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ICE(BERG) TRANSPORT COSTS*

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Iceberg transport costs are a key ingredient of modern trade and economic geography models. Using detailed information on Boston's nineteenth-century global ice trade, we show that the cost of shipping the only good that truly melts in transit is not well-proxied by this assumption. Additive cost components account for the largest part of per unit ice(berg) transport costs in practice. Moreover, the physics of the melt process and the practice of insulating the ice in transit meant that shipping ice is subject to economies of scale. This finding supports, from an unexpected historical angle, recent efforts to incorporate more realistic features of the transportation sector in trade and economic geography models.

Iceberg transport costs are one of the main ingredients of modern trade and economic geography models. This important *'trick of the genre'* (Krugman, 1998, p.164), was introduced by Samuelson (1954).[1] Transport costs are modelled by assuming that in order to deliver a quantity x of a good produced in i to another destination j, one needs to ship $\tau_{ij}x$ goods from i, where $\tau_{ij} > 1$. A constant fraction of the goods, $m_{ij} = \left(\frac{\tau_{ij}-1}{\tau_{ij}}\right)$, *melts* in transit. Total transport costs equal the cost of producing these *melted* goods.[2] As a result, per unit transport costs, $\mathcal{T}_{ij}$, are proportional to the good's producer price in i, p_i:

$$\mathcal{T}_{ij} = (\tau_{ij} - 1)p_i. \tag{1}$$

The iceberg assumption has important limitations. It abstracts from determinants of per unit transport costs that are not proportional to the good's producer price (e.g., specific tariffs, administrative barriers, freight costs). Also, it takes τ_{ij} as exogenous. Transport costs however often depend on the opportunity for return or onward cargoes or the competitiveness of the shipping industry, and tend to fall with individual shipment size and/or the overall quantity shipped on a route.

Despite these well-known shortcomings, see, e.g., Hummels (2007), assuming transport costs *'to be iceberg'* remains the standard in most general equilibrium models of trade and economic

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The data and codes for this paper are available on the Journal website. They were checked for their ability to reproduce the results presented in the paper.

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[1] In economic geography, von Thünen (1826) modelled the cost of transport in a very similar way. He justified it using the example of shipping grain, where part of the grain was eaten during the journey from farm to market by the horses pulling the cart of grain.

[2] Basically, the iceberg assumption implies that the transport sector produces transportation services using the exact same production function as the firm(s) producing the transported good.

geography. Its popularity stems from its synergy with the assumed utility and production functions. It provides for a mathematically elegant, tractable way to incorporate trade costs in these models, that, importantly, avoids the need to explicitly model a transport sector.

Recent papers show that deviations from iceberg transport costs can however have nontrivial (theoretical) implications. The presence of additive cost components, the degree of competition in the transport sector, the possibility to choose between different transportation modes (technologies), and the opportunity for return or onward cargoes at the destination can affect *trade flows* (see, e.g., Hummels *et al.*, 2009; Behrens and Picard, 2011; Brancaccio *et al.*, 2017; Coşar and Demir, 2018; Wong, 2019), the *type and quality of goods exported* (Alchian and Allen, 1964; Hummels and Skiba, 2004; Hummels and Schaur, 2013; Feenstra and Romalis, 2014), and even the *predicted welfare gains from trade cost reductions* (see, e.g., Behrens *et al.*, 2009; Irarrazabal *et al.*, 2015; Hornok and Koren, 2015a; Asturias, 2019). The presence of economies of scale in transport can induce firms to focus on fewer export markets, to send fewer, but larger, individual shipments while holding larger inventories in its export markets (Alessandria *et al.*, 2010; Hornok and Koren, 2015b), or to even combine shipments with other products (Holmes and Singer, 2018), possibly even made by other firms (Bernard *et al.*, 2018).

In this article, we shed light on the relevance of the iceberg assumption from an unexpected historical angle, providing empirical evidence that should only further encourage the above-mentioned attempts to *'move beyond shipping icebergs'* in trade and economic geography models. We do this using a detailed data set on the costs involved in shipping the product that gave its name to this important assumption: *ice*, the only product that literally melts in transit.

Our data primarily comes from the records of the Tudor Ice Company, Boston's leading ice exporting company that, during the nineteenth century, shipped over one million tons of natural ice all over the world on wooden sailing ships.[3] Ice(berg) transport costs in practice consisted of both a true *'iceberg'* component: *melt in transit*, as well as the standard transport cost components (*freight, landing, loading* and *insurance* costs). They are not well-proxied by the iceberg assumption for two main reasons:

First, the ice's freight, landing and loading costs were all additive. And, importantly, they were several orders of magnitude larger than the *ad valorem* melt and insurance costs. The ice trade's small, unimportant share in Boston's and each destination's overall port traffic, the importance of a destination's opportunities for profitable onward or return cargoes in determining freight rates, and of journey duration in determining freight rates as well as the insulation technology used in transit, make it very unlikely that any of these ice(berg) transport costs depended systematically on the price of the ice in Boston.

Second, ice(berg) transport costs in practice depended systematically on shipment size. Interestingly, it is melt in transit itself that is primarily to blame for this violation of the iceberg assumption. The physics of the melt process and the practice of insulating the ice in transit to prevent this melt, make ice(berg) transport subject to economies scale.

[3] Transporting actual icebergs from Antarctica to be used as a fresh water resource in the arid regions of South America, Australia and the Middle East has been seriously studied (see, e.g., Weeks and Campbell, 1973; Montfort and Oudendijk, 1979). For a very extensive RAND report on true iceberg transport costs, see Hult and Ostrander (1973). To date, no full iceberg has been shipped, but the idea is still very much alive (Gramer, 2017). Some companies are harvesting small icebergs for use in upmarket mineral water, beer, vodka or icecubes (see, e.g., Sarchet, 2015).

1. The Frozen Water Trade

The ice trade is by now a largely forgotten trade.[4] But, before the widespread adoption of artificial refrigeration and ice making in the early-twentieth century, natural ice was a heavily traded natural resource in almost all parts of the world. It was used for cooling purposes and the preservation and preparation of food, both by households and businesses. Ice houses, storing large quantities of ice, dotted the North American landscape, and many (wealthy) people's homes had a private ice cellar. To give an idea of the size of the trade, the 20 largest US cities consumed nearly 4,000,000 tons of ice in 1879 (Hall, 1880). New York alone consumed 500,000 tons per year (Encyclopedia Brittanica, 1881).

For most of history, the ice trade was very localised, with ice harvested from nearby frozen lakes, rivers or mountains. This changed in 1806 when Frederic Tudor shipped 130 tons of natural ice from Boston to the Caribbean island of Martinique. After further refining the process of insulating the ice during the voyage and at the destination, shipments to other Caribbean destinations and the main cities in the southern US quickly followed. In 1833 Tudor sent an experimental shipment to Calcutta, and upon its success expanded this long-distance ice trade to Brazil, Indonesia, China, the Philippines, Australia and even (around Cape Horn) Peru and San Francisco.[5] Drawn by the extreme profitability of the trade, other companies soon entered the market, further expanding Boston's ice trade.[6]

Figure 1 shows the rise and fall of Boston's tropical ice exports. The trade's heyday was around 1860. The rise of artificial ice making and refrigeration led to its eventual demise.[7] Natural ice first lost its competitiveness to artificial ice in tropical locations. The localised trade in natural ice lasted longer, eventually also dying out after WWI.[8]

2. Ice(Berg) Transport Costs in Practice

The ice was shipped from Boston on wooden sailing ships. The transport costs of each shipment consisted primarily of loading, freight, landing and insurance costs. On top of this, a fraction of the shipment literally melted in transit. Each cargo was insulated to limit this melt. Following his initial shipment to Martinique, Tudor quickly settled on the optimal insulation strategy. Shipping the ice in standardized rectangular blocks allowed it to be tightly stowed, limiting melt by minimising the outward exposure of the ice. And, sawdust and wood shavings, both in ample supply as waste products from Maine's lumber industry, were found to be the preferred insulation materials. For the shorter trips to the southern US and Caribbean, the ice was simply loaded onto the ship and covered on all sides with insulation material. For longer trips beyond the Caribbean, more precautions were taken and ships were fitted with a special insulated ice hold (The Mechanics' Magazine, 1836, p.10; or Scientific American, 1863, p.339).

[4] For a comprehensive historical account of the trade (see, e.g., Hall, 1880; or Weightman, 2003).

[5] Ice was mostly shipped to destinations where profitable return or onward cargo could be obtained. Boston boats previously sailed in ballast to these destinations. Ice replaced this ballast. Shipping ice without a profitable return or onward cargo was too costly.

[6] Ice in the tropics was often sold for more than 50 times its unit cost in Boston. Tudor was able to keep competition at bay in most far-flung tropical destinations (either by securing monopoly rights, or by simply lowering prices to an unprofitable level until the competitor's ice had completely melted). Competition was toughest in the southern US destinations.

[7] The North's naval blockade of southern US cities during the American Civil War spurred the development of artificial ice making machines efficient enough to compete with imported natural ice.

[8] The (very) localised trade of *artificially produced* ice still exists in many developing countries today. Eltjo still remembers the weekly deliveries of blocks of ice to his childhood home in Baghdad in 1955.

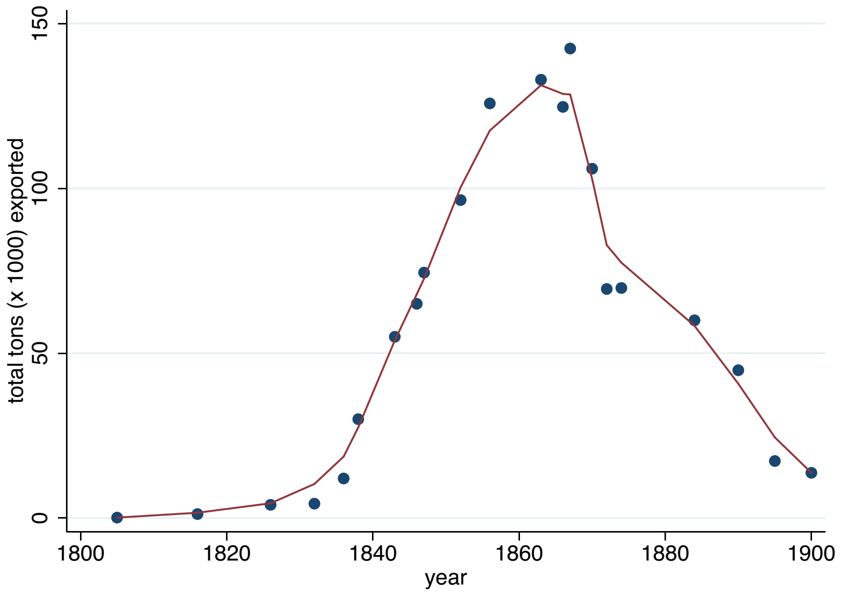

Fig. 1. *Boston's Global Ice Trade.*

Source. Herold (2011, p.168).

The Tudor Company chartered ships to deliver the ice in its tropical destinations. They were only chartered for the outward journey. Freight costs were usually paid on the intake weight (Parker, 1981, p.5; Wyeth, 1848, p.180). They were relatively low as most ships would otherwise have sailed in ballast.[9] The bills of lading specified additional melt mitigating measures to be taken by the crew during the voyage: the hold was to be kept closed at all times, and the meltwater had to be regularly pumped out until all the ice had been discharged (Proctor, 1981, p.5). Dock workers were hired to load the ice onto the ship in Boston and fitted it with insulation material. Upon arrival, the ice ships were oftentimes given right of way on the docks (to limit melt). Local dock workers were hired to offload the blocks of ice and stored them in the company's local ice house.[10]

2.1. *Melt and Transport Costs*

One scribble in the *Tudor Company Records* shows exactly how melt and transport costs together drove a wedge between the ice's unit cost in Boston and that in a particular destination. At the

[9] Prior to the ice trade, Boston's trade with the Caribbean, Asia, and South America was primarily a one-way trade: Boston ships sailed out in ballast and returned with cargoes of cotton, hemp, sugar and other tropical commodities (Boston Board of Trade, 1862; Parker, 1981, p. 6; Dickason, 1991, p. 64). The ice trade even expanded Boston's export portfolio: a few ships also carried apples, butter and cheese. Their main icy cargo ensured that these perishables arrived well-preserved at their destination.

[10] Ice was exempt of (im)port duties. There was simply no local industry to protect with import duties. Also, the Tudor Company effectively had a monopoly in most of its destinations, so that it would simply pass on any (im)port duties to the consumer(s).

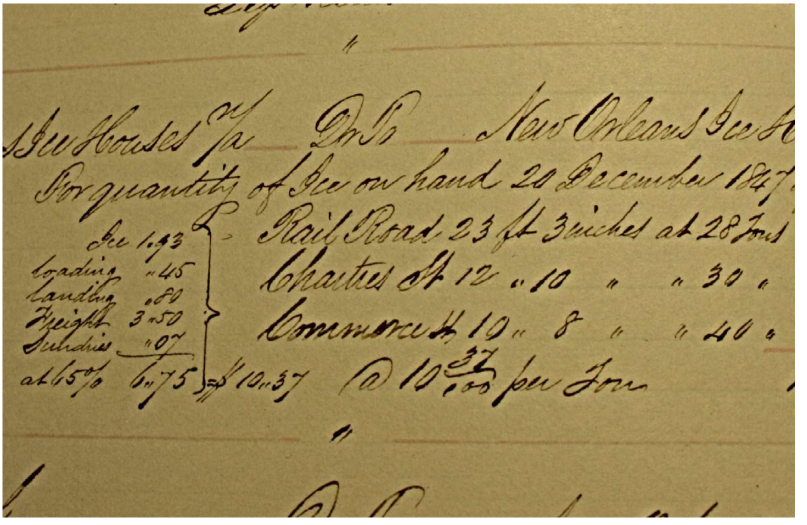

Fig. 2. *Calculation of Per Unit Cost of Ice in New Orleans (1847).*
Source. The Tudor Records, Tudor II, Volume 3.

end of each year, the Tudor Company had to value its remaining stock of ice in each destination for accounting purposes. It did this at the per ton cost of the ice in each destination.The scribble, shown on the left of Figure 2, is the only time that the Tudor Records detail how the firm calculated its unit costs in a particular destination (New Orleans in 1847).

First, they paid for the ice in Boston ($1.93 per ton). Next, they paid different transport costs per ton to ship the ice from Boston to its destination, i.e., loading ($0.45), freight ($3.50), landing ($0.80), and other (small) miscellaneous costs (sundries: $0.07). Finally, melt kicked in. Only a fraction of each unit shipped from Boston arrived at the destination: an iceberg transport cost in the literal sense. Overall, the cost per unit of ice *landed* in each destination equals the per unit cost of the ice *loaded* in Boston *including all transport costs* ($6.75 in total) divided by the fraction of the ice surviving the journey (65%, or 0.65),[11] explaining the $10.37 per ton at which the company valued its remaining stock of ice in New Orleans in 1847. For comparison, the sales price in New Orleans in that year averaged $35 per ton (Wetherell, 1863).

Using the scribble, we can write the transport costs incurred per ton of ice *landed in destination* j in year t as (all shipments depart from Boston so that we suppress the origin index i from now on):

[11] The Tudor Company Records do not further specify the 65% 'melt markup' in the scribble. It is hard to ascribe it to anything but melt however. The company had a very good idea of the substantial differences in melt that shipments to different destination were suffering (see also footnote 19). The cases of actual reported melt for New Orleans are 35%, 33% and 20%, and a shipment to Pensacola (1–2 sailing days closer to Boston than New Orleans) reports 27.5% melt; see Subsection 3.1 or Appendix A.1 for more details. The 35% used by the firm in the scribble is on the higher end of these numbers. The firm may have used a conservative melt estimate, or might also take melt at the destination into account. The only evidence that we have on local melt concerns the stock of ice in Calcutta. The percentage of local melt there is much higher (up to 50%) than would be implied by the difference between the 35% melt markup used in Figure 2 and the 29.3% average melt in transit to New Orleans in our data, making it unlikely that the reported producer price also takes local melt into account. If at all, the firm might have also taken the ice lost *while offloading* into account.

$$\mathcal{T}_{jt} = p_{jt} - p_t^B = \left(\frac{p_t^B + f_{jt}^{\text{load}} + f_{jt}^{\text{land}} + f_{jt}^{\text{freight}} + f_{jt}^{\text{sundries}}}{1 - m_{jt}} \right) - p_t^B$$
$$= \underbrace{\left(\frac{m_{jt}}{1 - m_{jt}} \right) p_t^B}_{\text{`pure melt' cost}} + \underbrace{\left( \frac{f_{jt}}{1 - m_{jt}} \right)}_{\substack{\text{`melt augmented'} \\ \text{transport cost}}}, \tag{2}$$

where $f_{jt} = f_{jt}^{\text{load}} + f_{jt}^{\text{land}} + f_{jt}^{\text{freight}} + f_{jt}^{\text{sundries}}$ denotes the transport cost per ton *loaded in Boston*. p_{jt} and p_t^B denote the producer price of the ice in j and in Boston respectively. f_{jt}^{load}, f_{jt}^{land}, f_{jt}^{freight} and f_{jt}^{sundries} capture the cost of loading the ice in Boston, the cost of offloading the ice in j, the freight costs involved in shipping the ice from Boston to j, and any other miscellaneous transport costs (notably insurance), respectively.[12] Finally, m_{jt} denotes the fraction of the ice that melts in transit.

Comparing equation (2) to (1), immediately reveals that ice(berg) transport costs in practice are well-approximated by the iceberg assumption if two conditions are met:

1. **Melt**: the fraction of ice melting in transit, m_{jt}, is exogenous; it does not depend on the price nor the quantity of the ice shipped.
2. **Transport costs**: the transport cost per ton of ice loaded in Boston, f_{jt}, is proportional to the producer price of the ice in Boston; it does not depend on the quantity of ice shipped.

The first condition is unique to the ice trade. Despite the fact that melt in transit poses a true *ad valorem 'iceberg'* cost, the iceberg assumption would still be violated if melt in transit varied systematically between shipments depending on either the price or quantity of the ice shipped. The second condition is nothing but the standard iceberg assumption, now applied to all costs involved in loading, offloading, insuring and transporting the ice between Boston and a particular destination.

3. Iceberg Transport Costs in Practice?

3.1. *Data*

Most of our data comes from the *Tudor Company Records* that are located in the Baker Library of the Harvard Business School. All our information on the prices and quantities of ice shipped from Boston, the freight, loading, landing and insurance costs incurred when shipping the ice, as well as on the (producer) prices in each destination are taken from these records. We complement it with information from the *US Maury Collection* on the average sailing days to each destination. The Maury collection, that is available through the US National Oceanic and Atmospheric Administration, contains information on the duration of over 12,000 voyages made by US ships over the period 1784–1863. Most of these trips (about 11,000) took place between 1830–63, exactly the period best covered in the Tudor Company Records. Finally, we collected data on actual melt in transit. With the exception of the average yearly fraction of ice lost in transit to Calcutta over the period 1833–50, the Tudor Company Records do not report melt. Our 47 melt observations come from a variety of sources, including newspapers, journal articles,

[12] The observed landing costs of individual shipments arriving in New Orleans in 1847 reveal that the firm also reports these costs as the landing costs per ton of ice *loaded in Boston*. The 65% 'melt markup' on these landing costs would not have been necessary if they had been reported per ton actually *offloaded*.

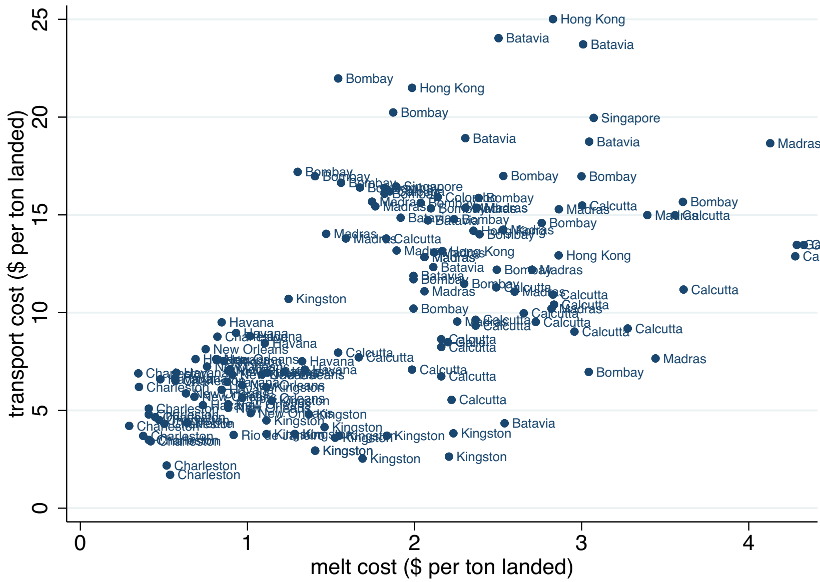

Fig. 3. *'Pure Melt' vs 'Melt Augmented' Transport Costs.*
Notes: The 'pure melt', and 'melt augmented' transport costs per ton landed are calculated as in (2), where we make use of our data on producer prices in Boston and in each destination, as well as the (predicted) melt on each route. This predicted melt measure is based on a regression of actual observed melt on the number of sailing days to each destination (distinguished by the type of insulation regime used by the Tudor Company); see Subsection 3.3 for the details.

contemporaneous accounts of the ice trade, and books written on the trade. Appendix A.1 details their exact sources.

Overall, our data set covers shipments to 28 destinations over the period 1806–80. Most observations are from the 1840–80 period however, the heyday of Boston's global ice trade (see Figure 1). From the Tudor Company Records alone we have information on 1,469 shipments of ice. For each of these shipments, we know the amount of ice loaded onboard in Boston, the cost of fitting, loading and insuring this ice, the price that the Tudor Company paid for it in Boston (its unit costs), as well as producer prices (unit costs) in each destination. Freight and landing costs are much less well recorded: we only observe these for 66 and 62 shipments respectively (for 59 shipments we observe both) that sailed from Boston to Calcutta (32), New Orleans (25), Charleston (7), Mobile (2), Bombay (2) and Madras (1) in the earlier years of our sample (1846–50). Appendix A.3 provides summary statistics of the most important variables for each destination reported in the Tudor Company Records.

3.2. *Melt vs Transport Costs*

Figure 3 shows the relative importance of the 'pure melt', and 'melt augmented' transport cost components that together make up ice(berg) transport costs in practice; see (2). It plots the average melt cost per ton of ice *landed in a destination* against the average transport cost per ton of ice *landed in a destination*.[13] These 'pure melt', and 'melt augmented' transport costs per ton

[13] Figure A2 shows that a very similar picture emerges when instead plotting the melt and transport costs per ton *loaded in Boston* against each other. Also, column 9 of Table A2 in Appendix A.3 reports the average transport cost per

are calculated as in (2), where we make use of our yearly data on producer prices in Boston and in each destination, as well as the (predicted) melt on each route. Inferring transport costs from producer price differentials is, in fact, a unique feature of our paper. Earlier papers typically rely on sales price differentials of identical goods between locations to do so (see, e.g., Anderson and van Wincoop, 2004; Atkin and Donaldson, 2015). Such sales prices differentials can however also reflect differences in consumer preferences or market structure between destinations.[14]

To all destinations, the transport costs component dominates the melt component in determining overall ice(berg) transport costs in practice. On average, 'pure melt' makes up just 15% of the total ice(berg) transport costs per ton. This is simply due to the fact that the producer price of the ice in Boston, p_t^B, was always (much) smaller than the combined transport cost per ton loaded onboard in Boston, f_{jt}.[15] We also observe substantial variation between destinations and years in both the melt and transport cost components, with the variation in the latter again being dominant in determining the overall variation in ice(berg) transport costs, both within- and between destinations.

In the next subsections, we focus on **Conditions 1** and **2**, and verify how well this variation in ice(berg) transport costs in practice is captured by the iceberg assumption.

3.3. *Melt*

We first establish whether or not the fraction of the ice that melts in transit is well-approximated by an exogenous constant that does not vary with the price nor quantity of the ice shipped; **Condition 1**. The Laws of Physics tell us that melt depends positively on the duration of the journey and the temperature difference between the ice and the surrounding sea/air. Also, it depends negatively on the value of the heat transfer coefficient (crucially determined by the measures taken to insulate the ice), and the exposed surface area of the ice.[16] Importantly, the latter implies an immediate violation of the iceberg assumption: all else equal, a factor x larger load of ice only increases the exposed surface area by approximately $x^{\frac{2}{3}}$, resulting in less melt *per unit of ice shipped*. Melt makes the transportation of ice subject to economies of scale.[17]

In this section we show that melt in transit, in the data, is nevertheless well approximated by the iceberg assumption. It is well captured by a destination-specific constant that depends primarily on the duration of the journey and the insulation regime chosen by the Tudor Ice Company. The

ton of ice *loaded in Boston* for each destination. It is more easily comparable to the per ton freight, loading and landing costs reported in the Tudor Company Records that are all per ton of ice loaded in Boston.

[14] The Tudor Ice Company sold the ice at prices ranging from two to twenty times the reported producer price, depending on the destination. It faced competition in its southern US markets, whereas it enjoyed full monopoly power in most of its Asian, Australian and South American markets. See Atkin and Donaldson (2015) for a detailed discussion on the use of price differentials between locations to infer transport costs.

[15] This result is robust to any plausible measurement error in the construction of our predicted melt measure; see Subsection 3.3. The median (mean) producer price of the ice in Boston is \$2.65 (\$2.82) per ton, so that even when all ice would have melted, the 'pure melt' cost would still be substantially smaller than the other transport cost components combined for all but the very closest destinations—see column 9 in Table A2.

[16] Newton's Law of Cooling approximates the convective heat transfer between the melting ice and its surroundings. It states that the energy transferred between the surrounding air and the ice (that drives melt) at time t equals: $dQ/dt = hA\Delta T(t)$, where h is the heat transfer coefficient, A the exposed surface area and $\Delta T(t)$ the temperature difference between the air and ice at time t. Precisely modelling the melting process is much more complicated, it involves among others physics, chemistry, and differential calculus, to take into account, e.g., the changing shape of the melting block, the nonconstant outside temperature, the purity of the ice, and the different modes of heat transfer (convection, conduction, advection or radiation) (see, e.g., Fukusako and Yamada, 1993).

[17] See also, e.g., Hummels and Skiba (2004), Stopford (2009), or Coşar and Demir (2018) for a discussion, and evidence, of economies of scale in transport (for different reasons than melt).

remaining variation in melt between shipments going to the same destination in the same year is not systematically related to shipment size.[18]

The Tudor Ice Company used two different insulation regimes: one for shipments to the US south and Caribbean, and another, better one for shipments to Asia, South America and Australia (see Section 2). This clearly shows in the data: the per ton cost of fitting and loading the ice onboard in Boston is an average \$0.51 (SD \$0.14) for 'standard' shipments to the US South and Caribbean, and an average \$1.16 (SD \$0.28) for 'tropics' shipments to destinations further away. Given this choice of insulation regime, melt depended primarily on the length of the journey.[19]

Figure 4 shows the relationship between melt and sailing days for shipments using a standard, tropics or minimal insulation regime. The latter concerns two of Tudor's earliest shipments to Martinique (in 1806) and Havana (in 1807), and two reshipments from the ship *Walpole* bound for Calcutta that had to make an emergency stop in Mauritius in 1854 (*New York Daily Tribune*, 1854). On average, one extra sailing day resulted in 2.25ppt, 1.36ppt, 0.42ppt additional melt loss in case of the minimal, standard and tropics insulation regime respectively.[20] Strikingly, variation in sailing days alone explains 82% and 80% of the variation in melt in case of the standard and the tropics insulation regime (55% in case of minimal insulation).[21]

One complication in showing the role of shipment size in explaining the remaining unexplained variance is that we observe melt ànd shipment size for only one 'standard' shipment to London, and ten 'tropics' shipments. Regressing both shipment size and the number of sailing days on melt for these ten 'tropics' shipments shows that shipment size is, conditional on the duration of the journey and insulation regime, not significantly related to melt.[22] But, of course, the (very) small sample could be to blame for this.

Under a mild assumption, we can however use the available shipment-specific information on the quantity of ice loaded onboard in Boston, and the total landing costs paid upon arrival in the destination *per ton loaded in Boston*—see footnote 12—to shed further light on the existence of a systematic relationship between melt in transit and shipment size. This information is available

[18] We do not pay explicit attention to the fourth melt determining variable: the temperature difference between the melting ice and the outside sea/air temperature. Most shipments left Boston at the same time of year (winter/early spring), so that there was hardly any variation between shipments sailing to the same destination in the outside sea/air temperature. Including the average January and/or July temperature in the destination to our regressions as a proxy for this, does not change the results shown in Figure 4 in any way, whereas these temperature variables themselves are highly insignificant.

[19] See Subsection 3.4.2 and Appendix A.2 for an in-depth discussion of the firm's choice of insulation regime. This choice, and thus melt in transit, in principle, does depend on the producer price of the ice in Boston. In practice, however, its single-most important determinant was a destination's sailing distance from Boston.

[20] Only in case of the minimal regime does this number change (to 1.69ppt) when including a constant to the regression.

[21] There is very little reason to believe that melt changed systematically over our sample period. Figure A3 in Appendix A.3 illustrates this for Calcutta, the only destination for which we observe melt for a sufficient number of years to draw meaningful inferences. The Tudor Company quickly settled on the optimal way to insulate the ice in transit (see Section 1). Also, there were no major improvements in the design of the ships used for transporting the ice nor in sailing techniques during our sample period. Ice was primarily shipped on wooden-hulled (to avoid rust) schooners, barques, brigs or full rigged ships. The faster clipper ships introduced in the second half of the nineteenth century were only sporadically used for the ice trade. Also, ice was not shipped on steamships. Until the late nineteenth century this was not profitable as there was simply not enough room left for the ice in the cargo hold after loading sufficient coal to take the steamship from Boston to its tropical destination. The data in the US Maury collection indeed shows no systematic change in the number of sailing days from Boston to any of the destinations in our sample. Figure A4 in Appendix A.3 illustrates this in case of New Orleans and Calcutta. Including year dummies to allow for general changes in shipping/insulation technology over the years in our sample hardly affects the point estimate of the relation between melt and the number of sailing days nor its significance.

[22] The estimated coefficient on the tons of ice loaded in Boston is 0.003 (SE 0.003). The estimated coefficient on the number of sailing days is very similar to that depicted in Figure 4: 0.41 (SE 0.04).

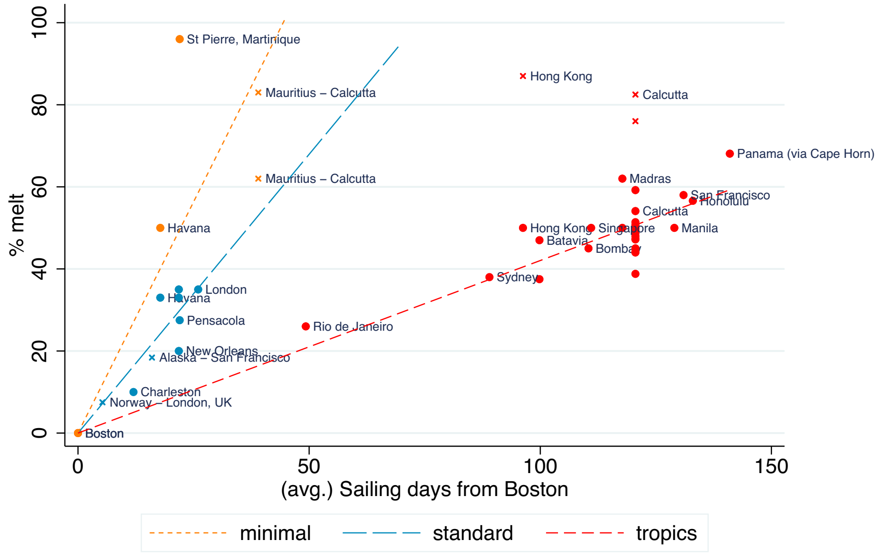

Fig. 4. *Sailing Days and Insulation Explain Melt in Transit.*
Notes: Minimal, *standard*, *tropics* refers to shipments with minimal insulation, good insulation (for shipments to the US south and Caribbean), and the best insulation (for shipments to South America, Asia and Australia) respectively. The plotted lines are fitted regression lines that are forced to go through the origin. The slopes of these lines are 2.25, 1.36, 0.42 for the minimal, standard, and tropics regime respectively (all significant at the 1% level using standard errors clustered at the destination level). The observations marked with an ‘x’ concern special observations. For the minimal and standard regimes, this concerns shipments with a different origin than Boston (two reshipments from the *Walpole* bound for Calcutta that had to make an emergency stop in Mauritius, one shipment from Norway to London, and the average melt loss over the period 1852–67 for 88 shipments between Kodiak, Alaska and San Francisco). For the tropics regime this concerns three outliers that are not used to draw the regression line: two documented failures (one to Hong Kong, and one to Calcutta), and one case in which melt is reported for a Calcutta shipment on the ship *Arabella* whose departure from Boston we cannot confirm in the Tudor Records. See Appendix A.1 for the exact source of each melt observation.

for 59 shipments. To see how this works, first note the following identity:

$$f_{jt}^{\text{land},k} = \frac{C_{jt}^k}{(Q^B)_t^k} = \underbrace{\left(\frac{Q_{jt}^k}{(Q^B)_t^k}\right)}_{1-m_{jt}^k} c_{jt}^k, \tag{3}$$

where k and t index individual ships and years respectively. m_{jt}^k denotes the fraction of ice that melted during ship k's transit from Boston to j, $(Q^B)_t^k$ and Q_{jt}^k the quantity of ice that ship k *loaded* in Boston and *landed* in destination j respectively, and C_{jt}^k and c_{jt}^k the total and per ton cost incurred to offload the surviving ice.

Using (3), we can infer the existence of a systematic relationship between melt and shipment size by looking at the significance of α in the following regression:

$$\ln f_{jt}^{\text{land},k} = \alpha \ln(Q^B)_t^k + \gamma_{jt} + \epsilon_{jt}^k, \tag{4}$$

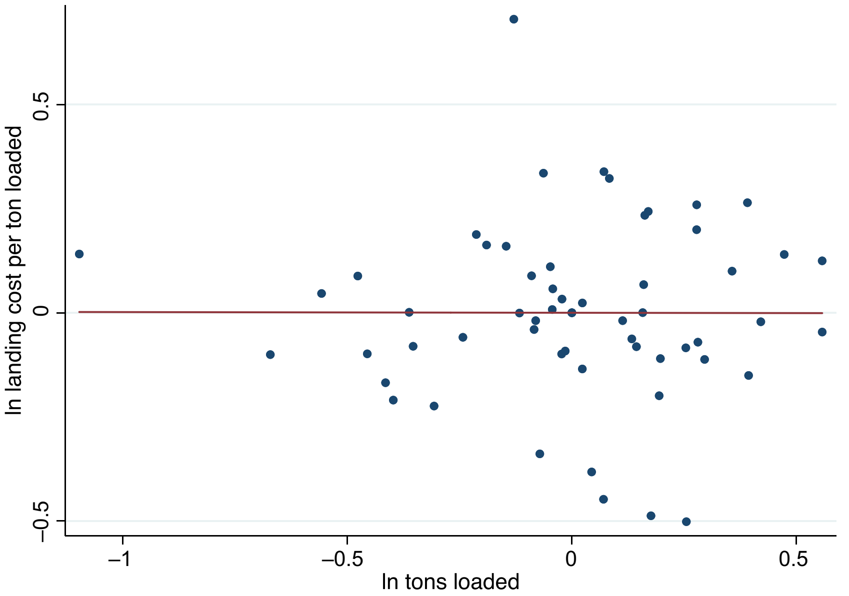

Fig. 5. *Melt in Transit Unrelated to Shipment Size (by boat).*
Notes: The figure plots the residuals of a regression of $\ln f_{jt}^{\text{land},k}$ on a full set of origin-destination-year dummies (on the y-axis) against the residuals of a regression of $(Q^B)_t^k$ on a full set of origin-destination-year dummies (on the x-axis).

where γ_{jt} captures any destination-year specific factors explaining differences in melt (notably the insulation regime used, (average) journey duration and the (average) outside sea/air temperature during the journey). Given that $f_{jt}^{\text{land},k}$ only proxies the fraction of ice surviving in transit up to c_{jt}^k—see (3)—the validity of this exercise depends crucially on the assumption that the quantity of ice loaded onboard in Boston, $(Q^B)_t^k$, is, *conditional upon the included destination-year fixed effects*, uncorrelated to a shipment's per ton landing cost, c_{jt}^k, that is, by construction, part of ϵ_{jt}^k in (4).[23]

Under this plausible assumption,[24] Figure 5 clearly shows no evidence that the variation in shipment size helps to explain the observed variation in melt in transit.[25] Of course, this does not lead us to question the Laws of Physics. What it does show, is that, in practice, variation in shipment size was a relatively unimportant determinant of the observed variation in melt in transit.[26] The unexplained variance in Figure 4 can much more likely be attributed to the

[23] Note that our inclusion of destination-year fixed effects also mitigates any reverse causality concerns. The landing costs per ton landed were determined by the local supply of and demand for dock workers. Given the small size of the ice trade in each destination's overall imports, it is very unlikely that they will have varied between ships sailing to the same destination in the same year. And, even if they did, this variation would not yet have been known at the time the boat departed from Boston. As such, they will not have been a causal driver of the observed differences in shipment size between ships sailing to the same destination in the same year.

[24] Dock workers hired to offload the ice were typically paid an hourly (or daily) wage, making it even unlikely that landing costs per ton depended on the quantity of ice *offloaded*.

[25] $\hat{\alpha} = -0.002$ (SE 0.102). It is depicted by the slope of the solid regression line in Figure 5.

[26] The γ_{jt} explain 87% of the overall variation in $\ln f_{jt}^{\text{land},k}$.

substantial variation between shipments in time in transit,[27] and in the adherence of the crew to the agreed melt mitigating measures (see Section 2).[28]

Summing up, the physics of the melting process itself implies an immediate violation of the iceberg assumption: transporting ice is subject to economics of scale. However, in practice, that these economies of scale were overshadowed by other, much more important, melt determining factors. Melt in transit primarily depended on the (average) duration of the journey and choice of insulation regime that both did not depend on the price nor quantity of ice shipped. As such, the iceberg assumption approximates the melt-related component of ice(berg) transport costs in practice rather well.

3.4. *Transport Costs*

Next, we turn to **Condition 2** and focus on the actual transport costs paid to transport the ice. As illustrated in Figures 3 and A2, these costs made up the lion's share of ice(berg) transport costs in practice, accounting for over 85% of them. From the scribble in the Tudor Archives, see Figure 2, we know that these transport costs consisted of four components: *freight* costs, *landing* costs, *fitting and loading* costs, and *sundries*. Sundries were a negligibly small part of total transport costs (2¢−7¢ per ton), that primarily consisted of the cost of insuring the ice in transit. These insurance costs were paid as a fixed percentage of the total value of the ice loaded onto a ship,[29] i.e., they adhere to the iceberg assumption by definition. We focus on the other three components from now on, and show that they are, in contrast to melt in transit and these insurance costs, not well-approximated by the iceberg assumption: they are additive cost components that, moreover, depend systematically on shipment size.

3.4.1. *Additive loading, freight and landing costs*

Per unit transport costs did vary substantially across the years and destinations served by the Tudor Company, and even between shipments sent to the same destination (see, e.g., Figure 3). At the same time, the Tudor Records show that the per ton cost of the ice in Boston was identical for all shipments sent out in the same year, regardless of the final destination. This complicates things as we lack the necessary variation in producer prices between shipments departing from Boston in the same year (to the same destination) to convincingly establish whether per unit transport costs are proportional to producer prices or are instead, at least partially, additive in nature using, e.g., the approach in Hummels and Skiba (2004).[30] Nevertheless, in this subsection, we set out why it is very unlikely that either the loading, freight, or landing costs were systematically related to the producer price of the ice in Boston. Instead all these costs were additive in nature, and did not depend on the ice's unit value at all.

Fitting and Loading: First, the ice had to be loaded on board and insulated. The dock workers loading the ice onto the ship were paid a daily or hourly wage. This wage depended

[27] In the US Maury data, the standard deviation of sailing days for shipments to Calcutta is 19 days on an average trip of 124 days. For New Orleans these numbers are 6 and 21 days respectively. See also Figure A4 in Appendix A.3.

[28] Also, (some of) the reported melt numbers are likely to include the ice lost while offloading. The number of sailing days and the choice of insulation regime are clearly imperfect predictors of this loss.

[29] 1–1.5%, with no systematic differences over time, between destinations, nor between shipments sent to the same destination in the same year.

[30] We could of course rely on the variation in the per ton cost of the ice in Boston over time in doing so. However, this would preclude us from allowing τ_{ij} in (1) to vary over the years. The destination-year dummies that would have to be included to the regression to do so, would simply leave us without any variation to identify the coefficient on producer prices. There is nothing in the iceberg assumption that does not allow τ_{ij} to (exogenously) vary over the years.

on the total number of ships in port that needed to be (off)loaded regardless of their cargo and destination/origin, and was often set by dock worker unions (Holmes and Schmitz, 2001). Even in the ice trade's heydays, ships carrying ice constituted a much too small fraction of Boston's total port traffic to have been an important determinant of these wages.[31] The Tudor Company did endogenously choose how well to insulate the ice in transit, trading off the cost of additional insulation material against the benefit of less expected melt. This choice did, in principle, did depend on the producer price of the ice in Boston (see Subsection 3.4.2). In practice however, the sailing distance from Boston was the only important determinant of this choice. As such, the cost of fitting and loading the ice per ton did not vary with producer prices.

Freight: The Tudor Company chartered the ships carrying the ice. Freight costs were relatively low as ice replaced the ballast that these ships would otherwise have had to carry to, and dispose of in, each destination. They were usually paid on the intake weight. A bargaining process with the owner of the ship determined the freight rate per ton paid by the Tudor Company (Proctor, 1981). Journey duration was one of the most important determinants of these freight costs. It determined the total wage bill paid to the crew, as well as the typical ship type plying the route (larger vessels were used in long-distance ocean shipping as they were better to handle on the high seas). But, we do also observe substantial differences in freight costs between destinations located at roughly equal sailing distance (compare, e.g., Calcutta and Galle to Batavia, Hong Kong and Singapore; or Kingston to Charleston; see also Table A2 in the Appendix). Generally, (average) freight rates were lowest to destinations offering the best opportunities for profitable return or onward cargoes, and to those importing little from Boston. The number of ships sailing out to these destinations in ballast, and thus potentially looking for ice to serve as a cheaper alternative, was simply the largest (explaining the low rates to, e.g., Calcutta and Kingston). On top of this, any differences in the experience of the ship owner/crew in sailing to a particular destination and/or in shipping ice, and how quickly the ship would be ready to depart mattered in explaining the observed variation in per ton freight costs between shipments going to the same destination in the same year.[32] It is very unlikely that the price that the Tudor Company paid for the ice in Boston had any bearing on the agreed freight rate per ton.

Landing: Finally, upon arrival in its final destination, the ice had to be offloaded. The local dock workers hired to do this were paid an hourly or daily wage. This wage depended primarily on the total number of ships in port that needed to be (off)loaded, as well as on the local supply of dock workers. As in Boston, the ice trade simply made up a much too small percentage of the total port traffic in each destination, for any of its characteristics to affect these costs. The price paid for the ice in Boston certainly did not have any bearing on these costs.

3.4.2. *Choice of shipping (insulation) technology*

As described in Section 2, the Tudor Company used two different technologies to insulate the ice in transit. Using the better insulation regime, a lower fraction of ice was lost per day in transit (see Figure 4), but at a higher per ton cost to insulate the ice on board. In other words, the firm

[31] Total foreign and coastal clearances from Boston's port were 3,198 and 2,526 in 1847 and 2,979 and 3,078 in 1849 (*The Merchants' Magazine and Commercial Review*, 1848; 1850). The number of foreign and coastal ice shipments by the Tudor Company in those years were only 13 and 35 in 1847 and 19 and 32 in 1849. And, in 1855, the total number of East Asia and Pacific clearances from Boston's port were 75 (*The Merchants' Magazine and Commercial Review*, 1856), of which only 9 ships carried Tudor ice.

[32] See North (1968; 1965) for more detail on the determinants of ocean freight rates in the nineteenth century.

faced a trade-off between a low *ad valorem*, high specific trade cost insulation technology and another, higher *ad valorem*, but lower specific trade cost technology.

Interestingly, this trade-off is very similar to that in Rua (2014) and Coşar and Demir (2018), who model the choice between breakbulk or container shipping, or that in Hummels and Schaur (2013) who focus on the choice of using air or ocean shipping. In the latter paper firms trade-off the higher additive cost of using air shipping against the benefit of being able to charge higher prices for goods that arrive more timely when using this mode of transport (see Hummels and Schaur, 2013, p.2939). Just as in our setting, time in transit increases the likelihood of using the more expensive shipping technology, as the cost savings in terms of quality loss (melt loss in our case) are larger when shipping goods to farther off destinations.

In Appendix A.2 we formally derive what determines the optimal choice of insulation technology. Just as in Hummels and Schaur (2013), Coşar and Demir (2018) or Rua (2014), this choice depends on the marginal cost of production, which in our case is simply the price that the Tudor Company paid for the ice in Boston. It implies that, even though ice(berg) transport costs in practice consisted for the largest part of additive transport cost components, see Subsection 3.4.1, the choice of insulation technology makes them, de facto, depend on producer prices. But, in contrast to the iceberg assumption, they, even those associated with melt, increase *less than proportionally* with these prices—see Figure A1 in Appendix A.2.

In practice, however, the Tudor Company always used the same insulation regime to a particular destination. It never changed this in response to the observed changes in ice prices in Boston. A destination's sailing distance from Boston was the single-most dominant factor determining this choice of insulation technology. The better, more expensive, insulation technology was simply the only option for all farther-off destinations, regardless of the price paid for the ice in Boston: all ice would melt away when using the other, cheaper insulation technology. For nearby destinations instead, the better, more expensive insulation regime is never used by the Tudor Company. We show suggestive evidence that producer prices were simply never high enough to induce a switch to using this technology for shipments to these destinations (see Figure A1).

As such, the role of the ice's producer price in Boston in determining the choice of insulation regime was very limited, if not absent. The loading, freight and landing costs paid to ship the ice to its various destinations did, in practice, not depend on the price paid for the ice in Boston, neither directly nor indirectly through their dependence on the Tudor Companies choice of insulation regime.

3.4.3. *Economies of scale*

Even though most of the ice(berg) transport costs in practice consisted of additive and not *ad valorem* cost components, one could still argue that they were, in fact, still *perfectly well-proxied* by an *ad valorem* iceberg specification. The lack of variation in the producer price of the ice between shipments leaving Boston in the same year implies that each individual shipment's per unit transport costs can be written as a shipment-specific constant multiplied by the prevailing producer price in Boston in that year; see (1). However, we show that, instead of being exogenous as implied by the iceberg assumption, this shipment-specific constant depends systematically on shipment size: shipping ice is subject to economies of scale. Interestingly, it is the practice of insulating the ice in transit that is primarily to blame for this.

We show this by regressing the available individual shipment-specific freight, fitting and loading, and landing costs per ton (as well as their sum) on a full set of destination-year dummies as well as the quantity of ice loaded onboard in Boston. An obvious concern in interpreting our

Table 1. *Iceberg Transport Costs in Practice?*

Dep.var.:	(1) $\ln f_{jt}^{\text{load},k}$	(2) $\ln f_{jt}^{\text{load},k}$	(3) $\ln f_{jt}^{\text{freight},k}$	(4) $\ln f_{jt}^{\text{land},k}$	(5) $\ln f_{jt}^{\text{load+freight+land},k}$
$\ln(Q^B)_t^k$	-0.235^{***}	-0.220^{***}	-0.013	-0.002	-0.064^{**}
	(0.038)	(0.038)	(0.006)	(0.102)	(0.018)
FEs	*jt*	*jt*	*jt*	*jt*	*jt*
N	1,469	63	63	59	54
R^2	0.92	0.94	0.87	0.86	0.78
R^2 if only FEs	0.90	0.93	0.87	0.86	0.78

Notes: Standard errors clustered at the destination level in parentheses. *, **, *** denotes significance at the 10%, 5%, 1% respectively. Column 2 shows results when restricting the sample to those shipments for which either also per unit freight costs or per unit landing costs are available.

results is that of reverse causality: lower transport costs causing the Tudor Company to send larger shipments. The inclusion of destination-year fixed effects however substantially limits these worries, as they take account of any differences in transport costs between destinations (over the years) that might have led the Tudor Company to ship more to some destinations than to others[33] (see also Hummels *et al.*, 2009, p.91; and Hummels and Schaur, 2013, p.2948, for a similar argument). In case of the fitting and loading and the landing costs, it arguably even completely deals with this concern. The labor costs per ton of ice loaded in Boston and per ton landed in its final destination, as well as the costs per yard of insulation material, were basically the same for shipments sent to the same destination in the same year (see Subsection 3.4.1). Any variation between shipments in the per ton cost of fitting and loading, or landing the ice was, thus, the result rather than the cause of differences between shipments in the quantity of ice loaded onto the ship (see also footnote 23).

Table 1 shows our findings. The bottom row of columns (1)–(5) shows that, in fact, most of the variation in all three transport costs components (as well as their combination) is picked up by the included destination-year dummies that capture many of the important transport cost determinants that we highlighted in Subsections 3.4.1 and 3.4.2. They do not explain all the variation in transport costs however: 7%–12% of this variation comes from differences in per unit transport costs between shipments sent to the same destination in the same year. If this remaining unexplained variation were purely idiosyncratic noise, one could still argue that the iceberg assumption *approximates* iceberg transport costs in practice quite well. However, the reported coefficient estimates in Table 1 show that this remaining *within destination-year* variation is systematically related to shipment size, i.e., the tons of ice loaded onboard in Boston: $(Q^B)_t^k$.

This is most clearly the case for the per ton cost of fitting and loading the ice on board in Boston (see columns 1 and 2).[34] The insulation material was applied to the exposed surface area of the ice. All else equal, increasing the size of a shipment by a factor x thus only increases the need for insulation material by approximately $x^{\frac{2}{3}}$, implying that the per ton cost to insulate the ice *falls* by a factor $x^{-\frac{1}{3}}$. If the per ton cost of fitting and loading consisted primarily of the cost of fitting, the estimated coefficient on ln shipment size should be close to -0.33. It is -0.235, and significantly different from -0.33 at the 2.2% level, indicating that the per ton cost of loading also mattered.

[33] Notably those caused by differences in journey duration, a destination's opportunities for onward/backhaul cargoes, local dock workers' wages, and the choice of insulation regime used in transit.

[34] Shipment size explains 19% of the *within destination-year* variation in the per ton cost of fitting and loading. Figure A5 in Appendix A.3 illustrates this.

The dock workers loading the ice on board were typically paid an hourly or daily wage. The per ton loading costs are therefor unlikely to have fallen with shipment size, explaining an estimated coefficient that is larger than -0.33.[35]

Column 3 shows that the per ton freight costs are not significantly related to shipment size. The estimated coefficient in column (3) is however significant at the 10.7% level, and does suggest the presence of economies of scale in transporting the ice: doubling shipment size lowers the freight cost per ton by 1.3%. It is not unlikely that we simply lack the power to reject the null hypothesis at the (only marginally higher) conventional significance levels due to the much smaller sample of shipments for which freight costs are available.[36] At the same time however, this result remains vulnerable to any remaining reverse causality concerns, which if anything would imply that our estimated coefficient is an underestimate of the true effect of shipment size on per ton freight costs, i.e., (further) weakening the case that differences in shipment size caused any of the observed between-shipment variation in freight costs per ton.

Finally, column 4 also shows no evidence of economies of scale in offloading the ice. This is not unexpected as the dock workers hired to offload the ice in each destination were typically paid a daily or hourly wage, making it unlikely that landing costs per ton depended much on the quantity of ice offloaded.[37] When we next sum up all three transport costs components, the significantly negative relationship with initial shipment size remains (see column 5). A 1% increase in shipment size decreases these per ton transport costs combined by 0.064%.

The presence of economies of scale in ice(berg) transport, particularly salient due to the practice of insulating the ice in transit, implies a clear violation of the iceberg assumption. And, in fact, we do find suggestive evidence that these economies of scale did affect the Tudor Company's shipping strategy, chartering the larger ships sailing to each destination. The average tonnage of the 4,535 foreign clearances out of Boston in 1846 and 1847 was 132 tons (*The Merchants' Magazine and Commercial Review*, 1848). The 29 ships carrying Tudor ice to a non-US destination in these same years held on average 462 tons. And, of the 99 ships carrying Tudor ice in 1847 and 1849, 48% were full rigged ships, the largest type of sailing vessel at the time, 44% were brigs or barks, both medium to large sailing vessels, and only 7% were the smaller schooners. Of Boston's total 11,951 clearances in these two years, only 6% were full rigged ships, 36% brigs and barks and 57% the smaller schooners (*The Merchants' Magazine and Commercial Review*, 1851).[38]

[35] Based on the difference in the average per unit cost of fitting and loading, and the average melt per sailing day between shipments using the standard or the tropical regime (see Figure 4), one can get a rough estimate of the ice's loading cost per ton: \$0.17 (this assumes it is constant across locations, and independent of shipment size). When regression the ln cost of fitting per ton, i.e., the cost of fitting and loading per ton in the data *minus this \$0.17*, on ln tons shipped and a full set of destination-year dummies, the estimated coefficient on ln tons shipped is -0.34 (SE 0.06). This is strikingly close to -0.33.

[36] The results shown in columns (1) and (2) suggest that selection issues may be limited: the estimated relationship between shipment size and the per unit cost of fitting and loading is almost identical when using all 1,469 shipments or the much smaller selected sample of 63 shipments for which either also per unit freight costs or per unit landing costs are available.

[37] Do remember however that the per unit landing costs in the data are only reported per ton of ice *loaded onboard in Boston*; see Subsection 2.1. They only proxy for the landing cost per ton of ice *offloaded* up to melt in transit; see (3). Only if melt were uncorrelated to initial shipment size, could the results in column 4 be taken as evidence that also the landing cost per ton of ice *offloaded* did not depend on initial shipment size. The physics of the melt process however implies a positive correlation between initial shipment size and melt, meaning that our estimate in column 4 is biased upwards. However, in Subsection 3.3 we showed that, in practice, other melt determining factors swamp shipment size in explaining actual melt in transit, so that we do expect this bias to be small.

[38] For Boston's foreign trade this pattern is even more pronounced. Of Boston's total 5,636 foreign clearances in 1847 and 1849, 5% were full rigged ships, 36% brigs and barks, and 59% schooners. For the 32 ships carrying Tudor

4. Conclusion

Iceberg transport costs are a key ingredient of modern trade and economic geography models. This article shows that the transportation of the good that lent its name to this important 'trick of the genre', *ice*, actually features many characteristics that have led people to criticise this assumption: additive transport cost components, economies of scale, the importance of backhaul/onward shipping opportunities and the endogenous choice of shipping technology. Using our data on Boston's nineteenth century global ice trade, we show that, as a result, ice(berg) transport costs in practice are not well-captured by the iceberg assumption. They consisted for the largest part of additive loading, freight and landing costs. Moreover, they depended systematically on shipment size. Interestingly, the practice of insulating the ice to limit melt in transit is primarily to blame for this violation of the iceberg assumption: ice(berg) transport is subject to economies scale.

Of course, these findings do not mean that we should immediately abandon the iceberg assumption in trade or economic geography models. But, we do think that the recent efforts to tractably incorporate more realistic features of the transport sector into these models (e.g., Alessandria *et al.*, 2010; Irarrazabal *et al.*, 2015; Brancaccio *et al.*, 2017; Asturias, 2019) should only be encouraged.

ice to a non-US destination in these years, these percentages are 72%, 28% and 0% respectively. By comparison, 7.5%, 35%, 56% of Boston's 6,315 coastal US clearances were full rigged ships, brigs and barks, and schooners. For the 67 of them carrying Tudor ice these percentages are 37%, 52% and 10% respectively. The lower number of ships sailing out in ballast to US coastal destinations is one explanation of this difference; another is the greater uncertainty about local market conditions in, and the longer delivery lags to, farther off destinations, leading the Tudor Company to prefer sending larger but less frequent shipments to those places (consistent with predictions by, e.g., Alessandria *et al.*, 2010).

Appendix A

A.1. Melt Data

Table A1. *Melt Observations and Their Sources.*

Destination	Year	% melt	Source
St Pierre, Martinique	1806	96	Scientific American (1863)
Havana, Cuba	1807	50	Kistler *et al.* (1984)
Calcutta, India	1833	44	The Mechanics' Magazine (1836)
Calcutta, India	1833; 1835–50		Tudor Company Records (1752–1863) *[yearly averages]*
Rio de Janeiro, Brazil	1834	26	The Rights of Man (1834, p.2), Tinhorão (2005)
Bombay, India	1835	45	The Asiatic Journal (1835)
Sydney, Australia	1839	38	Isaacs (2011)
Singapore	1845	50	Singapore Free Press and Mercantile Advertiser (1845)
Hong Kong	1846	87	Bunting (1981, p.22)
Hong Kong	1846	50	Ride *et al.* (1995, p.48)
New Orleans, USA	1847	35	Tudor Company Records (1752–1863)
Manila, Philippines	1847	50	Legarda (1999, p.311)
San Francisco, USA	1851	58	Hittell (1898, p.423)
London, UK	1852	35	Smith (1962)
Calcutta, India	1854	76	Smith (1962) *[not in Tudor Records]*
Mauritius—Calcutta, India	1854	62	Tudor Company Records (1752–1863)
Mauritius—Calcutta, India	1854	83	Tudor Company Records (1752–1863)
Madras, India	1858	62	Alden *et al.* (1858)
Madras, India	1858	50	Alden *et al.* (1858)
Honolulu, USA	1859	57	The Polynesian (1859)
Batavia, Indonesia	1860	47	De Economist (1860)
Charleston, USA	1860	10	Parker (1981, p.6)
New Orleans, USA	1860	20	Parker (1981, p.6)
Calcutta, India	1868	50	Scientific American (1863)
Havana, Cuba	1868	33	Scientific American (1863)
New Orleans, USA	1868	33	Scientific American (1863)
Batavia, Indonesia	1869	37.5	Java Bode (1869)
Pensacola, USA	1880	27.5	Hall (1880, p.35)
Panama (via Cape Horn)	1854*	68.1	Tomes (1855, p.204)
Norway—London, UK	1880	7.5	Blain (2006, p.8)
Kodiak, Alaska—San Francisco	1852–67	18.4	Saul (2018, p.14) *[overall average]*

* Exact year uncertain, Tomes (1855) describes Panama in 1855. In the Maury Collection the only boat sailing for Panama from Boston arrived in Panama on December 6, 1853 after a journey of 141 days.

A.2. Choice of Insulation Technology

As discussed in Section 1, the Tudor company used two different insulation technologies. One for shorter trips to the Southern US and Caribbean, and another, better, but more expensive one for the much longer trips to Asia, Australia, and those around Cape Horn. In this Appendix, we derive the firm's optimal choice of insulation technology. Of particular interest for our purposes, we show how this choice, and thus the ice's per unit transport cost, depends on the price paid for the ice in Boston.

The firm's choice problem is to choose that insulation technology that minimises its per unit 'production cost' of the ice in the destination, which is nothing but the price paid for the ice in Boston plus the transport costs paid for shipping the ice to its final destination. The former did not vary with the insulation technology used en route, so that this decision boils down to simply choosing that insulation technology that minimises the ice's per unit transport cost *per ton landed*—see (2). This depends on the costs associated with insuring, loading, transporting, and offloading the ice, as well as those associated with the ice that melted in transit. Choosing the better insulation technology raises the former while lowering the latter. Importantly, the cost savings associated with the lower melt loss when using the better insulation technology increase in the sailing days needed to reach the destination from Boston: using the *standard* instead of the better *tropics* insulation regime results in 0.94ppt more melt loss *per sailing day*—see Figure 4.

The Tudor Company is indifferent between using either insulation regime when they result in the same per unit transport costs, $\mathcal{T}_j$, i.e., using (2):

$$\mathcal{T}_j^{\mathrm{T}} = \mathcal{T}_j^{\mathrm{S}} \quad \Leftrightarrow \quad \frac{(\alpha^{\mathrm{T}} D_j)p^B + f_j^{\mathrm{T}}}{1-(\alpha^{\mathrm{T}} D_j)} = \frac{(\alpha^{\mathrm{S}} D_j)p^B + f_j^{\mathrm{S}}}{1-(\alpha^{\mathrm{S}} D_j)}, \tag{A1}$$

where superscripts T(ropics) and S(tandard) denote the insulation regime used, D_j is the number of sailing days from Boston to destination j, we have suppressed the year index t, and replaced m_j in (2) by the estimated linear relationship between melt loss (in ppt) and sailing days for the two insulation regimes, i.e., $m_j^{\mathrm{I}} = \alpha^{\mathrm{I}} D_j$, for $\mathrm{I} \in \{\mathrm{T}, \mathrm{S}\}$.

Rearranging (A1) we can easily derive how the choice of insulation regime depends on the prevailing producer price in Boston, p_B.[39] More specifically, given the number of sailing days from Boston, D_j, it is optimal to use the better *tropics* insulation regime if:[40]

$$p^B \;>\; p_j^* \;=\; \frac{(f_j^{\mathrm{T}} - f_j^{\mathrm{S}}) + (f_j^{\mathrm{S}}\alpha^{\mathrm{T}} - f_j^{\mathrm{T}}\alpha^{\mathrm{S}})D_j}{(\alpha^{\mathrm{S}} - \alpha^{\mathrm{T}})D_j}. \tag{A2}$$

As also illustrated in Figure A1, this implies that, in principle, upon taking explicit account of the choice of insulation regime, per unit ice(berg) transport costs in practice, both those associated with melt as well as with loading, shipping and landing the ice, did depend on producer prices in Boston. In contrast to the iceberg assumption, however, they increased *less than proportionally* in these prices.[41] Also, ceteris paribus, the longer the journey from Boston to a particular destination, the more likely that the more expensive, but better insulation regime was the optimal insulation technology to use ($\partial p_j^*/\partial D_j < 0$).

In the data we, however, never observe the Tudor Company switching the insulation technology used to any of its destinations, regardless of the variation in producer prices over the years in our sample. In practice, the price of the ice in Boston did not influence the Tudor Company's choice of insulation regime. Instead, sailing distance from Boston appears to have been the single-most important determinant of this choice. For the farther off destinations this can easily be explained by the fact that using the better, more expensive insulation regime was the only way to ensure that any ice would reach its final destination. Had the cheaper technology been used, all ice would

[39] Note that this is the case as long as f_j^{T} and f_j^{S} are not proportional to producer prices in Boston—as was the case in practice, see Subsection 3.4.1. If they were, the choice of insulation regime would not depend on p^B at all.

[40] *tropics* insulation regime: we could also let transport costs depend on distance, and, e.g., specify them as $f_j^{\mathrm{I}} + \gamma D_j$ instead of f_j^{I}, $\mathrm{I} \in \{\mathrm{T}, \mathrm{S}\}$. This would add the term $-\gamma D_j$ to the expression for p_j^* in (A2).

[41] This would have shown even more saliently had (many) more different insulation regimes been available to the firm, as long as a better insulation regime always came with a higher per ton cost of fitting and loading the ice on board, as well as less melt per day in transit.

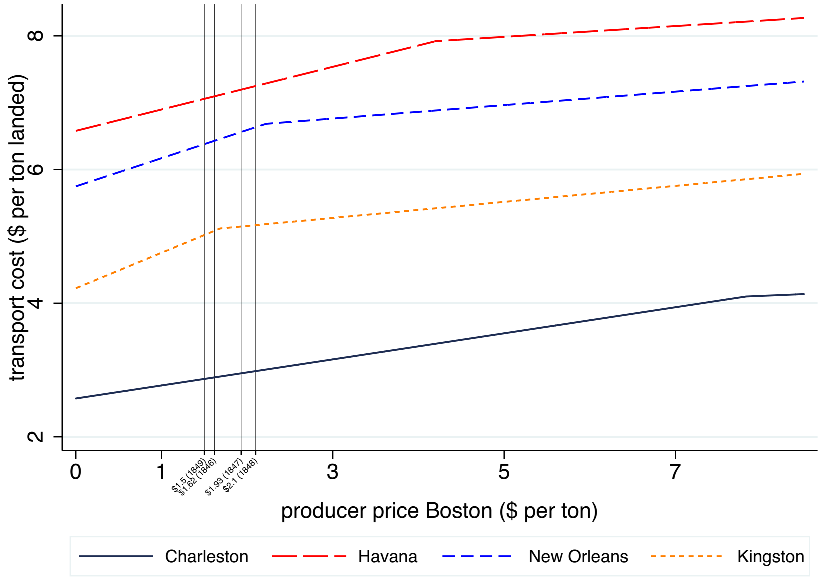

Fig. A1. *Ice(berg) Transport Costs and Producer Prices.*

Notes: The vertical lines correspond to the observed price paid for the ice in Boston in 1846, 1847, 1848 and 1849. The other lines depict the relationship between each destination's per unit ice(berg) transport costs and producer prices in Boston. They are drawn taking $\alpha^{\mathrm{S}} = 0.0136$ and $\alpha^{\mathrm{T}} = 0.0042$ (see Figure 4), and observed median values for $f_j^{\mathrm{S}} = f_j^{\mathrm{S,load}} + f_j^{\mathrm{S,freight}} + f_j^{\mathrm{S,land}}$ in the earliest years of our sample (1846–1850) for which data on freight and landing costs are available for several destinations. No shipment to these destinations ever used the *tropics* regime, so that we do not directly observe $f_j^{\mathrm{T,load}}$, $f_j^{\mathrm{T,freight}}$, nor $f_j^{\mathrm{T,land}}$. We infer $f_j^{\mathrm{T,load}}$ from all shipments sent beyond the Caribbean that all use the *tropics* regime, and approximate $f_j^{\mathrm{T,freight}}$ and $f_j^{\mathrm{T,land}}$ as follows. First, $f_j^{\mathrm{T,land}} = 1.5 f_j^{\mathrm{S,land}}$: applying and disposing of the additional insulation material when using the *tropics* regime increases the time to (off)load the ice by a factor 1.5. Second, $f_j^{\mathrm{T,freight}} = f_j^{\mathrm{S,freight}} \left(\frac{D_j + 1.5(D_j^{\mathrm{S,load}} + D_j^{\mathrm{S,land}})}{D_j + D_j^{\mathrm{S,load}} + D_j^{\mathrm{S,land}}} \right)$: the freight cost per ton using the *tropics* regime equals that when using the *standard* regime multiplied by the number of days one needs to charter the ship using the *tropics* regime relative to those needed when using the *standard* regime instead. The number of days one has to charter the ship is simply the sum of j's sailing days from Boston, D_j, and those spent loading, D_j^{load}, and offloading, D_j^{land}, the ice. It is larger for the *tropics* regime, but only because (off)loading the ice takes 1.5 times longer (see our earlier assumption above). For the *standard* regime we simply infer $D_j^{\mathrm{S,load}}$ from the observed average shipment size sent to j taking an average loading speed of 300 tons of ice per day (Forbes, 1875), and assume that landing the ice takes three times longer—loading involved placing regularly shaped, easy to handle, blocks of ice into the ship's hold at freezing temperatures, whereas landing meant offloading one, melted together, block of ice at tropical temperatures—i.e., $D_j^{\mathrm{S,land}} = 3D_j^{\mathrm{S,load}}$. For Havana and Kingston we, in addition, do not observe $f_j^{\mathrm{S,freight}}$ and $f_j^{\mathrm{S,land}}$. For these destinations, we set $f_j^{\mathrm{S,land}} = 0.81$, the observed landing cost per ton in New Orleans, and we infer $f_j^{\mathrm{S,freight}}$ from the corresponding number for New Orleans multiplied by the average overall transport cost per ton implied by the observed producer price in, and predicted melt loss to, each destination relative to that in New Orleans (see column (9) in Table A2). The producer price at which it is optimal to switch from using the *standard* to the *tropics* insulation regime, p_j^{B*} is 7.83, 4.20, 2.22 and 1.68 \$/ton for Charleston, Havana, New Orleans and Kingston respectively.

have simply melted in transit.[42] For the other, closer, destinations, the Tudor Company instead always used the cheaper technology.

The lack of (counterfactual) freight and landing cost data make it difficult to infer whether or not this choice was in fact optimal given the prevailing ice prices in Boston. However, making use of our estimated melt loss per sailing days for the two insulation regimes (see Figure 4), the observed per ton fitting and loading, freight and landing costs by destination, f_j^{S}, and assumptions to infer each destination's counterfactual f_j^{T} (see the *Notes* to Figure A1 for more details), Figure A1 plots the resulting relationship between the overall ice(berg) transport costs per ton landed and producer prices in Boston for four destinations for which the choice between the standard and tropics regime is in principle relevant: Charleston (12 sailing days), Havana (17.8 sailing days), New Orleans (21.8 sailing days), Kingston (25.5 sailing days).[43]

Figure A1 indeed shows suggestive evidence that, in the earliest years of our sample, the producer price of the ice in Boston never reached a level that should have induced the Tudor Company to switch from using the cheaper to the better, but more expensive insulation technology. Kingston is the exception here, where according to our calculations the Tudor Company should have switched to using the better insulation technology in 1847 and 1848. However, do note that for Kingston we needed to make additional assumptions to also infer its, otherwise unobserved, freight and landing costs under the *standard* insulation regime from the observed numbers for New Orleans (see the *Notes* to Figure A1).

[42] Given the estimated melt loss per day for the *standard* insulation regime, 1.36ppt per day, it is never an option to use this technology when sailing to destinations beyond 73.5 sailing days from Boston.

[43] For the other two furthest destinations within 73.5 sailing days from Boston, Pernambuco (41 days) and Rio de Janeiro (49 days), it is, based on similar calculations, optimal to use the *tropics* regime at any producer price in Boston, i.e., $\partial p_j^* < 0$.

A.3. Descriptives and Additional Figures

Table A2. *Descriptives for Destinations in Tudor Records.*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
						Cost per ton ($)			
Destination	Total tons	Avg. ton/ship	No. ships	E[% melt]	Sailing days	Loading	Landing	Freight	$\bar{f}_{j\cdot}$
Batavia, Indonesia	39,478	1,067	37	42.0	99.8	1.21	.	.	9.3 (3.6)
Bombay, India	110,182	958	115	46.4	110.4	1.25	.	6.24	8.1 (1.7)
Calcutta, India	154,634	822	187	50.7	120.6	1.22	0.27	3.35	5.1 (1.4)
Charleston, USA	54,498	277	197	16.3	12.0	0.55	0.67	1	3.9 (1.5)
Colombo, Sri Lanka	1,818	606	3	50.5	120	1.81	.	.	7.9 (.)
Galle, Sri Lanka	16,447	748	22	50.5	120	1.44	.	.	5.4 (1.7)
Havana, Cuba	179,282	549	325	24.2	17.8	0.58	.	.	5.6 (0.9)
Hong Kong	32,996	1,222	27	40.5	96.3	1.32	.	.	10.3 (3.3)
Kingston, Jamaica	74,265	485	153	34.6	25.5	0.57	.	.	3.0 (1.4)
Madras, India	65,364	647	101	49.5	117.8	1.28	.	3.49	6.8 (1.3)
Mobile, USA	8,526	194	44	29.9	22.0	0.63	0.47	1.89	4.0 (1.4)
New Orleans, USA	142,913	581	246	29.6	21.8	0.47	0.81	2.75	4.5 (0.7)
Pernambuco, Brazil	111	111	1	17.3	41.2	0.92	.	.	.
Rangoon, Myanmar	391	391	1	.	.	1.87	.	.	.
Rio de Janeiro, Brazil	2,372	593	4	20.7	49.3	1.78	.	.	3.0 (.)
Singapore	3,563	594	6	46.7	111	1.48	.	.	9.7 (1.3)

Notes: The descriptives in columns (1)–(3) and (6)–(8) are based on the individual shipment data taken from the Tudor Records (see Subsection 3.1 for more detail). Column (4) reports predicted melt to each destination in transit based on an insulation regime specific regression of observed melt in transit on the average number of sailing days from Boston to each destination (taken from the US Maury Collection, and shown here in column (5)). Figure 4 depicts this relationship for each of the insulation regimes. The US Maury Collection does not report information on a journey from Boston to Rangoon, explaining the missing values for the number of sailing days and expected melt for this destination. Column (9) reports each destination's average transport costs per ton of ice *loaded in Boston* over our sample period, accompanied by its standard error. It is calculated—see (2)—using our data on producer prices in Boston and each destination, in combination with the predicted melt numbers reported in column (4): $\bar{f}_{j\cdot} = \frac{1}{T_j}\sum_t \left(p_{jt}(1-m_j) - p_t^B\right)$, where T_j denotes the number of years for which we observe the necessary producer price data to calculate f_{jt}. Standard errors are missing for destinations where we observe f_{jt} in one year only.

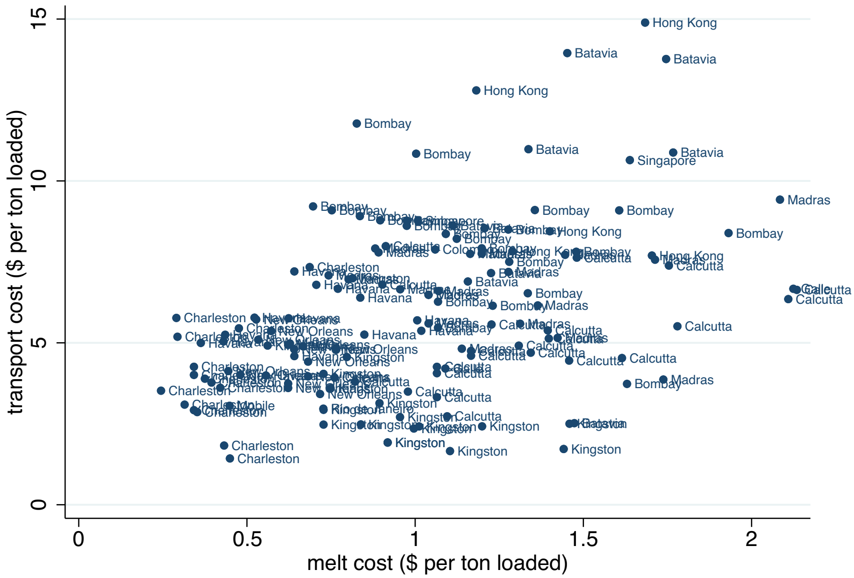

Fig. A2. *Melt and Transport Costs Per Ton Loaded.*

Notes: The melt, and transport costs *per ton loaded* are obtained by multiplying the 'pure melt', and 'melt augmented' transport costs *per ton landed* in (2) by $(1 - m_{jt})$. They are calculated making use of our data on producer prices in Boston and in each destination, as well as the (predicted) melt on each route. This predicted melt measure is based on a regression of actual observed melt on the number of sailing days to each destination (distinguished by the type of insulation regime used by the Tudor Company); see Subsection 3.3 for the details.

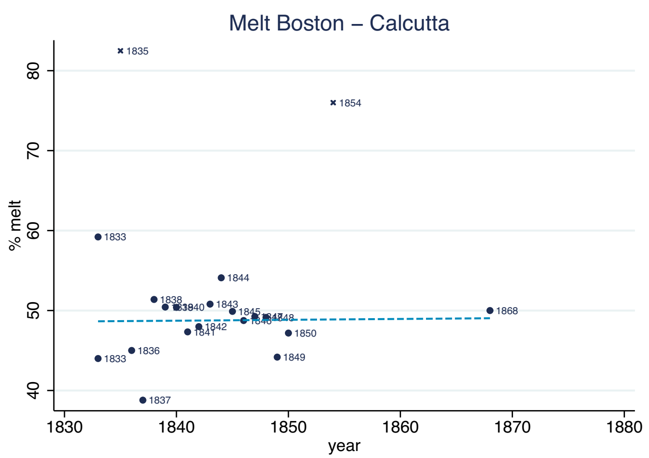

Fig. A3. *Melt Over Time.*

Notes: The slope of the fitted regression line is 0.01 (SE 0.14). The observations marked with an 'x' concern two outliers—the same two Calcutta outliers as in Figure 4. One, the 1835 observation, concerns a documented failure, and one, the 1854 observation, concerns melt reported for a shipment on the ship *Arabella* whose departure from Boston we cannot confirm in the Tudor Records.

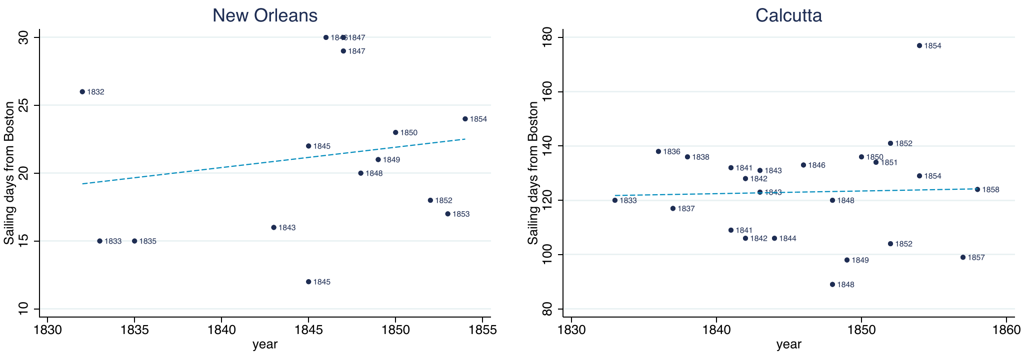

Fig. A4. *Sailing Days 1830–60—Maury Collection.*
Notes: The slope of the fitted regression line is 0.150 (SE 0.207) and 0.097 (SE 0.595) in case of New Orleans and Calcutta respectively.

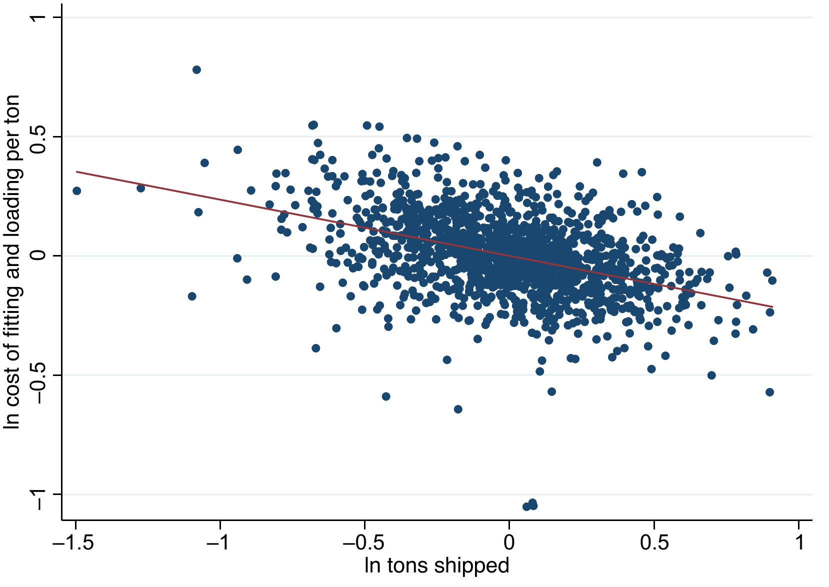

Fig. A5. *Cost of Fitting and Loading vs Shipment Size [by boat].*
Notes: The figure plots the relationship between the two variables controlling for a full set of destination-year dummies. In other words, it shows the relationship between the cost of fitting and loading per ton and shipment size for ships travelling to the same destination in the same year. That is, it plots the residuals of a regression of $\ln f_{jt}^{\mathrm{load},k}$ on a full set of destination-year dummies (on the y-axis) against the residuals of a regression of $\ln(Q^B)_t^k$ on a full set of destination-year dummies (on the x-axis).

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Additional Supporting Information may be found in the online version of this article:

Replication Package

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