

Article

Spatial-Temporal Ship Pollution Distribution Exploitation and Harbor Environmental Impact Analysis via Large-Scale AIS Data

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Abstract: Ship pollution emissions have attracted increasing attention in the maritime field due to the massive growth of maritime traffic activities. It is important to identify the ship emissions (SEs) magnitude and corresponding spatial and temporal distributions for the purposes of developing appropriate strategies to mitigate environment pollution. The aim of this study was to estimate ship pollution emissions with various typical merchant ship types under different sailing conditions. We estimated the emission variation with a ship traffic emission assessment model (STEAM2), and then the ship pollution emission distribution was further visualized using ArcGIS. We collected data from the automatic identification system (AIS) for ships in New York Harbor and further analyzed the spatiotemporal distribution of pollutant emissions from ships. The experimental results demonstrate that the ship pollutant emission volume in the New York Harbor area in 2022 was 3340 t, while the pollution in terms of CO, SO₂, C_xH_x, PM₁₀, NO_x, and PM_{2.5} was 136, 1421, 66, 185, 1384, and 148 t, respectively. The overall SEs from container ships, passenger ships, and tankers account for a large amount of pollution discharge. The pollutant emissions of container ships are significantly greater than that of their counterparts. Moreover, the spatiotemporal distributions of ship pollutant discharge can vary significantly among different ship types and sailing conditions.



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1. Introduction

With the continuous development of the shipping industry, maritime transportation plays a vital role in international trade and economic development, as shipping accounts for more than 80% of the goods volume for global trade activities. However, pollution from ship activities has become a serious problem. Ship emissions (SEs) pollution may degrade air quality, exacerbating the global warming problem and harming human health [1]. Approximately 3% of global greenhouse gas emission is derived from the shipping industry, and this figure may increase in the future with global trade development [2,3]. The global greenhouse gas (GHG) emissions from the shipping industry rose 9.6% from 977 million tons in 2012 to 1076 million tons in 2018. The latest Greenhouse Gas Emission Reduction Strategy for Ships report adopted by the International Maritime Organization (IMO) in 2023 shows that it is important to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030 compared to 2008 and to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040 compared to 2008 [4].

An automatic identification system (AIS) provides various maritime traffic participants with both static and kinematic data, such as ship position information, ship cargo data,

origin and destination ports, and ship speed [5]. AIS data may contain some outliers, and many studies have been conducted with machine-learning-related models to correct AIS data outliers [6]. Some researchers have proposed an ensemble framework based on a network of continuously operating reference stations that utilizes multiple interpolation methods to address the lack of AIS data [7–9]. With the increase in maritime activities, ship pollution reduction has been a subject of significant focus in the maritime community [10]. Many studies have been conducted to estimate the carbon emissions of the main engine, auxiliary engines, and boilers of ships under different sailing conditions [11]. A novel SE inventory supported by bottom-up activity was proposed to identify overall pollution discharge in the SE control areas [12]. The vessel emission inventory for the Pearl River Delta includes both identified and unidentified vessels [13]. The activity-based approach and data sample method were introduced to accurately calculate the ship exhaust emission inventory [14]. In addition, some efforts have recently been made to classify SE inventory compilation methods and enhance the compilation efficiency [15,16]. AIS data were widely used to estimate ship pollution discharge in the Baltic Sea region during 2009.

The accuracy of ship pollution discharge estimation may vary for different calculation models. The first detailed international description of the calculation methods and required calculation data for pollutant discharge from ships was presented around 2000 [17]. In 1999, the EPA issued a correction of the previously published emission factors for ships. The EPA has recently further studied crucial factors in SEs involved with main engine power, ship maneuvering activity pattern, etc. Currently, the main methods for pollution discharge from ships include ship-activity-based methods [18], methods based on modification of the virtual fleet [19], methods based on ship operating modes [20], and power-based methods [21]. The accuracy of SE estimation is continuously optimized and improved by classifying the ship types and sailing states or by utilizing a modular SE modeling system. The air pollutant emissions caused by ships were also explored using different time intervals (e.g., 1, 3, 30 min) using AIS data [22,23].

To develop effective emission measures to control the discharge of pollutants, different computational models and methods have been used by institutions and scholars for emission inventory estimation. Overall, SE estimation models can be roughly divided into fuel-consumption-based (top-down) models and approaches based on ship traveling activity (bottom-up). Yang et al. proposed a novel framework to exploit the highly temporal SE inventory using ship AIS data collected in the Tianjin Port area in China [24]. Additional efforts have also been made to explore activity-based methods to obtain accurate SE data [25,26]. Many studies were conducted to mitigate the insufficient ship data disadvantage with EPA rules, which suggested that larger ship gross tonnage can lead to greater ship pollution discharge [27]. Studies have also focused on linking Gaussian bubble-related models with AIS data records from ships sailing in different ports [28].

The application of a dynamic method can improve the estimation accuracy of ship pollution discharge [29]. Some scholars have conducted spatial analyses based on the geographic density of gas emission inventories [30]. The researchers analyzed pollution emissions from incoming and outgoing marine vessels at the Port of Incheon [31]. The STEAM2 model can be used to estimate pollutant emissions from ships in different scenarios by applying ship voyage data and relevant parameters [32–34]. Some researchers have determined the relationship between ship parameters and pollution emissions based on dynamic modeling of drag and load coefficients [35].

Previous studies were carried out to accurately quantify SE volume by considering various ship maneuvering factors. Little attention has been given to analyzing the spatial and temporal aspects of estimated emission characteristics. Jalkanen et al. proposed the STEAM model for calculating NO_x and SO_x emissions based on the information provided by AIS and then proposed the STEAM2 model with the addition of the estimation of CO and PM pollutants [32,36]. While models based on ship fuel consumption can show the distribution of SEs, power-based bottom-up models are used to not only calculate SEs but also to support a variety of kinematic data (ship speed, voyage, real-time longitude,

real-time latitude, etc.) [37,38]. In this study, six types of SE pollution were explored via bottom-up logic, and the STEAM2 method was employed to estimate the overall emissions via large-scale AIS data. We also analyzed spatiotemporal emission distributions for different ship types with the help of ArcGIS software [39]. The experimental results obtained, including the estimates of total SEs and the characteristics of the temporal and spatial distribution of pollution emitted by different types of ships, are summarized and discussed, and suggestions for future research directions are given.

2. Methods

2.1. Research Area

Ships are required to be equipped with AIS capability to ensure maritime traffic safety; the AIS data provide real-time information about ship movements in waterways. Moreover, ship officials on board can take the initiative to avoid potential maritime traffic accidents by negotiating with the officials on neighboring ships. AIS data can be broadly categorized into static and dynamic types. Specifically, static AIS data include the maritime mobile service identity (MMSI), ship name, ship type, cargo data, etc. The AIS dynamic data primarily include a timestamp, the ship's latitude and longitude, the speed, and the heading direction.

The study area for this research is the Port of New York, which is one of the busiest ports in the world. The Port of New York is one of the most important shipping and trade centers in the U.S. and globally accounts for 40% of U.S. East Coast trade, with an excellent logistics and transportation network connecting roads, railroads, and highways across the country. Cargo activity in the Port of New York has been on a steady upward trend in recent years, reaching a milestone in 2022 when container throughput exceeded 9 million units for the first time. In addition, scholars have analyzed the history and current state of New York Harbor through the lens of the urban political economy [40]. Considering that the emissions generated by the harbor have a significant impact on increasing health hazards, Hagler et al. established an air monitoring station to study the impact of enhanced emission control measures on air quality in New York Harbor [41]. Therefore, New York Harbor was chosen in this study for the analysis of pollution emission patterns.

The geographic boundaries of the study are from 40.48° N to 41.04° N latitude and 73.61° W to 74.31° W longitude (Figure 1), and the statistical timeframe for the data analyzed is from 1 January to 31 December 2022. We conducted a detailed study to assess the air emissions emitted by ships while navigating in New York Harbor. Note that data can be accessed by sending an email to the corresponding author. Figure 2 shows the geographic location of the port in detail, including latitude and longitude.

2.2. Research Techniques

The “bottom-up approach” is a commonly used method for estimating pollution emissions from ships. This method places emphasis on the specific details of the ship's activities and estimates pollution emissions by analyzing in detail the ship's sailing, maneuvering, berthing, and other specific activities. We first took the data provided by AIS (downloaded from www.marinecadastre.gov and accessed on 30 June 2023) as the basis and carried out processing such as data cleaning and multisource data fusion to determine the ship's engine type. Then, we collected the necessary modeling parameters of the ship's operation, such as the power of the main engine, the running time, and the load of the main engine. Finally, combining the factors such as the type of the ship and the state of the ship's voyage, the processed data were entered into the STEAM2 model, and then we utilized the specific emission factors to calculate the pollution emission of the ship in the area. The emission for a type of ship pollution (the measurement unit is g) caused by the ship's main engine, auxiliary engine, and boiler (the measurement unit is kWh) can be formulated as Equation (1) [11].

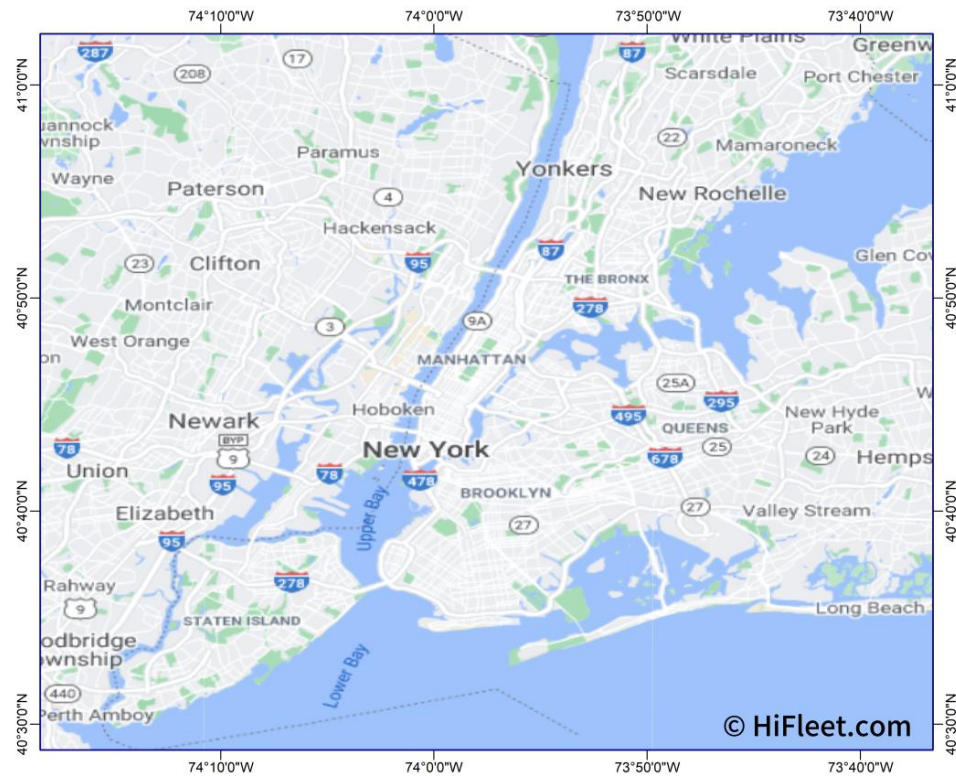


Figure 1. Specific study areas in the Port of New York.

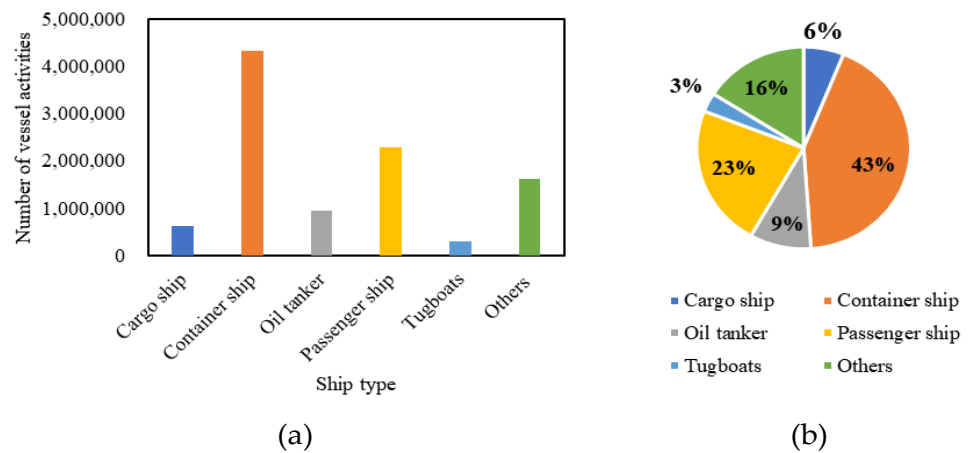


Figure 2. Vessel types in New York harbor waters in 2022; (a) number of vessel types; (b) proportion of vessel types.

$$E_{ij} = P \times LF_j \times T \times EF_i \quad (1)$$

where i represents the type of pollutants emitted by the ship, and j is the sailing state of the ship. E_{ij} denotes the emission of the i th pollutant at the j th sailing state, and the unit is tons. The symbol P indicates the rated power of the ship engine, and the unit is kW. LF_j is the engine load in the j th sailing conditions. The symbol T is the time for the ship to pass through each cross-section, and the unit is s, while the symbol EF_i denotes the emission factor of the i th ship pollutant.

2.2.1. Ship Type

We collected the ship AIS data needed for this study from publicly available datasets. Approximately 10.14 million ship activity datapoints were collected. These statistical data are generated when ships perform various activities during their voyages, which

were sampled from AIS data from 2022 for ships navigating in the vicinity of New York Harbor [42]. Figure 2a indicates that there were more than 10 million ship trajectory segment samples for the waterways. Figure 2b shows that container ships account for 43% or about 4.36 million vessel movements, which indicates that cargo in the Port of New York was primarily transported by container ships. Passenger ships, cargo ships, oil tankers, and tugboats account for 23%, 6%, 9%, and 3% of these movements. The overall ship pollution discharge for CO, SO₂, C_xH_x, PM₁₀, NO_x, and PM_{2.5} was approximately 136, 1421, 66, 185, 138, and 148 tons, respectively.

Emission inventories in datasheet format are the most common result of employing an AIS dataset to obtain SE data. Such an inventory provides a detailed description of quantitative emissions from each ship and can be used for visual pollution assessment. However, it cannot show the distribution of SEs or their spatial and temporal variability, nor can it identify the location of high-emission areas or the timing of emission peaks. In addition, the ability to explain the correlation between ship characteristics and emissions is limited. In this study, SE estimation was applied to identify useful knowledge for SE control. A typical SE inventory was analyzed in terms of spatial, temporal, and ship attributes.

2.2.2. Ship Sailing State

When a ship navigates the waterway and enters or leaves the harbor, the speed changes accordingly, and different speeds lead to different sailing conditions. The ship navigational state determines the working status for the diesel engine. We calculated the air pollutant discharge for different ship sailing statuses to accurately determine ship air pollutant discharge inventory. In this study, ship navigational conditions were classified into four driving modes via sailing speed distributions. More specifically, the ship is considered to be in a cruising state when its speed is more than 12 knots. The ship's state is classified as low-speed cruising when its speed is more than 8 knots and less than 12 knots. We consider the ship to be in the berthing state when the ship sailing speed is less than 1 knot.

The navigation speed of ships is usually slow due to the complex hydrological environment and narrow width of the waterway. This has a specific impact on the diffusion and environmental impact of SEs. There are few AIS data records for the berthing state in the collected AIS data, and thus the corresponding AIS data samples were categorized as the berthing status for the ship pollution analysis. Based on the public AIS data obtained from the Internet, the navigation states of the ships in the region were classified into four categories according to the navigation speed characteristics and the load ratio coefficient of the ship's major engine: the cruising state, low-speed cruising state, maneuvering state, and berthing state. The basis for the determination of each navigation state is shown in Table 1.

Table 1. Classification of sailing conditions.

Ship State	Ship State Determination
cruise	speed greater than 3 knots and load value larger than 65%; or speed greater than 12 knots
low-speed cruise	speed greater than 3 knots and load value falls in the interval 20% and 65%; or speed ranges from 8 knots to 12 knots
maneuvering	speed less than 1 knot and load value smaller than 20%; or speed ranges from 1 knot to 8 knots
berthing	other

In this study, the ship types were classified into six categories, namely, container ships, cargo ships, passenger ships, oil tankers, tugboats, and other ship types. Note that the other ship types include warships and additional ships for which AIS facilities may be unavailable. SEs are calculated with the ship's main engine power (auxiliary engines and boiler) and overall running time (i.e., duration for which ship engines are in working status). The time used for this study was obtained from the timestamp difference between

neighboring AIS data samples for the same ship. Ship engines can be broadly categorized into three main types according to their usage and performance, namely, the main engine, auxiliary engines, and boilers. The impact of emissions from auxiliary boilers was ignored in this case since ships' auxiliary boilers are usually used to generate steam or hot water and emit small amounts of pollutants.

2.2.3. Engine Power and Load

In the process of determining the main engine power of a ship, we used various methods to account for the lack of information on the rated power of the main and auxiliary engines in the AIS data publicly available on the Internet. Firstly, we queried the Lloyd's Register database to obtain accurate power information on the ship's main engine. Then, we used the ship MMSI provided in the AIS information as the key search factor to query the national maritime traffic safety management information service platform to obtain the ship's main engine power and other relevant records. Next, for the small number of ships with no available information on main engine power, we combined the ship's basic scales. Finally, for the few remaining ships where main engine power was not recorded, we extrapolated the ship's main engine power by combining the ship's basic dimensions and other data, including maximum design speed and load capacity.

The power rating of a ship's engine should be a constant when calculating pollutant discharge. However, the sailing speed in the cruising condition is generally 94% of the ship's maximum speed, the ship's main engine output is 83% of the ship's maximum continuous rated power, and the boiler is off in most cases. The unmatched ship's main engine power rating was assumed to be 1700 kW [43]. The auxiliary engine power can also be estimated by multiplying a ratio into the main engine rating power. The ratios used to determine the power of the main and auxiliary engines are shown in Table 2 [44].

Table 2. Coefficients used for estimating auxiliary engine power.

Ship Type	Coefficients
passenger ship	0.278
container ship	0.186
tugboat	0.269
cargo ship	0.222
oil tanker	0.211
others	0.269

The operating load factor of a ship's engine has a direct impact on the engine's internal combustion process, which in turn affects the emission of air pollutants. The internal combustion process is the main source of air pollutant emissions from ships, and energy efficiency is optimized when the engine is operated at a load factor of about 80 percent. The efficiency of the engine decreases significantly under conditions below this load factor, in particular, at low load factors of less than 20 percent, which usually occur when the ship is undergoing low-speed cruising, preparing for berthing, or leaving a port. The load factor of the ship's main engine is closely related to the actual traveling speed of the ship and its design speed; the specific relationship can be seen in Equation (2) [12].

$$LF_j = \left(\frac{V_a}{V_{max}} \right)^3 \quad (2)$$

where V_a demonstrates the ship sailing speed in real-world conditions, and the unit is knots. V_{max} denotes the maximum ship design speed value.

2.2.4. Emission Factors

To accurately calculate the pollution emissions from ships, it is necessary to obtain accurate emission factor data, which can be extrapolated through actual ship tests, simula-

tions, or based on existing research results. In practical applications, the emission factors are usually adjusted according to the actual operation of the ship (e.g., sailing speed, loading rate). The formula based on the power method used for calculating the ship emission factor in this study is shown in Equation (3) [43]:

$$EF = BEF \times LCF \times FCF \times CF \quad (3)$$

where BEF is the basic emission factor in grams per kilowatt; LCF is the low load correction factor, which is only corrected for the ship's main engine; FCF is the fuel correction factor; and CF is the correction factor for emission control technology.

Since different ship types and operating conditions may negatively affect the SE model, obtaining the appropriate emission coefficients is crucial for determining the pollution emissions from ships. The engines of the typical ship hosts in this study area are medium- and low-speed diesel engines, the type of fuel is diesel, and the sulfur content level of the diesel oil is in the range of 1% to 3.5% [45]. Our study focuses on the spatial and temporal characterization of pollutant emissions. The fuel oil for ships in the region was specified as diesel fuel with a sulfur content of 0.1%, with no emission control technology corrections considered, and the specific emission coefficients are shown in Table 3 [43].

Table 3. Emission coefficient distributions for main and auxiliary engines.

Engine Type	Oil	CO	C _x H _x	NO _x
main engine	203	1.1	0.5	13.2
auxiliary engine	217	1.1	0.4	13.9
boiler	290	0.2	0.1	2.0

Fuel oil greatly influences on the emission of sulfur dioxide and particulate matter from ships, and the influencing factor is mainly the sulfur content. We determined the emission factors for sulfur dioxide and particulate matter based on fuel consumption and sulfur content with formulas such as Equations (4)–(6) [43]:

$$BEF_{SO_2} = BESF \times 2 \times 0.97753 \times S \quad (4)$$

$$BEF_{PM_{10}} = 0.23 + BESF \times 7 \times 0.02247 \times (S - 0.0024) \quad (5)$$

$$BEF_{PM_{2.5}} = 0.92 \times BEF_{PM_{10}} \quad (6)$$

where BEF_{SO_2} is the basic emission factor for sulfur dioxide; $BEF_{PM_{10}}$ is the basic emission factor for PM_{10} ; $BEF_{PM_{2.5}}$ is the basic emission factor for $PM_{2.5}$; $BESF$ is the fuel consumption in grams per kilowatt; and S is the sulfur content of the fuel used by the ship.

3. Results

3.1. Analysis of Highly Contaminated Areas

Highly polluted areas in this study are those where the level of pollution due to ship activities exceeds that of other areas within the study area. Detecting highly polluted sea areas caused by SEs can help maritime regulatory and administrative departments take efficient measures to avoid further maritime pollution. To identify areas with high pollution, we first divided the study waters into grid cells, which are considered separate assessment areas. We calculated the total SEs within each grid cell based on the location and activity of ships within that grid. In this way, the impact of ship discharge on individual areas can be accurately quantified and localized to determine which grid cells are heavily polluted areas.

To obtain the spatial distribution of pollution values discharged from ships, we rasterized the grid by creating an 80×80 grid to evaluate the pollution discharged in the study area of the analysis. We calculated the pollutants discharged by each ship passing through the areas, and then, based on their geographic coordinates, we imported these emission

data as point attributes into the ArcGIS10.6 software. In this way, we summarized and analyzed the overall pollution discharge in the region. The visualization was obtained by collecting the spatial distribution of SEs in a hierarchical visualization scheme and spatially correlating the points in a grid in ArcGIS. Figure 3a–f show the distribution of CO, C_xH_x , NO_x , SO_2 , PM_{10} , and $PM_{2.5}$ pollutant emissions.

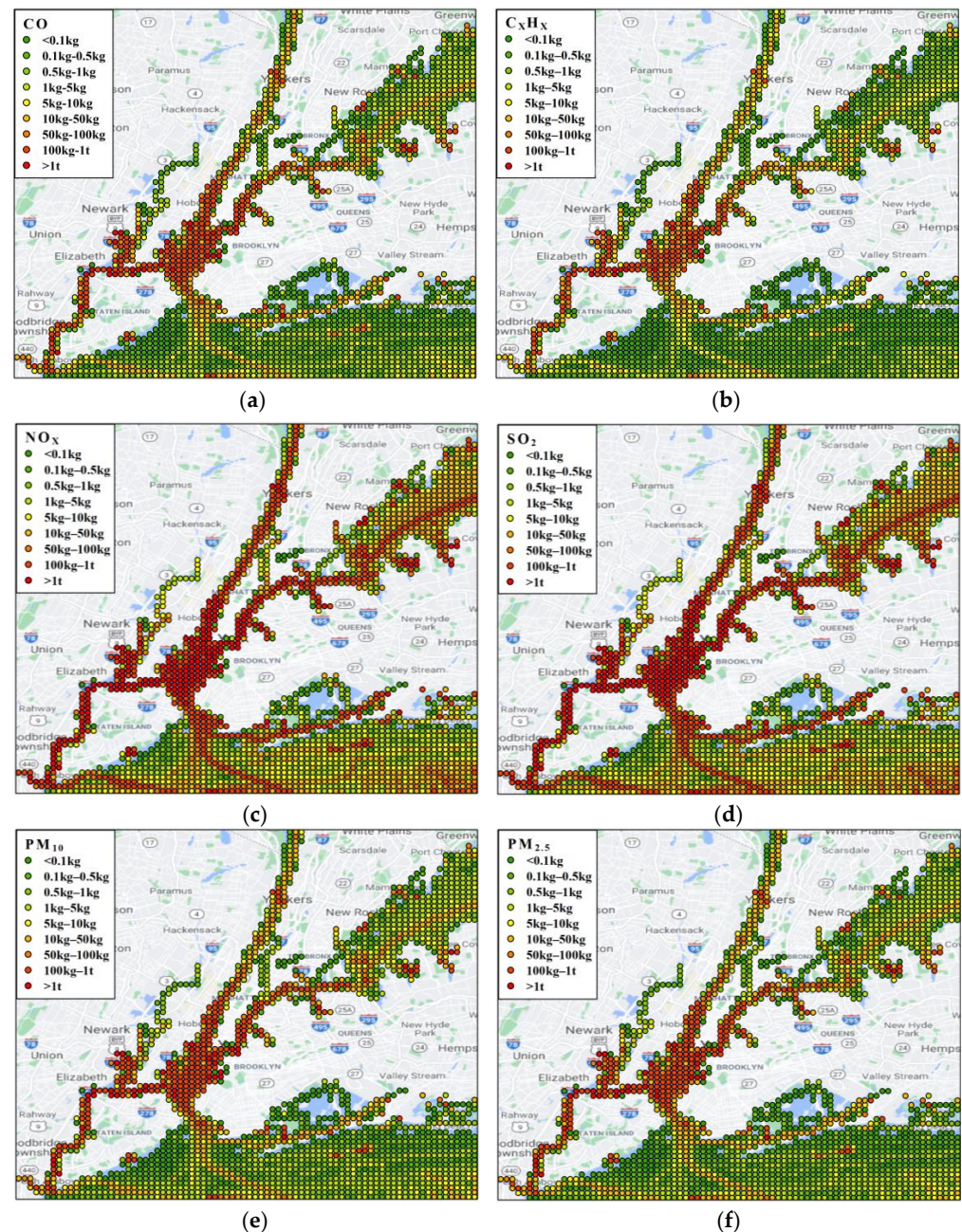


Figure 3. Typical ship pollution emission distributions in the study area; (a) Spatial distribution of CO; (b) Spatial distribution of C_xH_x ; (c) Spatial distribution of NO_x ; (d) Spatial distribution of SO_2 ; (e) Spatial distribution of PM_{10} ; (f) Spatial distribution of $PM_{2.5}$.

SEs in the port area were supposed to have a low volume considering that clean energy is consumed by ships in the port area. Ships are often required to use clean energy and shore-based power sources when entering ports to reduce emissions. In other words, the port area was supposed to suppress ship pollution discharge with the help of clean energy. However, ship pollution data in the study area indicated that there may be a large amount of ship pollution discharge in the port area. It can be observed that the high-pollution

areas of the harbor are mainly located around the sea area at the New York–New Jersey boundary, which is located near the mouth of the Hudson River and is an important ship traffic corridor. A large number of ships pass through this area, resulting in a high density of ships, and there are several harbors and terminals in the vicinity, which are important for cargo handling and ship docking. These activities generate large amounts of tailpipe emissions, wastewater emissions, and solid waste, resulting in high levels of pollutants. Moreover, this lower reach of the Hudson River that lies between the New York and New Jersey urban areas has a slower flow rate than that upstream and thus tends to accumulate pollutants; emissions from ships and wastewater are carried by the river to the vicinity of the New York–New Jersey boundary, contributing to higher levels of pollutants in the area.

In addition to the density of traffic flow, a reason for the high pollution in these areas may be the complex topographic conditions. The Hudson River is one of the largest rivers in the northeastern United States. Its mouth is located on the Atlantic coast, with a depth of more than 30 m in the Narrows, which is affected by the tides of the Atlantic Ocean. Large tidal variations result in changes in the river's water level and flow rate at different times and pose certain challenges to vessel passage and marine traffic. The coastline of the Hudson River estuary is more winding, with many bays, harbors, and channels. Due to river scouring and sediment load, a sand transport phenomenon occurs in the Hudson River estuary. Such a phenomenon may unexpectedly impact ship speed, ship traveling direction, and engine conditions. As a result, fuel consumption in the area may be considerably higher due to the difficulty of ship maneuvering.

3.2. Analysis of the Timing of Peak Emissions

3.2.1. Daily Ship Pollution Distribution Analysis

We divided the period of ship AIS data into hours based on the time distribution of ship berthing and de-berthing activities and considering that other time periods are not well characterized. The time period considered is from 00:00 to 12:00, as shown in Figure 4. The results show that the emission of each pollutant starts to rise from 02:00 a.m. and reaches the highest peak at 4:00 a.m., where it remains until 7:00 p.m. The ratio between the maximum and minimum values of each pollutant is approximately 1.5. Furthermore, the peak hour for pollutant discharge from ships approaching or leaving the port coincides with a period of enhanced atmospheric diffusion within the port. This reduces the impact of peak pollutant discharge from ships on the surrounding area's ambient air quality. After 8:00 a.m., the pollutant discharge from ships tends to level off, reducing the degree of pollution superposition during the peak traffic period. However, the pollutants emitted from ships have a more obvious impact on the surrounding ambient air quality during the time of poorer diffusion conditions, especially in the early morning and evening in summer, when the atmospheric stability is usually low, air convection is weak, and pollutants can easily spread in the lower airspace under hot conditions along with low wind speed. In such conditions, pollutants tend to accumulate at lower altitudes, which results in higher pollutant concentrations and poorer dispersion conditions.

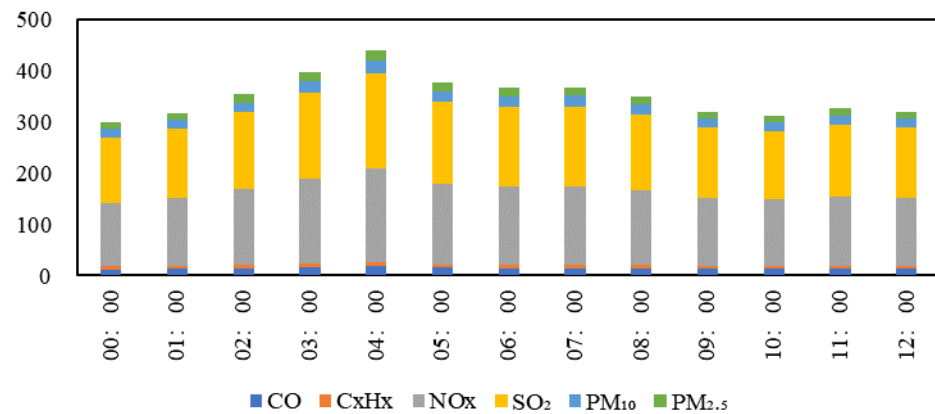


Figure 4. Daily ship pollution distributions in New York harbor area (unit: ton).

3.2.2. Monthly Ship Pollution Distribution Analysis

Figure 5 shows monthly variation in air pollutant discharge from ships in New York Harbor in 2022. The monthly variation rule of each pollutant is basically the same, and the emissions are lowest in June. May and June form the transition period from spring to summer when the weather is still generally cool and moderately humid. Together, this provides for more complete combustion of ship oil. In this way, the nitrogen oxides, particulate matter, and other incomplete combustion products can be significantly reduced. May and June are not peak shipping months and have wind velocities around New York Harbor that often favor the dispersion and dilution of pollutants and reduce the impact of pollution on land areas.



Figure 5. Monthly ship pollution distributions in New York harbor area (unit: ton).

Ship pollution was found to increase at peak times (approximately in July and October), and thus air quality in these months was worse due to the poorest atmospheric dispersion conditions in the spring. Shipping activity began to gradually increase in July when more ships entered and left New York Harbor, and higher levels of ship activity mean that more SEs are produced. The weather in the summer months is usually warmer and more humid, which can lead to incomplete fuel combustion, resulting in the production of more pollutants, such as NO_x and PM-related pollutants.

The relatively stable atmosphere in summer can lead to increased atmospheric stability, limiting the dispersion and dilution of pollutants and making them more likely to accumulate in the air. The weather begins to cool in October, which can lead to incomplete combustion. Lower temperatures may cause some ships to use high-sulfur fuels, which

can increase sulfur dioxide (SO_2) emissions. As the summer ends, atmospheric stability may begin to change, and weaker winds, lower stratospheric currents, and increased atmospheric stability may limit the dispersion and dilution of pollutants, causing emissions to accumulate at lower altitudes. October is the fall season and also marks the peak of some shipping activity, with more ships entering and exiting New York Harbor, resulting in higher levels of ship activity and corresponding SEs.

3.3. Analysis of High-Emission Ship Types

Figure 6 shows SEs for different ship types. It can be observed that container ships, passenger ships, and oil tankers accounted for a large amount of SEs in the research waterways. The main reason is that these three ship types comprise most of the ship traffic in the waterways. SO_2 and NO_x were the two most common ship pollution discharge types. Pollution discharge from container ships was found to account for most emissions. The emissions from passenger ships and oil tankers accounted for 31% and 17% of emissions, respectively.

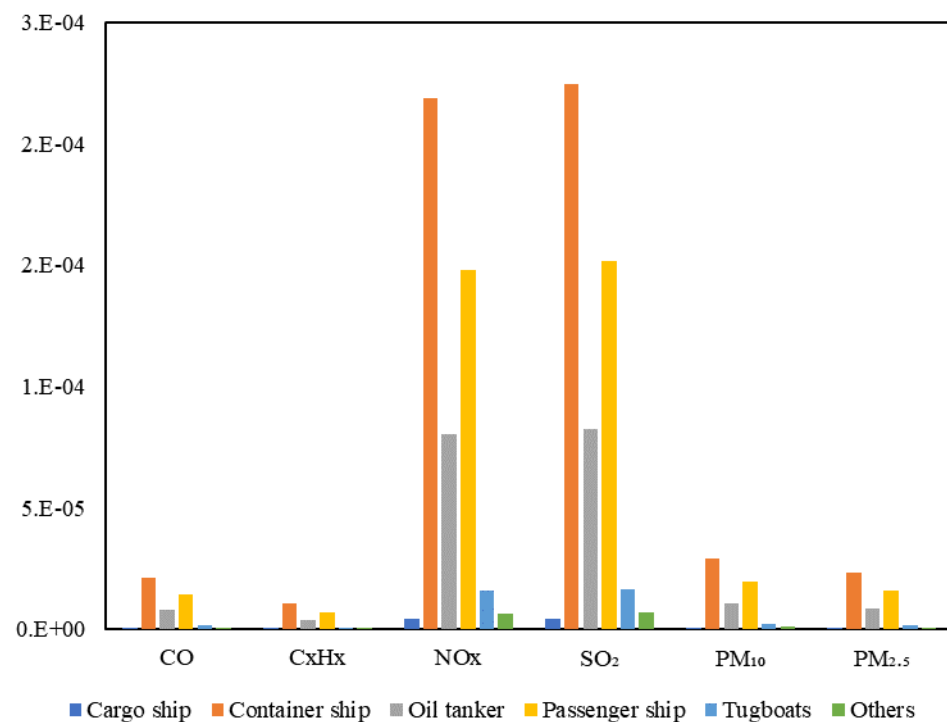


Figure 6. Comparison of total pollutant emissions from different ship types (unit: ton).

The CO emission volumes for the container ships, passenger ships, and oil tankers were 93.2, 33.5, and 7.5 tons, respectively. Note that the CO emission for the three ship types accounted for 98.7% of total CO emissions: 68.6%, 24.6%, and 5.5%, respectively. NO_x emissions from container ships, passenger ships, and oil tankers were 948.8, 340.8, and 76.0 tons; SO_2 emissions from container ships, passenger ships, and tankers were 974.2, 350.0, and 5.1 tons, and C_xH_x emissions from container ships, passenger ships, and tankers were 45.7, 15.6, and 3.4 tons, respectively.

This result may also be due to the broad disparity in ship sizes. Containers are usually constructed to international, national, regional, and employer standards. The dimensions of a container ship can be decided based entirely on obtaining the largest capacity. Container ships are available in various sizes and circulation capacities. However, the most regularly used container ships in the world are of constant size. Container ships have significant tonnage and engine power, and most of the container ships are seagoing and alternate overseas ships, which use a large amount of heavy fuel oil with high sulfur content. These features additionally contribute to their excessive emission of air pollutants. Tankers

have specific classification requirements and dimension specifications. There are certain requirements for the measurement of tankers associated with the load of the ship itself.

Passenger ships typically have large capacities and carry a large number of passengers. Together with their large-scale operations, this creates higher levels of passenger activity, which in turn generates higher levels of pollutant discharge. Passenger ships typically operate for long periods of time, which results in increased combustion. Some older passenger ships may use outdated, inefficient emission control technologies, and passenger ships typically use heavy fuels such as fuel oil or bunker fuel, which have high sulfur and carbon content and produce large amounts of pollutants, such as sulfur dioxide (SO₂) and particulate matter (PM), when burned. Container ships, passenger ships, and tankers are the primary vessel types in New York Harbor, and vessel activity is typically high. The high volume of vessel activity results in the accumulation and release of emissions, generating high levels of pollutant discharge.

3.4. Analysis of the State of High-Emission Navigation

The ship's sailing conditions can be categorized into four states according to the actual pace of the ship and the load ratio coefficient of the ship's major engine: the cruising state, low-speed maritime state, maneuvering state, and berthing state. According to the calculation of the SEs in this study, the duration of ordinary cruising, low-speed cruising, motorized operation, and berthing states accounted for 79%, 11.9%, 9%, and 4% of the ship's navigation, respectively.

The use of main engines, auxiliary engines, and boilers and the duration of activities under different navigational conditions vary greatly, resulting in varying pollutant emissions under different navigational conditions. In 2022, the highest pollutant emissions from vessels entering and exiting New York Harbor in all sailing conditions were from cruising, followed by low-speed cruising, then maneuvering, and finally berthing. The cruising time presented by each type of ship is longer than that for the other sailing conditions, and in the cruising state, the ship maintains continuous operation, unlike at the port of call or during berthing, when the operation time can be reduced. Prolonged high-speed operation also increases fuel consumption and reduces combustion efficiency, which can lead to increased pollutant discharge.

Figure 7 shows the emission of each pollutant under different sailing conditions. In the figure, the pollutant discharge in cruising, low-speed cruising, maneuvering, and berthing states is 2892.6, 37.3, 343.0, and 67.2 t, respectively, which accounts for 86.6%, 1.1%, 10.3%, and 2.0% of the total pollutant discharge. The pollutants accounting for a larger share of the emissions in the normal sailing state include SO₂ and NO_x, and the main reason for this phenomenon is that most of the cargo ships and cruise ships use heavy oil. The pollutants that account for a larger share of the emissions in the berthing state are particulate matter PM₁₀, SO₂, and NO_x, reflecting the variations between the pollutant discharge of the ship's auxiliary engine and boiler and the most critical engine and that the ship's docking time is typically long. Maneuvering and berthing emit approximately 45% of the total sulfur dioxide emissions. The emission of pollution to the atmosphere from ships is the highest during regular voyages; this is because, in order to ensure a smooth voyage and arrival at the destination on time, ships in the cruising condition usually sail at higher speeds, and high-speed operation increases fuel consumption and decreases combustion efficiency, resulting in increased pollutant discharge. Therefore, the use of low-sulfur fuel or cleaner fuels, the strict regulation of fuel quality, the introduction and enforcement of the use of emission control equipment, and the application of ship energy-efficiency technologies will help to reduce pollutant discharge during sea cruising.

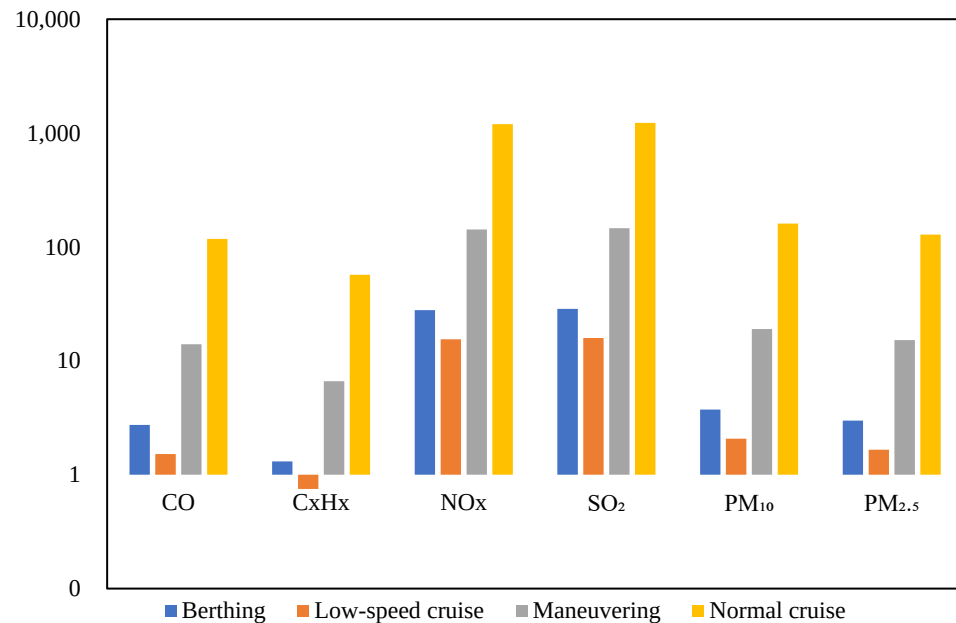


Figure 7. Comparison of pollutant emissions from ships of different sailing conditions (unit: ton).

4. Discussion

Currently, there are many research results on SE pollution. Air pollutants emitted from ships in the marine environment are important factors affecting the quality of the marine environment, and analyzing SE inventories is very important for quantifying the quality of the emissions in a specific geographic area and monitoring the changes in emissions over time. It is also crucial to studying pollution in the marine environment. Various inventory methods have been proposed globally to manipulate fuel emissions from ships. In this study, the top-down STEAM2 model was used to produce results with high precision and spatial and temporal resolution in terms of applicability, complexity, computation time, and accuracy of results [16].

New York Harbor is situated at the boundary between New York and New Jersey, and this location is highly polluted. The harbor has a wide range of maritime activities and complicated topographic conditions. The distribution of pollutant emissions from ships is influenced by the type of ship, fuel type and quality, port and channel conditions, and watershed environmental factors, with container ships accounting for the largest share of vessel movements in New York Harbor waters in 2022, at 43%, according to the AIS archives. Figure 2 indicates that emissions are intense during July and October when elements such as wind direction, wind speed, and temperature affect the direction of dispersion and dilution of pollutants and there is the most ship activity [30]. SO₂ and NO_x account for an extraordinarily large proportion of all the sources of air pollution from SEs, with 41.4% and 42.5%, respectively. Combustion of marine engine fuel is one of the major sources of air pollution. Prior to the implementation of pollutant discharge reduction from ships, high-sulfur oil was an important contributor to the elevated concentration of SO₂ in the atmosphere. Given the high sulfur oxide emissions revealed in this study, limiting the sulfur content in fuel oil is an important measure to reduce the environmental impact of SEs. The type and quantity of pollutants can be effectively mitigated by reducing the sulfur content in fuel, thus improving air quality and protecting the natural environment.

The use of low-sulfur oils can be effective in decreasing pollutant discharge from ships, and the widespread use of low-sulfur fuels limits the desire for gasoline types, lessening their impact on world pollutant discharge. Port operations also involve other critical activities such as various types of cargo handling, including equipment, railroad tracks, and trailers, which are major contributors to port pollution [1]. Therefore, to enable a comprehensive understanding of port pollution as soon as possible, it is important to develop a broad port emission inventory or one that includes both ships and other port-

related land transportation vehicles. The promotion of electric and hybrid ships can reduce direct emissions from ships, especially in ports and sensitive waters, and energy-efficient ship technologies can also be adopted, such as hull design optimization, speed control, and shaft system improvements, to reduce fuel consumption and emissions. Ship nitrogen oxide (NO_x) emissions can be decreased by installing exhaust fuel remedy devices, such as scrubbers or selective catalytic reduction (SCR) devices, which eliminate or convert pollution for the duration of the combustion process.

There are a number of limitations to the top-down research approach to the STEAM2 model used in this study. The calculation of SE inventories requires a large quantity of data, including ship working parameters, cargo transportation, and gasoline consumption, and there are uncertainties in the availability and accuracy of these data. The STEAM2 model usually uses regional parameters and data, which may lead to inconsistent emissions from different regions and may not fully consider the characteristics of different regions and ports. Effective scenario simulation modeling can provide a more comprehensive and accurate assessment of the main sources of SEs [46]. The method is based on historical data and the technological level and cannot fully consider possible future technological advances and improvements, and the effects of emission reduction measures cannot be monitored and predicted. This approach should be combined with SE prediction modeling to assess the ship pollutant discharge inventory [47].

Within the confines of this research, we navigated the challenges posed by extensive AIS datasets sourced from www.marinecadastre.gov encompassing a wealth of samples and longitudinal data sequences. The foundational STEAM model was engineered to calculate emissions of nitrogen oxides (NO_x) and sulfur oxides (SO_x). Advancements in the enhanced STEAM2 model have broadened its scope to accommodate the estimation of carbon monoxide (CO) and particulate matter (PM) emissions, thus enhancing its functionality for a more comprehensive assessment of atmospheric pollutants. We employed the STEAM2 model to precisely gauge the emission of pollutants from ships within New York Harbor. We then analyzed emission patterns using these data and the given formulas. This examination uncovered seasonal fluctuations and spatial distributions, thereby offering robust data-driven support for environmental stewardship and the diminution of pollutant discharge. Should there be interest in the data and code utilized in our study, these materials can be obtained by contacting the corresponding author via email.

The research conducted in this study involved a thorough examination of ship pollution emissions, drawing upon the qualitative analysis of expert experience to confirm the alignment of experimental outcomes with anticipated effects. The meticulous calculation process underlying our findings was based on the STEAM2 model, a well-established and widely recognized framework within the academic community that was recommended for its credibility. Despite the robust methodology employed, we acknowledge the absence of empirical legislative data as a limitation in our current analysis. To address this, future endeavors will include a comprehensive quantitative analysis, wherein the precision and dependability of the emission estimation model will be carefully validated through a direct comparison between the experimentally derived emission estimates and actual regulatory data. This forthcoming validation step will serve to reinforce the integrity of the model and ensure its applicability for informing environmental policy decisions related to maritime pollution.

In summary, the experimental results of this study have laid a solid foundation for the subsequent exploration of alternative methods for assessing pollution emissions from ships. Based on these results, we plan to deepen our understanding of the research topic by utilizing multiple data sources, gradually adopting a more comprehensive approach, and expanding the scope of the study. By integrating different datasets and analytical techniques, we can refine our assessment procedures and validate the results, which will help advance our understanding of ship-generated pollution and inform future policy directions targeting the ecological footprint of the marine industry.

5. Conclusions

In this study, the STEAM2 model was used to calculate the emissions of six pollutants from various types of ships in different sailing states. Then, ArcGIS was utilized to realize the visual distribution of the pollutant emissions, and spatiotemporal analysis was carried out to reveal the hidden potential information in the calculated emission inventory and visualize the pollutant emissions of the ship exhausts in New York Harbor waters in a specific period of time. In 2022, the volume of emissions of ship pollution in New York Harbor waters was 3340 t, of which CO, SO₂, C_xH_x, PM₁₀, NO_x, and PM_{2.5} accounted for 136, 1421, 66, 185, 138, and 148 tons, respectively, with SO₂ having the highest level of emission, accounting for 42.5%. The essential sources of air pollution from ships in the waters of New York Harbor are container ships, passenger ships, and oil tankers.

The high-pollution area of the harbor is concentrated in the waters at the New York and New Jersey dividing line, and the high density of ships and complex topographic conditions are important reasons for the high pollution levels. Pollutant emissions from different sailing conditions in 2022 were characterized in this study. The navigational state with the highest pollutant emissions for vessels entering and leaving New York Harbor was cruising, followed by low-speed cruising, then maneuvering, and finally berthing. Emissions were the lowest throughout the year in June. May and June form the transition period from spring to summer, as the weather is generally still relatively cool with moderate humidity, which is conducive to more complete fuel combustion. Two peaks of pollutant discharge occur throughout the year in July and October, respectively. Since the atmospheric dispersion prerequisites in spring are the worst, the effect of ship emissions on ambient air fine particulate matter is very high in this season. Based on the three regular evaluation tasks, areas with excessive air pollution and various types of ship emission were explored.

Based on the panel data model, the influencing factors of pollution emissions from ships can be further explored from the perspective of shipping alliances in order to reduce the level of pollution emissions from the entire fleet [48]. The large-scale AIS data used in this study resulted in a significant increase in the complexity of data processing and the difficulty of the mining analysis task, and future research further requires us to use precise feature extraction techniques and carefully review data to ensure the accuracy of the analysis results. Since we were unable to obtain the existing sensor data, the emissions of the six pollutants from different ship types under different sailing conditions were calculated in this study. The results of the study, which were qualitatively analyzed by experienced experts, intuitively show that the characteristics of the pollutant emissions from the ships are in line with the expected pattern, and future studies will be quantitatively analyzed by comparing the results of the study with the existing sensor data. In addition, the new model will be improved from a more local small-scale point of view, and an environmental impact model will be established to combine marine traffic flow data with environmental monitoring data. Future studies should also investigate the effects of meteorological conditions such as wind speed and direction on pollutant emissions. It is important to understand how wind direction and speed affect the dispersion and transportation of SEs and how pollutant concentrations vary under different wind conditions and could advance studies in assessing ship pollutant emissions in port areas.

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