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Speed under Sail during the Early Industrial Revolution (*c.* 1750–1830).

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Abstract

We measure technological progress in oceanic shipping directly by using a large database of daily log entries from British, Dutch, and Spanish ships to estimate daily sailing speed in different wind conditions from 1750 to 1850. Against the consensus among economic (but not maritime) historians that the technology of sailing ships was fairly static during this time, we find that average sailing speeds of British East India Company and navy ships in moderate to strong winds rose considerably after 1770s. Driving this progress was the introduction of coppering in the 1780s but subsequent rises are probably due to a continuous evolution of sails and rigging, and improved hulls that allowed a greater area of sail to be set safely in a given wind. By contrast, speeds of Dutch and Spanish vessels were stagnant. Using separate data on crossing times of Atlantic mail packets, we find steady progress from the 1750s, followed by marked improvements when American packets appeared in the 1820s.

JEL: N0
Keywords: Technological progress, shipping.

1 Introduction.

With its hundreds of squares yards of canvas sails making it the most effective means of harnessing inorganic energy in the pre-industrial world, the sailing ship represented a fundamental transportation technology of the western world until the mid-nineteenth century. Given the strong incentives, both military and commercial, to improve the performance of such vessels, it may seem surprising that the consensus among economic historians going back to North (1968) and Harley (1988) is that, between the Dutch fluyt in the sixteenth century and the iron steamship in the nineteenth, maritime technology was effectively stagnant.

Previous efforts to measure technical progress in ocean shipping have been indirect, typically measuring changes in the cost of shipping freight or, less commonly, in the length of voyage. This paper instead takes a direct approach, measuring how daily sailing speeds of vessels in different wind conditions evolved through time. To do this we use the large CLIWOC database that, in an effort to reconstruct oceanic climate conditions, compiled over 280,000 log book entries from British, Dutch, Spanish and French ships 1750 and 1850. These give information about daily position, wind speed and direction, along with details on the type of ship.

Against the orthodoxy of technical stasis, both East India Company (EIC) and Royal Navy ships show broadly similar patterns of improvement throughout the period. Speed is fairly static until the 1770s. Between 1780 and the early nineteenth century sailing speed rises markedly, especially in fresher breezes where it improves by around a third over the period. By contrast, sailing speed of Dutch and Spanish vessels was stagnant.[1]

The final set of British records that we examine is the passage time of Post Office sailing packets sailing to and from New York, and these reveal an improvement of 15 per cent between 1750 and 1829. This slow progress changes however when American packets appeared in the 1820s, and by the late 1830s the fastest packets were sailing fifty per cent faster than they had done in the 1750s (with 1850s clippers, in turn, sailing 50 per cent faster than the best packets).

What explains these improvements in sailing speed? Half of this improvement occurs in the 1780s as these ships' hulls were coppered to against weeds and barnacles. Some of the subsequent rise probably reflects incremental improvement in sails and rigging. A major source of improvement for the East India Company (but not introduced into the Royal Navy until the 1830s and most merchant ships in the 1840s) was the replacement of traditional stepped decks, which shipped water each time the vessel dipped into a heavy sea, with flush (flat) decks and watertight hatches (possibly derived from Indian designs). More important for most vessels was increas-

[1]The French data in CLIWOC are too fragmentary to be used.

ing hull strength caused by a greater use of iron reinforcing which meant that they flexed and leaked less. Besides increasing seaworthiness, these improvements allowed more sails to be set safely, especially in stronger winds.

Our findings of notable improvements in ship speed during the Industrial Revolution are in keeping with a growing reaction against the orthodoxy in economic history that the technological progress of the late eighteenth century was largely confined to cotton spinning, iron making, and steam engines, with other sectors mired in stasis. The steady improvements in shipping technology outlined here support the view of a more broadly based advance across many manufacturing with sectors such as brewing, pottery, glass, hydraulics and mechanical engineering showing signs of technological dynamism in this period.[2]

Although we conclude that Walton, North and Harley were incautious in extrapolating from Atlantic freight to shipping in general, our results do not otherwise contradict theirs. North and Harley analysed the highly competitive North Atlantic route. This cost minimising market made it optimal for merchant ships to operate well within a technological frontier being pushed outwards by the expensive vessels of the Royal Navy and East India Company funded by a government, and a large monopoly respectively. It should also be noted that our analysis does directly address productivity: its sole concern is with sailing speed.

This raises the natural incentive of why ships had an incentive to sail faster. For warships, mail packets, and slave ships the motivation is obvious. For East Indiamen, given that each round trip lasted two years, the need for speed is less clear until we remember the risks that they ran from privateers until 1815, and pirates into the 1830s: Lubbock (1922, 84–95). However, for ordinary merchant shipping on the North Atlantic the returns from saving a day or two on a crossing were marginal.

The rest of the paper is as follows. After a literature review, we outline the major improvements in maritime technology affecting sailing speed during the seventeenth and eighteenth centuries in Section 3 In Sections 4 and 5 study the rise in the sailing speed of EIC and Royal Navy ships. Section 6 analyses the sailing speed of Dutch vessels, and Section 5.3 examines British post office packets.

[2]Ssee Mokyr (2009, 131–144) for a survey; and more recent contributions such as Tomory (2012) on gas lighting, Gerhold (2014) on coaching, and Kelly and Ó Gráda (2016) on watches.

2 Literature Review.

On the North Atlantic route, Walton (1967; 1968) and North (1968) found that freight rates fell from 1600 to 1850. Simply asserting that technological progress in shipping was negligible, North instead attributed these falling prices to increased specialization permitted by larger markets, the development of backhaul freight (either colonial produce or immigrants), lower turnaround times, and smaller crews allowed by the suppression of piracy. Harley (1988) however showed that North's price falls were largely due to denser packing of cotton bales and that, when a more reliable price index was estimated, freight rates were constant before steamships in the 1850s.

Rönnbäck (2012), corroborating earlier work by Klein (1978), subsequently found that the average length of voyage of slave ships on the middle passage fell from about ninety days around 1700 to sixty a century later, an improvement he attributed to better knowledge of seasonal winds (see also Rönnbäck and Solar 2014). Solar (2013) finds that the voyage length of EIC ships to Bombay fell by 28 per cent between the early 1770s and the 1820s while VOC times to Batavia between the 1770s and 1790 were largely unchanged, consistent with our findings here.

3 Technology.

The dismissal of technological progress in shipping by North and Harley runs against the extensive lists of innovation in histories of maritime technology such as Naish (1957) and Harland (1985). Davis (1972, 71) found that average tonnage per crewman on ships entering London rose by 50 per cent between 1686 and 1766, and conjectured that this improvement reflected an important but unknown innovation in ship design. Improvements in the seventeenth century include chain pumps and thicker planking of hulls; but the most important are to sails and rigging: shrouds set up with deadeyes and chains; ratlines for access to the sails; the replacement of four masts by three leading to a more divided and easily handled sail plan; the replacement of spritsails by fore-and-aft jibs; and the appearance of triangular staysails between masts.

Replacing the clumsy whipstaff with the steering wheel from the 1690s made ships more manageable in heavy seas and gave the helmsman a clear view of how the sails were filling. This allowed him to make precise course adjustments to maximise sailing performance (McGowan 1980, 15–16; Rodger 2004, 221–222). The major advances in the theory and practice of navigation that took place in the late eighteenth century are outlined by Kelly and Ó Gráda (2017) and there is the possibility that improved charts and dead reckoning enabled ships to sail faster by reducing the need to move cautiously in unfamiliar waters.

Although Naish (1958) suggests that by the early eighteenth century the square rigged sailing ship was a mature technology (albeit one that was able to compete successfully with steam ships on long distance routes until the second half of the nineteenth century: Harley 1971), ship design altered fundamentally in the late eighteenth century with the gradual appearance of iron-reinforced ships with a single flush deck and watertight hatches, an innovation that is probably of similar importance to the well known appearance of copper sheathing.

3.1 Coppering.

From classical times, shipworms that eat rapidly through wooden hulls were a known threat to vessels, and a common solution, used continually by Spain and intermittently by Britain, was to coat hulls with lead sheets. From the 1760s, the British Admiralty experimented with copper plating that not only was lighter and protected against shipworm but reduced biological fouling allowing ships to sail faster, as contemporaries quickly noticed (Knight, 1973).[3] As a result, every ship in the Royal Navy was coppered between 1779 and 1781 (Harris, 1966). Naturally, in a world before scientific metallurgy, the effective use of copper sheathing progressed by slow and often costly—in seamen's lives as well as money— empirical trial and error.

The main problem was galvanic action with iron (something not understood until the 1820s) that caused the bolts and pintles holding the keel and rudder onto the ship to corrode rapidly and led to several major disasters. There were active discussions by the middle of 1783 of suspending coppering but the problem was solved by replacing the iron nails fixing the plates to the hull with difficult to install, short-lived, and extremely expensive cop-

[3]The resistance of a hull is proportional to its surface area times its velocity squared, so that reducing surface area by eliminating weeds and barnacles had a major impact on performance at the low speeds of ships in our period.

per ones (Staniforth 1985; McCarthy 2005, 101–115). By 1790 the practice of coppering had spread to the East India Company, and slave ships (Harris, 1966; Solar, 2013; Solar and Hens, 2015; Solar and Rönnbäck, 2015).

3.2 Seaworthiness.

In the decades covered by the CLIWOC data—between the 1750s and the 1820s—other improvements in ship construction may be plausibly linked to increases in speed, but the fuzzy chronology of their diffusion means the link cannot be identified with any precision.

One such improvement was the gradual increase in the strength of ship hulls. Joining many wooden planks together to form a large hull (over 800 for a 176 foot long warship) results in poor structural integrity, so that large ships sagged (hogged) under their own weight, and flexed badly (worked) in heavy seas, letting in water and losing speed (Robertson, 1921, 11-12).

Leading late eighteenth century efforts to improve the shear strength of hulls was EIC Surveyor (chief architect) Gabriel Snodgrass who introduced iron knees to bolt decks firmly to hulls (something that had been used intermittently since the early eighteenth century but whose adoption was limited by the expense of wrought iron before Cort's puddling and rolling process in 1784: Goodwin 1997) , and diagonal bracing between ships' ribs to create a rigid box-truss that resisted twisting in high waves (Snodgrass, 1797). Forced by wartime timber shortages to use shorter planks, and consequently facing even greater problems of rigidity, these innovations were gradually introduced into the Royal Navy after 1803 by Robert Seppings (Seppings, 1814; Lambert, 1991, 60–64). Through the period, hull timbers were attached by wooden treenails (which expanded when wet to give a tight fit) but emphasis on their quality increased through time: for instance, a Lloyd's Register from 1834 lists acceptable types of wood, and the number to be used on different widths of planking (McCarthy, 2005, 123).

Their cheapness meant that iron knees were becoming more widespread in merchant ships by the 1820s (Partington, 1826, 103–104) but diagonal framing appears to have been uncommon until its use in the innovative Blackwall Frigates of the 1830s (see below) leading one contemporary to describe them as "the strongest merchant ships ever built in England" (Anon, 1839, 181). Their neglect of bracing may simply reflect the fact that, being fairly small vessels built for owners anxious to minimize cost and little concerned with speed, merchant ships were already sufficiently strong for their purposes without the expense of extra reinforcing.

One important but typically overlooked improvement in maritime technology (not mentioned for example by Naish, 1958 or Unger, 2013) was the gradual appearance of flush decked ships. Since medieval times, European ships had a stepped deck, raised at both ends and lower in the middle. This offered an effective fighting platform but at the cost of seaworthiness: the low waist deck caused the vessel to ship water each time it dipped in a heavy sea, flooding lower decks. As well as being prone to foundering, these ships were structurally weak (Blackburn, 1836, 97).

In response, Snodgrass began to build East Indiamen with a single flush deck and hatches that were stronger and more watertight in heavy seas: see Parkinson (1937, 135–138) who argues that Snodgrass was influenced by the design of Bengal rice ships when working as a young shipwright in India.[4] However, although the Royal Navy adopted other EIC innovations, despite the urging of Snodgrass (1797) they remained opposed to flush decks which were not introduced until the 1830s. Even then the qualities of these "Symonds Frigates" were vigorously disputed, with one senior politician quipping that "except religion, he knew no subject that excited such bitter controversy" (Leggett, 2015, 26–58).

An important influence of these warships, however, was on merchant shipping, where the Blackwall Yard that built them used their design as a basis for their fast and seaworthy "Blackwall Frigates" built from the late 1830s until the 1870s and widely imitated (Lubbock, 1922, 131–137 and *passim*). These appear to be the first important type of ordinary merchant ship to have used flush decks: discussing stepped decks in the 1820s James (1822, 18) noted that "the generality of merchant vessels are, to this day, built in that manner."

It is likely, in addition, that gradual increases in speed also occurred from incremental improvements in sails and gradual learning by doing among builders (who tended to duplicate successful designs) and seamen. A major determinant of the performance of a sailing ship is its trim—the rake and position of its masts, the amount and positioning of its ballast, the slackness of its shrouds—so that identical ships would perform very differently de-

[4]For a contemporary illustration of such a flush-deck Indiaman see Clark (1910, 36–37).

pending on how carefully these were optimized for different sea conditions (Blackburn, 1836, 124–126; Robertson, 1921, 13–14).

3.3 Scientific Contributions.

Regarding scientific efforts to improve ship speed and handling, hydrodynamics and ship design became a major area of empirical and theoretical research from the early eighteenth century, largely through the efforts of the French Academie des Sciences. The topic of its annual prize essay often concerned aspects of ship design, attracting leading mathematicians such as d'Alembert, Bouguer (who Ferreiro, 2007 sees as the first true naval architect) and, most notably, Euler who made repeated studies of hydrodynamics through his career culminating in his 1749 *Scientia Navalis* (Nowacki 2006; 2008). Hydrodynamical theory, however, simply proved too complex for eighteenth century mathematics—with the first successful results only coming with Froude over a century later—and the ships built on Euler's principles performed poorly (Naish, 1958, 577). Similarly, the efforts of the Royal Society in 1664 to design a streamlined hull for the 80 gun *Royal Katherine* resulted in a ship so unstable that its beam had to be widened to traditional dimensions (Jones, 2013, 53).

More fruitful were systematic efforts to use scale models to test ship design. Against Newton's mechanical theory of fluid resistance in Book II of the *Principia,* which implied that resistance of a vessel depended solely on the shape of its bow, the numerous experiments carried out by William Beaufoy for the Society for the Improvement of Naval Architecture from 1790–1793 highlighted the key role of stern and side friction; while continued experiments by his associates showed how ships could be made much longer relative to their width without compromising their handling. However, although Beaufoy's findings had considerable influence on later steamship design, they were ignored by the Royal Navy (Schaffer, 2004).

4 Data Sources.

This paper derives ship speeds in different wind conditions from a new source: ships' daily logbooks compiled by the CLIWOC (Climatological Database for the World's Oceans) project) to chart oceanic weather conditions from 1750 to 1850 (Können and Hoek 2006; Wheeler et al. 2006).[5] As well as wind direction and speed, CLIWOC gives daily observations of each ship's direction, distance covered, longitude, and latitude. We use the daily change in longitude and latitude to compute how far the ship had sailed, referred to as course made good (this excludes any extra distance caused by tacking into the wind). Although latitude could be computed accurately, most longitude estimates in this period were made by dead reckoning (Kelly and Ó Gráda, 2017), so our dependent variable of ship speed will be measured with some error which will lead to attenuation of the estimated impact of the explanatory variables.

CLIWOC gives the direction of wind and its estimated speed, translated from verbal descriptions in the logbooks (for example "gentle trade wind") into the standard Beaufort scale. We exclude observations that CLIWOC identifies as coastal (where speed may have been reduced for fear of running aground), days with no wind, and days where position remained unchanged indicating that the ship was in port or at anchor. At the other end, we exclude observations with winds above 34 knots (gale force), where recorded ship speed is implausibly high (above 10 knots), or where reported ship speed is more than half wind speed.[6]

4.1 British Data.

Applying these criteria, we end up with 11037 observations from 1750 to 1829 for the EIC, and 14063 from 1750 to 1808 for the Royal Navy.[7] To see whether big ships sailed faster, we measure the size of the ship from its tonnage. Although the theoretical maximum hull speed of a ship is proportional to the length of its waterline, meaning that longer ships can sail faster than shorter ones, vessels of our period sailed so slowly that this maximum speed is not an issue.[8]

As well as daily observations for the EIC and Royal Navy, we have voyage duration for ships of the British Post Office to and from New York from

[5] The data and accompanying documentation are available at http://www.ucm.es/info/cliwoc/cliwoc15.html.

[6] These outliers do not affect the random forest algorithm but lead to misleadingly low estimates of its ability to predict out of sample observations.

[7] CLIWOC also records some naval observations between 1809 and 1827—fewer than 100 per year, which give too sparse a coverage to allow reliable inferences to be made.

[8] The tonnage of Royal Navy ships is taken from CLIWOC, and that of East Indiamen from the "East India Company Ships" website: http://eicships.info.

1755 to 1825. Usually the voyage westward was direct, with the return voyage stopping for several days in Halifax, Nova Scotia. Details of each voyage have been assembled by Olenkiewicz (2013). This gives us data on the length of 1234 voyages.

4.2 Dutch and Spanish Data.

CLIWOC contains 126,000 records for Dutch ships. Unfortunately, about half of these do not tell what sort of ship the record concerns, and in many other cases the ship position is not recorded. We focus on three classes of internally homogeneous records that span long periods: those belonging to the Dutch East India Company (VOC), the Middelburgsche Commercie Compagnie (MCC: a slave trading company), and frigates, corvettes, and brigs of the Dutch navy.

The VOC and Admiralty records mostly concern voyages to and from the East Indies, whereas the MCC observations follow the triangular route down to West Africa, across to the Caribbean, and back. Leaving out coastal observations and days when there was no breeze or the ship was at anchor, gives 19200 observations.

A difficulty with the Dutch data is that descriptions of wind conditions in log books do not always appear to have been carefully translated into modern wind forces: for 11800 observations the ship was supposedly sailing at least half as fast as the wind, something not possible for ships of this era.

Besides CLIWOC, we have data on the duration of all 8,194 voyages undertaken by ships of the VOC during the seventeenth and eighteenth centuries compiled by Bruijn, Gaastra and Schöffer (1987).[9] We focus on the 3,754 voyages eastward between Dutch ports and Batavia (present day Jakarta) between 1595 and 1795, and 1,945 return voyages (many ships remained in the east to engage in local trade, unlike the EIC which had most ships for the country trade built locally), after subtracting the length of time spent laying over at the Cape of Good Hope.

CLIWOC reports 54,000 observations for Spanish ships, with all but 4,000 falling into into three categories: paquebote (packet boat), fragata (frigate), and navio (a larger two-deck ship of the line). However, 24,000 observa-

[9] These are available at http://resources.huygens.knaw.nl/das/index_html_en.

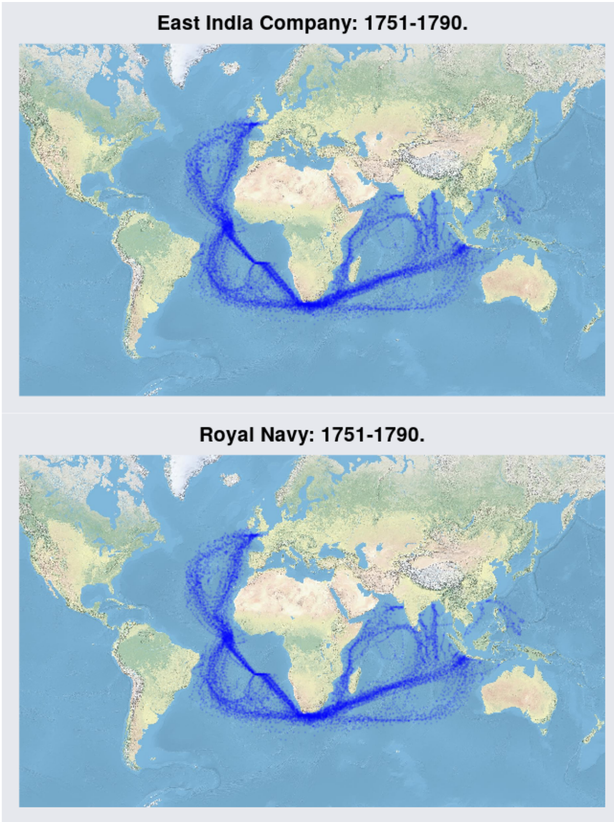

Figure 1: Daily positions of East India Company and Royal Navy ships, 1751–1790.

tions are for days with no wind, and another 8,000 report average sailing speeds above 10 knots. Excluding coastal observations, and ships sailing faster than half wind speed leaves 14100 observations.

5 Britain.

We consider first the performance of British ships: the daily sailing speed of East Indiamen and warships in different conditions, and the average crossing times of postal packets; but start with some summaries of the routes and wind conditions encountered by the first two categories.

Figure 1 plots the daily position for all observations for EIC and Royal Navy ships from 1751 to 1770, showing the circular courses taken by ships following oceanic winds and currents. The bunching of daily positions

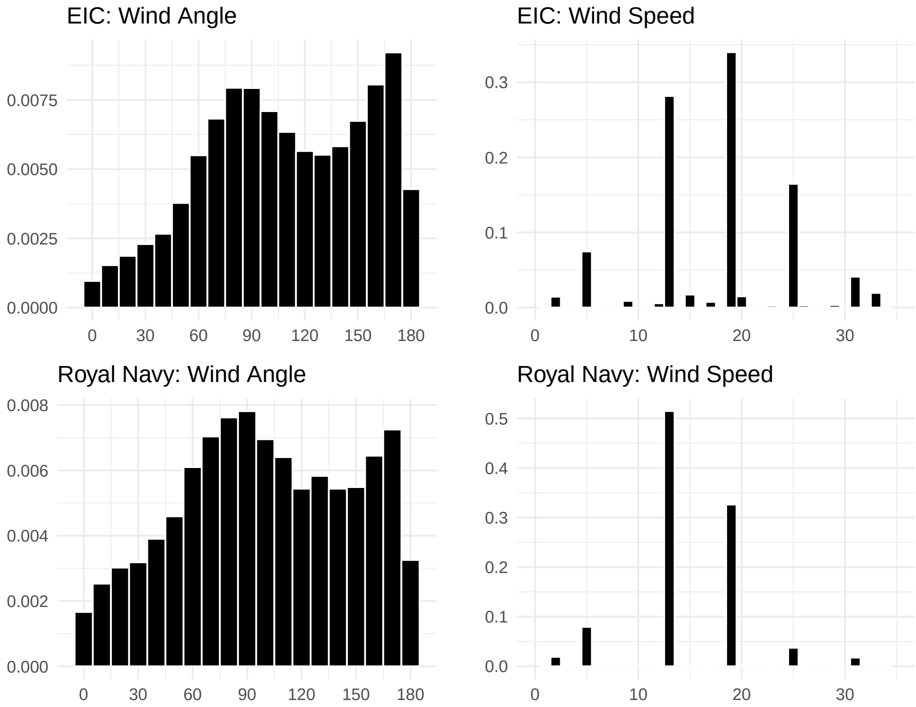

Figure 2: Distribution of points of sail and wind speed for the East India Company and Royal Navy.

around the equator, and as ships made the difficult eastward run around the southern tip of Africa, are evident.

The wind conditions encountered in our sample are summarized in Figure 2. For the Royal Navy, it can be seen that the commonest condition is a Moderate Breeze of 11–16 knots, Force 4, with Fresh Breezes of Force 5 and Light Breezes of Force 2 also common. For the East India Company, whose route took its ships through the South Atlantic and to the edge of the Roaring Forties, higher winds of Force 6 and sometimes Force 7 occur. For both the EIC and Royal Navy, observations of Force 3 are uncommon: given that Force 4 is the modal observation, it seems likely that these were conflated with Force 2 when CLIWOC coded the verbal wind descriptions.

The wind angle is the angle of direction that the ship followed that day relative to the wind: an angle of zero degrees means it was heading straight into the wind. It can be seen that the commonest points of sail were before the wind, as the ship followed prevailing winds and currents, or at right

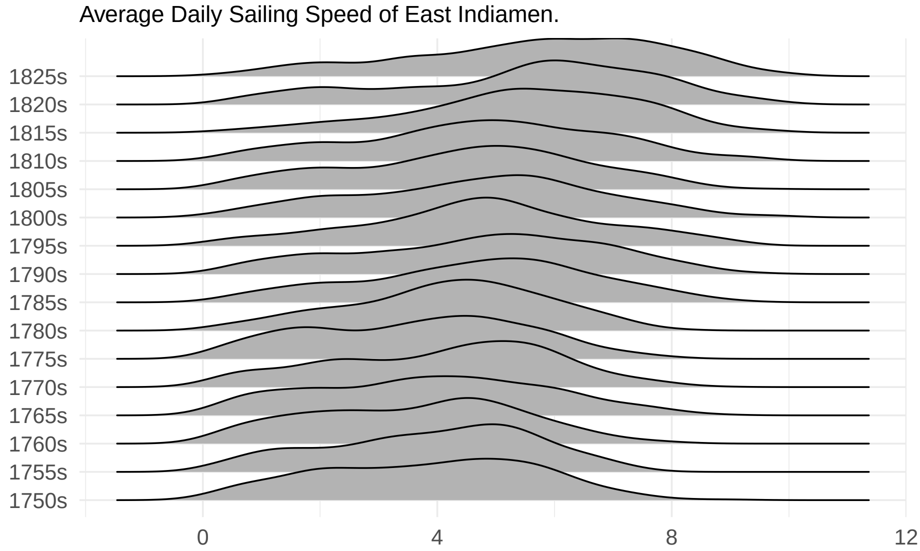

Figure 3: Distribution of average daily sailing speeds for the British East Company by half decade, 1750–1829.

angles to it where a ship's sails work most efficiently and its speed is maximized.

5.1 Britain: East India Company.

Figure 3 gives the density of average daily sailing speed by half decade for EIC ships (the smoothing process means that there is sometimes a small probability mass below zero).[10] It is evident that there is a notable jump in speed in the late 1780s—when ships were coppered—with speeds then static during the Napoleonic period probably reflecting convoying and, perhaps, the paucity of observations. After 1815, speed rises again, especially at the upper end.

The same thing is shown by the boxplots in Figure 4 where median speed is steady at around 4 knots until 1780 and then jumps to 5 knots in the early 1780s, and rises to around 6 knots in the late 1820s.[11] The EIC lost its mono-

[10]There are fewer observations during the wartime periods 1755-1765, and 1785–1815 so estimates for these times should be treated with caution. The three wars in this period are the Seven Years War, 1756–1763; the American War of Independence, 1779–1784; and the Revolutionary and Napoleonic Wars, 1792–1815 excluding temporary cessations.

[11]A boxplot shows the median and inter-quartile range, with the lines above and below corresponding to an approximate 95 per cent interval.

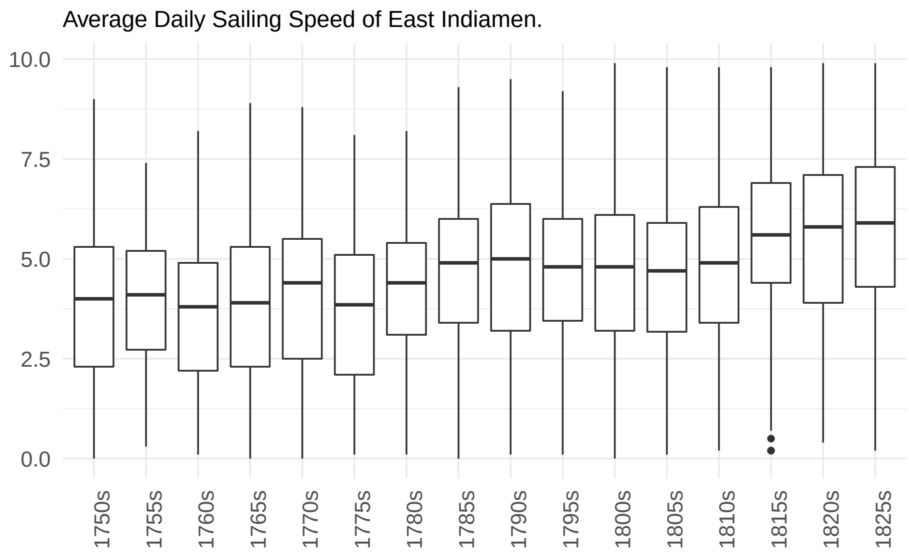

Figure 4: Average daily sailing speed for the British East Company by half decade, 1750–1829.

poly on the India trade in 1813 (see Bogart 2015), creating the possibility that its ships then faced commercial pressures to sail faster, but all of our observations after this time are for ships on the China route where it retained its monopoly until its dissolution in 1832.[12]

We would expect there to be a highly non-linear relationship between speed and its determinants, resulting in OLS estimates that are misleading or simply wrong. This leads us to use the statistical learning technique of random forests which is robust to non-linearity and changing interactions between variables, and is noted for its high predictive power.[13] The explanatory power of the forest may be gauged by training it on one sample of the data, and seeing how well it predicts observations in another, test sample.

One key deficiency of traditional random forests for our purposes is that they have low power when it comes to detecting sharp discontinuities of the sort associated with treatment effects such as, in our case, coppering in the 1780s. This limitation has been remedied by the generalized random forest approach of Athey, Tibshirani and Wager (2016).

[12]We are grateful to Peter Solar for this observation.
[13]See, for example, Berk (2008, 193–254).

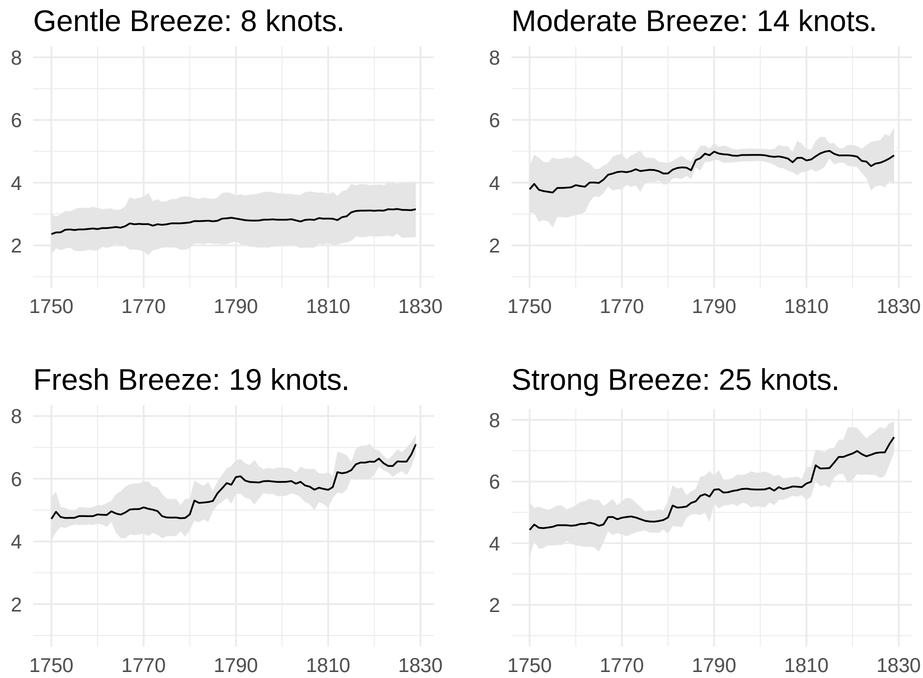

Figure 5: Predicted sailing speed from generalised random forest at different wind forces for an East Indiaman sailing at 90 degrees to the wind, 1750–1829. Shaded areas are two standard deviation bands.

Our central explanatory variables are year, wind speed, and angle to the wind. In addition we have data on daily longitude and latitude and the tonnage of the vessel. A dummy variable for wartime, when ships sailed in slower convoys, can have no explanatory power because the random forest can choose splits based on individual years.

We partition the data into a 95 per cent training sample and a 5 per cent test sample. If tonnage is left out, Table 1 shows that the ability of the fitted forest to predict speed in the test sample is high, with a squared correlation of 0.55 (adding tonnage of ships increases this explanatory power only to 0.56: larger ships did not sail appreciably faster). The importance of each explanatory variable can be assessed by looking at what proportion of tree splits were made using that variable. Wind speed and angle to the wind are, predictably, the most important accounting for 0.64 and 0.16 of splits, followed by year with 0.12, with latitude and longitude having 0.04 each.

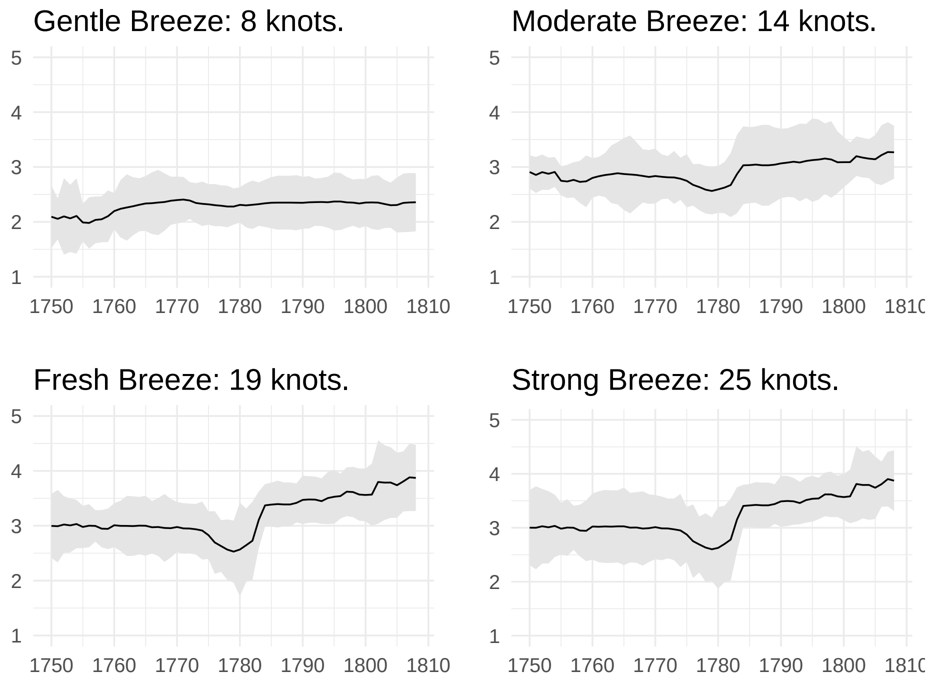

Figure 6: Predicted sailing speed from generalised random forest at different wind forces for a Royal Navy ship sailing at 90 degrees to the wind, 1750–1808. Shaded areas are two standard deviation bands.

Figure 5 gives the predicted sailing speed by year for a ship sailing at 90 degrees to the wind, at different wind forces. (Longitude and latitude were omitted from the underlying random forest to simplify presentation: this caused explanatory power to fall only to 0.48.) It can be seen that in a gentle breeze sailing speed rises moderately but steadily from about 2.5 to 3.25 knots across the period. By contrast, in moderate breezes speed rises somewhat from 4 to 4.5 by 1780 and then increases to around 5 by 1790, and does not improve afterwards.

The real improvements in the average speed that appears in Figures 3 and 4 result from better performance in stronger winds. In a fresh or strong breeze, speed jumps from 5 to 6 knots during the period of coppering in the 1780s and then, after wartime stagnation, rises to 7 knots by 1830.

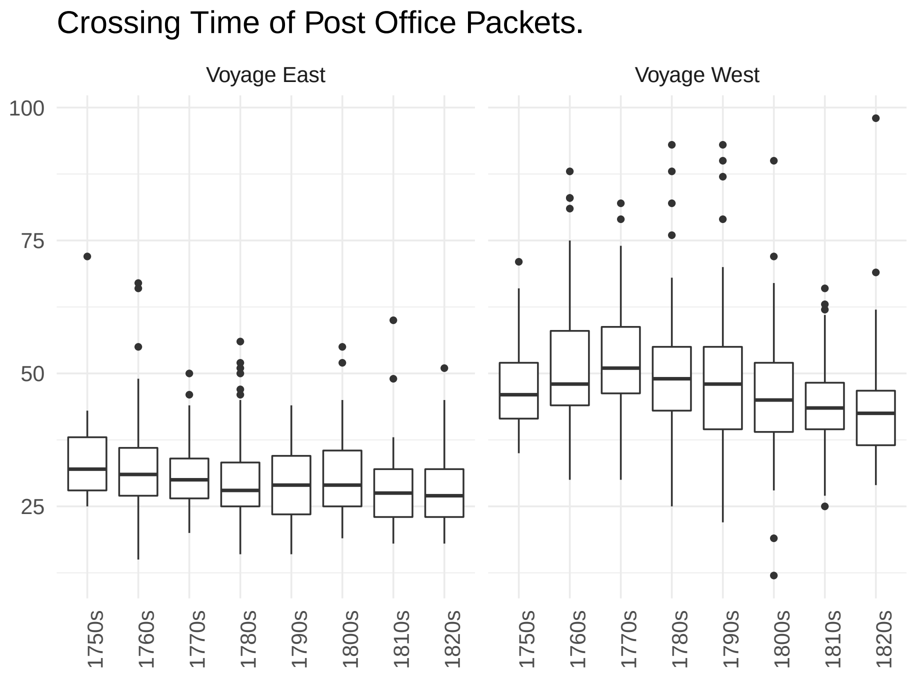

Figure 7: Crossing time for Post Office Packets, 1755–1825.

5.2 Britain: Royal Navy.

We repeat the analysis for the Royal Navy. As Table 1 shows, overall predictive power is 0.46 (this rises only to 0.47 if tonnage is added). As we would expect from the diversity of roles undertaken by these ships, this is somewhat lower than the EIC and average speed is also considerably lower. Year accounts for around 10 per cent of splits. Excluding longitude and latitude led correlation to fall to 0.38.

Figure 6 gives the predicted speed for a ship sailing at 90 degrees to the wind from 1750 to 1808, and it can be seen immediately that the pattern is very similar to the EIC with a notable jump occurring with coppering, but a steady rise after, especially in stronger winds. Overall sailing speed in stronger winds rises by around a third from 1770 to 1808, with about half of this improvement accounted for by coppering.

5.3 Britain: Post Office Packets.

From 1755 to 1825, the British Post Office operated fast sailing packets between Falmouth, in the southwest of England, and New York. Figure 7 shows the sailing time in days, excluding stopovers in Halifax, for each eastward and westward voyage for which precise arrival and departure times at each port are recorded: time in Halifax is often not reported in early decades. In wartime, packets sailed unescorted so their speed did not fall, but services were sometimes suspended or went only as far as Halifax.

It can be seen that eastward voyages—along the great circle route up the Canadian coast, and following winds and currents—are a good deal faster than westward ones, and that there is a slow downward trend—about a day per decade—in both series. Although all packets were coppered in the 1780s (Harris, 1966) the absence of a fall in crossing times during this decade is notable. Passages east were largely unaffected by season, but the slower westward passage times rise markedly in winter, with January voyages taking an average of two weeks longer than April ones.[14]

From 1819, commercial American packets—flush-decked vessels that were the direct ancestors of clipper ships—began carrying passengers and freight between New York and Liverpool with average sailing times in the 1820s of 24 days west and 38 days east (Clark, 1910, 38–39). Part of this jump in sailing speed over Post Office packets probably lay in the superior seamanship of their crews and the strong incentives of captains (who typically owned a substantial share in their vessel, and attracted passengers by individual reputations for fast crossings) to sail as hard as possible (Albion, 1938).[15] However, subsequent technological progress among these American packets can be gauged by seeing how much their sailing speed improved after their first appearance. By the late 1830s the ships of the Collins Line—whose flat bottomed hulls, originally intended to clear sandbars at the mouths of some harbours, turned out to make them considerably

[14]Years vary by storminess. However, running regressions that included the estimates of Cook, D'Arrigo and Mann (2002) on the seasonal strength of the North Atlantic Oscillation—the pressure differential between Iceland and the Azores, which determines the strength of westerly airflows—found that it had no explanatory power for sailing speed.

[15]By contrast, although the fact that their crews were immune to the press gang allowed them to attract good seamen, Post Office packets were noted for absentee captains and crews who loaded as much private cargo on board as possible, to the detriment of their sailing speed. Their occasional, unprovoked attacks to plunder smaller ships led to calls that packets should have their guns removed: Wardle (1948, 279–280).

faster than the traditional design of deep V-shaped hulls, as well as allowing more cargo to be carried—were averaging crossings in 20.5 and 30.5 days respectively (Fox, 2004, 6).[16] In other words, the average sailing speed of North Atlantic packets rose by half between the 1750s and 1840.

6 Netherlands and Spain.

CLIWOC gives daily data on the sailing speed of different categories of Dutch and Spanish ships. In contrast to British ships, these show no improvement over the period.

We summarize the generalized random forest results for the various classes of Dutch and Spanish ships considered here, and include EIC and Royal Navy results for comparison. The table shows the relative importance of each explanatory variable in the random forest, the predictive power of the fitted tree for a separate five per cent sample, the median speed in each group, and the number of observations that were usable.

It can be seen that for the Spanish and Dutch data, Year has little explanatory power (with the exception of Dutch warships where data continue into the mid-nineteenth century): speed did not rise with time. The problematic wind speed data are evident in the Dutch series: whereas it is the dominant variable for British and Spanish data (excepting the small sample of Navios, where speed falls through time) it has a less of an impact than angle to wind in Dutch records.

Looking at speed, it can be seen that all Dutch and Spanish ships (except Dutch frigates where records extend to 1850) sail a good deal slower than British East Indiamen. Among these ships, as might be expected, Spanish mail packets perform best.

6.1 Netherlands.

Figure 8 gives boxplots of average daily sailing speeds of the three main classes of Dutch ship in CLIWOC: those belonging to the VOC and MCC, and frigates, corvettes, and brigs of the Admiralty. The gap in Admiralty

[16] The fastest crossings took 16 days, with ships sometimes able to average 12 knots over a day (fifty per cent above the fastest EIC speeds in the 1770s in Figure 4), and reach a maximum speed in optimal conditions of 14 knots (Clark, 1910, 46). These speeds were easily surpassed by clippers: in 1854 one ship maintained over 19 knots for one day, a record not beaten until 1984: https://en.wikipedia.org/wiki/Speed_sailing_record.

	Year	Wind	Angle	Lat	Long	R^2	Median	N
Britain								
EIC	0.122	0.637	0.158	0.039	0.043	0.551	4.7	11,037
Royal Navy	0.088	0.646	0.166	0.056	0.043	0.459	3.7	14,063
Netherlands								
Frigates	0.055	0.186	0.588	0.116	0.054	0.380	4.8	14,618
VOC	0.034	0.369	0.424	0.101	0.072	0.317	3.6	5,409
MCC	0.022	0.158	0.600	0.068	0.152	0.373	3.0	6,581
Spain								
Fragata	0.052	0.624	0.157	0.080	0.087	0.301	3.2	4,568
Paquebote	0.037	0.592	0.227	0.050	0.093	0.390	4.0	6,861
Navio	0.079	0.239	0.095	0.460	0.126	0.483	2.6	2,715

The first five columns give the relative explanatory power of each covariate, measured by the percentage of tree splits made using that variable. R^2 is the squared correlation between the predicted and observed speed for a five per cent test sample of observations. Median is the median sailing speed in the sample, and N is the number of observations.

Table 1: Summary of generalized random forests for daily sailing speed of British, Dutch, and Spanish vessels.

observations corresponds to the French occupation from 1796 to 1814. It can be seen that there was little progress in any class of vessel, except that the median speed of naval vessels rises from around 4 knots before the French occupation to 5 knots after. The failure of the Dutch VOC to copper most of its ships until after 1815, whereas most EIC and Royal Navy ships had been coppered by the mid-1780s, is almost certainly a factor here (Solar and de Zwart, 2017). The Dutch Navy, however, seems to have coppered its fleet in the early 1780s (van Beek, 1829);[17] this may account for the very small increase in speed recorded in the second half of the 1780s.

It is particularly notable that no increase occurs in the speed of MCC slave ships, whose average speed was extremely low. It might be expected that for vessels carrying a rapidly depreciating human cargo in tropical heat, maximizing speed would have been a commercial imperative and led to the rapid adoption of coppering, as Solar and Rönnbäck (2015) found for British slave ships. However, our data give no evidence of a rise in speed in the late 1780s of the sort we observed for the EIC and Royal Navy; perhaps it is no coincidence that by this time the Dutch transatlantic slave trade was in terminal decline (Postma, 1975).

As well as daily CLIWOC data, we also have information on the duration of all VOC voyages between the Netherlands and Batavia from the early seventeenth to the late eighteenth century. For each voyage we know

[17]We are grateful to Peter Solar for this reference.

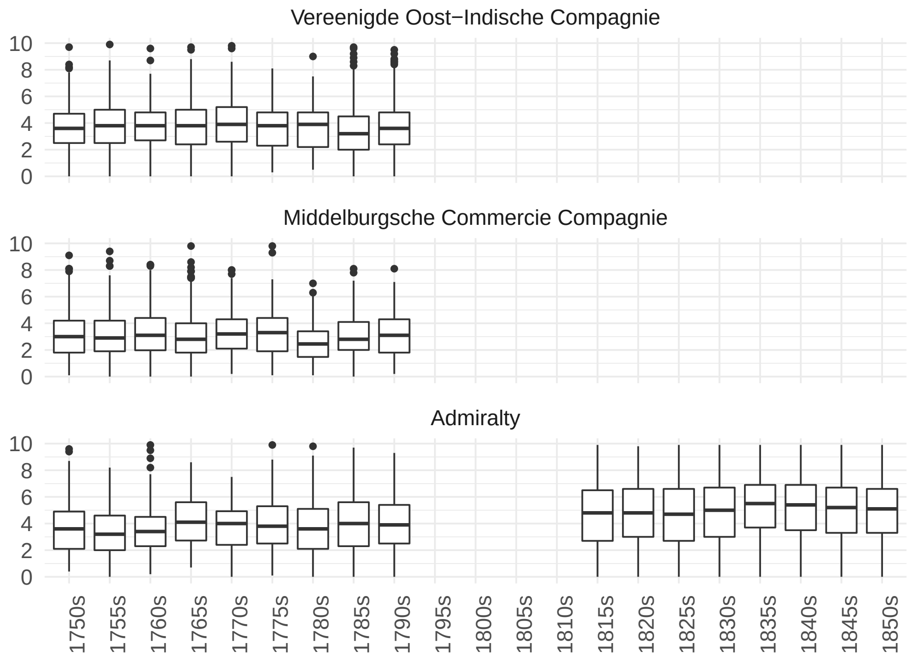

Figure 8: Average daily sailing speed for Dutch vessels, 1750–1854.

the age and tonnage of the ship. Applying a random forest to the data, the estimated model from the training sample had virtually no power to predict the withheld test sample: there was effectively no improvement in speed through time, or appreciable fall in wartime. This virtual stagnation is consistent with the findings of van Zanden and van Tielhof (2009) and van Lottum and van Zanden (2014) that the productivity growth of Dutch shipping ceased after 1650 and suggests that Dutch complaints through the eighteenth century about the technological conservatism of the VOC (Unger, 2013) were well founded.[18]

[18]The technological stagnation of the VOC is also revealed by shipboard mortality, and losses of vessels. The data give the number on board at the start of the voyage east, and the number who died en route. Sailing for months in tropical heat took a heavy toll—the median mortality was 6 per cent, and on a quarter of voyages it exceeded 12 per cent—that did not improve with time. These mortality figures are for ships that survived the voyage, and many did not. If we measure losses as ships whose destination port and date of arrival are left blank, of ships leaving the Netherlands, 3.8 per cent did not reach their destination, and this rate remains constant through the period, and the risk of loss is unaffected by the tonnage of the ship or its age. Losses on ships leaving Batavia are an implausibly high 10.8 per cent suggesting possible inaccuracies in these records, although the higher risks of wrecks on

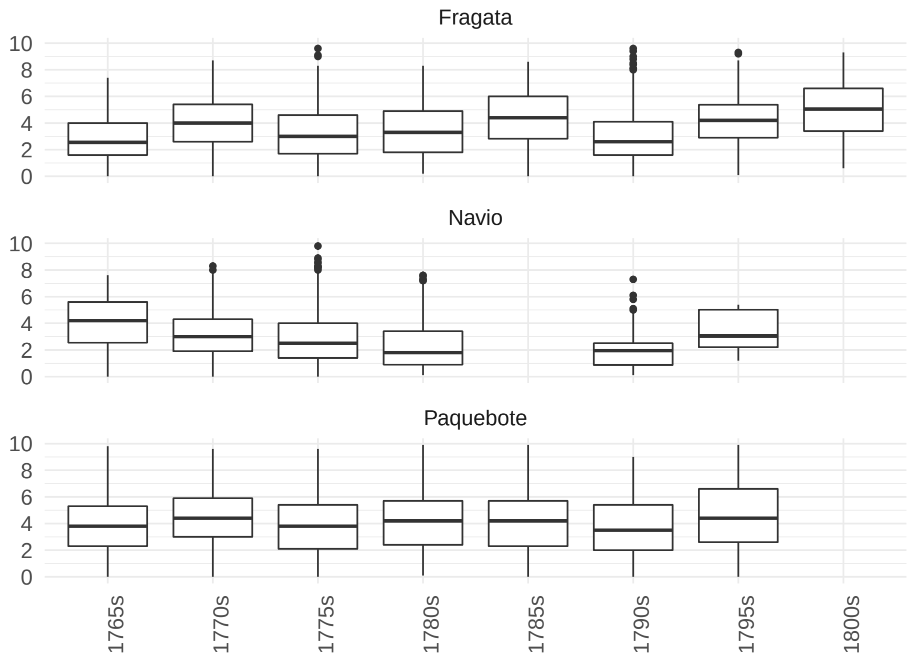

Figure 9: Average daily sailing speed for Spanish vessels, 1760–1805.

6.2 Spain.

The three main classes of Spanish ship for which data are available in CLIWOC are plotted in Figure 9. As with the Dutch vessels it can be seen that there is negligible improvement in sailing speed over this period.

7 Conclusions.

Analyses of the European economy between the early sixteenth and nineteenth centuries typically number shipping among its most dynamic sectors (see, for example, Barbour, 1930; Davis, 1972; Menard, 1991; Shepherd and Walton, 1972; Unger 2011; 2013). Europe's merchant fleet expanded from about one million tons around 1600 to 3.5 million tons by 1800, an average growth of about one per cent per annum (Unger, 1998, 258). Driving this growth was expanding trade: de Vries (2010) calculates that the Europe-

local voyages should not be discounted, as well as the fact, as a referee suggested, that the valuable cargo in returning ships may have made them a more tempting target for piracy.

Asia trade grew by an average of over one per cent per annum from around 1500 to 1800, while the much more important Atlantic trade grew at least twice as fast. For comparison, from Maddison's estimates, GDP in Western Europe grew by around 0.4 per cent per year between 1600 and 1820.[19]

The incentives to introduce stronger, faster, and safer ships are clear and in this paper we outlined the several improvements in ship design during this period. To analyse whether they affected ship performance we looked at a large database of daily sailing speeds of British, Dutch, and Spanish vessels, and found that although speed of Dutch and Spanish ships was stagnant, the speed of EIC and Royal Navy ships rose substantially after 1770, especially in stronger winds. Part of this improvement was due to coppering, as emphasized by Solar (2013), but substantial progress continued subsequently. Looking at crossing times of packet ships we found steady improvement of British Post Office packets over the period, but very substantial rises when American packets appeared in the 1820s.

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