International Shipping Consequences of a Navigable Arctic

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Abstract: Global warming will open up trans-Arctic shipping lanes as ice cover recedes. Given the established causal effect of shipping distance on trade volume, these lanes will affect trade between regions for which trans-Arctic routing is preferable to current options. This paper calculates optimal naval routes between important container ports on four maps of the Earth: the current world map, projected world maps immediately after either the Northwest or Northeast Passages become navigable, and a projected world map with a totally navigable Arctic. Decreases in optimal route lengths due to trans-Arctic routing are integrated with existing literature on the relationship between shipping distance and trade volume in order to project the direct influence of Arctic navigability on trade volumes. Conclusions suggest a strongly regional effect—routing between certain northern economies is shortened by up to 45%, implying trade volume increases of up to 20%. Alongside clear benefactors in the global north, even ports as far south as Singapore and Santos, Brazil can take advantage of Arctic routing in certain circumstances. However, many other regions are unaffected.

1 Introduction

Arctic melting is a pressing consequence of global warming. Climatological projections suggest that Arctic summers will be completely ice-free before mid-century (USGCRP 2014). There are two directly coupled geographic effects of this melting: loss of ice cover in the Arctic, and rise in sea levels. The consequences of rising sea levels are well-studied, and rightfully so: per USGCRP, roughly 80% of global cities, containing a large fraction of all human population and an even larger fraction of all valuable infrastructure and capital stock, are coastal. However, the loss of Arctic ice cover will also have a direct effect on trade: it will enable trans-Arctic navigation. In fact, newly navigable (albeit prohibitively hazardous and thus generally unused) routes already exist—the Northwest Passage, which traverses the Canadian Arctic Archipelago, and the Northeast Passage, which follows the northern coast of Russia (ESA 2007). As Arctic melting continues to decrease ice hazard on these routes and in the Arctic as a whole, they will become viable options for commercial shipping. Once available, these causeways will decrease the minimum naval distance between pairs of countries such as Japan and Germany, streamlining shipping. This paper projects the direct effect of these newly opened shipping lanes on future international trade volumes.

The inverse causality between physical distance and bilateral trade is a longstanding empirical observation captured by the gravity model, which linearly relates the log bilateral trade volume between two countries $\ln(T_{ij})$ to the log great-circle distance[1] between those two countries $\ln(D_{ij})$ via an elasticity α. The gravity model has substantial predictive

[1] Colloquially, great-circle distance is distance "as the crow flies".

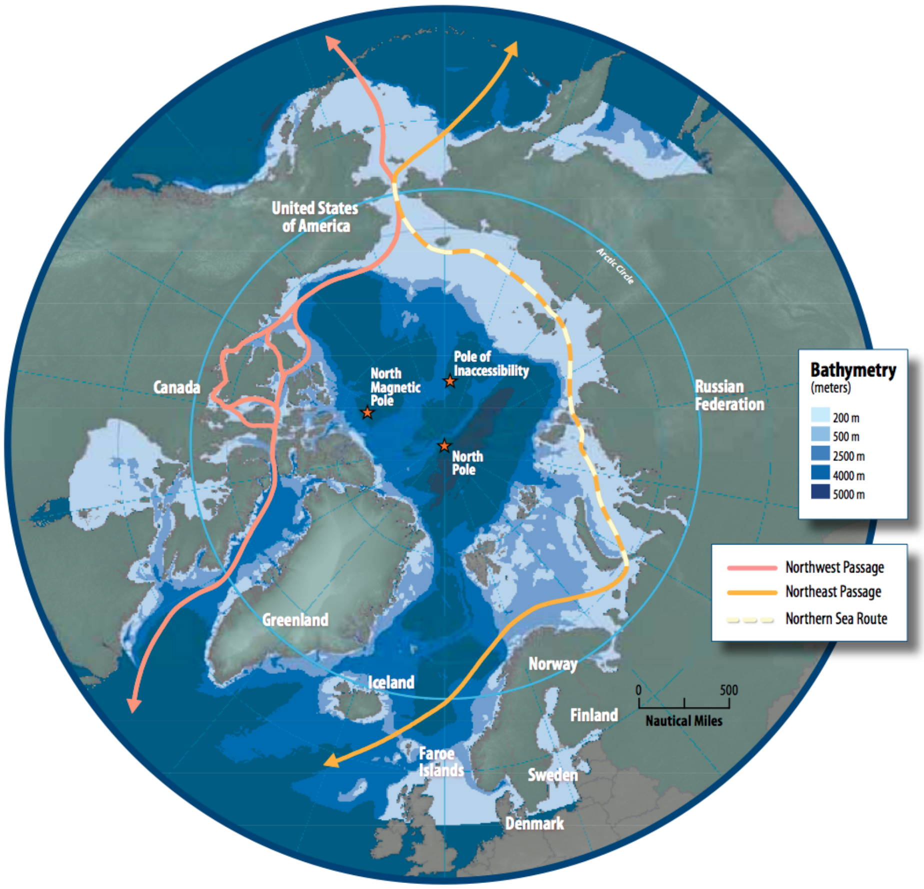

Image 1: Map of Northeast and Northwest Passages (Harder 2009). Northern Sea Route (in dashes) is a subset of the larger Northeast Passage.

power—a meta-analysis of 1,467 distance effects across 103 papers found a mean elasticity of $\alpha = -.9$, corresponding to nearly direct inverse correlation (Disdier et al. 2008). Despite this predictive power, the conventional gravity model is not useful in analyzing naval routing—the great-circle distances between points on Earth are unchanged by Arctic melting.

Thankfully, modified gravity model analyses exist which deal with naval routing distance instead of great-circle distance. Of particular note is Feyrer (2009) which uses the eight-year Suez Canal closure between 1967 and 1975 due to the outbreak of the Six Days war as a natural experiment to identify the specific effect of changes in naval routing distance on trade volumes (Feyrer 2009). Traditional gravity models struggle to establish causality because great-circle distances are constant with respect to time—for instance, France and Belgium are geographically close and have close trade ties, but it is not clear whether distance is the direct cause of that trade closeness or whether there are intermediate variables in play such as cultural integration. Feyrer's key insight is that the Suez canal closure provides an opportunity for an exogenous shock to naval routing distance, circumventing any omitted variable bias. The abrupt nature of the canal's initial closure and eventual reopening allows them to be treated as exogenous shocks, permitting causal inference. Feyrer studies the impulse response of trade volume to shocks in naval routing distance and finds a steady-state elasticity of $\alpha \approx -.3$. This result is particularly relevant in light of the fact that the Suez Canal bears striking resemblance to the Arctic in a routing sense: both, when navigable, provide significant naval shortcuts for extremely long and indirect shipping routes[2].

The contribution of this paper is to project future changes in international trade volumes caused by the onset of Arctic navigability. These projections are made by calculating the changes in minimum naval routing distances between pairs of major ports when trans-Arctic navigation is allowed, and then integrating those changes with Feyrer's (2009) conclusions about the causal relationship between naval routing distance and trade volume[3]. By inte-

[2]An interesting note from the results of this paper is that many of the shipping routes which originally benefited most from the construction of the Suez Canal, such as those connecting Europe to Asia, are also those which further benefit most from Arctic navigability.

[3]This research method was conceived and designed in late 2020. The irony that the Suez Canal was unexpectedly closed soon afterward (for six days, no less!) after a streak of uninterrupted operation since the Six Days War is not lost on the author.

grating these fractional projections with current trade volume data, total fractional changes in trade volume by country and region-wide effects are also assessed.

Other literature which studies trade volume with a similar exogenous-shock methodology to Feyrer (2009) includes Martincus et al. (2013) and Feyrer (2019). Martincus et al. (2013) studies the regional variation in Chilean trade activity after an earthquake severely damaged infrastructure in certain parts of the country (Martincus et al. 2013). Similar to the outbreak of the Six Days War, this earthquake was a dark horse event which created exogenous variation in an independent variable affecting trade volume. Just as longstanding cultural or institutional effects might muddle the direct causal effect of naval routing distances, it would be impossible to understand the causal effect of infrastructure development on trade activity without an exogenous shock to infrastructure—earthquakes provide such a shock.

Meanwhile, Feyrer (2019) reapplies the naval routing data from Feyrer (2009) in parallel with great-circle distance calculations to analyze the synthetic "shock" of the rapid expansion of air travel between 1960 and 1995 as an alternative to maritime cargo shipping (Feyrer 2019). Naval shipping is constrained to naval routing, while air shipping travels along great-circles, so for a given trip the two modes of transit traverse different distances. Feyrer observes a correlation between changes in bilateral trade volume and the ratio between great-circle distance and naval routing distance—that is to say, as air travel grew in popularity relative to sea travel, country pairs which became comparatively "closer" to one another increased bilateral trade volume. While less obviously connected to the situation of Arctic shipping than Feyrer's study of the Suez Canal, this merits mention as an additional application of naval routing data alongside a time-series development to identify a distance effect on trade volume.

Disdier et al. (2008) as well as by Boisso (1997) raise the possibility that the elasticity value α may change over time. Disdier et al. conclude robustness across all possible confounders except time period, wherein they note that "distance effects decreased slightly between 1870 and 1950 and then began to rise" (Disdier et al. 2008). Boisso studies the period 1960-1985 and concludes that distance effects increased through the early portion of the sample (consistent with the trend from Disdier et al.) but then reversed course in 1970 and began to decrease (Boisso et al. 1997). Collectively, the studies suggest that α time-varies about 10% between 1870 and 1985. These studies deal with great-circle gravity models as opposed to naval routing ones, and the elasticity α derived from exogenous naval routing shock in Feyrer (2009) is substantially different than the elasticities α studied by Disdier et al. (2008) and Boisso (1997). Nonetheless, it is possible that naval routing models experience α time variation as well. This is a relevant concern for this paper: Arctic melting has a decades-long time horizon, and the foundational conclusion $\alpha = -.3$ from Feyrer (2009) derives from an event which happened several decades ago. Thus, it is possible that the elasticity value α derived by Feyrer is obsolete due to technological progress or other unknown factors. Determining a way to directly address this possibility is outside the scope of this paper, but it will be kept in mind as a potential source of uncertainty.

2 Research Design

2.1 Data

This paper integrates two forms of data: naval routing distance data and bilateral trade volume data. Additionally, a manually created country-to-port mapping is necessary for the integration of the two data sets.

Naval routing distance data were synthesized by the author via an adapted version of the methodology used in Feyrer (2009). A world map based on geographic data from CIESIN[4] was subdivided into a grid of 1-latitude-degree by 1-longitude-degree nodes. Each node in the grid is connected to its immediate and diagonal neighbors by an undirected edge with associated distance value equal to the great-circle distance between the two nodes. Then, nodes identified as land by CIESIN were dropped, yielding a graph mapping the locations on Earth accessible by oceangoing cargo vessels. The four maps on which pathfinding was performed were then created from this baseline in the following ways:

- Current-day world map: no change from baseline.
- Northwest Passage Navigable: latitude threshold for ice cover receded in the Canadian Arctic Archipelago until a navigable route appears.
- Northeast Passage Navigable: latitude threshold for ice cover receded north of Eurasia until a navigable route appears.

[4] http://sedac.ciesin.columbia.edu/povmap/ds_global.jsp

- Total Arctic Navigability: latitude threshold for ice cover fully receded, i.e. no[5] ice obstructions in the Arctic.

Using an A* graph traversal algorithm with a heuristic function of great-circle distance to the destination node, the shortest navigable route between any two nodes in the graph can be found on each of the maps. For the purposes of this study, the nodes of interest were those at the coordinates of a broad selection of 29 of the highest-volume container ports in the world with geographically redundant ports dropped—see Appendix 1 for the full list of ports used. The shortest navigable route between each combination of two of these ports was found on all four maps.

The graph-traversal algorithm tends to overestimate the true distance between two points because it must travel on the provided grid instead of in an arbitrary direction—see Appendix 2 for analytical derivation of this overestimation factor. Including diagonal edge connections significantly reduces the average error factor from $\frac{4}{\pi} \approx 1.27$ to a manageable $\frac{8}{\pi}(\sqrt{2}-1) \approx 1.05$ at the equator. This error increases at nonzero latitudes, reaching 1.06 at 60°N and 1.07 at 75°N. This latitude dependence is relevant because there is a systemic latitude bias in the routing data—routes which optimize through the Arctic tend to occupy higher latitudes for much of their route length, so their length is systemically overestimated by $\sim 1\%$ more than the non-Arctic routes are. This means that when distance ratios are taken (see Analytical

[5]The North Pole is technically still left obstructed due to computational problems with allowing it as a viable pathfinding location. Specifically, the North Pole is actually 360 degenerate nodes with latitude/longitude coordinates

$$(90, \text{Long}), \text{Long} \in \{0, 1, 2, ..., 357, 358, 359\}$$

and pathfinding cannot properly handle pairs of nodes separated by zero distance, so this is a necessary and ultimately inconsequential exception.

Methodology) they will be systemically overestimated by $\sim 1\%$. This bias is taken into account and adjusted for in the results.

A separate concern is that noise in this overestimation factor might propagate into noise in the results of this analysis. Significant noise in the overestimation of a route's length may arise when the route is either extremely short or very direct and equatorial[6]. Fortunately, these cases are not relevant to the conclusions of this paper. Very short routes such Busan-Shanghai never benefit from Arctic navigability in the first place. Direct routes such as Tokyo-Los Angeles never benefit from Arctic navigability either. Arctic routes are never sufficiently short to trigger the first condition, and traverse topologically curved regions of the grid. Thus, the routes which are relevant to this analysis are overestimated without much noise, so this is not a serious issue.

Bilateral trade volume data were obtained from International Monetary Fund Direction of Trade statistics[7]. Because this analysis seeks to project only the marginal effect of Arctic routing, no projections were formed about how these trade volumes might change in the decades between now and the eventual point of projected Arctic navigability. Rather, the average annual total bilateral trade volume (i.e. the sum total in both directions) was identified between each pair of countries over the period 2010-2019 in order to dampen any outlying effects which might be captured from a one-year slice. In absolute terms,

[6]Deviation from the expected overestimation factor can only arise in situations where the angle made between the optimal travel angle and the grid lines is extremely consistent throughout the route. This can happen by fluke due to sample size (i.e. when a route is very short) or because the route is a straight line on a topologically flat graph (i.e. the route is direct and confined to equatorial regions, as the map warps toward the poles).

[7]https://data.imf.org/?sk=9D6028D4-F14A-464C-A2F2-59B2CD424B85

these average annual trade volume numbers will grow significantly by mid-century; even a conservatively estimated 2.5% annual GDP growth rate implies that global GDP will more than double between 2020 and 2050. The utility of these data is therefore not in their absolute value, but in their proportional value with respect to each other.

In order to integrate port-level distance data with country-level trade data, a mapping between ports and countries must also be manually created. Most of the major import-export economies of the world already contain one of the encoded ports; for the purposes of this analysis, the only notable exception is France, whose trade is routed through the Port of Antwerp in Belgium. Like Feyrer (2009), Canadian and American trade data are split into fractional east ("[E]") and west ("[W]") components due to the massive naval routing difference between the two North American coasts. "Canada [E]" and "United States [E]" are both assigned to the Port of New York, while "Canada [W]" is assigned to the Port of Vancouver and "United States [W]" is assigned to the Port of Los Angeles. Feyrer (2009) uses an 80%-20% east-west split for trade data, with robust results for variation of this split. This paper uses the same baseline split, although separated results for the west and east subdivisions of these countries will also be presented directly. Results are conveniently linear with respect to combination of countries, so the implications of alternate east-west splitting fractions can be easily produced from these separated results.

2.2 Analytical Methodology

Gravity models broadly take the form

$$\ln(T_{ij}) = C_{ij} + \alpha \ln(D_{ij}) + U_{ij} \iff T_{ij} \sim D_{ij}^{\alpha} \tag{1}$$

where T_{ij} is the volume of bilateral trade between countries i and j, D_{ij} is some measure of distance between countries i and j, C_{ij} is some function which encodes all non-distance information specific to i and j[8], and U_{ij} are residuals. Feyrer (2009) uses minimum naval routing distance as the distance metric D and estimates a corresponding elasticity $\alpha \approx -.3$. Then, the proportionality relation

$$\frac{T_{ij,\,new}}{T_{ij,\,old}} = (\frac{D_{ij,\,new}}{D_{ij,\,old}})^{\alpha} \iff T_{ij,\,new} = T_{ij,\,old}(\frac{D_{ij,\,new}}{D_{ij,\,old}})^{\alpha} \tag{2}$$

can be used to project fractional changes in bilateral trade volume between countries i and j due to Arctic shipping, where *old* variables refer to the present day and *new* variables refer to one of the three future scenarios studied, corrected for expected overestimation[9]. T_{old} values come from the bilateral trade data, while D values come from the naval routing data for the relevant port pair. We denote the fractional changes in distance $\frac{D_{ij,\,new}}{D_{ij,\,old}} \doteq \Delta D_{i,j}$ and the corresponding fractional changes in bilateral trade volume $\frac{T_{ij,\,new}}{T_{ij,\,old}} \doteq \Delta T_{i,j}$.

Extending from (2), the fractional change in the bilateral trade volume between two disjoint sets of countries S_1 and S_2 (for instance, the countries of North Europe and the

[8] $C_{i,j}$ is therefore constant with respect to changes in distance.

[9] Note that during discussion of results, data will be referred to as:

- The "Totally Navigable" case if the *new* variables come from the Total Arctic Navigability map.
- The "NW Passage" case if the *new* variables come from the Northwest Passage Navigable map.
- The "NE Passage" case if the *new* variables come from the Northeast Passage Navigable map.

countries of Northeast Asia) can be calculated as

$$\frac{T_{S_1,S_2,\,new}}{T_{S_1,S_2,\,old}} = \frac{\sum_{i\in S_1,j\in S_2} T_{i,j,\,new}}{\sum_{i\in S_1,j\in S_2} T_{i,j,\,old}} = \frac{\sum_{i\in S_1,j\in S_2} T_{i,j,\,old}\cdot \Delta T_{i,j}}{\sum_{i\in S_1,j\in S_2} T_{i,j,\,old}} \tag{3}$$

In keeping with the notational logic established earlier, we denote these fractional changes in country-set-to-country-set trade volume $\frac{T_{S_1,S_2,\,new}}{T_{S_1,S_2,\,old}} \doteq \Delta T_{S_1,S_2}$.

A useful special case of (3) is that in which one set contains only country i and the other set contains all countries except country i (i.e. $S_1 = \{i\}$ and $S_2 = \bigcup_{j\neq i}\{j\}$). With this setup, (3) calculates the fractional change in trade volume between country i and the rest of the world, i.e. the fractional change in country i's total trade volume. Denoting country i's trade volume as $T_{\{i\},\bigcup_{j\neq i}\{j\}} \doteq T_i$, (3) becomes

$$\frac{T_{i,\,new}}{T_{i,\,old}} = \frac{\sum_{i'\in\{i\},j'\in\bigcup_{j\neq i}\{j\}} T_{i',j',\,old}\cdot \Delta T_{i',j'}}{\sum_{i'\in\{i\},j'\in\bigcup_{j\neq i}\{j\}} T_{i',j',\,old}} = \frac{\sum_{j\neq i} T_{i,j,\,old}\cdot \Delta T_{i,j}}{\sum_{j\neq i} T_{i,j,\,old}} \tag{4}$$

In keeping with the notational logic established earlier, we denote these fractional changes in single-country trade volume $\frac{T_{i,\,new}}{T_{i,\,old}} \doteq \Delta T_i$.

The results presented in this paper utilize all three of these fractional change metrics. The bilateral country-pair trade volume changes $\Delta T_{i,j}$, as well as the reductions in routing distance $\Delta D_{i,j}$ from which they directly follow, are discussed for all port pairings which optimally route through the Arctic in at least one of the cases studied. Then, relevant ports are clustered into five geographic regions (North Europe, Northeast Asia, North America, Southeast Asia, Mediterranean) and bilateral region-pair trade volume changes $\Delta T_{S_1,S_2}$ are discussed. Finally, fractional changes in single-country trade volumes ΔT_i are discussed for the countries most heavily impacted by Arctic navigability.

2.3 Discussion of Robustness

The possible sources of unaccounted-for systemic error in this research design are the following, in decreasing order of likely impact:

1) Error in the true elasticity term α. The possible time variation of α is discussed for conventional gravity models in Disdier et al. (2008) and Boisso (1997), where it is implied that α may have varied by up to 10% between 1870 and 1985. Using this as a rule of thumb, it seems entirely feasible that the naval-routing α value arrived at in Feyrer's (2009) analysis of the Six Days War might vary by about 10% of its value by 2050, the rough time horizon of the projections made in this paper. Additionally, Feyrer (2009) lists an estimation error on the α value of roughly 10%; taken as independent sources of error, this implies an overall estimation error of the true 2050 α value of $\sqrt{10\%^2 + 10\%^2} \approx 14\%$. For a given projected fractional trade increase ΔT, replacing α with some scaled value $c * \alpha$ propagates through to change ΔT into ΔT^c—see Analytical Methodology. If ΔT is sufficiently close to 1, this approximately changes $\Delta T - 1$ by a factor of c; for instance, if trade were going to increase by 20% with the standard $\alpha = -.3$ value, then using $\alpha = 90\% * -.3 = -.27$ will change that projected increase to roughly $90\% * 20\% = 18\%$[10]. All ΔT in this paper are sufficiently close to 1 that this rule of thumb holds, so the rough margins of error due to possible α variation are about 14% across the board. Note that misestimation of α would result in an identical systemic bias in all results presented in this paper, regardless of region.

2) Unrepresentative baseline mapping of the Earth. There are two potential sub-problems

[10]This is due to the small x approximation $(1 + x)^n \approx 1 + nx$.

which might arise during generation of the graph for pathfinding which could skew results. The first is one of the main differences between this paper's graphing methodology and Feyrer's (2009): whereas Feyrer integrates oceanic current data to modify the "distance" between two adjacent nodes, this paper ignores currents. The primary reason for this omission is that the inclusion of currents renders great-circle distance an invalid heuristic function for the A* pathfinding algorithm, forcing the use of the naive and prohibitively inefficient Dijkstra's algorithm. It further slows the computational process by removing the symmetry in routing distance between ports, requiring twice the normal amount of pathfinding. Currents are also projected to change due to climate change and are poorly documented in the Arctic, so the availability of high-quality relevant data is limited.

Currents are nonetheless an important consideration when dealing with the robustness of this analysis. The existence of systemic currents such as the Gulf Stream suggests that there may be systemic shortenings of routes from particular source areas to particular destination areas, as well as lengthenings of routes in the opposite direction. A prevailing current through the Arctic might even lead to interesting situations where a pair of ports i and j might optimize the $i \to j$ trip through the Arctic but optimize the $j \to i$ trip through a non-Arctic route. Accurately assessing the effects of these currents post-pathfinding is impossible—simply adding currents on top of the routes deemed optimal is not useful because those routes would almost certainly not be deemed optimal in the first place on a globe with currents.

In order to estimate the magnitude of error which might be introduced by currents, consider the following rough analysis: based on a conservatively estimated average current speed of 1 knot, conservatively estimated maximum current speed of 7 knots, and an average cargo shipping speed of 20 knots, we conclude that current magnitudes distort the velocity of cargo ships by roughly 5% in a random direction with potential to distort velocity by a maximum of 35% (Gordon & Cenedese, 2018). Ignoring the transverse component of this velocity distortion due to computational intractability, we are left with an average change in forwards speed of $\pm 5\% * \frac{\int_0^{\pi} |\cos\theta| d\theta}{\pi} = \pm 5\% * \frac{2}{\pi} \approx \pm 3.2\%$ and corresponding maximum change in forwards speed of $\pm 23\%$.

Note, however, that this noise is not noise assigned to full port-to-port routes, but rather differential distance accounting. Over the course of a route, during which vessel direction and current direction/speed are variable (albeit internally correlated), it is unlikely that current noise will reach nearly this extent. A rough rule-of-thumb estimate of 1% noise due to currents and potential for systemic bias in certain routes of perhaps 10% seems appropriate. Note also that any systemic biases affecting the route $A \to B$ should affect the route $B \to A$ in a strongly negatively correlated fashion, although the possibilities of asymmetric routing between port pairs means that this does not cancel out the bias entirely. An analytically sound estimation of this negative correlation is as-of-yet undeveloped. Intuition suggests that regionally systemic currents probably bias bilateral port-to-port average distances by no more than a maximum of 3% on top of the existing random 1% noise. Note that this bias is *regionally* systemic—the same currents which might render the distance between Los Angeles and Tokyo over- or under-estimated will likely bias the estimation of the distance

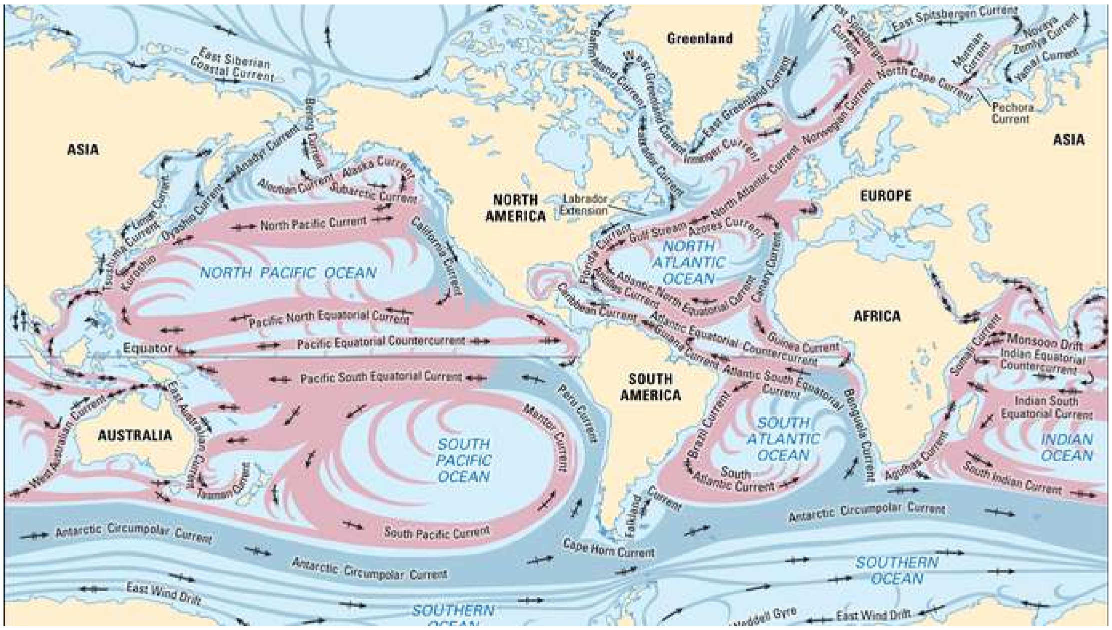

Image 2: Map of systemic ocean currents (Gordon & Cenedese, 2018).

between Vancouver and Busan in a similar manner. Finally, note that because this study discusses ratios constructed from pairs of distances charted through distinct independent regions (Arctic vs. non-Arctic routes), we arrive at a possible regionally systemic bias in results due to currents of up to roughly 5% and random noise in results due to currents of up to roughly 2%.[11]

Another possible problem with the underlying map is that this analysis assumes that the Earth is spherical, when in reality it is geoidic. Feyrer (2009) also assumes a spherical Earth. Similar to the problem with currents, modelling the Earth as a geoid is unfeasible because it invalidates the great-circle heuristic function for pathfinding, leading to unreasonable computation times. This simplification likely leads to slight underprojection of the

[11] This error estimation is non-rigorous and mostly useful for identifying the order of error magnitude as opposed to a useful specific value. Ultimately, this should be rectified by re-calculating route lengths on a stronger computer with currents implemented, not by deriving higher-quality estimators of error.

consequences of Arctic routing, as traversing the squashed pole of a geoid is slightly faster than traversing the pole of a sphere. In order to rigorously understand the skew factor, additional geometric analysis would have to be incorporated into the discussion in Appendix 2. However, in a practical sense the geoidicity of the Earth is a very small deviation from the spherical approximation—GIS estimates suggest the equatorial diameter of the Earth is less than .34% greater than the North-South diameter, which leads to a trivially small possibility for error. Thus, rigorous estimation of this error is unnecessary.

3) Systemic error due to insufficient port count, i.e. assignment of existing trade volumes to unrepresentative ports. There is inherent inaccuracy in the country-to-port mapping process because it is patently unrealistic to assume that all of a country's trade flows through a single port. Feyrer (2009) employs a similarly imprecise country-to-port mapping method to produce the α value used in this paper, so this inaccuracy might also prompt α uncertainty as discussed in point 1. However, the simplified country-to-port mapping process should not create any sort of systemic bias in the routing data versus a more granular approach. The computation time necessary to pathfind between N ports scales as N^2, and synthesizing the distance data for all pairs of the $N = 29$ ports used in this analysis (see Appendix 1) already requires more than 100 hours of computation time on the author's machine. Increasing N by anything more than perhaps a factor of 1.5 would have been time-prohibitive. Because this inaccuracy represents an "unknown unknown" as opposed to a quantifiable error, it is impossible to address without more precise specification.

4) Systemic error arising from the pathfinding process similar to that discussed at length

in Appendix 2. It is possible that some other unaccounted-for geometric error in the pathfinding algorithm exists which systemically affects the results, although it is unclear where such an error would arise. Without more knowledge about what such an error would be, it is impossible to project its effects, although sanity checks conducted during development suggest that the overestimation error is the only meaningful one present in the pathfinding process. Like point 3, this is an unknown unknown.

5) Systemic Error in the IMF Direction of Trade data. It is possible that systemic error in the IMF Direction of Trade data exists. However, it seems exceedingly unlikely that such an error would go unnoticed in data published by a reputable aggregator such as the IMF. Therefore, this is not a significant concern.

In sum, the various robustness concerns raised in this section point to three quantitatively identifiable forms of error in the projected fractional changes in trade volumes which might arise:

- A global uniform bias due to α mis-estimation up to about 14% of results.
- Regionally-correlated biases due to currents up to about 5% of results.
- Noise due to currents up to about 2% of results.

It seems that these three forms of error are independent of one another. These errors will be noted in the Conclusion section.

3 Discussion of Results

3.1 Port-Level Results

The underlying results of this analysis are the synthetic naval routing distance data. These data are recorded in Appendices 3.1, 3.3, and 3.5, which respectively tabulate the fractional reductions in optimal naval routing distance $\Delta D_{i,j}$ due to Arctic routing between the tested ports in the Totally Navigable case, the NW Passage case, and NE Passage case. The corresponding projected fractional increases in trade volume between the tested ports $\Delta T_{i,j}$ are respectively recorded in Appendices 3.2, 3.4, and 3.6.

Even before integration with the trade volume data, these naval routing distance data warrant discussion. Perhaps most importantly, they set the stage for the surprisingly wide variety of ports which will benefit from Arctic navigability. Intuition (no doubt informed by a lifetime of looking at maps which misrepresent scale at extreme latitudes) might lead one to expect that only the northernmost pairs, such as Tokyo-Hamburg, would benefit from traversing the Arctic. Indeed, in the Totally Navigable case Tokyo-Hamburg is shortened by 45.4% when routed through the Arctic, leading to a predicted trade volume increase along that route of 19.9%. The data suggest that intuition significantly underestimates the efficiency of trans-Arctic shipping: on the Asian side, ports as far south as Singapore (barely north of the equator) can benefit from Arctic routing to north European ports. On the European side, even ports deep inside the Mediterranean like Piraeus (Greece) can benefit from Arctic routing to northeast Asian ports. In the Americas, Arctic routing provides a viable alternative to the Panama Canal for transcontinental shipping, illustrated in particular by the fact that Tokyo (Japan)-Santos (Brazil) optimally routes through the Arctic in the Totally Navigable and NW Passage cases, despite Santos's position 24° south of the equator. Another illustration of this is Vancouver's (Canada) dramatically improved routing to a variety of ports. Vancouver currently routes through the Panama Canal for non-Asian destinations, so there is huge added value in being able to route through the Arctic to reach Europe and even some Middle-Eastern ports such as Jeddah (Saudi Arabia).

An additional point which merits immediate mention is that, for many port pairings, limiting Arctic navigability to the Northwest and/or Northeast Passages only hinders distance reduction slightly versus the Totally navigable case. This is indicative of the fact that the real speedup is in getting to traverse the Arctic at all, as opposed to getting to take an optimal straight-line route through it. This trend becomes clearer in later sections when data are synthesized into high-level aggregations.

3.2 Region-Level Results

It is instructive to aggregate the port-level data into region-level data, with trade-volume-weighted averages taken across the ports examined in each of the 5 affected regions: Northeast Asia, North Europe, North America, Southeast Asia, and the Mediterranean. These data are recorded in Figure 1, which displays the aggregate average fractional reductions in optimal naval routing distance due to Arctic routing between each of these 5 affected regions alongside the corresponding aggregate fractional trade volume increases between the regions.

Regional Connection	Totally Navigable Dist. Reduc.	Totally Navigable Trade Incr.	NW Passage Dist. Reduc.	NW Passage Trade Incr.	NE Passage Dist. Reduc.	NE Passage Trade Incr.
NE As. to N Eu.	36.7%	14.8%	24.7%	9.0%	33.9%	13.4%
N Am. to N Eu.	15.5%	5.8%	6.5%	2.2%	13.0%	4.7%
N Eu. to SE As.	14.6%	5.0%	4.3%	1.4%	12.1%	4.1%
NE As. to N Am.	6.6%	2.3%	6.6%	2.3%	3.2%	1.0%
Med. to NE As.	5.9%	2.0%	3.0%	1.0%	4.0%	1.3%
Med. to N Am.	5.2%	1.7%	2.9%	1.0%	3.6%	1.2%
N Am. to SE As.	4.8%	1.6%	4.8%	1.6%	2.2%	0.7%

Figure 1: Weighted average percent distance shortening of naval routing and corresponding expected trade volume increase for regional connections affected by Arctic navigability. Results tabulated for the Totally Navigable case (columns 2&3), the NW Passage case (columns 4&5), and the NE Passage case (columns 6&7). Results displayed for every region pair for which Arctic routing is significantly preferable to present-day optimal routing in at least one case.

Larger geographic trends in the effect of Arctic navigability are quite apparent in these aggregates: in the Totally Navigable case, by far the largest expected trade volume increase is 14.8% between Northeast Asia and North Europe due to an average distance reduction of 36.7% between the regions. Intuitively, this makes sense—the existing maritime routes between the two regions are extremely long and indirect, routing either across both the Atlantic and Pacific Oceans through the Panama Canal or around nearly the entire Eurasian landmass through the Suez Canal. This new accessibility holds even into South Asia, with the "breakeven point" for equidistance with North Europe occurring roughly around the Strait of Malacca—that is to say, ports on the Indian Ocean side of Malacca will be better served routing through the Suez Canal, while ports on the Pacific Ocean side of Malacca will prefer Arctic routing. The equivalent breakeven point for connections to the Mediterranean is understandably much farther north, with only Northeast Asian ports preferring to route to the Mediterranean through the Arctic.

It is clear from looking at a map that the geometry of these Asia-Europe Arctic routes is

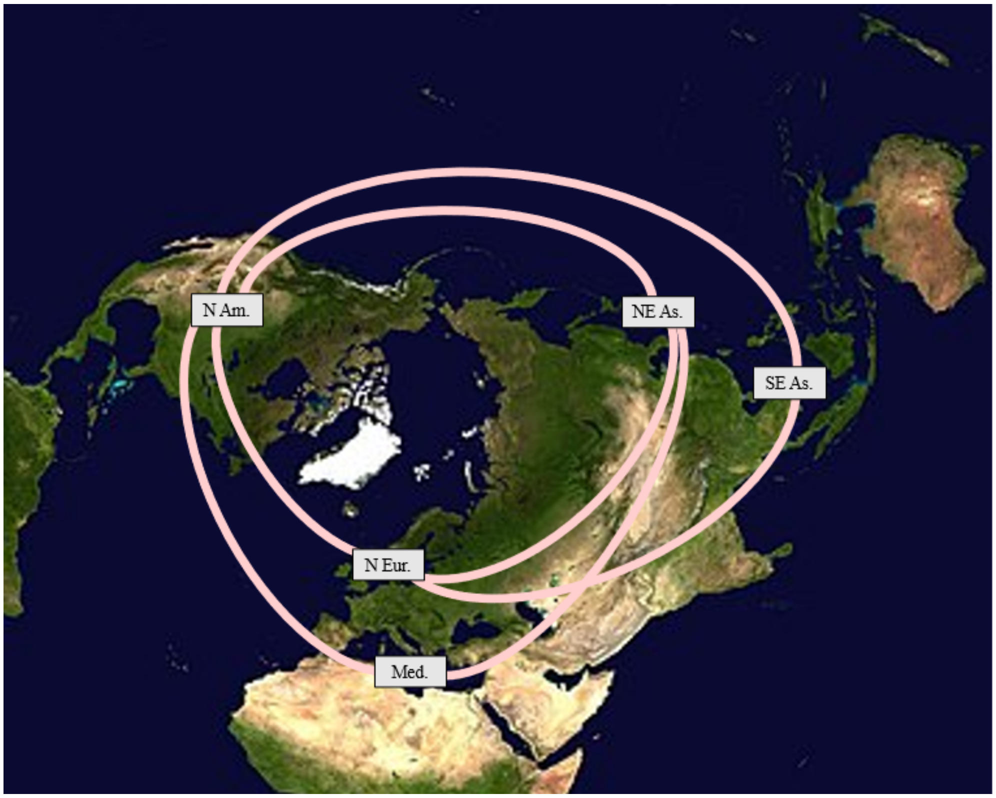

Figure 2: Regional connections which benefit from Arctic navigability in at least one case. This Boreal projection more effectively illustrates opportunities for trans-Arctic navigation than conventional projections. Shape of connections is arbitrary and should not be construed as informational. Backing map courtesy of Hellerick (2018).

such that even in the Totally Navigable case, the optimal routes tend to run relatively close to the Northeast Passage. This is evidenced by the fact that the NE Passage case data for these region pairs look barely different than the Totally Navigable case data, while the NW Passage case Arctic routes provide much less distance reduction.

Perhaps less intuitive than the Asian-European connection is that between North America and the rest of the regions, considering there are relatively direct sea routes between most European/Asian ports and the North American east/west coasts, respectively. The reason for the substantial predicted increase in trade volume between North America and the rest of the regions is that Arctic routing substantially decreases the distance from Europe to the North American west coast, and from Asia to the North American east coast. To dismiss this change on the grounds that Eurasians will ship solely to their closer North American coast would be misguided—even in the present day, the Panama Canal makes shipping from, say, Tokyo to New York City over water a viable and oft-used alternative to shipping to the American west coast and then railing cargo across the continent. The geometry of these new shipping routes is once again made clear by comparing the Totally Navigable case to the NW/NE Passage case: Northeast Asia-East North America routes directly through the Northwest Passage, while North Europe-West North America routes much more efficiently through the Northeast Passage than the Northwest Passage.

Implicitly important are the regions omitted from this chart. Ports in Sub-Saharan Africa, the Indian Ocean, Latin America, and Oceania will be effectively indifferent to Arctic navigability as a routing option. The major trade volume increases due to Arctic navigability project to happen almost entirely in the global North, an area which is generally already better-developed and is expected to avoid the worst of the ecological effects of global warming when compared to hotter and more agriculturally-dependent societies in equatorial and sub-equatorial regions. Furthermore, use of Arctic shipping lanes will result in lowered traffic through chokepoints such as the Suez and Panama Canals. Therefore, we conclude, that Arctic navigability will continue to reinforce general expectations that climate change will negatively impact the global North comparatively less than other regions.

3.3 Country-Level Results

The individual country-level projected total changes in trade volume ΔT_i are recorded in Figure 3, which tabulates country-level aggregate projections for all countries with a projected trade volume increase of at least .5% in the Totally Navigable case.

		Totally Nav.		NW Passage		NE Passage	
Country	Curr. Vol. ($BN)	Proj. Increase ($BN)	Proj. Increase (%)	Proj. Increase ($BN)	Proj. Increase (%)	Proj. Increase ($BN)	Proj. Increase (%)
Japan	1468.2	35.9	2.4%	27.8	1.9%	26.6	1.8%
China	3987.0	82.5	2.1%	57.8	1.5%	60.2	1.5%
South Korea	1029.8	17.9	1.7%	13.4	1.3%	13.1	1.3%
United States [E]	3055.8	53.1	1.7%	53.1	1.7%	23.9	0.8%
Germany	2587.3	40.0	1.5%	20.1	0.8%	35.7	1.4%
United States	3819.7	58.0	1.5%	53.1	1.4%	27.2	0.7%
United Kingdom	1129.4	16.3	1.4%	8.5	0.8%	14.0	1.2%
Denmark	198.4	2.4	1.2%	1.3	0.6%	2.2	1.1%
Ireland	214.9	2.6	1.2%	1.3	0.6%	2.2	1.0%
The Netherlands	1121.3	14.4	1.2%	7.4	0.6%	12.6	1.0%
Philippines	140.4	1.6	1.1%	1.0	0.7%	1.0	0.7%
Sweden	318.5	3.5	1.1%	1.9	0.6%	3.2	1.0%
Canada [W]	179.9	1.9	1.0%	1.0	0.5%	1.6	0.9%
France	1200.0	11.7	1.0%	6.0	0.5%	10.1	0.8%
Poland	430.4	3.9	0.9%	2.1	0.5%	3.5	0.8%
Canada	899.5	7.0	0.8%	6.1	0.7%	3.9	0.4%
Hong Kong	1022.5	7.8	0.8%	4.7	0.5%	5.0	0.5%
Belgium	865.7	6.3	0.7%	3.3	0.4%	5.5	0.6%
Canada [E]	719.6	5.1	0.7%	5.1	0.7%	2.3	0.3%
United States [W]	763.9	4.9	0.6%	0.0	0.0%	3.3	0.4%

Figure 3: Current average annual trade volume and projected increase in annual trade volume (gross, based on current average gross, and fractional) due to Arctic navigability for countries with at least .5% projected fractional increase in Totally Navigable Case. Results tabulated for the Totally Navigable case (columns 2&3), the NW Passage case (columns 4&5), and the NE Passage case (columns 6&7). Current average annual trade volume based on 2010-2019 average.

Comparison of the magnitudes of these aggregate data with the region-level aggregate data may be initially surprising—the magnitude of the country-level fractional trade increases tends to be on the order of just a few percent, much smaller than some of the particularly notable region-pair-level fractional trade increases such as North Europe-Northeast Asia's 14.8%. The reason for this disparity is that the region-level $\Delta T_{S_1,S_2}$ describes the fractional increase in trade across the connection between regions S_1 and S_2, while the country-level ΔT_i incorporate all bilateral trade ties that country i has, including all trade conducted on unaffected routes. Most countries conduct a relatively small portion of their total international trade with very far-flung partners, and these far-flung partnerships tend to be the only ones affected by Arctic routing. Thus, the effects of Arctic navigability get diluted in an absolute sense when wrapped into the larger fold of a country's overall trade volume. An illustrative example is Germany: on a routing level, Germany's port of Hamburg benefits enormously from Arctic navigability to reach places such as Northeast Asia. However, Germany primarily trades with European economies, and intra-European trade is unaffected by Arctic navigability. This is why $\Delta T_{\text{Germany}} \approx 1.5\%$ can be much smaller than $\Delta T_{N\ Eu.,\ NE\ As} =\approx 14.8\%$ without contradiction.

The results of this aggregation largely agree with the implications of the region-level aggregation: the countries projected to experience the largest fractional trade volume increase are all Northeast Asian, North European, or North American alongside a couple of Southeast Asian countries. These data also back up the idea that North European countries such as Germany and the United Kingdom will benefit more from the Northeast Passage opening than the Northwest Passage, while the Northwest Passage is comparatively valuable for North American economies[12].

[12]This is the only meaningful conclusion in this analysis which *is* affected significantly by the East-West mix chosen for the United States and Canada, as can be seen from the included [E]/[W] splits charted in

However, the integration of existing national trade ties helps accentuate the importance of certain regional pairs. It is instructive to note that $\Delta T_{United\,States}$ is much larger than ΔT_{Canada}, suggesting that the United States benefits significantly more from Arctic routing than Canada does. This is an unintuitive result, given Canada's comparatively northern position. The reason for this result is that unaffected American-Canadian bilateral trade comprises a huge fraction of Canada's total trade volume, but a much smaller fraction of the United States' much larger total trade volume. Thus, Canada's benefit is diluted as a share of its overall trade volume by the fact that that trade volume is comparatively intra-regional. It is also interesting to note that the United States' eastern subdivision benefits substantially more from Arctic routing than its western subdivision, while Canada's east-west benefits skew the other way. This is because Vancouver is substantially farther north than the American western port of Los Angeles, better positioning it to take advantage of Arctic routing.

Related to this observation is the fact that the table in Figure 3 is led by the three Northeast Asian countries. The relatively strong impact on these countries versus their primarily European and North American trade partners is reflective of the fact that intra-regional trade comprises a relatively small fraction of these countries' trade volumes. Intra-European trade and intra-American trade (alongside the other unaffected connections these regions lean on, such as the connection between the North American east coast and Europe) dilute the effect of Arctic routing far more than the comparatively low-volume intra-Asian

Figure 3.

trade network does, so the Northeast Asian countries are more acutely affected by the benefits of Arctic navigability than their bilateral partners on the affected routes.

The national increases in trade volume depicted in Figure 3 are primarily driven by increased trade along far-flung inter-regional routes. For instance, most of Germany's trade partnerships will be unaffected by Arctic routing, while its trade with regions such as Northeast Asia will dramatically increase—recall that trade volumes between North Europe and Northeast Asia are projected to increase by 14.8% on average. Thus, Arctic routing will have a globalizing effect, increasing trade between distant regions.

4 Conclusion

In this paper, the effects of future Arctic navigability on global trade are projected using existing empirical conclusions about the elasticity of trade volume with respect to naval routing distance. By identifying pairs of major container ports which optimally route through the Arctic when given the chance, it is shown that Arctic navigability will have a significant positive effect on global trade volumes. This effect is highly regional, with many routes unaffected while some are shortened by up to 45%, implying trade volume increases on those routes of up to 20%. Even in the near future, where only the southernmost edges of the Arctic are navigable, the Northwest and Northeast Passages will still provide distance shortenings of up to 33% and 43%, respectively.

There are three main potential sources of error in the fractional results of this analysis: global bias (up to 14%) due to the strength of the elasticity relation, regional bias (up to 5%) due to currents, and random noise (up to 2%) due to currents. These biases appear mutually independent, so in isolated samples we expect an overall error margin of up to $\sqrt{14\%^2 + 5\%^2 + 2\%^2} = 15\%$. Then, the aforementioned "headline" distance reductions are more precisely reported as $45 \pm 7\%$ with a totally navigable Arctic, $33 \pm 5\%$ with a navigable Northwest Passage, and $43 \pm 6\%$ with a navigable Northeast Passage. In the rest of the conclusion, numerical figures will continue to be reported with the relevant error applied.

Quantitative analysis reveals a large number of optimal Arctic routes which are somewhat unintuitive due to longstanding cartographic norms which misrepresent the size of the Arctic. Ports as unusually located as Singapore (Singapore), Jeddah (Saudi Arabia), and Santos (Brazil) are found to benefit from access to Arctic routing in certain cases. On a regional level, the northern economies of Europe, Asia, and America benefit most from Arctic navigability. Trans-Arctic travel dramatically improves routing between these regions, projecting to increase North European-Northeast Asian trade by $14.8 \pm 2.2\%$ and North European-North American trade by $5.8 \pm .9\%$. The dramatically increased efficiency of travel between North Europe and Asia even continues down toward key Southeast Asian economies, with trade between these regions projecting to increase by $5.0 \pm .7\%$. The geometry of these regions means that they interact differently with the different possible near-term Arctic passages: North Europe will benefit much more from a navigable Northeast Passage, while North America will benefit more from a navigable Northwest Passage. Northeast Asia is generally ambivalent between the two, trading significantly with both counterparts.

On a national level, the impact of these large projected region-to-region trade volume increases is diluted by the generally large portion of countries' trade which travels along unaffected routes. Nations in regions with rich intra-regional trade activity such as Europe tend to have smaller projected increases in total national trade volumes than regions with comparatively less intra-regional trade activity such as Asia, leading to the three greatest aggregate increases being the three Northeast Asian economies in the sample (Japan, China, and South Korea, with respective $2.4 \pm .3\%$, $2.1 \pm .3\%$, and $1.7 \pm .2\%$ increases in total trade volume).

It is imperative to remember that Arctic melting is not an isolated phenomenon, and the corresponding rise in sea levels is expected to wreak havoc on coastal economies all around the world. This coupled effect is particularly important to keep in mind given that all of the ports studied in this paper are, by definition, coastal. Projecting the outcome of this sea level rise is a separate, complex economic problem for which this analysis does not propose a solution.

In sum, Arctic navigability projects to significantly increase trade between northern economies in different regions. A less direct but nonetheless important result is that Arctic routing is optimal for a surprisingly large set of ports. This is significant because it means that a navigable Arctic, far from being a niche route taken only for specific shipments, will likely be a high-volume shipping zone with containers from all over the world. Alongside the broad economic questions addressed in this paper, the creation of important new causeways for shipping will likely have implications in the geopolitical sphere, where natural questions about freedom of navigation and strategic port construction arise. Freedom of navigation is a particularly important concern given the difficulties associated with maintaining a safe

Arctic shipping route (particularly as the United States Navy, the traditional guarantor of safe navigation, is not well-suited to icebreaking operations) as well as the huge economic value of Arctic navigability to key geopolitical actors such as China.

References

United States Global Change Research Program. “Third National Climate Assessment.” 2014.

Smith, Laurence C., and Scott R. Stephenson. “New Trans-Arctic shipping routes navigable by midcentury.” Proceedings of the National Academy of Sciences 110, no. 13 (2013): E1191-E1195.

European Space Agency. “Satellites Witness Lowest Arctic Ice Coverage in History.” 2007.

Feyrer, James. “Trade and income—exploiting time series in geography.” American Economic Journal: Applied Economics 11, no. 4 (2019): 1-35.

Boisso, Dale, and Michael Ferrantino. “Economic distance, cultural distance, and openness in international trade: Empirical puzzles.” Journal of Economic integration (1997): 456-484.

Berthelon, Matias, and Caroline Freund. “On the conservation of distance in international trade.” Journal of International Economics 75, no. 2 (2008): 310-320.

Disdier, Anne-Célia, and Keith Head. “The puzzling persistence of the distance effect on bilateral trade.” The Review of Economics and statistics 90, no. 1 (2008): 37-48.

Martincus, Christian Volpe, and Juan Blyde. “Shaky roads and trembling exports: Assessing the trade effects of domestic infrastructure using a natural experiment.” Journal of International Economics 90, no. 1 (2013): 148-161.

Feyrer, James. “Distance, trade, and income-the 1967 to 1975 closing of the suez canal as a natural experiment." National Bureau of Economic Research Working Paper Series w15557 (2009).

Hellerick. *Physical map of the world in Hellerick triaxial boreal projection.* 2018. Digital. 4400×4400 px. Wikimedia Commons, upload.wikimedia.org/wikipedia/commons/0/0a/Physical_world_map_in_Hellerick_triaxial_boreal_projection_-_shallow.jpg.

Gordon, Arnold L. and Cenedese, Claudia. "Ocean current". Encyclopedia Britannica, 30 May. 2018, https://www.britannica.com/science/ocean-current.

Susie Harder. *Map of the Arctic region showing shipping routes Northeast Passage, Northern Sea Route, and Northwest Passage, and Bathymetry* [sic]. 2009. Digital. 1003×952 px. Wikimedia Commons, https://upload.wikimedia.org/wikipedia/commons/thumb/b/bc/Map_of_the_Arctic_region_showing_the_Northeast_Passage_the_Northern_Sea_Route_and_Northwest_Passage_and_bathymetry.png.

Appendix

Appendix 1: List of Ports

Region	Port	Longitude (°)	Latitude (°)	Dropped due to Routing Irrelevance?
N Eu.	Hamburg (Germany)	10 E	54 N	
	Rotterdam (The Netherlands)	4 E	52 N	
	Antwerp (Belgium)	4 E	51 N	
	Felixstowe (United Kingdom)	1 E	52 N	
NE As.	Tokyo (Japan)	140 E	35 N	
	Busan (South Korea)	129 E	35 N	
	Shanghai (China)	121 E	31 N	
N Am.	Vancouver (Canada)	123 W	49 N	
	New York (United States)	74 W	41 N	
	Los Angeles (United States)	118 W	34 N	
SE As.	Kaohsiung (Taiwan)	120 E	23 N	
	Hong Kong (Hong Kong)	114 E	22 N	
	Manila (Philippines)	121 E	15 N	
	Saigon (Vietnam)	107 E	11 N	
	Laem Chabang (Thailand)	101 E	12 N	Y
	Port Klang (Malaysia)	101 E	3 N	Y
	Singapore (Singapore)	104 E	1 N	Y
	Tanjung Priok (Indonesia)	107 E	6 S	Y
Med.	Tanger-Med (Morocco)	6 W	36 N	
	Valencia (Spain)	0	39 N	
	Gioia Tauro (Italy)	16 E	38 N	
	Piraeus (Greece)	24 E	38 N	
Ind. Oc.	Jeddah (Saudi Arabia)	39 E	21 N	
	Colombo (Sri Lanka)	80 E	7 N	Y
	Dubai (United Arab Emirates)	55 E	25 N	Y
	Mumbai (India)	73 E	19 N	Y
	Salalah (Oman)	54 E	17 N	Y
Lat. Am.	Santos (Brazil)	46 W	23 S	
	Colon (Panama)	80 W	9 N	Y

Appendix 1.1: Initial set of container ports analyzed by naval routing algorithm. Integer latitude and longitude listed correspond to node in graph used to represent the port during pathfinding. If a port has no routes improved due to Arctic routing, it is dropped from future tables.

Appendix 2: Derivation of Pathfinding Overestimation Error

On a flat square grid without diagonal connections, the most efficient way to travel a distance D at an angle α relative to horizontal is to traverse $\cos(\alpha)D$ steps horizontally and $\sin(\alpha)D$ steps vertically. Then, the expected overestimation error is given by

$$\frac{\int \cos(\alpha)D + \sin(\alpha)Dd\alpha}{\int Dd\alpha} = \frac{4}{\pi}$$

If diagonal connections are added, the most efficient way to travel a distance D at an angle α relative to the closest non-diagonal axis is to traverse $(\cos(\alpha)-\sin(\alpha))D$ steps along that closest non-diagonal axis and then $\sqrt{2}\sin(\alpha)D$ steps along the closest diagonal axis. Then, the expected overestimation error is given by

$$\frac{\int (\cos(\alpha) - \sin(\alpha))D + \sqrt{2}\sin(\alpha)Dd\alpha}{\int Dd\alpha} = \frac{\int \cos(\alpha)D + (\sqrt{2}-1)\sin(\alpha)Dd\alpha}{\int Dd\alpha} = \frac{8}{\pi}(\sqrt{2}-1)$$

Deriving the expected overestimation error at a general point on the sphere requires non-Euclidean geometry. Consider an arbitrary location on a sphere $x \doteq (\theta, \phi)$ where θ is the longitude and ϕ is the latitude. From x, moving differentially at an angle α relative to the "horizontal" (the tangent of the ϕ line of latitude) entails moving differentially in the direction $(\cos(\phi)\cos(\alpha), \sin(\alpha))dv$. For $\alpha \in [-\pi/4, \pi/4]$ this is most efficiently achieved on our grid by moving a differential distance $(\cos(\alpha) - |\sin(\alpha)|)\cos(\phi)dv$ along the horizontal and then a differential distance $\sqrt{1+\cos^2(\phi)}|\sin(\alpha)|dv$ along the closest diagonal. For $\alpha \in [-\pi/2, -\pi/4) \cup (\pi/4, \pi/2]$ this is most efficiently achieved on our grid by moving a differential distance $(|\sin(\alpha)| - \cos(\alpha))dv$ along the vertical and then a differential distance $\sqrt{1+\cos^2(\phi)}\cos(\alpha))dv$ along the closest diagonal. Then, the total expected overestimation error is given by

$$\frac{\int_0^{\pi/4} \cos(\phi)\cos(\alpha) + (\sqrt{1+\cos^2(\phi)} - \cos(\phi))\sin(\alpha)d\alpha}{\int_0^{\pi/4} \sqrt{\cos^2(\phi)\cos^2(\alpha) + \sin^2(\alpha)}d\alpha} +$$

$$\frac{\int_{\pi/4}^{\pi/2} (\sqrt{1+\cos^2(\phi)} - 1)\cos(\alpha) + \sin(\alpha)d\alpha}{\int_{\pi/4}^{\pi/2} \sqrt{\cos^2(\phi)\cos^2(\alpha) + \sin^2(\alpha)}d\alpha}$$

Analytical evaluation of this is impossible in closed form due to an elliptical integral in the denominator. Numerical approximation of this value at various latitudes ϕ produces the stated values.

Appendix 3.1:
Port-to-Port Distance Decrease, %, Totally Navigable Case

		N Europe				NE Asia			N America			SE Asia				Mediterranean					
		Hamburg	Rotterdam	Antwerp	Felixstowe	Tokyo	Busan	Shanghai	Vancouver	New York	Los Angeles	Kaohsiung	Hong Kong	Manila	Saigon	Tanger-Med	Valencia	Gioia Tauro	Piraeus	Jeddah	Santos
N Eu.	Hamburg					45.4	39.6	33.4	35.9		15.9	26.2	22.1	20.1	5.6						
	Rotterdam					42.1	35.8	29.1	32.8		11.5	21.2	16.8	14.7							
	Antwerp					41.9	35.6	28.8	32.5		11.1	20.9	16.5	14.4							
	Felixstowe					42.6	36.4	29.7	33.5		12.3	21.8	17.4	15.3							
NE As.	Tokyo	45.4	42.1	41.9	42.6					20.2						23.5	16.6				0.8
	Busan	39.6	35.8	35.6	36.4					19.9						15.4	7.9				
	Shanghai	33.4	29.1	28.8	29.7					19.0						6.8					
N Am.	Vancouver	35.9	32.8	32.5	33.5											16.9	16.2	14.8	14.2	12.7	
	New York					20.2	19.9	19.0				18.2	17.8	17.1	4.6						
	Los Angeles	15.9	11.5	11.1	12.3																
SE As.	Kaohsiung	26.2	21.2	20.9	21.8					18.2											
	Hong Kong	22.1	16.8	16.5	17.4					17.8											
	Manila	20.1	14.7	14.4	15.3					17.1											
	Saigon	5.6								4.6											
Med.	Tanger-Med					23.5	15.4	6.8	16.9												
	Valencia					16.6	7.9		16.2												
	Gioia Tauro								14.8												
	Piraeus								14.2												
	Jeddah								12.7												
	Santos					0.8															

Appendix 3.1: Percent distance shortening of naval routing between ports due to total Arctic navigability. Results displayed for every port pair for which Arctic routing is preferable to present-day optimal routing; port pairs without preferable Arctic routing are left blank.

Appendix 3.2:
Port-to-Port Trade Volume Increase, %, Totally Navigable Case

		N Europe				NE Asia			N America			SE Asia				Mediterranean					
		Hamburg	Rotterdam	Antwerp	Felixstowe	Tokyo	Busan	Shanghai	Vancouver	New York	Los Angeles	Kaohsiung	Hong Kong	Manila	Saigon	Tanger-Med	Valencia	Gioia Tauro	Piraeus	Jeddah	Santos
N Eu.	Hamburg					19.9	16.3	13.0	14.3		5.3	9.5	7.8	7.0	1.7						
	Rotterdam					17.8	14.2	10.9	12.7		3.7	7.4	5.7	4.9							
	Antwerp					17.7	14.1	10.7	12.5		3.6	7.3	5.6	4.8							
	Felixstowe					18.1	14.5	11.2	13.0		4.0	7.7	5.9	5.1							
NE As.	Tokyo	19.9	17.8	17.7	18.1					7.0						8.4	5.6				0.2
	Busan	16.3	14.2	14.1	14.5					6.9						5.1	2.5				
	Shanghai	13.0	10.9	10.7	11.2					6.5						2.1					
N Am.	Vancouver	14.3	12.7	12.5	13.0											5.7	5.4	4.9	4.7	4.2	
	New York					7.0	6.9	6.5				6.2	6.1	5.8	1.4						
	Los Angeles	5.3	3.7	3.6	4.0																
SE As.	Kaohsiung	9.5	7.4	7.3	7.7					6.2											
	Hong Kong	7.8	5.7	5.6	5.9					6.1											
	Manila	7.0	4.9	4.8	5.1					5.8											
	Saigon	1.7								1.4											
Med.	Tanger-Med					8.4	5.1	2.1	5.7												
	Valencia					5.6	2.5		5.4												
	Gioia Tauro								4.9												
	Piraeus								4.7												
	Jeddah								4.2												
	Santos					0.2															

Appendix 3.2: Percent projected trade volume increase between ports due to total Arctic navigability. Results displayed for every port pair for which Arctic routing is preferable to present-day optimal routing; port pairs without preferable Arctic routing are left blank.

Appendix 3.3:
Port-to-Port Distance Decrease, %, NW Passage Case

		N Europe				NE Asia			N America			SE Asia				Mediterranean					
		Hamburg	Rotterdam	Antwerp	Felixstowe	Tokyo	Busan	Shanghai	Vancouver	New York	Los Angeles	Kaohsiung	Hong Kong	Manila	Saigon	Tanger-Med	Valencia	Gioia Tauro	Piraeus	Jeddah	Santos
N Eu.	Hamburg					33.0	26.7	20.0	20.2			12.1	7.8	5.8							
	Rotterdam					30.7	23.9	16.8	18.6			8.3	3.6	1.4							
	Antwerp					30.7	24.0	16.8	18.7			8.3	3.6	1.4							
	Felixstowe					31.6	24.9	17.8	19.9			9.4	4.7	2.5							
NE As.	Tokyo	33.0	30.7	30.7	31.6					20.2						16.9	9.8				0.8
	Busan	26.7	23.9	24.0	24.9					19.9						8.5	0.8				
	Shanghai	20.0	16.8	16.8	17.8					19.0											
N Am.	Vancouver	20.2	18.6	18.7	19.9											9.5	9.1	8.3	8.0		
	New York					20.2	19.9	19.0				18.2	17.8	17.1	4.6						
	Los Angeles																				
SE As.	Kaohsiung	12.1	8.3	8.3	9.4					18.2											
	Hong Kong	7.8	3.6	3.6	4.7					17.8											
	Manila	5.8	1.4	1.4	2.5					17.1											
	Saigon									4.6											
Med.	Tanger-Med					16.9	8.5		9.5												
	Valencia					9.8	0.8		9.1												
	Gioia Tauro								8.3												
	Piraeus								8.0												
	Jeddah																				
	Santos					0.8															

Appendix 3.3: Percent projected trade volume increase between ports due to Northwest Passage navigability. Results displayed for every port pair for which Arctic routing is preferable to present-day optimal routing; port pairs without preferable Arctic routing are left blank.

Appendix 3.4:
Port-to-Port Trade Volume Increase, %, NW Passage Case

		N Europe				NE Asia			N America			SE Asia				Mediterranean					
		Hamburg	Rotterdam	Antwerp	Felixstowe	Tokyo	Busan	Shanghai	Vancouver	New York	Los Angeles	Kaohsiung	Hong Kong	Manila	Saigon	Tanger-Med	Valencia	Gioia Tauro	Piraeus	Jeddah	Santos
N Eu.	Hamburg					12.8	9.8	6.9	7.0			3.9	2.5	1.8							
	Rotterdam					11.6	8.5	5.7	6.4			2.6	1.1	0.4							
	Antwerp					11.6	8.6	5.7	6.4			2.6	1.1	0.4							
	Felixstowe					12.1	9.0	6.1	6.9			3.0	1.5	0.8							
NE As.	Tokyo	12.8	11.6	11.6	12.1					7.0						5.7	3.1				0.2
	Busan	9.8	8.5	8.6	9.0					6.9						2.7	0.2				
	Shanghai	6.9	5.7	5.7	6.1					6.5											
N Am.	Vancouver	7.0	6.4	6.4	6.9											3.0	2.9	2.6	2.5		
	New York					7.0	6.9	6.5				6.2	6.1	5.8	1.4						
	Los Angeles																				
SE As.	Kaohsiung									6.2											
	Hong Kong									6.1											
	Manila									5.8											
	Saigon									1.4											
Med.	Tanger-Med					5.7	2.7		3.0												
	Valencia					3.1	0.2		2.9												
	Gioia Tauro								2.6												
	Piraeus								2.5												
	Jeddah																				
	Santos					0.2															

Appendix 3.4: Percent projected trade volume increase between ports due to Northwest Passage navigability. Results displayed for every port pair for which Arctic routing is preferable to present-day optimal routing; port pairs without preferable Arctic routing are left blank.

Appendix 3.5:
Port-to-Port Distance Decrease, %, NE Passage Case

		N Europe				NE Asia			N America			SE Asia				Mediterranean					
		Hamburg	Rotterdam	Antwerp	Felixstowe	Tokyo	Busan	Shanghai	Vancouver	New York	Los Angeles	Kaohsiung	Hong Kong	Manila	Saigon	Tanger-Med	Valencia	Gioia Tauro	Piraeus	Jeddah	Santos
N Eu.	Hamburg					42.9	37.0	30.7	32.6		12.1	23.4	19.3	17.3	2.5						
	Rotterdam					39.5	33.1	26.2	29.4		7.5	18.3	13.8	11.6							
	Antwerp					39.2	32.8	25.9	29.0		7.0	17.9	13.4	11.2							
	Felixstowe					39.8	33.4	26.6	29.8		8.0	18.6	14.2	12.0							
NE As.	Tokyo	42.9	39.5	39.2	39.8					9.6						19.3	12.3				
	Busan	37.0	33.1	32.8	33.4					9.8						11.0	3.4				
	Shanghai	30.7	26.2	25.9	26.6					9.4						2.3					
N Am.	Vancouver	32.6	29.4	29.0	29.8											11.9	11.4	10.4	10.0		
	New York					9.6	9.8	9.4				8.9	8.8	8.2							
	Los Angeles	12.1	7.5	7.0	8.0																
SE As.	Kaohsiung	23.4	18.3	17.9	18.6					8.9											
	Hong Kong	19.3	13.8	13.4	14.2					8.8											
	Manila	17.3	11.6	11.2	12.0					8.2											
	Saigon	2.5																			
Med.	Tanger-Med					19.3	11.0	2.3	11.9												
	Valencia					12.3	3.4		11.4												
	Gioia Tauro								10.4												
	Piraeus								10.0												
	Jeddah																				
	Santos																				

Appendix 3.5: Percent projected trade volume increase between ports due to Northeast Passage navigability. Results displayed for every port pair for which Arctic routing is preferable to present-day optimal routing; port pairs without preferable Arctic routing are left blank.

Appendix 3.6:
Port-to-Port Trade Volume Increase, %, NE Passage Case

		N Europe				NE Asia			N America			SE Asia				Mediterranean					
		Hamburg	Rotterdam	Antwerp	Felixstowe	Tokyo	Busan	Shanghai	Vancouver	New York	Los Angeles	Kaohsiung	Hong Kong	Manila	Saigon	Tanger-Med	Valencia	Gioia Tauro	Piraeus	Jeddah	Santos
N Eu.	Hamburg					18.3	14.9	11.6	12.6		3.9	8.3	6.6	5.9	0.8						
	Rotterdam					16.3	12.8	9.5	11.0		2.4	6.3	4.6	3.8							
	Antwerp					16.1	12.7	9.4	10.8		2.2	6.1	4.4	3.6							
	Felixstowe					16.4	13.0	9.7	11.2		2.5	6.4	4.7	3.9							
NE As.	Tokyo	18.3	16.3	16.1	16.4					3.1						6.6	4.0				
	Busan	14.9	12.8	12.7	13.0					3.1						3.6	1.0				
	Shanghai	11.6	9.5	9.4	9.7					3.0						0.7					
N Am.	Vancouver	12.6	11.0	10.8	11.2											3.9	3.7	3.3	3.2		
	New York					3.1	3.1	3.0				2.8	2.8	2.6							
	Los Angeles	3.9	2.4	2.2	2.5																
SE As.	Kaohsiung	8.3	6.3	6.1	6.4					2.8											
	Hong Kong	6.6	4.6	4.4	4.7					2.8											
	Manila	5.9	3.8	3.6	3.9					2.6											
	Saigon	0.8																			
Med.	Tanger-Med					6.6	3.6	0.7	3.9												
	Valencia					4.0	1.0		3.7												
	Gioia Tauro								3.3												
	Piraeus								3.2												
	Jeddah																				
	Santos																				

Appendix 3.6: Percent projected trade volume increase between ports due to Northeast Passage navigability. Results displayed for every port pair for which Arctic routing is preferable to present-day optimal routing; port pairs without preferable Arctic routing are left blank.