Supplement of Atmos. Chem. Phys., 21, 13835–13853, 2021
https://doi.org/10.5194/acp-21-13835-2021-supplement

Supplement of

Ship emissions around China under gradually promoted control policies from 2016 to 2019

Xiaotong Wang et al.

Correspondence to: Huan Liu (liu_env@tsinghua.edu.cn)

Supplementary Methods

S1 General calculation formula in SEIM v2.0

The emission calculation in this study was made for each individual vessel, with a breakdown into three different engine types (main engine, auxiliary engine, and boiler) and four operation modes (At berth, at anchorage, maneuvering, and at sea). Transient emissions are calculated by multiplying emission factors (per unit power) by engine load ratios, with adjustment factors for fuel type and sulfur content. Total emissions are aggregated using transient emissions multiplied by time durations. The equations (1), (2) and (3) provide the emission calculation for main engine (ME) auxiliary engine (AE) and boiler in SEIM v2.0 model.

$$E^{\mathrm{ME}} = \sum_{t=1}^{n} \mathrm{MCR} \times \mathrm{EF}_{p,i,j,k}^{\mathrm{ME}} \times \mathrm{LF}_t \times \mathrm{LLAF}_p \times \Delta T_t \times 10^{-6} \quad (1)$$

$$E^{\mathrm{AE}} = \sum_{t=1}^{n} P_{v,s,m}^{\mathrm{AE}} \times \mathrm{EF}_{p,i,k}^{\mathrm{AE}} \times \Delta T_t \times 10^{-6} \quad (2)$$

$$E^{\mathrm{Boiler}} = \sum_{t=1}^{n} P_{v,s,m}^{\mathrm{Boiler}} \times \mathrm{EF}_{p,i}^{\mathrm{Boiler}} \times \Delta T_t \times 10^{-6} \quad (3)$$

Where MCR is the maximum continuous rated power (kW) for each vessel; $\mathrm{EF}_{p,i,j,k}^{\mathrm{ME}}$ is the emission factor for fuel type *i*, engine type *j*, emission standard *k* and species *p* (g/kW·h); LF_t is the load factor in time interval *t*, LLAF_p is the low load adjust factor for species *p*, which is applied when the load factor is less than 20%; ΔT_t is the time interval of the *t*-th continuous AIS signal (h); *n* is the total number of AIS signal time intervals under each category. $P_{v,s,m}^{\mathrm{AE}}$ and $P_{v,s,m}^{\mathrm{Boiler}}$ is the operating power (kw) of AEs and boiler of ship type *v* and size bin *s* (divided by dead weight tonnage) under operating mode *m* (kW); $\mathrm{EF}_{p,j,k}^{\mathrm{AE}}$ is the emission factor of pollutant *p* for AEs using fuel type *i* and complying with emission standard *k* (g/kW·h); $\mathrm{EF}_{p,i}^{\mathrm{Boiler}}$ is the emission factor of pollutant *p* for boilers using fuel type *i* (g/kW·h). Detailed description was provided in the Methods of our previous study (Liu et al., 2016).

S2 Automatic Identification System (AIS) data

The temporal and spatial coverage of AIS data were examined to guarantee the quality of ship emission inventories. The full year AIS data including both satellite signals and territorial signals from 2016 to 2019 were used for our emission calculations in this study. Fig. S1a showed the homogeneity of the AIS signals in this study in terms of time. It is noticeable that during February (Spring Festival Holiday in China) and May to August (Fishing-off Season in China), the number of daily AIS signals is lower than average (approx. 5 million/day). Missing signals or anomalies occasionally exist, which could due to multiple factors, such as disruption to satellites, equipment maintaining, data transmission fault etc., Besides, Bad weather could be a reason for interference of signal transmission. After the adoption of the 10-minute interpolation method, the AIS signal is expanded to about twice the original, and some periods with long intervals have been obviously supplemented. Fig. S1 (b) and (c) exhibited the change of spatial coverage of AIS signals in inland waters and coastal waters around China. The number of AIS messages transmitted per year is increasing over the span of this study's years of interest. This is evident from Fig. S1 (d) which demonstrates the improvement in AIS coverage between 2016 and 2019.

S3 Ship technical specifications database (STSD)

In this study, the extended Ship Technical Specification Database (STSD) was applied for ship emission calculation (Liu et al., 2016). The data from Lloyd's Register, China Classification Society (CCS) and Global Fishing Watch (GFW) (Kroodsma et al., 2018) were the most significant sources. In the current STSD, there are 101,638 ocean-going vessels (OGVs, defined here as vessel having an IMO number), a bit more than that recorded by United Nations Conference on Trade and Development (UNCTAD), e.g., 97,136 in 2019 (https://unctadstat.unctad.org/wds), which might due to the difference in OGV definition. The STSD provides static data which describes ship properties including vessel type, rated engine speed, rated engine power, length, width, height, design max speed, dead weight tonnage (dwt), maximum draught, build year, etc. Since STSD has incorporated data from GFW, CCS as well as Classification Societies of other East Asian countries, it also includes ships that are smaller than 500 Gt and usually don't have IMO numbers along China's coast, which take a large part in terms of the number of ships. However, the data is sometimes incomplete. Either excluding those particular ships from our computation or assigning default values to the property will lead to substantial inaccuracies. To correct the static data and reduce the error, we applied a machine learning method, Gradient Boosting Regression Tree (GBRT) to predict missing values based on other completed properties (Liu et al., 2016). This method previously applied for approximately 30% of the total ocean-going vessels in East Asia. However, as we updated the STSD to involved more than 350 thousand vessels, this kind of vessels only account for approximately 5% in terms of amount.

S4 Emission factors (EFs) connected with the DECA policy

In this study, the average fuel sulfur content for heavy fuel oil (HFO) was assumed to be 2.43% and that for maritime gas oil (MGO) was 1.3%. These assumptions were consistent with our previous studies based on the investigation of global fleet from *IMO Greenhouse Gas Study* (IMO, 2014; IMO, 2020). The implementation of China's domestic emission control area (DECA) required low sulfur fuel, i.e., MGO with sulfur content <0.5% m/m for ships entering the area. Despite the mandatory date, some regions actually implemented the DECA policy ahead of time, such as Shenzhen port and ports in Yangtze River Delta (YRD). Meanwhile, fuel consumed by river vessels are demanded to use general diesel oil (GDO) with phased requirements, with sulfur content followed by 0.035%, 0.005% and 0.001%. Table S1 summarizes the actual performance of DECA from 2016 to 2019 and the corresponding fuel type in different area, including both the coastal seas and inland rivers. Emission factors for different fuel types are shown in Table S5, which were either directly obtained from *Third IMO Greenhouse Gas study 2014* and related studies, or converted by the ratio of fuel sulfur content to the baseline, as illustrated in our previous work (Liu et al., 2016). In SEIM v2.0, a two-step method for was applied for ship emission estimation to be in line with the policy requirements, including the baseline EF selection and fuel correction factor (FCF) application:

- At the first stage, the baseline ship emissions were calculated for each two consecutive AIS signals based on the vessel's instantaneous power and the power-based baseline emission factors. The baseline EFs were selected according to fuel type of vessel recorded in STSD, including the liquified natural gas (LNG), HFO and MGO-0.13%. The GDO was only applied for river vessels, and the sulfur content for GDO was determined by time of AIS signals.
- In the policy-abutted modification module, the final ship emission would be further adjusted by the FCF. Due to the complexity of the DECA boundary, it would be time-consuming to judge whether it is in the DECA polygon for each AIS signal point. Thus, the intermediate output resulted from the first stage was grouped and aggregated by desired spatial resolution (e.g., $0.05° \times 0.05°$) and other fields to reduce computing costs. For each

aggregated emission record, vessels would be judged weather it was operating inside the DECA and needed to switch oil based on the signal time, geographical locations (latitude and longitude coordinates) and operating status. If the result of judgment is that the oil needs to be switched, the FCF, resulted from the quotient of the emission factors of the switched fuel and original fuel, would be further multiplied in the emission calculation formula.

Supplementary Figures

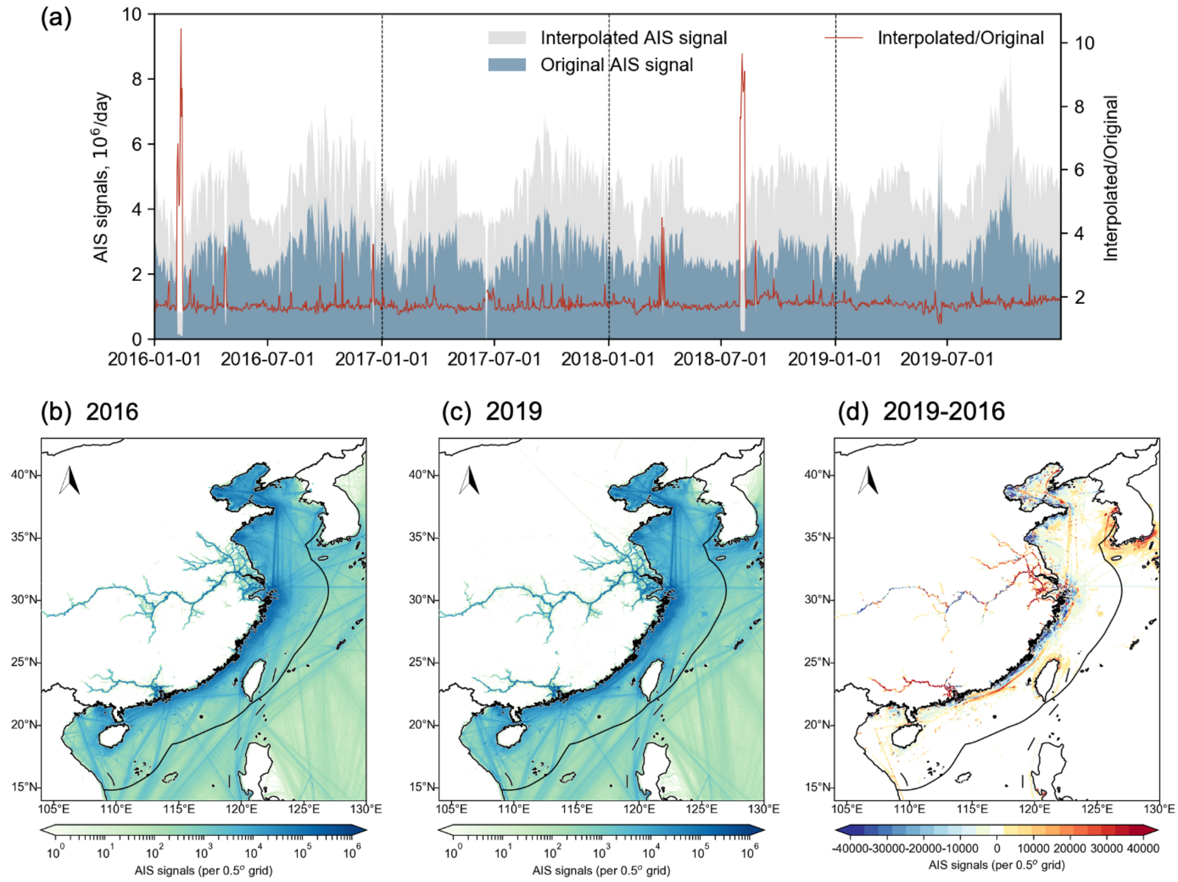

Fig. S1 Temporal and spatial coverage of AIS data in rivers and 200 Nm coastal zone of China from 2016 to 2019. (a) Daily evolution of AIS signals. (b) Spatial distribution of AIS signals in 2016. (c) Spatial distribution of AIS signals in 2019. (d) Spatial difference between 2016 and 2019.

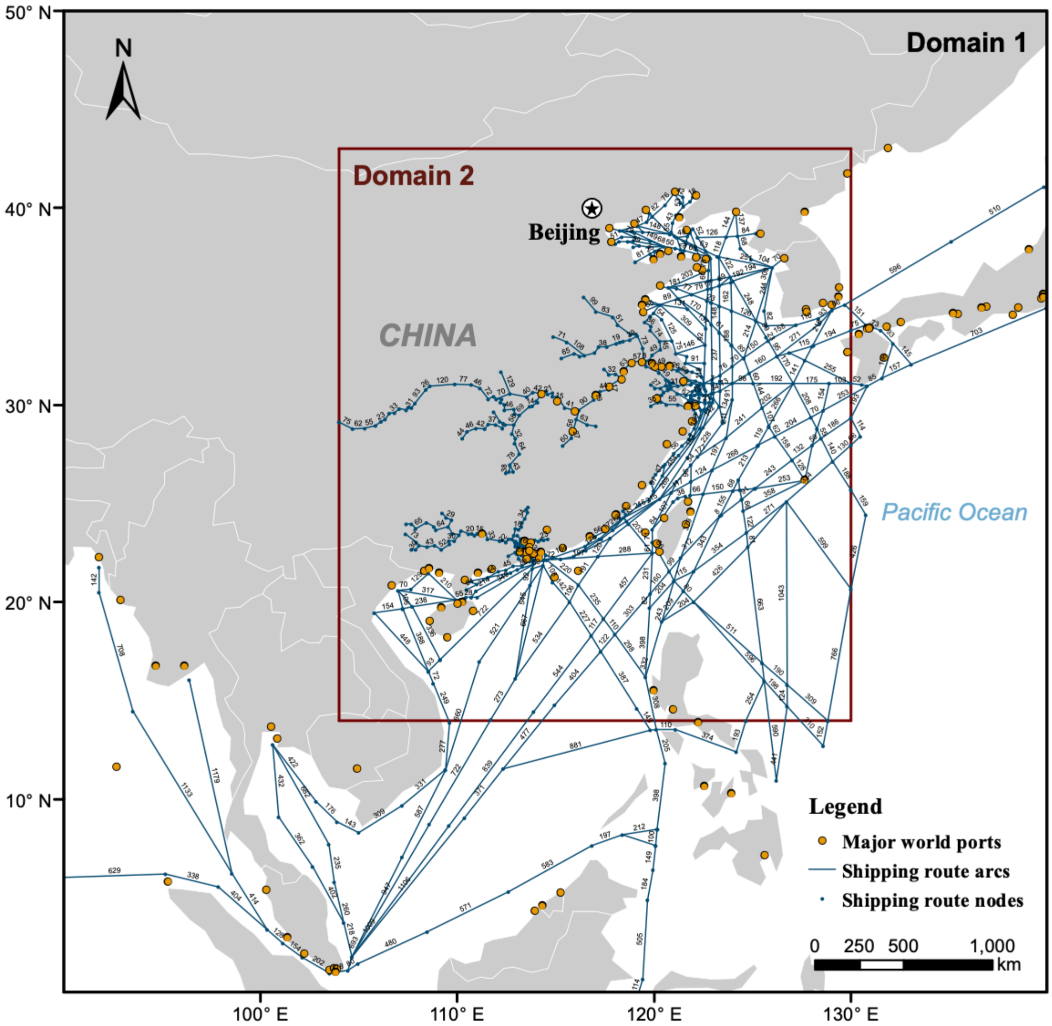

Fig. S2. The shipping route network established in this study. The figures next to the shipping route arcs are the geodesic distances calculated from the ArcGIS tool.

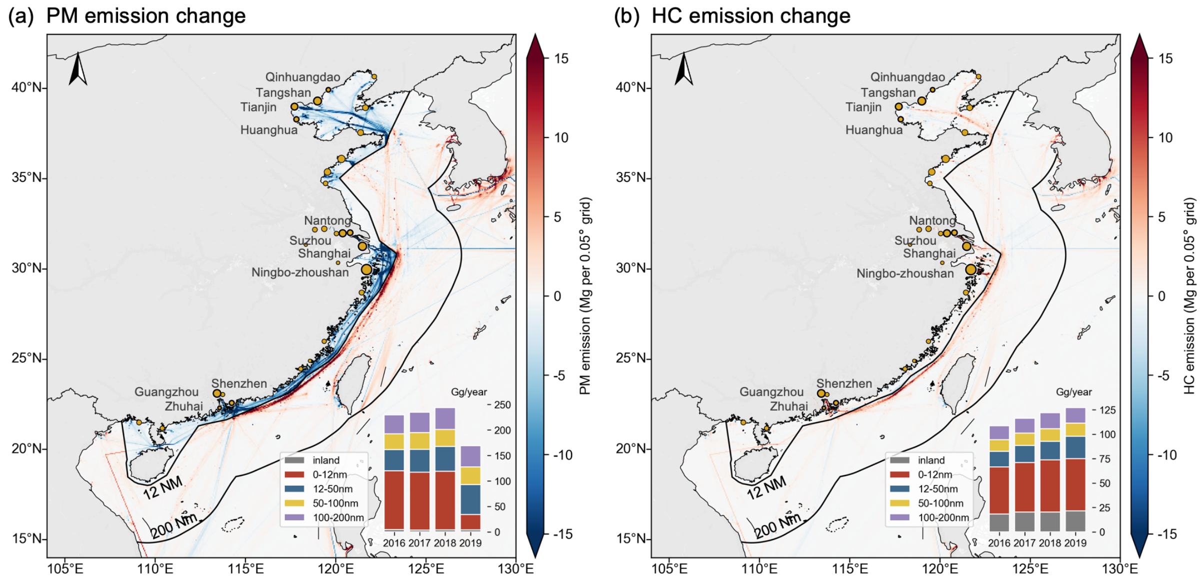

Fig. S3. Spatial distribution changes of PM and HC emissions from shipping over China in 2019 compared to 2016.

Supplementary Tables

Table S1. Actual implementation of China's step-by-step DECA policy

Region and ports		**DECA 1.0**			**DECA 2.0**
		2016	**2017**	**2018**	**2019**
Coastal	BSA		(Berth, MGO-0.5%) Tianjin, Qinhuangdao, Tangshan, Huanghua	(Berth, MGO-0.5%) All region	(All modes , MGO-0.5%) 12 nautical miles
	YRD	(Apr. – Dec., Berth, MGO-0.5%) Shanghai, Ningbo-Zhoushan, Suzhou, Nantong	(Berth, MGO-0.5%) Shanghai, Ningbo-Zhoushan, Suzhou, Nantong; (Sep. – Dec., Berth, MGO-0.5%) All region	(Berth, MGO-0.5%) All region; (Oct. – Dec., all modes, MGO-0.5%) Shanghai, Ningbo-Zhoushan, Suzhou, Nantong	
	PRD	(Oct. – Dec., Berth, MGO-0.5%) Shenzhen	(Berth, MGO-0.5%) Shenzhen, Guangzhou, Zhuhai	(Berth, MGO-0.5%) All region	
	Other area				
River		GDO-0.035%	(Jul. to Dec.) GDO-0.005%	GDO-0.001%	GDO-0.001%

Note: Yellow background stands for low sulfur oil；Green background stands for general diesel oil.

Table S2. Total emission of air pollutants and GHGs in relevant studies and this study

Based Year	SO_2	NO_X	PM_{10}	$PM_{2.5}$	HC	Reference
2013	1300	1910	164	-	69	(Fu et al., 2017)
2013	1010	1443	107	87	67	(Li et al., 2018)
2014	1194	2208	181	167	112	(Chen et al., 2017)
2014	999	1149	-	120	36	(Huang et al., 2019)
2016	1795 (38.1%)	2528 (32.3%)	230 (40.0%)	-	109 (57.7%)	This study
2017	1824 (40.3%)	2670 (39.8%)	235 (43.3%)	-	116 (68.7%)	This study
2018	1894 (45.7%)	2802 (46.7%)	244 (48.7%)	-	122 (76.8%)	This study
2019	1264 (-2.8%)	2858 (49.6%)	169 (3.0%)	-	127 (84.5%)	This study

Note: The percentages in brackets show the relative changes in emissions of the target year compared to 2013.

Table S3. Proportion of China ship emission in the globe

Year	SO_2	NO_X	PM	HC
OGV emission around China (Mg)				
2016	1510	1263	160	62
2017	1628	1333	170	67
Global OGV emission from 4th IMO GHG report (Mg) (IMO, 2020)				
2016	15781	8943	1352	654
2017	16202	9252	1399	675
Contribution of OGV around China waters to global OGV emissions				
2016	9.6%	14.1%	11.8%	9.5%
2017	10.0%	14.4%	12.2%	10.0%
Average	9.8%	14.3%	12.0%	9.7%

Table S4. Emission structures of ship emission in rivers and 200 Nm zone of China in 2016-2019 (Unit: %)

Statistical dimension		2016				2017				2018				2019			
		NO_X	SO_2	PM	HC	NO_X	SO_2	PM	HC	NO_X	SO_2	PM	HC	NO_X	SO_2	PM	HC
Vessel type	Auto carrier	1	1.1	1.1	0.9	1	1.1	1.1	0.9	1	1.1	1.1	0.9	1.1	1.3	1.3	0.9
	Bulk carrier	32.2	24.1	24.3	35.3	32.9	24.1	24.4	36	32.2	23.4	23.6	35.1	33	23.1	23.4	35.6
	Container	27.5	31.7	32.6	27.5	28.9	34.5	35.3	28.7	31.4	37.5	38.4	31.2	30.7	42.9	43.2	30.5
	Cruise	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
	General cargo	4.1	4.6	4.6	3.7	3.9	4.3	4.3	3.5	3.9	4.4	4.3	3.4	3.9	4.6	4.5	3.5
	Miscellaneous	2.2	2.2	2.3	2.1	2	2	2.1	1.9	1.9	1.8	1.9	1.8	2.1	1.4	1.6	2
	Ocean Tug	1.3	0.2	0.2	1.5	1.3	0.2	0.3	1.6	1.3	0.2	0.3	1.6	1.3	0.2	0.3	1.5
	Ro-Ro	3	3.3	3.2	2.6	2.8	3	2.9	2.4	2.6	2.7	2.6	2.2	3.2	2	2.1	2.9
	Reefer	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.2
	Chemical tanker	4	4.7	4.6	3.7	4	4.7	4.6	3.6	3.7	4.5	4.4	3.4	3.8	5.4	5.2	3.5
	Oil tanker	6.3	8.5	7	5.8	6.3	8.2	6.9	5.9	6.3	8.1	6.9	5.9	6.6	9	7.8	6.2
	LPG	1	1.6	1.3	1	1.1	1.6	1.3	1	1.1	1.7	1.4	1	1.1	1.8	1.5	1
	LNG	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
	Fishing	7.9	8.7	8.9	6.7	6.4	7.1	7.2	5.3	5.9	6.4	6.5	4.9	5.4	3.8	4.1	4.6
	Others	8.9	8.7	9.1	8.8	8.9	8.6	9	8.8	8.1	7.6	7.9	8	7.3	4	4.5	7.4
Fuel type and sulfur content (m/m)	HFO	79.5	98.2	98.1	74.8	45.5	84.5	81.9	41.7	83.9	99	99	79.1	80.4	98.3	98.4	75.8
	LNG	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0	0	0.1	0.1	0.1	0.1	0.1
	MGO-0.5%	4.7	1.7	1.7	4.2	38.1	15.3	17.7	37	1.6	0.7	0.6	1.3	3.5	1.4	1.3	2.8
	MGO-0.1%	0.8	0.1	0.2	0.8	0.8	0.1	0.2	0.8	0.8	0.1	0.2	0.8	0.7	0	0.1	0.7
	GDO-0.035%	0	0	0	0	0	0	0	0	13.6	0.2	0.2	18.6	7.3	0.1	0.1	9.8
	GDO-0.005%	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	10.8
	GDO-0.001%	14.8	0	0	20	15.5	0	0	20.3	0	0	0	0	0	0	0	0

Table S4. Emission structures of ship emission of NO_X, SO_2, PM, HC of China in 2016-2019 (Unit: %; continued)

Statistical dimension		2016				2017				2018				2019			
		NO_X	SO_2	PM	HC	NO_X	SO_2	PM	HC	NO_X	SO_2	PM	HC	NO_X	SO_2	PM	HC
OGV/CV/RV	OGV	59.7	70.4	69.6	56.9	61	73.1	72.5	57.8	64.1	77	76.4	60.9	65.8	87.6	86.5	62.4
	CV	27.1	29.4	30.2	24.9	24.2	26.8	27.4	22.1	21.6	23	23.6	19.8	19.3	12.4	13.5	18.1
	RV	13.2	0.2	0.2	18.2	14.9	0.1	0.1	20.1	14.3	0	0	19.3	14.9	0	0	19.6
Vessel build period	< 2000	9.4	9.7	9.5	7.7	8.3	8.4	8.2	6.7	7.8	8	7.8	6.3	8.4	8.8	8.5	6.9
	2000 – 2010	69.7	62.7	63.4	70.3	67.8	59.9	60.4	68.4	65.1	56.2	56.7	65.6	62.1	47.9	48.8	62.8
	2010 – 2016	18.2	24.2	23.8	19.2	17.8	23.5	23.2	18.5	17.7	23.3	23	18.4	18.9	27.3	27	19.5
	> 2016	2.6	3.4	3.4	2.8	6.2	8.2	8.2	6.4	9.4	12.6	12.5	9.7	10.6	16	15.7	10.8
DWT range (ton)	0 – 9999	45.2	35.5	35.6	47.2	42.5	31.5	31.4	44.9	39.2	27.5	27.4	41.7	38.8	18.4	19	41.4
	10000 – 19999	8	9.3	9.2	7.4	7.7	9	8.9	7	7.5	8.9	8.7	6.8	7.3	8.8	8.7	6.7
	20000 – 29999	6.3	7.2	7.3	5.8	6.6	7.8	7.8	6.1	6.9	8.2	8.2	6.4	6.9	9	9	6.4
	30000 – 39999	5.1	5.8	5.9	4.8	5	5.8	5.8	4.7	5.2	6	6.1	4.8	5.2	6.3	6.3	4.9
	40000 – 49999	4.8	5.7	5.5	4.4	4.9	5.8	5.7	4.5	4.9	5.8	5.6	4.5	5.2	6	5.8	4.8
	50000 – 59999	5	5.9	5.9	4.8	5.5	6.4	6.4	5.2	6.2	7.1	7.2	5.8	6.6	8.3	8.3	6.3
	60000 – 79999	5.7	6.7	6.6	5.4	6.3	7.3	7.3	6	7.4	8.3	8.3	6.9	7.8	9.4	9.4	7.2
	80000 – 99999	2.7	3.1	3.2	2.7	2.8	3.3	3.4	2.8	2.8	3.3	3.4	2.8	2.7	3.8	3.8	2.6
	100000 – 119999	4.9	6	6	5.1	4.6	5.7	5.7	4.7	4.4	5.4	5.5	4.5	4.3	6.7	6.5	4.5
	120000 – 159999	3.9	4.7	4.8	4.1	4.8	5.9	6	5	5	6.2	6.4	5.3	4.8	7.4	7.3	5
	160000 – 199999	4.9	5.8	5.9	4.9	5.5	6.6	6.8	5.4	6.5	8	8.2	6.5	6.3	9.5	9.5	6.3
	> 200000	3.5	4.3	4	3.2	3.9	4.8	4.6	3.7	4.1	5.3	5.1	3.9	4.1	6.6	6.3	3.9
Operating mode	Cruising	69.5	70	71.2	63.9	70	73.3	74	64.3	70.9	73.4	74.6	65.4	70.5	77.1	78	64.9
	Maneuvering	19	14.1	16.1	26.6	18.8	13.7	15.6	26.3	17.9	12.7	14.4	25.3	18.2	11.1	12.7	25.6
	Anchorage	2	2.2	2.3	2	1.7	2	2	1.7	1.4	1.7	1.7	1.5	1.4	1.3	1.3	1.5
	Berth	9.5	13.7	10.4	7.5	9.6	11.1	8.4	7.7	9.8	12.2	9.3	7.9	9.9	10.4	8	8

Table S5. Emission factors for different fuel types used in this study (Unit: g/kW·h)

Fuel type	Emission Source	Engine type	PM	NO_x (Tier 0[d])	NO_x (Tier I)	NO_x (Tier II)	SO_2	HC
HFO (2.43% S)	ME	SSD[a]	1.335	18.1	17	15.3	9.261	0.6
		MSD[b]	1.33	14	13	11.2	10.215	0.5
	AE		1.339	14.7	13	11.2	10.782	0.4
	Boiler		2.1	14.85	14.85	14.85	0.1	0.1
MGO (0.05% S)	ME	SSD	0.31	17.01	15.98	14.38	1.81	0.6
		MSD	0.31	13.16	12.22	10.53	1.98	0.5
	AE		0.32	13.82	12.22	10.53	2.12	0.4
	Boiler		0.2	1.974	1.974	1.974	3.1	0.1
MGO (0.13% S)	ME	SSD	0.199	17.01	15.98	14.38	0.515	0.6
		MSD	0.2	13.16	12.22	10.53	0.568	0.5
	AE		0.202	13.82	12.22	10.53	0.599	0.4
	Boiler		0.112	1.974	1.974	1.974	0.825	0.1
GDO (0.035 %S)	ME	SSD	0.0192	17.01	15.98	14.38	0.133	0.6
		MSD	0.0192	13.16	12.22	10.53	0.147	0.5
	AE		0.0193	13.82	12.22	10.53	0.155	0.4
GDO (0.05% S)	ME	SSD	0.0028	17.01	15.98	14.38	0.019	0.6
		MSD	0.0027	13.16	12.22	10.53	0.021	0.5
	AE		0.0028	13.82	12.22	10.53	0.022	0.4
GDO (0.001% S)	ME	SSD	0.001	17.01	15.98	14.38	0.004	0.6
		MSD	0.001	13.16	12.22	10.53	0.004	0.5
	AE		0.001	13.82	12.22	10.53	0.004	0.4
LNG		Otto[c]	0.03	1.3	1.3	1.3	0.003	0.5

[a, b, c] mean slow speed diesel engine (SSD), medium speed diesel engine (MSD) and Otto-cycle LNG-fueled engine, respectively.
[d]Tier 0 refers to all ships constructed prior to January 1, 2000 which did not have an IMO Tier requirement at the time of construction.

Supplementary References

Chen, D., Wang, X., Li, Y., Lang, J., and Zhao, Y.: High-spatiotemporal-resolution ship emission inventory of China based on AIS data in 2014, Science of The Total Environment, 609, 776-787, 2017.

Fu, M., Liu, H., Jin, X., and He, K.: National- to port-level inventories of shipping emissions in China, Environmental Research Letters, 12, 114024, 10.1088/1748-9326/aa897a, 2017.

Huang, Z., Wang, H., Tang, Y., Peng, D., and Ma, D.: Emission Prediction of Marine for 2030 in China, Vehicle Emission Control Center (VECC), Beijing, 60pp, 2019.

IMO: Fourth IMO GHG Study - Final Report, CE Delft, 2020.

Li, C., Borken-Kleefeld, J., Zheng, J., Yuan, Z., Ou, J., Li, Y., Wang, Y., and Xu, Y.: Decadal evolution of ship emissions in China from 2004 to 2013 by using an integrated AIS-based approach and projection to 2040, Atmos. Chem. Phys., 18, 6075-6093, 10.5194/acp-18-6075-2018, 2018.