Ice(berg) Transport Costs

Maarten Bosker and Eltjo Buringh*

May 2017 - preliminary version - do not quote

Abstract

Iceberg transport costs are one of the main ingredients of modern trade and economic geography models: transport costs are modelled by assuming that a fraction of the goods shipped "melts in transit". In this paper, we investigate whether the iceberg assumption applies to the costs of transporting the only good that literally melts in transit: ice. Using detailed information on Boston's nineteenth-century Global Ice Trade, we show that iceberg transport costs in practice were a combination of a true *ad-valorem* (iceberg) cost: melt in transit, and *per unit* freight and (off)loading costs. The physics of the melt process and the practice of insulating the ice in transit imply an immediate violation of the iceberg assumption: shipping ice is subject to economies scale.

Keywords: iceberg transport costs, nineteenth-century Boston ice trade
JEL codes: F1, N7, N51

1 Introduction

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] The iceberg assumption assumes that in order to deliver

*Bosker: Erasmus University Rotterdam, The Netherlands, Tinbergen Institute and CEPR, email:bosker@ese.eur.nl. Buringh: Utrecht University, The Netherlands, email: e.buringh@uu.nl.
Acknowledgements: We thank the staff at the Harvard Baker Library for their help with accessing the records of the Tudor Ice Company, and Atty de Waard for her help with finding contemporary newspaper articles on the Ice Trade. Also, we are grateful for comments and suggestions from seminar attendants in Utrecht, Rotterdam, the London School of Economics, and Oxford University. In this respect, we thank Sacha Kapoor, Bastian Westbrock and Vincent Rebeyrol in particular.

[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 oxen pulling the cart of grain.

x goods produced in location 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 away* in transit. Total transport costs equal the cost of producing these *melted* goods.[2] As a result, per unit transport costs are a destination-specific percentage of the good's producer price in i, p_i: $p_{ij}^{\text{transport}} = (\tau_{ij}-1)p_i$. The iceberg assumption's popularity in trade and economic geography models comes 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, also avoids the need to explicitly model the transport sector.

In practice however, per unit transport costs are typically not (only) of the iceberg type (Hummels, 2007; Hummels and Skiba, 2004; Irarrazabal et al., 2015). They consist of true ad-valorem (iceberg) costs that are a destination-specific percentage of the good's producer price (e.g. insurance, ad-valorem tariffs) as well as additive cost components (e.g. shipping costs, specific tariffs):

$$p_{ij}^{\text{transport}} = \alpha_{ij}p_i + f_{ij} \tag{1}$$

, where both α_{ij} and f_{ij} can be specific to the good shipped and/or the specific shipment route. Moreover, transportation often exhibits economies of scale, so that per unit transport costs depend on the quantity shipped, x_{ij}. Importantly, deviations from iceberg transport costs have nontrivial theoretical implications. The presence of additive cost components can e.g. affect the predicted welfare gains from trade cost reductions (Irarrazabal et al., 2015), and/or firms' export choices (the well known Alchian-Allen effect). The presence of economies of scale in transport can induce firms to focus on fewer export markets, and/or to make use of fewer, but larger, individual shipments, possibly even combining shipments with those of other firms.

In this paper, we assess the relevance of the iceberg assumption using a detailed data set on the costs involved in shipping the only product that literally melts away in transit: ice. Our data primarily comes from the records of the Tudor Ice Company, Boston's leading ice exporting company that, during nineteenth century, shipped over one million tons of natural ice all over the world on wooden sailing ships.

We first show that iceberg transport costs in practice consisted of both an ad-valorem (iceberg) component: *melt in transit* and *insurance*, and several per unit cost components: *freight, landing* and *loading* costs. Given that the producer price of the ice sent out in the

[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.

same year was identical regardless of the final destination, the iceberg assumption implies that all these transport costs combined should be well-captured by a destination-year-specific constant; see (1). Although most of the variation in per unit transport costs is indeed driven by destination-year specific factors, we find significant variation in these costs between shipments of ice sent to the same destination in the same year. More importantly, this variation is not random but systematically related to shipment size. The physics of the melt process and the practice of insulating the ice in transit implied an immediate violation of the iceberg assumption: ice(berg) transport is subject to economies scale.

2 The Frozen Water Trade

The Ice Trade is by now a largely forgotten trade.[3] 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, where large quantities of ice were stored, dotted the landscape, and many wealthy homeowners 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, this trade was very localized, with ice harvested from nearby frozen lakes, rivers or mountains.

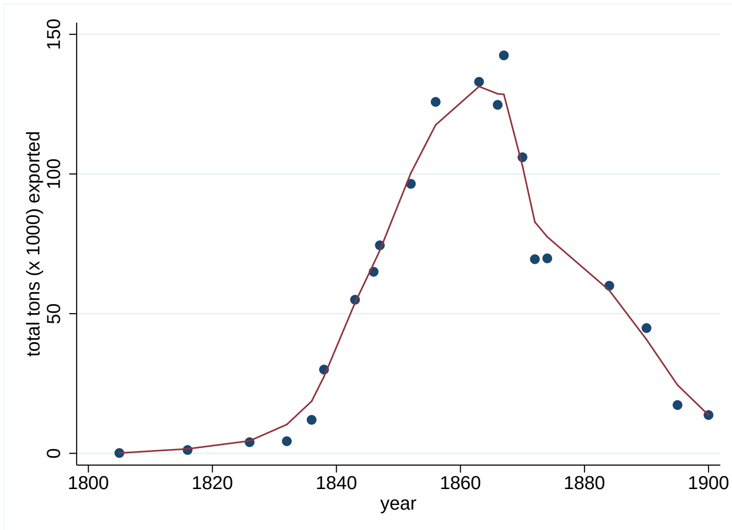
This changed in 1806 when Frederic Tudor shipped 130 tons of natural ice from Boston to the Caribbean island of Martinique. After further refining the process of insulating the ice during the voyage and at the destination, shipments to other Caribbean destinations and the main cities in the southern US quickly followed. In 183 Tudor sent an experimental shipment to Calcutta, and upon its success expanded this long-distance ice trade to Rio de Janeiro, Indonesia, China, the Philippines, Australia and even (around Cape Horn) Peru and San Francisco.[4] Drawn by the extreme profitability of the trade, other companies soon entered the market, further expanding Boston's ice trade.[5]

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

[4] Ice was mostly shipped to destinations where profitable return freights could be obtained. Boston boats previously sailed in ballast to these destinations. Ice replaced this ballast. Shipping ice without a profitable return freight was often too costly.

[5] 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 price to an unprofitable level until the competitor's ice had completely melted away).

Figure 1: Boston's Global Ice Trade



SOURCE: HEROLD (2011, P.168)

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.[6] Natural ice first lost its competitiveness to artificial ice in tropical locations. The localized trade in natural ice lasted longer, eventually also dying out after WWI.[7]

2.1 Iceberg 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 away in transit. Each cargo was insulated to limit this melt. Following his initial shipment to Martinique, Tudor quickly settled on the optimal insulation strategy. First, shipping the ice in standardized rectangular blocks allowed it to be tightly stowed, limiting melt by minimizing the outward exposure of the ice. Second, 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

Competition was toughest in the Southern US destinations.

[6]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.

[7]The (very) localized trade of artificial ice lasted even longer. One of the authors still remembers the weekly deliveries of blocks of ice to his childhood home in Baghdad in 1955.

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)).

The Tudor Company hired the ships delivering the ice to its tropical destinations. Dock workers were hired to load the ice onto the ship and fit it with insulation material. Freight costs were usually paid on the intake weight (Parker (1981, p.5); Wyeth (1848, p.180)). They were relatively low as many of the ships would otherwise have sailed in ballast.[8] 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)). 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.[9]

3 Iceberg transport costs in practice?

3.1 Data

The data that we have collected allow us to quantify all of these iceberg transport costs. It draws from a variety of sources. Most of our information 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 U.S. National Oceanic and Atmospheric Administration, contains information on the duration of over 12,000 voyages made by U.S. ships over the period 1784-1863. Most of these trips (about 11,000) took place between 1830-1863, exactly the period best covered in the Tudor Company Records. Finally, we

[8]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 (Dickason (1991, p.64); Parker (1981, p.6); Boston Board of Trade (1862)). 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.

[9]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).

collected data on actual melt in transit. With the exception of the average yearly fraction of ice lost to Calcutta over the period 1833-1850, the Tudor Company Records do not report melt. Our 44 melt observations come from a variety of sources, including newspapers, journal articles, 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 1806-1880. Most observations are from the 1840-1880 period however, the heyday of Boston's Global Ice Trade (see Figure 1). From the Tudor Records alone we have information on 1,465 shipments of ice. For each of these shipments, we know the amount of ice loaded onboard in Boston, the cost of fitting (i.e. insulating), loading and insuring this ice, the (producer) price that the Tudor Company paid for it in Boston (i.e. its unit costs), and producer prices in each destination (see Section 3.3). Freight and landing costs are much less well recorded: we only observe these for 66 and 63 shipments respectively (for 59 shipments we observe both). These observations primarily concern shipments to Calcutta (32 over the period 1845-1854) and New Orleans (25 over the period 1846-1849), the others went to Charleston (7), Mobile (2), Bombay (2) and Madras (1) over the period 1847-1850. Table 3 in Appendix A.2 provides summary statistics of the most important variables for each destination reported in the Tudor Company Records.

3.2 Iceberg melt

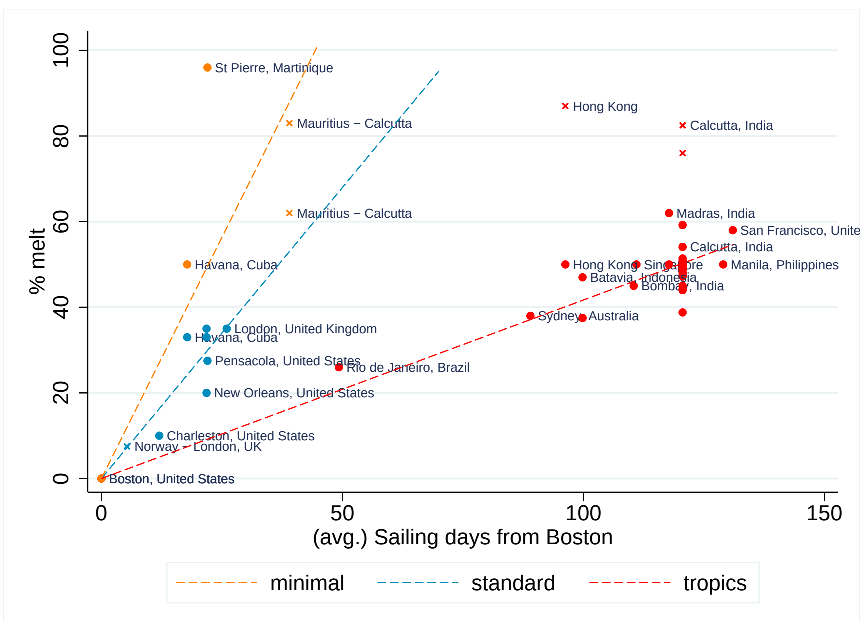
The iceberg assumption is more than just a convenient assumption when it comes to the cost of shipping ice. The ice actually melts in transit. The Laws of Physics tell us that this melt depends positively on the duration of the journey and the temperature difference between the ice and the surrounding 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.[10] Importantly, the latter implies an immediate violation of the iceberg assumption: doubling the load of ice only increases the exposed surface area by approximately $2^{\frac{2}{3}}$, resulting in less melt *per unit of ice shipped.* Melt makes

[10] 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).

the transportation of ice subject to economies of scale.

In this section we show that melt, in the data, is nevertheless well approximated by the iceberg assumption. Melt in transit 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 remaining variation in melt between shipments going to the same destination in the same year is not systematically related to shipment size.[11]

Figure 2: 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; and one shipment from Norway to London). 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.

[11] 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. Almost all shipments left Boston at the same time of year (winter/early spring). Conditional on the choice of insulation regime (that is almost one-for-one related to the shipping route taken, see also footnote 12), there was hardly any variation between shipments 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 2 in any way, whereas these temperature variables themselves are highly insignificant.

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 2.1). This clearly shows in the data: the cost of fitting and loading per ton of ice shipped from Boston is an average $0.51 (SD $0.14) for 'standard' shipments to the US South and Caribbean, and an average $1.16 (SD $0.27) for 'tropics' shipments to destinations further away. Given the choice of insulation regime, melt depended primarily on the length of the journey.[12] Figure 2 shows this 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.[13] 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 respectively (55% in case of minimal insulation).

Figure 3 shows that the remaining unexplained variance in melt is unlikely to be the result of variation in shipment size. One difficulty in showing this, is that we only observe melt ànd shipment size for eight individual shipments.[14] But, under a mild assumption, the shipment-specific information on the quantity of ice shipped from Boston and the total landing costs paid upon arrival in the destination is sufficient to infer the existence of a systematic relationship between melt in transit and shipment size. This information is

[12]The choice of insulation regime also depended on the length of the journey. Using the estimated relationship between melt and distance for the two regimes (see Figure 2), in combination with the observed unit cost of the ice in Boston and overall transport costs, one can calculate the journey length at which a profit maximizing firm should switch from using the standard to the tropics insulation regime: in our data this is 30 sailing days. The furthest destination that falls under the standard regime in our data according to the cost of fitting and loading per ton is Kingston, Jamaica at 25.5 sailing days from Boston. The closest destination that falls under the tropics regime is Rio de Janeiro at 49.3 sailing days from Boston.

[13]Only in case of the minimal regime does this number change (to 1.69ppt) when including a constant to the regression. Also, including year dummies does neither change the point estimate of the relation between melt and number of sailing days nor its significance.

[14]One 'standard' shipment to London, and eight 'tropics' shipments. Regressing shipment size and number of sailing days on melt for these eight 'tropics' shipments confirms that shipment size is, conditional on the duration of the journey and insulation regime, not significantly related to melt; also the estimated coefficient on the number of sailing days is almost identical to that depicted in Figure 2: 0.40 (SE 0.05).

available for 65 shipments. To see this, first note the following identity:

$$\underbrace{\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)}_{\text{observed}} = \underbrace{\left(\frac{Q_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)}_{1-m_{Bjt}^{k}} c_{jt}^{k,\text{landed}} \tag{2}$$

, where m_{Bjt}^{k} denotes the fraction of ice that melted during ship k's transit. $Q_{jt}^{k,\text{landed}}$ and $Q_{Bt}^{k,\text{loaded}}$ are the quantity of ice that ship k landed in destination j and loaded in Boston (B) in year t, respectively. $C_{jt}^{k,\text{landed}}$ and $c_{jt}^{k,\text{landed}}$ denote the total and per ton cost respectively incurred to offload the surviving ice on ship k in destination j in year t.

Using (2), 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:

$$\ln\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right) = \alpha \ln Q_{Bt}^{k,\text{loaded}} + \gamma_{Bjt} + \epsilon_{Bjt}^{k} \tag{3}$$

, where γ_{Bjt} captures any origin-destination-year specific factors explaining differences in melt (notably the insulation regime used, (average) journey length and outside sea/air temperature during the journey). Given that $\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)$ only proxies the fraction of ice surviving in transit up to $c_{jt}^{k,\text{landed}}$, see (2), the validity of this exercise depends crucially on the assumption that the quantity of ice taken on board in Boston is, conditional upon the included origin-destination-year fixed effects, uncorrelated to a shipment's landing cost *per ton* that is, by construction, part of ϵ_{Bjt}^{k}.

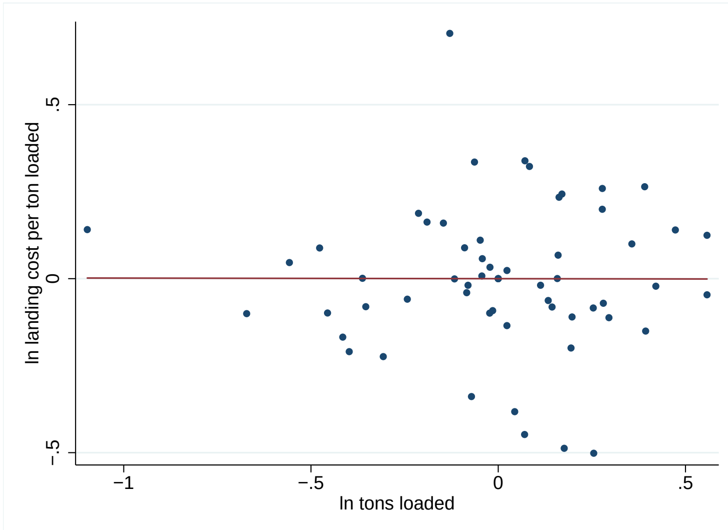
Under this very plausible assumption[15], Figure 3 clearly shows no evidence that the variation in shipment size helps to explain the observed variation in melt in transit.[16] Of course, this does not lead us to question the Laws of Physics. What it does show is that, in practice, variation in shipment size was a relatively unimportant determinant of the observed variation in melt loss. The unexplained variance in Figure 2 can much more likely be attributed to the substantial variation between shipments in time in transit[17] and in the (unobserved) adherence of the crew to the agreed melt mitigating measures (see Section 2.1).

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

[16] $\hat{\alpha} = -0.002$ (SE 0.102). It is depicted by the slope of the solid regression line in Figure 3.

[17] 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.

Figure 3: Melt in transit unrelated to shipment size [by boat]



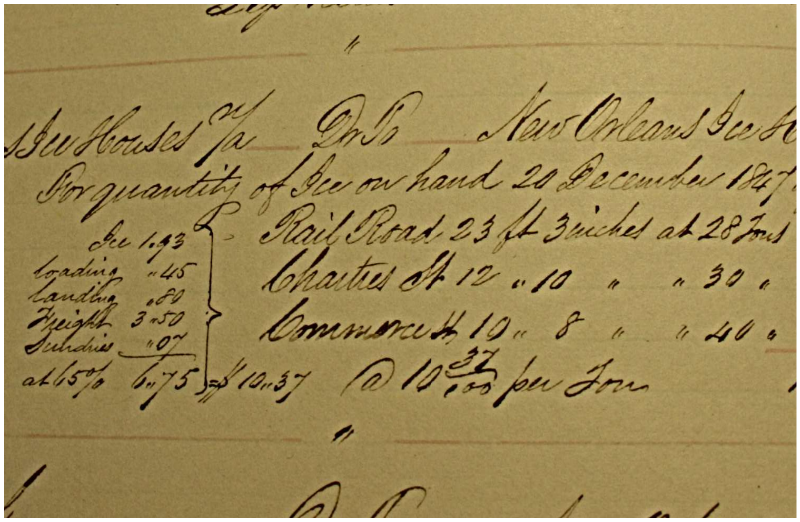
NOTES: The figure shows the relationship between relative shipment size and the (inferred) relative fraction of the ice arriving at the destination *conditional* on including a full set of origin-destination-year dummies. That is, it plots the residuals of a regression of $\ln\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)$ on a full set of origin-destination-year dummies (on the y-axis) against the residuals of a regression of $\ln Q_{Bt}^{k,\text{loaded}}$ on a full set of origin-destination-year dummies (on the x-axis).

In sum, the physics of the melting process implies an immediate violation of the iceberg assumption: transporting ice is subject to economics of scale. However, our data shows that these economies of scale were, in practice, completely overshadowed by other, more important, melt determining factors. Melt in transit primarily depended on two destination-specific constants: the (average) duration of the journey and choice of insulation regime. As such, the iceberg assumption approximates the melt-related costs of shipping ice rather well.

3.3 Iceberg melt and iceberg transport costs

Iceberg melt is however only one of the components of the overall costs of shipping ice. Iceberg transport costs, defined broadly as all costs incurred to load, offload, transport and insure a shipment of ice, also matter. One scribble in the Tudor Records shows us exactly how these two, together, drive a wedge between the ice's unit cost in Boston and that in a particular destination. At the 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 unit (ton) cost of the ice in each destination in a given year. Observing these

Figure 4: Calculation of per unit cost of ice in New Orleans (1847)


For quantity of Ice on hand 20 December 1847
Ice 1.93 Rail Road 23 ft 3 inches at 28 Tons
loading .45 Chartres St 12 " 10 " " 30 "
Landing .80
Freight 3.50 Commerce St 10 " 8 " " 40 "
Sundries .07
at 65% 6.75 $10.37 @ 10 37/100 per Ton

SOURCE: the Tudor Records, Tudor II, Volume 3

producer prices is crucial for our purposes as we can ascribe any differences in them between destinations to differences in transport costs.[18]

The scribble, shown on the left of Figure 4, is the only time that the Tudor Records detail how the firm calculated its unit costs in a particular destination. First, they paid for the ice in Boston ($1.93 per ton). Next, they paid different *per unit* transport costs 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: the cost of this melted ice poses a true *ad valorem* iceberg transport cost. Overall, the cost per unit of ice *in each destination* equals the per unit cost of the ice loaded in Boston including all transport costs (in total $6.75) divided by the fraction of the ice surviving the journey (65%, or 0.65), explaining the $10.37 per ton at which the company valued its remaining

[18]Producer prices are very different from the *sales prices* in each destination. Sales prices would also reflect any differences in consumers preferences or market structure between destinations. They ranged from 2 to 20 times the reported producer price, depending on the destination. The Tudor Company e.g. faced stiff 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 discussion on how price differentials between locations can or cannot be used to infer transport costs.

stock of ice.[19] For comparison, the sales price in New Orleans in that year averaged \$35 per ton (Wetherell, 1863). An important note is in place at this point. The Tudor Company Records do not specify why they use the 65% markup. It is hard to ascribe it to anything but melt however. The company had a very good idea of the substantial differences in average (predicted) melt that shipments to different destination were suffering (see also footnote 12). Based on Figure 2, the average predicted melt to New Orleans is 30%. The cases of actual reported melt for New Orleans are 35%, 33% and 20%, and a shipment to Pensacola (very close to New Orleans) reports 27.5% melt. The 35% used by the firm in the scribble is on the higher end of these numbers.[20]

Using the scribble, the overall wedge between producer prices in Boston and a destination j can be written as the product of a melt- and a transport cost markup:

$$\tau_{Bjt}^{\text{total}} = \left(\frac{p_{jt}}{p_{Bt}}\right) = \underbrace{\left(\frac{1}{1 - m_{Bjt}}\right)}_{\text{melt markup}} \underbrace{\left(1 + \frac{p_{Bjt}^{\text{load}} + p_{jt}^{\text{land}} + p_{Bjt}^{\text{freight}} + p_{Bjt}^{\text{sundries}}}{p_{Bt}}\right)}_{\text{transport cost markup}} = \tau_{Bjt}^{\text{melt}}\ \tau_{Bjt}^{\text{transport}} \qquad (4)$$

, where p_{Bjt}^{load} and p_{jt}^{land} denote the per unit cost of loading and offloading the ice in Boston and the destination respectively, p_{Bjt}^{freight} are the per unit freight costs paid to ship the ice from Boston to its destination, and $p_{Bjt}^{\text{sundries}}$ captures other miscellaneous costs incurred. Equation (4) shows that making the iceberg assumption to model the cost of shipping ice assumes that a destination-specific fraction, $\tilde{m}_{Bjt}$, of each unit shipped *"melts away"* in transit. What makes the ice shipping business unique is that this fraction does not only depend on transport costs; true melt in transit matters as well: $\tilde{m}_{Bjt} = \left(\frac{\tau_{Bjt}^{\text{melt}}\ \tau_{Bjt}^{\text{transport}} - 1}{\tau_{Bjt}^{\text{melt}}\ \tau_{Bjt}^{\text{transport}}}\right)$.

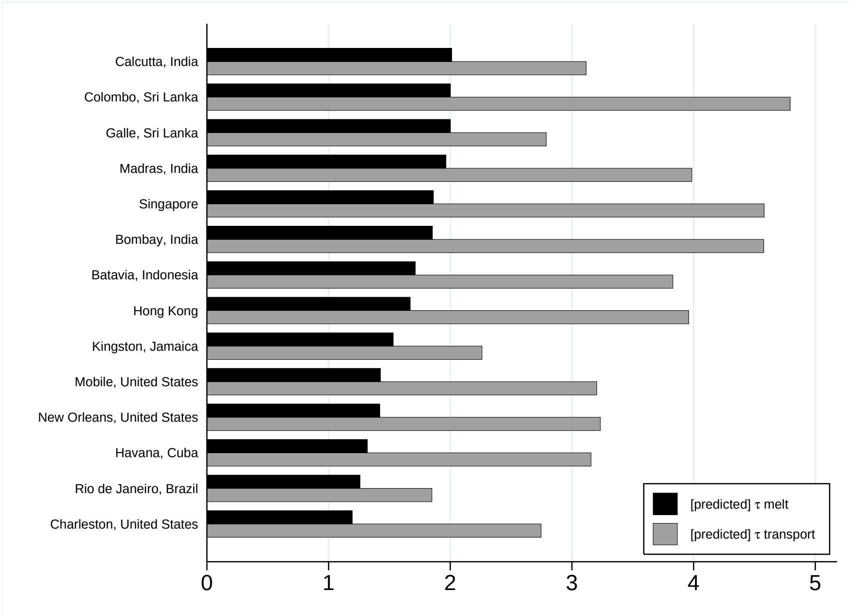
Figure 5 shows the relative importance of iceberg melt and iceberg transport costs in determining a destination's average $\bar{\tau}_{Bj}^{\text{total}}$. For each destination[21] it shows its average transport cost markup $\hat{\tau}_{Bj}^{\text{transport}} = \bar{\tau}_{Bj}^{\text{total}} / \hat{\tau}_{Bj}^{\text{melt}}$, where $\bar{\tau}_{Bj}^{\text{total}}$ is the average wedge between

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

[20]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 4 and the 30% average melt in transit to New Orleans. It suggests that, if at all, the firm also takes the ice lost while offloading into account. This is not captured by our predicted melt measure that is based solely on the number of sailing days and the choice of insulation regime.

[21]Figure 5 includes only destinations for which we observe both producer prices and melt in transit.

Figure 5: $\hat{\tau}^{\text{melt}}_{Bj}$ and $\hat{\tau}^{\text{transport}}_{Bj}$



a destination's unit cost of ice and that in Boston, as well as its average melt markup $\hat{\tau}^{\text{melt}}_{Bj} = \frac{\hat{m}_{Bj}-1}{\hat{m}_{Bj}}$. We take each destination's $\hat{m}_{Bjt}$ from the estimated relationship between melt, the average number of sailing days and the insulation regime used, as shown in Figure 2. It is a time-invariant measure. There is, however, very little reason to believe that melt changed systematically over our sample period. Figure 6 in Appendix A.2 shows this for Calcutta, the only destination for which we observe melt for a sufficient number of years to draw meaningful conclusions. The Tudor Company quickly settled on the optimal way to insulate the ice in transit (see Section 2). 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.[22] The data in the US Maury collection confirms this: it shows no systematic change in sailing days from Boston to any of the destinations over our sample period.

On average, the melt markup is half as large as a destination's average transport cost markup. To all destinations, per unit transport costs outweigh melt in determining the overall cost of shipping ice. Note that this result is robust to any plausible measurement error in our predicted melt measure. Only when using unrealistically high predicted melt

[22]Ice was primarily shipped on wooden-hulled (to avoid rust) schooners, barques or brigs. 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. 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 (and back).

fractions in (4), would τ_{Bj}^{melt} take the lion's share of $\tau_{Bjt}^{\text{total}}$.

In section 3.2 we saw that melt in transit is well-approximated by a destination specific constant. Given that transport costs overshadow the importance of melt in determining the overall cost of shipping ice, we would be too quick to conclude from this that the iceberg assumption provides a good approximation of all costs involved in shipping ice. In the remainder of the paper, we therefor abstract from iceberg melt, and ask ourselves how well iceberg transport costs in practice are approximated by the iceberg assumption.

3.4 "Iceberg transport costs" in practice?

From (4) we know that these iceberg transport costs in practice consisted of four components: *freight* costs, *landing* costs, *fitting and loading* costs, and *sundries. Sundries* were a negligibly small part of total transport costs that primarily consisted of the costs paid for insuring the ice in transit. The Tudor Records show that these insurance costs were paid as a fixed percentage of the total value of the ice loaded onto a ship[23], i.e. they adhere to the iceberg assumption by definition. We focus on the other three components from now on, and ask how well they are approximated by the iceberg assumption.

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. Strictly speaking, the iceberg assumption then implies that we should find no differences in the per ton transport cost of shipments going to the same destination in the same year; see (1). To verify this, we use our individual shipments data and regress the freight, loading and landing costs per ton (as well as their sum) on a full set of destination-year dummies. Table 1 shows our findings.

The bottom row of columns (1)-(5) shows that all three transport costs components (or their combination) are well captured by a destination-year specific constant. They do not explain all the variation in transport costs however, as would be implied by the iceberg assumption. 7%-12% of the variation in per unit transport costs remains unexplained. 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 (as we found to be the case for iceberg melt, see Figure (3)). However, the reported coefficient estimates in Table 1 show that this remaining *within destination-year* variation is systematically related to shipment size.

This is most clearly the case for the per unit cost of fitting and loading the ice on board

[23] 1-1.5%, with no systematic differences over time, between destinations, nor between shipments sent to the same destination in the same year.

Table 1: Iceberg transport costs in practice?

	(1)	(2)	(3)	(4)	(5)
Dep.var.:	$\ln p_{Bjt}^{\text{load,k}}$	$\ln p_{Bjt}^{\text{load,k}}$	$\ln p_{Bjt}^{\text{freight,k}}$	$\ln p_{jt}^{\text{land,k}}$	$\ln p_{Bjt}^{\text{load+freight+land,k}}$
$\ln (\text{tons ice})_{Bjt}^{k}$	-0.235***	-0.215***	-0.013	-0.002	-0.064**
	(0.038)	(0.035)	(0.006)	(0.102)	(0.018)
FEs	jt	jt	jt	jt	jt
N	1,465	62	63	60	54
R^2	0.92	0.94	0.87	0.87	0.78
R^2 if only FEs	0.90	0.93	0.87	0.87	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.

in Boston (see columns 1 and 2).[24] 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. These did not fall (as much) with shipment size, explaining why the estimated coefficient is larger than -0.33.[25]

Column 3 shows that we do not find that the per ton freight costs are significantly related to shipment size. Note however that the estimated coefficient in column 3 is significant at the 10.3% level(!), and does suggest 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.[26] Freight costs were usually paid on the intake weight. A bar-

[24] Shipment size explains 19% of the *within destination-year* variation in the per ton cost of fitting and loading. Figure 7 in Appendix A.2 illustrates this.

[25] 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 2), one can get a rough estimate of the loading cost per ton of \$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.

[26] 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

gaining process with the owner of the ship determined the freight rate per ton paid by the Tudor Company (Proctor, 1981). The small positive coefficient in column 3 suggests that shipment size was a relatively minor input in this bargaining process. Differences in the experience of the ship owner/crew in sailing to a particular destination, how quickly the ship would be ready to depart, and the scope for a profitable return freight, probably mattered much more.

Finally, column 4 shows no evidence of economies of scale in offloading the ice. This is not unexpected as the dock workers hired to offload the ice were typically paid an hourly (or daily) wage, making it unlikely that landing costs per ton depended on the quantity of ice actually offloaded.[27] 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 significantly decreases overall iceberg transport costs 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.

4 Conclusion

Iceberg transport costs are one of the main ingredients of modern trade and economic geography models. This paper shows that this assumption does not accurately proxy the transport costs associated with shipping the only product that literally melts in transit: ice. The data on Boston's nineteenth-century global Ice Trade shows that these costs in practice consisted of both an ad-valorem (iceberg) component: *melt in transit* and *insurance*, and several per unit cost components: *freight, landing* and *loading* costs. And, although most of the variation in per unit transport costs is explained by destination-year specific factors, we find significant variation in these costs between shipments of ice sent to the same destination in the same year. More importantly, this variation is not random but systematically related to shipment size. The physics of the melt process and the practice

using all 1,465 shipments or the much smaller selected sample of shipments for which either also per unit freight costs or per unit landing costs are available.

[27]Do remember however that the per unit landing costs in the data are only reported per ton of ice *loaded onboard in Boston*; see Section 3.3. They only proxy for the landing cost per ton of ice *offloaded* up to melt in transit; see (2). 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 imply a positive correlation between initial shipment size and melt, meaning that our estimate in column 4 is biased upwards. However, in Section 3.2 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.

of insulating the ice in transit implied an immediate violation of the iceberg assumption: ice(berg) transport is subject to economies scale.

References

Alden, H., Hartman, L., Allen, F., and Wells, T. (1858). *Harper's Magazine*, volume 16. Harper's Magazine Company.

Atkin, D. and Donaldson, D. (2015). Who's getting globalized? the size and implications of intra-national trade costs. NBER Working paper 21439.

Blain, B. B. (2006). Melting markets: the rise and decline of the anglo-norwegian ice trade, 1850-1920.

Boston Board of Trade (1862). *Annual Report*.

Bunting, W. (1981). The east india ice trade. In Proctor, D., editor, *The Ice Carrying Trade at Sea*, pages 19–27.

De Economist (1860). Ijs-verbruik. vol.9:456–472.

Dickason, D. G. (1991). The nineteenth-century indo-american ice trade: an hyperborean epic. *Modern Asian Studies*, 25(01):53–89.

Encyclopedia Brittanica (1881). volume 16. Black, Edinburgh, 9th edition.

Fukusako, S. and Yamada, M. (1993). Recent advances in research on water-freezing and ice-melting problems. *Experimental Thermal and Fluid Science*, 6(1):90–105.

Hall, H. (1880). *The Ice Industry of the United States with a Brief Sketch of Its History and Estimates of Production*. US Department of the Interior, Census Division, Tenth Census.

Herold, M. W. (2011). Ice in the tropics: the export of crystal blocks of yankee coldness to india and brazil. *Revista Espaço Acadêmico*, 11(126):162–177.

Hittell, T. (1898). *History of California*, volume v. 3. N. J. Stone.

Hummels, D. (2007). Transportation costs and international trade in the second era of globalization. *Journal of Economic Perspectives*, 21(3):131–154.

Hummels, D. and Skiba, A. (2004). Shipping the good apples out? an empirical confirmation of the alchian-allen conjecture. *Journal of Political Economy*, 112(6):1384–1402.

Irarrazabal, A., Moxnes, A., and Opromolla, L. D. (2015). The tip of the iceberg: a quantitative framework for estimating trade costs. *Review of Economics and Statistics*, 97(4):777–792.

Isaacs, N. (2011). Sydney's first ice. *Sydney Journal*, 3(2):26–35.

Java Bode (1869). January 1.

Kistler, L. H., Carter, C. P., and Hinchey, B. (1984). Planning and control in the 19th century ice trade. *The Accounting Historians Journal*, pages 19–30.

Krugman, P. (1998). Space: The final frontier. *Journal of Economic Perspectives*, 12(2):161–174.

Legarda, B. J. (1999). *After the Galleons: Foreign Trade, Economic Change & Entrepreneurship in the Nineteenth Century Philippines.* Ateneo de Manila University Press, Quezon City, Manila, Philippines.

National Climatic Data Center (1998). The Maury Collection: Global Ship Observations, 1792-1910. Accessible through http://icoads.noaa.gov/maury.html.

New York Daily Tribune (1854). October 20.

Parker, W. L. (1981). The east coast ice trade of the united states. In Proctor, D., editor, *The Ice Carrying Trade at Sea*, pages 1–16.

Proctor, D. (1981). *The Ice Carrying Trade at Sea.* National Maritime Museum, London.

Ride, L., Ride, M., and Mellor, B. (1995). *An East India Company Cemetery: Protestant Burials in Macao.* Number v. 1. Hong Kong University Press.

Samuelson, P. A. (1954). The transfer problem and transport costs, ii: Analysis of effects of trade impediments. *The Economic Journal*, 64(254):264–289.

Scientific American (1863). Ice - its collection, storage and distribution. *Scientific American*, 8(21):338–339.

Singapore Free Press and Mercantile Advertiser (1845). page 2. August 28.

Smith, P. C. F. (1962). *Crystal Blocks of Yankee Coldness: The Development of the Massachusetts Ice Trade from Frederick Tudor to Wenham Lake, 1806-1880.* Wenham Historical Association and Museum.

The Asiatic Journal (1835). Cargo of ice. *The Asiatic Journal and Monthly Register for British and Foreign India, China, and Australia*, page 169.

The Mechanics' Magazine (1836). *The Ice Trade between America and India*, volume XXV. J. Cunningham, Mechanics' Magazine Office, London.

The Rights of Man (1834). vol.1(12). June 7.

Tinhorão, J. (2005). *Os sons que vêm da rua.* Editora 34.

Tudor Company Records (1752-1863). Baker Library. Harvard Business School, Boston, Massachusetts.

von Thünen, J. H. (1826). *Der isolierte Staat in Beziehung auf Nationalökonomie und Landwirtschaft.*

Weightman, G. (2003). *The Frozen Water Trade: A True Story.* Hyperion.

Wetherell, L. (1863). The ice trade. In *Report of the Commissioner of Agriculture for the year 1863*, pages 439–449. Congress, U.S., Washington D.C.

Wyeth, N. (1848). The ice-trade of the united states. In Little, C. C. and Brown, J., editors, *The American Almanac and Repository of useful knowledge, for the year 1849*, pages 175–180. Cambridge: Metcalf and Company.

A Appendixes

A.1 Melt data

Table 2: 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; 1835-1850		Tudor Company Records (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 (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 (1863)
Mauritius - Calcutta, India	1854	83	Tudor Company Records (1863)
Madras, India	1858	62	Alden et al. (1858)
Madras, India	1858	50	Alden et al. (1858)
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)
Norway - London, UK	1880	7.5	Blain (2006, p.8)

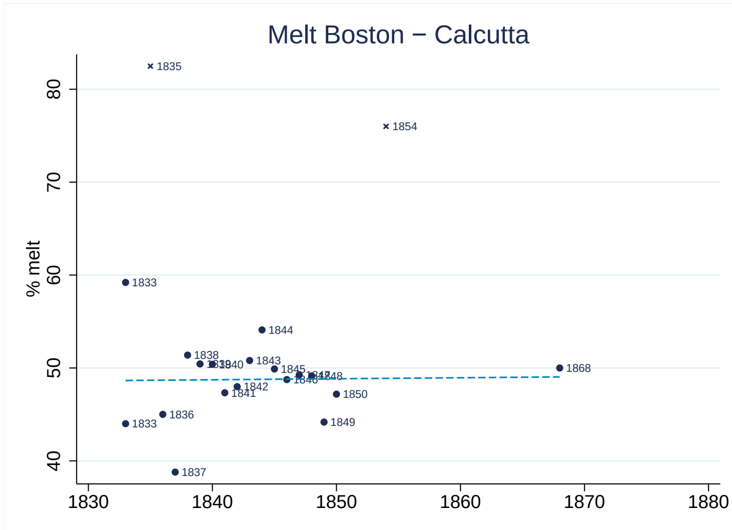
A.2 Descriptives and Additional Figures

Table 3: Descriptives for destinations in Tudor Records

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	total	avg.	no.		sailing	cost per ton ($)		
Destination	tons	ton/ship	ships	E[% melt]	days	loading	landing	freight
Batavia, Indonesia	39478	1067	37	41.8	99.8	1.21	.	.
Bombay, India	109651	962	114	46.2	110.4	1.25	.	6.24
Calcutta, India	154176	824	186	50.4	120.6	1.22	0.27	3.35
Charleston, USA	54498	277	197	16.3	12.0	0.55	0.67	1
Colombo, Sri Lanka	1818	606	3	50.2	120	1.81	.	.
Galle, Sri Lanka	16447	748	22	50.2	120	1.44	.	.
Havana, Cuba	179282	549	325	24.2	17.8	0.58	.	.
Hong Kong	32996	1222	27	40.3	96.3	1.32	.	.
Kingston, Jamaica	74265	485	153	34.7	25.5	0.57	.	.
Madras, India	64325	650	99	49.3	117.8	1.29	.	3.49
Mobile, USA	8526	194	44	29.9	22.0	0.63	0.47	1.89
New Orleans, USA	142913	581	246	29.7	21.8	0.47	0.81	2.75
Pernambuco, Brazil	111	111	1	17.2	41.2	0.92	.	.
Rangoon, Myanmar	391	391	1	.	.	1.87	.	.
Rio de Janeiro, Brazil	2372	593	4	20.6	49.3	1.78	.	.
Singapore	3563	594	6	46.4	111	1.48	.	.

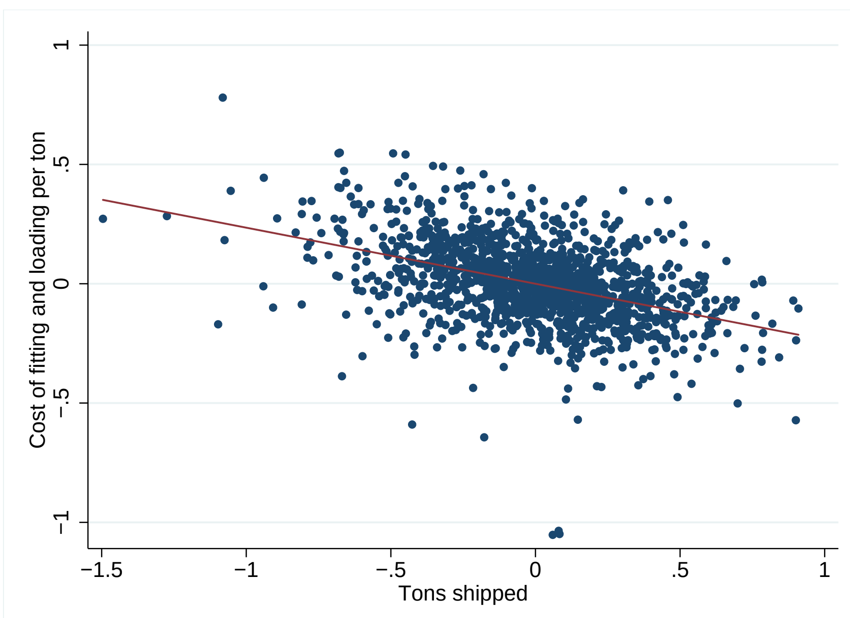
NOTES: The descriptives in columns (1)-(3) and (6)-(8) are based on the individual shipment data taken from the Tudor Records (see Section 3.1 for more detail). Column (4) reports predicted melt to each destination in transit based on an insulation regime specific regression of observed melt in transit 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 2 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.

Figure 6: 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 2. One, the 1835 observation, concerns a documented failures, 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.

Figure 7: 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 $\ln p_{Bjt}^{\text{load,k}}$ on a full set of destination-year dummies (on the y-axis) against the residuals of a regression of $\ln(\text{tons ice})_{Bjt}^{k}$ on a full set of destination-year dummies (on the x-axis).