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SOLVING THE LONGITUDE PUZZLE: A STORY OF CLOCKS, SHIPS AND CITIES

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In the nineteenth 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 to precisely measure longitude at sea. Identification exploits the fact that the navigation advantages provided by the chronometer were limited to offshore navigation under a cloudy sky and were therefore different across different sea regions. Using high-resolution data on climate, ship routes, and demography, we show that the chronometer led to major changes in the prevailing transoceanic sailing routes and, through this channel, affected the global distribution of cities and population and guided the expansion of the British Empire.

JEL Classification: F1, F15, F43, R12, R4

Keywords: Longitude, Chronometer, Gravity, Globalization, Trade, Development

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

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19 December 2022

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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 nineteenth 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 marine chronometer, "one of the most important inventions of the era of the Industrial Revolution" on a par with the spinning jenny and the steam engine (Mokyr (2017)). A large historical literature has emphasized the exceptional role that this innovation had on the expansion of the 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 the chronometer has been extensively studied in the historical literature, to the best of our knowledge no one has studied the causal impact of this innovation on navigation and comparative development in a systematic econometric framework. We use global data on climate, ship routes, demography and colonial history together with a novel identification strategy to empirically investigate (i) the role of the adoption of the marine chronometer in reshaping the transoceanic sea routes and (ii) the impact of these changes on the distribution of cities, population and European colonies 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 prominent 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 inferred from the position of the sun, but how could one measure the time in Greenwich when navigating an ocean? As we will see in the next section, this puzzle stumped some of the greatest minds of the second millennium.

The first solution, the lunar distance method, came in the 1750s and was based on the observation of the angular distance between the moon and a celestial body. This method, which was quickly adopted by all the major navies of the period, had however an important drawback: it would produce a reliable

[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).

measure of the longitude at sea only when the stars were perfectly visible at night. While it made long distance oceanic navigation feasible along those routes that were normally characterized by a clear sky, it would be of little use in more cloudy sea regions. The final solution came some decades after with the marine chronometer, a precise clock invented by John Harrison, that worked on moving vessels and that could keep the Greenwich time with minimal error. A seaman equipped with a well-functioning chronometer could infer both the latitude and the longitude of its position by observing the altitude of the sun, without the need to rely on other celestial objects. Although determining the position of the sun would still be impossible under a sky completely darkened over several hours (a rather rare event), the advent of the chronometer reduced dramatically the weather requirements to find the longitude in the open sea. We will discuss the details in the following section but essentially this is due to three reasons: 1) the minimum requirements in terms of clear sky for measuring the altitude of the sun during the day are less stringent than the requirements to measure the distance of celestial bodies at night, 2) cloud coverage during the day is generally lower compared to cloud coverage during the night, 3) the lunar method could still be used as a backup solution during the night, if the sky was completely covered by clouds during the day but clear during the night. The result was that the introduction of the chronometer opened to navigation new portions of the oceans. Notice that the lunar method would still continue to be used, especially as a means for checking the chronometer error and rate. One of the very first chronometers was tested by the British explorer James Cook in his second South Sea voyage starting out in 1772. When the voyage was nearly over, Cook wrote to the Secretary of the Admiralty: "[the] Watch has exceed the expectations of its most zealous advocate and by being now and then corrected by lunar observations has been our faithful guide through all vicissitudes of climate". The first prototypes of chronometer equipped mainly survey and exploratory vessels, while the adoption for war and merchant vessels started in the nineteenth century. The very first large user was the East India Company, the major engine behind the colonial expansion of the British Empire, which had a fleet fully equipped with time keepers already in the mid 1790s. The adoption for other British war and merchant vessels started in the nineteenth century, and the transition of the major European navies towards the chronometer was completed only in the 1840s.

How did this innovation change navigation? We answer this question using CLIWOC (García-Herrera et al. (2005)), a database of 287,000+ ship logbook entries from the East India Company and the British, French, Dutch, and Spanish navies, covering the years between 1750 and 1855 with daily information on ships' positions and weather conditions.

We start by studying the impact of the adoption of the chronometer on the speed of navigation. To do this, we first rely on a triple-difference identification strategy, which exploits the fact that the chronometer became a widely available technology only in the nineteenth century and that the advantages of the time keeper to measure the longitude were particularly evident when navigating in the open sea (as opposed to navigating along the coast) and under a cloudy sky (rather than a clear sky). We show that: 1) there was an exceptional increase in the relative speed of vessels navigating in cloudy regions – where the lunar method could not be applied – compared to vessels navigating in clear-sky regions in the first half of the nineteenth century; 2) this relative change in speed is fully explained by open sea routes, while we do not observe it for coastal navigation – this is in line with the historical accounts according to which navigating coastal water was based almost exclusively on sightings of landmarks. The estimated impact of the chronometer is exceptionally large: our benchmark triple-difference estimates point towards an increase in speed under a cloudy sky of approximately a third. Second, to confirm that our results are not driven by other contemporary potential changes in the shipping industry, which favour differentially navigation under a covered sky, we consider an alternative identification strategy, relying on the fact that the gains from the chronometer were more pronounced when parallel sailing was not feasible (see the Historical Background section for details). Finally, we conduct a series of additional robustness checks. Crucially, we show that results are not driven neither by pre-trends nor by measurement errors in the dependent variable. This latter check is particularly relevant in this context as sailing speeds measured with the chronometer are likely to be more accurate compared to previous methods.

Not surprisingly, this 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 fact with a second set of estimates: we show a relative increase in the number of observations of ships navigating under clouded skies, relative to clear skies, starting from the 1820s. One more time, this change is fully explained by open sea navigation, while we do not observe it for coastal navigation.

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 distance 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.[2]

[2]Our optimized sailing times suggest that, although the chronometer reduced the effective distance to Europe of almost any other region of the world, this reduction was very heterogeneous across different regions. For instance, there are large 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

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, but the increase was disproportionally larger in the treated coastal cells starting from the very beginning of the nineteenth century. It used to be difficult to reach these cells from Europe using the lunar method and, unsurprisingly, until the eighteenth 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.[3] 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.

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 twentieth century and are not fully explained by the dynamics in a specific continent. Finally, we provide some suggestive evidence that the contribution of the chronometer to the human geography of the world is, at least partially, a result of its impact on the European colonial expansion in the nineteenth century. Specifically, using data on European colonies spanning more than two centuries (from 1660 to 1885), we show that the chronometer guided the expansion of the British Empire, in the first decades of the nineteenth century, in Asia, Africa and Oceania (while the colonization of the Americas was completed well before its invention).

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

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.

[3]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.

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 nineteenth 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 nineteenth century. Admittedly, these back-of-the-envelope calculations are very crude estimates and should be interpreted cautiously for a series of reasons. First, 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. Second, 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 and others. 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. Third, our estimates on the impact of the chronometer on human geography are contingent to a variety of forces that were explosively driving globalization and the emergence of capitalism and modern growth at the same time. Without doubt, the gains from this innovation were amplified by other innovations in the ship-building industry, advances in geography and astronomy, and changes in the economic, institutional and social background of European societies in the late modern period. In a sense, the causal effect of the chronometer recovered by our estimates should be interpreted as conditional on colonial powers already having reached a state of development, that allowed them to fully exploit the gains from this innovation.

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 (2022) 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 eighteenth 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 nineteenth 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.[4] 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 eighteenth and the nineteenth 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 long-standing 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 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

[4] 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 (2021) 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.

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 eighteenth century.[5] 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 nineteenth 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, and of European colonies across the globe. We close the paper with some concluding remarks.

2 Historical background

2.1 The "discovery" of the longitude

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 eighteenth 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

[5] 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, Leonhard Euler, 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 fifteenth 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 sand-glass. 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 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.[6] In this way, the sea captains of the fifteenth, sixteenth and seventeenth 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 fifteenth 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 routinised. 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.[7]

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

[6] This way of navigating was known as "running down a westing (easting)" if going westbound (eastbound), or parallel sailing.

[7] 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)).

vulnerable to the dreaded disease of scurvy, and frequent shipwrecks.[8] Second, following lines of latitude means that ships could not take the most direct route (a great circle) or a route with more favourable winds and currents, further extending the length and duration of the voyage. Third, transoceanic 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.[9] The compound loss of lives, ships and honour 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 sixteenth century, were offered by all the major sea powers for the solution to the longitude puzzle.[10]

The prize was successful, and it produced two working solutions: an astronomical one and a mechanical one.

The astronomical solution was the lunar distance method. Longitude is 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. To a first approximation, local time can be calculated by measuring the altitude of the sun or other prominent stars with a sextant. The lunar method used the movement of the moon across the star background as a clock to infer the time at the standard meridian. Specifically, 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.[11]

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 crucially on weather conditions. Measuring lunar distances was impossible under a cloudy sky. As we will show in the

[8]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 skilful navigators of his time, thought that 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.

[9]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)).

[10]Already in the seventeenth 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.

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

empirical section, this limitation inhibited navigation along the cloudiest transoceanic routes. Moreover, this methodology was complex and time-consuming: in the 1750s, it required to expert seamen four hours of mathematical calculations.

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.[12] The chronometer had several advantages compared to the lunar method. First, computing the longitude with the time keeper was relatively "easy". The dramatic reduction in time spent on calculations allowed navigators to take multiple longitude recordings per day, increasing precision. Second, no night-time observations were needed, as both the latitude and the local time could be inferred from the altitude of the sun (see next subsection for details). In principle, this meant that seamen could infer, with relatively limited error boundaries, their coordinates at sea as long as the sky was not so leaden that the position of the sun could not be inferred (a rather rare event in the open sea).

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".[13] 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 transoceanic trade was the East India Company (EIC). Davidson (2019) analyses 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 eighteenth 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 EIC was the major engine behind the colonial expansion of the British Empire in Africa, Asia and Oceania. As one of its directors admits, the EIC 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)).

The adoption was slower outside of the EIC. For the Royal Navy, around 1800, the policy was to supply ships going abroad, with one chronometer in case of private ships, and two for flagships (May and Howse (1976)). Notice that, for security, a ship needed at least three chronometers, so that if one

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

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

went wrong the error could be detected. Few officers would be buying their own chronometer, but the high price tags implied that most officers could not afford it. Around 1815, the total world census of marine timekeepers grew to approximately five thousand instruments (Sobel (1995, p.163), Landes (1983, p.184)). Still, until the 1820s chronometers were concentrated on the ships of the EIC, the British Royal Navy and the Royal French Navy. It's only in the 1830s that chronometers started to be mass adopted by other European merchant ships. The transition to this new technology was only completed in the 1840s.

2.2 Longitude by chronometer

To explain how the chronometer was used to infer the longitude at sea, we need to introduce the two different time scales that are generally used by seamen when referring to the local time. The local mean time is a uniform time scale determined by the average motion of the Sun. The local apparent time is the time measured by the sundial or sextant with noon occurring when the sun crosses the observer's meridian. The elapsed time between two successive meridian passages can differ over 24 hours by up to 30 seconds.[14] The cumulative effect is that the local apparent time can lead or lag the local mean time by up to 15 minutes approximately, depending on the time of the year and the latitude.

The longitude of a certain location can be measured as the difference between the local mean time and the mean time in a fixed location, say Greenwich. The chronometer on board reports the Greenwich mean time (GMT), but how can one establish the local mean time? The observer would first infer the local apparent time by measuring the altitude of the sun. He would then convert the local apparent time into the local mean time using the "equation of time", a series of mathematical operations that crucially depend on the latitude of the observer. Generally, small errors in the measured latitude translate into large errors in longitude, unless the observation of the sun is taken sufficiently close to the prime vertical (as much as east or west as possible compared to the observer). In this case, even a noisy latitude measurement would translate into a precise estimate of the longitude.[15]

How were the coordinates recorded in practice while navigating in the open sea? The general method of finding the position at sea was based on two observations of the sun. The first observation – the ante-meridian (a.m.) observation – was done when the sun laid close to the prime vertical. The altitude of the sun was measured and the chronometer time noted. The second observation was done at noon and was used to determine the latitude.[16] The noon latitude was then moved backwards to the time of the

[14]The difference between the two local times comes from the fact that the apparent solar day is not of constant length throughout the year: because the orbit of the earth around the sun is elliptical with sun at one of its foci, the apparent angular motion of the sun is faster when the sun is nearer to the earth and slower when away.

[15]If the observation is taken sufficiently close to the prime vertical, in the parallels between 60° S and 60° N, an error of 10' in the latitude will not perceptibly affect the computation of the longitude (see Lecky, 1925).

[16]The latitude can be derived by the altitude of the sun and the local apparent time of the observation. The noon is the best moment to measure the latitude, as the sun would keep a similar altitude for a longer period of time. Thus, even if the exact moment of the noon could not be determined, observations of the altitude of the sun around noon would have relatively low measurement errors.

a.m. observation using an estimation of the course and distance sailed between the two observations.[17] Using this "estimated" latitude at the time of the a.m. observation, the measured altitude of the sun at the a.m. observation, and the time of the a.m. observation, the "equation of time" was used to back up the a.m. longitude.

Of course, calculating the longitude using the timekeeper would still require the position of the sun to be visible in the sky. The chronometer would not be useful in a sky completely overcast during long period of times. Still, the invention of the chronometer reduced the weather requirements to calculate the longitude compared to the lunar method for three main reasons: 1) less stringent requirements for the visibility of the sun during the day, 2) usually less cloud cover during the day than at night and 3) the lunar method could be used as a fallback during night-time if the sky was totally cloudy during the day but clear at night. For few voyages in CLIWOC in the eighteenth century, we can track at the same time the position of the vessel, whether the chronometer was used to measure the longitude, and the cloud coverage on the day of the measurement. Out of 69 longitude entries obtained using the chronometer (admittedly, a rather small sample) for which weather information is available, 60 percent happened under a cloudy weather or thick hazy weather. Applying the lunar method to infer the longitude under such conditions would have been simply impossible. In the 1830s, Captain Thomas H. Sumner introduced the idea that two inaccurate readings could still define the position of the ship reasonably well by figuring out where lines of the possible position intersect (the method was called position-line navigation). Sumner's method was a second revolution in navigation as it allowed ships equipped with reliable chronometers to find their positions at sea even in the most overcast skies.

3 Data

Our aim is to show (1) how the chronometer revolutionised transoceanic sailing routes between the eighteenth and nineteenth centuries; (2) how this change affected both the distribution of cities and population outside of Europe and the expansion of Western colonies. 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 information on historical 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 global demography and colonization patterns, we rely on data on urban population, population density and colonial history (sub-section 3.3). Table I reports the summary statistics for these data.

[17] If the latitude at noon could not be measured because of weather conditions, the noon sight of the previous day would be used to infer an estimated a.m. latitude.

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 East India Company and the British, Dutch, French, and Spanish navies over the years 1750-1855; approximately, it covers a tenth of the logbooks produced by these nations during this time period (García-Herrera et al. (2006)). For 4,764 voyages, it provides complete information on the date and place of departure and arrival, plus a series of ship characteristics, along with daily information on weather and sea condition. The dataset includes daily coordinates, making it possible to track both sailing routes and speeds.

Figure 2 shows the spatial distribution of entries in CLIWOC. The Atlantic and Indian oceans are well covered. Navigation in the Pacific was instead normally relatively close to the coast, with relatively few voyages directly connecting the Americas with East Asia and Australia. The temporal coverage, depicted in Figure A1, shows that the data are more or less evenly distributed in time, although political factors (e.g. Napoleonic Wars) cause numbers to fluctuate in certain decades, with a clear drop in the number of observations in the first two decades of the 1800s. Finally, Table A1 reports the distribution of entries across different nationalities. As can be seen, the great majority of observations is provided by the Dutch and the British navies, while less observations are available for the Spanish and French ones. Notice that the four different nationalities 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. Throughout our empirical analysis, we show the robustness of our results, based on the CLIWOC data, when considering changes within the same navy. Importantly, one third of the British ships in the sample belongs to the East India Company: as illustrated in the Historical Background section, the great majority of these ships was already equipped with a chronometer in the 1790s.

We use this database to construct the two main outcome variables in Section 4.1: 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. Rows 1 and 2 in panel (a) of Table I 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 by in every decade.

CLIWOC provides systematic information on whether the longitude entry in the database is obtained using dead reckoning as opposed to celestial observations (notice that celestial observations can be associated with both the lunar method and the chronometer). Figure A2 shows the total number and shares of longitude entries obtained from dead reckoning per decade. Both panels confirm the historical narrative described in Section 2. Dead reckoning is used disproportionally more in the eighteenth century, presumably because it was the only available method to measure longitude in the open sea when the sky was not perfectly clear. In the following century, the number of longitude observations obtained by dead reckoning declines steadily.

3.2 Weather data

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

We draw our data on cloud coverage from two separate sources.

The first source is the NASA Earth Observations (NEO) database, which provides information on cloud fraction (e.g., the portion of a grid cell that is covered by cloud).[18] Cloud fraction is measured from space using satellite sensors. Specifically, we use monthly data from February 2000 to January 2016. These data are then averaged to obtain a contemporary monthly measure of average cloud coverage.

The second source that we use to identify cloudy skies are the daily information on weather conditions available from the historical ship logbooks in the CLIWOC dataset. The main advantage of these data, compared to the NEO data, is that they capture prevailing climatic conditions in the eighteenth and nineteenth century. This source comes, however, with two caveats. First, it does not have global coverage: information are only available for those grid cells that are crossed by the ships in CLIWOC. Second, data entries are rarely comparable across different logbooks (the international agreement on standardization of meteorological observations on board ships was only reached in 1854), which implies that some imputation is needed to construct an homogenous measure of cloud coverage. Specifically, there are three different variables in the CLIWOC logbooks 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] To convert these three variables into a consistent measure of cloud coverage, we proceed in the following way. 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 re-classify the numerical values from a scale (1-10) to a scale (1-3) with 1 indicating a clear sky, 2 hazy sky, and 3 cloudy sky.[20] Fourth, we take the grid averages of these

[18] Data source: https://neo.gsfc.nasa.gov

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

[20] Specifically, the newly constructed variable takes on a value of 1 for values of the original numeric variable from 1 to 2.5, 2 for values of the original numeric variable from 2.6 to 7.5, and 3 for values of the original numeric variable from 7.6 to 10.

values to obtain a single numeric value for each cell.

Figure 3 compares the historical average cloud coverage inferred from the CLIWOC records (panel (a)) and the present-day average cloud coverage constructed from the NEO dataset (panel (b)). Reassuringly, the two measures are clearly highly correlated. Pairwise correlation is 0.24. Appendix Figure A3 illustrates both the unconditional Kernel density of cloud coverage from the NEO dataset and the same Kernel density conditional on whether grid cells are characterized by clear, hazy or cloudy sky in CLIWOC. As expected, the estimated density function of cloud coverage in NEO shifts towards the right as we move to grid cells with worse weather conditions in CLIWOC.

The summary statistics on the variables for cloud cover constructed from the NEO dataset and the CLIWOC dataset are reported in the rows 3-4 of panel (a), Table I.

Cloud coverage data alone reveal an interesting pattern: starting from the nineteenth century we observe a relative increase in the number of entries of ships navigating under cloudy sky compared to clear sky. We show this relationship in Appendix Figure A4, 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 hazy and cloudy areas in the second half of the sample: 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 (2022). Specifically, we use average monthly data, which are available, from August 1999 to June 2002.[21]

3.3 Data on urbanization, population and colonial history

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 I for the hundred years between 1750 and 1850, all three increased by approximately 36-40 percent. Finally, data on colonization come from the Atlas of Colonialism, a repository of historical maps, maintained by a community of volunteers though open collaboration and a wiki-based editing

[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. The 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 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

system. We download every map available for the years between 1660 and 1885 (i.e., for the years: 1660, 1754, 1822 and 1885).[23] As our intent is to capture the expansion of the British Empire, we disregard maps before 1660, which do not record any British colony. The summary statistics on British and overall European colonization are reported in panel (c), Table I. One clear caveat of this atlas is that it is not an academic data source. Still, we did check every entry and find it consistent with the history of European colonialism.

4 Results

In this section, we report the results of our empirical analyses.

The first subsection studies the impact of the introduction of the chronometer on navigation. We report two main findings: 1) starting in the nineteenth 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 subsection is CLIWOC, a large database of historical sailing ship logbooks. We use a triple-difference research design: the identification strategy exploits the fact that the chronometer was particularly beneficial in offshore – rather than coastal – navigation under cloudy sky. A second identification exercise is based on the fact that offshore navigation under cloudy sky was relatively less dependent on the chronometer when parallel sailing was feasible.

The second subsection focuses on 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 nineteenth century and for approximately half of the increase in the total urban population outside of Europe. We conclude by showing that the British expansion, as facilitated by the chronometer, is a potential channel to explain our results on urbanization.

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

[23] Figure A5 shows European colonization in Africa, Asia and Oceania for the relevant years in our analysis.

of the sky, during the period 1750-1855. The historical narrative suggests that the chronometer was mass-adopted only in the first half of the nineteenth 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 start by exploiting the fact that the advantages of the chronometer, compared to the lunar method, were practically limited to open sea navigation under a covered 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 by estimating the following difference-in-difference regression for open sea observations:

$$ln(speed)_{esit} = \alpha(clouds_i \times post_t) + \beta_1 clouds_i + \beta_2 post_t + \gamma X_{esit} + \epsilon_{esit} \quad (1)$$

where e, s, i and t index respectively 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). $clouds_i$ identifies the cloudy grid cells. In the benchmark estimates, this is an indicator variable that identifies those cells in which the average score of cloud coverage (recorded by ships in CLIWOC passing through the cell) is strictly above 2 (which indicates a hazy sky) on a scale of 1 (clear sky) to 3 (cloudy sky). In robustness checks, we will also use a continuous measure (provided by the NEO dataset), which measures average cloud coverage during the years 2000-2016 and ranges from 0 (perfectly clear sky) to 1 (overcast sky). $post_t$ is an indicator variable for logbook entries taken during and after 1800. X_{esit} is a set of covariates: in the benchmark specification, this set includes grid cell and time fixed effects. The unit of observation is each entry in the CLIWOC logbooks, with the exclusion of coastal navigation entries.[24]

The results of these regressions are shown in Table II. Column 1 presents the estimated α when there are no additional controls in the regression. Starting from the nineteenth century, while the chronometer is adopted, ships sailing under a cloudy sky experienced a 20 percent (18 log-points) larger increase in speed relative to ships sailing under a clear or hazy sky. In column 2, cloud coverage is measured using the NEO data. In this case, the estimates of the difference-in-difference coefficient points towards an increase in sailing speeds of ships navigating under a perfectly clear sky relative to an overcast sky in

[24]CLIWOC includes information on logbook entries originally recorded as coastal. However, this variable is not 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 distances set 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.

the order of 63 percent (49 log-points). Notice that, in column 2, coefficients are generally more noisily estimated. This is likely due to the fact that, while estimates in column 1 are based on weather conditions reported in the CLIWOC dataset (and, thus, contemporaneous to the sailing voyages in our sample), the NEO data only capture present-day average weather conditions in a certain cell.

In both columns, the difference-in-difference coefficient is always estimated to be statistically significant. Specifically, Table II reports three 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, we cluster standard errors at the voyage level to address similar concerns of arbitrary correlation of the residual terms within single voyages. Third, since residuals from adjacent cells are unlikely to be independent from each other, we allow for spatial clustering of standard errors following Conley (1999). Throughout the paper we use a spatial autocorrelation cutoff of 1,000 kilometres when presenting the Conley standard errors. The choice of this cutoff is explained by the Appendix Figure A6, which shows the Conley standard errors of the difference-in-difference coefficient in the benchmark specification, using variable cutoffs ranging from 100 kilometres to 1,000 kilometres. As can be seen, from around 800 kilometres, additional increases in cutoffs do not produce any significant increase in the magnitude of standard errors.

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

First, 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 nineteenth 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 nineteenth century in detail later in this subsection). To address this point, in column 3, we control for cell and decade fixed effects. In this case, the estimated α is reduced by approximately two thirds compared to the first column, but it is still suggestive of large speed gains generated by the chronometer in open sea navigation with unfavorable weather conditions.

Second, 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) and Kelly et al. (2021)). 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 above. To rule them out, in column 4 we add a battery of controls to capture the time-varying influence of wind patterns on sailing speed. Specifically, we control for the latitude, prevailing speed, and wind direction (relative to the sailing direction) in the cell in which the ship is navigating, interacted with the *post* fixed effect. Results are practically unchanged.

Third, the estimates might be driven by changes in the sample of ships included in the CLIWOC database across the different decades. For instance, during the Napoleonic Wars, there is a drop in the number of French and British ships covered in the CLIWOC data. To address this point, in column 5 of Table II, we control for the nationality of the ship interacted with the *post* fixed effect: results are practically unaffected. In column 6 of Table II we take a step forward and show that the estimates are generally robust to also controlling for ship fixed effects. 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 darkened sky of ships that had been built well before this innovation.

Overall, the results in Table II 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 cloudy sky that we observe in the nineteenth 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. Table III presents the estimates from the following triple-difference specification:

$$\begin{aligned} ln(speed)_{esit} = {} & \mu(clouds_i \times post_t \times open\ sea_i) + \beta_1 clouds_i + \beta_2 post_t + \beta_3 open\ sea_i \\ & + \beta_4(clouds_i \times open\ sea_i) + \beta_5(open\ sea_i \times post_t) + \beta_6(clouds_i \times post_t) + \gamma X_{esit} + \epsilon_{esit} \end{aligned} \quad (2)$$

where $open\ sea_i$ is an indicator for grid cells farther from the coast.

The estimate of the triple-difference coefficient (μ in equation 2) in Table III indicates that, following the diffusion of the chronometer, the increase in speed under a cloudy sky was approximately doubled in open sea navigation compared to coastal navigation. These findings are robust to our alternative measure of a covered sky based on the NEO dataset (column 2), to the inclusion of a battery of cell and decade fixed effects (column 3) and when controlling sequentially for the series of confounding factors discussed above: latitude, wind patterns and speed (interacted with *post* and *open sea* fixed effects) (column 4), ship nationality (interacted with *post* and *open sea* fixed effects) (column 5), and ship fixed effects (column 6).

The estimates of μ can be interpreted as the average impact of the chronometer on sailing speed under the identifying assumptions that (i) there were no other contemporaneous improvements in maritime technology that affected the relative sailing speed under clouded sky vis-à-vis clear sky differentially between open sea navigation and coastal navigation (ii) the chronometer only affected sailing speed in open sea navigation under a clouded sky.

Notice that these identifying assumptions require that, until the nineteenth century, sailing speeds in open sea did not systematically follow different trends compared to coastal navigation. To test this parallel trend assumption, we estimate the following equation:

$$\begin{aligned} ln(speed)_{esit} = &\sum_{t=1750}^{1850} \mu_t(clouds_i \times open\ sea_i) + \beta_1(open\ sea_i \times post_t) \\ &+ \beta_2(clouds_i \times post_t) + \gamma X_{esit} + \delta_i + \delta_t + \epsilon_{esit} \end{aligned} \quad (3)$$

The estimated coefficients (μ_t in equation 3) are plotted in Figure 4 – the omitted decade is the 1780s: as discussed in the Historical Background section, no chronometer was available in these years. A clear pattern emerges: as expected it's only in the 1800s that we observe a differential increase in sailing speed under a cloudy sky in open sea navigation compared to coastal navigation. The estimated coefficients for μ_t increased throughout the first half of the nineteenth century. This result is clearly not driven by pre-trends: none of the estimated coefficients before 1800 is statistically significant, and they are all orders of magnitude smaller with respect to those estimated for the decades of the nineteenth century.

A potential concern is that this triple-difference setting might not capture the impact of the chronometer but rather of other contemporaneous innovations, which affect differentially offshore sailing under a covered sky, and that emerged in the exact same decade in which the chronometer started to be used in navigation. 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. There was, therefore, another setting in which the speed gains from the chronometer stood out: when parallel open sea sailing was not feasible. Table IV shows the estimates from this alternative triple-difference equation:

$$\begin{aligned} ln(speed)_{esit} = &\rho(not\ parallel_i \times clouds_i \times post_t) + \beta_1 clouds_i + \beta_2 not\ parallel_i + \beta_3 post_i \\ &+ \beta_4(not\ parallel_i \times post_t) + \beta_5(clouds_i \times post_t) + \beta_6(clouds_i \times not\ parallel_t) + \gamma X_{esit} + \epsilon_{esit} \end{aligned} \quad (4)$$

where *not parallel*$_i$ is a dummy variable for when navigation does not follow a straight parallel line.[25]

In the first three columns of Table IV, we limit our analysis to offshore navigation. The estimates point towards a relative increase in sailing speed under a cloudy sky, in the years that followed the diffusion of the chronometer, differentially larger when not sailing along a parallel compared to parallel sailing. Column 1 reports the estimates without controls: the relative increase in sailing speed under a cloudy sky was around 25 log points (7.8-3.4+20.7) when not sailing along a parallel, while it was close to nil (7.8-3.4) and not statistically significant when sailing along the parallel. The estimated ρ remains

[25] We define "*not parallel*" as a dummy equal to 1 when, passing from one grid cell to another, 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.

positive and statistically significant when controlling for cell and decade fixed effects (column 2) or our usual full set of controls (column 3). The last three columns contain the results of a placebo exercise in which we repeat the triple-difference estimates in the first three columns using the sample of coastal navigation rather than offshore navigation. In this case, as expected, the triple-difference coefficient is not statistically different from zero.

Dealing with measurement error

One potential concern related with the previous estimates is that the chronometer is indeed very likely to have induced a systematic reduction in the measurement error of daily coordinates. In this case, measurement error in the dependent variable would be systematically correlated with the treatment. To overcome this issue, we replicate all the main results in this subsection with a tweak. We change the dependent variable: rather than measuring the speed of the vessel, we consider an indicator for whether the ship is moving very fast or very slow (observations with intermediate speed values are excluded from the sample). While the exact speed of the vessel might be measured with error (as well as its position), it's unlikely that seamen would confuse (extremely) fast with (extremely) slow sailing.

Table V replicates the estimates reported in Table III using this new dependent variable. The first three columns show the estimated coefficients of the triple-difference regression without controls. Each column corresponds to a different definition of fast and slow sailing. Column 1 identifies fast (slow) navigation if sailing speed is above (below) the 25th percentile in the overall sample. In column 2 and 3 the cutoff values to define fast navigation are respectively the 33rd and the 50th percentile in the sample of speed entries. Reassuringly, the estimated coefficients on the triple-difference regressor are positive throughout all the three columns, statistically significant, and very similar in size to the coefficients estimated in Table III. Specifically, these estimates confirm that the first half of the nineteenth century witnessed a relative increase in the number of records with fast sailing speeds, as compared to records with slow sailing speeds, under an adverse sky conditions compared to clear sky and that this happened disproportionally in offshore navigation as compared to coastal navigation. In columns 4-6, we confirm that these results are robust to the inclusion of the usual full set of controls.

Finally, appendix Table A2 replicates the results in Table IV using our three indicators of fast sailing as dependent variable. Once again, the regression results are robust to these different definitions of the dependent variable and confirm that the beginning of the nineteenth century is characterized by a disproportional increase in the instances of fast navigation under a cloudy sky when ships were not following a parallel navigation route. This change is notable in offshore navigation (columns 1-3) but not in coastal navigation (columns 4-6).

4.1.2 The impact of the chronometer on prevailing sailing routes

Overall, this first set of empirical results indicates a large impact of the chronometer on the average speed of sailing vessels. Importantly, this impact was asymmetric depending on prevailing weather conditions and distance from the coast. We now study how this differential impact of the chronometer on sailing speeds affected sailing routes worldwide.

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 1750-1855.

To capture changes in navigation routes, we estimate the following equation for open sea observations:

$$voyages_{it} = \alpha(clouds_i \times post_t) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it} \tag{5}$$

where $voyages_{it}$ denotes the frequency at which 1° x 1° grid cell i is crossed by ships in decade t in the CLIWOC dataset. As before, $clouds_i$ is an indicator for mostly clouded sky in the grid cell and $post_t$ is an indicator variable for logbook entries taken in the first half of the nineteenth century. X_{it} denotes a vector of controls, while δ_i and δ_t denote the cell and decade fixed effects.[26]

Regression results are reported in Table VI. Column 1 presents the benchmark specification (with grid cell and decade fixed effects but without additional controls). In the 1800s, we observe an increase in the relative number of voyages under a cloudy sky compared to the pre-chronometer times. The estimated α is positive and statistically significant. Specifically, α is estimated to be approximately 0.68. This is a large number. In the period 1750-1800, the average number of sailing observations in cells with clear sky was approximately two times compared compared to cells with covered sky (2.6 crossing per decade compared to 1.3). This large difference was reduced by almost half in the following five decades. In column 2, we add to the difference-in-differences specification controls for wind speed and absolute level of latitude, all interacted with the *post* fixed effect, without noticing any effect on the estimates of the difference-in-difference coefficient. In the following two columns, we repeat the same analysis using the NEO data (rather than the CLIWOC ones) to capture global cloud coverage. In this case, the point estimates for α are generally larger (the NEO definition of cloudy sky is stricter) and slightly noisier (the NEO data refers to contemporary weather conditions) but confirm the general findings in the first two columns. A potential concern is that this difference-in-difference setting might not capture the impact of the chronometer but rather of other contemporaneous innovations, which affect differentially sailing under a leaden sky compared to clear sky. As in the previous section, to overcame this potential omitted variable problem, we leverage on fact that the advantages provided by the chronometer in a cloudy sky are practically limited to offshore navigation and do not apply to coastal navigation. The last two columns of Table VI reports the estimates from the following triple-difference specification:

[26] We report standard errors clustered at the grid cell level and using spatial clustering following Conley (1999).

$$voyages_{it} = \mu(clouds_i \times post_t \times open\ sea_i) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it} \tag{6}$$

The estimates of the triple-difference coefficient μ in Table VI indicate that the relative increase in crossings of cells with heavy cloud coverage, as compared to clear cells, is disproportionally explained by changes in open sea sailing as compared to coastal sailing.

Finally, to test the parallel trend assumption we estimate the following dynamic equation:

$$voyages_{it} = \sum_{t=1750}^{1850} \mu_t(clouds_i \times open\ sea_i) + \beta_1(open\ sea_i \times post_t) + \beta_2(clouds_i \times post_t) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it} \tag{7}$$

The estimated μ_t coefficients are plotted in Figure 5. Starting from the 1810s, we observe a disproportional relative increase in the number of voyages under a covered sky in offshore navigation compared to coastal navigation. 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 specification of equation 7 also allows us to check that our findings are not driven by pre-trends. In fact, with some exceptions, estimated coefficients before 1810 are smaller compared to those for the decades of the nineteenth century.[27]

The combination of the estimates illustrated in subsection 4.1 shows that the chronometer increased sailing speed under clouded sky and, through this channel, changed transoceanic 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 particularly unfavorable weather.

4.2 The Chronometer and urbanization

During the nineteenth 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-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). We conclude looking at a potential channel for these results: the expansion of the British Empire (4.2.4).

[27]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.

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 use data from the Center for International Earth Science Information Network (CIESIN) to identify whether it was land or sea, we use monthly data from the US National Oceanic and Atmospheric Administration (NOAA) to compute the average velocity and direction of the sea-surface winds, and we use monthly data from NASA Earth Observations (NEO) to compute average cloud coverage. As already discussed, the NEO dataset reports contemporary measures of cloud coverage. Still, as shown in the Data section, these measures are strongly correlated with the CLIWOC measures of cloud coverage, which are instead measured for the years covered by our sample. To compute the optimized sailing distances, we rely on the NEO data rather than the CLIWOC data as the former has global coverage, while the latter only covers grid cells reported in the CLIWOC logbooks.

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.[28] 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 a cloudy sky is substantially slower than sailing under a clear sky when using the lunar method. To measure how cloud coverage reduces sailing speed under the lunar method, we rely on the benchmark estimates of the triple-difference equation 2 which we report in Table III. The estimated coefficient on the triple-interaction, when NEO data are used to identify a clouded sky, is roughly 0.5, meaning that using a lunar navigation method under such weather conditions, 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 Dijkstra'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).[29,30] Appendix Table

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

[29]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.

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

A3 reports summary statistics. In May, the average optimized sailing time dropped by a third: from 256 days using the lunar method to 187 days using the chronometer. Yet, the impact of the chronometer on sailing time is heterogeneous across the world, as can be seen in Figure A7. 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.[31] 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,

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

and the coasts of China and Japan).

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 A8 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 from and to Europe, generated by the chronometer, and cities and population development outside of Europe, following a difference-in-differences approach:

$$ln(1 + Y_{it}) = \sum_{t=1750}^{1900} \alpha_t [\ln(lunar_{it}) - ln(chrono_{it})] + \eta_i + \eta_t + \gamma X_{it} + \epsilon_{it} \quad (8)$$

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 VII 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 1830, 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-nineteenth century, and of almost 5 percent by 1900. These results are not driven by pre-trends: the estimated coefficients for the eighteenth century are relatively small compared to the coefficients estimated for the nineteenth 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 nineteenth 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 VII are robust to a list of checks.

First, from a qualitative point of view, results are very similar when focusing on the extensive margin of the urbanization outcomes. In the Appendix Table A4, the dependent variables are dummies that identify those coastal cells in which the variables urban population and built-up area are different than zero. This is an important robustness exercise because the majority of the coastal cells in our sample (53 percent) do not have any city/built-up area (the population variable, instead, is zero in less than 5 percent of the coastal sample).

Second, 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 VII 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.

Third, 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 VII. The results on urbanization rates are robust to this exercise with the estimated coefficients' sizes being very similar to the results illustrated in Table VII.

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 VII 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, as shown in 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 nineteenth century.[32] 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, 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.

4.2.4 A potential channel: the chronometer and the geography of the British Empire

A narrative literature has argued that solving the longitude puzzle reshaped human geography in Asia, Africa, and Oceania by guiding the expansion of the British Empire.[33] A prominent example comes from the very first time that the chronometer was used as a tool to measure longitude in a sailing voyage. In July 1772, HMS Resolution and Adventure sailed from Plymouth under James Cook command. The objective of the mission was to both test the accuracy of Harrison's chronometer for the Longitude Board and to map as many areas as possible in the Antarctic region and in the Southern Pacific.[34] The log of this voyage is full of praise for the watch: "it [the chronometer] gave Cook the confidence to begin the accurate mapping of the Pacific." (Berthon and Robinson (1991, p.128)). The future English acquisition of land in the Pacific is already hinted in Cook's voyages. For instance, Cook claimed the Eastern Coast of Australia and New Zealand as British soil, after being able to accurately map these islands.[35] These proclamations helped ensuring that Britain and not other European powers ultimately colonized the great majority of Oceania in the first half of the nineteenth century. In the preface to the published account of his last voyage, James Cook urged "Great Britain [..] must take the lead in reaping the full advantage of her own discoveries." Within a few years of Cook's death in 1779 such a process was well under way. In 1787, a convict fleet of 11 ships ("the First Fleet") left Portsmouth on a 8-month long

[32] The average log-change in the coastal urban population outside of Europe in the nineteenth 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($lunar$)-ln($chrono$))×I(1850)] in column 1 of Table VII). Then, the average log-change in the coastal urban population outside of Europe due to the chronometer according to our estimates is -3.2×-0.32=1.03.

[33] An example of this historical literature is the book titled "Longitude and Empire" by Brian Richardson (2010).

[34] The instructions were "to prosecute discoveries as near as the South Pole as possible".

[35] In 1642, Dutch explorer Abel Tasman was the first European to have officially chartered the location of New Zealand. Still, after Tasman's voyage, New Zealand was only a "ragged line" on the world map, which might or might have not been the coast of an unknown southern land. The coordinates were so far from reality that it took nearly 130 years for another European, James Cook, to land in New Zealand again.

voyage to New South Wales to establish the first British settlement in Australia. "Given the small size of the convoy's ships, their safe arrival within a few days of each other was a phenomenal achievement." The key of this success were the four chronometers on board, including the K1 chronometer, an exact copy of the one that was used by James Cook few years before (de Grijs and Jacob (2021)).[36] The official incorporation of New Zealand happened some decades later.

Was the contribution of the chronometer to the British colonization of Australia and New Zealand an isolated case? Or it was an example of a more general contribution in shaping the borders of the British Empire? To address this question, we estimate the following equation:

$$Y_{it} = \sum_{t=1660}^{1885} \alpha_t[\ln(lunar_{it}) - ln(chrono_{it})] + \eta_i + \eta_t + \gamma X_{it} + \epsilon_{it} \tag{9}$$

The unit of observation is a 1° x 1° grid cell along the coast of Africa, Asia and Oceania, captured in year t (the Americas are excluded from the sample as the colonization of the American continent by European powers was completed well before the invention of the chronometer). Y_{it} is a dummy that identifies European colonies at four separate moments of time: 1660, 1754, 1822 and 1885. As in the previous subsection, the main regressor is the reduction in sailing days of a round-trip to Europe when using the chronometer compared to the lunar distance method. The omitted year is 1754, the latest year in our sample predating the advent of the chronometer.

Results are reported in Table VIII. The estimates in the first two columns show that the asymmetric reduction in sailing times induced by the chronometer had a significant impact on the shape of the British empire in 1822. A one percent reduction in the shipping time of a return trip to Europe generated an increase in the probability of being colonized by Britain in 1822 by approximately 2 percent. The impact of the chronometer is much lower (and not statistically significant) by 1885. This has probably two main reasons: first, the great majority of the world had already been colonized by the European by this time, and second, our measure of changes in sailing times induced by the chronometer is computed for sailing ships, while most British ships in 1885 are propelled by steam. As expected, there is no evidence of pre-trends in 1660. In the last two columns of Table VIII, the dependent variable is a dummy that identifies European colonies rather than British colonies. As can be seen, results are practically unchanged. This is not surprising as more than three quarters of the coast that is colonized by Europeans between 1754 and 1822 is colonized by the East India Company and the British navy.

The share of the coast of Africa, Asia and Oceania that was colonized by England passed from 0.1

[36] In the journal kept by the captain, there are constant remainders to the importance of the chronometers on board, the precautions used to wind them, and the way in which the longitude was communicated from the flagship to the other ships of the convoy. "The precautions necessary to prevent the timekeeper from being let down were ordered by Captain Phillip who, with Captain Hunter or Mr. Dawes, were always to be present at the winding it at noon. And it was ordered to be the duty of the lieutenant who brought 12 o'clock to see it done and the officer who relieved him was not to take charge of the deck until he was informed that it was done. The sentinel at the cabin door was also ordered to plant himself inside the cabin, on hearing the bell ring at noon, and not to go out to be relieved until he was told, or saw, that the timekeeper was wound up by one of the officers. The management of the timekeeper for keeping the longitude by it was given to Lieutenant Dawes of the Marines."(Bradley (1969)).

percent in 1660 to 0.3 percent in 1754 to 21 percent in 1822 to 35 percent in 1885 (see Figure A5 in the Appendix for detailed colonization maps). A back of the envelope calculation, based on the most conservative estimates produced in Table VIII, suggests that the chronometer might explain most (63 percent) of the direction of the British expansion between 1754 and 1822. Although such a calculation must be taken with a grain of salt, it is at least suggestive, that one of the channels through which the chronometer changed human and urban geography in the nineteenth century was by guiding the expansion of the British Empire in the very first decades of the century.

5 Concluding remarks

In the nineteenth 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 the comparative development in the nineteenth 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 clouded 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 nineteenth 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. Although we present some empirical evidence suggesting that European (and particularly British) colonization might provide a relevant mediating mechanism, we still don't 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 I: Summary statistics

	Obs.	Mean	St. Dev.	Min	Max	Source	Unit of observation
Panel (a): Historical Navigation							
Ship speed (km/h)	228,206	7.68	3.97	1	18	CLIWOC 2.1	logbook entry
Number of voyages	119,647	1.96	4.28	0	185	CLIWOC 2.1	grid cell × decade
Clouds coverage, continuous [1-3]	9,551	1.70	0.36	1	3	CLIWOC 2.1	grid cell (sea)
Clouds coverage, continuous [0-1]	9,551	0.58	0.15	0	1	NEO (NASA)	grid cell (sea)
Panel (b): Urbanization and Population							
Urban population 1750 (inhabitants/grid cell)	16,436	2,613.42	24,623.88	0	1,488,598	HYDE 3.2	grid cell (land)
Population density 1750 (inhabitants/km sq. per grid cell)	16,436	4.22	15.94	0	272	HYDE 3.2	grid cell (land)
Built-up area 1750 (built-up area in km sq. per grid cell)	16,436	0.01	0.04	0	2	HYDE 3.2	grid cell (land)
Urban population 1850 (inhabitants/grid cell)	16,436	5,601.94	32,856.77	0	1,485,495	HYDE 3.2	grid cell (land)
Population density 1850 (inhabitants/km sq. per grid cell)	16,436	7.34	28.56	0	692	HYDE 3.2	grid cell (land)
Built-up area 1850 (built-up area in km sq. per grid cell)	16,436	0.02	0.09	0	4	HYDE 3.2	grid cell (land)
Change in urban population 1750-1850 (percentage)	16,436	0.40	0.84	-2	2	HYDE 3.2	grid cell (land)
Change in population density 1750-1850 (percentage)	16,436	0.37	0.62	-2	2	HYDE 3.2	grid cell (land)
Change in built-up area 1750-1850 (percentage)	16,436	0.36	0.81	-2	2	HYDE 3.2	grid cell (land)
Panel (c): Colonial history							
British colony in 1660	2,971	0.01	0.10	0	1	Authors	grid cell (coast)
British colony in 1754	2,971	0.03	0.16	0	1	Authors	grid cell (coast)
British colony in 1822	2,971	0.21	0.41	0	1	Authors	grid cell (coast)
British colony in 1885	2,971	0.35	0.48	0	1	Authors	grid cell (coast)
European colony in 1660	2,971	0.09	0.29	0	1	Authors	grid cell (coast)
European colony in 1754	2,971	0.14	0.35	0	1	Authors	grid cell (coast)
European colony in 1822	2,971	0.34	0.47	0	1	Authors	grid cell (coast)
European colony in 1885	2,971	0.59	0.49	0	1	Authors	grid cell (coast)

Notes: Coastal grid cells in panel (c) refers to grid cells within 2 degrees from the coastline.

TABLE II: Chronometer and speed: difference-in-differences

	Dependent variable: ln(speed)					
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post	0.180	0.495	0.057	0.054	0.042	0.042
	(0.038)***	(0.067)***	(0.023)**	(0.021)**	(0.021)**	(0.019)**
	[0.021]***	[0.057]***	[0.017]***	[0.017]***	[0.016]**	[0.016]***
	{0.054}***	{0.235}**	{0.021}***	{0.020}***	{0.019}**	{0.017}**
Clouds	-0.120	-0.339				
	(0.031)***	(0.059)***				
	[0.015]***	[0.039]***				
	{0.041}***	{0.138}**				
Post	0.277	-0.005				
	(0.007)***	(0.041)				
	[0.008]***	[0.035]				
	{0.028}***	{0.134}				
Observations	224871	224871	224871	224871	224871	224871
Clouds source	CLIWOC	NEO	CLIWOC	CLIWOC	CLIWOC	CLIWOC
Grid cell FE			Y	Y	Y	Y
Decade FE			Y	Y	Y	Y
Latitude × Post				Y	Y	Y
Wind × Post				Y	Y	Y
Nationality FE × Post					Y	Y
Ship FE						Y

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC. Sample refers to offshore navigation thus including 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 sky mostly covered by clouds in CLIWOC as explained in sub-section 3.2, except for column 2 where it is the fraction of sky above a grid cell covered by clouds as reported in NEO; *Post* is a dummy variable equal to 1 if logbook recording is dated after 1800 (including); *Grid cell FE* are fixed effects for $1^\circ \times 1^\circ$ grid cells; *Decade FE* are fixed effects for decades; *Latitude* is the absolute level of latitude, interacted with *Post*; *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*; *Nationality FE* are fixed effects for ship nationality, interacted with *Post*; *Ship FE* are fixed effects for individual ships. Standard errors clustered at the grid cell level in parentheses, clustered at the voyage level in square brackets, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE III: Chronometer and speed: triple-difference

	Dependent variable: ln(speed)					
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post × Open sea	0.400	0.561	0.355	0.415	0.403	0.387
	(0.192)**	(0.272)**	(0.243)	(0.238)*	(0.227)*	(0.243)
	[0.169]**	[0.197]***	[0.185]*	[0.198]**	[0.185]**	[0.208]*
	{0.190}**	{0.317}*	{0.166}**	{0.185}**	{0.169}**	{0.197}**
Clouds × Post	-0.220	-0.067	-0.297	-0.360	-0.361	-0.346
	(0.188)	(0.263)	(0.242)	(0.237)	(0.226)	(0.242)
	[0.169]	[0.191]	[0.184]	[0.197]*	[0.185]*	[0.208]*
	{0.182}	{0.218}	{0.165}*	{0.185}*	{0.169}**	{0.196}*
Post × Open sea	0.102	-0.195	0.016	0.075		
	(0.059)*	(0.138)	(0.051)	(0.130)		
	[0.033]***	[0.095]**	[0.038]	[0.136]		
	{0.056}*	{0.161}	{0.040}	{0.153}		
Clouds × Open sea	-0.013	-0.170				
	(0.156)	(0.189)				
	[0.134]	[0.145]				
	{0.141}	{0.226}				
Post	0.175	0.190				
	(0.059)***	(0.132)				
	[0.033]***	[0.091]**				
	{0.055}***	{0.098}*				
Open sea	0.427	0.541				
	(0.041)***	(0.090)***				
	[0.025]***	[0.070]***				
	{0.042}***	{0.108}***				
Clouds	-0.108	-0.168				
	(0.153)	(0.180)				
	[0.133]	[0.142]				
	{0.137}	{0.173}				
Observations	228206	228206	228206	228206	228206	228206
Clouds source	CLIWOC	NEO	CLIWOC	CLIWOC	CLIWOC	CLIWOC
Grid cell FE			Y	Y	Y	Y
Decade FE			Y	Y	Y	Y
Latitude × Post × Open Sea				Y	Y	Y
Wind × Post × Open Sea				Y	Y	Y
Nationality FE × Post × Open Sea					Y	Y
Ship FE						Y

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 sky mostly covered by clouds in CLIWOC as explained in sub-section 3.2, except for column 2 where it is the fraction of sky above a grid cell covered by clouds as reported in NEO; *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; *Grid cell FE* are fixed effects for $1^\circ \times 1^\circ$ grid cells; *Decade FE* are fixed effects for decades; *Latitude* is the absolute level of latitude, interacted with *Post* and with *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 with *Open sea*; *Nationality FE* are fixed effects for ship nationality, interacted with *Post* and with *Open sea*; *Ship FE* are fixed effects for individual ships. Standard errors clustered at the grid cell level in parentheses, clustered at the voyage level in square brackets, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE IV: Chronometer, speed and parallel sailing: triple-difference

	Dependent variable: ln(speed)					
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post × Not Parallel	0.207	0.100	0.118	-0.427	-0.480	-0.286
	(0.046)***	(0.040)**	(0.040)***	(0.315)	(0.318)	(0.307)
	[0.033]***	[0.034]***	[0.033]***	[0.326]	[0.370]	[0.354]
	{0.052}***	{0.048}**	{0.047}**	{0.314}	{0.307}	{0.293}
Clouds × Post	-0.055	-0.044	-0.070	0.152	-0.054	-0.263
	(0.049)	(0.040)	(0.039)*	(0.195)	(0.334)	(0.386)
	[0.031]*	[0.032]	[0.031]**	[0.186]	[0.280]	[0.302]
	{0.054}	{0.043}	{0.041}*	{0.185}	{0.229}	{0.258}
Clouds × Not Parallel	-0.034	-0.043	-0.054	0.031	0.095	-0.060
	(0.029)	(0.032)	(0.031)*	(0.260)	(0.224)	(0.216)
	[0.020]*	[0.021]**	[0.021]***	[0.258]	[0.316]	[0.299]
	{0.038}	{0.041}	{0.040}	{0.254}	{0.260}	{0.247}
Post × Not Parallel	0.146	0.076	0.068	0.285	0.267	0.229
	(0.011)***	(0.009)***	(0.009)***	(0.092)***	(0.079)***	(0.076)***
	[0.011]***	[0.009]***	[0.009]***	[0.053]***	[0.054]***	[0.053]***
	{0.042}***	{0.036}**	{0.035}*	{0.082}***	{0.072}***	{0.071}***
Not Parallel	0.484	0.483	0.488	0.414	0.460	0.514
	(0.009)***	(0.007)***	(0.007)***	(0.083)***	(0.065)***	(0.067)***
	[0.007]***	[0.006]***	[0.006]***	[0.037]***	[0.041]***	[0.042]***
	{0.032}***	{0.027}***	{0.026}***	{0.066}***	{0.058}***	{0.054}***
Clouds	-0.021			-0.157		
	(0.029)			(0.129)		
	[0.018]			[0.126]		
	{0.041}			{0.134}		
Post	0.078			-0.108		
	(0.011)***			(0.092)		
	[0.011]***			[0.046]**		
	{0.045}*			{0.077}		
Observations	206577	206577	206577	2754	2754	2754
Coastal vs. Offshore	offshore	offshore	offshore	coast	coast	coast
Grid cell FE		Y	Y		Y	Y
Decade FE		Y	Y		Y	Y
Latitude × Post			Y			Y
Wind × Post			Y			Y
Nationality FE × Post			Y			Y

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, passing from one grid cell to another, 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 sky mostly covered by clouds in CLIWOC 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; *Grid cell FE* are fixed effects for 1° × 1° grid cells; *Decade FE* are fixed effects for decades; *Latitude* is the absolute level of latitude, interacted with *Post*; *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*; *Nationality FE* are fixed effects for ship nationality, interacted with *Post.* Standard errors clustered at the grid cell level in parentheses, clustered at the voyage level in square brackets, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE V: Dealing with measurement error: triple-difference

	Dependent variable: fast or slow ship with speed cutoff at..					
	25th perc.	33rd perc.	50th perc.	25th perc.	33rd perc.	50th perc.
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post × Open sea	0.274	0.239	0.185	0.379	0.369	0.221
	(0.148)*	(0.113)**	(0.104)*	(0.220)*	(0.153)**	(0.128)*
	[0.128]**	[0.101]**	[0.101]*	[0.159]**	[0.109]***	[0.113]*
	{0.138}**	{0.110}**	{0.110}*	{0.145}***	{0.104}***	{0.109}**
Clouds × Post	-0.132	-0.110	-0.085	-0.384	-0.373	-0.217
	(0.145)	(0.110)	(0.102)	(0.219)*	(0.152)**	(0.127)*
	[0.127]	[0.100]	[0.100]	[0.158]**	[0.108]***	[0.112]*
	{0.132}	{0.104}	{0.105}	{0.145}***	{0.104}***	{0.108}**
Post × Open sea	0.197	0.142	0.081			
	(0.033)***	(0.033)***	(0.030)***			
	[0.020]***	[0.019]***	[0.017]***			
	{0.035}***	{0.033}***	{0.029}***			
Clouds × Open sea	-0.086	-0.034	0.036			
	(0.132)	(0.096)	(0.095)			
	[0.118]	[0.091]	[0.090]			
	{0.122}	{0.093}	{0.094}			
Post	0.113	0.126	0.119			
	(0.032)***	(0.032)***	(0.030)***			
	[0.019]***	[0.018]***	[0.017]***			
	{0.027}***	{0.026}***	{0.025}***			
Open sea	0.245	0.253	0.232			
	(0.018)***	(0.017)***	(0.019)***			
	[0.013]***	[0.012]***	[0.011]***			
	{0.021}***	{0.021}***	{0.020}***			
Clouds	-0.005	-0.061	-0.105			
	(0.130)	(0.093)	(0.094)			
	[0.118]	[0.090]	[0.090]			
	{0.120}	{0.090}	{0.092}			
Observations	110723	150716	228206	110723	150716	228206
Grid cell FE				Y	Y	Y
Decade FE				Y	Y	Y
Latitude × Post × Open Sea				Y	Y	Y
Wind × Post × Open Sea				Y	Y	Y
Nationality FE × Post × Open Sea				Y	Y	Y

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC. Dependent variable is an indicator for whether the ship is moving very fast or very slow excluding from the sample, respectively, intermediate observations within the top and bottom 25^{th}, 33^{rd} or 50^{th} percentiles; *Clouds* is a dummy equal to 1 assigned to grid cells with sky mostly covered by clouds in CLIWOC 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; *Grid cell FE* are fixed effects for $1^\circ \times 1^\circ$ grid cells; *Decade FE* are fixed effects for decades; *Latitude* is the absolute level of latitude, interacted with *Post* and with *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 with *Open sea*; *Nationality FE* are fixed effects for ship nationality, interacted with *Post* and with *Open sea.* Standard errors clustered at the grid cell level in parentheses, clustered at the voyage level in square brackets, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE VI: Chronometer and routes: difference-in-differences and triple-difference

	Dependent variable: number of voyages					
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post	0.677 (0.099)*** {0.139}***	0.794 (0.104)*** {0.151}***	0.364 (0.179)** {0.540}	1.858 (0.255)*** {0.707}***	0.128 (0.215) {0.257}	0.096 (0.227) {0.259}
Clouds × Post × Open sea					0.548 (0.237)** {0.283}*	0.698 (0.250)*** {0.288}**
Post × Open sea					-1.156 (0.185)*** {0.185}***	-1.306 (0.288)*** {0.529}**
Observations	118492	118492	118492	118492	119647	119647
Coastal vs. Offshore	offshore	offshore	offshore	offshore		
Clouds source	CLIWOC	CLIWOC	NEO	NEO	CLIWOC	CLIWOC
Grid cell FE	Y	Y	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y	Y	Y
Latitude × Post (× Open Sea)		Y		Y		Y
Wind × Post (× Open Sea)		Y		Y		Y

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 sky mostly covered by clouds in CLIWOC as explained in sub-section 3.2, except for columns 3 and 4 where it is the fraction of sky above a grid cell covered by clouds as reported in NEO; *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; *Grid cell FE* are fixed effects for $1^\circ \times 1^\circ$ grid cells; *Decade FE* are fixed effects for decades; *Latitude* is the absolute level of latitude, interacted with *Post* - and double interacted with *Open sea* in columns 5 and 6; *Wind* is wind speed, interacted with *Post* - and double interacted with *Open sea* in columns 5 and 6. 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 cutoff of 1,000 kilometres in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE VII: 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(population 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
	{1.533}	{1.497}	{0.666}	{0.093}	{1.600}	{1.629}	{0.688}	{0.048}
ln(lunar)-ln(chrono) × I(1760)	0.174	0.068	-0.153	-0.007	0.533	0.281	0.201	0.006
	{1.451}	{1.423}	{0.614}	{0.091}	{1.570}	{1.608}	{0.670}	{0.048}
ln(lunar)-ln(chrono) × I(1770)	0.158	0.103	-0.062	-0.002	0.298	0.179	0.122	0.003
	{1.373}	{1.352}	{0.569}	{0.088}	{1.537}	{1.585}	{0.653}	{0.048}
ln(lunar)-ln(chrono) × I(1790)	0.152	0.212	0.108	0.008	-0.254	-0.133	-0.064	-0.003
	{1.294}	{1.282}	{0.499}	{0.085}	{1.463}	{1.520}	{0.624}	{0.047}
ln(lunar)-ln(chrono) × I(1800)	0.467	0.592	0.389	0.026	-0.387	-0.146	-0.040	-0.004
	{1.178}	{1.169}	{0.436}	{0.080}	{1.387}	{1.445}	{0.587}	{0.046}
ln(lunar)-ln(chrono) × I(1810)	1.017	1.192	0.579	0.050	-0.488	-0.078	-0.057	-0.005
	{1.056}	{1.053}	{0.405}	{0.072}	{1.270}	{1.325}	{0.538}	{0.044}
ln(lunar)-ln(chrono) × I(1820)	1.591	1.828*	0.828**	0.079	-0.531	0.040	-0.014	-0.002
	{1.009}	{1.007}	{0.399}	{0.067}	{1.156}	{1.205}	{0.493}	{0.041}
ln(lunar)-ln(chrono) × I(1830)	2.337**	2.672***	1.047**	0.112*	-0.596	0.154	-0.028	0.002
	{1.037}	{1.029}	{0.408}	{0.064}	{1.106}	{1.151}	{0.469}	{0.038}
ln(lunar)-ln(chrono) × I(1840)	2.622**	3.058***	1.274***	0.128**	-0.783	0.122	-0.036	0.006
	{1.062}	{1.052}	{0.423}	{0.064}	{1.111}	{1.152}	{0.468}	{0.035}
ln(lunar)-ln(chrono) × I(1850)	3.204***	3.743***	1.539***	0.168**	-0.844	0.243	0.029	0.014
	{1.164}	{1.143}	{0.457}	{0.068}	{1.212}	{1.253}	{0.513}	{0.035}
ln(lunar)-ln(chrono) × I(1860)	3.873***	4.489***	1.788***	0.200***	-0.980	0.279	0.128	0.025
	{1.245}	{1.221}	{0.499}	{0.075}	{1.376}	{1.422}	{0.609}	{0.040}
ln(lunar)-ln(chrono) × I(1870)	4.423***	5.217***	1.895***	0.243***	-1.198	0.208	0.236	0.038
	{1.340}	{1.331}	{0.534}	{0.085}	{1.555}	{1.610}	{0.682}	{0.049}
ln(lunar)-ln(chrono) × I(1880)	4.630***	5.579***	2.016***	0.290***	-1.662	-0.134	0.180	0.048
	{1.471}	{1.466}	{0.596}	{0.104}	{1.768}	{1.845}	{0.761}	{0.063}
ln(lunar)-ln(chrono) × I(1890)	4.909***	6.053***	2.087***	0.339***	-2.162	-0.479	0.120	0.055
	{1.600}	{1.609}	{0.652}	{0.126}	{2.014}	{2.108}	{0.829}	{0.079}
ln(lunar)-ln(chrono) × I(1900)	4.839***	6.178***	2.155***	0.387**	-2.952	-1.115	0.015	0.057
	{1.676}	{1.693}	{0.706}	{0.152}	{2.229}	{2.350}	{0.886}	{0.095}
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 chronometer (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 1° × 1° 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 cutoff of 1,000 kilometres. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE VIII: European colonization

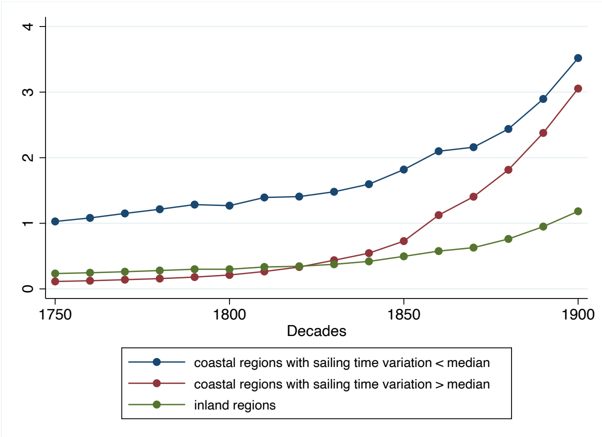
Dependent variable:	British colony		European colony	
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1660)	0.195	0.192	0.169	0.174
	{0.995}	{0.569}	{0.978}	{0.467}
ln(lunar)-ln(chrono) × I(1822)	1.937**	1.668***	1.699*	1.420**
	{0.941}	{0.609}	{0.963}	{0.630}
ln(lunar)-ln(chrono) × I(1885)	0.813	0.472	0.637	0.228
	{1.196}	{0.763}	{1.165}	{0.627}
Observations	11884	11884	11884	11884
Grid cell FE	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y
Latitude x Decade FE		Y		Y

Notes: Table reports OLS estimates. Unit of observation is a $1^\circ \times 1^\circ$ grid cell and the omitted year is 1754. Sample refers to coastal regions thus including land grid cells within 2 degrees from the coastline. Dependent variables are indicators for being a British colony (columns 1 and 2) or a European colony (columns 3 and 4) taking value one from the first time they are recorded as colonies onwards; *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronometer (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 $1^\circ \times 1^\circ$ grid cell and 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 cutoff of 1,000 kilometres. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

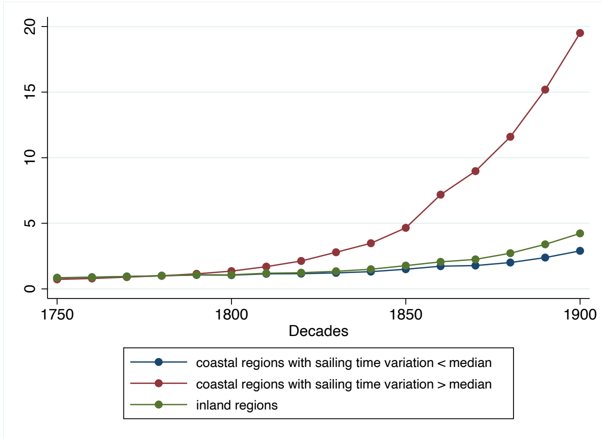
Figures

Figure 1: Urban population density (excluding Europe)

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

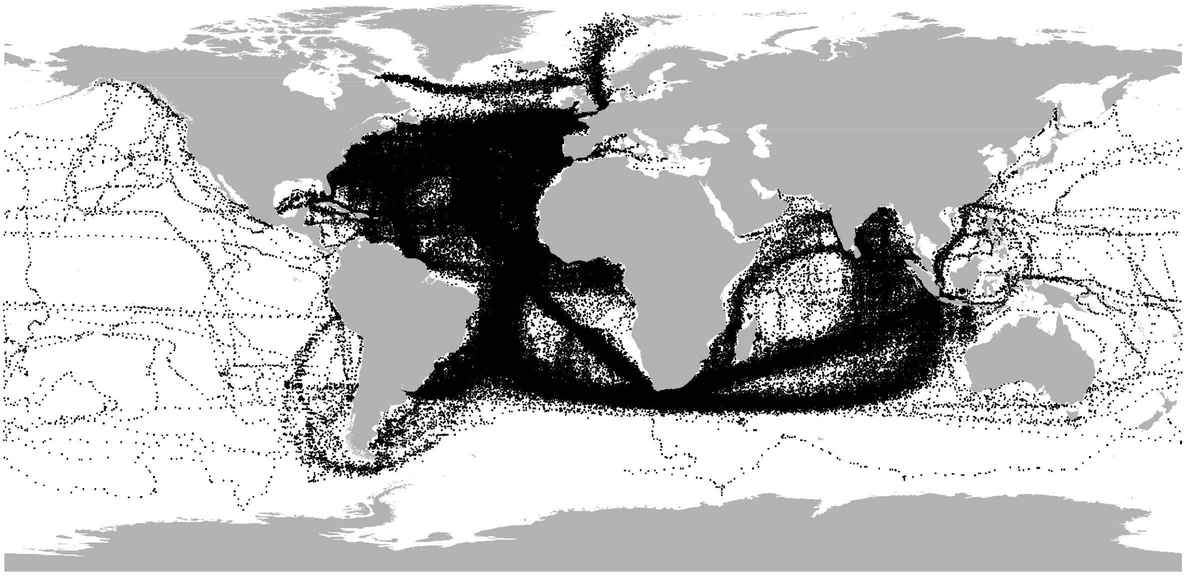


(b) Relative urban density growth % (1780 = 1)



Notes: Figures depict worldwide urban population density excluding Europe. Panel (a) shows average urban density (urban inhabitants per square kilometre); 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 the methodology illustrated in sub-section 4.2.1.

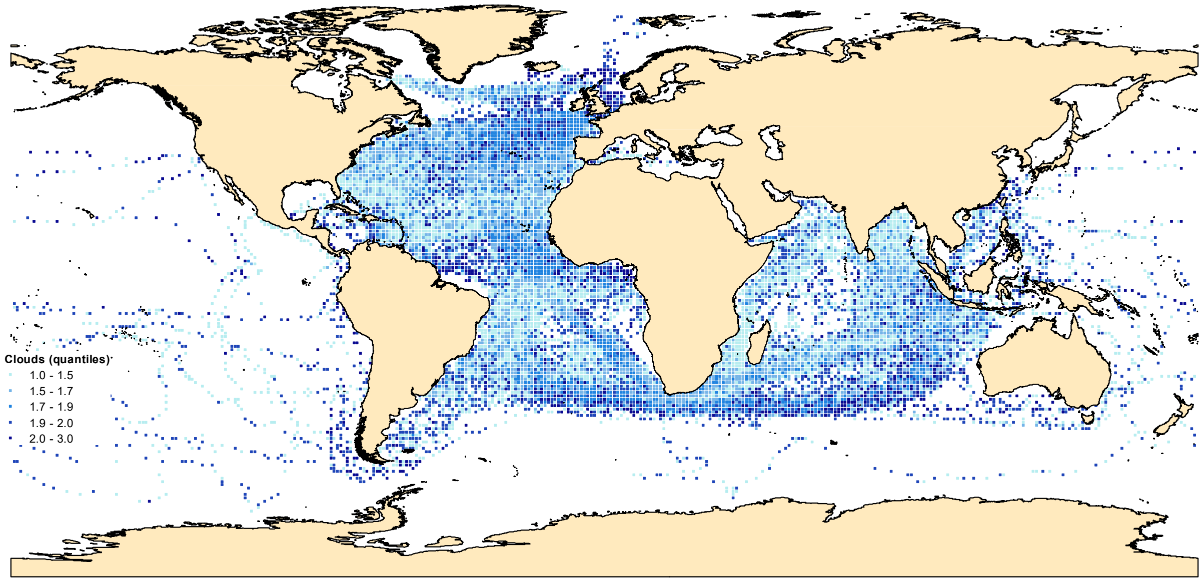
Figure 2: CLIWOC spatial distribution



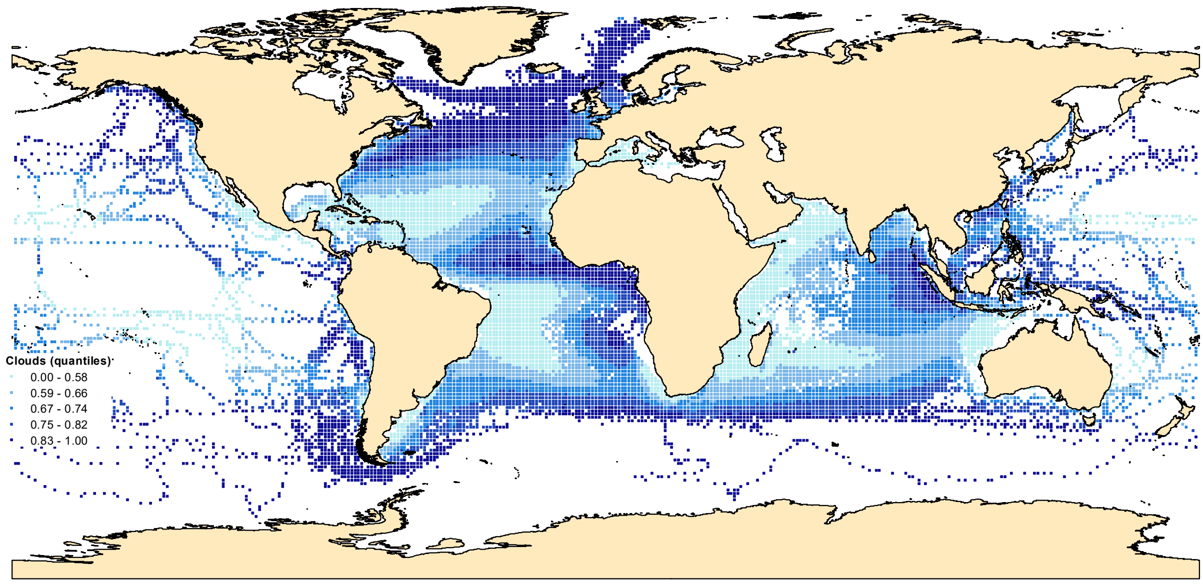
Notes: The unit of observation is a $1^\circ \times 1^\circ$ grid cell and the sample includes grid cells available in the entire CLIWOC dataset.

Figure 3: Cloud coverage

(a) Average cloud coverage using CLIWOC

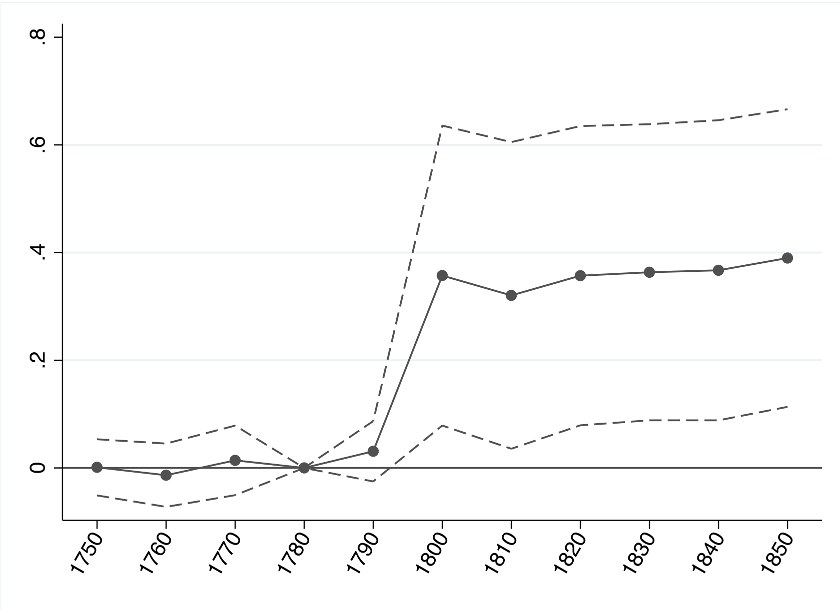


(b) Average cloud coverage using NEO



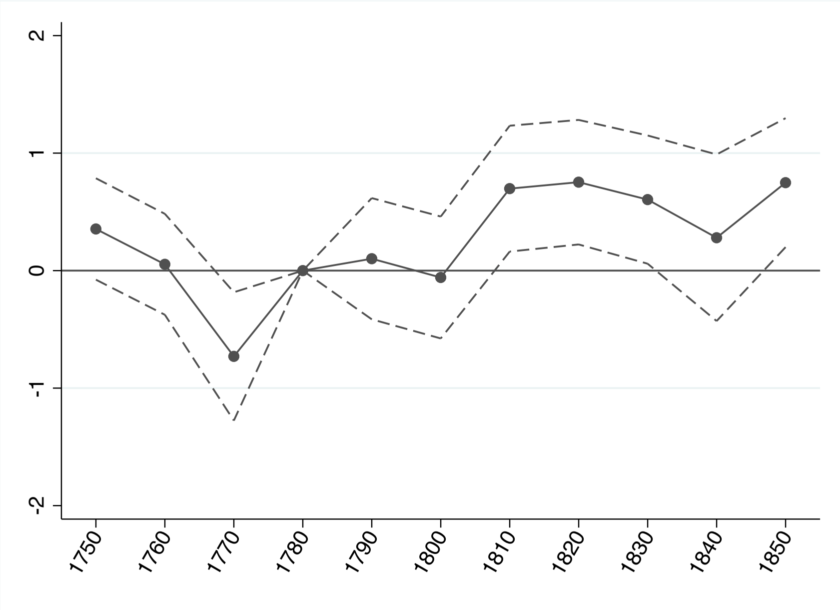
Notes: Panel (a) displays average cloud coverage distribution, in five quantiles, constructed using data from CLIWOC and following the procedure described in sub-section 3.2. Panel (b) shows average coverage distribution, in five quantiles, with contemporary cloud data provided by NASA Earth Observations,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

Figure 4: Chronometer and speed: pre-trends



Notes: Estimated coefficients from the regression $ln(speed)_{esit} = \sum_{t=1750}^{1850} \mu_t(clouds_i \times open\ sea_i) + \beta_1(open\ sea_i \times post_t) + \beta_2(clouds_i \times post_t) + \gamma X_{esit} + \delta_i + \delta_t + \epsilon_{esit}$ where the omitted decade is the 1780s and: 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 sky mostly covered by clouds in CLIWOC 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 $1° \times 1°$ grid cells at least 5 kilometres away from the coastline; δ_i and δ_t are fixed effects for $1° \times 1°$ grid cells and decades. Controls are: absolute level of latitude, wind force (one per each wind direction with respect to ship trajectory – against, semi-against, in favour, semi-in favour), and ship nationality fixed effects, all interacted with *Post* and with *Open sea*. Dashed lines indicate 90 percent confidence intervals, with standard errors corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres.

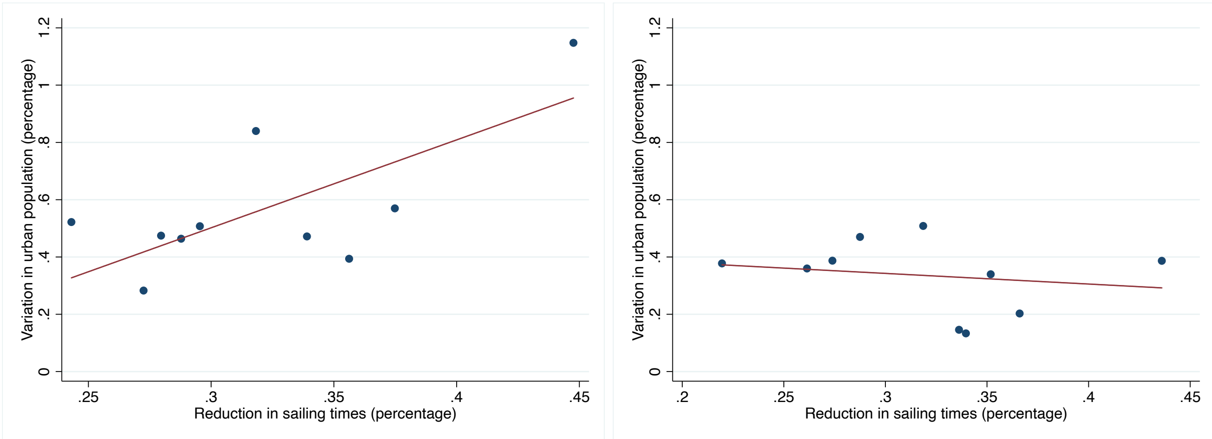
Figure 5: Chronometer and routes: pre-trends



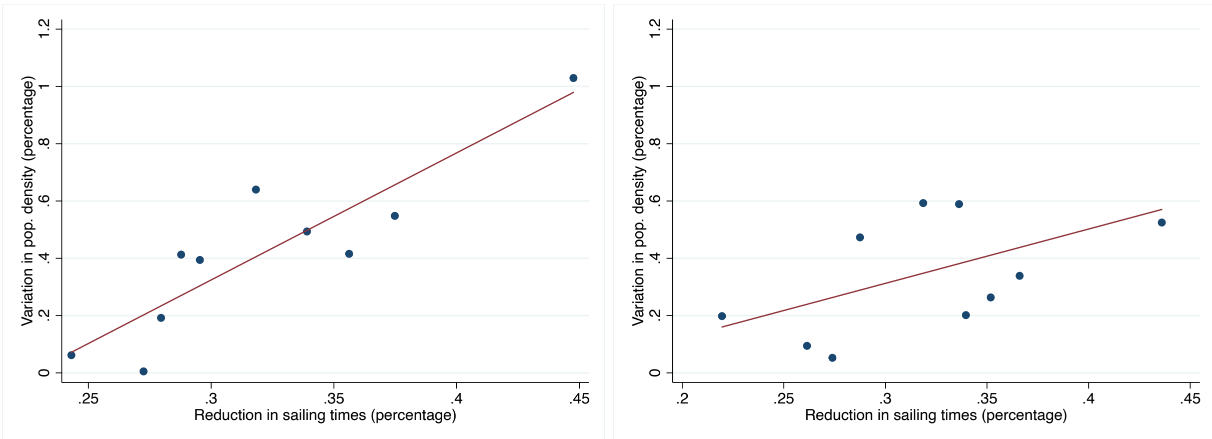
Notes: Estimated coefficients from the regression $voyages_{it} = \sum_{t=1750}^{1850} \mu_t(clouds_i \times open\ sea_i) + \beta_1(open\ sea_i \times post_t) + \beta_2(clouds_i \times post_t) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it}$ where the omitted decade is the 1780s and: dependent 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 sky mostly covered by clouds in CLIWOC as explained in sub-section 3.2; *Open sea* is a dummy for $1^\circ \times 1^\circ$ grid cells at least 5 kilometres away from the coastline; δ_i and δ_t are fixed effects for $1^\circ \times 1^\circ$ grid cells and decades. Controls are: absolute level of latitude and wind force, all interacted with *Post* and with *Open sea*. Dashed lines indicate 90 percent confidence intervals, with standard errors corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres.

Figure 6: Correlation between the estimated changes in sailing times to Europe (induced by the chronometer) and changes in urban population, population density and built-up area

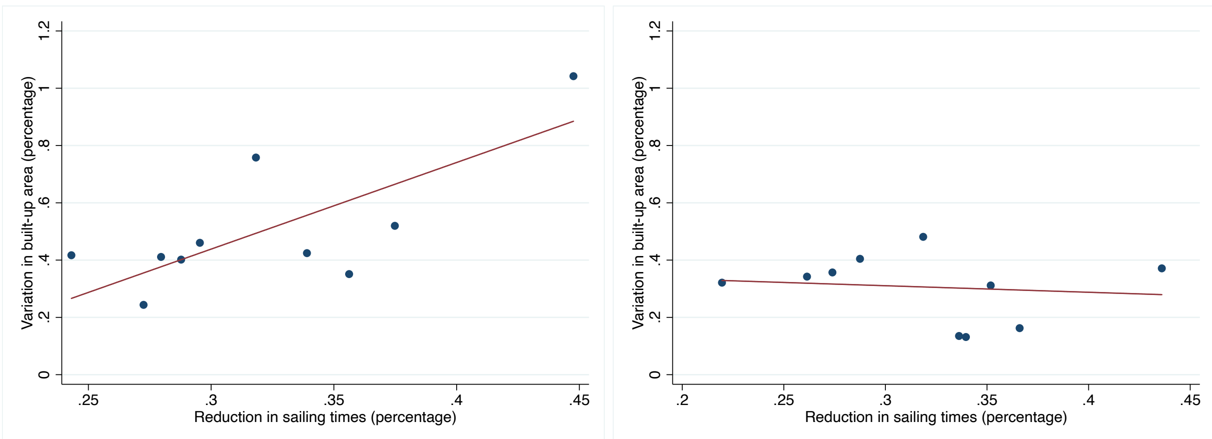
(a) Urban population on the coast and inland



(b) Population density on the coast and inland



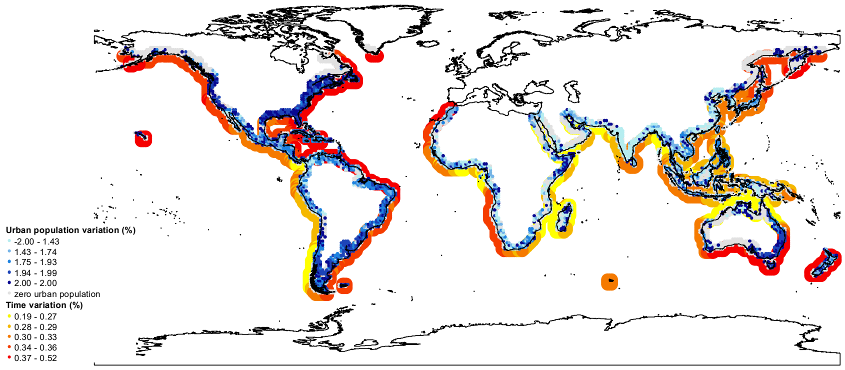
(c) Built-up area on the coast and inland



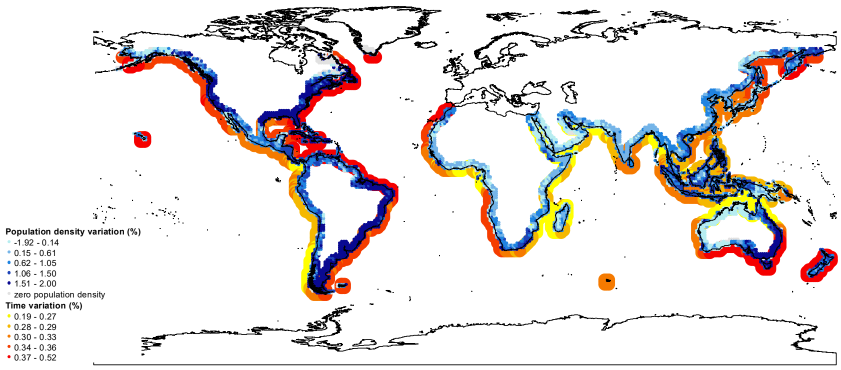
Notes: Binscatters display percentage reduction in minimum sailing times of a return trip from Europe under chronometer with respect to lunar method, against percentage variation in (a) urban population, (b) population density and (c) built-up area between 1750 and 1850. Panels on the left show correlations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

Figure 7: Comparing the estimated changes in sailing times to Europe (induced by the chronometer) against changes in urban population, population density and built-up area

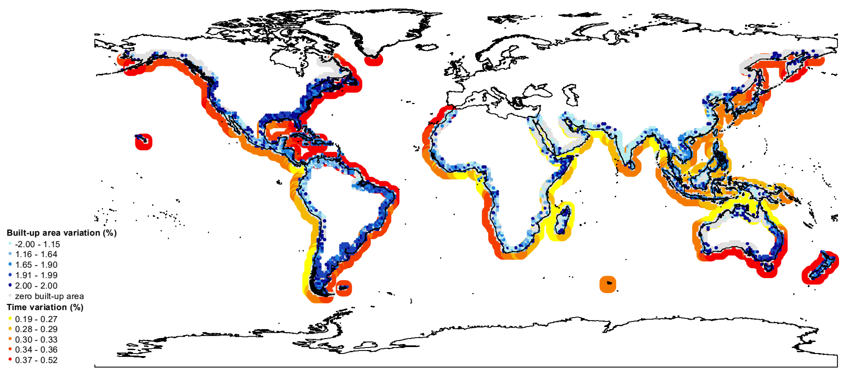
(a) Urban population



(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: Distribution of entries in CLIWOC across different ship nationalities

	Observations	Logbooks
British	94,859	669
Dutch	122,561	624
French	10,469	19
Spanish	48,827	402
Other	1,106	5

Notes: Number of entries and distinct logbooks in the CLIWOC dataset by nationality.

TABLE A2: Chronometer, speed and parallel sailing: dealing with measurement error

	Dependent variable: fast or slow ship with speed cutoff at..					
	25th perc.	33rd perc.	50th perc.	25th perc.	33rd perc.	50th perc.
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post × Not Parallel	0.088	0.085	0.095	-0.251	-0.111	-0.110
	(0.040)**	(0.033)***	(0.027)***	(0.307)	(0.204)	(0.137)
	[0.030]***	[0.027]***	[0.025]***	[0.305]	[0.212]	[0.190]
	{0.044}**	{0.040}**	{0.035}***	{0.272}	{0.199}	{0.149}
Clouds × Post	-0.079	-0.083	-0.077	-0.306	-0.352	-0.153
	(0.037)**	(0.031)***	(0.026)***	(0.171)*	(0.176)**	(0.140)
	[0.027]***	[0.024]***	[0.023]***	[0.171]*	[0.145]**	[0.131]
	{0.037}**	{0.033}**	{0.030}***	{0.173}*	{0.163}**	{0.119}
Clouds × Not Parallel	-0.039	-0.032	-0.042	-0.070	-0.129	-0.098
	(0.033)	(0.027)	(0.022)*	(0.284)	(0.167)	(0.117)
	[0.020]**	[0.017]*	[0.015]***	[0.280]	[0.177]	[0.186]
	{0.035}	{0.033}	{0.027}	{0.235}	{0.149}	{0.147}
Post × Not Parallel	0.122	0.108	0.084	0.136	0.110	0.132
	(0.009)***	(0.008)***	(0.007)***	(0.055)**	(0.050)**	(0.039)***
	[0.009]***	[0.008]***	[0.007]***	[0.044]***	[0.038]***	[0.032]***
	{0.030}***	{0.028}***	{0.026}***	{0.045}***	{0.048}**	{0.045}***
Not Parallel	0.444	0.421	0.357	0.322	0.324	0.280
	(0.007)***	(0.006)***	(0.005)***	(0.039)***	(0.046)***	(0.039)***
	[0.006]***	[0.005]***	[0.004]***	[0.035]***	[0.030]***	[0.025]***
	{0.021}***	{0.020}***	{0.019}***	{0.035}***	{0.038}***	{0.036}***
Observations	91146	130069	206577	1439	1912	2754
Coastal vs. Offshore	offshore	offshore	offshore	coast	coast	coast
Grid cell FE	Y	Y	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y	Y	Y
Latitude × Post	Y	Y	Y	Y	Y	Y
Wind × Post	Y	Y	Y	Y	Y	Y
Nationality FE × Post	Y	Y	Y	Y	Y	Y

Notes: Table reports OLS estimates. Unit of observation is an entry in CLIWOC. Dependent variable is an indicator for whether the ship is moving very fast or very slow excluding from the sample, respectively, intermediate observations within the top and bottom 25^{th}, 33^{rd} or 50^{th} percentiles; *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, passing from one grid cell to another, 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 sky mostly covered by clouds in CLIWOC 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; *Grid cell FE* are fixed effects for $1^{\circ} \times 1^{\circ}$ grid cells; *Decade FE* are fixed effects for decades; *Latitude* is the absolute level of latitude, interacted with *Post*; *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*; *Nationality FE* are fixed effects for ship nationality, interacted with *Post.* Standard errors clustered at the grid cell level in parentheses, clustered at the voyage level in square brackets, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometres in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE A3: Additional summary statistics

	Obs.	Mean	St. Dev.	Min	Max	Source	Unit of observation
Optimized shipping time - Lunar method (days)	4,793	256.35	109.17	43	417	Authors	grid cell (coast)
Optimized shipping time - Chronometer (days)	4,793	187.62	81.36	29	298	Authors	grid cell (coast)

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

TABLE A4: Chronometer and urbanization: the extensive margin

	COASTAL REGIONS			**INLAND REGIONS**		
Dependent variable:	urban population (dummy)		built-up (dummy)	urban population (dummy)		built-up (dummy)
	(1)	(2)	(3)	(4)	(5)	(6)
ln(lunar)-ln(chrono) × I(1750)	0.178	0.194	0.178	0.020	-0.027	0.020
	{0.200}	{0.194}	{0.200}	{0.240}	{0.260}	{0.240}
ln(lunar)-ln(chrono) × I(1760)	0.131	0.135	0.131	0.022	-0.005	0.022
	{0.191}	{0.186}	{0.191}	{0.240}	{0.260}	{0.240}
ln(lunar)-ln(chrono) × I(1770)	0.078	0.077	0.078	0.022	0.018	0.022
	{0.177}	{0.171}	{0.177}	{0.229}	{0.249}	{0.229}
ln(lunar)-ln(chrono) × I(1790)	0.035	0.033	0.035	0.008	0.016	0.008
	{0.181}	{0.175}	{0.181}	{0.216}	{0.235}	{0.216}
ln(lunar)-ln(chrono) × I(1800)	0.072	0.070	0.072	0.018	0.028	0.018
	{0.159}	{0.154}	{0.159}	{0.202}	{0.220}	{0.202}
ln(lunar)-ln(chrono) × I(1810)	0.154	0.141	0.154	0.036	0.052	0.036
	{0.147}	{0.143}	{0.147}	{0.186}	{0.202}	{0.186}
ln(lunar)-ln(chrono) × I(1820)	0.236*	0.210	0.236*	0.066	0.084	0.066
	{0.141}	{0.138}	{0.141}	{0.174}	{0.189}	{0.174}
ln(lunar)-ln(chrono) × I(1830)	0.346**	0.300**	0.346**	0.078	0.092	0.078
	{0.155}	{0.151}	{0.155}	{0.174}	{0.189}	{0.174}
ln(lunar)-ln(chrono) × I(1840)	0.340**	0.292*	0.340**	0.040	0.044	0.040
	{0.155}	{0.150}	{0.155}	{0.175}	{0.190}	{0.175}
ln(lunar)-ln(chrono) × I(1850)	0.398**	0.320**	0.398**	0.041	0.040	0.041
	{0.169}	{0.162}	{0.169}	{0.189}	{0.205}	{0.189}
ln(lunar)-ln(chrono) × I(1860)	0.489***	0.399**	0.489***	-0.011	-0.020	-0.011
	{0.173}	{0.166}	{0.173}	{0.198}	{0.216}	{0.198}
ln(lunar)-ln(chrono) × I(1870)	0.563***	0.473***	0.563***	-0.060	-0.084	-0.060
	{0.183}	{0.177}	{0.183}	{0.221}	{0.240}	{0.221}
ln(lunar)-ln(chrono) × I(1880)	0.534***	0.435**	0.534***	-0.141	-0.180	-0.141
	{0.187}	{0.181}	{0.187}	{0.250}	{0.273}	{0.250}
ln(lunar)-ln(chrono) × I(1890)	0.576***	0.494**	0.576***	-0.251	-0.308	-0.251
	{0.195}	{0.192}	{0.195}	{0.297}	{0.324}	{0.297}
ln(lunar)-ln(chrono) × I(1900)	0.530**	0.459**	0.530**	-0.374	-0.446	-0.374
	{0.207}	{0.210}	{0.207}	{0.337}	{0.369}	{0.337}
Observations	76688	76688	76688	186288	186288	186288
Grid cell FE	Y	Y	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y	Y	Y
Latitude x Decade FE		Y			Y	

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, *Inland regions* include the rest of land grid cells. Dependent variables are indicator variables taking value of one if urban population (inhabitants/grid cell) and built-up area (e.g. cities in km^2 per grid cell) are, respectively, greater than zero; *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronometer (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 $1^\circ \times 1^\circ$ 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 cutoff of 1,000 kilometres. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE A5: Chronometer, urbanization and population density; robustness check using 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
	{1.943}	{1.998}	{0.819}	{0.101}
ln(lunar)-ln(chrono) × I(1760)	0.301	0.282	-0.311	-0.007
	{1.844}	{1.899}	{0.766}	{0.099}
ln(lunar)-ln(chrono) × I(1770)	0.208	0.200	-0.147	-0.004
	{1.754}	{1.807}	{0.716}	{0.096}
ln(lunar)-ln(chrono) × I(1790)	0.030	0.041	0.190	0.007
	{1.625}	{1.676}	{0.635}	{0.091}
ln(lunar)-ln(chrono) × I(1800)	0.251	0.274	0.523	0.023
	{1.483}	{1.530}	{0.568}	{0.086}
ln(lunar)-ln(chrono) × I(1810)	0.756	0.797	0.811	0.047
	{1.341}	{1.382}	{0.527}	{0.078}
ln(lunar)-ln(chrono) × I(1820)	1.401	1.459	1.196**	0.080
	{1.260}	{1.295}	{0.505}	{0.072}
ln(lunar)-ln(chrono) × I(1830)	2.165*	2.234*	1.464***	0.118*
	{1.275}	{1.305}	{0.504}	{0.069}
ln(lunar)-ln(chrono) × I(1840)	2.422*	2.494*	1.801***	0.142**
	{1.311}	{1.344}	{0.526}	{0.068}
ln(lunar)-ln(chrono) × I(1850)	2.856**	2.936**	2.139***	0.182**
	{1.425}	{1.462}	{0.576}	{0.072}
ln(lunar)-ln(chrono) × I(1860)	3.454**	3.547**	2.692***	0.222***
	{1.544}	{1.584}	{0.621}	{0.079}
ln(lunar)-ln(chrono) × I(1870)	4.278**	4.364**	3.062***	0.279***
	{1.691}	{1.740}	{0.665}	{0.090}
ln(lunar)-ln(chrono) × I(1880)	4.428**	4.505**	3.423***	0.339***
	{1.844}	{1.900}	{0.738}	{0.109}
ln(lunar)-ln(chrono) × I(1890)	4.723**	4.784**	3.642***	0.405***
	{2.004}	{2.067}	{0.817}	{0.131}
ln(lunar)-ln(chrono) × I(1900)	4.502**	4.543**	3.909***	0.473***
	{2.089}	{2.150}	{0.890}	{0.157}
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 $1^\circ \times 1^\circ$ grid cell and the omitted decade is 1780-1789. *Coastal regions* include land grid cells within 2 degrees from the coastline. Dependent 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 chronometer (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 $1^\circ \times 1^\circ$ 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 cutoff of 1,000 kilometres. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE A6: Chronometer, urbanization and population density; robustness check excluding continents one-by-one

	COASTAL REGIONS				
Dependent variable:	ln(urban population)				
	(1)	(2)	(3)	(4)	(5)
ln(lunar)-ln(chrono) × I(1750)	0.204	-0.475	0.413	0.246	0.337
	{1.651}	{1.585}	{1.015}	{1.855}	{1.696}
ln(lunar)-ln(chrono) × I(1760)	0.180	-0.248	0.261	0.209	0.258
	{1.557}	{1.513}	{0.958}	{1.748}	{1.604}
ln(lunar)-ln(chrono) × I(1770)	0.183	-0.062	0.143	0.185	0.208
	{1.470}	{1.438}	{0.906}	{1.644}	{1.517}
ln(lunar)-ln(chrono) × I(1790)	0.195	0.312	-0.001	0.170	0.128
	{1.382}	{1.381}	{0.817}	{1.535}	{1.428}
ln(lunar)-ln(chrono) × I(1800)	0.614	0.756	-0.015	0.542	0.429
	{1.258}	{1.259}	{0.779}	{1.394}	{1.301}
ln(lunar)-ln(chrono) × I(1810)	1.262	1.519	-0.011	1.217	0.975
	{1.129}	{1.123}	{0.760}	{1.254}	{1.163}
ln(lunar)-ln(chrono) × I(1820)	1.938*	2.229**	0.190	1.876	1.524
	{1.081}	{1.073}	{0.737}	{1.204}	{1.105}
ln(lunar)-ln(chrono) × I(1830)	2.857**	3.000***	0.532	2.731**	2.231**
	{1.112}	{1.100}	{0.719}	{1.257}	{1.127}
ln(lunar)-ln(chrono) × I(1840)	3.194***	3.355***	0.789	3.057**	2.428**
	{1.137}	{1.121}	{0.722}	{1.298}	{1.157}
ln(lunar)-ln(chrono) × I(1850)	3.858***	4.108***	1.121	3.788***	2.846**
	{1.244}	{1.228}	{0.720}	{1.431}	{1.279}
ln(lunar)-ln(chrono) × I(1860)	4.540***	4.841***	1.771**	4.668***	3.356**
	{1.332}	{1.318}	{0.819}	{1.512}	{1.376}
ln(lunar)-ln(chrono) × I(1870)	5.198***	5.267***	2.073**	5.426***	3.841***
	{1.434}	{1.416}	{0.941}	{1.610}	{1.485}
ln(lunar)-ln(chrono) × I(1880)	5.428***	5.507***	2.072*	5.831***	3.934**
	{1.583}	{1.554}	{1.084}	{1.748}	{1.634}
ln(lunar)-ln(chrono) × I(1890)	5.772***	5.737***	2.296*	6.329***	4.021**
	{1.722}	{1.701}	{1.323}	{1.872}	{1.779}
ln(lunar)-ln(chrono) × I(1900)	5.656***	5.695***	2.426	6.371***	3.791**
	{1.805}	{1.789}	{1.544}	{1.956}	{1.856}
Observations	64896	50208	60400	63824	67424
Grid cell FE	Y	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y	Y
Excluded continent	Africa	Asia	N. America	S./C. America	Oceania

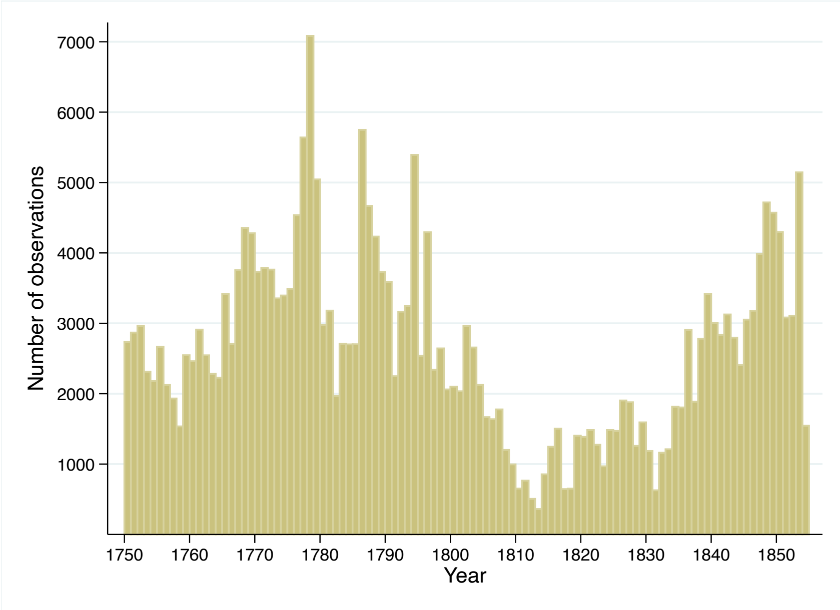
Notes: Table reports OLS estimates. Unit of observation is a $1^\circ \times 1^\circ$ grid cell and the omitted decade is 1780-1789. *Coastal regions* include land grid cells within 2 degrees from the coastline. Dependent variable is the natural logarithm of 1 plus urban population (inhabitants/grid cell); *ln(lunar)-ln(chrono)* is the difference of optimized sailing times by lunar method and by chronometer (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 $1^\circ \times 1^\circ$ grid cell and decade fixed effects; *Continent linear trends* are linear trends for all continents in the sample (Africa, America, Asia, Oceania); *Excluded 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 cutoff of 1,000 kilometres. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

TABLE A7: Chronometer, urbanization and population density in inland regions; controlling for the 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
	{1.567}	{1.568}	{0.675}	{0.047}
ln(lunar)-ln(chrono) × I(1760)	0.533	0.331	0.199	0.005
	{1.540}	{1.542}	{0.657}	{0.046}
ln(lunar)-ln(chrono) × I(1770)	0.295	0.185	0.121	0.003
	{1.509}	{1.514}	{0.641}	{0.046}
ln(lunar)-ln(chrono) × I(1790)	-0.251	-0.145	-0.062	-0.003
	{1.438}	{1.449}	{0.613}	{0.046}
ln(lunar)-ln(chrono) × I(1800)	-0.381	-0.160	-0.035	-0.003
	{1.365}	{1.376}	{0.577}	{0.045}
ln(lunar)-ln(chrono) × I(1810)	-0.485	-0.112	-0.053	-0.004
	{1.250}	{1.262}	{0.530}	{0.043}
ln(lunar)-ln(chrono) × I(1820)	-0.526	0.012	-0.007	-0.001
	{1.138}	{1.148}	{0.485}	{0.040}
ln(lunar)-ln(chrono) × I(1830)	-0.591	0.131	-0.023	0.004
	{1.087}	{1.097}	{0.461}	{0.037}
ln(lunar)-ln(chrono) × I(1840)	-0.777	0.108	-0.026	0.008
	{1.090}	{1.100}	{0.460}	{0.034}
ln(lunar)-ln(chrono) × I(1850)	-0.837	0.235	0.040	0.016
	{1.188}	{1.199}	{0.503}	{0.034}
ln(lunar)-ln(chrono) × I(1860)	-0.968	0.313	0.141	0.027
	{1.352}	{1.367}	{0.599}	{0.039}
ln(lunar)-ln(chrono) × I(1870)	-1.178	0.292	0.253	0.040
	{1.532}	{1.553}	{0.672}	{0.048}
ln(lunar)-ln(chrono) × I(1880)	-1.626	0.044	0.200	0.050
	{1.747}	{1.770}	{0.751}	{0.062}
ln(lunar)-ln(chrono) × I(1890)	-2.108	-0.175	0.141	0.058
	{1.992}	{2.005}	{0.819}	{0.077}
ln(lunar)-ln(chrono) × I(1900)	-2.876	-0.650	0.038	0.059
	{2.201}	{2.193}	{0.877}	{0.093}
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 $1^\circ \times 1^\circ$ 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 chronometer (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 $1^\circ \times 1^\circ$ 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 polygon 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 cutoff of 1,000 kilometres. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

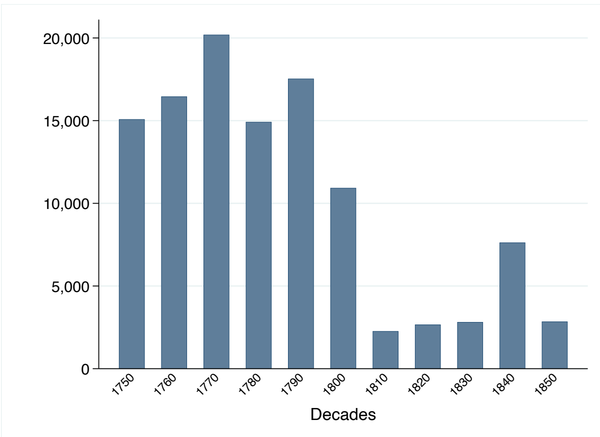
Figure A1: CLIWOC temporal distribution



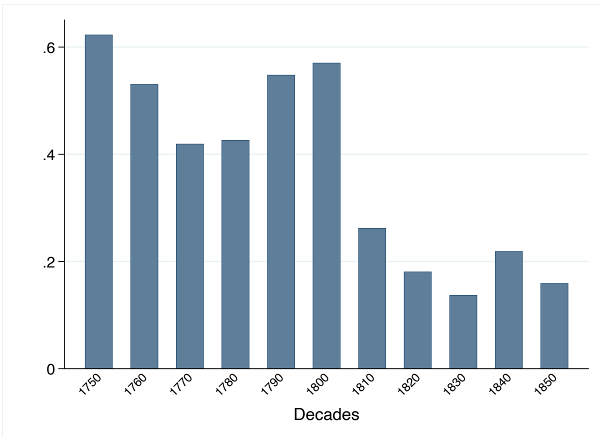
Notes: The unit of observation is an entry in the CLIWOC dataset from 1750 to 1855.

Figure A2: Longitude recordings based on dead reckoning in CLIWOC

(a) Total observations

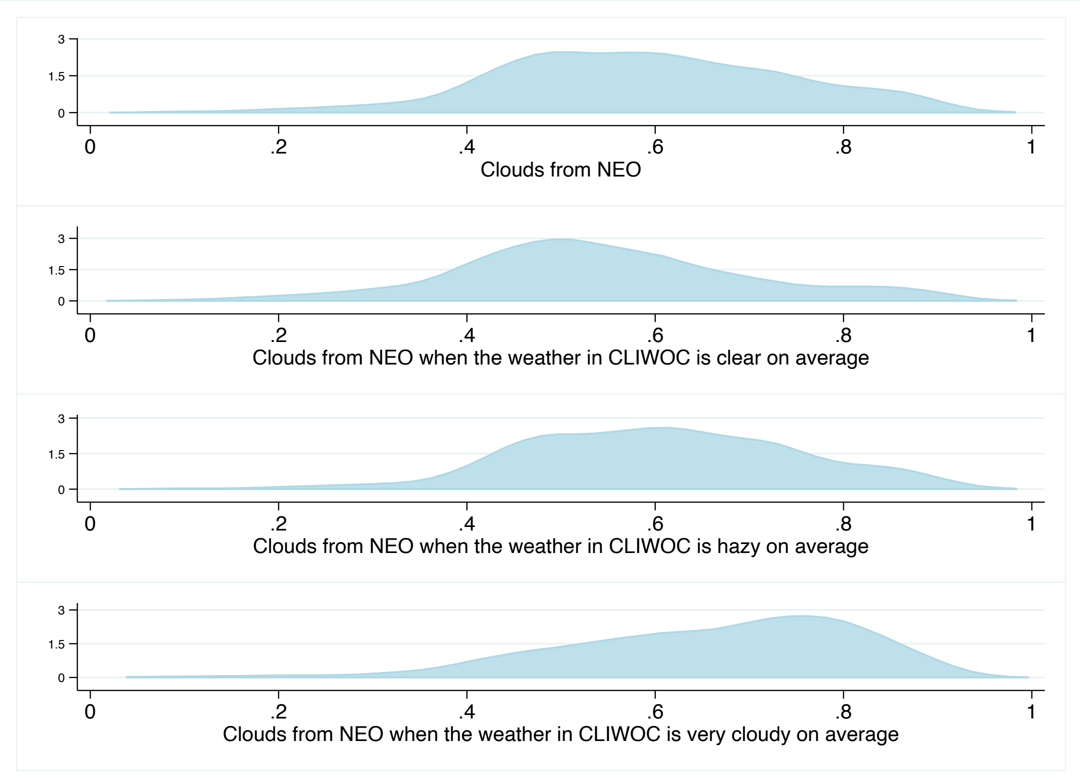


(b) Shares



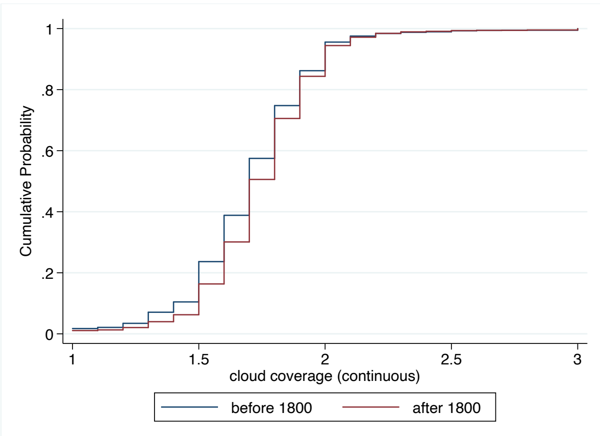
Notes: The unit of observation is an entry in the CLIWOC dataset from 1750 to 1855.

Figure A3: NEO cloud coverage distribution for different CLIWOC weather conditions



Notes: Figure show kernel density estimations of cloud coverage in the NEO data for three ranges of cloud coverage derived from CLIWOC. In this figure the three categories group values of the newly constructed coverage variable between 1 and 1.5, 1.6 and 2, and above 2, respectively.

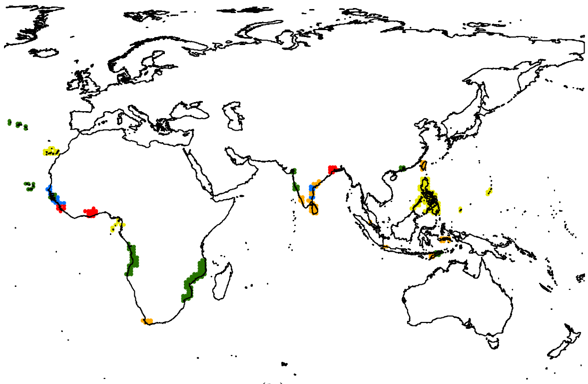
Figure A4: Cumulative distribution of the cloud coverage encountered by ships in CLIWOC (comparing entries in the eighteenth and nineteenth century)



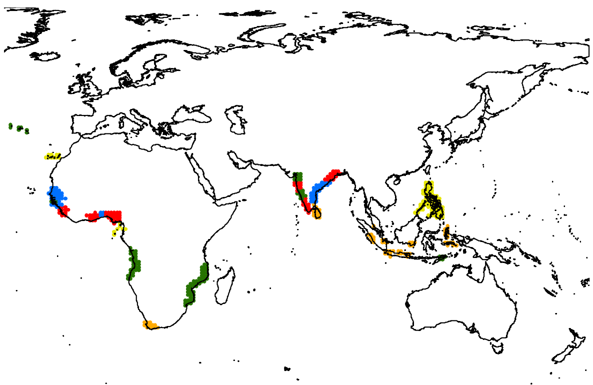
Notes: Cumulative distribution functions of cloud coverage before and after 1800 using the entire CLIWOC dataset. Cloud coverage values range between 1 and 3 as explained in sub-section 3.2.

Figure A5: European colonization

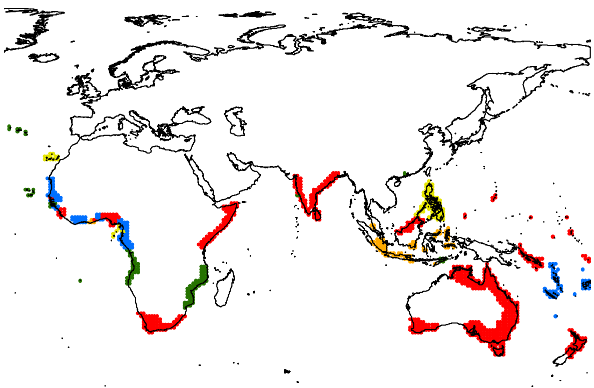
(a) 1660



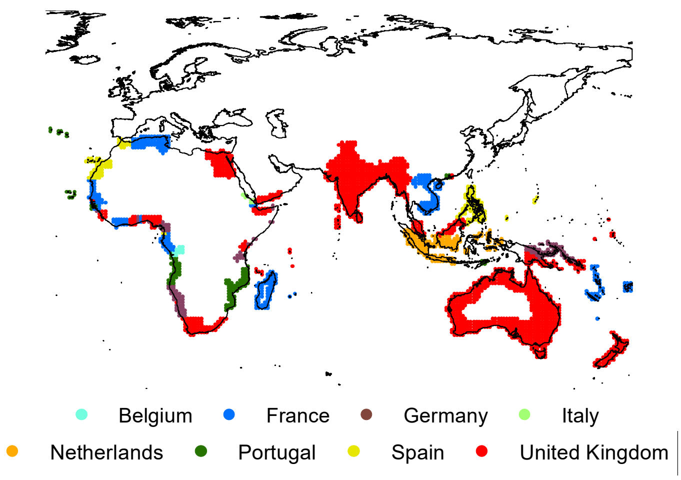
(b) 1754



(c) 1822

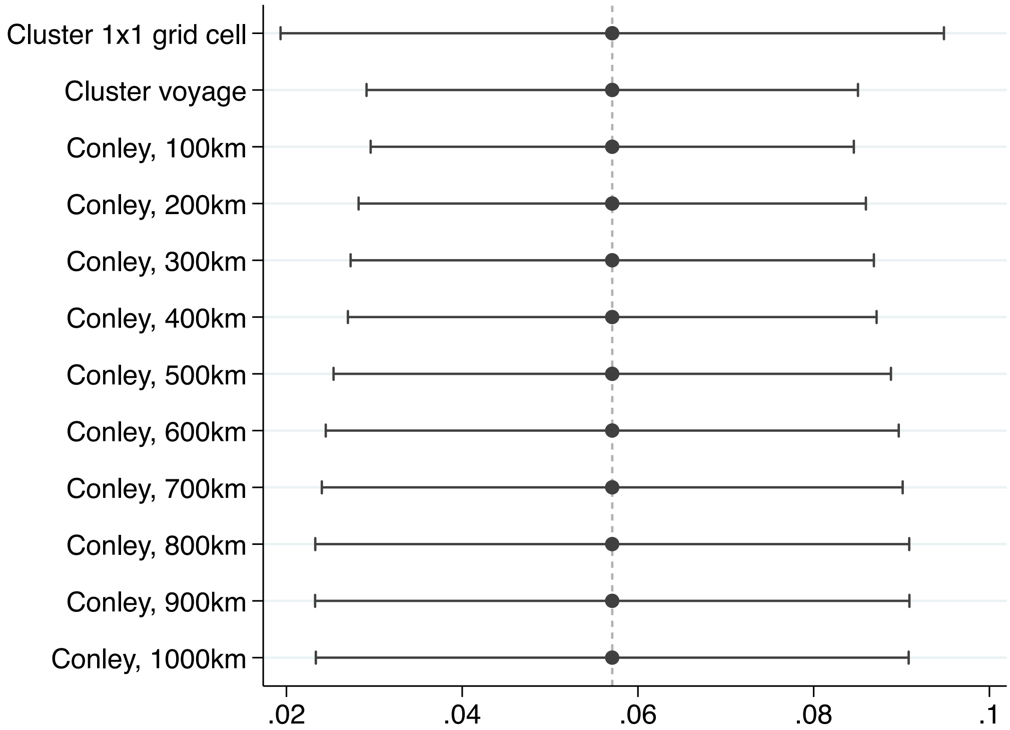


(d) 1885



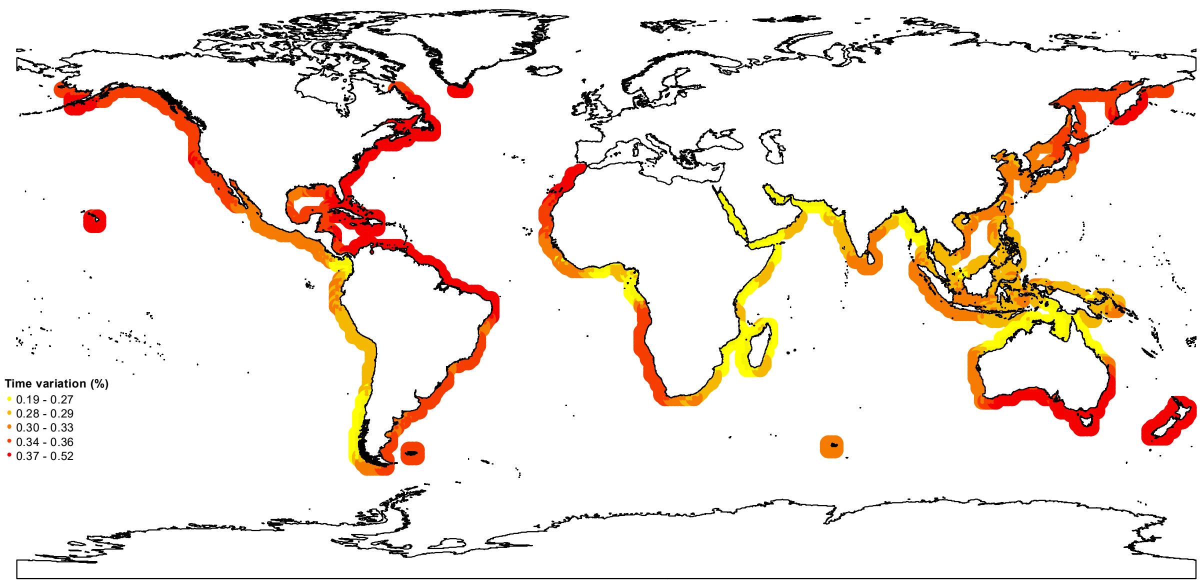
Notes: The unit of observation is a 1° × 1° grid cell.

Figure A6: Standard errors



Notes: Figure reports coefficients and standard errors estimated for column 3, Table II. The top coefficients correspond to the specification with standard errors clustered at the level of 1° × 1° grid cell and of voyage, respectively. Following coefficients allow for spatial autocorrelation of errors (implementing Conley (1999) standard errors) up to 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1,000 kilometres, respectively.

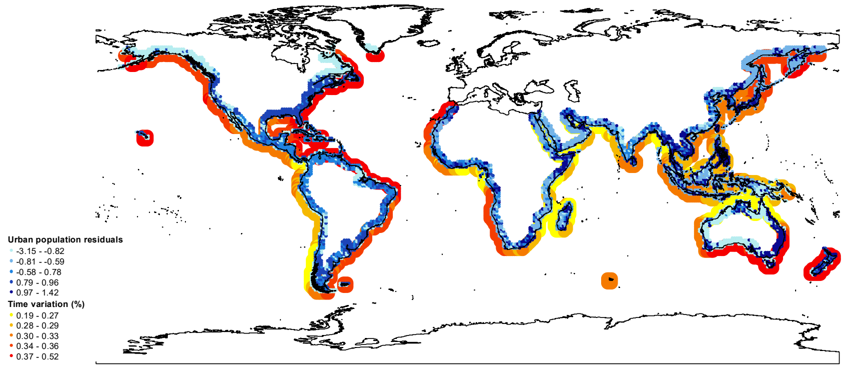
Figure A7: Estimated changes in sailing times to Europe induced by the chronometer



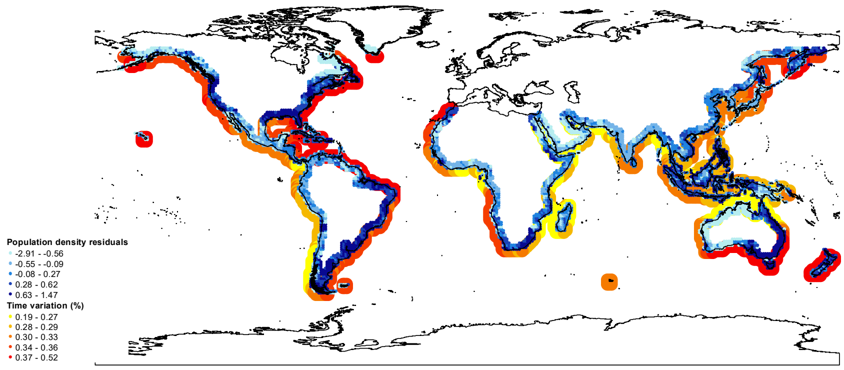
Notes: Figure displays quintiles of the estimated percentage reduction in minimum sailing times of a return trip from Europe to any other coastal cell outside of Europe induced by the invention of the chronometer.

Figure A8: Comparing the estimated changes in sailing times to Europe (induced by the chronometer) against changes in urban population, population density and built-up area, after netting out the continent fixed effects

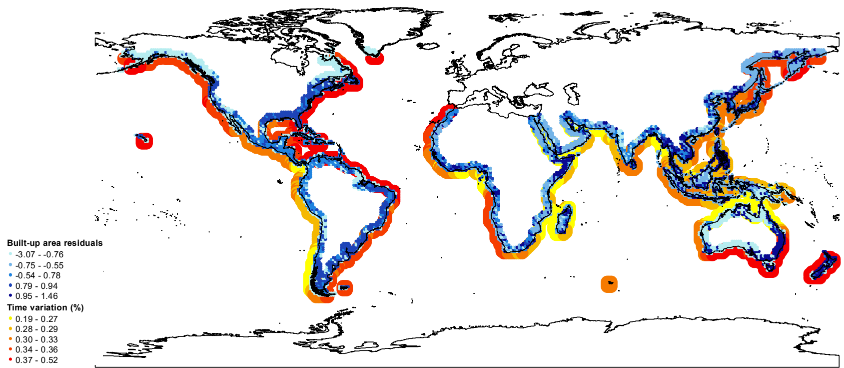
(a) Urban population



(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.