"No joke. A vessel with a cargo of 80 tons of ice has cleared out from this port for Martinique. We hope this does not prove to be a slippery speculation." Boston Gazette (Feb, 1806)

Iceberg transport costs

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< VERY PRELIMINARY: DO NOT QUOTE >

Abstract/Introduction

Iceberg transport costs are one of the main ingredients of any modern quantitative trade or economic geography model. By making the iceberg assumption that to deliver q goods produced in location i to location j, $\tau_{ij}x$ goods have to be shipped from location i (with $\tau_{ij} > 1$), one avoids the need to explicitly model the transport sector. In this paper we assess some of the underlying assumptions and implications of the iceberg assumption using data in the only business where the product literally melts in transit: the ice trade. The ice trade flourished in 19th century Boston. From its harbor large quantities of ice were shipped over vast distances, even to tropical locations in Asia, South America and Australia.

Iceberg transport costs: the assumption and its implication for price differences between locations

The iceberg assumption was introduced in economic analysis by Samuelson (1954) [1]. To avoid the need to model an entire transport sector, he simply assumed that in order to deliver a quantity q of a good produced in location i to another location j, one has to ship $\tau_{ij}\, q$ goods from location i ($\tau_{ij} > 1$). Transport costs are incurred as a constant fraction of the good (τ_{ij}-1) simply "melts away" in transit, so that the overall per unit cost of transport is a constant fraction of the per unit value of the good shipped:

$$T_{ij} = (\tau_{ij} - 1)\, p_i \qquad (1)$$

, where p_i is the price of the good in location i. The iceberg assumption thus assumes that transport costs are a constant (exogenous) fraction of the per unit value of the good shipped. Importantly, this fraction does not depend on the amount of the good shipped, nor the price of the good shipped.

[1] In economic geography Von Thunen (1826) already introduced a similar notion. He modelled the cost of transport in a very similar way. He gave the example of shipping grain to the market, where part of the grain would be consumed by the oxen pulling the cart of grain.

On top of this, in virtually all modern quantitative international trade and economic geography models the iceberg transport cost assumption also provides a very nice synergy with the assumed utility and/or production functions. It results in a mathematically elegant, tractable way to incorporate trade costs into these models. It is e.g. a cornerstone of virtually all models providing a theoretical foundation of the gravity equation in international trade (see Allen et al, 2015). Krugman (1998) even called it one of the "tricks" of the genre in an overview paper on the role of space in economic models of trade and location.

In all these models there exists a direct relation between the price of the good in the location where it is produced and its price in a foreign location:

$$p_j = (\tau_{ij}\, p_i)\, \varphi_j \qquad (2)$$

The terms in brackets is simply the cost price of the good in location *j*, which depends on the price of the good in location *i* multiplied by the "iceberg factor" τ_{ij} (put differently, this cost price is nothing but the price of the good plus the cost of transport involved in shipping the good from *i* to *j*). The markup φ_j on the other hand reflects the fact that the firm shipping the good from *i* to *j* may have a different degree of market paper in *j*, resulting from notably a different market structure (less/more competitive) or consumer preferences. If conditions are identical in the two markets, $\varphi_j = 1$. In case the firm has more respectively less market power in *j*, φ_j is larger respectively smaller than 1.

Our data on the 19th century ice trade allows us to:

(1) calculate the iceberg fraction τ_{ij} for different locations using data on the percentage of ice that melts in transit on the different routes, the transport costs (i.e. all cost associated with the transport of ice) from Boston to different locations, and the markup φ_j in several destination cities,

(2) verify how well the melt implied iceberg transport costs can explain the variation in actual transport costs between destinations, and

(3) verify how well the melt-implied iceberg transport cost can explain the variation across different export destination in the wedge between the price of ice in each destination and that in Boston.

Before we turn to our data and empirical analysis however, we first provide a brief history of the ice trade.

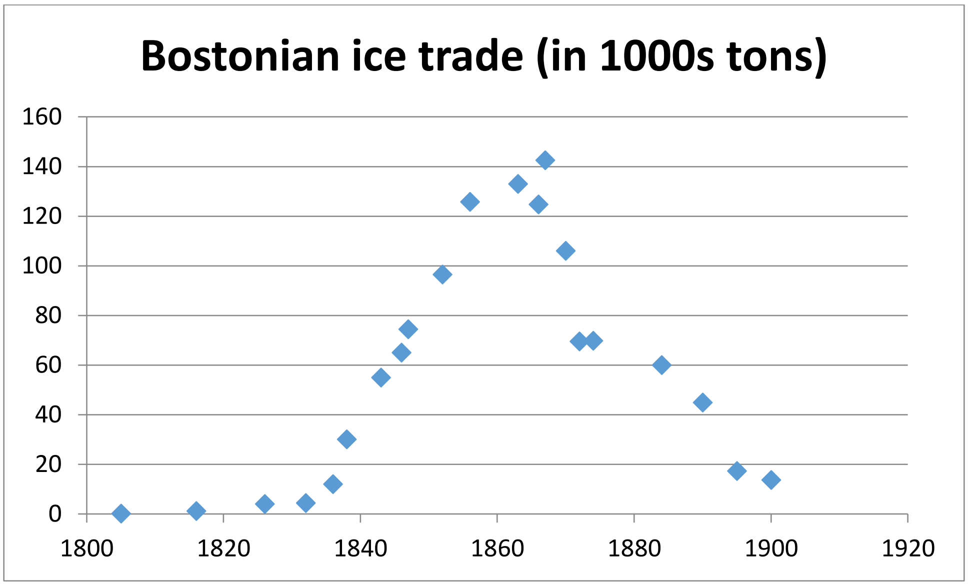
A brief history of the trade in natural ice

The use of ice or snow for cooling foodstuffs or drinks goes back a long time in history. The first historical mention (circa 1770 BCE) of an ice house, and the cooling of drinks with the collected and stored ice can be found on a Babylonian clay tablet (Dalley, 2002, 91). Ice pits from approximately a millennium later have been excavated in China. In the sixth century BCE snow cooled wine was drunk in Greece (Curtis, 2001, 296). The Greek historian and writer Xenophon says that Alexander the Great has used pits to store ice for subsequent use. In the Roman Empire snow was imported from the mountains to Rome and sold in shops in the first centuries CE (James and Thorpe, 1995). In the early modern period snow, collected from nearby mountains, in combination with nitre was already used for ice cream making in Naples (Calarescu, 2013). All over the world numerous ice houses dating from the early modern period and even from before that time show that collecting blocks of ice in winter and storing it for later use was wide-spread before the age of artificial refrigeration.

The history of the American long distance ice trade starts with the American merchant Frederic Tudor from Boston who saw commercial opportunities where others did not (Encycl. Brit. 9th ed, vol xii, 614). To the ridicule of his peers he started exporting 130 tons of natural ice collected from frozen New-England ponds to the tropical island of Martinique in 1806 by sailing ship. During his first few voyages he did not yet make a profit, as he had to overcome quite some technical difficulties in this totally new field of commerce. In a fairly short time he however developed ways of conserving more ice during transport, built better isolated ice houses at his point of departure and at his destinations to store his merchandise, and also found less labour intensive ways for the storage and harvesting of the ice in winter from nearby frozen ponds. To prevent his ice melting during transport Tudor found out he could very well use saw dust and wood shavings as an isolation material. Saw dust was an abundant waste product from the local saw mills in New England, while the ice could be harvested for only a small sum from frozen ponds in the neighbourhood. This ice harvesting was largely done by workers with special implements who were otherwise unemployed during the harsh and long New-England winters.

It turned out to be a very lucrative business. Frederic Tudor is believed to have been the first American millionaire and was even called the ‘ice king’. But, because of the rather low barriers of entrance to this profitable market (the easy hire of means of transport and helping hands, the wide availability of saw dust and of natural ice in the freezing north-eastern winters) it was not before long that there were quite a number of competitors in this icy trade. Figure 1 shows the rise and demise of the Boston ice trade over the course of the 19th century. The Boston ice trade grew spectacularly in the first half of the nineteenth century. After circa 1860 Boston became less important as an export harbour of American ice because its leading role had been taken over by a number of other places in the North East mainly along the river Hudson and in Maine.

Figure 1. Ice shipped from Boston in the nineteenth century.



Source: Herold (2011, 168).

The total amount of natural ice that was consumed in 1879 in the largest twenty cities of the US was nearly 4,000,000 tons (Hall, 1883, 5). By that time, most of the ice harvested was used in the US itself, where large amounts were sold to brewers, the food industries (fish and meat) and hospitals, and to private consumers. New York City alone then consumed around 500,000 tons per year (Encycl. Brit. 9th ed, vol xii, 614). Nevertheless a considerable part of American ice was exported, notably to the East and West Indies, but also to South America, and the West coast of the United States.

In 1833 Frederic Tudor started to export ice to India. There it was sold at 3 pence per pound (about 6 $ cents), a price that was half that of the local ice that was produced in a labour intensive natural process. This local "Hooghly" ice was scraped from special porous ceramic pans containing boiled water and located in shallow pits filled with straw that were exposed overnight to a cool dry breeze from the north west. The water in the pans then evaporated at the expense of its own heat, and the consequent cooling produced a thin layer of ice (Encycl. Brit, 9th ed, vol xii, 612).

The nineteenth-century export of natural ice from the northern hemisphere to tropical countries was very successful. Over the years American sailing ships brought thousands of tons of ice to Cuba, the West Indies, Sri Lanka, Indonesia, India, Brazil, Australia and China to name their more important destinations. There were several reasons for this exporting success of natural ice in the nineteenth century. In hot tropical conditions people were prepared to pay considerably more for ice than in cooler climates, and nineteenth-century mechanical refrigeration techniques were not yet developed far enough to allow artificial ice to meet this need. Furthermore ships with tropical export products as jute, cotton or rubber coming to Boston generally had to sail back in ballast because there was not enough return freight, which made loading ice instead of ballast a favourable option for Bostonian traders. In the second half of the nineteenth century American ice from Boston was transported all over the world by sailing boats in voyages that could last for half a year or more. The various regimes of isolation used for 'fitting and loading' and the final price of the ice still made such lengthy trips worthwhile despite the unavoidable partial loss of ice by melt during all voyages.

After circa 1860 natural ice got more and more competition from artificial ice produced in special refrigerating machines. During the American civil war the southern states underwent a sea blockade by the northerners. This stopped the previous influx of northern ice to cities such as Savannah, Charleston and New Orleans. The sea blockade made that the southern states tried to switch to ice from refrigeration machines. At first this was still a rather messy process, which could not produce the same quality ice as nature did for free. Later on as science (thermodynamics) and technology (adiabatic expansion of gasses and sealing of the toxic and flammable chemicals) progressed artificial cooling had become much more competitive. In 1898-99 the cost of manufacturing one ton of artificial ice in England was 25 new pence while one ton of natural ice imported from Norway to England was more than three times as expensive and came to 79 new pence (David, 1995, 61). Around this time natural ice had lost out to its artificial competitor, explaining the demise of the trade.

Data

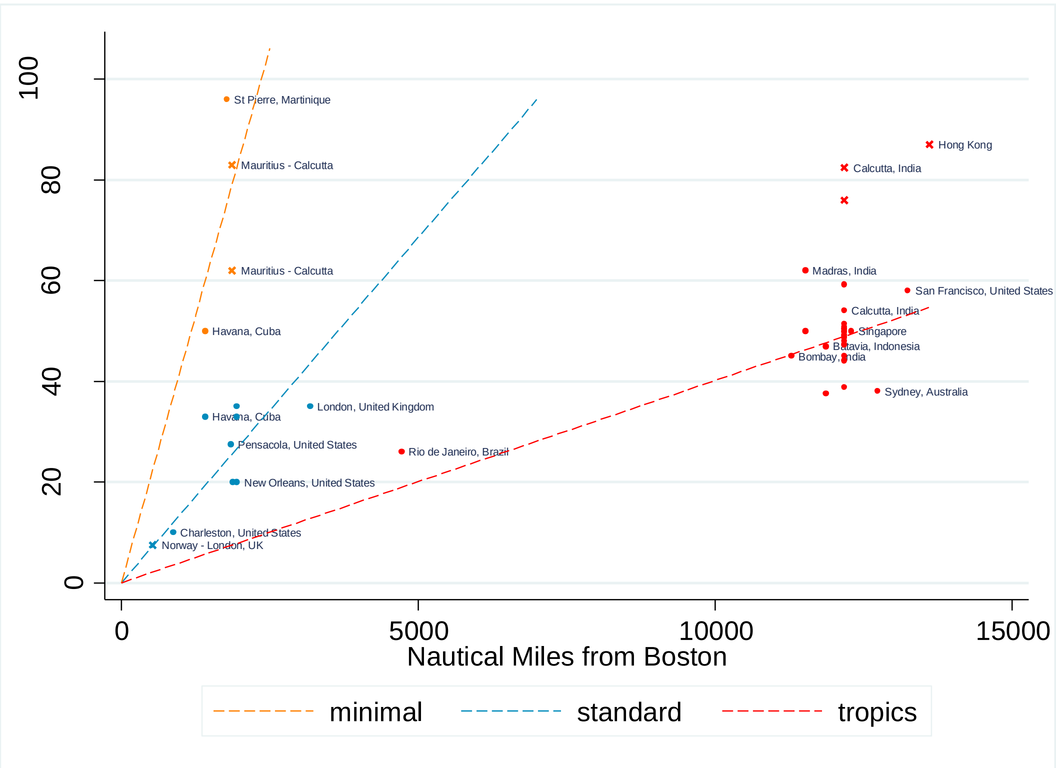
Our dataset consists of information on the ice trade between (mostly) Boston and 26 different export destinations in the Americas, Europe and Asia in the period between 1806 (when Frederick Tudor exported his first shipment of ice to Martinique) and 1880. For 16 of these destination we observe the percentage melted in transit for at least one journey. Besides melt we also have (unbalanced) information on the cost price of the ice in Boston, the sales and inventory price of ice in the destination city, the cost of fitting and loading the ice onto the boat(s) in Boston, the insurance paid on each shipment (we use contemporary exchange rate to express all prices in US$), the amount of ice shipped, the number of shipments, and the stock of ice at hand in each destination city. For each destination, we also know the length (in nautical miles) of the journey from Boston (from www. seadistances.org). Of course we calculate these distance without taking the Suez or Panama Canal into account. Finally, from the Clioinfra-project, and the Encyclopedia Brittanica, we have information on the population size of all destination at several points during the 19th century.

Our data comes mostly from the Tudor Archives; the Tudor company records that are today located at Harvard's Baker Library. We complement it with information from contemporaneous accounts of the US ice trade, newspaper articles, and journal articles, as well as more recent historical accounts of the trade. For a complete overview of all our sources, see the Data Appendix.

Melt, packing regime and distance

We start in Figure 2 below to show the relationship between the percentage of the ice melted during the journey from Boston to a particular destination, and that destination's distance (in nautical miles) from Boston. In doing this we distinguish between three different packing/isolation regimes. As documented in Algemeen Handelsblad (Aug.1834), or Wyeth (1849) the ice shipping companies had different packing/isolation regimes for the longer (tropical) journeys to the East Indies and South America, and those to the Southern United States and West Indies. Looking at the data from the Tudor Archives this is confirmed. The average cost of fitting and loading the ice on the ship is 0.51 (st.dev 0.14) $ per ton for shipments to the Southern United States and the West Indies and 1.15 (st.dev 0.27) $ per ton for shipments to the East Indies or South America.

Figure 2. Melt, packing regime and distance



Notes: the observations marked with a "X" denote the two "Walpole-reshipments" in case of the minimal regime, a shipment from Norway instead of from Boston in case of the standard regime, and two exceptionally high losses to Calcutta and Hong Kong (as noted in the respective original sources), as well as a case of reported melt by a third source that cannot be verified in the Tudor Archives (it concerns a shipment carried by the ship Arabella in 1854 – this ship(ment) does not appear in the Tudor Archives in 1854, 1853 or 1855. Given their exceptional nature, the "X" observations in the "tropics" regime are not used in the calculation of the slope of the regression lines shown in the Figure. All regression lines go through the origin.

Besides this "tropics" and "standard" packing regime, we also distinguish a third "minimal" packing regime. The latter applies to the first two ships to ship ice from Boston to the West Indies (to Martinique in 1806 and to Havana, Cuba in 1807), as well as to the two ships that shipped ice from Mauritius to Calcutta in 1854. These two ships carried ice from the ship "Walpole" that had left Boston with ice for Calcutta. The Walpole however got into trouble on the Indian Ocean (New York Tribune, Sep.1854). It fortunately did not sink, but was brought to Mauritius. The remaining ice was put on two other ships (the Veanne and the Ferdinand) that delivered it to Calcutta, but without any isolation in place (Tudor Archives).

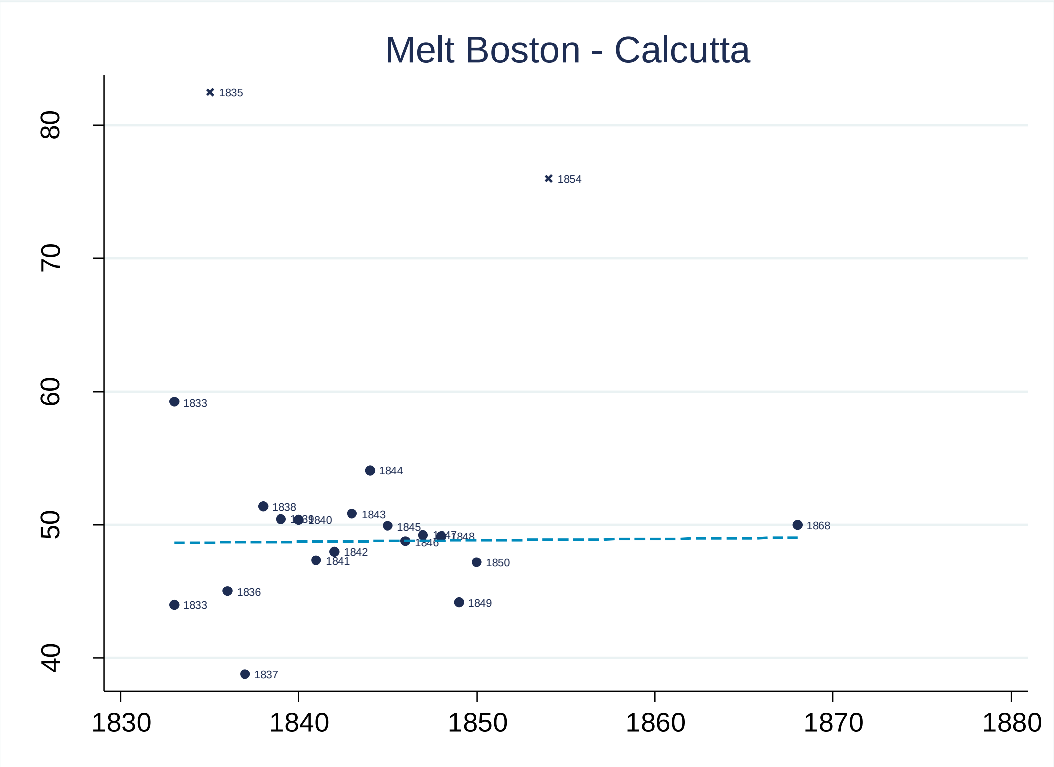
Figure 2 clearly shows the expected relationship, the longer the journey (distance and voyage time are clearly correlated) the more ice melts in transit. What is also evident is that the better isolated packing regime the weaker the relationship between melt and distance becomes. The variation in nautical miles from Boston explains 98.5%, 92.8%, 96.3% of the variation in melt in transit in case of the "tropics", "standard" and "minimal" regime respectively. An additional nautical mile travelled in each of these respective packing/isolation regimes amounts to 0.004ppt, 0.014ppt, 0.042ppt additional mile, clearly showing the effectiveness of the two packing/isolation regimes.

Endogenous variation in melt – endogenous iceberg transport costs?

As a first examination of the validity of the exogeneity assumption imposed by the iceberg-approach to modelling trade costs, we verify (1) whether we can find systematic variation over time in these melt in transit, (2) the relevance of the only economic variable that should be related to melt according to the simple physics of melt: the percentage melted depends on the outward exposure of the ice mass shipped, i.e. under the assumption of a similar way of stowing the blocks, and a similar isolation regime, a larger shipment of ice has relatively less outward exposure and should show a lower percentage of ice lost to melt. See Appendix A for more details.

Figure 3 shows the percentage of melt reported over the period 1833 – 1868 for the route for which we have the most comprehensive coverage of melt in our sample, i.e. Boston - Calcutta. Note that also a simple regression of percentage melted on the year in which this melt was reported (of course controlling for distance travelled) shows no significant relation between melt and the specific year of transport.

Figure 3. Melt over time on the Boston – Calcutta route

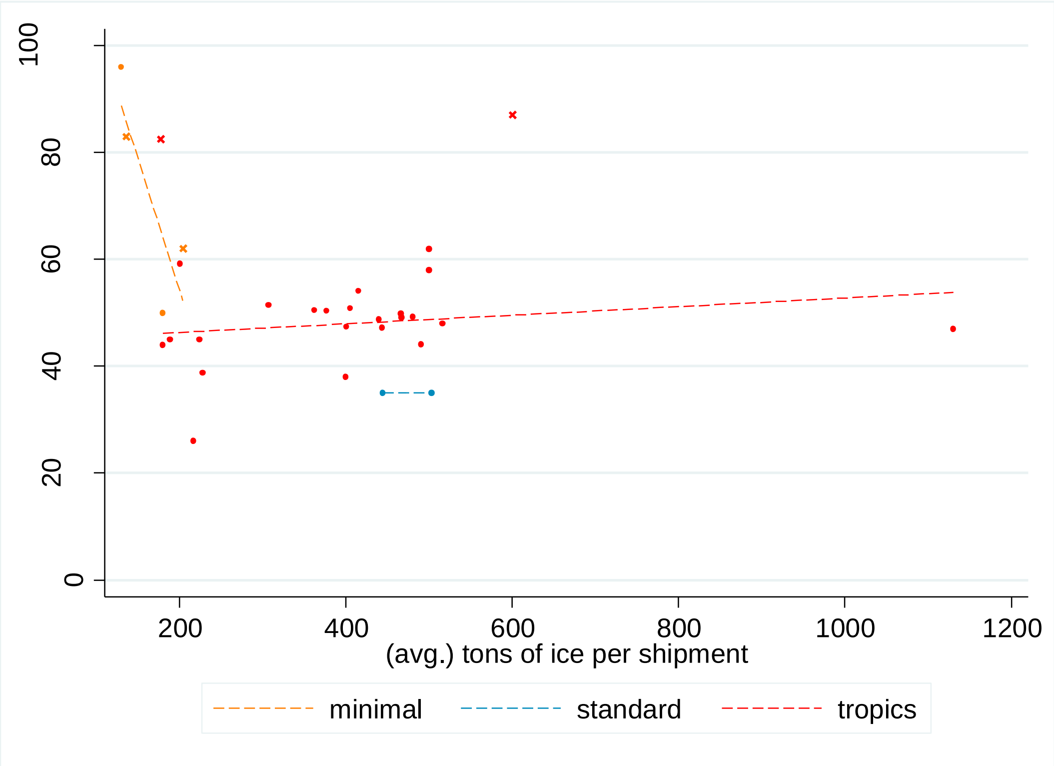


Notes: the two observation marked with an "X" concern the reported 1835 "complete failure" as well as the reported melt on the 1854 shipment on the ship "Arabella" that cannot be verified in the Tudor Archives (see also the notes to Figure 2). The line in the figure depicts a simple fitted regression line through all data points except the ones markup by an "X".

Figure 3 shows that the percentage melted does not show any systematic tendency to drop over time. It confirms the fact that isolation methods did not significantly improve over the time period considered (not that surprising given its reliance throughout our sample period on sawdust, wood-shavings, etc).

As a second "exogeneity test", we verify the possible existence between the amount of ice shipment and the iceberg factor. Modelling trade costs in the "iceberg fashion" makes the (strong) assumption that trade costs are exogenous (to any of the economic forces in the specific trade or economic geography model), and a simple, constant fraction of the initial amount of shipped. However, the physical properties of the melting process say that one of the important factors determining this process is the surface area of the ice (i.e. 1kg of ice would melt much faster if shaped as a long line of ice compared to when shaped as a square), the other important factor is of course the outside temperature (as well as the initial temperature of the ice when loaded onto the ship in Boston), and the heat conductivity of the isolation used in each different packing regimes. As such, the exogeneity assumption of transport costs as modelled by the iceberg approach, can immediately be contested in the ice trading business since melt should depend on the amount of ice shipped (or more precisely the exact size and shape of the hull of the ship carrying the ice). Ice was usually shipped in blocks of 44 inch square (Hall, 1883), so that melt of the shipment depends on the way these blocks where stowed in the hold of the ship. Figure 4 shows the relationship between melt and average shipment size for those observations for which we have information on the number and size of ice shipments.

Figure 4. Shipment size and melt



Notes: observations marked with an "X" are the same as those described in the notes to Figure 3.

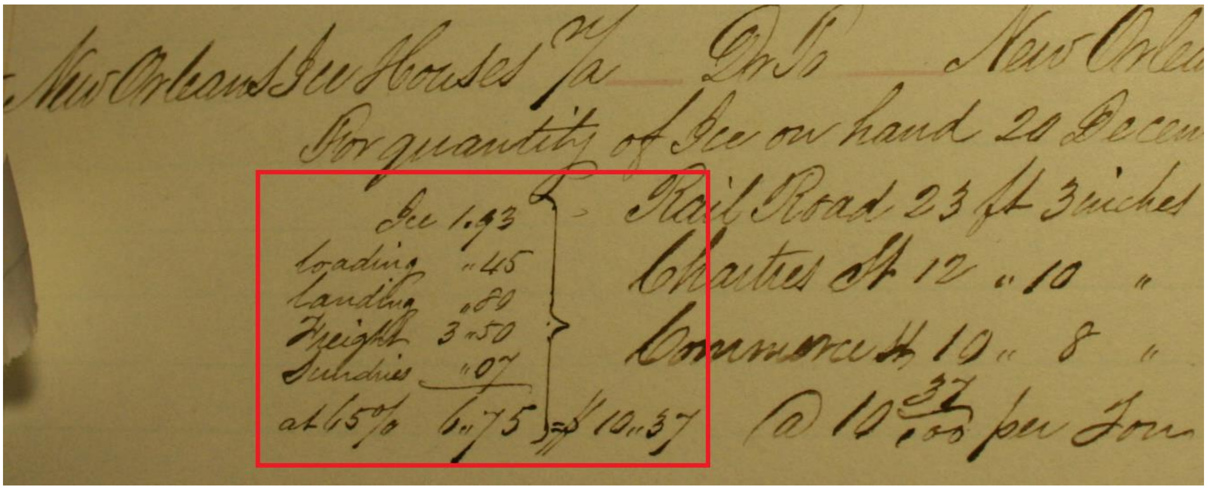
Only in case of the "minimal" packing regime can we confirm this negative relationship between average tons of ice per shipment and the percentage melted in transit. For both the "standard" and the "tropics" packing regime we do not find this relationship. Of course this does not lead us to doubt the physics behind the melting process; but what is does show is that the packing regimes used to isolate the ice in transit were quite effective (in case of the standard packing regime we would need (much) more observations on the size of shipments in order to fully substantiate our claim[2]). In fact, one could take the pattern shown in Figure 4 as tentative evidence that isolation was done with more care on larger shipments and/or that blocks were arranged in a more melt-resistant way in the holds of larger boats. In any case, Figure 4 does mean that we do not find an immediate rejection of the exogeneity of the iceberg trade costs in the iceberg shipping business (as would be implied by the laws of physics).

[2] Relating predicted melt (see the next section for more on this) to average shipment size gives us much more observations for this "standard" regime in particular. Also when using predicted melt we find no evidence of a significantly negative relationship between melt and average shipment size.

Iceberg transport costs and actual trade costs

Next we turn comparing the variation in melt-implied iceberg transport costs with the a measure of actual iceberg transport costs, i.e. all costs incurred in order to ship one ton of ice from Boston to a specific destination. These costs consist not only of transport costs, but also of all cost incurred when loading (including isolation), landing, and insuring a shipment of ice. For many years/destinations the cost of insurance, as well as of fitting and loading the ice on board the ship is reported in the Tudor Archives. Transport and landing costs however are reported more sporadically, making it difficult to directly take overall trade costs from the data. However, one scribble in the Tudor Archive showed us how we can infer these overall trade costs making use of the cost price of ice in Boston, the inventory price assigned to the ice in each destination, and the (expected) percentage melt in transit. This scribble is shown in Figure 5 below:

Figure 5. The inventory price in New Orleans, 1847 explained



Source: Tudor Archives, Tudor II vol.3

It provides the only reference to how the inventory price in a destination was calculated in the accounting records of the Tudor company. This inventory price is the cost price of a ton of ice in a particular location. The 65% markup in Figure 5 is nothing but the expected percentage of the ice to remain upon arrival in New Orleans, i.e. 100% - expected % melted. As such, the scribble in Figure 5 shows us how we can calculate trade costs (in $ per ton) as a percentage of the cost price of the ice in Boston:

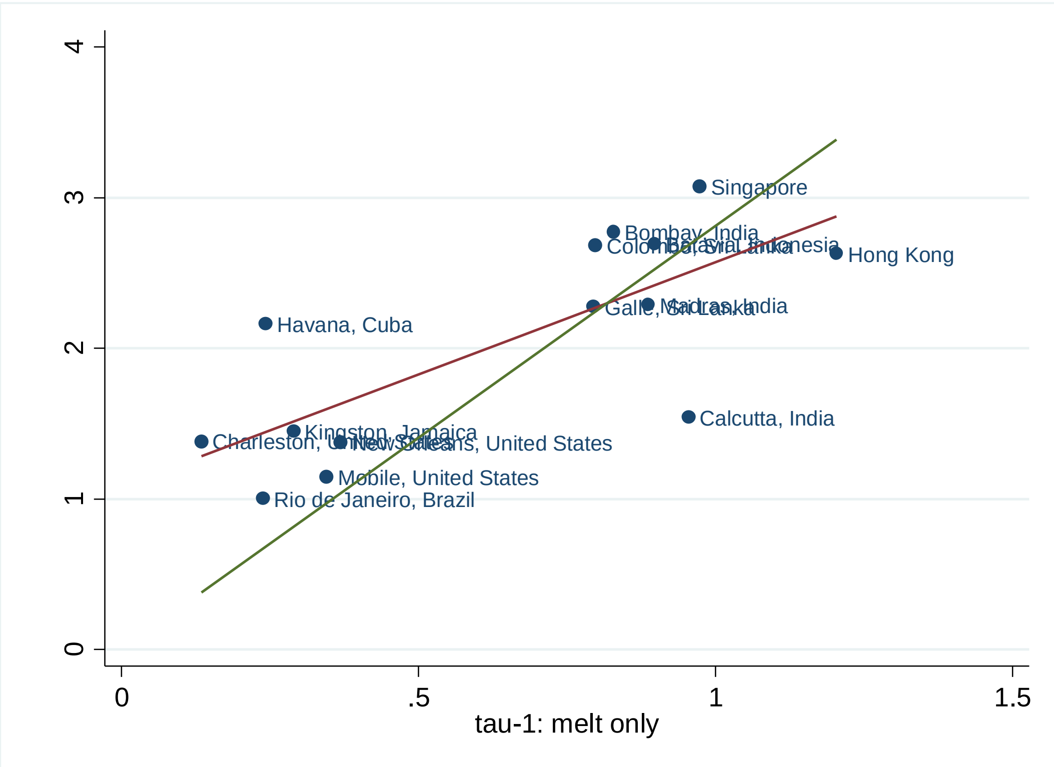
$$T_{ij} / p_i = (p_j^{inv}/p_i)(1-m_{ij}) - 1 \qquad (3)$$

, where m_{ij} is the fraction of ice melted in transit. We calculate this fraction using our available information on the inventory price in different destinations in different years, as well as the cost price of the ice in Boston in different years, as well as the predicted melt incurred on the journey to each location. We calculate the latter as melt predicted according to the relationship between distance and melt shown in Figure 2 (which depends on the packing regime). Figure 6 below plots the resulting (estimated) percentage of the cost price of the ice paid in transport to the same percentage as implied when making the iceberg trade cost assumption, see (1). The latter can be calculated from the observed expected melt on a particular journey only:

$$(T_{ij}/p_i) = \tau_{ij}^{melt} - 1 = 1/(1-m_{ij}) - 1 \qquad (4)$$

It is important to note that given the stability of the melt in transit over our sample period (see Figure 3), we from now on focus on how well the implied iceberg factor is related to the observed between variation in the actual observed trade costs between Boston and each destination city.

Figure 6. Melt implied iceberg transport costs vs. Price implied iceberg transport costs



Notes: the red line depicts a fitted regression line (including a constant in the regression), the green line depicts a fitted regression line forced to go through the origin.

As shown by the figure the fit between the melt-implied iceberg fraction and that implied when making use of the relationship between the cost price in Boston and the inventory price in each destination is not perfect. However the relationship between the two is quite strong: the between variation in the melt-implied theory consistent "iceberg fraction" of the value of the good paid to ship ice between Boston and the various destination cities explains about 60% of the between variation in the actual observed fraction of the cost price of the ice in Boston paid in transit.

Overall foreign price markup and the iceberg factor

TO BE COMPLETED

Conclusions

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Appendix A. The physics behind the melt in transit

It seems incredible that without any additional artificial refrigeration and after a half-year journey on a boat sailing through the tropics there still is any ice left to sell. However, physics confirms the original insights of Frederic Tudor. At sea level melting ice always has a temperature of zero degrees centigrade (= 273 K) and the following formula describes the heat transfer coefficient (h) in $W/(m^2.K)$:

$$h = Q / (A * \Delta T),$$

in which Q is the actual heat flux in Watts (J/s), A is the heat transfer surface area in m^2 and ΔT is the temperature difference in degrees Kelvin. Air has a heat transfer coefficient of 0.025 $W/(m^2.K)$, while oak wood has a value of around 0.15 $W/(m^2.K)$. The melting heat of ice is $3.34*10^5$ J/kg. The formula above allows us to do a purely theoretical exercise and make a rough back-of-the-envelope calculation how much ice melts during a trip to the tropics. Assuming that sailing a ship from Boston to Calcutta cost 150 days, with an also assumed average temperature difference of 40^o K between the melting ice and the local air temperature we can estimate the loss of an original load of 162 tons (180 m^3) of ice. The volume of this load of ice will have been around $4 * 5 * 9$ m^3, and then we get a value of A of 202 m^2 ([4*5 + 4*9 + 5*9]*2). This means that per second there is a heat flux of $1.212*10^3$ J, assuming the isolating wood to have had a value of 0.15 $W/(m^2.K)$. For the whole trip of 150 days this leads to heat flux of $1.57*10^{10}$ J (1212*3600*24*150), which would be equivalent to some 47 tons of ice melted. Theoretically we would have expected a loss of some 30% on this trip. (The melt will have been somewhat higher, because in this zero-order approximation we did not correct for the ice volume becoming smaller – and its remaining surface area relatively larger – due to the loss of ice during the trip). Because the amount of melting of the ice is a function of its surface area (which is a power of 2) and the volume/weight of the ice increases with a power of 3, doubling the initial amount of ice means relatively less melt. Instead of a total melt of 2 we have a melt of only $2^{0.67}$ after doubling our load of ice, which is 1.59 times as much. So size really matters in the ice trade: the less ice you have, the sooner it melts.

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