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Technical Information

Development of Air Pollutants Emission Inventories for Ships around Japan on a High Geographical Resolution

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ABSTRACT This study developed a database of emission inventories from ships around Japan using the activity data in the 2015 Japanese fiscal year. The emission of air pollutants from ships was estimated for fuel combustion in main engine, auxiliary engines, and boilers onboard. The ships' operations for the emission estimation in the exhaust gas consist of ships in navigation, ships at anchor, and fishing boats. For the emission estimation regarding navigation ships, data from Automatic Identification System (AIS) received at the stationary stations on land in Japan were used in this study to calculate the activity. The emission amounts were compared between the sea (Seto Inland Sea (SIS) and Tokyo Bay) and prefectures surrounding those ocean areas. The ship emission ratios in total anthropogenic emissions including the land part reached SO_2: 29%, PM: 40%, and NO_x: 22% for the SIS area. In Tokyo Bay, the ship emission ratios in total reached SO_2: 36%, PM: 28%, and NO_x: 13%, and the emission intensities per unit area for SO_2 and $PM_{2.5}$ are approximately three times higher than those in the other regions, respectively. Therefore, the shipping traffic density is relatively higher compared to transportation on land, and the emission is condensed locally. Assuming that the 2020 global sulphur limit switched to a sulphur content of 0.50% m/m, SO_2 emissions could be reduced to 24% in SIS and 22% in Tokyo Bay, sulphate emissions could be reduced to 23% in SIS and 21% in Tokyo Bay, and PM emissions could be reduced to 39% in SIS and 36% in Tokyo Bay. Therefore, the 2020 global sulphur limit should reduce the emission from ships around the Japan coastal area and improve the air quality in congested water areas such as SIS and Tokyo Bay.

KEY WORDS Shipping emission, MARPOL Annex VI, Sulphur, Marine fuel oil, AIS

1. INTRODUCTION

Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) contains regulations regarding the emission of air pollutants from ships. One regulated target of Annex VI is to reduce the sulphur emissions from ships. At the 70th session of the Marine Environment Protection Committee (MEPC 70), held in October 2016, the MEPC adopted the sulphur content in the fuel oil on board ships to be less than 0.50% m/m from January 1, 2020, from the previous limit of 3.50%. Therefore, all ships now use marine fuel oil with a sulphur content of less than 0.50%. Strengthening this regulation in MARPOL, Annex VI (the 2020 global sulphur limit) aims to reduce sulphate (SO_4^{2-} in particulate matter (PM)) and sulphur dioxide (SO_2) emissions from ships. Thus, the 2020 global sulphur limit could reduce $PM_{2.5}$ concentrations in and around the area with a higher density of shipping traffic.

In Japan, the environmental air quality standard for $PM_{2.5}$ is set as 35 μg m^{-3} and 15 μg m^{-3} for the average daily and annual concentrations, respectively. Uno *et al.* (2017) reported a decrease in the impact of transboundary air pollution in Japan, and the achievement rate for $PM_{2.5}$ has improved in the past several years. For example, 765 out of 818 (93.5%) ambient air monitoring stations in Japan achieved the standard for $PM_{2.5}$ in 2018 (Ministry of the Environment Japan, 2020a). However, the achievement rate remains low at the Okayama and Kagawa prefectures. In 2018, 7 out of 18 ambient air monitoring stations in Okayama (38.9%) and 8 out of 12 in Kagawa (66.7%) achieved the standard for $PM_{2.5}$. These rates were the first and second lowest among all prefectures in Japan. Fig. 1 shows that both prefectures are geologically located in western Japan and across the Seto Inland Sea (SIS).

The coastal area surrounding SIS contains several large point sources of air pollutants, and the density of ship traffic is higher than the average in Japan. Moreover, SIS is located in a semi-enclosed area surrounded by the Chugoku Mountains (north side) and Shikoku mountains (south side). Thus, it is critical to evaluate the local weather characteristics and contribution of each emission to the air quality around SIS. If air pollutants emitted from ships affect the air quality around SIS, strengthening the regulation of sulphur content in marine fuel could improve the achievement rate for $PM_{2.5}$ at prefectures around SIS. The possibility of improvement can also be expected in other areas such as Tokyo Bay with enormous shipping traffic. To evaluate the mechanism of increasing concentrations and consider the efficacy of control measures for $PM_{2.5}$, an appropriate air quality model is critical, and emission inventories for air pollutants are required as input data of the air quality model.

In this context, this study develops a database of emission inventories from ships around Japan. One database was estimated using the activity data in the 2015 Japanese fiscal year. The other database was estimated by considering using marine fuel oil with a sulphur content of less than 0.50%. The reduced amount of SO_2 and sulphate, as expected by the 2020 global sulphur limit, is also discussed considering the comparison between the two estimated databases.

This research was performed by the Environment Research and Technology Development Fund (JPMEERF 20185002) of the Environmental Restoration and Conservation Agency of Japan. An outline of the fund and its recent activities, including this research, are introduced in Ohara and Ono (2018).

2. METHODOLOGY

The emission database for ships, developed by the

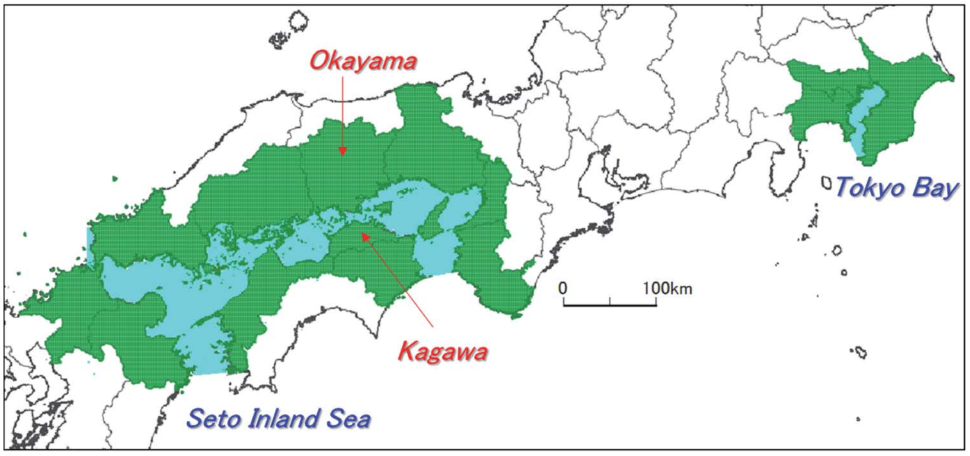

Fig. 1. Location and area of Seto Inland Sea (21,827 km^2) and Tokyo Bay (1,380 km^2). The prefectures surrounding these ocean areas are also highlighted.

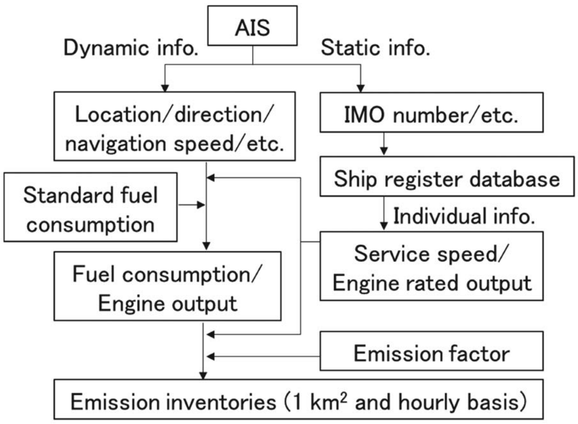

Fig. 2. Schematic diagram of the approach for the emission estimation regarding navigation ships.

Sasagawa Peace Foundation, formerly known as the Ocean Policy Research Foundation (OPRF), were widely used as input data in studies regarding the air quality model in Japan (OPRF, 2011). However, because the database was developed based on the activity data of ships in 2005, the emission database for ships had to be adjusted using the latest activity data. Therefore, in this study, while following the method of OPRF (2011), the emission of air pollutants from ships was estimated for fuel combustion in main engine, auxiliary engines, and boilers. In addition to emissions in the exhaust gas, non-methane volatile organic compounds (NMVOCs) emissions discharged from the cargo tanks of oil/chemical tankers were considered. However, this study summarized the methodology and part of the estimated results for emissions in the exhaust gas.

The ship' operational types for the emission estimation in the exhaust gas consist of ships in navigation, ships at anchor, and fishing boats. Fig. 2 and Fig. 3 are schematic diagrams of the emission estimation approach. The activity data and sulphur content in the fuel were updated for the 2015 Japanese fiscal year. The target substances were SO_2, SO_4^{2-} in PM, nitrogen oxides (NO_x), NMVOCs, and carbon monoxide (CO).

In this study, the areas of SIS (21,827 km^2) and Tokyo Bay (1,380 km^2), and the prefectures surrounding these sea areas are highlighted as a comparison analysis of the emission between land and sea. As shown in Fig. 1, the 11 prefectures of Wakayama, Osaka, Hyogo, Okayama, Hiroshima, Yamaguchi, Fukuoka, Oita, Ehime, Kagawa, and Tokushima (in total 61,260 km^2) surround SIS, and the three prefectures of Chiba, Tokyo, and Kanagawa (in total 9,612 km^2) surround Tokyo Bay.

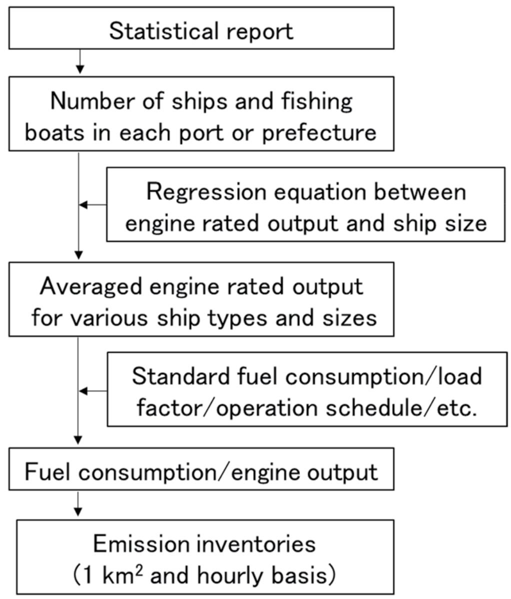

Fig. 3. Schematic diagram of the approach for the emission estimation of anchored ships and fishing boats.

2.1 Emission Factors

Air pollutant emissions can be expressed as a product of activity data and emission factors (EFs). Because SO_2 is formed during the combustion of sulphur contained in the fuel used, its unit of EFs is expressed by g-SO_2/g-fuel. Thus, the fuel amount consumed by both main and auxiliary engines and boilers during ship navigation and anchoring is needed as activity data for emission estimation. The global information on sulphur content in the fuel used is needed to decide SO_2 EFs. In this study, it was assumed that all ocean-going ships used residual marine fuel oil, and the average sulphur content as 2.45% (International Maritime Organization, 2016) was applied for SO_2 EF of the ocean-going ships. Regarding domestic ships and fishing boats in this study, the consumption ratio of residual marine fuel oil, distillate marine fuel oil, and light oil was assumed following the domestic statistical investigation in Japan, and the average sulphur content of 2.33%, 0.40%, and 0.001% was applied, respectively (Japan Federation of Coastal Shipping Association, 2017). Regarding SO_2 EFs after the 2020 global sulphur limit, it was estimated that the sulphur content of residual fuel oil used by ocean-going and domestic ships would be reduced to 0.50%.

OPRF (2011) derived EFs for PM and sulphate, as shown in Eqs. 1 and 2, respectively, by using the result of component analysis of ship exhaust gas (Kurok *et al.*, 2007).

$$\text{PM EF (g/kWh)} = 0.585 \times \text{S (\%)} + 0.281, \quad (1)$$

$$\text{sulphate EF (g/kWh)} = 0.267 \times \text{S (\%)} - 0.009, \quad (2)$$

where S (%) is the sulphur content in marine fuel oil. These equations are the regression lines derived from the emission intensity of the sulphur content in several marine fuels quantified using the dilution method (ISO 8178-1). The unit of EFs (g/kWh) shows that the activity data required for PM and sulphate emissions (g/h) estimation are the engine output (kW) of the main and auxiliary engines during ship navigation and anchoring.

For this study, the EFs of NO_x was utilized from the regulated values by MARPOL Annex VI of the International Maritime Organization (IMO). The MARPOL Annex VI required the limit values of NO_x according to the keeled year of each ship (Tier 1 and Tier 2). For the older ships excluded from the regulation, this study assumed that the engines on those ships would emit NO_x by 30% more than the limit of Tier 1. The limit value unit is g/kWh, and is calculated from the engine's rated speed. The activity data for PM required for estimating NO_x emissions (g/h) are the engine output (kW) of the main and auxiliary engines during ship navigation and anchoring. Since most ships are navigated based on less than the limit value of IMO NO_x regulations, the estimated amount of NO_x emission in this study was a conservative result compared with the actual emission.

Refer to OPRF (2011) regarding the EFs for the other pollutants.

2.2 Activity Data

2.2.1 Activity Data for Navigation Ships

Data from the Automatic Identification System (AIS) received from the stationary stations on land in Japan were used in this study to calculate the activity for navigation ships applying the same method as OPRF (2011). AIS was originally introduced in 2002 for the purpose of collision prevention, and it exchanges dynamic information (position, speed) among ships and AIS stations. Although the target year for the estimation was the entire 2015 in this study, because of costs, only the monthly AIS data for September 2015 were used for the estimation. Then, the monthly data were extrapolated by multiplying it by approximately 12 to obtain the annual emission amount. Fig. 4 shows the number of ships entering the 161 major domestic ports per day in Japan for each month of the 2015 Japanese fiscal year. Though there was no large difference for the number of ships among each month, September 2015 has the highest number of ships entering these major domestic ports; therefore, the estimated annual emission amounts in this study were conservative results compared with the actual situation. The raw AIS data were aggregated geographically by approximately 1 km^2, and hourly basis.

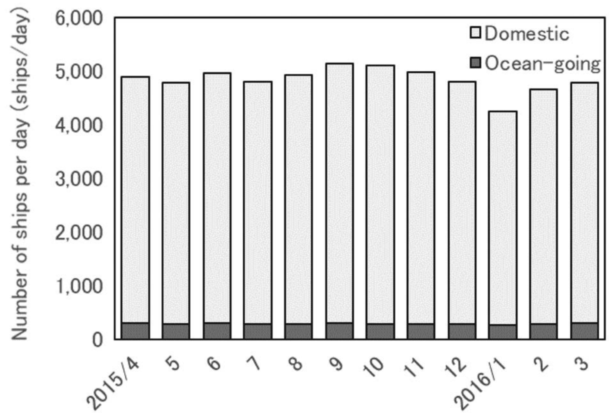

Fig. 4. Number of ships entering the 161 major domestic ports per day in Japan for each month of the 2015 Japanese fiscal year.

The satellite AIS data are also available (Johansson *et al.*, 2017; Winther *et al.*, 2014) for the emission estimation from ships but were excluded from this study because the capture rate of ships by the satellite became lower in congested water areas such as SIS and Tokyo Bay (Aratani *et al.*, 2015).

Eqs. 3 and 4 show the calculation method of NO_x and SO_2 emissions, of which the required activity data are the engine output (kWh) and fuel consumption (g-fuel), respectively.

$$NO_x \text{ emission (g/h)} = \text{EFs (g/kWh)} \times \text{engine-rated output (kW)} \times \text{load factor (\%)}, \quad (3)$$

$$SO_2 \text{ emission (g/h)} = \text{fuel consumption (g-fuel/h)} \times \text{S in fuel (\%)} \times M_{SO_2}/M_S - \text{sulphate} \times M_{SO_2}/M_{SO_4}, \quad (4)$$

where EFs is the emission factor as the NO_x limitation required in MARPOL Annex VI, M_{SO_2} is the molecular weight of SO_2, MS is the molecular weight of sulphur, M_{SO_4} is the molecular weight of sulphate, and S in fuel is the sulphur content (%) in marine fuels. Furthermore, the load factor and fuel consumption are calculated using Eqs. 5 and 6, respectively.

$$\text{Load factor }(\%) = 85\% \times (Vn^3/Vs^3), \quad (5)$$

$$\text{fuel consumption }(g/h) = \text{SFC }(g/kWh) \times \text{engine-rated output }(kW) \times \text{load factor}, \quad (6)$$

where Vn is the navigation speed of each ship (knots), Vs is the service speed of each ship (knots), and SFC is the standard fuel consumption.

The value of Vn was obtained from AIS data. The same values of SFC shown in OPRF (2011) were adopted according to the ship size and type. The engine-rated output and service speed are the individual information of each ship. Furthermore, the built year information of each ship is necessary to determine the EFs of NO_x, which is also individual information. Because individual information is excluded from the AIS data, domestic and global register databases were used to derive the necessary individual information with the AIS data (The Japan Shipping Exchange, 2017; IHS Markit, 2017).

2.2.2 Activity Data for Anchored Ships

The emission of air pollutants from anchored ships was estimated based on fuel combustion by auxiliary engines and boilers. The number of ships entering each port in Japan was estimated and classified by ship size and type based on the annual report of the port survey obtained from the Portal Site of Official Statistics of Japan website (https://www.e-stat.go.jp/). The engine-rated output of auxiliary engines, which is crucial for the emission, was estimated from the regression fitting between the engine-rated output and ship size created for various ship types using the same methods as OPRF (2011).

The total estimated activity data of each port were distributed equally to every geographical mesh in each port area. The spatial and temporal basis aggregation equaled those for the activity data for navigation ships stated in paragraph 2.2.1. Refer to OPRF (2011) for other parameters such as engine load factor and SFC.

2.2.3 Activity Data for Fishing Boats

The emission of air pollutants from fishing boats was estimated based on the fuel combustion in engines onboard. The number of fishing boats registered in each prefecture in Japan was estimated and classified by ship size and type, based on the Fishery Census in 2013, which was the closest survey year to 2015. The data can be obtained from the Portal Site of Official Statistics of Japan website (https://www.e-stat.go.jp/). The engine-rated output of the main engine, critical for the emission estimation, was estimated from the regression equation between the engine-rated output and ship size using the same methods as OPRF (2011).

The spatial and temporal basis aggregation was the same as those for the activity data for navigation ships stated in paragraph 2.2.1. Refer to OPRF (2011) for other parameters such as engine load factor and SFC, and the method for apportioning the activity data to the ocean area.

3. RESULTS AND DISCUSSION

3.1 Uncertainty for the Estimation

The uncertainty associated with the bottom-up estimation of this study was evaluated by comparing the estimated results of fuel consumption with its statistical data; in other words, the top-down approach. It is challenging to evaluate the uncertainty of fuel consumption for international ships because no statistical information exists showing the actual fuel consumption data around Japan. On the other hand, the navigation area for domestic ships is generally within the reception range of terrestrial AIS stations in Japan. Also, statistical data are available for the actual fuel consumption of ships involving domestic navigation because the fuel is taxied. Thus, in this section, the uncertainty for the estimation was assessed regarding the ships for domestic navigation.

The fuel consumption of domestic ships obtained using the bottom-up approach was 2,339 Gg year^{-1} when navigating and 480 Gg year^{-1} when anchoring, totaling 2,819 Gg year^{-1}. On the other hand, the statistical results of fuel consumption using the top-down approach in the 2015 Japanese fiscal year, which were compiled using the General Energy Statistics in Japan (Agency for Natural Resources and Energy, 2020), were reported as 959 Gg year^{-1} for passenger ships and 2,221 Gg year^{-1} for cargo ships, totaling 3,180 Gg year^{-1}. Consequently, the estimated result is approximately 89% of the statistics, suggesting that the estimation of the activity using the bottom-up approach in this study had sufficiently low uncertainties against the top-down approach. It was considered that the underestimation was caused by ships not captured by or unequipped with AIS.

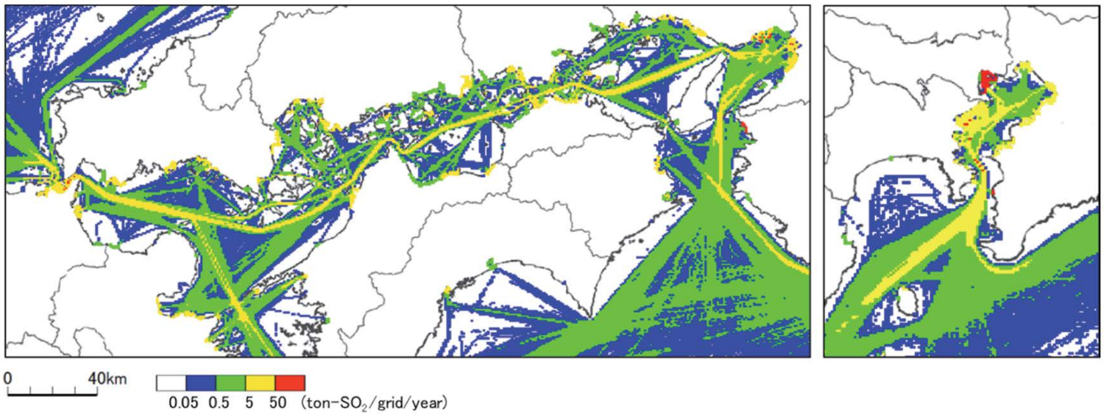

Fig. 5. Horizontal distribution of estimated SO_2 emission (tonne/grid/year) from ships centered around Seto Inland Sea and Tokyo Bay.

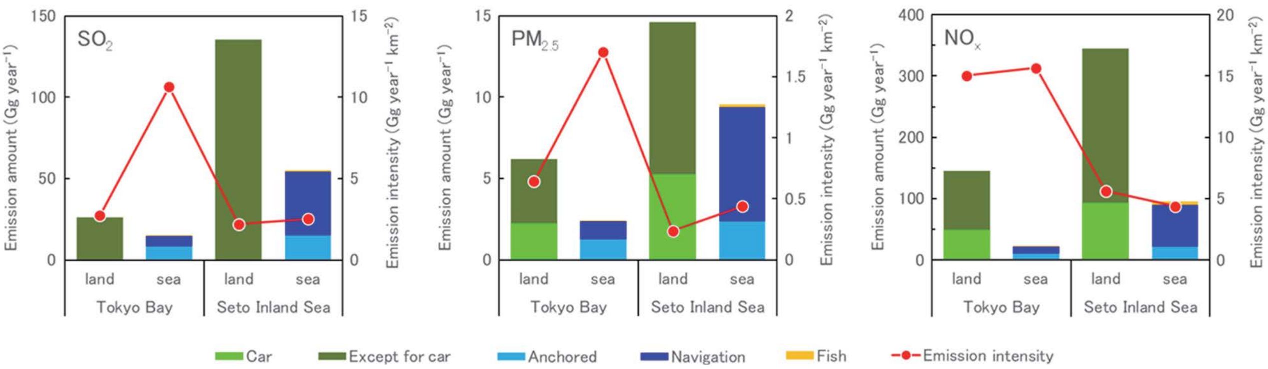

Fig. 6. Total amount of SO_2, PM, and NO_x emissions accumulated for the areas of Seto Inland Sea (21,827 km^2) and Tokyo Bay (1,380 km^2), and the prefectures surrounding these sea areas (61,260 km^2 and 9,612 km^2, respectively).

3.2 Comparison of the Emission between Land and Sea

Fig. 5 exemplifies the horizontal distribution of estimated SO_2 emission intensities (tonne/grid/year) from ships centered around SIS and Tokyo Bay. Because the geographical resolution is high (approximately 1 km^2), shipping routes are clearly captured in this study.

Fig. 6 shows the total SO_2, PM, and NO_x emissions accumulated for the areas of SIS and Tokyo Bay, and the prefectures surrounding these sea areas. Regarding the emissions on land, $PM_{2.5}$ and other air pollutant emission inventories from the Ministry of the Environment were used (Ministry of the Environment Japan, 2020b). The target year of the emissions on land is the 2015 Japanese fiscal year, which matches the year for ship emission estimated in this study.

PM emissions from ships were calculated using the EFs shown in Eqs. 1 and 2. The EFs were derived from the regression lines calculated from the emission intensity of the sulphur content in several marine fuels quantified using the dilution method (ISO8178). Ikame *et al.* (2011) reported that the PM mass concentration obtained using the dilution method for combusting distillate marine fuel oil had a size distribution smaller than 2 μm. The size distribution was quantified using the Electrical Low-Pressure Impactor and the filter method. This study compared the PM size distribution changes depending on the properties of the fuel oil, but the estimated PM emissions from ships were directly compared with the $PM_{2.5}$ emissions on land.

Fig. 6 shows that the emission amounts of SO_2, PM, and NO_x were the largest on land surrounding SIS, covering a wide land area of 11 prefectures. The total emissions from ships in SIS were SO_2: 55.0 Gg $year^{-1}$, PM: 9.6 Gg $year^{-1}$, and NO_x: 95.6 Gg $year^{-1}$. The ship emission ratios in total (land and sea) reached 29%, 40% and

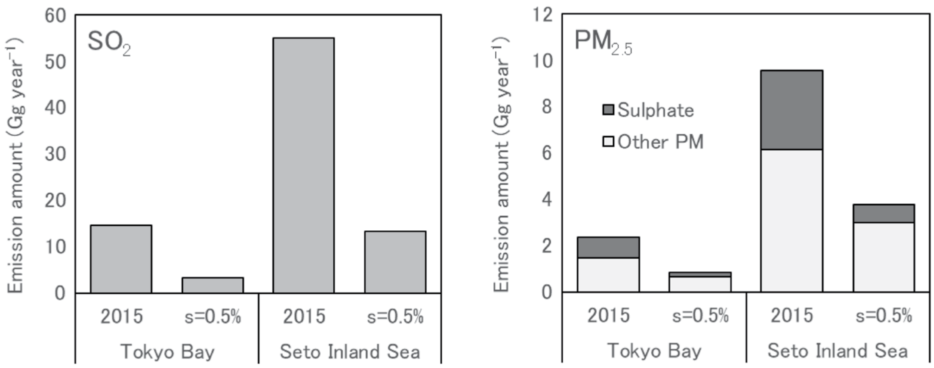

Fig. 7. Expected reduction in SO_2 and PM emissions in Seto Inland Sea and Tokyo Bay because of the 2020 global sulphur limit.

22% for SO_2, PM and NO_x, respectively in the SIS area. Regarding Tokyo Bay, the total emissions from ships were SO_2: 14.7 Gg year^{-1}, PM: 2.4 Gg year^{-1}, and NO_x: 21.6 Gg year^{-1}. The ship emission ratios in total (land and sea) reached 36%, 28% 13% for SO_2, PM and NO_x, respectively in the Tokyo Bay area. In Tokyo Bay, the emission intensities per unit area for SO_2 and $PM_{2.5}$ are approximately three times higher than those in the other regions, respectively. Therefore, the shipping traffic density is relatively higher compared to transportation on land, and the emission is condensed locally.

3. 3 Emission Reduction of SO_2 and Sulphate Expected by the 2020 Global Sulphur Limit

Fig. 7 shows the expected reduction of SO_2 and PM emissions in SIS and Tokyo Bay led by the 2020 global sulphur limit. Assuming that the 2020 global sulphur limit switched to a sulphur content of 0.50%, SO_2 emissions could be reduced to 24% in SIS and 22% in Tokyo Bay, sulphate emissions could be reduced to 23% in SIS and 21% in Tokyo Bay, and PM emissions could be reduced to 39% in SIS and 36% in Tokyo Bay. The decrease in other PM originated from the decreasing water content associated with sulphate, which was explained in EFs of PM (Eq. 1) quantified by the dilution method (ISO8178-1). The ratio of sulphate to SO_x ($=SO_2+$sulphate) emissions was calculated as approximately 6% on a weight basis in both areas.

4. CONCLUSIONS

This study developed a database of emission inventories from ships around Japan. The first set of the database was estimated using the activity data in the 2015 Japanese fiscal year. The second set was estimated by considering using marine fuel oil with a sulphur content of less than 0.50%. The reduced amount of SO_2 and sulphate, as expected by the 2020 global sulphur limit, was also discussed by considering the comparison between the two estimated databases. In this study, while applying the same method of OPRF (2011), the emission of air pollutants from ships was estimated for fuel combustion in main engine, auxiliary engines, and boilers onboard. The ships' operations for the emission estimation in the exhaust gas consist of ships in navigation, ships at anchor, and fishing boats. For the emission estimation regarding navigation ships, data from AIS received at the stationary stations on land in Japan were used in this study to calculate the activity. Because individual information, such as the engine-rated output, service speed, and the launch year information, was excluded in the AIS data, domestic and global register databases were used to derive the necessary individual information with the AIS data.

Since the developed database in this study has a high geographical resolution (approximately 1 km^2), shipping routes were clearly captured on the emission map of the horizontal distribution. The fuel consumption of domestic ships obtained from the bottom-up approach was 2,819 Gg year^{-1}. On the other hand, the statistical result of fuel consumption using the top-down approach was 3,180 Gg year^{-1}. Consequently, the estimated result is approximately 89% of the statistics, suggesting an underestimation but consistency in the estimation for this study.

The emission amounts were compared between the sea (SIS and Tokyo Bay) and prefectures surrounding those ocean areas. The emission amounts of SO_2, PM, and NO_x were the largest on the land surrounding SIS, covering a wide land area of 11 prefectures. The ship emission ratios in total (land and sea) reached SO_2: 29%, PM: 40%, and NO_x: 22% for the SIS area. In Tokyo Bay, the ship emission ratios in total (land and sea) reached SO_2: 36%, PM: 28%, and NO_x: 13%, and the emission intensities per unit area for SO_2 and $PM_{2.5}$ are approximately three times higher than those in the other regions, respectively. Therefore, the shipping traffic density is relatively higher compared to transportation on land, and the emission is condensed locally. Assuming that the 2020 global sulphur limit switched to a sulphur content of 0.50%, SO_2 emissions could be reduced to 24% in SIS and 22% in Tokyo Bay, sulphate emissions could be reduced to 23% in SIS and 21% in Tokyo Bay, and PM emissions could be reduced to 39% in SIS and 36% in Tokyo Bay. Although the modeling approach is essential to evaluate the efficiency of emission regulation for air quality, the 2020 global sulphur limit should reduce the emission from ships around the Japan coastal area and improve the air quality in congested water areas such as SIS and Tokyo Bay. Furthermore, the database of the emission inventories from ships developed in this study would contribute to the modeling study regarding the air quality in Japan.

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