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Comparative Analysis, Use Recommendations, and Application Cases of Methods for Develop Ship Emission Inventories

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Highlights:

- This study sorted out and categorized main inventory compilation methods.
- Five main methods were compared and characterized by their applicability, complexity, time of calculation, accuracy of results, ability to distinguish vessel types and sources of emissions.
- A new method was proposed to develop an emission inventory based on a vessel energy consumption reporting system. This method is believed to have the potential advantages to produce results of higher accuracy, higher temporal and spatial resolutions.
- Five main methods were used to calculate emission inventories in three cases at different scales.
- This study recommends the use of different inventory compilation methods under different circumstances.

Abstract: Ship exhaust emissions have been considered as a significant source of air pollution that has an adverse impact on the global climate and human health. It is of vital importance to create an accurate ship emission inventory for the purpose of formulating effective control measures. A wide range of inventory compilation methods have been proposed around the globe, and there has long been a pressing need to analyze and compare these methods in depth. This study sorted out and categorized inventory compilation methods of ship emissions in recent decades. Five main methods were compared and analyzed by their applicability, complexity, time of calculation, accuracy of results, etc. In addition, a new method was proposed to develop an emission inventory based on a vessel energy consumption reporting system. This method is believed to have the potential advantages to produce results of higher accuracy and temporal and spatial resolutions. To perform the validation, three cases at different scales were selected in part of China and surrounding maritime waters (large-scale), the Yangtze River Delta region (medium-scale), and Tianjin Port (small-scale), respectively. The analysis results show that: each of methods have different technical characteristics. Computed results significantly between methods, with the maximum deviation of up to 87%. It is advisable that the optimal method should be chosen based on the actual needs in inventory compilation and the data available. In terms of accuracy of results, Methods 1 and 5 offer moderately high accuracy; Method 2 provides average accuracy; while Methods 3 and 4 produce low accuracy. In terms of resolution of results, Methods 1 and 5 provide high-resolution temporal and spatial distribution of ship emissions; Method 2 delivers low-resolution spatial distribution; while Methods 3 and 4 are incapable of spatial distribution. In terms of applicability, Method 1 applies to the calculation of inventories of varying scales; Method 2 is more applicable to small-scale calculations, such as a port; Methods 3, 4, and 5 are more desirable for large-scale calculations, such as a country. The

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author recommends Methods 5, 1, 3, and 2/4 in a descending order of preference for large-scale ship emissions inventory compilations; recommends Method 5 (if accuracy is the first priority) or Method 1 (if temporal and spatial resolutions are given first priority), followed by Methods 2, 3, and 4 in a descending order of preference for small/medium-scale ship emissions inventory compilations. These results may serve to help inventory compilers choose an applicable method and support improvements in inventory compilation methods.

Keywords: vessel; air pollutants; emission inventory

1. Introduction

Maritime transportation carries around 90% of freight movement in this world and makes quite some contribution to climate change and worsening air quality [1]. Out of all emissions caused by the sea transportation, ship emissions pick up a high proportion. A large amount of air pollutants such as NO_x, SO_2, PM, etc., are emitted from ship engines, which greatly affect air quality and public health in port cities [2,3]. In order to identify the effect of ship emissions on air quality and formulate effective control measures, creating ship emission inventories is of vital importance [4].

Compared with other sources of pollution, the compilation of shipping-related emission inventories started quite late but has been evolving quickly. A variety of calculation methods have been developed so far. Corbett et al. built a global ship emission inventory on international ocean shipping fuel statistics and emission factors of different types of fuel and engines in 1997 [5]. Most ship emission inventories were based calculation of fuel consumption, and the methods have evolved accordingly for a long period of time thereafter. Kesgin et al., for example, created ship emission inventories for the Strait of Turkey based on fuel consumption and provided future emission forecasts [6]; in China, the pollutant emissions from ships were usually calculated by the statistics of fuel consumption of ships before 2007. In Europe, Endresen et al. [7] and Eyring et al. [8] improved the fuel-based method with average data of ship engines, created global ocean-going vessel emission inventories, and applied the Automated Mutual-Assistance Vessel Rescue System (AMVER) to derive spatial distribution of emissions. Czermański et al. proposed an energy consumption approach to estimate container ship emissions by using datasets on container shipping and average vessel speed records generated via AIS [9].

Thereafter, variations of the activity-based method by engine power have been increasingly applied to the compilation of ship emission inventories. A lot of scholars have estimated, in a top-down approach, ship emissions based on statistical vessel calls at ports, and average engine power and running hours of engines, among others. Entec in the UK [10], for example, used this method to calculate ship emissions, compared the pros and cons of this statistical method and other methods, and proposed an improved method that can reduce uncertainty of the inventories in a report on quantifying ship emissions at ports in EU member states. The port of Los Angeles [11] and the Port of Long Beach [12] in the U.S. employed this method to calculate ship emission inventories at the ports. The U.S. Environmental Protection Agency [13] also used this method to calculate American ship emission inventories in a report filed with the International Maritime Organization (IMO) requesting to establish ship emission-controlled areas. Fu et al. [14] used visa data to aggregate vessel calls at the Port of Shanghai and produced an activity-based ship emission inventory for the port in 2010.

Since around 2007, ship emission inventories have been constantly refined. People began to use IMO's Automatic Identification System (AIS), Long Range Identification and Tracking (LRIT), and International Comprehensive Ocean Atmosphere Data Set (ICOADS), among other ship activity data of high temporal and spatial resolutions, to calculate emission inventories in a bottom-up approach. The U.S. EPA established an emissions inventory system STEEM based on probability distribution of historical ship movements and the distances of routes derived from the AMVER and ICOADS data [15]. Entec in the UK used the activity-based method to calculate the ship emission inventory for UK waters in 2007 based on AIS data [16]. From the year of 2014 onwards, the AIS activity-based method gained fast progress and has been applied in different regions and polished by many scholars, hence it is one of the most widely recognized compilation methods of ship emission inventories in the world. Winther et al., based on satellite AIS data, arrived at ship BC, NO_x, and SO_2 emission inventories in the Arctic Region in 2012, and forecasted ship emissions in the same region in 2020, 2030, and 2050 [17]. Jalkanen et al. built a ship emission assessment model using the AIS and thereby created ship emission inventories of high temporal and spatial resolutions for the Baltic Sea between 2006 and 2009 [18]. Goldsworthy et al., also by using AIS data, created ship emission inventories for Australia and by applying a refined AIS data processing method took the accuracy of ship emission inventories to the next level [19]. With the help of AIS data, Pokhrel et al. created ocean-going ship emission inventories for the Port of Inchon in 2005 and examined the impact of emissions by ocean-going vessels on air pollution in inland regions under the action of land and sea breezes [20]. Based on high-quality AIS data, Liu et al. calculated the ship emissions inventory in the East Asian area, and calculated health and climate impacts of ocean-going vessels in East Asia [21]. Huang et al. integrated multi-source maritime information to estimate ship emissions in the ocean environment [22]. Fan et al. built an automatic identification system-based model to estimate the ship emissions in the YRD and the East China Sea within 400 km of the coastline [23]. Chen et al. also used the AIS activity-based method to produce ship emission inventories for some maritime waters of China and tried to characterize the resulting ship emissions [24]. In addition, some scholars combined a variety of inventory compilation methods or several sets of ship activity data to deliver ship emission inventories for maritime waters of China. Li et al. [25], for example, combined AIS data with vessel calls at ports. Meanwhile, many scholars amended the ship emission factors through methods such as testing on actual ships, in order to constantly enhance accuracy of a variety of calculation methods for an emissions inventory [26–28].

To sum up, each of the compilation methods for vessel air pollutant emission inventories developed around the globe so far differ sharply in applicability, requirements for use, and patterns of results, among other things. The choice of a correct method largely determines the accuracy and usability of the results of the calculated inventory. However, no study has systematically sorted out and compared different methods with analysis so far. It is difficult for inventory compilers to pick out a method suited to the actual needs quickly.

In this study, the main vessel inventory compilation methods developed over the last decades are reviewed and categorized systematically for the first time. Five main methods are analyzed in detail and characterized by the principle of calculation, applicability, complexity and time of calculation, accuracy of results, temporal and spatial resolutions of results, ability to calculate for transit vessels, and ability to distinguish vessel types, operating modes, and sources of emissions. Meanwhile, an exploratory idea is proposed to develop an inventory compilation method based on a vessel energy consumption reporting system. This method has potential advantages to produce results of higher accuracy and temporal and spatial resolutions. On that basis, the study recommends inventory compilation methods in corresponding orders of preference for different scales of space and application requirements and validates main features and patterns of results of the said main methods with three cases, for the large-scale regions, represented by part of China and surrounding maritime waters, the Yangtze River Delta region and Tianjin Port, for the medium-scale and small-scale regions, respectively. The study may serve to help inventory compilers choose an applicable method and support improvements in inventory compilation methods.

2. Analysis of Methods for Vessel Inventory Calculation

2.1. Introduction of Calculation Methods

Varied inventory compilation methods for ship emissions are available. These methods can be categorized into "top-down" and "bottom-up" approaches by the way of compilation and into "activity-based method" and "fuel-based method" by the principle of calculation. The "activity-based method" calculates atmospheric emissions of pollutants based on engine activities, while the "fuel-based method" on ship fuel consumption. Based on different ship activity level data employed, these two main categories can be subdivided into activity-based method by dynamic vessel data, activity-based method by vessel calls at ports, fuel-based method by regional energy consumption, fuel-based method by passenger ton kilometer (PTK)/freight ton kilometer (FTK), and fuel-based method by energy consumption per vessel. For details on the logical relations among main methods, please see Figure 1. We will present an analysis of five main compilation methods widely used across the world currently (Li et al., 2019).

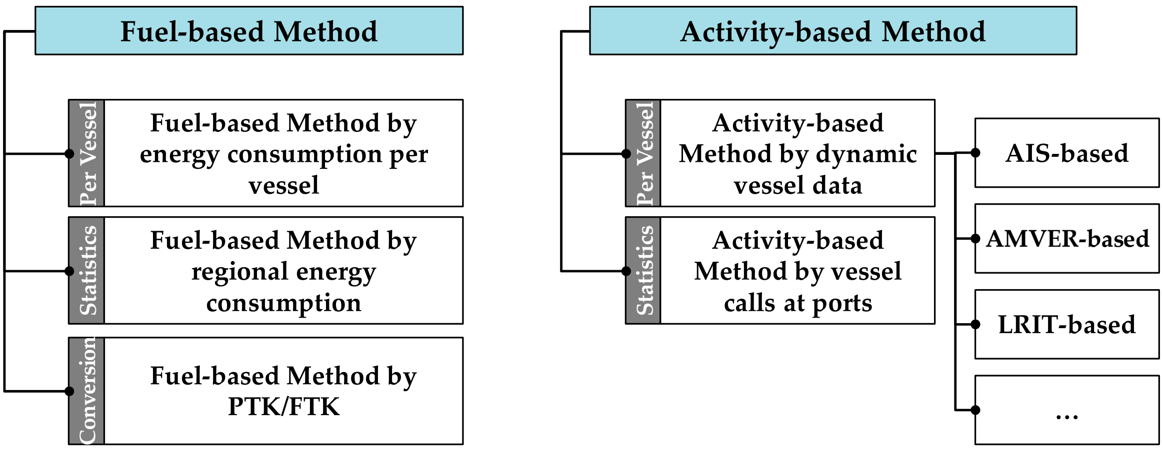


Figure 1. Relations among main inventory compilation methods for ship emissions.

2.1.1. Method 1 Activity-Based Method by Dynamic Vessel Data

This activity-based method is a bottom-up inventory compilation approach for ship emissions based on dynamic vessel activity data for activity levels. At present, the main sources of dynamic vessel activity data are ① AMVER, ② ICOADS, ③ LRIT, and ④ AIS from the International Maritime Organization (IMO). The first three systems were built earlier, which have higher coverage over Atlantic-Ocean-going vessels, but lower coverage over vessels in other regions. AIS is a novel digital shipping assistance system that enables real-time transmission of position, navigation speed, and other activity information of vessels equipped with AIS. Thanks to its high global penetration rate and high-quality AIS data, the AIS-based method is the most widely used and most technically mature compared to ①~③.

The AIS device installed on vessels broadcasts a signal at intervals of a few seconds to a few minutes with vessel position, navigation speed, status and time among, other information. We matched AIS data with the ship technical specifications database, calculated amount and position of air pollutants emitted between two immediate AIS signals based on engine power and running hours of each vessel, and summed emissions by the number of vessels to establish an inventory of vessel emissions in a region. Owing to its principle of calculation and basic data inputs, this method produces high-precision results with desired temporal and spatial resolutions. See Equations (1)–(4).

(a) Total Emissions.

The emission from one ship equals all emissions from engines and boilers of this ship in each AIS signal session. Vessel emission in a calculation scope is the sum of total vessel emissions during all AIS signal sessions in the scope.

$$SE = \sum_{p}\sum_{s}(SE_M + SE_A + SE_B) \tag{1}$$

where
SE is total vessel emissions in the calculation scope (g).
SE_M is emissions from main engines (g).
SE_A is emissions from auxiliary engines (g).
SE_B is emissions from boilers (g).
p is the number of ships in the calculation scope.
s is the number of AIS signals per ship in the calculation scope.

(b) Emissions from Main Engines.

$$SE_M = P_M \times LF_M \times T_M \times AF \times EF_t \tag{2}$$

where
P_M is main engines' rated powers (kW).
LF_M is load factors of main engines (dimension free).
T_M is running hours of main engines (h).
AF is adjustment factor for emission control measures (dimension free).
EF_t is emission factors (g/kW·h) of atmospheric pollutants of t.
t is vessel fuel type (such as heavy oil, diesel oil, LNG).

(c) Emissions from Auxiliary Engines.

$$SE_A = P_A \times T_A \times AF \times EF_t \tag{3}$$

where
P_A is auxiliary engines' powers (kW), a product of auxiliary-engine-rated powers and load factors, or a product of main engine powers and empirical factors of power for the main engine and auxiliary engine.
T_A is running hours for auxiliary engines (h).

(d) Emissions from Boiler.

$$SE_B = P_B \times T_B \times AF \times EF_t \tag{4}$$

where
P_B is boiler power (kW).
T_B is running hours for boiler (h).

2.1.2. Method 2 Activity-Based Method by Vessel Calls at Ports

This activity-based method calculates emissions by ship activity levels suggested from ship calls arriving at and departing from ports. With a theory similar to the activity-based method by dynamic ship data, this method does not calculate emissions per vessel at every moment, but generalizes and averages emissions by vessels of the same type and tonnage. It is a top-down approach. See Equations (5)–(8).

(a) Total Emissions.

$$SE = \sum_{a}\sum_{b}(SE_M + SE_A + SE_B) \tag{5}$$

where

a is the number of ship type.
b is the number of tonnage types.

(b) Emissions from Main Engines.

$$SE_M = N_{a,b} \times P_M \times LF_M \times \frac{D}{S} \times AF \times EF \tag{6}$$

where

$N_{a,b}$ is the call of ship type-a and tonnage-b; the number of calls for inbound vessels used in inbound vessel emission calculation, the number of calls for outbound vessels used in outbound vessel emission calculation, and the average of the numbers of inbound and outbound vessels used in emission calculation for vessels at birth.

D is calculation distance (nm).
S is the average speed (kn).

(c) Emissions from Auxiliary Engines.

$$SE_A = N_{a,b} \times P_A \times T_A \times AF \times EF \tag{7}$$

where

T_A is calculated by D/S for ship cruising and maneuvering. Other T_A is the duration at berth.

(d) Emissions from Boiler.

$$EP_B = N_{a,b} \times P_B \times T_B \times AF \times EF \tag{8}$$

2.1.3. Method 3 Fuel-Based Method by Regional Energy Consumption

The fuel-based method could be refined by the availability of "fuel consumption data". Method 3 as one of such methods is the fuel-based method by regional energy consumption, which refers to directly obtaining fuel consumption by vessels in an observed region by means of research or statistics, among others, and then combining with an emission factor per unit fuel to arrive at vessel emissions. It is a top-down approach. The accuracy of its results and distinguishability of vessel types mainly depend on the precision and resolution of fuel consumption data obtained. Refer to Equation (9) for more details.

$$SE = \sum_t (F_t \times EF_t) \tag{9}$$

where

F_t is total fuel-t consumption (kg).
EF_t is emission factor of atmospheric pollutants of fuels-t (g/kg fuels).

2.1.4. Method 4 Fuel-Based Method by PTK/FTK

When fuel consumption by vessels in an observed region is not directly available, fuel consumption can be estimated from PTK/FTK (Method 4a). In addition, passenger/freight transport load and passenger/freight average distance can be used to calculate PTK/FTK, before converting it to fuel consumption by vessels (Method 4b). This is a top-down approach. Refer to Equations (9)–(12) for more details.

$$F_t = (\beta \times PTK + FTK) \times YX_t \tag{10}$$

where

β is the conversion coefficient of energy consumption from passenger turnover to freight turnover. The recommendation is to use 0.065 if no data is available.

PTK is passenger turnover (10^4 persons·km); if not available, Equation (11) can be used instead.

FTK is freight turnover (10^4 t·km); if not available, Equation (12) can be used instead.

YF_t is energy intensity per turnover unit (kg/10^4 t·km). The recommendation is to use 50 if no data is available.

$$PTK = \frac{PL}{PD} \tag{11}$$

where

PL is passenger load (10^4 persons).

PD is passenger average distance (km).

$$FTK = \frac{FL}{FD} \tag{12}$$

where

FL is freight load (10^4 t).

FD is freight average distance (km).

2.1.5. Method 5 Fuel-Based Method by Energy Consumption per Vessel

As the International Maritime Organization (IMO) is calling for cutting green gas emissions from ocean shipping, some countries and regions are building a vessel energy consumption reporting system designed to report fuel consumption data per vessel per voyage in a real-time manner. Based on the data, some scholars are working on a fuel-based method per vessel per voyage for energy consumption, that is, an inventory compilation method based on activity level per vessel per voyage, with the fuel-based method as the core principle. It is foreseeable that this method will make breakthrough in vessel emissions inventory compilation and result in an uplift in result accuracy compared to the currently dominant AIS activity-based method. For this reason, we tried to discuss this method though it is still under development and yet to be published. Judging by the principle of calculation and basic data used, this method should be a bottom-up refined approach with high temporal and spatial resolutions and high precision in the calculation results. Refer to Equations (13)–(14) for more details.

(a) Total Emissions.

$$SE = \sum_p \sum_r (SE_{p,r}) \tag{13}$$

where

r is the total number of voyages per vessel.

(b) Emission per vessel per voyage.

$$SE_{p,r} = Y_{p,r} \times EF_t \tag{14}$$

where

$Y_{p,r}$ is fuel consumption on voyage r of vessel p (kg).

EF_t is fuel-t emission factor for main engines, auxiliary engines, and boilers (g/kg fuel).

2.1.6. Others

On top of the above-mentioned methods, there are variations of the methods that are based on other types of vessel activity data and vessel energy consumption data. In addition, besides the employment of one method alone, multiple methods can be used simultaneously. The relatively common approach is to use fuel consumption or the statistics of the calls of vessels arriving at and departing from ports to get the sum of ship emissions in the observed region, before using AIS data or LRIT data, etc., to analyze how to arrange the temporal and spatial distribution of emissions amount. The fuel-based method by energy consumption per vessel can also be employed to calculate the fuel consumption per voyage, before using the AIS-based activity method to distribute the fuel consumption or emissions per voyage to this segment of the navigation track; thus, further refining the spatial distribution per voyage.

2.2. Comparative Analysis

2.2.1. Sorting Out of Data Required for Each Method

Table 1 sets forth a summary of the five methods discussed above, including the principle of calculation, the features of each method, and the basic data used. The calculation principles, data requirements, and calculation formulae for particulate matter and gaseous pollutants are the same, and only the values of some calculation factors such as emission factors are different.

Table 1. Calculation principle and required data of the main methods.

Name			**Method 1 Activity-Based Method by Dynamic Vessel Data**	**Method 2 Activity-Based Method by Vessel Calls**	**Method 3 Fuel-Based Method by Regional Energy Consumption**	**Method 4 Fuel-Based Method by PTK/FTK**	**Method 5 Fuel-Based Method by Energy Consumption per Vessel**
Type of Method			Bottom-up	Top-down	Top-down	Top-down	Bottom-up
Principle of Calculation			Activity-based	Activity-based	Fuel-based	Fuel-based	Fuel-based
Data Requirements	Vessel Activity Level Data	Source data	Dynamic vessel activity data, such as AIS data	Number of vessels calls arriving at ports	Regional vessel energy consumption data	PTK and FTK	Energy consumption per vessel
		Computed data based on source data	Real-time position per vessel Working hours per vessel under different operating modes	Number of vessels by type/tonnage	Total fuel consumption by vessels in an observed region Fuel type	PTK/FTK by vessel type	Position per vessel per voyage Fuel consumption per vessel per voyage Fuel type, etc.
	Basic Vessel Information		Power of engines and boilers per vessel Real-time engine load per vessel Engine low-load adjustment factor Fuel information Adjustment factor for emission control measures, etc.	Average of power of engines and boilers of vessels of the same type/tonnage Average of engine load factors of vessels of the same type/tonnage under different operating modes, etc.	/	Intensity of energy consumption per turnover unit ($t/10^4$ t·km)	Adjustment factor for emission control measures
	Emission Factor		Power-based emission factor (g/kW·h)	Power-based emission factor (g/kW·h)	Fuel-based emission factor (g/kg fuel), etc.	Fuel-based emission factor (g/kg fuel), etc.	Fuel-based emission factor (g/kg fuel), etc.

2.2.2. Comparison of Main Characteristics of Each Method

Based on an analysis of the principle of calculation and features of data inputs, we summarized the applicability, complexity and time of calculation, accuracy of results, temporal and spatial resolutions of results, ability to calculate for transit vessels, distinguishability of vessel types, distinguishability of operating modes, among other pros and cons of five methods in Table 2.

Method 1 and 5 undertake calculations per vessel, and therefore feature high temporal and spatial resolutions and high accuracy in results which are sensitive to vessel type and tonnage. It is, however, complicated and requires cumbersome calculation work. Comparatively speaking, Method 1 has higher temporal and spatial resolutions, but emissions are converted from engine power and running hours, making it less accurate than Method 5; Method 5, using energy consumption data per voyage, provides lower temporal and spatial resolutions than Method 1, but higher accuracy of results, as emissions are based on actual energy consumption data, free from the error caused by conversion.

Method 2 involves generalization and averaging on top of Method 1. It makes calculation easier but produces less accurate results than Method 1 and is void of temporal and spatial distribution. Usually, vessel call statistics are based on vessels at birth at a port or in a region, broken down by vessel type and tonnage. Hence, the calculation results of Method 2 are type/tonnage-sensitive.

Table 2. Comparison of technical characteristics and applicability of main methods.

Name	**Method 1 Activity-Based Method by Dynamic Vessel Data**	**Method 2 Activity-Based Method by Vessel Calls**	**Method 3 Fuel-Based Method by Regional Energy Consumption**	**Method 4 Fuel-Based Method by PTK/FTK**	**Method 5 Fuel-Based Method by Energy Consumption per Vessel**
Applicability for Different Scales	Large scale = Medium scale = Small scale	Small scale > Medium scale > Large scale	Large scale > Medium scale > Small scale	Large scale > Medium scale > Small scale	Large scale > Medium scale > Small scale
Complexity and Time of Calculation	★ High and long	★★ Medium and medium	★★★ Low and short	★★★ Low and short	★ High and long
Accuracy of Results	★★★★ Moderately high	★★★ Average	★★ Moderately low	★ Low	★★★★★ High
Temporal Resolution of Results	★★ Fine	☆ No	☆ No	☆ No	★ Moderately fine
Spatial Resolution of Results	★★ Fine	☆ No Resolution by region/country depends on activity level data	☆ No Unclear scope of calculation	☆ No Unclear scope of calculation	★ Moderately fine
Ability to Calculate for Transit Vessels (no mooring)	Yes	No	No	No	Yes
Vessel Type Separation	Yes	Yes	No	No	Yes
Operating Mode Separation	Yes	Yes	No	No	Dependent on whether activity level data calculates energy consumption by operating modes
Emission Source Separation	Yes	Yes	No	No	Dependent on whether activity level data calculates energy consumption by emission source

Notes: ">" represents "superior to". "=" represents "equivalent to". ☆ (hollow pentagram) means that the method does not have the ability. ★ (solid pentagram) indicates that the method has the ability. The more solid the pentagrams, the more complete and significant the ability. See the text descriptions in each box for specific degree descriptions. **Large scale** regions are generally regions over 1000 km, such as countries and states; **medium scale** regions are generally regions between 100 and 1000 km, such as the Yangtze River Delta region and the Bohai Sea Rim region in China; and **small scale** regions are generally regions under 100 km, such as ports and cities.

Methods 3 and 4 are mainly based on statistical data and both non-refined calculation methods, which are more applicable for quick and rough estimation of a region's total emissions, or to effectively reflect the long-term trend of emission changes over years. It is not complicated, but the results are of low accuracy and void of temporal and spatial distribution. Moreover, with respect to Method 3, most countries and regions produce fuel consumption statistics in two ways. One way is to sum up fuel consumption by vessels registered in the region. The other way is to sum up fuel refills/sales in the region. Both figures may deviate from the actual fuel consumption by vessels in the region; with respect to Method 4, PTK/FTK refers to the turnover of vessels registered in this region, which has some discrepancy compared with the actual energy consumption from vessels navigating in this region, and on top of this, this method has difficulty in accurately estimating emissions of deadhead vessels. Hence, Methods 3 and 4 have low accuracy and unclear objects and boundary of calculation.

2.2.3. Analysis of Applicability of Each Method

This study recommends Methods 5, 1, 3, 4/ 2 in a descending order of preference for large-scale ship emissions inventory compilation, as shown in Figure 2; recommends Method 5 (if accuracy is the first priority) or Method 1 (if temporal and spatial resolutions are given first priority), followed by Methods 2, 3, and 4 in a descending order of preference for small- and medium-scale ship emissions inventory compilation, as shown in Figure 3. The granularity and accuracy of source data obtained are of vital importance and have some effect on the order. The best calculation method shall be determined subjected to realities.

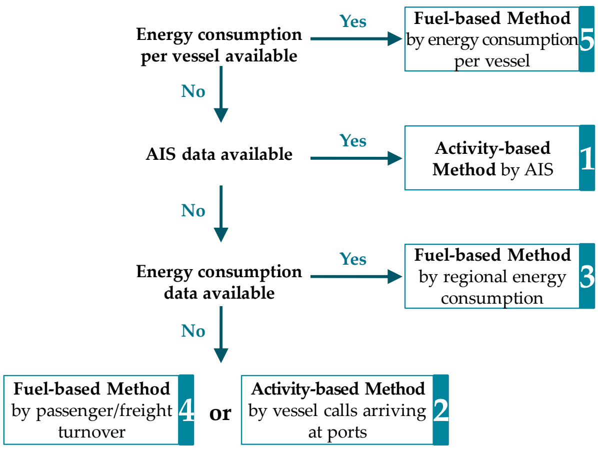


Figure 2. Methods recommended for large-scale inventory compilation.

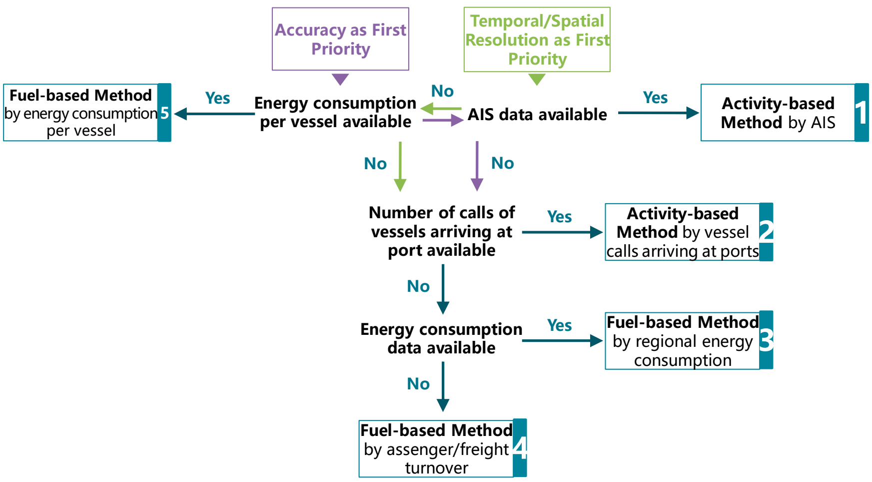


Figure 3. Methods for medium/small-scale inventory compilation.

3. Case Studies

To further examine the features of the said methods, the author chose three typical regions representing large-scale, medium-scale, and small-scale calculations, and applied different methods to arrive at SO_2 emission inventories for sea-going ships and ocean-going vessels. The patterns of computed results by five methods are detailed in Section 3.2 and compared in Section 3.3.

3.1. Scope of Research

(1) Observed Regions.

The space is delineated in a different way for each method. Taking the activity-based method by dynamic vessel data as an example, the paper roughly delineated space as follows: the large-scale region observed covers part of China and surrounding maritime waters (102.0° E~126.0° E, 12.6° N~41.6° N), see ① in Figure 4; the medium-scale region observed is the Yangtze River Delta region (120.0° E~124.0° E, 27.6° N~33.6° N), see ② in Figure 4; and the small-scale region observed is Tianjin Port (117.35° E~118.34° E, 38.64° N~39.24° N), see ③ in Figure 4.

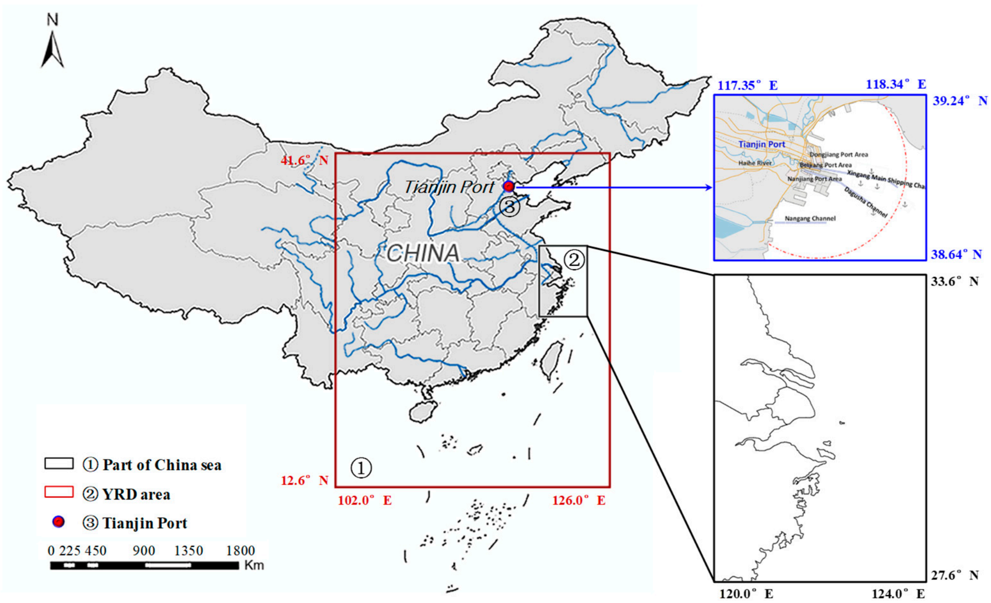


Figure 4. Sketch map of the study area.

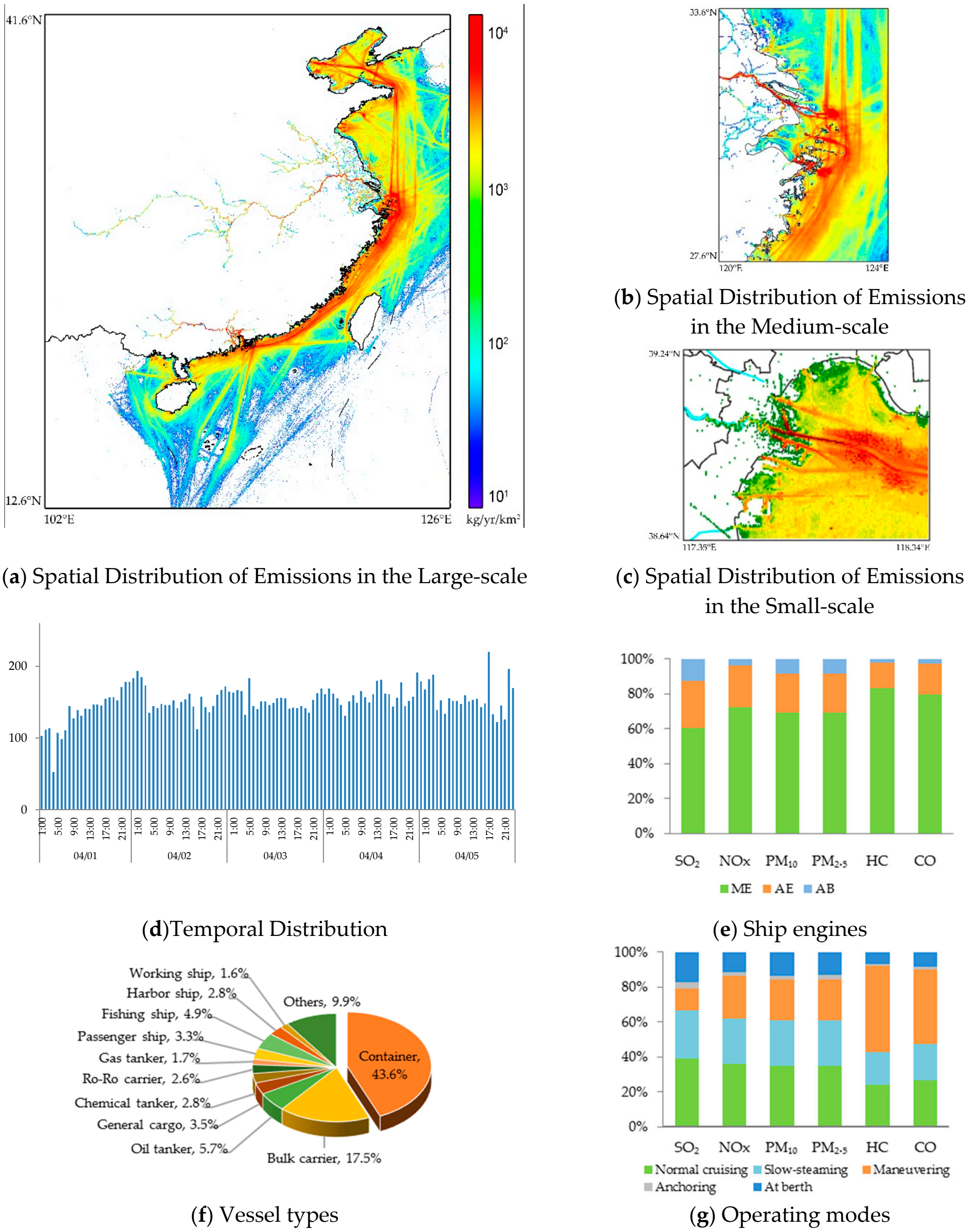
(2) Time Frame.

The time frame is from 1 January to 31 December 2014. As we all know, China began to double down on shipping-related air pollution control from 2015 onwards. All regions phased in some measures to cut emissions, for example, by replacement with low-sulfur fuel in vessels, use of vessels powered by clean energy such as LNG, and use of shore power supply in berthing, etc. For this reason, the computed results of ship emissions between 2015 and 2019 need to be adjusted for the complicated pollution control policies implemented across the country. As accurate information about the regions to which such controls were applied and to what extent they were used is not available, therefore, to avoid the interference by the policies, the paper chose 2014, the year immediately preceding the roll-out of those controls, as the time frame observed. The effect of different kinds of atmospheric control measures on ships is not considered, if any.

3.2. Patterns of Computed Results by Different Methods

3.2.1. Method 1 Activity-Based Method by Dynamic Vessel Data (AIS)

The temporal and spatial boundaries of calculation in Method 1 are clear-cut (Figure 4). We calculated the ship emission inventories for three observed regions by Method 1 and illustrated the computed results in Figure 5. Figure 5a–c represents the spatial distribution of emissions in large-scale, medium-scale, and small-scale observed regions, respectively. With the spatial resolution as fine as 50 m, Method 1 is able to clearly show high-emission areas. Let us take the emission inventory for the large-scale observed region as an example. Figure 5d shows the temporal distribution of emissions summed up on an hourly basis. The temporal resolution in Method 1 can be as fine as 10 s. Figure 5e illustrates the distribution of emissions from main engines, auxiliary engines, and boilers. Figure 5f represents the distribution of emissions by vessel type and Figure 5g by operating mode (cruising status) (Chen et al., 2017).



(**a**) Spatial Distribution of Emissions in the Large-scale

(**b**) Spatial Distribution of Emissions in the Medium-scale

(**c**) Spatial Distribution of Emissions in the Small-scale

(**d**)Temporal Distribution

(**e**) Ship engines

(**f**) Vessel types

(**g**) Operating modes

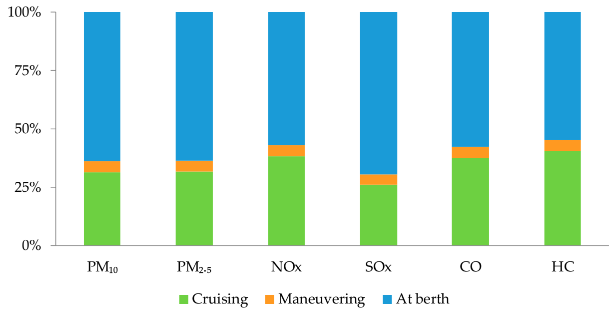
Figure 5. Diagrams of computed results by Method 1.

3.2.2. Method 2 Activity-Based Method by Vessel Calls at Ports

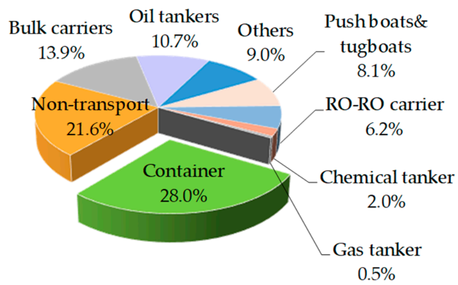
The patterns of the computed results by Method 2 are presented in Table 3 and Figure 6. No spatial distribution is available. The results reflect pollutant emissions by vessel type and operating mode. The temporal boundaries of calculation in Method 2 are clear-cut, while the spatial boundaries are moderately clear, extending outwards by a certain distance from the center of each port. As shown in Figure 4, the large-scale, medium-scale, and small-scale observed regions extend outwards by about 300, 150, and 20 nm, respectively.

Table 3. Computed results of SO_2 emissions by vessels in Method 2. Unit: 10^4 t.

	Large-Scale Part of China and Surrounding Maritime Waters	Medium-Scale Yangtze River Delta Region	Small-Scale Tianjin Port
SO_2 emissions by vessels	88.2	28.7	2.3



(**a**) Operating modes



(**b**) Vessel types

Figure 6. Diagrams of computed results by Method 2 (small-scale region, Tianjin port).

3.2.3. Method 3 Fuel-Based Method by Regional Energy Consumption

We calculated the ship emission inventories for three observed regions of three scales by Method 3. No spatial distribution is available. The results reflect total air pollutant emissions by vessels in the observed regions and are set forth in Table 4.

Table 4. Computed results of SO_2 emissions by vessels in Method 3. Unit: 10^4 t.

	Large-Scale Part of China and Surrounding Maritime Waters	Medium-Scale Yangtze River Delta Region	Small-Scale Tianjin Port
SO_2 emissions by vessels	98.7	19.1	1.4

The temporal boundaries of calculation in Method 3 are clear-cut, while the spatial boundaries are unclear, dependent on the statistical range of fuel consumption data, which is either fuel consumption by vessels registered in the region or fuel refills in the region. Hence, it is difficult to clearly define the spatial boundaries of calculation, especially for medium-scale and small-scale regions.

3.2.4. Method 4 Fuel-Based Method by PTK/FTK

We calculated the ship emission inventories for three observed regions of three scales by Method 4a and 4b. No spatial distribution is available. The results reflect total air pollutant emissions by vessels in the observed regions and are set forth in Table 5.

Table 5. Computed results of SO_2 emissions by vessels in Method 4. Unit: 10^4 t.

	Large-Scale Part of China and Surrounding Maritime Waters	Medium-Scale Yangtze River Delta Region	Small-Scale Tianjin Port
Method 4a	211.8	67.9	4.7
Method 4b	90.72	13.70	0.35

The temporal boundaries of calculation in Method 4 are unequivocal. The spatial boundaries in Method 4a are very unclear, as its source data is statistics of PTK/FTK, which is usually total turnover handled by all vessels registered in the region worldwide. Hence, the result is often higher than that of other methods. The spatial boundaries in Method 4b are fairly unclear, but compared to Method 4a, it is able to limit the scope of calculation to the observed region to some extent by using the variable "transport distance".

3.2.5. Method 5 Fuel-Based Method by Energy Consumption per Vessel

The calculation platform for Method 5 is under development. Based on the principle of calculation and the analysis of source data, the results of Method 5 are of a pattern similar to that of Method 1, that is, providing relatively fine temporal and spatial distribution and the distribution of emissions by vessel type and tonnage. The temporal and spatial boundaries of calculation in Method 5 are distinct.

3.3. Comparison of Emission Calculation Results

As discussed in Sections 2.2.2 and 3.2, the methods differ in the objects of calculation and the delineation of spatial boundaries. We tried our best to adjust the objects of calculation and spatial boundaries in all methods to make them as consistent as possible, so as to have a general understanding of the variances in total ship emissions derived from different methods.

Table 6 and Figure 7 indicate that the computed results of Methods 2, 3, and 4b are on the low side, while those of Method 4a are on the high side, if the computed results of Method 1 are settled for as the benchmark. The computed results for the large-scale inventory can be sorted in the ascending order of deviation as Methods 1, 3, 4b, 2, and 4a, while those for the medium-scale and small-scale inventories similarly as Methods 1, 2, 3, and 4.

Table 6. Comparison of illustrative computed results by each method. Unit: 10^4 t.

Scale	Region as Example	Item	Method 1 Activity-Based Method by Dynamic Vessel Data	Method 2 Activity-Based Method by Vessel Calls at Ports	Method 3 Fuel-Based Method by Regional Energy Consumption	Method 4 Fuel-Based Method by PTK/FTK.	
						a. Statistics PTK/FTK	b. Traffic Load × Distance
Large-scale	Part of China and surrounding maritime waters	SO_2 Emissions	119.0	88.2	98.7	211.8	90.72
		Deviation from Method 1	–	−25.9%	−17.1%	+78.0%	−23.8%
Medium-scale	Yangtze River Delta region	SO_2 Emissions	36.2	28.7	19.1	67.9	13.70
		Deviation from Method 1	–	−20.9%	−47.3%	+87.3%	−62.2%
Small-scale	Tianjin port	SO_2 Emissions	2.9	2.3	1.4	4.7	0.35
		Deviation from Method 1	–	−19.8%	−51.2%	+59.4%	−88.1%

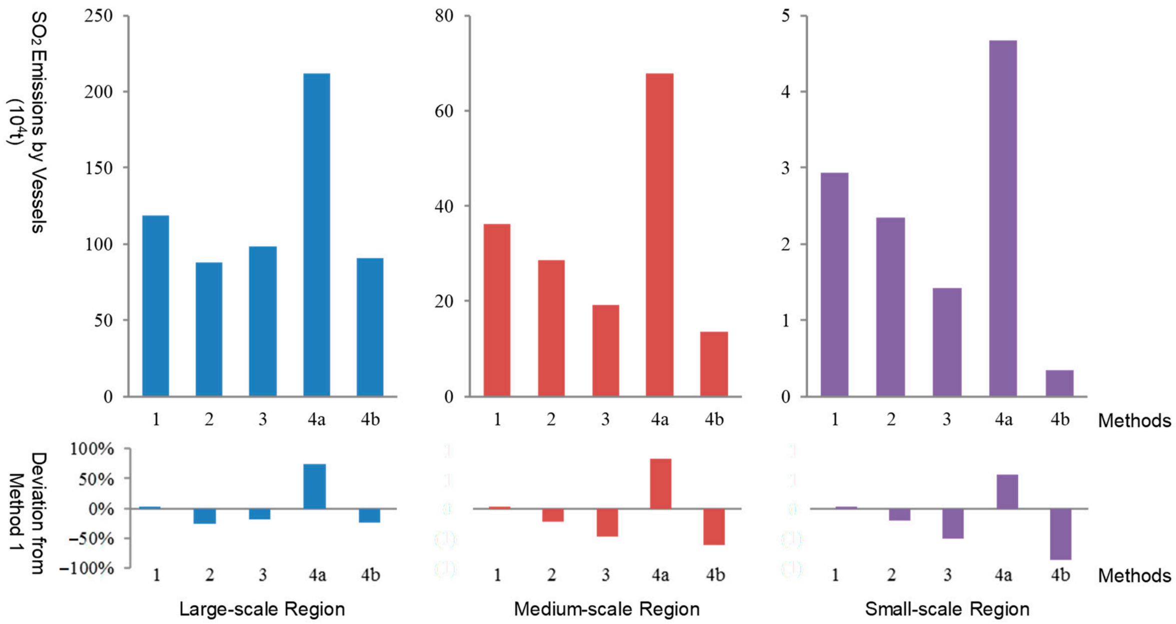


Figure 7. Comparison chart of illustrative computed results by each method.

To be more specific, Method 2 is more applicable to the calculation of the small-scale inventory. As the scale grows, so does the deviation. Methods 3 and 4 are preferred for the calculation of the large-scale inventory. As the scale grows, the deviation is smaller. The computed results in the case studies are consistent with the conclusion introduced in Section 2.2.

4. Conclusions

(1) A concept of calculation method for inventory was proposed based on fuel consumptions per ship and voyage fetched in the energy consumption reporting rule for ships. According to such principal analysis, this method improved further on the basis of various existing methods in terms of accuracy of results and also boasts of a great advantage on the temporal and spatial resolutions, etc., which can be regarded as a thought for improving the development of the compilation methods for inventory going forward.

(2) This study analyzed five inventory compilation methods for ship emissions, including the activity-based method by dynamic vessel data (Method 1), activity-based method by vessel calls at ports (Method 2), fuel-based method by regional energy consumption (Method 3), fuel-based method by PTK/FTK (Method 4), and fuel-based method by energy consumption per vessel (Method 5). Each of the said methods have different technical features. In terms of applicability, Method 1 applies to the calculation of inventories of varying scales; Method 2 is more applicable to small-scale calculation, ports, for example; Methods 3, 4, and 5 are more desirable for large-scale calculations, countries, and states, for example. In terms of accuracy of results, Methods 1 and 5 offer moderately high accuracy, Method 2 provides average accuracy, while Methods 3 and 4 produce low accuracy. In terms of resolution of results, Methods 1 and 5 provide high-resolution temporal and spatial distribution of ship emissions; Method 2 delivers low-resolution spatial distribution, while Methods 3 and 4 are incapable of spatial distribution.

(3) Based on the case study, the computed results vary from one method to another significantly, with the maximum deviation of up to 87%. Hence, it is advisable that the optimal inventory compilation method for ship emissions should be chosen based on the actual needs in inventory compilation and the data available, using as reference the comparison tables of the features of different methods (Tables 1 and 2) and the

preference order of recommended methods (Figures 1 and 2) provided herein, so as to deliver the best possible results. In a nutshell, the author recommends: Methods 5, 1, 3, and 2/ 4 in a descending order of preference for large-scale ship emissions inventory compilation; Method 5 (if accuracy is the first priority) or Method 1 (if temporal and spatial resolutions are given first priority), followed by Methods 2, 3, and 4 in a descending order of preference for small/medium-scale ship emission inventory compilations.

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