Decadal evolution of ship emissions in China from 2004 to 2013 by using an integrated AIS-based approach and projection to 2040

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1. Domain and ship categorization

Domain choose explain: According to the "United Nations convention on the law of the sea" approved by United Nations conference on the third law of the sea in 1982, which indicated that 200 nautical miles (Nm) exclusive economic zone (EEZ) belongs to the scope of the jurisdiction of the state, further explain in article 56 of the convention mentioned the right regulation of EEZ including the jurisdiction on the area of artificial islands, installations and science research and Marine environmental protection fields, that is to say the research domain of ship emissions in China expand to 200 Nm zone is acceptable. However, science research does not mean the legislative power, have jurisdiction over 12 Nm of ship emissions control area (ECA) needs to be approved by IMO, e.g., Beihai ECA, Mediterranean ECA. The scope of these international ECAs are 200 Nm, which support the domain in this study, and also enhance the referable of this study. By the way, the domain chosen in this study reflects our focus on densely populated areas and does not represent any national boundaries.

There were 18000 km coastline covered 31760 harbors in this region, which contains 5675 coast harbors and 2001 10kt carrier harbors. More detail for 10kt carrier harbors in table SI-1, SI-2.

Table SI-1 the distribution of 10kt carrier ports in China, 2013

Port size	Coast port	River port	Total
Total	1607	394	2001
[10kt, 30kt]	567	169	736
[30kt, 50kt]	254	102	356
[50kt, 100kt]	532	116	648
≥100kt	254	7	261

Table SI-2 the distribution of the function of 10kt carrier ports in China, 2013

Function	Container	Coal	Metal orea	Crude Oil	Oil product	Chemical	Food	General bulk	General cargo	Total
Number	321	206	61	68	124	157	6	414	345	2001

Four sub-categories were classified by cargo types, i.e. container ships carrying containers, cargo ships carrying dry bulk like ore, construction materials, coal and its products, tankers carrying chemicals, gas, oil and its products, and others. More detailed information for sub-categorizes of DWT.

Table SI-3 Classification Basis of Different Operation Modes

Operation Mode	Description	Ship Speed
Cruise (At sea)	Ship operating at service speed, usually in inland waters, offshore open waters or broad fairways	Over 8 knots
Maneuvering	Ship operating at lower speed as it approaches berth/pier/dock or anchorage	1 to below 8 knots
Hotelling (At berth)	Ship at berth or anchored with propulsion engines switched off	Below 1 knot

*knot is a unit of sailing speed measuring, 1 knot=1sea mile/hour; sea mile is a unit of distance measuring, 1 sea mile=1.852km (China Standard), so 1 knot≈1.852 km/h.

Table SI-4 DWT Classification of Different Ship Types

OGV	CV	RV	OGV	CV	RV
Container	Container	Container	Chemical Tanker	Chemical Tanker	Chemical Tanker
DWT <10000	DWT <3000	DWT＜500	DWT<5000	DWT <3000	DWT＜500
DWT 10000-19999	DWT 3000-4999	DWT 500-1000	DWT5000-9999	DWT 3000-5000	DWT＞500
DWT 20000-29999	DWT 5000-9999	DWT＞1000	DWT 10000-19999	DWT 5000-9999	
DWT 30000-39999	DWT >10000		DWT 20000-39999	DWT >=10000	
DWT 40000-49999			DWT >=40000		
DWT 50000-74999			Conventional Cargo Ship	Conventional Cargo Ship	Conventional Cargo Ship
DWT 75000-99999			DWT <2000	DWT <5000	DWT＜500
DWT >=100000			DWT 2000-4999	DWT 5000-9999	DWT 500-1000
Gas Tanker	Gas Tanker	Gas Tanker	DWT 5000-9999	DWT 10000-29999	DWT＞1000
DWT <5000	DWT <3000	DWT＜500	DWT 10000-29999	DWT >=30000	
DWT 5000-9999	DWT 3000-4999	DWT＞500	DWT >=30000		
DWT 10000-19999	DWT 5000-9999		Dry Bulk Carrier	Dry Bulk Carrier	Dry Bulk Carrier
DWT 20000-39999	DWT >=10000		DWT <10000	DWT <3000	DWT＜500
DWT >=40000			DWT 10000-29999	DWT 3000-4999	DWT 500-1000
Oil Tanker	Oil Tanker	Oil Tanker	DWT 30000-59999	DWT 5000-9999	DWT＞1000
DWT <10000	DWT <3000	DWT＜500	DWT 60000-99999	DWT >=10000	
DWT 10000-29999	DWT 3000-4999	DWT＞500	DWT >=100000		
DWT 30000-59999	DWT 5000-9999		Tug	Tug	Tug
DWT 60000-119999	DWT >=10000		Passenger ship	Passenger ship	Passenger ship
DWT >=120000			Fishing ship	Fishing ship	Fishing ship
			Others	Others	Others

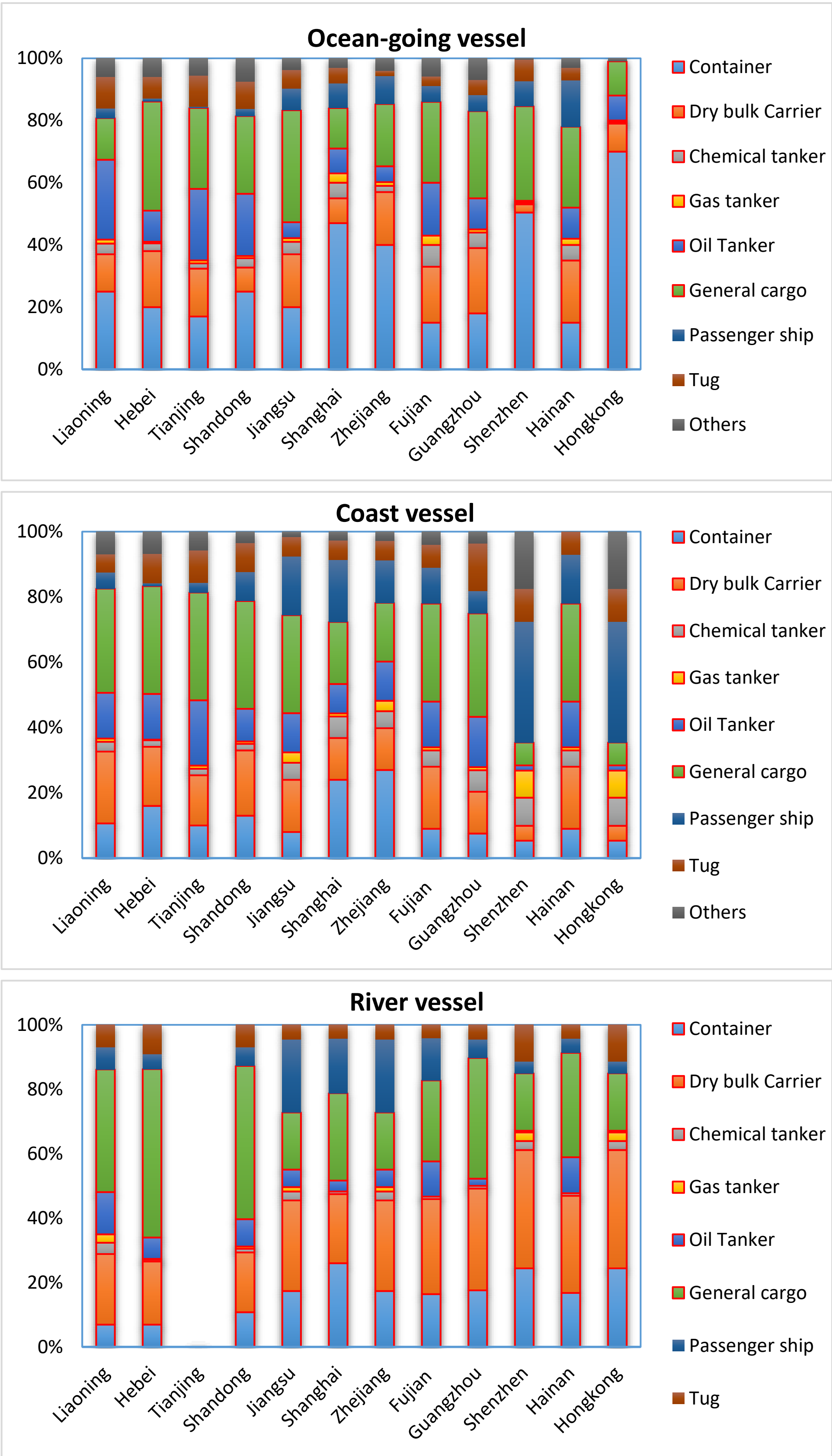

Fig. SI-2 Summary of the stock of ship types navigated in different regions for OGVs, CVs and RVs

2. AIS data information

According to the most advanced study (Liu et al., 2016), the introduction of automatic vessel position reporting systems has significantly reduced the uncertainty concerning ship activities and their geographical distribution. However, using shipping activity data for research remains a challenging task (Dalsoren et al., 2009; Liu et al., 2016). Different with Liu's study, this study established a model for ship activity data calculation by using a continuously trajectories AIS dataset but not comprehensive in China Sea. Here I given a comparison of AIS data (Dalsoren et al., 2009; Liu et al., 2016) to demonstrate that the representativeness of our ship information dataset in China Sea is acceptable (table SI-5).

Table SI-7 ship information statistics in China and in the other studies

Study area	Year	Archived AIS messages	Number of ship with AIS	Number of ship information
China Sea	2013	3.5E+08	700	12,600
East Asia	2013	2.0E+09	18,324	18,324
Baltic sea	2009	2.6E+08	11,606	11,606

The AIS was introduced by the IMO international Convention for the Safety of Life at Sea. Which include shore-based and satellite-based data. The shore-based data is featured by high temporal resolution (every 30 seconds), but only covers ships less than 50 nautical miles from the shore. For the areas beyond 50 nautical miles, satellite-based data in 2-h interval was used.

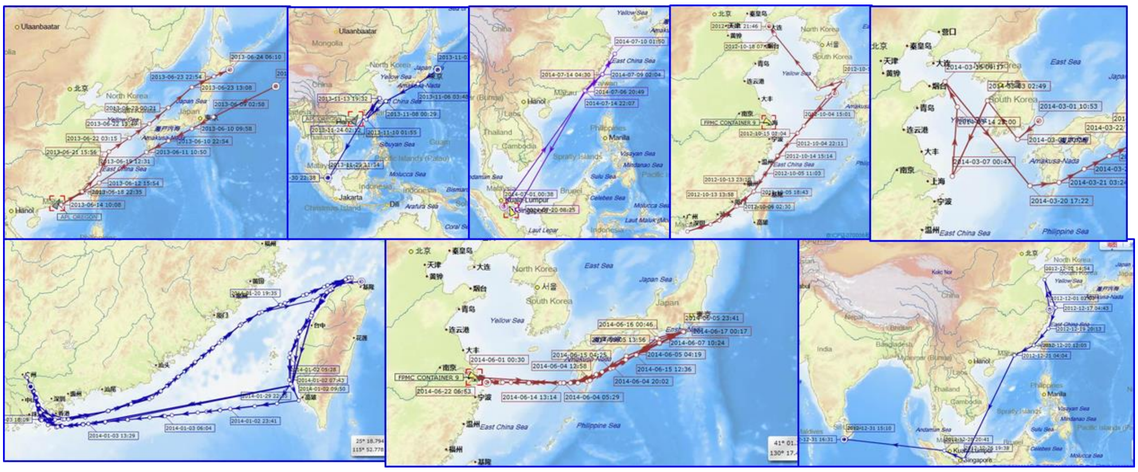

Fig. SI- 1 A demonstration of historical AIS-based ship trajectories on a digital map

3. Fuel consumption information

For fuel consumption rate (Kg coalstandard/KtNm), the value of different ship types can be obtained from CCTD in 2010-2015, but the value of OGVs are not within the typical ranges of corresponding ship type from IMO report (IMO, 2009), as detailed in Fig. SI-2, that maybe caused by the statistics of the international trade in ocean going cargo companies. So the median value of the range provided by IMO were used to estimate in cargo-based approach.

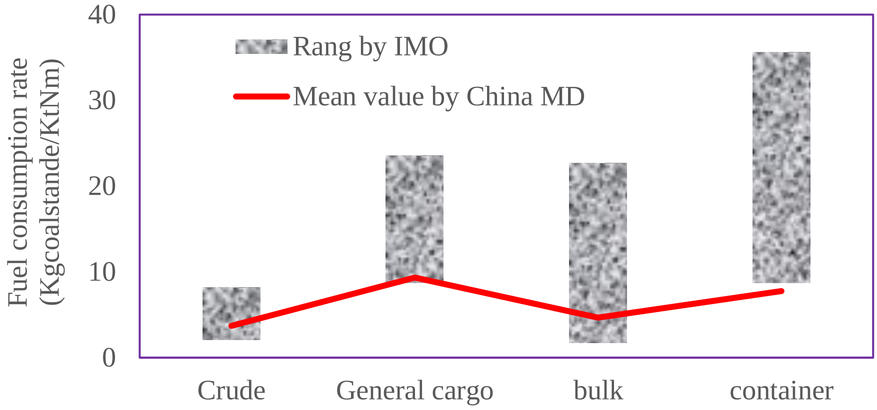

Fig. SI-3 Date sources of fuel consumption rate range

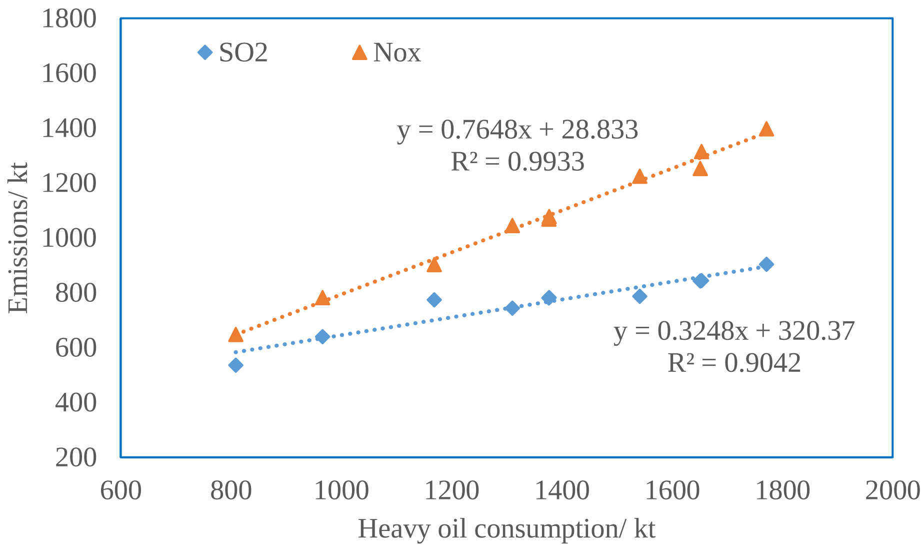

Fig. SI-4 Relationship between fuel consumption and ship emissions from 2004 to 2013

4. Ship engine and emission factor

For ship engine, the slow speed diesel engine were dominated by the international brands, e.g. MAN SE (from Germany, share 78% stock of market), Wärtsilä (from Dutch, share 21% stock of market), this is to say that the emission factor for SSD of ship engine used in China can refer to the international value. However, the medium speed diesel engine (430 kW< P < 14,940 kW) were dominated by the local diesel engine brands, e.g. Zichai, Weichai, Guangchai, Zhongcedongli. Which covered more than 80% of the total population of MSD, mainly used for the main engine and auxiliary engine of river ship and fishing ship, therefore, the emission factor of river vessel refers to the result measured by the local studies (Zhang et al., 2015).

Statistics for main engine speed by vessel type and gross tonnage has been determined from the available database. The RPM value, available for approximately 68% of the main engines, has been used to determine if the engine is high speed diesel (HSD), medium (MSD) or slow (SSD) speed. Consistent with earlier studies (Entec, 2002, 2010; Ng et al., 2012), HSD engines were defined as engines with an RPM>1000, MSD engines were defined as engines with an RPM ≤1000 and RPM >300, and SSD engines were defined as engines with an RPM≤300. The main engine types for three vessel size ranges were determined by identified the number of vessels with HSD, MSD and SSD. For the classification of different operation modes were shown in table SI-3.

The SO_2 emission depend on engine type and sulphur content of fuel oil. Due to the value of sulfur content statistics by China Marine Bunker (Fan et al., 2016) were higher than global averages reported by the IMO Maritime Environment Protection Committee (MEPC, 67th) , so, sulfur content for MHO and MDO were set as 2.7% and 0.5% in this study, and a sulphur content corresponding to the sulphur limit required in the ECA is assumed in both main engines, auxiliary engines and boilers, meanwhile, the key issue of SO_2 generation rate from the sulphur in fuel oil were solved by literature review, set as 83%, 90% and 94% for slow speed diesel (SSD), medium speed diesel (MSD) and high speed diesel (HSD), respectively (USEPA ship report; Liu et al., 2016; Fan et al., 2016). For NOx emission, as shown in table SI-6, MARPOL Annex VI given a progressive reductions in NOx emissions from marine diesel engine, with more stringent controls being a “Tier II” emission limit required for those marine diesel engines installed on or after 1 January 2011; then with the most stringent controls being “Tier III” emission limit for marine diesel engines installed on or after 1 January 2016. Marine diesel engines installed on or after 1 January 1990 but prior to 1 January 2000 are also required to comply with “Tier I” emission limits, if an approved method for that engine has been certified by an Administration. On the other hand, fuel type and quality sulphur content as a major factor influencing the emissions of PM, HC and CO, and engine type also have effects on PM. As detail shown in table SI-7.

$$SO_2 \text{ Emission} = \text{Fuel consumption} \times 2 \times S\% \times R$$

Table SI-8 NOx emission factors used in this study (unit: g/kg Fuel)

Fuel type	Engine type	Emission Stander	Model year	Emission Factor
MHO (2.7%sulfur content)	SSD	Tier 0[1]	≤1999	79.7
	MSD		≤1999	61.7
	SSD	Tier1	2000-2010	74.9
	MSD		2000-2010	57.3
	SSD	Tier2	2011–2015	67.4
	SSD		2011–2015	49.3
MDO (0.5%sulfur content)	SSD	Tier 0[a]	≤1999	78.3
	MSD		≤1999	60.8
	SSD	Tier1	2000-2010	73.7
	MSD		2000-2010	56.2
	SSD	Tier2	2011–2015	66.4
	SSD		2011–2015	48.4
	HSD	Before Tier 3[b]	All	46.1
MHO/MDO	Boiler[3]	All	All	15.7
LNG or other clean energy	SSD	Tier 3[b]	＞2016	14.8
	MSD		＞2016	11.3
	HSD		＞2016	9.2

[a]IMO 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.

[b]Tier 3 means conduct NOx emission control measures, e.g. LNG-fueled engine, Emission gas recycle, Selective catalytic reduction of NOx (SCR), that means the control policies of Emission Control Area (ECA). [3] Which means Boiler engine.

Table SI-9 Emission factors used in ship emission estimates (unit: g/kg Fuel)

Activity Type	**Engine Type**		**Fuel Type**	**Sulfur content**	**PM_{10}**	**$PM_{2.5}$**	**HC**	**CO**
OGVs/CVs[a]	ME[c]	SSD	MHO	2.7%	6.1	5.7	2.6	6.1
OGVs/CVs	ME[c]	SSD	MDO	0.5%	2.2	1.7	2.6	6.1
OGVs/CVs	ME[c]	MSD	MHO	2.7%	6.1	5.7	2.2	4.8
OGVs/CVs	ME[c]	MSD	MDO	0.5%	2.2	1.7	2.2	4.8
OGVs/CVs	AE[d]	HSD	MHO	2.7%	6.1	5.7	1.7	4.8
OGVs/CVs	AE[d]	HSD	MDO	0.5%	2.2	2.2	1.7	4.8
OGVs/CVs	BE[e]	HSD	MDO	0.5%	1.3	1.0	0.4	0.9
RVs[b]	ME[c]	HSD	MDO	0.5%	1.7	1.7	1.7	6.0

[a, b]OGVs, CVs and RVs mean Ocean-going vessels, Coast vessels and River vessels, respectively.

[c, d, e]ME, AE and BE mean main engine, auxiliary engine and boiler engine, respectively.

Besides, the relationship of ship types to engine types and fuel types were the essential in emission estimation, shown in table SI-8. On the other hand, fuel type and sulfur content are the most important specification in ship fuels. According to the previous research (Ng et al., 2012; Fan et al, 2016; Liu et al., 2016), for three engine types in vessel types with the main fuel types has been identified. On the other hand, no specific ship emission control regulation was assigned in this study domain in 2013 except a two-year industry-led voluntary fuel switch initiative (the Fair Winds Charter, S% ≤0.5%) in Hong Kong in January 2011. Therefore, sulfur content for MHO and MDO were set as 2.7% and 0.5% (set value refer the domestic vessels ranges from 0.2% to 2.0%, provided by China Marine Bunker, CMB) (Fan et al., 2016).

Table SI-10 Relationship of ship types to engine types and fuel types

	Ship types	**Engine Types**			**Fuel Types**		
		DWT≤5000GT	5000＜DWT＜25000	≥25000GT	ME	AE	BE
OGVs and CVs	Dry Bulk Carrier	MSD	MSD	SSD	MHO	MHO	MDO
	Container	MSD	MSD	SSD	MHO	MHO	MDO
	General cargo ship	MSD	SSD	SSD	MHO	MHO	MDO
	Tanker	MSD	SSD	SSD	MHO	MHO	MDO
	Others	MSD	MSD	SSD	MDO	MDO	MDO
River ships			HSD			MDO	

*SSD, MSD, HSD mean Slow speed diesel engine, Medium speed diesel engine, High speed diesel engine, respectively. MHO and MDO mean Marine heavy oil and Marine diesel oil.

Table SI-11 Low load adjustment multipliers for emission factors

LF	SO_2	NO_X	CO	PM	HC
0.01	1.00	11.47	19.32	19.17	59.28
0.02	1.00	4.63	9.68	7.29	21.18
0.03	1.00	2.92	6.46	4.33	11.68
0.04	1.00	2.21	4.86	3.09	7.71
0.05	1.00	1.83	3.89	2.44	5.61
0.06	1.00	1.6	3.25	2.04	4.35
0.07	1.00	1.45	2.79	1.79	3.52
0.08	1.00	1.35	2.45	1.61	2.95
0.09	1.00	1.27	2.18	1.48	2.52
0.1	1.00	1.22	1.96	1.38	2.2
0.11	1.00	1.17	1.79	1.3	1.96
0.12	1.00	1.14	1.64	1.24	1.76
0.13	1.00	1.11	1.52	1.19	1.6
0.14	1.00	1.08	1.41	1.15	1.47
0.15	1.00	1.06	1.32	1.11	1.36
0.16	1.00	1.05	1.24	1.08	1.26
0.17	1.00	1.03	1.17	1.06	1.18
0.18	1.00	1.02	1.11	1.04	1.11
0.19	1.00	1.01	1.05	1.02	1.05
0.20	1.00	1.00	1.00	1.00	1.00

5. Uncertainties estimation

Uncertainties of emissions factors and activity time for estimation were shown as following.

Table SI-5 Uncertainties of emissions factors for estimation

Pollutants	Categories	Distribution types	Mean	Confidence interval
SO_2	MHO（2.7%）	Weibull	11.3	(-18.2%, 11.3%)
	MDO（0.5%）*	Weibull	1.4	(-74.8%, 107.4%)
NOx	SSD	Gamma	16.3	(-19.7%, 21.6%)
	MSD	Gamma	13.8	(-9.6%, 10.4%)
	HSD*	Gamma	11.5	(-26.0%, 29.2%)
CO	OGVs/CVs	Gamma	1.3	(-22.4%, 25.0%)
	RVs	Gamma	1.3	(-22.4%, 25.0%)
PM_{10}	MHO（2.7%）	Gamma	1.5	(-14.7%, 16.4%)
	MDO（0.5%）*	Weibull	0.4	(-42.4%, 34.6%)
$PM_{2.5}$	MHO（2.7%）	Weibull	1.3	(-14.7%, 16.4%)
	MDO（0.5%）*	Gamma	0.4	(-42.4%, 34.6%)
HC	OGVs/CVs	Gamma	0.5	(-32.7%, 36.5%)
	RVs	Weibull	0.4	(-65.3%, 72.0%)

Table SI-6 Uncertainties of time-in-modes for estimation

Ship types		Modes	Distribution types	Mean/hours	Lower bound of uncertainty	Upper bound of uncertainty
OGVs	Tanker	Maneuvering	Weibull	4.3	-28%	31%
		Hoteling	Weibull	25.3	-17%	16%
	Cargo ship	Maneuvering	Gamma	3.4	-15.1%	20.9%
		Hoteling	Weibull	15.8	-9.8%	6.0%
	Container ship	Maneuvering	Weibull	3.7	-11%	10%
		Hoteling	Weibull	22.2	-16%	17%
	Others	Maneuvering	Weibull	1.1	-62.1%	96.5%
		Hoteling	Gamma	17.2	-50.0%	60.1%
CVs	Tanker	Maneuvering	Gamma	2.3	-35.9%	53.8%
		Hoteling	Normal	23.5	-15.3%	19.0%
	Cargo ship	Maneuvering	Gamma	3.2	-84.3%	160.4%
		Hoteling	Gamma	16.8	-17.5%	18.7%
	Container ship	Maneuvering	Normal	3.9	-53.0%	46.7%
		Hoteling	Weibull	19.1	-29.9%	29.4%
	Others	Maneuvering	Gamma	2.7	-84.8%	164.9%
		Hoteling	Gamma	17.7	-84.2%	172.6%

6. Emissions intensity calculation

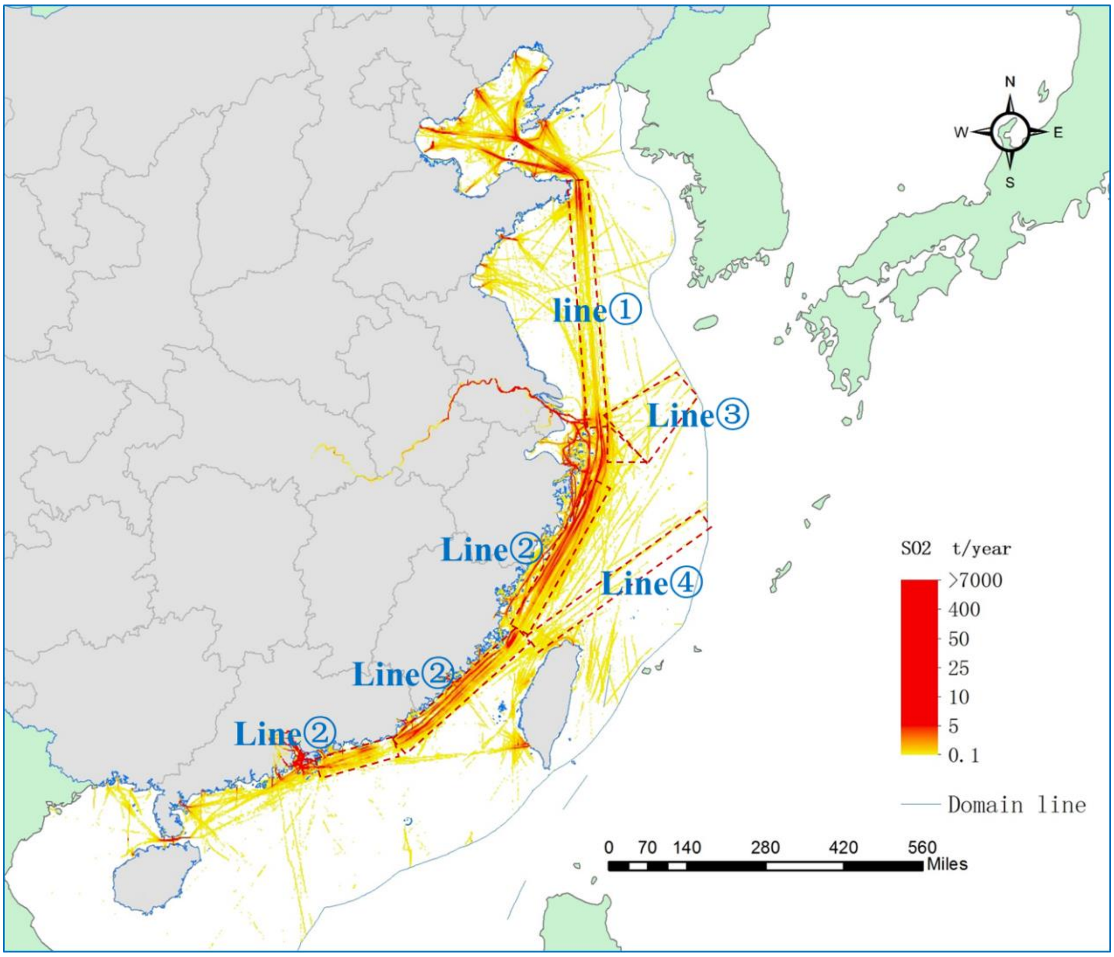

Fig. SI-5 Spatial allocation of typical navigating lines in Emission intensities calculation

7. Emission trends analysis

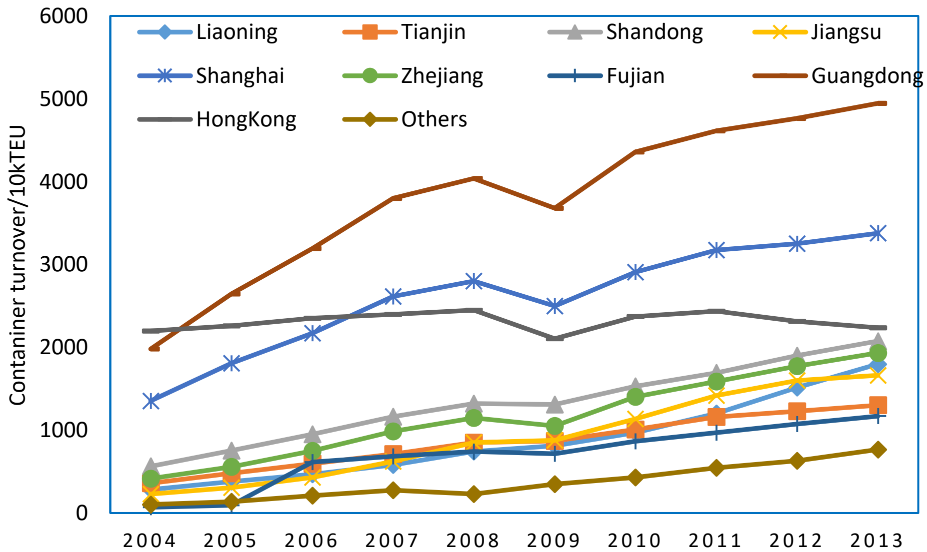

Fig. SI-6 Trends of container turnover from different provinces

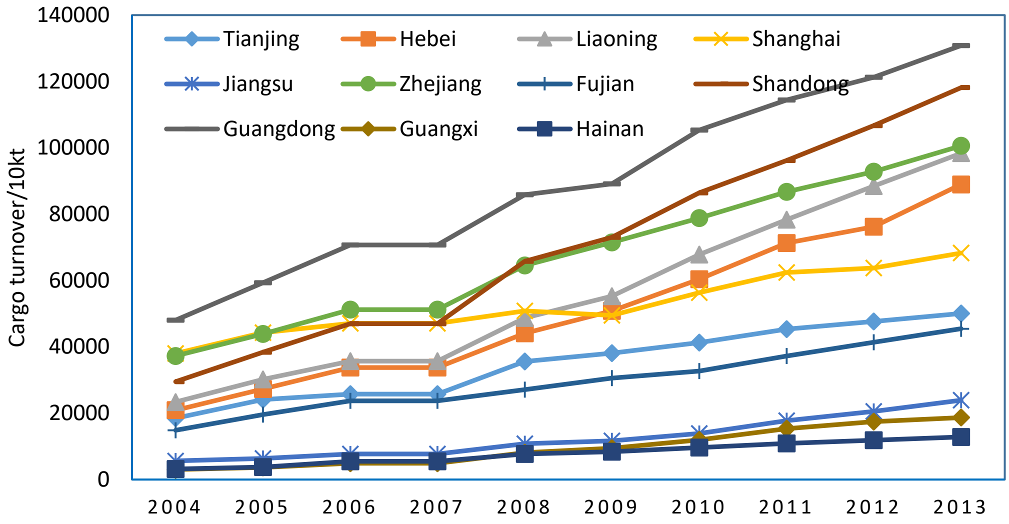

Fig. SI-7 Trends of cargo turnover from coast ports in different provinces

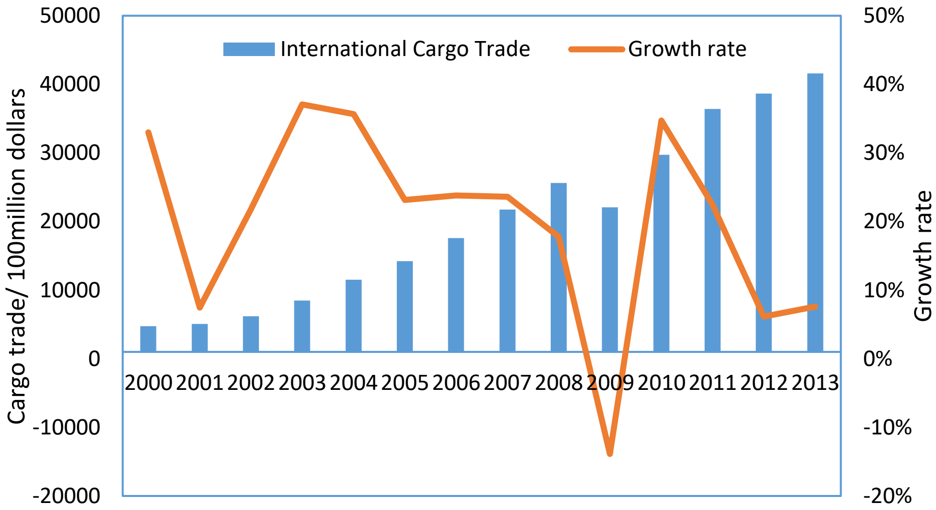

Fig. SI-8 Trends of international cargo trade and growth rate in China

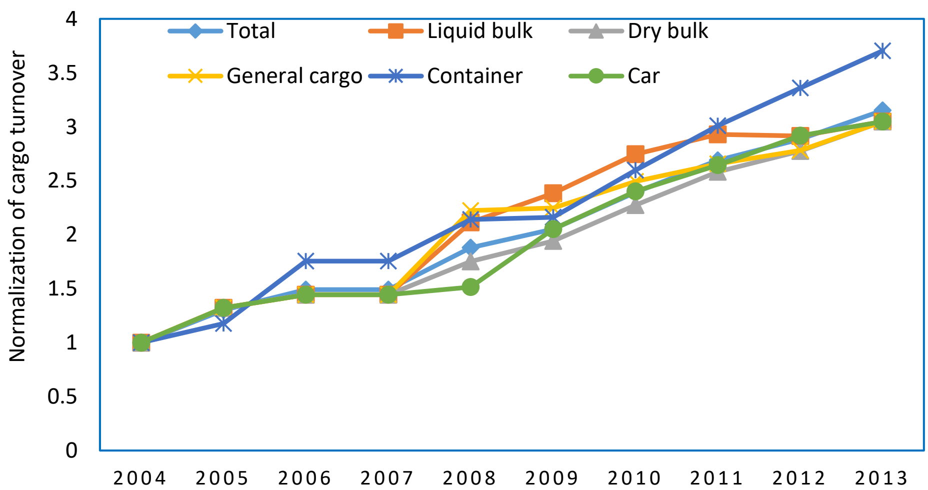

Fig. SI-9 Trends of cargo turnover with different cargo types in China from 2004 to 2013