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Supplementary information

Trade-linked shipping CO_2 emissions

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Supplementary Information of

Trade-linked shipping CO_2 emissions

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Supplementary Discussion

1. Energy efficiency of international shipping voyage

Based on the Voyage-based Shipping Emission Inventory Model (VoySEIM), a total of ~790,000 international voyages are identified for the whole year of 2018, covering thousands of origin-destination (OD) bilateral pairs. Among all vessel types, containers, general cargoes, and bulk carriers are observed with more frequent activities, accounting for 23.9%, 20.3% and 16.2% of the total voyages, respectively. The abundant identified OD voyages by the VoySEIM could provide an almost full-sample evaluation of the operating status of the current vessel fleet.

For each voyage, the energy efficiency operational indicator (EEOI) is estimated as the ratio of the ship's CO_2 emissions to its transport work (tons of cargo multiplied by the nautical miles transported). Supplementary Fig. 2 shows the distribution of the voyage-based EEOI for different vessel types and its variation with size and voyage distance. It can be observed that bulk carriers and oil tankers show better performance in operating efficiency, indicated by their lower EEOIs, 7.7 and 10.7 g CO_2 ton^{-1} NM^{-1}, respectively, This may due to their relatively higher vessel capacity utilization, which also been reported in previous evaluations of the global fleet[1,2]. In contrast, Ro-Ro ships, reefers, miscellaneous and liquid gas tankers are estimated to have higher EEOIs due to their relatively large propulsion power and energy consumption intensity during the navigation as well as worse capacity utilization[3].

For most vessel types, the EEOI decreases with the ship size, expressed as dead weight tonnage (DWT). For example, the median EEOI of Very Large Crude Carrier (VLCC) with DWT over 200,000 tons is estimated to be ~ 4.0 g CO_2 ton^{-1} NM^{-1}. However, liquid gas tankers are found to have higher EEOIs when their DWT exceeds 40,000 tons. As for the impact of distance, we found that longer trading routes generally tend to employ larger ships operating with lower EEOI. However, there are exceptions that the Ro-Ro ships are estimated with high EEOI when the voyage distance is more than 14,000 NM.

2. Advantages of GTEMS model in interpreting trade-related emissions

Compared with the model based on observed shipping activities (VoySEIM), a prominent advantage of the GTEMS model is that it combines interdisciplinary methods to fairly account shipping emissions to traders. Although both models can generate shipping emissions for origin-destination (OD) pairs, the GTEMS model reveals emissions of exporter-importer trade pairs, while VoySEIM is only able to evaluate emissions of departure-arrival country pairs. When shipping emissions are accumulated to countries, there will be discrepancies between results of these two models.

On the one hand, the symmetrical shape of the voyage matrix resulted from the VoySEIM (Supplementary Fig. 1) indicates that the voyage of maritime transportation is dominated by round-trip. Thus, the direction of voyages cannot be simply regarded as the export direction of goods, since the vessel may be in ballast condition of its round trips. On the other hand, voyages between the departure and arrival countries are not necessarily related to direct trade activities of the same country pairs. A typical case is that transit countries will capture much more shipping voyages induced by trade belonging to the third parties than their own maritime trades. To illustrate the impact of transshipment, Supplementary Fig. 3 is provided to compare the international shipping CO_2 emissions attributed to typical countries estimated by VoySEIM and GTEMS, respectively, including two major maritime transit countries (Singapore and Spain) and two other countries (Italy and Canada). It can be observed from the bar charts that shipping emissions attributed to these countries estimated by GTEMS are at similar level. However, shipping emissions estimated by VoySEIM are much higher for Singapore and Spain. The spatial intensity of shipping emissions also appears to be higher for Singapore and Spain compared to Italy and Canada, as shown on maps. Therefore, regarding shipping voyages equally as bilateral trade flows would result in considerably high deviations of trade-linked shipping emission accountings for transit countries.

As GTEMS model calculate shipping emissions based on trade data and standardized bilateral trading routes, it has advantages in characterizing trade-linked shipping emissions by distinguishing the shipping emissions related to trade export or import, and excluding the impact of transshipment. Meanwhile, by using voyage-based EEOIs inherited from VoySEIM as key parameters input of GTEMS, the final estimated trade-linked shipping emissions are also capable of reflecting heterogeneities of vessel energy operating efficiencies between different trade pairs.

Supplementary Methods

1. Preprocess of BACI trade data

To prepare trade input data for GTEMS model, the original BACI trade data obtained from the CEPII (http://www.cepii.fr) was preprocessed by merging commodity chapters and merging countries. As the over-specific commodity types have similarities with regard to the maritime vessels and emission characteristics, the 6-digit HS code were thus combined to HS 4-digit level with a final of > 1,200 commodities. At the same time, countries with unremarkable international trade (including both value and volume) and GDPs (retrieved from https://en.wikipedia.org/wiki/List_of_countries_by_GDP_(nominal)) are merged into “others”, which are considered to contribute less to international shipping emissions. The following is a detailed description of the step-by-step filtering basis for country selection.

a. Sort countries by GDP, international trade value and trade volume, respectively, for the year 2018, in which the trade value and volume all represent the sum of exports and imports.
b. Select the top 50 country for each economic indicator and combined them together. Thus, a total of 61 countries/regions were initially selected, as shown in the updated Supplementary Table 4.
c. Inland countries in the list, including Ukraine, Kazakhstan, Austria, Czechia, Belarus, Switzerland, Hungary, Romania and Slovakia, were then filtered out.
d. Use "Other Asia" as a proxy for trade of Taiwan, and then merged it into China. The trade of Hong Kong and Macao was also merged into China.
e. In this way, a total of 49 countries/regions were finally selected, accounting for 90%, 85% and 87% of world GDP, international trade value and trade volume, respectively. Other countries/regions were merged to “others” in the current version of GTEMS.

2. International voyage identification method

The international voyages were identified based on vessel speed and navigation trajectory reported by AIS signals. By connecting the exact coordinate positions of all AIS signals in chronological order, the whole year of historical trajectory for each vessel can be restored. We defined the continuous AIS signals for a particular ship as an international trade voyage from country A to country B only when: 1) the first and the last AIS signals are located inside the coastal areas of the departure country A and arrival country B, respectively; 2) the speeds of the departure and the arrival AIS signals are both less than 1 knots; 3) the speeds of the rest AIS signals during the navigation route are all more than 1 knots. In this AIS-based voyage identification method, the definition of the coastal area boundaries is crucial. Some trading countries (e.g., China, US, etc.) have thousands of ports located on different coastlines, and each port may have multiple docks. As our study focus on the international trade between different countries, we depicted coastal areas of each country rather than circling out all possible berthing areas. For some countries containing discrete coastlines (e.g., the west coast, east coast, Alaska or other islands of the US), each area was depicted separately. Given a tolerance of the coordinate error in AIS signals, the coastal areas were depicted under the principle of: 1) covering the major berth and anchorage areas of the majority of the ports, 2) excluding the nearby shipping lanes, 3) avoid conflicts with other countries, 4) extend the area to as far as the exclusive economic zone (EEZ) when the above requirements are satisfied. Following the above method, we finally depicted >50 independent coastal boundaries, covering more than 30 individual countries and other coastal countries merged by continent.

3. Estimation method of seaborne trade proportion

As the macroscopic trade statistical data of BACI incorporate commodities from all transport modes without identifying modal use, we collected trade data from UN Comtrade, Eurostat and the US census with the mode of transport to split the seaborne trade from the total trade. The SF for trade pairs related to European countries can be directly calculated from Eurostat data. For non-EU countries, the SF for trade import and export related to the US can be obtained from the US census, and that for trade pairs related to some of the other countries can be further obtained from UN Comtrade. These direct data sources provide 68% of the global trade volume of the country pairs for the SF calculation. For the remaining country pairs without direct data on modal use, the SFs were estimated by the ratio of the land transport infeasibility index (LTII) and the seaborne proportion (SP') of commodities pre-estimated by transoceanic countries (Equation 4).

A LTII matrix was established based on the countries' geographical locations and the land transport network. For non-adjacent country pairs located on different continents or separated by ocean or land, the land transport is basically impossible and thus the TLII was set to 1; for land-adjacent trading partners, the index is otherwise assumed 0.5. There are some exceptions. Intracontinental land-adjacent trading partners in Asia are also more likely to trade by sea, since the economically developed areas are mostly along the coast. In such conditions, the TLII index was set to 0.8. Intra-Europe trades have very high shares of rail and road transport, thus the TLII index was set to 0.3. The trade between Russia and European countries also has partial land transportation benefited from the well-developed railway network, thus the index was adjusted to 0.5.

The SF' for determined by commodity characteristics can be estimated by transoceanic countries (LTII = 1) based on available modal-split data. For transoceanic countries, the trade goods of the country pairs can only be transported by air or sea, rather than other land-based tools, e.g., road, railway and pipeline, etc. Thus, the SF of transoceanic countries for different commodities could be used as a proxy to predict the possibility that the commodity be transported by sea rather than by air. Statistical results based on the available trade data show that that sea transport is mostly adapt to bulk goods with lower value and higher weight (e.g., HS 26 - ores, HS 27 - mineral products, HS 10 - cereals), while the perishable goods (e.g., HS 01 - live animals), precious commodities (e.g., HS 71 - precious metals, HS 91- clocks and watches) generally have lower seaborne proportions since they may be more likely to be transported via air (Supplementary Fig. 5).

Finally, we applied the same imputation method (Equation 4) to the countries with available modal use data for SF verification. Results in Supplementary Fig. 6 show that the estimated seaborne trade was generally consistent with the statistical data and the correlation coefficients are all higher than 0.88. Most of the points are on the 1:1 line since the country pairs are transoceanic, while a small part of that deviate from the line, which basically have relatively low trade volume.

4. Comparison of shipping emissions for Brazil's export

The estimated shipping emissions from GTEMS model at the bilateral and commodity level were verified by comparing with a case study for Brazil. The study of Schim van der Loeff et al. (2018) pioneers trade-related shipping emission analysis and presented the top commodity-specific and country-specific shipping CO_2 emissions driven by Brazil's exports in 2014. Using our approach to estimate Brazil’s export results for year 2014, we performed a comparison with Schim van der Loeff et al. (2018), as shown in Supplementary Fig. 11.

The total seaborne trade value for Brazilian exports estimated using our GTEMS model is slightly higher than that of Schim van der Loeff's (2018) study (567 v.s. 510 billion USD). The comparisons for the trade quantity are similar to that of the trade value (208 v.s. 178 million tons). It may due to the minor discrepancies in data sources (BACI in this study v.s. shipping manifests of Brazil). Regarding the share ratios, it can be observed that the shares of trade value and quantity by commodity or by the import country are basically consistent for the two studies. These results indicated the reliability of our GTEMS approach on determining the seaborne transported trade quantities at country level.

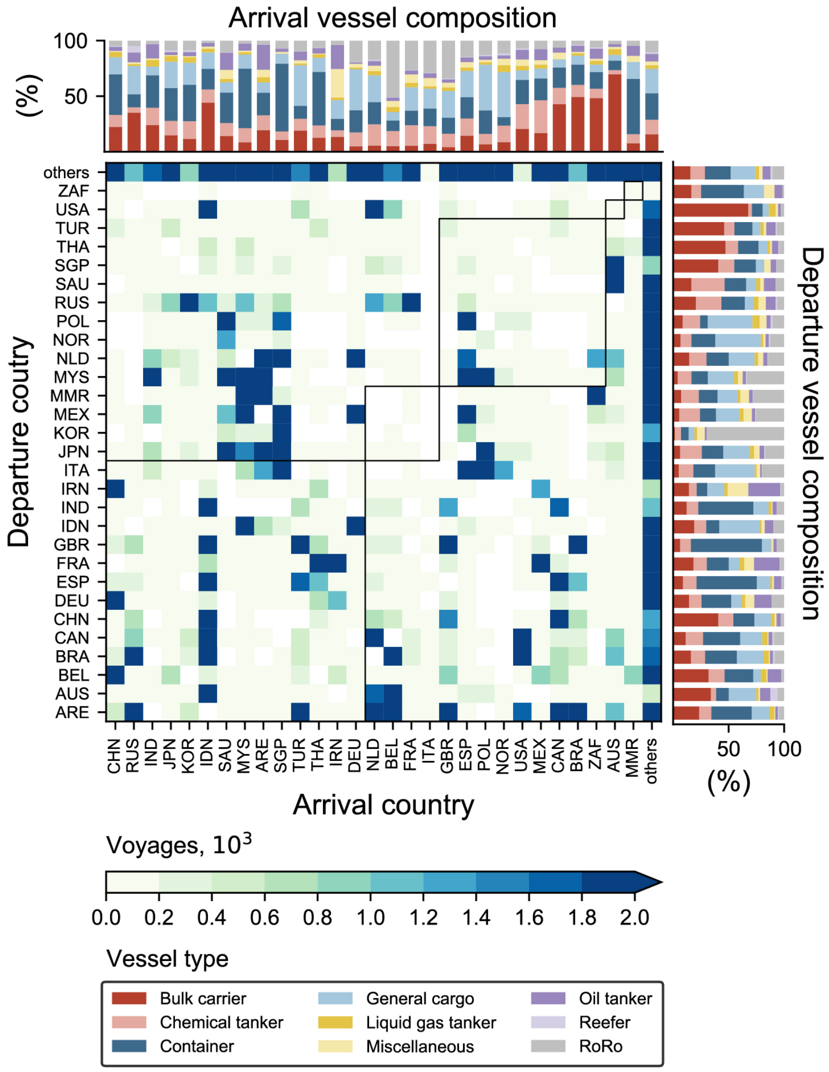
In terms of the CO_2 emission, the shares accounted by commodity and the import country by GTEMS model and by Schim van der Loeff's (2018) both shows the similar trends. Regarding the commodity composition, the ore (HS 26) contributed the most, followed by oil seed (HS 12). Regarding the import country, trade imported by China contributed the most, followed by Japan. However, the total shipping CO_2 emission driven by Brazil's exports estimated by GTEMS model is 59 Mt, 2.3 times as much as that from Schim van der Loeff's (2018) results (26 Mt). The major reasons causing the emission difference may come from two aspects:

1) The commodities' direct/final import countries. The emissions estimated by Schim van der Loeff et al. (2018) are based on the shipping manifests and AIS voyages, which record commodities' first arrival ports, while that estimated by GTEMS are based on trade data, which report commodities' final import country. Differences would arouse in emission accounting when commodities need multiple transshipment. This could be observed from the result of Singapore, for which the emission estimated by Schim van der Loeff et al. (2018) is higher than that by GTEMS, while the opposite is true for other countries.
2) Ballast leg conditions. The emissions estimated by Schim van der Loeff et al. (2018) only consider the laden leg of a voyage as they mentioned. In contrast, both the laden and the ballast leg are considered in the GTEMS model, benefited from the EEOI estimated based on the full-sample of global fleet considering the total capacity utilization (TCU). This would result in more shipping emissions related to Brazil's exports in GTEMS model, especially for bulk good, such as ore and oil seed.

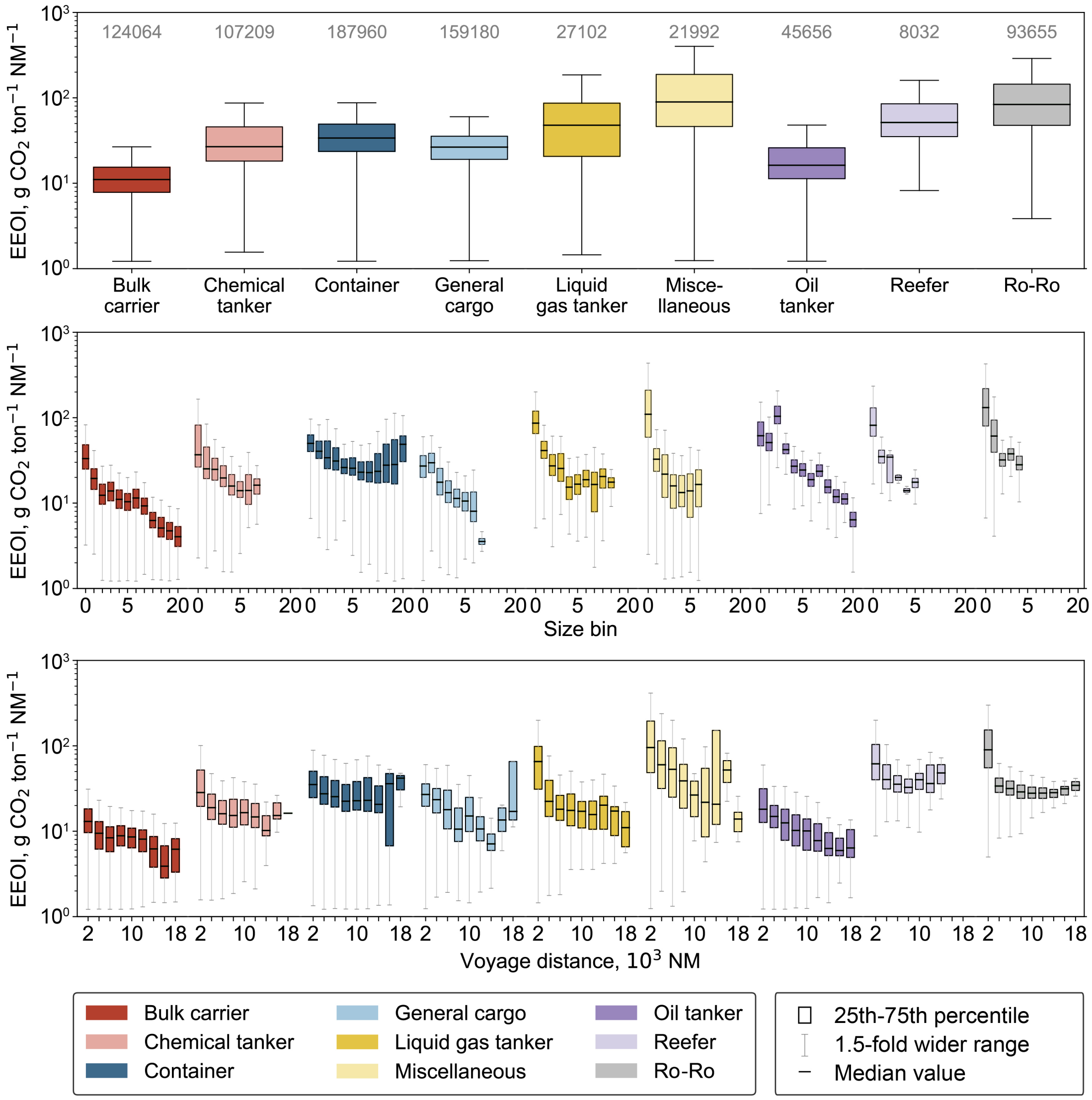
In sum, the purpose of this study is to fully allocate the global international shipping emissions to trade pairs and commodities, in which emissions generated from all links are considered, including cases that are once hard to be involved, such as the empty-load condition.

As the shipping emission resulted from the GTEMS model can correspond with the 4th IMO GHG Study at the global level, and the intermediate parameters have been verified step-by-step, we consider the results basically reasonable.

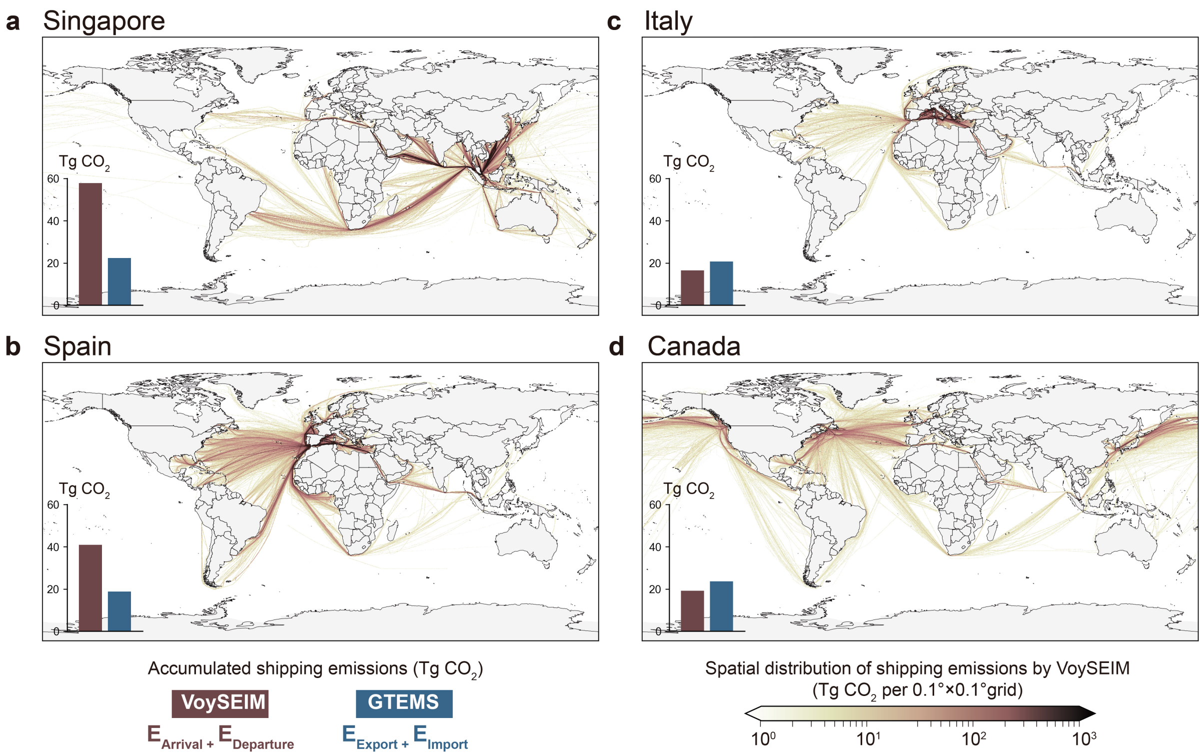
Supplementary Figures



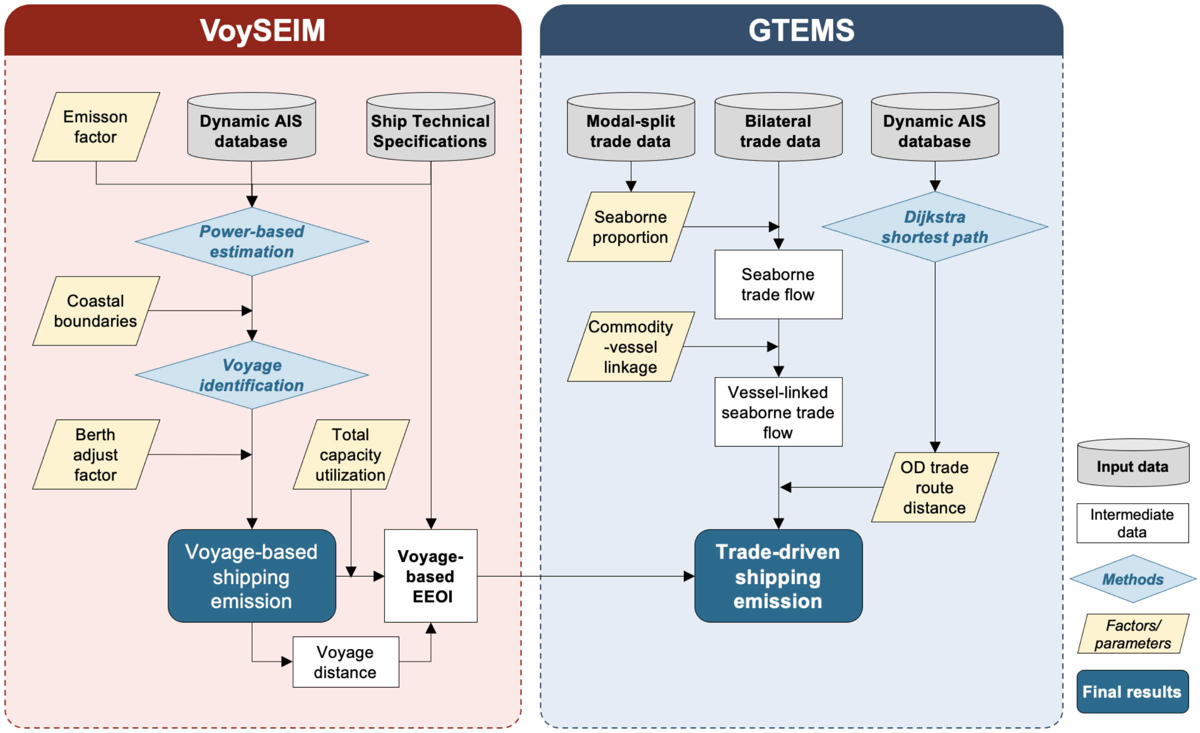
Supplementary Fig. 1 | International shipping voyages and the vessel type composition identified by VoySEIM. The origin-destination (OD) heat map shows the identified shipping voyages related to each departure-arrival country/region pair. The right and top panels summarize the vessel type composition of total voyages departure from and arrival at each country, respectively. Countries are arranged in the order of Asia, America, Europe, Oceania and Africa and others, discriminated with the black solid lines in the heat map.



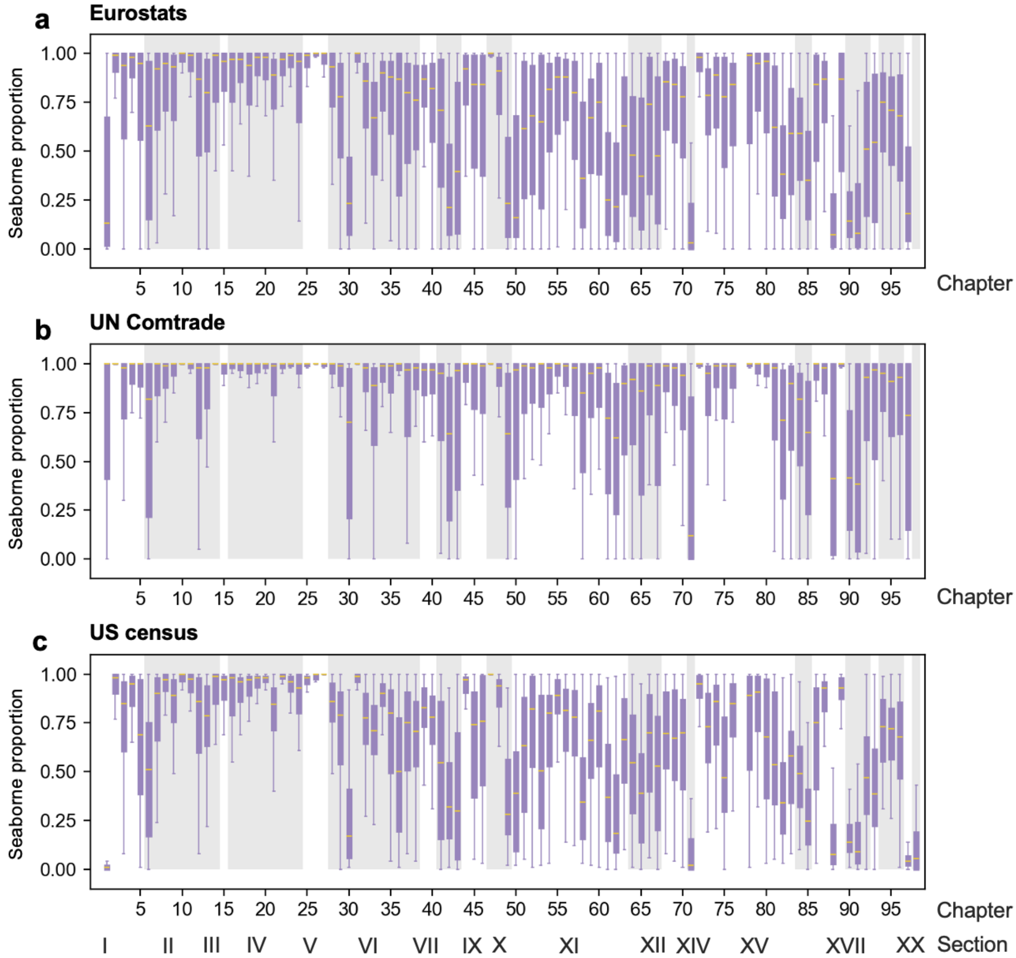
Supplementary Fig. 2 | International shipping energy efficiency operational indicators based on shipping voyages from full sample AIS data. (a) Distribution of estimated EEOI by vessel type. (b) and (c) Distribution of estimated EEOI classified by vessel type and size bin (b) and shipping voyage distance (c). The size bin 0 to 20 indicated the dead weight tonnage of vessels varying from lowest to highest, with details described in Supplementary Table 5. The numbers on the top of (a) refer to number of voyages identified for different vessel types.



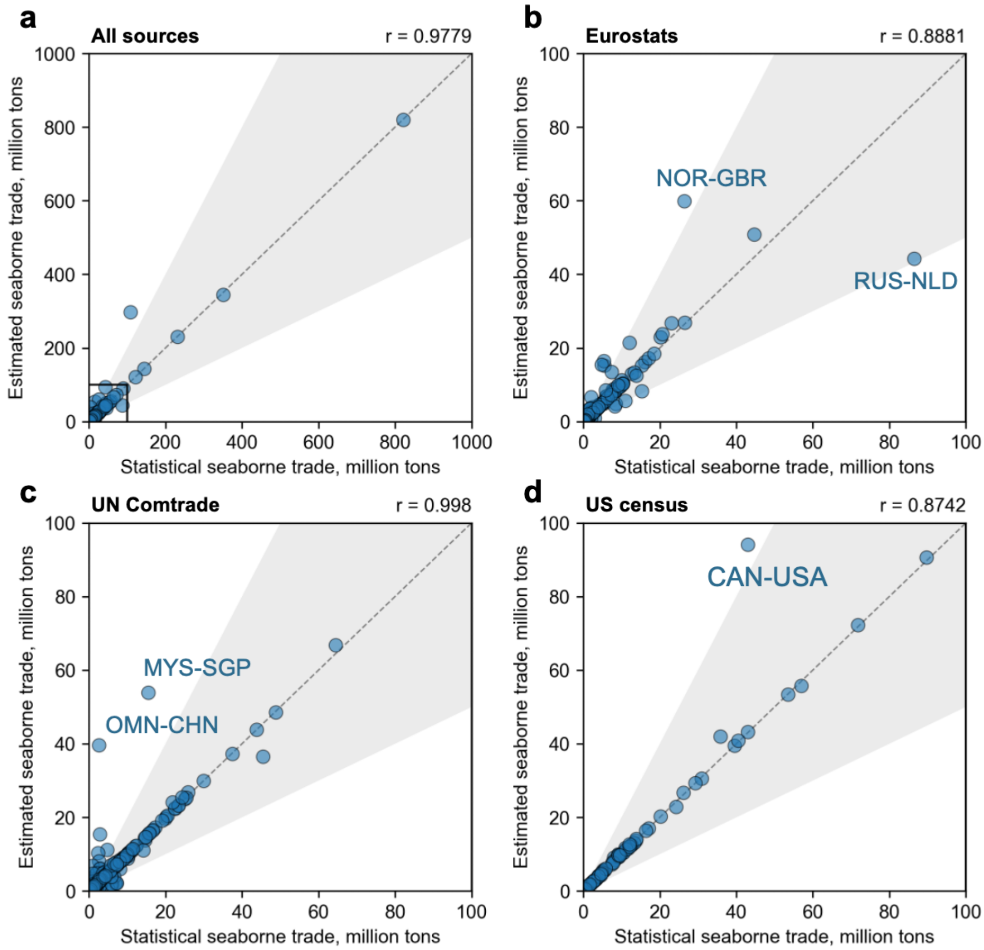
Supplementary Fig. 3 | International shipping CO_2 emissions attributed to typical countries. The maps show the spatial distribution of shipping emission estimated by VoySEIM. The bar chart on each map compares the country-linked shipping emission estimated from VoySEIM and GTEMS. (a) and (b) are typical transshipment centers, while (c) and (d) are countries with similar shipping emission volumes resulted from GTEMS. Maps are made with Natural Earth.



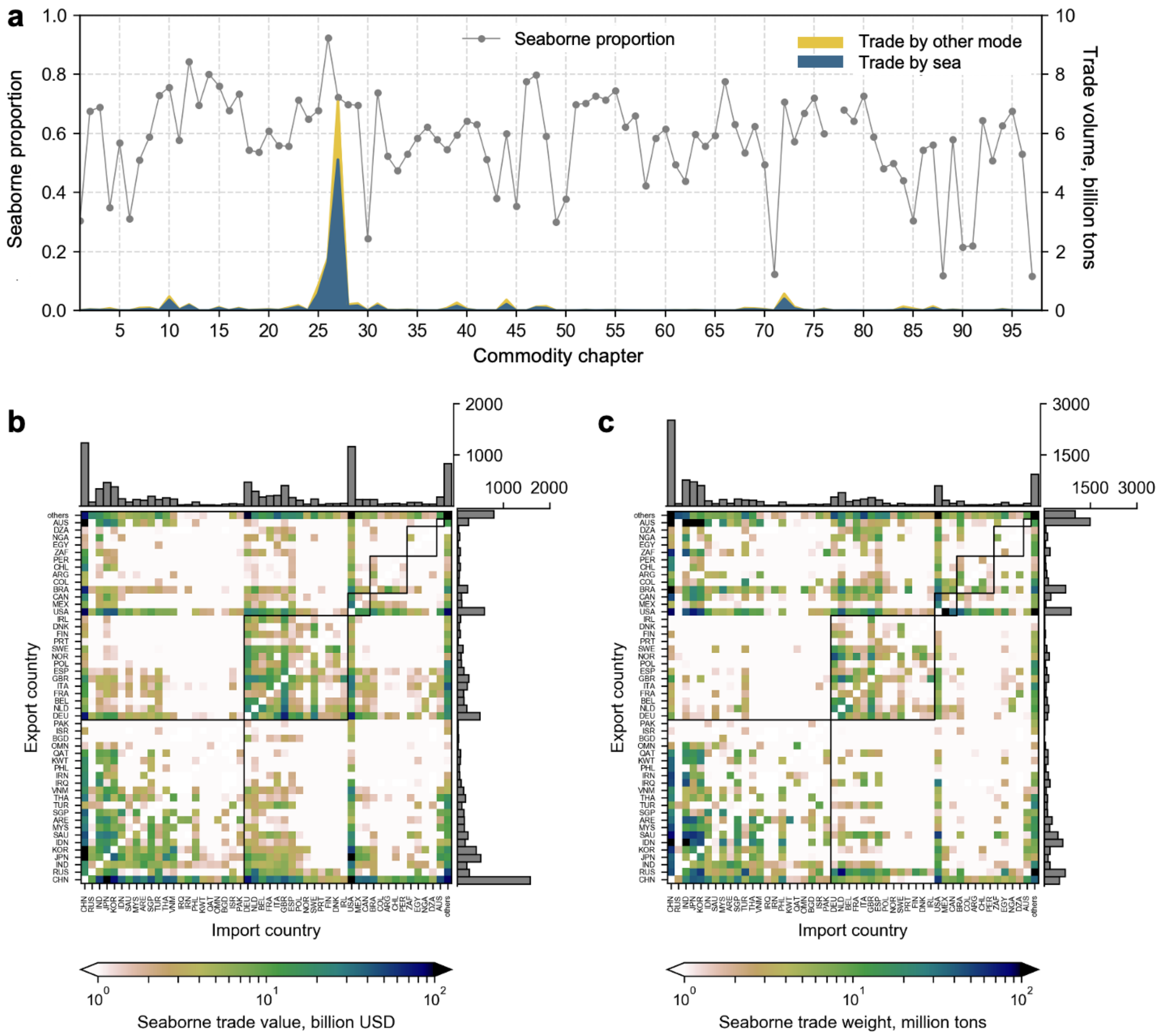
Supplementary Fig. 4 | Structure of the VoySEIM-GTEMS model system developed in this study.



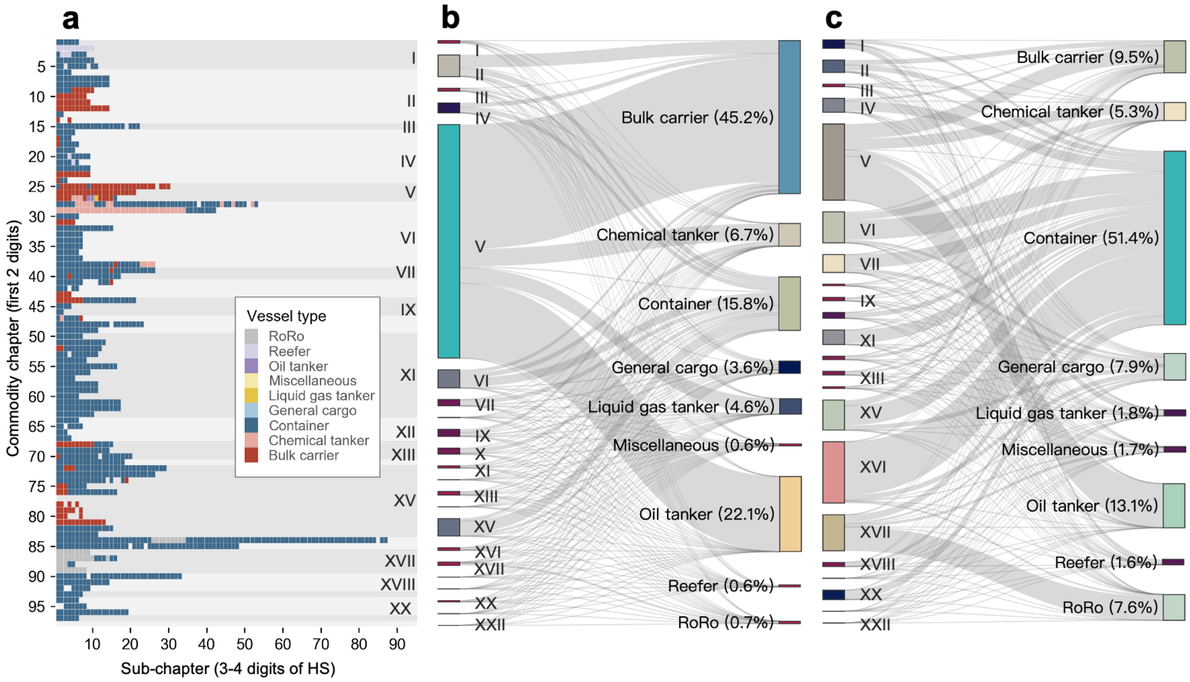
Supplementary Fig. 5 | Distribution of the seaborne trade proportion in different commodity chapters (2-digit HS code) between transoceanic country pairs according to the trade data from (a) Eurostats, (b) UN Comtrade and (c) US census. The commodity sections and chapters classified by HS system are described in Supplementary Table 3.



Supplementary Fig. 6 | Comparison of seaborne estimated seaborne trade with statistics from (a) all sources, (b) Eurostats, (c) Comtrade and (d) US census. The dotted lines indicate that the ratio of the two values is 1:1, and the gray shadows indicate that the deviations are within ±100%. The correlation coefficients (r) are listed on the upper right corner of each panel.



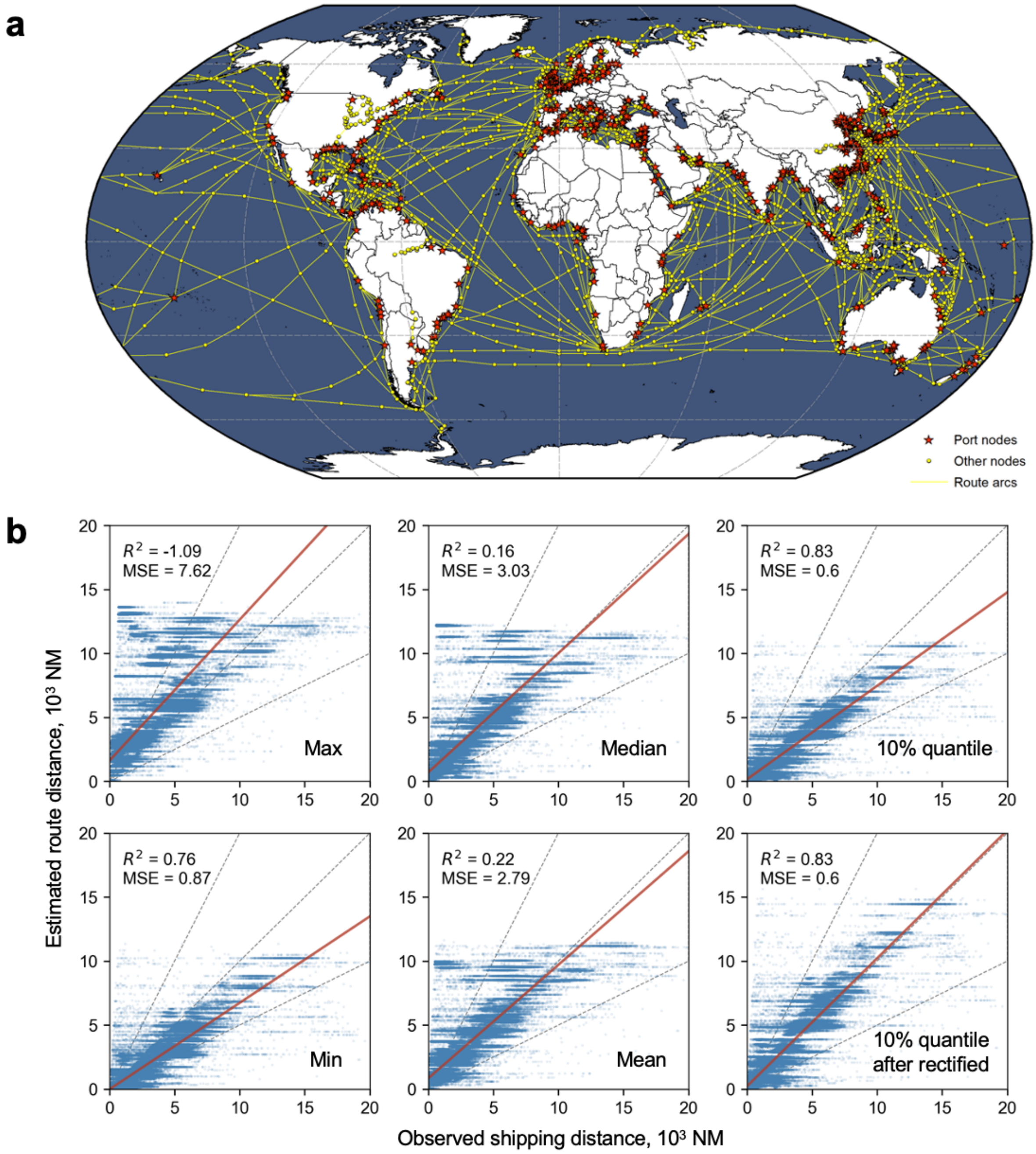
Supplementary Fig. 7 | Estimated maritime trade classified by commodity chapter and trading country. (a) Seaborne proportion and trade volume by commodity chapter. (b) Origin-destination matrix of seaborne trade value. (c) Origin-destination matrix of seaborne trade volume. Countries are arranged in the order of Asia, Europe, Americas, Africa, Oceania and others, distinguished by black solid lines in the heat map. The commodity sections and chapters classified by HS system are described in Supplementary Table 3.



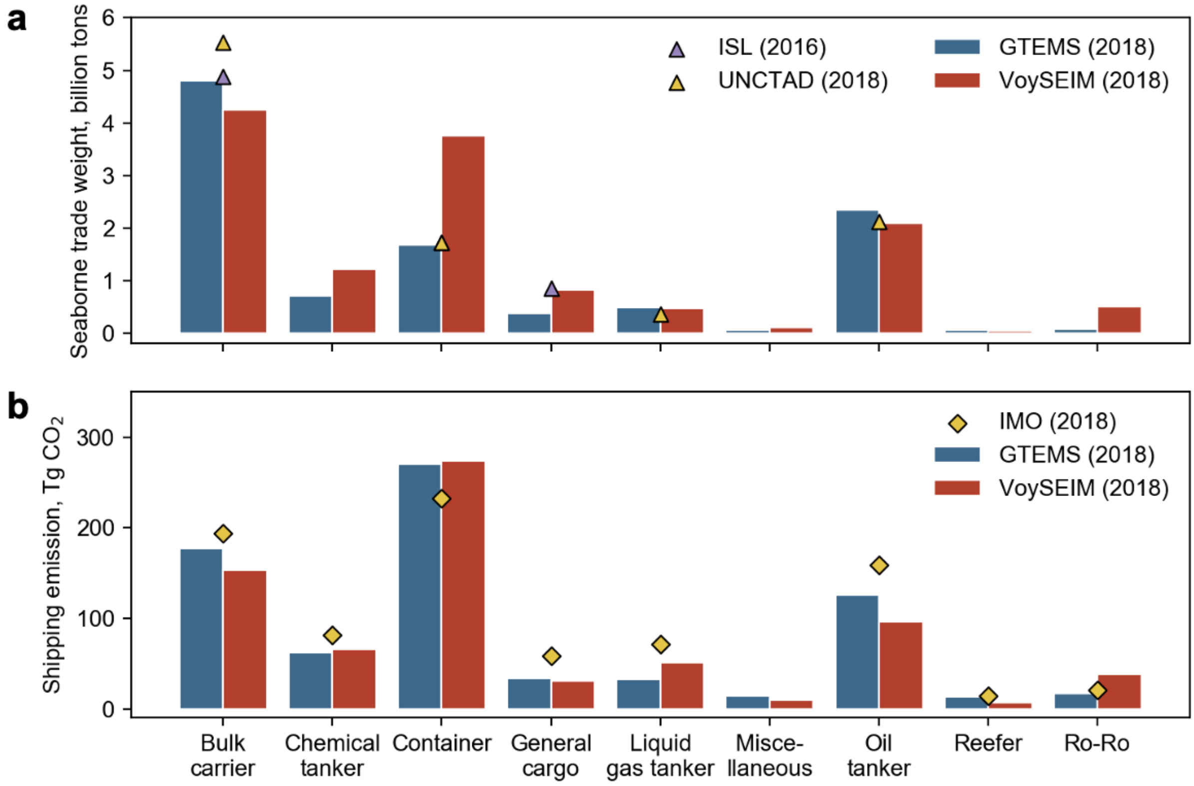
Section description:

I Animal products	VI Chemical products	XI Textile	XVI Mechanical & electrical parts	XXI Art collection
II Plant products	VII Plastic products	XII Shoes, hats, feathers	XVII Vehicle equipment	XXII Unclassified goods
III Animal and vegetable oils	VIII Leather products	XIII Stone ceramic glass products	XVIII Optical precision instruments	
IV Food, beverage, tobacco	IX Woodwork	XIV Jewelry and precious metals	XIX Weapons, ammunition	
V Minerals	X Pulp products	XV Base metal products	XX Miscellaneous products	

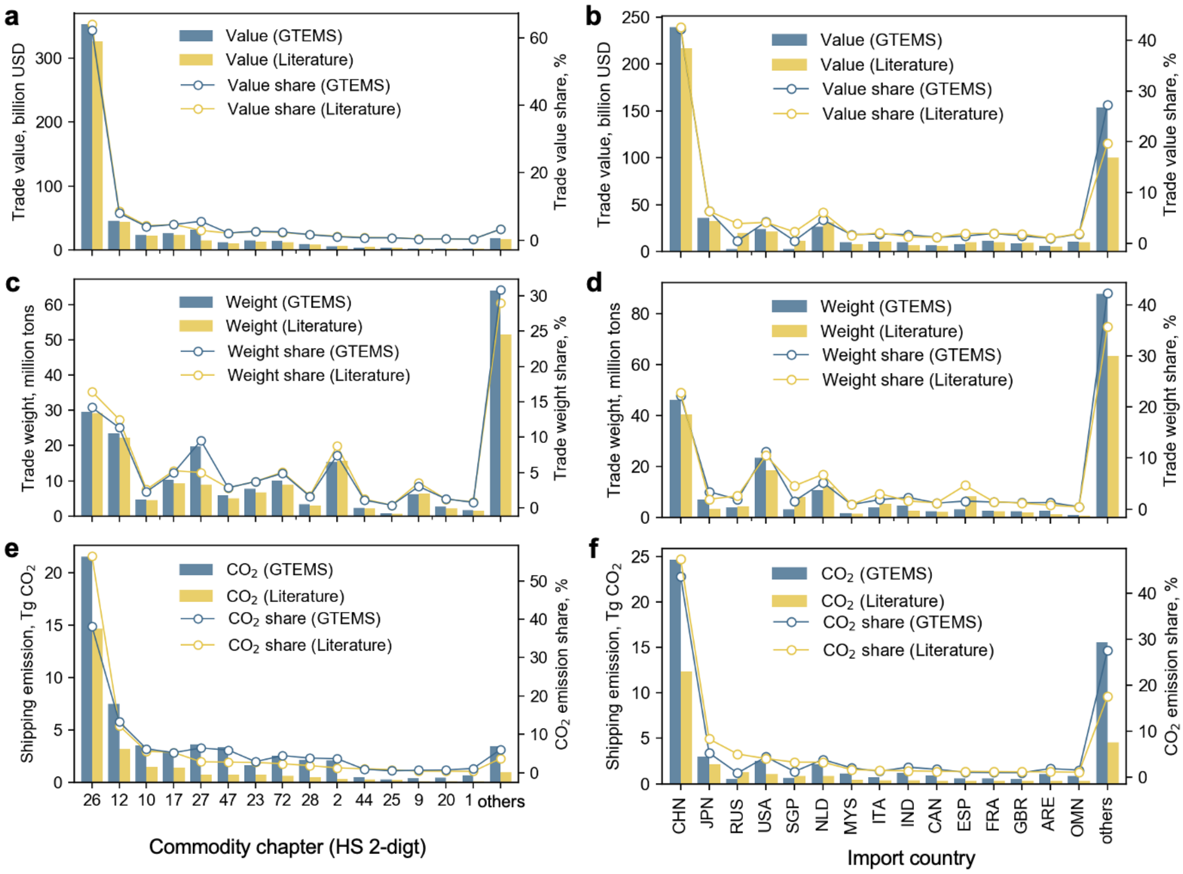
Supplementary Fig. 8 | Commodity-Vessel linkage profile and the estimated transportation flows. (a) Principal transport vessel type for more than 1000 sub-chapters (4-digit level HS code). (b) Commodity transportation flow by weight. (c) Commodity transportation flow by value. The commodity sections and chapters classified by HS system are described in Supplementary Table 3.



Supplementary Fig. 9 | Global shipping route network and verification of estimated route distance. (a) Global shipping route network developed based on AIS data. (b) Comparison of the estimated bilateral route distance based on Dijkstra algorithm and the observed shipping distance calculated by VoySEIM. The observed shipping distance is represented by the maximum, minimum, median, mean, 10% quantile, and the rectified value of the 10% quantile. The red solid lines in (b) are the fitting curves. Maps are made with Natural Earth.



Supplementary Fig. 10 | Comparison of the (a) seaborne trade weight and (b) shipping CO_2 emission estimated by GTEMS and VoySEIM model for different vessel types. Statistics retrieved from other studies and reports are used for validation**.** The years in brackets refer to the base year.



Supplementary Fig. 11 | Comparison of Brazil's seaborne exports and shipping CO_2 emission estimated by GTEMS model and the previous study[4]. (a) Seaborne trade value by commodity. (b) Seaborne trade value by import country. (c) Seaborne trade weight by commodity. (d) Seaborne trade weight by import country. (e) Shipping CO_2 emissions by commodity. (f) Shipping CO_2 emissions by import country. The target year is 2014. The commodity sections and chapters classified by HS system are described in Supplementary Table 3.

Supplementary Tables

Supplementary Table 1 | Comparison of global shipping CO_2 emissions from different studies.

Model/Method	Basic data	Base year	Shipping CO_2 emission (Tg)		References
			Total shipping	International	
VoySEIM	AIS	2018	1089.3	727.3	This study
GTEMS	Trade	2018	-	746.2	This study
IMO vessel-based	AIS	2018	1056	919	IMO, 2020[5]
IMO voyage-based	AIS	2018	1056	740	IMO, 2020[5]
IEA fuel-based	Fuel	2018	-	706	IEA, 2020[6]
STEAM	AIS	2015	831	-	Johansson et al, 2017[7]

Supplementary Table 2 | Top 30 bilateral flows of international shipping CO_2 emission and their proportions in global maritime trade.

Bilateral flow	CO_2 emission		Maritime trade weight		Maritime trade value	
	Ranking	Share	Ranking	Share	Ranking	Share
BRA - CHN	1	5.42%	2	3.30%	12	0.74%
AUS - CHN	2	3.38%	1	7.73%	5	1.23%
CHN - USA	3	1.59%	16	0.54%	1	4.04%
USA - CHN	4	1.33%	9	0.84%	7	0.98%
CHN - DEU	5	0.99%	185	0.09%	9	0.83%
AUS - JPN	6	0.94%	3	2.17%	39	0.32%
AUS - IND	7	0.93%	5	1.35%	117	0.15%
IDN - CHN	8	0.91%	4	2.01%	30	0.39%
USA - IND	9	0.87%	34	0.41%	95	0.19%
SAU - CHN	10	0.80%	11	0.80%	18	0.49%
USA - JPN	11	0.78%	12	0.68%	22	0.43%
DEU - CHN	12	0.72%	227	0.07%	10	0.80%
USA - KOR	13	0.72%	21	0.48%	19	0.46%
SAU - USA	14	0.62%	18	0.50%	63	0.24%
AUS - KOR	15	0.60%	6	1.14%	78	0.21%
CHL - CHN	16	0.60%	62	0.23%	50	0.29%
CAN - CHN	17	0.59%	22	0.47%	66	0.24%
CHN - GBR	18	0.58%	206	0.08%	20	0.46%
SAU - JPN	19	0.54%	14	0.57%	40	0.32%
CHN - BRA	20	0.54%	164	0.10%	37	0.33%
IRN - CHN	21	0.50%	19	0.50%	75	0.21%
IND - CHN	22	0.49%	36	0.40%	80	0.21%
IDN - IND	23	0.49%	7	1.14%	111	0.16%
QAT - KOR	24	0.49%	68	0.22%	108	0.16%
IRQ - USA	25	0.47%	52	0.28%	161	0.12%
SAU - KOR	26	0.47%	27	0.45%	58	0.26%
IRQ - CHN	27	0.47%	24	0.46%	67	0.24%
KWT - CHN	28	0.45%	44	0.35%	83	0.20%
USA - MEX	29	0.44%	8	1.01%	119	0.15%
QAT - CHN	30	0.44%	73	0.21%	144	0.12%
others		71.83%		71.42%		85.02%

Supplementary Table 3 | Descriptions of commodity sections and chapters in HS code.

Section	Chapter (HS 2-digit)	Description
I	01- 05	Live Animals; Animal Products
II	06 - 14	Vegetable Products
III	15	Animal or Vegetable Fats & Oils
IV	16 - 24	Prepared Foodstuffs; Beverages, Spirits & Vinegar; Tobacco
V	25 - 27	Mineral Products
VI	28 - 38	Chemical Products
VII	39 - 40	Plastics & Articles thereof; Rubber & Articles thereof
VIII	41 - 43	Hides, Skins, Leather & Furskins; Travel Goods & Handbags
IX	44 - 46	Wood & Articles of Wood; Manufactures of Plaiting Materials
X	47 - 49	Wood Pulp; Paper & Articles of Paper
XI	50 - 63	Textiles & Textile Articles
XII	64 - 67	Footwear & Headgear; Articles of Feather; Artificial Flowers; Articles of Human Hair
XIII	68 - 70	Articles of Stone, Plaster, Cement, Asbestos or Mica; Ceramic Products & Glassware
XIV	71	Pearls, Precious or Semi-Precious Stones, Precious Metals, Metals Clad with Precious Metal, & Articles thereof; Imitation Jewelry
XV	72 - 83	Base Metals & Articles of Base Metal
XVI	84 - 85	Machinery & Mechanical Appliances; Electrical Equipment
XVII	86 - 89	Transport Equipment
XVIII	90 - 92	Precision or Medical Instruments & Apparatus; Clocks & Watches; Musical Instruments
XIX	93	Arms & Ammunition
XX	94 - 96	Furniture; Toys & Games/Sports Requisites; Miscellaneous Manufactured Articles
XXI	97	Works of Art, Collectors' Pieces & Antiques
XXII	98	Commodities Not Classified According to Kind

Supplementary Table 4 | Statistics of international trade import and export from BACI data in 2018.

No. of selected country	ISO abbreviation	Country name	GDP* (Billion USD)	GDP ranking	Trade export** Value (Billion USD)	Trade export** Quantity (Million tons)	Trade import Value (Billion USD)	Trade import Quantity (Million tons)	Sum of trade export and import Value (Billion USD)	Sum of trade export and import Trade value ranking	Sum of trade export and import Quantity (Million tons)	Sum of trade export and import Trade quantity ranking	Note
1	CHN	China	13895	2	2678	756	1677	2619	4355	1	3374	1	
2	USA	USA	20580	1	1446	1898	2422	953	3868	2	2852	2	
3	AUS	Australia	1433	13	253	1487	225	90	478	24	1577	3	
4	MEX	Mexico	1222	15	457	123	426	1063	882	10	1186	4	
5	RUS	Russian Federation	1670	12	428	1046	236	135	665	16	1182	5	
6	IND	India	2713	7	327	243	488	810	814	12	1054	6	
7	DEU	Germany	3964	4	1482	379	1181	511	2662	3	891	7	
8	BRA	Brazil	1885	9	246	712	170	161	416	26	872	8	
9	JPN	Japan	4955	3	754	143	673	725	1426	4	868	9	
10	NLD	Netherlands	914	17	525	295	567	544	1092	8	839	10	
11	KOR	Rep. of Korea	1725	10	629	205	519	618	1147	6	823	11	
12	IDN	Indonesia	1042	16	207	614	183	171	389	28	785	12	
13	CAN	Canada	1716	11	430	515	381	205	811	13	720	13	
14	SAU	Saudi Arabia	787	18	267	477	131	84	397	27	561	14	
15	BEL	Belgium-Luxembourg	544	23	394	241	454	274	849	11	515	15	
16	FRA	France	2788	6	570	187	642	319	1211	5	506	16	
17	ITA	Italy	2092	8	537	149	497	343	1034	9	492	17	
18	GBR	United Kingdom	2861	5	450	165	663	313	1112	7	478	18	
19	ESP	Spain	1422	14	327	171	373	264	700	14	435	19	
20	MYS	Malaysia	359	36	258	221	197	204	455	25	425	20	
21	ARE	United Arab Emirates	422	29	240	293	242	111	481	23	405	21	
22	SGP	Singapore	373	32	260	126	331	261	591	18	387	22	
23	TUR	Turkey	778	19	182	132	204	199	386	29	332	24	
24	THA	Thailand	507	25	276	135	235	184	511	22	319	25	
25	POL	Poland	587	21	246	115	273	177	519	20	292	26	
26	ZAF	So. African Customs Union	368	34	119	229	92	63	211	37	291	27	
27	NOR	Norway	434	28	128	235	90	39	218	35	274	28	
28	VNM	Viet Nam	245	46	268	99	248	157	516	21	256	29	
29	IRQ	Iraq	224	49	88	207	43	32	131	45	239	31	
30	IRN	Iran	446	27	63	152	51	33	113	48	184	33	
31	COL	Colombia	334	39							183	34	
32	SWE	Sweden	555	22	161	95	160	88	321	32	183	35	
33	PHL	Philippines	347	38	97	55	115	127	211	36	182	36	

34	KWT	Kuwait									171	37	
35	QAT	Qatar			73	135	35	30	108	50	164	38	
36	EGY	Egypt	250	44	36	50	82	109	118	47	158	39	
37	NGA	Nigeria	397	30							149	41	
38	ARG	Argentina	518	24	61	100	64	46	126	46	146	43	
39	OMN	Oman									141	44	
40	CHL	Chile	298	41	77	64	72	62	149	43	127	45	
41	DZA	Algeria									126	47	
42	PRT	Portugal	242	47	68	40	95	72	163	41	111	49	
43	FIN	Finland	276	42	79	48	74	62	153	42	110	50	
44	BGD	Bangladesh	274	43									
45	DNK	Denmark	357	37	100	35	102	61	202	38			
46	IRL	Ireland	383	31	182	21	100	47	282	33			
47	ISR	Israel	371	33	59	20	76	59	135	44			
48	PAK	Pakistan	315	40									
49	PER	Peru	222	50									
	OAS	Other Asia, nes			376	77	267	267	643	17	344	23	Merged to China
	UKR	Ukraine			51	160	60	87	111	49	247	30	Excluded for inland
	KAZ	Kazakhstan									199	32	Excluded for inland
	AUT	Austria	455	26	172	64	178	86	350	31	150	40	Excluded for inland
	CZE	Czechia	249	45	187	73	182	74	369	30	147	42	Excluded for inland
	BLR	Belarus									126	46	Excluded for inland
	HKG	China, Hong Kong SAR	362	35	112	14	580	107	692	15	121	48	Merged to China
	CHE	Switzerland	705	20	298	23	289	61	587	19			Excluded for inland
	HUN	Hungary			119	42	111	53	231	34			Excluded for inland
	MAC	China, Macao SAR			1	0	11	107	13		107		Merged to China
	ROU	Romania	241	48	82	46	98	57	180	39			Excluded for inland
	SVK	Slovakia			86	38	87	50	173	40			Excluded for inland
Sum of the top 50 countries for each item			**80101**		**17007**	**12948**	**16748**	**13371**	**33753**		**26803**		
			93%		93%	86%	91%	89%	92%		89%		
Sum of the finally selected 49 countries			**78089**		**15949**	**12648**	**15212**	**12777**	**31160**		**26153**		
			90%		87%	84%	83%	85%	85%		87%		
Global total			**86439**		**18362**	**15008**	**18361**	**15009**	**36723**		30015		

*GDP Source: World Development Indicators. World Bank. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD. Retrieved 21 June 2021.

**Trade data source: BACI. Centre d'Etudes Prospectives et d'Informations Internationales（CEPII). http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=37. Retrieved 11 June 2020.

Supplementary Table 5 | Total capacity utilization (TCU) determined by vessel type and DWT range.

Size bin	DWT range (ton)	Bulk carrier	Chemical tanker	Container	General cargo	Liquid gas tanker	Miscella-neous	Oil tanker	Reefer	Ro-Ro
0	0 - 9999	0.7	0.8	0.47	0.71	0.52	0.66	0.78	0.67	0.66
1	10000 - 19999	0.54	0.64	0.45	0.54	0.52	0.66	0.63	0.67	0.45
2	20000 - 29999	0.54	0.52	0.45	0.54	0.52	0.66	0.34	0.67	0.45
3	30000 - 39999	0.5	0.52	0.37	0.54	0.52	0.66	0.34	0.67	0.37
4	40000 - 49999	0.5	0.52	0.37	0.54	0.52	0.66	0.34	0.67	0.37
5	50000 - 59999	0.5	0.52	0.36	0.54	0.62	0.66	0.34	0.67	0.36
6	60000 - 79999	0.43	0.52	0.36	0.54	0.62	0.66	0.35	0.67	0.36
8	80000 - 99999	0.43	0.52	0.36	0.54	0.62	0.66	0.34	0.67	0.36
10	100000 - 119999	0.51	0.52	0.36	0.54	0.62	0.66	0.34	0.67	0.36
12	120000 - 159999	0.51	0.52	0.34	0.54	0.62	0.66	0.36	0.67	0.34
16	160000 - 199999	0.51	0.52	0.34	0.54	0.62	0.66	0.36	0.67	0.34
20	> 200000	0.56	0.52	0.34	0.54	0.44	0.66	0.43	0.67	0.34

Supplementary Table 6 | Berth adjust factor (BAF) determined by vessel type and DWT range.

Size bin	DWT range (ton)	Bulk carrier	Chemical tanker	Container	General cargo	Liquid gas tanker	Miscella-neous	Oil tanker	Reefer	Ro-Ro
0	0 - 9999	1.25	1.12	1.07	1.15	1.53	1.33	2.08	1.51	1.20
1	10000 - 19999	1.13	1.1	1.08	1.24	1.16	1.13	2.36	1.10	1.07
2	20000 - 29999	1.12	1.17	1.06	1.22	1.17	1.07	2.18	1.04	1.06
3	30000 - 39999	1.09	1.16	1.06	1.16	1.10	1.09	1.71	1.07	1.12
4	40000 - 49999	1.18	1.13	1.07	1.12	1.08	1.08	1.51	1.08	1.07
5	50000 - 59999	1.10	1.15	1.04	1.09	1.11	1.15	1.46	-	-
6	60000 - 79999	1.12	1.08	1.04	1.08	1.04	1.13	1.27	-	-
8	80000 - 99999	1.08	1.05	1.03	1.12	1.06	-	1.85	-	-
10	100000 - 119999	1.08	1.06	1.02	-	1.03	-	1.31	-	-
12	120000 - 159999	1.04	-	1.02	-	1.02	-	1.27	-	-
16	160000 - 199999	1.05	-	1.02	-	-	-	1.21	-	-
20	> 200000	1.03	-	1.01	-	-	-	1.13	-	-

Supplementary Table 7 | Comparison of EEOI with IMO Report[5]

Vessel type	Size bin	DWT range in this study	EEOI (g CO_2 ton^{-1} NM^{-1})			Size range in IMO	Size unit in IMO
			This study	IMO Opt. 1	IMO Opt. 2		
Bulk carrier	0	0 - 9999	33.2	44.9	36.6		
	1	10000 - 19999	19.42	12.8	12.1	10000-34999	
	2	20000 - 29999	12.34				
	3	30000 - 39999	13.85				
	4	40000 - 49999	11.07	9.5	8.9	35000-59999	
	5	50000 - 59999	10.36				
	6	60000 - 79999	11.47	7.8	7.5		
	8	80000 - 99999	9.26				
	10	100000 - 119999	6.24				
	12	120000 - 159999	5.1	5.4	5.3		
	16	160000 - 199999	4.73				
	20	> 200000	4.03	4.8	4.7		
Chemical tanker	0	0 - 9999	36.78	82.7	55.1	0-4999	
				39.9	37.7	5000-9999	
	1	10000 - 19999	25.18	27.2	24.9		
	2	20000 - 29999	24.81	16.8	15.8		
	3	30000 - 39999	19.69				
	4	40000 - 49999	15.83				
	5	50000 - 59999	13.97	12.9	12.1		
	6	60000 - 79999	14.05				
	8	80000 - 99999	16.21				
Container	0	0 - 9999	50.03	36.7	35	0-999	TEU
	1	10000 - 19999	40.47	27.4	26.8	1000-1999	TEU
	2	20000 - 29999	33.96	18.5	19.4	2000-2999	TEU
	3	30000 - 39999	31.09	17.1	16.9	3000-4999	TEU
	4	40000 - 49999	26.09	16.3	16.2	5000-7999	TEU
	5	50000 - 59999	25.6	13.6	13.4	8000-11999	TEU
	6	60000 - 79999	22.97	10.7	10.5	12000-14499	TEU
	8	80000 - 99999	22.76	8.5	8.3	14500-19999	TEU
	10	100000 - 119999	23.55	8	7.9	20000+	TEU
	12	120000 - 159999	27.82				
	16	160000 - 199999	28.28				
	20	> 200000	48.85				
General cargo	0	0 - 9999	27.13	38.9	34.5	0-4999	
				31.8	30.4	5000-9999	
	1	10000 - 19999	29.7	28.4	26.7		
	2	20000 - 29999	17.55	14.6	13.7		

	3	30000 - 39999	13.25				
	4	40000 - 49999	11.34				
	5	50000 - 59999	10.55				
	6	60000 - 79999	8.03				
	8	80000 - 99999	3.55				
Liquid gas tanker	0	0 - 9999	86.28	67.1	56.2	0-4999	cbm
				20.8	20.4	5000-9999	cbm
	1	10000 - 19999	41.2	16.4	16.3	10000-19999	cbm
	2	20000 - 29999	27.27				
	3	30000 - 39999	25.46				
	4	40000 - 49999	15.36				
	5	50000 - 59999	16.64	16.9	16.9	20000+	cbm
	6	60000 - 79999	18.78				
	8	80000 - 99999	16.5				
	10	100000 - 119999	20.49				
	12	120000 - 159999	17.59				
Miscellaneous	0	0 - 9999	109.65				
	1	10000 - 19999	32.6				
	2	20000 - 29999	21.83				
	3	30000 - 39999	15.9		47	0+	
	4	40000 - 49999	13.28				
	5	50000 - 59999	13.88				
	6	60000 - 79999	16.52				
Oil tanker	0	0 - 9999	61.42	114.6	95.8	0-4999	
				64.6	58.6	5000-9999	
	1	10000 - 19999	51.18	52.2	41.9		
	2	20000 - 29999	103.9				
	3	30000 - 39999	42.16	26.6	21.9		
	4	40000 - 49999	27.07				
	5	50000 - 59999	24.39				
	6	60000 - 79999	18.8	15.4	14		
	8	80000 - 99999	23.6	12	11		
	10	100000 - 119999	15.41	8.9	8.4		
	12	120000 - 159999	11.88				
	16	160000 - 199999	11.15	5.6	5.5		
	20	> 200000	6.36				
Reefer				218.1	202.6	0-1999	
	0	0 - 9999	81.51	113.9	107.5	2000-5999	
				85.9	82.2	6000-9999	
	1	10000 - 19999	34.97	63.2	62.9	10000+	

	2	20000 - 29999	34.54			
	3	30000 - 39999	19.98			
	4	40000 - 49999	14.02			
Ro-Ro	0	0 - 9999	131.19	269	221.5	0-4999
				66.2	63.5	5000-9999
	1	10000 - 19999	60.94	55.3	53.4	10000-14999
	2	20000 - 29999	31.98			
	3	30000 - 39999	37.78	27.9	27.1	15000+
	4	40000 - 49999	28.09			

*Default size unit: ton

Supplementary references

1 Adland, R., Jia, H. & Strandenes, S. P. The determinants of vessel capacity utilization: The case of Brazilian iron ore exports. *Transportation Research Part A: Policy and Practice* **110**, 191-201, doi:10.1016/j.tra.2016.11.023 (2018).

2 Jia, H., Adland, R., Prakash, V. & Smith, T. Energy efficiency with the application of Virtual Arrival policy. *Transportation Research Part D: Transport and Environment* **54**, 50-60, doi:10.1016/j.trd.2017.04.037 (2017).

3 UCL. The existing shipping fleet's CO2 efficiency. https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/MEPC%2068%20INF%2024%20REV1%20The%20existing%20shipping%20fleet%20CO2%20efficiency.pdf (UCL Energy Institute, 2015).

4 Schim van der Loeff, W., Godar, J. & Prakash, V. A spatially explicit data-driven approach to calculating commodity-specific shipping emissions per vessel. *Journal of Cleaner Production* **205**, 895-908, doi:10.1016/j.jclepro.2018.09.053 (2018).

5 IMO. Forth IMO Greenhouse gas study. (International Maritime Organization, 2020).

6 IEA. Global Energy Review. https://www.iea.org/reports/global-energy-review-2020 (International Energy Agency, 2020).

7 Johansson, L., Jalkanen, J.-P. & Kukkonen, J. Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. *Atmospheric Environment* **167**, 403-415, doi:10.1016/j.atmosenv.2017.08.042 (2017).