Response to comments

Reviewer #1:

1. The cargo-based approach is very unclear. How do you get emissions other than 2013? This method is the key for the whole paper. The authors use only ten lines to give a very brief description. Without detailed data, it's hard to prove the results are convinced.

Response: In equation (2), cargo-based approach is to estimate emissions by transport volume, transport distance, fuel consumption, and emission factor. In the revised manuscript, we explain briefly the methods in determining transport volume and transport distance in lines 4-21 of page 6, and provide more detailed explanation in section 3 and 4 of the support information (SI), respectively. Determination of fuel consumption rate and emission factor are introduced in section 2.3.2 and 2.3.3, respectively.

1.1 I suggest to list all the data in tables.

Response: We list detailed transport volume data for all 100 ports in Table SI-5, and transport distance for ocean-going vessels (OGVs) and coast vessel (CVs) in Table 2, more data for transport distance calculation in Table SI-6 and Figure SI-1(b).

1.2 What is the transport volume? Is it based on port statistic? How many ports with transport volume do you have? How do you generate regional transport volume based on port statistics?

Response: Transport volume is the real weight of transport cargo for a period time. Yes, it is based on port statistics and was extracted from the statistic yearbook of 100 Chinese ports in 6 port clusters. Due to the lack of transport volume in difference ship types, the stock of waterway cargo types in different provinces was separated into OGVs, CVs and RVs using the province-specific throughput of coastal ports and river ports, and it was then adjusted by the contributions of foreign trade in the main ports. Additional, the regional transport volume statistics include liquid cargo, dry bulk, general cargo, and container, corresponding to tanker, bulk ship, general cargo ship, container ship, respectively. Regional transport volume is determined by classifying ports into port clusters (regions). There are six port clusters in this study, including Bohai, Shandong, YRD, Western Taiwan Strait, PRD and Beibu Gulf. We list detailed transport volume data for all 100 ports in Table SI-5. The above information shown in lines 5-10 of page 6 and section 3 of the SI.

1.3 Do you considered those ship only pass the region without a destination in that region? If those ships were overlooked, are the results still reliable?

Response: We did roughly estimate the contribution from passing ships, and concluded that their contribution is relatively low but with potentially high uncertainties. Therefore, we decide to exclude it into this study to avoid negative impact on the results.

The research domain is 200Nm to the coast of Mainland China. The main routes in this domain include all routes from/to Chinese ports and the passing routes, mainly from Busan, Korea to Southeast Asia (Busan route) and from Taiwan to destinations other than Mainland China ports (Taiwan route). In order to study the fraction of Busan route and Taiwan route in our research domain, we extracted a real-time AIS map, and highlighted the passing ship routes by red lines.

There were 368 shipping route from/to Korea in 2013, including 85 Southeast Asia routes and 26

Europe routes. As the throughput of Busan port accounted for 75.4% of total throughput (17686kt) in Korea, we estimated that Busan route roughly accounted for 7100kt throughput. With around 800Nm passing distance in our research domain, we estimated the fuel consumption from Busan route was around 70kt HFO. The total throughput in Taiwan was 14 million TEU in 2013, including 2.5 million TEU between Taiwan and Mainland China. Therefore, Taiwan route contributed around 11.5 million TEU. If we assume 1TEU=15t and the average travel distance was 500Nm, the fuel consumption from Taiwan route was around 1070kt HFO. Therefore, the total consumption of Busan route and Taiwan route was around 1140kt HFO, only 7% of total fuel consumption in our research domain. Therefore, we believe excluding the passing route would not significantly impact our analysis results.

We briefly mention the exclusion of passing route in lines 14-15 of page 4 of the manuscript, and provide detailed explanation in section 2 of SI.

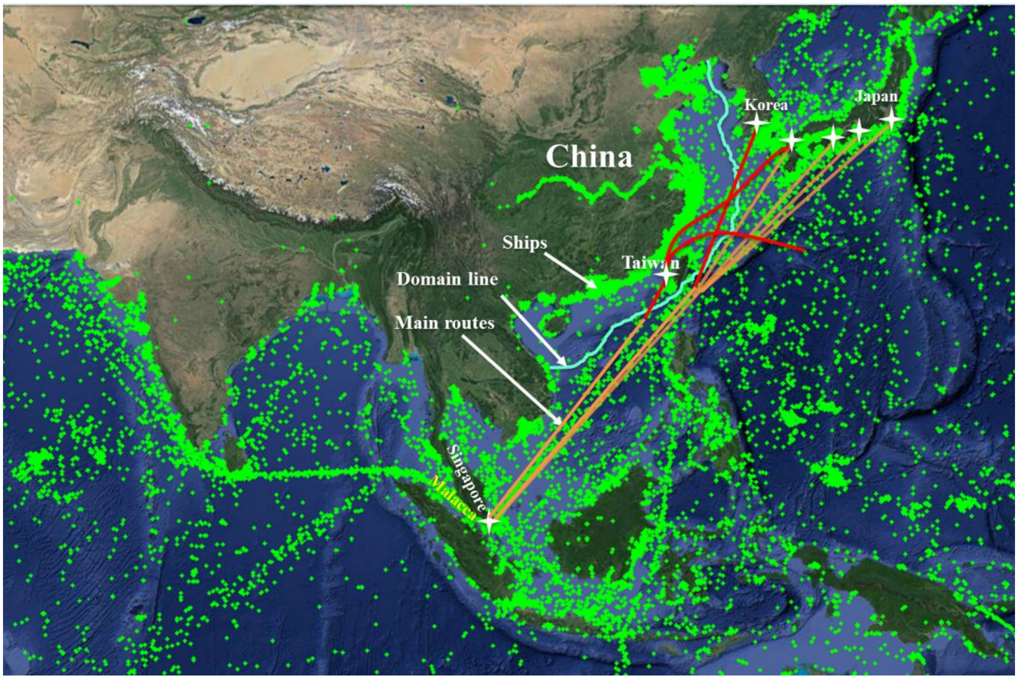

Fig. SI-1 Major shipping routes extracted from a real-time AIS digital map (passing routes are highlighted in red)

1.4 How do you define the transport distance? With AIS information only, you cannot get the origin and destination of each trip. Fig. SI-1 didn't explain how you get the distance.

Response: Transport distance is the weight-based length along common routes of OGVs and CVs in the research domains of 12Nm and 200Nm, respectively. Specifically, transport distances of OGVs were calculated as the average of main international routes from main ports in a particular port cluster, as shown in Fig. SI-2(a), and then multiply by the fraction of regular routes to Korea, Japan, South China Sea and Pacific, respectively (see Table SI-6); transport distances of CVs were derived from transport distances between port clusters measured by AIS data and digital map. Some illustrations are given in Fig. SI-2(c) for readers to understand the AIS-based digital map. We collected information more than 1000 regular routes, including their departure and arrival ports. We classified departure and arrival ports into port clusters, and then used AIS data and digital map to calculate transport distances between port clusters (Fig. SI-2(b)). It should be emphasized that the departure and arrival port information for the regular route information is not collected by AIS data. AIS data is only used to calculate inter-port cluster transport distance. The above information shown in lines 10-19 of page 6 and section 4 of the SI.

1.5 do you mean that all the cargo share the same transport distance? Is it true?

Response: This is not true. Table 2 lists transport distances for OGVs and CVs in different regions within 12Nm and 200Nm calculated from more than 1000 shipping routes. Detailed calculation procedure of transport distances for OGVs and CVs are provided in lines 10-19 of page 6. We didn't calculate transport distance of RVs as we directly use fuel consumption of 5.2 tce/10Kt provided by Statistics Communique of China on the Traffic and Transportation Industry Development, as shown in section 7 of the SI.

1.6 Section 2.3.2. No data was provided at all! How can I evaluate your calculation results without any input data? You can decide to provide data in tables or delete all the related results.

Response: We add detailed data about transport volume in Table SI-5 and transport distance in Table SI-6(b) and Figure SI-1(b), respectively. We also provide detailed explanation on the calculation process in sections 3 and 4 of the SI.

1.7 The data source should be clearly provided in linkage or with DOI. Such general description, such as "China yearbook", means nothing to most of the audients who can not read Chinese!

Response: The yearbook is only published in Chinese. The linkages are provided in the reference list. Unfortunately, some raw data, such as vessel calling number and cargo volume, was provided by local marine departments without any linkage or reference material.

2. How's the quality of the AIS database? It seems the authors make calculation based on very limited AIS data.

Response: AIS database used in this study is limited in number but with high representativeness, because of 1) this study is not aimed to calculate emissions from each AIS data point, therefore does not need all AIS data; 2) the objective of using AIS data in this study is to accurately identify ship activity characteristics and main parameters, e.g. transport distance, time-in-mode, loading factor, therefore it is a must that AIS data matches well with source categories in the emission inventory; 3) strict selection criteria were adopted. First, ship categories and weight tonnage of OGVs, CVs and RVs were analyzed (Fig. SI-4). The number of ship route in different weight tonnages for different ship categories were then calculated. Prefer to frequent active ships within this study domain, 700 AIS trajectories with high representativeness were then selected; 4) In comparison with Liu et al. (2016) which used East Asia as target domain, the area of research domain in this study was around 71% and covered 69% of ship information, including all regular routes. This meant that the density of ship information in this study was comparable with Liu et al. (2016). Therefore, we believe the AIS database used in this study, although with relatively limited number, had indeed high quality and representativeness.

The above information is added in lines 11-13 of page 8 and section 5 of the SI.

2.1 Page 6, Line 10-13, I was confused by the two methods you mentioned. Monthly variation is not from AIS? You have only one day per month for AIS? If so, is there large weekly or monthly variation *of shipping activity in China?*

Response: Monthly variation of fuel consumption is derived from cargo throughput instead of AIS mainly for the following two reasons. 1) Within a year, the structure of cargo types and transport routes in a particular port generally don't have significant changes. Therefore, ship activity has significant correlation with cargo throughput. Monthly variation of cargo throughput can be used as a substitute for monthly variation of fuel consumption; 2) Monthly variations of fuel consumption in different years tend to be different as they are largely affected by the fluctuation of international trade. In this study, we used monthly variation of cargo throughput from 2000 to 2013 to account for such annual variation.

In addition, we examined the density distribution of AIS data and found that the weekly and daily variations were not obvious, as shown in Fig. SI-3. Therefore, it is reasonable to use data from one day to account for monthly variation.

The above information is added in lines 26-31 of page 6 and section 5 of the SI.

2.2 Page 7, line 26, only 700 AIS-based trajectories from 2013? That means, you have two trajectories for each day. If so, how can you estimate emissions from other ships?

Response: No. We have the entire one-year data for all 700 trajectories. We have revised the expression as "approximately 700 AIS-based navigation trajectories with entire one-year data from 2013 were collected" to avoid misunderstanding. The above information is revised in lines 8 of page 8.

3. The ship information database is far from enough. Only 5000 ships from LRS and 7600 RVs from local MDs were collected. How many ships were observed in your AIS or port calls database? You may lose most of the ships by doing this. You mentioned another study reported 18000 ships, which actually cannot support your study. If you want to catch 20000 ships travelling in to your study domain, you need to prepare a database much larger than this number. So the missing ships in your database is at least more than half.

Response: Our AIS database included 700 trajectories and port calls database included 9.54 million port calls, including 6.58 million for RVs and 2.96 million for OGVs and CVs. In comparison with a previous study (Liu *et al.*, 2016) which used East Asia as target domain, the area of research domain in this study was around 71% and covered 69% of ship information, including all regular routes. This meant that the density of ship information in this study was comparable with Liu et al. (2016). Therefore, we believe the AIS and ship databases used in this study, although with relatively limited number, had indeed high quality and representativeness. Another objective of this study is establish a methodology in using limited AIS data to develop ship emission inventory. Such a methodology can be used in other parts of the world, as most of the time it is unable to collect a complete set of AIS information.

The above information is added in lines 11-16 of page 8, Table 3, and section 5 of the SI.

4. What is the boundary of China Sea area? Do 200nm regions all belong to China? Without a boundary, the emissions can't be considered as the China's emissions. What is the definition of China's emission control area? Through the manuscript, it seems the 200 nm is defined as the emission control zone. It seems very strange to me. The zone is extended to other countries, like Viet Nam, Korea and etc.

Response: Current domestic emission control areas (DECAs) in China only covers 12Nm in three main port clusters. The main target of this study is to investigate the effect of DECA delineation in assisting emission control, therefore used 200Nm as one of the scenarios, solely for research purpose. We selected 200Nm for two reasons. 1) 200Nm is the border for exclusive economic zones (EEZ), and 2) 200 Nm offshore has been officially approved by International Maritime Organization (IMO) and been used by North America ECA. We want to emphasize that our 200Nm scenario does not include territorial sea of other countries, even if it is within 200Nm offshore of China, as illustrated in Fig.1. In addition, the setting of our research domain does not involve any political consideration. The above information is added in lines 30-31 of page 3 and lines 3-5 of page 4.

5. Page 14, line 8-11, why the fuel consumption were in a good agreement with those in cargo and container turnover? In the past 30 years in US, the fuel consumption increased much slower than the cargo turnover. Because the ship fleet gets larger and more fuel efficient. Actually, authors calculated fuel consumption based on the cargo turnover. It's your assumption the fuel should be in the same trend with cargo, not a conclusion. So, this conclusion is not correct.

Response: We made a mistake here. Fig. 6 shows that the fuel consumption doubled during 2004-2013, and container and cargo transport volume almost tripled as shown in Fig. 7. The relevant sentence has been revised in lines 19-24 of page 14.

6. All the abbreviations should be listed with full name when first appeared, and using only abbreviations for latter. Such as MHO, line 18 Page 8, line 12 page 9. There are a lot of these errors. . .

Response: Revised accordingly.

7. Usually we don't say marine heavy oil, but HFO (heavy fuel oil).

Response: Revised accordingly.

8. The format of references need to be checked carefully. Some references missed information, e.g. journal name. For example: Li C., Yuan Z.B., Ou J.M., Fan X.L., Ye S.Q., Xiao T., Shi Y.Q., Huang Z.J., Ng S.K.W., Zhong Z.M., and Zheng J.Y.. 2016. An AIS-based high-resolution ship emission inventory and its uncertainty in Pearl River Delta region, China. 573:1-10. http://dx.doi.org/10.1016/j.scitotenv.2016.07.219 For journal names, both the abbreviation and full name were used, e.g. Atmosphere Chemical Physic and Atmos. Chem. Phys.

Response: Revised accordingly.

9. Figure 2 and 3 should be put into supplementary information.

Response: Revised accordingly.

Reviewer #2:

1. The advantage(s) of the ship emission inventory developed in this study over previous ones are not sufficiently highlighted in the manuscript. In the Conclusions, the authors may give some suggestions for the modelers and other users who want to make a choice among different ship emission inventories.

Response: The advantages of ship emission inventory are threefold. 1) We used two different methods (cargo-based and port-based) to estimate and mutually validate emissions; 2) We calculated the ten-year trend of ship emissions from 2004-2013, and made projections in different scenarios with implementation of DECA; 3) We established a methodology in using limited AIS data to develop ship emission inventory. Such a methodology can be used in other parts of the world, as most of the time it is unable to collect a complete set of AIS information. The above advantages are discussed in the Implication section of the manuscript.

The above information is added in lines 31-32 of page 18, and lines 1-4 of page 19.

2. BC and OC are important components for air quality, visibility and climate simulations, and they are included in nearly all emission inventories for modeling purpose. However, BC and OC are not considered (or reported) in this work. Is it easy to add these two components?

Response: We added BC and OC analysis in the revision.

3. P3, L13: The literature (He at al., 2015) cannot be found in the References list.

Response: We instead provide three peer-reviewed publications for the Multi-resolution Emission Inventory for China (MEIC) (Li et al., 2014; Zheng et al., 2014; Liu et al., 2015).

4. P4, L4: Better to provide specific names of the three classification schemes.

Response: Specific names are provided in the revision.

5. P26, Fig.5a: Should the line colors of the coast match those in the pie? Green color (for YRD in the pie) cannot be found in the lines for the coast.

Response: Revised accordingly.

6. P28, Fig.7: The current color bar is not clear to see. Are the ship emissions associated with Taiwan ports taken into account? How about the emissions over the South China Sea?

Response: We have changed the color bar to become more visually clear. Taiwan ports were not taken into account due to the absence complete data sources. Our research domain only covered 200Nm offshore, therefore didn't account for the entire South China Sea.

7. The term 'HC' is used in the text while the term 'VOC' is given in Tables 8 and 9. There are so many abbreviations used in the manuscript. The authors might consider giving a list of abbreviations as Appendix?

Response: All VOCs have been changed to HCs. We also provide a list of abbreviations as Appendix, as suggested.

Reference:

Li, M., Zhang, Q., Streets, D. G., He, K. B., Cheng, Y. F., Emmons, L. K., Huo, H., Kang, S. C., Lu, Z., Shao, M., Su, H., Yu, X., and Zhang, Y.. 2014. Mapping Asian anthropogenic emissions of non-methane volatile organic compounds to multiple chemical mechanisms, Atmospheric Chemistry & Physics, 14, 5617–5638, doi:10.5194/acp-14-5617-2014.

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., and He, K. B.. 2015. High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010, Atmospheric Chemistry & Physics, 15, 13299–13317, doi:10.5194/acp-15-13299-2015.

Liu H., Fu M.L., Jin X.X., Shang Y. Shindell D., Faluvegi G., Shindell C., He K.B., 2016. Health and climate impacts of ocean-going vessels in East Asia. Nature climate change. doi: 10.1038/NCLIMATE3083.

Zheng, B., Huo, H., Zhang, Q., Yao, Z. L., Wang, X. T., Yang, X. F., Liu, H., and He, K. B.. 2014. High-resolution mapping of vehicle emissions in China in 2008, Atmospheric Chemistry & Physics, 14, 9787–9805, doi:10.5194/acp-14-9787-2014.

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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Abstract. Ship emissions contribute significantly to air pollution and pose health risks to residents of coastal areas in China, but the current accounting remains incomplete and coarse due to data availability and inaccuracy in estimation method. In this study, an Automatic Identification System (AIS)-based integrated approach was developed to address this problem. This approach utilized detailed information from AIS and cargo turnover and the number of vessels calling information, thereby capable of quantifying sectoral contributions by fuel types and emissions from ports, rivers, coastal and over-the-horizon ship traffic. Based upon the established methodology, ship emissions in China from 2004 to 2013 were estimated, and those to 2040 in every five year interval under different control scenarios were projected. Results showed that for the area within 200 nautical miles (Nm) of the Chinese coast, SO_2, NO_X, CO, PM_{10}, $PM_{2.5}$, hydrocarbon (HC), black carbon (BC) and organic carbon (OC) emissions in 2013 were 1,010, 1,443, 118, 107, 87, 67, 29 and 21 kt/yr, respectively, which doubled over these ten years. Ship source contributed ~10% to the total SO_2 and NOx emissions in the coastal provinces of China. Emissions from the proposed Domestic Emission Control Areas (DECAs) within 12 Nm constituted approximately 40% of the all ship emissions along the Chinese coast, and this percentage would double when the DECAs boundary is extended to 100 Nm. Ship emissions in ports accounted for about one quarter of the total emissions within 200 Nm, within which nearly 80% of the emissions were concentrated in the top ten busiest ports of China. SO_2 emissions could be reduced by 80% in 2020 under 0.5% global sulfur cap policy. In comparison, a similar reduction of NOx emissions would require significant technological change and would likely take several decades. This study provides solid scientific support for ship emissions control policy-making in China. It is suggested to investigate and monitor the emissions from the shipping sector in more detail in the future.

1. Introduction

Although more than 30% reduction in ambient $PM_{2.5}$ levels have been achieved during the past several years in major city clusters in China due to stringent control measures, the ambient $PM_{2.5}$ levels are still far higher than the World Health Organization (WHO) Air Quality Guidelines of 10 g/m^3 annual average. Strengthened reduction efforts are needed to reduce the adverse impact of ambient $PM_{2.5}$ on public health. In comparison with tightened controls on power plants, industry and road vehicle sectors, controls on ship emissions, one of the most significant contributors to ambient $PM_{2.5}$ pollution along the river and in coastal areas (Liu *et al.*, 2016), are still lax in China. Ship emissions control have been put on the agenda of $PM_{2.5}$ reduction in the coming years (Ye, 2014; Yang *et al.*, 2015; Fu *et al.*, 2016).

However, estimation of ship emissions in China remain incomplete and largely inaccurate. Locally, ship emission inventories are generally compiled in limited provinces and ports (Fu *et al.*, 2012; Bao *et al.*, 2014; Song, 2014; Tan *et al.*, 2014; Yang *et al.*, 2015), while in global inventories, ship emissions from China are of coarse temporal (monthly) and spatial (1°×1°) resolutions (Endresen *et al.*, 2003; Corbett *et al.*, 2007; Paxian *et al.*, 2010). A recent study develops ship emission inventory in Asia with spatial resolution of 3 km×3 km (Liu *et al.*, 2016), however, characteristics of coastal and ship traffic emissions, sector-based contributions in Chinese ports and their temporal characteristics remain unknown. Furthermore, estimates from domestic (Fan *et al.*, 2016; Li *et al.*, 2016) and international studies (Endresen *et al.*, 2003, 2007; Corbett *et al.*, 2003, 2007) are associated with large uncertainties due to inconsistency in estimation approaches and data sources, thus hampering the formulation of an effective ship emissions control strategy. Therefore, detailed and reliable ship emission inventories are needed in estimating potentials of ship emission reduction and the formulation of air pollution and public health improvement strategies.

Automatic Identification System (AIS) data, an automatic vessel position reporting system, has been widely recognized as a reliable data source that can significantly reduce the uncertainty in ship activities and their geographic distribution (Wang *et al.*, 2008; Dalsoren *et al.*, 2009; Bandemehr *et al.*, 2015). The accuracy of ship emissions estimates based on cargo volumes (Schrooten *et al.*, 2009) and vessel arrived numbers (Yang *et al.*, 2007; Yau *et al.*, 2012; Li *et al.*, 2016) can be improved by using AIS data. Recent studies use AIS data to estimate emissions from all ships at a given time or each single trip in an entire year in Asia and Europe (Liu *et al.*, 2016; Jalkanen *et al.*, 2016). However, the entire AIS database is not freely available to the public, especially in East Asia, and the data before 2012 is not suitable for use due to significant absence of data from a limited number of satellites and shore-based radars (He *et al.*, 2013). Therefore, establishing an integrated ship emission estimation and validation approach capable of handling incomplete AIS dataset is essential to enhance the usage of AIS data. This integrated approach improves temporal resolution and accuracy of ship emission estimates by cross-validation between port-based and cargo-based methods, thereby providing more detailed estimations on sector-based contribution of fuel consumption and emission of air pollutants.

This integrated approach is also capable of estimating historical decadal evolution of ship emissions, A few studies indicate that ship emissions in China has more than doubled over the last decade (Liu *et al.*, 2016), and their evolutions in the future decades are certainly of great interest to atmospheric science community and policy-makers, as development of ship emissions control policy, e.g. Chinese Domestic Emission Control Areas (DECAs) (Ministry of Transport of China, 2015) and 0.5% global sulfur cap (International Maritime Organization (IMO), 2016), profoundly impact both domestic shipping sectors and international trade stakeholders, however, these decadal ship emission data are currently unavailable in inter-annual trends of SO_2 (Lu *et al.*, 2010) and NOx (Zhao *et al.*, 2013) emissions from anthropogenic sources and the Multi-resolution Emission Inventory for China (MEIC) (Li *et al.*, 2014; Zheng *et al.*, 2014; Liu *et al.*, 2015). Rebuilding historical ship emission data will not only address data gap in current emission inventories, but also can help forecast future port and ship emissions, and assess the effectiveness of ship emission control measures.

In this study, we illustrated development of the integrated AIS-based ship emission estimation and validation approach by combining detailed information in cargo turnover and the number of vessels calling. Emissions from river vessels, ports, and ocean-going vessels (OGVs) up to a distance of 200 nautical miles (Nm) from the Chinese coast were calculated. Estimations during 2004-2013 were used as a basis for projections upon different control scenarios at five-year intervals until 2040. Current legislation and the DECAs policy were factored into the scenarios. SO_2 and NOx emission reductions by additional emissions control policies on ships and ports were evaluated. This study demonstrates the first effort in estimating national-scale ship emissions in China with improved accuracy by combining information of port-based vessel arrived numbers and province-based cargo volume.

2. Approach and data sources

2.1. Domain and ship categorization

The study domain includes all ports in China and offshore waters within 200 Nm of the coast (17.93 to 41.82°N, 105.28 to 124.43°E). Based on the proposed DECAs and approved global ECAs approved by IMO (IMO, 2010; 2016), ship emissions within 12 and 200 Nm from the coastline of China, excluding offshore islands, were estimated (Fig. 1). To identify the transport distance and activity time-in-modes for ship emissions estimations, six port groups were defined geographically, namely Bohai, Shandong, Yangtze River Delta (YRD), Western Taiwan Strait, Pearl River Delta (PRD) and Beibu Gulf. The reason for choosing the 200 Nm offshore as one of the research domains is to assess how the setting of ECAs influences emission reductions on shipping sources. More information about the domain is presented in the Section 1 of Supporting Information (SI) with Tables SI-1 and SI-2.

In this study, ships were classified by three classification schemes, namely OGVs, coastal vessels (CVs) and river vessels (RVs), as detailed in Table SI-3. Four sub-categories were classified by ship types, i.e. cargo ship, container, tanker, and others. Three sub-categories were classified by ship flag and customs declarations to the Marine Department (MD) of China, i.e. OGVs operated under a foreign flag or engaged in international trade, CVs operated under the Chinese flag and not engaged in international trade, and RVs operated in the rivers and statistically independent in local MDs. Three sub-categories were classified by operational modes, i.e. at sea, maneuvering and at berth (IMO, 2014), as indicated in Table SI-4. Emissions from the main engine (ME), auxiliary engine (AE) and auxiliary boilers (AB) were considered. Ships traveled through the research domain but did not call at any port in mainland China were not included, their major shipping routes extracted from a real-time AIS digital map shown in Fig. SI-1, and their potential influence was analyzed in Section 2 of the SI.

2.2. Approach

2.2.1. Estimation approaches

Different emission estimation approaches were described for shipping emission inventories worldwide (Dalsoren *et al*., 2009), in East Asia (Liu *et al*., 2016), and on a regional scale (Li *et al*., 2016). In this study, an AIS-based integrated approach were established to identify emissions contributions and their historical trends. This approach integrated two AIS-based methods to address the problems of data availability and completeness. One is the port-based approach, which makes use of the AIS-based ship activity time-in-mode in 2013 to fill the data gap in port-based vessel calling number. This enables a detailed characterization of ship emissions and their uncertainties. The other is the cargo-based approach which used province-specific cargo volume data categorized by cargo type and trade type. By combining this activity data with the average distances of major navigation routes between ports obtained from AIS-based digital map, the historical emissions can be estimated. The cargo-based approach considers the effects of trade type, ship type structure, fuel quality and port function on ship emissions. Meanwhile, cross-validation between different statistical methods ensures robust and reliable inventory estimates. Detailed of two approaches were introduced in the following sections.

1) Port-based approach

The port-based approach calculates ship emissions based on engine activity, as shown by Eq. (1) (U.S.EPA, 2000, 2008; Ng *et al.*, 2012):

$$E_k = \sum_{i=1}^{n} VAN_i \times P_{lj} \times LF_{ljm} \times T_{ljm} \times EF_{ljk} \quad (1)$$

where *i, j, k, l, m,* and *n* represents a single voyage, engine type, pollutant, dead weight tonnage (DWT) class in ship type, activity mode, and total vessel arrived number, respectively. *E* is emission (g), *VAN* is the vessel arrived number, *P* is the average installed engine power (kW), *LF* is the average engine load factor, *T* is the average operation time in three activity modes (h), and *EF* is the emissions factor corresponding to the engine and fuel types (g/kW·h).

In this equation, *VAN* were further divided into sub-categories according to ship type and DWT. The engine power and load factors of the ME were estimated using the Propeller Law based on the relationship between the instantaneous speed and the design speed, together with the detailed technical information of ship engine which was widely used in the estimation of ship emissions (ICF international, 2009). Owing to the lack of information and similar propulsion ratios for AE and AB (Ng *et al.*, 2012), the propulsion ratios and load factors for different ship types and operational modes were obtained from technical reports (U.S.EPA, 2008; Starcrest Consulting Group, 2009). Due to the difference in the DWT sub-class range and distribution of ship profile in different studies, adjustments were made for major ship types such that the AE and AB engine defaults better corresponded with the ship size and tonnage (Entec UK Limited, 2010; Ng *et al*. 2012). In addition, AE was assumed to be off when the ship speed was more than 8 knots (except for container and passenger ships), and those ships with diesel-electric engines were assumed not to use their boilers.

An AIS-based ship trajectory was used to define the cruising time and maneuvering time for OGVs and CVs, which included the position, time, status, speed and course of ship. For RVs, the cruising time was calculated as the average transport distance divided by average ship speed, and considering the main navigation routes in different regions. The hoteling time can be calculated using publicly available data regarding ship activity in the main ports of China, such as the ship name, ship type, destination harbors, departure times and arrival times (http://www.chinaports.com/). The calculation results are listed in Table 1. More information regarding emissions estimations is presented in the SI.

2) Cargo-based approach

A cargo-based approach considering the fuel consumption rate and transport distance is shown in Eq. (2):

$$E_k = \sum_{l=1}^{n} Q_{lr} \times TD_r \times F_{lm} \times EF_k \times 10^{-6} \quad (2)$$

where l, k, r, and m is ship type, pollutant, activity region and fuel type, respectively. Q is the transport volume (kt); TD is the average transport distance along the main navigation route (Nm); F is the fuel consumption rate (kg of fuel /kt·Nm); and EF is the emissions factor (g/kg of fuel).

Transport volume, transport distance, fuel consumption rate and emission factor are therefore essential factors to estimate emissions in historical years. Transport volume is the real weight of transport cargo for a period time. It was extracted from the annual report of 100 Chinese ports in 6 port clusters. Due to the lack of transport volume in different ship types, the stock of waterway cargo types in different provinces was separated into OGVs, CVs and RVs using the province-specific throughput of coastal ports and river ports, and it was then adjusted by the contributions of foreign trade in the main ports. Detailed transport volume data for all 100 ports is provided in Table SI-5. Transport distance is the weight-based length along common ship routes of OGVs and CVs. Specifically, transport distances of OGVs were calculated as the average of main international routes from main ports in a particular port cluster, and then combine the fraction of regular routes to Korea, Japan, South China Sea and Pacific, respectively (Table SI-6); transport distances of CVs were derived from transport distances between port clusters measured by AIS data and digital map. We collected information of more than 1000 regular routes, including their departure and arrival ports (sample as Fig. SI-2(b)). We classified departure and arrival ports into port clusters, and then used AIS data and digital map to calculate transport distances between port clusters. Calculation process of transport distances and AIS-based ship trajectories were shown in Fig. SI-2. The calculation results are presented in Table 2. Determination of fuel consumption rate and emission factor are introduced in detail in section 2.3.2 and 2.3.3, respectively.

2.2.2. Temporal and spatial allocation

Ship fuel consumption were temporally and spatially allocated using surrogates from AIS data and other official statistics. Because ship fuel consumption are significantly correlated with port throughput and main navigation routes, the average monthly throughput data in 2010-2013 were used to depict monthly variations in fuel consumption from container ships and cargo ships so as to account for the difference among annual variation caused by the fluctuations in international trade. As the weekly and daily variations of fuel consumption were very small as illustrated in density distribution of AIS data (Fig. SI-3), using one-day data per month can well reproduce the monthly variation of fuel consumption. As we didn't have hourly cargo transport data, diurnal variation of fuel consumption was determined based on AIS ship track data.

A dot-density-weighted algorithm was applied for the spatial allocation of emissions. This algorithm used the density of data "dots" to calculate spatial surrogates by weighting emissions from different pollutant types and navigation modes. The emissions in different ports and water areas were defined based on hotelling and cruising information. According to the weights of the above spatial surrogates in every grid cell, the ship emissions were distributed in 3 km × 3 km grid cells covering the research domain.

2.2.3. Uncertainty

Previous studies indicated that the uncertainties in ship emissions were mainly introduced by time-in-mode, load factors and emission factors (Yang *et al.*, 2007; Ng *et al.*, 2013), but these uncertainties were not quantified. In this study, AIS data were used to quantitatively characterize the uncertainties associated with time-in-modes and load factors using a bootstrap simulation approach. Statistical methods and expert judgment were used to estimate uncertainties in the emission factors. The uncertainty ranges of emission factors and time-in-modes are presented in Tables SI-7 and SI-8, respectively. Using Monte Carlo simulation approach, the propagation of uncertainties in the above inputs into the estimated results were evaluated. This quantitative assessment revealed key contributors of uncertainties, which called for attention for further inventory improvement and refinement.

2.3. Data sources and validation

2.3.1. Port distribution and ship activity

To ensure the reliability and precision of the emissions estimates, verification of the input data is important. Here, the difference in input data from different data sources were analyzed, and the potential reasons for the variations were discussed. Specifically, data at the national-level, provincial-level and port-level from different statistical departments, e.g. National Bureau of Statistics, MD and Port Association, were compared. Other parameters in the port-based approach, including vessel call, ship type stock, engine power, load factor and activity time-in-mode, were also examined.

Table 3 lists the vessel calls based on MDs. The difference between the statistics provided by the national MD and some local MDs might be caused by the existing differences in statistical methods and different classifications of vessel calls, e.g., regular shipment, international trade, domestic trade, and local shipment. To address these differences, port-based vessel calls were summarized based on 11 regional MDs defined by the Ministry of Transport of China (MD Report, 2015, unpublished) using the same statistical approach. The RVs data were obtained directly and solely from the national MD. As the ship statistics by MD were not classified based on DWT, an adaptive sampling approach based on real-time AIS data was adopted by considering port sizes and wharf structures to remove errors in individual sampling periods. A summary of the stock of ship types that navigated in different regions is presented in Fig. SI-4. The detailed data sources are shown in Fig. SI-5.

The activity information for different ship types was collected from various sources. Information for more than 5,000 OGVs and CVs was acquired from Lloyd's Register of Ships (LRS). Registration information regarding nearly 7,600 RVs was acquired from local MDs. Liu *et al*. (2016) reported that almost 18,000 ships navigated in the East Asian Sea, which supported the representativeness of samples used in this study. The LRS and MD registration databases provided the registration number, ship type and tonnage, major sea routes, fuel type, engine information, and other relevant information for emissions estimates.

Specifically, approximately 700 AIS-based navigation trajectories with entire one-year data from 2013 were collected, including 350 million AIS messages with 3 million operation hours covering OGVs, CVs and RVs and major ship types. In comparison with the AIS dataset in East Asia for 2013 (Liu *et al*., 2016), the area of research domain in this study was around 71% and covered 69% of ship information, including all regular routes. This meant that the density of ship information in this study was comparable with Liu et al. (2016). Based on this AIS dataset, ship activity profiles were established by considering different regions, ship types and size categories, e.g. time-in-modes, load factors and spatiotemporal surrogates. More information regarding the AIS data is presented in Table SI-9.

2.3.2. Cargo transport trends and fuel consumption statistics

Based on the cargo transport statistics, there were no significant differences between different statistical departments, such as China Port Statistics Yearbook (CPSY), China Statistics Yearbook, and Statistics Communique of China on the Traffic and Transportation Industry Development (CCTD). Because CPSY provides both national and provincial cargo transport balances and covers OGVs, CVs and RVs on the provincial scale, transport volume balances was adopted for estimation from 2004 to 2013. Transport volume of cargo types in 6 ports clusters with 100 Chinese ports from 2004 to 2013 were shown in Table SI-5(a-k), more information about transport volume were shown in SI.

The fuel consumption rates of OGVs and CVs used in this study were based on the median values of the range provided by the IMO report (IMO, 2015), and they accounted for the differences between container, general cargo, bulk carrier and tanker ships; for RVs, the value of 5.2 tce/10kt was provided by the CCTD. More information regarding fuel consumption rates is presented in Fig. SI-6.

2.3.3. Emission factors

Apart from activity data, pollutant emission factors are also imperative for emission inventory development. Emission factors were described per kWh (Li *et al*., 2016; Fan *et al*., 2016; Liu *et al.*, 2016) and per kilogram fuel consumption (Jin *et al.*, 2009; Bao *et al.*, 2014) in different studies. To make emission factor units from the literature consistent and to analyze their uncertainties, a fuel consumption rate of 227 g/kWh was calculated for heavy fuel oil (HFO) and a rate of 217 g/kWh was calculated for marine diesel oil (MDO) and gas oil (Ng *et al*., 2012). In China, most RV engines were produced by Chinese manufacturers, such as Zichai, Weichai, and Guangchai. Therefore, the average value of emission factors obtained via field measurements on local ships were used in this study (Zhang *et al*., 2015).

Given that the marine ship industry is associated with international trade and technology, there are no significant differences in ship engine emissions for OGVs. To reduce the uncertainties in emissions estimates due to emission factors, the relationships between emission factors by pollutant and ship characteristics, such as engine type, fuel type, sulfur content and emissions standards, were identified using a quantitative assessment approach. In this study, SO_2 emissions were calculated using both the sulfur balance approach and the sulfur transfer rate, which were dependent upon the engine type (U.S.EPA, 2006; IMO, 2016; Fan *et al.*, 2016). As indicated in Table 4, sulfur contents of fuel consumption for OGVs, CVs and RVs were determined by considering the global average value (IMO, 2016) and the local and national statistical values (Fan *et al.*, 2016). The global background values of sulfur contents used for estimation are shown in Fig. SI-7. To assess the historical and future trends of NOx emissions under control policies with different NOx emission standards, NOx emission factors under different influence factors were determined from the IMO study (IMO, 2008) and Liu *et al*. (2016), as detailed in Table SI-10. Emissions of particulate matter, hydrocarbon (HC), CO, black carbon (BC) and organic carbon (OC) were determined based on the engine types and fuel types (USEPA, 2006, 2009; Zhang *et al*., 2015), as shown in Table SI-11. All emission factors were selected according to local emission characteristics for navigational areas, ship types and DWT values, as listed in Table SI-12. Low-load adjustment multipliers were applied when the load factors of ME were below 20% to account for the low combustion correction coefficient during low main engine loading conditions (ICF International, 2009), as indicated in Table SI-13.

2.3.4. Control scenarios and factors for emission projection

Ship emissions in China are largely associated with international trade pattern and ship engine technology development. Future ship emissions are therefore determined by multiple factors, including trade and political (e.g. DECA, emissions standard), economic (e.g. Gross Domestic Product (GDP), shipbuilding industry), social (e.g. sulfur content of HFO, population), and technological (e.g. engine type, after-treatment devices). In this study, fuel consumption was used to predict baseline ship emission scenarios since there are strong associations between fuel consumptions and ship emissions

(Fig. SI-8), and emission control scenarios were used to adjust baseline emissions under different control strategies.

Changes of ship fuel consumption in every five-year interval from 2015 to 2040 in China were estimated by the output data from a predication model with high reliability (IEA, 2016). Specifically, estimation of marine fuel consumption in 2013 was used as the base-year value. Fuel consumptions associated with inland and coastal navigation sources (oil and gas) were used to predict fuel consumptions of CVs and RVs, whereas international marine bunkers were used to predict fuel consumptions of OGVs.

Ten scenarios were designed for SO_2 and NOx emissions reductions based on global sulfur cap of 0.5% by 2020 as planned by the IMO. Because NOx emission reductions depend on new engine technologies such as exhaust gas recirculation (EGR), selective catalyst reduction (SCR), and liquefied natural gas (LNG) engines, a 20-year lifetime for ship engines was assumed for the engine renewal period. Current legislation and DECAs were factored into the scenarios. Additional emissions control policies targeting SO_2 and NOx emissions from vessels and ports were evaluated based on emissions reductions, including a baseline, SO_2-DECA (SECA) and NOx-DECA (NECA), as detailed in Table 5. Future emissions were calculated at a 5-year interval.

3. Results

3.1. Characteristics of ship emissions in 2013

3.1.1. Estimation of fuel consumption in ports and sea

In 2013, there was no ship emission control measure in China. Ship emissions were therefore largely determined by fuel consumption. We start this section by discussing fuel consumption characteristics in ports and sea which can be indicative of and verify ship emissions in 2013.

The integrated approach is used to estimate ship fuel consumption in China in 2013, as shown in Table 6. Total fuel consumption based on port-based and cargo-based approaches exhibited a good agreement within 12 and 200 Nm to the coastline (deviation < 15%). More than 85% of MDO was consumed within 12 Nm, and almost 80% was contributed by RVs and CVs, particularly by RVs. Conversely, only 35% of HFO was consumed within 12 Nm, and OGVs dominated its consumption. Although there were differences in the MDO estimations of CVs and RVs between two approaches, they were mainly associated with small CVs that were categorized as RVs in port under the port-based approach. Here, the results of port-based approach were used for comparison. Total fuel consumption within 200 Nm was estimated to be 17,035 kt in 2013, within which 2,730 kt of MDO was consumed in rivers and coastal waters. Fuel consumption in the overlapping area estimated by Liu et al. (2016)

was almost 25% greater than that in this study because of differences in domain size and estimation approach.

Fig. 2 showed the spatial allocation maps of MDO and HFO, which were calculated by the dot density of AIS data from RVs and CVs within 50 Nm and from OGVs within 200 Nm of the coastline, respectively. As most MDO was consumed by RVs and low-power CVs, the spatial distribution of MDO follows the coastline and rivers, especially in the YRD region. OGVs predominantly consume HFO, therefore the highest densities of HFO appear in the development areas of international trade and near the international navigation routes, such as the YRD, PRD, Bohai and regular routes connecting YRD and PRD.

We further examined the port activity and fuel consumption for the top ten ports in China, as detailed in Table 7. The results indicated that Shanghai and Ningbo-Zhoushan contributed to ~28% of total HFO consumption, Hong Kong, Shenzhen and Guangzhou contributed 23%, whereas 36% of total HFO consumed outside the top ten ports. HFO consumption in all ports accounted for ~30% of the total ship fuel consumption within 12 Nm. In comparison, nearly 70% of the total MDO was consumed within 12 Nm of the top ten ports, and 42% was consumed in ports. Shanghai, Guangzhou and Suzhou were the largest MDO consumption ports in China (43% of the total MDO), as a great number of RVs were operated in the dense waterways of the YRD and PRD. It is interesting to note that the ranks of ship fuel consumption were not the same as those of cargo throughput, container throughput and vessel arrived number. The difference was mainly caused by port conditions and target clients, which further causes huge differences in emissions from different ship types. Using cargo throughput, container throughput or vessel arrived number to represent ship emissions would therefore generate misleading results. Our results suggest that the consideration of ship type and DWT is crucial for accurate estimation of ship emissions.

Previous studies reported a strong correlation between emissions and the distance from the coastline in the YRD region (Fan *et al*., 2016; Liu *et al*., 2016). In this study, by taking advantage of the port-based approach, fuel consumption of ocean traffic can be determined in a designated port, and fuel consumption from different coastal port clusters can be identified. As shown in Fig. 3(a), HFO consumption from the YRD, PRD and Bohai regions accounted for more than 85% of the total consumption in China, with YRD itself of 46%. This provides solid evidence for the DECAs in these three regions proposed by the Chinese government in 2016. Fig. 3(b) shows the cumulative distribution of HFO with the distance to the coastline, which indicated that the DECAs within 12 Nm covered about 40% of the HFO from the total ship sector within 200 Nm, and can reach 80% when the distance was extended to 100 Nm.

3.1.2. Compilation of ship emission inventory and uncertainty

Based on the above fuel consumption results, ship emission inventory in 2013 in China were calculated by combining with fuel-based emission factor. Table 8 lists ship emissions within 200 Nm of the coastline in 2013. Emissions of SO_2, NOx, PM_{10}, $PM_{2.5}$, CO and HC were 1,010, 1,443, 118, 107, 87 and 67 kt/yr, respectively. Compared with the total anthropogenic emissions in MEIC (Li *et al.*, 2014; Zheng *et al.*, 2014; Liu *et al.*, 2015), emissions from ships accounted for about 10% of the total SO_2 emission and 9% of the total NOx emission from all sectors in coastal provinces. Cargo ships (general cargo ships and dry bulk carriers), container ships and tankers (chemical tankers, gas tankers and oil tankers) were the main contributors of all pollutants, accounting for 38-42%, 37-39% and 14-17% of total pollutants emitted within 200 Nm of the coast, respectively. These results are in line with previous estimates (Liu *et al.*, 2016). The AE was responsible for 20% of SO_2 and NOx, similar to 26% in East Asia (Liu *et al.*, 2016) but significantly higher than the global fraction of 10% (Paxian *et al.*, 2010) and lower than 40-60% from local ports or regions (Ng. *et al.*, 2013; Fan *et al.*, 2016; Li *et al.*, 2016). These diversified results were mainly resulted from ship navigating time in cruising mode in different research domains, and the simplifications on basic parameters of AE and AB, e.g. lower output power of cargo ships and container ships in this study than those in Liu *et al*. (2016). We also noted that RVs contributed to 6% of NOx and 2% of SO_2 in the shipping sector, which was not reported in previous studies. The majority of ship emissions occurred during ship cursing, whereas ship emissions at berth and during maneuvering only comprised 14% and 5% of total ship emissions, respectively.

Table 9 summarizes the estimated means and the associated uncertainty ranges of pollutant-based ship emissions in 2013 using Monte Carlo methods. CO emission showed relatively large uncertainties, ranging from 109 to 143 kt in the 95% confidence interval with relative errors of -10% to 18%. In comparison, the uncertainties in SO_2 and NOx were relatively small, ranging from 991 to 1,058 kt and from 1,348 to 1,556 kt, respectively, with relative errors of -6% to 9% in the 95% confidence intervals. The high uncertainties in CO estimates were mainly caused by the differences in emission factors from different sources (USEPA, 2006; ICF International, 2009; Liu *et al.*, 2016), which varied between engine type, combustion conditions and operation modes. Overall, the uncertainties reported in this study were larger than those reported in large-scale studies (~±5%) and lower than those in small-scale studies (~±20%) (Li *et al.*, 2016; Liu *et al.*, 2016).

3.1.3. Temporal characteristics

Fig. 4 shows the monthly and diurnal variations of emissions from different ship types. Based on the temporal surrogates of container and cargo transport in the southern (south of YRD) and northern (north of YRD) port groups from 2010 to 2013, the monthly variations in container and cargo ship emissions were similar with small variations. Additionally, emissions were slightly higher in August and December and lower in February. This was mainly due to increased ship activity in the summer and winter, whereas relatively less cargo transport during the long public holiday of Spring Festival in February. These variations were generally consistent with some local studies (Ng *et al.*, 2013; Li *et al.*, 2016) but differed from Fan *et al*. (2016), which indicated that ship emissions were the highest in April and no significant differences in total emissions were observed in June, November and December. Passenger ships exhibited a bimodal monthly variation pattern, with peaks in August and December.

Ferries were the only type that exhibited significant diurnal patterns. With an hourly percentage of less than 1% at midnight and in the early morning, fuel consumption from ferries increased dramatically starting at 8 am, reached a peak at 10-11 am, then slightly declined and reached another peak at 5 pm. Fuel consumption from other ship types remained constant over the course of a day because these ships were generally used for long-distance transport and sailed at all times under the 24-hour rotation system.

3.1.4. Geographic distribution and emissions intensity

Fig. 5 shows the spatial allocation of SO_2 (3 km × 3 km) in the ship emission inventory in 2013, with the main ports and navigation routes highlighted. It is clear that the emission distribution is strongly consistent with the current regular navigation routes. Specifically, the lines south of YRD are more aggregated, whereas those north of YRD were more scattered and concentrated in the ports of Dalian, Tianjin and Qingdao and the transport routes in between, as shown in Fig. SI-9. By contrast, the emissions over the PRD were concentrated on the lines to the north and in the estuary. Because the YRD region is a fast-developing international shipping center and the convergence area of the south and north waterways, the emissions were very intensive in this region.

Previous studies showed that ship emissions were commonly concentrated, and ship emissions from different geographical areas, such as traffic hubs (Fan *et al.*, 2016), ports (Ng *et al.*, 2013), coastal areas (Ng *et al.*, 2012; Goldsworthy *et al.*, 2015; Li *et al.*, 2016), and the Sea (Jalkanen *et al.*, 2009; Tournadre *et al.*, 2014; Liu *et al.*, 2016), were discussed. In this study, special analysis was conducted with regard to emissions from DECAs and typical shipping routes in China.

Table 10 presents the emission intensities of SO_2, NOx and PM_{10} in three DECAs and along four typical shipping routes (Fig. SI-9). The results indicated that all DECAs and shipping routes contributed significantly emissions to coastal waters. Only covering 19% of the total area within 200 Nm, the DECAs and shipping routes contributed to almost 36-38% and 27-29% of total emissions, respectively. As YRD-DECA has the highest traffic concentration in East Asia, the average intensities of SO_2, NOx, and $PM_{2.5}$ emissions were six times those of East China Sea (Liu et al., 2016). With three busy ports (Hong Kong, Guangzhou and Shenzhen), the intensity of PRD-DECA was approximately eight times higher than average emission intensities of the South China Sea (Liu *et al.*, 2016). A previous study indicated that emission values greater than 8 t/yr/km^2 were common in the busy fairways of the East China Sea (Fan *et al.*, 2016), but the values associated with traffic hubs are still ambiguous. Table 10 presents the SO_2, NOx, and $PM_{2.5}$ emission intensities at four traffic hubs along shipping routes. The route between the YRD and PRD (including the Taiwan Strait) is one of the busiest sea-routes in the world, and the emission intensities were similar to those in the PRD-DECA and much greater than those of the Bohai-DECA. By contrast, the sum of emissions intensities of the other three regular routes were slightly less than the route between the YRD and PRD as they became scattered to the Bohai, South Korea and Japan.

3.2. Ship emissions from 2004 to 2013

3.2.1. Trends in ship activities

Fig. 6 shows the multi-year estimation of HFO consumption in main port clusters within 200 Nm offshore using a cargo-based approach from 2004 to 2013. HFO consumption in China increased from 8,040 kt in 2004 to 17,035 kt in these ten years with an annual growth rate of 9%. This change has been driven by the rapid increase in international trade (10% growth in the external trade of cargo) due to the economic boom (10% growth in GDP) during this period.

Although fuel consumption had more than doubled from 2004 to 2013, the growth of cargo and container turnover in most port groups were even more significant (Fig. SI-10). We expect the difference would become even larger as a result of technological revolution on diesel engine in the future. In addition, the growth rate of top-scale port clusters (PRD and Shanghai) were relatively lower than others. Specifically, traffic in the Jiangsu and Liaoning port clusters even recorded an almost five-fold increase. Such a significant increase was largely contributed by the dramatic growth of domestic trade in China, which highlighted the urgent need for emission control on RVs and CVs. There was a slight drop in traffic in 2008 amid the general increase trend in these ten years, which was largely caused by the declined external trade in most ports in China resulted from the global economic crisis (Fig. SI-11).

3.2.2. Emission trends

Fig. 7 uses SO_2 and NOx as examples to show the trends of ship emissions in China from 2004 to 2013. The results indicated that emissions increased first, leveled off or even decreased slightly in 2008 and 2009, and then increased rapidly afterwards. The drop in 2008 was mainly caused by decreased container turnover due to weakened international trade market during the international financial crisis.

This period was followed by a rapid increase with the global economic recovery after 2009. During these ten years, seaborne trade for both cargo and container transport in China tripled, but the increase of pollutant emission were slower, e.g. 1.7 times for SO_2 and 2.2 times for NOx. The low growth rate of SO_2 compared to that of NOx emissions was caused by the improvement in the sulfur content of global HFO from 3.5% to 2.7% over the past ten years (Fig. SI-7). In comparison, emission factors of NOx decreased slightly due to technological difficulties in further improving ship engines. The increasing trends for SO_2 and NOx were different from those for land-based anthropogenic sources, SO_2 emissions from power plants and other major sources have decreased substantially since 2005 due to the application of emissions control technologies (Lu *et al*. 2010), and NOx emissions declined continuously after 2011 (Zhao *et al.*, 2013).

3.3. Estimation of ship emissions during 2013-2040

3.3.1. Impacts of various SO_2-DECA policies

Fig. 8(a) shows SO_2 emission reductions based on the global sulfur cap of 0.5%, and the results indicated that SO_2 emissions will be reduced by over 80% when the 0.5% sulfur cap is achieved in 2020. Emissions can be further reduced by 86%, 91% and 94% within 12, 100 and 200 Nm, respectively, by expanding DECA regions with 0.1% sulfur content in oil. These results indicated the importance of lowering the sulfur content of global marine oil.

If the 0.5% global sulfur cap fails to achieve, China could make its own effort to reduce SO_2 emission from ships, as shown in Fig. 8(b). The proposed DECAs policy within 12 Nm in three regions can reduce SO_2 emissions by over 20%. Further scenarios with different DECAs strategies were calculated from 2020 to 2040. SO_2 emissions can be reduced by over 50% by expanding the DECAs regions to 100 Nm of the entire Chinese coast and using 0.5% sulfur content fuel. An additional 25% reduction is expected by expanding the DECA to 200 Nm and using 0.1% sulfur content fuel. 94% of SO_2 emissions can be mitigated in total.

3.3.2. Impacts of NOx-DECA policies

Currently, the effective approaches for limiting NOx emissions from ships depends on the development of new ship engines, such as EGR, LNG, and SCR engines. Thus, reductions in NOx emissions were associated with passive step-by-step controls if no enforcement measures were implemented for existing ships. Therefore, the assumption of a 20-year ship lifetime was used in this study. Fig. 8(c) shows future NOx emissions with or without a NOx-DECA in China. If there is no emissions control plan for 'Tier III' ship engines, the emission from engines with 'Tier II' NOx emission standards will peak in 2030, and with the elimination of 'Tier 0' ship engines, a 13%

reduction in NOx emissions can be achieved by 2040. By contrast, if China implements a NOx-DECA within 200 Nm of China coastline in 2020, NOx emissions can be reduced by 80%.

4. Discussion

4.1. Implications for policy-making

This study showed a significant increase of ship emissions in China from 2004-2013, which highlighted the urgent need for effective control of ship emissions. Application of cleaner fuels and environmentally friendly ship engines are possible means to reduce ship emissions in China. This study also provided justifications for the establishment of DECAs in China.

To improve regional air quality and facilitate the structural adjustment of industry, an implementation plan for DECAs in the waters of the Bohai, YRD and PRD regions was established in December 2015. This was a health-based initiative that is anticipated to have positive long-term effects on those who live and work in DECAs and nearby. Shanghai as a demonstration city has observed positive impact after implementation of this policy for one year. However, many issues still may hinder successful implementation of the policy. We believe the following tasks are essential: 1) more technical guidelines and standards regarding the exhaust emissions of ships and the use of shore power and other clean energy, e.g., supervision guidelines for DECAs, should be issued; 2) qualitative and quantitative emissions management should be improved by strengthening monitoring procedures, responsible parties and managers should be quickly spotted, and the illegal emissions of air pollutants from ships should be banned; 3) smooth communication and regional cooperation should be enhanced, e.g., communication with shipping and energy enterprises to increase the supply of low-sulfur fuel and offset shipping costs in cooperation with multiple environmental authorities for joint prevention and control; 4) awareness from different stakeholders should be enhanced, e.g. alleviation of community and public attention, strengthening social responsibility of governments and corporations, optimization of standardized management and service function, and investment in public health mechanisms in port areas; and 5) future phases of emissions control policies should be formulated, e.g. enhancement of the DECAs policy from local to regional, national and continental scales based on scientific findings to formulate both short-term and long-term effective ship emission control strategies.

4.2. Call for more comprehensive data

We used an integrated AIS-based methodology to represent the characteristics and trends of ship emissions in China. In this methodology, it was assumed that the empirical statistics of voyages along regular routes and in ports were correlated with the ship type and geography and that emission factors changed along with changes in oil quality and engine technology. Uncertainty in ship activity parameters and emissions factors will impact the accuracy of the emissions characteristics and trends. Discrepancies in total ship emissions existed in global-, regional- and port-scale studies. The key reason for the emissions discrepancies was not only the uncertainty in annual activity rates and emission factors but also the quality of different data sources and variations in the assumptions underlying different methods. For example, the Ports of Los Angeles and Long Beach (*PoLa)* study assumed that the ship AE was shut down when the ship speed exceeded 8 knots (except for passenger ships; Starcrest Consulting Group, 2009; Ng *et al.*, 2013), but there were other studies assuming that the AE worked all the time (IMO, 2015; Liu *et al.*, 2016). Additionally, BEs were used on OGVs in the IMO study but were not included in ships with diesel-electric engines in the *PoLa* study.

Moreover, the estimation of emissions factors were characterized in most studies, but some studies only considered fuel type and engine type (Fan *et al.*, 2016). Some studies also ignored missing ships in the AIS dataset (Ng *et al.*, 2013; Li *et al.*, 2016). Due to uncoordinated control policies in different regions and the poor performance of the port environmental statistics system in China, field surveys and measurements must be conducted, more accurate local assumptions must be made and a standardized methodology for estimating ship emission inventories is needed.

Small differences in the assumptions can yield large errors in the emission estimates. To avoid this problem, we suggest maximizing the collaboration with other related entities (e.g., engine manufacturers, regulatory agencies, port authorities, vessel owners, the published literature and commercial entities) to gain a more complete and unbiased understanding, fill data gaps, and mutually validate approaches. Subsequently, plans to conduct field surveys and measurements to establish local databases and validate these assumptions should be made. Examples include the engine operation conditions of different ship types under local navigational conditions (especially under the current national emissions reduction framework), the tendency of fuel quality and engine technology, and the integrity and accuracy of the real-time data obtained from the AIS dataset.

To establish a standardized methodology for estimation, some suggestions are proposed: 1) fill the data gap and optimize data quality by implementing various measures, e.g. data integrity and volume checks, data longevity assessment, separation of real data from assumptions/defaults, separation of activity-based values from those based on factors or equipment, provision of valid data ranges for factors and equipment, improvement in geospatial data collection, and establishment of quality assurance and quality control (QAQC) measures; 2) standardize data collection procedures, verify the existing results, conduct third party reviews of findings, and update existing inventories with these findings; 3) develop a regulatory framework, e.g. cross-comparison datasets, limiting interpretation errors, evaluating data quality, and performing data logging and emissions testing; and 4) conduct vessel boarding programs to collect actual vessel and operational parameters, e.g. equipment duty cycle, engine operation, fuel use and fuel switching data, main, auxiliary and boiler loads according to mode, and operational parameters according to mode.

A robust emissions inventory is essential for planning and tracking as environment challenges broaden, thus, further refinement of ship emission inventories should be conducted to ensure regulatory emissions inventories are accurate and to track the progress of emissions reductions strategies. In addition, because coastal areas in China are densely populated, more assessment studies should be conducted based on reliable emission inventories to develop sustainable, cost-effective, environmental and human health solutions, e.g. health risk assessments, air quality assessments, and cost-benefit evaluations of control policies.

5. Summary and Conclusions

We demonstrated a good agreement in ship emissions estimation by AIS-based integrated approach based on different data sources, and these results provided solid evidence for better understanding national-, regional- and local-scale ship emissions in China. The results indicated that ship emissions within 200 Nm of the Chinese coast were 1,010, 1,443, 118, 107, 87, 67, 29 and 21 kt/yr for SO_2, NOx, PM_{10}, $PM_{2.5}$, CO, HC, BC and OC in 2013, respectively. Ship emissions constituted approximately 10 % of the total NOx and SO_2 emissions in coastal cities. Approximately 40% of the pollutants from ships were emitted within 12 Nm of the coast, and would be doubled within a distance of 100 Nm. Therefore, the expansion of the DECAs could greatly improve the control effect. YRD, PRD and Bohai Regions contributed 46%, 27% and 15% to the total HFO emissions, respectively. Additionally, about 65% of ship emissions came from the top ten ports, which also contributed to 24% of the total emissions within 200 Nm. In addition to the proposed DECAs, more attention should be paid on the emissions along regular navigational lines near coastlines, especially the Taiwan Strait and South-North routes. Furthermore, ship emissions have doubled over the past ten years, and SO_2-DECA and NOx-DECA control policies can potentially achieve >80% emission reductions in the future. For NOx, similar reductions could be achieved via strict engine emissions controls, low-sulfur fuel oil and a switch to propulsion with natural gas. However, such policies would not provide substantial benefits until 2040 because decades are needed to implement fleet-wide changes. Potential reduction efforts are of considerable regional importance because ship emissions along the Chinese coast account for almost half of the total ship emissions in East Asia.

This study established a methodology in using limited AIS data to develop ship emission inventory. Such a methodology can be used in other parts of the world, as most of the time it is unable to collect a complete set of AIS information. The emission estimation and uncertainty analysis in this study have great reference values for modelers and other emission inventory users. The AIS-based spatial and temporal allocation methods have great representativeness, and could well satisfy the simulation requirement by the models.

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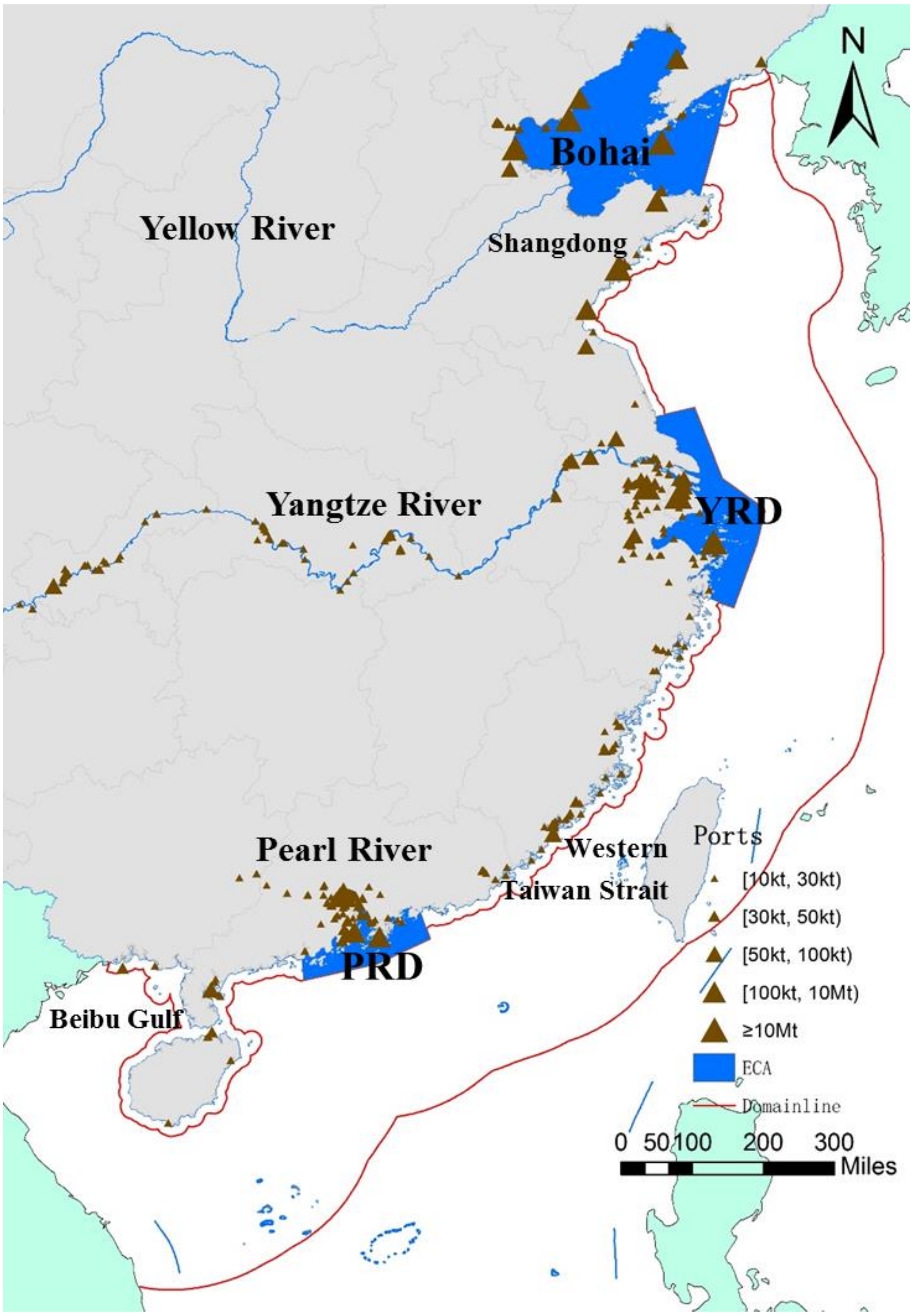

Fig. 1 The location of the research domain, port groups and DECAs in this study

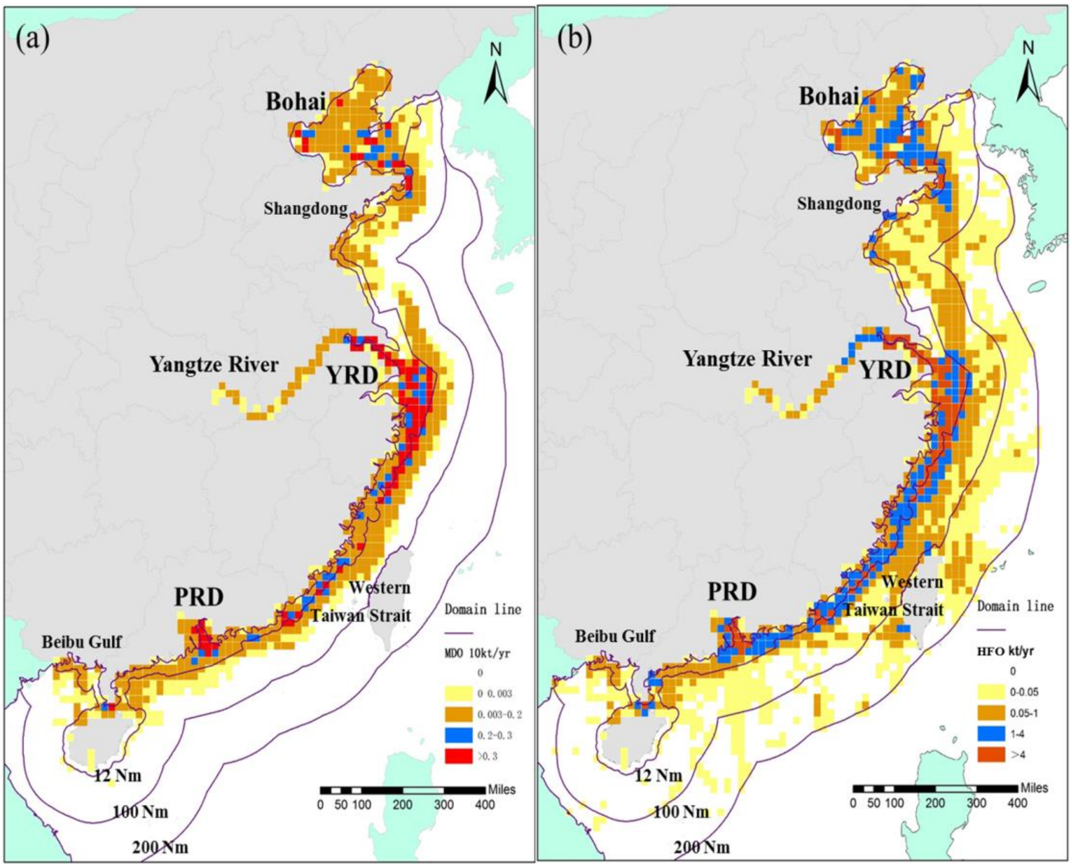

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Fig. 2 Spatial distribution of marine diesel oil MDO (a) and HFO (b) consumption by ships (27 km × 27 km)

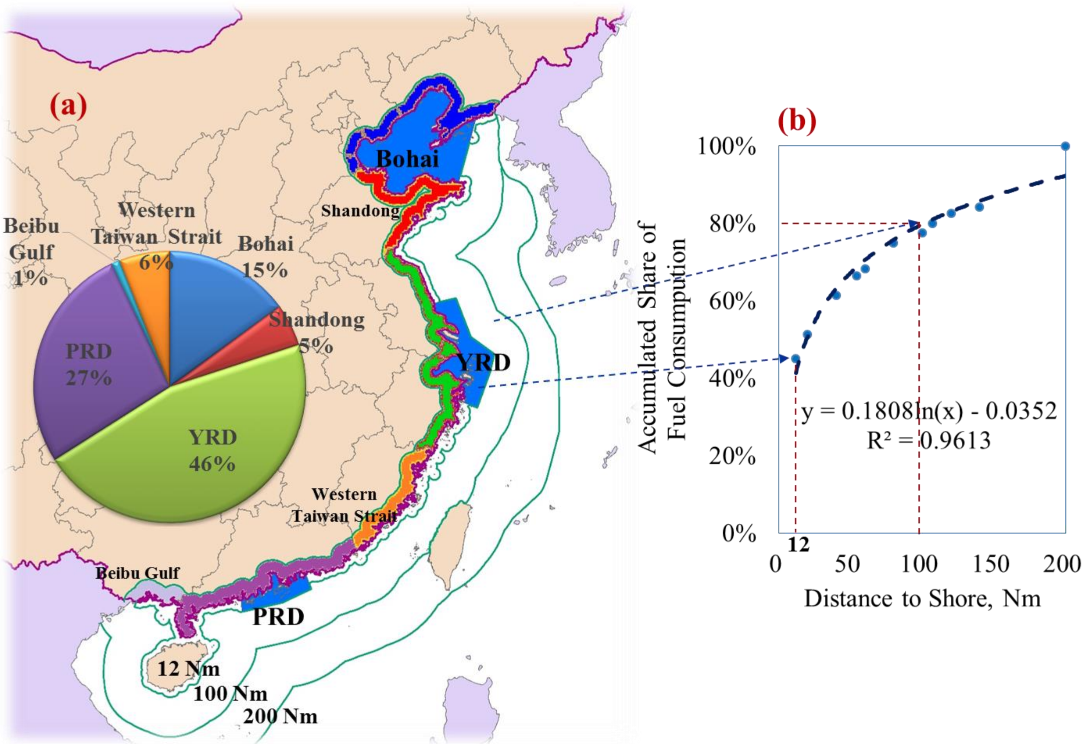

Fig. 3(a) Fuel consumption contributions of different port groups within 200 Nm and (b) the cumulative distribution of fuel consumption within 200 Nm

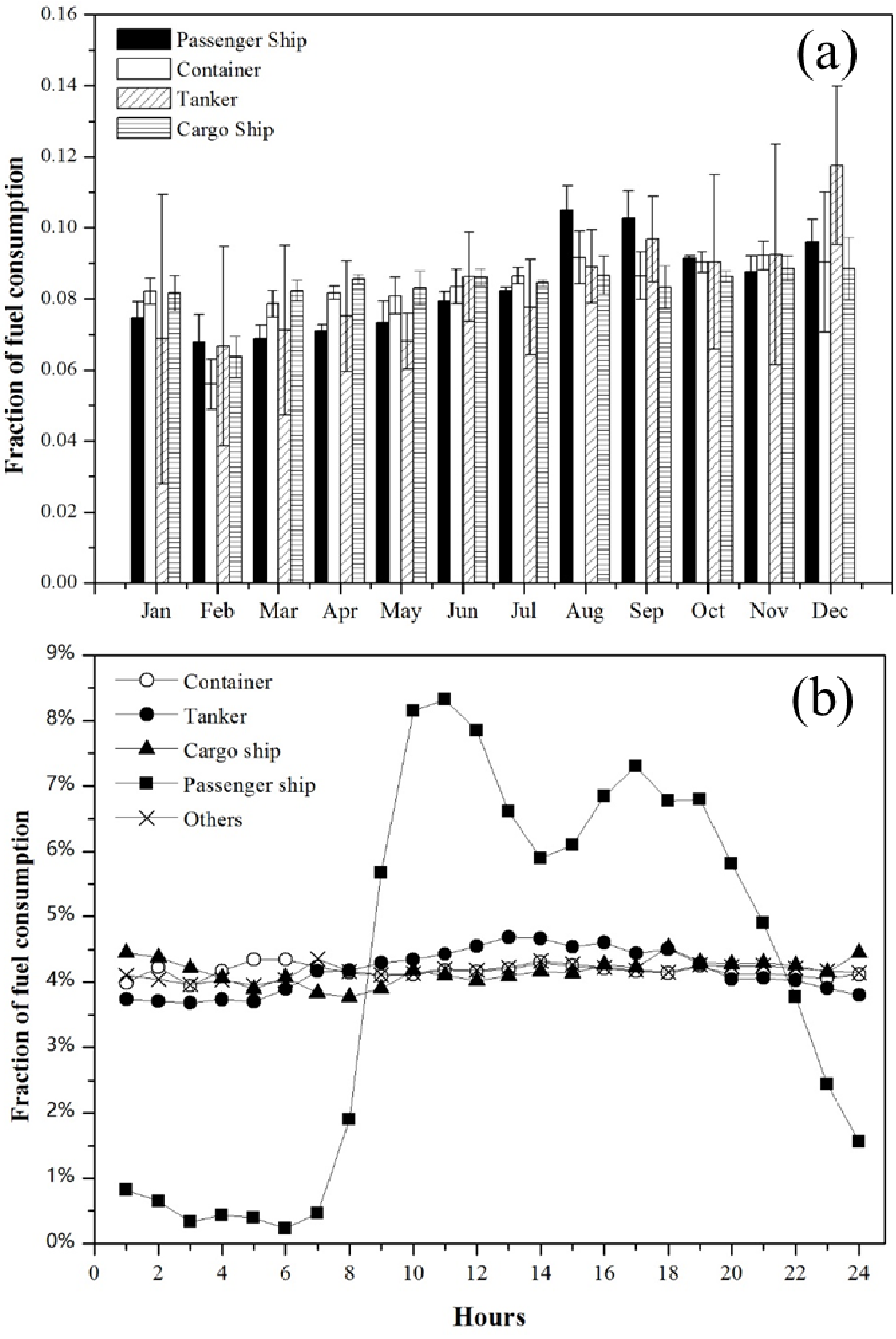

Fig. 4 Monthly (a) and diurnal variations (b) in annual fuel consumption by vessel type

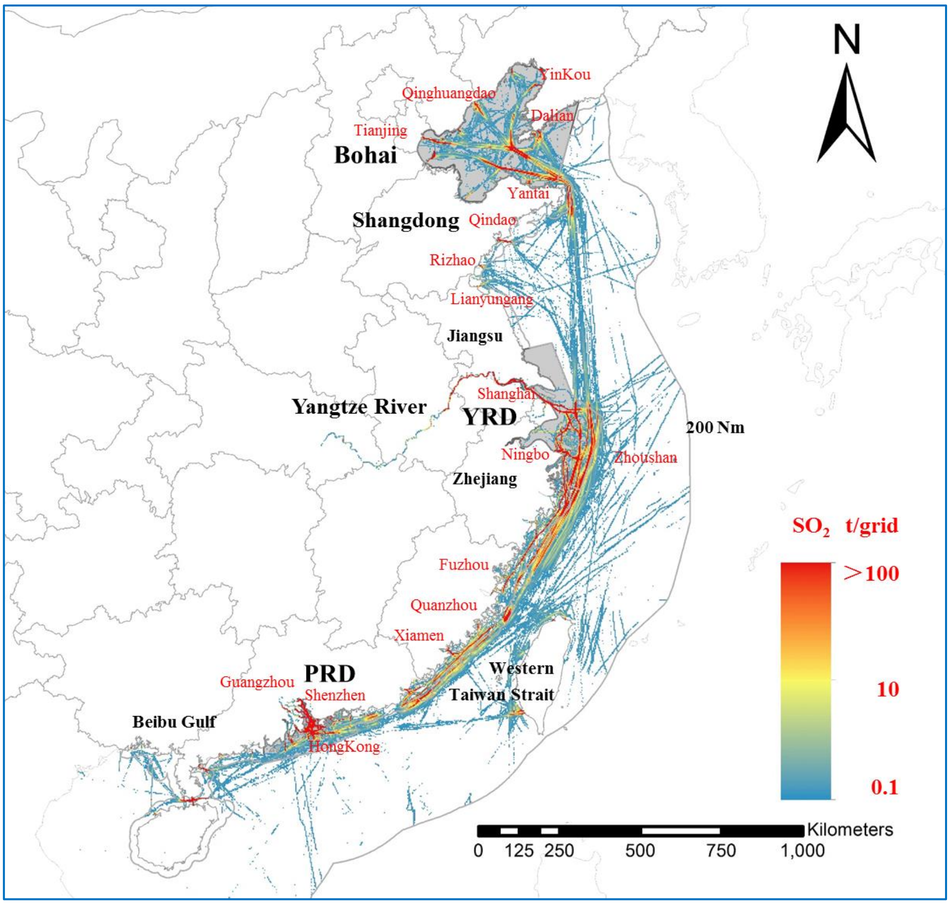

Fig. 5 Spatial distribution of SO_2 ship emission in China (3 km × 3 km)

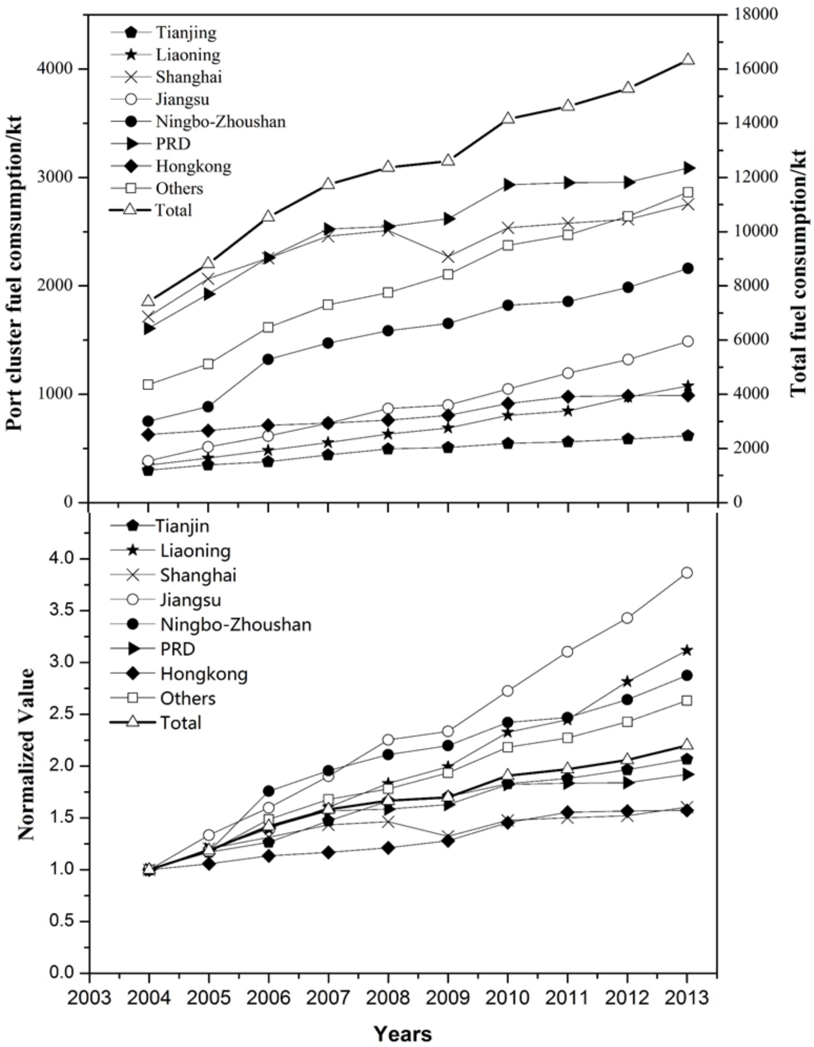

Fig. 6 Trends in HFO consumption in port clusters in China from 2004 to 2013: (a) fuel consumption and (b) normalized fuel consumption

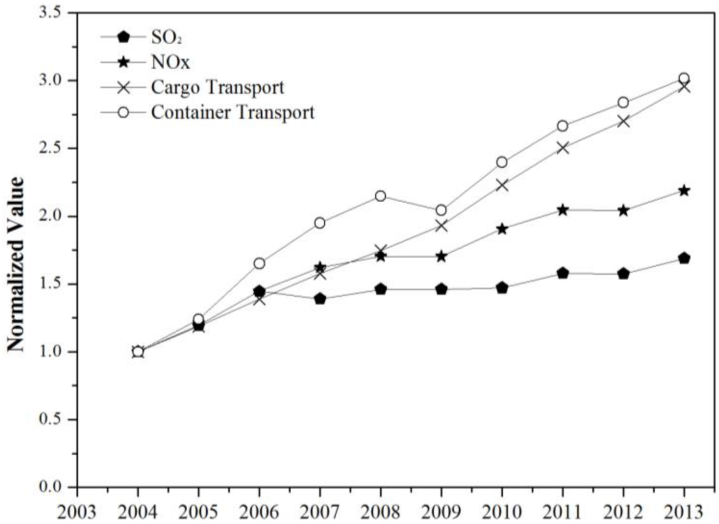

Fig. 7 SO_2 and NOx emissions and their aggregated emissions from cargo and container transport from 2004 to 2013

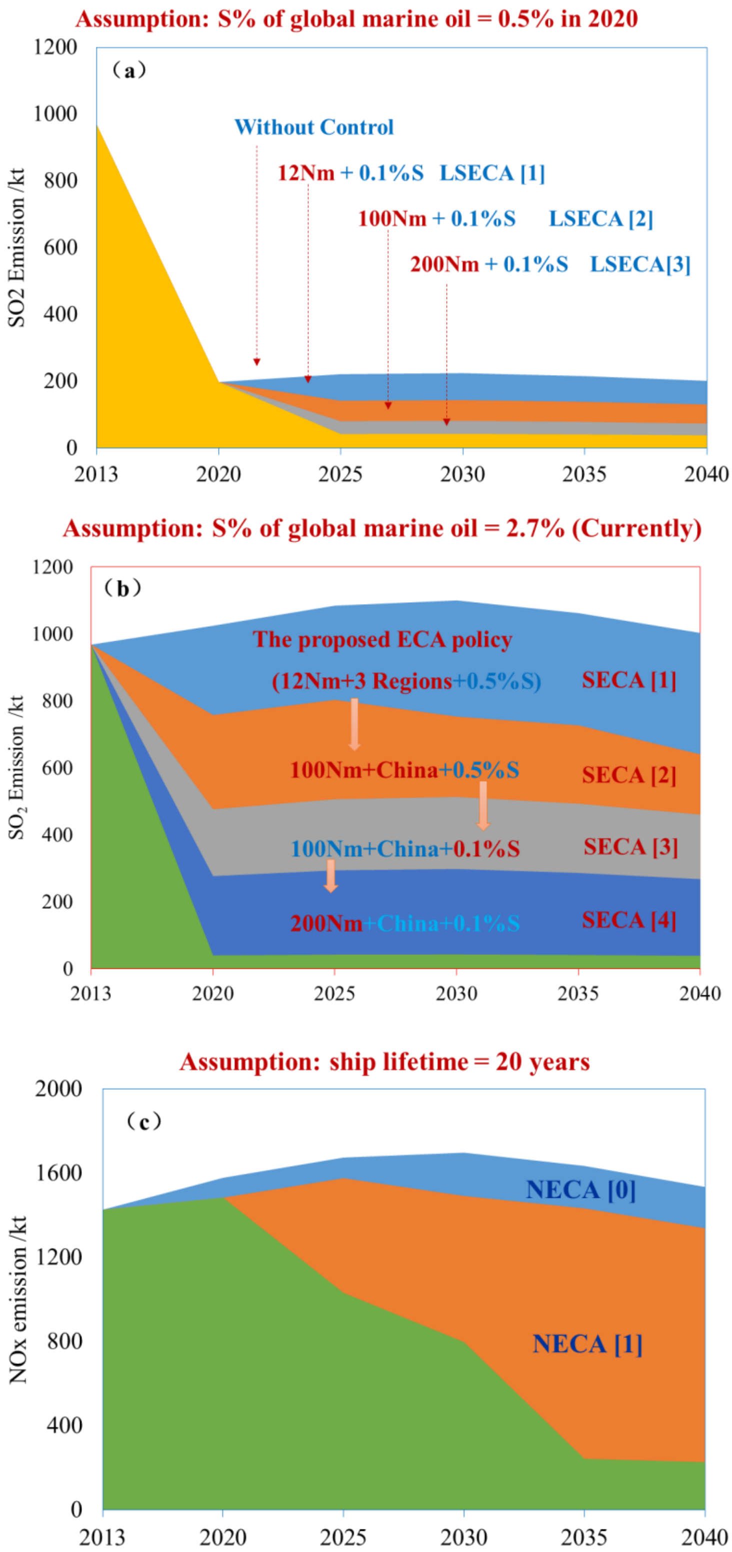

Fig. 8 SO_2 and NOx emissions from the shipping sector under SO_2-ECA (a, b) and NOx-ECA (c) with different control policies from 2013 to 2040

Table 1 Time-in-mode for different ship types within 12 Nm and 200 Nm of the coast (unit: hours/voyage)

Ship types		**Cruising**						**Maneuvering**	**Hotelling**
		Bohai	Shandong	YRD	Western Taiwan Strait	PRD	Beibu Gulf	China	China
					200Nm				
OGVs	Tanker	64.1	61.4	73.4	40.5	73.3	46.8	4.3	25.3
	Cargo	53.4	51.2	61.1	33.7	61.1	39.0	3.4	15.8
	Container	41.8	40.1	47.8	26.4	47.8	30.6	3.7	22.2
	Others	53.1	50.9	60.8	33.5	60.7	38.8	1.1	17.2
CVs	Tanker	52.2	36.5	47.9	37.5	53.6	42.4	2.3	23.5
	Cargo	45.3	31.7	41.5	32.5	46.5	36.8	3.2	16.8
	Container	37.7	26.4	34.6	27.1	38.7	30.6	3.9	19.1
	Others	45.1	31.5	41.3	32.4	46.3	36.6	2.7	17.7
					12Nm				
OGVs	Tanker	20.9	11.8	20.4	14.4	19.6	9.2	4.3	25.3
	Cargo	17.4	9.8	17.0	12.0	16.3	7.7	3.4	15.8
	Container	13.6	7.7	13.3	9.4	12.8	6.0	3.7	22.2
	Others	17.3	9.8	16.9	11.9	16.2	7.6	1.1	17.2
CVs	Tanker	16.8	9.0	16.5	11.2	15.7	6.7	2.3	23.5
	Cargo	14.6	7.8	14.3	9.7	13.6	5.8	3.2	16.8
	Container	12.2	6.5	11.9	8.1	11.4	4.9	3.9	19.1
	Others	14.5	7.8	14.2	9.7	13.6	5.8	2.7	17.7
RVs	All ships	2.3						7.5	23.3

Table 2 Transport distance for OGVs and CVs in different regions (unit: Nm)

Regions[a]	**OGVs within 12Nm**	**OGVs within 200Nm**	**CVs within 12Nm**	**CVs within 200Nm**
Bohai	313	961	219	679
Shandong	177	921	117	475
YRD	306	1100	214	622
Western Taiwan Strait	216	607	146	487
PRD	293	1099	204	697
Beibu Gulf	138	703	88	551

[a]The average transport distance of ships arriving in/departing the corresponding port region.

Table 3 Summary of ship calls number by marine department in 2013

Marine Department[a]	OGV	CV	RV	Total
Liaoning	9541	31618	56520	97679
Hebei	4904	22935	165	28004
Tianjin	8780	13871	0	22651
Shandong	15097	20040	2231	37368
Jiangsu	12886	17802	906648	937336
Shanghai	18592	23835	623587	666014
Zhejiang	17915	81759	398653	498327
Fujian	10317	38911	85777	135005
Guangdong	14281	65681	1270203	1350165
Shenzhen[b]	13704	7166	122186	143056
HongKong[c]	11672	15404	77374	104450
Hainan[d]	2475	9466	10869	22810
Sum	140164	348488	3554213	4042865

[a]Ordered from north to south China.
[b]the MD of Shenzhen was independent of the Guangdong MD;
[c]refers to the HKMD official website.
[d]the domain corresponding to statistics compiled by the Hainan MD covered the ports in Hainan and Guangxi provinces.

Table 4 Sulfur transfer rates of different engine types used in this study

Engine types	USEPA, 2006	IMO, 2014	Fan et al., 2016	This study[a]
SSD	82.9%	82.9%	81.8%	82.5% ± 0.5%
MSD	90.2%	91.4%	89.8%	90.5% ± 0.7%
HSD	96.6%	96.5%	89.8%	94.3% ± 3.2%

[a]Calculated based on the average values reported in previous studies.

Table 5 Ship emissions reduction analysis scenarios of SO_2-DECA and NOx-DECA

Scenario		Description	Code
SO_2-DECA		No DECAs control	SECA[0]
	International oil quality standards would be achieved (S%=0.5%) by 2020	Shipping in DECA should use low sulfur content fuel(S%=0.1%)within 12Nm	LSECA[1]
		Shipping in DECA should use low sulfur content fuel(S%=0.1%)within 100Nm	LSECA[2]
		Shipping in DECA should use low sulfur content fuel(S%=0.1%)within 200Nm	LSECA[3]
	Improve the international oil quality (S%=2.7%)	Implement the DECA policy proposed in 2016; shipping in Bohai, YRD and PRD region within 12Nm should use low Sulphur content fuel (S%=0.5%)	SECA[1]
		Shipping in all of China within 100Nm should use low Sulfur content fuel (S%=0.5%)	SECA[2]
		Shipping in all of China within 100Nm should use low Sulfur content fuel (S%=0.1%)	SECA[3]
		Shipping in all of China within 200Nm should use low Sulfur content fuel (S%=0.1%)	SECA[4]
NOx-DECA		No controls, namely NOx controls under 'Tier 0', 'Tier I', 'Tier II'	NECA[0]
		Create NOx-DECAs under 'Tier III'	NECA[1]

Table 6 Comparison of HFO consumption in China in 2013 (unit: kt)

Sources	Domains	OGVs	CVs	RVs	Total
This work:MDO-M1/M2[a]	12 Nm[c]	310/317	703/732	1156/1390	2170/2439
This work:HFO-M1/M2[a]	12 Nm[c]	3690/4157	1814/2102	0/0	5504/6260
This work:MDO-M1/M2[a]	140 Nm[c]	410/336	1007/849	1156/1390	2573/2574
This work:HFO-M1/M2[a]	140 Nm[c]	8368/8801	5380/5258	0/0	13748/14059
This work:MDO-M1/M2[a]	200 Nm[c]	456/492	1007/849	1156/1390	2620/2730
This work:HFO-M1/M2[a]	200 Nm[c]	10946/11777	5380/5258	0/0	16326/17035
Liu et al., 2016[b]	China sea	22455		--	22455
Liu et al., 2016[b]	East Asian sea	35087		--	35087
China Energy Statistic Yearbook	Sales of HFO in transport sector	--	--	--	15888

[a]M1/M2 represent cargo-based and port-based approach, respectively; MDO and HFO represent marine diesel oil and marine Heavy oil.

[b]Calculated using CO_2 emissions and an emission factor of 3591.12 g CO_2/ kg of Fuel (IMO Report, 2009).

[c]The distance to Chinese shore.

Table 7 Port activity and fuel consumption in the top ten ports in China

Port	Cargo throughput /10 kt	Container throughput /10 kTEU	# of ship calls /VAN	HFO/ kt		MDO/ kt	
				FC within 12 Nm	FC in port	FC within 12 Nm	FC in port
Shanghai	68273	3362	666018	1058	296	410	213
Ningbo-Zhoushan	80978	1735	401164	1027	222	170	100
Hong Kong	27606	2235	104450	590	143	110	36
Guangzhou	45517	1531	479229	520	140	370	138
Shenzhen	23398	2328	143052	531	140	120	50
Tianjin	50063	1301	22651	345	54	0	0
Suzhou	45435	531	105795	271	59	260	26
Dalian	40746	1001	40465	225	39	90	10
Xiamen	19088	801	56670	184	44	76	13
Qingdao	45003	1552	14481	146	38	60	0
Sum	446107	16376	2033975	4897	1176	1665	586
All ports	1176705	19021	4042865	6260	1826	2439	1024
Sum/All	38%	86%	50%	78%	64%	68%	57%

Table 8 Summary of ship emissions in China (within 200 Nm of the coast) in 2013

Categories		SO_2	NOx	CO	PM_{10}	$PM_{2.5}$	BC	OC	HC
Ship types	Cargo ship	38%	41%	42%	39%	41%	43%	41%	40%
	Container	39%	37%	37%	39%	37%	38%	39%	39%
	Tanker	17%	15%	15%	16%	17%	14%	15%	14%
	Others	6%	7%	7%	5%	6%	5%	5%	7%
Engine types	Main engine	79%	79%	80%	79%	81%	86%	81%	82%
	Auxiliary engine	20%	20%	20%	20%	18%	12%	18%	17%
	Auxiliary boiler	1%	1%	1%	1%	1%	2%	1%	1%
Ship trade types	OGVs	67%	63%	63%	68%	67%	70%	70%	57%
	CVs	31%	31%	32%	30%	31%	27%	29%	30%
	RVs	2%	6%	5%	2%	3%	3%	1%	12%
Activity modes	Cruising	79%	79%	69%	76%	76%	61%	57%	65%
	Maneuvering	5%	6%	13%	8%	8%	27%	25%	19%
	Hotelling	16%	15%	18%	16%	17%	12%	18%	16%
Total/ kt		1010	1443	118	107	87	29	21	67

Table 9 Uncertainties in emission estimates

	Species	Emission estimate (kt)	Mean (kt)	95%CI (kt)	Uncertainty	Previous studies	
						Li et al. (2016)	Liu et al. (2016)
Port-based	SO_2	1010	972	(911, 1058)	(-6.3%, 8.8%)	(-21.2%, 28.6%)	(-3.8%, 3.8%)
	NO_X	1443	1433	(1348, 1556)	(-5.9%, 8.6%)	(-22.1%, 30.6%)	(-3.6%, 3.6%)
	CO	118	122	(109, 143)	(-10.4%, 18.1%)	(-22.6%, 30.3%)	(-4.6%, 4.6%)
	PM_{10}	107	113	(103, 128)	(-8.4%, 13.5%)	(-22.7%, 30.7%)	(-3.8%, 3.8%)[a]
	$PM_{2.5}$	87	98	(89, 111)	(-8.4%, 13.5%)	(-22.8%, 31.5%)	--
	BC	29	37	(26,51)	(-29.7%, 37.8%)	--	--
	OC	21	18	(15,23)	(-16.7%, 27.8%)	--	--
	HC	67	73	(66, 82)	(-8.6%, 13.8%)	(-24.5%, 33.3%)	(-4.0%, 4.0%)[b]

[a, b] were the results of PM and NMVOC, respectively.

Table 10 Emission intensities in three DECAs and along typical navigation lines

		DECA			Topical Transport Line[a]				Total within 200 Nm
		Bohai-DECA	YRD-DECA	PRD-DECA	① Bohai &YRD	② PRD &YRD	③ Korea &YRD	④ Janp & PRD	
Sea area (10^4 km^2)		7.70	5.35	2.29	2.62	5.90	2.55	2.99	156.56
Emissions (kt)	SO_2	73	190	104	22	180	26	12	1010
	NOx	107	283	156	33	270	39	18	1443
	$PM_{2.5}$	8	22	12	2	18	3	1	107
Intensity (t/km^2)	SO_2	0.94	3.55	3.07	0.83	3.05	1.03	0.41	0.65
	NOx	1.39	5.29	4.60	1.25	4.57	1.54	0.61	0.92
	$PM_{2.5}$	0.11	0.42	0.36	0.08	0.31	0.10	0.04	0.07

[a] Geographic location of transport lines shown in Fig. SI-9.

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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Abbreviations

AB: Auxiliary Boilers

AE: Auxiliary Engine

AIS: Automatic Identification System

BC: Black Carbon

CCTD: Statistics Communique of China on the Traffic and Transportation Industry Development

CO: Carbon monoxide

CPSY: China Port Statistics Yearbook

CVs: Coastal Vessels

DECAs: Domestic Emission Control Areas

DWT: Dead Weight Tonnage

ECA: Emission Control Area

EGR: Exhaust Gas Recirculation

GDP: Gross Domestic Product

HC: Hydrocarbon

HFO: Heavy Fuel Oil

ICF international: A global Consulting and Technology Services Company

IMO: International Maritime Organization

LNG: Liquefied Natural Gas

LRS: Lloyd’s Register of Ships

MD: Marine Department

MDO: Marine Diesel Oil

ME: Main Engine

MEIC: Multi-resolution Emission Inventory for China

NECA: NOx-DECA, Domestic Emission Control Areas for NO_x Control

Nm: Nautical Miles

NMVOC: Non-methane Volatile Organic Compounds

NOx: Nitrogen oxide

OGVs: Ocean-going Vessels

OC: Organic Carbon

PM: Particulate Matter

PoLa: Los Angeles and Long Beach

PRD: Pearl River Delta Region

QAQC: Quality Assurance and Quality Control

RVs: River Vessels

SCR: Selective Catalyst Reduction

SECA: SO_2-DECA, Domestic Emission Control Areas for SO_2 Control

SI: Supporting Information

SO2: Sulfur dioxide

tce/10kt： Ton of Standard Coal Equivalent per 10 Kiloton

U.S.EPA: United States Environment Protection Agency

VAN: Vessel Arrived Number

WHO: world health organization

YRD: Yangtze River Delta Region

1. Domain and ship categorization

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 ore	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

2. Potential influence of transit ships

We did roughly estimate the contribution from passing ships, and concluded that their contribution is relatively low but with potentially high uncertainties. Therefore, we decide to exclude it into this study to avoid negative impact on the results. The research domain is 200Nm to the coast of Mainland China. The main routes in this domain include all routes from/to Chinese ports and the passing routes, mainly from Busan, Korea to Southeast Asia (Busan route) and from Taiwan to destinations other than Mainland China ports (Taiwan route). In order to study the fraction of Busan route and Taiwan route in our research domain, we extracted a real-time AIS map, and highlighted the passing ship routes by red lines (Fig. SI-1).

There were 368 shipping route from/to Korea in 2013, including 85 Southeast Asia routes and 26 Europe routes. As the throughput of Busan port accounted for 75.4% of total throughput (17686kt) in Korea, we estimated that Busan route roughly accounted for 7100kt throughput. With around 800Nm passing distance in our research domain, we estimated the fuel consumption from Busan route was around 70kt HFO. The total throughput in Taiwan was 14 million TEU in 2013, including 2.5 million TEU between Taiwan and Mainland China. Therefore, Taiwan route contributed around 11.5 million TEU. If we assume 1TEU=15t and the average travel distance was 500Nm, the fuel consumption from Taiwan route was around 1070kt HFO. Therefore, the total consumption of Busan route and Taiwan route was around 1140kt HFO, only 7% of total fuel consumption in our research domain. Therefore, we believe excluding the passing route would not significantly impact our analysis results.

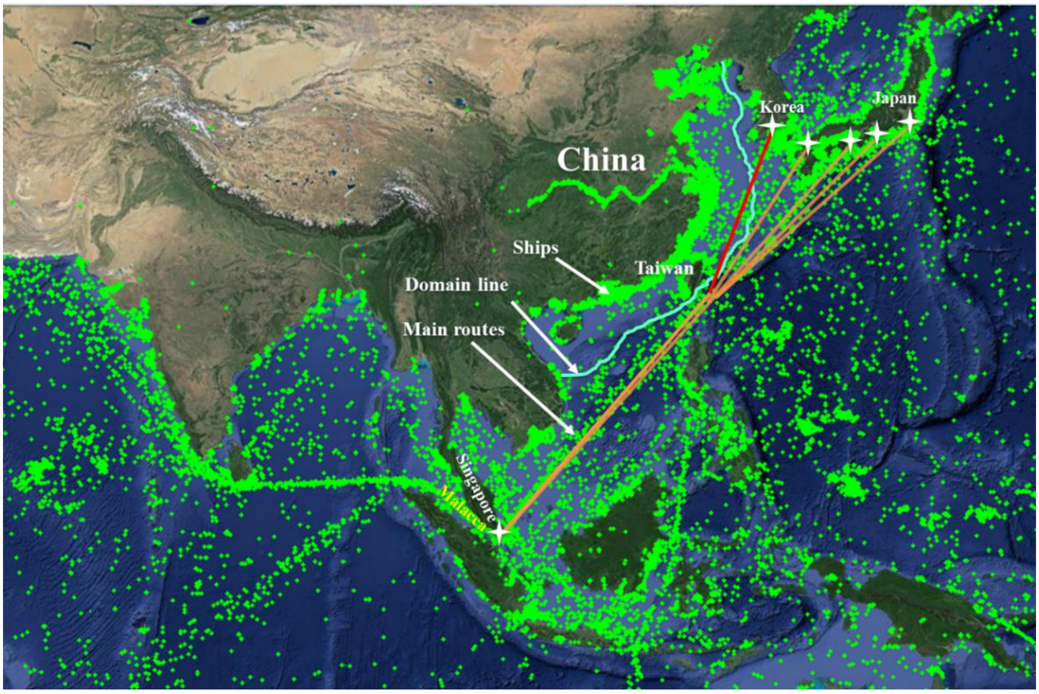


Fig. SI-1 Major shipping routes extracted from a real-time AIS digital map

3. Transport volume information

Transport volume is the real weight of transport cargo for a period time, different statistic approaches used for the Yangtze River ports and other coast ports, the former statistics output cargo weight, and the later statistics input cargo weight. Transport volume statistics from the Chinese National Statistics Bureau and China port statistical yearbook with different classification, but no significant differences of the total amount.

There are 92 Chinese ports with cargo types-based transport volume statistic in this study. Raw data shown below. The regional transport volume statistics including liquid cargo, dry bulk, general cargo, container corresponding to tanker, bulk ship, general cargo ship, container ship, respectively. Among them, liquid cargo cover oil and gas; dry bulk cover ore, coal and building material; general cargo cover food, wood and chemical material; container cover container and roro-car.

Table SI-5 shown in the last.

4. Transport distance information

Transport distance is the weight-based length along common routes of OGVs and CVs in the research domains of 12Nm and 200Nm, respectively. Specifically, transport distances of OGVs were calculated as the average of main international routes from main ports in a particular port cluster, as shown in Fig. SI-2(a), and then multiply by the fraction of regular routes to Korea, Japan, South China Sea and Pacific, respectively (see Table SI-6); transport distances of CVs were derived from transport distances between port clusters measured by AIS data and digital map. Some illustrations are given in Fig. SI-2(c) for readers to understand the AIS-based digital map. We collected information more than 1000 regular routes, including their departure and arrival ports. We classified departure and arrival ports into port clusters, and then used AIS data and digital map to calculate transport distances between port clusters (Fig. SI-2(b)).

Table SI-6 (a) Information of international regular routes from Chinese ports

Destination country/region	Number of regular routes	Fraction
America	115	12%
Japan	110	11%
Korea	78	8%
Southeast Asia	89	9%
Europe	80	8%
Australia	22	2%

Mediterranean	34	3%
Taiwan	38	4%
Black Sea	10	1%
Others	422	42%
Total	998	100%

Table SI-6(b) Port cluster-specific transport distance and its fraction

Port cluster	**Main route**	**Transport distance/Nm**	**Fraction within the port cluster**
PRD	Korea	1250	22%
	Japan	1442	35%
	South China Sea	1082	23%
	Pacific	354	20%
Shandong	Korea	361	34%
	Japan	847	35%
	South China Sea	2130	21%
	Pacific	550	10%
YRD	Korea	436	10%
	Japan	888	15%
	South China Sea	1858	40%
	Pacific	516	35%
Bohai	Korea	450	30%
	Japan	1423	40%
	South China Sea	813	15%
	Pacific	900	15%
Western Taiwan Strait		607	100%
Beibu Gulf		703	100%

(a)

(b)

Arrival \ Departure (N → S)	Yingkou	Dalian	Tianjin	Qingdao	Shanghai	Ningbo-Zhoushan	Xiamen	Shenzhen	Guangzhou
Yingkou	0	4	10	1	6	2	0	0	3
Dalian	4	0	49	49	17	5	0	2	18
Tianjin	9	48	0	22	2	1	0	0	1
Qingdao	0	19	12	0	61	40	3	0	9
Shanghai	7	20	6	31	0	152	25	27	8
Ningbo-Zhoushan	2	2	0	18	166	0	27	33	17
Xiamen	0	0	0	3	22	13	0	31	6
Shenzhen	0	2	0	1	15	11	27	0	12
Guangzhou	0	0	0	0	1	0	3	29	0
Total	22	95	77	125	290	224	85	122	74

e.g. The share of transport distance between Bohai and PRD region $= \frac{36}{285} =$ 12.6%

(c)

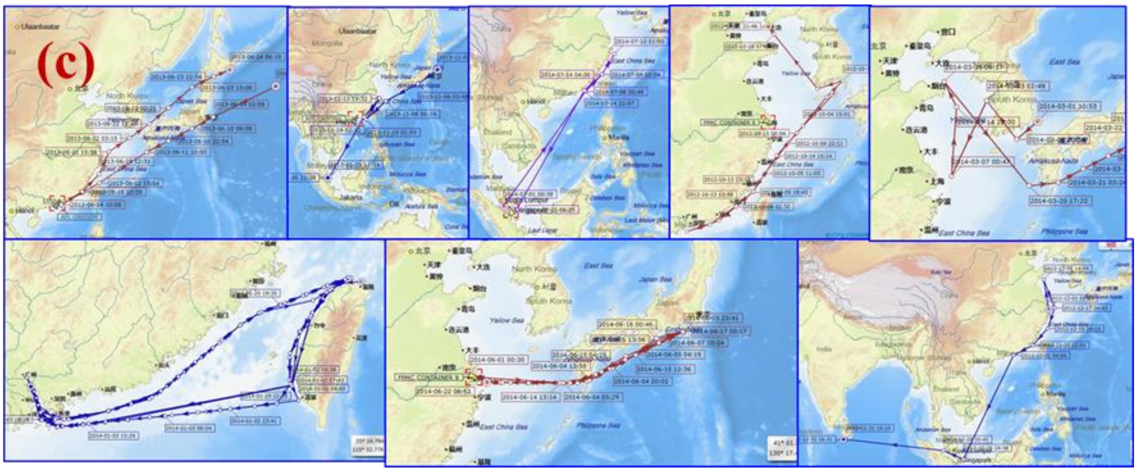


Fig. SI-2 (a) the major international routes in the world (the average transport distance of OGVs can be calculated by using the distance of those ocean-going routes by combining Table SI-6(a))

(b) samples of transport distances calculation process in determining the fraction within the port cluster (area with color were all routes for PRD; area with deep colors were the routes between Bohai and PRD, calculation process shown in this figure, with the same way, then can calculate the share of all routes, and the weight-based transport distance can be calculated by combining each routes' distances)

(c) the sample of calculation process on the share of transport distance among different region (transport distance can be calculated by using the AIS-based digital map with the distance measuring tool)

5. Uncertainties estimation

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

Table SI-7 Uncertainties of emissions factors for estimation

Pollutants	Categories	Distribution types	Mean	Confidence interval
SO_2	HFO（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}	HFO（2.7%）	Gamma	1.5	(-14.7%, 16.4%)
	MDO（0.5%）	Weibull	0.4	(-42.4%, 34.6%)
$PM_{2.5}$	HFO（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%)
BC*	All	Weibull	0.3	(-97.7%, 126.5%)
OC*	All	Weibull	0.2	(-68.2%, 111.6%)

*the value of BC and OC were the ratio of $BC/PM_{2.5}$ and $OC/PM_{2.5}$, respectively.

Table SI-8 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. 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-9).

Table SI-9 ship information statistics in China and in the other studies

Study area	Year	Area Million km^2	Archived AIS messages	Number of ship with AIS	Number of ship information
China Sea	2013	3.0	3.5E+08	700	12,600
East Asia	2013	4.2	2.0E+09	18,324	18,324
Baltic sea	2009	0.4	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.

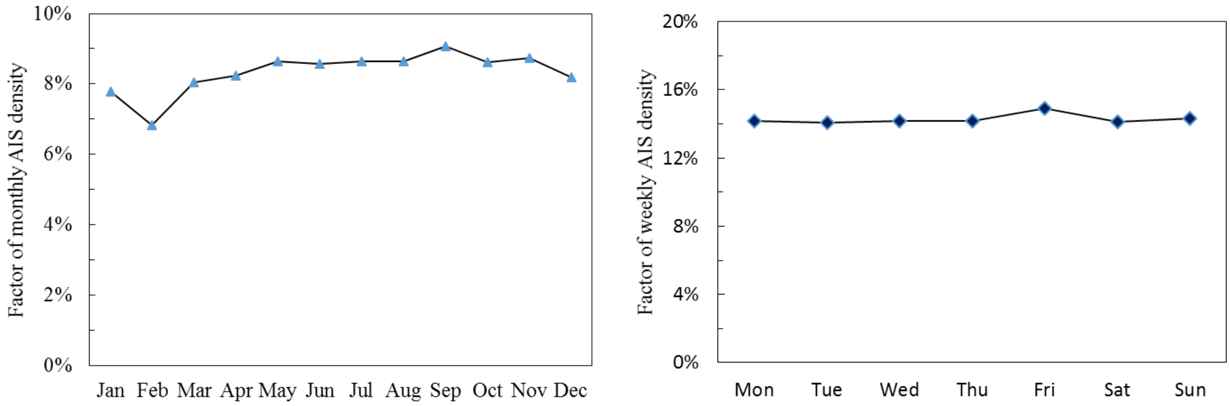
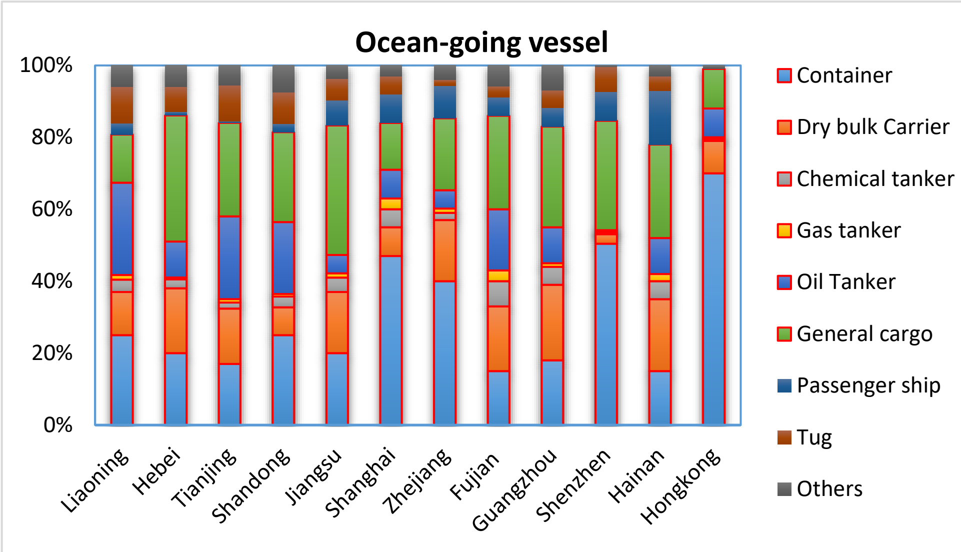
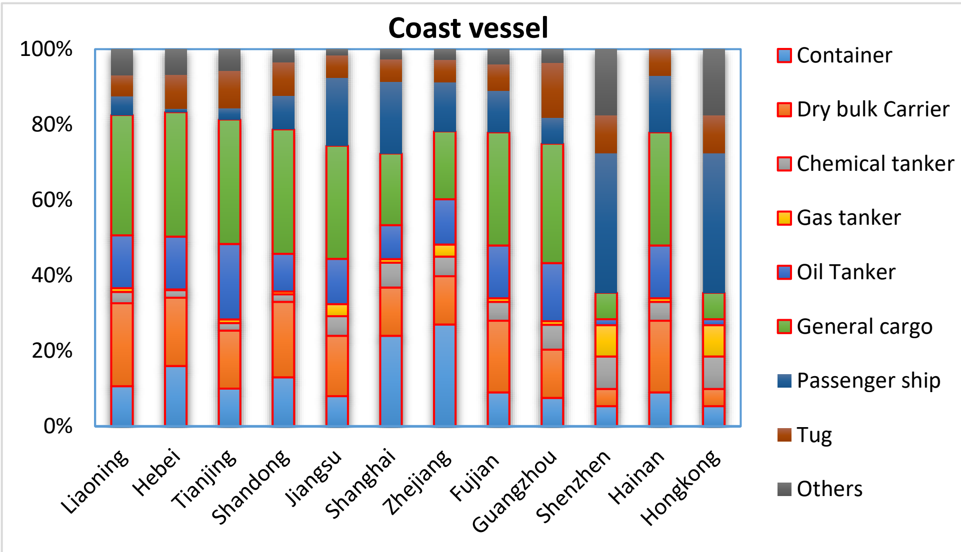


Fig. SI-3 the monthly and weekly variation of ship fuel consumption by using AIS dot-density in 2013





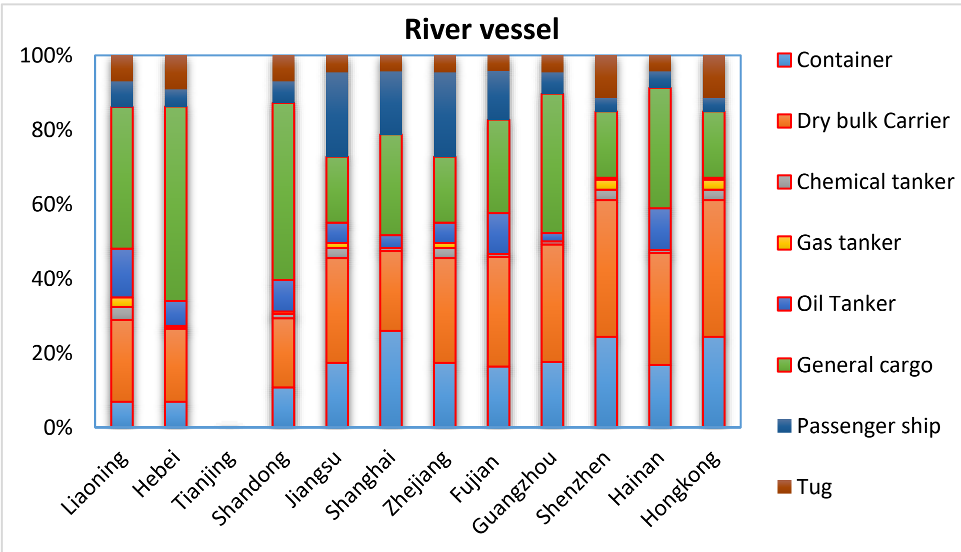


Fig. SI-4 Summary of the stock of ship types navigated in different regions for OGVs, CVs and RVs

5

7. Fuel consumption information

For fuel consumption rate (Kg tce/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, 2015), as detailed in Fig. SI-6, 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. For the fuel consumption rate for RVs, which refer to the value from CCTD, 5.2 tce/10kt, that why we do not need the transport distance of RVs.

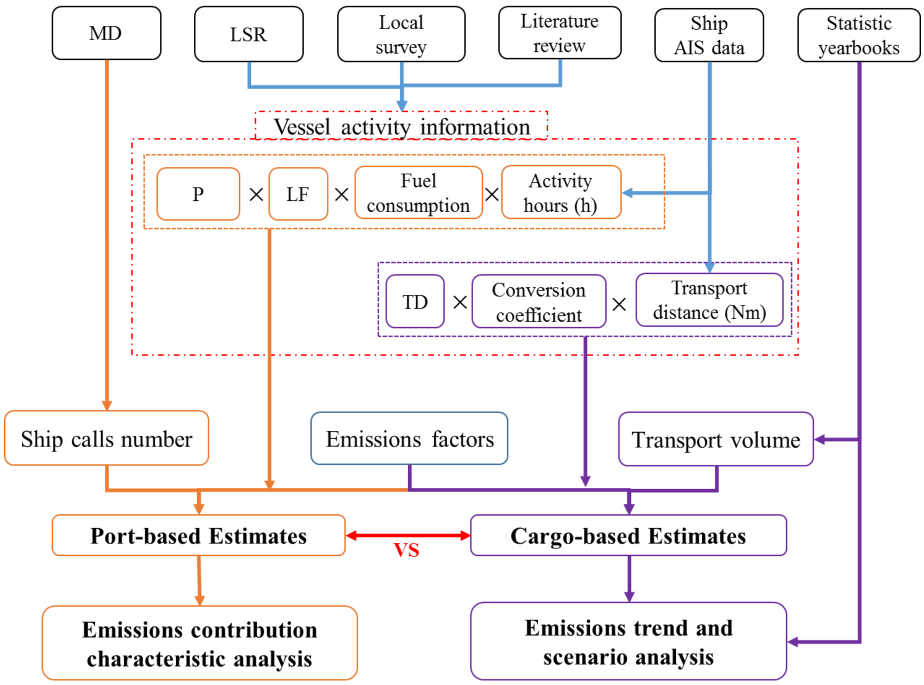


Fig. SI-5 Data sources and flowchart used for emissions estimates in this study

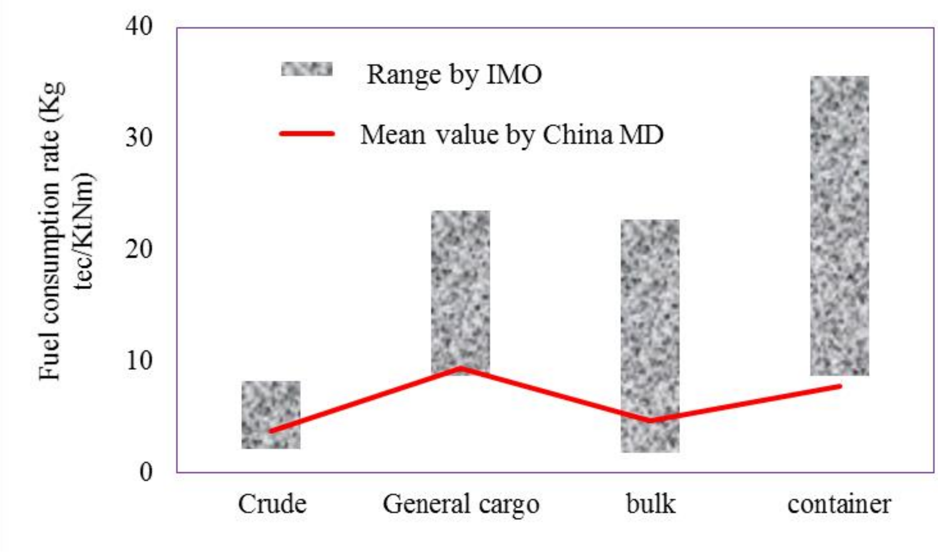


Fig. SI-6 Range of fuel consumption rate used in this study

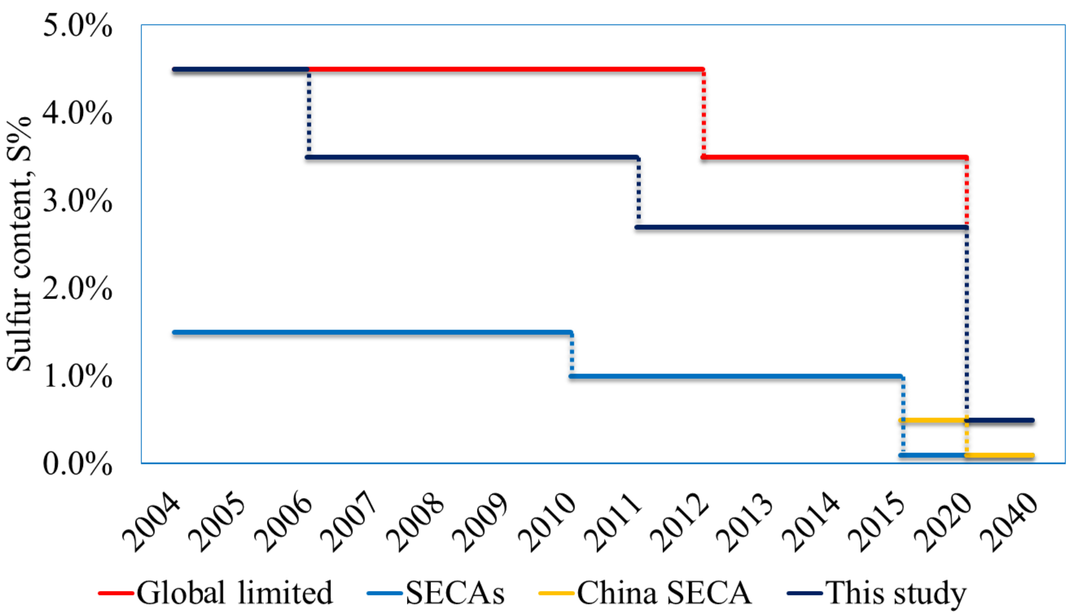


Fig. SI-7 The sulfur content of HFO in this study

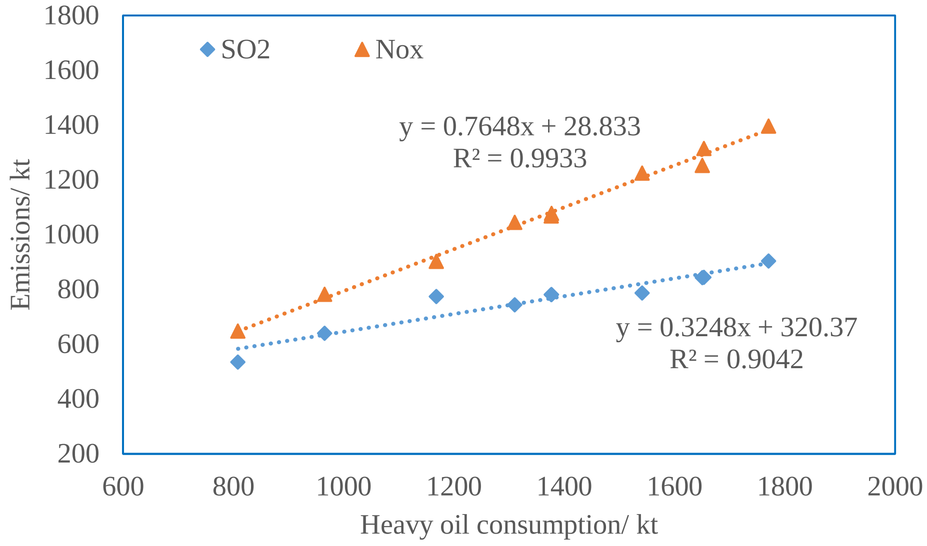


Fig. SI-8 Relationship between fuel consumption and ship emissions from 2004 to 2013

8. 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 HFO 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 HSD, MSD, HSD, respectively (USEPA ship report; Liu et al., 2016; Fan et al., 2016). For NOx emission, as shown in table SI-10, 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-11.

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

Table SI-10 NOx emission factors used in this study (unit: g/kg Fuel)

Fuel type	Engine type	Emission Stander	Model year	Emission Factor
HFO (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
HFO/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-11 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	BC[f]	OC[f]
OGVs/CVs[a]	ME[c]	SSD	HFO	2.7%	6.1	5.7	2.6	6.1	0.36	0.23
OGVs/CVs	ME[c]	SSD	MDO	0.5%	2.2	1.7	2.6	6.1	0.36	0.23
OGVs/CVs	ME[c]	MSD	HFO	2.7%	6.1	5.7	2.2	4.8	0.16	0.18
OGVs/CVs	ME[c]	MSD	MDO	0.5%	2.2	1.7	2.2	4.8	0.16	0.18
OGVs/CVs	AE[d]	HSD	HFO	2.7%	6.1	5.7	1.7	4.8	0.16	0.18
OGVs/CVs	AE[d]	HSD	MDO	0.5%	2.2	2.2	1.7	4.8	0.16	0.18
OGVs/CVs	BE[e]	HSD	MDO	0.5%	1.3	1.0	0.4	0.9	0.58	0.12
RVs[b]	ME[c]	HSD	MDO	0.5%	1.7	1.7	1.7	6.0	0.58	0.12

[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.

[f]the value of BC and OC were the ratio of $BC/PM_{2.5}$ and $OC/PM_{2.5}$, respectively. Refer to zhang et al., 2015.

Besides, the relationship of ship types to engine types and fuel types were the essential in emission estimation, shown in table SI-12. 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 HFO 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-12 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	HFO	HFO	MDO
	Container	MSD	MSD	SSD	HFO	HFO	MDO
	General cargo ship	MSD	SSD	SSD	HFO	HFO	MDO
	Tanker	MSD	SSD	SSD	HFO	HFO	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. HFO and MDO mean Marine heavy oil and Marine diesel oil.

Table SI-13 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

9. Emissions intensity calculation

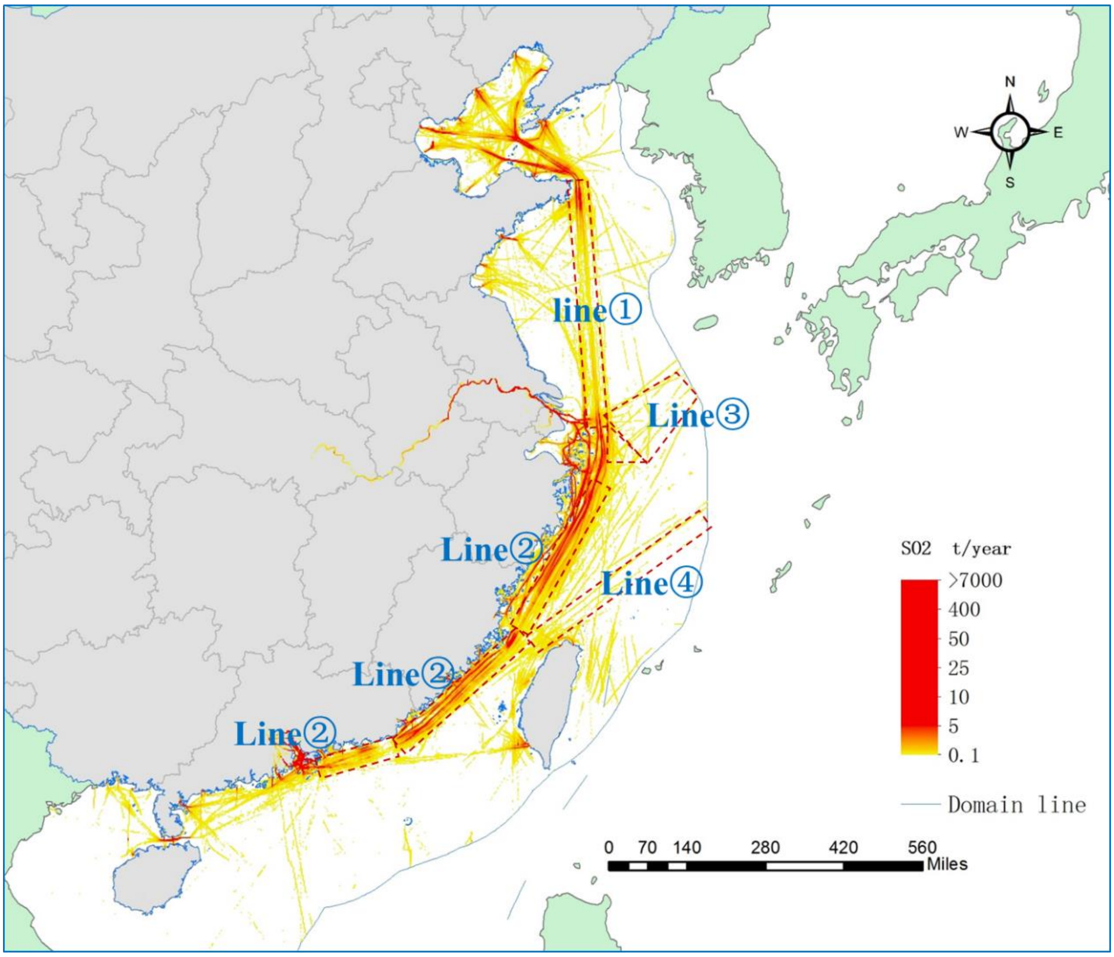
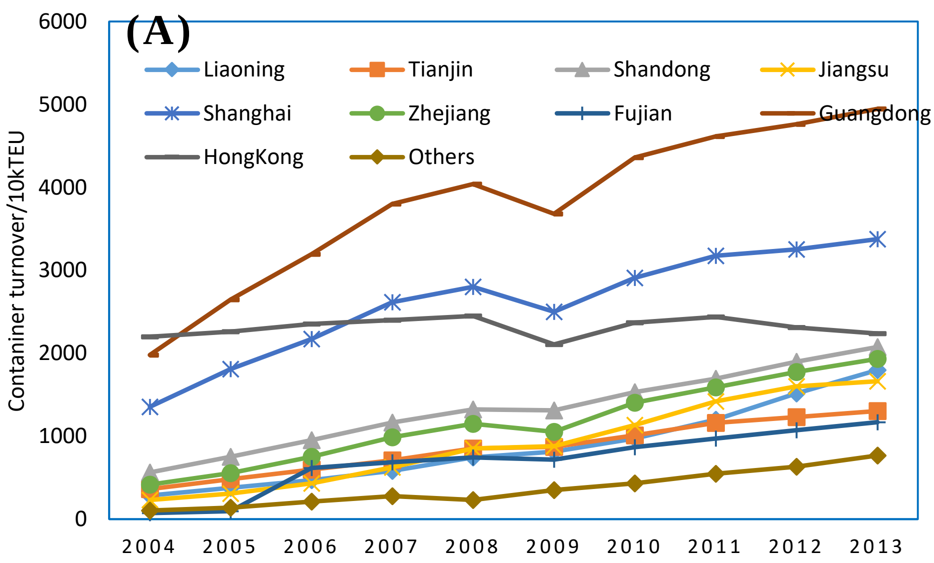


Fig. SI-9 Spatial allocation of typical navigating lines in Emission intensities calculation

10. Emission trends analysis



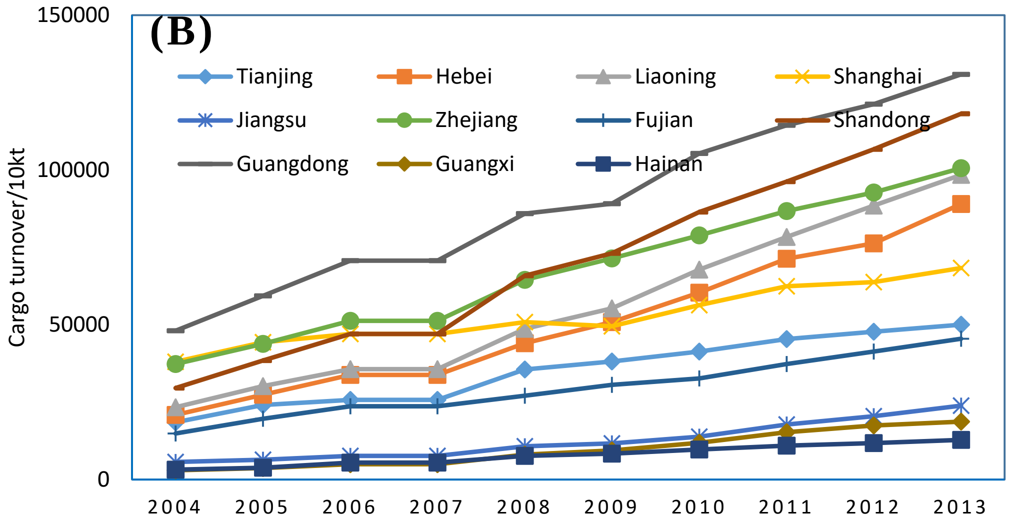


Fig. SI-10 Trends of container turnover (a) and cargo turnover (b) from coast ports in different provinces

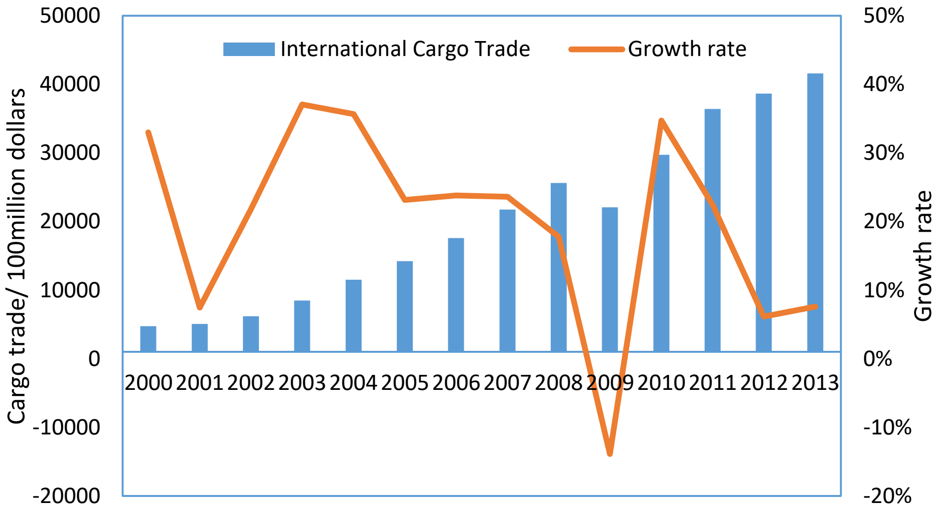


Fig. SI-11 Trends of international cargo trade and growth rate in China

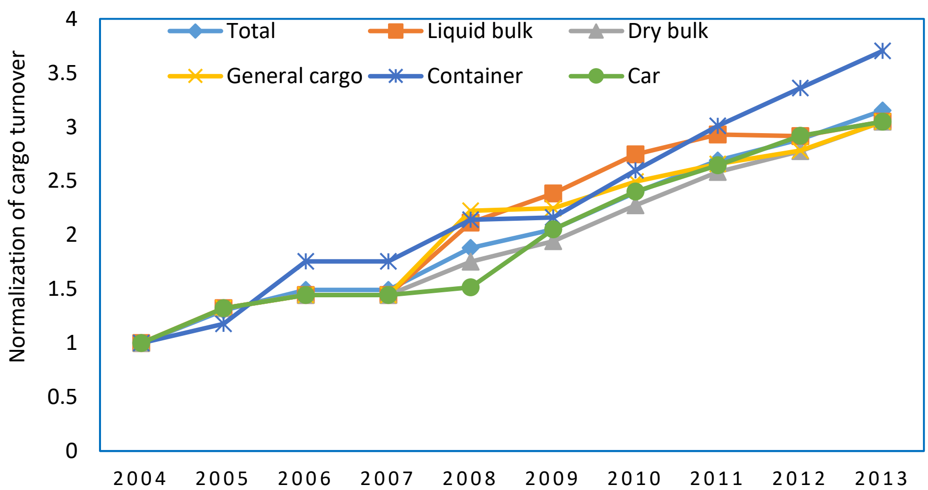


Fig. SI-13 Trends of cargo turnover with different cargo types in China from 2004 to 2013

Table SI-5(a) Raw data of transport volume for cargo-based approach in 2013

Year: 2013		Ports	Cargo transport (10Kt)						Ocean-going Cargo transport （10Kt）	Container transport (10000TEU)
				Dry bulk			Liquid cargo	General Cargo		
Port clusters	Province		Total	Ore	Building materials	Coal	Oil and Gas	Others (Chemical, food, wood, etc.)		
1.Bohai	Heilongjiang	Heilongjiang	1245	656	22	55	5	508	0	0
	Ji`ning	Ji`ning	13379	0	35	2	1465	11878	0	0
	Hebei	Total	39594	10284	0	28084	1160	0	7008	67
		Huanghua	8310	1360	0	6847	92	0	1471	12
		Qinghuaidao	12681	308	0	11914	440	0	2245	19
		Tangshan	18603	8616	0	9323	628	0	3293	36
	Tianjin	Tianjin	25040	5409	300	4481	2654	11500	13372	651
	Liaoning	Total	49217	11072	7774	3656	12071	13745	9891	899
		Dalian	20381	815	3900	1400	5300	8450	5884	501
		Yingkou	16038	5122	2241	1281	5282	1848	3111	265
		Jingzhou	4266	600	484	975	0	2160	426	48
		Dandong	6025	4100	1150	0	0	700	452	75
		Huludao	1023	435	0	0	0	588	3	0
		Panjin	1498	0	0	0	1489	0	17	10
2.Shandong	Shandong	Total	57337	15555	235	5197	6537	28690	34185	1038
		Qingdao	22894	6822	40	1041	3214	11000	16912	776
		Yantai	14345	1032	130	1393	1108	10500	5323	108
		Rizhao	15904	7163	65	1807	1768	5000	10825	102

		Weihai	2009	17	0	694	55	1200	600	33
		Dongying	715	46	0	64	265	340	200	0
		Binzhou	283	279	0	0	4	0	0	0
		Langfang	1171	197	0	198	124	650	325	3
3.YRD	Shanghai	Shanghai	38794	4715	6712	6534	2427	16725	18853	1681
	Zhejiang	Total	967	0	0	0	0	0	20398	967
		Jiaxing	3023	0	1916	1057	0	0	430	51
		Ningnbo-Zhoushan	43200	19435	0	3963	4400	14535	19208	868
		Taizhou	2815	0	1688	563	0	555	489	8
		Wenzhou	3686	1476	0	1291	0	890	244	29
		Hangzhou	4690	0	610	1126	844	2110	0	0
		Jiaxing-river	5557	0	3100	2150	0	300	0	7
		Huzhou	7660	919	6737	0	0	0	26	4
		Shaoxing	672	0	672	0	0	0	0	0
		Ningbo-river	26	0	0	0	0	26	2	0
		Lanxi	35	0	0	0	0	35	0	0
		Quzhou	0	0	0	0	0	0	0	0
		Lishui	2	0	0	0	0	2	0	0
		Qingtian	9	0	0	0	0	9	0	0
	Hubei	Hubei	24409	6911	0	1320	255	15842	213	54
	Hunan	Hunan	23097	7711	0	888	452	14032	106	15
	Jiangsu	Total	70630	24313	9865	25633	4445	5542	7482	831
		Changzhou	2234	992	0	1235	0	0	237	7
		Jiangyin	4543	1185	2903	395	60	0	481	0
		Lianyungang	6463	4555	1093	67	274	0	685	472
		Nanjing	10553	2116	1723	2747	1713	2255	1118	0

		Nantong	6276	2937	0	2621	688	0	665	30
		Jiangsu	11450	5721	0	5220	243	0	1213	265
		Taizhou	4338	511	0	3589	230	0	460	9
		Wuxi	10315	1084	4146	3570	498	1017	1093	0
		Suqian	925	736	0	138	51	0	98	0
		Xuzhou	1320	147	0	1160	13	0	140	0
		Yancheng	2113	1443	0	651	16	0	224	3
		Yangzhou	5003	216	0	2103	389	2270	530	26
		Zhenjiang	5097	2672	0	2137	269	0	540	19
	Jiangxi	Jiangxi	8676	561	2600	745	91	4665	17	14
	Sichuan	Sichuan	2392	114	45	193	27	2000	0	13
	Anhui	Total	19839	4397	6441	2799	262	5910	0	26
		An`qing	1505	96	323	256	128	700	0	2
		Chizhou	1958	551	451	169	24	762	0	1
		Tongling	2954	509	466	459	11	1506	0	1
		Wuhu	4675	1279	790	874	61	1653	0	14
		Ma`an`shan	3748	1439	1381	384	13	529	0	4
		Hefei	1061	184	330	75	15	453	0	5
		Fuyang	510	1	413	56	1	38	0	0
		Liuan	180	81	90	0	0	9	0	0
		Huainan	808	1	303	394	0	110	0	0
		Bengbu	372	1	266	15	0	89	0	0
		Chuzhou	1308	22	1029	25	0	232	0	0
		Xuancheng	75	18	43	0	0	14	0	0
		Bozhou	521	0	448	37	0	36	0	0
		Xiuzhou	659	0	104	555	0	0	0	0
		Huangshan	6	0	4	0	0	2	0	0

4.Western Taiwan Strait	Fujian	total	23322	2185	0	4183	1389	14980	9282	585
		Fuzhou	6478	1624	0	1569	99	3089	2978	99
		Xiamen	9970	368	0	1195	224	7757	4687	400
		Quanzhou	5487	193	0	690	701	3818	1195	85
		Putian	1412	0	0	730	366	316	422	0
5.PRD	Guangdong	Total	78184	6163	27109	12022	7606	22440	25277	2476
		Guanzhou	23599	3668	4149	3876	913	10117	5731	775
		Shenzhen	11662	421	6587	215	669	2606	9087	1164
		Zhuhai	5011	134	1204	811	691	2128	1018	44
		Foshan	2737	12	654	431	257	1247	1123	138
		Dongguan	5594	8	2626	2152	500	201	1070	99
		Zhongshan	3438	0	2315	118	123	816	338	66
		Jiangmen	3369	0	1941	858	142	381	447	47
		Huizhou	4023	3	1205	350	1941	516	930	8
		Zhaoqing	1477	6	869	173	38	356	136	35
		Shantou	2519	0	692	693	64	1006	714	64
		Chaozhou	525	0	0	438	26	61	317	0
		Jieyang	1255	0	286	317	149	504	0	0
		Shanwei	334	0	0	329	5	0	69	1
		Yangjiang	1028	393	24	321	24	267	582	0
		Zhanjiang	9003	1515	3875	682	1153	1664	2987	23
		Maoming	1185	1	0	88	733	358	637	5
		Shaoguan	40	0	0	39	0	0	0	0
		Heyuan	0	0	0	0	0	0	0	0
		Meizhou	63	0	50	0	0	13	0	0
		Qingyuan	504	0	212	106	0	21	0	1
		Yunfu	818	3	424	26	178	182	91	6

6.Beibu Gulf	Guangxi	Total	5387	1117	1156	2325	31	677	2574	78
		Fangcheng	3485	0	0	0	0	0	0	45
		Qinzhou	722	0	0	0	0	0	0	0
		Beihai	613	0	0	0	0	0	0	0
		Guigang	349	42	17	262	6	18	192	6
		Liuzhou	22	22	0	0	0	0	8	0
		Nanning	27	3	0	23	0	0	9	0
		Wuzhou	123	4	0	55	26	20	43	20
	Guizhou	Guizhou	492	0	0	0	0	492	0	0
	Hainan	Hainan	6420	0	2183	1733	321	1965	1187	71
	Yunnan	Yunnan	247	0	0	0	0	247	0	0

* Data from China port statistical yearbook in 2014.

Table SI-5(b) raw data of transport volume for emission trends estimation in 2013

2013	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	588353	47390	345523	58345	9511	109244	792	27852
Coast ports		Sum	378065	37413	187844	29557	8484	97347	726	25905
	Bohai	Tianjin	25032	3033	11383	1568	651	7608	46	1441
	Bohai	Hebei	44492	1182	40138	2147	68	1026	0	0
	Bohai	Liaoning	49177	5687	17180	6139	899	14191	90	5981
	YRD	Shanghai	34137	1621	11952	2707	1681	17122	70	737
	YRD	Jiangsu	11954	167	8005	1014	277	2768	0	0
	YRD	Zhejiang	50296	7796	28072	2144	955	9830	117	2454
	WTS	Fujian	22738	1359	11071	2610	585	7445	22	253
	Shandong	Shandong	59069	6966	30101	4308	1038	11379	87	6315

	PRD	Guangdong	65416	7581	22192	5052	2210	23974	202	6618
	Beibu Gulf	Guangxi	9337	1079	6415	945	50	852	1	48
	Beibu Gulf	Hainan	6420	945	1336	925	71	1155	93	2060
River ports		Sum	210288	9977	157680	28788	1027	11897	66	1947
	Bohai	Liaoning	23	0	17	7	0	0	0	0
	Bohai	Ji`ning	31	0	31	0	0	0	0	0
	Bohai	Heilongjiang	233	5	179	40	0	0	1	9
	YRD	Shanghai	4651	25	3857	769	0	0	0	0
	YRD	Jiangsu	95040	6371	65348	16895	555	6406	2	20
	YRD	Zhejiang	18730	518	16600	1515	12	98	0	0
	YRD	Anhui	19809	295	16899	2349	27	230	4	37
	WTS	Fujian	218	0	180	39	0	0	0	0
	YRD	Jiangxi	13122	125	12205	619	15	174	0	0
	Shandong	Shandong	3674	0	3604	71	0	0	0	0
	YRD	Henan	101	0	86	15	0	0	0	0
	YRD	Hubei	13110	370	9209	1787	54	787	28	958
	YRD	Hunan	11572	539	9932	912	15	191	0	0
	PRD	Guangdong	12771	1342	7096	1452	266	2881	0	0
	Beibu Gulf	Guangxi	5331	74	3901	886	28	472	0	0
	YRD	Chongqing	6838	225	4420	750	46	521	32	923
	YRD	Sichuan	4098	28	3576	355	13	140	0	0
	Beibu Gulf	Guizhou	492	62	166	265	0	0	0	0
	Beibu Gulf	Yunnan	248	0	196	52	0	0	0	0

* Data from China port statistical yearbook in 2014. WTS is "Western taiwan strait"

Table SI-5(c) raw data of transport volume in 2012

2012	Port clusters	Ports	Total		Bulk cargo		Container		Car	

				Liquid cargo		General cargo	10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	538802	45313	314550	53218	8874	99074	757	26649
Coast ports		Sum	343988	35913	168320	26802	7899	87993	697	24960
	Bohai	Tianjin	23849	3071	11208	1561	615	6721	42	1288
	Bohai	Hebei	38117	1213	34105	2124	45	676	0	0
	Bohai	Liaoning	44251	5337	15401	#VALUE!	757	12367	76	5217
	YRD	Shanghai	31870	1624	10806	2521	1627	16240	64	680
	YRD	Jiangsu	10252	200	6735	812	252	2506	0	0
	YRD	Zhejiang	46380	7567	25267	1971	880	8906	130	2671
	WTS	Fujian	20680	1340	10113	2235	537	6654	29	338
	Shandong	Shandong	53328	6156	27034	3395	950	9956	86	6788
	PRD	Guangdong	60633	7147	20449	4699	2128	22248	189	6091
	Beibu Gulf	Guangxi	8719	1149	6003	845	41	679	1	45
	Beibu Gulf	Hainan	5910	1111	1202	712	69	1042	82	1844
River ports		Sum	194815	9400	146230	26416	975	11081	60	1689
	Bohai	Liaoning	25	0	15	10	0	0	0	0
	Bohai	Ji`ning	32	0	32	0	0	0	0	0
	Bohai	Heilongjiang	232	#VALUE!	172	40	0	1	1	15
	YRD	Shanghai	4910	37	4077	797	0	0	0	0
	YRD	Jiangsu	87457	6709	60395	14070	548	6278	1	7
	YRD	Zhejiang	19586	325	17031	2170	7	61	0	0
	YRD	Anhui	18049	285	15030	2506	23	194	4	36
	WTS	Fujian	230	0	184	45	0	0	0	0
	YRD	Jiangxi	12636	136	11842	530	12	128	0	0
	Shandong	Shandong	3301	0	3257	45	0	0	0	0
	YRD	Henan	118	0	81	38	0	0	0	0

	YRD	Hubei	11759	350	8444	1516	48	668	25	783
	YRD	Hunan	10934	448	9170	1116	15	201	0	0
	PRD	Guangdong	9755	776	4912	1429	254	2639	0	0
	Beibu Gulf	Guangxi	4749	37	3625	713	23	374	0	0
	YRD	Chongqing	6251	201	3980	775	40	447	30	849
	YRD	Sichuan	3853	41	3468	253	8	92	0	0
	Beibu Gulf	Guizhou	579	54	216	310	0	0	0	0
	Beibu Gulf	Yunnan	195	0	155	41	0	0	0	0

* Data from China port statistical yearbook in 2013.

Table SI-5(d) raw data of transport volume in 2011

2011	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	502057	45539	292744	50875	8184	88727	732	24172
Coast ports		Sum	318012	36314	153776	26500	7316	78985	669	22438
	Bohai	Tianjin	22669	3239	10795	1480	580	5965	38	1192
	Bohai	Hebei	35650	1143	32012	1870	39	626	0	0
	Bohai	Liaoning	39172	5251	14275	5590	600	9558	65	4500
	YRD	Shanghai	31216	1654	10703	2657	1587	15610	56	592
	YRD	Jiangsu	8876	121	5327	1116	244	2313	0	0
	YRD	Zhejiang	43350	8217	22088	2381	792	7874	133	2792
	WTS	Fujian	18640	1278	8554	2416	485	6050	30	343
	Shandong	Shandong	48094	5253	24807	3580	846	8869	74	5587
	PRD	Guangdong	57228	7982	18646	4271	2052	20658	195	5673
	Beibu Gulf	Guangxi	7666	1108	5425	503	37	583	1	49

	Beibu Gulf	Hainan	5453	1072	1148	638	56	882	78	1713
River ports		Sum	184045	9225	138969	24375	868	9743	64	1734
	Bohai	Liaoning	15	0	11	4	0	0	0	0
	Bohai	Ji`ning	35	0	35	0	0	0	0	0
	Bohai	Heilongjiang	229	5	161	48	0	1	1	16
	YRD	Shanghai	5163	67	4404	693	0	0	0	0
	YRD	Jiangsu	81466	6791	55593	13774	465	5304	1	6
	YRD	Zhejiang	17837	311	15634	1871	3	22	0	0
	YRD	Anhui	18710	278	16308	1908	20	172	5	46
	WTS	Fujian	209	0	154	55	0	0	0	0
	YRD	Jiangxi	11779	103	11064	494	10	119	0	0
	Shandong	Shandong	3219	0	3023	196	0	0	0	0
	YRD	Henan	101	0	92	9	0	0	0	0
	YRD	Hubei	10832	287	7825	1340	43	589	27	790
	YRD	Hunan	10532	215	9448	711	12	159	0	0
	PRD	Guangdong	9625	861	4840	1310	256	2614	0	0
	Beibu Gulf	Guangxi	4014	41	3008	660	21	305	0	0
	YRD	Chongqing	5803	177	3571	783	34	395	31	878
	YRD	Sichuan	3538	48	3200	224	6	66	0	0
	Beibu Gulf	Guizhou	546	44	263	240	0	0	0	0
	Beibu Gulf	Yunnan	231	0	191	40	0	0	0	0

* Data from China port statistical yearbook in 2012.

Table SI-5(e) raw data of transport volume in 2010

2010	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight

Unit:10kt		Total	446612	42698	257659	47724	7307	76590	705	21941
Coast ports		Sum	282232	34274	135126	23938	6573	68538	649	20358
	Bohai	Tianjin	20663	3315	9392	1472	505	5458	33	1026
	Bohai	Hebei	30172	842	27382	1451	31	499	0	0
	Bohai	Liaoning	33895	5156	11921	4918	485	7833	66	4067
	YRD	Shanghai	28160	1564	9682	2516	1454	13996	38	403
	YRD	Jiangsu	6924	175	4314	530	196	1905	0	0
	YRD	Zhejiang	39423	7536	19996	1883	702	6138	173	3871
	WTS	Fujian	16344	1336	7196	2147	434	5372	25	293
	Shandong	Shandong	43211	4950	22564	4137	766	7595	61	3966
	PRD	Guangdong	52650	7768	17209	3865	1934	18707	181	5102
	Beibu Gulf	Guangxi	5962	638	4371	450	28	463	2	41
	Beibu Gulf	Hainan	4831	996	1102	571	41	574	71	1590
River ports		Sum	164380	8425	122534	23787	734	8052	57	1583
	Bohai	Liaoning	81	0	81	0	0	0	0	0
	Bohai	Ji`ning	34	0	34	0	0	0	0	0
	Bohai	Heilongjiang	198	6	138	40	0	1	1	2
	YRD	Shanghai	4510	67	3730	713	0	0	0	0
	YRD	Jiangsu	72565	6054	47978	14332	372	4195	1	7
	YRD	Zhejiang	16971	319	15343	1309	0	1	0	0
	YRD	Anhui	16251	304	14014	1806	11	103	3	25
	WTS	Fujian	191	0	127	65	0	0	0	0
	YRD	Jiangxi	10566	111	9880	469	9	107	0	0
	Shandong	Shandong	3273	31	2952	291	0	0	0	0
	YRD	Henan	70	0	66	4	0	0	0	0
	YRD	Hubei	9392	274	6398	1442	39	546	25	733
	YRD	Hunan	9627	260	8605	629	11	134	0	0

	PRD	Guangdong	8479	792	4186	1088	246	2414	0	0
	Beibu Gulf	Guangxi	3354	29	2565	582	15	179	0	0
	YRD	Chongqing	4834	133	2995	571	28	331	28	805
	YRD	Sichuan	3194	42	2929	180	4	44	0	0
	Beibu Gulf	Guizhou	445	7	216	222	0	0	0	0
	Beibu Gulf	Yunnan	210	0	173	37	0	0	0	0

* Data from China port statistical yearbook in 2011.

Table SI-5(f) raw data of transport volume in 2009

2009	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	382854	37063	220221	43025	6120	63764	638	18739
Coast ports		Sum	243686	29477	117441	22866	5510	57208	579	16697
	Bohai	Tianjin	19056	2644	9795	1592	435	4436	20	591
	Bohai	Hebei	25437	513	23530	961	29	435	0	0
	Bohai	Liaoning	27630	4146	9075	6063	406	5859	36	2488
	YRD	Shanghai	24734	1489	8416	2316	1250	12310	20	204
	YRD	Jiangsu	5854	201	3506	712	153	1436	0	0
	YRD	Zhejiang	35731	6972	16850	1772	559	4920	235	5219
	WTS	Fujian	15271	975	7843	1741	358	4501	18	212
	Shandong	Shandong	36536	4265	18699	3415	656	6909	53	3249
	PRD	Guangdong	44562	6954	15266	3245	1618	15716	136	3382
	Beibu Gulf	Guangxi	4704	378	3554	472	18	278	1	23
	Beibu Gulf	Hainan	4173	943	909	579	30	411	61	1332
River ports		Sum	139169	7632	102781	20159	610	6557	60	2042
	Bohai	Shanxi	0	0	0	0	0	0	0	0

	Bohai	Liaoning	127	0	127	0	0	0	0	0
	Bohai	Ji`ning	42	0	42	0	0	0	0	0
	YRD	Heilongjiang	179	4	119	45	0	0	1	11
	YRD	Shanghai	4869	31	4229	609	0	0	0	0
	YRD	Jiangsu	60539	5396	41454	10473	287	3210	1	7
	YRD	Zhejiang	16141	289	14614	1238	0	0	0	0
	WTS	Anhui	13225	233	10531	2354	10	95	2	14
	YRD	Fujian	145	0	130	15	0	0	0	0
	Shandong	Jiangxi	7505	127	6927	365	8	87	0	0
	YRD	Shandong	2407	8	2225	174	0	0	0	0
	YRD	Henan	44	0	43	2	0	0	0	0
	YRD	Hubei	8336	252	5512	1193	34	457	19	923
	PRD	Hunan	8470	242	7569	550	10	110	0	0
	Beibu Gulf	Guangdong	6819	863	2204	1648	222	2105	0	0
	YRD	Guangxi	2748	18	2025	554	12	152	0	0
	YRD	Chongqing	4306	126	2277	538	26	299	37	1067
	Beibu Gulf	Sichuan	2550	43	2292	151	3	44	1	21
	Beibu Gulf	Guizhou	389	1	177	211	0	0	0	0
		Yunnan	170	0	141	30	0	0	0	0
		Shanxi	160	0	145	15	0	0	0	0

* Data from China port statistical yearbook in 2010.

Table SI-5(g) raw data of transport volume in 2008

2008	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	351119	32881	198751	42542	6416	63102	637	13844

Coast ports		Sum	224467	26045	105008	23966	5837	57346	565	12104
	Bohai	Tianjin	17797	2360	8943	1940	425	4296	20	259
	Bohai	Hebei	22033	525	20162	902	33	444	0	0
	Bohai	Liaoning	24342	3579	7606	4905	372	5186	44	3067
	YRD	Shanghai	25404	1510	8282	2499	1401	12996	23	117
	YRD	Jiangsu	5385	195	2849	933	151	1408	0	0
	YRD	Zhejiang	32259	6413	15165	2547	574	4679	243	3457
	WTS	Fujian	13535	699	6686	1795	372	4355	0	0
	Shandong	Shandong	32895	3765	16271	3035	661	7026	108	2799
	PRD	Guangdong	42928	5823	15542	4111	1810	16390	70	1064
	Beibu Gulf	Guangxi	4045	316	2908	539	17	262	1	22
	Beibu Gulf	Hainan	3846	863	597	762	23	307	58	1320
River ports		Sum	126652	6837	93743	18576	579	5756	72	1740
	Bohai	Liaoning	42	0	42	0	0	0	0	0
	Bohai	Ji`ning	42	0	42	1	0	0	0	0
	Bohai	Heilongjiang	280	6	188	66	0	0	2	21
	YRD	Shanghai	3681	40	2886	756	0	0	0	0
	YRD	Jiangsu	52768	4535	35294	10368	275	2563	1	10
	YRD	Zhejiang	15560	236	14342	982	0	0	0	0
	YRD	Anhui	13634	196	11959	1324	12	119	1	36
	WTS	Fujian	176	0	157	20	0	0	0	0
	YRD	Jiangxi	5997	133	5472	331	7	61	0	0
	Shandong	Shandong	2530	0	2469	61	0	0	0	0
	YRD	Henan	53	1	50	3	0	0	0	0
	YRD	Hubei	7985	200	5493	1124	30	352	29	818
	YRD	Hunan	8012	258	6949	720	7	85	0	0
	PRD	Guangdong	6470	1028	1942	1380	210	2121	0	0

	Beibu Gulf	Guangxi	2338	18	1560	649	10	112	0	0
	YRD	Chongqing	3947	148	2234	445	27	300	33	820
	YRD	Sichuan	2459	38	2227	133	4	45	7	18
	Beibu Gulf	Guizhou	379	3	250	126	0	0	0	0
	Beibu Gulf	Yunnan	158	0	73	66	0	0	1	19

* Data from China port statistical yearbook in 2009.

Table SI-5(h) raw data of transport volume in 2007

2007	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	314818	27657	181158	35080	5459	57408	506	13514
Coast ports		Sum	200491	21756	96355	18883	4899	51398	452	12099
	Bohai	Tianjin	15338	1960	7400	1373	380	4105	22	500
	Bohai	Hebei	19468	487	17705	859	29	417	0	0
	Bohai	Liaoning	21086	2820	6917	3565	349	5165	38	2618
	YRD	Shanghai	24462	1313	8258	2182	1279	12396	35	312
	YRD	Jiangsu	4613	124	2710	629	120	1149	0	0
	YRD	Zhejiang	28944	5193	14735	1820	530	4844	151	2354
	WTS	Fujian	12690	703	6226	1577	338	4116	6	66
	Shandong	Shandong	28199	3268	14124	2375	537	5777	71	2656
	PRD	Guangdong	39143	4960	13768	3420	1502	14674	89	2320
	Beibu Gulf	Guangxi	3260	301	2304	394	15	244	1	17
	Beibu Gulf	Hainan	3284	632	581	577	27	398	48	1096
River ports		Sum	114327	5838	85113	16270	538	5763	52	1342
	Bohai	Liaoning	23	0	22	1	0	0	0	0
	Bohai	Ji`ning	69	0	69	0	0	0	0	0

	Bohai	Heilongjiang	324	6	235	64	0	0	1	18
	YRD	Shanghai	3518	29	2834	655	0	0	0	0
	YRD	Jiangsu	46053	3586	31171	8680	252	2607	1	9
	YRD	Zhejiang	15507	332	14019	1116	5	40	0	0
	YRD	Anhui	11816	172	10244	1255	13	118	1	27
	WTS	Fujian	133	0	115	18	0	0	0	0
	YRD	Jiangxi	6546	100	6036	333	7	77	0	0
	Shandong	Shandong	2206	0	2157	49	0	0	0	0
	YRD	Henan	44	0	39	4	0	0	0	0
	YRD	Hubei	7632	202	5303	1058	30	394	22	675
	YRD	Hunan	5973	221	5163	515	6	75	0	0
	PRD	Guangdong	6231	829	2635	1031	167	1736	0	0
	Beibu Gulf	Guangxi	2103	22	1463	480	10	138	0	0
	YRD	Chongqing	3328	119	1993	371	22	253	22	593
	YRD	Sichuan	2216	26	1974	152	5	56	3	9
	Beibu Gulf	Guizhou	320	18	169	133	0	0	0	0
	Beibu Gulf	Yunnan	156	0	97	49	0	0	0	10

* Data from China port statistical yearbook in 2008.

Table SI-5(i) raw data of transport volume in 2006

2006	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	278517	22434	163565	27619	4502	51714	375	13184
Coast ports		Sum	176516	17468	87703	13800	3961	45450	339	12095
	Bohai	Tianjin	12880	1560	5857	807	335	3915	24	741
	Bohai	Hebei	16903	449	15248	815	26	390	0	0

	Bohai	Liaoning	17829	2062	6228	2226	326	5145	32	2168
	YRD	Shanghai	23520	1117	8235	1865	1158	11797	48	507
	YRD	Jiangsu	3842	54	2572	326	89	890	0	0
	YRD	Zhejiang	25629	3973	14305	1093	487	5009	59	1250
	WTS	Fujian	11844	708	5767	1360	304	3878	11	132
	Shandong	Shandong	23503	2772	11977	1714	413	4528	34	2513
	PRD	Guangdong	35359	4098	11995	2730	1195	12958	109	3577
	Beibu Gulf	Guangxi	2475	286	1700	250	13	226	0	13
	Beibu Gulf	Hainan	2722	401	566	392	30	490	39	873
River ports		Sum	102002	4839	76483	13964	498	5771	32	944
	Bohai	Liaoning	4	0	3	1	0	0	0	0
	Bohai	Ji`ning	97	0	97	0	0	0	0	0
	Bohai	Heilongjiang	367	7	283	63	0	0	1	14
	YRD	Shanghai	3355	18	2782	555	0	0	0	0
	YRD	Jiangsu	39338	2637	27048	6993	230	2652	1	8
	YRD	Zhejiang	15454	427	13696	1250	9	80	0	0
	YRD	Anhui	9998	149	8529	1185	13	116	2	19
	WTS	Fujian	89	0	73	16	0	0	0	0
	YRD	Jiangxi	7096	68	6600	334	8	94	0	0
	Shandong	Shandong	1882	0	1846	36	0	0	0	0
	YRD	Henan	34	0	29	5	0	0	0	0
	YRD	Hubei	7279	205	5113	992	30	437	16	532
	YRD	Hunan	3934	183	3376	310	5	65	0	0
	PRD	Guangdong	5991	630	3329	681	125	1352	0	0
	Beibu Gulf	Guangxi	1868	26	1366	310	10	165	0	0
	YRD	Chongqing	2710	89	1752	297	18	206	12	366
	YRD	Sichuan	1973	13	1721	171	6	67	0	0

	Beibu Gulf	Guizhou	261	33	88	140	0	0	0	0
	Beibu Gulf	Yunnan	153	0	121	32	0	0	0	0

* Data from China port statistical yearbook in 2007.

Table SI-5(g) raw data of transport volume in 2005

2005	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	242694	20572	149990	25327	3782	34715	344	12090
Coast ports		Sum	150447	15786	79260	12471	3501	31999	306	10930
	Bohai	Tianjin	12035	1629	6113	842	240	2677	25	774
	Bohai	Hebei	13671	369	12547	671	7	84	0	0
	Bohai	Liaoning	15104	2133	6445	2303	189	1979	34	2244
	YRD	Shanghai	22159	1337	9858	2232	904	8125	58	607
	YRD	Jiangsu	3193	48	2314	293	51	538	0	0
	YRD	Zhejiang	21923	3759	13537	1034	278	2409	56	1183
	WTS	Fujian	9803	653	5325	1255	246	2448	11	122
	Shandong	Shandong	19201	2242	9686	1386	377	3855	28	2032
	PRD	Guangdong	29640	3665	10729	2442	1189	9605	97	3199
	Beibu Gulf	Guangxi	1835	221	1314	194	8	96	0	10
	Beibu Gulf	Hainan	1887	305	432	299	14	186	30	665
River ports		Sum	92248	4503	71159	12992	281	2716	30	879
	Bohai	Liaoning	1	0	0	0	0	0	0	0
	Bohai	Ji`ning	48	0	48	0	0	0	0	0
	Bohai	Heilongjiang	456	9	351	78	0	0	1	18
	YRD	Shanghai	5375	29	4457	889	0	0	0	0
	YRD	Jiangsu	34581	2411	24733	6394	102	1036	1	8

	YRD	Zhejiang	13514	376	12038	1098	0	1	0	0
	YRD	Anhui	8579	128	7352	1022	6	61	2	16
	WTS	Fujian	102	0	84	18	0	0	0	0
	YRD	Jiangxi	6814	65	6394	324	3	30	0	0
	Shandong	Shandong	1143	0	1121	22	0	0	0	0
	YRD	Henan	28	0	23	4	0	0	0	0
	YRD	Hubei	6997	206	5135	996	14	125	16	534
	YRD	Hunan	2645	122	2242	206	8	76	0	0
	PRD	Guangdong	5528	583	3081	631	134	1233	0	0
	Beibu Gulf	Guangxi	1604	24	1266	287	3	27	0	0
	YRD	Chongqing	2626	89	1756	298	11	116	13	366
	YRD	Sichuan	1731	12	1551	154	1	14	0	0
	Beibu Gulf	Guizhou	249	31	84	134	0	0	0	0
	Beibu Gulf	Yunnan	138	0	109	29	0	0	0	0

* Data from China port statistical yearbook in 2006.

Table SI-5(k) raw data of transport volume in 2004

2004	Port clusters	Ports	Total	Liquid cargo	Bulk cargo	General cargo	Container		Car	
							10k TEU	Weight	Number(10t)	Weight
Unit:10kt		Total	168034	13876	101169	17083	2669	27751	232	8155
Coast ports		Sum	111369	11320	56837	8943	2541	26430	220	7838
	Bohai	Tianjin	8314	1064	3994	550	192	2200	16	505
	Bohai	Hebei	9368	251	8522	456	10	139	0	0
	Bohai	Liaoning	10554	1349	4076	1457	164	2252	21	1419
	YRD	Shanghai	17943	947	6982	1581	821	8003	41	430
	YRD	Jiangsu	2688	39	1859	235	55	555	0	0

	YRD	Zhejiang	17545	2840	10226	781	287	2804	42	894
	WTS	Fujian	6636	419	3415	805	169	1919	7	78
	Shandong	Shandong	13271	1557	6730	963	246	2609	19	1412
	PRD	Guangdong	22154	2644	7740	1762	811	7700	70	2308
	Beibu Gulf	Guangxi	1403	165	982	145	7	104	0	7
	Beibu Gulf	Hainan	1495	229	324	224	14	218	22	500
River ports		Sum	56665	2730	43152	7878	220	2372	18	533
	Bohai	Liaoning	3	0	2	1	0	0	0	0
	Bohai	Ji`ning	16	0	16	0	0	0	0	0
	Bohai	Heilongjiang	152	3	117	26	0	0	0	6
	YRD	Shanghai	3230	17	2678	534	0	0	0	0
	YRD	Jiangsu	24439	1669	17122	4427	109	1215	1	5
	YRD	Zhejiang	8317	231	7391	674	2	20	0	0
	YRD	Anhui	4583	68	3921	545	4	40	1	9
	WTS	Fujian	66	0	55	12	0	0	0	0
	YRD	Jiangxi	2526	24	2368	120	1	13	0	0
	Shandong	Shandong	769	0	754	15	0	0	0	0
	YRD	Henan	9	0	8	1	0	0	0	0
	YRD	Hubei	2332	69	1712	332	5	42	5	178
	YRD	Hunan	2375	110	2029	186	5	50	0	0
	PRD	Guangdong	4239	446	2358	483	94	951	0	0
	Beibu Gulf	Guangxi	986	14	753	171	3	49	0	0
	YRD	Chongqing	875	30	585	99	4	39	4	122
	YRD	Sichuan	1385	10	1222	121	3	32	0	0
	Beibu Gulf	Guizhou	232	29	78	125	0	0	0	0
	Beibu Gulf	Yunnan	100	0	79	21	0	0	0	0

* Data from China port statistical yearbook in 2005.