + c_i + \epsilon_{irt}$$

Table 13 presents results. I estimate the effect of mean temperature on yield ratios without any control variables (column 1) and then including year fixed effects (column 2). The relationship is positive but not significant. Then, I add country fixed effects and region fixed effects in columns 3 and 4. The size of the coefficient increases and it is significant. In columns 5 to 8, as in the previous section, I control for various control variables: precipitation, how many battles took place in a country in each year, whether a country had access to the ocean or was an Atlantic trader. The coefficient size is robust to the inclusion of these controls. The standard errors also increase and the significance of the coefficient lies at 10 percent.

6 Heterogeneity in the Effect of Temperature on City Size

In this section, I explore heterogeneity in the effect of changes in temperature on city size along climatic and economic dimensions. In particular, I explore whether the effect of changes in mean temperature vary with access to trade and with initial temperature.

6.1 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 diverse. De Vries (1976: 7f.) finds that grain-growing villages were more affected by harvest failure than places with more diverse economies. Burgess et al. (2011) find that short-term temperature shocks in India only affected rural, not urban, areas because the former depended on agriculture. Burgess and Donaldson (2010) find 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 to the specification three interaction terms. 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 have more potential to specialize on 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 were an important means of reducing transportation costs. Cities located near waterways might therefore be better able to engage in 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. It had been established as an alliance between two trading cities in north Germany, Hamburg and Lübeck, that joined forces to fight piracy in the North and Baltic Sea (Merriman, 2010: 24). Later, more than 30 other cities joined it as members or as kontor cities that had constant offices of the Hanseatic league. The League granted each member 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 at the North and Baltic Sea, others, such as Cologne and Dortmund, were not. At its peak in the 14th century it controlled the sea routes of the North and Baltic Sea from London to Novgorod. In the period under study the Hanseatic League was beyond its most influential time. Yet, its members were still likely to be on average more involved in trading activities than the other European cities.

Column (1) of table 7 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 that were not part of the Hanseatic League, was significantly larger compared to bigger, better connected cities. In column (5), all interaction terms are included. The result confirms the previous results. The estimated effect of a change in mean temperature is significantly lower for relatively small cities with less access to trade. The sizes of the coefficients on the interaction terms are slightly decreased. This is consistent with the idea that the interacted variables are likely to be correlated. The size of the coefficients on the interactions is also interesting. They 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.

6.2 Climatic Heterogeneity in the Effect of Temperature on City Size

The Intergovernmental Panel on Climate Change (IPCC; Parry, 2007; Kovats, 2014) predicts that the effect of temperature change on agricultural productivity will be different in different climate zones. "In mid- to high-latitude regions [far from the equator], moderate warming benefits cereal crop and pasture yields, but even slight warming decreases yields in seasonally dry and tropical region," (Parry et al., 2007: 38)[14]. Predictions for regions within Europe yield the same pattern. It is predicted that the relatively warm region of Southern Europe will be affected negatively by even small increases in temperature. The temperate region of Northern Europe, in contrast, might even benefit from initial and small increases in warming . “Climate change is expected to impede economic activity in Southern Europe more than in other sub-regions [...] climate change is likely to increase cereal yields in Northern Europe (medium confidence, disagreement) but decrease yields in Southern Europe (high confidence),” (Kovats et al. 2014: 1271).

In this section, I test whether the effect of temperature change on city size during the Little Ice Age varies across climate zones within Europe. In their 2014 report, the IPCC divides Europe into five climate zones: Southern climate, Northern, Continental, Atlantic and Alpine climate. The warmest region within Europe is the Southern European climate zone[15].

The question arises whether this relatively warm climate zone was differently affected by temperature changes during the Little Ice Age compared to the rest of Europe. To test this hypothesis, I estimate the baseline regression (1) as described in section 4.1, but restrict the sample to cities within the Southern European climate zone.

Columns 1 to 3 of table 12 show baseline results for the whole sample city and year fixed effects, geographic controls, and historical controls. Columns 4 to 6 show results for the same specifications but the sample is restricted to cities located within the Southern European climate zone. Results indicate significant differences in the effect of temperature on city size between the two samples. The positive coefficients in columns (1) to (3) indicate that temperature decreases have had an overall negative effect on city size. The negative coefficients in columns (4) to (6) indicate that temperature decreases have had an overall positive effect on cities located within the relatively warm Southern European climate zone. This result is consistent with predictions by the IPCC (Parry, 2007; Kovats et al. 2014) that the effect of initial temperature changes will depend on an area’s climate. Again, it is important to note that these predictions only refer to initial and small changes in temperature.

6.3 Implications for current climate change

In the previous sections, I estimate the effects of long-term temperature changes on city size as an indicator for economic growth. In this section, I discuss implications of these findings for the economic effects of the current period of human-induced climate change. It is important to point out that such an exercise comes with various interpretative challenges. For example, we currently experience a period of warming, while the Little Ice Age was a period of overall cooling. Research on temperature and agricultural productivity shows, however, that a one degree decrease in temperature away from the optimum has a smaller effect compared to a one degree increase in temperature above the optimum (Schlenker et al., 2009). If this holds, then

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[14] Agronomic evidence supports this prediction. Schlenker et al. (2009), for example, find that increases in temperature up to a certain point lead to increases in yield. After reaching an optimum further increases lead to a steep decline in yield.

[15] For a map of the Southern European sub-region as defined in the IPCC report, see Kovats (2014: 1274). The region includes most of Portugal and Spain, southern France, most parts of Italy, the Balkan coast and Greece.

the estimates derived from a period of cooling are likely to be smaller compared to the estimated effects of an episode of warming and would rather under- than overestimate the economic effects of temperature change.

Next, socio-economic and political conditions of Early Modern Europe were very different compared to current-day Europe. One indicator of these differences is the declining importance of the agricultural sector and the structural transformation of the European economy as a whole. While in 1600 and 1700 43.2 and 26.8 percent of UK GDP came from agriculture, this number has shrunk to 1 percent in 2012. In certain developing countries today, however, the share of GDP from agriculture are relatively similar to shares of GDP from agriculture in Early Modern Europe. In Burkina Faso, Chad, and Mali between 35 and 56 percent of GDP come from the agricultural sector. (Broadberry et al., 2011; World Bank, 2014). Even though developing countries' economies are of course still very different from Early Modern European economies[16] these numbers show that both rely heavily on agriculture. Agricultural productivity has consistently been identified as an important mechanism through which temperature affects economic outcomes (e.g. Burgess et al., 2014). This mechanism may affect vulnerability to adverse climate change today as in the past. It is therefore plausible that estimates in the current paper can still be relevant to understanding the economic effects of current warming today, e.g. when thinking about the effects of climate change in developing countries. This paper's finding that long-term changes in temperature changes can have important economic effects, even when examining a period of 250 years, over which people are likely to adapt to the best of their ability may also apply to 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 (e.g. Dell et al. 2012).

Another approach to formulating valid implications from historical settings is to use within-sample comparison. For example, results in the present paper show important heterogeneity in the effect of temperature changes conditional on their economic structure. Cities that depend on average less on agriculture, have overall more advanced economic structures and are better connected to trade are significantly less affected by temperature changes. This theoretical mechanism is likely to be still at work today. For example, Burgess and Donaldson (2010) find that trade openness mitigates the effects of weather shocks. It is consequently plausible that the mitigating effect of trade openness still mitigates the effects of adverse long-run climate changes today as in the past.

Mindful of these interpretative challenges one might ask which implications these results hold for the effect of current global warming? In the following, I combine results on the effects of temperature changes for Southern Europe with predictions of temperature changes in Southern Region from the latest IPCC report[17]. I obtain information on predicted temperature changes for the Southern European climate region from the Atlas of Global and Regional Climate Projections

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[16] The shares of GDP from services, for example, are mostly higher than in Early Modern economies. Technical advances, such as the interenet or mobile telecommunication, lower transaction costs in most developing countries.

[17] I focus on the Southern European climate zone as already during the Little Ice Age its climate was such that the local economy benefited from temperature decreases, hence had already reached its temperature optimum. According to the IPCC, this is also true for current-day Southern Europe as well as most parts of the world with even warmer climate.

(Kovats et al., 2013: 1354ff.). Changes in the 20 year mean temperature relative to a baseline period (1986-2005) are available for the periods 2016-2035, 2046-2065, and 2081-2100. For years between these periods, I assume linearly increasing temperatures. Between 2016 and 2011 the average mean temperature (measured as 20 year moving averages) is predicted to increase by 1.35 degree Celsius. I apply the most conservative estimates derived from column 4 of table 12 and calculate the decreases in annual growth that additional warming would imply. I calculate that annual growth between 2016 and 2100 will be reduced by close to 5% per year. This result is close to the most pessimistic estimates of the impact of climate change (e.g. Stern, 2007).

Results in the previous section indicated that relatively large cities which are likely to be less dependent on agriculture were significantly less affected by temperature changes. The question arises how the predicted effects of climate change would change if one applies estimates from cities (in Early Modern Europe) with relatively advanced economies. To investigate this hypothesis I estimate the baseline specifications including only cities located in the Southern Climate Zone and include an interaction term of the dummy variable BigCity and temperature.

$$CitySize_{it} = \beta + \gamma MeanTemperature_{it} + \theta MeanTemperature \times BigCity_{it} + a_t + i_i + c_{it} + \epsilon_{it} \tag{6}$$

The variable BigCity is 1 for all cities that were larger than the median at the beginning of the study period. As before, the specification include year fixed effects a, city fixed effects, and an array of geographic and historical control variables. Table 13 reports results. Consistent with previous results the coefficient on the interaction term has a positive sign and brings the coefficient close to zero. In other words, the estimated effects of temperature changes in smaller for relatively big cities compared to relatively small cities. For comparison, I also show results for cities within temperate climate. Here, again, the effect of temperature is significantly closer to zero for big cities compared to small cities. These results indicate that a city's economic structure substantially affects its economic vulnerability to climatic change. The estimated reduction of the predicted warming until 2100 lies between 0 and 3.65 percent compared to 5% overall.

As laid out above, these results should be interpreted conditional on socio-economic conditions under which the estimates where produced, i.e. the socio-economic conditions of Southern Early Modern Europe. They should be extrapolated with caution and only if there is theoretical reason to believe that similar conditions exist or that similar theoretical mechanisms are still at work that could plausibly lead to similar heterogeneity in the effect of climate change on economic outcomes today.

7 Conclusion

This paper provides empirical evidence on the economic effects of long-term climatic change over a period of 250 years. The underlying question is whether we can still observe an effect of climatic change even if agents have time to adjust. The main findings show that climatic change does have important economic effects, even in the long-run. This implies that, under given circumstances, e.g. with high dependency on agriculture and slow technological change, adaptation is not strong enough to compensate for economic losses from agriculture. Further results indicate that agricultural productivity is an important channel through which temperature changes affect economic outcomes. Based on this finding, the paper investigates whether cities that were less dependent on agricultural productivity, i.e. relatively large cities with access to waterways or access to long-distance trade networks, were differently affected by temperature changes. Findings show that economically more advanced cities that relied less on agriculture were significantly less affected by temperature changes. Further results indicate that cities were differently affected by temperature changes depending on the climate zone they were located in. Cities with relatively warm climate benefited from temperature decreases while cities with more temperate climate were negatively affected by temperature decreases. Applied to the current situation of global warming these results indicate important heterogeneity in the economic effects of long-run climate change depending on an economy's dependency on agriculture and its current climate. This implies that the ability of many developing countries - that are characterized by high dependency on agriculture and are located in relatively warm climate zones - to counter the adverse effects of climate change might be very limited - even in the long-run.

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8 Tables

Table 1: Summary Statistics

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 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. 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 Coast								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 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 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 Coast 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 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. The sample in columns 3 and 4 is restricted to cities that were not capital cities between 1600 and 1750. Regression 3 includes cities that are located more 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 includes cities that were not 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)
Mean Temperature	0.564***	0.259**	0.526*
	(0.127)	(0.127)	(0.299)
Fixed Effects			
City FE	yes	yes	yes
Year FE	yes	yes	
Country in 1600 × Year FE			yes
Linear Time Trend			
Country in 1600		yes	
Observations	6,360	6,360	6,360
R-Squared	0.885	0.895	0.899

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 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. Country in 1600 is defined as the sovereign state that a city was located in in 1600 according to (Nussli, 2012).

TABLE 6 - Robustness Using Alternative Standard Errors

	Ln City Size					
	Clustered at...					
	City Level		**Grid Cell Level**		**Conley SE**	
	(1)	(2)	(3)	(4)	(5)	(6)
Mean Temperature	0.487***	0.483**	0.487***	0.483**	0.487***	0.483**
	(0.144)	(0.208)	(0.172)	(0.224)	(0.173)	(0.200)
City Fixed Effects	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes
Geographic Controls (× Year fixed effects)	yes	yes	yes	yes	yes	yes
Historical Controls (× Year fixed effects)		yes		yes		yes
Observations	6,360	6,360	6,360	6,360	6,360	6,360
R-Squared	0.887	0.894	0.887	0.894	0.887	0.894

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. The grid cell level refers to the grid cell of the underlying temperature data set (Luterbacher et al., 2004) 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 - The Effect of Temperature on Urbanisation

	Urbanisation (urban population as share of the entire population)			
	(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 8 - 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 left-hand-side 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 9 - The effect of yearly temperature on yearly wheat prices

	Wheat Prices (grams of silver per kg)										
	All Cities	**Amsterdam**	**London**	**Leipzig**	**Antwerp**	**Paris**	**Strasbourg**	**Munich**	**Florence**	**Naples**	**Madrid**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Mean Temperature	-0.110***	-0.0908**	-0.140**	-0.0214	-0.110	-0.126***	-0.0354	-0.0401	0.118**	0.251***	0.0276
	(0.0215)	(0.0373)	(0.0575)	(0.0315)	(0.0707)	(0.0413)	(0.0462)	(0.0428)	(0.0552)	(0.0530)	(0.0771)
City Fixed Effects	yes										
Year Fixed Effects	yes										
Observations	2,111	282	425	215	133	355	361	316	307	248	278
R-Squared	0.663	0.021	0.014	0.002	0.018	0.026	0.002	0.003	0.015	0.084	0.000

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 left-hand-side variable is the yearly wheat price in grams of silver. 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/Florence (1500-1860), Naples (1514-1803), Madrid (1501-1800). Mean temperature is annual year temperature. Regression 1 includes the complete sample. Regressions 2 to 11 include one city. Robust standard errors are in parentheses and clustered at city level.

TABLE 10 - The effect of yearly temperature on yearly yield ratios

	Yield Ratios							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Mean Temperature	0.182 (0.285)	0.139 (0.282)	0.499** (0.162)	0.430*** (0.111)	0.459*** (0.112)	0.451*** (0.112)	0.434** (0.142)	0.543* (0.259)
Year Fixed Effects		yes	yes	yes	yes	yes	yes	yes
Region fixed Effects			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	702	702	702
R-Squared	0.017	0.321	0.732	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 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 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. 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 - Exploring Climatic Heterogeneity

	Ln City Size					
	All Cities			**Cities with Southern Climate (IPCC, 2014)**		
	(1)	(2)	(3)	(4)	(5)	(6)
Mean Temperature	0.564***	0.487***	0.483**	-0.790**	-1.237***	-1.390***
	(0.127)	(0.144)	(0.208)	(0.377)	(0.443)	(0.408)
City Fixed Effects	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes
Geographic Controls (× Year fixed effects)		yes	yes		yes	yes
Historical Controls (× Year fixed effects)			yes			yes
Observations	6,360	6,360	6,360	2,367	2,367	2,367
R-Squared	0.885	0.887	0.894	0.933	0.936	0.938

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 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. Columns(1) to (3) include baseline results. Columns (4) to (6) include results for the same specification as in columns (1) to (3) except that the sample has been restricted to cities located in the Southern European Climate Zone as defined in Kovats et al. (2014). The Southern European climate zone includes most of Portugal and Spain, southern France, most parts of Italy, the Balkan coast and Greece.

TABLE 13 - Economic Heterogeneity by Climate Zone

	Ln City Size					
	Cities with Southern Climate (IPCC, 2014)			**Cities with Temperate Climate (IPCC, 2014)**		
	(1)	(2)	(3)	(4)	(5)	(6)
Mean Temperature	-1.570***	-2.002***	-2.043***	0.733***	0.737***	1.085***
	(0.519)	(0.550)	(0.520)	(0.256)	(0.268)	(0.305)
Mean Temperature *BigCity	1.719***	1.686***	1.411**	-1.003***	-0.822***	-0.723***
	(0.611)	(0.613)	(0.607)	(0.204)	(0.199)	(0.219)
City Fixed Effects	yes	yes	yes	yes	yes	yes
Year Fixed Effects	yes	yes	yes	yes	yes	yes
Geographic Controls (× Year fixed effects)		yes	yes		yes	yes
Historical Controls (× Year fixed effects)			yes			yes
Observations	2,367	2,367	2,367	3,993	3,993	3,993
R-Squared	0.933	0.936	0.939	0.862	0.865	0.874

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 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. Columns(1) to (3) include results for the Southern European climate zone as defined in Kovats, 2014. Columns (4) to (6) include results for the same specification as in columns (1) to (3) except that the sample includes all cities located outside the Southern European climate zone. An interaction term MeanTemperature*BigCity has been added to all specification. It is an interaction between MeanTemperature and the dummy variable BigCity that is 1 for all cities larger than the median city in 1600.

9 Appendix

TABLE A1 - Robustness to different outcome variables

	Log city size (500) (1)	**Log Citysize (1)** (2)	**Log Citysize (1000)** (3)	**Number of inhabitants (absolute numbers)** (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.