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Spatial–Temporal Distribution Characteristics and Correlation Analysis of Air Pollutants from Ships in Inland Ports

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Abstract: The ship air pollution problem has become a global issue and poses a threat to the environment as well as the health of residents in the port area. This study used Automatic Identification System (AIS) data combined with a list of air pollutant emissions from ships. The total amount of air pollutant emissions was obtained. The spatial and temporal distribution characteristics of air pollutants on ships were analyzed, and the correlation of pollutant concentrations was studied on the three major ports. The three main intensive ports are Cuntan Port, Guoyuan Port, and Luoqi Port, and the Pearson correlation analysis is conducted based on the Statistical Product and Service Solutions (SPSS). The results showed that: (1) The air pollutant emissions from ships in China Chongqing port region during September to December 2021 were mainly dominated by CO_2 and NO_X. (2) The air pollutant emissions from ships in the Yangtze River Basin were highest in October 2021 and lowest in December. (3) The correlation between $PM_{2.5}$ and CO_2 showed the largest in Cuntan Port and Luoqi Port, and the correlation between CO and CO_2 is the largest in Guoyuan Port. It is suggested to establish deceleration zones and emission control zones in Cuntan Port and Guoyuan Port, and to use shore power for berthing in Luoqi Port. We also suggest improving fuel quality and combustion quality, post-treating ship exhaust emissions, increasing port shore power facilities to reduce ship air pollutant emissions, and providing a reference for environmental protection in inland ports.

Keywords: inland ports; air pollutants from ships; spatial and temporal distribution characteristics; correlation study

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1. Introduction

The booming shipping industry has brought huge economic benefits to port areas; however, the problem of pollution from ship emissions cannot be underestimated [1–3]. Atmospheric pollutants are divided into primary pollutants and secondary pollutants. Direct pollution of the air is called primary pollutants, and is mainly sulfur dioxide, carbon monoxide, nitrogen oxides, nitrogen dioxide, particulate matter, etc. Primary pollutants place reactive substances into the atmosphere through physical and chemical changes, making new pollutants called secondary pollutants, mainly sulfuric acid and sulfate, nitric acid and nitrate, ozone, and photochemical smog. Carbon dioxide, nitrogen oxides, sulfur oxides, carbon monoxide, particulate matter 2.5, particulate matter 10, and other air pollutants in the ship emission inventory are serious hazards to human health and the environment [4–6]. Port area emissions have become an important factor affecting the ambient air quality of Chinese port cities, and port low emission zone planning is an important measure to control port pollution. Due to the high energy consumption and high emission characteristics of ports, the corresponding greenhouse gas emissions are also increasing, and the ecological and environmental problems of ports are becoming increasingly serious. In order to promote the low-carbon and green development of Chongqing ports it is necessary to study the spatial and temporal emission patterns and correlations of pollutants from port ships, construct a pollution gas emission inventory, and scientifically formulate emission reduction strategies for the long-term development of

Chongqing ports. Construction of pollutant gas emission inventory and the scientifically formulated emission reduction strategies for the long-term development of Chongqing Ports should be implemented, contributing to the success of the Sustainable Development Goals-UN 2030 Agenda [7]. To achieve effective control of air pollutant emissions from ships, we first need to obtain accurate emission inventories and emission characteristics of ships [8,9]. In response to this situation, the calculation model of the emission inventory is being continuously improved [10–12]. Researchers used a ship traffic emission assessment model (STEAM) to calculate Baltic Sea ship exhaust emissions [13]. Based on this, the researchers further proposed the extended ship traffic emissions assessment model (STEAM2). They added the calculation of particulate matter (PM) and CO. Moreover they researched the analysis of ship load and fuel variation, and conceptualized the model based on the fuel consumption initially in 2017 by using the path regeneration algorithm and the data-assimilation method for the global ship air pollutant emission problem [14].

Based on the above research results, scholars have combined GIS to visualize and analyze the pollution situation, mostly focusing on coastal cities, such as the study of spatial distribution of air pollutants from ships in Tianjin port [15,16]. The scholars conducted actual emission tests on 12 inland vessels in the Jiangsu section of the Beijing–Hangzhou Canal using the Portable Emission Measurement System (PEMS) and analyzed the emissions of CO, NO_X, and PM under different operating conditions [17]. In recent years, with the development of shipping trade and the increasingly serious problem of ship air pollution, more and more scholars began to pay attention to the problem of ship air pollution in inland areas. Through the analysis of the current situation and characteristics of ship air pollutant emissions in the Baiyangdian region of Hebei Province, it was found that the emission of hydrocarbon pollutants is the most serious [18]. The researchers used the Automatic Identification System (AIS) to obtain the ship activities and made a "bottom-up" emission inventory of Nanjing Longtan port area in 2014, and proposed emission reduction paths for ships in port based on the analysis of emission characteristics [19,20]. Since these research methods only analyze the distribution characteristics of air pollutant emissions from regional ships and ignore the correlation of pollutant concentrations, this limits the further development of targeted air pollution prevention and control programs in the region. The scholars analyzed the characteristics of ozone concentration changes in Chongqing atmosphere and made a correlation analysis between ozone precursors and meteorological factors, and the results indicated that there was a good negative correlation between ozone concentration and NO_X concentration trends; through the correlation analysis of atmospheric pollutants and meteorological elements in Beibei area of Chongqing, the results showed that the concentrations of atmospheric pollutants PM_{10}, SO_2, and $PM_{2.5}$ have a change pattern of decreasing and then increasing. Moreover, the cyclicality of the NO_2 change pattern is not obvious [21–23]. However, the port area of Chongqing has complex hydrological characteristics and rich port trade features. The correlation analysis of air pollutant concentrations of regional ships only cannot accurately describe the spatial and temporal distribution characteristics of air pollutants of ships between different ports and the interaction effects between pollutant concentrations [24,25]. Therefore, integrating the distribution characteristics of ship air pollutant emissions in the inland port region and the development and limitations of correlation studies, this study selects Chongqing port region as the study area. In this paper, the total amount of air pollutant emissions from ships is obtained by using the list of air pollutant emissions from ships, it studies the differences of ship air pollution emissions in different time periods and spatial locations, and conducts correlation analysis for CO_2, NO_X, SO_X, CO, and $PM_{2.5}$ concentrations emitted by ships in Cuntan port, Guoyuan port, and Luoqi port. This paper provides reasonable emission reduction measures for air pollution caused by shipping trade in Chongqing ports.

2. Study Area and Subjects

The study area includes three major ports in the main city of Chongqing in China, Cuntan Port, Guoyuan Port, and Luoqi Port (106.25° E–107.06° E, 29.40° N–29.19° N), as shown in Figure 1. Among them, Cuntan Port has nine berths, mainly serving containers and commercial roll-on/roll-off vehicles; Guoyuan Port is connected with Yuhuai Railway and has 16 berths, with a total accumulated cargo throughput of 8.98 million tons; Luoqi Port has nine berths and is an important node of the industrial belt along the river. In order to promote "One Belt, One Road" and the Yangtze River Economic Belt, the foreign trade import container business of Cuntan Port has been transferred to Guoyuan Port. In this paper, the three most representative ports in Chongqing were selected for the study, among which Cuntan Port is the tourism window of Chongqing. Guoyuan Port is the largest port in Chongqing, and Luoqi Port is the port with the best implementation of low-carbon green measures. In this paper, the three representative ports and the ship emissions were selected and are summarized. The purpose is to speculate the ship air pollutant emission of other ports in Chongqing. Through the pilot study of the three ports, we evaluate and determine the adoption of stricter emission control requirements, expansion of emission control areas, and other further initiatives, such as extending the emission control requirements to other port areas in Chongqing.

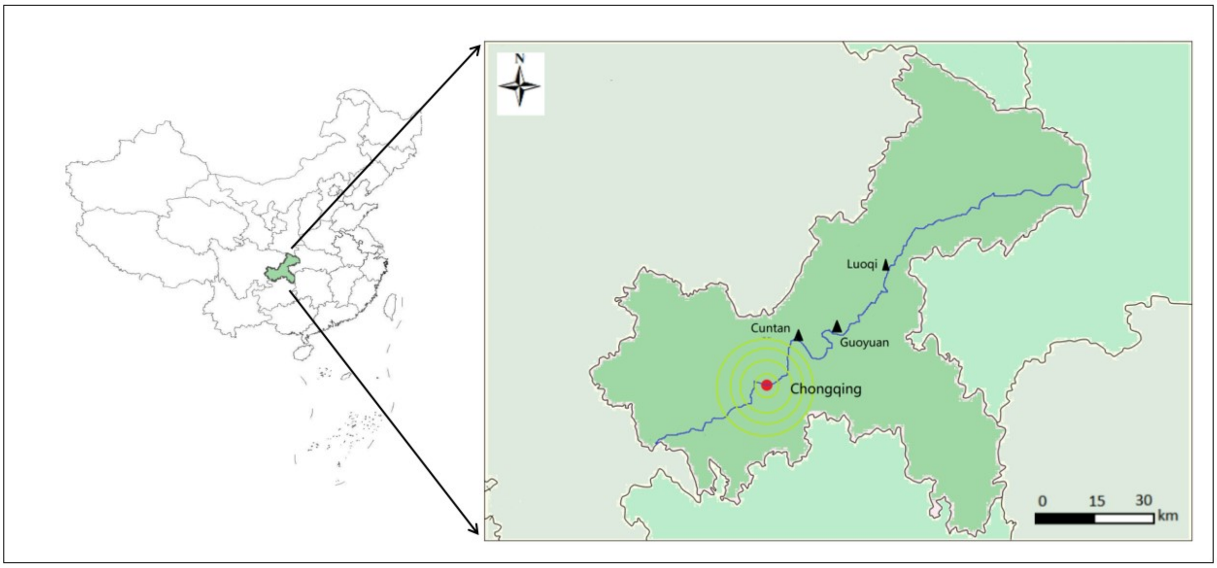

Figure 1. Study area.

The research period of this paper is from September to December 2021. According to statistics, the average monthly flow of Chongqing Yangtze River basin in December, January, February, and March is 4345 m^3/s, 4280 m^3/s, 4225 m^3/s, and 4395 m^3/s. The average monthly flow in April, May, October, and November is 7858 m^3/s, 7733 m^3/s, 7890 m^3/s, and 8033 m^3/s. The average monthly flow in June, July, August, and September is 19,252 m^3/s, 21,111 m^3/s, 15,864 m^3/s, and 26,291 m^3/s. The dry period of Yangtze River, when the water level is low and the navigation conditions are poor in Chongqing is January, February, March, and December. The mid-water period when the navigation conditions are the best is April, May, October, and November. The flood period, when the water level is high and the flow velocity is high, is June, July, August, and September. We selected the ship air pollutants in September during the flood period, October and November during the mid-water period, and December during the dry water period to study the changes in the Yangtze River in the three periods. Moreover, we can infer the ship pollutant emissions in other months of the year.

The ship types are classified into cargo ships, tankers, passenger ships, special ships, tugboats, container ships, law enforcement ships, and other types of ships. Moreover, the types of air pollutants involved include CO_2, NO_X, SO_X, CO, $PM_{2.5}$, and PM_{10}. The ship activity states are classified into four different driving modes according to the sailing speed: cruising state (speed > 12 kn), slow state (8 kn < speed $\leq$ 12 kn), maneuvering state (1 kn < speed $\leq$ 8 kn), and moored state (speed $\leq$ 1 kn).

3. Calculation of Air Pollutant Emissions from Ships

3.1. Ship Air Pollutant Emission Inventory

The ship automatic identification system (AIS) has the role of identifying ships through the built-in the Global Positioning System (GPS). It can accurately obtain the position, heading, speed, and other information of the target ship. For the emission of air pollutants from ships, the publicly available AIS information is translated and decoded to obtain data containing basic ship information such as ship name, ship type, ship length, ship width, time stamp, latitude and longitude, speed, heading and destination, etc. A certain frequency is used to obtain the AIS data, and cleaning, automated identification of abnormal data, and supplementation of missing data are carried out (the website is https://coast.noaa.gov/htdata/CMSP/AISDataHandler/2021/ (accessed on 1 Sptember 2021)). According to the STEAM2 model, the emission inventory of ships in Chongqing port area is calculated, in which CO_2 mainly depends on the carbon content of consumed fuel; NOx emission mainly depends on the temperature and duration of the combustion cycle of ship engines; SO_X, $PM_{2.5}$, and PM_{10} mainly depend on the quality and consumption of ship fuel; and CO emission depends on the engine load and engine power. Infrared radiation temperature measurement is a surface temperature measurement method that does not interfere with either the surface or the surrounding medium. Moreover, it has the advantages of high resolution, high sensitivity, high reliability, and short response time. Considering the complex and variable environment and ship characteristics in this region of Chongqing, a localized ship air pollution emission calculation model needs to be established. In this paper, the "bottom-up" power method is chosen to calculate the ship air pollutant emissions in the Chongqing port area [26], and the ship air pollution emission calculation model is shown in Equation (1) below:

$$E = MCR \times LF \times EF \times FCF \times DP \times DU \times T \times 10^{-6} \quad (1)$$

Among them, *E* represents the pollutant emission (t), *MCR* represents the power (kW), *LF* represents the load factor, *EF* represents the emission factor, *FCF* represents the fuel correction factor, *DP* represents the machine-pitch matching factor, *DU* represents the mainframe low load correction factor, and *T* represents the time (h).

The ship motor power (*MCR*) is proportional to the product of the torque and frequency. The load factor (*LF*) is the product of the load factor of the main auxiliary machine. In this study, diesel with a sulfur content of 2.7% is used as the basic emission factor (*EF*), and light diesel with a sulfur content of 0.1% is introduced as the fuel correction factor (*FEF*) for the emission factor. The mainframe low load correction factor (*DU*) is 1.25 [27].

3.2. Total Air Pollutant Emissions from Ships

The ship emissions of air pollutants CO, NO_X, PM_{10}, $PM_{2.5}$, SO_X and greenhouse gas CO_2 from September to December 2021 in this study area are 95.03 t, 873.87 t, 25.04 t, 18.80 t, 43.44 t, and 61,002.97 t, respectively, totaling 62,059.16 t. The most emitted is CO_2, followed by NO_X, the third and fourth are CO and SO_X, and the least emitted is $PM_{2.5}$. The emission of air pollutants from the main and secondary engines under different sailing conditions is shown in Table 1 below.

Table 1. Emissions of air pollutants from main engine and auxiliary under different vessel status (t).

Vessel Status	CO	NO_X	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Main engine cruise	27.52	263.41	6.38	5.10	11.51	16,165.09
Main engine sailing	35.68	341.49	9.81	6.62	14.92	20,956.93
Main engine maneuvering	1.39	8.30	0.23	0.18	0.37	521.86
Auxiliary cruise	0.68	5.81	0.19	0.15	0.37	520.62
Auxiliary low flight	1.78	15.27	0.51	0.40	0.97	1368.67
Auxiliary maneuvering	0.13	1.11	0.04	0.03	0.07	99.52
Auxiliary mooring	27.85	238.49	7.89	6.31	15.22	21,370.28
Total	95.03	873.87	25.04	18.80	43.44	62,059.16

As can be seen from Table 1, among the seven states of the main engine and auxiliary engine of the ship, the sum of the pollutant concentrations in the mooring state of the auxiliary mooring reaches the highest, followed by the cruising state of the main engine. The sum of the pollutant concentrations in the maneuvering state of the auxiliary aircraft is the smallest, and the mooring state is one of the most important and frequent activities of the ship to ensure the safe mooring of the ship. From the perspective of the discharge of the main engine and the auxiliary engine, the sum of the pollutant concentrations in the three states of the main engine is greater than the sum of the pollutant concentrations in the four states of the auxiliary engine. From the perspective of pollutant types, the total amount of greenhouse gas CO_2 emissions is the largest, reaching 62,059.16 t, followed by NO_X, CO, SO_X, PM_{10}, and $PM_{2.5}$, mainly CO_2 gas emissions.

4. Data Analysis

4.1. Temporal Distribution Characteristics

4.1.1. Monthly Distribution of Ship Air Pollutant Emissions by Major Ship Types

Different types of ships in the study area mainly include cargo ships, passenger ships, oil tankers, special ships, tugboats, and pilot boats. From September to December 2021, the regional cargo ships, passenger ships, oil tankers, special ships, tugboats, and pilot boats emitted air pollutants of 42,763.43 t, 9012.90 t, 4959.95 t, 514.82 t, 260.98 t, and 44.11 t respectively. The different functions of the ships themselves lead to large differences in total air pollutant emissions, so it is important to calculate their total pollution emissions from September to December based on the main ship types to understand the pollutant emission patterns of different ships in different months, as shown in Table 2 and Figure 2 for the month distribution of pollution emissions from the main ship types.

Table 2. Major ship type pollutant month emissions (t).

Type	September	October	November	December
Cargo ship	10,754.80	11,768.71	11,717.90	8522.03
Passenger ship	2183.89	1904.63	1752.68	3171.70
Oil Tanker	1318.87	1751.62	870.40	1019.07
Special ship	140.92	144.55	172.40	56.95
Tugboat	119.18	105.35	25.51	16.75
Pilot vessel	7.42	5.72	13.83	17.98
Other types	324.77	1332.26	2189.30	235.55

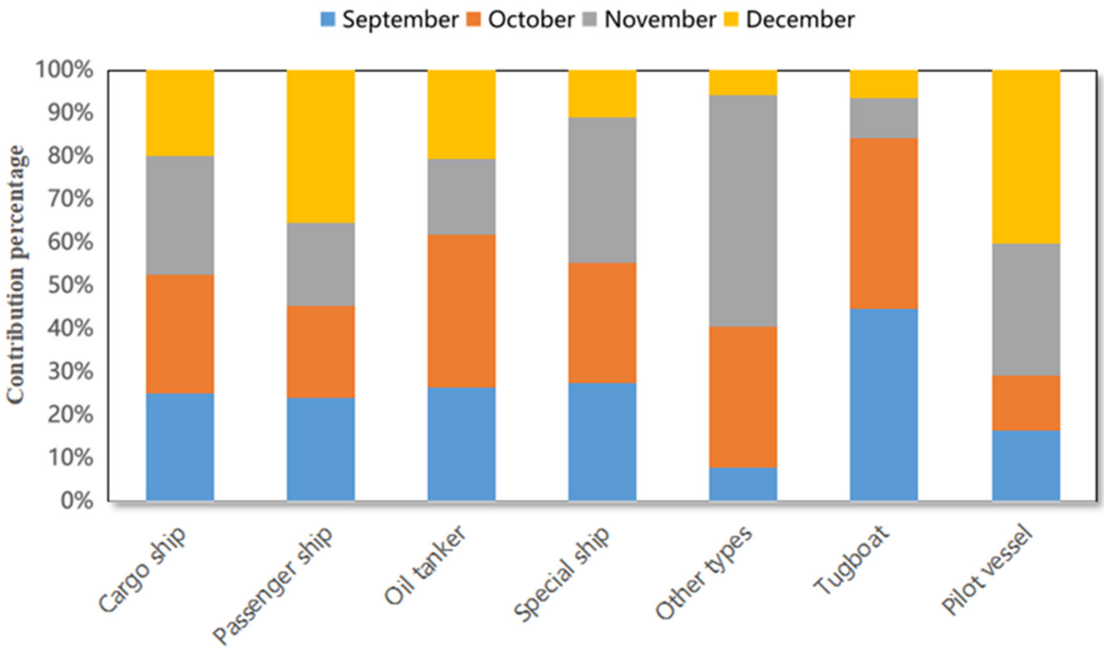

Figure 2. Main ship type pollution emission month distribution.

As can be seen from the monthly emission table of major ship type pollutants, in terms of ship types, the pollutant emissions of cargo ships reached a maximum of 11,768.71 t in October, followed by passenger ships, oil tankers, other types of ships, special ships, tugboats, and pilot vessels. In terms of months, in September, tugboats discharged the highest total amount of pollutants, and other types of ships had the least. In October, tugboat emissions were the largest, and cargo ships, oil tankers, and special ships discharged closely. In November, other types of ships emitted the most and tugboats the least. In December, passenger ships and pilot ships emitted similar amounts of pollutants, with tugboats and other types of vessels having the least.

Cargo ships and oil tankers both emit the most in October, with cargo ships emitting the least in December and oil tankers emitting the least in November; special ships and other types of ships both emit the most in November and the least in December; passenger ships and pilot ships both emit the most in December, with passenger ships emitting the least in November and pilot ships emitting the least in October. The tugboat emits the most in September and the least in December; because September is the transition period from flood to mid-water, the current is more turbulent and the water level is lower than that in mid-water, so the tugboat activity level increases; while December is the dry water period, the current is calm and the water level is higher, so the tugboat activity level decreases. The distribution of pollution emission month of the main vessel types above shows that the vessel activity level is related to the environment characteristics of the Yangtze River Three Gorges Reservoir Area.

4.1.2. Monthly Distribution of Ship Air Pollutant Emissions by Major Pollutant Type

The emissions of atmospheric pollutants CO_2, NO_X, CO, SO_X, PM_{10}, and $PM_{2.5}$ from ships in the study area can be seen from Figure 3, with CO_2 and NO_X dominating and $PM_{2.5}$ as the least, and the temporal distribution pattern of atmospheric pollutant emissions in the study area is basically consistent. The ship activity level in the Yangtze River Three Gorges Reservoir Area, the characteristics of the channel environment, the autumn–winter, and flooding periods and the dry period influence the poor navigation conditions during the dry and flooding periods, and the ship flow is relatively small, while the navigation conditions during the mid-water period are better and the ship flow is larger. In December, the water level is low, the flow is slow, and the navigation conditions are poor, so the flow of vessels in the region is reduced, which makes the discharge of pollutants low.

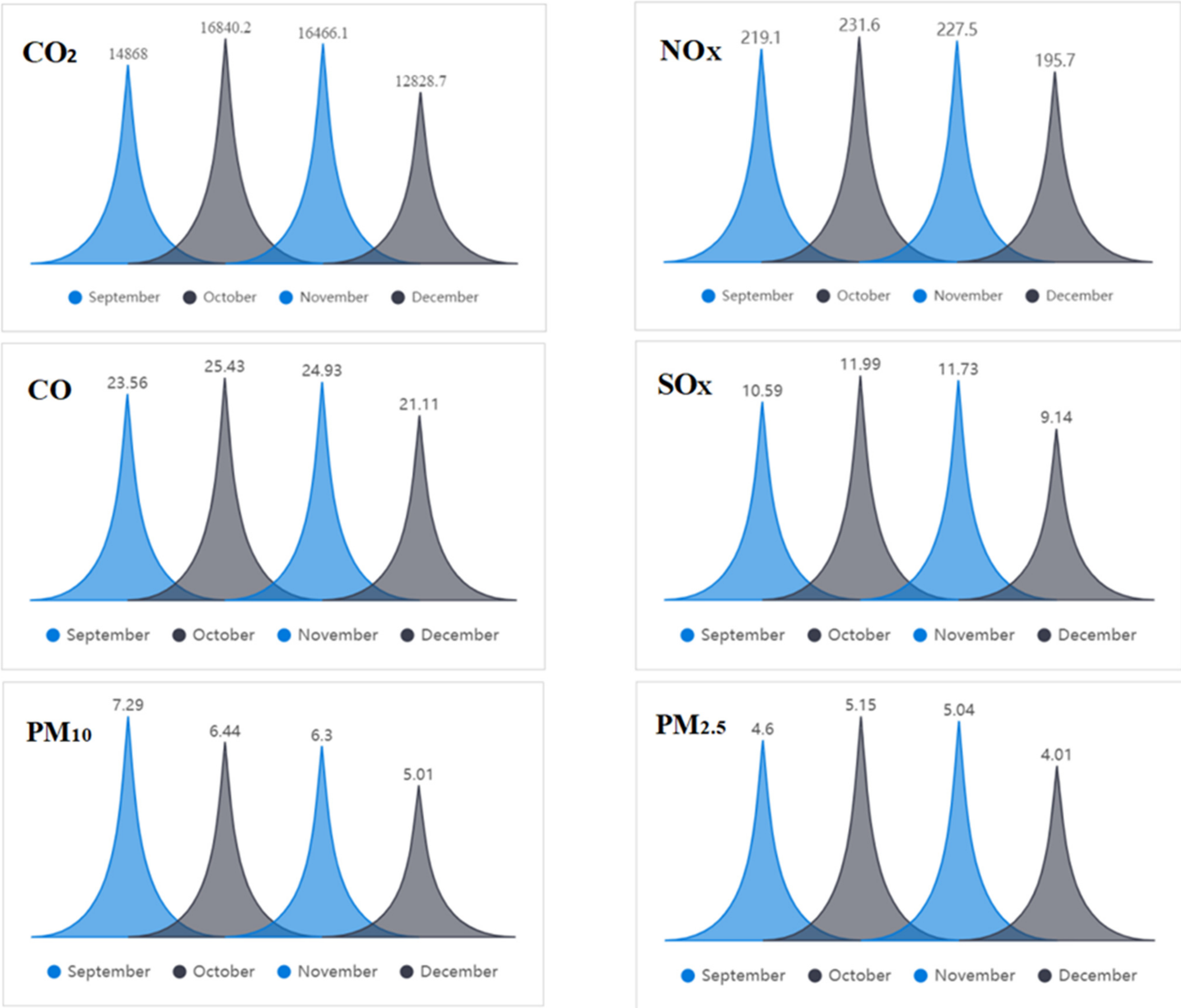

Figure 3. Major ship air pollutant emission month distribution.

4.2. Spatial Distribution Characteristics

Spatial analysis is the quantitative study of phenomena, and its conventional ability is to manipulate spatial data to make it different forms and extract its potential information. Spatial analysis mainly uses the joint analysis of spatial data and spatial models to explore potential information about spatial targets. In this paper, the spatial analysis module is used to objectively and comprehensively evaluate the current situation of air pollutants in ships in the Yangtze River Basin of Chongqing so as to reflect the degree of pollution in the region and the spatial distribution.

In this paper, the geographic information system was used to analyze the spatial distribution of atmospheric pollutants on ships [28–30]. We first calculated pollution emissions from the acquired AIS data and recorded the corresponding latitude and longitude locations to generate emission files, with latitude and longitude locations as spatial data and emissions as attribute data [31–34]. Then, the spatial analysis of the emission file data was performed, and finally the spatial distribution map of various air pollutant emissions generated in the form of layout view was obtained using GIS, as shown in Figure 4.

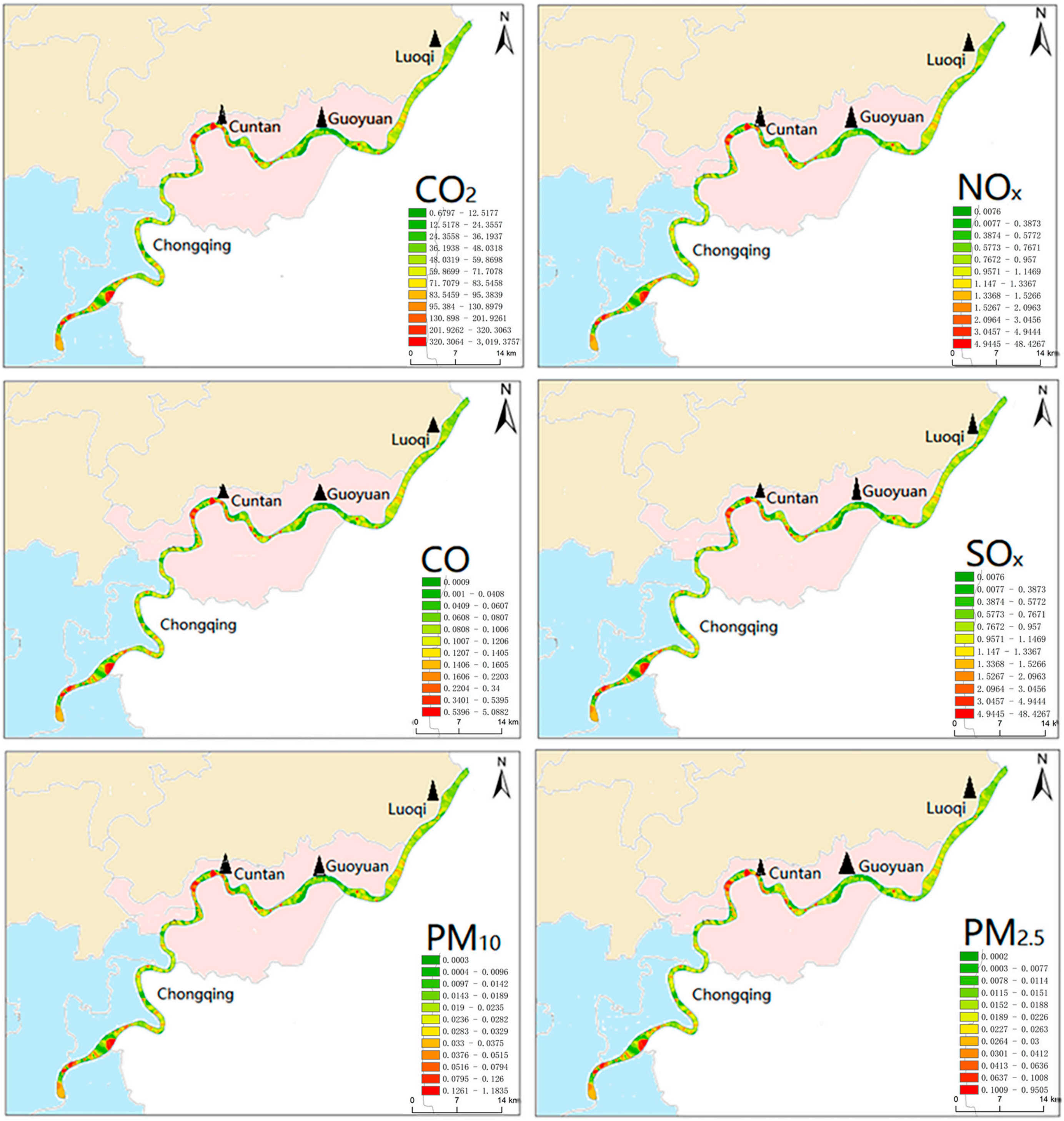

Figure 4. Spatial distribution of air pollutant emissions from ships.

From Figure 4, it can be seen that the distribution trends of CO_2 and SO_X emissions from ships in Chongqing port area are similar, showing a low trend in the upstream and downstream of the Yangtze River and a high trend in the midstream, especially concentrated in the area along the Cuntan Port to the Port of Guoyuan. For NO_X, it is mainly concentrated in the Cuntan Port; PM_{10} and $PM_{2.5}$ units of emissions are the lowest of all pollutants, with Guoyuan Port and Luoqi Port dominating the most. In summary, the spatial distribution of ship air pollutant emissions in Chongqing port area is mainly concentrated in Cuntan Port, Guoyuan Port, and Luoqi Port, among which Guoyuan Port is the most densely distributed, which is related to the distribution of Chongqing ports and the level of ship activities, the specific intrinsic correlation is studied in detail in the correlation section.

4.3. Correlation Analysis

Port greenhouse gas CO_2 emissions exacerbate global climate change, and global sea level rise caused by climate change also poses a huge threat to the sustainable development of ports. The direct carbon emissions generated by port activities mainly include the emissions generated by port vessels through fuel consumption, and the corresponding carbon emissions are generated by cargo ships, passenger ships, oil tankers, special ships, tugboats, and pilot ships in Cuntan Port, Guoyuan Port, and Luoqi Port to varying degrees. Therefore, the CO_2 correlation of the three ports was studied, combined with the ship's own ship activity law, so as to formulate different emission reduction measures. The ship activities in these three ports are different: In Cuntan Port, which is focused on development of tourism and shipping, passenger ship activities are more frequent, and air particulate matter emissions are more. Guoyuan Port is a port for Chongqing's trade in and out, and as such has many cargo ships and high carbon emissions. Luoqi Port is the port with the best implementation of current low-carbon green measures, so the emission of pollutants is better controlled.

By combining the above study and the characteristics of Chongqing's port activities it can be seen that Cuntan Port is the core functional area of international consumption, international business, and international exchanges connecting ports and urban transportation, and is the main activity area of passenger ships. Guoyuan Port is a new window of logistics pattern in the western region, plays a demonstration role in promoting the green development of the Yangtze River Economic Belt, and is the main activity port for cargo ships and passenger ships. Located in the upper reaches of the Yangtze River in Chongqing, the Port of Loraine serves as a link between ship trade in the eastern region. The ship activities of the above three representative ports have their own characteristics and distribution laws, thus showing the different characteristics of the correlation of atmospheric pollutants of ships. Therefore, different ports have no way to implement regional emission reduction measures together. Moreover, it is necessary to formulate atmospheric environmental protection policies according to the characteristics of each port.

Firstly, the SPSS tool was used to test the normal distribution for the ports of the study area, Cuntan Port, Guoyuan Port, and Luoqi Port, and the available data of CO_2 emissions from ships in the area were subjected to the quantile-quantile plot (Q-Q) test of natural analysis. Moreover, the results are shown in Figure 5. From Figure 5, the CO_2 concentrations of Cuntan Port and Guoyuan Port in Chongqing in 2021 are approximately near a straight line on the Q-Q chart, indicating an approximate normal distribution, among which the fluctuation of Luoqi Port is the largest, while the fluctuation of Cuntan Port data is smaller. On the one hand, the Chongqing shipping hub is concentrated in Cuntan Port and Guoyuan Port, on the other hand, it may be related to factors such as flooding period and dry period in autumn and winter; the fluctuation of Guoyuan Port data is the smallest. On the other hand, this may be related to the flooding period and dry water period in autumn and winter. In general, the data obtained from this study based on the ship pollutant emission inventory are not significantly different from the theoretical normal distribution and satisfy the normal distribution, which are feasible data and can be further analyzed for correlation.

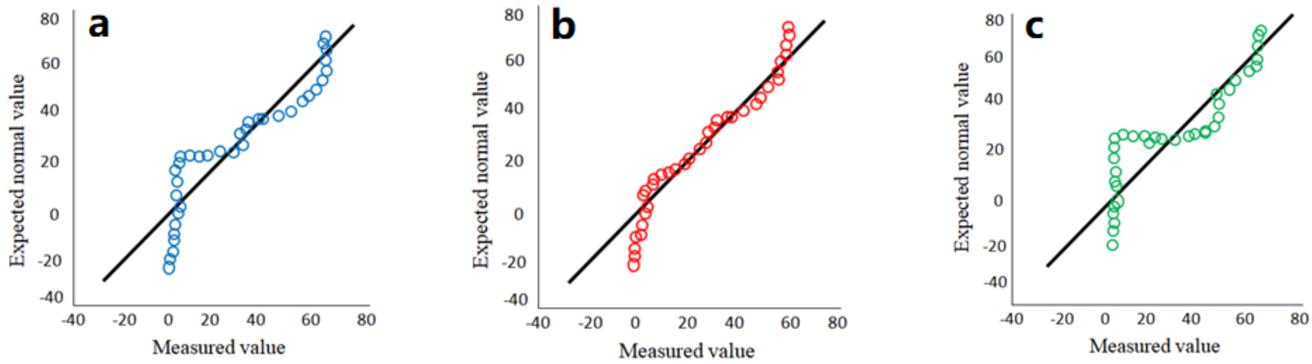

Figure 5. Normal Q−Q plots of CO_2 concentration (**a**) Cuntan Port; (**b**) Guoyuan Port; (**c**) Luoqi Port.

We can make an analysis from the information in Table 3. In the Pearson correlation analysis [35–37], CO_2, NO_X, SO_X, CO, and $PM_{2.5}$ were selected as the research objects, CO_2 as the dependent variable, Y, NO_X, SO_X, CO, and $PM_{2.5}$ as the independent variables, X1, X2, X3, and X4, and SPSS software was used to analyze the correlation of the mass concentration data of vessels in Cuntan Port and Guoyuan Port area of Chongqing main city from September to December 2021. The correlation analysis was conducted on the mass concentration data of five types of pollutants emitted in September to December of 2021, and the correlation and correlation characteristics criteria: 0.8–1.0 is highly correlated, 0.5–0.8 is significantly correlated, 0.3–0.5 is real correlation, and 0–0.3 is micro correlation [38]. As can be seen from Table 1, the CO_2 concentrations emitted from ships in Cuntan Port, Guoyuan Port, and Luoqi Port area of Chongqing are positively correlated with NO_X, SO_X, CO, and $PM_{2.5}$ concentrations, among which $PM_{2.5}$ is the most correlated with CO_2 at Cuntan Port and Luoqi Port, but CO is the most correlated with CO_2 at Guoyuan Port, which is mainly related to the fact that ships are densely concentrated at Guoyuan Port; the correlation coefficients with CO_2 that have significant positive correlation. The correlation coefficients of pollutants basically follow $PM_{2.5} > SO_X > NO_X$, so we can conclude that in the main port area of Chongqing, the closeness of the relationship between the air pollutants emitted by ships affecting the quality concentration is $PM_{2.5}$, SO_X, and NO_X.

Table 3. Correlation analysis results of Cuntan Port, Guoyuan Port, and Luoqi Port.

Port	Pollutant	Y (CO_2)	X1(NO_X)	X2(SO_X)	X3(CO)	X4($PM_{2.5}$)
Cuntan	CO_2	1.000	0.758	0.942	0.535	0.957
	NO_X		1.000	0.797	0.849	0.764
	SO_X			1.000	0.582	0.957
	CO				1.000	0.538
	$PM_{2.5}$					1.000
Guoyuan	CO_2	1.000	0.662	0.841	0.978	0.943
	NO_X		1.000	0.551	0.660	0.770
	SO_X			1.000	0.845	0.817
	CO				1.000	0.943
	$PM_{2.5}$					1.000
Luoqi	CO_2	1.000	0.763	0.844	0.871	0.905
	NO_X		1.000	0.688	0.747	0.854
	SO_X			1.000	0.990	0.938
	CO				1.000	0.966
	$PM_{2.5}$					1.000

The correlation between $PM_{2.5}$ and CO_2 is the highest in Cuntan Port and Luoqi Port. It is known in the section of ship air pollutant emission inventory in section three, CO_2 mainly depends on the carbon content of consumed fuel. $PM_{2.5}$ mainly depends on the quality and consumption of ship fuel. We can take some measures to reduce carbon emission and control pollution. On one hand, we can increase the quality of ship fuel. Moreover, we can reduce the fuel consumption and improve the effectiveness of fuel use. We can improve the efficiency of the power engine. Moreover, we can reduce the fuel consumption rate of prime movers and boilers of main engines and generators, etc. We can save lighting, air conditioning, and other equipment and reduce the use of fuel. On the other hand, CO is most correlated with CO_2 at Guoyuan Port, and CO emissions depend on engine load and engine power. The original ships with higher power can reduce the power and improve the propulsion efficiency. By taking appropriate measures in the three ports, $PM_{2.5}$ and CO emissions are reduced, and thus CO_2 emissions are reduced. These measures contribute to pollution control.

5. Study on Ship Pollution Control in Chongqing Port Area

By analyzing the spatial and temporal distribution of air pollutants from ships and the correlation situation, we can see that the air pollutants from ships are mainly concentrated in the area from Cuntan Port to Guoyuan Port. The air pollutants from ships near the port area spread to the surrounding areas and have an important impact on the air quality around the port. In order to ensure the air quality of Chongqing port area and the health of residents, it is recommended to adopt corresponding control techniques for ship air pollution emissions.

Recommendation one is to improve fuel quality and combustion quality. The most direct way to reduce air pollution emissions from ships is to improve fuel quality, such as imposing limits on fuel sulfur content. Another important way to improve fuel quality is to replace fuel with clean fuel energy, which includes wind energy, solar energy, oil–gas–electric hybrid, and liquid natural gas. The design of diesel engine internal structure can also be optimized, such as the use of variable compression ratio piston, the oil film evaporation combustion method can effectively improve the combustion quality.

Recommendation two is post-treatment of exhaust emissions from ships. Before the atmospheric pollutants emitted from ships enter the atmosphere, special equipment is added at the rear of diesel engines to further treat the exhaust gas so that the content of harmful components and pollutants in the exhaust gas is reduced. At present, the post-treatment technology of ship exhaust gas is mainly divided into two methods: physical treatment technology and chemical treatment technology [39]. The physical technology mainly includes electrostatic separation method, water washing method, and particle filtration method, etc.

Recommendation three is port shore power. The diesel engine stops working during the ship's port call, and the daily power supply on board is supplied by the ship's auxiliary engine. Although the pollution emission from the ship's auxiliary engine is relatively small compared with that of the ship's main engine, large amounts of pollutants are generated during the long stopping period, which, together with the large number of ships around the port and the large noise of the auxiliary engine operation, seriously affects the physical and mental health of residents around the port [40]. By adding port shore power facilities in the port or regional ship docking-concentrated places, the power supply from the port directly to the ship replaces the previous ship generator set burning fuel oil to generate electricity, which can reduce ship pollution emission to a large extent.

Chongqing has not formulated measures for the discharge of atmospheric pollutants from ships suitable for the port according to the characteristics of different ports, as it lacks corresponding basic research, has failed to form an effective and unified supervision and management system, and lacks technical standards and control technology for port and ship emissions. Combined with the above-mentioned spatial–temporal distribution map of ship atmospheric pollutant emissions and correlation research, ships have the most frequent activities in the watershed from Cuntan Port to Guoyuan Port, and the density of atmospheric pollutant emissions is the largest. According to the scale of the port and the characteristics of the port, the establishment of deceleration zones and emission control areas in Cuntan Port and Guoyuan Port, and the use of shore power as the first choice in Luoqi Port achieves better results.

6. Conclusions

In this paper, the emission inventory was used to study the atmospheric pollutants of ships in the Chongqing port area in combination with AIS data. On this basis, GIS technology is applied to systematically study the temporal and spatial distribution characteristics of atmospheric pollutants of ships. Pearson correlation analysis was used for the pollutant-dense areas of Cuntan Port, Guoyuan Port, and Luoqi Port. Moreover, the prevention and control of air pollution from ships in the Chongqing port area was analyzed. The conclusions reached are as follows:

(1) In this paper, according to the ship's atmospheric emission inventory, the atmospheric pollutant emissions of the main and auxiliary aircraft under different navigation conditions were obtained. Among them, the emissions of air pollutants such as CO_2, NO_X, SO_X, CO, PM_{10}, and $PM_{2.5}$ were 61,002.97 t, 873.87 t, 43.44 t, 95.03 t, 25.04 t, and 18.80 t, respectively. Analysis was carried out from the condition of the vessel and the type of contaminant. The sum of the concentrations of each pollutant in the mooring state of the auxiliary aircraft is high. The sum of the concentrations of each pollutant in the auxiliary motor maneuvering state is small. The pollutants are mainly CO_2 and NO_X, of which the main ones are the emission of greenhouse gas CO_2;

(2) The temporal distribution characteristics of atmospheric pollutants on ships were analyzed. Because the level of ship activity is related to the hydrological environment characteristics of the Three Gorges Reservoir Area of the Yangtze River, as well as the different functions of the ship itself, there is a large difference in the total amount of air pollutant emissions. It is affected by factors such as the level of ship activity in the Three Gorges Reservoir Area of the Yangtze River, the hydrological characteristics of the waterway environment, autumn and winter, and flood periods and dry water periods. In October 2021, the air pollutants of ships in the Chongqing port area were higher than in other months, while December was low. On the other hand, the spatial distribution characteristics of air pollutants on ships were analyzed. This is related to the degree of distribution of Chongqing ports and the level of ship activity;

(3) Correlation studies were conducted on the concentrations of atmospheric pollutants in ships at three ports. The ship activities of the three representative ports have their own characteristics and distribution laws. Therefore, it shows the different characteristics of the correlation of air pollutants on ships. Among them, $PM_{2.5}$ is most correlated with CO_2 in Cuntan Port and Luoqi Port, but CO is most correlated with CO_2 in Guoyuan Port. This reflects the new situation of the transfer of foreign trade import container business in Chongqing Cuntan Port Area to Guoyuan Port Area. Moreover, Chongqing's shipping hubs are concentrated in Cuntan Port and Guoyuan Port.

Different ports need to implement regional emission reduction measures according to their own characteristics. Cuntan Port and Guoyuan Port shall establish deceleration zones and emission control areas. The Luoqi Port uses shore power as its first choice. It is recommended to improve the quality of ship fuel by imposing limits on the sulfur content of fuel oil and replacing clean fuel energy, add special equipment to the tail of the diesel engine for post-treatment of exhaust gases, and add port shore power facilities to control pollution emissions where port or regional ship calls are concentrated.

Although the research in this paper can provide a reference for the prevention and control of air pollution from inland ships to a certain extent, there are some limitations to the study. On the one hand, there is uncertainty in the estimation process of ship emission inventories. To this end, identifying emission inventory uncertainties can effectively promote the improvement of future emission inventories. There is an urgent need to improve the completeness and accuracy of emission inventories. In addition, this paper only used the ship air pollutant data from September to December 2021 which covers dry periods, moderate water periods, and flood periods; however, no more datasets are included. Later, more comprehensive data sets can be combined to further study the characteristics of air pollutants emitted by ships. In addition, we will formulate more perfect measures for the protection of the atmospheric environment in ports.

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