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

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ABSTRACT

The chronometer, one of the greatest inventions of the modern era, allowed for the first time for the precise measurement of longitude at sea. We examine the impact of this innovation on navigation and urbanization. Our identification strategy leverages the fact that the navigational benefits provided by the chronometer varied across different sea regions depending on the prevailing local weather conditions. Utilizing high-resolution data on climate, ship routes, and urbanization, we argue that the chronometer significantly altered transoceanic sailing routes. This, in turn, had profound effects on the expansion of the British Empire and the global distribution of cities and populations outside Europe.

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 eighteenth 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

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[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).

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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 urbanization in a systematic econometric framework. We use global data on climate, ship routes, urbanization 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.

In principle, the longitude of a ship in the open sea can 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 can be inferred from the position of the sun, but how could one measure the time in Greenwich when navigating an ocean? The first solution to this longitude puzzle, 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 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, that could keep the Greenwich time with minimal error. Although determining the longitude would still require inferring the local time from the position of the sun, the advent of the chronometer reduced dramatically the weather requirements (see Section 2.2 for an extensive explanation), thus opening new portions of the oceans to navigation. 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; mass adoption only happened in the nineteenth century.

The empirical analysis is composed of three parts.

In the first part, we study how the chronometer changed navigation. Our main data source is 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 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. Not surprisingly, this differential impact of the chronometer across different sea regions led to a complete reorganization of the major sailing routes of the time. We document this phenomenon with a second set of estimates, highlighting two significant changes in sailing routes attributable to the advantages offered by the chronometer. First, we show a relative increase in the number of observations of ships navigating under cloudy skies compared to clear skies, starting from the 1810s. This change is predominantly seen in open sea navigation and is not evident in coastal navigation. Second, we find that the rise in crossings through cloudy regions in the open sea is largely due to instances of non-parallel navigation. As detailed in the Historical Background section, when sailors were not able to measure their longitude, they would typically navigate along the coast until they reached the latitude of their destination, and then proceed along a constant latitude in the open sea until arrival. The introduction of the chronometer allowed sailors to traverse cloudy regions without being restricted to parallel navigation.

In the second part of our empirical investigation, we study how the chronometer reshaped the geography of the world. Using the estimates from the first part on the change in sailing speeds induced by the chronometer under different weather conditions, we develop a route optimization algorithm, which produces the optimal routes and sailing times between Europe and the rest of the world, with and without the chronometer technology. We then validate this algorithm against data on sailing times across different ports inferred from the Lloyd's List, a daily publication with shipping information covering the main ports of the period.

In the third part of the empirical analysis, we study the impact of this change in geography induced by the chronometer on urbanization. We construct a large panel database spanning every $1° \, x \, 1°$ grid cell of the non-European world from 1750 to 1900. The database combines information on the change in the predicted optimal sailing times to and from Europe induced by the chronometer with information on urbanization and population density that are constructed using two (admittedly imperfect) datasets provided by Reba et al. (2016) and Klein Goldewijk et al. (2017). The research design follows a difference-in-differences approach, which compares changes in sailing time for a round trip to Europe, induced by the invention of the chronometer, with local changes in urban population and population density.

Fig. 1 presents the intuition for our identification strategy. The figure 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 disproportionately 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

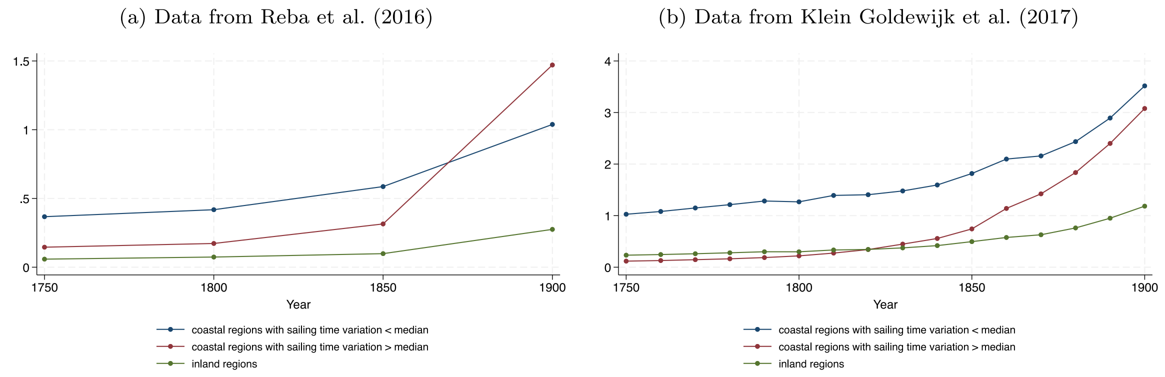


Fig. 1. Urban population density (excluding Europe).
Notes: Figures depict world-wide urban population density (urban inhabitants per square kilometer) excluding Europe using data from Reba et al. (2016) in panel (a) and from Klein Goldewijk et al. (2017) in panel (b). Sailing time variation refers to 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 subsection Section 4.2.1.

cells. In the nineteenth century, these regions completely changed their urban landscape and, within a century, they reached levels of urbanization comparable to the other coastal cells. 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 required for a round trip from Europe enabled by the chronometer is associated with an increase in urban population of approximately 1.7 percent in 1850 and 4.7 percent in 1900. In contrast, we find no impact of the chronometer on urban population in the inland grid cells. Pre-trend checks and a comprehensive set of robustness exercises lend support to a causal interpretation of these estimates. Further, these large effects are not fully explained by dynamics specific to any particular continent. An important caveat regarding this analysis stems from the two datasets employed to measure urbanization. As detailed in the Data section, one dataset (Reba et al., 2016) provides a meaningful number of observations only every fifty years, while the other one (Klein Goldewijk et al., 2017) heavily relies on imputation based on strong functional form assumptions. Nevertheless, it is reassuring that both datasets yield essentially the same results.

In the last part of the article, we provide some suggestive evidence that the contribution of the chronometer to urbanization is likely to be, 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 was likely guiding the expansion of the British Empire, in the first decades of the nineteenth century, in Asia, Africa and Oceania.

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 led to massive shifts in the distribution of cities and urban population. 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. British colonization seems an important channel.

The estimated impact of the chronometer on urban population 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 more than a third 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 might explain approximately a fifth of the total increase in urban population outside of Europe. 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 urbanization rates are crude estimates and thus suboptimal. 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 urbanization 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.

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, (ii) the change in sailing times induced by the chronometer, and (ii) the impact of the latter change on the distribution of cities and population outside of Europe, and of European colonies across the globe. Section 5 relates our results with the previous literature. 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 one of the most pressing scientific dilemma of the day and an important driver in research efforts in astronomy, geometry, mathematics, and physics (Boistel, 2010). Some of the greatest minds of the European scientific establishment and mathematical practitioners including Galileo Galilei, Giovanni Cassini,[2] John Flamsteed, Edmund Halley,[3] Isaac Newton, Leonhard Euler, Johannes Kepler[4] (Vanpaemel, 1989; Withers, 2015; Perkins, 2020; de Grijs and Jacob, 2021) and all the major European courts promoted international endeavor for centuries through scientific patronage, the establishment of scientific societies, standing committees, schools and observatories, and longitude prizes (Higgitt, 2021).

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.[5] 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 routinized. Portuguese sailors would head down to Cape Verde Island (16° N), then swing out towards the coast of Brazil, and finally turn eastward when the latitude 35° S was reached.[6]

This way of navigating came with high costs. First, without knowing the longitude, sailors could miss islands and even continents and would be left not knowing whether their target destination lay to the east or to the west. The results were long voyages due to continual course corrections, leaving sailors vulnerable to the dreaded disease of scurvy, and frequent shipwrecks.[7] Second, following

[2] Galileo Galilei proposed to use the orbits of Jupiter's four moons as a universal clock to determine the longitude at sea. This method proved useful and accurate on land after Giovanni Cassini published the tables of Jupiter's moons.

[3] Both the Paris Observatory (founded in 1667) and the Royal Greenwich Observatory (founded in 1675) were established in pursuit of solving the longitude problem. John Flamsteed founded the Greenwich observatory under the King's instruction 'to apply himself with the most exact Care and Diligence to the rectifying the Tables of the Motions of the Heavens, and the places of the fixed Stars, so as to find out the so much desired Longitude of Places for perfecting the art of Navigation.' His successor was Edmond Halley.

[4] Isaac Newton was the main scientific advisor behind the first Longitude Act of 1714 and later a Commissioner of the Board of Longitude. Among the recipients of prizes offered by this Board for contributing to the solution of the longitude puzzle were mathematicians of the caliber of Johann Bernoulli, Leonhard Euler, Jesse Ramsden, and Michael Taylor, as well as some of the greatest astronomers of the time.

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

[6] 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).

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

lines of latitude means that ships could not take the most direct route (a great circle) or a route with more favorable winds and currents, further extending the length and duration of the voyage. Third, 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.[8] The compound loss of lives, ships and honor led to the famed Longitude Act of 1714, in which the British Parliament promised a princely reward to the person who could discover the means of finding the longitude. This was the last of a long list of prizes and rewards that, starting from the sixteenth century, were offered by all the major sea powers for the solution to the longitude puzzle.[9]

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.[10]

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 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.[11] 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".[12] 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) analyzes the logs of more than 580 voyages by the EIC in the period 1770–1792. In 1780, 52 percent of longitude entries were measured using the lunar method while the remainder relied on dead reckoning; the chronometer was still not available on any of the EIC vessels. The turning point for the use of the chronometer by the EIC was the last decade of the 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 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 is only in the

[8] 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).

[9] 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.

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

[11] Chronometers were capable of maintaining precise time even when sea conditions were not favorable 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).

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

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.[13]

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 h by up to 30 s.[14] The cumulative effect is that the local apparent time can lead or lag the local mean time by up to 15 min 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 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) 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. 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 revolutionized 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 Section 3.1) and on cloud coverage and sea-surface winds (Section 3.2). To study the impact of the chronometer on global urbanization and colonization patterns, we rely on data on urban population, population density, and colonial history (Section 3.3). Table 1 reports the summary statistics for these data.

[13] Unfortunately, no consistent data on the number of chronometers produced (by a country or a navy) exist. Meanwhile, we can show that the public attention to such a new technology featured the British press since the beginning of the century. We report in Figure A1 the count of the word "chronometer" found in the British historical newspapers available through the British Newspaper Archive. The positive trend in the mentions starts exactly at the turn of the century, and continues for decades. A similar pattern can be seen even when adjusting the trend for the increasing number of newspaper issued (published or included in the Archive) by deflating the mentions of chronometers with the count of an uncorrelated word such as "Monday".

[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).

Table 1
Summary statistics.

	Obs.	Mean	St. Dev.	Min	Max	Source	Unit of observation
Panel (a): Historical Navigation							
Ship speed (km/h)	228,369	7.68	3.97	1	18	CLIWOC 2.1	logbook entry
Number of crossings	119,647	1.96	4.28	0	185	CLIWOC 2.1	grid cell × decade
Actual sailing times (days)	724	39.49	41.96	2	254	Lloyd's List	port × decade
Clouds coverage (continuous [1-3] - data from Cliwoc)	9551	1.70	0.36	1	3	CLIWOC 2.1	grid cell (sea)
Clouds coverage (continuous [0-1] - data from NEO)	9551	0.58	0.15	0	1	NEO (NASA)	grid cell (sea)
Panel (b): Urbanization and Population							
Urban population 1750 (inhabitants) (urb. settl.=5,000 inhab.)	16,436	984.01	13,628.11	0	900,000	Reba et al. (2016)	grid cell (land)
Urban population 1900 (inhabitants) (urb. settl.=5,000 inhab.)	16,436	4,197.05	53,688.62	0	4,455,00	Reba et al. (2016)	grid cell (land)
Urban population 1750 (inhabitants) (urb. settl.=25,000 inhab.)	16,436	899.60	13,441.61	0	900,000	Reba et al. (2016)	grid cell (land)
Urban population 1900 (inhabitants) (urb. settl.=25,000 inhab.)	16,436	4,193.47	53,686.34	0	4,455,00	Reba et al. (2016)	grid cell (land)
Urban population 1750 (inhabitants)	16,436	2,613.42	24,623.88	0	1,488,598	HYDE 3.2	grid cell (land)
Population density 1750 (inhabitants/km sq.)	16,436	4.22	15.94	0	272	HYDE 3.2	grid cell (land)
Built-up area 1750 (built-up area in km sq.)	16,436	0.01	0.04	0	2	HYDE 3.2	grid cell (land)
Urban population 1900 (inhabitants)	16,436	13,702.30	66,165.89	0	2,427,498	HYDE 3.2	grid cell (land)
Population density 1900 (inhabitants/km sq.)	16,436	9.57	33.72	0	654	HYDE 3.2	grid cell (land)
Built-up area 1900 (built-up area in km sq.)	16,436	0.04	0.22	0	13	HYDE 3.2	grid cell (land)
Panel (c): Colonial history							
British colony in 1660	2976	0.01	0.10	0	1	Atlas of Colonialism	grid cell (coast)
British colony in 1754	2976	0.03	0.16	0	1	Atlas of Colonialism	grid cell (coast)
British colony in 1822	2976	0.21	0.41	0	1	Atlas of Colonialism	grid cell (coast)
British colony in 1885	2976	0.35	0.48	0	1	Atlas of Colonialism	grid cell (coast)
European colony in 1660	2976	0.09	0.29	0	1	Atlas of Colonialism	grid cell (coast)
European colony in 1754	2976	0.14	0.35	0	1	Atlas of Colonialism	grid cell (coast)
European colony in 1822	2976	0.34	0.47	0	1	Atlas of Colonialism	grid cell (coast)
European colony in 1885	2976	0.59	0.49	0	1	Atlas of Colonialism	grid cell (coast)

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

3.1. Historical navigation data

Information on historical navigation come from two different sources.

The first source is the Climatological Database for the World's Oceans (CLIWOC) 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 more than 4,800 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.

Fig. 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 A2, 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. Moreover, when the CLIWOC project was closed, while the Spanish logbooks had been almost entirely digitized, the majority of Dutch, British, and French logbooks had remained unexamined.[18] Throughout our empirical analysis, we show the robustness of our results, based on the CLIWOC data,

[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.

[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.

[18] The final report of the CLIWOC project specifies that: "The British, Dutch and Spanish sources have contributed equally to the database, each providing approximately 100,000 days of noon observations. French logbooks have also been used, but no other significant European sources exist for ocean voyages prior to 1850. The database will, however, continue to develop. Whilst the Spanish logbooks have been extensively studied, over 50 per cent of Dutch and over 90 per cent of British and French logbooks remain wholly unexamined. There are several thousand such items. They cover most of the oceanic areas and embrace the CLIWOC period and earlier times as far back as the mid-seventeenth century".

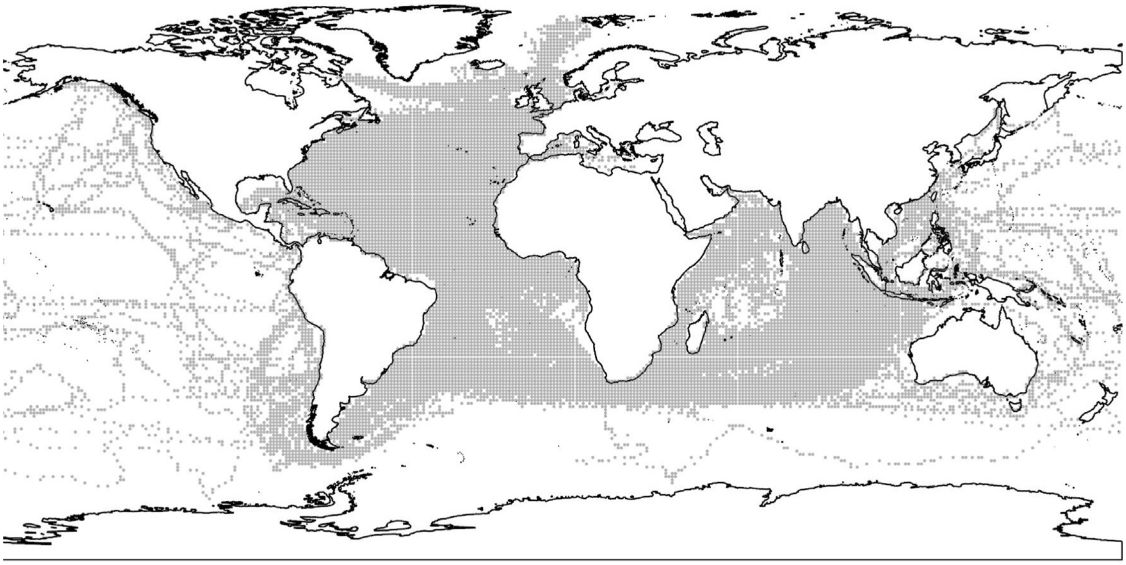


Fig. 2. CLIWOC spatial distribution.
Notes: The unit of observation is a $1^\circ \times 1^\circ$ grid cell and the sample includes grid cells available in the entire CLIWOC dataset.

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 two outcome variables in Section 4.1: daily sailing speeds and navigation routes. Sailing speeds are computed by dividing the distance between two consecutive logbook entries by the days elapsed between entries. We exclude observations in which the resulting speed is unrealistically high (above the 99th percentile) or low (below the 1st percentile), and voyages with less than five logbook entries. 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 1 report summary statistics for these two variables: on average, sailing speed is 7.68 km 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 studied, 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 A3 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 disproportionately 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.[19]

The second source of information on historical navigation is the Lloyd's List, a daily London-based publication that printed the most up-to-date shipping information for ports world-wide. We digitize daily issues of the magazine every five years between 1770 and 1845. However, as information becomes richer from 1810 onwards, we digitized issues for each month up until 1805 and only for May from 1810 onwards, in an attempt to keep the panel roughly balanced.[20] For every issue of the Lloyd's List and every non-British port in the issue, we digitized the latest date of ship movements in the port and the date of publication of the issue. We then compute the difference in the number of days between these two dates for every port in every issue and subtract one.[21] Juhász and Steinwender (2018) use this value as a measure of the "information lag", the time it takes for news from each port to reach London. We then calculate, for each decade from 1770s to 1840s, the minimum information lag for each port across all the issues of the Lloyd's List that we have digitized for that decade. This value corresponds to the minimum sailing time between foreign ports and Great Britain in each decade under the assumptions that (1) ships were the fastest way for news to travel from these ports to

[19] The reason for which we continue to observe dead reckoning observations throughout the second half of the nineteenth century is presumably because calculating the longitude using the chronometer requires two readings of the chronometer (one at sunrise and one at noon) and a dead-reckoning measure to infer the distance sailed between these two observations.

[20] Only a handful of data points are available for the years before 1770. Data are available at https://www.maritimearchives.co.uk/lloyds-list.html and https://www.uspcs.org/resource-center/research-projects/lloyds-list-newspapers-2/

[21] We subtract one day to account for the time lost in the publication process.

Great Britain until the 1840s, and (2) there was at least one direct voyage between these ports and Great Britain in the decade. Both hypotheses are realistic: the telegraph was not in use yet and the ports in our sample were all relatively large and well-connected to Europe.

We exclude from the sample those ports for which navigation to England would take less than two days (including all Irish ports and ports facing the British Channel): as we have seen in the Historical Background section, the chronometer was useless for voyages lasting less than two days (the first day is possible to infer the longitude from the port of origin, while the second day, it is necessary to wait for the noon observation of the sun to be able to infer the longitude using the chronometer).[22] We end up with a dataset comprising 367 foreign ports (see Figure A4) and 724 observations at the port×decade level. Summary statistics for this variable are shown in row 3 of Table 1. Figure A5 depicts the distribution of voyage durations in the eighteenth and nineteenth centuries separately, illustrating a reduction in the median route length alongside the emergence of some long routes in the right tail.

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).[23] 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 is 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 homogeneous 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.[24] 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.[25] Fourth, we take the grid averages of these values to obtain a single numeric value for each cell.

Fig. 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. Figure A6 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 4–5 of panel (a), Table 1.

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 Figure A7, 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).[26]

22 We exclude, therefore, the Belgian ports, the port of Bailiwick of Guernsey and the following French ports: Abbeville, Boulogne, Caen, Calais, Cherbourg-en-Cotentin, Dieppe, Dunkirk, Fécamp, Granville, Le Havre, Honfleur, Le Légué, Morlaix, Quilleboeuf, Rouen, Saint-Malo, Saint-Valery-sur-Somme, Tréport. We also exclude all ports that we could not geolocate.

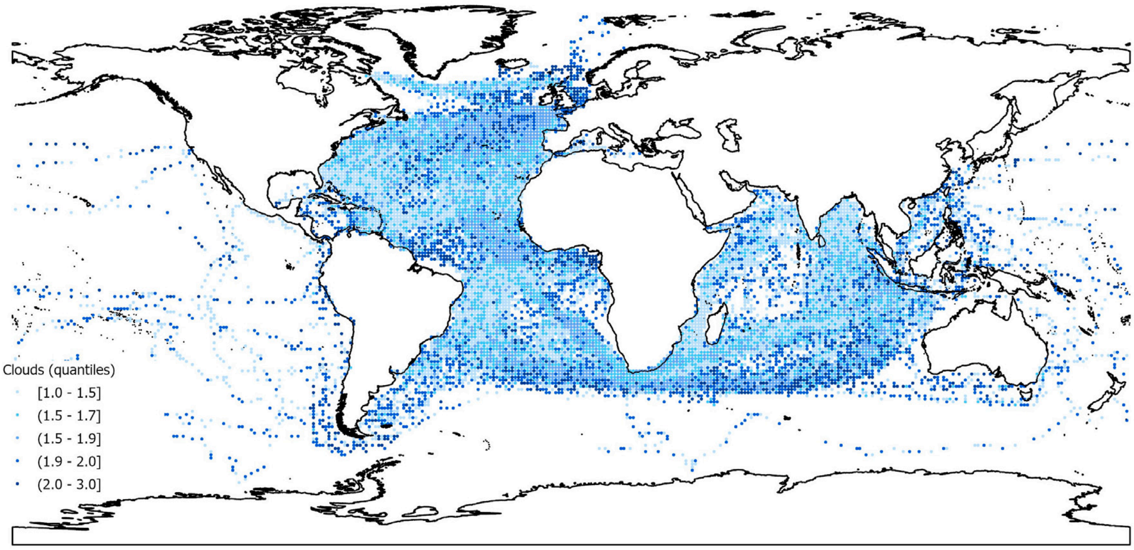
23 Data source: https://neo.gsfc.nasa.gov

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

25 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.

26 Specifically, we use average monthly data in May and January for the years between 2000 and 2002. Data source: http://woce.nodc.noaa.gov/woce v3/wocedata 2/sat mwf/sat mwf2/.

(a) Average cloud coverage using CLIWOC



(b) Average cloud coverage using NEO

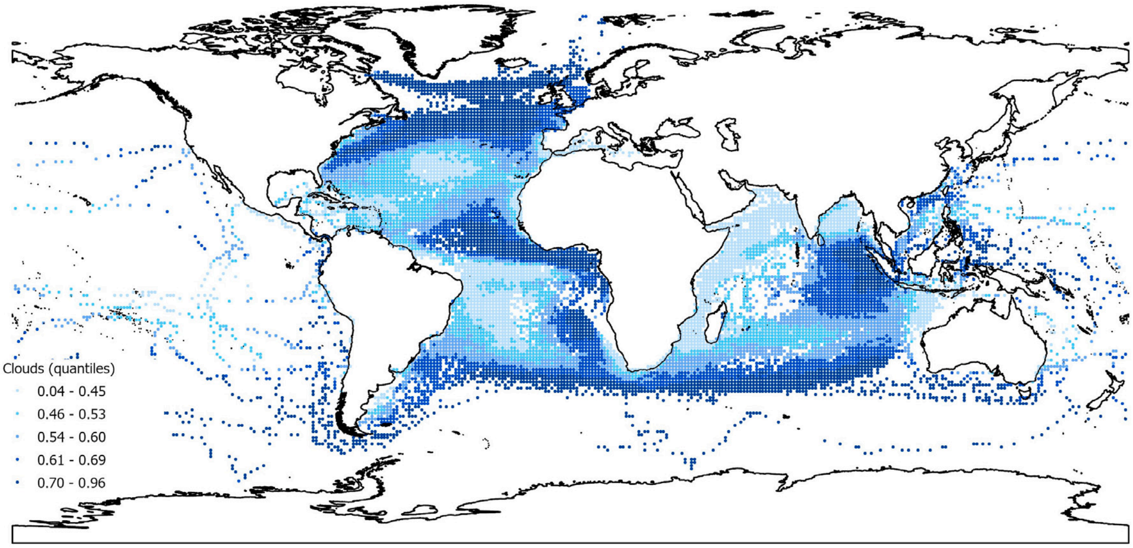


Fig. 3. Cloud coverage.
Notes: Panel (a) displays average cloud coverage distribution, in five quantiles, constructed using data from CLIWOC and following the procedure described in Section 3.2. Panel (b) shows average coverage distribution, in five quantiles, with contemporary cloud data provided by NASA Earth Observations, also described in Section 3.2. The unit of observation is a $1^\circ \times 1^\circ$ grid cell and the sample includes grid cells available in the entire CLIWOC dataset.

3.3. Data on urbanization, population and colonial history

We rely on two alternative, readily available datasets to construct measures of urbanization rates in the 18th and 19th centuries. Unfortunately, each of these datasets is far from perfect.

The first dataset is provided by Reba et al. (2016). It is an unbalanced panel, combining annual information on the population of geocoded settlements, originally collected by Chandler (1987) and Modelski (2003). Appendix Figure A8 shows the number of recorded entries in each decade from 1750 to 1900. As can be seen, the vast majority of entries are concentrated in the years 1750, 1800, 1850, and 1900, while only a handful of entries are available for the years in between. For each settlement in the dataset, we use linear interpolation to fill the gaps and then keep the population estimates every half century from 1750 to 1900. We apply two thresholds to define a city: 5,000 and 25,000 inhabitants. We then aggregate urban population, calculated based on these two thresholds, at the level of each 1° x 1° grid cell. The first four rows of panel (b) of Table 1 report summary statistics relative to these variables.

In robustness checks, we also use data on urbanization and population density from HYDE 3.2 (History Database of the Global Environment, Klein Goldewijk et al., 2017), a database originally compiled to reconstruct historical land use and providing information with a spatial resolution of 5 arc minutes (approximately 85 square km at the equator) every decade.[27] This dataset is constructed using various sources, including Lahmeyer (2004), Helders (2005), and Tobler (1995), as well as local studies. Still, the vast majority of data points are essentially educated guesses based on interpolation, back projection, and a series of strong functional assumptions and calibration procedures (see Guinnane, 2023, for a thorough review). All results based on these data should be interpreted with extreme caution. We downloaded the data for each decade between 1750 and 1900 on urban population, population density (inhabitants/km^2), and built-up area (built-up area in km^2). We then aggregate these variables within a one-degree latitude-by-longitude cell. The last six rows of panel (b) of Table 1 report summary statistics for these variables.

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 system.[28] We download every map available for the years between 1660 and 1885 (i.e., for the years: 1660, 1754, 1822 and 1885).[29] 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 1. 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 analyzes data from CLIWOC, a database of historical sailing books, and describes the impact of the chronometer on navigation. It documents that, starting from the nineteenth century, this new technology not only increased the speed of sailing vessels but it did it in an asymmetric way across different portions of the Oceans, depending on the prevailing weather conditions; in turn, this led to a change in the prevailing sailing routes of the time.

The second subsection shows precisely how the chronometer reshaped the geography of the world. Using the estimates from the first subsection on the change in sailing speeds induced by the chronometer under different weather conditions, it develops a route optimization algorithm, which produces the optimal routes and sailing times between Europe and the rest of the world, with and without the chronometer technology to infer the longitude at sea. It then validates this algorithm against data on sailing times across different ports inferred from the Lloyd's List, a daily publication with shipping information covering the main ports of the period.

Finally, the third subsection studies the impact of this change in geography induced by the chronometer on urbanization. It argues that those coastal regions that became relatively more accessible to Europe, because of the chronometer, experienced a relatively larger increase in urbanization rates. A (rather imperfect) back-of-the-envelope calculation suggests a major role of the chronometer in fostering urbanization rates outside of Europe throughout the nineteenth century. It concludes by showing that the British expansion, as facilitated by the chronometer, is likely an important channel to explain these results.

4.1. Navigation and the chronometer

4.1.1. The impact of the chronometer on sailing speed

How did the chronometer change navigation? We start by analyzing one of the most relevant aspects: sailing speed. The main data source is the CLIWOC dataset, which provides historical daily information on both the position of several thousands of British, French, Dutch and Spanish ships and the conditions of the sky, 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:

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

27 https://themasites.pbl.nl/tridion/en/themasites/hyde/index.html

28 https://commons.wikimedia.org/wiki/Atlas_of_colonialism

29 Figure A9 shows European colonization in Africa, Asia and Oceania for the relevant years in our analysis.

Table 2
Chronometer and speed: difference-in-differences.

	Dependent variable: ln(speed)						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Clouds × Post	0.182	0.495	0.058	0.055	0.043	0.043	0.029
	(0.038)***	(0.067)***	(0.023)**	(0.021)***	(0.021)**	(0.019)**	(0.012)**
	[0.021]***	[0.057]***	[0.017]***	[0.017]***	[0.016]***	[0.016]***	[0.012]**
	{0.054}***	{0.235}**	{0.021}***	{0.020}***	{0.019}**	{0.018}**	{0.013}**
Clouds	−0.121	−0.338					−0.025
	(0.031)***	(0.059)***					(0.010)***
	[0.015]***	[0.039]***					[0.009]***
	{0.041}***	{0.138}***					{0.010}**
Post	0.278	−0.005					
	(0.007)***	(0.041)					
	[0.008]***	[0.035]					
	{0.028}***	{0.134}					
Observations	225 033	225 033	225 033	225 033	225 033	225 033	173 827
Clouds source	CLIWOC	NEO	CLIWOC	CLIWOC	CLIWOC	CLIWOC	CLIWOC
Grid cell FE			Y	Y	Y	Y	Y
Decade FE			Y	Y	Y	Y	Y
Latitude × Post				Y	Y	Y	
Wind × Post				Y	Y	Y	
Nationality FE × Post					Y	Y	
Ship FE						Y	
Grid cell × Decade 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 kilometers 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 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 favor, semi-in favor), 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 kilometers in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

where e, s, i and t index respectively the entry in CLIWOC, the ship in the observation, the $1^\circ\ x\ 1^\circ$ 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.[30]

The results of these regressions are shown in Table 2. 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 the order of 63 percent (49 log-points).

In both columns, the difference-in-difference coefficient is estimated to be statistically significant. Specifically, Table 2 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 kilometers when presenting the Conley standard errors. The choice of this cutoff is explained by Figure A10, which shows the Conley standard errors of the difference-in-difference coefficient in the benchmark specification, using variable cutoffs ranging from 100 kilometers to 1,000 kilometers. As can be seen, from around 800 kilometers, additional increases in cutoffs do not produce any significant increase in the magnitude of standard errors.

[30] 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 kilometers, 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 kilometers.

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 Section 4.1.2). 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; 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.[31]

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 2, we control for the nationality of the ship interacted with the *post* fixed effect: results are practically unaffected. In column 6 of Table 2 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.

In the last column of Table 2, rather than considering the overall average cloud coverage of the cell, we consider the monthly average cloud coverage and exploit its within-year variation. We limit our analysis to cells for which we have CLIWOC observations for at least two different months and add grid cell by decade fixed effects. The estimated difference-in-difference coefficient is approximately half of the benchmark results in column 3, but still statistically significant.

Overall, the results in Table 2 suggest large impacts of the chronometer on sailing speed and do not seem to be driven by other contemporaneous technological developments, nor by changes in the composition of ships or in the sailing routes in the CLIWOC dataset. Still, a causal interpretation would be misleading as we cannot rule out other unobservables driving the relative increase in speed under 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 3 presents the estimates from the following triple-difference specification:

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

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

The estimate of the triple-difference coefficient (μ in Eq. (2)) in Table 3 indicates that, the increase in speed under a cloudy sky after 1800 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:

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

The estimated coefficients (μ_t in Eq. (3)) are plotted in Fig. 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 is 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 increase 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.

[31] Specifically, we control for the direction of the wind with respect to ship trajectory and define wind as in favor, semi-favor, 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°.

Table 3
Chronometer and speed: triple-difference.

	Dependent variable: ln(speed)					
	(1)	(2)	(3)	(4)	(5)	(6)
Clouds × Post × Open sea	0.402	0.562	0.356	0.417	0.407	0.391
	(0.192)**	(0.272)**	(0.243)	(0.238)*	(0.226)*	(0.242)
	[0.169]**	[0.197]***	[0.185]*	[0.198]**	[0.185]**	[0.209]*
	{0.190}**	{0.317}*	{0.166}**	{0.185}**	{0.170}**	{0.197}**
Clouds × Post	−0.220	−0.067	−0.298	−0.361	−0.364	−0.348
	(0.188)	(0.263)	(0.242)	(0.237)	(0.225)	(0.241)
	[0.169]	[0.191]	[0.184]	[0.197]*	[0.185]**	[0.208]*
	{0.182}	{0.218}	{0.165}*	{0.185}*	{0.169}**	{0.197}*
Post × Open sea	0.102	−0.195	0.015	0.075		
	(0.059)*	(0.138)	(0.051)	(0.131)		
	[0.033]***	[0.095]**	[0.038]	[0.136]		
	{0.056}*	{0.162}	{0.040}	{0.153}		
Clouds × Open sea	−0.013	−0.170				
	(0.156)	(0.189)				
	[0.134]	[0.145]				
	{0.141}	{0.226}				
Post	0.176	0.190				
	(0.059)***	(0.132)				
	[0.033]***	[0.091]**				
	{0.055}***	{0.098}*				
Open sea	0.426	0.541				
	(0.041)***	(0.090)***				
	[0.025]***	[0.070]***				
	{0.042}***	{0.109}***				
Clouds	−0.108	−0.168				
	(0.153)	(0.180)				
	[0.133]	[0.142]				
	{0.137}	{0.173}				
Observations	228 369	228 369	228 369	228 369	228 369	228 369
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 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 kilometers 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 favor, semi-in favor), 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 kilometers in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

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 is unlikely that seamen would confuse (extremely) fast with (extremely) slow sailing.

Table A2 replicates the estimates reported in Table 3 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 3. 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

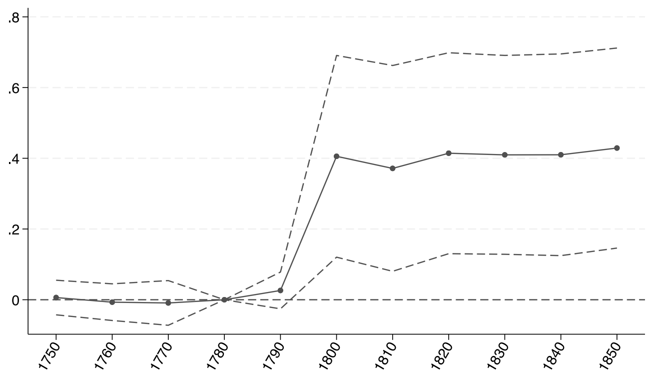


Fig. 4. Chronometer and speed: pre-trends.
Notes: Estimated coefficients from the regression $ln(speed)_{esit} = \sum_{t=1750}^{1850} \mu_t(clouds_i \times open\ sea_i) + \beta_1(open\ sea_i \times post_t) + \beta_2(clouds_i \times post_t) + \gamma X_{esit} + \delta_i + \delta_t + \epsilon_{esit}$ where 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 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 kilometers 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, wind force (one per each wind direction with respect to ship trajectory — against, semi-against, in favor, semi-in favor), 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 kilometers.

disproportionately 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.

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 world-wide.

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:

$$crossings_{it} = \alpha(clouds_i \times post_t) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it} \tag{4}$$

where $crossings_{it}$ denotes the frequency at which $1^\circ\ x\ 1^\circ$ 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.[32]

Regression results are reported in Table A3. 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 crossings 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 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 the following column, we repeat the same analysis using the NEO data (rather than the CLIWOC ones) to capture global cloud coverage. In this case, the point estimate for α is slightly noisier (the NEO data refers to contemporary weather conditions) but confirms the finding of the first column. In column 3, 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. The same conclusion applies for column 4 when we also control for ships' nationality.

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 column of Table A3 reports the estimates from the following triple-difference specification:

$$crossings_{it} = \mu(clouds_i \times post_t \times open\ sea_i) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it} \tag{5}$$

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

The estimates of the triple-difference coefficient μ in Table A3 indicate that the relative increase in crossings of cells with heavy cloud coverage, as compared to clear cells, is disproportionately 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:

$$crossings_{it} = \sum_{t=1750}^{1850} \mu_t(clouds_i \times open\ sea_i) + \beta_1(open\ sea_i \times post_t) + \beta_2(clouds_i \times post_t) + \gamma X_{it} + \delta_i + \delta_t + \epsilon_{it} \tag{6}$$

The estimated μ_t coefficients are plotted in Figure A11. Starting from the 1810s, we observe a disproportional relative increase in the number of passages 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 Eq. (6) also allows us to check that our findings are not driven by pre-trends. In fact, with one exception, estimated coefficients before 1810 are substantially smaller compared to those for the decades of the nineteenth century.[33]

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 as the chronometer. To confirm that the chronometer is indeed the main driver of these results, we exploit the fact that offshore navigation under a cloudy sky is relatively less dependent on the chronometer when sailing along a parallel. As explained in the Historical Background section, before solving the longitude puzzle, sailors would cross overcast portions of the oceans by navigating along the coast until reaching the latitude of their destination and then following a line of constant latitude in the open sea until reaching destination. We should expect, therefore, the invention of the chronometer to reduce the need to sail in parallel under an overcast sky, allowing sailors to take the most direct route to their destination.

In Table 4, we show that this is indeed the case. We re-estimate Eq. (4), except that the dependent variable is not the total number of crossings but either the number of parallel crossings (panel (a)) or the number of non-parallel crossings (panel (b)) in grid cell i in the decade t. In the benchmark estimates, we define a parallel crossing as a logbook entry in a certain cell, followed by another entry on the same parallel. The results shows that, following the invention of the chronometer, there was a large relative increase in the number of non-parallel crossings under overcast skies compared to clear skies. The relative increase of crossing under overcast skies is instead modest and barely statistically significant for parallel crossings. These results are robust to a battery of robustness checks, such as using a Poisson estimator (column 2), including the usual set of control variables, wind patterns, latitude and ship nationality (column 3), using the modern NEO data for clouds coverage (columns 4 and 5), and using different definitions of parallel navigation (Table A4).[34]

These results are not driven by pre-trends. To show this, we allow the impact of cloud coverage to be different in each decade. We take the 1780s as the omitted decade and plot the estimated coefficients in Figure A12 separately for non-parallel crossings and parallel crossings.

The combination of the estimates illustrated in the whole Section 4.1 shows that (1) the chronometer disproportionately increased sailing speed when sailing offshore under a cloudy sky, and through this channel (2) changed the prevailing transoceanic routes connecting Europe to the rest of the world. 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 a new geography of the world

As discussed in the previous subsection, the chronometer reduced sailing speeds and affected sailing routes, in an asymmetric way across different Oceanic regions. In this subsection, we investigate how these changes not only led the non-European world closer to Europe, but also did so unevenly, with some regions becoming significantly closer than others. We proceed in two steps. In Section 4.2.1, we illustrate how we use a route optimization algorithm to derive sailing times between Europe and the rest of the world with and without the chronometer technology, while in Section 4.2.2 we validate these predicted optimal sailing times comparing them with the duration of actual sailing voyages derived from the Lloyd's dataset.

33 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.

34 Table A4 replicates the results in columns 1 and 4 of Table 4 using different definitions of parallel navigation. Specifically, in Table 4 we consider that a ship is sailing on a parallel if we observe two subsequent entries of its position in the logbooks that form an angle of 270 degrees (navigating fully westward) or 90 degrees (navigating fully eastward) allowing for a buffer of ± 0.5 degrees. Table A4 shows that results are rather robust with cutoffs from ± 0.25 to ± 1 degree, independently on whether we use CLIWOC or NEO data for cloud coverage.

Table 4
Chronometer and parallel sailing: difference-in-differences.

	Panel (a): Dependent variable: number of parallel crossings				
	(1)	(2)	(3)	(4)	(5)
Clouds × Post	0.017	0.253	0.006	0.036	0.070
	(0.010)	(0.210)	(0.011)	(0.021)*	(0.030)**
	{0.009}*		{0.009}	{0.025}	{0.033}**
	Panel (b): Dependent variable: number of non-parallel crossings				
	(1)	(2)	(3)	(4)	(5)
Clouds × Post	0.661	0.231	0.353	0.322	0.472
	(0.094)***	(0.072)***	(0.081)***	(0.168)*	(0.211)**
	{0.133}***		{0.105}***	{0.527}	{0.553}
Observations	118 492	118 492	118 492	118 492	118 492
Estimation	OLS	Poisson	OLS	OLS	OLS
Clouds source	CLIWOC	CLIWOC	CLIWOC	NEO	NEO
Grid cell FE	Y	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y	Y
Latitude × Post			Y		Y
Wind × Post			Y		Y
Nationality			Y		Y

Notes: Table reports OLS estimates in columns 1, 3–5, and Poisson estimates in column 2. Unit of observation is a grid cell-by-decade. Sample refers to offshore navigation thus including all $1^\circ \times 1^\circ$ grid cells at least 5 kilometers away from the coastline. Dependent variable is the number of crossings of a grid cell in a decade that are made following a parallel line in panel (a) and not following a parallel line in panel (b), 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 Section 3.2, except for columns 4 and 5 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* is wind speed, interacted with *Post*; *Nationality* are controls for the share of different nationalities crossing a grid cell per decade. Standard errors clustered at the grid cell level in parentheses in columns 1, 3, 4 and 5, robust standard errors in parentheses in column 2, and corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometers in curly brackets. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

4.2.1. Predicted optimal sailing times

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.[35] 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 Eq. (2) which we report in Table 3. 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 shortest predicted optimal sailing time for a round trip from each non-European coastal cell to either Great Britain[36] or the entire Europe[37] when using either the lunar method or the chronometer and in the months of

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

[36] Specifically, we consider the grid cell (latitude=50.5 to 51.5; longitude=−4.5 to −5.5), which lies close to Portsmouth, Plymouth and Cork.

[37] We consider the closest European port, listed in the Lloyd's List at least 15 times in May 1845 (the last month for which we collected data in the Lloyd's List).

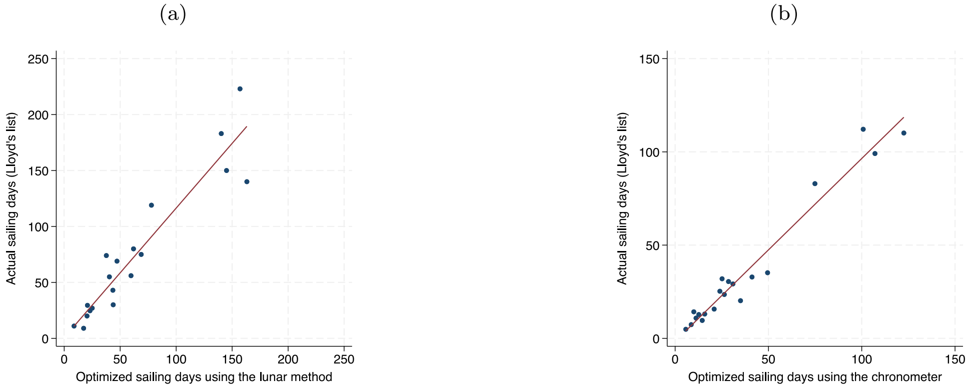


Fig. 5. Sailing times from Lloyd's List vs. predicted optimal sailing times.
Notes: Figure shows binscatters comparing Lloyd's List sailing times in the years 1770–1790 and predicted optimal sailing times using the lunar method in panel (a), and comparing Lloyd's List sailing times in the years 1830–1845 and predicted optimal sailing times using the chronometer in panel (b).

either May or January (we exclude the coast of Antarctica and the Mediterranean coast of Africa from these calculations).[38] Notice that the algorithm is far from being ideal. For instance, it does not consider inaccurate maps and safety concerns (due to dangerous rocks along the coast that could increase the probability of shipwrecks) when calculating optimized routes.

Table A5 reports summary statistics. For instance, in the month of May, the average predicted optimal sailing time to Great Britain 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 A13. For instance, there are large relative effects on European routes towards South East India and Ceylon, which lie under a generally cloudy sky (see Fig. 3), while the chronometer had substantially less impact on the sailing routes towards West India and neighboring Pakistan, a region where the Indian Ocean lays under mostly clear skies and lunar navigation was possible.

4.2.2. Predicted optimal sailing times versus real sailing times

How well can these predicted optimal sailing times predict the actual sailing times of the eighteenth and nineteenth century? To address this question, we proceed in two steps.

First, as described in the Data section, we derive from the Lloyd's List the actual sailing times (expressed in number of days) from the most relevant non-British ports to Great Britain in each decade from the 1770s until the 1840s. Fig. 5 compares the sailing times derived from the Lloyd's List to the predicted optimal sailing times using the contemporaneous technology for finding the longitude at sea. Panel (a) compares sailing times in the years 1770–1790 to predicted optimal sailing times under the lunar method, while panel (b) compares sailing times in the years 1830–1845 to predicted optimal sailing times using the chronometer.[39] As can be seen, in both cases, the correlation between actual sailing times and predicted optimal sailing times is close to one.[40]

Second, we estimate the following equation:

$$ln(SailingTime_{it}) = \sum_{t=1770}^{1840} \alpha_t(\ln(lunar_i) - ln(chrono_i)) + \eta_i + \eta_t + \gamma X_{it} + \epsilon_{it} \quad (7)$$

where the dependent variable is the log of the actual sailing times in the Lloyd's List while the main regressor is the log-change in the optimized sailing times induced by the chronometer, as predicted by our optimizing algorithm. We allow the coefficients on this regressor 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 unit of observation is a non-British port i in a decade t and η_i and η_t are respectively the port and decade fixed effects. X_{it} includes additional controls. In particular, we control for continent linear trends and the month in which the actual sailing times are captured. The latter is an important control as we digitized data from the Lloyd's List in every month until 1810 and, only for the month of May, thereafter. Fig. 6 shows the results of this exercise: the routes that are predicted to have the most significant reduction in sailing times following the invention of the chronometer according to our optimization algorithm were also the routes that experienced the largest reduction in actual sailing times. As can be noticed, this result is not driven by pre-trends.

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

[39] Predicted optimal sailing times are here calculated as the average time required to move between two ports in both directions.

[40] Figure A14 repeats the same exercise excluding the Southern European Mediterranean ports. This is an important robustness check as information could travel from Southern Europe to Northern Europe (reaching eventually London) through faster means than sailing ships.

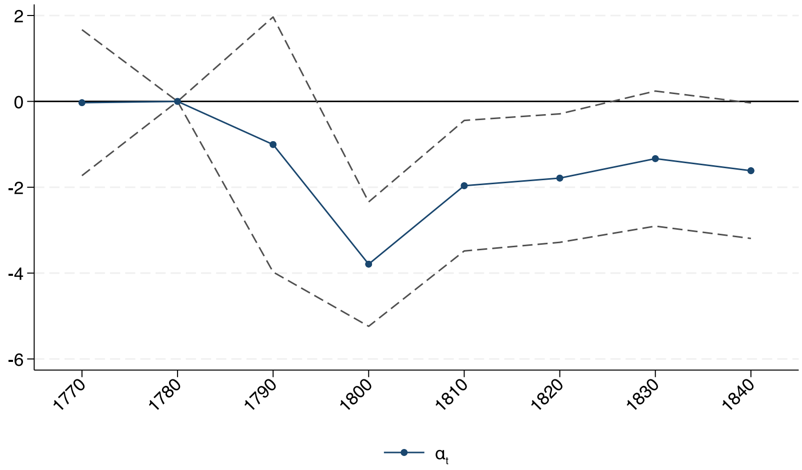


Fig. 6. Actual vs. predicted optimal sailing times.
Notes: Estimated coefficients from regression (7) where the omitted decade is the 1780s. Bars indicate 90 percent confidence intervals, with standard errors corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometers.

4.3. 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 quadrupling and moving towards the coast. The aim of this subsection is understanding the role of the chronometer in explaining these phenomena. Specifically, we show how the changes in sailing distances between Europe and the rest of the world (derived in Section 4.2.1) can explain the shifts in urban population outside of Europe using both descriptive evidence 4.3.1 and a difference-in-differences approach 4.3.2. We conclude looking at a potential channel for these results: the expansion of the British Empire 4.3.3.

4.3.1. Descriptive evidence

Our main data source for historical demographic information is the dataset provided by Reba et al. (2016), which contains annual information on the population of geocoded settlements world-wide. For our analysis, we use linear interpolation to fill gaps between missing years and then keep the population estimates every half century from 1750 to 1900. We apply two thresholds to define a city: 5,000 and 25,000 inhabitants. We then aggregate urban population, calculated based on these two thresholds, at the level of each 1° x 1° grid cell, focusing on regions outside Europe. Finally, we match each of these grid cells to the predicted optimal sailing time from its nearest coastal cell to Europe using either the chronometer or the lunar method. Specifically, in our benchmark analysis we consider the duration of a round trip to the busiest grid cell in the CLIWOC dataset, which essentially captures the English Channel and the Celtic Sea (latitude=50.5 to 51.5; longitude=−4.5 to −5.5), in the month of May. For robustness checks, we also use data on urbanization and population density from HYDE 3.2 (History Database of the Global Environment, by Klein Goldewijk et al. (2017)).

Fig. 7 shows decile-binscatter correlations between the reduction in predicted optimal sailing times of a round trip to Europe due to the use of the chronometer and the increase in urban population between 1750 and 1900. 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.[41] In coastal regions a strong positive correlation emerges: places that got closer to Europe thanks to the chronometer experienced larger relative changes in urbanization and population density. For instance, in panel (a), the average increase in urban population between 1750 and 1900 was about 20 percentage points in coastal grid cells that were in the top decile in terms of percentage reductions in sailing times to Europe, compared to around 4 percentage points in coastal grid cells that were in the bottom decile. Changes in sailing distances to Europe do not seem to affect inland regions (right panels of Fig. 7), which suggests that changes in urbanization and population density on the coast did not come at the expenses of inland territories. This positive correlation is robust to using the two different thresholds we adopt to define a city in the Reba et al. (2016)'s dataset, i.e. 5,000 (panel (a)) and 25,000 (panel (b)) inhabitants, and to using the data on urban population from the HYDE dataset (panel (c)).

Which regions of the world drive these correlations? Fig. 8 displays two world maps showing the geographic distribution of the reductions in predicted optimal sailing times of a return trip from Europe, made possible by the chronometer, and the changes in urbanization along the corresponding coast. Reductions in sailing times are expressed in quintiles, where darker colors indicate larger changes. In panel (a) urbanization information is provided in the form of two snapshots: settlements already existing in 1750

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

(light blue triangles) and those present by 1900 (dark blue circles). The coastal regions of the non-European world that experienced the largest number of new settlements in the years between 1750 and 1900, when the transition to the chronometer was certainly completed, match those that became relatively closer to Europe (e.g., the east and north-western coasts of North America, the north-east coast of South America, the south-east coast of Australia, New Zealand, and the coasts of China and Japan). These qualitative results hold if we use the HYDE 3.2 dataset to capture urbanization rates (see panel (b)).[42]

4.3.2. Difference-in-difference analysis

To test the causal impact of the chronometer on urban development outside of Europe, we estimate the following difference-in-differences approach:

$$Y_{it} = \sum_{t} \alpha_t [\ln(lunar_i) - ln(chrono_i)] + \eta_i + \eta_t + \gamma X_{it} + \epsilon_{it} \tag{8}$$

where i indexes a 1° x 1° grid cell, and t denotes four years: 1750, 1800, 1850 and 1900. Y_{it} captures urbanization intensity and is measured in two different ways: either as an extensive margin: a dummy for grid cells with urban population above a certain threshold (5,000 and 25,000 inhabitants); or as an intensive margin: the log of one plus urban population. η_i and η_t are grid cell and year fixed effects, X_{it} is a vector of continent linear trends to capture potentially different (linear) continental trajectories in urbanization. The main regressor is the log reduction in the predicted optimal sailing time (expressed in days), induced by the advent of the chronometer, on a return trip from Europe to cell i. We allow the coefficient on this regressor to vary over time (the omitted year is 1750).

The upper panel of Table 5 reports the estimated α_t coefficients from Eq. (8) on the sample of coastal grid cells. The first two columns use the extensive margin of urbanization as outcome variable, while the second two exploit the intensive margin, adopting 5,000 (columns 1 and 3) and 25,000 (columns 2 and 4) inhabitants as thresholds to define a city. All four columns show consistently similar effects. The correlation between the reduction in predicted optimal sailing times and urbanization is positive starting from 1800 and it becomes large and statistically significant from 1850. Interpreting the coefficients in the last column 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 1.7 percent by the mid-nineteenth century, and of 4.7 percent by 1900.[43]

The results in the upper panel of Table 5 are robust to a list of checks.

First, the sailing times used so far consider the duration of a round trip to the busiest European grid cell in Europe, which captures essentially British ports. In Table A6, we show that results are consistent if we consider a round trip to the large ports of other European colonial powers (France, Netherlands, Portugal, Spain or Germany) or to the closest large European port.[44]

Second, the estimated coefficients on the changes in sailing times are robust when considering predicted optimal 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 5 used predicted optimal sailing times for the month of May, Table A7 uses the predicted optimal sailing times for the month of January. Results are remarkably similar.

Third, we show that results are not driven by any specific continent. In Table A8 we remove one by one all continents from the sample and re-estimate the all specifications of Table 5. The results on urbanization rates are robust to this exercise with the estimated coefficients' sizes being very similar to the results illustrated in Table 5.

Fourth, we show that results are robust to different calibrations of the optimal route algorithm. In particular, in Table A9, we use two alternative calibrations of the relative increase in speed induced by the chronometer in a cloudy sky as compared to a clear sky. The first calibration uses the estimates from the sailing speed difference-in-difference regression reported in Table 2, while the second calibration uses the estimates from the triple-difference regression reported in Table 3.

Did the urbanization of coastal regions, induced by the chronometer, come at the expense of inland development? The estimates in the bottom panel of Table 5 are an attempt to address this question. When limiting the analysis to hinterland regions, we find that,

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[42] We refer to Appendix Figure A15 for similar figures using HYDE's population density and built-up area measures. Similarly to the map in panel (c) of Fig. 8, 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 A16 reports additional maps similar to those in Fig. 8 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 world-wide development of coastal cities and population.

[43] An alternative way to look at this process of urbanization is to measure the outcome variable in terms of growth rates rather than levels. Doing so could reconcile the finding of a level effect of the chronometer on sailing speed (Fig. 4) with the almost exponential urban population growth in coastal location shown in Fig. 1. We approach this exercise by making two choices. First, we turn to the urbanization data provided by Klein Goldewijk et al. (2017), as we can explore the relationship in question at a higher temporal frequency, i.e. every decade. Second, we restrict the time period sample to the one for which we have data when producing Fig. 4 (1750s till 1850s). The estimated coefficients are shown in Figure A17, where the omitted category is the growth rate of urban population between 1780 and 1790 (in the figure labeled as year 1790), to reflect the fact that for the estimated regression coefficients plotted in Fig. 4 the omitted decade was the 1780s. Consistently with (i) the spur in speed under cloud coverage shown in Fig. 4 starting in the decade 1800–1810, and (ii) the synchronized upward trajectory of urban population density shown in Fig. 1, we find positive statistically significant coefficients on urban population growth rates starting in 1800, almost continuously constant throughout the sample period, and importantly no pre-trends for the decades prior to 1790.

[44] To obtain a list of the largest port of the nineteenth century in each European country, we make use once again of the shipping news contained in the Lloyd's List newspapers, and we consider those ports that are listed at least 15 times in May 1845 (the last month for which we collected data in the Lloyd's List).

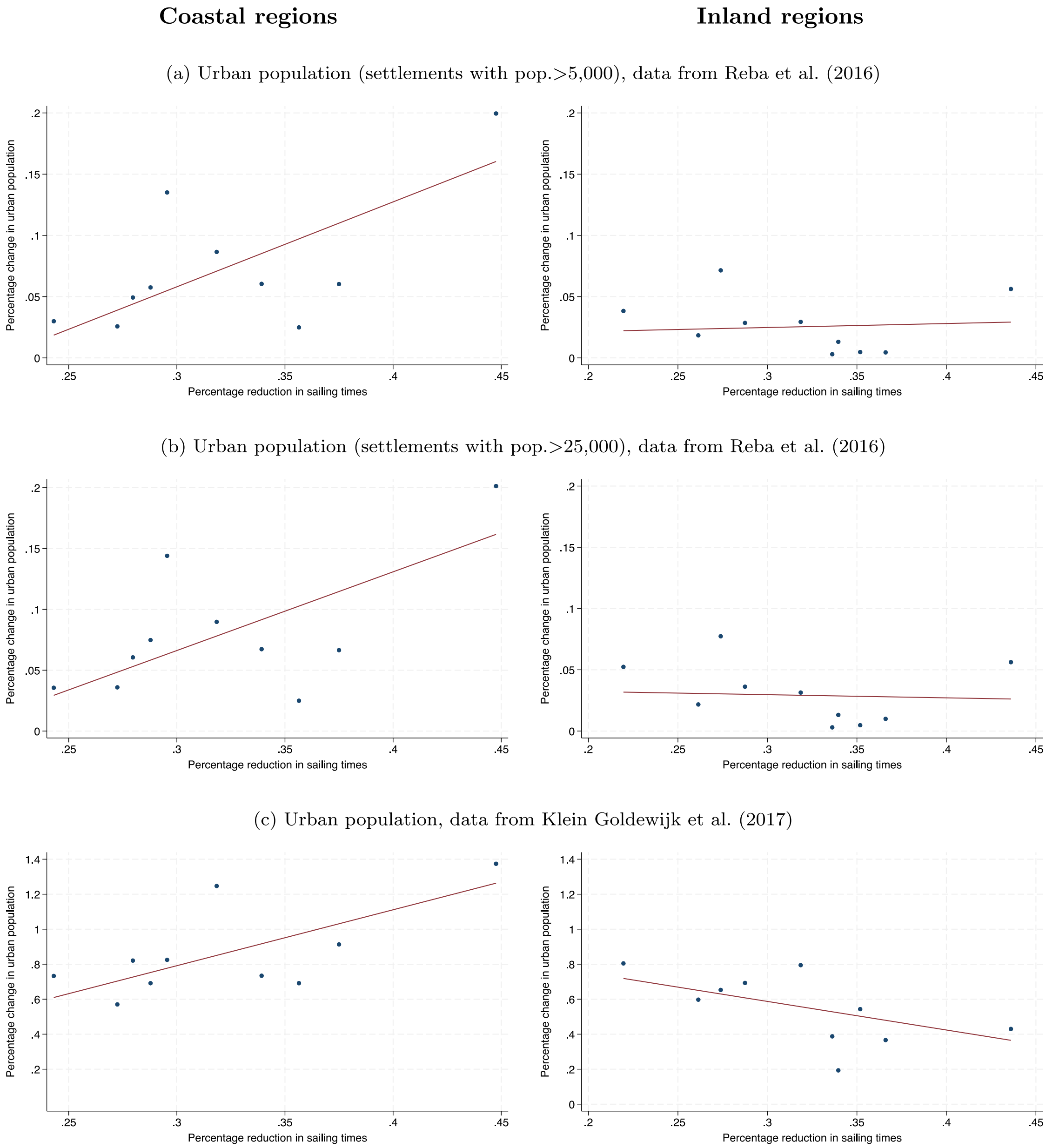
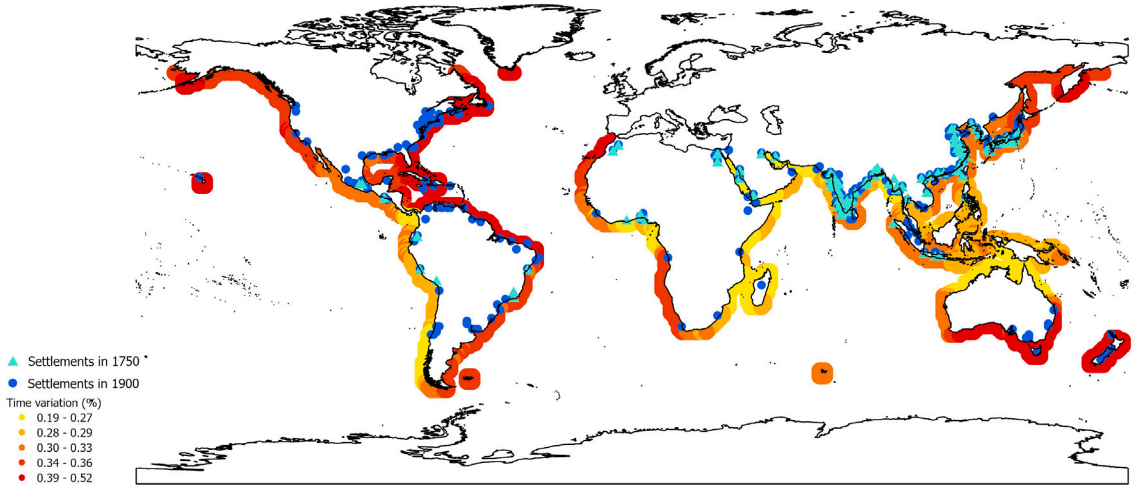


Fig. 7. Decile-binscatter correlations between the percentage reduction in predicted optimal sailing times to Europe (induced by the chronometer) and percentage changes in urban population.
Notes: Each panel corresponds to a different proxy for urban population; figures on the left show binscatters on the coastal regions, while figures on the right focus on the inland areas.

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 Table A10.

As discussed in Section 3.3, the urbanization data from Reba et al. (2016) are far from ideal. Table A11 shows that our results are robust to the use of an alternative dataset to measure urban population: HYDE 3.2. The main results are illustrated in column 1. Note that HYDE provides data for every decade; in the regression, the omitted decade is the 1780s, the last decade before the introduction of the chronometer in navigation. To simplify the discussion, we also plot the estimated α_t coefficients in Fig. 9. As shown, there are no pre-trends: the estimated coefficients for the eighteenth century are relatively small compared to those for the nineteenth century and are not statistically different from zero. The estimated α_t coefficients begin to increase in the 1810s and become statistically significant in the 1830s. The magnitudes of the coefficients in 1850 and 1900 are comparable to those obtained using Reba et al. (2016)'s dataset. The qualitative results are similar when using built-up area to capture urbanization (column 2).

(a) Urban population (settlement definition pop.>25,000), data from Reba et al. (2016)



(b) Urban population, data from Klein Goldewijk et al. (2017)

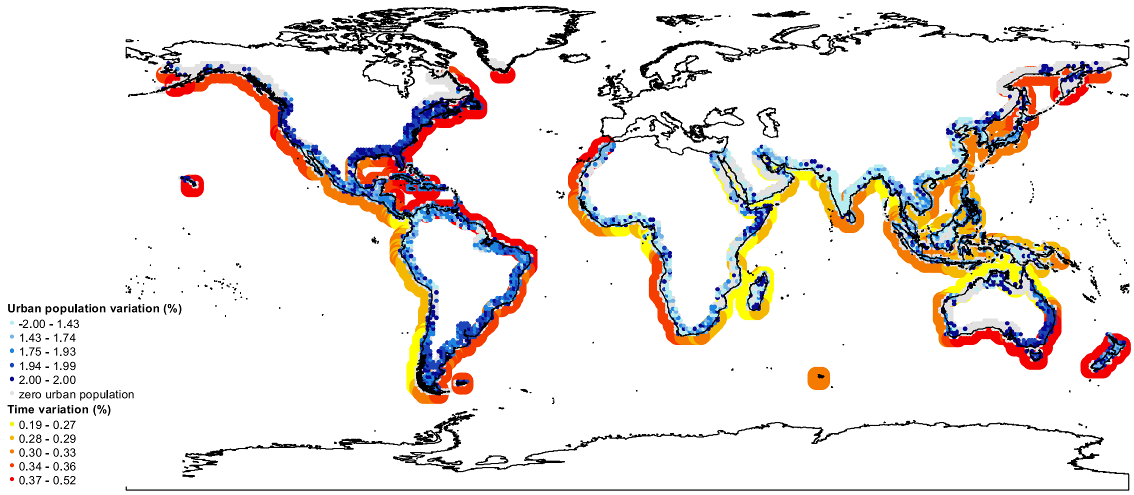


Fig. 8. Comparing the changes in predicted optimal sailing times to Europe (induced by the chronometer) against changes in urban population.
Notes: Maps display the percentage reduction in predicted optimal sailing times of a return trip from Europe under chronometer with respect to lunar method, against: urban settlements presents in 1750 and 1900 using data from Reba et al. (2016) in panel (a); the percentage variation in urban population between 1750 and 1900 using data from Klein Goldewijk et al. (2017) in panel (b). (The reader is referred to the web version of this article for the color representation of this figure.)

Finally, also when using HYDE, changes in sailing distances to Europe do not correlates with changes in the urbanization in inland regions (columns 4 and 5). One advantage of using the HYDE dataset is that it provides information not only on urbanization but also on population density. In column 3 of Table A11, we report the difference-in-difference estimates when the dependent variable is population density. Also in this case, there are no pre-trends, and the estimated α_t coefficients become sizeable and significant only during the nineteenth century. 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; by 1900 the effect on population density is 40 percent higher. In the Appendix, we further show that the results on urbanization and population density when using the HYDE dataset are robust to the same set of checks that we ran when using our benchmark urbanization data (see Tables A12-A17).

In summary, both the 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 significant changes in urbanization rates and population density across the globe. Those regions of the world that became more accessible to Europe experienced a significant

Table 5
Chronometer and urbanization.

	COASTAL REGIONS			
	extensive margin (dummy urban settlement)		intensive margin (ln(1+urban population))	
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1800)	0.058	0.103	0.612	1.106
	{0.071}	{0.087}	{0.886}	{1.044}
ln(lunar)-ln(chrono) × I(1850)	0.086	0.155*	1.068	1.742*
	{0.074}	{0.083}	{0.876}	{0.975}
ln(lunar)-ln(chrono) × I(1900)	0.429***	0.419**	4.820***	4.736**
	{0.143}	{0.163}	{1.752}	{1.943}
Observations	19 192	19 192	19 192	19 192
Urban settlement definition	pop>5,000	pop>25,000	pop>5,000	pop>25,000

	INLAND REGIONS			
	extensive margin (dummy urban settlement)		intensive margin (ln(1+urban population))	
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1800)	−0.054	−0.034	−0.553	−0.349
	{0.048}	{0.048}	{0.544}	{0.553}
ln(lunar)-ln(chrono) × I(1850)	−0.018	−0.030	−0.201	−0.322
	{0.040}	{0.041}	{0.460}	{0.468}
ln(lunar)-ln(chrono) × I(1900)	0.043	−0.006	0.442	−0.027
	{0.085}	{0.087}	{0.982}	{1.006}
Observations	46 552	46 552	46 552	46 552
Grid cell FE	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y
Continent linear trends	Y	Y	Y	Y
Urban settlement definition	pop > 5000	pop > 25,000	pop > 5000	pop > 25,000

Notes: Table reports OLS estimates. Unit of observation is a 1° × 1° grid cell and the omitted decade is 1750s. *Coastal regions* include land grid cells within 2 degrees from the coastline, *Inland regions* include the rest of land grid cells. Dependent variable is an indicator variable for grid cells containing at least one urban settlement with a population above 5,000 or 25,000 inhabitants in columns 1 and 2, and the natural logarithm of one plus the population in a grid cell when including only urban settlements that have more that 5,000 or 25,000 inhabitants in columns 3 and 4; *ln(lunar)-ln(chrono)* is the difference of predicted optimal sailing times by lunar method and by chronometer (in log of days) for a return voyage from Europe to world-wide coastal regions using May data for wind and coverage; *Urban settlement definition* indicates the threshold in terms of urban population used to define a urban settlement. *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). Standard errors are corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometers. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

increase in urbanization, with a particularly rapid development of coastal areas, while the hinterland was not affected. Our benchmark estimates suggest that the invention of the chronometer may account for a sizeable share—approximately two-thirds—of the increase in the urban population living along the coast outside of Europe between 1750 and 1850.[45] As slightly more than 60 percent of the total increase in urban population in this century was concentrated along the coast, the chronometer might be able to explain approximately 40 percent of the total increase in urban population outside of Europe. Admittedly, these back-of-the-envelope calculations are crude and should be interpreted cautiously, as they rely on the assumption that the rollout of the chronometer was uniform across different trade routes and was complete by the end of the period of the analysis period. Additionally, the data on urbanization have important limitations.

4.3.3. 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.[46] 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

[45] The average log-reduction in predicted optimal sailing times for a round trip to Europe induced by the chronometer is −0.32, and the benchmark estimated elasticity of the coastal urban population outside of Europe with respect to sailing times to Europe is −1.1 (see the estimated coefficient on [(ln(*lunar*)-ln(*chrono*))×I(1850)] in column 3 of Table 5). Using these figures, the average log-change in the coastal urban population outside of Europe attributable to the chronometer between 1750 and 1850 is calculated as −1.1 × −0.32 = 0.35, compared to the observed log-change of 0.52.

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

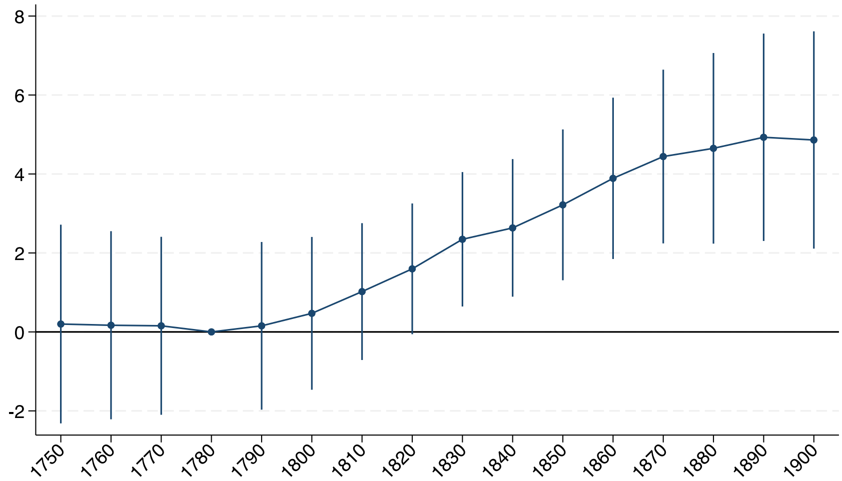


Fig. 9. Pre-trends using HYDE's data.
Notes: Graph shows the coefficients of column 1 of Table A11 as estimated from Eq. (8), using the log of one plus urban population as outcome variable. Vertical bars indicate 90 percent confidence intervals, with standard errors corrected for spatial autocorrelation by implementing Conley (1999) standard errors with a spatial autocorrelation cutoff of 1,000 kilometers.

to map as many areas as possible in the Antarctic region and in the Southern Pacific.[47] 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.[48] 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 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).[49] 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:

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

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 6. The estimates in the first two columns imply that a 1 percent reduction in the shipping time of a return trip to Europe is associated with an approximately 2 percent increase in the probability of being colonized by Britain in 1822.

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47 The instructions were "to prosecute discoveries as near as the South Pole as possible".

48 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.

49 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).

Table 6
European colonization.

Dependent variable:	British colony		European colony	
	(1)	(2)	(3)	(4)
ln(lunar)-ln(chrono) × I(1660)	0.195	0.052	0.171	−0.305
	{0.993}	{1.000}	{0.971}	{0.886}
ln(lunar)-ln(chrono) × I(1822)	1.912**	2.564***	1.675*	2.710***
	{0.938}	{0.943}	{0.961}	{0.955}
ln(lunar)-ln(chrono) × I(1885)	0.785	1.273	0.674	2.718**
	{1.192}	{1.271}	{1.154}	{1.125}
Observations	11 904	11 904	11 904	11 904
Grid cell FE	Y	Y	Y	Y
Decade FE	Y	Y	Y	Y
Latitude × 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 predicted optimal sailing times by lunar method and by chronometer (in log of days) for a return voyage from Europe to world-wide 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 absolute level of latitude, 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 kilometers. *, ** and *** indicate significance at the 10, 5 and 1 percent levels, respectively.

This suggests that the chronometer, which reduced sailing times to Europe by an average of 30 log points in this sample, played a significant role in guiding the expansion of the British Empire during the early decades of the nineteenth century. However, by 1885, the correlation between reductions in sailing times and British colonization becomes weaker and noisier. This is likely due to the fact that our measure of changes in sailing times is based on sailing ships, while by 1885, most British ships were steam-powered. As expected, there is no evidence of pre-trends in 1660.

In the last two columns of Table 6, the dependent variable is a dummy that identifies European colonies rather than British colonies. The estimated difference-in-difference coefficients for 1822 are very similar to those in the earlier columns. This is not surprising as more than three quarters of the coast that is colonized by Europeans between 1754 and 1822 was occupied by Britain. As in the previous two columns, the estimated coefficients for 1885 are noisier and are affected by the inclusion of controls.

5. Relationships with the previous literature

The findings described in the previous section relate to several existing literatures.

First, they speak to the long-standing debate on the impact of globalization on living standards. Specifically, it relates to a line of research that has used natural experiments of history to study the impact of changes in market access on local economic development. In this context, exogenous shocks to market access were derived from new transportation or communication technologies,[50] temporary disruptions in the shipping industry[51] or the opening of new markets.[52] Our work offers a rather global view compared 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 precisely assess the impact of market access on the local standard of living, but only on population density and urbanization (see Jedwab and Vollrath, 2015 for a review on the close relationship between urbanization and per-capita GDP in the last five centuries). 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 underpin the precise mechanism behind our main results: we cannot distinguish whether changes in distances to Europe impacted the non-European world through trade, migration, transfers of culture, technology and institutions or other channels. We leave these topics to further work.

[50] A transformation paper in this literature is Donaldson (2018), who studies the impact of the development of the railroad network on real income and welfare in the Indian context. Donaldson and Hornbeck (2016) and Hornung (2015) undertake similar studies for 19th-century US and Prussia. Feyrer (2021) studies the impact of international trade by exploiting the asymmetric effect on the geographical isolation of countries induced by improvements in the aircraft technology in the 1970s. 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. Steinwender (2018) focuses on the impact of the establishment of the transatlantic telegraph in 1866 on information frictions and trade integration across the Atlantic.

[51] For instance, Juhász (2018) uses the Napoleonic Blockade (1806–1814) to study the short and long-term impact of temporary trade restrictions on development and technology adoption. Feyrer (2021) studies the asymmetric effects induced from the temporary closing of the Suez Canal between 1967 and 1975.

[52] See for instance the work of Nunn (2008), Nunn and Wantchekon (2011) on the rise of the Atlantic slave trade and the long-term impact it had in the African continent.

Second, our work relates to a literature on the impact of locational advantages on the history of urban development. We refer to Hanlon and Heblich (2022) for a rich review of this literature. Highlighting some works that relate to ours, Henderson et al. (2018) cites the decline in shipping transportation costs as the most important technological change during the history of urbanization over the past few centuries: by facilitating sea trade, such changes moved urban population towards the coasts. Similarly, Motamed et al. (2014) shows that access to low-cost transportation facilitates city growth using world-wide data on rural and urban population history over the last 2,000 years. Within this literature, we follow a series of works that have exploited natural experiments of history to study the impact of market access on the location and size of cities. For instance, Redding and Sturm (2008) exploit changes in market access induced by the division and reunification of Germany in the 19th century. Nagy (2023) studies the impact of US railroads on urbanization and city formation in the 19th century.[53] Fajgelbaum and Redding (2022) investigates how the interaction of falling international trade costs and internal trade costs affected the distribution of population and cities in Argentina in the 19th century. Ellingsen (2024) goes back to the Spanish Americas and shows how changes in market access induced by a trade reform in the second half of the eighteenth century led to a substantial reconfiguration of the urban geography of these regions. Also in this case, a crucial advantage of our approach is to have a global perspective, rather than being focused on a specific country or a limited set of countries.

Third, 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 (Crafts and Wolf, 2014), electricity (Fiszbein et al., 2020), and the introduction of the potato in the Old World (Nunn and Qian, 2011).

Last, our findings add to a vibrant and rich debate 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 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.[54] 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.

6. Concluding remarks

In the nineteenth century, the world underwent an unprecedented change in its urban landscape. Outside of Europe, urban population quadrupled. 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 played an important role. Specifically, we show that solving the longitude puzzle 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. Those coastal regions that became relatively closer to Europe were also the regions that experienced the largest increases in urban population. Overall, the magnitude of the empirical estimates points towards the chronometer being an important determinant behind 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 several caveats. First, we are unable to assess the impact of this innovation—and the subsequent

[53] See also Atack et al. (2010) on the relationship between the expansion of railroads in the US Midwest and urbanization.

[54] 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.

reduction in sailing distances—on local standards of living in the affected regions. Data limitations restrict the scope of our analysis to urbanization rates. Second, as we largely discussed, the urbanization data we use are far from ideal. Third, 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 do not know if Europe exerted its impact through trade, migration or transfers of culture, technology and institutions. We leave these important research questions to future work.

Declaration of competing interest

We declare that we have no relevant or material financial interests that relate to the research described in the paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jinteco.2025.104067.

Data availability

Replication package for the manuscript INEC-D-23-00036R1 (Original data) (Mendeley Data).

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