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Solving the longitude puzzle: A story of clocks, ships and cities

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Abstract

In the 19$^{\text{th}}$ century, the process of European expansion led to unprecedented changes in the urban landscape outside of Europe, with the urban population moving towards the coast and tripling in size. We argue that the majority of these changes can be explained by a single innovation, the chronometer, which allowed European explorers and merchants to measure longitude at sea. We use high-resolution global data on climate, ship routes, and demography from 1750 to 1900 to investigate empirically (i) the role of the adoption of the marine chronometer in re-routing trans-oceanic navigation, and (ii) the impact of these changes on the distribution of cities and population across the globe. Our identification relies on the differential impact of the chronometer across trans-oceanic sailing routes.

Keywords: Longitude, Chronometer, Gravity, Globalization, Trade, Development
JEL Codes: F1, F15, F43, R12, R4

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1 Introduction

"It is well known by all that are acquainted with the Art of Navigation, that nothing is so much wanted and desired at sea, as the Discovery of the Longitude, for the safety and quickness of voyages, the preservation of ships, and the lives of men."[1]

Until the 19th century, accurate offshore navigation was an impossible dream. There was no method or technology to determine longitude precisely in the open sea. The longitude puzzle was finally solved with the invention and mass-production of the marine chronometer in the mid-1790s. The chronometer was "one of the most important inventions of the era of the Industrial Revolution (though rarely mentioned [...])" (Mokyr (2017)), on a par with the spinning jenny and the steam engine. A large historical literature has emphasized the exceptional role of this innovation on the expansion of Western civilization. In the words of William Andrewes (1996, p.5): "[solving the longitude puzzle] allowed not only safer but also more direct (and hence faster) passage across the oceans, resulting in greater intercontinental trade and the creation of new markets. [...] These developments in turn caused massive shifts in population, significantly expanding the influence of some cultures while suppressing or even eradicating others."

Although it has been covered widely in the narrative historical literature, to the best of our knowledge no one has studied the causal impact of the chronometer on navigation and comparative development in a systematic econometric framework. We use global data on climate, ship routes, and demography and a novel identification strategy to empirically investigate (i) the role of the adoption of the marine chronometer in reshaping the trans-oceanic sea routes and (ii) the impact of these changes on the distribution of cities and population across the globe.

Locations on earth are identified using a grid. Horizontal lines, the latitude, indicate distance north or south of the equator, while vertical lines, the longitude, indicate distance east or west of the prime meridian, which runs through Greenwich, England. Historically, latitude could be found relatively easily by measuring the altitude of a celestial body (e.g., the Sun or a star) above the horizon; the challenge was how to find the longitude. In theory, it could be inferred by comparing the time in a fixed location, say Greenwich, with the local time, since the earth rotates on its axis 15 degrees every hour. Local time could be measured by observing the position of the Sun, but how could one measure the time in Greenwich when navigating an ocean? This puzzle stumped some of the greatest minds of the second millennium, including Galileo Galilei and Isaac Newton.

The first solution, the lunar distance method, came in the 1750s and was based on observations of the angular distance between the Moon and a celestial body. This method, which was quickly adopted, had a major problem: it did not work on an overcast sea. It made long distance oceanic navigation safe along

[1] "An act for providing a public reward for such person or persons as shall discover the longitude at Sea" (Acts of Parliament of Great Britain, 1713).

those few routes characterized by a clear sky throughout the year. The second, more permanent solution was invented by John Harrison (1693-1776). The marine chronometer, a precise clock that worked on moving vessels and that could keep Greenwich time with minimal errors. The first prototypes equipped mainly survey and exploratory vessels, while mass adoption for war and merchant vessels started in the 19$^{\text{th}}$ century. One of the first large users, as early as the mid 1790s, was the East India Company, the major engine behind the expansion of British trade and colonisation in Africa, Asia and Oceania.[2]

How did this innovation change navigation? We answer this question using CLIWOC, a database of more than 287,000 ship logbook entries from British, French, Dutch, and Spanish ships between 1750 and 1855, which captures daily information on the ship's position and weather conditions. The database does not record whether a chronometer was available on-board: we rely instead on the historical fact that chronometers became widely available to sailors in the 19$^{\text{th}}$ century and then study whether, in this new century, there were changes in ships' speeds and routes that were compatible with the changes made possible by the new technology. Specifically, we exploit the fact that the chronometer's advantage over the lunar method was limited to open sea navigation under overcast sky. We find an exceptional increase in the relative speed of vessels navigating in cloudy regions (where celestial observations were not possible) compared to vessels navigating in clear-sky regions starting from the first decade of the 19$^{\text{th}}$ century. This relative change in speed is fully explained by open sea routes, and we do not observe it for coastal navigation. The estimated impact of the chronometer is exceptionally large: our benchmark triple-difference estimates point towards an increase in speed under an overcast sky of around 31 percent. The identifying assumption here is that no other contemporaneous improvement in maritime technology had all the of following characteristics (i) it speeds up navigation under an overcast sky relative to navigation under a clear sky (ii) it produces this differential impact on open sea navigation but not on coastal navigation (iii) its implementation dates to the first decade of the 19$^{\text{th}}$ century.

Not surprisingly, the differential impact of the chronometer across different sea regions led to a complete reorganisation of the major sailing routes of the time. We document this with a second set of estimates: we show a relative increase in the number of observations of ships navigating under overcast skies, relative to clear skies starting from the 19$^{\text{th}}$ century. This change is fully explained by open sea navigation, while we do not observe a similar variation in coastal navigation.

These results survive a battery of robustness checks. First, we show that they are not explained by pre-trends: as expected, the impact of the chronometer starts in the 19$^{\text{th}}$ century and the impact is persistent over the first half of the century. Second, results are robust when controlling for the time-varying impact of wind patterns on navigation. This rules out the differential impact of the evolution of sails and rigging in open sea navigation over overcast sea contemporaneous to the diffusion of the

[2]As one of its directors admits, the East India Company was "an empire within an empire". In 1803, it had an army of 260,000, twice the size of Britain's standing army, and was responsible for approximately half of British international trade (Farrington (2002)).

chronometer as a potential explanation of the outcome we observe. Having established the revolutionary impact of the chronometer on the length and duration of sailing routes around the world, we quantify its long-term effects on the expansion of the Western civilization and global comparative development.

The empirical analysis is based on the construction of a large database spanning every 1° x 1° raster point of the non-European world in every decade from 1750 to 1900. The database combines information on local population density and urbanization rates, which are constructed using HYDE 3.2 (Klein Goldewijk et al. (2017)), with optimized sailing times to and from Europe, a proxy for exposure to Western civilization. To measure sailing times, we construct a global grid of sea raster points and a directed network of bilateral sailing times between all adjacent cells, which are a function of the prevailing weather conditions in the adjacent cells (i.e. average cloud coverage and wind patterns) and the technology used to compute the longitude (i.e. the lunar method or the chronometer). We then use a minimum distance algorithm to compute, for every coastal grid cell, the minimum sailing time of a return trip from Europe under the two different technologies.[3]

The research design follows a difference-in-differences approach which compares changes in sailing time from and to Europe, induced by the invention of the chronometer, with local changes in urban population and population density.

Figure 1 presents the intuition for our identification strategy. Panel (a) compares average urban density from 1750 to 1900 between inland and coastal grid cells, with the latter divided into two equal size groups depending on whether the shift from the lunar method to the chronometer produced a reduction in their sailing times to Europe below or above the median. All three groups experienced an increase in urban density from 1750. However, only the treated coastal cells experienced a substantial increase in their urban density in the 19th century. It used to be difficult to reach these cells from Europe using the lunar method and, unsurprisingly, until the 18th century, they were characterized by a level of urban density comparable to inland cells. The diffusion of the chronometer completely changed their urban landscape and, within a century, they reached levels of urbanization comparable to the other coastal cells.[4] For example, the coastal regions that experienced the largest reduction in sailing times from and to Europe are the east coast of the Americas and the northern part of the west coast, the south-east coasts of Australia and New Zealand, and China and Japan. We notice here that these are some of the regions of the non-European world that experienced the largest increase in urbanization and population density between 1750 and 1900, when the transition to the chronometer was certainly completed.

[3]Moving from the lunar method to the chronometer has a very heterogenous impact on sailing times across different regions of the world. For instance, there are large relative effects on European routes towards South East India and Ceylon, which lie under a generally cloudy sky, while the chronometer affected substantially less the sailing routes towards West India and the bordering Pakistan, two regions that overlook a portion of the Indian Ocean characterized by clear sky most of the year and where navigation using the lunar method is generally feasible.

[4]These changes are even more evident when considering absolute changes in urban density. Panel (b) in Figure 1 illustrates the increase in urban density relative to the 1780s, the last decade without chronometers.

Our difference-in-differences estimates corroborate the message coming from these raw data. When looking at coastal grid cells outside of Europe, we find that a one percent reduction in the time of a return trip from Europe enabled by the chronometer is associated with an increase in urban population above 3 percent in 1850 and an increase in population density of approximately 1.5 percent. We do not find any impact of the chronometer on urban population and population density in the inland cells. Pre-trend checks and a long list of robustness exercises support a causal interpretation of the estimates. These large effects persist until the first decade of the 20th century and are not fully explained by the dynamics in a specific continent.

In sum, both simple raw data and our difference-in-differences estimates support the view that the invention of the chronometer had large but geographically uneven effects on navigation, and through this channel, led to massive shifts in global population and the distribution of cities. The coastal regions that got relatively closer to Europe in terms of travel times experienced a massive relative increase in urban population and population density. The impact of the chronometer on these two variables is similar in magnitude to other great innovations that have captured the attention of economists in recent years. For instance, Nunn and Qian (2011) exploit a similar difference-in-differences design to evaluate the impact of the diffusion of the potato in the Old World. Their estimates suggest that the potato accounts for approximately a quarter of the increase in total population and a third of the increase in urbanization rates between 1700 and 1900 in the Old World. Our estimates suggest that the invention of the chronometer accounts for approximately three quarters of the increase in the urban population living along the coast outside of Europe during the 19th century. As slightly more than half of the total increase in urban population in this century was concentrated along the coast, the chronometer is able to explain more than a third of the total increase in urban population outside of Europe. The chronometer also explains a similar portion of the increase in population density during the 19th century. Admittedly, these back-of-the-envelope calculations are very crude estimates and should be interpreted cautiously, as they are based on the assumption that the rollout of the chronometer was uniform across different trade routes and was completely finished by the end of the period of analysis. Also, data on population density and urbanization rates are crude estimates based on a mix of subnational-level census counts and a series of geospatial information including land cover, roads, slope, urban areas, village locations etc. These data are the result of state-of-the-art global demographic models but demographic reconstruction estimates are far from being an ideal dataset to work with.

These findings contribute to several existing literatures. The first is the literature on the role of international connections and market access in the comparative development of the late modern period. Specifically, it relates to recent works that have used innovation in the shipping technologies or policy changes to study the impact of trade on economic development. In a recent working paper, Ellingsen (2021) shows that the increase in market access induced by a change in trade policies across the Spanish

Empire in the Americas led to a substantial reconfiguration of the economic geography of these regions in the second half of the 18th century. Juhász (2018) exploits the Napoleonic Blockade (1806-1814) as a source of exogenous variation for trade distances between Britain and different French regions. She then documents how temporary trade restrictions had long-term effects on technology adoption in different French departments throughout the 19th century. Nunn (2008) argues that the underdevelopment of Africa can be explained by its slave trades (1400-1900). The exogenous variation is generated by the relative distance of contemporary African countries to the main arrival ports for slaves throughout the period. Steinwender (2018) focuses on the impact of the establishment of the transatlantic telegraph in 1866 on information frictions and trade integration across the Atlantic.[5] Our work offers a more global view with respect to this literature. We do not focus on a single country or continent, but we rather look at the entire non-European world for the period from 1750 to 1900. Using high-resolution data, we show that the chronometer, by reducing distances to Europe in an asymmetric way across different regions, led to a large and persistent change in the distribution of cities and population around the world. Our global view and the high-resolution data come, however, with two caveats. First, we are not able to assess the impact of changes in the geographical isolation of a region on the local standard of living. Global data on per-capita GDP, mortality, household consumption or health outcomes are simply not available at a finer level than country level for the 18th and the 19th century. Second, we are not able to assess which channels delivered the changes in economic geography observed in the countries whose proximity to Europe was changed by the chronometer. We do not know if Europe exerted its impact through trade, migration or transfers of culture, technology and institutions. We leave these topics to further work.

Second, our paper speaks to a quantitative literature on the impact of general-purpose modern technologies on the geography of economic activity. For instance, it closely relates to works on the impact of the printing press (Dittmar (2011)), the steam engine (Fernihough and O'Rourke (2021)), the railroads (Hornung (2015), and Donaldson and Hornbeck (2016)), the steamship (Pascali (2017)), the telegraph (Steinwender (2018)), and electricity (Fiszbein et al. (2020)).

Third, our findings add to one of most longstanding debates in economic history: the sources of changes in productivity in the shipping industry during the Industrial Revolution. The traditional view is that the impact of technological progress in shipping was negligible up to 1850. This was famously

[5]There have been a large number of studies on the impact of trade on economic development in the last century. In a seminal contribution, Frankel and Romer (1999) use a cross-country regression framework to show a large impact of trade on economic development. The causal channel is identified using a geographic instrument: the point-to-point great circle distance across countries. Rodriguez and Rodrik (2000) question the validity of such a time-invariant geographical instrument on the basis that it might be capturing omitted geographical characteristics correlated with local economic development. To solve this limitation, Feyrer (2009) and Feyrer (2019) generate time-varying geographic instruments exploiting two different natural experiments: the improvements in aircraft technology and the closing of the Suez Canal between 1967 and 1975. In a similar vein, Campante and Yanagizawa-Drott (2018) study the impact of international long-distance flights on the global spatial allocation of activity, exploiting variation due to regulatory and technological constraints. Going back in time, Bakker et al. (2021) document a positive correlation between market-access to large coastal areas and the presence of archaeological sites from the Iron Age, a time when ships began to cross open water routinely on a unprecedented scale.

argued by Walton (1967) and North (1968) when discussing the reduction in freight rates from 1600 to 1850 on the North Atlantic routes and reaffirmed by Harley (1988), who showed that North's price fall was largely explained by denser packing of cotton bales and was limited to cotton shipping. Measuring technological progress with shipping rates is problematic: creating an index with limited historical data is notoriously complicated (e.g., currency conversions, deflating indexes, non-standardized weights and measures) and shipping rates respond not only to technological changes but also to changes in economic activity, market structure and the political environment. A second strand of literature has focused on shipping speed rather than shipping rates to measure technological advances and productivity growth in the industry. Rönnbäck (2012) uses data on the average length of voyages of slave ships to document a large increase in the speed of ships throughout the 18^{th} century.[6] Kelly and Ó Gráda (2019) report a large increase in the speed of the East India Company and the Royal Navy ships after 1770, especially in stronger winds. They attribute this differential improvement to the introduction of coppering and argue that subsequent rises in speed were probably "due to a continuous evaluation of sails and rigging, and improved hulls". Pascali (2017) studies the impact of the introduction of the steamship in the shipping industry. This work exploits the fact that the steamship produced an asymmetric change in shipping times across routes and countries and finds that this innovation can explain the majority of the increase in global trade in the second half of the 19^{th} century. A surprising feature of this literature is that, to the best of our knowledge, it has largely ignored what was arguably the most important advance in marine navigation in the second millennium, the marine chronometer.

The paper is organized as follows. In Section 2 we describe the historical background, illustrating the "quest for longitude": we explain the different methods sailors have used to measure longitude at sea and the revolutionary impact of the chronometer. In Section 3 we describe the data used for the empirical analysis in detail. In Section 4 we lay out the empirical strategy and investigate (i) the effect of the adoption of the chronometer on navigation and (ii) the impact of the chronometer on the distribution of cities and population outside of Europe. We close the paper with some concluding remarks.

2 Historical Background

For centuries the concept of discovering a method to compute the longitude was a synonym for attempting the impossible. In Jonathan Swift's classic novel, the good captain Gulliver reflects that, were he immortal, he would like to see "the discovery of the longitude, the perpetual motion, the universal medicine, and many other great inventions brought to the utmost perfection." For any maritime power in the 18^{th} century the quest to calculate longitude was the most pressing scientific dilemma of the day – and had been for centuries. The longitude problem was the main driver of the European

[6] Klein (1978) and Morgan (1993) find similar increases in speed for transatlantic sailing voyages. See Solar (2013) for the reduction in the duration of outward voyages to Asia.

research efforts in mathematics, geometry and astronomy. The greatest minds of the European scientific establishment including Johannes Kepler, Galileo Galilei, Giovanni Cassini, Christiaan Huygens, Robert Hook, Isaac Newton, and Edmund Halley were involved and all the major European courts promoted international endeavour for centuries through scientific patronage, the establishment of scientific societies and observatories, and longitude prizes.

While a sufficiently precise method of finding latitude at sea had been known since the 15th century, until the 1750s it was not feasible to measure longitude precisely a few days after losing sight of land. To gauge their distance west or east of the origin port, sea-captains relied on "dead reckoning". Typically, the speed of the ship would be computed by throwing a log overboard and observing how quickly the ship receded from this temporary guidepost, the direction would be determined from the stars, and the time of navigation was kept with a sandglass. In principle, these three measurements sufficed to compute changes in the longitude day by day after leaving the origin port. However, they suffered from large, cumulative errors. Such errors were exacerbated on cloudy days, when it was difficult to measure the direction of the ship, and under strong winds and ocean currents, which made it harder to measure speed accurately. After a few days of navigation, it was practically impossible to establish the longitude with a reasonable precision. How could Europeans cross the Atlantic and the Indian ocean then? The answer is simple: sailors took advantage of their knowledge of the latitude. They would turn to the latitude of their destination and then follow a line of constant latitude.[7] In this way, the sea captains of the 15th, 16th and 17th century could eventually fetch up at a place known to be at a certain latitude. The discovery of the sea route to India is an example of this navigation strategy. In the 15th century, Portuguese ships had already begun to work their way down the African coast. This was not easy because, in these waters, winds and currents run against southing vessels. An important turning point was the discovery of St. Helena and its latitude. The island became a reference point for further explorations of the Southern Atlantic. Eventually, it took almost a century to finally round out the tip of Africa and turn north into the Indian Ocean. Once the latitude of the tip of Africa (35° S) was known, the circumnavigation of Africa could be routinized. Portuguese sailors would head down to Cape Verde Island (16° N), then swing out towards the coast of Brazil, and finally turn eastward when the latitude 35° S was reached.[8]

This way of navigating came with high costs. First, without knowing the longitude, sailors could miss islands and even continents and would be left not knowing whether their target destination lay to the East or to the West. The results were long voyages due to continual course corrections, leaving sailors vulnerable to the dreaded disease of scurvy, and frequent shipwrecks.[9] Second, following lines of latitude

[7] This way of navigating was known as "running down a westing (easting)" if going westbound (eastbound).

[8] Columbus followed a similar strategy. "Columbus was convinced that the Indies could be reached by going west; and like a darts player leaning as far forward as possible, the closer to get to the target, he jumped out into the ocean sea from the westernmost port in the Canaries. He did so not knowing how fare he would have to go before reaching the land [...] he systematically underestimated his daily run with a view to keeping his men patient." (Landes (1996, p.24)).

[9] One of the many examples of the cost of sailing without the knowledge of the longitude is the voyage of the HMS Centurion in 1741. The HMS Centurion was the flagship of a fleet of six vessels that were supposed to round Cape Horn from east to west. George Anson, the admiral of the fleet and one the most skillful navigators of his time, thought that

means that ships could not take the most direct route (a great circle) or a route with more favorable winds and currents, further extending the length and duration of the voyage. Third, trans-oceanic vessels were limited to navigating by latitude alone and this confined them to a few narrow shipping lanes, at the mercy of pirate ships and war vessels flying the wrong flag.

An important turning point in the quest for longitude was a naval disaster in 1707, when a British fleet lost its position and ended up on the rocks of the Isles of Scilly.[10] The compound loss of lives, ships and honor led to the famed Longitude Act of 1714, in which the British Parliament promised a princely reward to the person who could discover the means of finding the longitude. This was the last of a long list of prizes and rewards that, starting from the 16th century, were offered by all the major sea powers for the solution to the longitude puzzle.[11]

The prize was successful, and it produced two working solutions. The first one was the lunar method. Longitude is basically the distance east-west on the Earth's surface and can be expressed as the difference in time between two points (since the earth rotates on its axis 15 degrees every hour). To find how far east or west the ship has sailed, a navigator has to be able to calculate the time at a standard meridian and subtract it from the local time. Local time can be calculated by the position of the Sun. The lunar method used the movement of the Moon across the star background as a clock to infer the time at the standard meridian. This time could be inferred from the distance of the Moon with respect to selected stars. This method became viable in the 1750s as two practical problems, predicting the Moon's position and measuring the distances between the Moon and the stars, were solved.[12]

The lunar method revolutionized navigation within few years. For the following five decades it gave expert navigators the means to circumnavigate Africa, led to unprecedented levels of trade with Asia, and laid the groundwork for the European colonization of Asia and Oceania. The lunar approach had one important drawback though: its precision in measuring the longitude relied on weather conditions. Measuring Moon distances was impossible under a cloudy sky. As we will show in the empirical section, this limitation inhibited navigation along the cloudiest trans-oceanic routes. Moreover, this methodology was so complex and time-consuming (in 1750, it required four hours of mathematical calculations) that it was limited to a small elite of sea-captains.

The final solution to the longitude problem came from the invention of the chronometer, a mechanical watch able to keep the time of the standard meridian with sufficient precision.[13] The chronometer, unlike

he had already passed the Cape and headed north. He was wrong: the fleet had not passed the Cape and he found land straight ahead. He had then to resume his westerly course for weeks and, when he finally managed to pass the Cape, he had lost two ships of his fleet. He then headed north to the island of Juan Fernandez to take supplies. Once he reached the latitude of the island, he made a second mistake: he decided to head west, while the island was on the east. It took him approximately two weeks to realize the miscalculation and then other 10 days to sail eastward and reach the island. In the meanwhile, half of the crew of the HMS Centurion had died of scurvy.

[10] Four ships sank and 2,000 sailors lost their lives. The incident was attributed to a combination of factors including the inability of navigators to accurately measure the position of the ships, and inadequate compasses (May (1960)).

[11] Already in the 17th century, Galileo Galilei was applying for the Spanish and Dutch longitude prizes, established in 1567 and 1627. The British and the French prizes were established in 1714.

[12] The theory was originally proposed by Johann Werner in 1514.

[13] Chronometers were capable of maintaining precise time even when sea conditions were not favourable for navigation.

the lunar method, benefited from several advantages. It made it much easier to compute the longitude: the only thing a sailor had to do was compare his local time at sea, determined by angular observation of the Sun, and the time at the reference point, as indicated by the chronometer. No night-time observations were needed, freeing navigators from their dependence on clear skies. Moreover, the dramatic reduction in time spent on calculations allowed navigators to take multiple longitude recordings per day, increasing precision.

The first chronometer that officially passed the precision requirements of the Longitude prize was produced by John Harrison in 1760 and finally tested in 1772, on the second expedition of Captain Cook, who famously wrote "our error [in Longitude] can never be great, so long as we have so good a guide as the watch".[14] Despite its advantages, the adoption of the chronometer was a relatively slow process, initially hampered by the high production costs. British survey and exploratory vessels were the first to be equipped with chronometers: it took two more decades for the first industrial production of the instrument and the consequent adoption on merchant ships. The first mass adopter for trans-oceanic trade was the East India Company (EIC). Davidson (2019) analyzes the logs of more than 580 voyages by the EIC in the period 1770-1792. In 1780, 52 percent of longitude entries were measured using the lunar method while the remainder relied on dead reckoning; the chronometer was still not available on any of the EIC vessels. The turning point for the use of the chronometer by the EIC was the last decade of the 18th century. From 1790 to 1792, within just two years the longitude measurements based on the chronometer passed from being a minority to cover more than 82 percent of total entries. The adoption was slower outside of the EIC but by 1815 the transition from the lunar method to the chronometer was probably completed among all major naval powers.[15] In the following sections we describe how this innovation changed the trans-oceanic sea routes, and through this channel, produced long-term effects on the global distribution of cities' population around the globe that we can still observe today.

3 Data

Our aim is to show (1) how the chronometer revolutionised trans-oceanic sailing routes between the 18th and 19th centuries; (2) how this change, because it was asymmetric, affected the distribution of cities and population outside of Europe. In this section, we discuss the broad range of data we collected to measure these outcomes. Specifically, to study the change in navigation patterns induced by the chronometer, we collected historical information on prevailing ocean sailing routes (described in sub-section 3.1) and on cloud coverage and sea-surface winds (sub-section 3.2). To study the impact of the chronometer on

The pendulum, a rival of chronometers on land, was debarred by the ship's motion and by the difference in gravity at different latitudes (Hewson (1951)). Further, a chronometer was superior to normal watches as it was built in such a way that outside temperature could not affect its inside mechanical components (Harbord (1883, p.54)).

[14] The citation is reported by Ritchie (1962, p.75).

[15] Sobel (1995, p.163) noted that "The total world census of marine timekeepers grew from just one in 1737 to approximately five thousand instruments by 1815".

global demography, we rely on data on urban population and population density (sub-section 3.3). Table 1 reports the summary statistics for this set of data.

3.1 Historical Navigation Data

Information on historical navigation patterns comes from CLIWOC (Climatological Database for the World's Oceans, García-Herrera et al. (2005)). This dataset contains 287,114 daily logbook entries from the British, Dutch, French, and Spanish navies covering the years 1750-1855.[16] For 4,764 voyages, it provides complete information on the date and place of departure and arrival, plus a series of ship characteristics. The dataset includes daily coordinates, making it possible to track the sailing route (along with daily information on weather and sea conditions).

We use this database to construct the two main outcome variables in Section 4: daily sailing speeds and routes. Sailing speeds are computed by dividing the distance between two consecutive logbook entries by the time elapsed between entries. We exclude observations in which the resulting speed is unrealistically high (above 99th percentile) or low (below 1st percentile or zero). To study changes in navigation routes, we compute the frequency with which each 1° x 1° grid cell appears in the dataset in every decade, to balance the panel. Rows 1 and 2 in panel (a) of Table 1 report summary statistics for these two variables: on average, sailing speed is 7.68km per hour and a 1° x 1° grid cell is navigated 1.96 times per decade. Both variables have high variability. For instance, there are remote places in the open ocean that are crossed only once in the century, and busy areas like the English Channel where hundreds of British and Dutch ships pass every decade. We collected two other series from CLIWOC to use as control variables: the nationality and the type of vessel (see rows 3-7 in panel (a) of Table 1 for summary statistics). While CLIWOC does not include systematic data on chronometers on board of ships, it provides information on whether dead reckoning was used to measure longitude.[17] Figure 2 reports the total number of observations for which this method was used and the share with respect to the total recordings. Both panels confirm the historical narrative described in Section 2: the practice of dead reckoning to measure longitude persists during the years in which the lunar method is mostly used to compute the longitude at sea, and it declines at the turn of the century, corresponding to the widespread diffusion of chronometers.

3.2 Weather Data

We collect data on two climatic features that crucially affect ocean navigation under sail: cloud coverage and wind patterns.

[16] In private correspondence, the authors of the dataset estimated that the digitised logbooks capture approximately a tenth of the logbooks produced by these nations over the century covered. Moreover, in CLIWOC the four different national navies are not uniformly represented through time. This is the result of an attempt to keep the number of voyages roughly constant in each decade, while compensating for the limited data available in the Dutch, French and Spanish archives for the wartime period 1793-1815.

[17] Sporadic notes on chronometers on board of ships are available for 0.04 percent of the total observations.

We draw our data on cloud coverage from the CLIWOC data, which captures historical observations, and the NASA Earth Observations (NEO),[18] which is based on contemporary observations. The CLIWOC dataset is a digitised version of the daily information on weather conditions from historical ship logbooks. The main advantage of this source is that it captures prevailing climatic conditions in the 18th and 19th century. Unfortunately, however, data entries are rarely comparable across different logbooks (the international agreement on standardization of metereological observations on board ships was only reached in 1854). Specifically, there are three different variables in CLIWOC describing cloud coverage: one of them is a numerical variable with values ranging from 1 to 10, the other two are string variables containing either words (e.g.'clouded' or 'clear sky') or codes for cloud shapes or coverage.[19] We create our own measure of prevailing cloud coverage in a certain cell. First, we establish a link between the numerical values and the string ones using those entries in the logbooks in which both values are present. Second, we use this link to impute a numerical value for those entries in which only a string value is available. Third, we take the grid averages of these values to obtain a single numeric value for each cell. Forth, we convert these numeric values into a variable for prevailing clear, hazy or overcast sky in that cell.[20]

Figure 3 panel (a) is an illustration of the distribution of cloud coverage that we calculated from the CLIWOC records, and therefore registered only for grid cells listed in the dataset. To validate our imputation exercise, we compare our imputed coverage distribution with contemporary cloud coverage data provided by NEO, which we show in Figure 3 panel (b). Reassuringly, the two variables appear to be highly correlated.

The summary statistics on the dummies for overcast sky constructed from the CLIWOC dataset and from the NEO dataset are reported in the rows 8-9 of panel (a), Table 1.

Cloud coverage data alone reveal an interesting pattern: starting from the 19th century we observe a relative increase in the number of entries of ships navigating under overcast sky compared to clear sky. We show this relationship in Figure 4, which plots the cumulative distribution function of cloud coverage encountered while sailing before and after 1800. This descriptive evidence suggests a reorientation of sailing routes towards more cloudy areas: in the following section, we will argue that this is mainly the result of the invention and diffusion of the chronometer.

Data on speed and direction of sea-surface winds are provided by the US National Oceanic and Atmospheric Administration (NOAA), as in Pascali (2017) and Ellingsen (2021). Specifically, we use average monthly data, which are available, from August 1999 to June 2002.[21]

[18] Data source: https://neo.sci.gsfc.nasa.gov; We use average monthly data from February 2000 to January 2016.

[19] We use the conversion scale provided by Koek and Können (2005) to convert these codes into cloud coverage.

[20] Specifically, clear skies are associated with values of the numeric variable from 0 to 2.5, cloudy skies with values from 2.6 to 7.5, overcast skies with values from 7.6 to 10.

[21] Data source: http://woce.nodc.noaa.gov/woce v3/wocedata 2/sat mwf/sat mwf2/. Pascali (2017) verifies that average velocity and direction of sea-surface winds from NOAA are compatible with the historical wind information reported in the CLIWOC dataset. This article computes optimal sailing times between countries and compares the optimised routes by sail with a set of actual voyages of sailing ships taken from CLIWOC, proving they overlap. When using wind data

3.3 Data on Urbanization and Population

Data on urbanization and population density come from HYDE 3.2 (History Database of the Global Environment, Klein Goldewijk et al. (2017)), a database originally compiled to reconstruct historical land use.[22] We download raster data for each decade between 1750 and 1900 with granular data on urban population (urban population per grid cell), population density (inhabitants/km^2 per grid cell), and built-up area (built-up area in km^2 per grid cell). We aggregate these variables within a one-degree latitude-by-longitude cell. The three variables display similar growth patterns. For instance, as shown in panel (b) of Table 1 for the hundred years between 1750 and 1850, all three increased by approximately 36-40 percent.

4 Results

In this section, we report the results of our empirical analyses. Our first analysis is the impact of the introduction of the chronometer on navigation. We report two main findings: 1) Starting in the 19^{th} century, the chronometer triggered an asymmetric change in sailing times across different routes, 2) as a result of this differential impact, the major transcontinental sailing routes of the time changed completely, with new itineraries emerging and others being abandoned. The main data source for this part of our study is CLIWOC, a large database of historical sailing ship logbooks. We use a triple-difference research design and the identification strategy exploits the advantages of the chronometer, which enabled navigation in all cloud conditions, over the earlier tools that limited open sea navigation to routes with clear skies. The second part of our analysis is the impact of this new technology on comparative development. The main data source is HYDE 3.2, a database with high-resolution historical data on urbanization and population density. Using a difference-in-differences approach, we show that coastal regions that became relatively more accessible to Europe, because of the chronometer, experienced a relatively larger increase in urbanization rates and population growth. A back-of-the-envelope calculation suggests that the effect of the chronometer in reducing sailing times might account for the vast majority of the increase in the coastal urban population outside of Europe during the 19^{th} century, and for approximately half of the increase in the total urban population outside of Europe.

in regressions, we also control for the direction of the wind with respect to ship trajectory and define wind as in favour, semi-favour, semi-against or against if the ship-to-wind angle is, respectively, less than 45°, between 45° and 90°, between 90° and 135°, or between 135° and 180°.

[22] https://themasites.pbl.nl/tridion/en/themasites/hyde/index.html

4.1 Navigation and the Chronometer

4.1.1 The impact of the chronometer on sailing times

How did the chronometer change navigation? We start by analysing one of the most relevant aspects: sailing speed. The main data source is the CLIWOC dataset, which provides historical daily information on both the position of several thousands of British, French, Dutch and Spanish ships and the conditions of the sky (clear vs. overcast), during the period 1750-1855. The historical narrative suggests that the chronometer was mass-adopted only in the first half of the 19^{th} century: the data covers, therefore, the five decades before the beginning of the diffusion of this new technology and the five following decades. The database has information on the position of the ship, the date of the measurement, the conditions of the sky and other characteristics of the ship. We infer the speed of the ship by calculating the time and distance covered between consecutive entries. Unfortunately, the database does not state whether there was a chronometer on the ship, so we cannot simply compare the speed of vessels that used and did not use a chronometer. To understand the impact of the chronometer on sailing speed, we exploit instead the fact that the advantages of the chronometer, compared to the lunar method, were practically limited to open sea navigation under an overcast sky (i.e., during coastal navigation, longitude could be inferred from other fixed points on the coast, while during open sea navigation under a clear sky, longitude could be inferred using the lunar method).

We start with a regression for open sea observations:

$$speed_{esit} = \sum_{t=1750}^{1850} \alpha_t clouds_i + \beta clouds_i + \gamma X_{esit} + \delta_t + \epsilon_{esit} \quad (1)$$

where e, s, i and t index the entry in CLIWOC, the ship in the observation, the 1° x 1° grid cell in which the ship is positioned, and the decade of the observation. $speed_{esit}$ measures the speed of ship s in entry e (expressed in km/h), $clouds_i$ is an indicator for navigating under overcast sky, X_{esit} is a set of covariates and δ_t denotes decade fixed effects.[23] The unit of observation is each entry in the CLIWOC logbooks, with the exclusion of coastal navigation entries.[24] The omitted decade is 1780-1789, the last decade before the first appearence of the chronometer in British and Dutch vessels. The estimates of α_t can be interpreted as the average impact of the chronometer on sailing speed in the open sea in each decade under the identifying assumptions that (i) there were no other contemporaneous improvements in maritime technology that changed the relative speed of travel under an overcast sky compared to a

[23]We report two sets of standard errors. First, we allow for arbitrary correlation of the residual terms within a grid cell, therefore clustering standard errors at the grid cell level. Second, since residuals from adjacent cells are unlikely to be independent from each other, we allow for spatial clustering of standard errors following Conley (1999). Although spatially clustered standard errors are generally larger, this correction matters little for the precision of our estimates, as can be seen in the discussion of the results.

[24]CLIWOC includes information on logbook entries originally recorded as coastal. However, this variable is recorded in a precise way as some cells are listed as coastal in certain voyages but not in others. To uniquely define cells as coastal, we create coastal buffers along the coastline with ArcMap, setting the distance at 5, 10, 15, 20, 30 and 50 kilometres, and compare the instances in which the original variable from CLIWOC coincides with any of our estimated buffers. The coast buffer which minimizes the mistake rate is 5 kilometres, with a margin of error of 3.52 percent.

clear sky and (ii) the chronometer only affected sailing speed under an overcast sky.

The results of these regressions are shown in Table 2. Column 1 presents the benchmark specification without controls. A clear pattern emerges: between the omitted decade, the 1780s, and the first decade of the 19^{th} century there is an exceptional increase in the relative speed of vessels navigating in cloudy regions compared to vessels navigating in clear sky regions. Specifically, between the decade 1780-1789 and the decade 1800-1809, sailing ships sailing under an overcast sky experienced a 20 percent larger increase in speed relative to ships sailing under a clear sky. This relative change in sailing speed persisted throughout the first half of the 19^{th} century and is not driven by pre-trends. Note that in the specifications of Table 2, none of the estimated coefficients before 1800 are statistically significant, and they are orders of magnitude smaller with respect to those for the decades of the 19^{th} century.

Overall, these results suggest large effects of the chronometer on sailing speed but, admittedly, they are also compatible with other explanations.

First, there might be other technological improvements in the sailing technology contemporaneous to the chronometer. Obvious candidates are the continuous evolution of sails and rigging, and improved hulls that allowed for a greater area of sail to be set safely in a given wind (see Kelly and Ó Gráda (2019)). All of these innovations are likely to affect navigation differentially depending on wind conditions and, as wind patterns and cloud coverage are generally correlated variables, might explain the results in column 1. To rule them out, in column 2 we add a battery of controls to capture the time-varying influence of wind patterns on sailing speed. Specifically, we control for the prevailing speed and wind direction (relative to the sailing direction) in the cell in which the ship is navigating, interacted with decade fixed effects. Results are practically unchanged.

Second, the benchmark estimates might be driven by changes in the sample of ships included in the CLIWOC database across the different decades. As discussed in the Data section, the database is far from giving a representative sample of the global international shipping industry of the time and the composition of the sample, in terms of the technological features of the sailing ships, is changing over time. When countries are at war (e.g. the Napoleonic wars), the sample is skewed towards war ships rather than trade ships. In this case our estimates might be capturing changes in the composition of the sample of surveyed ships rather than changes in average sailing speed. This is particularly relevant when looking at the nationality of the ships in the sample. For instance, observations covering British ships are concentrated in the first eight decades of the sample, while observations covering Dutch ships are more numerous in the last decades. Dutch ships were slower than British ships and the speed gap increased in the last decades of the 18^{th} century, especially under strong wind conditions (Solar and de Zwart (2017)). To address this point, in column 3 of Table 2, we control for the nationality of the ship interacted with decade fixed effects: results are practically unaffected. In Table A1, we take a step forward and show that the estimates are generally robust to also controlling for the type of the ship and, even, for ship fixed effects.[25] The inclusion of ship fixed effects is motivated by the fact the chronometer was an easy update on a sailing ship and, hence, the diffusion of chronometer was likely to change the relative speed under overcast sky of ships that had been built well before this innovation.

Third, the geographical coverage of the CLIWOC sample is limited and is changing over time as new sailing routes enter the database in the second part of the sample: this might affect the interpretation of the previous estimates if the new 19^{th} century routes are relatively faster than earlier routes for reasons unrelated to the invention of the chronometer (we discuss the change in sailing routes in the 19^{th} century in detail later in this subsection). To address this point, in column 4 we control for the absolute level of latitude of the entry in the logbook interacted with time decade: once again, the inclusion of this set of controls does not affect the estimates.

Overall, the results in Table 2 suggest large impacts of the chronometer on sailing speed and do not seem to be driven by other contemporaneous technological developments, nor by changes in the composition of ships or in the sailing routes in the CLIWOC dataset. Still, a causal interpretation would be misleading as we cannot rule out other unobservables driving the relative increase in speed under overcast sky that we observe in the 19^{th} century. To address this point, we leverage another specific aspect of the chronometer: its differential advantage in open sea navigation compared to coastal navigation. Longitude could be determined when a known landmark was in sight, even without a chronometer. Therefore, we expect the chronometer to have a differential impact on coastal vis-à-vis open sea navigation. We test this hypothesis by estimating a difference-in-differences specification separately for ships sailing along the coast and in the open sea:

$$speed_{esit} = \alpha clouds_i + \beta post_t + \gamma(clouds_i \times post_t) + \delta X_{esit} + \epsilon_{esit} \qquad (2)$$

where $post_t$ is an indicator variable for logbook entries taken during and after 1800, as inferred from the previous table.

The results are in Table 3. Columns 1-5 show the results for coastal navigation, and columns 6-10 for open sea navigation. Let's start by considering the benchmark specification without any additional control. The estimated γ is negative for coastal navigation (column 1), while positive and statistically significant for open sea navigation (column 6): between the second half of the 18^{th} century and the first half of the 19^{th} century, sailing under an overcast sky became relatively slower along the coast and faster in open sea. When focusing on offshore navigation, sailing speeds increase by 32 percentage points (28 log-points) under a clear sky and 58 percentage points (46 log-points) under an overcast sky. This points towards very large effects of the introduction of the chronometer on sailing speeds.

[25] For the ca. 4,800 journeys included in our regression sample, CLIWOC contains more than 900 different ship names. Some names are duplicated, so in the regressions we use combinations of ship names and nationality to identify individual ships. The original CLIWOC variable for ship types contains about one hundred different unique values and is missing for ca. 30 percent of the logbooks. We clean this variable of typos and harmonize ship types across nationalities, ending up with 13 different major types (e.g. brig, corvette, frigate, or sloop).

These findings are robust when controlling sequentially for a series of potentially confounding factors discussed above: wind patterns and speed (columns 2 and 7), ship nationality (columns 3 and 8), and latitude (columns 4 and 9). They are also robust when controlling jointly for all these factors (columns 5 and 10).

In addition, we test that the findings for coastal and open sea navigation are statistically different from each other, that is, that ships under overcast skies with a chronometer on board become significantly faster in open waters compared to coastal regions. We estimate a triple-difference regression given by:

$$\begin{aligned} speed_{esit} = &\alpha clouds_i + \beta post_t + \gamma open\ sea_i + \delta(clouds_i \times post_t) \\ &+ \theta(clouds_i \times open\ sea_i) + \mu(clouds_i \times post_t \times open\ sea_i) + \rho X_{esit} + \epsilon_{esit} \end{aligned} \tag{3}$$

where $open\ sea_i$ is an indicator for grid cells farther from the coast. The results, shown in the last column of Table 3, confirm the historical accounts: the effect of the chronometer is significantly stronger when sailing in the open sea. The estimate of the triple-difference coefficient (μ in equation 3) indicates that following the diffusion of the chronometer, ship speed in overcast open waters increases by about a third.

A potential concern is that the triple-difference setting might not capture the impact of the chronometer but rather of other contemporaneous innovations, which affect differentially offshore sailing under an overcast sky. We use an alternative identification strategy to rule out this explanation. As explained in the Historical Background section, before solving the longitude puzzle, sailors navigated by inferring their latitude in the open sea by measuring the altitude of a celestial body (e.g., the Sun or a star) above the horizon. To cross the oceans, ships would navigate along the coast until reaching the latitude of their destination and then follow a line of constant latitude in the open sea. This was another setting in which the innovation of the chronometer stood out: when parallel open sea navigation was not feasible. Column 1 in the Appendix table A2 shows the estimates from the following difference-in-differences equation:

$$speed_{esit} = \alpha not\ parallel_i + \beta post_t + \gamma(not\ parallel_i \times post_t) + \epsilon_{esit} \tag{4}$$

where $not\ parallel_i$ is a dummy variable for when navigation does not follow a straight parallel line.[26] We limit the analysis to offshore navigation. The estimates point towards an increase in sailing speeds in the years that followed the diffusion of the chronometer almost exclusively limited to non-parallel sailing: the increase in sailing speed was around 8 percent (and not statistically significant) when sailing along a parallel, and 23 percent (and statistically significant) when not sailing along a parallel. In the following column, we report the estimates of a triple-difference equation which confirms that this asymmetric change in sailing speeds in the post-chronometer years is almost fully explained by sailing observations under an overcast sky, while it is less evident under a clear sky (when the lunar method is a viable alternative for computing the longitude). The last column contains the results of a placebo exercise

[26] We define "*not parallel*" as a dummy equal to 1 when two subsequent logbook entries' coordinates form an angle larger or smaller than 270 degrees (fully westward) or 90 degrees (fully eastward), allowing for a buffer of ±0.5 degrees.

in which we repeat the triple-difference regression using the sample of coastal navigation rather than offshore navigation. In this case, as expected, the triple-difference coefficient is comparatively small and not statistically significant.

Overall, this first set of empirical results indicates a large impact of the chronometer on the average speed of sailing vessels. Moreover, this impact was asymmetric depending on prevailing weather conditions and distance from the coast.

4.1.2 The impact of the chronometer on prevailing sailing routes

Using the CLIWOC logbooks entries, we create a new balanced panel: each grid cell ever navigated and reported in one of CLIWOC logbooks appears in the dataset in every decade from 1750-1850. Then, we estimate the following equation for open sea observations:

$$voyages_{it} = \sum_{t=1750}^{1850} \alpha_t clouds_i + \beta clouds_i + \gamma X_{it} + \delta_t + \epsilon_{it} \tag{5}$$

where $voyages_{it}$ denotes the frequency at which 1° x 1° grid cell i is crossed by ships in decade t, $clouds_i$ is an indicator for navigating under an overcast sky, X_{it} is a set of covariates and δ_t denotes decade fixed effects.[27] The omitted decade is 1780s.

Regression results are reported in Table 4. Column 1 presents the benchmark specification without controls. The estimated β captures the average correlation throughout the sample between the cloud coverage of the cell i and the number of voyages passing by the same cell: unsurprisingly, an overcast sky is generally associated with less voyages. The estimated α_t coefficients capture changes in this correlation over time with respect to the omitted decade. Starting from the 1810s, we observe an increase in the relative number of voyages under an overcast sky compared to the pre-chronometer times. The estimated coefficient on α_t in 1810 is 0.83, while the average number of crossings per cell is 0.71. This large effect is also stable in time: from 1810 to the end of the sample period the coefficients on each decade are all very similar in size and generally statistically significant at conventional levels. The relative increase in voyages under an overcast sky occurred one decade after the increase in sailing speed under an overcast sky. This is consistent with a short learning process: it took ten years for the shipping industry to fully reoptimize the sailing routes to the new technology. The specification of equation 5 also allows us to check that our findings are not driven by pre-trends. In fact, with some exceptions, estimated coefficients before 1810 are orders of magnitude smaller compared to those for the decades of the 19$^{\text{th}}$ century.[28]

The results in column 1 are robust when controlling for wind patterns (column 2), latitude (column

[27] As in the previous analysis on ship speed, we report standard errors clustered at the grid cell level and using spatial clustering following Conley (1999).

[28] The negative results for decade 1770-1779 can be partially explained by a particular historical event. During the 1776-1777 Spanish-Portuguese War a Spanish large convoy of 116 ships kept sailing exclusively around the island of Santa Catarina (Brazil) and the city of Colonia del Sacramento (Uruguay). Some of the ships involved in this particular expedition are present in CLIWOC and they count for ca. 5,000 records. If we drop these observations from the sample, as they are a sort of massive outlier of an almost static convoy, the coefficients on decade 1770 are no longer significant.

3) or both (column 4) interacted with decade fixed effects.

Once again, to rule out that our results are capturing other innovations that improved navigation under overcast skies in the 19th century, we exploit the fact that the advantages of the chronometer were limited to open sea navigation and did not apply to coastal navigation. We estimate difference-in-difference regressions separately for coastal and open sea navigation, of the following form:[29]

$$voyages_{it} = \alpha clouds_i + \beta post_t + \gamma(clouds_i \times post_t) + \delta X_{it} + \epsilon_{it} \tag{6}$$

where $post_t$ is an indicator variable for logbook entries taken during and after 1800. The results of these regressions are reported in Table 5. A comparison between the estimated γ coefficients in columns 1 and 5, benchmark specifications without controls for coastal and for open sea navigation, show that the increase in crossings of overcast areas during the 19th century is a phenomenon restricted only to open sea navigation, a result that remains stable when also controlling for the time-changing effect of wind force and absolute latitude levels. The estimates for open sea navigation (columns 5-8) indicate an additional increase of about 0.67-0.79 voyages on average in cells with overcast sky from the 18th to the 19th century, relative to the increase in cells with clear sky, which amounts to almost 50 percent more voyages with respect to the 19th century mean number of voyages per grid cell.

We add to the difference-in-differences specification controls for wind speed (columns 2 and 6) and absolute level of latitude (columns 3 and 7), all interacted with the $post_t$ indicator, without noticing any effect on the estimates.

The last column of Table 5 reports a triple-difference regression, which shows that the findings for coastal and open sea navigation are statistically different from each other.

The combination of the estimates illustrated in subsection 4.1 shows that the chronometer increased sailing speed under overcast sky and, through this channel, changed trans-oceanic routes from Europe to the rest of the word. The results are not explained by pre-trends and are robust to controlling for the time-varying impact of wind patterns on navigation, thus indicating that our estimates are not capturing a differential impact of the evolution of maritime technology on open sea navigation or in overcast sky conditions.

4.2 The Chronometer and Urbanization

During the 19th century, European expansion led to major changes in the locations and sizes of urban centers outside of Europe, with the urban population tripling and moving towards the coast. Here we illustrate how we derive changes in sailing distances to Europe made possible by the chronometer (sub-

[29] For the regressions relative to coastal navigation, we drop coastal grid cells reported in CLIWOC as either departure or arrival ports, this way fixing a mechanical positive relationship between an overall increase in voyages and the number of ships passing through coastal cells to depart from or to reach their final destinations.

sub-section 4.2.1) and then show how these changes can explain the shifts in urban population outside of Europe using both descriptive evidence (4.2.2) and a difference-in-differences approach (4.2.3).

4.2.1 Optimized sailing distances

To measure sailing times to and from Europe, we construct a global grid of one-by-one degree square raster points and then create a directed network of bilateral sailing times from each ocean cell to each of its eight adjacent grid cells. These times are a function of the technology to compute the longitude (i.e. the lunar method vs. the chronometer) and the prevailing weather conditions in the adjacent cells. For each square, we used data from the Center for International Earth Science Information Network (CIESIN) to identify whether it was land or sea, we took monthly data from the US National Oceanic and Atmospheric Administration (NOAA) on the average velocity and direction of the sea-surface winds, and from NASA Earth Observations (NEO) we took monthly data on average cloud coverage.

The sailing times to adjacent cells using the chronometer are determined by the velocity and direction of the wind along the path, together with the polar diagram of a typical sailing vessel.[30] Notice that, as average weather conditions change across the months, these sailing times also change.

The sailing times to adjacent cells using the lunar method, by contrast, must take into account cloud cover, in addition to the polar diagram of the vessel and wind patterns. We showed previously that sailing under an overcast sky is substantially slower than sailing under a clear sky when using the lunar method. To understand how cloud coverage reduces sailing speed under the lunar method, we re-estimate equation (3) using the NEO data on contemporaneous cloud coverage rather than the CLIWOC data. The advantage is that the NEO data have global coverage, while the CLIWOC data only covers grid cells that are reported in the logbooks. The results are reported in the Appendix Table A3. The estimated coefficient on the triple-interaction is roughly 0.5, meaning that using a lunar navigation method under an overcast sky, journey time will be about twice what it would be if a chronometer were used.

Once the sailing time from each cell to all of its adjacent cells is computed, we can construct a directed graph in which each raster cell is a node. We end up with different directed graphs, depending on the technology used to calculate longitude and the sailing month. The Djikstra's algorithm is then used to compute the shortest travel time between any two cells within these graphs. Following this procedure, we compute the sailing time for a round-trip from Europe to any other coastal cell outside of Europe when using either the lunar method or the chronometer and in the month of May or January (we exclude the coast of Antarctica and the Mediterranean coast of Africa from these calculations).[31,32] Appendix Table A4 reports summary statistics. In May, the average optimized sailing time dropped by a third: from 256

[30] The polar diagram defines the maximum boat speed achievable for a given wind speed and wind angle.

[31] Specifically, we select the grid cell (latitude=51; longitude=-5) as starting point. This cell lies close to Portsmouth, Plymouth and Cork, three recurring European departure ports in CLIWOC.

[32] The Mediterranean coast of Africa was so close to Europe that neither the chronometer nor the lunar method were necessary to reach it.

days using the lunar method to 187 days using the chronometer. Yet, the impact of the chronometer on sailing time is heterogenous across the world, as can be seen in Figure 5. For instance, there are large relative effects on European routes towards South East India and Ceylon, which lie under a generally cloudy sky (see Figure 3), while the chronometer had substantially less impact on the sailing routes towards West India and neighbouring Pakistan, a region where the Indian Ocean lays under mostly clear skies and lunar navigation was possible.

4.2.2 Descriptive evidence

Our main data source for historical demographic information is the HYDE 3.2 dataset, which contains decade-level data on urban population, population density, and built-up area worldwide, with a spatial resolution of 5 arc minutes. For our analysis, we collapse this refined information at a 1° x 1° grid cell level, and we then match each land grid cell with the sailing variation reduction of the closest coastal grid cell.

Figure 6 shows decile-binscatter correlations between the percentage reduction in sailing times of a return trip from Europe due to the use of the chronometer and the percentage increase in total urban population, population density and built-up area outside of Europe between 1750 and 1850. The left figures in panels (a), (b) and (c) only look at coastal regions, while the figures on the right look at the corresponding inland areas.[33] In coastal regions a strong positive correlation emerges: places that became more accessible to Western civilization thanks to the chronometer experienced larger relative changes in urbanization and population density. For instance, the average increase in urban population between 1750 and 1850 was about 100 percent in places that were in the top decile with respect to sailing times reduction, compared to around 30 percent for places in the bottom decile. Changes in sailing distances to Europe do not seem to affect inland regions (right panels of Figure 6), which suggests that changes in urbanization and population density on the coast did not come at the expenses of inland territories.

What regions of the world drive these correlations? Figure 7 displays a series of world maps showing the geographic distribution of the reductions in sailing times of a return trip from Europe, made possible by the chronometer, and the changes in urbanization rates and population density along the corresponding coast. The variations are expressed in quintiles, where darker colors indicate larger changes. The coastal regions of the non-European world that experienced the largest increase in both urbanization and population density between 1750 and 1900, when the transition to the chronometer was certainly completed, match those that became relatively closer to Europe in terms of variation in sailing times (e.g., the east and north-western coasts of North America, the south-east coast of Australia, New Zealand, and the coasts of China and Japan).

[33] We define coastal regions as land grid cells within 2 degrees of the coastline.

These maps reveal some continental clustering. For instance, when comparing America and Oceania with Africa, we find that America and Oceania display, at the same time, larger increases in urbanization and population density along the coast and larger reductions in sailing times compared to Africa. Still, the correlation between the changes in urbanization/population density and the changes in sailing times is robust when limiting our analysis to within-continent variations. Figure A1 reports additional maps similar to those in Figure 7 with the only difference that depicted quantities are the residuals from regressing the raw data on continent fixed effects. We can see that even within continents, there is a positive correlation between the reduction in sailing times, induced by the chronometer, and the increase in urbanization rates and population density along the coast, further suggesting that chronometers did play an important role in shaping the worldwide development of coastal cities and population.

4.2.3 Difference-in-difference analysis

To test the causal impact of the chronometer, we estimate the relationship between the reduction in sailing times to Europe, generated by the chronometer, and cities and population development outside of Europe, following a difference-in-differences approach:

$$Y_{it} = \sum_{t=1750}^{1900} \alpha_t [\ln(lunar_{it}) - ln(chrono_{it})] + \eta_i + \eta_t + \gamma X_{it} + \epsilon_{it} \tag{7}$$

where i indexes a 1° x 1° grid cell, and t denotes a decade. Y_{it} captures either total urban population, or population density, or built-up area. η_i and η_t are grid cell and decade fixed effects, and X_{it} is a set of controls. The main regressor is the difference in sailing days of the lunar method compared to the chronometer on a return trip from Europe to cell i. We allow the coefficient to vary over the decades. The omitted decade is 1780-1789, the last decade before the first appearance of the chronometer in British and Dutch vessels.

The first four columns of Table 6 report the estimated α_t coefficients on a sample of coastal grid cells, mirroring Figure 7. In all specifications, we control for continent linear trends to capture potentially different (linear) continental trajectories in urbanization and population density rates. The results in column 1 show that the reduction in the sailing times induced by the chronometer had a significant positive impact on coastal urban population worldwide starting from 1820, right after the mass diffusion of this new technology. The estimated impact of the chronometer is large: we find that a one percent reduction in the time of a return trip from Europe generated by the chronometer is associated with an increase in urbanization rates of 3.2 percent by the mid-19$^{\text{th}}$ century, and of almost 5 percent by 1900. These results are not driven by pre-trends: the estimated coefficients for the 18$^{\text{th}}$ century are relatively small compared to the coefficients estimated for the 19$^{\text{th}}$ century and not statistically different than zero. Moreover, the main results are substantially unchanged when controlling for the time-varying impact of latitude (column 2).

The chronometer seems to produce a large effect also on population density (column 3) and built-up area (column 4). For both variables, the estimated coefficients are sizeable, significant only during the 19^{th} century, and continuously increasing in size. As early as 1850 a one percent reduction in sailing times from Europe is associated with an increase in coastal population density of 1.5 percent and of built-up area of 0.17 percent, and by 1900 the effect on population density is 40 percent higher and on built-up area is 2.3 times larger.

The results in the first four columns of Table 6 are robust to a list of checks.

First, the estimated coefficients on the changes in sailing times are robust when considering optimized sailing times in spring (when the majority of journeys from Europe start) or in winter (when departure rates from Europe are at their lowest). While Table 6 used optimized sailing times for the month of May, the Appendix Table A5 uses the optimized sailing times for the month of January. Results are unchanged.

Second, we show that results are not driven by any specific continent. In Table A6 we remove one by one all continents from the sample and re-estimate the benchmark specification of column 1 in Table 6. The results on urbanization rates are robust to this exercise with the estimated coefficients' sizes being very similar to the results illustrated in Table 6.

Did the urbanization of coastal regions, induced by the chronometer, come at the expense of inland development? The estimates in columns 5-8 of Table 6 are an attempt to address this question. When limiting the analysis to hinterland regions, we find that, unlike coastal regions, urbanization and population density are not affected by shocks to the sailing proximity to Europe induced by the chronometer. This finding is robust when controlling for the time-varying impact of the distance of the cell from the coast (see Appendix Table A7).

In sum, both preliminary descriptive data and our difference-in-differences estimates support the view that the invention of the chronometer had large effects on navigation, and through this channel, led to exceptional changes in urbanization rates and population density across the globe. Those regions of the world that became more accessible to Europe experienced a significant increase in urbanization, with a particularly rapid development of coastal areas, while the hinterland was not affected. Our estimates suggest that the invention of the chronometer accounts for the great majority (71 percent) of the increase in the urban population living along the coast outside of Europe during the 19^{th} century.[34] As slightly more than half of the total increase in urban population in this century was concentrated along the coast, the chronometer is able to explain more than a third of the total increase in urban population

[34] The average log-change in the coastal urban population outside of Europe in the 19^{th} century is 1.44; the average log-change in sailing times to Europe induced by the chronometer is -0.32; the estimated elasticity of coastal urban population outside of Europe with respect to sailing times to Europe is -3.2 (see the coefficient on $[(\ln(lunar)\text{-}\ln(chrono))\times I(1850)]$ in column 1 of Table 6). Then, the average log-change in the coastal urban population outside of Europe due to the chronometer according to our estimates is $-3.2\times -0.32=1.03$.

outside of Europe, and a similar portion of the increase in population density. Admittedly, these back-of-the-envelope calculations are very crude estimates and should be interpreted cautiously, as they are based on the assumption that the rollout of the chronometer was uniform across different trade routes and was completely finished by the end of the period of analysis. Also, data on population density and urbanization rates are crude estimates based on a mix of subnational-level census counts and a series of geospatial information including land cover, roads, slope, urban areas, village locations, etc. These data are the result of state-of-the-art global demographic models but demographic reconstruction estimates are far from being an ideal dataset to work with.

5 Concluding Remarks

In the 19th century, the world underwent an unprecedented change in its urban landscape. Outside of Europe, urban population tripled. This expansion of urbanization was concentrated along the coast and was vastly uneven across different regions of the world. What led to these changes? The process of European expansion, through trade, migration and colonization, was likely to be the major driver, but why is it that some regions experienced spectacular changes in their cities, while some others did not? What explains the timing of these changes?

We argue that the invention and diffusion of the maritime chronometer provides an answer to these fundamental questions about comparative development in the 19th century.

We present two pieces of empirical evidence. We show that solving the longitude constraint by adopting the chronometer reduced sailing times in open sea under overcast skies, while having relatively little effect on coastal navigation and open sea navigation under clear skies. This produced an asymmetric change in the sailing times between Europe and the rest of the world. We also establish that the shift of cities and population towards the coast is almost entirely explained by those regions that became relatively closer to Europe, in terms of sailing times, following the adoption of the chronometer. Overall, the magnitude of the empirical estimates points towards the chronometer being the innovation responsible for these massive global movements of cities and population towards the coast that we observe in the Americas, Asia, China and Oceania during the 19th century.

Our empirical estimates are based on a high-resolution grid that covers every non-European region of the world over 150 years. The global scope of the dataset means we can confirm that our empirical evidence is not driven by a particular region or continent. In fact, the impact of the chronometer is similar for all major continents outside of Europe. Moreover, the long period of time captured in the panel allows us to exclude that the empirical estimates are driven by pre-existing trends. Our global view and the grid-level exercise comes, however, with two caveats. One, we are not able to assess the impact of this innovation, and the subsequent reduction in sailing distances, on the local standards of living of the treated regions. Two, we do not assess through which channel the changes in the proximity to Europe induced changes in economic geography. For instance, we do not know if Europe exerted its impact through trade, migration or transfers of culture, technology and institutions. We leave these important research questions to future work.

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Tables

Table 1: Summary statistics

	Obs.	Mean	St. Dev.	Min	Max
Panel (a): Historical Navigation					
Ship speed (km/h)	229,586	7.68	3.96	1	18
Number of voyages	119,647	1.96	4.28	0	185
Nationality - British	83,828				
Nationality - Dutch	103,031				
Nationality - French	6,341				
Nationality - Spanish	35,762				
Nationality - Others	624				
Cloud coverage (dummy [0/1] - constructed from CLIWOC)	10,540	0.08	0.27	0	1
Cloud coverage (continuous [0-1] - data from NEO)	10,540	0.59	0.15	0	1
Panel (b): Urbanization and Population					
Sailing time reduction (percentage)	4,793	0.32	0.06	0	1
Urban population 1750 (inhabitants/grid cell)	16,436	2,613.42	24,623.88	0	1,488,598
Population density 1750 (inhabitants/km sq. per grid cell)	16,436	4.22	15.94	0	272
Built-up area 1750 (built-up area in km sq. per grid cell)	16,436	0.01	0.04	0	2
Urban population 1850 (inhabitants/grid cell)	16,436	5,601.94	32,856.77	0	1,485,495
Population density 1850 (inhabitants/km sq. per grid cell)	16,436	7.34	28.56	0	692
Built-up area 1850 (built-up area in km sq. per grid cell)	16,436	0.02	0.09	0	4
Change in urban population 1750-1850 (percentage)	16,436	0.40	0.84	-2	2
Change in population density 1750-1850 (percentage)	16,436	0.37	0.62	-2	2
Change in built-up area 1750-1850 (percentage)	16,436	0.36	0.81	-2	2

Notes: Summary statistics for key variables. See Section 3 for a detailed description of data sources and variables construction. Unit of observation in Panel A: logbook entry for ship speeds and nationalities, grid cell-by-decade for the number of voyages, grid cell for cloud cloverage. Unit of observation in Panel B: grid cell.

Table 2: Chronometer and Speed: Decade level

	Dependent variable: ln(speed)				
	(1)	(2)	(3)	(4)	(5)
Clouds × I(1750-1759)	-0.014	-0.025	-0.032	-0.001	-0.004
	(0.044)	(0.043)	(0.043)	(0.043)	(0.040)
	[0.101]	[0.092]	[0.090]	[0.092]	[0.071]
Clouds × I(1760-1769)	-0.052	-0.066	-0.044	-0.038	-0.032
	(0.054)	(0.051)	(0.050)	(0.052)	(0.044)
	[0.116]	[0.103]	[0.094]	[0.104]	[0.074]
Clouds × I(1770-1779)	0.024	0.000	-0.005	0.024	-0.011
	(0.048)	(0.046)	(0.049)	(0.049)	(0.046)
	[0.074]	[0.066]	[0.066]	[0.076]	[0.055]
Clouds × I(1790-1799)	-0.005	0.007	-0.001	-0.007	-0.004
	(0.038)	(0.038)	(0.036)	(0.038)	(0.036)
	[0.083]	[0.074]	[0.072]	[0.084]	[0.068]
Clouds × I(1800-1809)	0.212	0.212	0.178	0.197	0.181
	(0.044)***	(0.044)***	(0.043)***	(0.044)***	(0.042)***
	[0.067]***	[0.066]***	[0.062]***	[0.068]***	[0.061]***
Clouds × I(1810-1819)	0.144	0.159	0.094	0.135	0.117
	(0.063)**	(0.062)**	(0.062)	(0.062)**	(0.061)*
	[0.079]*	[0.073]**	[0.074]	[0.079]*	[0.063]*
Clouds × I(1820-1829)	0.030	0.044	0.021	0.012	0.032
	(0.058)	(0.054)	(0.054)	(0.058)	(0.050)
	[0.083]	[0.073]	[0.076]	[0.081]	[0.065]
Clouds × I(1830-1839)	0.164	0.183	0.117	0.150	0.137
	(0.052)***	(0.049)***	(0.051)**	(0.053)***	(0.048)***
	[0.070]**	[0.060]***	[0.066]*	[0.065]**	[0.053]**
Clouds × I(1840-1849)	0.181	0.187	0.137	0.175	0.145
	(0.054)***	(0.049)***	(0.052)***	(0.054)***	(0.048)***
	[0.073]**	[0.064]***	[0.068]**	[0.066]***	[0.057]**
Clouds × I(1850-1859)	0.166	0.164	0.119	0.153	0.116
	(0.048)***	(0.045)***	(0.047)**	(0.049)***	(0.044)***
	[0.070]**	[0.064]**	[0.066]*	[0.064]**	[0.055]**
Clouds	-0.114	-0.091	-0.067	-0.115	-0.056
	(0.033)***	(0.032)***	(0.031)**	(0.033)***	(0.029)*
	[0.046]**	[0.042]**	[0.039]*	[0.047]**	[0.037]
Observations	226211	226211	226211	226211	226211
Decade FE	Y	Y	Y	Y	Y
Wind x Decade FE		Y			Y
Nationality x Decade FE			Y		Y
Latitude x Decade FE				Y	Y
Clusters	10709	10709	10709	10709	10709

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC and the omitted decade is 1780-1789. Sample includes all $1^{\circ} \times 1^{\circ}$ grid cells at least 5 kilometres away from the coastline. Dependent variable is the natural logarithm of the speed of a ship (km/h); *Clouds* is a dummy equal to 1 assigned to grid cells with overcast sky as explained in sub-section 3.2, interacted with indicator variables for different decades; *Decade FE* are fixed effects for decades; *Wind* controls are four variables for average wind force, one per each wind direction with respect to ship trajectory (against, semi-against, in favour, semi-in favour), interacted with decade dummies; *Nationality* are fixed effects for ship nationality, interacted with decade dummies; *Latitude* is the absolute level of latitude, interacted with decade dummies. Standard errors clustered at the grid cell level in parentheses, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km in square brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table 3: Chronometer and Speed: Difference-in-Difference and Triple-Difference

	Dependent variable: ln(speed)										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Clouds × Post	-0.217	-0.198	-0.223	-0.173	-0.183	0.180	0.195	0.122	0.166	0.128	-0.183
	(0.188)	(0.191)	(0.184)	(0.188)	(0.184)	(0.038)***	(0.034)***	(0.037)***	(0.038)***	(0.034)***	(0.183)
	[0.189]	[0.190]	[0.187]	[0.175]	[0.172]	[0.076]**	[0.067]***	[0.068]*	[0.072]**	[0.054]**	[0.172]
Clouds	-0.108	-0.077	-0.113	-0.112	-0.064	-0.121	-0.106	-0.079	-0.121	-0.066	-0.064
	(0.153)	(0.155)	(0.146)	(0.155)	(0.145)	(0.031)***	(0.029)***	(0.030)***	(0.030)***	(0.025)***	(0.144)
	[0.103]	[0.120]	[0.097]	[0.104]	[0.102]	[0.061]**	[0.054]*	[0.050]	[0.060]**	[0.041]	[0.102]
Post	0.175	0.176	0.534	0.078	0.560	0.277	0.461	0.092	0.237	0.214	0.560
	(0.058)***	(0.103)*	(0.323)	(0.108)	(0.326)*	(0.007)***	(0.022)***	(0.044)**	(0.015)***	(0.054)***	(0.325)*
	[0.078]**	[0.158]	[0.322]*	[0.127]	[0.317]*	[0.042]***	[0.121]***	[0.086]	[0.113]**	[0.220]	[0.317]*
Clouds × Post × Open sea											0.311
											(0.186)*
											[0.175]*
Clouds × Open sea											-0.002
											(0.147)
											[0.111]
Post × Open sea											-0.345
											(0.329)
											[0.363]
Open sea											-0.905
											(0.164)***
											[0.226]***
Observations	3375	3375	3375	3375	3375	226211	226211	226211	226211	226211	229586
Coastal vs. Offshore	coastal	coastal	coastal	coastal	coastal	offshore	offshore	offshore	offshore	offshore	
Wind x Post (x Open sea)		Y			Y		Y			Y	Y
Nationality x Post (x Open sea)			Y		Y			Y		Y	Y
Latitude x Post (x Open sea)				Y	Y				Y	Y	Y
Clusters	222	222	222	222	222	10709	10709	10709	10709	10709	10931

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC. Dependent variable is the natural logarithm of the speed of a ship (km/h); *Clouds* is a dummy equal to 1 assigned to grid cells with overcast sky as explained in sub-section 3.2; *Post* is a dummy variable equal to 1 if logbook recording is dated after 1800 (including); *Open sea* is a dummy for $1^\circ \times 1^\circ$ grid cells at least 5 kilometres away from the coastline; *Coastal vs. Offshore* indicates if a grid cell is either on the coast or in the open sea; *Wind* controls are four variables for average wind force, one per each wind direction with respect to ship trajectory (against, semi-against, in favour, semi-in favour), interacted with *Post* - and double interacted with *Open sea* in column 11; *Nationality* are fixed effects for ship nationality, interacted with *Post* - and double interacted with *Open sea* in column 11; *Latitude* is the absolute level of latitude, interacted with *Post* - and double interacted with *Open sea* in column 11. Standard errors clustered at the grid cell level in parentheses, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km in square brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table 4: Chronometer and Routes: Decade level

	Dependent variable: number of voyages			
	(1)	(2)	(3)	(4)
Clouds × I(1750-1759)	0.361	0.396	0.401	0.416
	(0.101)***	(0.101)***	(0.102)***	(0.102)***
	[0.361]	[0.394]	[0.430]	[0.438]
Clouds × I(1760-1769)	0.056	0.085	0.098	0.110
	(0.113)	(0.113)	(0.115)	(0.115)
	[0.378]	[0.408]	[0.434]	[0.440]
Clouds × I(1770-1779)	-0.739	-0.811	-0.796	-0.829
	(0.121)***	(0.123)***	(0.124)***	(0.125)***
	[0.453]	[0.491]*	[0.508]	[0.517]
Clouds × I(1790-1799)	0.102	0.092	0.119	0.112
	(0.090)	(0.090)	(0.091)	(0.091)
	[0.373]	[0.390]	[0.393]	[0.400]
Clouds × I(1800-1809)	0.066	0.117	0.171	0.188
	(0.085)	(0.086)	(0.087)**	(0.087)**
	[0.285]	[0.304]	[0.315]	[0.319]
Clouds × I(1810-1819)	0.830	0.912	0.939	0.973
	(0.091)***	(0.092)***	(0.094)***	(0.094)***
	[0.258]***	[0.276]***	[0.284]***	[0.288]***
Clouds × I(1820-1829)	0.886	0.972	1.009	1.043
	(0.098)***	(0.099)***	(0.100)***	(0.101)***
	[0.273]***	[0.291]***	[0.297]***	[0.302]***
Clouds × I(1830-1839)	0.734	0.788	0.842	0.861
	(0.118)***	(0.120)***	(0.120)***	(0.121)***
	[0.307]**	[0.321]**	[0.327]**	[0.329]***
Clouds × I(1840-1849)	0.399	0.388	0.483	0.470
	(0.182)**	(0.181)**	(0.183)***	(0.182)***
	[0.436]	[0.436]	[0.441]	[0.434]
Clouds × I(1850-1859)	0.881	0.939	0.979	1.001
	(0.114)***	(0.116)***	(0.117)***	(0.117)***
	[0.294]***	[0.308]***	[0.312]***	[0.314]***
Clouds	-1.174	-1.284	-1.275	-1.324
	(0.098)***	(0.099)***	(0.102)***	(0.101)***
	[0.243]***	[0.261]***	[0.270]***	[0.275]***
Observations	118492	118492	118492	118492
Decade FE	Y	Y	Y	Y
Wind x Decade FE		Y		Y
Latitude x Decade FE			Y	Y
Clusters	10772	10772	10772	10772

Notes: Table reports OLS estimates. Unit of observation is a grid cell-by-decade and the omitted decade is 1780-1789. Sample includes all 1° × 1° grid cells at least 5 kilometres away from the coastline. Dependent variable is the number of crossings of a grid cell in a decade; *Clouds* is a dummy equal to 1 assigned to grid cells with overcast sky as explained in sub-section 3.2, interacted with indicator variables for different decades; *Decade FE* are fixed effects for decades; *Wind* is wind speed, interacted with decades dummies; *Latitude* is the absolute level of latitude, interacted with decade dummies. Standard errors clustered at the grid cell level in parentheses, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km in square brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table 5: Chronometer and Routes: Difference-in-Difference and Triple-Difference

	Dependent variable: number of voyages								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Clouds × Post	0.128	0.083	0.159	0.096	0.677	0.734	0.773	0.794	0.096
	(0.206)	(0.223)	(0.183)	(0.218)	(0.094)***	(0.097)***	(0.098)***	(0.099)***	(0.217)
	[0.381]	[0.385]	[0.319]	[0.375]	[0.302]**	[0.323]**	[0.340]**	[0.343]**	[0.375]
Clouds	-0.386	-0.373	-0.340	-0.357	-1.218	-1.331	-1.310	-1.362	-0.357
	(0.105)***	(0.110)***	(0.097)***	(0.113)***	(0.094)***	(0.096)***	(0.099)***	(0.099)***	(0.112)***
	[0.131]***	[0.134]***	[0.111]***	[0.128]***	[0.254]***	[0.278]***	[0.298]***	[0.302]***	[0.128]***
Post	0.178	0.100	-0.011	-0.166	-0.978	-2.137	-0.458	-1.472	-0.166
	(0.174)	(0.163)	(0.133)	(0.237)	(0.033)***	(0.157)***	(0.050)***	(0.143)***	(0.235)
	[0.365]	[0.375]	[0.202]	[0.351]	[0.312]***	[1.264]*	[0.525]	[1.222]	[0.351]
Clouds × Post × Open sea									0.698
									(0.238)***
									[0.490]
Clouds × Open sea									-1.005
									(0.150)***
									[0.321]***
Post × Open sea									-1.306
									(0.275)***
									[1.284]
Open sea									4.414
									(0.238)***
									[1.039]***
Observations	1155	1155	1155	1155	118492	118492	118492	118492	119647
Coastal vs. Offshore	coastal	coastal	coastal	coastal	offshore	offshore	offshore	offshore	
Wind x Post (x Open ea)		Y		Y		Y		Y	Y
Abs. Latitude x Post (x Open sea)			Y	Y			Y	Y	Y
Clusters	105	105	105	105	10772	10772	10772	10772	10877

Notes: Table reports OLS estimates. Unit of observation is a grid cell-by-decade. Dependent variable is the number of crossings of a grid cell in a decade; *Clouds* is a dummy equal to 1 assigned to grid cells with overcast sky as explained in sub-section 3.2; *Post* is a dummy variable equal to 1 if logbook recording is dated after 1800 (including); *Open sea* is a dummy for $1^\circ \times 1^\circ$ grid cells at least 5 kilometres away from the coastline; *Coastal vs. Offshore* indicates if a grid cell is either on the coast or in the open sea; *Wind* is wind speed, interacted with *Post* - and double interacted with *Open sea* in column 9; *Latitude* is the absolute level of latitude, interacted with *Post* - and double interacted with *Open sea* in column 9. Standard errors clustered at the grid cell level in parentheses, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km in square brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table 6: Chronometer, Urbanization and Population density

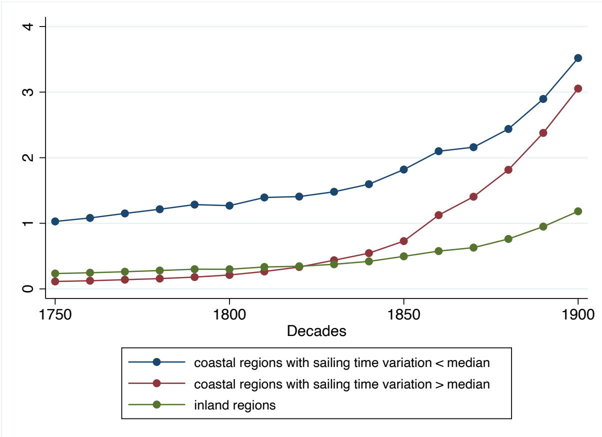
	COASTAL REGIONS				INLAND REGIONS			
Dependent variable:	ln(urban population)		ln(population density)	ln(built-up area)	ln(urban population)		ln(populaiton density)	ln(built-up area)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(lunar)-ln(chrono) × I(1750)	0.206	0.058	-0.247	-0.012	0.758	0.381	0.279	0.008
	(1.159)	(1.138)	(0.511)	(0.083)	(1.078)	(1.105)	(0.470)	(0.035)
ln(lunar)-ln(chrono) × I(1760)	0.174	0.068	-0.153	-0.007	0.533	0.281	0.201	0.006
	(1.096)	(1.079)	(0.474)	(0.082)	(1.056)	(1.088)	(0.458)	(0.035)
ln(lunar)-ln(chrono) × I(1770)	0.158	0.103	-0.062	-0.002	0.298	0.179	0.122	0.003
	(1.035)	(1.023)	(0.442)	(0.079)	(1.033)	(1.069)	(0.447)	(0.035)
ln(lunar)-ln(chrono) × I(1790)	0.152	0.212	0.108	0.008	-0.254	-0.133	-0.064	-0.003
	(0.973)	(0.968)	(0.393)	(0.076)	(0.983)	(1.024)	(0.429)	(0.034)
ln(lunar)-ln(chrono) × I(1800)	0.467	0.592	0.389	0.026	-0.387	-0.146	-0.040	-0.004
	(0.888)	(0.884)	(0.344)	(0.073)	(0.934)	(0.975)	(0.406)	(0.034)
ln(lunar)-ln(chrono) × I(1810)	1.017	1.192	0.579*	0.050	-0.488	-0.078	-0.057	-0.005
	(0.800)	(0.800)	(0.320)	(0.065)	(0.853)	(0.892)	(0.373)	(0.032)
ln(lunar)-ln(chrono) × I(1820)	1.591**	1.828**	0.828***	0.079	-0.531	0.040	-0.014	-0.002
	(0.772)	(0.772)	(0.314)	(0.061)	(0.781)	(0.817)	(0.344)	(0.030)
ln(lunar)-ln(chrono) × I(1830)	2.337***	2.672***	1.047***	0.112*	-0.596	0.154	-0.028	0.002
	(0.785)	(0.783)	(0.321)	(0.057)	(0.758)	(0.792)	(0.332)	(0.028)
ln(lunar)-ln(chrono) × I(1840)	2.622***	3.058***	1.274***	0.128**	-0.783	0.122	-0.036	0.006
	(0.803)	(0.800)	(0.334)	(0.057)	(0.769)	(0.802)	(0.335)	(0.026)
ln(lunar)-ln(chrono) × I(1850)	3.204***	3.743***	1.539***	0.168***	-0.844	0.243	0.029	0.014
	(0.881)	(0.870)	(0.360)	(0.061)	(0.833)	(0.867)	(0.361)	(0.026)
ln(lunar)-ln(chrono) × I(1860)	3.873***	4.489***	1.788***	0.200***	-0.980	0.279	0.128	0.025
	(0.941)	(0.929)	(0.391)	(0.067)	(0.936)	(0.972)	(0.421)	(0.029)
ln(lunar)-ln(chrono) × I(1870)	4.423***	5.217***	1.895***	0.243***	-1.198	0.208	0.236	0.038
	(1.015)	(1.013)	(0.419)	(0.078)	(1.054)	(1.096)	(0.471)	(0.037)
ln(lunar)-ln(chrono) × I(1880)	4.630***	5.579***	2.016***	0.290***	-1.662	-0.134	0.180	0.048
	(1.111)	(1.114)	(0.462)	(0.093)	(1.192)	(1.247)	(0.525)	(0.047)
ln(lunar)-ln(chrono) × I(1890)	4.909***	6.053***	2.087***	0.339***	-2.162	-0.479	0.120	0.055
	(1.213)	(1.224)	(0.505)	(0.113)	(1.343)	(1.407)	(0.572)	(0.058)
ln(lunar)-ln(chrono) × I(1900)	4.839***	6.178***	2.155***	0.387***	-2.952**	-1.115	0.015	0.057
	(1.276)	(1.295)	(0.549)	(0.137)	(1.479)	(1.559)	(0.612)	(0.070)
Observations	76688	76688	76688	76688	186288	186288	186288	186288
Grid cell FE	Y	Y	Y	Y	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y	Y	Y	Y	Y
Latitude x Decade FE		Y				Y		

Notes: Table reports OLS estimates. Unit of observation is a 1° × 1° grid cell and the omitted decade is 1780-1789. *Coastal regions* include land grid cells within 2 degrees from the coastline, *Inland regions* include the rest of land grid cells. Dependent variables are the natural logarithm of 1 plus, in turn, urban population (inhabitants/grid cell), population density (inhabitants/km^2 per grid cell) and built-up area (e.g. cities in km^2 per grid cell); *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronomter (in log of days) for a return voyage from Europe to worldwide coastal regions using May data for wind and coverage (inland grid cells are assigned navigation times of the closest coastal gird cell); *Grid cell FE* and *Decade FE* are grid cell and decade fixed effects; *Continent linear trends* are linear trends for all continents in the sample (Africa, America, Asia, Oceania); *Latitude* is the latitude level, interacted with decade fixed effects. Standard errors are corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

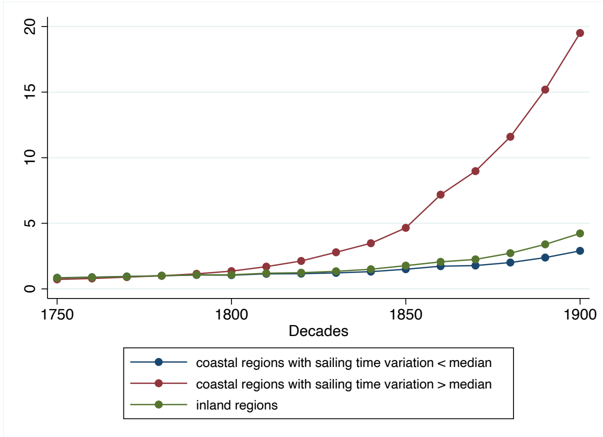
Figures

Figure 1: Urban population density (excluding Europe)

(a) Urban density (urban inhab./km sq.)



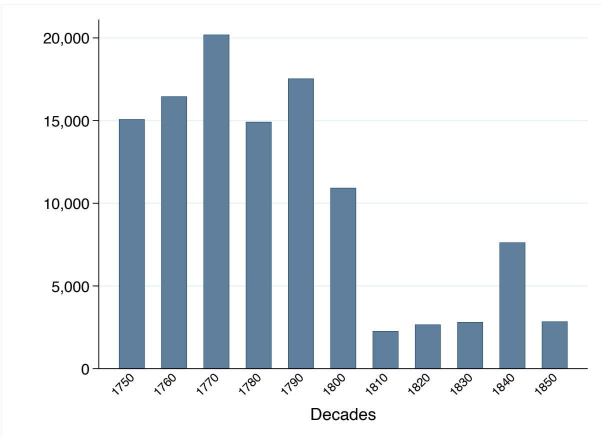
(b) Relative urban density growth % (1780 = 1)



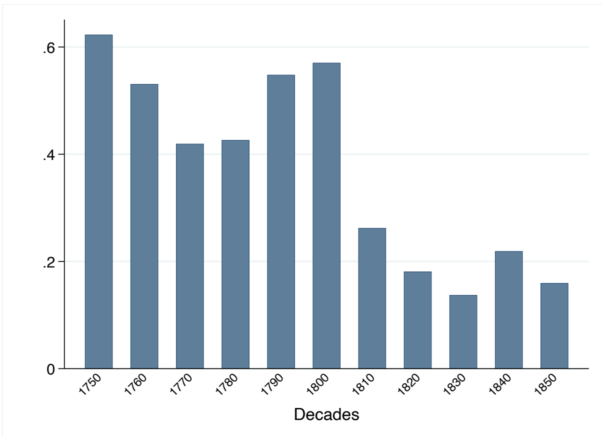
Notes: Figures depict worldwide urban population density excluding Europe. Panel (a) shows average urban density (urban inhabitants per square kilometer); Panel (b) shows the percentage change in urban density relative to the decade 1780-1789. Sailing time variation refers to the reduction in the sailing time of a return trip from Europe when longitude is calculated using a chronometer rather than the lunar method. Sailing time variations are estimated using a methodology illustrated in sub-section 4.2.1.

Figure 2: Longitude recordings with dead reckoning

(a) Total observations



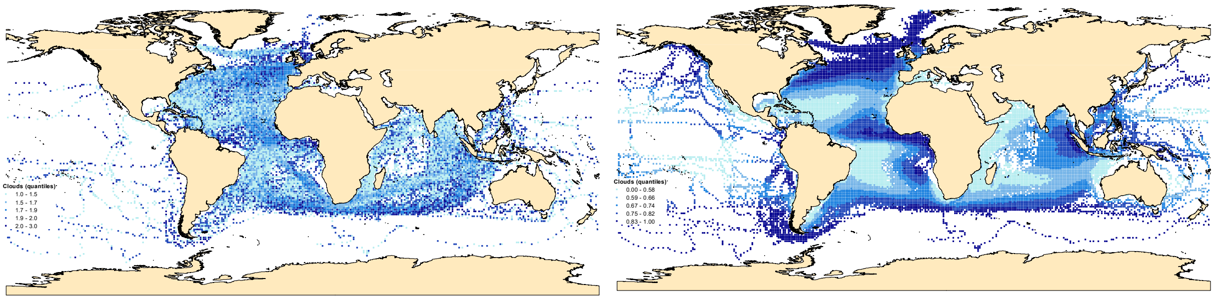
(b) Shares



Notes: The unit of observation is an entry in the CLIWOC dataset.

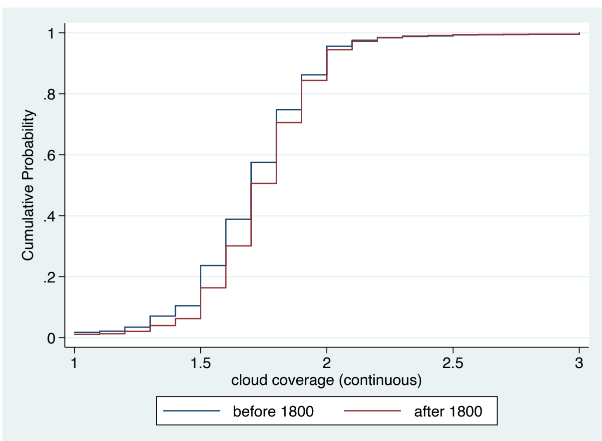
Figure 3: Cloud coverage

(a) Average cloud coverage using CLIWOC (b) Average cloud coverage using NEO



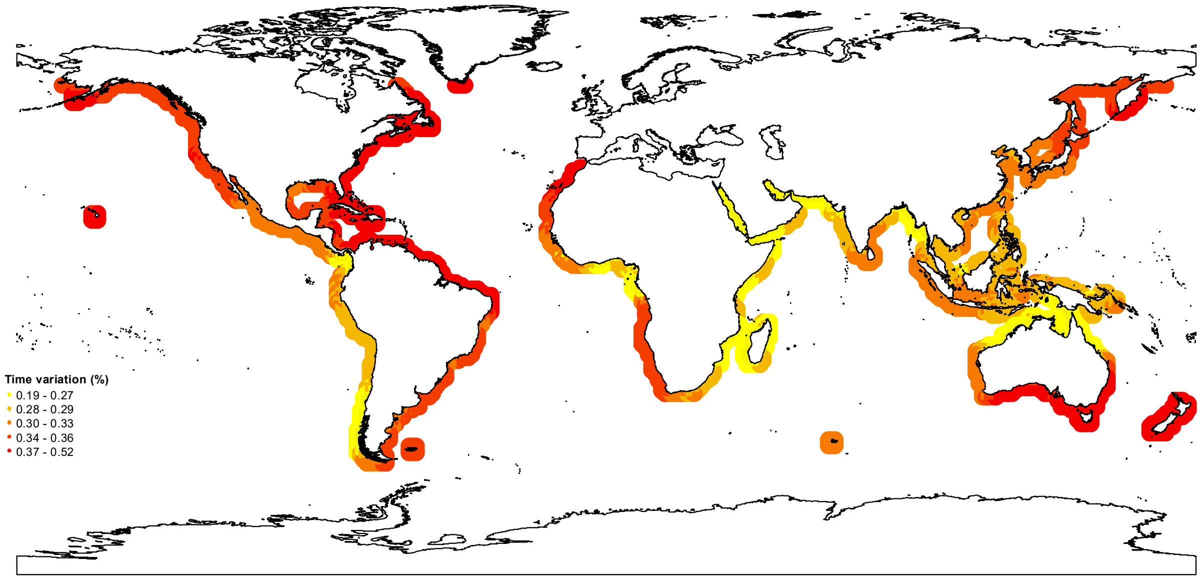
Notes: Panel (a) displays average cloud coverage distribution, in five quantiles, constructed using data from CLIWOC and following the procedure described in sub-section 3.2. Panel (b) shows average coverage distribution, in five quantiles, with contemporary cloud data provided by NASA Earth Observations, also described in sub-section 3.2. The unit of observation is a $1^\circ \times 1^\circ$ grid cell and the sample includes grid cells available in the CLIWOC dataset.

Figure 4: CDF of cloud coverage



Notes: Cumulative distribution functions of cloud coverage before and after 1800 using the CLIWOC dataset. Cloud coverage values range between 1 and 3 as explained in sub-section 3.2.

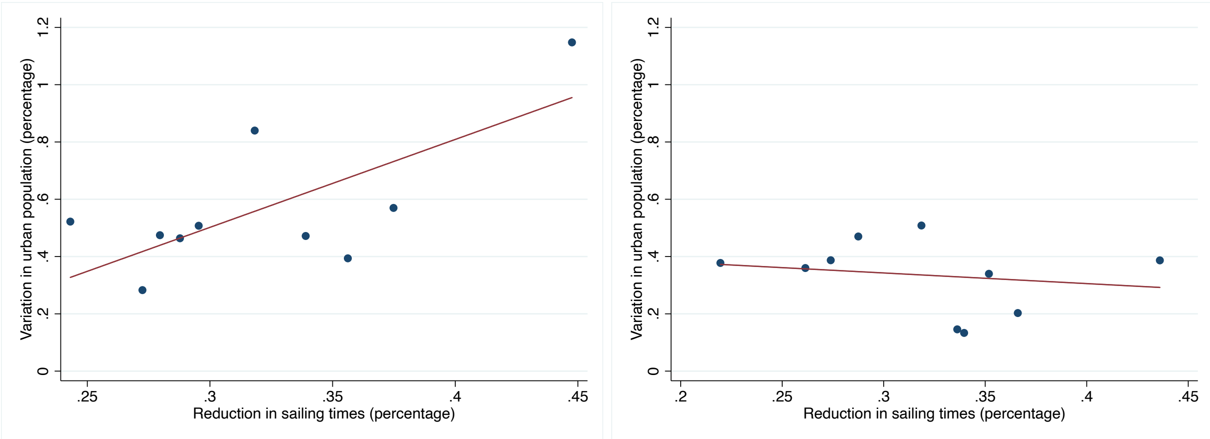
Figure 5: Reduction in sailing times



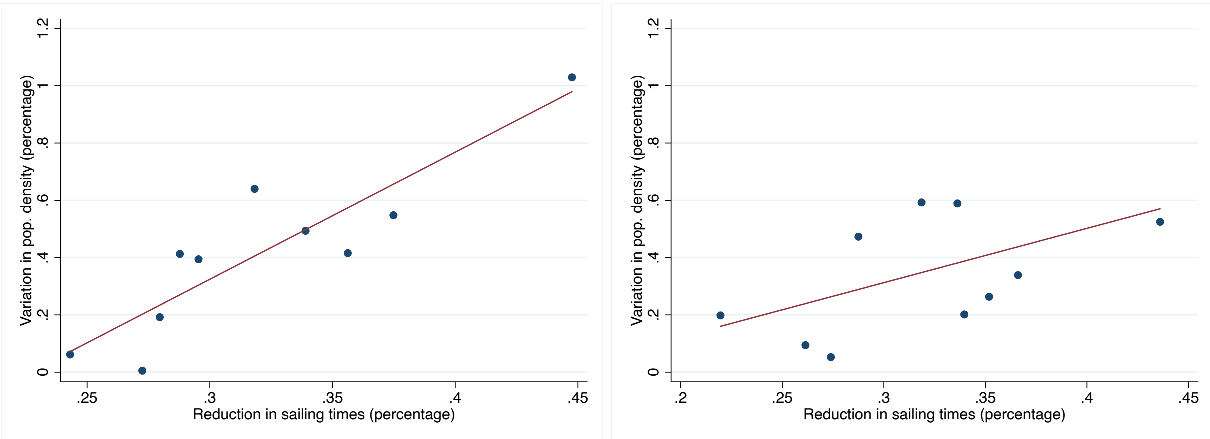
Notes: Figure displays quintiles of the estimated percentage reduction in minimum sailing times of a return trip from Europe to any other coastal cell outside of Europe induced by the invention of the chronometer.

Figure 6: Variation in urbanization, population density and in sailing times: Correlations

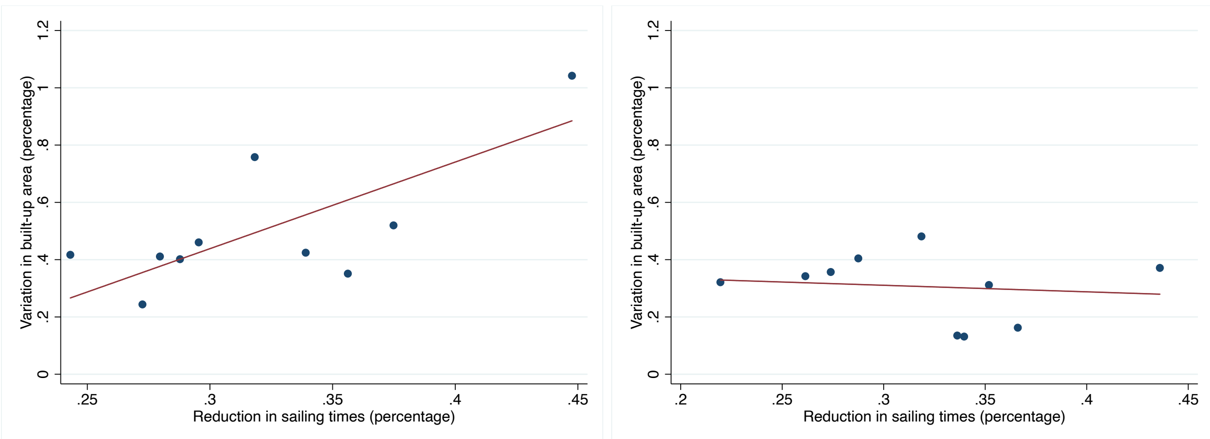
(a) Urban population on the coast and inland



(b) Population density on the coast and inland



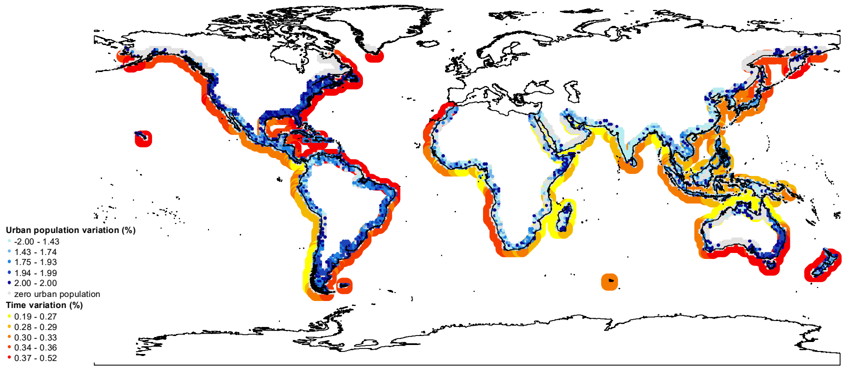
(c) Built-up area on the coast and inland



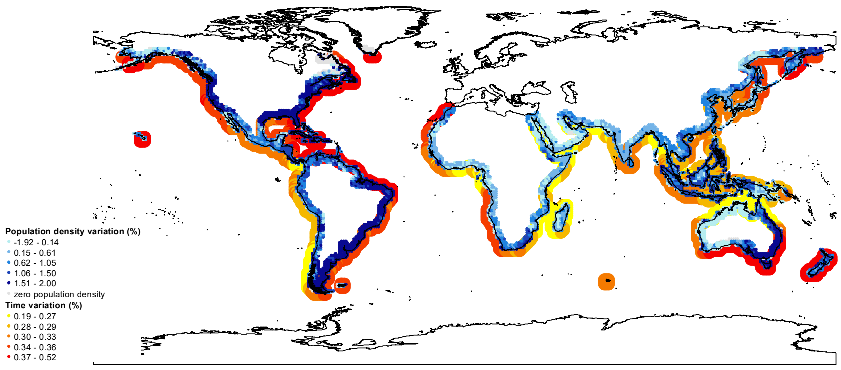
Notes: Binscatters display percentage reduction in minimum sailing times of a return trip from Europe under chronometer with respect to lunar method, against percentage variation in (a) urban population, (b) population density and (c) built-up area between 1750 and 1850. Panels on the left show correlations on the coastal regions, while panels on the right focus on the inland areas.

Figure 7: Variation in urbanization, population density and in sailing times: Geographic distribution

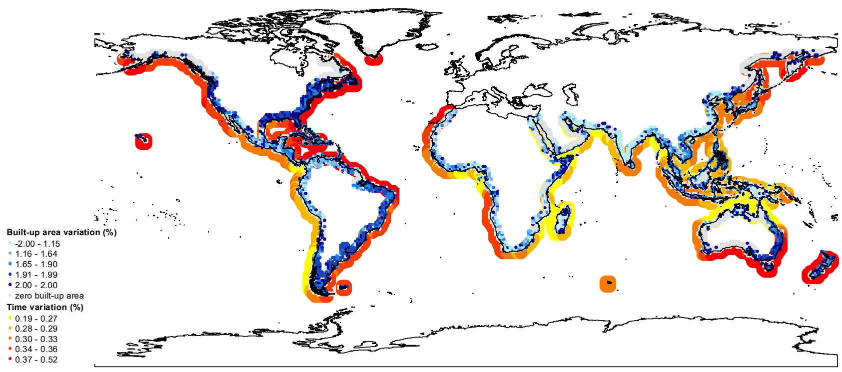
(a) Urban population



(b) Population density



(c) Built-up area



Notes: Maps display the percentage reduction in minimum sailing times of a return trip from Europe under chronometer with respect to lunar method, against the percentage variation in (a) total urban population, (b) average population density and (c) average built-up area between 1750 and 1900.

Appendix: Additional Tables and Figures

Table A1: Chronometer and Speed: Decade level

	Dependent variable: ln(speed)		
	(1)	(2)	(3)
Clouds × I(1750-1759)	-0.014	-0.031	0.003
	(0.044)	(0.041)	(0.065)
	[0.101]	[0.076]	[0.119]
Clouds × I(1760-1769)	-0.052	-0.043	-0.023
	(0.054)	(0.048)	(0.063)
	[0.116]	[0.087]	[0.125]
Clouds × I(1770-1779)	0.024	-0.007	0.063
	(0.048)	(0.040)	(0.050)
	[0.074]	[0.055]	[0.080]
Clouds × I(1790-1799)	-0.005	-0.007	0.057
	(0.038)	(0.034)	(0.048)
	[0.083]	[0.067]	[0.086]
Clouds × I(1800-1809)	0.212	0.145	0.190
	(0.044)***	(0.040)***	(0.062)***
	[0.067]***	[0.054]***	[0.085]**
Clouds × I(1810-1819)	0.144	0.101	0.091
	(0.063)**	(0.059)*	(0.088)
	[0.079]*	[0.065]	[0.103]
Clouds × I(1820-1829)	0.030	0.015	-0.001
	(0.058)	(0.050)	(0.074)
	[0.083]	[0.065]	[0.097]
Clouds × I(1830-1839)	0.164	0.108	0.136
	(0.052)***	(0.049)**	(0.072)*
	[0.070]**	[0.058]*	[0.085]
Clouds × I(1840-1849)	0.181	0.129	0.215
	(0.054)***	(0.051)**	(0.059)***
	[0.073]**	[0.060]**	[0.081]***
Clouds × I(1850-1859)	0.166	0.112	0.164
	(0.048)***	(0.046)**	(0.067)**
	[0.070]**	[0.061]*	[0.090]*
Clouds	-0.114	-0.053	-0.139
	(0.033)***	(0.030)*	(0.041)***
	[0.046]**	[0.031]*	[0.056]**
Observations	226211	226211	122900
Decade FE	Y	Y	Y
Ship FE		Y	
Ship type FE			Y
Clusters	10709	10709	9529

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC and the omitted decade is 1780-1789. Sample includes all $1^\circ \times 1^\circ$ grid cells at least 5 kilometres away from the coastline. Dependent variable is the natural logarithm of the speed of a ship (km/h); *Clouds* is a dummy equal to 1 assigned to grid cells with overcast sky as explained in sub-section 3.2, interacted with indicator variables for different decades; *Decade FE* are fixed effects for decades; *Ship FE* are fixed effects for individual ships (combinations of ships' names and nationality); *Ship type FE* are fixed effects for different type of ships harmonized across nationalities (this information is missing for ca. 30 percent of the logbooks). Standard errors clustered at the grid cell level in parentheses, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km in square brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table A2: Robustness: Not sailing along the parallels

	Dependent variable: ln(speed)		
	(1)	(2)	(3)
Post × Not Parallel	0.155	0.145	0.277
	(0.011)***	(0.011)***	(0.091)***
	[0.056]***	[0.057]**	[0.134]**
Post	0.076	0.078	-0.101
	(0.011)***	(0.011)***	(0.090)
	[0.060]	[0.062]	[0.117]
Not Parallel	0.482	0.483	0.422
	(0.009)***	(0.009)***	(0.082)***
	[0.042]***	[0.043]***	[0.110]***
Clouds × Post × Not Parallel		0.195	-0.438
		(0.046)***	(0.315)
		[0.076]**	[0.254]
Clouds × Post		-0.046	0.145
		(0.049)	(0.194)
		[0.080]	[0.211]
Clouds × Not Parallel		-0.033	0.023
		(0.029)	(0.260)
		[0.059]	[0.123]
Clouds		-0.023	-0.150
		(0.029)	(0.128)
		[0.063]	[0.136]
Observations	207917	207917	2794
Coastal vs. Offshore	offshore	offshore	coastal
Clusters	10705	10705	222

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC. Dependent variable is the natural logarithm of the speed of a ship (km/h); *Post* is a dummy variable equal to 1 if logbook recording is dated after 1800 (including); *Not Parallel* is a dummy equal to 1 when two subsequent logbook entries' coordinates form an angle bigger or smaller than 270 degrees (fully westward) or 90 degrees (fully eastward), allowing for a buffer of ±0.5 degrees; *Clouds* is a dummy equal to 1 assigned to grid cells with overcast sky as explained in sub-section 3.2; *Coastal vs. Offshore* indicates if a grid cell is either on the coast or in the open sea. Standard errors clustered at the grid cell level in parentheses, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km in square brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table A3: Chronometer and Speed: Triple-Difference

	Dependent variable: ln(speed)
	(1)
Clouds × Post × Open sea	0.525
	(0.252)**
Clouds × Post	-0.029
	(0.243)
Clouds × Open sea	-0.126
	(0.169)
Post × Open sea	-0.165
	(0.130)
Clouds	-0.204
	(0.160)
Post	0.162
	(0.124)
Open sea	0.518
	(0.080)***
Observations	235822
Clusters	14219

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC. Dependent variable is the natural logarithm of the speed of a ship (km/h); *Clouds* is the fraction of a grid cell covered by clouds constructed with data from NASA Earth Observations; *Post* is a dummy variable equal to 1 if logbook recording is dated after 1800 (including); *Open sea* is a dummy for 1° × 1° grid cells at least 5 kilometres away from the coastline. Standard errors clustered at the grid cell level in parentheses. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table A4: Summary statistics

	Obs.	Mean	St. Dev.	Min	Max
Sailing times					
Optimized sailing times in May - Lunar method (days)	4,793	256.35	109.17	43	417
Optimized sailing times in May - Chronometer (days)	4,793	187.62	81.36	29	298

Notes: See sub-sub-section 4.2.1 for a detailed description of data sources and variables construction. Unit of observation: grid cell.

Table A5: Robustness: January data for clouds coverage and wind

	COASTAL REGIONS			
Dependent variable:	ln(urban population)		ln(population density)	ln(built-up area)
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1750)	0.491	0.459	-0.470	-0.010
	(1.483)	(1.519)	(0.637)	(0.087)
ln(lunar)-ln(chrono) × I(1760)	0.301	0.282	-0.311	-0.007
	(1.404)	(1.441)	(0.597)	(0.085)
ln(lunar)-ln(chrono) × I(1770)	0.208	0.200	-0.147	-0.004
	(1.333)	(1.368)	(0.561)	(0.082)
ln(lunar)-ln(chrono) × I(1790)	0.030	0.041	0.190	0.007
	(1.228)	(1.262)	(0.501)	(0.078)
ln(lunar)-ln(chrono) × I(1800)	0.251	0.274	0.523	0.023
	(1.122)	(1.153)	(0.451)	(0.074)
ln(lunar)-ln(chrono) × I(1810)	0.756	0.797	0.811*	0.047
	(1.020)	(1.046)	(0.420)	(0.067)
ln(lunar)-ln(chrono) × I(1820)	1.401	1.459	1.196***	0.080
	(0.965)	(0.988)	(0.400)	(0.062)
ln(lunar)-ln(chrono) × I(1830)	2.165**	2.234**	1.464***	0.118**
	(0.969)	(0.989)	(0.396)	(0.059)
ln(lunar)-ln(chrono) × I(1840)	2.422**	2.494**	1.801***	0.142**
	(0.996)	(1.018)	(0.413)	(0.058)
ln(lunar)-ln(chrono) × I(1850)	2.856***	2.936***	2.139***	0.182***
	(1.078)	(1.103)	(0.450)	(0.062)
ln(lunar)-ln(chrono) × I(1860)	3.454***	3.547***	2.692***	0.222***
	(1.171)	(1.198)	(0.489)	(0.068)
ln(lunar)-ln(chrono) × I(1870)	4.278***	4.364***	3.062***	0.279***
	(1.287)	(1.320)	(0.526)	(0.078)
ln(lunar)-ln(chrono) × I(1880)	4.428***	4.505***	3.423***	0.339***
	(1.409)	(1.445)	(0.584)	(0.093)
ln(lunar)-ln(chrono) × I(1890)	4.723***	4.784***	3.642***	0.405***
	(1.543)	(1.580)	(0.648)	(0.113)
ln(lunar)-ln(chrono) × I(1900)	4.502***	4.543***	3.909***	0.473***
	(1.621)	(1.655)	(0.709)	(0.136)
Observations	76688	76688	76688	76688
Grid cell FE	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y
Latitude x Decade FE		Y		

Notes: Table reports OLS estimates. Unit of observation is a 1° × 1° grid cell and the omitted decade is 1780-1789. *Coastal regions* include land grid cells within 2 degrees from the coastline. Dependent variables are the natural logarithm of 1 plus, in turn, urban population (inhabitants/grid cell), population density (inhabitants/km^2 per grid cell) and built-up area (e.g. cities in km^2 per grid cell); *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronomter (in log of days) for a return voyage from Europe to worldwide coastal regions using January data for wind and coverage; *Grid cell FE* and *Decade FE* are grid cell and decade fixed effects; *Continent linear trends* are linear trends for all continents in the sample (Africa, America, Asia, Oceania); *Latitude* is the latitude level, interacted with decade fixed effects. Standard errors are corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Table A6: Robustness: Excluding continents one-by-one

	COASTAL REGIONS			
Dependent variable:	ln(urban population)		ln(population density)	ln(built-up area)
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1750)	0.204	0.728	-0.475	0.337
	(1.258)	(1.032)	(1.227)	(1.280)
ln(lunar)-ln(chrono) × I(1760)	0.180	0.471	-0.248	0.258
	(1.186)	(0.986)	(1.167)	(1.209)
ln(lunar)-ln(chrono) × I(1770)	0.183	0.228	-0.062	0.208
	(1.119)	(0.947)	(1.107)	(1.142)
ln(lunar)-ln(chrono) × I(1790)	0.195	-0.120	0.312	0.128
	(1.049)	(0.888)	(1.059)	(1.072)
ln(lunar)-ln(chrono) × I(1800)	0.614	-0.301	0.756	0.429
	(0.956)	(0.857)	(0.968)	(0.979)
ln(lunar)-ln(chrono) × I(1810)	1.262	-0.469	1.519*	0.975
	(0.863)	(0.835)	(0.869)	(0.880)
ln(lunar)-ln(chrono) × I(1820)	1.938**	-0.430	2.229***	1.524*
	(0.835)	(0.804)	(0.839)	(0.845)
ln(lunar)-ln(chrono) × I(1830)	2.857***	-0.308	3.000***	2.231***
	(0.849)	(0.759)	(0.850)	(0.854)
ln(lunar)-ln(chrono) × I(1840)	3.194***	-0.108	3.355***	2.428***
	(0.867)	(0.750)	(0.865)	(0.874)
ln(lunar)-ln(chrono) × I(1850)	3.858***	0.362	4.108***	2.846***
	(0.949)	(0.707)	(0.950)	(0.968)
ln(lunar)-ln(chrono) × I(1860)	4.540***	1.582*	4.841***	3.356***
	(1.015)	(0.862)	(1.015)	(1.039)
ln(lunar)-ln(chrono) × I(1870)	5.198***	2.097**	5.267***	3.841***
	(1.096)	(1.002)	(1.094)	(1.123)
ln(lunar)-ln(chrono) × I(1880)	5.428***	2.298*	5.507***	3.934***
	(1.205)	(1.185)	(1.200)	(1.230)
ln(lunar)-ln(chrono) × I(1890)	5.772***	2.942**	5.737***	4.021***
	(1.314)	(1.469)	(1.317)	(1.342)
ln(lunar)-ln(chrono) × I(1900)	5.656***	3.419**	5.695***	3.791***
	(1.383)	(1.744)	(1.392)	(1.406)
Observations	64896	47536	50208	67424
Grid cell FE	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y
Excluded continent	Africa	Americas	Asia	Oceania

Notes: Table reports OLS estimates. Unit of observation is a $1^\circ \times 1^\circ$ grid cell and the omitted decade is 1780-1789. *Coastal regions* include land grid cells within 2 degrees from the coastline. Dependent variable is the natural logarithm of 1 plus urban population (inhabitants/grid cell); *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronomter (in log of days) for a return voyage from Europe to worldwide coastal regions using May data for wind and coverage; *Grid cell FE* and *Decade FE* are grid cell and decade fixed effects; *Continent linear trends* are linear trends for all continents in the sample (Africa, America, Asia, Oceania); *Dropped continent* is the continent dropped from the regression sample. Standard errors are corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

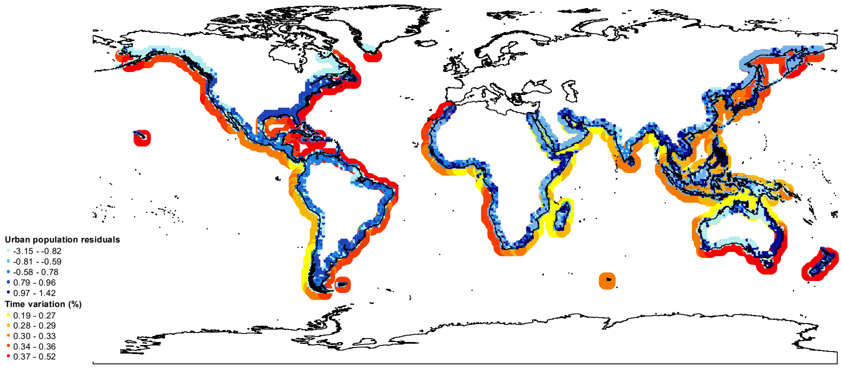
Table A7: Robustness: Distance from the coast

	INLAND REGIONS			
Dependent variable:	ln(urban population)		ln(population density)	ln(built-up area)
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1750)	0.760	0.479	0.275	0.007
	(1.053)	(1.073)	(0.461)	(0.034)
ln(lunar)-ln(chrono) × I(1760)	0.533	0.331	0.199	0.005
	(1.034)	(1.054)	(0.450)	(0.034)
ln(lunar)-ln(chrono) × I(1770)	0.295	0.185	0.121	0.003
	(1.012)	(1.033)	(0.439)	(0.034)
ln(lunar)-ln(chrono) × I(1790)	-0.251	-0.145	-0.062	-0.003
	(0.965)	(0.989)	(0.421)	(0.034)
ln(lunar)-ln(chrono) × I(1800)	-0.381	-0.160	-0.035	-0.003
	(0.918)	(0.942)	(0.399)	(0.033)
ln(lunar)-ln(chrono) × I(1810)	-0.485	-0.112	-0.053	-0.004
	(0.839)	(0.863)	(0.368)	(0.032)
ln(lunar)-ln(chrono) × I(1820)	-0.526	0.012	-0.007	-0.001
	(0.769)	(0.790)	(0.339)	(0.030)
ln(lunar)-ln(chrono) × I(1830)	-0.591	0.131	-0.023	0.004
	(0.744)	(0.766)	(0.327)	(0.027)
ln(lunar)-ln(chrono) × I(1840)	-0.777	0.108	-0.026	0.008
	(0.755)	(0.777)	(0.330)	(0.025)
ln(lunar)-ln(chrono) × I(1850)	-0.837	0.235	0.040	0.016
	(0.816)	(0.840)	(0.355)	(0.025)
ln(lunar)-ln(chrono) × I(1860)	-0.968	0.313	0.141	0.027
	(0.919)	(0.946)	(0.415)	(0.029)
ln(lunar)-ln(chrono) × I(1870)	-1.178	0.292	0.253	0.040
	(1.037)	(1.070)	(0.465)	(0.036)
ln(lunar)-ln(chrono) × I(1880)	-1.626	0.044	0.200	0.050
	(1.177)	(1.212)	(0.518)	(0.046)
ln(lunar)-ln(chrono) × I(1890)	-2.108	-0.175	0.141	0.058
	(1.328)	(1.357)	(0.565)	(0.057)
ln(lunar)-ln(chrono) × I(1900)	-2.876**	-0.650	0.038	0.059
	(1.462)	(1.482)	(0.606)	(0.069)
Observations	186288	186288	186288	186288
Grid cell FE	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y
Distance x Decade FE	Y	Y	Y	Y
Latitude x Decade FE		Y		

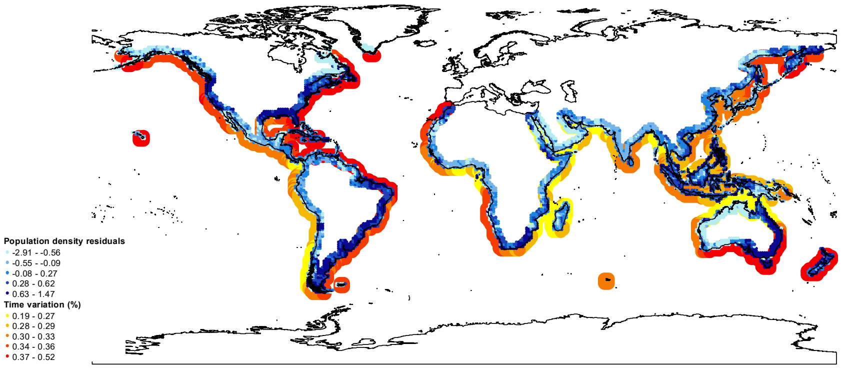
Notes: Table reports OLS estimates. Unit of observation is a 1° × 1° grid cell and the omitted decade is 1780-1789. *Inland regions* include all land grid cells at least 2 degrees away from the coastline. Dependent variables are the natural logarithm of 1 plus, in turn, urban population (inhabitants/grid cell), population density (inhabitants/km^2 per grid cell) and built-up area (e.g. cities in km^2 per grid cell); *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronomter (in log of days) for a return voyage from Europe to the closest worldwide coastal region using May data for wind and coverage (inland grid cells are assigned navigation times of the closest coastal gird cell); *Grid cell FE* and *Decade FE* are grid cell and decade fixed effects; *Continent linear trends* are linear trends for all continents in the sample (Africa, America, Asia, Oceania); *Distance* is the geodesic distance of a grid cell's polygone border from the coastline interacted with decade fixed effects; *Latitude* is the latitude level, interacted with decade fixed effects. Standard errors are corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cut-off of 500km. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

Figure A1: Robustness: Using regression residuals

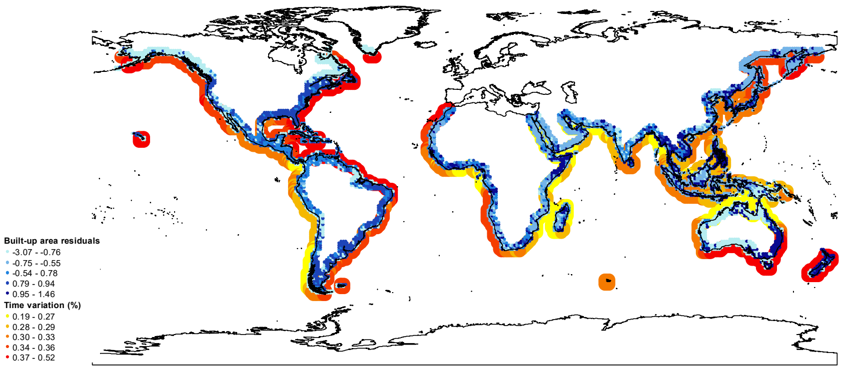
(a) Urban population



(b) Population density



(c) Built-up area



Notes: Maps display the percentage variation in minimum sailing times of a return trip from Europe under chronometer with respect to lunar method, against the residuals of regressions of percentage variation in (a) total urban population, (b) average population density and (c) average built-up area between 1750 and 1900, on continent fixed effects.