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Ship Emission Inventories in Estuary of the Yangtze River Using Terrestrial AIS Data

X. Yao, J. Mou, P. Chen & X. Zhang
Wuhan University of Technology, Wuhan, China

ABSTRACT: Estuary forms a transition zone between inland river and open sea. In China, the estuary of the Yangtze River plays a vital role in connecting the inland and oversea shipping, and witnesses heavy vessel traffic in the recent decades. Nowadays, more attentions have been directed to the issue of ship pollution in busy waterways. In order to investigate the ship emission inventory, this paper presents an Automatic Identification System(AIS) based method. AIS data is the realistic data of vessel traffic including dynamic information (position, speed, course, etc.) and static information (ship type, dimensions, name, etc.). According to ship dimensions, the power of engines is estimated for different ship types. By using AIS based bottom-up approach, ship emission inventories and shares of air pollutants and GHGs (Greenhouse gases) are developed. Spatial distribution of ship emissions is illustrated in the form of heat map. As a case study, the emission inventories are analyzed using AIS data of 2010 in the estuary, and following results are made:(1) shares of the emission are cruise ships 6.59%, bulk carriers 5.16%, container ships 52.96%, tankers 15.16%, fishing ships 9.16%, other ships 10.97%; (2) CO2 is the dominant part of the emission. (3) Areas of highest emission intensity are generally clustered around the South Channel, the North Channel and ports in the vicinity. The proposed method is promising because it is derived from the AIS data which contains not only real data of individual ship but also vessel traffic situation in the study area. It can server as a reference for other researchers and policy makers working in this field.

1 INTRODUCTION

The awareness of environmental protection, especially on air pollution issue, has been rising rapidly in the past few years. The International Maritime Organization(IMO) consecutively released series of Greenhouse Gas Research Report, which indicated that ship exhaust gas has become an important source of air pollution in certain regions such as big port cities. GHGs (CO_2, CO, CH_4 and N_2O), as a dominant composition of ship emissions, are assumed to increase by 50%-250% if no action is taken (Buhaug et al.,2009; Smith et al.,2014). Such pollutants, together with other ingredients of ship emissions such as SO_X, Particular Matter(PM), Hydrocarbon(HC) and Diesel Particular Matter(DPM), pose serious threat to the quality of the environment.

To investigate ship emissions and their influence on the environment, many researches have been conducted on estimating the quantity of emissions. Eyring et al. (2005) estimated the amount of global emissions of CO_2 and NO_X from 1950 to 2001 using fuel consumption and fleet numbers. Hulskotte and Gon (2009) proposed a method to estimate the emissions of ships at berth based on the actual fuel consumption and the fuel quality. Schrooten et al.

(2009) developed the total emissions using comprehensive maritime transport database of activity data, specific energy consumption, emission factors. These studies demonstrated useful methods to quantify ship emissions and their composition. However, the data for modelling the ship emission in certain area is very much limited. Therefore, calculating the ship emission inventory is challenging.

Since 2002 new ships and later all larger sea-going vessels (>300 GT) and all passenger vessels are required to carry an Automatic Identification System (AIS) on board. Through dedicated VHF frequencies, AIS information is transmitted between vessels, from vessels to shore, or vice versa. In simple terms, AIS is a technology to make ships "visible" to each other. AIS data is the realistic data of traffic data including dynamic information (position, speed, course, etc.) and static information (ship type, dimensions, name, etc.). Such development provides profound data foundation of individual ship activity information and regional traffic situation to study on ship emissions. Therefore, several researchers applied such perspective on their study as new approach to obtain ship emission inventories accurately.

The Ship Traffic Emission Assessment Model(STEAM) was established by Jalkanen et al. (2007) to estimate the emissions of SO_x, NO_x, CO_2 in the Baltic sea. Laurie and Brett (2014) established a model to calculate ship engine exhaust emissions in ports and extensive coastal waters using terrestrial Automatic Identification System data for ship movements and operating modes. Winther et al. (2014) calculated a detailed Black Carbon(BC), NO_x and SO_2 emissions inventories in the Arctic in 2012 and under two shipping scenarios (with or without arctic diversion routes). Meanwhile, they forecasted the emission for the years 2020, 2030 and 2050. Since ships emission inventory is closely linked with the activity of every ship, and AIS data can explicitly reflect individual ship activity and macroscopic traffic situation of certain region, methods based on AIS data can estimate emissions more accurately and become promising.

However, the relevant research and management of ship emission are backward in China to some extent. The drastic development of Chinese economy has boosted the increment of ship number and the intensity of ship traffic in congested water areas such as estuaries, which causes serious environment pollution due to ship emissions. The estuary of Yangtze River plays a vital role in connecting the inland and oversea shipping, and witnesses heavy vessel traffic. Such problems are obvious in this area. With improvement and implementation of ship pollution prevention and control requirements, government of China has been speeding up the establishment of the ship Emission Control Areas (ECA) all over the country. Three ECAs are established in the Pearl River Delta, the Yangtze River Delta and the Bohai Rim (Beijing City, Tianjin City and Hebei Province) respectively. The Yangtze River Delta has already started the implementation of emission reduction measures from April 1, 2016. Those port authorities encourage ships to use low sulfur fuel (less than 0.5%m/m) when they are mooring in the hub port areas along the Yangtze River delta ECA. To control the emission in ECAs, ship emission inventory should be developed. JIN et al. (2009) presented the emissions inventory of NO_x, HC, CO and PM10 for the Tianjin port in 2006 based fuel consumption data. FU et al. (2012) applied a bottom-up dynamic approach to calculate the ship emissions for Shanghai port. YE et al. (2014) presented the ship emissions inventories for Guangdong province in 2010 using two different methods for emission factors, and analyzed the temporal and spatial characteristics of emissions from different ship type. However, it is very difficult to build the bottom-up approaches with satisfactory accuracy for ship emission on the basis of fuel consumption or turnover volume of goods.

In this context, this paper presents a bottom-up AIS-based method to calculate the ship emission inventories in the estuary of Yangtze River. We establish emission calculation models for different ship types to present a detail CH_4, CO_2, CO, DPM, HC, N_2O, NO_x, PM_{10}, $PM_{2.5}$ and SO_x emission inventories for ships in the estuary of the Yangtze River in 2010. The emission contribution which comes from each ship type to the whole-year emissions inventories are reckoned. From emission spatial allocation, the highest emission period of each ship type is identified, and the shipping route comprised the region with the highest emissions can be distinguished.

Hopefully, the proposed method can serve as a reference for other researchers and policy makers working in this field.

2 METHODOLOGY

Emissions from the shipping industry will be calculated using a bottom-up AIS-based method and AIS data to derive vessel activity. The ship length interval, sailing speed, sailing time and position are abstracted from AIS data to calculate the ship emissions. The ships within the study area will be divided into several different types. Before developing the ship emissions inventory, the length between perpendiculars (Lpp) should be calculated using a formula. Lpp can be used as input parameter for calculation of the propulsion power. Then, a method will be developed based on the emissions calculation formula to enable the calculation of emissions using engine power, engine operating time, emissions factors and load factor. Fig.1 illustrates the framework to calculate the ships emissions.

2.1 *Emissions under different load conditions*

The ship emissions is closely related to speed of the ship because the load factor of main engine is different at different speed. Therefore, ship sailing state is divided into three statuses: in port or at anchor, maneuvering and cruising.

When ship speed is less than 1knot, we believe that the ship is in port or at anchor, at this time, the auxiliary engine is considered to be the sole working engine (WEN et al., 2016). The installed auxiliary engine power can be used to calculate the emissions with load factor and emission factors according to equation (1):

$$E_{ij} = P_i \times T \times LF_j \times EF_{ij} \quad (1)$$

where E is the emission in kilogram, P is engine power in kilowatt, T is working time of auxiliary engine in hour, LF is load factor of auxiliary engine in dimentionless, EF is emission factor in dimentionless, i stands for the ship type, j stands for the category of the pollutant.

However, the load factor of main engine is related to ship design maximum speed, which can be calculated as:

$$LF_j = (\overline{V} / V_s)^3 \quad (2)$$

where $\overline{V}$ is the mean velocity for a considerable period of time and V_s is the ship design maximum velocity. The unit of them are m/s.

When a ship is maneuvering, we believe that both main engine and auxiliary engine are working. If load of main engine is more than 20%, the emission factor of main engine can be regarded as constant. And if the load is less than 20%, emission factor is negatively correlated with load of main engine, so revision is needed, the formula as:

$$EF = EF_0 \times AF \quad (3)$$

where AF is revision factor when the main engine is under low load.

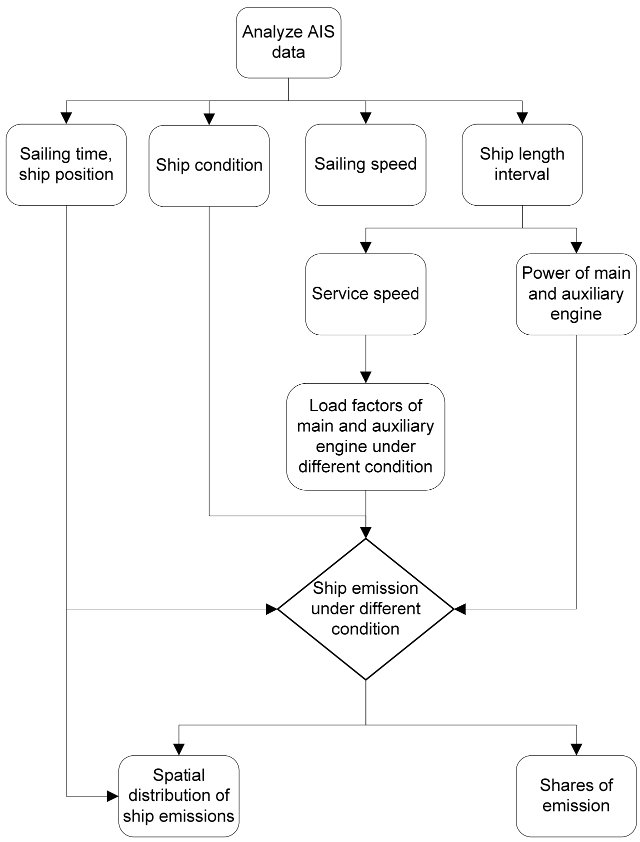


Figure 1. Framework to calculate the ships emissions

When a ship is in maneuvering, the ship emission is calculated as:

$$E_{ij} = P_{m,i} \times T_m \times LF_{m,j} \times EF_{m,ij} + P_{a,i} \times T_a \times LF_{a,j} \times EF_{a,ij} \quad (4)$$

where P_m stands for power of main engine, P_a stands for auxiliary engine.

When a vessel keeps her speed for a considerable long period of time, the state of this ship can be regarded as cruising, and both main engine and auxiliary engine participate in the work, so the formula to calculate ship emissions is same as equation (4).

2.2 *propulsive power*

Propulsive power of ship is the essential parameter to calculate ship emission. Main engine power (MP) and auxiliary engine power (AP) for each type of ship should be estimated before calculating the emission because different type of ship with different engine power and the data of engine power is limited. The propulsive power of cruise ships, bulk carriers, container ships, tankers fishing ships and other ships were calculated by using the methodology of Kristensen (2012) and Kristensen and Lützen (2012). The estimation model for propulsive power of different ship type is not the same. Here they will not be detailed because of the limited space. Taking the process of calculating the propulsive power of container ships as an example. The length of waterline of a certain container ship should be obtained by analyzing AIS data, then length between perpendiculars (Lpp) can be calculated as:

$$Lpp = L_{wl} / 1.01 \quad (5)$$

where L_{wl} is the length of the container ship.

We could calculate the deadweight (DW) of this container ship by using equation (6) and (7), and equation (8) and (9) are used to calculate the propulsive power of main engine.

$$DW_{(Lpp \le 286.93m)} = -0.00591 Lpp^3 + 3.44776 Lpp^2 - 341.6925 Lpp + 10265 \quad (6)$$

$$DW_{(Lpp \ge 286.93m)} = 3.66734 Lpp^2 - 1383.89 Lpp + 175999 \quad (7)$$

$$MP_{(DW \le 64000t)} = -8.446 \times 10^{(-15)} DW^4 + 1.0035 \times 10^{(-9)} DW^3 - 3.745 \times 10^{(-5)} DW^2 + 1.24 DW - 2503 \quad (8)$$

$$MP_{(DW \ge 64000t)} = -3.092 \times 10^{(-6)} DW^2 + 1.11 DW - 14816 \quad (9)$$

Finally, the propulsive power of auxiliary engine is calculated according to functions developed by the IMO MEPC(IMO,2010) with assuming a sea margin of 85%:

$$AP_{(MP \le 10000kW)} = 0.05 MP / 0.85 \quad (10)$$

$$AP_{(MP \geq 10000kW)} = 0.025MP / 0.85 + 250 \quad (11)$$

The validation of power estimation was worked out by using a data set of 10 container ships from HIS Fairplay databases to ensure the accuracy of the emission inventory estimation to a higher level.

Table1 shows that the absolute errors of Lpp are less than 10%, and absolute errors of propulsive power of main engine are less than 15%, both of which are reasonable. But the absolute errors of auxiliary engine power are relatively large and the fluctuation of which is intense, probably due to collected data of the auxiliary engine power do not match main engine power.

2.3 *Emission factors*

Emission factor is also essential for calculating the ship emissions. In this manuscript, the emission factors are classified according to engine type, fuel type, and are referred from Shanghai emission inventory (FU et al.,2012) and the report of Port of Los Angeles Inventory of air emission (Agrawal et al.,2012). Those emission factors, expressed in g/kWh, are wildly accepted by most of the scholars, see Table 2 and Table 3.

3 CASE STUDY

3.1 *Study area and data source*

The estuary of the Yangtze River plays a vital role in connecting the inland and oversea shipping and witness heavy vessel traffic. With the development of inland and open sea shipping of China, traffic volume of inbound and outbound ship witnesses a rapid increment in the past few years. Shanghai port, whose container throughput is the largest among the world, has accelerate such trend. Therefore, air pollution due to ship emissions in this area needs more attention to study. This paper chose a rectangular area with coverage between latitudes 31° 00′ N and 31° 50′ N and longitudes 121° 05′ E and 122° 40′ E. South channel, North channel and other main shipping routes are included.

As for data source, AIS data of 2010 in this area are applied. In 2010, the world expo was held in Shanghai, China. Data quality of that year are very good thanks to the comprehensive surveillance and management on vessel traffic. Based on the whole year's AIS data, 14,845 cruise ships, 11,425 bulk carriers, 174,314 container ships, 50,060 tankers, 17,260 fishing ships and 38,971 other ships (pilot boat, tugboat, engineering ships and ships do not belong to these five specific types), are taken into study.

4 RESULT

4.1.1 *Ship emission inventory*

Parameters of the model to calculate emission inventories are obtained by analyzing the AIS data of the Yangtze River Estuary in 2010. According to equation (1) - (4), the emission inventory of study area in 2010 estimated (see Table 4). The quantity of emissions of some main pollutants are PM_{10} 18,862t, $PM_{2.5}$ 15,408t, SO_X 146,876t and NO_X 244,578t respectively. The largest emission of pollutant is always CO_2, which is in consistent with other similar study.

Table 1. Power estimation and verification of container ship

MMSI	real				estimated			error		
	L_{wl}(m)	Lpp(m)	MP(kW)	AP(kW)	Lpp	MP	AP	Lpp	MP	AP
212***000	220.23	210.26	35715	1320	218.0	313301171.5		3.7%	12.3%	11.3%
212***000	304	288.8	68520	3500	301.0	609732043.3		4.2%	11.0%	41.6%
304***000	147.87	140.3	13229	600	146.4	11707594.3		4.4%	11.5%	0.9%
538***590	161.3	149.6	12640	1720	159.7	14575678.7		6.8%	15.3%	60.5%
308***000	145.12	134	10860	940	143.7	11147577.9		7.2%	2.6%	38.5%
352***000	168.05	158	16253	1080	166.4	16127724.3		5.3%	0.8%	32.9%
356***000	182	172.5	19670	1230	180.2	19642827.7		4.5%	0.1%	32.7%
356***000	144.73	135.63	10860	940	143.3	11068575.5		5.7%	1.9%	38.8%
412***430	121.2	112	7342	430	120.0	6493.8	382.0	7.1%	11.6%	11.2%
412***880	99.9	93.9	2991	-	98.9	2681.6	157.7	5.3%	10.3%	-

Table 2. Emission factors of two type of main engine

engine	emission factors									
type	CH_4	CO_2	CO	DPM	HC	N_2O	NO_X	PM_{10}	$PM_{2.5}$	SO_X
SSD[1]	0.012	620.00	1.40	1.50	0.60	0.031	17.00	1.50	1.20	10.50
MSD[2]	0.010	683.00	1.10	1.50	0.50	0.031	13.00	1.50	1.20	11.50

[1] SSD stands for slow-speed diesel engine, the maximum rotation speed of which is less than 130 r/min.
[2] MSD stands for medium-speed diesel engine, the rotation speed of which is more than 130r/min.

Table 3. Emission factors of auxiliary engine

emission factors									
CH_4	CO_2	CO	DPM	HC	N_2O	NO_X	PM_{10}	$PM_{2.5}$	SO_X
0.005	683	0.2	1.5	0.4	0.031	13	1.5	1.2	12.3

Table 4. Emissions per pollutant of each ship type in 2010

	Cruise ships (t)	Bulk carriers (t)	Container ships (t)	Tankers (t)	Fishing ships (t)	Other ships (t)
CH_4	248	1083	2589	2381	1219	936
CO_2	165,839	115,815	1180,348	361,515	199,211	238,382
CO	1149	1740	11,583	4143	35,258	3510
DPM	2856	981	12,502	2585	3604	3591
HC	411	593	4115	1418	1244	1244
N_2O	32	39	305	95	31	90
NO_X	12,498	16,260	125,536	38,643	13,915	37,727
PM_{10}	1452	1882	14,627	4467	2232	4362
$PM_{2.5}$	1165	1506	117,048	3655	1927	3500
SO_X	11,673	14,664	117,158	35,020	15,501	35,000

Table 4 indicates that the emission of each pollutant in the Yangtze River Estuary is relatively large, which is much larger than that of Shanghai port (FU et al.,2012). For example, the emission of SO_X of Shanghai port in 2010 is 35400t, while that in the Yangtze River is 229,015t, the difference is 193,615t. The reason for this difference may be that the ship traffic flow in the Yangtze River Estuary is larger than that of the Shanghai port, and ships in the Yangtze River Estuary are always cruising, while ships in Shanghai port waters are always maneuvering or at anchor.

4.1.2 *Emission validation*

Although the methodology of this study is widely accepted around the world and the parameters fits our study, it is essential to validate the emission results. The emission of individual ship can be easily measured by device while it is challenging to test thousands ships in the estuary area. In addition, it is hard to compare our emission result with other researches due to quite different traffic volume, research area and time period. Therefore, the Energy Efficiency Operational Indicator(EEOI) will be used to validate our emission results. EEOI is defined as the ratio of mass of CO_2 emitted per unit of transport work. The basic expression is shown as equation (12). When the EEOI is similar to other researches, we believe that the emission estimation is reasonable.

$$EEOI = \frac{\sum_{k} FC_k \times C_{Fk}}{m_{cargo} \times D} \qquad (12)$$

where k is the fuel type, FC_k is the mass of consumed fuel in tons, C is the fuel mass to CO_2 mass conversion factor, m_{cargo} is the mass of the ship in tons, D is the sailing distance in nautical miles.

Table 5 shows the EEOI in our study comparing to other researches. The EEOI is calculated based on numbers of vessels within study area, while MEPC_684 and SUN et al. (2013) studied the single vessel. The comparison shows that the numbers are in same magnitude and because of some different condition, small difference exists which can be accepted.

Table 5. Comparison of EEOI

	This study	MEPC_684 case study	Second IMO GHG Study general/bulk	SUN et al. (2013)
EEOI 10^{-6}	12.6	13.5	14-27/5.5-46.3	78-409

4.1.3 *shares of ships emissions*

The total emissions per pollutant in the study area is CH_4 8457t, CO_2 2261,109t, CO 57,384t, DPM 26,118t, HC 9025t, N_2O 592t, NO_X 244,579t, PM_{10} 29,022t, $PM_{2.5}$ 128,801t, and SO_X 229,015t. **Fig. 1** shows the shares per pollutant of each ship type. The emissions from container ships is largest due to the number of container ships accounts for the largest proportion and the speed is relatively faster. Fishing ships contribute the largest share of CO emission because engine condition of fishing ships is always not up to standard, and the combustion of inferior fuel in the engine is not complete.

Large-sized container ship is not only the mainstream ship type of the current shipping industry, but also the future development of ship type, so it is reasonable to control the discharge of the container ship.

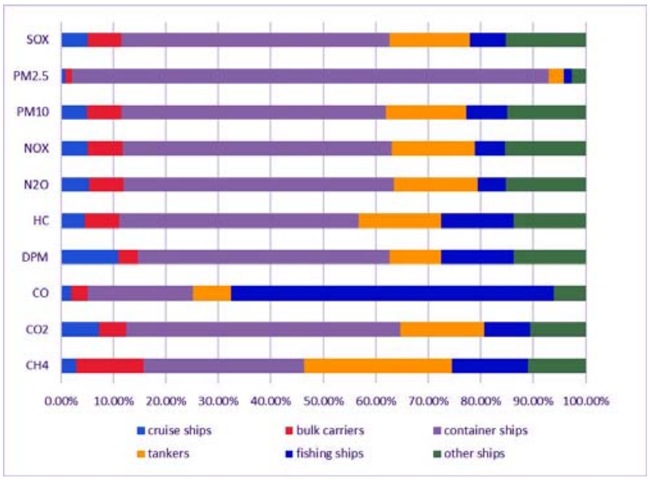
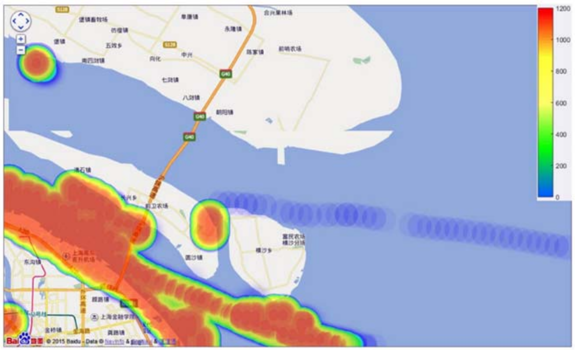


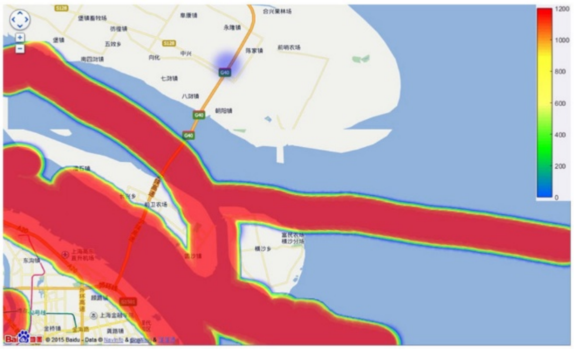
Figure 1. Shares of each ship type

4.1.4 *Patterns distribution of ship emissions*

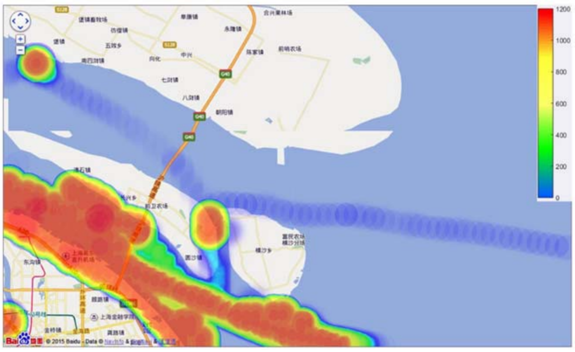
The emission result is calculated based on AIS data, and are presented as the form of heat maps. Fig. 2 shows the spatial distribution of CH_4, CO_2, CO, DPM, HC, N_2O, NO_X, PM_{10}, $PM_{2.5}$, SO_X emissions on January 3, 2010. The reason for showing the result of this day is that the number of ships on January 3 is same as the mean value and the proportion of all kinds of ships is consistent. The distributions of emission are very similar. Areas of highest emission intensity are generally clustered around the South channel, the North channel and some main jetties, followed by the area north of the Hengsha island for the shallow water depth. There are few small-sized fishing ships would sail in the water area north of the Hengsha island.



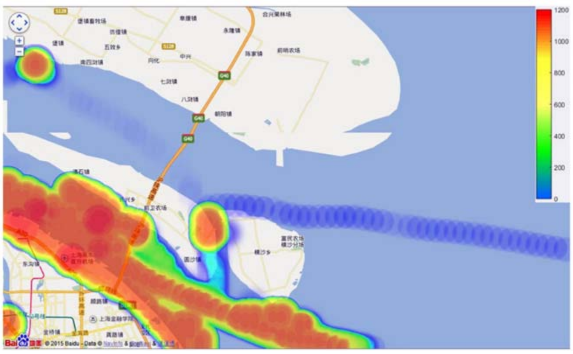
a. CH_4



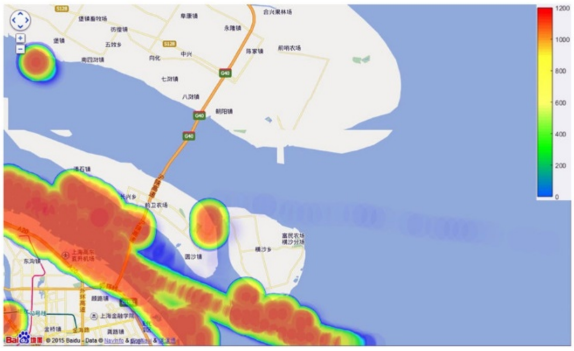
b. CO_2



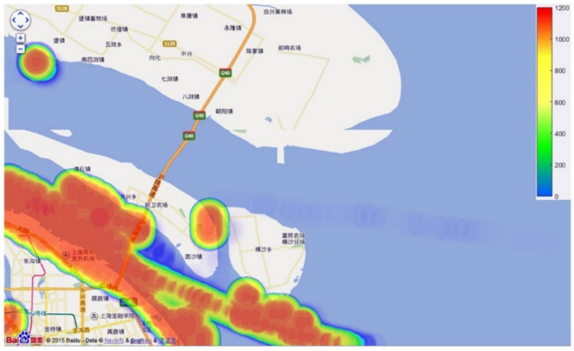
c. CO



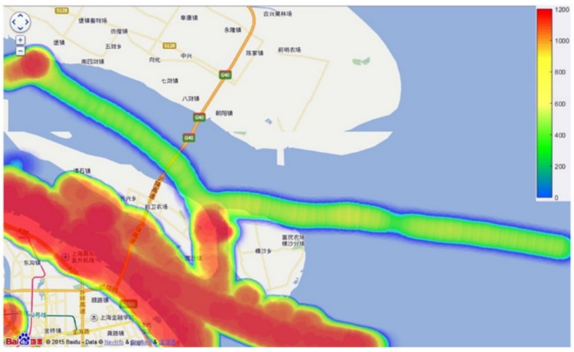
d. DPM



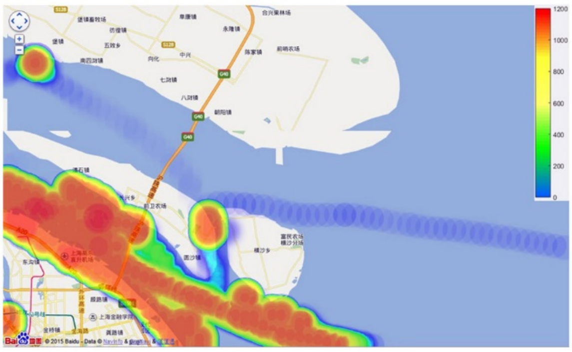
e. HC



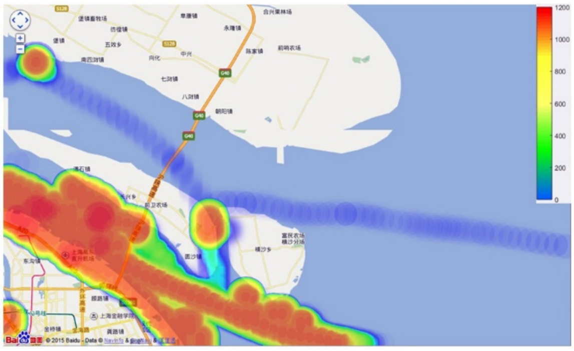
f. N_2O



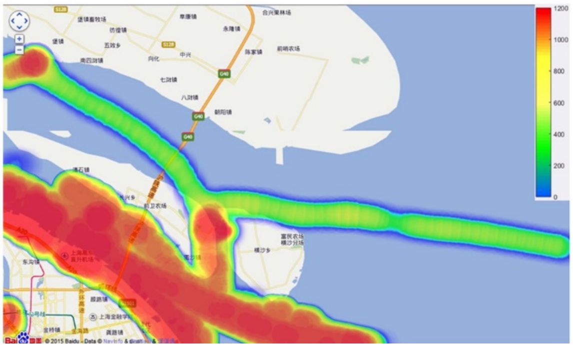
g. NO_X



h. PM_{10}



i. $PM_{2.5}$



j. SO_X

Figure 3. (a-j): Spatial distribution per pollutant on January 3, 2010

5 DISCUSSIONS

Calculating ship emissions using a AIS based method can obtain detail estimation of emissions. Emission inventories show that the pollution of the estuary is very serious and the amount of each pollutant in this area is larger than that of other ports area. While the shares of each pollutant is consistent with other researches. The amount of CO_2 is largest followed by NO_X and SO_X. The number of container ships is the largest which contributed the largest amount of pollution. Therefore, more attention should be paid to the control and reduction of emissions from container ships. Areas of highest emission intensity are generally clustered around the South Channel, the North Channel and ports in the vicinity.

It is difficult to make a precise inventory for some reasons:

1 AIS base station cannot receive the definitely accurate and complete AIS information from ships due to the technical error.
2 The static characteristics of a ship in AIS information are set by the ship operators, thus existing some man-made errors.
3 The type of ship obtained by analyzing AIS data does not match the ship itself in some cases.
4 In order to facilitate the calculation, in the classification of ship type, only select the more common five types, the relatively rare or a small number of ships are classified as other types.

6 DISCUSSION

The drastic development of Chinese economy has boosted the increment of ship number and the intensity of ship traffic in congested water areas such as estuaries, which causes serious environment pollution due to ship emissions. The estuary of the Yangtze River plays a vital role in connecting the inland and oversea shipping and witnesses heavy vessel traffic. Such problems are obvious in this area.

This paper established emission calculation models for different ship types based on AIS data, ship engine power functions and technology stratified emission factors to present a detail emission inventory for ships in the estuary of the Yangtze River in 2010. In this study, we calculated the propulsive power through several functions. Then, ship emissions in the study area in 2010 were estimated and emissions results are shown in the form of heat maps to analyze the spatial characteristics. The total emission per pollutant in the study area between latitudes 31°00′N and 31°50′N and longitudes 121°05′E and 122°40′E is CH_4 8457t, CO_2 4054,004t, CO 57,384t, DPM 26,118t, HC 9025t, N_2O 592t, NO_X 244,579t, PM_{10} 18,863t, $PM_{2.5}$ 15,408t and SO_X 146,877t.

After analyzing the AIS data broadcasted within the study area, ships are divided into cruise ships, bulk carriers, container ships, tankers, fishing ships and other ships. In 2010, the shares of total emissions are cruise ships 6.59%, bulk carriers 5.16%, container ships 52.96%, tankers 15.16%, fishing ships 9.16% and other ships 10.97%. Obviously, container ships accounts for the biggest proportion because the number of container ships is the largest.

It should be noted that there are some deficiencies in this study. We will solve them in a follow-up study. But this study also can be a pilot research to calculate the ship emission in busy waterways.

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