Science of the Total Environment 581–582 (2017) 186–198

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

Shipping emissions and their impacts on air quality in China

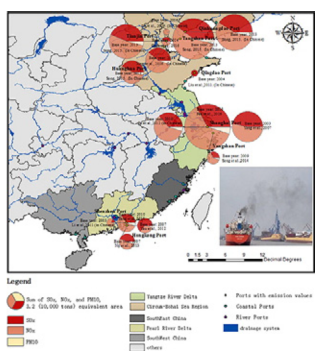
Yan Zhang [a], Xin Yang [a,*], Richard Brown [b], Liping Yang [b], Lidia Morawska [c,*], Zoran Ristovski [c], Qingyan Fu [d], Cheng Huang [e]

[a] Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention, Department of Environmental Science and Engineering, Fudan University, Shanghai 200433, China
[b] Biofuels Engine Research Facility, Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia
[c] International Laboratory for Air Quality and Health, Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia
[d] Shanghai Environmental Monitoring Center, Shanghai 200030, China
[e] Shanghai Academy of Environmental Sciences, Shanghai 200233, China

HIGHLIGHTS

- The first review of shipping emissions in China
- An overview of the broad field of ship emissions and their atmospheric impacts in China
- Future work in shipping related air pollution field has been outlooked.

GRAPHICAL ABSTRACT



China has >400 ports and waterway infrastructure construction has accelerated over the past years. Shipping emission and their impacts have been paid attentions in China. There have been an increasing number of studies published on shipping and port emissions of the main shipping areas in China, and quantitative contribution of shipping emissions to the local and regional air pollution.

ARTICLE INFO

Article history:
Received 13 October 2016
Received in revised form 3 December 2016
Accepted 14 December 2016
Available online 4 January 2017

Editor: D. Barcelo

Keywords:
Ship emission
China
Air pollution
Emission factor

ABSTRACT

China has >400 ports, is home to 7 of 10 biggest ports in the world and its waterway infrastructure construction has been accelerating over the past years. But the increasing number of ports and ships means increasing emissions, and in turn, increasing impact on local and regional air pollution. This paper presents an overview of the broad field of ship emissions in China and their atmospheric impacts, including topics of ship engine emissions and control, ship emission factors and their measurements, developing of ship emission inventories, shipping and port emissions of the main shipping areas in China, and quantitative contribution of shipping emissions to the local and regional air pollution.

There have been an increasing number of studies published on all the above aspects, yet, this review identified some critical research gaps, filling of which is necessary for better control of ship emissions, and for lowering their impacts. In particular, there are very few studies on inland ports and river ships, and there are few national scale ship emission inventories available for China. While advanced method to estimate ship emission based on ship AIS activities makes it now possible to develop high spatial- and temporal-resolution emission inventories, the ship emission factors used in Chinese studies have been based mainly on foreign measurements. Further, the contribution of ship emissions to air pollution in coastal cities, the dispersion of pollution plumes emitted by

* Corresponding authors.
E-mail addresses: yangxin@fudan.edu.cn (X. Yang), l.morawska@qut.edu.au (L. Morawska).

http://dx.doi.org/10.1016/j.scitotenv.2016.12.098
0048-9697/© 2016 Elsevier B.V. All rights reserved.

ships, or the chemical evolution process along the transmission path, have so far not been systematically studied in China.

© 2016 Elsevier B.V. All rights reserved.

Contents

1. Introduction

Ship emissions with their key components including SO_x, NO_x, HC and PM, which is composed of organic and elemental carbon (OC and EC), sulfates and metals, have a significant influence on coastal atmospheric environment. The global ship emissions and their influence on climate and air quality have been attracting interest worldwide over the past two decades (Corbett and Fischbeck, 1997; Capaldo et al., 1999; Lawrence and Crutzen, 1999; Eyring et al., 2005). However, over the last decade ship emissions in the East Asia region have increased rapidly, and taking NO_x as an example, have reached 2.8 Tg in 2013, which is almost double of 1.49 Tg in 2001 (Liu et al., 2016). Hazardous emissions from ships lead to increasing impacts on the quality of local, regional, and global atmosphere. This is particularly so in China, where with the significant development of the economy and shipbuilding industry, the total number of ships increases rapidly, and where pollution caused by ship emissions is becoming increasingly more serious.

China's shipping industry has experienced a rapid development over the past few years, and it is expected that Shanghai will become the international shipping center by 2020 (State Council of China, 2008). The container throughputs in China in 2014 were 202.4 million TEU, accounting for >25% of the world total. China has reached a nationwide port handling capacity of 12.75 billion tons and was home to 7 of 10 biggest ports in the world in 2015 (MOT, 2015). However, at the same time China has been experiencing heavy regional air pollution. Emissions of ships in ports and along shipping routes have contributed to worsening of the current severe air pollution situation. Recently, a scheme of areas in China has been promulgated for prevention of air pollution from ships (MOT, 2015).

In inland rivers, sea ports and straits, ship emissions are becoming one of the main sources of atmospheric pollution, with a large number of diesel-powered offshore and sea-going ships, of a large variety of types, differing in technical level and, working conditions. However, very few studies were conducted on ship emissions and ship emission inventories, with just a handful of studies published on ship emission inventories on port scale, port-cluster scale and national scale in China. Most of earlier studies to calculate ship emission were based on ship visa registration data or fuel burning data (Yang et al., 2007; Jin et al., 2009; Zhang et al., 2010; Fu et al., 2012). Recently, researchers have started estimating ship emissions based on automatic identification system (AIS) data (Ng et al., 2013; Fan et al., 2016). The impact of ship emission on atmospheric environment has also attracted recently an increasing level of attention (Liu et al., 2011; Yau et al., 2012; Zhao et al., 2013; Ye et al., 2014).

The aim of this work was to comprehensively review and summarize the studies reporting on all the relevant aspects of shipping emissions and their impacts on air quality in China. The scope of the review included ship engine emissions and control, ship emission factors and their measurements, building of ship emission inventories, shipping and port emissions of the main shipping areas in China, and contribution of shipping emissions to local and regional air pollution.

2. An overview of China's shipping and ports

China has >400 ports and is divided into 5 major port clusters, of which Pearl River, Yangtze River, and Bohai gulf port cluster are the largest and of most significant impacts (Fig. 1). China's waterway infrastructure construction has accelerated over the past years. The number of production berths of Chinese ports reached 31,259, of which 2221 were 10,000-ton-and-above berths. By the end of 2015, there were 169.5 thousands of transport ships across the country, with an aggregate tonnage of 272.4429 million DWT. China's waterway cargo transport volume amounted to 6.136 billion tons, and its waterway cargo turnover and container cargo volume reached 9.177245 trillion ton-km and 211.56 million TEU in 2015, up 146.7%, 65.4% and 126% from that in 2006, respectively (Fig. 2).

Cargo throughputs of major ports in Pearl River Delta (PRD), Yangtze River Delta (YRD) and Bohai-Rim area accounted for 7.9%, 28.6% and 18.9%, respectively, of that in national major coastal and inland river ports (MOT, 2014). For container throughputs, PRD, YRD and Bohai gulf hold 24.7%, 31.1% and 16.5%, respectively, of the national container throughputs of major ports in China (MOT, 2014).

3. Ship emission factors and ship emission inventory

3.1. Ship emission factors used in China

Many earlier studies in China used the ship emission factors from foreign references. For example, the emission factors used by Yang et al. (2007) for Shanghai ship emissions were two comprehensive European marine activity studies (Acurex Environmental Corporation,

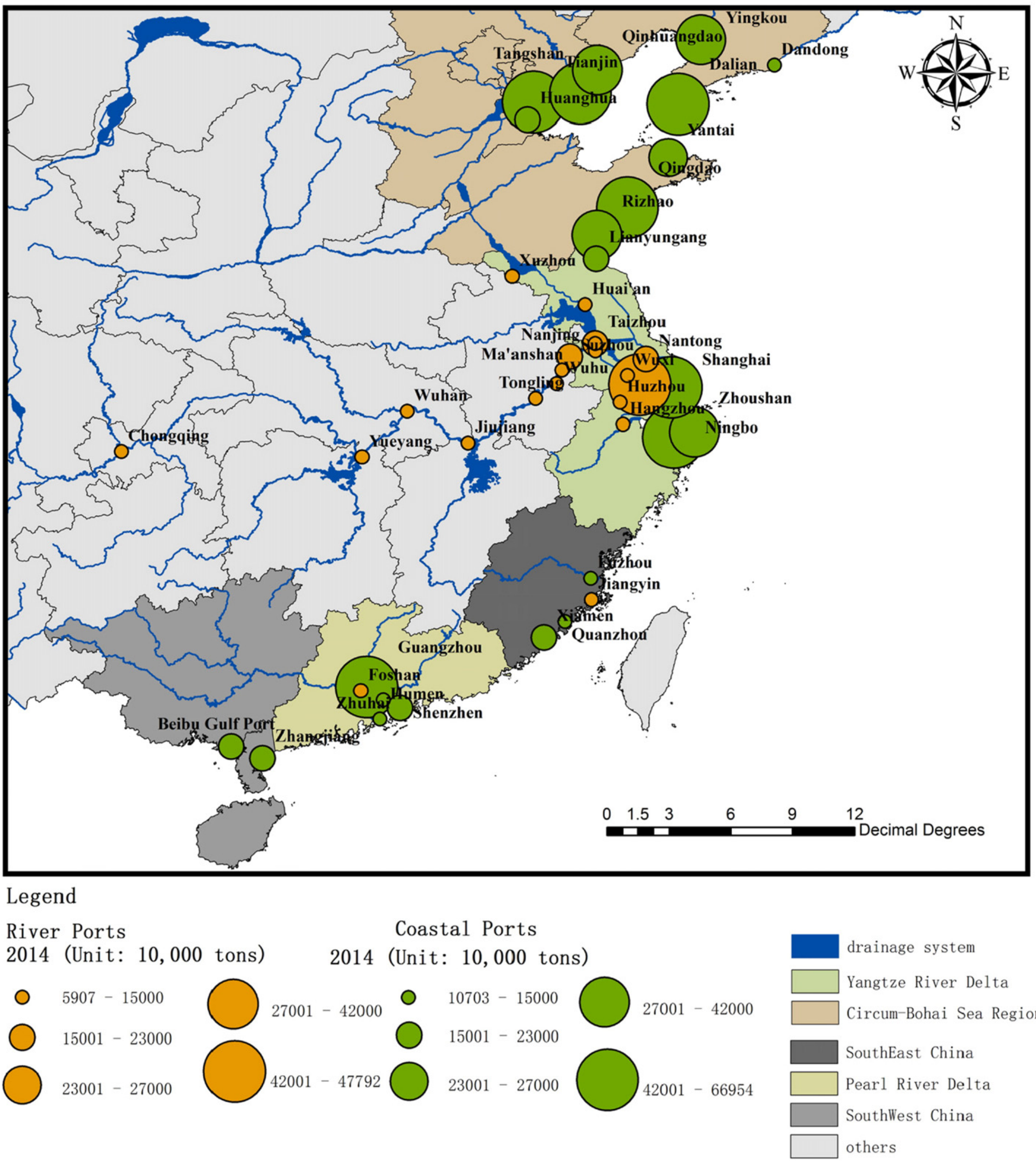


Fig. 1. Geographic positions and cargo throughputs of major coastal and inland ports in China.

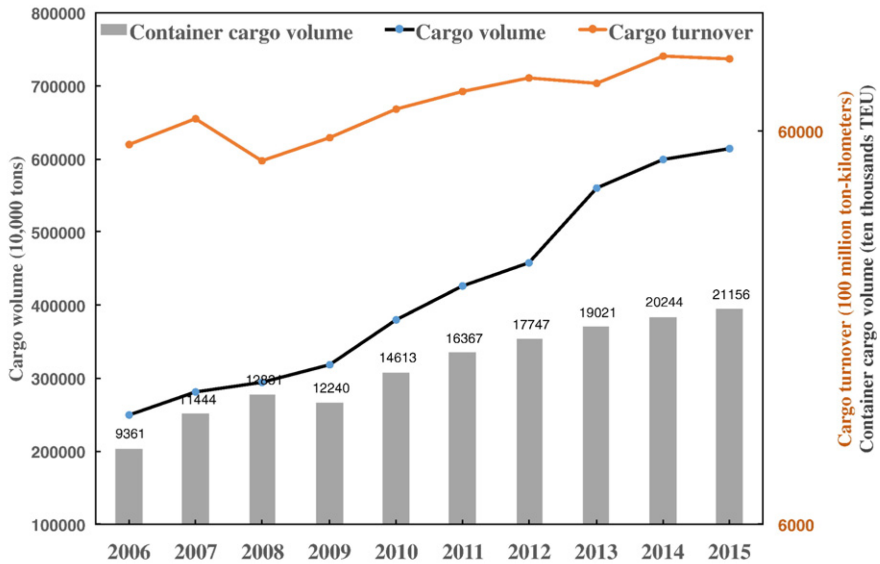


Fig. 2. Aggregate cargo volumes, cargo turnover volume and container cargo volume shipped by vessels in China (2006-2015). (Data source: the report on China's shipping development in 2014, 2015, MOT)

1996; Entec UK Limited, 2002). Except for PM emissions from vessels in internal waterways operating under cruising conditions, the emission factors were taken directly from the Entec UK Limited database (2002). The PM emission factors for vessels in internal waterways operating under cruising conditions were derived from Acurex Environmental Corporation (1996). Ship emission factors used by Fan et al. (2016) for the YRD and the East China Sea were based on the previous comprehensive studies and reports (Cooper and Gustaffson, 2004; ICF, 2009; USEPA, 2007; Goldsworthy and Goldsworthy, 2015). Emission factors used by Yau et al. (2012) for a Hong Kong study were based on a document by USEPA (2000). To summarize, the emission factors used by Chinese researchers are listed in Table 1.

Ye et al. (2014) calculated the NO_x, PM, VOCs and CO ship emissions in PRD based on combination of methods proposed by US ICF's report (2009), USEPA (2007), and Ng et al. (2012), with the equation for emission factors as follows:

$$\mathrm{EF} = \mathrm{a} \times FL^{-\mathrm{x}} + \mathrm{b} \tag{1}$$

where EF is the emission factor (g/kWh), *FL* is the engine loading factor, which is the ratio of the average load at the total capacity, expressed as a function of ship type and traveling mode, in terms of (actual speed / max speed of ship)^3; a, b and x are constants for a specific pollutant.

For calculation of SO_2 emission factor, instead of considering the parameters in Eq. (1), the sulfur content was considered, which leads to a different equation:

$$\mathrm{EF} = \mathrm{a} \times \left[\mathrm{S\%} \times \left(\frac{14.12}{FL} + 205.717\right)\right] + \mathrm{b} \tag{2}$$

where S% is the sulfur content in fuel. Parameters a, b and x are provided by the US Environmental Protection Agency (2000) listed in Table 2.

3.2. Real-time measurement of in-use ship emission

Several studies were conducted recently to measure emission factors based on in-use ships in China. For example, Fu et al. (2013) measured CO, HC NO_x and PM emission from 7 inland ships on the Grand Canal of China and derived distance-based and fuel-based emission factors under different operating modes. In their study, the particulate number size distribution analysis was done, and it was found that larger amounts of small size particle (Dp < 0.01 μm) appeared for maneuvering mode, which can affect regional air quality and human health. Song (2015) developed an emission inventory and researched emission character of inland and offshore ships. In that study, different types of total of 30 ships from different region were investigated, including 8 fishing ships from Dalian offshore, 11 cargos from Beijing-Hangzhou Grand Canal in Nanjing section of Jiangsu province, 3 containers and 1 tug from the Yangtze River Basin in Nanjing, 4 cargos and 2 passenger ships from the Pearl River in Guangdong, as well as a Yangtze River cruise from Yichang to Chongqing section. The engine power of fishing ships from Dalian to Dandong was either 260 kW or 330 kW. The engine power of cargos in Jiangsu province ranged from 88.3 to 300 kW. The engine powers were 214 kW and 230 kW for two passenger ships in Guangdong, respectively. There were two main engines for cargos, with power ranging from 960 to1350kW. For the containers and cruise in Yangtze River Basin, there were two main engines and two auxiliary engines on each ship, with the main engine power ranging from 880 to1620 kW.

Table 1
Emission factors used by Chinese researchers (g/kWh).

Vessel type	Main engine				Auxiliary engine				Reference
	NO_x	SO_2	PM	HC	NO_x	SO_2	PM	HC	
International vessels	7.4–14.3	10.8–13.5	2.1–2.3	0.9–1.7					Yang et al. (2003), referenced from Acurex Environmental Corporation, 1996; Entec UK Limited, 2002.
Coastal vessels	10.6–14.3	10.8–12.9	2.1–2.4	1.2–1.7	14.7	12.3	0.8	0.4	
Vessels ≥1000 ton DWT	13.3–13.8	12.0–12.1	1.5	0.9–1.5					
Ocean going/offshore	12.7–18.1	10.3–11.3	0.7–1.4	0.2–0.3	13.9	2.12	0.3	0.2	Fan et al. (2016), referenced from Cooper and Gustaffson, 2004; ICF, 2009; USEPA, 2007; Goldsworthy and Goldsworthy, 2015.
Ocean going/offshore	13.2–18.1	2.0–10.3	0.3–1.4	0.4–0.6	14–17.7	2.1–12.0	0.3–1.4	0.4	Yau et al. (2012), referenced from ICF, 2009, USEPA, 2007, and Ng et al., 2012.

Table 2
The constants used for emission factor calculations in Eqs. (1) and (2).

Emissions	a	x	b
SO_2	2.3735	–	0
NO_x	0.1255	1.5	10.4496
CO	0.8378	1	0
PM	0.0059	1.5	0.2551
HC	0.0667	1.5	0

Lou et al. (2016) measured exhaust emissions from inland ship in Suzhou River in Shanghai, China. They have compared particle number, CO, total HC, and NO_x from ship engines operating on pure diesel and the mixture of diesel and biodiesel. Zhang et al. (2016) measured exhaust from three different diesel-engine-powered offshore vessels in China (350, 600 and 1600 kW). They found that the emission factors for CO, NO_x, total VOC, and PM were higher for the low-engine-power than for the two higher-engine-power vessels. The emission factors of CO, HC, NO_x and PM were calculated and compared with the Moldanová et al.'s (2009) and Sinha et al.'s (2003) results, as shown in Table 3. Based on the testing results, the EFs of CO, NO_x, and PM from inland ships and offshore vessels in China are much higher than those reported in studies outside China.

In summary, these studies showed the significant influence of engine type on ship emissions. Knowledge of emission factors is critical to develop the ship emission inventories. But there are still some disparities between the local emission factors available from experimental studies. The available measured emission factors in China are usually higher than the reference values used in making emission inventory. But the number of sample ships for emission factors measurements in China is usually limited, therefore the representatively is questionable and should be improved before its wide application. More systematic local emission factors measurement data for different types of vessels in China are urgently needed to improve the shipping emission inventories in China.

3.3. Building ship emission inventory

The method of building ship emission inventories can be categorized as "top-down" and "bottom-up" approaches (Paxian et al., 2010; Miola and Ciuffo, 2011). Top-down emission inventories are calculated without considering the location of each vessel, and can be built statistically according to the spatial proxies of emission intensity. Bottom-up approaches are generally more accurate than the top-down ones, and rely on estimating the emissions based on ship movements and ship attributes, including ship type, speed, and engine power directly. Vessel visa data-based and an automatic identification system (AIS)-based, or others methods are used for building ship emission inventories.

3.3.1. Vessel visa data

Vessel visa refers to the maritime administrative licensing act for the vessels and vessel operators. The vessel visa data is information of vessels' entering into or departing from the port. A vessel visa data-based approach was used for the ship emission inventory estimation in Shanghai, Qingdao, Shenzhen, and the PRD (Yang et al., 2007; Fu et al., 2012; Liu et al., 2011; Zhang et al., 2010; Ye et al., 2014; Yang et al., 2015) in China.

Based on vessel visa data, Yang et al. (2007) estimated an emission inventory for marine ships in the Shanghai port in 2003 that took into account the various types of marine vessels under cruising, maneuvering, and hoteling conditions. They estimated marine emissions as annual activity rates multiplied by emission factors, based on vessel visa data. Emissions were allocated to 1 km × 1 km grid cells for the 129 km × 102 km Shanghai port study domain. Fu et al. (2012) updated the ship emission inventory in Shanghai to 2011 and the authors further increased the spatial distribution of gridded ship emission into routes defined by one-month AIS activity data.

Liu et al. (2011) established the sea traffic emission inventory based on vessel visa data, and its scope involved all ports along Qingdao coast, giving priority to pollutant discharge from in port and shipping lines, with the shipping lines divided into 20 routes.

Zhang et al. (2010) developed a regional non-road mobile source emission inventory for PRD based on the collected activity data and emission factors developed for PRD. This was done by categories with the use of appropriate estimation methods for different non-road mobile sources. The study developed ship emission inventory excluding fishing boat based on the vessel visa data, using fuel consumption-based method. Ye et al. (2014) utilized activity-based and fuel-based approaches to develop a marine emission inventory for 2010, including fishing boats in Guangdong Province, based on the vessel visa data. The inventory's temporal and spatial characteristics were investigated by analyzing passenger and cargo transportation flow and throughput, airway traffic capacity factors, as well as geographic coordinates of ports. Yang et al. (2015) used activity-based and fuel-based approaches to develop a marine emission inventory for 2010 for Shenzhen's port, based on the vessel visa data, using the vessels files from the Lloyd's register of shipping (LR) and vessel track data from the AIS to grid them into the routes.

Ye et al. (2014) studied the characteristics of marine vessel emissions and their effects on regional air quality in the PRD region. The emission inventories of passenger ships, cargo vessels and fishing boats in Guangdong Province were developed and the overall characteristics of marine emissions, along with the problems existing in inventory compilation, temporal allocation and spatial distribution were identified. The information on ships was obtained from the database of Lloyd's Register and from the documents of 482 ocean-going and offshore vessels which were surveyed. The engine power of the

Table 3
Emission factors (g/kWh) for different types of ships reported in literature.

Ship name, type of vessel or engine	Operating condition	CO	HC	NO_x	PM	Reference
Cargo vessel	Cruise	2.17	0.36	73.4	5.3	Moldanová et al., 2009
–	Entire voyage	51.7	5.4	75	7.2	Song, 2015
–	Cruise	23	3.9	86.3	3.7	
Haohai 0007	–	30.2	–	115	9.4	Zhang et al., 2016
Dongfanghong 2	–	6.93	–	35.7	0.72	
Xiangyanghong 08	–	9.2	–	31.6	0.16	
Commercial vessel	–	7–16	–	60–87	–	Williams et al., 2009
Diesel engine	–	7.4	–	87	7.6	Haglind, 2008
Ocean-going ships	–	19.5	–	22.3	–	Sinha et al., 2003
Ocean-going ships	–	3.0	–	65.5	–	Sinha et al., 2003
Cargo and passenger ships	–	7.4	–	57–87	1.2–7.6	Endresen et al., 2003
Ships operating in harbor areas	–	–	–	65–86	–	Pirjola et al., 2014
	–	–	–	25–79	–	
Ships operating in port	–	–	–	53	–	Diesch et al., 2013

investigated ships ranged from 2290 to 64,898 kW. By using the emission inventory estimation method provided in the US Environmental Protection Agency handbook (USEPA, 2000), the emission factors for Guangdong and Hong Kong vessels were calculated considering the vessels' DWT, engine power, operating characteristics and activity time under the different operating modes.

In earlier studies, yearly vessel visa data were most commonly used to obtain information on ship activities on the main shipping routes. But it was not possible to identify the detailed tracks of ships, which limited the temporal and spatial description of ship emissions. Also, the ship visa data covers only the ships entering into the port, which could not include the ships passing by the port area.

3.3.2. Automatic identification system (AIS) activity data

For safety, the International Maritime Organization (IMO) has introduced a requirement on international ships that are >300 GT, to carry an automatic identification system (AIS) and to regularly report information such as their call numbers, location, speed and navigation status via radio (Jalkanen et al., 2009; Petzold et al., 2011; MARIN, 2010; MARIN, 2011). Consequently, establishing an inventory based on single-ship activity is now possible and will greatly improve the spatial and temporal resolution of ship emission inventories. Thus the establishment of a ship emission inventory has undergone a revolutionary change.

Jalkanen et al. (2009) established the first ship emission inventory, which was based on AIS data from the Baltic Sea. The inventory included NO_x, SO_x and CO_2 emissions inventories for that port cluster area, and it was later expanded to cover PM and CO emissions in 2012 (Jalkanen et al., 2012). The work on building ship emission inventories in China, based on AIS data has focused on the ports of Dalian, Shenzhen, Hong Kong, the PRD, Yangshan, the YRD, and the Bohai-Rim area (Tan et al., 2014; Yau et al., 2012; Ng et al., 2013; Song, 2014; Fan et al., 2016; Song, 2015).

Based on parameters such as speed, sailing time and geographical information obtained from the AIS and the activity-based approach, Tan et al. (2014) developed an emission inventory of ocean-going vessels (OGV) for the Dalian coastal area for 2012. They chose the AIS data from September 1st to 20th of 2012 as basic data to estimate ship emission inventory. Yau et al. (2012) developed a detailed maritime emission inventory of ocean-going vessels (OGVs) in Hong Kong with the base year of 2007. The high-resolution vessel speed profiles determined using the AIS during 2009 were adopted for the speed data in the estimations. Ng et al. (2013) established a ship emission inventory for Hong Kong based on the AIS data, and the authors are now trying to extend its spatial scale to the PRD region. For the first time in China, the study used the AIS data to determine typical main engine load factors through vessel speed and operation mode characteristics. Song (2014) estimated both the in-port ship emissions inventory and the emissions associated with the economic cost in Yangshan port of Shanghai. A sophisticated activity-based methodology, supported by the ship-by-ship and real-time data from the AIS, was introduced to obtain accurate estimates of ship emissions. Fan et al. (2016) reported the first high-resolution (1 km × 1 km) regional-scale ship emission inventory for YRD port cluster and East China Sea. They built an AIS-based model to estimate the ship exhaust emissions for these two regions within 400 km of the coastline. The emission inventories for Tianjin port, as well as Circum-Bohai Sea Region were established by Song (2015), Chen et al. (2016) and Xing et al. (2016), based on parameters from the AIS and the activity-based approach.

Besides the above vessel visa data-based and the AIS-related methods, some other methods have been used in estimating ship emission inventories. Jin et al. (2009) estimated ship emissions for the Tianjin harbor for 2006 based on fuel consumption. They firstly chose suitable emission factors according to the vessel power, and then multiplied the emission factors by the ships' fuel consumption. The fuel consumption was determined by the cargo throughput of the port and the distance of the cargo transportation. Li and He (2011) studied the relationship between ship information and the ship emission inventory, and estimated SO_2 emissions for the Shenzhen port for 2003 based on detailed Hong Kong's ship information, emission inventory, and Shenzhen ship information.

In summary, in all methods, AIS-data-based one has recently been used for building ship emission inventories for some ports in China, and this method showed many merits in terms of high spatial and temporal resolution. However, there are still some problems that need to be resolved in future. Firstly, the availability of AIS data for different ship types is limited, as some ships, like inland ships or marine fishing ships, are not set up with AIS instruments. So the ship activities from AIS recording should be verified with the real world ship registering data. Also, when estimating the emissions of the ships with AIS, the common protocols should be established for processing of AIS data, so that ship emission inventories for different ports could be comparable with each other. With the better understanding of AIS data in China, more comprehensive methods are expected to be developed for more accurate emission inventory of shipping.

4. Overview of shipping and port emissions in China

There are many studies that reported ship and ship-related emissions in ports in China. Based on the previous studies, the ship emissions in ports and coastal regions in PRD, YRD, Bohai-Rim area and other regions have been combined in Table 4 and Fig. 3.

4.1. Pearl River Delta (PRD)

The PRD Region with densely distributed waterway network and ports has been one of the most prosperous marine trading areas in Guangdong Province. The PRD coastal port cluster is composed of >14 ports, including ports of Guangzhou, Shenzhen, Zhanjiang, Zhuhai, Shantou, Chaoshan, Jieyang, Shanwei, Huizhou, Humen, Zhongshan, Jiangmen, Yangjiang, and Maoming (Fig. 1).

Since Hong Kong and Shenzhen ports are the PRD's most significant port clusters, many studies have developed ship emission inventories for these areas (Fig. 3). Hong Kong Civic Exchange, Hong Kong Environmental Protection Department (EPD) and the Hong Kong universities also focused on ship emissions (Civic Exchange, 2009, 2010, 2012). In 2007, Hong Kong EPD developed an emission inventory of all ocean-going vessels on Hong Kong waters. During this process, Hong Kong University of Science and Technology used the AIS to gain the ship activity information with high resolution, and developed a high-accuracy gridding ship emission inventory. In order to further estimate the effect of ship emissions on the air quality near ports, using the *Pollutants in the Atmosphere and their Transport over Hong Kong* model (PATH). Ng et al. (2013) developed an exhaust emission inventory of OGVs for Hong Kong, with the results indicating that in 2007, container vessels contributed about 80%–82% of the emissions. The top five types of emitting ships, including ocean cruise, oil tanker, conventional cargo vessels and dry bulk carrier, accounted for about 98% of total emissions.

Yau et al. (2012) estimated the total emissions of NO_x, SO_2 and PM_{10} from 37,150 ship voyages of OGVs in 2007 in Hong Kong, respectively. The contribution of ship emissions during transiting was 60–68% of air pollutants' concentrations. The shipping route along the East Lamma Channel and the berthing location of the Kwai Chung and Tsing Yi Container Port comprised the regions with the highest emissions. The OGV emissions in Hong Kong contributed 0.05-0.07% out of the global total shipping emissions of NO_x, SO_2, and PM_{10} in 2007.

Li and He (2011) estimated ship emission inventory in 2003 for Shenzhen port. The results showed that the ship emissions of SO_2 were more than half of emissions from all the moving sources. Yang et al. (2015) reported the total emissions of SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$ and VOCs for 2010 of marine vessels in Shenzhen City.

Table 4
Ship emission in ports in China reported in literature.

Region	Port name	Air pollutants emission (unit: 10 thousand tons/year)						Study area	Methods and data	Base year	Reference
		SO_x	NO_x	CO	HC	$PM_{2.5}$	PM_{10}				
PRD	Hong Kong port	1.71	0.82	/	/	/	0.10	3216 km∗km	Power data based, AIS	2007	Yau et al., 2012
		1.24	1.45	0.14	/	/	0.14	3216 km∗km	Power data based, AIS	2007	Ng et al., 2013
	Shenzhen port	0.16	0.67	0.07	0.01	0.02	0.02	/	Port throughout based, using the referenced regression relationships	2003	Li and He, 2011 (in Chinese)
		1.36	2.33	0.22	/	0.17	0.22	113.6°E–114.5°E;22.1°N	Fuel + power data based, visa data	2010	Yang et al., 2015
	Guangdong Province	14.6	23.1	3	/	0.72	0.79	/	Fuel + power data based, visa data	2010	Ye et al., 2014 (In Chinese)
	PRD port cluster	6.29	9.16	1.05	/	/	0.23	/	Fuel + power data based, visa data	2006	Zhang et al., 2010. (In Chinese)
YRD	Shanghai port	5.12	5.82	/	0.46	/	/	13,158 km∗km	Fuel + power data based, visa data	2003	Yang et al., 2007
		3.54	5.73	0.49	0.21	0.37	0.46	24,336 km∗km	Power data based, visa data	2010	Fu et al., 2012 (in Chinese)
		8.16	15.18	0.71	/	1.14	1.23	24,336 km∗km	Power data based, AIS	2010	Fan et al., 2016
	Yangshan port	0.56	1.08	0.11	0.05	0.09	0.11	/	Power data based, AIS	2009	Song, 2015
	YRD port cluster	38	71	2.9	/	5.1	5.7	368,562 km∗km	Power data based, AIS	2010	Fan et al., 2016
Bohai-Rim area	Tianjin port	/	0.43	0.07	0.02	/	0.02	/	fuel consumption, cargo throughput of port	2006	Jin et al., 2009. (In Chinese)
		2.93	4.13	0.36	0.17	0.37	0.4	117.35°E–118.34°E; 38.46°N–39.24°N	Power data based, AIS	2014	Chen et al., 2016
		0.41	0.46	0.04	0.01	/	0.05	/	Power data based, AIS	2014	Xing et al., 2016 (In Chinese)
		6.05	7.27	0.57	0.24	0.49	0.54	/	Power data based, AIS	2013	Song, 2015. (In Chinese)
	Tangshan port	7.97	11.22	0.87	0.36	0.70	0.76	/			
	Qinhuangdao port	6.44	8.63	0.67	0.28	0.55	0.60	/			
	Huanghua port	2.63	3.46	0.27	0.11	0.23	0.25	/			
	Bohai gulf	23.09	30.58	4.79	0.99	1.97	2.15	/			
	Bohai gulf	12.07	17.38	1.44	0.61	/	1.53	/	Power data based, AIS	2014	Xing et al., 2016 (In Chinese)
Others	Qingdao port	0.52	/	/	/	/	/	/	Power data based, visa data	2004	Liu et al., 2011. (In Chinese)
	National inland river	/	81	17	4.3	/	3.6	/	Fuel data based	2010	Ye and Ge, 2013 (In Chinese)

Lu et al. (2013) characterized the emission trends of, and variations in source contributions to SO_2, NO_x, PM_{10} and VOCs in the PRD from 2000 to 2009. The results showed that non-road mobile sources were becoming an important SO_2 and NO_x contributor in this region. Zhang et al. (2010) reported that emissions from marine sources are the largest non-road mobile sources in the PRD region, accounting for 40–94% of the above listed pollutants. Ye et al. (2014) also estimated the total emissions of SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$ and VOCs from marine vessels in Guangdong Province. Emissions from passenger and cargo vessels were distributed mainly along the Xijiang River and within the high-level waterways of the PRD, while emissions in ports were concentrated in the coastal cities.

4.2. Yangtze River Delta (YRD)

The YRD region, including Shanghai, Jiangsu, and Zhejiang, is the core economic zone of China and also the confluence of the coastal shipping routes and inland water transportation on the Yangtze River. The YRD coastal port cluster is composed of >15 ports, including ports of Shanghai, Ningbo-ZhouShan, Zhenjiang, Nantong, Lianyungang, Taizhou, and Wenzhou (Fig. 1).

As the center of the YRD port cluster, Shanghai and Ningbo-Zhoushan have served as the largest two container ports in the world since 2013. Many studies about this region mainly focused on Shanghai port (Fig. 3). Yang et al. (2007) reported an air pollutant emission inventory for marine vessels in the Shanghai port in 2003. Emissions are allocated to 1 km × 1 km grid cells for the 129 km × 102 km study domain. Emissions of vessels under cruising and maneuvering conditions in the Outer Port and internal waterways were estimated. Total marine emissions of NO_x, SO_2, PM, HC, and CO_2 in 2003 were estimated. Fu et al. (2012) determined the total amounts of SO_2, NO_x, and $PM_{2.5}$ in the vicinity of Shanghai port in 2010. Song (2014) estimated both the in-port ship emissions inventory (CO_2, CH_4, N_2O, PM_{10}, $PM_{2.5}$, NO_x, SO_x, CO, and HC) in Yangshan port as a subport of Shanghai port. Fan et al. (2016) estimated the ship exhaust emissions in the YRD and the East China Sea within 400 km of the coastline. Within the same geographic area of Shanghai port in Fu's study, Fan's estimation of the emissions of SO_2, NO_x, and $PM_{2.5}$ surrounding Shanghai port were 2.3 times, 2.6 times and 3.0 times greater than Fu's estimation without considering the passing-by ships. That also implied the importance of the passing-by ships for completeness of the inventory.

4.3. Bohai-Rim area and other regions

Bohai-Rim area is the economical center of North China including Beijing, Tianjin, Hebei province, Shandong province and Liaoning province. There are several large coastal ports in this area, including Tianjin, Dalian, Tangshan, Yantai and other ports (Fig. 1). Jin et al. (2009) estimated the ship emissions including NO_x, HC, CO, and PM_{10} in Tianjin port in 2006, and predicted the ship emissions in 2010 and 2020, which provided the basic data for proposing the local emission regulations. Song (2015) estimated the ship emission of PM_{10}, $PM_{2.5}$, NO_x, SO_x, CO, HC, and CO_2 for ports located in Bohai-Rim area such as ports of Tianjin, Tangshan, Qinhuangdao and Huanghua in 2013. Tan et al. (2014) developed an emission inventory of ocean-going vessels (OGVs) in the Dalian coastal area in 2012.It was shown that about 75%

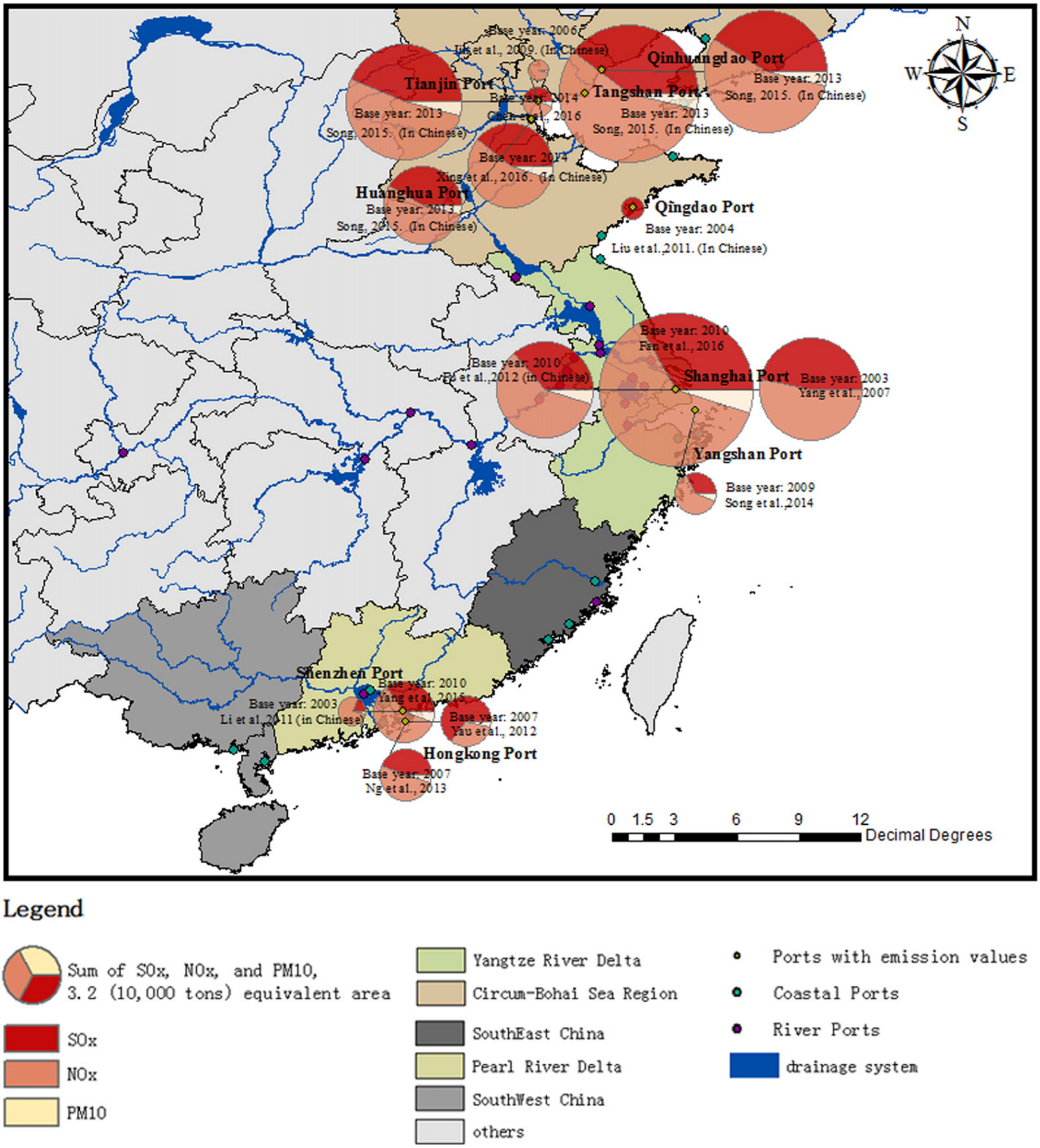


Fig. 3. Ship emissions of ports from studies in China. The ship emission values of SO_x, NO_x and PM_{10} in ports in China are from Table 4. Ship emissions in Tianjin port are from Jin et al. (2009), Song (2015), Chen et al. (2016), and Xing et al. (2016); ship emissions in Tangshan port, Qinhuangdao port, and Huanghua port are from Song (2015). Ship emissions in Qingdao port are from Liu et al. (2011). Ship emissions in Shanghai port are from Yang et al. (2007), Fu et al. (2013), and Fan et al. (2016). Ship emissions in Hong Kong port are from Ng et al. (2013), Yau et al. (2012). Ship emissions in Shenzhen port are from Li and He (2011) and Yang et al. (2015).

of emissions were emitted during berth hoteling, and that there were slight differences between vessels and pollutants. The spatial distribution of emissions in the port area was the densest. The four ship types: dry bulk carrier, container, cruise and oil tanker are dominant in emissions. The main engine was the major emission source, for container and RORO (RO IN RO OUT) ship, accounting for 90. 0% of the total emissions were from the main engine, while over 40.0% of the emissions of general cargo and cruise were from the auxiliary engine. Chen et al. (2016) built the ship emission inventory for Tianjin port in 2014 and found that the container ships and dry bulk cargo ships accounted for 70% of the total ship emission. Xing et al. (2016) estimated the total ship emission of SO_2, NO_x, CO, HC and PM in the whole Bohai Sea area.

There are some studies for other ports than PRD, YRD and Bohai-Rim area, and in particular, Fu et al. (2005) estimated the CO, HC, NO_x and PM from China's inland river ships in 2002, and Liu et al. (2011) developed the ship emission inventory for Qingdao.

In summary, ship emissions have been estimated for major ports in PRD, YRD, Bohai-Rim area port clusters. But there are big differences existing in the ship emissions reported for the same port, such as Tianjin and Shanghai port. Although the datasets are very different, the differences in the results are due to several other reasons like the calculation method, data sources and other variables (e.g. sulfur contents, emission factors).

5. Contribution of ship emission to local and regional air pollution in China

There are a few studies on contribution of ship emissions to urban pollution in China and they are based either on measurements or simulation. Some field measurements have been conducted near ports or in urban area to identify the contribution from ship traffic emission. Other studies are based on air pollution simulations based on ship emission inventory. Based on the previous studies, contribution of ship emissions to urban pollution in PRD, YRD, Bohai-Rim area and other regions have been combined in Table 5.

5.1. PRD

Yu et al. (2004) reviewed measurements of EC and OC from monitoring stations in Hong Kong. They noted that the EC levels at the stations to the north of the container port presented a seasonal trends, with concentrations higher in the summer than in the winter due to being downwind of ship emissions in the summer. They revealed that ship emissions at the port are important contributors to EC loadings in the air in Hong Kong. Yau et al. (2012) estimated exhaust emissions from on-going vessels in 2007 in Hong Kong, which demonstrated that these emissions accounted for 17%, 11% and 16% of the total Hong Kong emissions of NO_x, SO_2 and PM_{10}. As a follow up, Yau et al. (2013) studied the impact of ship emissions on the PM levels of the portside residential areas in Hong Kong. By using *Positive Matrix Factorization* (PMF) analysis, eight potential sources were identified. Residual oil (RO) combustion and marine diesel oil (MDO) were two of the sources, defined as ship emissions, which accounts for 12% and 7% of $PM_{2.5}$ respectively. The total contribution from ship emissions to ambient $PM_{2.5}$ mass at the sampling site was about 25%. Thus the result indicated that ship emissions influence to a large extent the ambient fine particle matter levels in portside areas. Kwok et al. (2012) applied the Tagged Species Source Apportionment (TSSA) algorithm in Community Multiscale Air Quality (CMAQ) model to study contributions from different sources to PM sulfates, SO_2 and EC in 2004 in Hong Kong by. They found that the vessels in the surrounding water area can contribute 8– 56% to the sulfate concentration in the city center. Ye (2014) used CMAQ to simulate the impact of ship emissions on air quality in PRD area. The result showed that ship emission increased the concentration of PM_{10}, NO_2 and SO_2, and were linked to the decrease in the O_3 concentration of in most of the PDR area. Yuan et al. (2006) applied two receptor models named Unmix and PMF to identify the sources of PM_{10}, of which concentration measurements were carried out in Hong Kong between 1998 and 2002. The study showed that the ships in and around Hong Kong contributed V, Ni, and sulfate to PM_{10} concentration.

5.2. YRD

Zhao et al. (2013) monitored SO_2, NO_2 and O_3 and collected aerosol samples of TSP, $PM_{2.5}$ and size-segregated particles in Yangshan Port of Shanghai. Elements' testing was conducted in the samples and in residual oil, including: V, Ni, Al, Fe, Si, Ca, Na, Mg, Mn, Zn, Co, Cr. According to the results, the contribution of ship emission to aerosol in Yangshan port is about 4%, and 64% of the primary $PM_{2.5}$ emitted by ships in the Shanghai port is transmitted to the inland area. The study also found that the air pollution level in Yangshan port is similar to this inland, and that the peaks of ship-related pollutant concentrations are far more than the average concentration inland because of the ship emissions. Furthermore, the authors applied back trajectory analysis in HYSPLIT model, which revealed that ship traffic was responsible for SO_2, NO_2 and V mainly under the costal airflows. Fu et al. (2014) collected $PM_{2.5}$ particles in spring in 2011 in Shanghai and studied the V/Fe ratio, to show that the bioavailable Fe could be perturbed heavily by ship emission in this region.

According to Fu et al. (2013) study, the contributions of ship traffic emissions to SO_2, NO_x and $PM_{2.5}$ concentrations in Shanghai are 12.0%, 9.0% and 5.3%, respectively. Fan et al. (2016) estimated ship emissions and found that they accounted for 15%, 14% and 4% of the total anthropogenic SO_2, NO_x and $PM_{2.5}$ emissions in YRD and the East China Sea. They applied forward trajectory analysis to six high emission areas in YRD to study the potential impact of ship emission to the surrounding atmospheric environment. The result showed that 20-50% of airflow from ship emission hot spots are transported to YRD inland, that the offshore area are affected significantly, and that the ship emissions have a larger impact on atmospheric environment in YRD in the summer than in the winter.

5.3. Bohai-Rim area and other regions

Zhang et al. (2014) have collected ambient air samples at Tuoji Island in Bohai Sea strait, the analyses of which, together with back trajectory air mass analysis, showed that V is a good tracer of shipping emissions at Tuoji Island. The annual average primary $PM_{2.5}$ contributed

Table 5
Contributions of ship emission to air quality of ports and cities in China reported in literature.

Region	City/port name	Contribution of ship emissions (%)					Methods and data	Period	Reference
		SO_2	NO_x	$PM_{2.5}$	PM_{10}	Sulfate			
PRD	Hong Kong	11	17	/	16	/	Emission inventory	2007	Yau et al., 2012
	Kwai Chung and Tsing Yi container terminals	/	/	25	/	/	PMF[a] analysis of aerosol by field measurement	2009.8–2010.3	Yau et al., 2013
	Hong Kong	/	/	/	/	8– 56	TSSA[b] using CMAQ air quality model	2004	Roger et al.,2012
YRD	Yangshan port, Shanghai	/	/	4	/	/	Vanadium as tracer based on field measurement	2011.8	Zhao et al., 2013
	Shanghai	12	9	5.3	/	/	Emission inventory	2010	Fu et al., 2012
Bohai-Rim area and other regions	Tianjin	10	8.6	3.0	2.4	/	Emission inventory	2014	Chen et al., 2016
	Tuoji Island	/	/	2.94	/	/	Vanadium as tracer based on field measurement	2012	Zhang et al., 2014
	Qingdao	8	12.9	/	/	/	A multiple source atmospheric diffusion model	2004	Liu et al., 2011

[a] PMF: Positive Matrix Factorization.
[b] TSSA: Tagged Species Source Apportionment.

by shipping emissions was 0.65 $\mu g \cdot m^{-3}$ at Tuoji Island, accounting for 2.94% of the total primary $PM_{2.5}$, with a maximum of 3.16% in summer and a minimum of 2.39% in autumn. According to a study by Chen et al. (2016), the ship emissions were equivalent to 11%, 9.4% and 3.1% of the non-ship anthropogenic SO_2, NO_x and $PM_{2.5}$, i.e., accounted for 10%, 8.6% and 3% of SO_2, NO_x and $PM_{2.5}$ emitted from total of the anthropogenic sources in Tianjin, respectively.

Liu et al. (2011) used a multiple source atmospheric diffusion model based on GIS to conduct spatial simulations of coastal emission volumes in Qingdao, with the results showing that the contributions of SO_2 and NO_x from ships to the local air pollution were 8% and 12.9% respectively.

In summary, the potential influence of ship emissions in major ports on air quality in China were usually studied by percentages of annual ship emissions in urban or regional emission inventory and episodic field measurements. The systematic long period and short term impact of ship emissions on atmospheric environment need to be addressed in future.

6. Control of ship engine emissions

6.1. Emissions from marine diesel-oil and gas-oil ship engines

In order to meet increasingly stringent emission regulations proposed by the IMO, China's engine manufacturers and researchers have focused attention on the mechanisms of emissions and their control technologies, which resulted in a number of studies reported on this topic.

Hu (2013) studied the effects of exhaust gas recirculation (EGR) on emission characteristics of a medium-speed marine diesel engine by using the GT-Power (Gamma Technologies) simulation model. In order to reduce emissions and keep the brake specific fuel consumption (BSFC) low, the impact of injection timing, injection pressure, intake pressure and Miller timing were investigated. The results showed that under the D2 (ISO 8178) test cycle (for constant-speed auxiliary engines test cycle D2 should be applied), the weighted NO_x emissions of the diesel engine decreased to 1.87 g/kWh, which could meet the IMO Tier III emission legislation. However, the combustion of the diesel engine deteriorated, soot emissions went up, and the weighted BSFC increased by 4.07%. With optimization of injection timing, the injection pressure, the intake pressure and Miller timing led to an increase of NO_x emission.

Lü et al. (2010) studied the effect of diesel quality on particulate matter (PM) and smoke emissions of marine diesel engines. During the experiment, ordinary commercial diesel was used. The results showed that in comparison to the Euro II diesel (European Union Standard EN 590), the ordinary commercial diesel PM and smoke emissions were higher by 28.9%–41.5% and 2.35%–9.32% respectively. The smoke emissions with two types of diesel were almost the same under various operation conditions for an auxiliary engine, but there were noticeable variations at medium and high loads for a main engine.

Sun (2001) investigated the characteristics of water-emulsified fuel and their effect on the emissions of a diesel engine. The results showed that the NO_x emissions and exhaust temperature decreased with the increase of water in the emulsions, but the soot and PM emissions increased when emulsions contained excessive water, and when engine load was low. Wang et al. (2010) constructed simulation models of a diesel engine working process with an electronic-controlled unit pump fuel injection system, by using BOOST and HYDSIM software. Key model components were optimizing the NO_x emission by matching to the combustion system, an electronic-controlled unit pump combining, application of the Miller cycle and injection timing adjustment. An optimized matching scheme was then calibrated by three-dimensional CFD analysis software, considering injection, spray and combustion. The results showed that under an E3 test cycle (MARPOL 73/78) (for propeller-law-operated main and propeller-law-operated auxiliary engines the test cycle E3 should be applied), NO_x emissions can meet the requirement of the IMO Tier II regulation. Yin et al. (2005) studied NO_x emissions of a Wärtsilä W6L20C marine medium diesel engine on a test bench, and showed that the level of emissions changed slightly with speed, when the main engine operated on propeller characteristic within the steady operating zone. A more obvious change in NO_x emissions was observed for different propeller operating conditions due to different ship resistance. Tian (2012) tested the NO_x emissions of a medium-speed marine diesel engine according to the test program recommended by the IMO, and reported that changing only the injection timing can reduce NO_x emissions, but fuel efficiency became worse under such conditions. Yin et al. (2013) tested emissions of a marine medium-speed diesel engine against propulsion characteristics. The results showed that CO emissions were lower and HC emissions higher under the condition of low speed and load, while CO emissions were higher and HC emissions lower under high speed and heavy load. The highest NO_x emissions were at a speed of about 800 rpm and the specific NO_x emission (i.e. per unit of engine work) decreased with the increase in engine speed and load. Yan et al. (2011) researched the effect of nozzle parameters on combustion and emission characteristics of a high-pressure common-rail marine diesel engine, and the combustion process and emissions of a marine diesel engine equipped with three types of nozzles were tested on the bench and calculated using three dimensional CFD software. This research revealed that both spray orifice number, r, and diameter of the nozzle can affect fuel atomization and evaporation, fuel/air mixing and further affect NO_x and soot emissions. Huang et al. (2015) studied the effect of the combustion chamber parameters on the combustion process and emission concentrations of the 4190ZLC-2 marine diesel engine by using AVL FIRE. The results showed that for the smaller throat diameter NO_x emissions were lower, while the soot emissions higher. The smaller the center-crown height, the higher were NO_x emissions and the lower the soot emissions. With increase of bowl bottom radius, the maximum temperature and the pressure in cylinder increases gradually, and bowl bottom radius also had great influence on the emissions of the diesel engine. Yang et al. (2016) measured NO_x, SO_2 and greenhouse gas emissions and showed that fuel consumption when using biodiesel was about 1.4% lower than when using 0# diesel under the rated conditions of 80% load, and that CO emissions were reduced by 17%, and the SO_2 emissions were about 30% lower than those of 0# diesel. Other emissions were almost identical. This terminology corresponds to the 6 types of diesel commonly used in China classified according to their freezing point (temperature), 5#, 0#, −10#, −20#, −35# and −50# diesel oil.

In summary, simulation analysis and experimental tests were most commonly used to study the emission mechanisms and control. The emissions from marine diesel oil/marine gas oil can be controlled by optimizing the configuration of fuel injection system, diesel injection parameters, combustion chamber and Miller timing or using EGR technology. The effects of diesel quality, fuel type, water-emulsified fuels and biodiesel on emissions were studied as well. Some technologies can be used to reduce NO_x emissions, but this can lead to an increase of soot and PM concentration as well as worsened fuel efficiency. Therefore, an optimized or tradeoff scheme should be further researched.

6.2. Emissions from heavy fuel oil engines

Heavy fuel oil used in marine main diesel engines is a residue from crude oil refining and containing a lot of the contaminants removed from the lighter oils. Zhang et al. (2012) simulated the spray, ignition, combustion process, and concentration distribution and its total NO_x emission in a 6S70MC low-speed marine engine under the rated operating mode. The results showed that the pre-mixing combustion occupied a very small percentage of total combustion duration, and basically showed the unimodal diffusion combustion characteristics. Zhang et al. (2011) also studied the combustion and emission of a 7S60MCC low-speed marine diesel engine based on the traditional thermodynamic and Miller cycle. The results showed that the highest temperature at TDC during compression stroke decreased markedly, which led to a decrease of NO_x emissions. Wang et al. (2014) studied the effect of Miller cycle strength on the NO_x emissions of a low-speed diesel engine by using 3-D simulation. The results showed that controlling Miller cycle strength can significantly reduce NO_x emissions, and exhaust valve closes 10°CA lately each, NO_x can be reduced by 6–7%, when the Miller cycle is increased to a certain level. Strengthening the Miller cycle will lead to NO_x emission reduction, fuel economy reduction and the need to use an appropriately matched high performance turbocharger, which will increase the engine cost. Wang et al. (2014) studied the effect of swirl ratio on combustion and emissions of a marine two-stroke diesel engine, based on 3-D simulation. The results showed that within a specific range of swirl ratio ($SR < 9.4$), the increase of swirl ratio led to an increase of NO_x emission. Wang et al. (2015) tested the emissions of a large-scale low-speed two-stroke crosshead common-rail diesel engine with electronic fuel injection according to MARPOL 1973/78 Annex VI, and analyzed the emission characteristics of THC, NO_x, CO_2, CO and O_2 with different engine loads under propulsion characteristic condition. The results showed that the NO_x and CO_2 emissions reduced significantly comparing with those of traditional marine diesel engines.

Heavy fuel engines are widely applied to large inland rivers, coastal and ocean-going ships in China. NO_x, SO_x and PM emissions from heavy fuel engines are far higher than marine diesel oil/marine gas oil engines due to their poor fuel quality. In order to meet increasingly strict regulations proposed by IMO in the future, EGR and SCR technologies are likely to be adopted to reduce NO_x emissions, low-sulfur fuel should be used to reduce SO_x emissions in inland river, coastal and offshore ships. Normally, experimental research on performance and emission characteristics of heavy fuel oil engines was only conducted in industries due to the high cost of experiments, and the large laboratory facilities required. There is therefore very little literature relating to emissions of heavy fuel oil engines in China.

6.3. Emissions from dual fuel engines

In recent years, marine dual fuel engines have been developed by engine manufacturers and increasingly applied to inland river and offshore ships in China. However, current dual fuel engines in China were mainly modified from existing diesel engines, the diesel injection systems are mechanical pumps, and natural gas is supplied into the intake pipe using single-point or multi-point gas injection technologies. Normally, the proportion of gas fuel to total fuels (natural gas and diesel) supplied to cylinders is not >80%. This means that the engine's fuel efficiency and emission performance are not at an optimum. Jing (2011) studied the performance of the dual fuel engine. The results showed that under the same engine load, increasing the ratio of diesel will lead to an increase of NO_x and decrease of CO, especially at low and medium load. With the increase of the advance angle of diesel injection, NO_x emission increased. Zhang (2014) compared the emission characteristics of ship diesel/natural gas dual-fuel engines when the engine operates under the diesel model and dual fuel model. The diesel supply system was the traditional mechanical pump and natural gas was injected into the intake manifold using a multi-point injection system. The results showed that when comparing the diesel model, NO_x and soot emissions were reduced, while HC and CO emissions, as well as exhaust temperature, increased when the engine operated under the dual fuel model. He (2015) created a GT-Power model of marine dual fuel engine and simulated the effect of the natural gas replacement rate, injection timing of diesel on the performance and emissions of the marine dual fuel engine. The results indicated that a higher natural gas replacement rate can improve the fuel economy and NO_x emission can be improved when the injection timing was properly retarded. Long and Wang (2016) conducted an experiment on a modified dual fuel engine based on a Z6170 diesel engine and studied the effect of the natural gas replacement rate on engine economy and emissions. The results showed that with the increase of the natural gas replacement rate, fuel consumption and HC emission increased, and NO_x and CO emission showed different characteristics at higher and lower engine load. Qian (2015) researched the economy and emission performance of the dual fuel engine. A traditional marine engine was converted into a dual fuel engine with a single point of gas intake after the supercharger. In the load characteristics contrast test between the original engine and the dual fuel engine, the results showed that the economy of the dual fuel engine declined slightly, the NO_x emission was at the same level with the original engine, while the HC and CO emissions rose sharply. The simple modification had no advantage over the original engine on economy and emission performance. Yu et al. (2015) studied the effect of different liquefied natural gas gasification temperatures on the performance of marine natural gas/diesel dual fuel engines. According to the propulsion characteristics, the initial conditions used for simulation and emissions were acquired when the engine operated at 25%,50%,75% and 100% load and gasification temperature of Liquid Natural Gas (LNG) was 20 °C. Numerical simulation was adopted to analyze the effects of different LNG gasification temperatures on emissions of the engine. The results showed that decreased LNG gasification temperature can reduce CH_4 and CO_2 emissions. NO emissions reduced by 22%, and soot emissions reduced by 67%.

In China, dual fuel engines are considered to be an effective measure to reduce the dependence on fossil oil and control hazardous emissions from inland river ships, fishing ships and ocean-going ships. However, current dual fuel engines applied in inland river and fishing ships were modified from original diesel engines. The diesel supply systems are by a mechanical pump, so the replacement ratio of diesel oil is no >80%. Although SO_x and PM emissions can be reduced, the NO_x emissions are the same as unmodified diesel engines. At present, high performance dual fuel engines are being developed by many engine manufacturers, which use common-rail diesel injection and single or multipoint gas injection technology. The maximum diesel replacement ratio can be up to 95%, so NO_x, SO_x and PM emissions can be reduced by 90% by using lean burn technology, but a more complex fuel supply system is required, and more sophisticated control strategies will need to be developed.

In summary, while there is a body of studies conducted on various aspects of engine emissions, as well as of fuel used, however, there are still significant gaps in data and knowledge. Further, the existing information has so not been utilized for overall assessment of ship emission control in China, or emission control.

7. Summary

There have been many studies published addressing the ship and port emissions of major coastal ports and routs in China. But the studies on inland ports and river ships are rare. Also, there are few national scale ship emission inventories developed. Advanced method to estimate ship emission based on ship AIS activities makes it now possible to develop high spatial- and temporal-resolution emission inventories. However, the limitations and uncertainties of AIS data application in ship emission inventory should be addressed and verification method should be developed. Also, the ship emission factors used for the inventories were based mainly on foreign experience, and it is urgent to obtain local ship emission factors for China.

There are a number of studies, which focused on the influence of ship activities on local air quality. But, the contribution of ship emissions to air pollution in coastal cities, the dispersion process of ship plume, or the chemical evolution process along the transmission path, have so far not been studied systematically. Further research is necessary to provide scientific basis for regional haze pollution control and guide the future efforts on the Marine Emission Control Area in China.

List of abbreviations

AIS	automatic identification system
BSFC	brake specific fuel consumption
DMP	diesel particulate matter
EGR	exhaust gas recirculation
EPD	Environmental Protection Department
LNG	Liquid Natural Gas
MDO	marine diesel oil
OGVs	ocean-going vessels
PM	particulate matter
PMF	Positive Matrix Factorization
PRD	Pearl River Delta
IMO	International Maritime Organization
RO	residual oil
TDC	top dead center
TSSA	Tagged Species Source Apportionment
YRD	Yangtze River Delta

Acknowledgement

This work was supported by the National Natural Science Foundation of China (21677038, 91544224), the Science and Technology Commission of Shanghai Municipality (15DZ1205404, 14ZR1402800, 14DZ1202900), the Ministry of Science & Technology of China (2012YQ220113-4), the National Key Technology R&D Program of Ministry of Science and Technology of China (2014BAC16B01) and the Ministry of Environmental Protection of China (201409008). The authors are grateful to the Australia-China Centre for Air Quality Science and Management (ACC-AQSM) for helpful discussions in preparing the manuscript. Great thanks are given to Qianzhu Fan and Junlan Feng from Fudan University for their efforts in collecting data and plotting some figures.

References

Acurex Environmental Corporation, 1996. Marine vessel emissions inventory and control strategies. Acurex Environmental Final Report FR-119-96. South Coast Air Quality Management District.

Capaldo, K., Corbett, J.J., Kasibhatla, P., Fischbeck, P., Pandis, S.N., 1999. Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean. Nature 400 (6), 743–746.

Chen, D., Zhao, Y.H., Nelson, P., Li, Y., Wang, X.T., Zhou, Y., Lang, J.L., Guo, X.R., 2016. Estimating ship emissions based on AIS data for port of Tianjin, China. Atmos. Environ. 145, 10–18.

Civic Exchange, 2009. Green Harbours II: Reducing Marine and Port-related Emissions in the Pearl River Delta Region. Civic Exchange, Hong Kong.

Civic Exchange, 2010. Green Harbours II: Greening the Global Supply Chain: Exploring Partnerships to Reduce Marine Emissions in the PRD, Stakeholder Workshop Summary Report. Civic Exchange, Hong Kong.

Civic Exchange, 2012. Research Report of Participation and Decision of Ship Emission Reduction Science in Hong Kong and the Pearl River Delta, Hong Kong.

Cooper, D., Gustaffson, T., 2004. Methodology for Calculating Emissions from Ships: 1. Update of Emission Factors. Swedish Methodology for Environmental Data (SMED).

Corbett, J.J., Fischbeck, P., 1997. Emissions from Ships [J]. Science 278 (278), 823–824.

Diesch, J.-M., Drewnick, F., Klimach, T., Borrmann, S., 2013. Investigation of gaseous and particulate emissions from various marine vessel types measured on the banks of the Elbe in northern Germany. Atmos. Chem. Phys. 13, 3603–3618.

Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S., Berglen, T.F., Gravir, G., 2003. Emission from international sea transportation and environmental impact. J. Geophys. Res. Atmos. 108, 4560.

Entec UK Limited, 2002. Quantification of Emissions From Ships Associated With Ship Movements Between Ports in the European Community, European Commission, DG ENV C1.

Eyring, V., Köhler, H.W., Aardenne, J.V., 2005. Emissions from International Shipping: 1. The last 50 Years [J]. J. Geophys. Res. Atmos. 110, 3928–3950.

Fan, Q., Zhang, Y., Ma, W., Ma, H., Feng, J., Yu, Q., et al., 2016. Spatial and seasonal dynamics of ship emissions over the Yangtze river delta and east China sea and their potential environmental influence. Environ. Sci. Technol. 50, 1322–1329.

Fu, L.X., Cheng, L.L., Nian, G.L., 2005. Atmospheric Environmental Impact Report of Mobile Sources. Tsinghua University, Beijing (in Chinese).

Fu, Q.Y., Shen, Y., Zhang, J., 2012. On the ship pollutant emission inventory in Shanghai port. J. Saf. Environ. 12 (5), 57–64 (in Chinese).

Fu, M.L., Ding, Y., Ge, Y.S., Yu, L.X., Yin, H., Ye, W.T., Liang, B., 2013. Real-world emissions of inland ships on the Grand Canal, China. Atmos. Environ. 81, 222–229.

Fu, H.B., Shang, G.F., Lin, J., et al., 2014. Fractional iron solubility of aerosol particles enhanced by biomass burning and ship emission in Shanghai, east China [J]. Sci. Total Environ. 481 (2), 377–391.

Goldsworthy, L., Goldsworthy, B., 2015. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data – an Australian case study. Environ. Model. Softw. 63, 45–60.

Haglind, F., 2008. A review on the use of gas and steam turbine combined cycles as prime movers for large ships. Part I: background and design. Energy Convers. Manag. 49, 3458–3467.

He, S., 2015. Simulation and Optimization of the Performance and Emissions of Marine Dual Fuel Engine. Shanghai Jiaotong University, Master Thesis (in Chinese).

Hu, B.Z., 2013. The Research of Exhaust Gas Recirculation Effects on Medium Speedmarine Diesel Engine Performance and Emission Characteristics. (master thesis). China Ship Research and Development Academy (in Chinese).

Huang, J.L., Wen, P., Yin, Z.B., et al., 2015. Impact of combustion chamber on combustion process and emissions in 4190 type marine diesel engine. Navigation of China. 38, pp. 23–28 (in Chinese).

Jalkanen, J.P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., Stipa, T., 2009. A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. Atmos. Chem. Phys. 9, 9209–9223.

Jalkanen, J.P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., Stipa, T., 2012. Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. Atmos. Chem. Phys. 12, 2641–2659.

Jin, T.S., Yin, X.G., Jia, X.U., Yang, L., Wei-Hua, G.E., Mei-Ting, J.U., 2009. Air pollutants emission inventory from commercial ships of Tianjin harbor. Mar. Environ. Sci. 28 (6), 623–625 (In Chinese).

Jing, H.G., 2011. Study on Characteristics of Marine Dual Fuel Engine. (Master Thesis). Harbin Engineering University (in Chinese).

Kwok, R., Fung, J.C.H., Lau, A.K.H., et al., 2012. Tracking emission sources of sulfur and elemental carbon in Hong Kong/Pearl River Delta region [J]. J. Atmos. Chem. 69 (69), 1–22.

Lawrence, M.G., Crutzen, P.J., 1999. Influence of NOx emissions from ships on tropospheric photochemistry and climate [J]. Nature 402 (6758), 167–170.

Li, Z.H., He, L., 2011. Study on estimation method of ship emission inventory. Guangxi J. Light Ind. 5, 79–80 (In Chinese).

Liu, J., Wang, J., Song, C.Z., Qin, J.J., 2011. The establishment and application of ship emissions inventory in Qingdao port. Environmental Monitoring in China 27 (3), 50–53 (In Chinese).

Liu, H., Fu, M.L., Jin, X.X., Shang, Y., Shindell, D., Faluvegi, G., Shidell, C., He, K.B., 2016. Health and climate impacts of ocean-going vessels in East Asia. Nat. Clim. Chang. 18:1–5. http://dx.doi.org/10.1038/NCLIMATE3083.

Long, Y.X., Wang, Z.J., 2016. Effort of replacement ratio on the performance of LNG/diesel dual-fuel engine. Internal Combustion Engines, pp. 44–47.

Lou, D.M., Shi, L.H., Hu, Z.Y., Tan, P.Q., 2016. Experimental Study on Emissions Characteristics of Inland Ships Based on Different Fuel Qualities Ship Engineering. 7 pp. 1–6 (In Chinese).

Lü, L., Xu, J.H., Xu, W.Y., 2010. Effect of diesel oil quality on particulate and smoke emissions from marine diesel engine. Chinese Internal Combustion Engine Engineering 31, 44–48 (in Chinese).

Lu, Q., Zheng, J.Y., Ye, S.Q., Shen, X.L., et al., 2013. Emission trends and source characteristics of SO_2, NO_x, PM_{10} and VOCs in the Pearl River Delta region from 2000 to 2009. Atmos. Environ. 76, 11–20.

MARIN, June 2010. Emissions 2008: Netherlands Continental Shelf, Port Areas and OSPAR Region II.

MARIN, April 2011. Emissions 2009: Netherlands Continental Shelf, Port Areas and OSPAR Region II.

MARPOL 1973/78, Annex VI - Regulations for the Prevention of Air Pollution From Ships.

Miola, A., Ciuffo, B., 2011. Estimating air emissions from ships: meta-analysis of modelling approaches and available data sources. Atmos. Environ. 45, 2242–2251.

Moldanová, J., Fridell, E., Popovicheva, O., et al., 2009. Characterisation of particulate matter and gaseous emissions from a large ship diesel engine. Atmos. Environ. 43, 2632–2641.

MOT, 2014. The Report on China's Shipping Development in 2014 (in Chinese).

MOT, 2015. The Statistical Report on China's Traffic in 2015 (in Chinese).

Ng, S.K.W., Lin, C.B., Chan, J.W.M., et al., 2012. Study on Marine Vessels Emission Inventory, Final Report. Hong Kong, The Hong Kong Environmental Protection Department.

Ng, S.K.W., Loh, C., Lin, C., Booth, V., Chan, J.W.M., Yip, A.C.K., Li, Y., Lau, A.K.H., 2013. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. Atmos. Environ. 76, 102–112.

Paxian, A., Eyring, V., Beer, W., Sausen, R., Wright, C., 2010. Present-day and future global bottom-up ship emission inventories including polar routes. Environ. Sci. Technol. 44 (4), 1333–1339.

Petzold, A., Lauer, P., Fritsche, U., Hasselbach, J., Lichtenstern, M., Schlager, H., et al., 2011. Operation of marine diesel engines on biogenic fuels: modification of emissions and resulting climate effects. Environ. Sci. Technol. 45 (24), 10394–10400.

Pirjola, L., Pajunoja, A., Walden, J., Jalkanen, J.-P., Rönkkö, T., Kousa, A., Koskentalo, T., 2014. Mobile measurements of ship emissions in two harbour areas in Finland. Atmos. Meas. Tech. 7, 149–161.

Qian, L.Z., 2015. Experimental analysis of exhaust emissions in a dual-fuel marine engine. Ship Ocean Eng. 44, 141–145.

Sinha, P., Hobbs, P.V., Yokelson, R.J., et al., 2003. Emissions of trace gases and particles from two ships in the southern Atlantic Ocean. Atmos. Environ. 37, 2139–2148.

Song, S., 2014. Ship emissions inventory, social cost and eco-efficiency in shanghai Yangshan port. Atmos. Environ. 82 (1), 288–297.

Song, Y.N., 2015. Research of Emission Inventory and Emission Character of Inland and Offshore Ships. (Master thesis). Beijing Institute of Technology (in Chinese).

State Council of China, 2008. The Document to Promote Shanghai as International Centers of Economics and Shipping.

Sun, P., 2001. An investigation on NO_x and PM emissions of burning water emulsified fuel in a marine diesel engine. J. Internal Combustion Engine 19, 551–556.

Tan, J., Yanan, S., Yunshan, G., Jiaqiang, L., Lan, L., 2014. Emission inventory of ocean-going vessels in Dalian coastal area. Res. Environ. Sci. 27 (12), 1426–1431 (In Chinese).

The United States Environmental Protection Agency (USEPA), 2000,. Analysis of commercial marine vessels emissions and fuel consumption data, EPA420-R-00-002. Air and Radiation.

Tian, Z.B., 2012. Analysis of experiment on reducing the NO_x emission from medium speed marine diesel engine. Ship Ocean Eng. 41, 70–76.

US ICF International, 2009. Current Methodologies in Preparing Mobile Source Port-related Emission Inventories, Final Report.

USEPA, 2007. Draft Regulatory Impact Analysis: Control of Emissions of Air Pollution From Locomotives Engines and Marine Compression Ignition Engines Less Than 30 Litres per Cylinder, EPA 420-D-07-001.

Wang, H.F., Xu, J.X., Wang, X.Q., et al., 2010. Study on NO_x emission performance optimization of medium speed marine diesel engine. Ship Eng. 32, 20–25.

Wang, X.R., Liu, C.P., Yin, Z.F., et al., 2014. Simulation Study on Performance Effect of Miller Cycle on Marine Low-speed Diesel Engine. Ship Eng. 36, 29–33.

Wang, Z.C., Xu, L.P., Zhou, P.L., et al., 2015. Emission characteristic analysis of large-scale low-speed common-rail marine diesel engines with electronic fuel injection. J. Shanghai Maritime Univ. 36, 70–78 (in Chinese).

Williams, E.J., Lerner, B.M., Murphy, P.C., Herndon, S.C., Zahniser, M.S., 2009. Emissions of NO_x, SO_2, CO, and HCHO from commercial marine shipping during Texas air quality study (TexAQS) 2006. J. Geophys. Res. 114, D21306.

Xing, H., Duan, S., Huang, L., Liu, Q., 2016. AIS data-based estimation of emissions from sea-going ships in Bohai Sea areas. China Environ. Sci. 36, 953–960 (in Chinese).

Yan, P., Feng, M.Z., Ping, T., et al., 2011. Simulation research on effect of nozzle parameters on combustion and emissions for HPCR marine diesel engine. Chinese Internal Combustion Engine Engineering 32, 43–47 (in Chinese).

Yang, D., Kwan, S.H., Lu, T., Fu, Q., Cheng, J., Streets, D.G., Wu, Y., Li, J., 2007. An emission inventory of marine vessels in Shanghai in 2003. Environ. Sci. Technol. 41 (15), 5183–5190.

Yang, J., Yin, P.L., Ye, S.Q., Wang, S.S., Zheng, J.Y., Ou, J.M., 2015. Marine emission inventory and its temporal and spatial characteristics in the city of Shenzhen. Huangjing Ke Xue 36 (4), 1217–1226 (In Chinese).

Yang, Z.Y., Wei, H.J., He, X.Z., et al., 2016. Application of biodiesel in a marine diesel engine. J. Harbin Eng. Univ. 37, 71–75 (in Chinese).

Yau, P.S., Lee, S.C., Corbett, J.J., et al., 2012. Estimation of exhaust emission from ocean-going vessels in Hong Kong ☆[J]. Sci. Total Environ. 431 (5), 299–306.

Yau, P.S., Lee, S.C., Cheng, Y., et al., 2013. Contribution of ship emissions to the fine particulate in the community near an international port in Hong Kong [J]. Atmos. Res. 124 (2), 61–72.

Ye, S.Q., 2014. Study of Characteristics of Marine Vessel Emission and its Impact on Regional Air Quality of the Pearl River Delta Region[D]. South China University of Technology Guangzhou, China (In Chinese).

Ye, W.T., Ge, Y.S., 2013. Technical research of emission inventory of diesel engine for inland-waterways vessels in China. Beijing Institute of Technology (Technical Report of Project G1110-14902) (in Chinese).

Ye, S.Q., Zheng, J., Pan, Y., Wang, S., Qing, L.U., Zhong, L., 2014. Marine emission inventory and its temporal and spatial characteristics in Guangdong province. Acta Sci. Circumst. 34 (3), 537–547 (In Chinese).

Yin, Z.B., Li, Z.Q., Sun, P.T., 2005. Experimental investigation on NO_x-emission of a marine medium diesel engine and discussion on NO_x-emission measurement on board. China Sustainable Transportation. 27, pp. 81–84 (in Chinese).

Yin, Z.B., Xue, Y., Ma, H.T., Huang, J.L., 2013. Experimental investigation on emission characteristics of a marine speed diesel engine. Navigation of China. 36, pp. 37–40.

Yu, J.Z., Tung, J.W.T., Wu, A.W.M., et al., 2004. Abundance and seasonal characteristics of elemental and organic carbon in Hong Kong PM_{10} [J]. Atmos. Environ. 38 (10), 1511–1521.

Yu, H.L., Duan, S.L., Sun, P.T., 2015. Effects of LNG gasification temperature on combustion and emission characteristics of marine dual fuel engines. J. Propul. Technol. 36, 1369–1375.

Yuan, Z., Lau, A.K.H., Zhang, H., et al., 2006. Identification and spatiotemporal variations of dominant PM_{10} sources over Hong Kong [J]. Atmos. Environ. 40 (10), 1803–1815.

Zhang, Z.H., 2014. Design of Fuel Injection Control System for Marine Dual Fuel Engine. (Master Thesis). Harbin Engineering University (in Chinese).

Zhang, L.J., Zheng, J.Y., Yin, S.S., Peng, K., Zhong, L.J., 2010. Development of non-road mobile source emission inventory for the pearl river delta region. Environ. Sci. 31 (31), 886–891 (In Chinese).

Zhang, J.J., Wu, C.H., Wang, W., et al., 2011. Experimental study of combustion and emission on low speed marine diesel engine using miller cycle. Railway Locomotive & Car. 31, pp. 280–282.

Zhang, J.J., Wu, C.H., Hu, C.X., et al., 2012. Simulation research on the combustion and emissions of marine low-speed two stroke diesel engine. Diesel Engine. 34, pp. 20–25.

Zhang, F., Chen, Y., Tian, C., Wang, X., Huang, G., Fang, Y., Zong, Z., 2014. Identification and quantification of shipping emissions in Bohai Rim, China. Sci. Total Environ. 497–498C, 570–577.

Zhang, F., Chen, Y.J., Tian, C.G., Lou, D.M., Li, J., Zhang, G., Matthias, V., 2016. Emission factors for gaseous and particulate pollutants from offshore diesel engine vessels in China. Atmos. Chem. Phys. 16 (10), 6319–6334.

Zhao, M., Zhang, Y., Ma, W., et al., 2013. Characteristics and ship traffic source identification of air pollutants in China's largest port [J]. Atmos. Environ. 64, 277–286.