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Ice(berg) Transport Costs

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 ice(berg) transport costs in practice were a combination of a true ad-valorem iceberg cost: melt in transit, and freight, (off)loading and insurance 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.

JEL-Codes: F100, N700, N510.

Keywords: iceberg transport costs, nineteenth-century Boston ice trade.

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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 a quantity x of a good s produced in location i to another destination j, one needs to ship $\tau_{ij}^s x$ goods from i, where $\tau_{ij}^s > 1$. A constant fraction of the goods, $m_{ij}^s = \left(\frac{\tau_{ij}^s - 1}{\tau_{ij}^s}\right)$, *melts* in transit. Total transport costs equal the cost of producing these *melted* goods.[2] As a result, per unit transport costs are proportional to the good's producer price in i, p_i^s:

$$p_{ij}^{\mathrm{T},s} = (\tau_{ij}^s - 1)p_i^s \tag{1}$$

In practice however, per unit transport costs are typically not (only) of the iceberg type (see e.g, Hummels (2007); Hummels and Skiba (2004); Irarrazabal et al. (2015); Alessandria et al. (2010); Hornok and Koren (2015b)). They consist of true ad-valorem (iceberg) costs such as insurance or ad-valorem tariffs, as well as additive cost components that are not necessarily proportional to the good's producer price (specific tariffs, administrative barriers, freight costs):

$$p_{ij}^{\mathrm{T},s} = \alpha_{ij}^s p_i^s + f_{ij}^s \tag{2}$$

, where α_{ij}^s and f_{ij}^s can be specific to the good shipped and the shipment route. Finally, the iceberg assumption takes τ_{ij}^s as exogenous and identical for shipments of the same good (variety) on the same route. This is a strong assumption. Transport costs often depend on the opportunity for return or onward cargoes and the competitiveness of the shipping industry. Also, they tend to fall with individual shipment size and/or the overall quantity shipped on a route.

These deviations from iceberg transport costs all have nontrivial implications. The presence of additive cost components, the degree of competition in the transport industry and the opportunity for return or onward cargoes at the destination can affect the predicted welfare gains from trade cost reductions (Irarrazabal et al., 2015; Hornok and Koren, 2015a; Behrens et al., 2009; Asturias, 2016), trade flows (Brancaccio et al., 2017; Wong, 2017; Behrens and Picard, 2011), and/or the quality of goods exported (Alchian and Allen,

[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.

1964; Hummels and Skiba, 2004; Feenstra and Romalis, 2014). 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 products made by other firms (Bernard et al., 2016).

Despite these well-known drawbacks of assuming transport costs *"to be iceberg"*, it remains the standard in most general equilibrium models of trade and economic 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.

In this paper, we assess the relevance of the iceberg assumption 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.

We show that 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). Given that the producer price of the ice sent out on shipments in the same year was identical regardless of the final destination, the iceberg assumption implies that all these ice(berg) transport costs in practice combined should be well-captured by a destination-year-specific constant; see (2). 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. Interestingly, it is melt in transit itself that is 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.

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

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

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 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 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 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.[4] Drawn by the extreme profitability of the trade, other companies soon entered the market, further expanding Boston's ice trade.[5]

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]

3 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

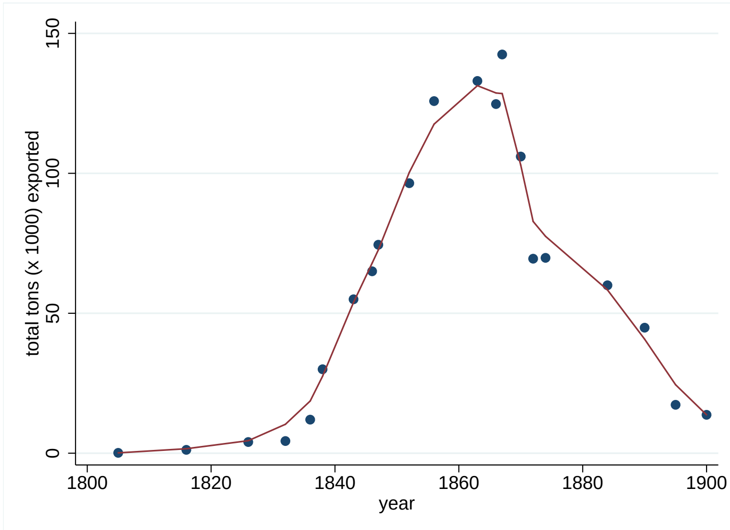
[4]Ice was mostly shipped to destinations where profitable return or onward freights could be obtained. Boston boats previously sailed in ballast to these destinations. Ice replaced this ballast. Shipping ice without a profitable return or onward freight was too costly.

[5]Ice in the tropics was often sold for more than fifty 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.

[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 *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.

Figure 1: Boston's global ice trade



Source: Herold (2011, p.168)

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 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 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.[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)). Dock workers were hired to load the ice onto

[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.

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.[9]

3.1 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 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. Comparing these yearly producer prices in each destination to the price at which the Tudor Company bought the ice in Boston, we can infer the average overall transport costs incurred when shipping ice from Boston to a particular destination.[10]

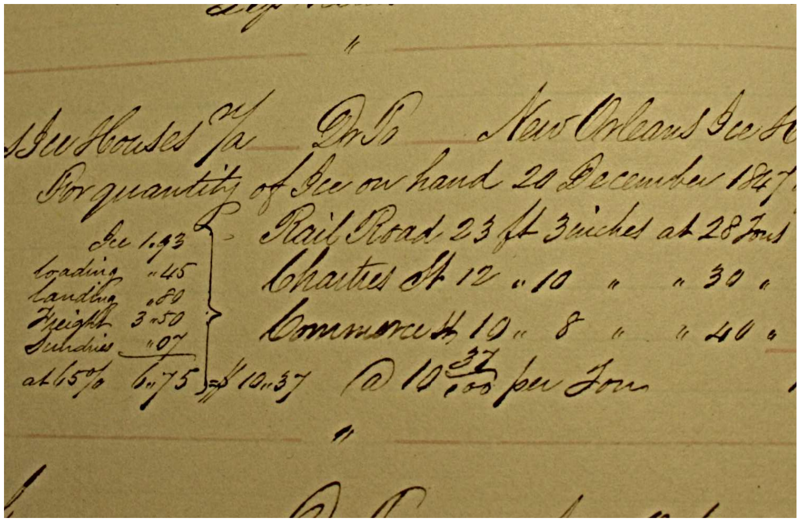
The scribble, shown on the left of Figure 2, is the only time that the Tudor Records detail how the firm calculated its unit costs in a particular destination (New Orleans in 1847). First, they paid for the ice in Boston ($1.93 per ton). Next, they paid different transport costs per ton to ship the ice 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 *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

[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).

[10]Observing producer prices is a unique feature of our paper. These producer prices are very different from the *sales prices* in each destination, that are typically used in earlier papers inferring transport costs from price differentials of identical goods between locations (see e.g. Atkin and Donaldson (2015) or Anderson and van Wincoop (2004)). A difficulty with using sales prices is that these can also reflect differences in consumers preferences or market structure between destinations. The Tudor Company sold the ice at prices ranging from two to twenty times the reported producer price, depending on the destination. The Tudor Company e.g. 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.

[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 17). 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 Section 4.1 or Appendix A.1 for more

Figure 2: Calculation of per unit cost of ice in New Orleans (1847)



Source: the Tudor Records, Tudor II, Volume 3

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 unit of ice *landed in destination* j (in year t) as:

$$
\begin{aligned}
p^{\mathrm{T}}_{Bjt} &= p_{jt} - p_{Bt} = \left(\frac{p_{Bt} + p^{\text{load}}_{Bjt} + p^{\text{land}}_{jt} + p^{\text{freight}}_{Bjt} + p^{\text{sundries}}_{Bjt}}{1 - m_{Bjt}} \right) - p_{Bt} \qquad (3) \\
&= \underbrace{\left(\frac{m_{Bjt}}{1 - m_{Bjt}} \right) p_{Bt}}_{\text{`pure' melt cost}} + \underbrace{\left( \frac{\tilde{p}^{\mathrm{T}}_{Bjt}}{1 - m_{Bjt}} \right)}_{\substack{\text{`melt augmented'} \\ \text{transport cost}}}
\end{aligned}
$$

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.

, where $\tilde{p}^{\mathrm{T}}_{Bjt} = p^{\mathrm{load}}_{Bjt} + p^{\mathrm{land}}_{jt} + p^{\mathrm{freight}}_{Bjt} + p^{\mathrm{sundries}}_{Bjt}$ denotes the transport cost per ton *loaded in Boston*. p_{jt} and p_{Bt} denote the producer price of the ice in destination j and in Boston respectively. p^{load}_{Bjt}, p^{land}_{jt}, $p^{\mathrm{freight}}_{Bjt}$ and $p^{\mathrm{sundries}}_{Bjt}$ 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_{Bjt} denotes the fraction of the ice that melts in transit.

Comparing equation (3) to equations (2) and (1), with s = ice, immediately reveals that ice(berg) transport costs in practice are well-approximated by the iceberg assumption if two conditions are met:

1. **Melt**, m_{Bjt}: melt in transit does not systematically differ between shipments sent to the same destination (in the same year); it is well-approximated by a destination-(year)-specific constant.

2. **Transport costs**, $\tilde{p}^{\mathrm{T}}_{Bjt}$: the transport cost per unit of ice loaded in Boston is proportional to the producer price of the ice in Boston; it does not systematically differ between shipments sent to the same destination (in the same year) that carry ice of the same per unit value.

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 sent to the same destination (in the same year). 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.

4 Iceberg transport costs in practice?

4.1 Data

Our data 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,

[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*.

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 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 1833-1850, the Tudor Company Records do not report melt. Our 45 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 1,468 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 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. Appendix A.2 provides summary statistics of the most important variables for each destination reported in the Tudor Company Records.

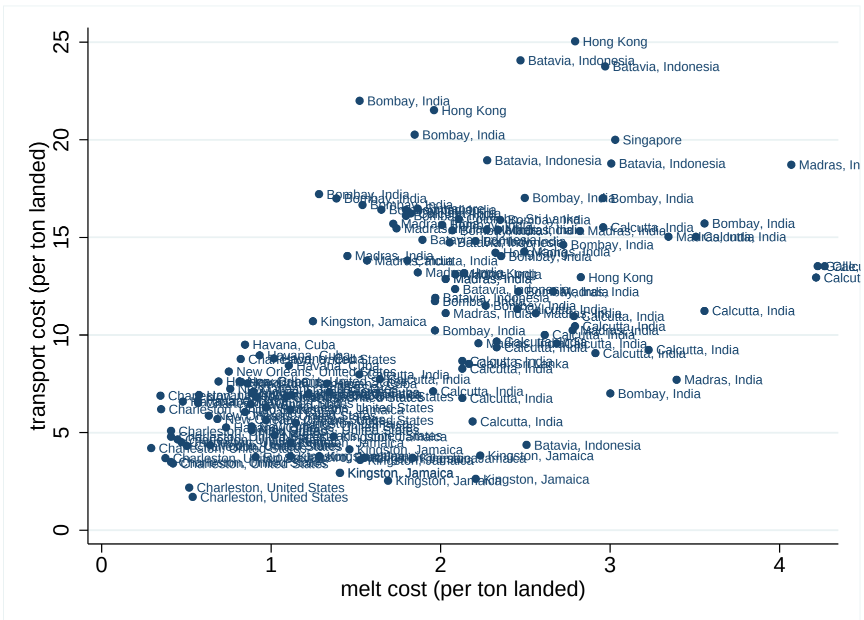
4.2 Melt vs. transport costs

Figure 3 shows the relative importance of the 'pure' melt-, and 'melt augmented' transport cost component that together make up ice(berg) transport costs in practice; see (3). 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] The 'pure' melt, and 'melt augmented' transport costs per ton are calculated as in (3), where we make use of our yearly data on

[13]Multiplying each of these components by $(1 - m_{Bjt})$ would give these costs per ton of ice *loaded in Boston*. Table 3 reports this average transport cost per ton of ice *loaded in Boston* for each destination, i.e. $\tilde{p}^{T,ice}_{Bjt}$ in (3). 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.

producer prices in Boston and in each destination, as well as the (predicted) melt on each route that is based on a regression of actual observed melt on the number of sailing days to each destination; see Section 4.3 for the details.

Figure 3: 'Pure' melt vs. 'melt augmented' transport costs



NOTES: the 'pure' melt, and 'melt augmented' transport costs per ton are calculated as in (3), 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 Section 4.3 for the details.

To all destinations, the transport costs component dominates the melt component in determining overall ice(berg) transport costs in practice. This is simply due to the fact that the producer price of the ice in Boston, p_{Bt}, was always (much) smaller than the combined transport cost per ton loaded onboard in Boston, $\tilde{p}^{\mathrm{T}}_{Bjt}$.[14] We also observe substantial variation between destinations and years in both the melt and transport cost components. In the next sections, we focus on Conditions **1** and **2**, and verify how well this variation in ice(berg) transport costs in practice is approximated by the iceberg assumption.

[14]Note that this result is robust to any plausible measurement error in the construction of our predicted melt measure; see Section 4.3.

4.3 Melt

We first establish whether or not the fraction of the ice that melts in transit is well-approximated by a destination specific constant; 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. And, 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.[15] 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.

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 remaining variation in melt between shipments going to the same destination in the same year is not systematically related to shipment size.[16]

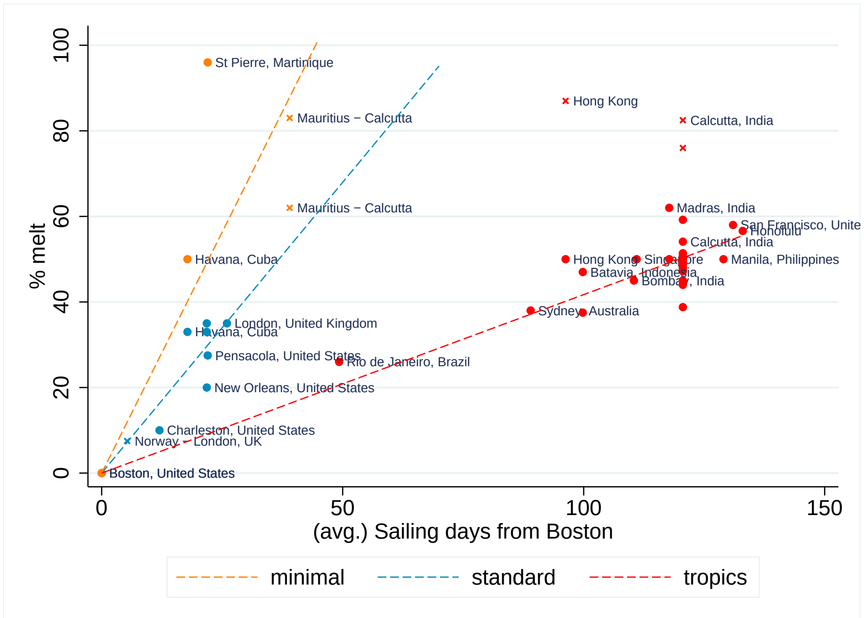
The Tudor Ice Company used two different insulation regimes: one for shipments to the US south and Caribbean, and another, better one for shipments to Asia, South America and Australia (see Section 3). This clearly shows in the data: the per ton cost of fitting and loading the ice onboard in Boston is an average \$0.51 (SD \$0.14) for 'standard' shipments to the US South and Caribbean, and an average \$1.16 (SD \$0.27) for 'tropics' shipments to destinations further away. Given this choice of insulation regime, melt depended primarily on the length of the journey.[17] Figure 4 shows the relationship between melt and sailing

[15]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).

[16]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). Conditional on the choice of insulation regime (that is almost one-for-one related to the shipping route taken, see also footnote 17), 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 4 in any way, whereas these temperature variables themselves are highly insignificant.

[17]The choice of insulation regime is also closely related to the length of the journey. Using the estimated relationship between melt and distance for the two regimes (see Figure 4), in combination with the observed

Figure 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; 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.

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.[18] Strikingly, variation in

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.

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

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).[19]

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 nine 'tropics' shipments. Regressing both shipment size and the number of sailing days on melt for these nine 'tropics' shipments shows that shipment size is, conditional on the duration of the journey and insulation regime, not significantly related to melt.[20] But, of course, the (very) small sample could be to blame for this.

Under a mild assumption, we can however use our shipment-specific information on the quantity of ice shipped from Boston and the total landing costs paid upon arrival in the destination to shed further light on the existence of a systematic relationship between melt in transit and shipment size. This information is available for 60 shipments. To see how this works, first note the following identity:

$$\underbrace{\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)}_{\text{observed}} = \underbrace{\left(\frac{Q_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)}_{1-m_{Bjt}^{k}} c_{jt}^{k,\text{landed}} \tag{4}$$

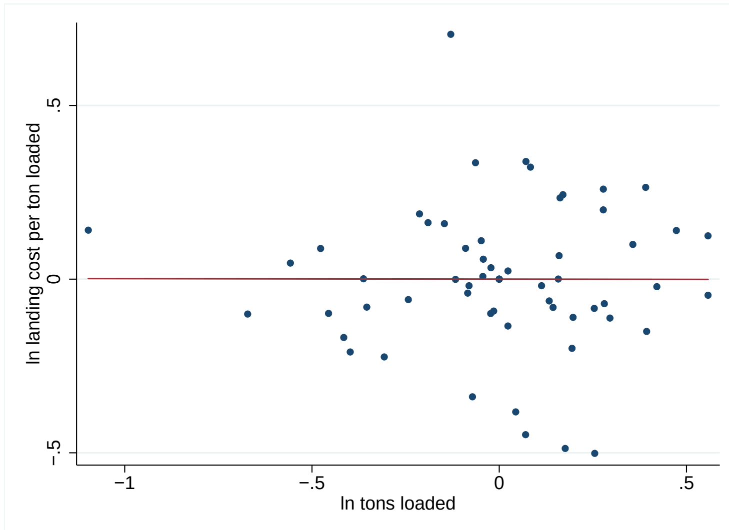
, where m_{Bjt}^{k} denotes the fraction of ice that melted during ship k's transit. $Q_{jt}^{k,\text{landed}}$ and $Q_{Bt}^{k,\text{loaded}}$ are the quantity of ice that ship k landed in destination j and loaded in Boston in year t, respectively. $C_{jt}^{k,\text{landed}}$ and $c_{jt}^{k,\text{landed}}$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

Using (4), we can infer the existence of a systematic relationship between melt and

[19] There is 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. 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 7 in Appendix A.2 illustrates this in case of New Orleans and Calcutta. Including year dummies to allow for general changes in shipping/insulation technology neither changes the point estimate of the relation between melt and the number of sailing days nor its significance.

[20] The estimated coefficient on the tons of ice loaded in Boston is 0.002 (SE 0.003). The estimated coefficient on the number of sailing days is very similar to that depicted in Figure 4: 0.39 (SE 0.03).

Figure 5: Melt in transit unrelated to shipment size [by boat]



NOTES: The figure 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).

shipment size by looking at the significance of α in the following regression:

$$\ln\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right) = \alpha \ln Q_{Bt}^{k,\text{loaded}} + \gamma_{Bjt} + \epsilon_{Bjt}^{k} \tag{5}$$

, where γ_{Bjt} captures any origin-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 $\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)$ only proxies the fraction of ice surviving in transit up to $c_{jt}^{k,\text{landed}}$, see (4), 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 plausible assumption[21], Figure 5 clearly shows no evidence that the variation in shipment size helps to explain the observed variation in melt in transit.[22] 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

[21] 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*.

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

variation in melt in transit[23]. The unexplained variance in Figure 4 can much more likely be attributed to the substantial variation between shipments in time in transit[24] and in the adherence of the crew to the agreed melt mitigating measures (see Section 3).[25]

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, our data shows that these economies of scale were, in practice, 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 component of ice(berg) transport costs in practice rather well.

4.4 Transport costs

Next, we turn to Condition **2** and focus on the actual transport costs paid to transport the ice. From (3) we know that ice(berg) 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 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[26], 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 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)).[27]

[23] The γ_{Bjt} explain 87% of the overall variation in $\ln\left(\frac{C_{jt}^{k,\text{landed}}}{Q_{Bt}^{k,\text{loaded}}}\right)$.

[24] 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 7 in Appendix A.2.

[25] 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.

[26] 1-1.5%, with no systematic differences over time, between destinations, nor between shipments sent to the same destination in the same year.

[27] 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}^{ice} in (1) to vary over the years. The destination-year

However, regardless of whether ice(berg) transport cost were actually proportional to producer prices or instead consisted primarily of additive cost components, we can still assess whether or not per unit transport costs are *well-proxied* by an ad-valorem, iceberg specification. In the absence of any differences in producer prices between shipments leaving Boston in the same year, the iceberg assumption strictly speaking implies:[28]

i. Exogenous differences in the (average) per ton transport costs between destinations; τ_{ijt} is not jointly determined with conditions in the ice trade.

ii. No differences in the per ton transport cost of shipments going to the same destination in the same year.

The first implication (**i.**) concerns any destination-specific factors determining the transport cost of ice.[29] These were certainly important: the degree of competition on the route, journey duration, the typical ship and insulation regime used, and the opportunities for profitable return or onward cargoes varied substantially between the destinations served by the Tudor Company. Figure 3 already aptly illustrated this. We lack the data to convincingly establish the (relative) importance of these different route-specific freight, landing or loading costs determinants. But, important for our purposes, it is very unlikely that any of them were endogenous to conditions in the ice trade.

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 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 Jr, 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.[30] 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 (see also Section 4.3). The former did not vary between destinations, leaving differences in expected melt as

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}^{ice} to (exogenously) vary over the years.

[28]See (2). These implications are necessary, but not sufficient for the iceberg assumption to hold.

[29]See North (1968, 1965) for more detail on the determinants of ocean freight rates in the 19th century.

[30]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 42 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.

the important factor determining the insulation regime used on shipments to a particular destination. This depended primarily on journey duration, which was clearly exogenous to conditions in the ice trade (see footnote 17).

Next, 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. 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 transport 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 3 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). Finally, upon arrival, the ice had to be offloaded. The local dock workers hired to do this were paid an hourly or daily wage. This wage depended on the total number of ships in port that needed to be (off)loaded, as well as on the local supply of dock workers. None of these destination-specific freight and landing cost determinants will have depended on conditions in the ice trade. Again, the ice ships simply made up a too small fraction of the total traffic between Boston and each destination.

To verify the iceberg assumption's second implication (**ii.**), 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 (as well as 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. 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

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	1,468	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).[31] 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. 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.[32]

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 10.3% 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

[31] Shipment size explains 19% of the *within destination-year* variation in the per ton cost of fitting and loading. Figure 8 in Appendix A.2 illustrates this.

[32] 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.

due to the much smaller sample of shipments for which freight costs are available.[33] Freight costs 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). 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 probably mattered much more in explaining the observed variation in per ton freight costs between shipments going to the same destination in the same year.

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 a daily or hourly wage, making it unlikely that landing costs per ton depended much on the quantity of ice offloaded.[34] 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 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.

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 460 tons. And, of the 99 ships carrying Tudor ice in 1847 and 1849, 49% 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).[35]

[33]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 1,465 shipments or the much smaller selected sample of shipments for which either also per unit freight costs or per unit landing costs are available.

[34]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 3.1. They only proxy for the landing cost per ton of ice *offloaded* up to melt in transit; see (4). 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 Section 4.3 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.

[35]For Boston's foreign trade this pattern is even more pronounced. Of Boston's total 5,636 foreign

5 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, and that lent its name to this important "trick of the genre": *ice*. Using our data on Boston's nineteenth century global ice trade, we document significant variation in per unit ice(berg) transport costs that is systematically related to shipment size. Interestingly, the physics of the melt process, and the practice of insulating the ice in transit to limit this melt, are primarily to blame for this violation of the iceberg assumption: ice(berg) transport is subject to economies scale. Of course, this finding does 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 transportation sector into these models (e.g., Alessandria et al., 2010; Irarrazabal et al., 2015; Asturias, 2016; Brancaccio et al., 2017) should only be encouraged.

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clearances in 1847 and 1849, 5% were full rigged ships, 36% brigs and barks, and 59% schooners. For the 32 ships carrying Tudor ice to a non-US destination in these years, these percentages are 72%, 27% 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)).

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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)
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)
Norway - London, UK	1880	7.5	Blain (2006, p.8)

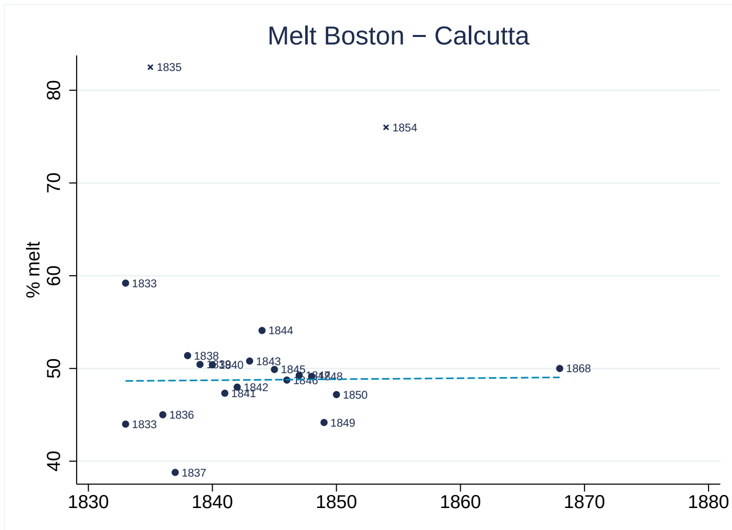
A.2 Descriptives and Additional Figures

Table 3: Descriptives for destinations in Tudor Records

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	total	avg.	no.		sailing	cost per ton ($)			
Destination	tons	ton/ship	ships	E[% melt]	days	loading	landing	freight	$\tilde{p}^{\mathrm{T}}_{Bjt}$
Batavia, Indonesia	39478	1067	37	41.8	99.8	1.21	.	.	9.3 (3.6)
Bombay, India	109651	962	114	46.2	110.4	1.25	.	6.24	8.2 (1.7)
Calcutta, India	154176	824	186	50.4	120.6	1.22	0.27	3.35	5.2 (1.4)
Charleston, USA	54498	277	197	16.3	12.0	0.55	0.67	1	3.9 (1.5)
Colombo, Sri Lanka	1818	606	3	50.2	120	1.81	.	.	8.0 (.)
Galle, Sri Lanka	16447	748	22	50.2	120	1.44	.	.	5.5 (1.8)
Havana, Cuba	179282	549	325	24.2	17.8	0.58	.	.	5.6 (0.9)
Hong Kong	32996	1222	27	40.3	96.3	1.32	.	.	10.4 (3.3)
Kingston, Jamaica	74265	485	153	34.7	25.5	0.57	.	.	3.0 (1.4)
Madras, India	64325	650	99	49.3	117.8	1.29	.	3.49	6.8 (1.3)
Mobile, USA	8526	194	44	29.9	22.0	0.63	0.47	1.89	4.0 (1.4)
New Orleans, USA	142913	581	246	29.7	21.8	0.47	0.81	2.75	4.5 (0.7)
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	.	.	3.0 (.)
Singapore	3563	594	6	46.4	111	1.48	.	.	9.8 (1.3)

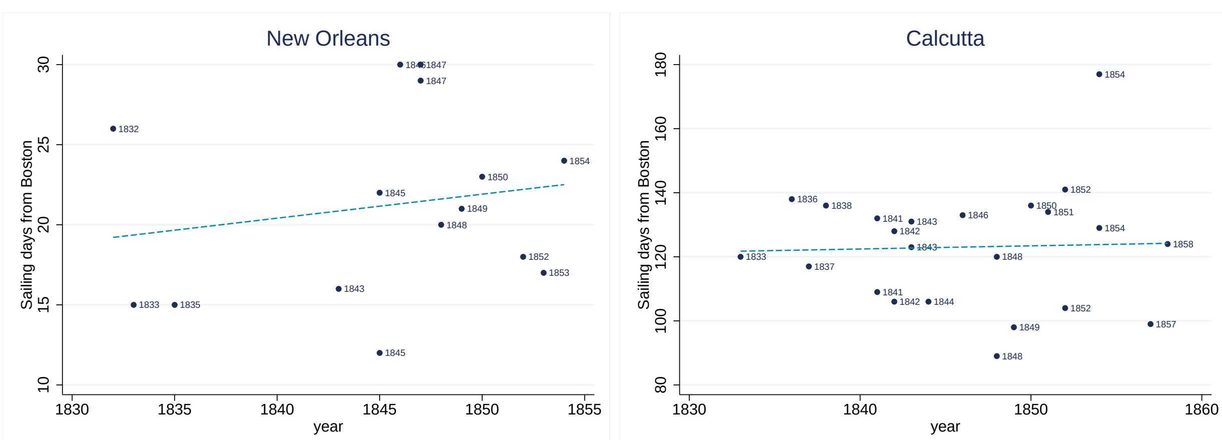
NOTES: The descriptives in columns (1)-(3) and (6)-(8) are based on the individual shipment data taken from the Tudor Records (see Section 4.1 for more detail). Column (4) reports predicted melt to each destination in transit based on an insulation regime specific regression of observed melt in transit 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*, i.e. p^{T}_{Bjt} in (3), accompanied by its standard error. It is calculated using our data on producer prices in Boston and each destination, in combination with the predicted melt numbers reported in column (4): $p^{\mathrm{T}}_{Bjt} = p_{jt}(1 - m_{Bjt}) - p_{Bt}$. Standard errors are missing for destinations where we observe p^{T}_{Bjt} in one year only.

Figure 6: Melt over time



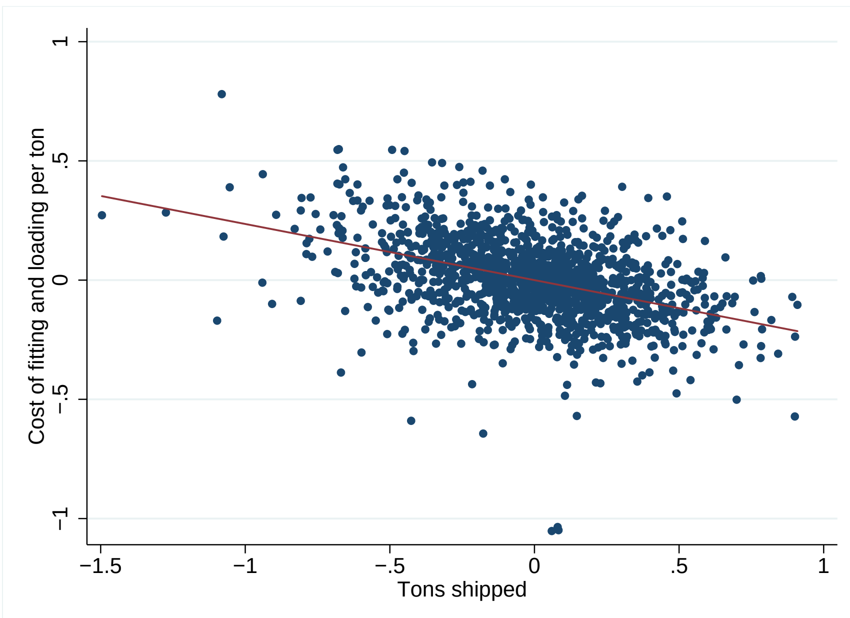
NOTES: the slope of the fitted regression line is 0.01 (SE 0.14). The observations marked with an "x" concern two outliers - the same two Calcutta outliers as in Figure 4. One, the 1835 observation, concerns a documented failure, and one, the 1854 observation, concerns melt reported for a shipment on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

Figure 7: Sailing days 1830-1860 - 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.

Figure 8: 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).