

Supplementary Information

Arctic Sea Route access reshapes global shipping carbon emissions

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Supplementary Table 1 | Projected vessel traffic via the Arctic Sea Route (ASR) under the Optimistic Trade Scenario (OTS) and Pessimistic Trade Scenario (PTS).

YEAR	Container	Bulk	Chemical	Gas	Oil	SUM
2025	550 451	620 506	437 360	215 148	351 290	2173 1755
2030	1592 1223	1715 1353	1061 817	561 336	883 659	5812 4388
2035	1887 1325	1920 1472	1277 899	738 369	1105 725	6927 4790
2040	2697 1701	2107 1507	1639 1028	1039 422	1474 829	8956 5487
2045	4123 2476	2587 1647	2237 1329	1568 582	2110 1096	12625 7130
2050	6483 3730	5314 3112	4105 2306	3209 1101	4094 1969	23205 12218
2055	7678 4246	6294 3456	6258 3343	5514 1763	6744 3001	32488 15809
2060	9675 5168	8670 4499	9015 4585	8953 2703	10494 4357	46807 21312
2065	11577 6023	10717 5308	12398 5992	13835 3982	15389 6014	63916 27319
2070	17234 8775	16573 7886	20098 9203	24938 6921	26217 9717	105060 42502
2075	18592 9297	18443 8430	24987 10903	34789 9376	34060 12057	130871 50063
2080	20995 10322	17390 7646	31939 13281	49228 13004	45955 15570	165507 59823
2085	27747 13531	25777 10982	49497 19676	84241 21847	75820 24676	263082 90712
2090	31679 15358	26786 11101	62364 23730	113242 28968	101952 32025	336023 111182
2095	41901 20252	41856 17402	82022 30071	159939 40720	145522 44465	471240 152910
2100	45504 21894	47536 20016	91856 33252	208050 52278	176295 53172	569241 180612

Note: Unit is voyages.

Supplementary Table 2 | The relationship between ship types and Harmonized System (HS) code.

Ship Type	HS Code
container	0601, 0603, 0604, 0903, 0904, 0905, 0906, 0907, 0908, 0909, 0910, 1203, 1204, 1210, 1211, 1302, 1801, 2401, 5301, 5302, 5303, 5305, 5306, 5307, 5308, 2712, 2801, 2802, 2803, 2805, 2812, 2813, 2817, 2819, 2820, 2821, 2822, 2823, 2824, 2825, 2826, 2837, 2840, 2841, 2842, 2843, 2844, 2845, 2846, 2942, 3001, 3002, 3003, 3004, 3005, 3201, 3202, 3203, 3204, 3205, 3206, 3207, 3208, 3209, 3210, 3211, 3212, 3213, 3215, 3301, 3303, 3304, 3305, 3306, 3307, 3401, 3404, 3405, 3407, 3501, 3502, 3503, 3504, 3505, 3506, 3507, 3601, 3602, 3603, 3604, 3605, 3701, 3702, 3703, 3704, 3705, 3706, 3707, 3802, 3803, 3805, 3806, 3807, 3808, 3809, 3810, 3811, 3812, 3813, 3814, 3815, 3817, 3818, 3819, 3820, 3821, 3822, 3916, 3917, 3918, 3919, 3920, 3921, 3922, 3923, 3924, 3925, 3926, 4007, 4008, 4009, 4010, 4011, 4012, 4013, 4014, 4015, 4016, 4017, 5904, 5906, 2914, 7321, 7322, 8418, 8422, 8450, 8451, 8471, 8501, 8502, 8503, 8504, 8505, 8506, 8507, 8508, 8509, 8510, 8511, 8512, 8513, 8515, 8516, 8517, 8518, 8519, 8521, 8522, 8523, 8525, 8526, 8527, 8528, 8529, 8530, 8531, 8532, 8533, 8534, 8535, 8536, 8537, 8538, 8539, 8540, 8541, 8542, 8543, 8544, 8545, 8548, 9001, 9002, 9005, 9006, 9007, 9008, 9010, 9011, 9012, 9013, 9014, 9015, 9016, 9018, 9022, 9024, 9025, 9026, 9027, 9028, 9029, 9030, 9031, 9032, 9033, 9101, 9102, 9103, 9104, 9105, 9106, 9107, 9108, 9109, 9110, 9111, 9112, 9113, 9114, 9405, 9504, 7202, 7205, 7206, 7207, 7216, 7217, 7218, 7220, 7221, 7222, 7223, 7224, 7226, 7227, 7228, 7229, 7301, 7302, 7303, 7304, 7305, 7306, 7307, 0301, 0302, 0307, 0508, 7101, 4104, 4105, 4106, 4107, 4112, 4113, 4114, 4115, 4201, 4202, 4205, 4302, 6401, 6402, 6403, 6404, 6405, 6406, 9605, 8405, 8406, 8410, 8412, 8413, 8414, 8415, 8416, 8417, 8419, 8420, 8421, 8423, 8424, 8425, 8426, 8427, 8428, 8429, 8430, 8431, 8432, 8433, 8434, 8435, 8436, 8437, 8438, 8439, 8440, 8441, 8442, 8443, 8444, 8445, 8446, 8447, 8448, 8449, 8452, 8453, 8454, 8455, 8456, 8457, 8458, 8459, 8460, 8461, 8462, 8463, 8464, 8465, 8466, 8467, 8468, 8469, 8470, 8472, 8473, 8474, 8475, 8476, 8477, 8478, 8479, 8481, 8482, 8483, 8484, 8486, 8514, 8805, 9017, 9508, 0501, 3006, 3406, 3606, 4206, 6601, 6602, 6603, 6701, 6702, 6703, 6704, 7105, 7113, 7114, 7116, 7117, 7118, 9003, 9004, 9019, 9020, 9021, 9023, 9201, 9202, 9205, 9206, 9207, 9208, 9209, 9402, 9403, 9404, 9503, 9505, 9506, 9507, 9601, 9602, 9603, 9604, 9606, 9607, 9608, 9609, 9610, 9611, 9612, 9613, 9614, 9615, 9616, 9617, 9618, 7309, 7310, 7311, 7312, 7313, 7314, 7315, 7316, 7317, 7318, 7319, 7320, 7323, 7324, 7325, 7326, 8201, 8202, 8203, 8204, 8205, 8206, 8207, 8208, 8209, 8210, 8211, 8212, 8213, 8214, 8215, 8301, 8302, 8303, 8304, 8305, 8306, 8307, 8308, 8309, 8310, 8311, 8480, 8487, 8607, 8608, 9301, 9302, 9303, 9304, 9305, 9306, 9307, 2620, 7106, 7107, 7108, 7109, 7110, 7111, 7112, 7115, 7401, 7402, 7403, 7404, 7405, 7406, 7407, 7408, 7409, 7410, 7411, 7412, 7413, 7415, 7418, 7419, 7501, 7502, 7503, 7504, 7505, 7506, 7507, 7508, 7602, 7603, 7604, 7605, 7606, 7607, 7608, 7609, 7610, 7611, 7612, 7613, 7614, 7615, 7616, 7801, 7802, 7804, 7806, 7901, 7902, 7903, 7904, 7905, 7907, 8001, 8002, 8003, 8007, 8101, 8102, 8103, 8104, 8105, 8106, 8107, 8108, 8109, 8110, 8111, 8112, 8113, 6801, 6802, 6803, 6804, 6805, 6806, 6808, 6809, 6810, 6811, 6812, 6813, 6814, 6815, 6901, 6902, 6903, 6904, 6905, 6906, 6907, 6908, 6909, 6910, 6911, 6912, 6913, 6914, 7001, 7002, 7003, 7004, 7005, 7006, 7007, 7008, 7009, 7010, 7011, 7013, 7014, 7015, 7016, 7017, 7018, 7019, 7020, 7104, 8546, 8547, 2616, 7102, 7103, 8708, 8708, 4801, 4802, 4803, 4804, 4805, 4806, 4807, 4808, 4809, 4810, 4811, 4812, 4813, 4814, 4816, 4817, 4818, 4819, 4820, 4821, 4822, 4823, 4901, 4902, 4903, 4904, 4905, 4906, 4907, 4908, 4909, 4910, 4911, 5905, 9704, 0201, 0202, 0203, 0204, 0205, 0206, 0207, 0208, 0209, 0210, 0303, 0304, 0305, 0306, 0401, 0402, 0403, 0404, 0405, 0406, 0407, 0408, 0409, 0410, 0502, 0504, 0505, 0506, 0507, 0510, 0511, 0701, 0702, 0703, 0704, 0705, 0706, 0707, 0708, 0709, 0710, 0711, 0712, 0713, 0714, 0801, 0802, 0803, 0804, 0805, 0806, 0807, 0808, 0809, 0810, 0811, 0812, 0813, 0814, 0902, 1101, 1102, 1103, 1104, 1105, 1106, 1107, 1108, 1109, 1208, 1404, 1501, 1502, 1503, 1504, 1505, 1506, 1507, 1508, 1509, 1510, 1511, 1512, 1513, 1514, 1515, 1516, 1517, 1518, 1521, 1522, 1601, 1602, 1603, 1604, 1605, 1701, 1702, 1703, 1704,

	1802, 1803, 1804, 1805, 1806, 1901, 1902, 1903, 1904, 1905, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2101, 2102, 2103, 2104, 2105, 2106, 2201, 2202, 2203, 2204, 2205, 2206, 2208, 2209, 2301, 2302, 2303, 2304, 2305, 2306, 2307, 2308, 2309, 2402, 2043, 4101, 4102, 4103, 4301, 5001, 5002, 5003, 5004, 5005, 5006, 5007, 5101, 5102, 5103, 5104, 5105, 5106, 5107, 5108, 5109, 5110, 0101, 0102, 0103, 0104, 0105, 0106, 5111, 5112, 5113, 5202, 5203, 5204, 5205, 5206, 5207, 5208, 5209, 5210, 5211, 5212, 5309, 5310, 5311, 5401, 5402, 5403, 5404, 5405, 5406, 5407, 5408, 5501, 5502, 5503, 5504, 5505, 5506, 5507, 5508, 5509, 5510, 5511, 5512, 5513, 5514, 5515, 5516, 5601, 5602, 5603, 5604, 5605, 5606, 5607, 5608, 5609, 5701, 5702, 5703, 5704, 5705, 5801, 5802, 5803, 5804, 5805, 5806, 5807, 5808, 5809, 5810, 5811, 5901, 5902, 5903, 5907, 5908, 5909, 5910, 5911, 6001, 6002, 6003, 6004, 6005, 6006, 6301, 6302, 6303, 6304, 6305, 6306, 6307, 6308, 6309, 6310, 8804, 8407, 8408, 8409, 8411, 8601, 8602, 8603, 8604, 8605, 8606, 8609, 8710, 8711, 8712, 8713, 8714, 8715, 8801, 8802, 8803, 9401, 4203, 4303, 4304, 6101, 6102, 6103, 6104, 6105, 6106, 6107, 6108, 6109, 6110, 6111, 6112, 6113, 6114, 6115, 6116, 6117, 6201, 6202, 6203, 6204, 6205, 6206, 6207, 6208, 6209, 6210, 6211, 6212, 6213, 6214, 6215, 6216, 6217, 6501, 6502, 6504, 6505, 6506, 6507, 4402, 4403, 4404, 4405, 4406, 4407, 4408, 4409, 4410, 4411, 4412, 4413, 4414, 4415, 4416, 4417, 4418, 4419, 4420, 4421, 4502, 4503, 4504, 4601, 4602
bulk carrier	0602, 0901, 1001, 1002, 1003, 1004, 1005, 1006, 1007, 1008, 1201, 1202, 1205, 1206, 1207, 1209, 1212, 1213, 1214, 5201, 2827, 2828, 2829, 2830, 2831, 2832, 2833, 2834, 2835, 2839, 3101, 3102, 3103, 3104, 3105, 3214, 3824, 3825, 3901, 3902, 3903, 3904, 3905, 3906, 3907, 3908, 3909, 3910, 3911, 3912, 3913, 3914, 3915, 4001, 4002, 4003, 4004, 4005, 4006, 2618, 2619, 7201, 7203, 7204, 7208, 7209, 7210, 7211, 7212, 7213, 7214, 7215, 7219, 7225, 1301, 1401, 4401, 4501, 7308, 8401, 8402, 8403, 8404, 9406, 2818, 2518, 2521, 2522, 2523, 2715, 3801, 3816, 6807, 7601, 2501, 2502, 2503, 2504, 2505, 2506, 2507, 2508, 2509, 2510, 2511, 2512, 2513, 2514, 2515, 2516, 2517, 2519, 2520, 2524, 2525, 2526, 2528, 2529, 2530, 2601, 2602, 2603, 2604, 2605, 2606, 2607, 2608, 2609, 2610, 2611, 2612, 2613, 2614, 2615, 2617, 2621, 2703, 3804, 4701, 4702, 4703, 4704, 4705, 4706, 4707, 2701, 2702, 2704, 2706, 2713, 2714
chemical tanker	1520, 2207, 2707, 2708, 2804, 2806, 2807, 2808, 2809, 2810, 2811, 2814, 2815, 2816, 2836, 2847, 2848, 2849, 2850, 2852, 2853, 2901, 2902, 2903, 2904, 2905, 2906, 2907, 2908, 2909, 2910, 2911, 2912, 2913, 2914, 2915, 2916, 2917, 2918, 2919, 2920, 2921, 2922, 2923, 2924, 2925, 2926, 2927, 2928, 2929, 2930, 2931, 2932, 2933, 2934, 2935, 2936, 2937, 2938, 2939, 2940, 3302, 3402, 3403, 3823
gas ships	2711
oil tanker	2709, 2710

Supplementary Table 3 | Variance Inflation Factor (VIF) Results.

Variable	VIF
num	2.30
tone	1.94
legal_new_o	4.72
legal_new_d	4.48
contig	1.19
diplo_disagreement	2.88
fta_wto	1.83
gdp_i	2.66
pop_i	2.20
gdp_j	2.48
pop_j	1.99
VA	1.31
Transport cost intensity in US\$ per ton-km	1.07
Distance	4.06

Note: The VIF table includes: **legal_new_o** and **legal_new_d**, dummies indicating whether the origin and destination countries, respectively, have recently signed bilateral or multilateral trade agreements; **fta_wto**, a binary flag for WTO-based free trade agreement status; **contig**, a dummy for shared borders; **diplo_disagreement**, a (logged) index of diplomatic tension; **gdp_i** and **gdp_j**, the origin and destination countries' GDPs (used as $\ln \text{gdp}_i$ and $\ln \text{gdp}_j$); **pop_i** and **pop_j**, the origin and destination populations (used as $\ln \text{pop}_i$ and $\ln \text{pop}_j$); **VA**, value-added trade (used as $\ln \text{VA}$); **Transport cost intensity**, transport cost per unit of trade in US\$ per ton-km (used as $\ln \text{Transport_cost_intensity}$); and **Distance**, the bilateral geographic distance (continuous; log-transformed where appropriate). The table also lists **num** (a count variable) and **tone** (a sentiment/tonality measure). Continuous predictors enter the model in logs when appropriate.

Supplementary Table 4 | Classification of Global Navigation Areas and Associated Operational Characteristics

Classification I	Classification II	Code	Overview of Technical and Economic Characteristics (Compared to OWA)
Non-Arctic	Open Water Areas	OWA	Benchmark
	Suez Canal	SUZ	Increased Suez Canal tolls and Gulf of Aden insurance surcharges
	Panama Canal	PNM	Increased Panama Canal tolls
	Land	LAN	Not navigable
	Northern Sea		Increased icebreaking tariff ^a ; reduced
Arctic	Route (Mandatory Icebreaking Service)	NSR	operational speed; higher fuel consumption at design speed; increased costs (capital, crew, maintenance, insurance, etc.)
	Northwest Passage (No Icebreaking Service)	NWP1	No icebreaking tariff, other characteristics similar to NSR but with greater variations ^b
	Northwest Passage (Requires Icebreaking Service)	NWP2	Actually not navigable ^c
	Other Navigable Arctic Sea Areas (No Icebreaking Service)	ONA1	No icebreaking tariff, other characteristics similar to NSR
	Other Navigable Arctic Sea Areas (Requires Icebreaking Service)	ONA2	Actually not navigable ^c
	Non-Navigable Arctic Areas	NNA	Not navigable

Note: To reflect varying navigation conditions, all global sea areas were classified into Arctic and non-Arctic zones and further subdivided into ten functional subregions based on environmental, technical, and economic criteria. Although mandatory tariffs for the Northern Sea Route (NSR) were officially lifted by Russia in 2014, most ship operators continue to use icebreaking services due to safety, insurance, and operational considerations (Gritsenko & Kiiski, 2016). In addition to sea ice, other constraints—such as narrow channels, shallow waters, and complex currents—were incorporated into the navigability assessment (Lu et al., 2014). Regions where large-scale icebreaking support is not feasible were conservatively classified as non-navigable in this study.

Supplementary Table 5 | Cost-Related Parameters for Non-Arctic Areas

Applicable Area	Parameter	Container	Bulk	Oil	Source
OWA SUZ PNM	Cap	0.0121	0.0064	0.0090	(Furuichi & Otsuka, 2015)
OWA SUZ PNM	Cre	0.00165	0.00165	0.00165	(Furuichi & Otsuka, 2015)
OWA SUZ PNM	Mai	0.00134	0.00071	0.00099	(Furuichi & Otsuka, 2015)
OWA SUZ PNM	Ins	0.00042	0.00022	0.00031	(Furuichi & Otsuka, 2015)
OWA SUZ PNM	fc ^a	0.00253	0.00152	0.00202	(T. Smith et al., 2015; T. W. P. Smith et al., 2015)
OWA SUZ PNM	v	27.13	21.43	19.53	(T. W. P. Smith et al., 2015)
SUZ	ac	8.57	8.57	8.57	(Furuichi & Otsuka, 2015)
PNM	ac	4.80	4.70	4.70	(Furuichi & Otsuka, 2015)
All Area	VOT	0.0434	0.0017	0.0046	(Verschuur et al., 2022; Wang et al., 2015)

Note: We derived the cost parameters through two complementary approaches: (1) adopting baseline values for non-Arctic regions, and (2) applying proportional adjustment coefficients to estimate Arctic-specific parameters relative to non-Arctic benchmarks. While prior studies have explored Arctic navigation costs at the voyage level, inconsistencies in scope and assumptions have hindered the establishment of standardized values. Theocharis et al. (2018) synthesized earlier estimates within a unified cost framework, which we used as a foundation. Building on this, we systematically identified proportional coefficients for Arctic regions relative to the OWA region and integrated them with non-Arctic values to obtain the final parameter set for Arctic navigation. Abbreviations: OWA, Open Water Areas; SUZ, Suez Canal; PNM, Panama Canal.

Supplementary Table 6 | Cost-Related Parameters for Arctic Areas

Ship Type	Area	Cre	Ins	fc ^a	v	Cap	Mai	LF	ac ^b	Source ^c
Bulk	NSR	1.15	1.58	0.46	0.66	1.12	1.15	1	2.42	(Chang et al., 2015; Chou et al., 2017a; Pierre & Olivier, 2015; Pruyn, 2016; Schøyen & Bråthen, 2011)
Container	NSR	1.1	1.36	0.62	0.71	1.21	1.4	0.81	2.17	(Chou et al., 2017b; Furuichi & Otsuka, 2015; Lasserre, 2014, 2015; Xu et al., 2011; Zhang et al., 2016; Zhao et al., 2016)
Oil	NSR	1.23	1.15	0.31	0.52	1.18	1.22	1	2.79	(Faury & Cariou, 2016; Schröder et al., 2017; Song & Zhang, 2013; Zhang et al., 2016)
Bulk	NWP1	1.15	1.74	0.40	0.62	1.12	1.15	1	0	(Chang et al., 2015; Chou et al., 2017a; Lasserre, 2015; Pierre & Olivier, 2015; Pruyn, 2016; Schøyen & Bråthen, 2011)
Container	NWP1	1.1	1.5	0.54	0.66	1.21	1.4	0.81	0	(Chou et al., 2017b; Furuichi & Otsuka, 2015; Lasserre, 2014, 2015; Xu et al., 2011; Zhang et al., 2016; Zhao et al., 2016)
Oil	NWP1	1.23	1.26	0.27	0.48	1.18	1.22	1	0	(Faury & Cariou, 2016; Lasserre, 2015; Schröder et al., 2017; Song & Zhang, 2013; Zhang et al., 2016)
Bulk	ONA1	1.15	1.58	0.46	0.66	1.12	1.15	1	0	(Chang et al., 2015; Chou et al., 2017a; Pierre & Olivier, 2015; Pruyn, 2016; Schøyen & Bråthen, 2011)
Container	ONA1	1.1	1.36	0.62	0.71	1.21	1.4	0.81	0	(Chou et al., 2017b; Furuichi & Otsuka, 2015; Lasserre, 2014, 2015; Xu et al., 2011; Zhang et al., 2016; Zhao et al., 2016)
Oil	ONA1	1.23	1.15	0.31	0.52	1.18	1.22	1	0	(Faury & Cariou, 2016; Schröder et al., 2017; Song & Zhang, 2013; Zhang et al., 2016)

Note: a. Values are derived using the proportional relationship between fuel consumption at design speed and the cubic dependency of fuel consumption on vessel speed (Faury & Cariou, 2016; Pruyn, 2016; Zhang et al., 2016). b. Values are expressed relative to the Suez Canal (SUZ) baseline. c. For Northern Sea Route (NSR) and Arctic Sea Areas with No Icebreaking Service (ONA1), average values from multiple studies are adopted. For Northwest Passage with No Icebreaking Service (NWP1), we first calculate its proportional coefficient relative to the NSR based on Lasserre (2015), and then apply this ratio to the NSR value to obtain the final estimate.

Supplementary Table 7 | Proportion of Arctic-routing voyages by vessel type and representative country pairs

Year	CHN-NLD Container	CHN-USA Oil	USA-NLD Oil	USA-NLD Bulk	AUS-NLD Bulk
2050-2054	0.04	0.01	0.00	0.02	0.00
2055-2059	0.04	0.00	0.00	0.01	0.00
2060-2064	0.10	0.00	0.02	0.04	0.00
2065-2069	0.10	0.00	0.02	0.04	0.00
2070-2074	0.16	0.02	0.03	0.05	0.07
2075-2079	0.19	0.01	0.04	0.05	0.07
2080-2084	0.12	0.02	0.03	0.04	0.03
2085-2089	0.20	0.01	0.03	0.06	0.07
2090-2094	0.15	0.02	0.03	0.06	0.00
2095-2099	0.32	0.02	0.05	0.07	0.13

Note: Abbreviations: CHN, China; NLD, Netherlands; USA, United States of America; AUS, Australia.

Supplementary Table 8 | Fuel composition in future scenarios

Fuel	2023	2025	2030	2035	2040	2045	2050
HFO scrubber	18.8%	17.7%	11.3%	4.2%	1.8%	0.6%	0
LSFO MGO	71.4%	67.6%	49.9%	25.5%	13.2%	7.9%	2.1%
LNG	8.1%	12.5%	12.6%	2.9%	0.9%	0.5%	0
LPG	0.6%	0.4%	0.8%	0.5%	0	0	0
fossil methanol	0	0.4%	0	0	0	0	0
bio-MGO	1.1%	1.4%	19.6%	25.3%	0	0	0
bio-LNG	0	0	1.6%	2.2%	1.9%	0	0
bio-methanol	0	0	0.6%	2.4%	2.4%	2.9%	2.9%
e-MGO	0	0	0	0	27.6%	26.3%	27.8%
e-LNG	0	0	0	0	0	1.5%	1.2%
e-NH ₃	0	0	0	0	8.9%	20.4%	27.6%
blue NH ₃	0	0	1.1%	3.2%	0.5%	0	0
CCS HFO scrubber	0	0	0.3%	4.3%	3.4%	2.5%	2.2%
CCS LSFO MGO	0	0	1.4%	22.4%	26.9%	23.0%	19.5%
CCS LNG	0	0	0.5%	5.9%	4.6%	3.3%	2.4%
CCS bio-MGO	0	0	0.3%	0.8%	0	0	0
CCS bio-LNG	0	0	0	0.3%	1.7%	0	0
CCS e-MGO	0	0	0	0	6.2%	9.8%	12.6%
CCS e-LNG	0	0	0	0	0	1.2%	1.9%

Note: Fuel composition assumptions are scenario-specific. The Business-as-Usual (BAU) scenario adopts 2023 fuel mix data, while the IMO 2023 strategy and non-green corridor components of the Green Corridor scenario use projected fuel structures for 2025–2050. Carbon capture and storage (CCS) rates follow estimates from Bin et al. (2018). To meet IMO 2023 strategy and FuelEU Maritime regulatory goals, the scenarios incorporate differentiated clean fuel pathways. Relative fuel shares—including those of electricity, hydrogen, and biofuels—are calibrated based on DNV’s scenario-based reports (DNV, 2022, 2023, 2024), which model the maritime energy transition through 2050. These reports account for dynamic variables such as fuel cost trajectories, technology adoption barriers, regulatory instruments (e.g., onboard carbon capture), fuel availability, infrastructure readiness, and energy efficiency improvements. Emission estimates are based on a tank-to-wake accounting approach, in line with prevailing maritime decarbonization standards. In the table, HFO denotes heavy fuel oil, while LSFO is low-sulfur fuel oil ($\leq 0.5\%$ sulfur under IMO 2020 rules); MGO is marine gas oil; LNG and LPG are liquefied natural gas and liquefied petroleum gas, respectively. NH₃ refers to ammonia as a marine fuel, with “blue NH₃” indicating ammonia produced from fossil feedstocks with carbon capture and storage. DNV (Det Norske Veritas) is the Norwegian classification society whose transition scenarios are referenced, IMO is the International Maritime Organization, and FuelEU (FuelEU Maritime) is the European Union regulation promoting the uptake of cleaner marine fuels. bio- for Bio-based (e.g., bio-MGO, bio-LNG, bio-methanol), and e- for Electro- (electrofuels, e.g., e-MGO, e-LNG, e-NH₃).

Supplementary Table 9 | Fuel Preferences of Green Corridors

Green Corridors	Fuel
Chile Piscocultura Corridor	bio-methanol, hydrogen,
Oslo-Rotterdam Corridor	hydrogen
Republic of Korea-United States Corridor	bio-methanol
Rotterdam-Singapore Corridor	e-NH ₃ , hydrogen, bio-methanol
South Africa-Europe Iron Ore Corridor	e-NH ₃
Western Australia-North Asia Iron Ore Corridor	e-NH ₃
European Green Corridors Network Corridor	bio-methanol
Network	
US-UK Corridor	Hydrogen, e-NH ₃ , bio-methanol
Arctic shipping routes	CCS LSFO MGO, CCS LNG, methanol

Note: The table lists preferred alternative fuels for selected green shipping corridors. For Arctic shipping routes, environmental sensitivity is prioritized. Fuels with high ecological risk — such as ammonia, due to its toxicity and potential for leakage — are excluded. Instead, lower-impact options such as carbon capture and storage (CCS)-equipped low-sulfur fuel oil (LSFO), marine gas oil (MGO), CCS liquefied natural gas (LNG), and methanol are designated to minimize risks to the fragile Arctic ecosystem.

In the table, e-NH₃ denotes electro-ammonia, produced using renewable electricity and electrolytic hydrogen as a zero-carbon marine fuel; the US-UK Corridor is shorthand for the United States–United Kingdom shipping corridor. bio- for Bio-based (e.g., bio-MGO, bio-LNG, bio-methanol), and e- for Electro- (electrofuels, e.g., e-MGO, e-LNG, e-NH₃).

Supplementary Table 10 | Specific Fuel Consumption (SFC) of Different Fuels

Main Fuel Type	Sub Fuel Type	SFC(g kwh ⁻¹)
Heavy Fuel Oil (HFO)	HFO scrubber	180
	CCS HFO scrubber	180
	LSFO MGO	170
	bio-MGO	170
Marine Gas Oil (MGO)	e-MGO	170
	CCS LSFO MGO	170
	CCS bio-MGO	170
	CCS e-MGO	170
	LNG	152
Liquefied Natural Gas (LNG)	bio-LNG	152
	e-LNG	152
	CCS LNG	152
	CCS e-LNG	152
	CCS bio-LNG	152
Liquefied Petroleum Gas (LPG)	LPG	190
	fossil methanol	337
methanol	bio-methanol	337
	e-NH ₃	373.3
NH ₃	blue NH ₃	373.3
	hydrogen	60
Hydrogen		

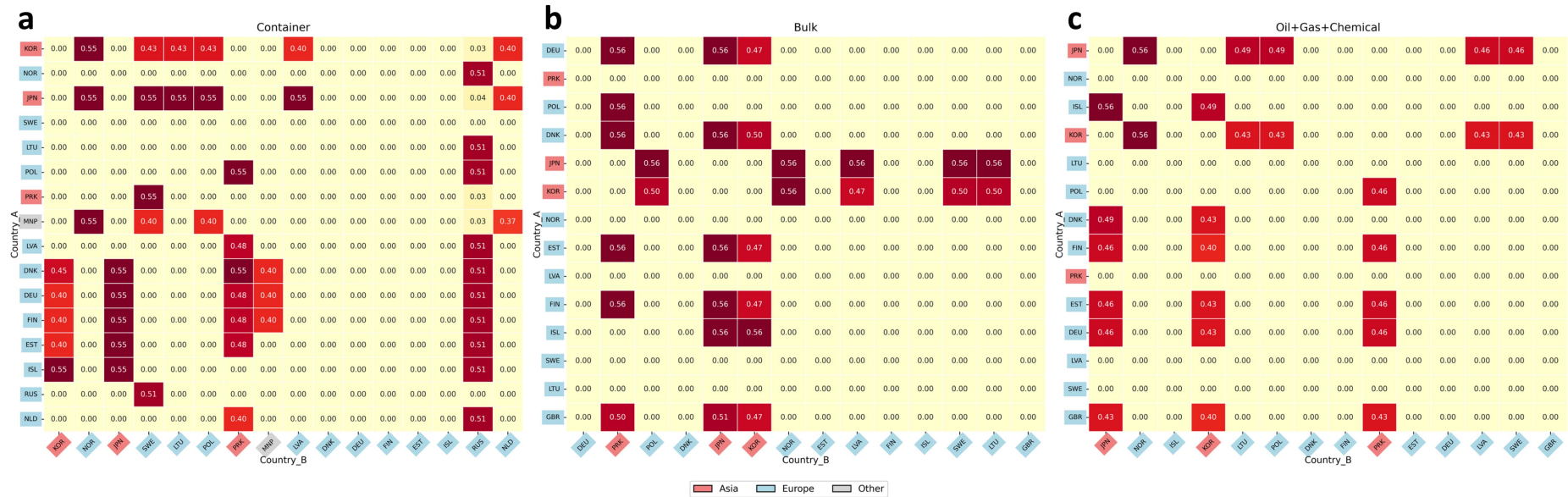
Note: This table is based on data from Ismail (2023). Since liquefied petroleum gas (LPG) Specific Fuel Consumption (SFC) data was unavailable, we adopted 190 g kWh⁻¹ — the median value within the standard marine engine SFC range (155–225 g kWh⁻¹) under optimal load conditions. The abbreviations used in the table are: SFC stands for Specific Fuel Consumption, HFO for Heavy Fuel Oil, MGO for Marine Gas Oil, LNG for Liquefied Natural Gas, LPG for Liquefied Petroleum Gas, NH₃ for Ammonia, and CCS for Carbon Capture and Storage, bio- for Bio-based (e.g., bio-MGO, bio-LNG, bio-methanol), and e- for Electro- (electrofuels, e.g., e-MGO, e-LNG, e-NH₃).

Supplementary Table 11 | Greenhouse-Gas (GHG) Emission Factors of Fuel Types (g CO_{2eq} g⁻¹ fuel)

Fuel	2023	2025	2030	2035	2040	2045	2050
HFO scrubber	3.163	3.163	3.163	3.163	3.163	3.163	3.163
CCS HFO scrubber	3.163	0.949	0.786	0.624	0.461	0.298	0.135
LSFO MGO	3.255	3.255	3.255	3.255	3.255	3.255	3.255
bio-MGO	1.628	1.628	1.628	1.628	1.628	1.628	1.628
e-MGO	1.628	1.628	1.628	1.628	1.628	1.628	1.628
CCS LSFO MGO	3.255	0.977	0.801	0.626	0.45	0.275	0.099
CCS bio-MGO	1.628	0.488	0.401	0.313	0.225	0.137	0.05
CCS e-MGO	1.628	0.488	0.401	0.313	0.225	0.137	0.05
LNG	2.779	2.779	2.779	2.779	2.779	2.779	2.779
bio-LNG	1.39	1.39	1.39	1.39	1.39	1.39	1.39
e-LNG	1.39	1.39	1.39	1.39	1.39	1.39	1.39
CCS LNG	2.779	0.834	0.682	0.53	0.378	0.226	0.074
CCS e-LNG	1.39	0.417	0.341	0.265	0.189	0.113	0.037
CCS bio-LNG	1.39	0.417	0.341	0.265	0.189	0.113	0.037
LPG	3.079	3.079	3.079	3.079	3.079	3.079	3.079
fossil methanol	1.424	1.424	1.424	1.424	1.424	1.424	1.424
bio-methanol	0.712	0.712	0.712	0.712	0.712	0.712	0.712
e-NH ₃	0.049	0.049	0.049	0.049	0.049	0.049	0.049
blue NH ₃	0.049	0.015	0.012	0.009	0.006	0.004	0.001
hydrogen	0	0	0	0	0	0	0

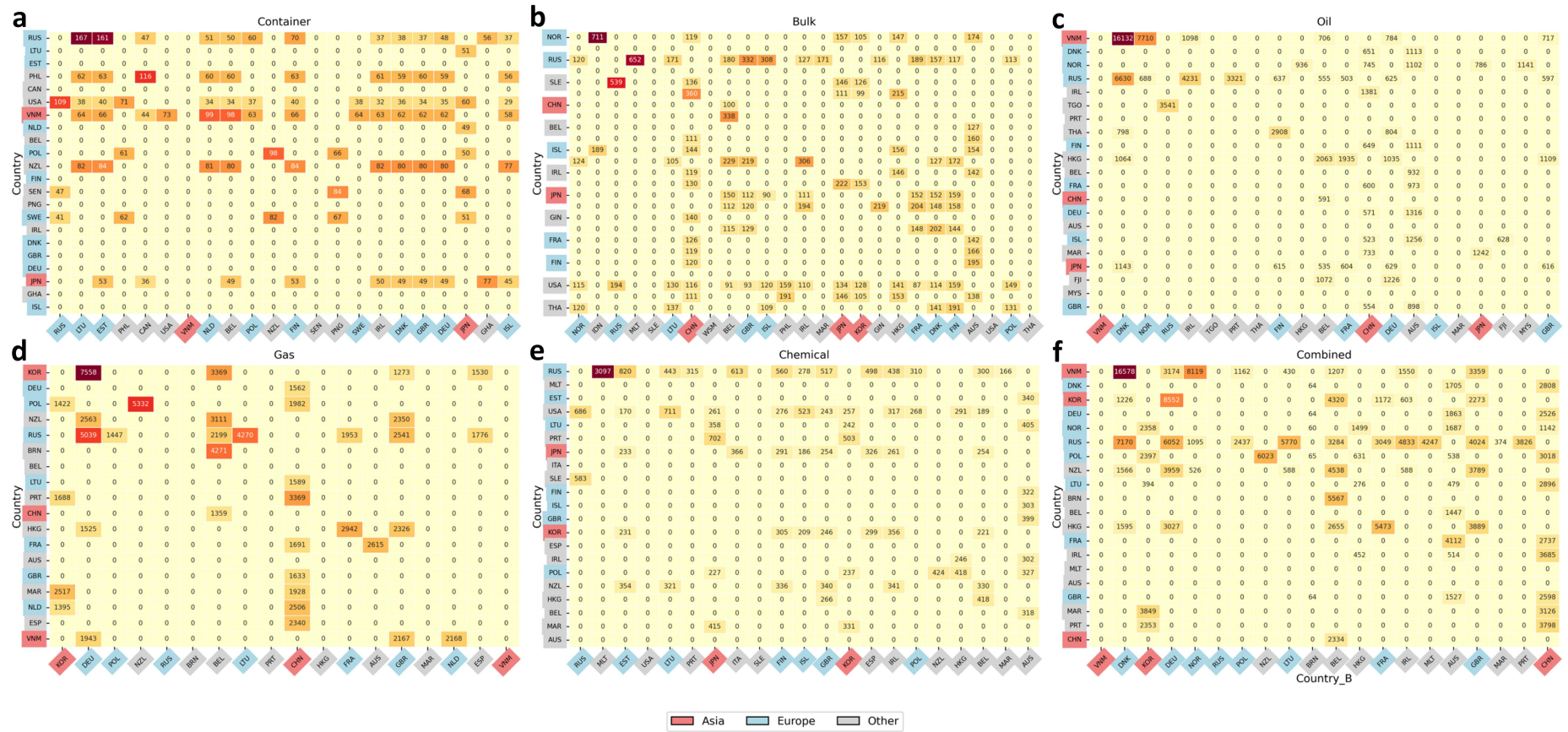
Note: Emission factors for heavy fuel oil (HFO), marine gas oil (MGO), liquefied natural gas (LNG), and methanol are taken from ClassNK (2023). For the corresponding bio- and e-fuel variants, we assume emission factors equal to 50% of their fossil counterparts (CO_{2e} basis). For fuels equipped with carbon capture and storage (CCS), emission factors are adjusted using a capture efficiency that increases from 70% in 2025 to 90% by 2050. The abbreviations used in the table are: GHG stands for Greenhouse Gas, HFO for Heavy Fuel Oil, MGO for Marine Gas Oil, LNG for Liquefied Natural Gas, LPG for Liquefied Petroleum Gas, NH₃ for Ammonia, CCS for Carbon Capture and Storage, bio- for Bio-based (e.g., bio-MGO, bio-LNG, bio-methanol), and e- for Electro- (electrofuels, e.g., e-MGO, e-LNG, e-NH₃).

Supplementary Figures



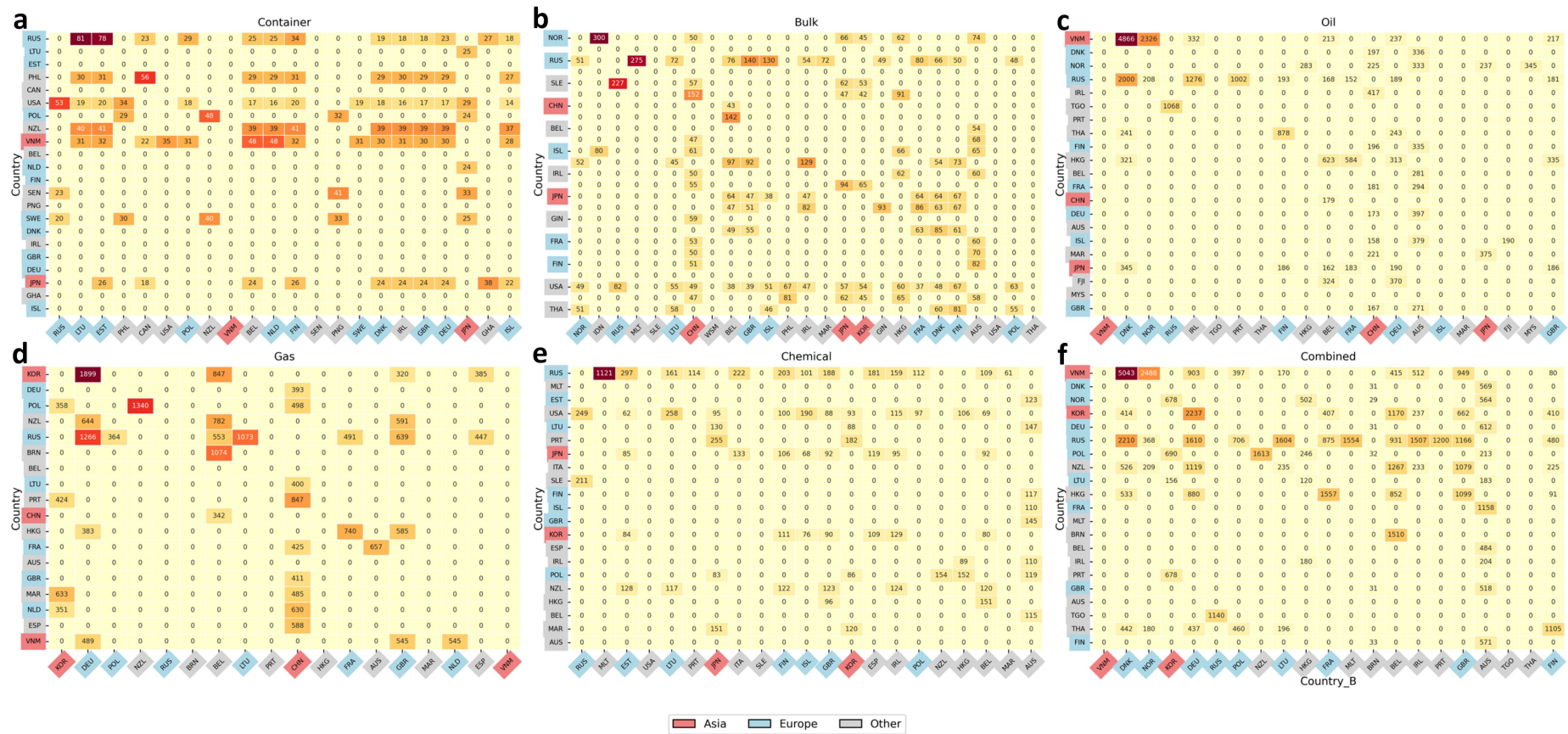
Supplementary Fig. 1 | Top 20 Country Pairs by Arctic Sea Route Dependence in 2100.

Each heatmap shows the top 20 country pairs with the highest share of voyages routed through the Arctic Sea Route (ASR) in 2100, by ship type: (a) container, (b) bulk, (c) oil + gas + chemical. Values denote the percentage of voyages between each country pair that used the ASR. Country labels are color-coded by region (Asia in red, Europe in blue).



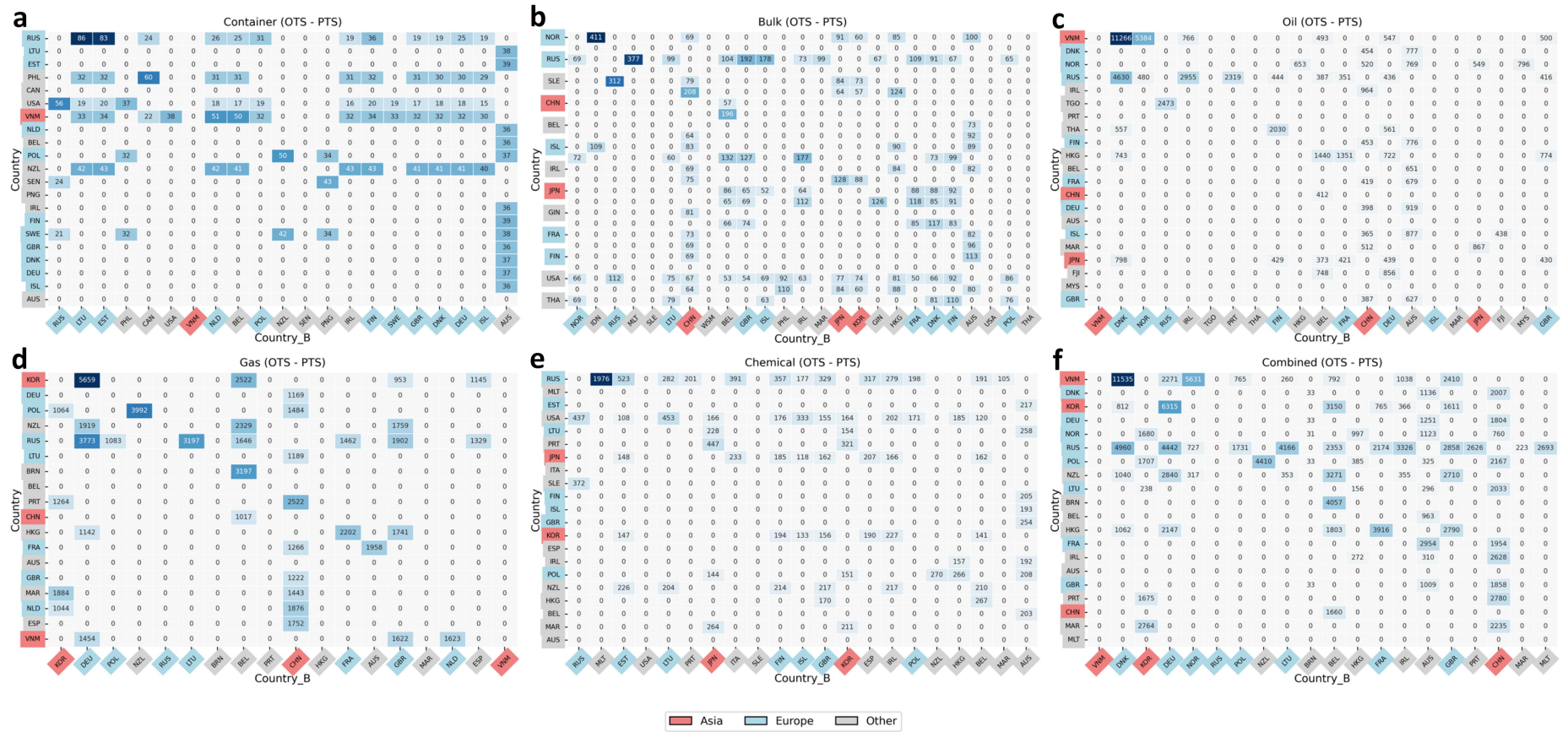
Supplementary Fig. 2 | Arctic Sea Route patterns by ship type under the Optimistic Trade Scenario (2100).

.Each heatmap shows the top 20 country pairs by voyage volume through the Arctic Sea Route (ASR) in 2100 under the Optimistic Trade Scenario (OTS), disaggregated by ship type: (a) container, (b) bulk, (c) oil, (d) gas, (e) chemical, and (f) combined (all vessel types). Country labels are color-coded by region (Asia in red, Europe in blue).



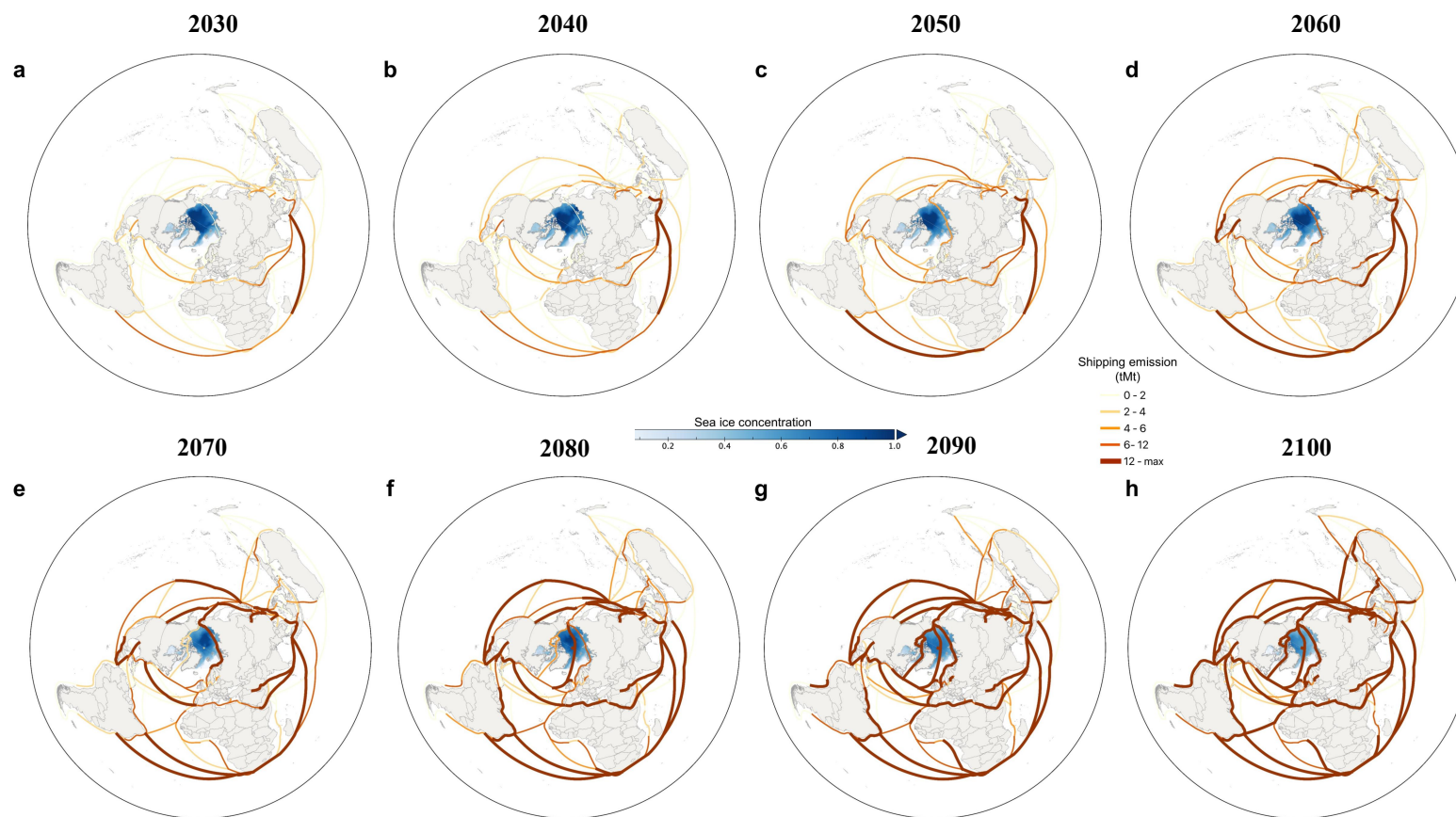
Supplementary Fig. 3 | Arctic Sea Route patterns by ship type under the Pessimistic Trade Scenario (2100).

Each heatmap shows the top 20 country pairs by voyage volume through the Arctic Sea Route (ASR) in 2100 under the Pessimistic Trade Scenario (PTS), disaggregated by ship type: (a) container, (b) bulk, (c) oil, (d) gas, (e) chemical, and (f) combined (all vessel types). Country labels are color-coded by region (Asia in red, Europe in blue).

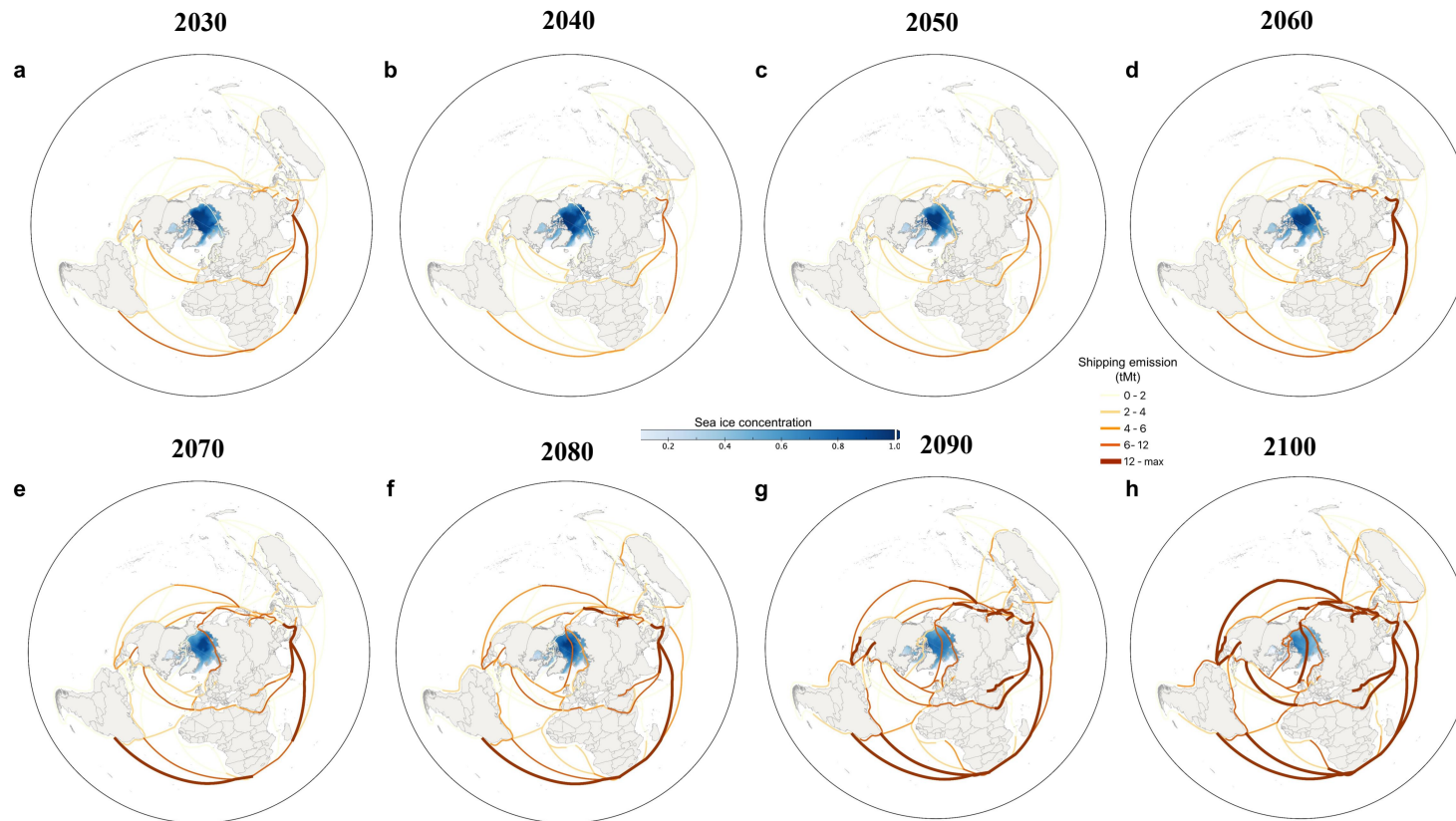


Supplementary Fig. 4 | Differences in Arctic Sea Route Voyages under Optimistic vs. Pessimistic Trade Scenarios in 2100.

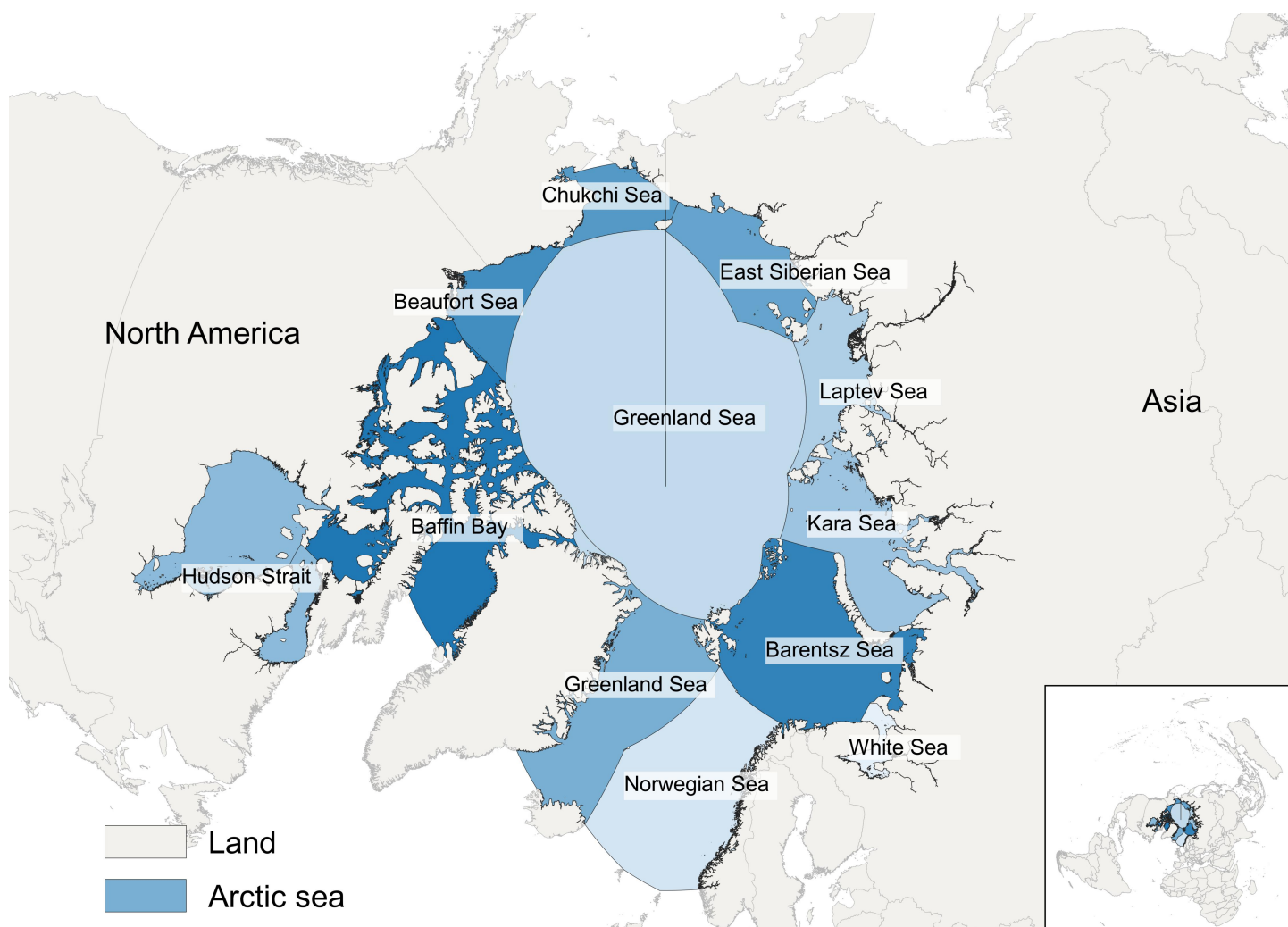
Each heatmap shows the difference in voyage counts through the Arctic Sea Route between the Optimistic Trade Scenario (OTS) and the Pessimistic Trade Scenario (PTS), across container (a), bulk (b), oil (c), gas (d), chemical (e), and total (f) vessels. Country labels are color-coded by region (Asia: red, Europe: blue). The Combined panel summarizes the total change across all ship types.



Supplementary Fig. 5 | Projected carbon emissions along major global shipping routes for five vessel types (container, bulk, chemical, gas, oil) under the business-as-usual (BAU) scenario with the Optimistic Trade Scenario (OTS). Emission intensity is rendered in yellow shades (darker = higher; units: Mt CO₂eq km⁻² yr⁻¹), overlaid on annual-mean sea-ice concentration in blue (which varies with projected climate conditions). Panels illustrate the temporal evolution of Arctic access and routing: (a) 2030, early-stage Arctic activity; (b) 2040, increased access; (c) 2050, significant growth; (d) 2060, continued expansion; (e) 2070, major routing shifts; (f) 2080, peak Arctic emissions in this scenario; (g) 2090, persistently high activity; (h) 2100, end-century state under BAU-OTS.

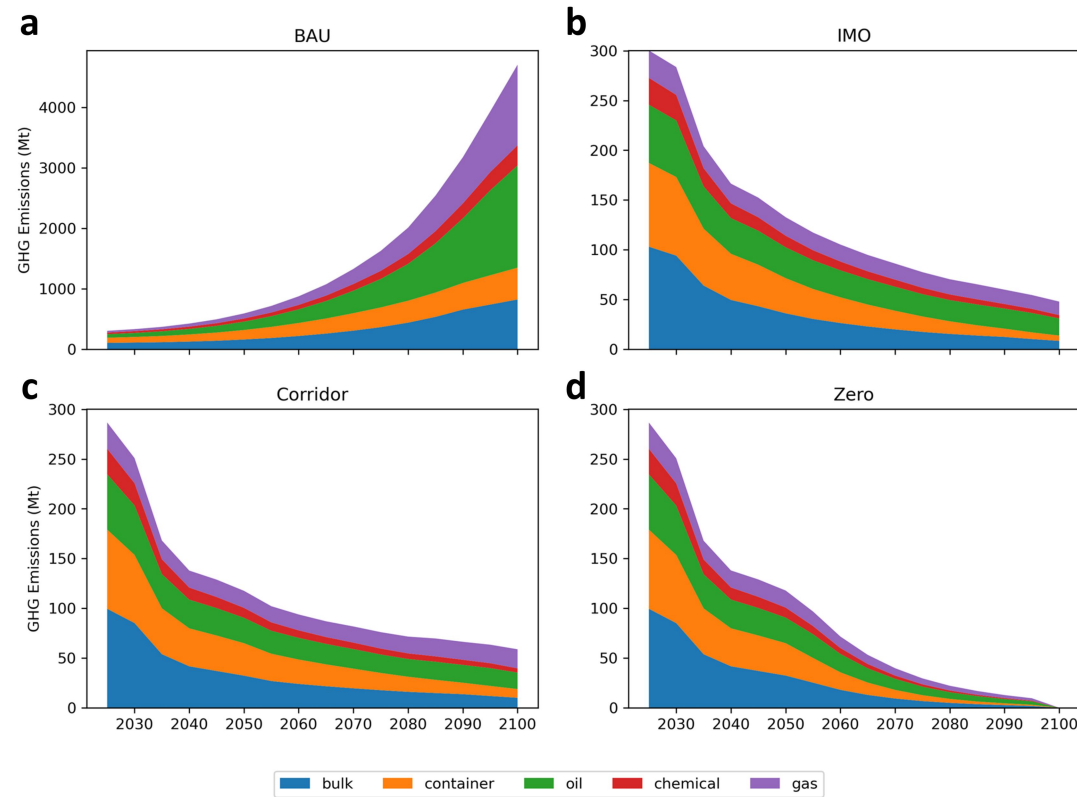


Supplementary Fig. 6 | Projected carbon emissions intensity along major global shipping routes for five vessel types (container, bulk, chemical, gas, oil) under the business-as-usual (BAU) scenario with the Pessimistic Trade Scenario (PTS). Projected annual carbon-emissions intensity for five vessel types (container, bulk, chemical, gas, oil) under the business-as-usual scenario with the Pessimistic Trade Scenario (PTS), shown for 2030–2100. Emission intensity is rendered in yellow shades (darker = higher; units: $\text{Mt CO}_2\text{eq km}^{-2} \text{yr}^{-1}$) over annual-mean sea-ice concentration in blue (varying with projected climate conditions). Panels trace the temporal evolution of Arctic access and routing under PTS: (a) 2030, early-stage Arctic activity; (b) 2040, limited growth in access; (c) 2050, development plateau; (d) 2060, continued yet constrained expansion; (e) 2070, routing shifts; (f) 2080, peak Arctic emissions in this scenario; (g) 2090, persistently high activity; (h) 2100, end-century state under BAU–PTS.

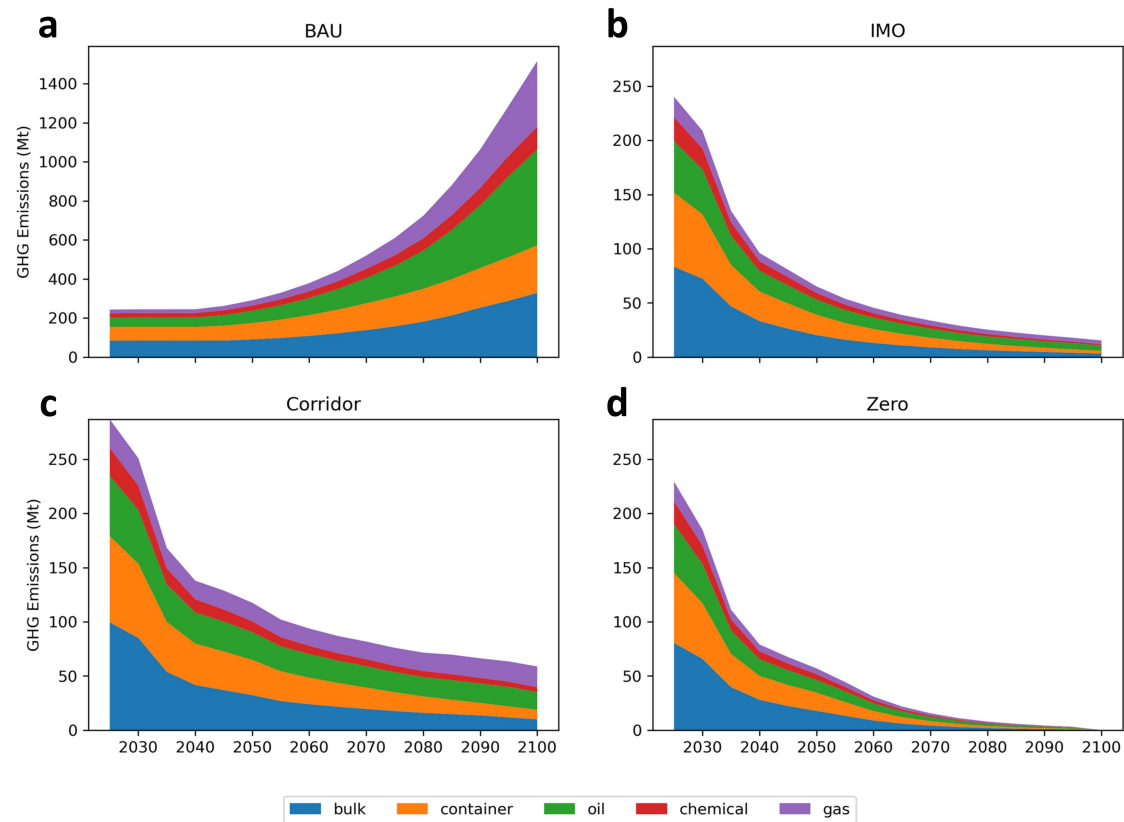


Supplementary Fig. 7 | Arctic sea area map with labeled subregions.

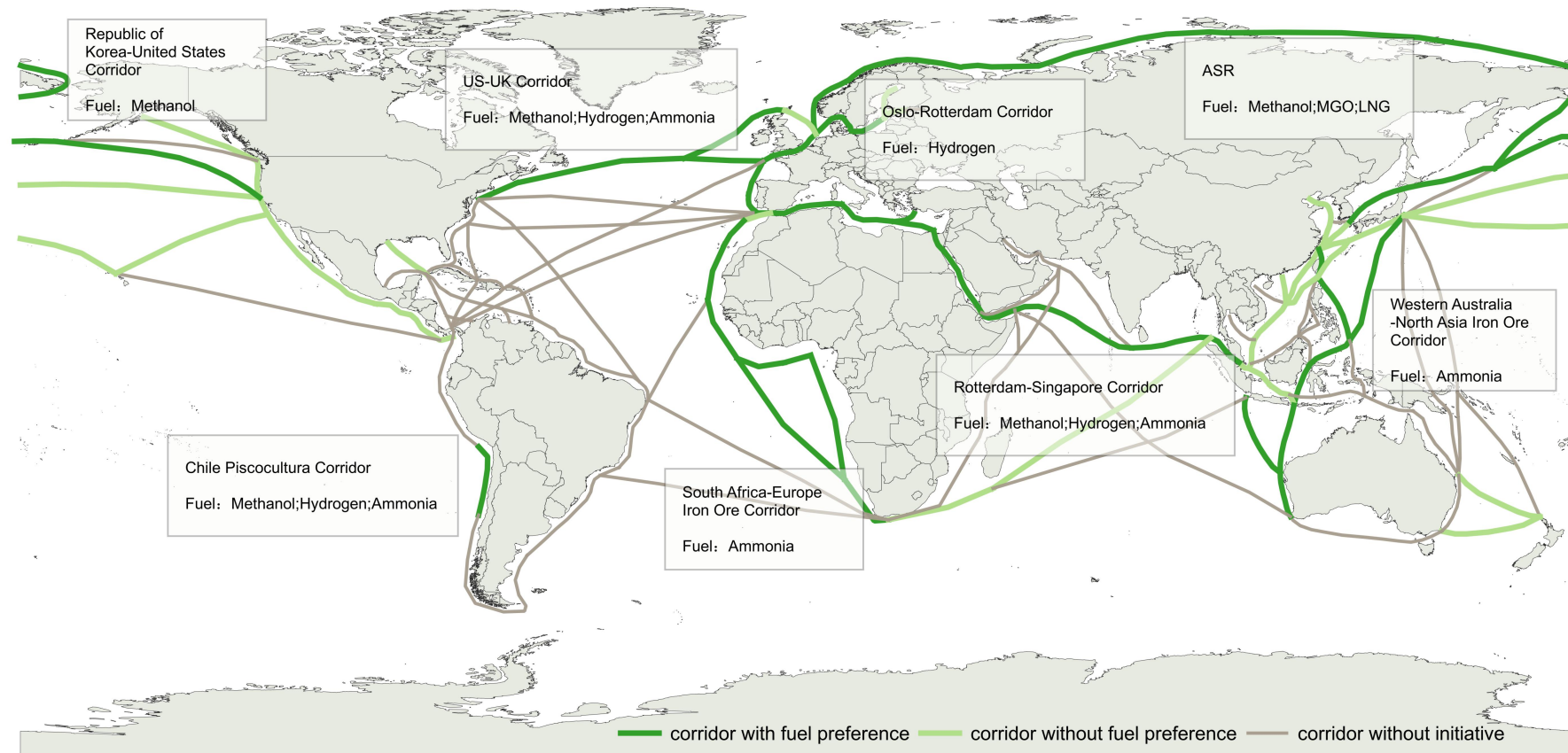
The figure delineates the boundaries and names of key Arctic maritime zones, including the Chukchi Sea, East Siberian Sea, Laptev Sea, Kara Sea, Barents Sea, and other adjacent waters.



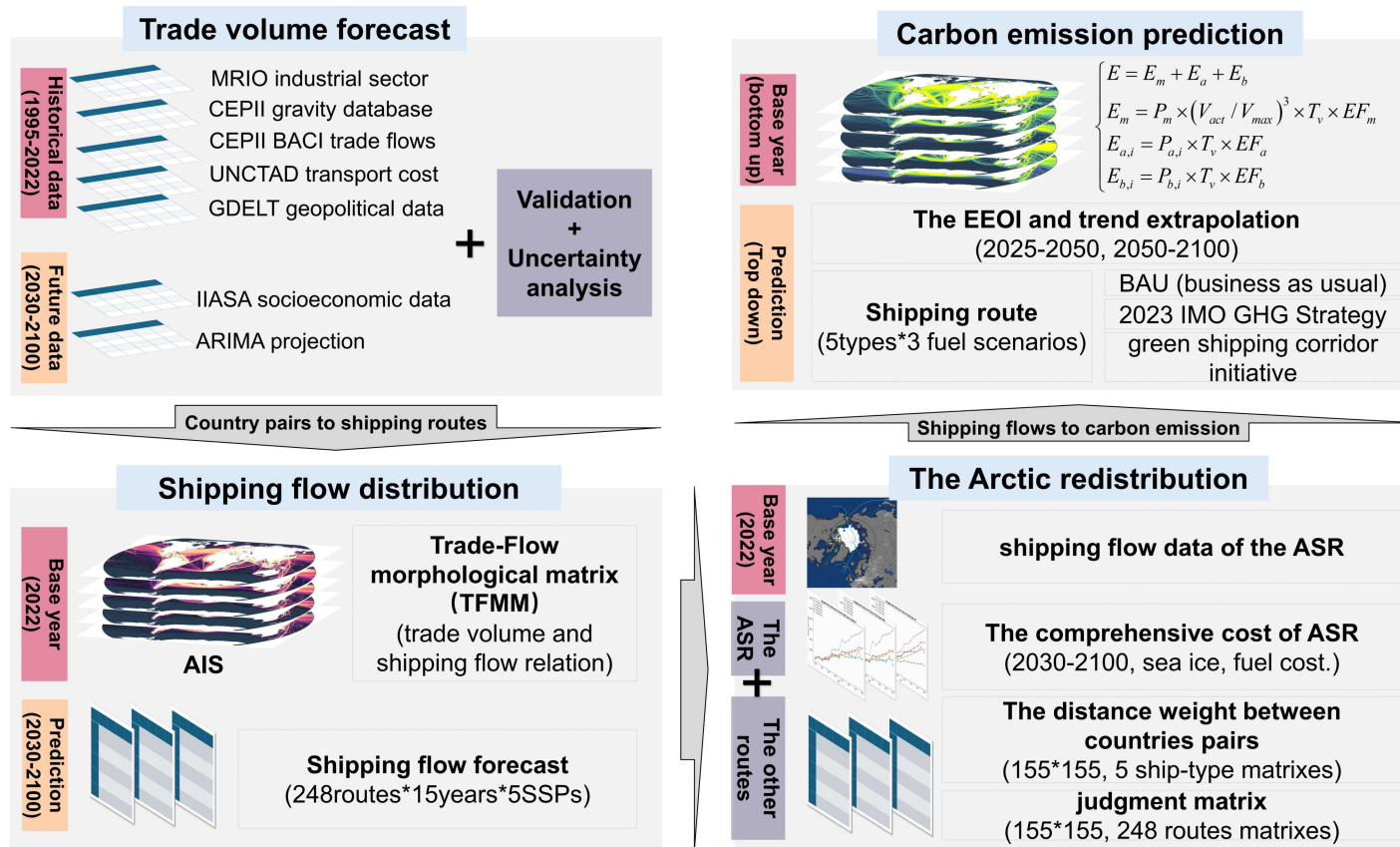
Supplementary Fig. 8 | Projected shipping carbon emissions by vessel type under one baseline and three decarbonization strategies, with Arctic Sea Route (ASR) access in the Optimistic Trade Scenario (OTS). Emissions are projected under four policy scenarios: a Business-as-Usual (BAU) baseline (a) and three decarbonization strategies—the IMO 2023 strategy(b), the Green Corridor strategy(c), and the Net-Zero strategy(d). IMO 2023 strategy refers to the 2023 IMO Strategy on the Reduction of GHG Emissions from Ships. IMO (International Maritime Organization) and GHG (greenhouse gas).



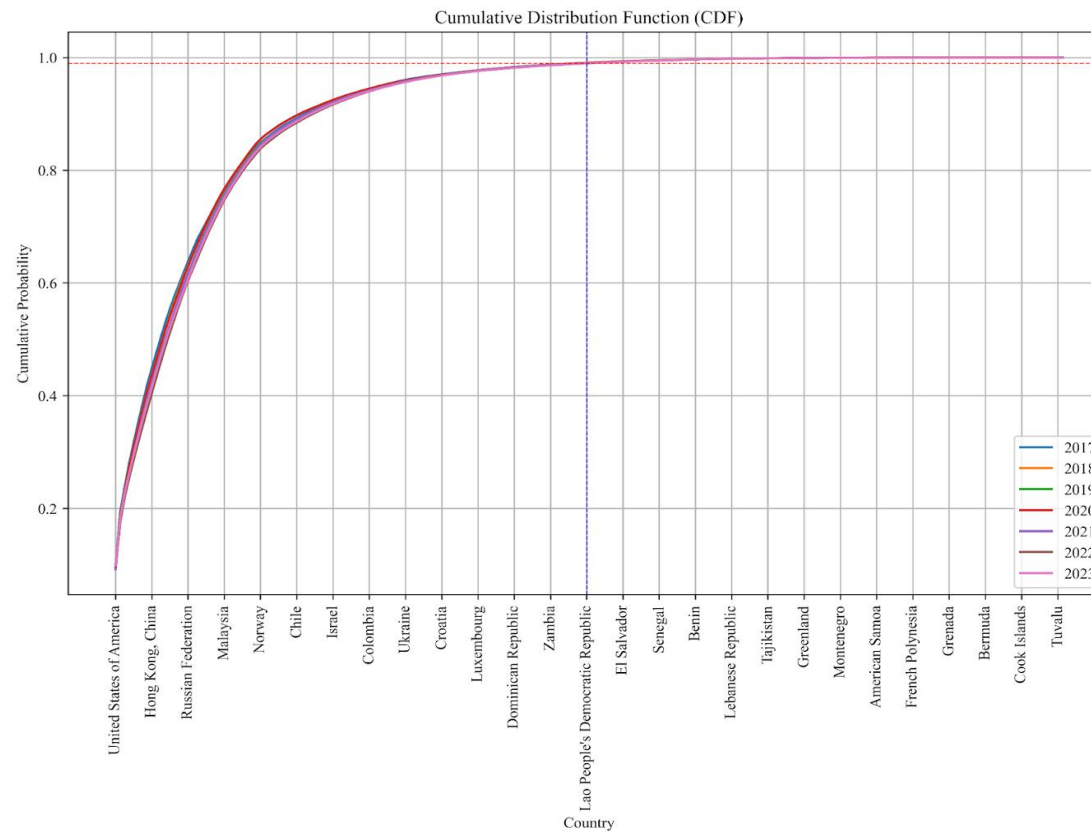
Supplementary Fig. 9 | Projected shipping carbon emissions by vessel type under one baseline and three decarbonization strategies, with Arctic Sea Route (ASR) access in the Pessimistic Trade Scenario (PTS). Emissions are projected under four policy scenarios: a Business-as-Usual (BAU) baseline (a) and three decarbonization strategies—the IMO 2023 strategy(b), the Green Corridor strategy(c), and the Net-Zero strategy(d).IMO 2023 strategy refers to the 2023 IMO Strategy on the Reduction of GHG Emissions from Ships. IMO (International Maritime Organization) and GHG (greenhouse gas).



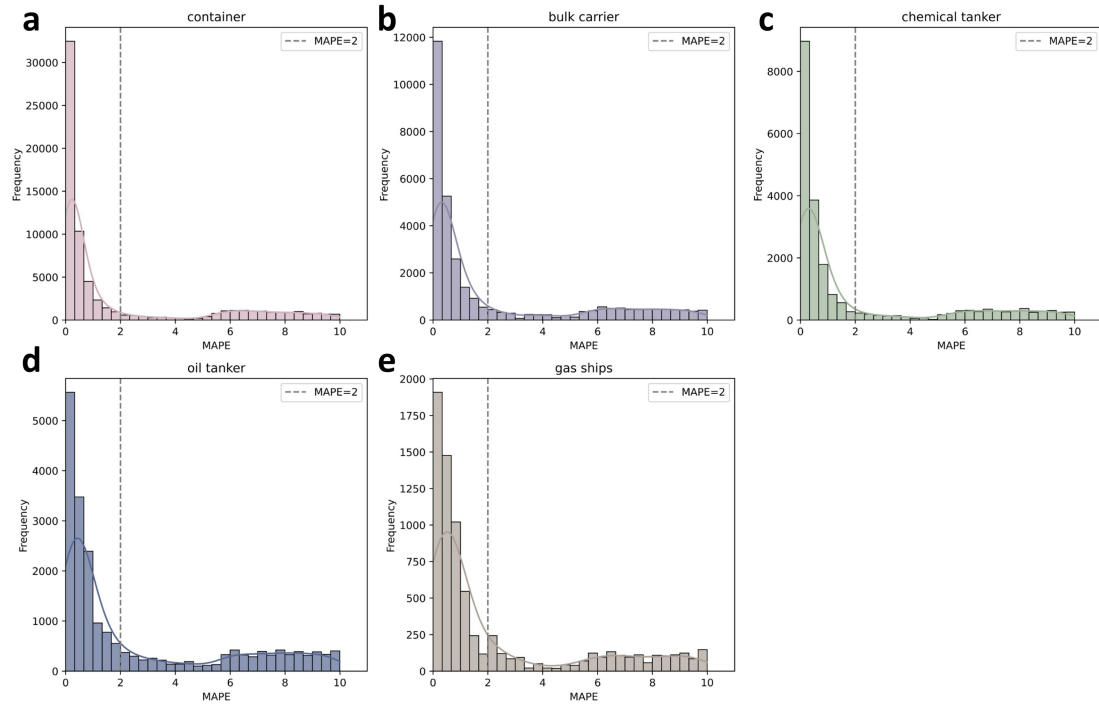
Supplementary Fig. 10 | The green shipping corridor spatial distribution, the main corridors are with the fuel preference. This map illustrates major international routes designated as green shipping corridors under the Green Corridor decarbonization strategy, which prioritizes accelerated deployment of low- and zero-carbon fuels in high-impact or ecologically sensitive regions. Corridors are classified by fuel-specific initiative level: green lines represent primary corridors where a preferred fuel has been identified, light green lines indicate corridors recognized as green shipping corridors but without a designated fuel choice (to be determined by future technological, economic, and infrastructure developments), and grey lines denote major routes not currently included in any formal green corridor initiative, where decarbonization may occur but not under the targeted, accelerated pathway.



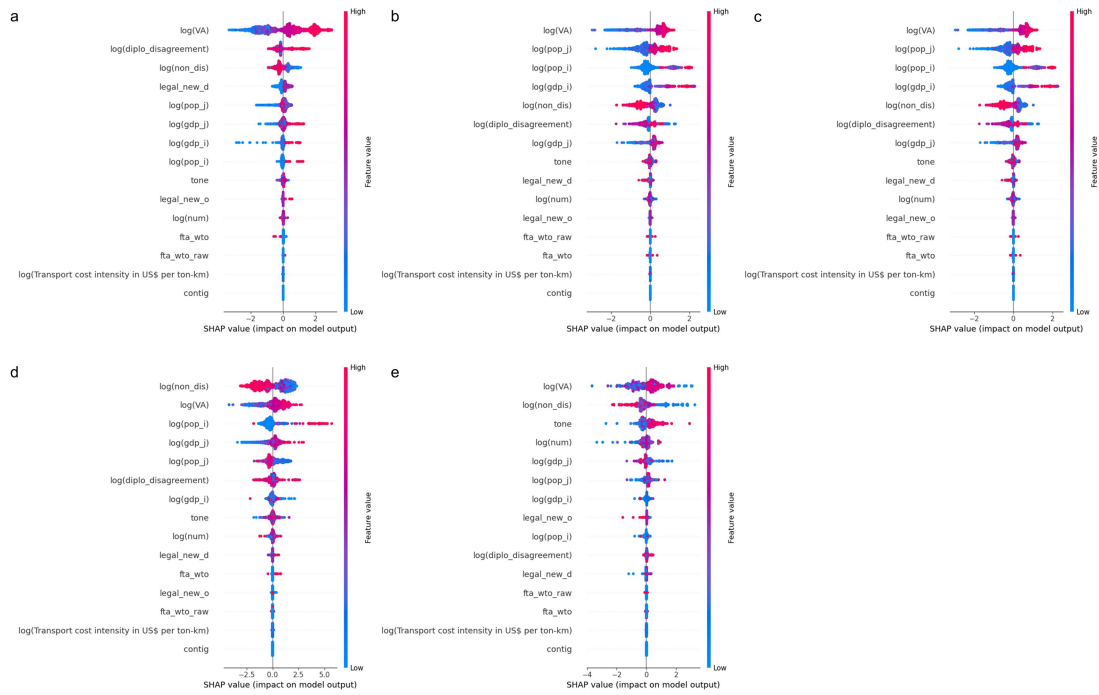
Supplementary Fig. 11 | Trade-Integrated Shipping Emission Projection (TISEP) Framework. This schematic illustrates the comprehensive, four-module framework developed in this study to project global maritime carbon emissions under future trade, climate, and policy scenarios. The TISEP model integrates historical data, predictive modeling, and scenario analysis to simulate how Arctic Sea Route (ASR) access will reshape shipping flows and emissions through the 21st century.



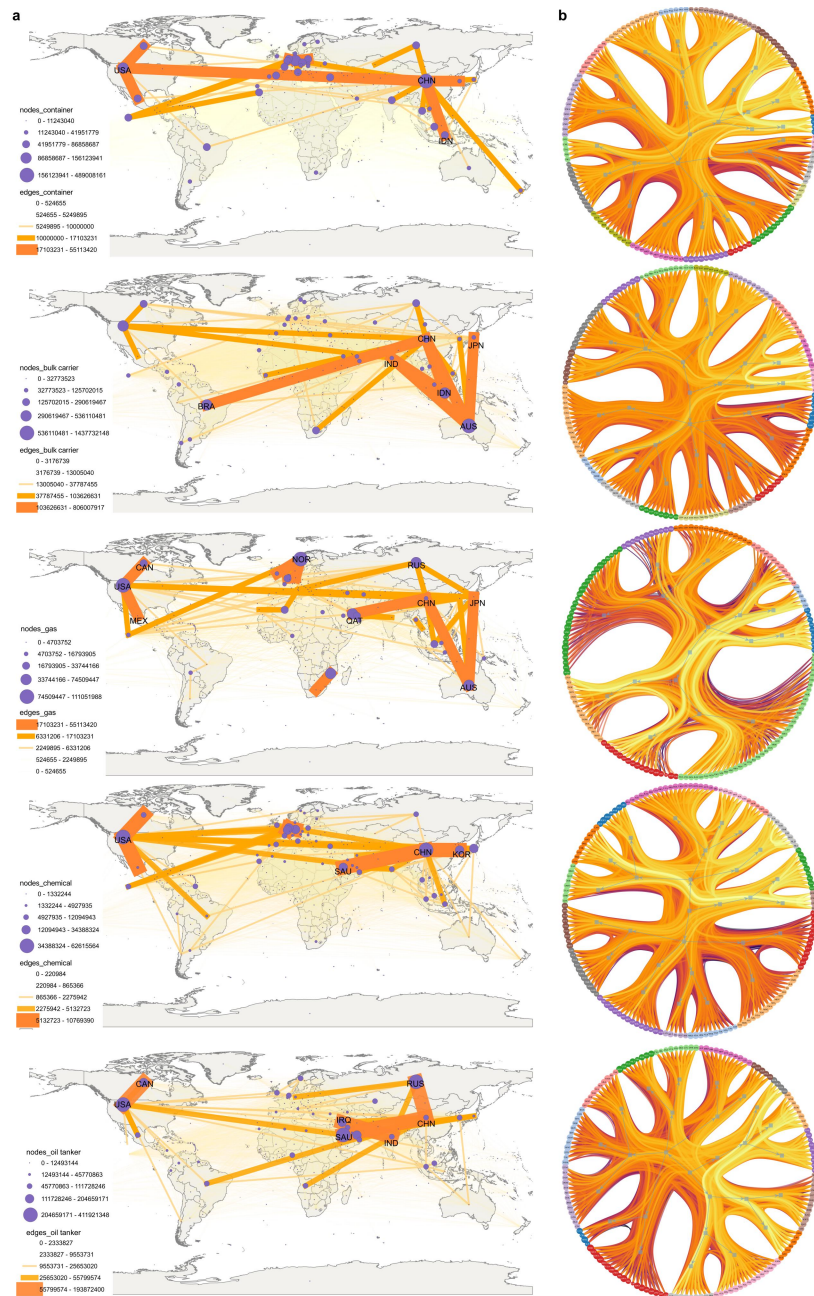
Supplementary Fig. 12 | The cumulative distribution of trade volumes by year. This figure shows the cumulative distribution function (CDF) of total global trade volume across all country pairs for each year from 2017 to 2023, plotting cumulative share (y-axis) against the rank of country pairs by trade volume (x-axis); the red dashed line marks the 98% cumulative probability threshold.



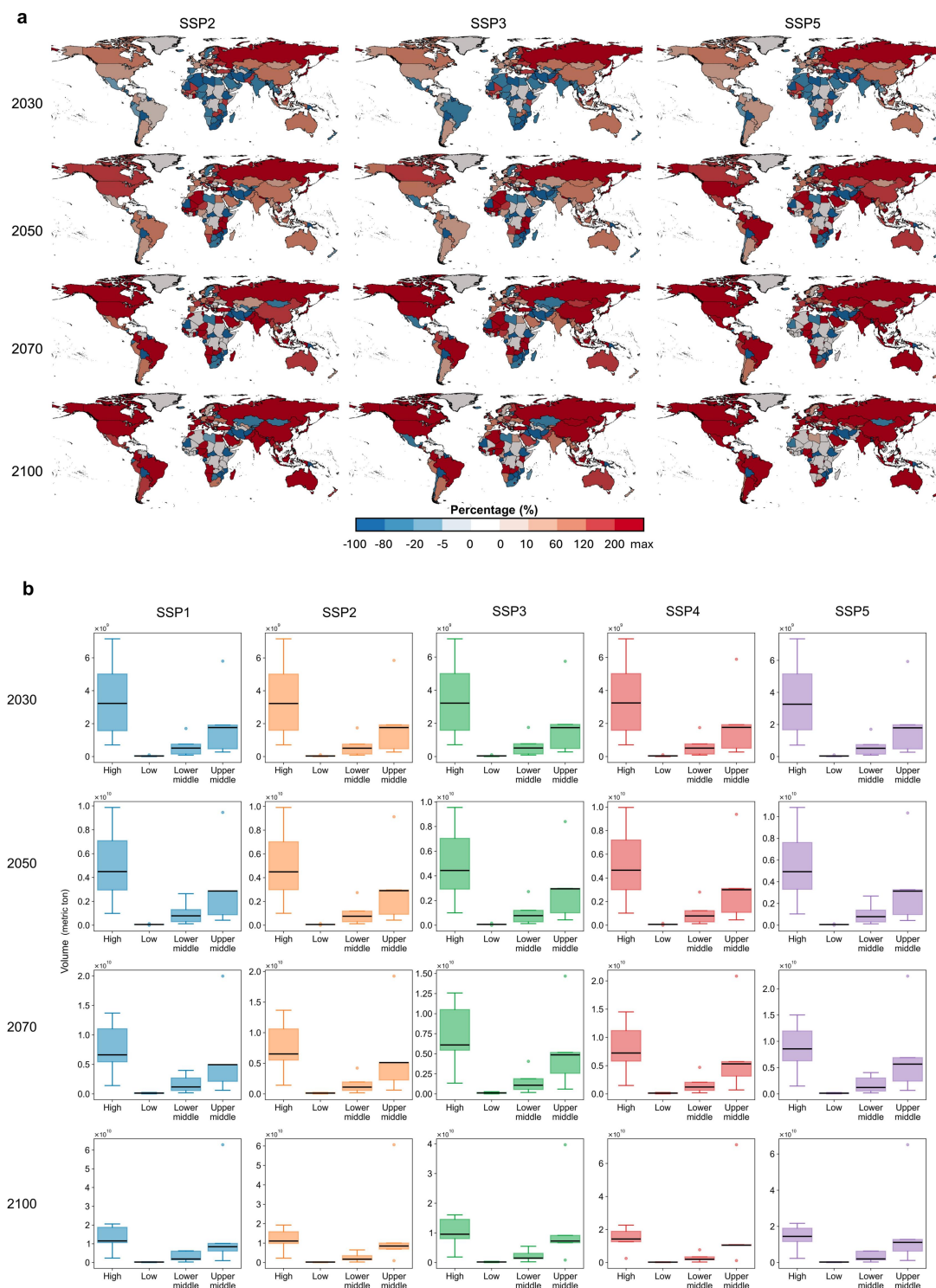
Supplementary Fig. 13 | Trade volume forecast validation and the SHapley Additive exPlanations (SHAP) values of the factors. Panels present the distribution of the best Mean Absolute Percentage Error (MAPE) values across different ship types for trade volume forecast, the dashed vertical lines in each panel represent a benchmark MAPE value of 2. The ship types analyzed are (a) Container ships, (b) Bulk carriers, (c) Chemical tankers, (d) Oil tankers, and (e) Gas ships.



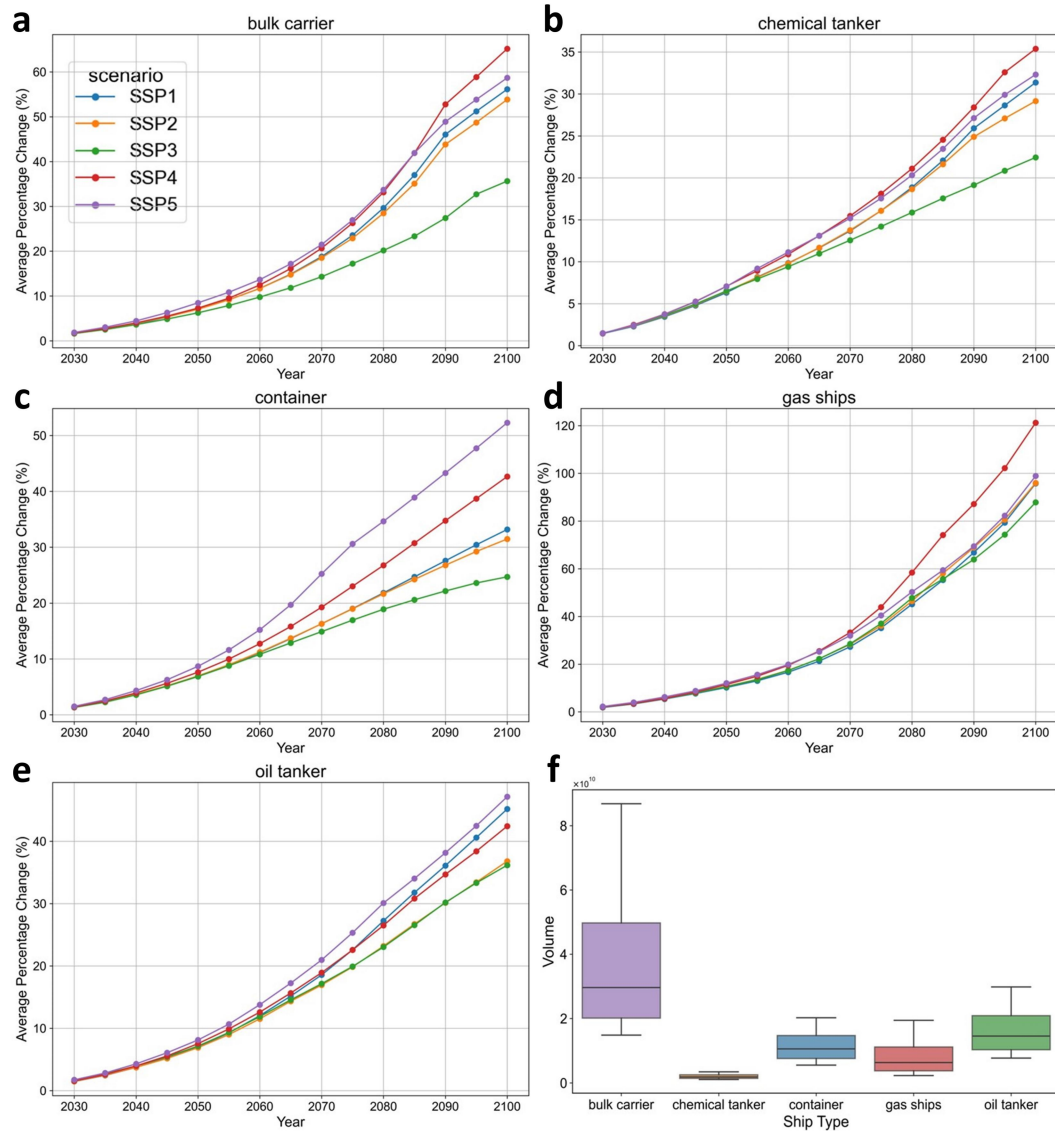
Supplementary Fig. 14 | SHapley Additive exPlanations (SHAP) values for the key factors influencing the trade volume forecast across all ship types. (a) Container ships, (b) Bulk carriers, (c) Chemical tankers, (d) Oil tankers, and (e) Gas ships.



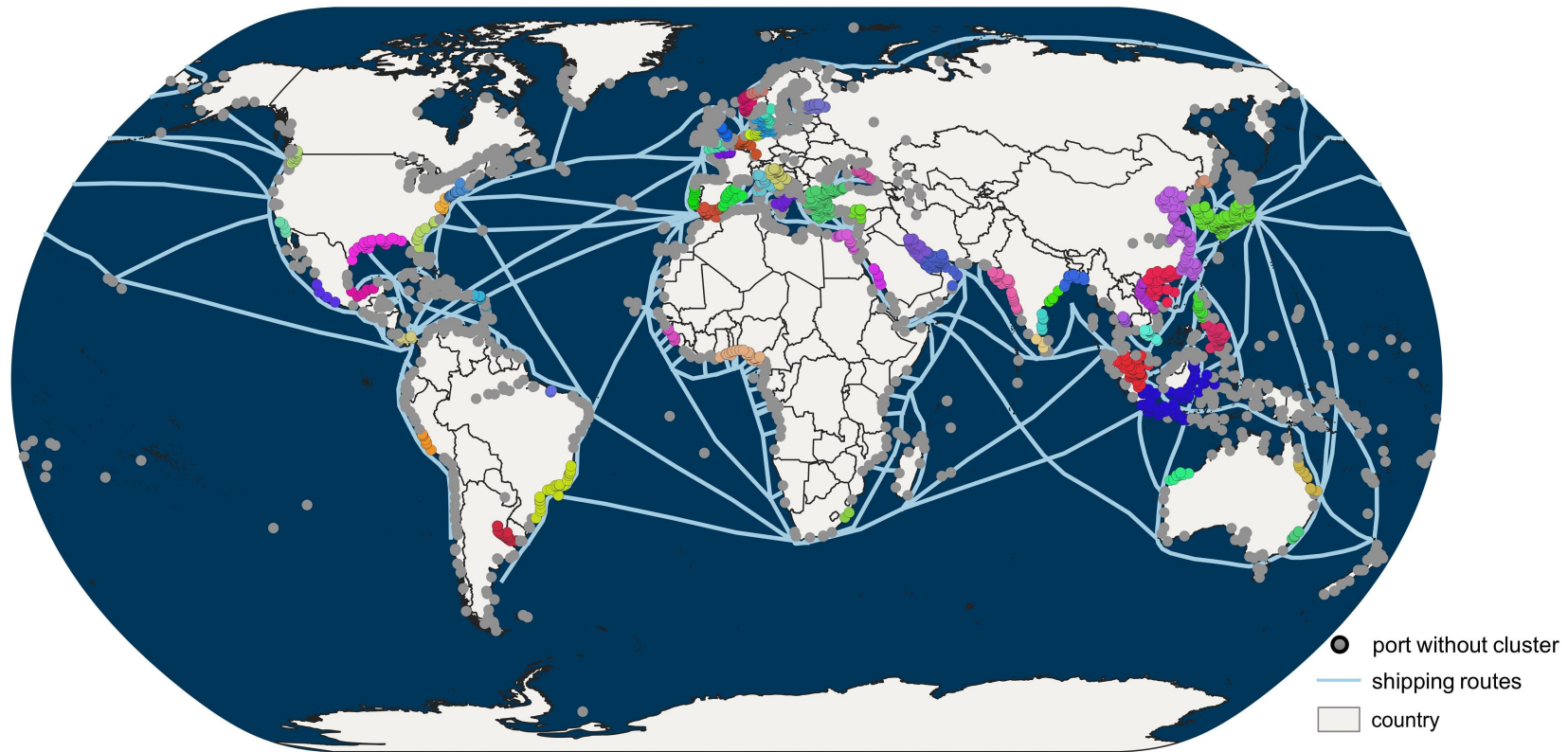
Supplementary Fig. 15 | Global trade network visualization for different vessel types. (a) Geographic distribution of trade networks by vessel type: container, bulk carrier, gas, chemical, and oil tanker. Each map shows key trade routes (orange lines) and hubs (purple circles), with line thickness indicating trade volume on each route. Node size represents trade volume at each hub. (b) Clustered network density of trade routes by vessel type: Circular diagrams show clusters of countries based on trade network proximity and density, with edge color intensity (yellow to orange) representing trade volume between clusters



Supplementary Fig. 16 | Trade volumes by country and income classification. (a) the year-on-year change of trade volume of selected years and scenarios (b) the sum of trade volumes of different income classifications by years and scenarios. Maps are made with Natural Earth.

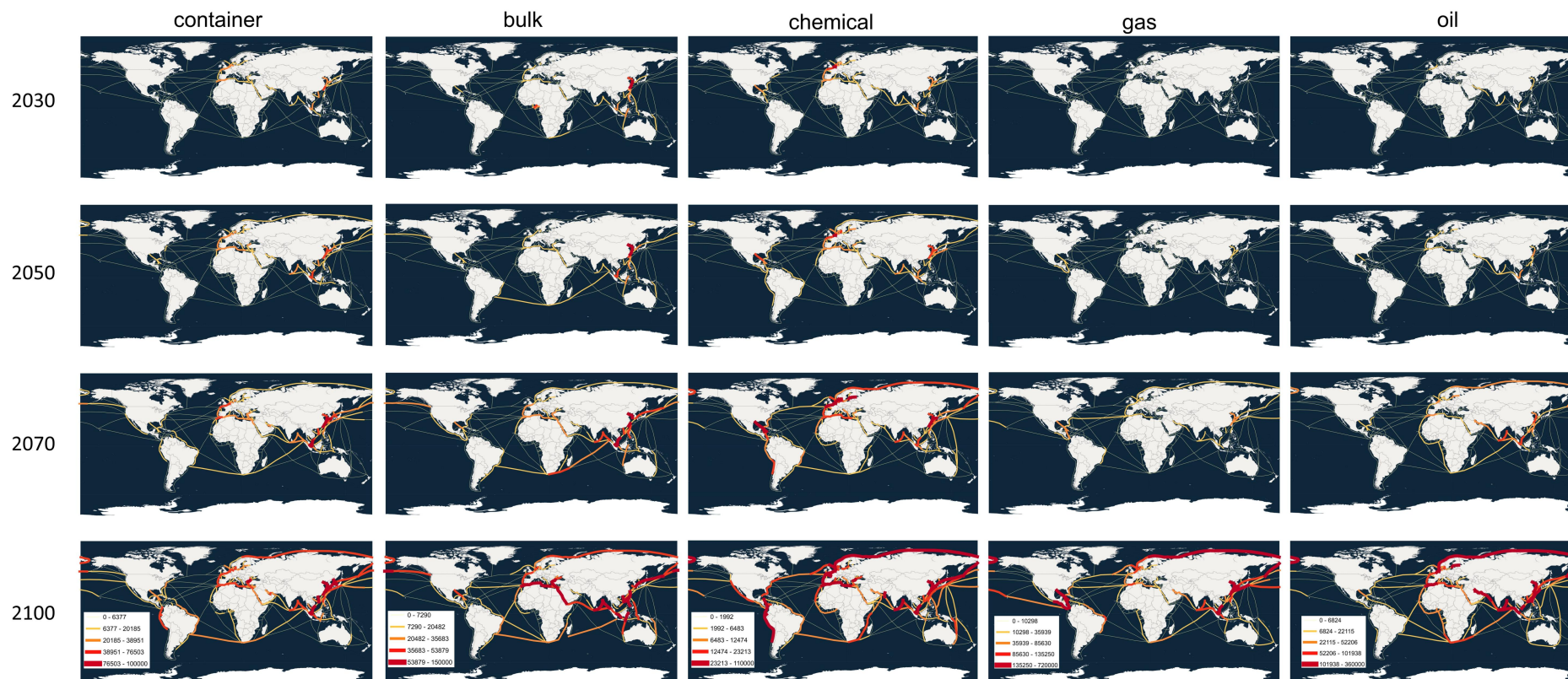


Supplementary Fig. 17 | The average percentage change and the trade volume distribution by vessel type of Shared Socioeconomic Pathway 2 (SSP2). Panels show projections for (a) bulk carriers, (b) chemical tankers, (c) container ships, (d) gas carriers, and (e) oil tankers. Each line graph illustrates the projected average annual percentage change in trade volume from 2030 to 2100 under five Shared Socioeconomic Pathways (SSP1–SSP5). Panel (f) presents a box plot of the total projected trade volume (metric tons) in 2100 for each vessel type under SSP2, which serves as the baseline scenario for shipping-flow projections in this study.

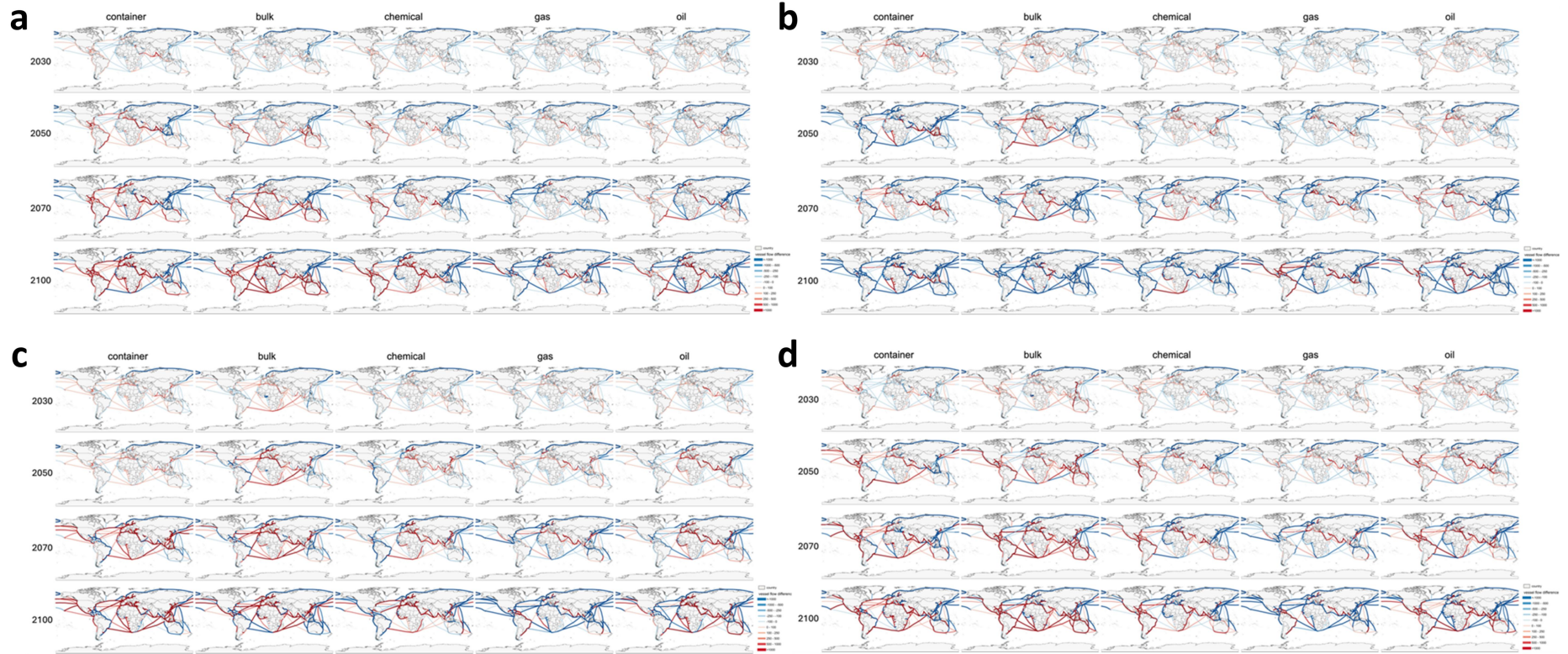


Supplementary Fig. 18 | The clusters of ports and the main shipping routes.

Note: This analysis focuses on international shipping flows, as domestic trade volumes are not reported in the BACI database. To identify major maritime corridors and port clusters, we applied the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm. DBSCAN detects clusters based on local point density and is well-suited for spatial networks due to its ability to capture arbitrarily shaped clusters without requiring a predefined number of groups. To account for variation in port size and significance, we weighted each port by its total deadweight tonnage (T-DWT) of inbound and outbound vessels. After sensitivity testing, we selected a neighborhood radius of 300 km and a minimum of 20 neighboring ports, resulting in the classification of 60 global port clusters.

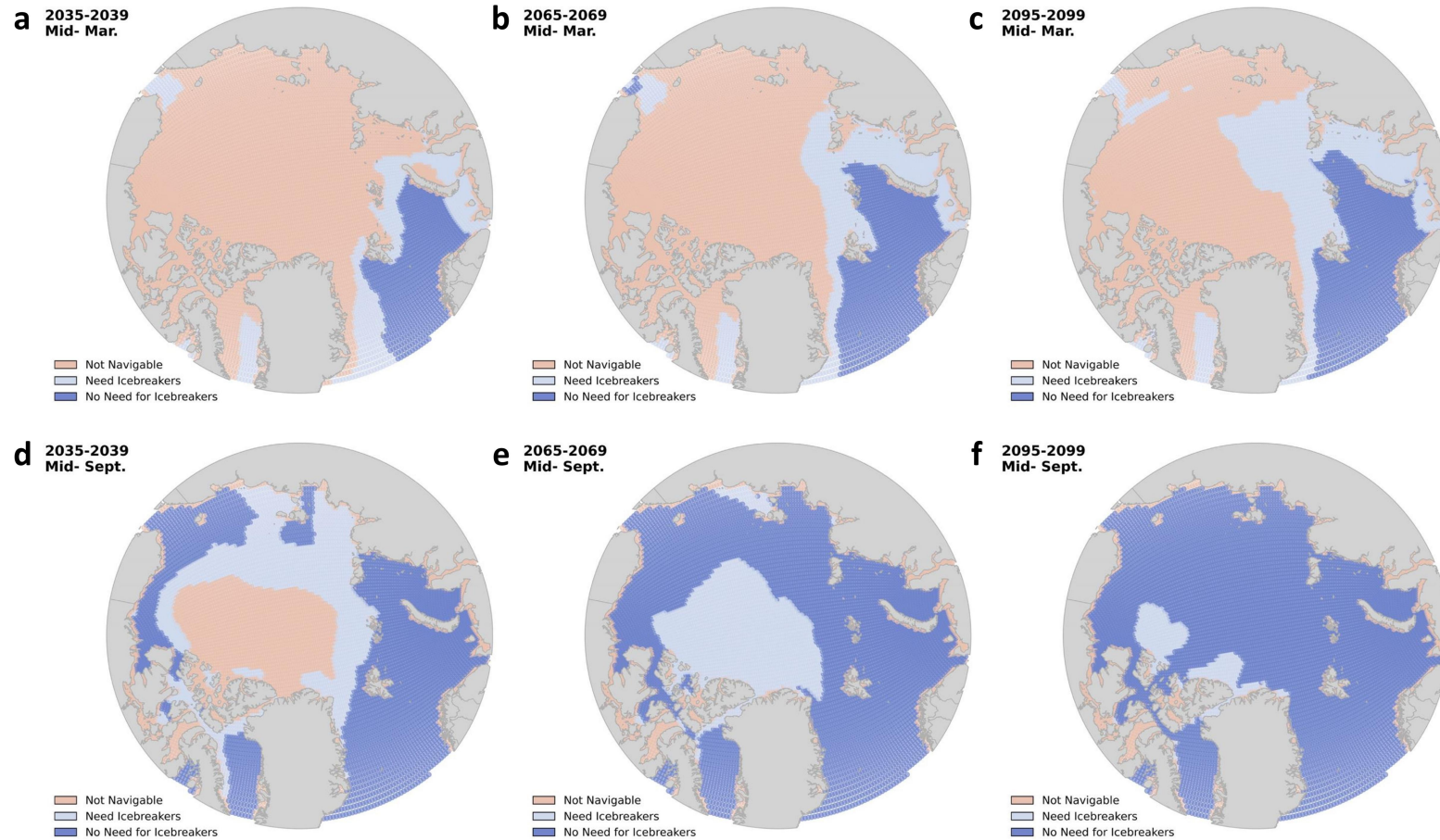


Supplementary Fig. 19 | Shipping flow distribution by vessel type under Shared Socioeconomic Pathway 2 (SSP2) Scenario. Maps illustrate global shipping flow patterns, highlighting port locations and main shipping routes of five vessel types (container, bulk, chemical, gas, and oil) in different future years (2030, 2050, 2070, 2100). The intensity of flow is represented by color gradients, where higher shipping flow volumes are indicated by warmer colors and lower volumes by cooler colors. The color legend in each panel indicates the range of shipping flow volumes, with varying scales across vessel types and years.

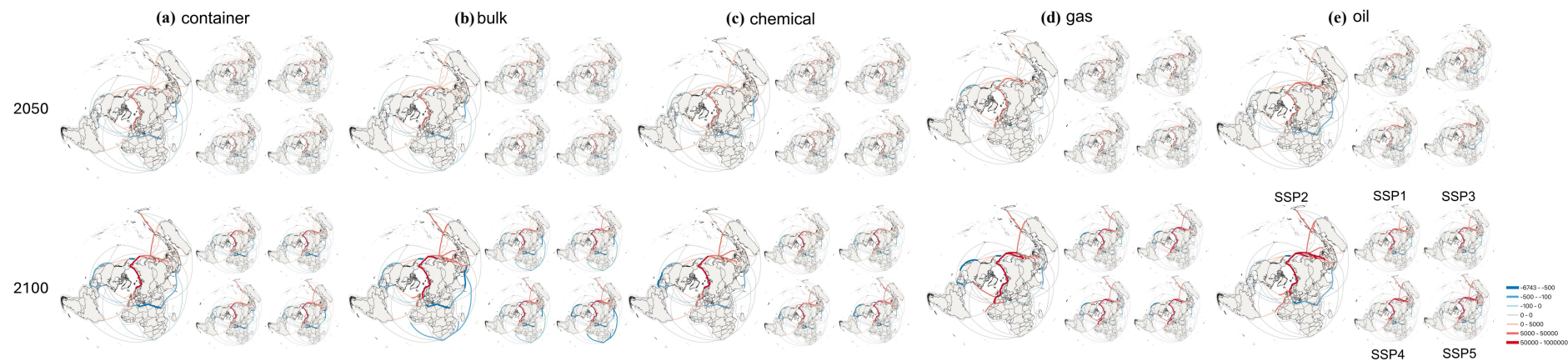


Supplementary Fig. 20 | Global shipping flow differences by vessel type under alternative Shared Socioeconomic Pathway (SSP) scenarios relative to SSP2. (a) SSP1 vs. SSP2, (b) SSP3 vs. SSP2, (c) SSP4 vs. SSP2, (d) SSP5 vs. SSP2.

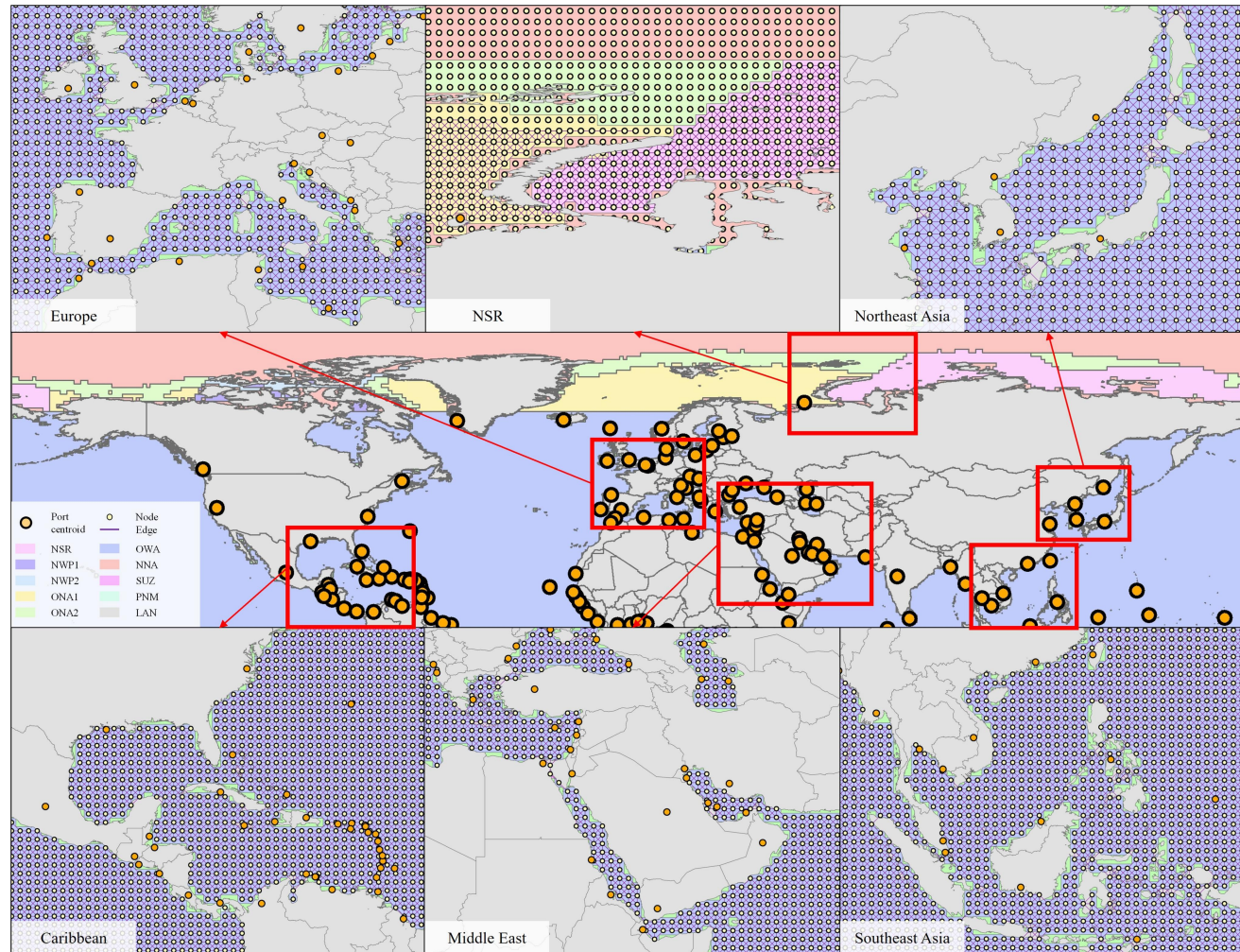
Note: Each panel shows spatial changes in global shipping flow distribution for major vessel types under different Shared Socioeconomic Pathways (SSPs), relative to SSP2, across selected years. Red indicates increased vessel flow and blue indicates reduced flow. The differences reflect how long-term socioeconomic development trajectories influence global maritime routing patterns and intensity.



Supplementary Fig. 21 | Projected Arctic Sea Route navigability under Shared Socioeconomic Pathway 2 (SSP2). Spatial distribution of vessel accessibility conditions—not navigable, requires icebreaker, or no icebreaker needed—derived from forecasts of sea-ice thickness (SIT), sea-ice concentration (SIC), and ice motion following the dynamic sea-ice modeling approach of Zhao et al. (2024). Simulations were conducted at 10-day intervals to capture seasonal and intra-seasonal variability. Panels show mid-March snapshots for (a) 2035–2039, (b) 2065–2069, (c) 2095–2099, and mid-September snapshots for (d) 2035–2039, (e) 2065–2069, (f) 2095–2099, highlighting the seasonal contrast and the long-term expansion of navigable waters, particularly in late summer.



Supplementary Fig. 22 | Global shipping flow differences under scenarios with and without the Arctic Shipping Route (ASR) opening, presented by vessel types (container, bulk, chemical, gas, oil) across five Shared Socioeconomic Pathways (SSPs) for the years 2050 and 2100. Columns correspond to vessel types—(a) container, (b) bulk, (c) chemical, (d) gas, (e) oil—and rows to the five Shared Socioeconomic Pathways (SSP1–SSP5) for the years 2050 (top) and 2100 (bottom). Differences are visualized by line thickness and color: red indicates increased flows and blue indicates decreased flows (darker shades = larger magnitude). The maps highlight how opening the Arctic Sea Route (ASR) reshapes global trade patterns across vessel types, scenarios, and time.



Supplementary Fig. 23 | Global distribution of navigation areas, port centroids, and cost-search grid (based on ice conditions in mid-September 2025).

The map shows the global distribution of navigation areas and the $1^{\circ} \times 1^{\circ}$ cost-search grid used in the route optimization model.

CHN_S - NLD Container

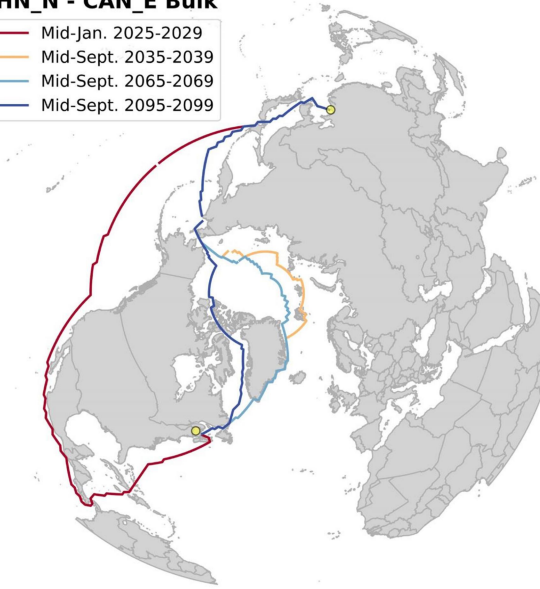
— Mid-Jan. 2025-2029
— Mid-Sept. 2035-2039
— Mid-Sept. 2065-2069
— Mid-Sept. 2095-2099



a

CHN_N - CAN_E Bulk

— Mid-Jan. 2025-2029
— Mid-Sept. 2035-2039
— Mid-Sept. 2065-2069
— Mid-Sept. 2095-2099



b

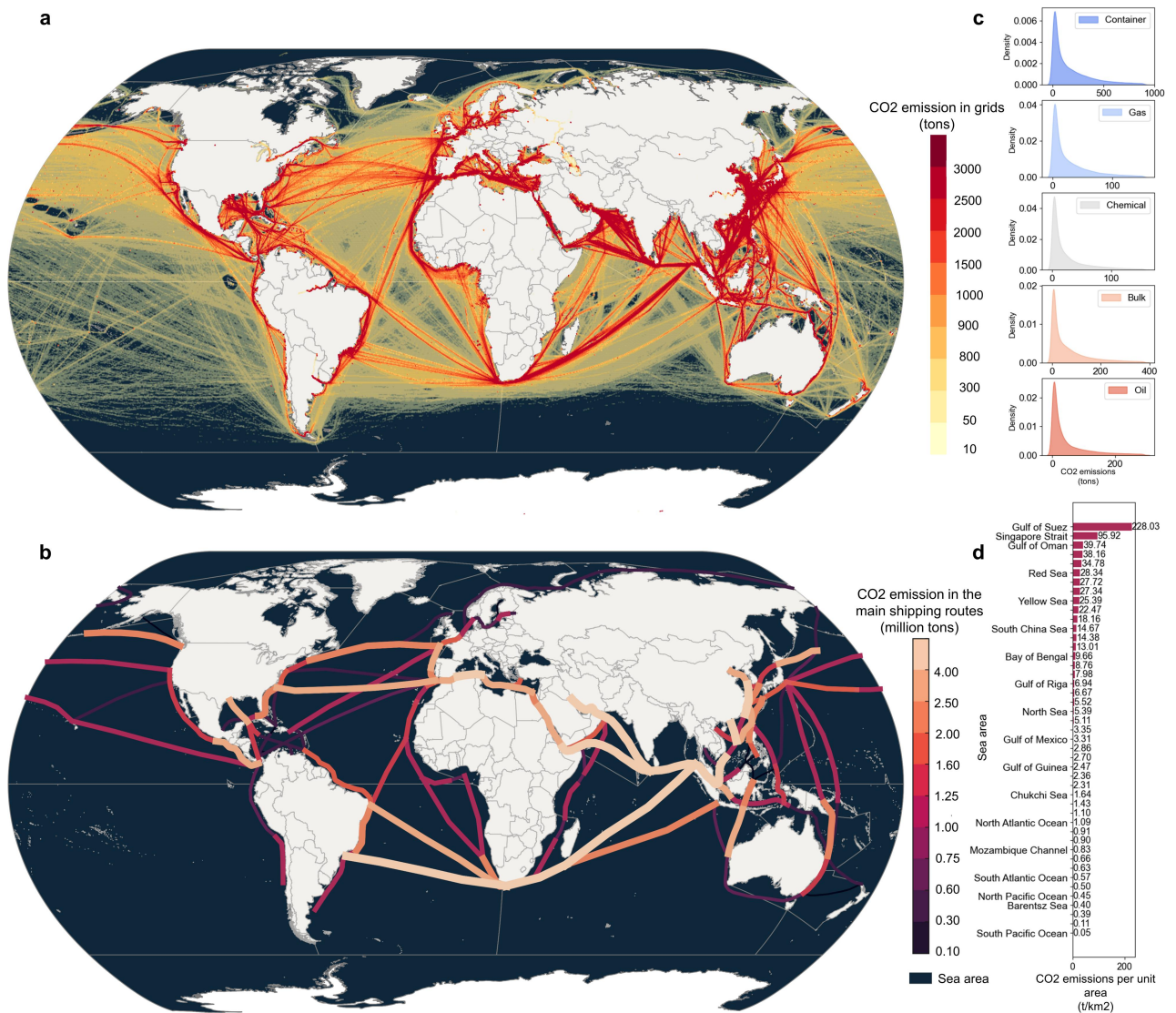
USA_W - RUS_T Oil

— Mid-Jan. 2025-2029
— Mid-Sept. 2035-2039
— Mid-Sept. 2065-2069
— Mid-Sept. 2095-2099

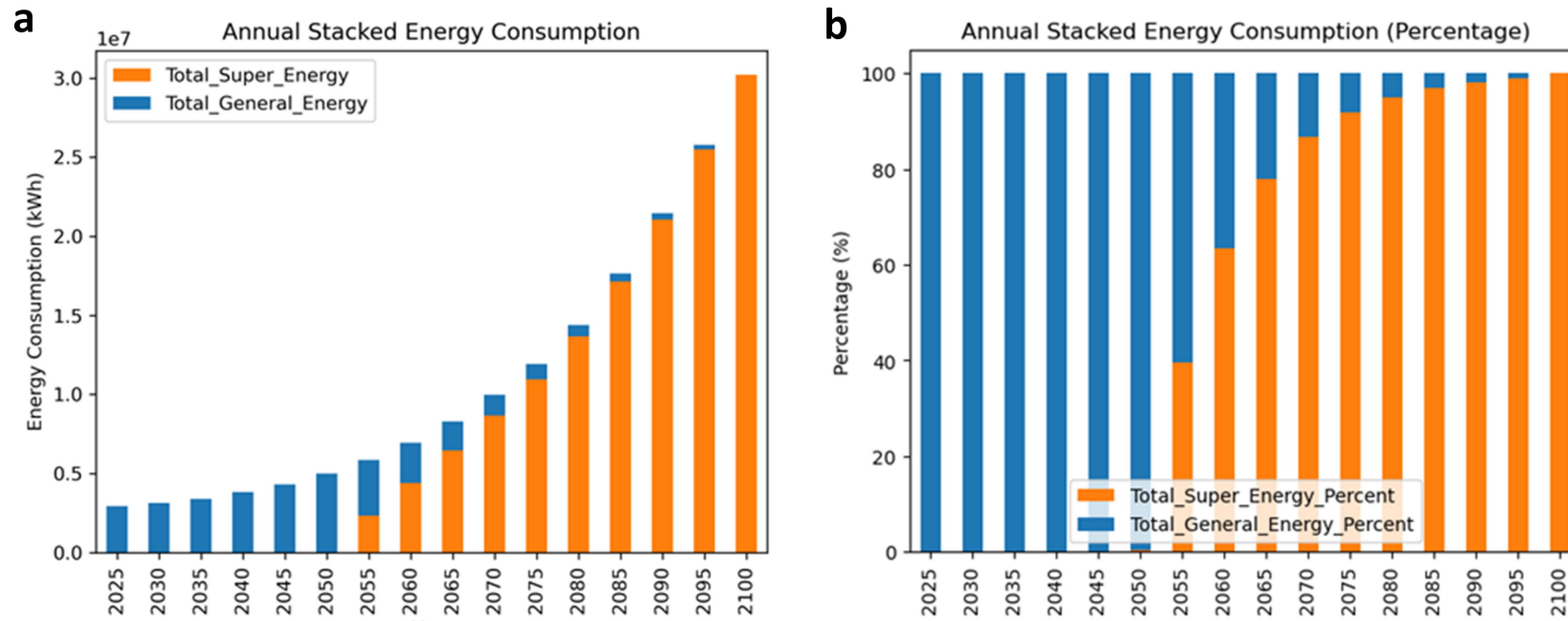


c

Supplementary Fig. 24 | Example of Path Search Results (CHN_S: Southern China; CHN_N: Northern China; CAN_E: Eastern Canada; USA_W: Western United States; RUS_T: Russian Baltic Region). Optimal maritime routes under varying ice conditions, illustrating the evolution of Arctic accessibility from 2025 to 2099. Panels: (a) CHN_S→NLD, container; (b) CHN_N →CAN_E, bulk; (c) USA_W → RUS_T, oil. Routes are computed with the grid-based cost model and shown for mid-January and mid-September windows to reflect seasonal navigability changes.



Supplementary Fig. 25 | Distribution of international shipping CO₂ emissions by vessel type for the base year 2022. (a) CO₂ emissions of all ships on a $0.25^\circ \times 0.25^\circ$ grid. The map highlights the major global shipping routes with the intensity of emissions depicted through a color gradient ranging from yellow (lower emissions) to dark red (higher emissions). (b) CO₂ emissions of all ships along main shipping routes. The thicker and darker lines correspond to higher emissions. (c) Kernel density estimation (KDE) of CO₂ emissions by grid and by vessel type. (d) CO₂ emissions of five kinds of vessel ships by sea area.



Supplementary Fig. 26 | Evolution of energy consumption under the Net-Zero strategy from 2025 to 2100.

(a) Annual energy use by category, distinguishing between zero-carbon fuels (electricity, hydrogen, nuclear) and conventional fuels—including fossil fuels and low-carbon alternatives—evolved from the Green Corridor strategy baseline.

(b) Proportional share of each fuel type over time, reflecting the transition from conventional to zero-carbon energy sources in the global fleet.

Supplementary Methods

Supplementary Method 1| Global Trade Volume Forecasting

(1) Data Sources and Preprocessing

Bilateral trade volumes were obtained from the CEPII BACI database, which compiles harmonized international trade data originally sourced from United Nations (UN) Comtrade. To isolate maritime trade specifically, total values were adjusted using seaborne trade proportions by commodity class. Commodity classifications follow the Harmonized System (HS), and each HS code was mapped to one of five vessel types—container, bulk, chemical, oil, and gas—based on dominant cargo characteristics. General cargo, which lacks specific HS codes, was grouped with containerized cargo in subsequent analyses. The mapping scheme is presented in [Supplementary Table 2](#). Landlocked countries were excluded due to the unavailability of AIS-derived maritime data. Despite these exclusions, the dataset captures over 98% of global trade volume, ensuring near-complete spatial and sectoral coverage ([Supplementary Fig. 12](#)). To capture value-added trade flows and account for indirect linkages across global supply chains, we incorporated the Eora Multi-Region Input–Output (MRIO) database. This enabled sectoral and regional decomposition of trade, enhancing the accuracy of volume estimates (Lenzen et al., 2012).

Future socioeconomic trajectories were aligned with the Shared Socioeconomic Pathways (SSPs), a set of five internally consistent development scenarios compiled by IIASA for the IPCC’s Fifth Assessment Report. Each SSP comprises quantitative projections of Gross Domestic Product (GDP) and population, along with qualitative narratives. In this study, socioeconomic projections were integrated under the assumption of consistency across Representative Concentration Pathways (RCPs), consistent with the AIM/CGE framework.

(2) Trade Volume Forecasting

A multivariate regression model was developed to forecast bilateral maritime trade volumes under different SSP scenarios. The model was trained on historical trade data and included a comprehensive set of macroeconomic, geographic, and institutional predictors, namely: Transport cost intensity ($\text{USD ton}^{-1} \text{ km}^{-2}$), World Trade Organization (WTO) and Free Trade Agreement (FTA) membership, Geographic contiguity, GDP and population of both trading partners, Legal agreement alignment, Diplomatic conflict indicators.

The full list of model variables is provided in [Supplementary Table 2](#). All predictors demonstrated low multicollinearity, with variance inflation factors (VIFs) below 5, ensuring stable and interpretable estimates. Model performance was evaluated by comparing predicted and observed trade volumes across the five vessel types. The model achieved low mean absolute percentage errors (MAPE) for container, bulk, and chemical tankers, indicating high predictive accuracy. Model fit was further validated using scatter plots of predicted versus observed values, which showed strong alignment for most ship types, especially containers and bulk carriers ([Supplementary Fig. 13](#)). By contrast, larger deviations were observed for oil and gas tankers due to reporting inconsistencies in UN Comtrade (Jiang et al., 2022), data sparsity, and the high volatility of energy trade linked to geopolitical shocks and decarbonization trends (Kramel et al., 2024; IMO, 2021). These issues were addressed through flow-adjusted processing, which improves reliability for energy-related trade estimates.

To further interpret the importance of each variable across vessel types, we employed SHAP (SHapley Additive exPlanations), which provides local and global measures of predictor influence. The SHAP results reveal that transport cost intensity, trade agreements, and geographic proximity are consistently strong positive drivers. Meanwhile, GDP and population exhibit heterogeneous effects depending on the economic scale of trading partners. Legal frameworks modestly enhance trade volumes, while diplomatic tensions show weak but consistent negative associations. These results are visualized by ship type in [Supplementary Fig. 14](#).

(3)Current Global Shipping Network Structure Analysis

To characterize the present-day maritime trade system, we aggregated bilateral trade volumes by vessel type and visualized the resulting networks ([Supplementary Fig. 15a](#)). Nodes represent countries and are sized by total trade volume; edges represent trade routes and are colored and weighted by bilateral trade intensity. The routes of container ships are widespread, with significant connections between North America, Europe, and Asia, indicating a global distribution network for containerized goods. The routes of bulk carriers are also globally spread but show a stronger concentration around Australia, Asia, and South America, likely due to the demand for bulk commodities such as coal, iron, and grains. The routes of gas and chemical carriers are more specialized, with key hubs like the USA, China, Japan, and the Middle East highlighted, reflecting regional dependencies in gas and chemical products. The network of oil tankers here shows concentrated routes from the Middle

East to major consumption regions, such as the USA, China, and Europe, emphasizing the global dependency on oil exports.

To examine global trade clusters, we applied the Louvain community detection algorithm to the weighted network, identifying cohesive regional groupings based on trade density. The circular clustering diagram ([Supplementary Fig. 15b](#)) reveals strong intra-regional connectivity within areas like Europe and Asia, and key inter-regional corridors such as Middle East–Asia (oil) and North America–Europe (container).

(4) Scenario-Based Forecasting of Trade Volumes

Future maritime trade volumes were projected under three Shared Socioeconomic Pathway (SSP) scenarios—SSP2 (middle-of-the-road), SSP3 (regional rivalry), and SSP5 (fossil-fueled development)—for four-time points: 2030, 2050, 2070, and 2100. All projections were computed as percentage changes relative to a 2022 baseline, using model outputs from the multivariate trade forecasting framework described earlier. Geospatial visualizations at the national level ([Supplementary Fig. 16a](#)) reveal distinct temporal and spatial patterns. In SSP5, global trade expands rapidly, with widespread and intense increases across most countries—particularly in North America, Europe, and East Asia—by 2100. In contrast, SSP3 exhibits uneven and often subdued growth, with some countries (notably in lower-income regions) even experiencing declines in early periods. SSP2 presents moderate, globally distributed growth patterns, representing a middle path between the high-expansion and low-cooperation extremes.

To assess distributional equity, we also analyzed trade volume trajectories across four World Bank income groups—high, upper-middle, lower-middle, and low income—using boxplot visualizations ([Supplementary Fig. 16b](#)). Across all scenarios and timeframes, high-income countries consistently dominate global trade volumes, as indicated by taller box plots. However, SSP5 shows a notable broadening of distribution within this group, suggesting divergence among advanced economies due to differentiated growth paths. Upper-middle and lower-middle income groups exhibit moderate growth, especially under SSP2 and SSP5, whereas low-income countries remain marginal, with minimal gains and compressed distributions. This reflects their limited integration into global trade networks and lower baseline economic capacity.

The compressed trade volume ranges under SSP3 and SSP4 highlight the effects of regionalization and sustainability-driven slow growth, while the wider spread in

SSP5 reflects the expansionary, technology- and fossil-fuel-intensive nature of the scenario. As time progresses, especially toward 2100, all income groups show upward trends in SSP5, pointing to a scenario of global trade intensification. In comparison, growth under SSP2 and SSP3 is more subdued and stratified, particularly for developing economies, revealing divergent development trajectories and implications for trade inclusivity.

Finally, when disaggregated by vessel type, SSP2 forecasts reveal that container and bulk carriers dominate projected trade volume increases, while oil and gas tankers exhibit flatter growth profiles, in line with energy transition dynamics ([Supplementary Fig. 17](#)).

Supplementary Method 2 | Arctic navigability prediction method

We selected Coupled Model Intercomparison Project Phase 6 (CMIP6) models that provide the required variables at high horizontal resolution (≈ 100 km). Sea ice thickness (SIT), sea ice concentration (SIC), and sea ice motion (SIM) data were resampled to $25 \text{ km} \times 25 \text{ km}$ using inverse distance weighting (IDW) interpolation. In this research, the Distance between Indices of Simulation and Observation (DISO) was constructed to quantify the comprehensive quality of CMIP models to select the model of the following evaluation. A lower DISO suggests a better performance. In the DISO, we calculated the correlation coefficient (CC) and root-mean-square deviation (RMSE) as the metrics for both SIT and SIC. The metrics of RMSE and mean absolute error (MAE) were used for SIM speed and angle, respectively. The equations of DISO can be defined as:

$$\begin{aligned} DISO_{1i} &= \sqrt{(norCC_{1i}-1)^2 + norRMSE_{2i}^2} \\ DISO_{2i} &= \sqrt{norRMSE_{2i}^2 + norMAE_{2i}^2} \\ DISO_{3i} &= \sqrt{DISO_{SIC}^2 + DISO_{SIT}^2 + DISO_{SIM}^2} \end{aligned} \quad (1)$$

where $i = 0, 1, \dots, m$, and m is the total number of CMIP6 models. $DISO_{1i}$ denotes the DISO for both SIT and SIC, and $norCC_{1i}$ and $norRMSE_{1i}$ are the normalized CC and RMSE. $DISO_{2i}$ denotes the DISO for SIM, and $norRMSE_{2i}$ and $norMAE_{2i}$ are the normalized RMSE and MAE. $DISO_{3i}$ indicates the model's overall situation of SIC, SIT, and SIM. The normalization equation can be expressed as

$$norM_i = \frac{M_i - \min(M)}{\max(M) - \min(M)} \quad (2)$$

where M indicates the selected metric, such as CC, RMSE, and MAE. When $i = 0$, the metrics of CC, RMSE, and MAE between the observed data and itself are 1, 0, and 0, respectively.

The navigability is represented by the risk index outcome (RIO) value of POLARIS, which combines the ice class of the vessel. For each ice condition and corresponding SIT, there is a risk index value (RIV) determined by the vessel's ice class and without icebreaker escort. The calculation method is shown in the following equations:

$$\begin{aligned}
 RIV_{PC7} &= \begin{cases} 3, & SIT=0 \\ 2, & 0 < SIT \leq 0.30 \\ 1, & 0.30 < SIT \leq 0.70 \\ 0, & 0.70 < SIT \leq 0.95 \\ -1, & 0.95 < SIT \leq 1.20 \\ -2, & 1.20 < SIT \leq 2.0 \\ -3, & 2.0 < SIT \end{cases} \\
 RIV_{OW} &= \begin{cases} 3, & SIT=0 \\ 1, & 0 < SIT \leq 0.10 \\ 0, & 0.10 < SIT \leq 0.15 \\ -1, & 0.15 < SIT \leq 0.30 \\ -2, & 0.30 < SIT \leq 0.50 \\ -3, & 0.50 < SIT \leq 0.70 \\ -4, & 0.70 < SIT \leq 0.95 \\ -5, & 0.95 < SIT \leq 1.20 \\ -6, & 1.20 < SIT \leq 2.00 \\ -7, & 2.00 < SIT \leq 2.50 \\ -8, & 2.50 < SIT \end{cases} \quad (3)
 \end{aligned}$$

$$RIO = (C_1 \times RIV_1) + (C_2 \times RIV_2) + \dots + (C_n \times RIV_n) \quad (4)$$

where, RIV_{PC7} and RIV_{IB} are the RIV of PC7 and OW ship, respectively; SIT is sea ice thickness (m); $C_1 \dots C_n$ are the SIC (in tenths) of ice types within the ice regime; and $RIV_1 \dots RIV_n$ are the corresponding RIVs for each ice condition.

In addition to SIT, there is a comprehensive calculation with SIM considered, the threshold of which is 0.15 m/s. A normalized negative risk value from -1 to 0 will be assigned when the SIM exceeds the threshold, which does not differentiate between vessel types. The calculation is performed using the following equation:

$$COMRIV = \begin{cases} w_1 x_1 + w_2 x_2, & RIO \geq 0, SID \leq 0.15 \\ w_1 \times (-1) + w_2 \times (-1), & else \end{cases} \quad (5)$$

where, COMRIV represents comprehensive risk index value, w_1 and w_2 are the weight of the risk index (equals 0.75 and 0.25 respectively); x_1 is the normalized

value of the risk index, ranging from -1 to 1 , with negative and positive holding the same before and after normalization; x_2 is the normalized SID (non-negative and ranging from 1 to 0 where SIM given beyond the threshold). The normalization is constructed with respective daily maximum and minimum values.

Supplementary Method 3 | Grid-Based Route Search Method

To estimate bilateral shipping costs between countries or regions, we developed a global $1^\circ \times 1^\circ$ grid-based route search and cost calculation framework based on heuristic algorithms. This method consists of two main components:

(1) Construction of the Global Shipping Cost Network

The global surface was discretized into 1-degree square cells, each classified into one of ten types based on geographic and navigational features ([Supplementary Fig. 23](#)). Land boundaries were sourced from Natural Earth, and the Arctic region was defined using the Arctic Circle ($66^\circ 34'N$). The boundaries of the Northern Sea Route (NSR) and Northwest Passage (NWP) followed the definitions provided by the Russian government (2020) and restricted waterway locations identified by Lu et al. (2014).

Each navigable cell center was treated as a node in the network, with connections (edges) to adjacent cells in eight directions. Edge weights represent the cost of traversing between nodes and were determined by the grid type and associated cost parameters. To ensure spatial accuracy, we applied the Haversine formula to compute great-circle distances between connected nodes. These distances, combined with the technical and economic attributes of each grid cell, were used to derive generalized cost values for each segment.

(2) Optimal Route and Cost Estimation Between Countries or Regions

For each country or region, the origin and destination were defined using port centroids, calculated as the average port location weighted by the total deadweight tonnage (DWT) of inbound and outbound shipping traffic. Countries with multiple distinct coastlines (e.g., the United States, Canada, Australia, Russia, and China) were assigned multiple centroids, corresponding to key maritime regions (e.g., U.S. East and West Coasts, Russia's Arctic and Baltic regions).

Using the constructed grid network, we applied the Dijkstra algorithm to identify the least-cost maritime path between all country (or regional) pairs for each projection year from 2022 to 2100 ([Supplementary Fig. 24](#)). For countries with multiple

centroids, total national shipping costs were computed as a DWT-weighted average across coastlines. The routing and cost computations were implemented using the Python graph package for network science.

Supplementary Discussion

Global shipping flow trajectories by vessel type under SSP2 and alternative SSP scenarios

[Supplementary Fig. 8](#) presents projected global shipping flow distributions for five vessel types under the SSP2 scenario, representing a “middle-of-the-road” trajectory for socioeconomic and environmental development. The analysis spans four key time points—2030, 2050, 2070, and 2100—and reveals distinct temporal and spatial dynamics in global maritime trade as shaped by evolving demand, geopolitical trends, and Arctic navigability.

Container Ships: Container shipping—an indicator of trade-driven transport—shows dense traffic in 2030 across the Northern Hemisphere, particularly along trans-Atlantic and trans-Pacific corridors connecting Europe, East Asia, and North America. By 2050, these flows will intensify, especially between Asia and Europe, reflecting deepening trade integration. In 2070, Arctic access will enable more direct East Asia–Europe routes, diminishing reliance on the Suez Canal. By 2100, near year-round Arctic navigation will transform this route into a strategic global corridor.

Bulk Carriers: In 2030, bulk shipping will be concentrated along resource-export routes from South America, Australia, and Southeast Asia to industrial economies in East Asia and Europe. By 2050, rising demand in South and Southeast Asia will drive a shift in flow intensity across the Indian Ocean. By 2070, the Arctic begins to accommodate bulk traffic—particularly linking Russia and Scandinavia with East Asia. By 2100, this Arctic corridor will become essential for Russian exports, altering global resource transport dynamics.

Chemical Tankers: Flows in 2030 will follow major industrial belts near the U.S., Europe, and East Asia. The Gulf of Mexico and the Middle East serve as key origin points. By 2050, intensified industrial activity in Asia will strengthen routes linking the Middle East and South/East Asia. Arctic access begins in 2070 and becomes central by 2100, facilitating faster delivery and reducing pressure on southern chokepoints.

Gas Carriers: Gas routes in 2030 are anchored by exports from Russia, the U.S., and the Middle East, serving energy-intensive markets in Europe and East Asia. By 2050, growth in Asian LNG demand will expand flows across the Indian Ocean.

Arctic access in 2070 significantly enhances Russian LNG deliveries to Asia. By 2100, the Arctic will become a core route for gas transport.

Oil Tankers: Oil flows in 2030 largely reflect traditional patterns, linking the Middle East, West Africa, and the North Sea with Asia, Europe, and North America. By 2050, Asia's growing demand will boost Indian Ocean traffic. In 2070, the Arctic begins supporting oil flows from Russia to Asia. By 2100, it will function as a major alternative to traditional southern routes.

These projections underscore a structural reconfiguration of maritime trade pathways under SSP2. As Arctic sea ice declines, northern corridors are poised to complement—and in some cases challenge—established global shipping routes.

[Supplementary Fig. 9](#) presents the projected differences in global shipping flows by vessel type between SSP1–5 and the baseline SSP2 from 2030 to 2100. The comparisons highlight how long-term socioeconomic trajectories influence the spatial and temporal distribution of maritime activity across key vessel classes: container, bulk, chemical, gas, and oil.

SSP1 – Sustainability (vs. SSP2): Under SSP1, container flows steadily intensify along major global corridors—particularly between Europe, Africa, Asia, and the Americas—driven by growing demand and infrastructure investments. Bulk flows increase in the Indian Ocean and around Africa, suggesting shifting resource trade toward emerging markets. Gas and oil tankers show growing reliance on the Middle East–Asia links. By 2100, the Arctic emerges as a complementary route for container, bulk, and chemical shipping.

SSP3 – Regional Rivalry (vs. SSP2): SSP3 reflects a fragmented world, with trade patterns shifting toward regional hubs. Container and chemical flows contract across trans-Pacific routes and concentrate along coastal and Atlantic-facing regions. Bulk shipping intensifies in the Indian Ocean, West Africa, and Southeast Asia, aligned with industrial growth in the Global South. Gas and oil flows pivot westward, with notable growth along Latin America–Africa–Europe corridors.

SSP4 – Inequality (vs. SSP2): Shipping under SSP4 becomes increasingly regionalized. Container, bulk, and chemical routes shrink across global corridors and instead concentrate within Asia, the Middle East, and parts of Africa. Gas and oil flows similarly localize, with heightened activity between the Middle East and Asia.

The contraction of long-distance trade suggests a world shaped by economic asymmetries and regional prioritization.

SSP5 – Fossil-fueled Development (vs. SSP2): SSP5 shows strong growth in long-distance maritime trade across all vessel types. Container flows expand along trans-Pacific and trans-Atlantic routes, driven by globalized high-growth economies. Bulk and chemical shipping intensify in the Indian Ocean and East Asia, reflecting increased extraction and industrial output. Gas and oil tankers follow similar trajectories, with robust flows linking the Middle East to Asia and Europe, and energy-intensive regions becoming major import centers.

Across scenarios, container and energy-related flows exhibit the most pronounced spatial shifts, with the Indian Ocean, Middle East, and Arctic emerging as key maritime zones. These divergences underscore the central role of socioeconomic pathways in shaping the geography of future global shipping. We adopt SSP2 as the core scenario for our main analysis because it represents a “middle-of-the-road” pathway in which global socioeconomic trends follow historical patterns without extreme deviations toward sustainability or fragmentation. This scenario reflects moderate assumptions regarding population growth, economic development, and international cooperation, providing a balanced baseline for assessing future shipping flows and emissions. Moreover, SSP2 is widely used in IPCC assessments and ensures comparability with existing climate–economy projections, making it a robust reference for evaluating the impacts of Arctic accessibility under plausible global development trajectories.

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