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

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Recent studies consistently find important economic effects of year-to-year weather fluctuations. I study the economic effects of long-term and gradual climate change over 250 years in the Little Ice Age (1600–1850), during which people and economies had time to adapt. Results show significant negative economic effects of long-term climate change. Temperature impacted the economy through its effect on agricultural productivity and mortality. To adapt to the Little Ice Age, economies increased trade and changed land use. I discuss the relevance of these results for understanding the impact of today's climate change, especially in developing countries.

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

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

The Little Ice Age brought a significantly colder climate to large parts of Europe.[4] It is the most recent climatic episode preceding the current human-induced period of climate change. It represents the largest temperature change since the beginning of recorded history (Aguado and

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

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

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

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

Burt 2007, 483). Historical evidence suggests that the Little Ice Age affected numerous outcomes in various parts of Europe. Harvest failure in the Czech Republic and Switzerland in the 1770s has been linked to adverse weather (Pfister and Brázdil 2006), the heights of military recruits in Bavaria in the eighteenth century were affected by lower temperatures (Baten 2002), and witch hunts increased in Switzerland and Germany during periods of particularly adverse weather conditions between the sixteenth and eighteenth centuries (Behringer 1999; Oster 2004).

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

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

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

In section IV, I study three mechanisms through which temperature may have affected city size: the effect of temperature on agricultural productivity, on mortality, and on migration. To investigate the Little Ice Age's effect on agricultural productivity, I estimate the effect of temperature on

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

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

yield ratios and wheat prices.[7] The cooler temperatures during the Little Ice Age decreased yield ratios and increased wheat prices.[8]

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

Another important question in the climate change debate is to understand how economies adapt to climate change. Following Costinot, Donaldson, and Smith (2016), I examine two important adaptation strategies: adaptation through trade and adaptation through changes in land use.[9] To examine whether economies adjusted trade in response to the Little Ice Age, I collect data from the Sound Toll Registers on 900,000 ship passages to 750 European destinations between 1591 and 1857 (STR 2018). I show that trade volumes increased in response to cooler temperatures. These results are driven by cooler temperatures during the growing season. I then examine heterogeneity in the economic effects of temperature change on city size and show that the effects of temperature change were significantly smaller for cities that participated in long-distance maritime trade compared with those that did not. This effect is driven by cities with a relatively high number of trading partners.

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

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

[8] Lower yield ratios mean that less grain was harvested per grain sown. Because city-level demand changes only gradually, yearly fluctuations in wheat prices offer a plausible reflection of changes in supply.

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

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

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

This paper contributes to studies examining the economic impacts of climate change using historical data (Behringer 1999; Berger and Spoerer 2001; Baten 2002; Oster 2004; Pfister and Brázdil 2006; Kelly and Ó Gráda 2010;[10] Olmstead and Rhode 2011; Turner et al. 2012; Anderson, Johnson, and Koyama 2017) and using modern data.[11] Deschenes and Greenstone (2007, 2012), Dell, Jones, and Olken (2012), Burgess et al. (2017), Burke et al. (2018), and Diffenbaugh and Burke (2019) find negative effects of year-to-year changes in temperature on economic and noneconomic outcomes. My results contribute to this literature by showing that long-term and gradual temperature changes may also have an economic impact.

This study also contributes to work on adaptation to climate change using modern data. Barreca et al. (2015, 2016) show that the effect of an additional very hot day in US regions with a hot climate is substantially smaller compared with the effect of an additional very hot day in a US region with a cooler climate. The difference in effect sizes has shrunk over the course of the twentieth century but has not disappeared. Hsiang (2010) shows that cyclones cause less damage per cyclone in countries that have historically been exposed to cyclones more often but that adaptation to changes in cyclone risk is minimal. Burke and Emerick (2016) find little adaptation to climate change in US agriculture, there is slow adoption of energy efficiency programs (Fowlie, Greenstone, and Wolfram 2015), and patterns of migration poorly adapted to increased flooding (Boustan, Kahn, and Rhode 2012). Carleton et al. (2018) show that higher income reduces climate impacts, indicating that economies with higher incomes are better at adapting to climate change. Since the studies use modern data, their results are likely to be informative of effect sizes and future impacts. Overall, these papers show that economies are adjusted

[10] The existence of the Little Ice Age has been debated (e.g., Büntgen and Hellmann 2013; Kelly and Ó Gráda 2013, 2014a, 2014b). In this paper, I identify effects on city size using temperature changes from the long-term mean at the city level. Whether these temperature changes qualify as a separate climatic period at the European scale does not affect the interpretation of my results.

[11] A number of papers in urban economics estimate the effect of temperature on city size (Glaeser, Kolko, and Saiz 2001; Rappaport and Sachs 2003; Rappaport 2007). While this literature analyzes the effect of temperature as an amenity, this paper analyzes the effect of temperature as a factor in the economy's production function.

to long-term climatic conditions but respond slowly to change in these conditions. My study contributes to this literature by documenting that adaptation through trade took place in the long run and that it effectively shielded cities from the negative impacts of adverse climatic change. These results chime with work by Burgess and Donaldson (2010) that explores trade and resilience to adverse weather and climate.

A general drawback of empirical studies is the limited ability to extrapolate to other time periods or world regions. Based on an extensive data-collection effort, Carleton et al. (2018) produce estimates and predictions of current and future climate impacts on mortality at a global scale while also taking into account costs and benefits of adaptation. The paper thereby unites the virtues of IAMs (global coverage and predictions of future impacts) and the virtues of empirical approaches (estimates based on econometric measurement).

The remainder of the paper is organized as follows: section I provides historical background on the Little Ice Age and on urban growth in early modern Europe. Section II describes the data. Section III introduces the estimation strategy and presents the main results. Section IV examines mechanisms through which temperature's effect on city size has operated by focusing on temperature's effects on agricultural productivity, mortality, and migration. Section V investigates evidence on adaptation to temperature change by examining whether economies adjust trade and land-use patterns in response to temperature changes and whether the effect of temperature on city size varies with a city's access to trade. Section VI concludes.

I. The Little Ice Age

The Little Ice Age was a climatic period from about 1400 to 1900 that brought a colder climate to Europe (Cronin 2009, 298).[12] It is the most recent period of climatic change before the current period of human-induced warming. In Europe, average annual temperatures fell by about 0.5°–1°C.[13] Figure 1 shows the Little Ice Age in the context of temperatures over the past 2,000 years (adapted from Moberg et al. 2005). Temperatures started decreasing at around 1400, marking the beginning of the Little Ice Age.[14] At 1500, when my temperature data start, the Little

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

[13] This is the equivalent of a fall in temperature of 1°–2°F.

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

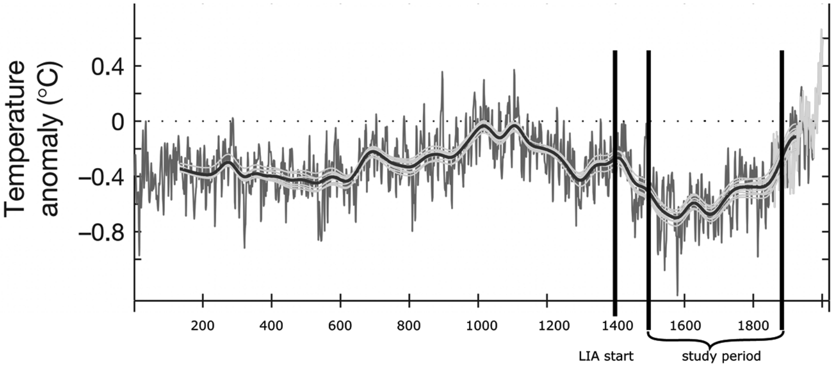

FIG. 1.—Temperature over the past 2,000 years. This figure shows the temperature graph "Estimations of Northern Hemisphere Mean Temperature Variations" from Moberg et al. (2005) with some modifications: a vertical black bar "Little Ice Age (LIA) start" and two black bars "study period" (this is the time period for which I have temperature data), and years on the *x*-axis have been added. In the original article, the graph is part of a larger graphic.

Ice Age had begun; 1600 and 1700 both mark temperature lows. For cities in my sample, temperatures during the seventeenth century were lower compared with temperatures during the sixteenth century (see figs. 2, A.2; figs. A.1–A.6 are available online). After 1700, temperatures reverted and reached the pre–Little Ice Age mean over the course of the nineteenth century.

Other world regions besides Europe were also affected—for example, China, Japan, India, and west Africa (e.g., Zhang et al. 2007 and Fan 2010 for China; Grove 2004, 560; Cronin 2009, 300; Parker 2013). The Little Ice Age has been linked to decreases in agricultural productivity (Baten 2002; Pfister and Brázdil 2006) and to social unrest. Witch hunts reappeared in parts of Europe, especially during the coolest periods of the Little Ice Age (Behringer 1999; Oster 2004).

There is debate among climatologists about the causes of the Little Ice Age, but reduced levels of energy emitted by the sun and increases in volcanic activity mattered.[15] Historical evidence shows that many people noticed signs not only of year-to-year temperature change but of long-term temperature change. Glaciers expanded; tree lines in the high Alps fell; high mountain pastures had to be abandoned. Peasants everywhere noticed delays in fruit blossoming and delays in the beginning of growing periods, haymaking seasons, or the grape-ripening period (Behringer 2005, 93–94). Larger land estates kept meticulous records of such key

[15] Low levels of solar energy were caused by a reduced number of sunspots (Eddy 1976, 1189). High volcanic eruptions cool the surface of the earth by sending large quantities of sulfate gases into the atmosphere. These scatter solar radiation back to space (Cronin 2009, 300–309).

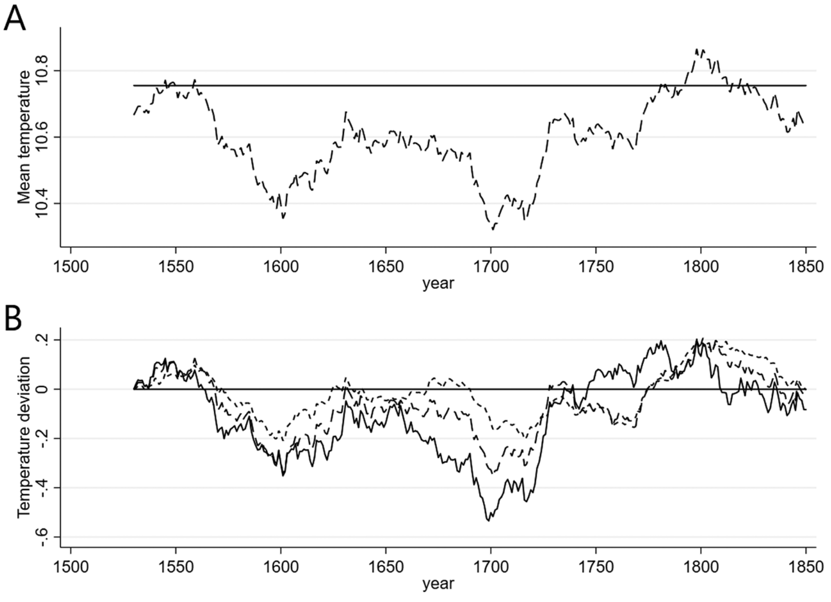

Fig. 2.—Temperature variation over the study period. *A*, Mean temperature (30-year moving average) over the course of the study period (dashed line). The solid line is the temperature mean from 1900 to 1950, after the end of the Little Ice Age and before the onset of global warming. *B*, Changes in the long-term mean in temperature for three groups of cities: cities with strong cooling (below the 25th percentile in temperature change; solid line) and with weak cooling (above the 75th percentile in temperature change; short-dashed line) and cities with moderate cooling (between the 25th and 75th percentile in temperature change; long-dashed line) in the seventeenth century. The solid line is the temperature mean from 1500 to 1530 from which temperature deviations are measured.

dates; smaller estates and peasants used reference points during the ecclesiastical calendar to keep track of them. Even small changes in these key dates had potentially large effects on living standards—for example, when shorter growing periods reduced the harvest.[16]

II. Data

The main data set for this paper is a balanced panel of 2,120 European cities. Its two key components are data on annual temperature for Europe

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

for each year since 1500 from Luterbacher et al. (2004) and data on city size in 1600, 1700, 1750, 1800, and 1850 from Bairoch (1988).

I use the size of European cities as a proxy for economic growth. The data include European cities that had more than 5,000 inhabitants at least once between 800 and 1850. The final data set includes 2,120 cities.[17]

The temperature data are reconstructed temperatures taken from Luterbacher et al. (2004).[18] The data contain annual gridded seasonal temperatures for European land areas. Each grid cell measures 0.5° × 0.5°, which corresponds to an area of about 50 km × 50 km (ca. 30 miles × 30 miles) in Europe. I assign temperature data to each city based on the temperature grid cell in which the city is located. The temperatures in this data set have been reconstructed based on temperature proxies (tree ring series, ice cores, ocean and lake sediments), historical records, and directly measured temperature for later years (Luterbacher et al. 2004, 1500).

I combine the two data sets as follows: city size is available in 1600, 1700, 1750, 1800, and 1850. For each time period, I calculate local mean temperature over the preceding 100 or 50 years.[19]

$$\text{If } t = 1600 \text{ or } t = 1700, \text{ Mean Temperature}_{it} = (\Sigma_{n=1}^{100} \text{Temperature}_{it-n})/100.$$

$$\text{If } t = 1750,\ t = 1800, \text{ or } t = 1850, \text{ Mean Temperature}_{it} = (\Sigma_{n=1}^{50} \text{Temperature}_{it-n})/50.$$

Figure 2*A* depicts average temperature over the course of the study period. The data span the period 1500–1850—the period when temperature decreased (ca. 1500–1700) and started going up again (ca. 1700–1850), reaching pre–Little Ice Age mean temperature over the course of the

[17] The original data set includes 2,191 cities. I drop 71 because temperature data are not available: nine cities are located outside of Europe, and 62 cities are located east of 40°E longitude. I use a version of the data set by Voigtländer and Voth (2012). They use linear interpolation to fill missing values for time periods between nonzero values. Furthermore, Bairoch records city size of cities below 1,000 inhabitants as having zero inhabitants. When using the natural log of city size as the outcome variable, I assume that cities below 1,000 inhabitants have 500 inhabitants. This is a realistic assumption, as the large majority of European cities were founded in antiquity, the High Middle Ages, or the late Middle Ages.

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

[19] The time periods are of different lengths due to the structure of the city size data. I examine whether results may be affected by differences in time periods and show main results weighted by time period lengths in table A.2 (tables A.1–A.8 are available online). The coefficient sizes and significance levels of results remain very similar.

nineteenth century. Figure 2*B* depicts the average temperature changes for three groups of cities: those experiencing strong, moderate, and weak cooling during the seventeenth century. Figure A.1 shows city-level temperature curves for 12 major European cities. The graphs show that cities were differently affected by cooling.[20]

Data on control variables are obtained as follows: data on local potato suitability, wheat suitability, and altitude are taken from the Food and Agriculture Organization (FAO)'s Global Agro-Ecological Zones (GAEZ) database (FAO 2012). Data on ruggedness are taken from Nunn and Puga (2012). Location of the Roman road network is taken from the Digital Atlas of Roman and Medieval Civilizations (McCormick et al. 2014). Data on country borders in early modern Europe and the extent of the Roman Empire in year 1 CE and information on the location of rivers in premodern Europe are taken from Nüssli (2016). Information on the spread of the Protestant Reformation in 1600 has been collected from Haywood et al. (2000). In sections IV and V, I introduce six more data sets for which I provide details in the respective section.

Summary statistics in table 1 show characteristics for all cities (col. 1), for those that experienced strong cooling (col. 2), and for those that experienced weak cooling (col. 3). Roughly 80% of cities in my sample experienced temperature decreases between the sixteenth and seventeenth centuries. For the remaining cities, average temperature change remained close to zero (<0.016°C; see fig. A.2). The table indicates that cities with strong cooling were larger in 1600 and were located in regions with initially warmer climates. City growth was higher in areas with stronger cooling. Geographic variables indicate relatively long distances to the ocean, higher potato and wheat suitability, and more cities being Protestant. If one found a positive effect of relatively large temperature decreases, one might be concerned that this effect could be due to these initial differences. The main results, however, indicate the opposite, that city growth was slowed down by relatively cold temperatures.

III. The Effect of Climate Change on Economic Outcomes—Empirical Strategy and Main Results

To examine whether temperature changes during the Little Ice Age (between 1600 and 1850)[21] affected city size, I use the panel data set for

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

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

TABLE 1
Summary Statistics

	All Cities (1)	Cities with Strong Cooling (2)	Cities with Weak Cooling (3)
City size in 1600	5.680	4.898	6.471
	(14.617)	(13.977)	(15.195)
Mean temperature in 1600	9.255	6.658	11.850
	(3.589)	(1.635)	(3.098)
City growth, 1600–1850	13.051	17.589	8.514
	(55.198)	(74.928)	(21.001)
Geographic control variables:			
Altitude	238.804	142.622	335.351
	(262.043)	(143.435)	(313.607)
Ruggedness	.126	.069	.183
	(.161)	(.081)	(.197)
Potato suitability	29.724	35.344	24.083
	(16.509)	(18.028)	(12.508)
Wheat suitability	43.273	49.189	37.334
	(22.018)	(22.880)	(19.383)
Historical control variables:			
Protestant Reformation:			
Catholic	.638	.414	.863
	(.481)	(.493)	(.344)
Lutheran	.126	.252	.000
	(.332)	(.434)	(.000)
Calvinist/Huguenot	.121	.110	.132
	(.326)	(.313)	(.339)

Note.—Data on city size, temperature, and control variables were collected from various sources as described in sec. II. Cities with strong cooling are cities that experienced a relatively large (above-median) decrease in long-term mean temperature from the sixteenth to the seventeenth century. Cities with weak cooling are cities that experienced a relatively small (below-median) decrease in long-term mean temperature between the sixteenth century (when my data start) and the height of the Little Ice Age in the seventeenth century.

2,120 European cities described in the previous section.[22] First, I examine the relationship between temperature and city size graphically, including all cities of the sample and conditional on city and time period fixed effects and geographic control variables. Figure 3 shows a positive relationship between temperature and city size. In the context of the Little Ice Age, this implies that a temperature decrease within a city is associated with decreases in city size.

In the baseline regression specification, I include city fixed effects, time period fixed effects, and an array of geographical and historical

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

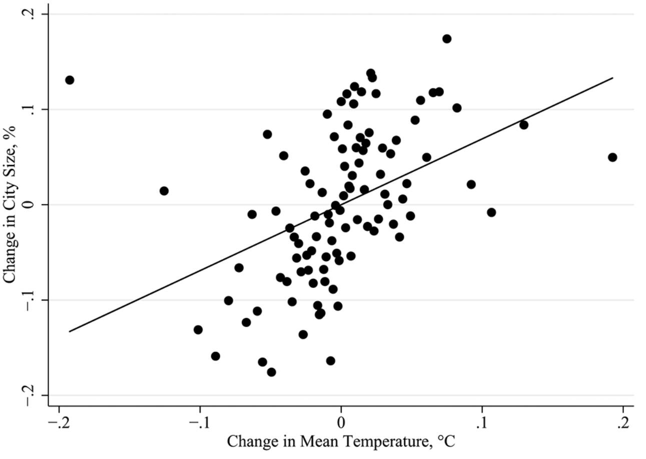

FIG. 3.—Change in mean temperature versus change in city size. This figure displays a binned scatterplot corresponding to the estimates from column 2 of table 2. I residualize log City Size and mean temperature with respect to city fixed effects, time period fixed effects, historical, and geographic control variables using an ordinary least squares regression. I then divide the sample into 100 equally sized groups and plot the mean of the *y*-residuals against the mean of the *x*-residuals in each bin.

control variables. Each control variable is interacted with a full set of time period indicator variables:

$$\begin{aligned} \log \text{City Size}_{it} = {} & \beta + \gamma \text{Mean Temperature}_{it} + \text{Time FE}_t \\ & + \text{City FE}_i + \delta X_{it} + \epsilon_{it}, \end{aligned} \tag{1}$$

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

A. *Standard Errors*

I report three types of standard errors for the main results in table 2: (1) standard errors assuming both spatial and serial correlation (following

TABLE 2

TEMPERATURE AND CITY SIZE

	log CITY SIZE					
	(1)	(2)	(3)	(4)	(5)	(6)
Mean temperature	.532	.724	.749	.931	.842	1.17
Standard error clusters:						
Assuming spatial and serial autocorrelation	(.262)**	(.268)***	(.269)***	(.328)***	(.265)***	(.429)***
Two-way (city and region × time period)	(.281)*	(.282)**	(.283)**	(.323)***	(.276)***	(.465)**
Temperature grid	(.193)***	(.212)***	(.213)***	(.274)***	(.211)***	(.386)***
Control variables:						
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Time period fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Country in 1600 linear time trend					Yes	
Country in 1600 × time period fixed effects						Yes
Historical controls (× time period fixed effects)	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls (× time period fixed effects)		Yes	Yes	Yes	Yes	Yes
Sample	All	All	Excluding capital cities	Excluding ocean cities	All	All
Observations	10,600	10,600	10,510	8,395	10,600	10,600
R^2	.767	.769	.759	.766	.779	.783

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

* $p < .1$.

** $p < .05$.

*** $p < .01$.

Conley 2008), (2) two-way clustered standard errors at the temperature grid level and the region × time period level, and (3) standard errors clustered at the temperature grid level of the underlying temperature data. The Conley spatial-serial standard errors assume standard errors to be spatially correlated within a radius of 400 km from each city and serially correlated across all time periods. The correlation is assumed to be linearly decreasing with distance and to be zero beyond the cutoff.[23] The two-way clustered standard errors are clustered at the temperature grid level and the region × time period level, where region indicates one of 10 European regions. The two-way clustered standard errors account for both spatial and serial correlation. Finally, I report standard errors clustered at the grid level of the underlying temperature data, as is commonly done in related papers using historical panel temperature data (e.g., Anderson, Johnson, and Koyama 2017).

The advantage of the Conley spatial-serial standard errors is that they assume spatial correlation within 400 km of each city. This may be preferable to assuming spatial correlation within a region, particularly for cities close to a region's border. The city of Strasbourg, for example, has been a major European crossroads since the thirteenth century and has been closely connected to the urban centers in nearby Belgium, Luxembourg, and the Germanic Holy Roman Empire. In addition, political borders vastly change over the course of my study period. Strasbourg, for example, has been part of both the German Holy Roman Empire and France at different points in time.[24]

B. *Controlling for Historical Determinants of City Size*

It is well established that economic and urban growth have been highly uneven across Europe, with especially high growth in northwestern Europe. I therefore include a range of historical control variables to account for drivers of urban growth within early modern Europe—for example, the overseas trade expansion of the Atlantic powers, human capital accumulation, the spread of Protestantism, and legacies of the Roman Empire (see app. A.2 [available online] for more information on historical control variables). If temperature changes were correlated with these historical factors, the estimated effect of temperature and city size would be biased unless these are included as control variables.

[23] Results are robust to choosing larger or smaller cutoffs (see table A.1).

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

C. Main Results

Table 2 reports results. The coefficient of interest is γ. It is the estimated effect of a 1°C increase in long-run mean temperature on city size conditional on control variables. The identification relies on the assumption that temperature changes are not correlated with other determinants of city size besides those that are controlled for.

The coefficient in column 1 is 0.532. The positive sign of the coefficient shows a positive relationship between mean temperature and city size. In other words, the finding indicates that relatively cool temperatures during the Little Ice Age had a negative effect on city size. This is the effect of experiencing cooler temperatures during periods of overall cooling (1500–1700) and during the period when cities came out of the Little Ice Age (1700–1850) and hence the effect of experiencing cooler temperatures for longer.

The coefficient indicates that a 1°C decrease in long-term mean temperature decreased city size by around 70%. To interpret the size of the coefficient, it is important to note that this coefficient is estimated based on long-term changes in temperature, which are substantially smaller than the difference in temperature between the warmest and the coldest year. The city with the largest decrease in long-term temperature from the sixteenth to the seventeenth century experienced a decrease of 0.28°C. Hence, this city would experience a decrease in city size due to temperature of 19.6% over a 100-year period. A decrease in temperature of 1 standard deviation decreased city size by 5% over a 100-year period.[25]

City size is used here as a proxy for economic growth. While the exact relationship between city size and economic growth in the early modern period is not known, Glaeser (1993) shows a correlation between city size and economic growth (measured as income growth) of 0.39 for American cities between 1960 and 1990. If the relationship was of a similar size in early modern Europe, then the result that a 1°C change in long-term temperature changes city size by around 70% translates into the result that a 1°C temperature change changes economic growth by 27%. This is roughly similar to Burke, Hsiang, and Miguel (2015), who find a 25% change in global GDP per capita for a temperature change between 1° and 2°C (pooled response, long-run effect) and decreases of around 80% in GDP per capita after 100 years for the poorest 20% of countries if temperatures increase by 4°–5°C by 2100 (under the "business as usual" Representative Concentration Pathway [RCP] 8.5/Shared Socioeconomic Pathway [SSP] 5 scenario).

[25] This is the standard deviation of the decrease in temperature from the sixteenth to the seventeenth century, which was the time period of the starkest temperature decreases during the Little Ice Age.

D. *Controlling for Geographic Determinants of City Size*

To further test the robustness of results, I include several geographic control variables in column 2 of table 2: altitude, soil suitability for potato cultivation, soil suitability for wheat cultivation, and terrain ruggedness. These may have affected city size through their effects on agricultural productivity.[26] Each variable is interacted with time period indicator variables to allow for time-varying effects of these variables. The coefficient increases with the inclusion of these controls, indicating that a 1 standard deviation decrease in temperature decreased city size by 7.3% over a 100-year period.

In columns 3 and 4, I exclude cities from the sample that may have been especially fast growing—namely, capital cities and cities located on the coast. The results remain robust. In columns 5 and 6, I show that the results are robust to including country-level time trends and to including country × time period fixed effects in the model. Countries are defined as countries in 1600 according to Nüssli (2016). The country-level linear time trends control for linear trends in city growth that are specific to a country—for example, because a country's institutional setup led to higher or lower city growth over time. The country × time period fixed effects control for factors at the country level that change over time and could affect the outcome variable—for example, a country's openness to trade.[27]

E. *Alternative Functional Forms of the Temperature Variable*

In the previous section, I estimated a linear effect of temperature on city size. A number of papers show that a temperature change toward the extremes of the temperature distribution can have especially harmful effects (Burgess et al. 2017). In this section, I estimate nonlinear temperature effects. Specifically, I measure the fraction of years over the past time period (50 or 100 years) during which the mean temperature fell within a specific temperature bin (e.g., below 0°, 0°–1°, 1°–2°C, etc.). London, for example, experienced 1 year with temperatures below 8°C, 21 years with temperatures between 8° and 9°C, 61 years with temperatures between 9° and 10°C, and 17 years with temperatures between 10° and 11°C between 1600 and 1700. Figure 4 plots coefficients on these

[26] Local vegetation, e.g., changes with higher altitudes and increased ruggedness (Beniston, Diaz, and Bradley 1997). Nunn and Qian (2011) show the importance of soil suitability for potato cultivation.

[27] Results in app. A.4 also show that estimates change little when weighing by city population or time period length.

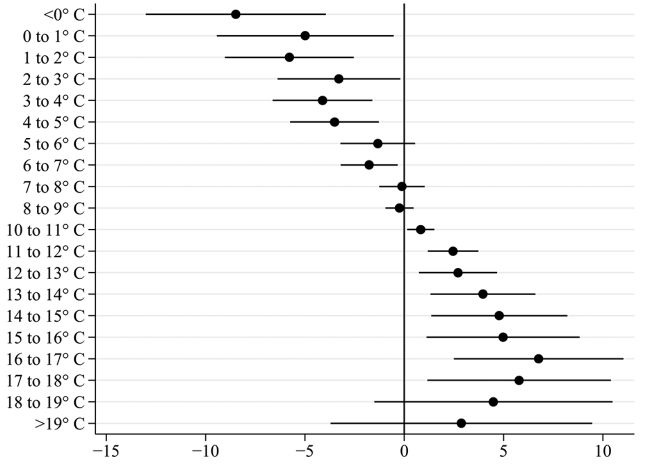

FIG. 4.—Estimated impact of the fraction of years per time period with mean temperature in a certain temperature bin. This figure plots coefficient sizes and confidence intervals of a regression of log city size on 20 temperature variables. Each variable measures the fraction of years over the past time period (50 or 100 years) during which the mean temperature in city *i* fell within a specific temperature bin (e.g., below 0°, 0°–1°, 1°–2°C, etc.). Temperature bin 9°–10°C is omitted as a reference category.

temperature variables. Temperature bin 9°–10°C is omitted as a reference category. The results indicate that a larger fraction of cooler years is correlated with smaller city sizes. Cities with a large fraction of very cold years experienced the smallest growth, and the effect on city size increases almost linearly with temperature until about 17°C. Above 17°C, the effect of temperature on city size declines, with the estimated effect of temperatures above 19°C being negative but not significant, suggesting that a large fraction of very hot years was not positive for city growth. These results show that the relationship between temperature and city size is indeed driven by the negative effect of especially cold years. Figure 4 also indicates that a linear functional form fits the temperature–city size relationship very well for the largest part of the temperature distribution.

IV. Why Does a Change in Temperature Affect City Size?

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

A. *The Role of Agricultural Productivity—The Effect of Temperature on Yield Ratios and Wheat Prices*

In a European climate, temperature is the most important determinant of the duration of the yearly growing period (Olesen and Bindi 2002, 243). During the Little Ice Age, temperature levels needed for plant growth were reached later in the year, which shortened growing seasons in Europe (Aguado and Burt 2007, 483). In England, for example, growing seasons were 5 weeks shorter in the seventeenth century compared with the thirteenth century (Grove 2004, 629).

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

The data on yield ratios are taken from Slicher van Bath (1963). The author provides a panel of crop yield data by year and location from the sixteenth to the nineteenth centuries for locations in 12 European countries.[28] Yield ratio is the ratio of harvested crop grains to crop grains used for sowing. A higher yield ratio indicates higher agricultural productivity. I define three temperature variables based on the temperature data from Luterbacher et al. (2004): yearly mean temperature, growing-season temperature, and nongrowing-season temperature. I also include Access to Ocean and Atlantic Trader (interacted with time period indicator variables) as control variables.[29]

I first regress yield ratio in location l and year τ on mean temperature in location l and year τ. I include location fixed effects for each location l and decade fixed effects for each decade d, as well as control variables interacted with decade fixed effects d:[30]

$$\begin{aligned}\text{Yield Ratio}_{l\tau} = \beta &+ \gamma\text{Temperature}_{l\tau} + \text{Location FE}_l + \delta X_{ld} \\ &+ \text{Decade FE}_d + \epsilon_{l\tau}.\end{aligned} \tag{2}$$

Results in column 1 of table 3 show that higher temperatures in 1 year are associated with higher yield ratios in the same year. A 1 standard

[28] Locations include different types of settlements, such as cities, land estates, and landholding monasteries.

[29] Access to Ocean is an indicator variable that is one for all cities located less than 10 km from the ocean. Atlantic Trader is an indicator variable that is one for all locations in countries engaging in Atlantic trade.

[30] The limited data availability for many years does not allow for the inclusion of year fixed effects, but decade fixed effects are likely to capture long-term trends in yield ratios over time—e.g., due to technological innovation. While yield data are provided for between 1 and 200 years, the panel is unbalanced. For the majority of locations (346 out of 551), yield data are provided for 1 year only. In some cases, where yield ratios are provided for longer time periods, average yield ratios are provided covering between 2 and 50 years. I include only locations with at least 10 independent observations.

TABLE 3
TEMPERATURE, YEARLY YIELD RATIOS, AND WHEAT PRICES

Variable	Yield Ratio (1)	Wheat Prices (2)	Yield Ratio (3)	Wheat Prices (4)
Mean temperature	.430***	−.111***		
	(.115)	(.0283)		
Growing-season temperature			.364***	−.115***
Season τ			(.116)	(.0221)
Nongrowing-season temperature			−.148	.0303*
Season τ			(.0952)	(.0171)
Growing-season temperature				−.0993***
Season $\tau - 1$				(.0191)
Nongrowing-season temperature				−.0151
Season $\tau - 1$				(.0166)
City fixed effects	Yes	Yes	Yes	Yes
Decade fixed effects	Yes		Yes	
Year fixed effects		Yes		Yes
Control variables (× year fixed effects)	Yes	Yes	Yes	Yes
Observations	205	2,731	205	2,714
R^2	.231	.684	.217	.682
Number of bootstrap units	12	10	12	10
Number of repetitions	999	999	999	999

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

* $p < .1$.

*** $p < .01$.

deviation increase in mean temperature increases yield ratio by 0.8 (up from 5.57, an increase of 14%).

In column 2, I introduce wheat prices as an alternative measure of agricultural productivity. I combine annual data on wheat prices for 10 European cities from Allen (2001) with yearly temperature data from Luterbacher et al. (2004). Wheat price data are available for Amsterdam, London, Leipzig, Antwerp, Paris, Strasbourg, Munich, Florence, Naples, and Madrid. As city-level demand changes only gradually, yearly fluctuations in wheat prices mostly reflect changes in supply. Determinants of agricultural productivity other than temperature, such as certain institutions or technologies, are unlikely to change immediately from year to year in response to temperature changes. The immediate effect of temperature on wheat prices therefore depends primarily on temperature's effect on agricultural productivity. I estimate the following specification to assess the effect of temperature on wheat prices:

$$\log \text{Wheat Price}_{i\tau} = \beta + \gamma \text{Temperature}_{i\tau} + \text{City FE}_i + \text{Year FE}_\tau + \delta X_{i\tau} + \epsilon_{i\tau}. \tag{3}$$

I regress log Wheat Price in city i and year τ on temperature in city i and year τ. I also include city fixed effects and time period fixed effects. The parameter $X_{i\tau}$ denotes additional control variables. The coefficient of interest is γ. It describes the relationship between changes in temperature and changes in wheat prices. The result in column 2 shows that higher temperature in one year is associated with lower wheat prices in the same year.

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

Wheat prices in year τ are the average wheat price over the calendar year τ. Hence, wheat prices in the later part of year τ—after the harvest—are determined by temperature in the growing season of year τ and temperature in the preceding nongrowing season of year τ. Wheat prices in the earlier part of year τ are determined by temperature in the growing-season year $\tau - 1$ and temperature in the preceding nongrowing season. In column 4, I therefore regress wheat prices in year τ on growing-season temperature in year τ and in year $\tau - 1$ as well as on the corresponding nongrowing-season temperatures. Results in column 4 show that warmer temperature during growing seasons significantly decreased wheat prices but that temperature during nongrowing seasons did not have an effect.

These results show that temperature during the growing season was particularly important for agricultural productivity during the Little Ice Age. This is consistent with the evidence on the importance of growing-season temperatures on present-day agricultural output (e.g., Guiteras 2009; Schlenker and Roberts 2009; Burgess et al. 2017, 32). Results in table A.5 show that results on the effect of long-term temperature changes on wheat prices are consistent with results estimated for the effect of year-to-year temperature changes.

B. *The Effect of Temperature on Mortality*

Another channel through which temperature may have affected city size is temperature's effect on mortality. To examine this channel, I construct a data set that records mortality for 404 English parishes at the yearly level for the years 1538–1838 using data from Wrigley and Schofield (1989). The underlying primary sources of the mortality data are parish registers (for more details, see Wrigley and Schofield 1989, 15–62). I geocode the parishes and combine them with the temperature data from Luterbacher et al. (2004). For this analysis, I aggregate both mortality and temperature at the level of the agricultural year. The agricultural year t starts with the beginning of the nongrowing season in the fall of year $t-1$ and ends with the end of the growing season in year t (for an overview of the different temperature variables, see fig. A.5). Temperature may have affected mortality through its effect on agricultural productivity (lower temperatures decrease food production, leading to malnutrition).[31] I estimate the effect of temperature on mortality with the following regression:

$$\begin{aligned}\text{Crisis Mortality}_{pt} = {} & \beta + \gamma\text{Temperature}_{pt-1} \\ & + \text{Parish FE}_p + \text{County}_c \\ & \times \text{Time Period FE}_t + \delta X_{pt} + \epsilon_{pt}.\end{aligned} \tag{4}$$

The dependent variable is an indicator variable, Crisis Mortality. The variable is one if mortality in at least 1 month during a year reached a crisis level as defined by Wrigley and Schofield (1989). Wrigley and Schofield (1989) define crisis mortality months as months in which the death rate in parish p was more than 10% above a 25-year moving average of mortality for this month and parish.

I regress Crisis Mortality$_{pt}$ on temperature during the past agricultural year and on temperature during the past growing and nongrowing season. The specification also includes all geographic and historical control variables (interacted with year indicator variables) as used in the main specifications for which there was variation within England: distance to Roman roads, distance to the ocean, altitude, soil suitability for potatoes, and ruggedness.[32] The specification further includes parish fixed effects and county × time period fixed effects.

[31] In app. A.5, I examine the impact of temperature on mortality through a health channel.

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

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

Then, I investigate whether access to markets mitigated the effects of temperature on crisis mortality. If markets allowed people to purchase products that had become costlier to produce and to sell products that were not affected, then markets could have helped people to mitigate the adverse effects of temperature. The data by Wrigley and Schofield (1989) provide information on the distance between a parish and the nearest market town. In columns 2, 3, 5, and 6 of table 4, I test whether a parish's distance to the closest market may have had an impact on the effect of adverse temperatures on crisis mortality.[33] For parishes far from a market (cols. 2 and 5), agricultural year temperature and growing-season temperatures had significant effects on crisis mortality, indicating that parishes farther away from markets experienced higher crisis mortality when temperatures fell. In parishes close to a market (cols. 3 and 6), the effect of temperature had the same sign but was smaller and insignificant. The coefficients indicate that a 1 standard deviation decrease in agricultural year temperature in $t - 1$ increases crisis mortality by 8% in places far from markets and by 4.6% in places close to markets, though the latter effect is not significant. These results show that places far from markets were significantly less resilient to temperature changes compared with places close to markets.

So far, I have studied the effect of temperature during the past agricultural year on mortality. It is plausible, however, that temperature over several years may also have affected mortality. Food reserves may delay the effect of temperature on mortality, and more than 1 year with adverse temperatures may be especially harmful after food reserves have been depleted. In the middle section of table 4, I show that cooler temperatures over the past 5 years increased mortality. Again, it is the growing-season period that

[33] I define parishes as far from a market if they are more than 4 km away from a market, which corresponds to the median distance between a parish and the nearest market town in the sample. Results are similar for other cutoffs.

TABLE 4

Temperature and Mortality

Variable	Mortality Crisis in Year t: All Parishes (1)	Mortality Crisis in Year t: Parishes Far from Market (2)	Mortality Crisis in Year t: Parishes Close to Market (3)	Mortality Crisis in Year t: All Parishes (4)	Mortality Crisis in Year t: Parishes Far from Market (5)	Mortality Crisis in Year t: Parishes Close to Market (6)
Agricultural year mean temperature in year $t-1$	−.0721*	−.105**	−.0617			
	(.0371)	(.0466)	(.0502)			
Growing-season temperature in year $t-1$				−.0626*	−.0829**	−.0449
				(.0322)	(.0330)	(.0514)
Nongrowing-season temperature in year $t-1$				−.00936	−.0216	−.0168
				(.0231)	(.0229)	(.0359)
Observations	118,500	118,500	56,400	118,500	56,400	59,700
R^2	.173	.173	.243	.173	.243	.227
Agricultural year mean temperature in years $t-1$ to $t-5$	−.106	−.240***	−.0949			
	(.0731)	(.0876)	(.106)			
Growing-season temperature in years $t-1$ to $t-5$				−.124**	−.160***	−.137
				(.0606)	(.0576)	(.0922)
Nongrowing-season temperature in years $t-1$ to $t-5$				.0426	−.0660	.0709
				(.0585)	(.0758)	(.0795)
Observations	118,500	56,400	59,700	118,500	56,400	59,700
R^2	.173	.243	.227	.173	.243	.227
Parish fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
County × year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Control variables (× time period fixed effects)	Yes	Yes	Yes	Yes	Yes	Yes

Note.—Observations are at the parish-year level. Regressions in cols. 1 and 4 use a sample of 404 English parishes with data for the years 1538–1840. In cols. 2, 3, 5, and 6, the sample is split between parishes less than 4 km and more than 4 km from the nearest market town. The dependent variable "Mortality Crisis" is an indicator variable that is one for parish i in year t if mortality in year t is more than 10% above a 25-year moving average of mortality in parish i. "Agricultural year mean temperature" is mean temperature over the agricultural year starting with the beginning of the nongrowing season in the fall of the preceding year and ending with the end of the growing season in the summer of the same year. "Growing-season temperature" in year t is temperature during spring and summer of year t. "Nongrowing-season temperature" in year t is temperature in the fall of year $t-1$ and the winter of year t. Standard errors are clustered at the temperature grid level of the underlying temperature data. Control variables include all control variables from the main specification (see table 2) that vary within England: distance to the nearest Roman road, distance to the ocean, altitude, soil suitability for wheat cultivation, soil suitability for potato cultivation, and ruggedness. All control variables are interacted with year indicator variables.

* $p < .1$.

** $p < .05$.

*** $p < .01$.

affected mortality, rather than the nongrowing season, and the estimated effect of growing-season temperature on mortality for the whole sample (col. 4) is mainly driven by the effect estimated for parishes relatively far from market towns (col. 5). Coefficient sizes indicate that a 1 standard deviation decrease in temperature over five past agricultural years increased crisis mortality by 9.3% in parishes far from markets and by 7.9% in parishes close to markets (though the latter effect is not significant). These results indicate larger temperature effects when temperature stays low over more than one agricultural year.

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

C. *The Effect of Temperature on Migration*

Another channel through which temperature may have affected city size is through temperature's effect on migration. Historical evidence indicates that economic crises (in particular, agricultural crises) increased migration in early modern Europe—for example, after the Great Irish Famine (Ó Gráda and O'Rourke 1997) and after times of agricultural crises in Sweden (Karadja and Prawitz 2019). The relationship between economic crises and migration, however, can be ambiguous. Poor people may have been entrapped in times of economic crisis, as they were unable to pay the costs of migration (Hatton and Williamson 1994). During the Great Irish Famine, for example, overseas migration increased more in richer parts of Ireland compared with poorer parts (Ó Gráda and O'Rourke 1997). Landless people in nineteenth-century Sweden did not move because of the prohibitively high costs of long-distance migration (Dribe 2003).

To examine the relationship between temperature changes and migration in early modern Europe, I use data on the location of birth and marriage of 6,350 couples in seven English parishes between 1571 and 1871 from Wrigley et al. (2018).[34] These parishes had certain urban characteristics (in particular, market rights) that make it plausible that inhabitants of the surrounding rural areas would have sought these out in times of crisis. Migrants were attracted by economic sectors "unaffected by the same

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

conditions which are producing economic stress in the place of origin" (Dribe 2003, 295).[35]

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

V. Adaptation to the Little Ice Age

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

A. Adaptation in Trade

To examine whether economies increased trade in response to the cooler temperatures of the Little Ice Age, I obtain information on 900,000 ship journeys to 750 destination ports in Europe representing 3,700 trade relationships between the years 1591 and 1857. The data include the exact date of the passage and tax levied on the cargo. I access these data from the Sound Toll Registers (STR 2018), a unique data source on European trade in the early modern period. The Sound toll was a historical toll

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

collected by the Danish state from all ships passing the Øresund strait (commonly known in English as the Sound) at the city of Helsingoer. The toll was proportionate to the ship's cargo value (Gøbel 2010).[36] In its time, the Sound, a narrow strait separating Sweden and Denmark, was one of Europe's most important shipping routes. It connected the Baltic region and the rest of Europe. The Baltic region was the main supplier of grain in the "European grain trade" of the early modern period. Virtually all ships supplying grain from the Baltic region to the rest of Europe had to pass through the Sound, as it was the only practical way in and out of the Baltic.

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

I define temperature variables measuring temperature over the past 5, 25, 50, and 100 agricultural years. The final data set is a balanced panel with information on 760 destination ports for the years 1591–1857.

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

$$\begin{aligned}\ln(\text{Number of Ship Arrivals})_{it} &= \beta + \gamma \text{Temperature}_{it} \\ &+ \delta \text{Market Access} + \text{Time FE}_t + \text{Destination Port FE}_i + \theta X_{it} + \epsilon_{it}.\end{aligned} \tag{6}$$

The specification estimates the relationship between the number of ships arriving at destination port i in year t and the temperature at destination port i in year t. The specification also includes destination port fixed effects, time period fixed effects, and geographic and historical control variables interacted with decade indicator variables. To control for each port city's market access, I control for distance to all other cities and (for a subsample) for city size both in each port city and in the other cities in the data set. Results in table 5 show a negative relationship between the number of ships arriving at a destination port and growing-season and nongrowing-season temperatures over the past 5, 25, 50, and 100 years (cols. 1–4). This relationship is not significant for growing-season temperatures over the previous 5 years. The relationship is significant at the 1% level for temperatures over the previous 25, 50, and

[36] The toll was determined as 1%–2% of the cargo value. To discourage ships from understating the value of their cargo, the right was reserved to purchase the cargo at the total value as in the customs forms (Gøbel 2010).

100 years. Hence, more ships arrived at ports that had experienced cooler temperatures. The coefficients indicate that a 1 standard deviation decrease in growing-season temperature over the past 25 years increases the number of incoming ships by 3%. When considering the subset of the sample for which city size data are available (cols. 5–8), the same temperature change increases the number of ship passages by 6.7%. Since the port cities with city size data are on average larger, possibly more developed port cities, this might indicate that these react more strongly to changes in temperature than smaller port cities.

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

B. Heterogeneity in the Effect of Temperature on City Size—Access to Trade

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

$$\begin{aligned}\ln \text{City Size}_{it} = {} & \beta + \gamma \text{Mean Temperature}_{it} + \alpha \text{Mean Temperature}_{it} \\ & \times \text{Trade}_i + \text{City FE}_i + \text{Time FE}_t + \delta X_{it} + \epsilon_{it}.\end{aligned} \tag{7}$$

First, I identify cities in the main data set that participated in long-distance trade. To do so, I first identify all cities that participated in Sound toll trade. One might be concerned that the decision to participate in Sound toll trade was endogenous to the temperature patterns during the Little Ice Age. As an alternative measure of participation in long-distance trade, I therefore identify all cities that were members of the Hanseatic League in 1400 (based on Droysen 1886), preceding the period I am studying.

As in the main specification, I regress ln City Size of city i in time period t on Mean Temperature, city fixed effects, time period fixed effects, and the usual geographic and historical control variables. In addition, I include a variable interacting a city's mean temperature with an indicator variable that is one if the city participated in Sound toll trade. Column 1 of table 6 shows the estimated effect of temperature for all cities. In column 2, I add an interaction term of temperature and an indicator variable that is one for all cities in the main data set that are part of the Sound toll trade. Results show that Sound toll traders are significantly less affected by temperature changes compared with nontraders. The corresponding

TABLE 5
Temperature and Trade (Number of Ship Arrivals)

Variable	ln Number of Ships							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Growing-season temperature in $t-1$ to $t-5$	−.101				−.159			
	(.0774)				(.163)			
Nongrowing-season temperature in $t-1$ to $t-5$	.0516				.182*			
	(.0505)				(.108)			
Growing-season temperature in $t-1$ to $t-25$		−.758***				−1.754***		
		(.277)				(.569)		
Nongrowing-season temperature in $t-1$ to $t-25$		.00971				.537		
		(.187)				(.406)		
Growing-season temperature in $t-1$ to $t-50$			−1.362***				−2.734***	
			(.422)				(.843)	
Nongrowing-season temperature in $t-1$ to $t-50$			−.230				.497	
			(.281)				(.586)	
Growing-season temperature in $t-1$ to $t-100$				−1.984**				−5.500***
				(.776)				(1.457)

Nongrowing-season temperature in $t-1$ to $t-100$				−.715				−.0791
				(.576)				(1.228)
Destination port fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Distance to other cities	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City size					Yes	Yes	Yes	Yes
Control variables (× 50 year period fixed effects)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	202,920	202,920	202,920	202,920	58,740	58,740	58,740	58,740
R^2	.267	.268	.268	.268	.442	.442	.443	.444
Number of destination ports	760	760	760	760	220	220	220	220

NOTE.—Observations are at the destination port–year level, with data for 760 destination ports and the years 1591–1857. The dependent variable is the natural log of the number of ship passages arriving at port i in year t. "Growing-season temperature" in year t is temperature during spring and summer of year t. "Nongrowing-season temperature" in year t is temperature in the fall of year $t-1$ and the winter of year t. All specifications include destination port fixed effects, year fixed effects, and geographic and historical control variables interacted with decade fixed effects. Historical controls include information on a country's religious denomination in 1600 (for details, see table 2), whether a country had a university town in 1500, whether it was engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, and its distance to the ocean. Five geographic control variables control for the country's mean altitude, its mean soil suitability for wheat cultivation, its mean soil suitability for potato cultivation, and mean ruggedness. Standard errors are clustered at the level of the temperature grid cell of the underlying temperature data.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

TABLE 6
HETEROGENEITY IN THE EFFECT OF TEMPERATURE

		Sound Toll Trade		Hanseatic Trade	
	(1)	(2)	(3)	(4)	(5)
Mean temperature	.724***	.865***	.872***	.740***	.855***
	(.189)	(.210)	(.210)	(.190)	(.208)
Mean temperature × trade		−.688***		−.956***	
		(.187)		(.174)	
Mean temperature × number of trade partners <25th percentile			−.386		−.578*
			(.328)		(.324)
Mean temperature × number of trade partners >25th percentile			−.783***		−.688***
			(.188)		(.189)
Observations	10,600	10,600	10,600	10,600	10,600
R^2	.485	.486	.486	.486	.486
Number of cities	2,120	2,120	2,120	2,120	2,120

NOTE.—Column 1 reports ordinary least squares estimates of the main specification (identical to col. 2 in table 2) for comparison. Column 2 shows results when including an interaction term between "Mean temperature" and "Sound Toll Trade," an indicator variable that is one for all cities that were destination cities in the Sound toll trade. Column 3 shows results when including two interaction terms: one interaction term between "Mean temperature" and the indicator variable "number of trade partners <25th percentile," which is one for all cities in the Sound toll trade network whose number of trading partners was below or equal to the 25th percentile, and another interaction term between "Mean temperature" and the indicator variable "number of trade partners >25th percentile," which is one for all cities whose number of trading partners exceeded the 25th percentile. Standard errors are clustered at the temperature grid level of the underlying temperature data. All specifications include city and time period fixed effects. Historical and geographical controls are as defined in table 2. All control variables are interacted with time period indicator variables.
* $p < .1$.
*** $p < .01$.

specification when treating only members of the Hanseatic League as traders shows that these cities were also significantly less affected by temperature changes, with their coefficient turning even slightly negative (col. 4).

If trade helped cities to overcome adverse effects of temperature change, then better access to trade may have helped more. In column 3, I explore whether differences in trade intensity mattered. I use each city's number of trading partners as a measure of trade intensity. The first interaction term is one for cities that engage in Sound toll trade but have relatively few trading partners (below the 25th percentile, trading with up to four different cities). The second interaction term is one for cities that engage in Sound toll trade and have a higher number of trading partners (above the 25th percentile). Results in column 3 show that while both interaction terms are negative, only the coefficient on the interaction term for cities with a relatively high number of trading partners is significant, and it is twice as large as the coefficient on the interaction term for cities with relatively few trading partners. The mitigating effect of trade is larger for cities that trade more. The estimated effect of a 1 standard deviation decrease in temperature is estimated to reduce city size by 0.6%. For cities in the Sound toll trade but with few trading partners, a 1 standard deviation decrease in temperature is estimated to reduce city size by 3.5% (compared with 9.8% for cities that do not participate in the Sound toll trade). This distinction can also be seen for Hanseatic traders but is less strong. Cities with many Hanseatic trade partners are significantly less affected by temperature than cities without Hanseatic trade partners. Cities with few Hanseatic trade partners are less affected than cities without Hanseatic trade partners (significant at the 10% level), but the estimated effect of temperature on them is still larger than for cities with many Hanseatic trade partners.[37]

These results show that trade was an effective way of shielding an economy from the negative effects of temperature changes, especially for cities that had a higher number of trading partners. The findings are also consistent with work examining modern developing countries—such as, for example, findings showing that trade openness has mitigated the adverse effects of weather shocks in India (Burgess and Donaldson 2010). Alternatively, it is important to note that the decision to join the Hanseatic League in 1400, while not related to the temperature patterns I am studying, is also not random. Members of the Hanseatic League are likely to have been different from other cities on other dimensions than trade—for example, a higher level of human capital or a more diversified economy. These may have helped overcome climate-related shocks irrespective of trading relations.

These results provide an opportunity to calculate how expensive (in terms of city population levels) the Little Ice Age would have been for cities within the Sound toll trade network had they not been part of this group. To do so, I compute the temperature effect for Sound toll cities and compare it with the effect if they had not been Sound toll cities.[38] A loss of 1,186,000 inhabitants, representing 3% of the total population of Sound toll cities over the study period, would have been the cost of not being part of the Sound toll trade network. This is almost four times as high as the temperature effect that these trading cities actually experienced.

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

[38] The estimated temperature effect for Sound toll cities equals 0.177 (by adding main temperature effect and temperature effect for Sound toll cities). I multiply this by the actual temperature change that Sound toll cities experienced and calculate the change in city size that is due to change in temperature. This is the estimated change in city size due to temperature for Sound toll cities. The calculated temperature effect for Sound toll cities lies at a loss of 307,000 inhabitants, or 1.6% of the total population over the study period. I then add these changes to the actual city sizes to calculate city size in Sound toll cities that would have occurred if they had not experienced any temperature change–related effect. Then, I use the main temperature effect for non–Sound toll cities (0.865) to calculate the change in city size that Sound toll cities would have experienced if they had not been Sound toll cities.

C. *Trade Opportunities and the Effect of Temperature*

The Sound Toll Registers represent one of the most comprehensive sources on trade in early modern Europe, but they do not capture inland trade. In this section, I construct a measure of potential inland trade opportunities for all cities in the data set. I then estimate whether cities with larger trade opportunities are differently affected by temperature changes compared with cities with smaller trade opportunities. This measure is guided by the gravity model for trade (Isard 1954). The size of trade flows in the gravity model depends on the respective economies' sizes and distance between these economies. To construct the measure, I identify the number and sizes of cities located up to 50 km from each city in the data set and add up their total size.[39] Then, I estimate the main specification but for two separate groups of cities: cities with relatively large trade opportunities and cities with relatively small trade opportunities. Cities with relatively large trade opportunities are defined as cities with an above-median number of cities within 50 km that are of above-median total size. Cities with relatively small trade opportunities are defined as cities with a below-median number of cities within 50 km that are of below-median total size. Results in columns 2 and 5 of table 7 show that the estimated effect of temperature on city size for cities with high trade opportunities is close to zero (col. 2), whereas the estimated effect of temperature on city size for cities with low trade opportunities is large and significant at 1% (col. 5).

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

In columns 3, 4, 6, and 7, I estimate the effect of temperature for cities with large trade opportunities and low or high ruggedness (cols. 3 and 4)

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

TABLE 7
Trade Opportunities, Natural Barriers, and the Effect of Temperature

		Cities with High Trade Opportunities			Cities with Low Trade Opportunities		
	All Cities (1)	All (2)	Ruggedness Low (3)	Ruggedness High (4)	All (5)	Ruggedness Low (6)	Ruggedness High (7)
Mean temperature	.72***	.05	−.85	.96	.80***	.63*	1.08**
	(.21)	(.62)	(.74)	(1.03)	(.25)	(.33)	(.42)
Control variables:							
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time period fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Historical controls (× time period fixed effects)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographic controls (× time period fixed effects)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	10,600	4,595	2,290	2,305	4,755	2,375	2,380
R^2	.767	.78	.80	.76	.77	.82	.73

Note.—Observations are at the city-year level. The regression in col. 1 shows the baseline specification and the whole sample (identical to col. 2 in table 2). The dependent variable is the natural log of the number of city inhabitants. "Mean temperature" is year temperature averaged over the periods 1500–1600, 1600–1700, 1700–1750, 1750–1800, and 1800–1850. "Cities with High Trade Opportunities" are cities with an above-median number of trading partners that are of above-median size within a radius of 50 km around the city. "Cities with Low Trade Opportunities" are cities with a below-median number of trading partners that are of below-median size within a radius of 50 km around the city. "Low (High) Ruggedness" is below-median (above-median) ruggedness in a radius of 5 km around the city. All specifications include city and time period fixed effects. Control variables are as defined in table 2 and are interacted with time period indicator variables.

* $p < .1$.
** $p < .05$.
*** $p < .01$.

and small trade opportunities and low or high ruggedness (cols. 6 and 7). For each subgroup of cities, cities exposed to a low degree of ruggedness are less affected by temperature changes compared with cities in the same subgroup but exposed to a high degree of ruggedness. The coefficient for cities with large trade opportunities but a high degree of ruggedness is large and positive (not significant), indicating that these cities were on average negatively affected by temperature decreases. The rugged terrain may have prevented them from taking advantage of trade opportunities in their surroundings. The coefficient for cities with large trade opportunities and a low degree of ruggedness is small and negative (not significant), indicating that these cities were on average not negatively affected by temperature decreases and that they may have even benefited. In the subgroup of cities with low trade opportunities, the estimates show that all cities are affected by temperature changes but that the estimated effect for cities with a high degree of ruggedness is substantially larger.

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

D. *Adaptation in Land Use*

Another way of adapting to climate change in Costinot, Donaldson, and Smith (2016) is to adjust land use according to an economy's comparative advantage. In the early modern period, the expansion of cropland and pasture was one strategy to increase agricultural output.[40]

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

In this section, I examine the relationship between temperature changes during the Little Ice Age and two outcome variables: the natural log of a country's total pasture and the natural log of a country's total cropland. For this purpose, I use information on a country's total pasture and total cropland from the History Database of the Global Environment (Klein Goldewijk 2010; Klein Goldewijk, Beusen, and Janssen 2010; Klein Goldewijk et al. 2011). It is important to keep in mind that these data are calculated based on current-day and historical population, cropland, and pasture data that are also estimates. The calculation depends on a number of assumptions that are hard to verify, such as agricultural technology or the amount of land that a farmer could handle. Other processes that are likely to have influenced national cropland and pasture area, such as trade, across country boundaries are not taken into account. On the other hand, the database is unique in providing internally consistent information on historical land-use patterns for 42 European countries (within constant boundaries of 2012) for each decade since 1500.[41] Mindful of the limitations of the data, I use information on land use for each decade between 1500 and 1850 and combine them with temperature variables at the country and decade level. To estimate whether changes in

[40] It is well documented, e.g., that agricultural land in England was expanded by clearing forests (Merriman 2009, 167). Similarly, the Dutch expanded farmland by draining marshes (Tol and Langen 2000).

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

land use were related to changes in temperature during the Little Ice Age, I estimate the following regression:

$$\begin{aligned}\text{Land Use}_{id} = \beta + \gamma\text{Temperature}_{id} + \text{Decade FE}_d \\ + \text{Country FE}_i + \delta X_{id} + \epsilon_{id}.\end{aligned} \tag{8}$$

The temperature variables measure temperature over the past 10, 25, 50, and 100 agricultural years. I include decade and country fixed effects as well as the usual geographical and historical control variables interacted with decade indicator variables.

Results in table 8 show a positive relationship between the outcome variables and temperature. This indicates that countries that were less

TABLE 8
TEMPERATURE AND LAND USE

	Ln Total Pasture				Ln Total Cropland			
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Agricultural year mean temperature, years $t-1$ to $t-10$	.03 (.08)				.01 (.06)			
Agricultural year mean temperature, years $t-1$ to $t-25$		.11 (.16)				.05 (.13)		
Agricultural year mean temperature, years $t-1$ to $t-50$			.50** (.24)				.40** (.17)	
Agricultural year mean temperature, years $t-1$ to $t-100$				2.38*** (.85)				2.12*** (.52)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Decade fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variables (× decade fixed effects)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	570	570	570	570	570	570	570	570
R^2	.994	.994	.994	.995	.997	.997	.997	.998

NOTE.—Observations are at the country-decade level. The sample contains data for 48 European countries (treated as constant over time in the boundaries of 2012) for every 10 years between 1500 and 1850. The dependent variables are the natural log of the area of pasture and the natural log of the area of cropland. "Agricultural year mean temperature" is the mean temperature over the agricultural year starting with the beginning of the nongrowing season in fall and ending with the end of the growing season in summer. All specifications include country fixed effects, decade fixed effects, and historical and geographic control variables as in the main specification. Historical controls include information on a country's religious denomination in 1600 (for details, see table 2), whether a country had a university town in 1500, whether it was engaging in Atlantic trade, whether it was part of the Roman Empire in year 1 CE, and its distance to the ocean. Five geographic control variables control for the country's mean altitude, its mean soil suitability for wheat cultivation, its mean soil suitability for potato cultivation, and mean ruggedness. All control variables are interacted with decade indicator variables. Standard errors are clustered at the country level.

** $p < .05$.

*** $p < .01$.

affected by cooler temperatures of the Little Ice Age expanded areas for pasture and crops, possibly to benefit from their relatively higher agricultural productivity. While the coefficients are positive throughout, they are not significantly different from zero until considering up to 50 years of agricultural year temperatures. This is consistent with the high economic and political costs that accompany processes of land reclamation. As countries less affected by temperature changes increase their agriculturally productive land, countries more affected by temperature changes may have benefited from increases in supply if they are in trade relations with these economies.

VI. Conclusion

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

My results also underline the importance of the agricultural sector as a channel through which temperature affects the economy. On the one hand, access to trade and the role of the agricultural sector for an economy have undergone fundamental change since the early modern period. On the other hand, many developing countries' economies clearly have less advantageous trade relationships and a larger share of the population work in agriculture compared with more developed countries. The findings highlight the vulnerability to climate change of such agriculture-dependent economies with limited access to trade.

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