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Sanctions or sea ice: Costs of closing the Northern Sea Route

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A B S T R A C T

Either sea ice or recent sanctions on Russia could close or shorten the use of the Northern Sea Route (NSR). Using 16 climate realizations and shipping routes to estimate the value of an NSR transit, we find that closure costs could be as high as $3.3 billion, with possible overall losses as high as $10 billion. Ultimately, sanctions are as expensive as sea ice. The estimates used to produce these findings may be used by other researchers to assess possible future cost savings as climate change continues to affect global transportation.

1. Introduction

As sea ice diminishes, the increase in open water (Goldstein et al., 2018) on Russia's northern coast above the Arctic Circle has brought new opportunities for the Northern Sea Route (NSR) administered by Russia (Boylan, 2021). The NSR attracts attention in international transit shipping for its key advantage over the Suez Canal, its shorter distance, which reduces sailing time, costs and greenhouse gas emissions. The NSR has become an increasingly active and important as a shipping route (Gunnarsson, 2021; Gunnarsson and Moe, 2021) for the transport of goods and raw materials, in part because of these advantages and also due to accelerating Russian industrial development (Cao et al., 2022; Buixadé Farré et al., 2014; Liu and Kronbak, 2010; Bartsch et al., 2021). At the same time, Russia's invasion of Ukraine has resulted in near worldwide condemnation and the imposition of sanctions on Russian goods, services, individuals, and transportation (Tollefson, 2022; Farrell and Newman, 2022).[1] Thus, while changes in Arctic open water affect sea route accessibility, another source of variability is human activity, either economic or geo-political (Lynch et al., 2022).

Both sea ice and sanctions, or even the threat of sanctions, can inhibit travel on the NSR (Boone, 2021). Russia claims the NSR is fully within its territorial waters while other international users characterize at least segments of the route as a strait to be used for international navigation or as an exclusive economic zone (EEZ) (Norchi and Lynch, 2022; Moe, 2020). Accordingly, how segments of the NSR can be traversed may vary. The United Nations Convention on the Law of the Sea preserves the right of innocent passage for all international users in territorial seas, the right of transit passage in international straits, and freedom of navigation within an EEZ. Contrary to the international law of the sea, yet under its domestic maritime law, Russia requires permits and levies fees for NSR transit. Regardless, it is likely either that worldwide sanctions would prohibit such payments, or that international insurance companies would refuse to insure such travel, functionally preventing transit (Miller and Ruiz, 2014). Alternatively, it is possible that Russia itself will close the NSR for strategic reasons (Goncharova and Stoyanova, 2021).

NSR transits are increasing: in 2021 alone, there were 85 completed passages through the Northern Sea Route (CHNL Information

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[1] For example, while previously up to 300,000 jets used Russian airspace prior to the invasion of Ukraine in February 2022, the closure of Russian airspace in March 2022 has caused large route deviations, adding up to six additional hours of flight time and thousands more gallons of fuel costing tens of thousands of dollars per trip on some routes (Kammel and Wilkes, 2022; Bachman et al., 2022).

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Office, 2022). While 14 of these trips were between Russian ports (Russian cabotage), the remaining 71 had at least one port not in Russia (Fig. 1). Among these 71, 29 were "destination" transits that began or ended at a Russian port. Slightly less than half of the 85 NSR passages (42 trips) were international NSR transits that did not involve a Russian port at either end, but instead both started at and ended at international ports around the world to move goods and services. These 42 international transits were perhaps undertaken due to cost savings of this route over the Suez Canal route or the notably longer route around the Cape of Good Hope, which is 3880 miles longer and takes an additional 12 days. Since about 51 ships transit the Suez Canal daily carrying some $10 billion of goods (Suez Canal Authority, 2022; Yeung, 2021), NSR transits in 2021 equated to a day or more of Suez Canal traffic.

Sanctions preventing NSR transits do not matter if sea ice conditions prevent transit anyway. In this paper, we examine different scenarios to determine possible NSR navigability in 2022 (Guivarch et al., 2022). To do so, we examine 16 Coupled Model Intercomparison Project Phase 6 (CMIP6) climate realizations to determine a plausible range of season lengths (Li et al., 2021). Five of the 16 realizations, or over 25%, have sea ice estimates suggesting that the NSR is unpassable in 2022. Therefore, it is sea ice rather than sanctions that would close the NSR in these scenarios. For the remaining realizations, the estimated season length varies from 47 days to 170 days, long enough for goods to transit the NSR and achieve cost savings.

We then estimate the savings for a transit using the NSR instead of the Suez Route. The shorter distance reduces direct costs and takes less time, further reducing costs. Accounting for NSR transit frequency, we then allocate "lost" transits across sea ice closures and possible sanctions on travel through Russian waters using historical values and the 16 realizations. Collectively, the cumulative cost of closing the NSR for the 2022 season could range from just under $900 million to as much as almost $3.3 billion. If valued at a day's worth of Suez traffic, it could be as high as $10 billion. We also calculate the lost reduction in CO_2 for each of the 16 realizations; while CO_2 numbers drop, the reduction is worth only between $180,000 and $18 million at current social cost of carbon or offset prices.

Despite exponential growth in NSR use over the past five years, we assume usage would be only at the intensity of use in 2021. For these voyages, being forced by sanctions or sea ice to take a longer route raises costs and time. Thus, blocked access to the shorter NSR route means direct cost increases to shippers (and ultimately consumers) through greater fuel costs, labor costs, and shipping times. Ultimately, if sea ice makes the route impassible, the cost is due to nature, but if sanctions do so, the cost is due to geopolitics.

2. Season length estimates from CMIP6

We use 16 climate realizations from Coupled Model Intercomparison Project Phase 6 (CMIP6) under a high emissions pathway, namely the Shared Socioeconomic Pathway 5 and the Representative Concentration Pathway 8.5 scenario (hereinafter referred to as SSP5–8.5). While more than one realization is provided for some models, we use only one ensemble member from each model to account for consistency. The CMIP6 simulations reasonably capture Arctic sea ice volume and extent as compared to its precedent phase (Davy and Outten, 2020). As a result, while these projections are not intended for predictive seasonal forecasts of ice cover, we postulate that they offer a plausible range of outcomes for purposes of this calculation.

The Arctic maritime accessibility model is widely used to quantify maritime accessibility shaped by the Arctic climate and adapt it to include the Polar Operational Limit Assessment Risk Indexing System (POLARIS) (Li et al., 2021; IMO 2016). Within the POLARIS framework, the viability of ship operation is quantified by Risk Index Outcome (RIO) values, defined as

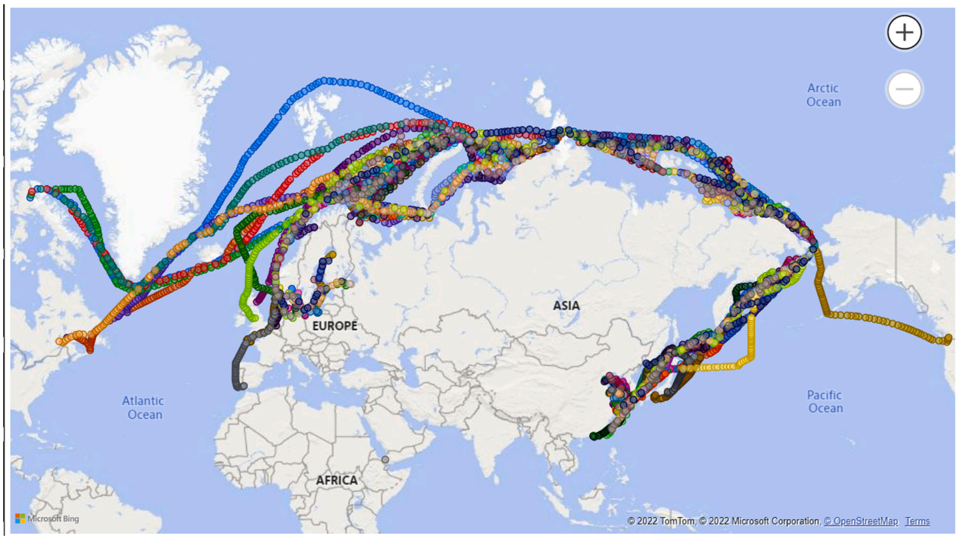

Fig. 1. International transits of the Northern Sea Route (NSR) in 2021 where at least one port was not in the NSR. Picture courtesy of the Center for High North Logistics Information Office (CHNL Information Office 2022).

$$RIO = \sum_{k=1}^{n} C_k RIV_k$$

where C_k and RIV_k refer to ice concentration and the associated Risk Index Value (RIV) of a particular ice category k, respectively. The RIV can be further deduced from ice type and vessel class. Specifically, the ice type can be approximated by ice thickness range with a look-up table and an open water (OW) vessel class. The derived RIV ranges from -8 to +3, with higher values yielding lower risks. By summing all ice categories together, the RIO suggests a "go or no-go" situation, with a value range of -80 (worst-case conditions) to +30 (optimal conditions). A positive RIO is indicative of a normal operation of OW vessel class, under which condition the risk level is acceptable. The travel speed to navigate safely through the ice is determined by the relationship between RIO and IMO-recommended speed. A map of the resulting gridded speeds is then used to identify optimal least-cost routes with the implementation of Dijkstra's algorithm. The optimal route and its travel time are only recorded when transit can be realized from the start location of Rotterdam, the Netherlands, to the destination location of the Bering Strait. The Arctic maritime accessibility model is conducted independently for individual ensemble members.

For a given ice year from April 1 to March 31 of the following calendar year (Mudryk et al., 2021), the recorded navigable days are counted toward season length calculation. A season length includes continuously navigable days unseparated by gaps of impassable days. Due to high variability at the opening and closing of a shipping season, seven days and five days are used empirically to chop off the season shoulder to make it more practical and realistic. Doing so also accords with the custom of experienced ship operators waiting until sea ice conditions stablize to avoid the unnecessary loss.

Estimates of season length vary considerably by realization (Table 1). Four realizations suggest that sea ice extent will suggest that there are not sufficient navigable days in a row across the NSR transits to run in 2022, and another realization suggests only one will be possible. The rest vary from a low season length of 47 days to a high season length of 170 days.

3. Sea ice and sanction transit cost estimates

The Rotterdam-Yokohama route is about 37% shorter using the NSR than using the Suez Canal (Farré et al., 2014; Cao et al., 2022). Since both fuel and days at sea are major components of shipping expenses, we assume shipping costs vary with distance. The cost of shipping has increased more than nine-fold since the start of the pandemic (Fig. 2). This rise predates the current situation in Ukraine and is instead part of larger worldwide logistic supply chain issues. As of March 11, 2022, it cost $13,382 to ship a standard double large container, referred to as a forty foot equivalent unit (FEU), from China/East Asia to Europe (Freightos, 2022). All estimates herein are expressed in 2022 US dollars.

Assuming a post-Panama container ship that can hold about 2500 FEUs (Cao et al., 2022) and using current shipping rates, transit via the NSR could save about $12,389,739 per ship, compared to transit via the Suez Canal route. (See the Supplement for detailed calculations.)

The NSR is not only shorter, but faster, even accounting for slower shipping speeds in Arctic conditions which we estimate in our model. The total number of days of shipping time including through the NSR for each of the 16 realizations was estimated from Rotterdam to Yokohama. These transit times were then compared with the number of days by ship from Rotterdam to Yokohama via

Table 1
Estimated Season Length based on CMIP6 Realization using routes estimated by the Arctic maritime accessibility model. Days saved is estimated by subtracting days of transit time estimated for each model from time of Suez route in days. Number of transits is estimated by adjusting estimated season length for rate of NSR ship transits in 2021.

CMIP6 realization	Season length	Estimated transits	Days saved
CESM2-WACCM	0	0	0.0
GFDL-CM4	0	0	0.0
MIROC6	0	0	0.0
NorESM2-MM	0	0	0.0
BCC-CSM2-MR	1	0	6.0
CNRM-CM6–1	47	33	7.3
MIROC-ES2L	55	38	7.0
CESM2	64	44	6.5
ACCESS-CM2	74	51	6.0
NorESM2-LM	92	64	7.3
IPSL-CM6A-LR	102	71	8.0
AWI-CM-1–1-MR	110	77	6.9
NESM3	112	78	0.1
MPI-ESM1–2-LR	119	83	7.7
MPI-ESM1–2-HR	123	86	6.9
MRI-ESM2–0	170	119	7.8
Full 180 day	180	126	6.5

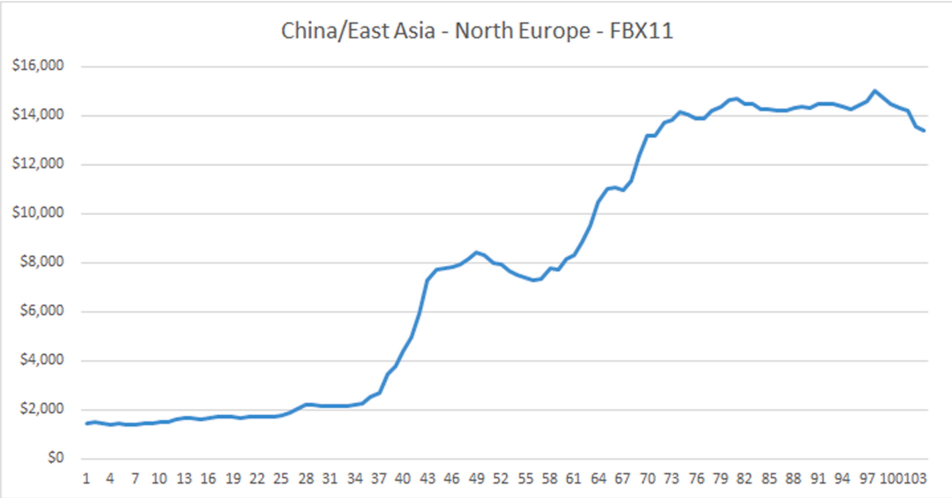

Fig. 2. Forty-foot Equivalent Unit (FEU) container prices since the beginning of the COVID-19 pandemic. Source: FBX11 data index courtesy of Freightos Limited.

the Suez Canal route to generate the number of transit days saved (Table 1).

Having goods on a ship instead of delivered bears a large indirect cost that is a function of the time delay and the value of goods carried. The average ship carrying cargo through the Suez Canal holds about $193.3 million of cargo (Yeung, 2021). Each additional day in transit costs between 0.6% and 2.1% of the value of the goods shipped (Hummels and Schaur, 2013). Assuming similar valuations for ships taking the NSR instead of the Suez Canal, and assuming a day's delay is worth 1% of the value, delays cost the owners of the goods (not the shippers) close to $2 million/day. Since NSR transits save about seven days, using the NSR saves an additional $13.5 million per transit.

Overall, each transit using the NSR instead of the Suez for the Rotterdam-Yokohama route saves about $26 million per ship transit. This savings per transit is then accumulated across the number of transits per season. We assume a similar rate of entrance into the NSR to that of 2021, or one ship every 34 hours (Table 1).

Assuming a possible season length of six months (180 days), we can allocate NSR closure costs due to sea ice or sanctions. If the NSR were open for travel for all 180 days, and assuming a ship transits every 34 hours, the direct cost savings to global shippers from *lower* shipping costs could exceed $1.56 billion (Table 2). If cargo is valued at about 1% per day, global shippers could save another $1.7 billion by getting their cargo to port about seven days sooner; if valued at 2.1%, savings could reach $3.6 billion. Thus, total savings could vary from a high of $2.5 billion to $5.2 billion from just these two costs (Table 2 and Table 3).

These costs could be allocated across NSR days closed, with closure resulting from sea ice reducing season length, or season length that is unable to be used due to sanctions. For realizations with no transits due to a lack of navigable days caused by sea ice, all costs would be allocated to sea ice. In contrast, for realizations with significant navigable season length, NSR inaccessibility due to sanctions is high. Across the realizations, the cost savings due to a shorter distance are approximately equal to the days saved/value of cargo calculations.

4. CO_2 savings and valuation of CO_2 savings

We then calculate the reduction in CO_2 by using the NSR instead of the Suez Canal route (Table 4). A 2,500 FEU container ship moving at 20 knots uses about 82 tonnes of marine fuel a day (Notteboom and Carriou, 2009). We then multiply an estimate of the number of days saved per trip (Table 1) for each of the 16 realizations to find an estimate of the fuel saved per trip by using the NSR instead of the Suez Canal route. These numbers vary depending on the realization, but generally suggest that using the NSR instead of the Suez Canal would save 500 to 650 tonnes of marine fuel per transit.

The fuel is then converted to CO_2 at 3.114 $kgCO_2$/kg fuel (XYZ, 2022; Krantz, 2016; Herdzik, 2021; Olmer et al., 2017) to estimate the tonnes of CO_2 emitted per transit, suggesting that the shorter NSR route reduces CO_2 emissions by 1,500 to 2,000 tonnes of CO_2.

Table 2
Estimates of shipping savings and time savings lost due to sea ice or sanctions assuming a 180 day season.

CMIP6 realization	Lost shipping cost due to sea ice	Lost shipping cost due to sanctions	Lost time costs due to sea ice	Lost time costs due to sanctions	Total sea ice costs	Total sanction costs
CESM2-WACCM	$ 1,561,107,122	$ -	$ 1,714,770,874	$ -	$ 3,275,877,996	$ -
GFDL-CM4	$ 1,561,107,122	$ -	$ 1,714,770,874	$ -	$ 3,275,877,996	$ -
MIROC6	$ 1,561,107,122	$ -	$ 1,714,770,874	$ -	$ 3,275,877,996	$ -
NorESM2-MM	$,1561,107,122	$ -	$ 1,714,770,874	$ -	$ 3,275,877,996	$ -
BCC-CSM2-MR	$ 1,561,107,122	$ -	$ 1,714,770,874	$ -	$ 3,275,877,996	$ -
CNRM-CM6–1	$ 1,152,245,733	$ 408,861,389	$ 1,250,528,633	$ 464,242,240	$ 2,402,774,366	$ 873,103,629
MIROC-ES2L	$ 1,090,297,038	$ 470,810,084	$ 1,201,709,288	$ 513,061,585	$ 2,292,006,326	$ 983,871,670
CESM2	$ 1,015,958,603	$ 545,148,519	$ 1,161,053,667	$ 553,717,207	$ 2,177,012,270	$ 1,098,865,726
ACCESS-CM2	$ 929,230,430	$ 631,876,692	$ 1,120,913,587	$ 593,857,287	$ 2,050,144,017	$ 1,225,733,979
NorESM2-LM	$ 768,163,822	$ 792,943,300	$ 808,668,970	$ 906,101,904	$ 1,576,832,791	$ 1,699,045,204
IPSL-CM6A-LR	$ 681,435,649	$ 879,671,474	$ 619,407,120	$ 1,095,363,753	$ 1,300,842,769	$ 1,975,035,227
AWI-CM-1–1-MR	$ 607,097,214	$ 954,009,908	$ 689,147,005	$ 1,025,623,869	$ 1,296,244,219	$ 1,979,633,777
NESM3	$ 594,707,475	$ 966,399,647	$ 1,692,952,880	$ 21,817,994	$ 2,287,660,355	$ 988,217,641
MPI-ESM1–2-LR	$ 532,758,780	$ 1,028,348,342	$ 485,905,678	$ 1,228,865,196	$ 1,018,664,458	$ 2,257,213,538
MPI-ESM1–2-HR	$ 495,589,563	$ 1,065,517,560	$ 561,021,184	$ 1,153,749,689	$ 1,056,610,747	$ 2,219,267,249
MRI-ESM2–0	$ 86,728,173	$ 1,474,378,949	$ (87,871,498)	$ 1,802,642,371	$ (1,143,324)	$ 3,277,021,320
Full 180 day	$ -	$ 1,561,107,122	$ -	$ 1,714,770,874	$ -	$ 3,275,877,996

Table 3
Lost time costs for different valuation rates assuming NSR is open due to sea ice but closed due to sanctions. Total savings is value of 180 season plus value of shipping cost savings for 180 day season from Table 2.

CMIP6 realization	0.60%	1%	1.40%	1.80%	2.10%
CESM2-WACCM	0	0	0	0	0
GFDL-CM4	0	0	0	0	0
MIROC6	0	0	0	0	0
NorESM2-MM	0	0	0	0	0
BCC-CSM2-MR	0	0	0	0	0
CNRM-CM6–1	$ 278,545,344	$ 464,242,240	$ 649,939,136	$ 835,636,032	$ 974,908,704
MIROC-ES2L	$ 307,836,951	$ 513,061,585	$ 718,286,220	$ 923,510,854	$1,077,429,329
CESM2	$ 332,230,324	$ 553,717,207	$ 775,204,089	$ 996,690,972	$1,162,806,134
ACCESS-CM2	$ 356,314,372	$ 593,857,287	$ 831,400,202	$ 1,068,943,116	$1,247,100,302
NorESM2-LM	$ 543,661,143	$ 906,101,904	$ 1,268,542,666	$ 1,630,983,428	$1,902,813,999
IPSL-CM6A-LR	$ 657,218,252	$ 1,095,363,753	$ 1,533,509,255	$ 1,971,654,756	$2,300,263,882
AWI-CM-1–1-MR	$ 615,374,321	$ 1,025,623,869	$ 1,435,873,416	$ 1,846,122,964	$2,153,810,124
NESM3	$ 13,090,796	$ 21,817,994	$ 30,545,191	$ 39,272,389	$ 45,817,787
MPI-ESM1–2-LR	$ 737,319,118	$ 1,228,865,196	$ 1,720,411,274	$ 2,211,957,353	$2,580,616,911
MPI-ESM1–2-HR	$ 692,249,814	$ 1,153,749,689	$ 1,615,249,565	$ 2,076,749,441	$2,422,874,347
MRI-ESM2–0	$ 1,081,585,423	$ 1,802,642,371	$ 2,523,699,320	$,3244,756,269	$3,785,548,980
180 day season	$ 1,028,862,524	$ 1,714,770,874	$ 2,400,679,223	$ 3,086,587,573	$3,601,018,835
Total savings	$ 2,588,534,624	$ 3,274,442,974	$ 3,960,351,323	$ 4,646,259,673	$5,160,690,935

The number of estimated transits per season (Table 1) for each of the 16 realizations, assuming the NSR is not shut due to sea ice, is then multiplied by the tonnes of CO_2 emitted per transit to estimate reduction of CO_2 emissions per season. If sea ice allowed these transits, but sanctions or other issues prevented NSR use, this would then be the estimate of additional CO_2 emissions due to having to take the longer Suez Canal route. Using only transits allowed by the reduction of sea ice, CO_2 reduction over a season varies significantly across the 16 realizations, from about 61,000 tonnes for CNRM-CM6-1 to over 238,000 tonnes for MRI-ESM2-0. If sea ice retreats enough to allow a full 180-day season, about 226,500 fewer tonnes of CO_2 would be emitted than if these ships took the longer Suez Canal route.

The value of this potential CO_2 reduction varies depending on the source of the market value of carbon (Table 4). One potential market price for a tonne of CO_2 is the value of voluntary offsets, yet even these vary: voluntary aviation offsets sell for US$2.98/$CO_2$tonne, while nature offsets sell for almost 2.5 times as much at US$7.40/$CO_2$tonne (Live Carbon Prices Today, 2022). Other alternatives include the prices for compliance markets. Recent auction results of the Regional Greenhouse Gas Initiative (RGGI), an initiative of eastern states within the United States, had a clearing price of U.S. $13.90 (Regional Greenhouse Gas Initiative, 2022), while offsets sold for more than twice that at U.S. $ 30.83 on the other side of the country in California (Live Carbon Prices Today, 2022). Across the Atlantic, spot CO_2 prices for an EU Allowance (EUA) under the European Union Emission Trading Scheme (EU ETS) were US$78.95, or more than 2.5 times that of the California price and more than 5.5 times that of the RGGI price, although it has notable volatility (Fig. 3). Finally, the United States values the social cost of carbon at US$51 (de Vogue and Nilsen, 2022; Clark and Farah, 2022; Samuel, 2022).

Even for a full 180 day season, values range from just under US$650,000 to US$17 million (Table 4). As these are far less than the values for either fuel or the time value of the goods, these values are not included in the total value calculations.

5. Conclusion

Both geophysical causes (sea ice) and geopolitical causes (sanctions) could close the NSR to transit cargo traffic. Both are expensive: a single transit could save $26 million. Over a season, this could cumulate to as much as $3 billion to $5 billion, depending on the cargo and value of goods shipped. For five of the realizations, NSR closure due to geophysical causes costs the full $3 to $5 billion as sea ice keeps the NSR shut all season. But for the rest, the average season length is about 97 days, suggesting that about $1.6 billion costs are due to geophysical reasons, but additional closure due to sanctions cost another $1.7 billion, so sanctions are at least as expensive as sea ice.

These numbers could be conservative. The 2021 closure of the Suez by the Ever Given was estimated to cost the world $400 million an hour or up to $10 billion a day due to reduction of global trade for each day the Suez was blocked (New Zealand Foreign Affairs and Trade, 2021). Since international through traffic on the NSR in 2021 was around what travels through the Suez in a day, these estimates may underestimate total global costs.

Table 4
CO_2 savings and valuation of CO_2 saved at different rates..

CMIP6 realization	Tonnes fuel/ trip saved	Tonnes CO_2/ trip saved	Saved tonnes CO_2/season	CO_2 voluntary aviation offset @ $2.98	CO_2 voluntary nature offset @ $7.40	CO_2 compliance NE RGGI @ $13.90	CO_2 compliance CA @$30.83	CO_2 compliance EUA Spot @ $78.95	CO_2 US social cost @ $51.00
CESM2-WACCM	0.0	0	–	$ -	$ -	$ -	$ -	$ -	$ -
GFDL-CM4	0.0	0	–	$ -	$ -	$ -	$ -	$ -	$ -
MIROC6	0.0	0	–	$ -	$ -	$ -	$ -	$ -	$ -
NorESM2-MM	0.0	0	–	$ -	$ -	$ -	$ -	$ -	$ -
BCC-CSM2-MR	481.2	1498.5	–	$ -	$ -	$ -	$ -	$ -	$ -
CNRM-CM6–1	582.1	1812.8	59,822.2	$ 178,270	$ 442,684	$ 831,529	$ 1,844,318	$ 4,722,963	$ 3,050,932
MIROC-ES2L	558.7	1739.8	66,113.1	$ 197,017	$ 489,237	$ 918,971	$ 2,038,265	$ 5,219,626	$ 3,371,766
CESM2	520.8	1621.6	71,351.9	$ 212,629	$ 528,004	$ 991,792	$ 2,199,780	$ 5,633,235	$ 3,638,949
ACCESS-CM2	481.8	1500.5	76,524.4	$ 228,043	$ 566,280	$ 1,063,689	$ 2,359,247	$ 6,041,600	$ 3,902,743
NorESM2-LM	585.9	1824.4	116,760.2	$ 347,945	$ 864,025	$ 1,622,967	$ 3,599,716	$ 9,218,216	$ 5,954,769
IPSL-CM6A-LR	638.4	1988.0	141,148.4	$ 420,622	$ 1,044,498	$ 1,961,963	$ 4,351,606	$ 11,143,669	$ 7,198,571
AWI-CM-1–1-MR	551.2	1716.4	132,161.8	$ 393,842	$ 977,997	$ 1,837,049	$ 4,074,547	$ 10,434,172	$ 6,740,250
NESM3	11.6	36.0	2811.5	$ 8378	$ 20,805	$ 39,079	$ 86,677	$ 221,965	$ 143,385
MPI-ESM1–2-LR	612.7	1907.8	158,351.4	$ 471,887	$ 1,171,801	$ 2,201,085	$ 4,881,974	$ 12,501,845	$ 8,075,922
MPI-ESM1–2-HR	555.2	1728.7	148,672.0	$ 443,043	$ 1,100,173	$ 2,066,541	$ 4,583,559	$ 11,737,658	$ 7,582,274
MRI-ESM2–0	626.8	1952.0	232,288.3	$ 692,219	$ 1,718,933	$ 3,228,807	$ 7,161,448	$ 18,339,160	$ 11,846,702
Full 180 day	563.2	1753.7	220,965.2	$ 658,476	$ 1,635,142	$ 3,071,416	$ 6,812,356	$ 17,445,200	$ 11,269,224

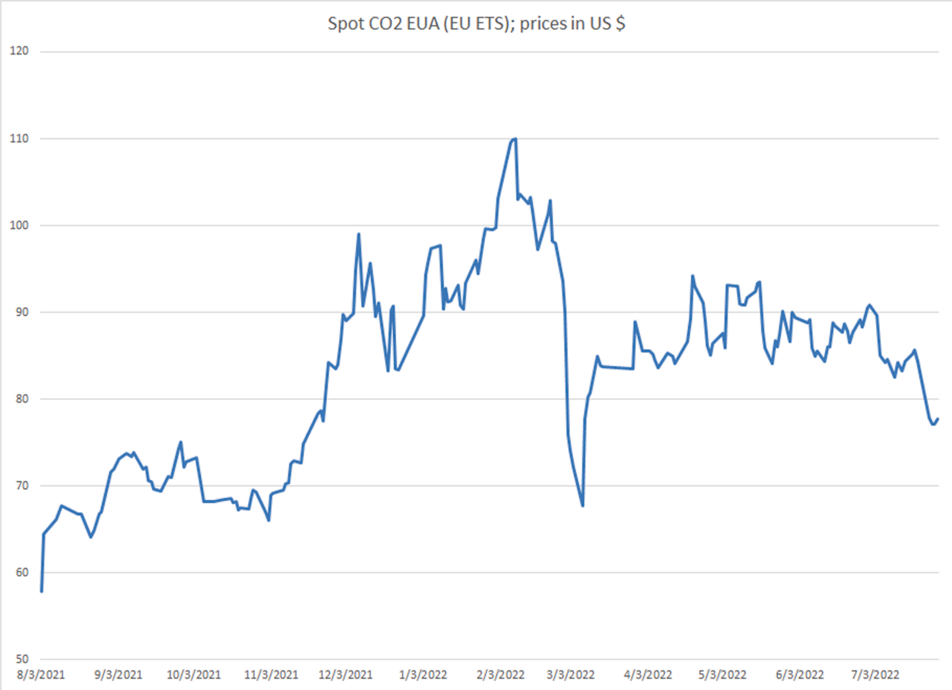

Fig. 3. Spot CO_2 EU Allowance (EUA) prices in US$. Source: Bloomberg EUETSSY1 TPGE Index.

CRediT authorship contribution statement

Michael A. Goldstein: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Amanda H. Lynch:** Funding acquisition, Methodology, Resources, Visualization, Writing – review & editing. **Xueke Li:** Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Charles H. Norchi:** Validation, Writing – review & editing.

Data availability

The datasets used in this study are freely available at esgf-node.llnl.gov/search/cmip6. Data for FBX01 courtesy of Freightos, Ltd.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.frl.2022.103257.

References

Bachman, J., Lee, D., Pohjanpalo, K., 2022. Siberian 'Detour' Forces Airlines toRetrace Cold War Era Routes. Bloomberg.com. March 12. Sourced on July 31, 2022 at. https://www.bloomberg.com/news/articles/2022-03-12/siberian-detour-forces-airlines-to-retrace-cold-war-era-routes.

Bartsch, A., et al., 2021. Expanding infrastructure and growing anthropogenic impacts along Arctic coasts. Environ. Res. Lett. 16 https://doi.org/10.1088/1748-9326/ac3176.

Boone, C., 2021. What is holding back the Northern Sea Route? Russia International Affairs Council. June 28, 2021. Retrieved on March 17, 2022 from. https://russiancouncil.ru/en/blogs/carter-boone/what-is-holding-back-the-northern-sea-route/.

Boylan, B.M., 2021. Increased maritime traffic in the Arctic: implications for governance of Arctic sea routes. Mar. Policy 131, 104566. https://doi.org/10.1016/j.marpol.2021.104566.

Buixadé Farré, A.B., Stephenson, S.R., Chen, L., Czub, M., Dai, Y., Demchev, D., Efimov, Y., Graczyk, P., Grythe, H., Keil, K., Kivekäs, N., Kumar, N., Liu, N., Matelenok, I., Myksvoll, M., O'Leary, D., Olsen, J., Pavithran, S., Petersen, A.P.E., Raspotnik, A., Ryzhov, I., Solski, J., Suo, L., Troein, C., Valeeva, V., van Rijckevorsel, J., Wighting, J., 2014. Commercial Arctic shipping through the Northeast Passage: routes, resources, governance, technology, and infrastructure. Polar Geogr. 37 (4), 298–324. https://doi.org/10.1080/1088937X.2014.965769.

Cao, Y., Liang, S., Sun, L., Liu, J., Cheng, X., Wang, D., Chen, Y., Yu, M., Feng, K., 2022. Trans-Arctic shipping routes expanding faster than the model projections. Glob. Environ. Change 73, 02488. https://doi.org/10.1016/j.gloenvcha.2022.102488.

CHNL Information Office, 2022. Transit voyages on the NSR in 2021. Retrieved from https://arctic-lio.com/transit-voyages-on-the-nsr-in-2021-the-results-as-of-the-current-date/on May 6, 2022.

Clark, L., Farah, N.H., 2022. Federal agencies can use social cost of carbon — For now. E&E News ClimateWire. May 27, 2022. Sourced on July 30, 2022 at. https://www.eenews.net/articles/federal-agencies-can-use-social-cost-of-carbon-for-now/.

Davy, R., Outten, S., 2020. The arctic surface climate in CMIP6: status and developments since CMIP5. J Clim 33, 8047–8068. https://doi.org/10.1175/JCLI-D-19-0990.1.

de Vogue, A., Nilsen, E., 2022. Supreme Court allows Biden administration to continue counting the costs of planet-warming emissions, for now. CNN.com. May 26, 2022. Sourced on July 30, 2022 at. https://www.cnn.com/2022/05/26/politics/supreme-court-social-cost-of-carbon-ruling-climate/index.html.

Farrell, H., Newman, A.L., 2022. Weak links in finance and supply chains are easily weaponized. Nature 605, 219–222. https://doi.org/10.1038/d41586-022-01254-5.

Freightos, Ltd., 2022. https://fbx.freightos.com/freight-index/FBX01 , sourced March 16, 2022.

Goldstein, M.A., Lynch, A.H., Zsom, A., Arbetter, T., Chang, A., Fetterer, F., 2018. The step-like evolution of Arctic open water. Sci. Rep. 8, 16902. https://doi.org/10.1038/s41598-018-35064-5.

Goncharova, A.R., Stoyanova, I.A., 2021. Strategic significance of port infrastructure in social and economic development of the Russian Federation and its regions. ЭконоМика в проМышленности (Russian Journal of Industrial Economics) 14 (2), 164–171. https://doi.org/10.17073/2072-1633-2021-2-164-171 (In Russian). https://ecoprom.misis.ru/jour/issue/download/53/52#page=20.

Guivarch, C., Gallic, T.Le, Bauer, N., et al., 2022. Using large ensembles of climate change mitigation scenarios for robust insights. Nat. Clim. Chang. 12, 428–435. https://doi.org/10.1038/s41558-022-01349-x.

Gunnarsson, B., 2021. Recent ship traffic and developing shipping trends on the Northern Sea Route—Policy implications for future arctic shipping. Mar. Policy 124, 104369. https://doi.org/10.1016/j.marpol.2020.104369. ISSN 0308-597X.

Gunnarsson, B., Moe, A., 2021. Ten years of international shipping on the Northern Sea Route: trends and challenges. Arct. Rev. 12, 4–30. https://doi.org/10.23865/arctic.v12.2614.

Herdzik, J., 2021. Decarbonization of marine fuels—the future of shipping. Energies 14, 4311. https://doi.org/10.3390/en14144311.

Hummels, David L., Schaur, Georg, 2013. Time as a trade barrier. American Econ. Rev. 103 (7), 2935–2959. https://doi.org/10.1257/aer.103.7.2935.

IMO, 2016. Guidance on methodologies for assessing operational capabilities and limitations in ice. MSC.1/Circ.1519, 6 June 2016. Retrieved from: https://www.nautinst.org/uploads/assets/uploaded/2f01665c-04f7-4488-802552e5b5db62d9.pdf.

Kammel, B., Wilkes, W., 2022. Flight routes are being thrown intochaos with closure of Russian airspace. Bloomberg.com. March 4. Sourced on July 31, 2022 at. https://www.bloomberg.com/news/articles/2022-03-04/global-flight-routes-get-thrown-into-chaos-with-russian-airspace-closed.

Krantz, Gustav, 2016. CO2 and sulphur emissions from the shipping industry. TransOleum (October). Sourced on July 30, 2022 at https://www.egcsa.com/wp-content/uploads/CO2-and-sulphur-emissions-from-the-shipping-industry.pdf.

Li, X., Stephenson, S.R., Lynch, A.H., Goldstein, M.A., Bailey, D.A., Veland, S., 2021. Arctic shipping guidance from the CMIP6 ensemble from operational to infrastructural timescales. Clim. Change 167 (23). https://doi.org/10.1007/s10584-021-03172-3.

Liu, M., Kronbak, J., 2010. The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. J Transp. Geogr. 18 (3), 434–444. https://doi.org/10.1016/j.jtrangeo.2009.08.004.

Live Carbon Prices Today. Sourced July 30, 2022 at https://carboncredits.com/carbon-prices-today/.

Lynch, A.H., Norchi, C.H., Li, X., 2022. The interaction of ice and law in Arctic marine accessibility. Proc. Natl. Acad. Sci. 119 (26), e2202720119 https://doi.org/10.1073/pnas.2202720119.

Miller, A.W., Ruiz, G.M., 2014. Arctic shipping and marine invaders. Nat. Clim. Chang 4, 413–416. https://doi.org/10.1038/nclimate2244.

Moe, A., 2020. A new Russian policy for the Northern sea route? State interests, key stakeholders and economic opportunities in changing times. Polar J. 10 (2), 209–227. https://doi.org/10.1080/2154896X.2020.1799611.

Mudryk, L.R., Dawson, J., Howell, S.E.L., Derksen, C., Zagon, T.A., Brady, M., 2021. Impact of 1, 2 and 4 °C of global warming on ship navigation in the Canadian Arctic. Nat. Clim. Chang. 11, 673–679. https://doi.org/10.1038/s41558-021-01087-6.

New Zealand Foreign Affairs and Trade, 2021. The Importance of the Suez Canal to Global Trade. Retrieved on May 8, 2022 from https://www.mfat.govt.nz/en/trade/mfat-market-reports/market-reports-middle-east/the-importance-of-the-suez-canal-to-global-trade-18-april-2021/#:%7E:t%E2%80%A6.

Norchi, C.H., Lynch, A.H., 2022. Arctic Navigation and Climate Change: Projections from Science for the Law of the Sea. International Law Studies 99, 491–516. https://digital-commons.usnwc.edu/ils/vol99/iss1/18/.

Notteboom, T., Carriou, P., 2009. Fuel surcharge practices of container shipping lines: is it about cost recovery or revenue making?. In: Proceedings of the 2009 International Association of Maritime Economists (IAME) Conference, June, Copenhagen, Denmark. 2009 International Association of Maritime Economists (IAME) Conference, Denmark. https://pdfcoffee.com/2009-iame-notteboom-amp-cariou-pdf-free.html.

Olmer, N.B., Comer, B., Roy, X., Mao, D., Rutherford, 2017. Greenhouse gas emissions from global shipping, 2013-2015. International Council on Clean Transportation. October. Sourced on July 30, 2022 at: https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf.

Regional Greenhouse Gas Initiative, 2022. Allowance prices and volumes. Sourced on July 30, 2022 at https://www.rggi.org/auctions/auction-results/prices-volumes.

Samuel, S., 2022. The Supreme Court just okayed Biden's "social cost of carbon." It's still way too low. Vox.com. May 27, 2022. Sourced on July 30, 2022 at. https://www.vox.com/future-perfect/22643358/social-cost-of-carbon-mortality-biden-discounting.

Suez Canal Authority, 2022. Navigation statistics. Retrieved on March 16, 2022 from https://www.suezcanal.gov.eg/English/Navigation/Pages/NavigationStatistics.aspx.

Tollefson, J., 2022. What the war in Ukraine means for energy, climate and food. Nature 604, 232–233. https://doi.org/10.1038/d41586-022-00969-9.

XYZ https://www.transportmeasures.org/en/wiki/manuals/sea/calculation-of-fuel-co2-emissions/. Sourced July 30, 2022.

Yeung, J., 2021a. Suez Canal authorities need to remove up to 706,000 cubic feet of sand to free the ever given. CNN.com. March 26, 2021. Retrieved on March 16, 2022 from. https://www.cnn.com/2021/03/25/middleeast/suez-canal-ship-sand-intl-hnk/index.html.