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High-spatiotemporal-resolution ship emission inventory of China based on AIS data in 2014

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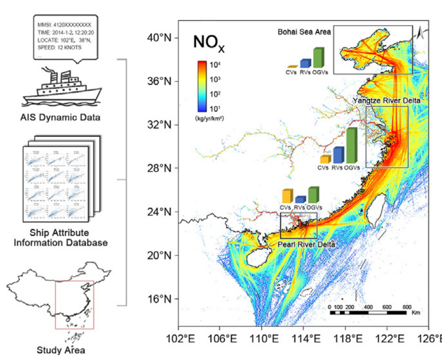
HIGHLIGHTS

- First comprehensive ship emission inventory in China including OGVs, RVs and CVs
- Full year AIS data of >15 billion reports (166,546 vessels) were used for estimation.
- Detailed spatial distribution and monthly variation of ship emissions were presented.
- Emission differences of the major port clusters (BSA, YRD and PRD) were analyzed.
- Emissions for the 24 major ports in China were presented.

GRAPHICAL ABSTRACT



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ABSTRACT

Ship exhaust emissions have been considered a significant source of air pollution, with adverse impacts on the global climate and human health. China, as one of the largest shipping countries, has long been in great need of in-depth analysis of ship emissions. This study for the first time developed a comprehensive national-scale ship emission inventory with 0.005° × 0.005° resolution in China for 2014, using the bottom-up method based on Automatic Identification System (AIS) data of the full year of 2014. The emission estimation involved 166,546 unique vessels observed from over 15 billion AIS reports, covering OGVs (ocean-going vessels), CVs (coastal vessels) and RVs (river vessels). Results show that the total estimated ship emissions for China in 2014 were 1.1937×10^6 t (SO_2), 2.2084×10^6 t (NO_X), 1.807×10^5 t (PM_{10}), 1.665×10^5 t ($PM_{2.5}$), 1.116×10^5 t (HC), 2.419×10^5 t (CO), and 7.843×10^7 t (CO_2, excluding RVs), respectively. OGVs were the main emission contributors, with proportions of 47%–74% of the emission totals for different species. Vessel type with the most emissions was container (~43.6%), followed by bulk carrier (~17.5%), oil tanker (~5.7%) and fishing ship (~4.9%). Monthly variations showed that emissions from transport vessels had a low point in February, while fishing ship presented two emission peaks in May and September. In terms of port clusters, ship emissions in BSA (Bohai Sea Area), YRD (Yangtze River Delta) and PRD (Pearl River Delta) accounted for ~13%, ~28% and ~17%, respectively, of the total emissions in China. On the contrast, the average emission intensities in PRD were the highest, followed by the YRD and BSA regions. The establishment of this high-spatiotemporal-resolution ship emission inventory fills the gap of national-scale ship emission inventory of China, and the corresponding ship emission characteristics are expected to provide certain reference significance for the management and control of the ship emissions.

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1. Introduction

Emissions from ships have been recognized as a significant contributor to the atmospheric environment in coastal areas. Exhaust pollutants such as SO_2, NO_X, particulates and carbonaceous compounds would adversely impact regional air quality, global climate and even human health (Capaldo et al., 1999; Dalsøren et al., 2009; Endresen et al., 2003; Eyring et al., 2010; Papanastasiou and Melas, 2009). Unlike the increasingly strict emission control policies of land-based sources, policies and regulations for the prevention and control of ship emissions remain insufficient (Kiliç and Deniz, 2010; Zhang et al., 2013). With the rapid development of the maritime industry, the impact of exhaust pollutants from ships on air quality could become more serious in the near future (Corbett et al., 2010; Eyring et al., 2005; Olesen et al., 2009; Vutukuru and Dabdub, 2008). Thus, in order to identify the effect of ship emissions on air quality and formulate effective control measures, creating detailed ship emission inventories is of vital importance.

In the past two decades, numerous attempts have been made to establish ship emission inventories around the world. The original global-scale ship emissions were approximated based on fuel consumption data (Corbett and Fischbeck, 1997; Corbett et al., 1999). These emissions were further allocated to each grid location across the ship traffic profile derived from certain vessel data set, such as the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and the Automated Mutual-assistance Vessel Rescue system (AMVER) (Endresen et al., 2003, 2007; Wang et al., 2008). Afterwards, the inventory accuracy and resolution were gradually improved on a regional scale; for example, the Waterway Network Ship Traffic, Energy and Environment Model (STEEM) was developed by using massive historical ship movements and ship attribute information to more accurately allocate emissions for North America (Corbett et al., 2010; ICF, 2009; Wang et al., 2007, 2008). The “bottom-up” method is proven to be more accurate. This method is based on high-frequency AIS dynamic data and it calculates emissions for each individual ship traveling between its successive AIS positions. It reports and merges the emissions of all the intervals for all vessel voyages. The first attempt to use this method was applied to the Baltic Sea area, in which the Ship Traffic Emission Assessment Model (STEAM) was built based on comprehensive AIS data (Jalkanen et al., 2009, 2012). This method has been widely applied to ship emission inventories at national and regional scales, such as in Europe, the Arctic, America and Australia (Cotteleer et al., 2012; Goldsworthy and Goldsworthy, 2015; Jalkanen et al., 2014; Johansson et al., 2013; Starcrest, 2015a, 2015b; Winther et al., 2014).

So far in China, the AIS-based method was mostly applied to calculate ship emissions for single ports or port clusters, such as in the YRD and PRD regions (Fan et al., 2016; Song, 2014; Fu et al., 2012; Li et al., 2016; Ng et al., 2013; Yau et al., 2012). Li et al. (2016) developed a ship emission inventory for the PRD region (excluding Hong Kong port) based on vessel calls and approximately 700 AIS-based navigation trajectories. Fan et al. (2016) estimated the ship exhaust emissions in the YRD and the East China Sea within 400 km of the coastline for 2010 based on the sampling AIS data for February, April, June, September, November and December. Along with the increased number of vessels and activities, the ship emission inventory needed to be updated accordingly. To our knowledge, studies have rarely been carried out specifically at the national level in China, only Liu et al. (2016) estimated the emissions from OGVs in East Asia and presented their health and climate impacts, but the emissions from CVs and RVs were not included, and the emissions for single ports in China were not discussed either. According to the World Shipping Council (http://www.worldshipping.org/), China accounted for 70% of the top 10 ports in the world, and its container throughput in 2014 was 202.66 million twenty equivalent units (TEU), accounting for 29.9% of the world's total throughput. Therefore, a comprehensive ship emission inventory of China and a detailed understanding of the emission characteristics are highly required for the supplementing and perfecting of the national air emission inventory.

In this study, the first national-scale emission inventory of SO_2, NO_X, PM_{10}, $PM_{2.5}$, HC, CO and CO_2 from ships (including OGVs, CVs and RVs) in China was developed with $0.005° \times 0.005°$ resolution, using the state-of-the-art bottom-up method based on high-frequency AIS data of a full year (2014). We calculated emissions from each ship during each movement (usually in several seconds) and totaled all periods of emissions in the entire year from 166,546 vessels involved in AIS data (over 15 billion reports) to obtain the total annual ship emissions. Lloyd's database and the China Classification Society (CCS) database were combined as the main sources for building a comprehensive ship attribute information database (SAID) to supply key information for ship emission calculations. Emission characteristics from various perspectives, such as ship type, operating mode, discharge equipment, monthly variation and spatial distribution, will be discussed. Regional differences of the major port clusters, including BSA, YRD and PRD, will be analyzed and compared to previous studies. Emissions for the 24 major ports in China were also presented. The results would be used to assess the impact of ship emissions on the national air quality in our later study and are expected to support the management and control of the ship emissions.

2. Methodology

2.1. Study area and vessel classification

The study area was established to cover all emissions from OGVs, CVs and most of the RVs in mainland China and adjacent waters within the latitude of 12.6°N to 41.6°N and the longitude of 102.0°E to 126.0°E, as shown in Fig. 1. The major port clusters (BSA, YRD and PRD) and nearly all ports (including coastal ports and inland ports) were included in this region. The exhaust emissions from OGVs, CVs and RVs were all estimated, separately. OGVs were defined by both the International Maritime Organization (IMO) number and the Maritime Mobile Service Identify (MMSI) number, while CVs had only MMSI codes for identification (Li et al., 2016). RVs were generally recognized by the ship's registration information and navigation condition. Possibilities exist where some of the ships were not explicitly classified at the time of registration, statistical records on the navigation trajectories for each vessel were thus used instead for further identification. Vessels who had never navigated beyond the national boundary through the whole year were grouped into RVs, regardless of their MMSI numbers or IMO codes. This treatment would contribute to a certain degree of inaccuracy.

2.2. Data sources

Establishing a ship emission inventory requires detailed ship activity data and the corresponding ship attribute information. In this study, the dynamic AIS data for the full year of 2014 (365 days in total) were used to provide ship activity data, such as transmit time, geographical position (longitude and latitude), actual sailing speed, navigation status, etc. Since AIS transmits signals at intervals of 3 s to a few minutes, emissions from ships can be calculated as least once within a distance of no more than 1 km, even if the ship is moving at high speed. Therefore, the high-frequency dynamic AIS data determines the high spatiotemporal resolution of the ship emission inventory. To ensure the inventory reflecting the real situation as detailed as possible, all the effective dynamic AIS messages (over 15 billion) within the study area were retained after excluding the erroneous and duplicated records. In this way, 166,546 vessels with valid MMSI were actually involved in the estimation, of which OGVs, CVs and RVs accounted for 11.7%, 25.9% and 62.4%, respectively. Compared to previous studies on regional ship emission inventories related to China, the AIS data used in this study is more comprehensive from the aspects of vessel number, time span, temporal precision and the total number of reports (Fan et al., 2016; Liu et al., 2016).