Study on Characteristics of Ship Emissions from Surrounding China Seas

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Abstract. In order to analyse the characteristics of air pollutants emissions from coastal vessels in China, this study collects and analyses the static data and emission parameters of ships both at home and abroad based on the data of automatic identification system. Based on the actual navigation Data of ships, the paper also analyses the emission characteristics under the condition of five vessels including port, mooring, low speed and cruise in port, and statistics the emissions according to different sea areas, and gives the ship atmosphere of the three emission control areas In China Pollutant emissions. The results show that the SO2, NOX and PM10 produced in the vicinity of China's coastal waters within a year are about 879,800 tons, 1,378,400 tons and 117,300 tons, respectively. Source of emission analysis shows that the host is the main source of emissions from the three main sources of emissions on the ship's main engine, auxiliary engines and boilers. Spatial analysis of ship-borne pollutants shows that 90% of ship emissions occur within 96 nautical miles of the coastline to the baseline of the territorial sea.

1. Introduction
Prosperous maritime trade is a powerful driving force to promote the prosperity and development of China's economy, but at the same time, the ship will emit large quantities of pollutants SO2, NOX and PM10 during the voyage, the ship increased activity, the ship air pollutants Emerging emissions are becoming more serious, and the enormous pressure and challenges brought to the air quality of the port area are not small. Hey. The current research has few researches on ship emissions, and there is no dilemma in the control of ship emissions “unclear base”. Therefore, estimating the ship's atmospheric emission inventory is an important basis for preventing and controlling ship air pollution. The method of calculating the current emission inventory ship has two kinds: a first estimating method according to the fuel amount of fuel consumed by the ship; the second collection vessel ship speed, flight time using an automatic identification system (automatic identification system, AIS), the dynamic method of real-time navigation data such as geographical location. The advantage of the dynamic method over the fuel method is that it can obtain emissions from different time periods and navigational conditions, and can provide more effective data support for ship air pollutant emission reduction.

At present, China's research on ship emissions inventory has just started. Only a few coastal cities have initially developed ship emission inventory for local ports based on foreign research results. For example, Yang et al method based ship engine power, the development of emissions inventories grid ship Shanghai in 2003 with a resolution of 1km×1km,greatly improves the accuracy of an inventory of ships, and space distribution characteristics of emissions from ships Analysis[1]. Jin Taosheng and others used Tianjin Port as the research object, conducted on-the-spot investigation of the shipping
vessels in the port area, and estimated the emissions of pollutants from the Tianjin Port in 2006 using the emission factor method based on fuel consumption. Types include NOx, HC, CO and PM10 and predict ship emissions in 2010 and 2020, for the development of local marine pollution control laws and regulations provide an important basis [2]. Liu Jing and other port-based units have established an inventory of Qingdao's marine atmospheric emission sources from the bottom up, and used the self-developed GIS-based geographic information system-based composite source atmospheric diffusion model for source analysis. SO2 and the NOx concentration contribution of local atmospheric pollutants respectively 8.0% and 12.9% [3]. Fu Qingyan and others estimated the inventory of air pollution sources for ships in Shanghai in 2010[4]. Ye Siqi et al. used the emission factor method based on ship engine power and fuel consumption to estimate the ship emission inventory of Guangdong Province in 2010, and based on this, studied the spatial and temporal distribution characteristics of various types of ship emissions in the region [5]. Tan Jianwei et al. used the ship automatic identification system to collect real-time navigation data such as ship speed, navigation time and geographical location information of ocean-going vessels, and used the dynamic method to calculate the emissions inventory of Dalian Port Ocean Shipping in 2012 [6]. Yang Jing and others estimated the Shenzhen ship emission inventory in 2010 [7]. Wang Zheng et al. used AIS data to calculate and analyze the pollutants of bulk carriers on board voyages and carbon dioxide emissions in China's surrounding waters [8, 9]. The existing researches are based on the scope of a region or port area, and there are few studies on the emissions of the coastal areas around China.

This study uses the ship's buried position and speed information collected by the ship automatic identification system in China's coastal areas, and uses the dynamic method to estimate the 2014 pollution emission inventory of the active ships in the area. The ship's atmosphere is obtained with a 1Km×1Km grid. The spatial distribution of pollutant emissions to visually identify the spatial distribution of contaminants.

2. Research Method

2.1 Research Areas and Objects
Research area: In the coastal areas of China (sea area within 105°~125° east longitude and 16°~41° north latitude ), the base year is 2014, and the type of ships studied is merchant and fishing ships (excluding warships). The gaseous emissions studied were SO2, NOX and PM10.

2.2 Calculation Method
Ship pollution emission inventory The calculation method of the ship method based on the AIS data-based dynamic method is calculated by multiplying the energy output of the ship main engine, the ship auxiliary machine and the boiler (unit: kW·h) by the emission factor corresponding to various emissions. Based on the functional relationship, the emission factor used in the calculation is measured in g/kW·h.

The Equation 1 given below is the basic formula for calculating the ship's emissions based on power, the calculation formula of the ship auxiliary machine and boiler output power.

\[ E_i = \text{Load} \times \text{LF} \times \text{Act} \times \text{EF}_i \times \text{FCF} \times \text{CF}_i \]

among them:

- \(E_i\) The amount of emissions for a certain type of pollutant, in g;
- \(\text{Load}\) The load power for the ship's main engine, ship auxiliary equipment or boiler under certain ship operating conditions. In the specific calculation, when the host load is less than 20%, the host load power needs to be adjusted, and the maximum continuous power is multiplied by its low load adjustment coefficient (LF). The auxiliary machine power needs to be adjusted according to different ship conditions. The specific adjustment measures are The auxiliary machine power is multiplied by the ship auxiliary machine load proportional coefficient; the boiler load refers to its power, kW; \(\text{Act}\) is the time for the ship to sail, the unit is: h. \(\text{EF}_i\) is the emission factor of this pollutant, the unit is: g / kW · h; \(\text{FCF}\) is the fuel correction coefficient, dimensionless unit; \(\text{CF}_i\) is the emission correction factor, dimensionless unit.

Equation 2 is the formula for the low load adjustment factor of the ship's main engine.
\[ LF = \left( \frac{\text{Speed\_Actual}}{\text{Speed\_Maximum}} \right)^3 \] (2)

among them:

\( LF \) is the ship's main engine low load adjustment factor, dimensionless unit. See Table 1.2.

\( \text{Speed\_Actual} \) The actual speed of the ship's navigation, unit: section; \( \text{Speed\_Maximum} \) is the maximum designed speed of the ship, unit: section.

The ship's emission inventory calculated by the institute includes pollutant emit from the main engine, auxiliary machinery and boilers. In the calculation process, the ship's operating conditions are divided into four types: cruise, port maneuver, port and anchor. The calculation assumes that when the ship is in the cruise phase and the main load is greater than 20%, the boiler is turned off [8].

When the ship is equipped with abatement devices, it is necessary to use the emission control factor to correct the pollutant emissions. The ship selected for this study has not been installed, so the technical control factor for the abatement in the calculation is 1, and the obtained data is that the ship is not installed. Emissions under the condition of the emit device.

2.3 Emission Factors and Other Parameters

Emission factors within the ocean-going vessels of emission factors shall be close to the other party, and therefore the emission factors selected air pollutant emission inventories used US EPA [10] (see Table 1 to Table 3). Load factor divided into a main host hospital auxiliary engine load factor and engine load factor, Yuan auxiliary engine will vary depending the type and mode of operation of the ship main engine load factor determined by the maximum speed and the actual sail sailing speed, the present study reference ICF The research results [10] select the engine load factor (see Table 4, Table 5, Table 6). The activity time of different working conditions of the ship is extracted by AIS data. Generally, ocean-going vessels use marine diesel (MDO) and residual oil (RO) according to different ship navigation conditions. Marine diesel is used when entering and leaving the port, and the port is switched to residual oil through a valve at a certain distance from the port. See the fuel correction coefficient. Table 7.

| Table 1. Ship host pollutant emission factor \( EFi \) (Unit of measurement: g/kW·h ) |
|---------------------------------|-----------------|-----------------|-----------------|
| Ship type                       | Year of construction | \( PM_{10} \) | \( NO_X \) | \( SO_2 \) |
| Low speed diesel engine         | 2000 years ago    | 1.05            | 18.1           | 10.5          |
| Medium speed diesel engine      | 2000 years ago    | 1.11            | 14             | 11.5          |
| Low speed diesel engine         | 2000-2010         | 1.05            | 17             | 10.5          |
| Medium speed diesel engine      | 2000-2010         | 1.11            | 13             | 11.5          |
| Low speed diesel engine         | 2011-2015         | 1.05            | 15.3           | 10.5          |
| Medium speed diesel engine      | 2011-2015         | 1.11            | 11.2           | 11.5          |

Note: Low speed diesel engine, maximum speed < 130r/min; medium speed diesel engine, speed > 130r/min

| Table 2. Ship auxiliary machine pollutant emission factor \( EFa \) (Unit of measurement: g/kW·h) |
|---------------------------------|-----------------|-----------------|-----------------|
| Year of construction           | \( PM_{10} \) | \( NO_X \) | \( SO_2 \) |
| \( \leq 1999 \)                | 1.11            | 14.7           | 12.3           |
| 2000-2010                      | 1.11            | 13             | 12.3           |
| 2011-2015                      | 1.11            | 11.2           | 12.3           |

| Table 3. Boiler emission factor \( EFbi \) (Unit of measurement: g/kW·h ) |
|---------------------------------|-----------------|-----------------|-----------------|
| \( PM_{10} \)                   | \( PM_{2.5} \) | \( NO_X \) | \( SO_2 \) |
| 0.8                             | 0.64            | 2.1             | 16.5            |
Table 4. Ratio of ship auxiliary engine to main engine power

| Ship type       | Auxiliary machine power to host power ratio ( % ) |
|-----------------|--------------------------------------------------|
| Car carrier     | 0.266                                            |
| Bulk carrier    | 0.222                                            |
| Container Ship  | 0.220                                            |
| Cruise ship     | 0.278                                            |
| General cargo ship | 0.191                        |
| Ocean tug       | 0.222                                            |
| Refrigerated ship | 0.406                           |
| Roll-on ship    | 0.259                                            |
| Tanker          | 0.211                                            |
| Other types     | 0.222                                            |

Table 5. Ship host low load adjustment factor LF (dimensionless)

| Load factor LF | PM_{10} | NO_{x} | SO_{2} |
|----------------|---------|--------|--------|
| 1%             | 19.17   | 11.47  | 5.99   |
| 2%             | 7.29    | 4.63   | 3.36   |
| 3%             | 4.33    | 2.92   | 2.49   |
| 4%             | 3.09    | 2.21   | 2.05   |
| 5%             | 2.44    | 1.83   | 1.79   |
| 6%             | 2.04    | 1.6    | 1.61   |
| 7%             | 1.79    | 1.45   | 1.49   |
| 8%             | 1.61    | 1.35   | 1.39   |
| 9%             | 1.48    | 1.27   | 1.32   |
| 10%            | 1.38    | 1.22   | 1.26   |
| 11%            | 1.3     | 1.17   | 1.21   |
| 12%            | 1.24    | 1.14   | 1.18   |
| 13%            | 1.19    | 1.11   | 1.14   |
| 14%            | 1.15    | 1.08   | 1.11   |
| 15%            | 1.11    | 1.06   | 1.09   |
| 16%            | 1.08    | 1.05   | 1.07   |
| 17%            | 1.06    | 1.03   | 1.05   |
| 18%            | 1.04    | 1.02   | 1.03   |
| 19%            | 1.02    | 1.01   | 1.01   |
| 20%            | 1       | 1      | 1      |

Table 6. Ship auxiliary machine load proportional coefficient LF_A

| Ship type         | Sailing state | Cruise | Low speed | Maneuvering | Berth |
|-------------------|---------------|--------|-----------|-------------|-------|
| Car carrier       |               | 0.15   | 0.30      | 0.45        | 0.26  |
| Bulk carrier      |               | 0.17   | 0.27      | 0.45        | 0.22  |
| Container Ship    |               | 0.13   | 0.25      | 0.48        | 0.19  |
| Cruise ship       |               | 0.80   | 0.80      | 0.80        | 0.64  |
| General cargo ship|               | 0.17   | 0.27      | 0.45        | 0.10  |
| Ocean tug         |               | 0.17   | 0.27      | 0.45        | 0.22  |
| Refrigerated ship |               | 0.20   | 0.34      | 0.67        | 0.32  |
| Roll-on ship      |               | 0.15   | 0.30      | 0.45        | 0.26  |
| Tanker            |               | 0.24   | 0.28      | 0.33        | 0.26  |
| Other types       |               | 0.17   | 0.27      | 0.45        | 0.22  |
Table 7. Fuel correction factor $FCF$ (dimensionless)

| Fuel              | PM$_{10}$ | NO$_X$ | SO$_2$ |
|-------------------|-----------|--------|--------|
| RO (2.7% S)       | 1         | 1      | 1      |
| MDO (1.5% S)      | 0.47      | 0.9    | 0.56   |

According to the state of navigation, it is divided into five categories: cruising, low-speed cruising, maneuvering in the port, anchoring, and docking. In this study, the speed and MCR joint discriminant method in the IMO third greenhouse gas research report were used to judge the navigation status. The basis for the division of different navigation conditions is shown in Table 8 [11].

For different types of ships, the MCR is variable. If only the speed discrimination method is adopted, it will cause a calculation error due to improper discrimination of the state.

Table 8. Judgment basis for ship navigation status

| Ship speed                  | status |
|-----------------------------|--------|
| Speed $< 1$ knot            | Berth  |
| $1$ knot $\leq$ Speed $\leq 3$ knots | Anchor |
| Speed greater than $3$, and less than $20\%$ of the MCR | maneuver |
| MCR greater than $20\%$, while less than $65\%$ of the MCR | Low speed |
| More than $65\%$ of MCR    | cruise |

3. Results and Discussion

3.1 Emissions in the Surrounding Waters of China

In 2014, the emission of ships in the surrounding seas of China is shown in Table 9. Among them, SO$_2$, NO$_X$ and PM$_{10}$ emit 879,800 tons, 1,378,400 tons and 117,300 tons respectively.

Table 9. Emissions of some coastal waters and ocean-going vessels in China in 2014

|                  | SO$_2$(10,000 tons) | NO$_X$(10,000 tons) | PM$_{10}$(10,000 tons) |
|------------------|---------------------|--------------------|------------------------|
| Total calculation area | 87.98               | 137.84             | 11.73                  |

According to the source of emissions, the SO$_2$, NO$_X$ and PM$_{10}$ emitted by the main engines accounted for 61.88%, 69.92% and 65.98% of the total emissions respectively; the SO$_2$, NO$_X$ and PM$_{10}$ emitted by the auxiliary machines accounted for the total emissions respectively of 36.51%, 28.6%, 32.91%; sulfur oxide emissions from a boiler, SO$_2$, NO$_X$ and PM$_{10}$ overall emissions are 1.61%, 1.48%, 1.07%. The proportion of ship emissions by source is shown in Figure 1.

Figure 1. Emission ratio by different sources
According to the navigation status, the SO$_2$, NO$_X$ and PM$_{10}$ emitted by the docking state accounted for 19.58%, 15.32% and 17.56% of the total emissions respectively; the SO$_2$, NO$_X$ and PM$_{10}$ emitted from the mobile state accounted for 15.15%, 14.52%, and 15.9%; mooring status emissions of SO$_2$, NO$_X$ and PM$_{10}$ accounted for 1.38% of the overall emissions, 1.48%, 1.92%; low-speed cruise sulfur oxide emissions and nitrogen oxide ThePM$_{10}$ accounted for 48.83%, 52.1%, and 49.24% of the total emissions, respectively; the SO$_2$, NO$_X$ and PM$_{10}$ emitted from the cruise state accounted for 15.06%, 16.59%, and 15.39% of the total emissions, respectively. Sailing ship emissions accounted for by the state of division as shown in Figure 2.

![Figure 2. Emission ratio of different navigational states](image)

### 3.2 Emissions from Different Sea Areas

This study analyzed the emissions of ships from different sea areas in 2014. The results are shown in Table 10.

#### Table 10. Ship emission from different areas of land

| from the coastline to the territorial sea baseline | SO$_2$ Emissions (10,000 tons) | Proportion (%) | NO$_X$ Emissions (10,000 tons) | Proportion (%) | PM$_{10}$ Emissions (10,000 tons) | Proportion (%) |
|--------------------------------------------------|-------------------------------|----------------|-------------------------------|----------------|-------------------------------|----------------|
| 12 nautical miles                                 | 59.57                         | 69.96%         | 92.96                         | 68.46%         | 8.10                          | 69.78%         |
| 24 nautical miles                                 | 66.37                         | 77.94%         | 104.39                        | 76.87%         | 9.04                          | 77.87%         |
| 48 nautical miles                                 | 71.75                         | 84.26%         | 113.46                        | 83.55%         | 9.78                          | 84.25%         |
| 96 nautical miles                                 | 77.25                         | 90.72%         | 122.62                        | 90.30%         | 10.53                         | 90.73%         |

The results show that the ship's emissions are generally decreasing with the growth rate away from the coastline. 90% of the ship's emissions occur within 96 nautical miles from the coastline to the territorial sea baseline.

### 3.3 Emission Control Area

Emission Control Area 2014 three sea areas as shown in Table 11, Bohai Emission Control Area annual emissions of SO$_2$, NO$_X$, PM$_{10}$ were 108,200 tons, 170,000 tons, 1.47 tons; length The annual emissions of SO$_2$, NO$_X$ and PM$_{10}$ in the Yangtze River Delta Emission Control Area are 146,300 tons, 22,640 tons and 19.99 million tons respectively; the annual emissions of SO$_2$, NO$_X$ and PM$_{10}$ in the Pearl River Delta Emission Control Area are 85,100 tons, 13.26 million tons and 1.16 million tons respectively.
Table 11. Emissions of the three major emission control areas

|                             | SO₂              | NOₓ              | PM₁₀             |
|-----------------------------|------------------|------------------|------------------|
|                             | Emissions (10,000 tons) | Proportion (%)  | Emissions (10,000 tons) | Proportion (%)  | Emissions (10,000 tons) | Proportion (%)  |
| Bohai Sea Emission Control Area | 10.82            | 12.50%           | 17               | 12.52%           | 1.47              | 12.67%           |
| Yangtze River Delta Emission Control Area | 14.63            | 16.90%           | 22.64            | 16.67%           | 1.99              | 17.15%           |
| Pearl River Delta Emission Control Area | 8.51             | 9.83%            | 13.26            | 9.76%            | 1.16              | 10.00%           |
| Sum of three emission control areas | 33.96            | 39.23%           | 52.9             | 38.95%           | 4.62              | 39.82%           |

3.4 Main Source of Error
The emissions inventory calculation involves many factors such as fuel quality, ship power, activity levels and emission factors, and the choice of each value will affect the accuracy of the emissions inventory. The main factor affecting the accuracy of the emission inventory is the impact of emission factors. China has not carried out systematic emission factor research work. The selection of foreign emission factors is an important source of uncertainty.

4. Conclusions
(1) In 2014, SO₂, NOₓ and PM₁₀ produced in the coastal waters of China in the past year were approximately 879,800 tons, 1,378,400 tons and 11.73 million tons respectively.
(2) Analysis of emission sources shows that from the three sources of main engines, auxiliary engines and boilers of the ship, the main engine is the main emission source, and the SO₂, NOₓ and PM₁₀ emitted by the main engine account for 61.88% of the total emissions respectively, 69.92%, 65.98%.
(3) The low-speed cruise state has the largest emission in the navigation state, and the SO₂, NOₓ and PM₁₀ emitted by the low-speed cruise state account for 48.83%, 52.1%, and 49.24% of the total emissions, respectively.
(4) Spatial analysis of pollutants emissions from ships indicates that 90% of ship emissions occur within 96 nautical miles from the coastline to the territorial sea baseline, that is, within 200 km of land.
(5) Ships account for a large proportion of emissions in the three emission control areas, at around 40%.
(6) Reduce the emission of pollutants by using low-sulfur oil or raising the level of the engine; under the working conditions in the port, the main machine emissions should be based on the use of shore power and low-sulfur oil as control means.

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6. References
[1] Yang, DQ, Kwan, SH, Lu, Y. An emission inventory of marine vessels in Shanghai in 2003. [J]. Environmental Science & Technology, 2007, 41(15).
[2] Jin Taosheng, Yin Xiaoge, Xu Jia et al. Inventory of Air Pollutants in Tianjin Port Transportation [J]. Marine Environmental Science, 2009, 28 (06): 623-625.
[3] Liu Jing, Wang Jing, Song fax establishment and application of emission inventory of air pollution in the port of Qingdao City Ship [J] China Environmental Monitoring, 2011, 27 (3): 50-53.
[4] Yan Qing, Shen Yin, Zhang Jian Shanghai ship emission inventory of air pollutants [J]. Journal of Safety and Environment 2012 (5): 57-64.
[5] Yesi Qi, Zheng Junyu, Panyue Yun, Guangdong Province, ships, and other sources of emissions inventory and research time and space [J] Distribution of Environmental Science, 34 (3): 537-547

[6] Tan Jianwei, Song Yanan, Ge Yunshan, etc. Dalian Ocean Basin Ocean Shipping Emission Inventory [J]. Environmental Science Research, 2014, 27 (12): 1426-1431.

[7] Yang Jing, Yin Peiling, Ye Siqi et al. Study on Ship Emission Inventory and Time and Space Characteristics in Shenzhen City [J]. Environmental Science, 2015: 36 (4): 1217-1226

[8] Wang Zheng, Zhang Wei, Geng Xiongfei, et al. Study on Ship Emission Inventory and Emission Characteristics of Typical Routes [J]. Transportation Energy Conservation and Environmental Protection, 2015: 12 (5): 44-49

[9] Wang Zheng, Liu Ying, Zhang Wei, et al. Study on carbon dioxide emission characteristics in the surrounding waters of China [J]. Energy Conservation and Environmental Protection, 2018: 3 (2)

[10] ICF International. Current methodologies in preparing mobile source port-related emission inventories. Final Report. [R]. 2009.

[11] IMO. Third IMO Greenhouse Gas Study 2014 [R]. 2015.