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Research Article

Assessing the impact of emission control areas policy on ship emissions in the Gulf of Thailand using AIS data

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Abstract
The rising concern over ship emissions has prompted the exploration of Emission Control Areas (ECAs) in various regions. This study provides a comparative analysis of ship emissions in non-ECA areas and offers insights for implementing ECA policies in the Gulf of Thailand. Utilizing Automatic Identification System (AIS) data from January 1 to 31, 2023, this study models ship emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM). Spatial analysis reveals critical emission hotspots associated with ship density, port locations, and major shipping lanes, identifying oil tankers as primary emitters. A comparative analysis with existing ECAs demonstrates that implementing an ECA in the Gulf of Thailand could substantially reduce emissions. The findings offer actionable insights for policymakers, including strategies like adopting low-sulfur fuels, optimizing shipping routes, and incentivizing cleaner technologies. Furthermore, this study highlights the importance of addressing economic challenges and ensuring comprehensive data collection to capture seasonal and demand-driven emission variations.

1. Introduction

Since 2023, the global and Thai economies have been continuously improving, leading to higher maritime transport revenues which have remained above pre-COVID levels (Sathapongpakdee, 2023). This economic growth has also driven an increase in energy consumption, particularly from maritime transport, which accounts for more than 80 % of global trade due to its energy efficiency in moving large volumes of goods (UNCTAD, 2024). Faber et al. (2021) state that pollution from maritime activities closely linked to public health includes nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM). Several studies have highlighted increasing concerns about pollutants, such as NOx, SO_2, PM_{10}, and $PM_{2.5}$, which significantly impact the environment and health (Aksoyoglu et al., 2016; Firląg et al., 2018; Hassellöv et al., 2013; Jalkanen et al., 2012). Reducing these emissions can lower the risk of illnesses and contribute to global climate change mitigation (Corbett et al., 2007; Li et al., 2016).

The U.S. Environmental Protection Agency (2016a) identified that significant emissions from diesel engines include particulate matter, nitrogen oxides, and toxic air pollutants like benzene and formaldehyde. These pollutants can cause serious health problems (U.S. Environmental Protection Agency, 2002, 2016b; International Agency for Research on Cancer, 2014), including human carcinogens, premature deaths, respiratory issues, and increased hospital admissions for heart and lung diseases. Therefore, it is crucial to understand the potential impacts of these emissions on air pollution, the marine environment, and the health of people living or working near ports. Emissions inventories provide essential information that can be used to reduce these health risks by identifying high-emission sources and implementing targeted reduction strategies valuable for maritime authorities, communities, and other stakeholders at the national, regional, and local levels in Thailand. This helps these groups make informed decisions about investments in emission reduction and operational changes by allowing the understanding of emission trends and of identifying reduction opportunities.

The International Maritime Organization (IMO) has adopted a set of regulations to prevent air pollution from ships, as outlined in Annex VI of the MARPOL Convention (Sustainable Ships, 2023; ClassNK, n.d.). Under MARPOL Annex VI, Emission Control Areas (ECAs) are designated marine areas where air emissions from ships are strictly controlled. These controls focus primarily on reducing sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), which are known to significantly contribute to air pollution and related health issues (Walker, 2016). Ships entering and leaving these areas are monitored, and penalties are imposed on non-compliant ships. For sulfur oxides (SO_x), the global sulfur cap was reduced from 3.50 to 0.50 %, effective January 1, 2020 (Sustainable Ships, 2023). MARPOL also includes provisions for the establishment of special sulfur emission control areas (SECAs), where stricter controls are enforced, limiting sulfur content to 0.1 %, as shown in **Figure 1**. For nitrogen oxides (NO_x), emission limits for diesel engines (Sustainable Ships, 2023) have been set depending on a ship's construction date, with NOx emission control areas (NECAs) in the North Sea, Baltic Sea, and the United States. Since 2010, ships sailing in EU ports have been required to use fuel oil with a maximum sulfur content of 0.1 % by mass. Meanwhile, China has planned to implement 0.5 % sulfur fuel regulations from 2016 to 2019, starting with the enforcement of low-sulfur fuel at berths in major ports in April 2016 in the Pearl River Delta, Yangtze River Delta, and Bohai Bay areas (DNV GL, 2018).

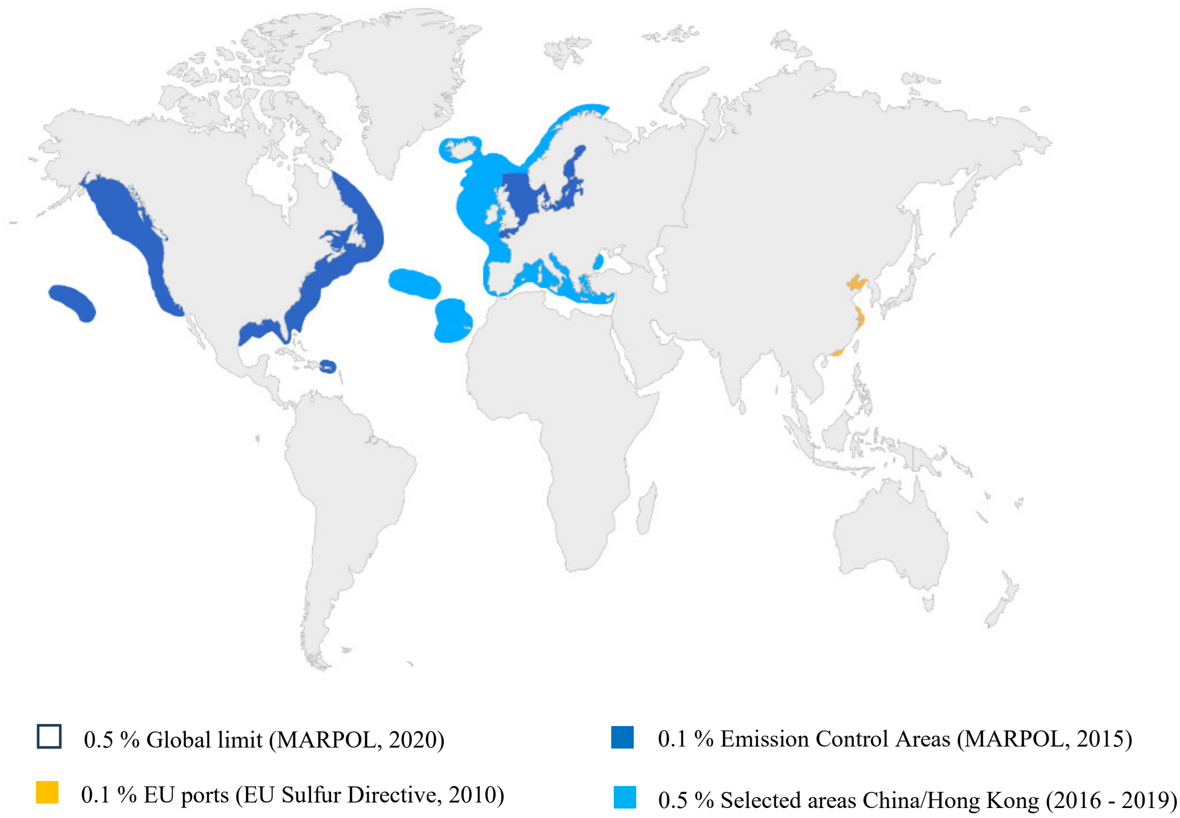

Figure 1 Global Emission Control Areas (ECA) and sulfur emission limits.
Source: DNV GL (2018).

Although the Gulf of Thailand is not currently designated as an Emission Control Area (ECA), it remains one of the busiest maritime transport regions in Southeast Asia. This study bridges the research gap by focusing on the Gulf of Thailand, an area with limited data on ship emissions despite its high maritime traffic density. By leveraging AIS data, the study provides a detailed spatial and temporal analysis of emissions, which have not been extensively explored in this region. The findings offer actionable insights for policymakers, including strategies to design localized ECA policies and adopt emission reduction technologies. This contribution is particularly significant, as it addresses the dual challenge of mitigating environmental impacts while supporting the economic growth of Thailand's maritime industry. The study's findings will serve as a foundation for future research and policy-making, particularly in designing tailored solutions for the Gulf of Thailand and similar density maritime regions.

2. Literature review

In recent years, the maritime industry has faced increasing pressure to mitigate environmental impacts, particularly from emissions generated by older ships (Sathapongpakdee, 2023). As fuel costs rise, and regulations on pollution tighten, there is a growing need for strategies that not only reduce emissions, but also keep operational costs manageable. According to Lindstad et al. (2011), among the most promising strategies is the reduction of ship speed and the optimization of fleet composition. Previous research suggests that reducing ship speed can lead to significant reductions in fuel consumption and, consequently, emissions. Walsh and Bows (2012) similarly identified altering the composition of fleets, such as incorporating larger, more energy-efficient ships, as a means of decreasing the environmental footprint of shipping operations. However, reducing sulfur content in marine fuel is a common method of controlling ship emissions, as there is a positive correlation between sulfur content and pollution levels (Dulebenets, 2016; Wang, 2007).

To monitor and manage emissions effectively, various methods have been proposed, including both "top-down" and "bottom-up" approaches (Miola & Ciuffo, 2011). The top-down method relies on statistical data, such as fuel consumption reports, providing a broad overview of emission trends. However, this method has limitations in accurately reflecting the spatial and temporal characteristics of emissions due to the extensive travel of ocean-going ships and the regional specificity of fuel consumption data (Smith et al., 2015). In contrast, bottom-up approaches depend on detailed activity data collected from individual ships, which are often considered more accurate for emission estimation, particularly in localized areas such as ports or specific maritime regions. These data, commonly collected through technologies like Automatic Identification Systems (AIS), offer a more precise understanding of ship activities and fuel consumption, leading to more accurate emission estimates. AIS data, which is widely available and provides real-time tracking of ships, has become a valuable tool in environmental studies, especially for emissions monitoring.

Many studies agree that, while the top-down method is suitable for estimating emissions across large regions, the bottom-up approach, with its reliance on granular AIS data, is more accurate for localized emission assessments. This accuracy has made the bottom-up approach the preferred method for studying ship emissions in various region (Li et al., 2023; Shi et al., 2020; Wan et al., 2019; Weng et al., 2022; Win & Watanabe, 2024; Yau et al., 2012).

Chen et al. (2021) highlighted the influence of seasonal variations on the dispersion of pollutants from ships in previous studies. For example, research conducted in the Yangtze River Delta region concluded that summer and spring show significant increases in inland transport ship-emitted PM2.5 due to stronger onshore winds and lower Planetary Boundary Layer (PBL) heights. Conversely, winter and autumn are associated with less dispersion due to weaker winds and higher PBL heights. Considering that this study focuses on January, a cooler month in Thailand, pollutant dispersion may be lower compared to other months, potentially impacting the overall emissions analysis of the Gulf of Thailand.

Additionally, existing literature on ECAs focuses on four main areas: 1) Evaluating compliance with, and the effectiveness of, ECA regulations, 2) Analyzing the environmental impacts resulting from ECA policies within ECA areas, 3) Optimizing shipping routes and sailing speeds within ECA water areas, and 4) Considering the influence of ECA policies on ship route selection. Therefore, this study aims to compare emissions from ships in non-ECA areas, specifically the Gulf of Thailand, with those in existing ECAs, and assess the potential for reducing emissions through the implementation of ECA or similar policies, with AIS data being utilized both during the data collection phase and the analysis phase to evaluate ship emissions.

3. AIS data

The Automatic Identification System (AIS) is an essential tool for maritime operations, providing critical data on ship movements and operations. According to International Maritime Organization (IMO) regulations (International Maritime Organization, 2003), AIS installation is mandatory for various classes of ships, including those of 300 gross tonnage and above engaged on international voyages, cargo ships of 500 gross tonnage and above not engaged on international voyages, and all passenger ships, regardless of size. The requirement for AIS installation was fully implemented by December 31, 2004. These systems enhance navigation safety by transmitting a ship's position, speed, and other relevant information to nearby ships and shore stations. Although primarily intended to prevent collisions and manage maritime traffic, AIS data is also widely used for research, operational analysis, and environmental impact studies (Svanberg et al., 2019), such as estimating emissions from ships.

AIS data typically comprises two types of information: static and dynamic (International Maritime Organization, 2015). Static data includes ship identifiers such as the International Maritime Organization (IMO) number, Maritime Mobile Service Identity (MMSI), ship name, type, and dimensions. This data is typically entered manually when the AIS is installed on the ship and does not change frequently. Dynamic data includes real-time information crucial for maritime navigation and safety. This data encompasses various parameters such as COG (Course Over Ground), which indicates the direction a ship is moving over the ground, measured in degrees from true north; SOG (Speed Over Ground), which represents the ship's speed over the ground, typically measured in knots; and ROT (Rate of Turn), which measures the rate at which a ship is turning, expressed in degrees per minute. Additionally, Position data provides the real-time location of the ship, specified by latitude and longitude coordinates, and Navigational Status indicates the current status of the ship, such as whether it is underway, at anchor, or moored. These dynamic data points are essential for monitoring and managing ship movements effectively. Dynamic data is continuously updated and transmitted at intervals that can range from every few seconds to minutes, depending on the ship's speed and activity. For example, ships at anchor transmit every three minutes, while ships traveling at high speeds or which are changing course frequently transmit every two seconds.

While AIS data is highly valuable, it comes with several challenges that need to be addressed to ensure data quality and reliability. AIS data can be noisy and incomplete, with potential inaccuracies in manually entered fields and missing transmissions. This can result from equipment malfunctions, environmental interference, or intentional disabling of AIS by ships. Due to the noise and potential inaccuracies, preprocessing of AIS data is essential. This involves filtering out erroneous data, interpolating missing values, and validating the accuracy of the static and dynamic information (Liu & Ma, 2022).

The AIS data utilized in this study was sourced from Spire through satellite. This study used a subset of parameters: timestamp, Maritime Mobile Service Identity (MMSI), latitude, longitude, speed, course, and heading, selected for their relevance in tracking ship movements and behaviors. The specific dataset used in this study focuses on ship movements in the Gulf of Thailand during the period of January 1 to 31, 2023. A total of 2,688,805 AIS message reports were collected from 364 ships. For the purposes of this study, only data pertaining to cargo ships were selected for examination to maintain relevance to the research objectives. These categories include Container, Bulk Carrier, Tanker, General Cargo, Ro-Ro/Passenger, and Reefer, totaling 223 ships. In contrast, the list of non-cargo ships, which includes types like Dredger, Fishing, Tug, Military Ops, Offshore/Supply, and Other, totaling 141 ships, were removed. However, this study represents a preliminary investigation of ship emissions in the Gulf of Thailand, constrained by the availability of AIS data for a single month. As such, the results may not fully capture seasonal variations or the overall emissions in the region. Expanding data collection to cover all seasons would be necessary to obtain a more comprehensive understanding of ship emissions and their environmental impact in the Gulf of Thailand.

4. Study area

This study designates the Gulf of Thailand as the analysis area, which spans latitudes from 6°N to 13°30’N and longitudes from 99°E to 104°E. It is bordered by Thailand, Cambodia, and Vietnam, and extends into the shallow South China Sea. The main ports in the Gulf of Thailand include Laem Chabang Port, Bangkok Port, and Maptaphut Port. Laem Chabang Port is the largest port in Thailand, handling a significant portion of the country’s import and export trade. Bangkok Port, located along the Chao Phraya River, serves as a major gateway for goods entering and leaving the capital city. Maptaphut Port is a key industrial port, primarily handling petrochemical products and other industrial goods (**Figure 2**).

5. Ship emission estimation

The data received from the AIS were analyzed, including ship positions, speeds, and operational modes, and linked to specific emission factors based on engine characteristics and fuel type. Accurate emission estimation relies on determining the engine's operating power and collecting data on engine specifications, such as size, fuel type, hours of operation, and load factors. Additionally, different operational modes, such as normal cruising, slow steaming, maneuvering, and hoteling, must be considered to ensure precise emission estimations. Ship emissions are estimated using this equation (Ng et al., 2013; Shi et al., 2020; Wan et al., 2019; Weng et al., 2022; U.S. Environmental Protection Agency, 2022; Yau et al., 2012);

$$E = P \times A \times EF \times LLAF \quad (1)$$

Which calculates emissions per ship in grams by considering engine operating power (P) in kilowatts, engine operating activity (A) in hours, emission factor (EF) in grams per kilowatt-hour, and a low load adjustment factor (LLAF). The LLAF is a unitless coefficient that represents the rise in propulsion emissions under low load operations (it remains 1 for auxiliary engines and boilers). This comprehensive equation is applied across different emission sources, including propulsion engines, auxiliary engines, and boilers.

The propulsion engine operating power and load factors can be calculated using Eqs. (2) and (3), taking into account ship type and subtype information to categorize similar ships and fill in missing characteristic data. This approach is primarily based on the findings from the Third IMO Greenhouse Gas Study (Smith et al., 2015).

$$P_{p,\,i} = P_{ref} \times (\frac{V_i}{V_{ref}})^3 \times SM \quad (2)$$

Where $P_{p,\,i}$ represents the propulsion engine operating power for operating mode i (kW), P_{ref} is the ship’s total installed propulsion power (kW), V_i is the average speed in operating mode i (kn), V_{ref} is the ship’s maximum speed (kn), and SM denotes the sea margin, which accounts for average weather conditions and is assumed to be 1.10 for coastal operations and 1.15 for at-sea operations (unitless).

$$LF_i = \frac{P_{p,i}}{P_{ref}} \tag{3}$$

Where LF_i is the propulsion engine load factor for operating mode i (unitless), $P_{p,i}$ is the propulsion engine operating power for operating mode i (kW) and P_{ref} is the ship's total installed operating power (kW)

The usage data for auxiliary engines and boilers are not available from ship activity data sets. Furthermore, these engines are typically excluded from ship characterization data sets. Due to limited resources, this study utilized statistical data from the Second IMO Greenhouse Gas Study (Buhaug et al., 2009) instead of directly collecting data on auxiliary engine and boiler usage from ships operating in the Gulf of Thailand, as shown in **Tables 1** and **2**.

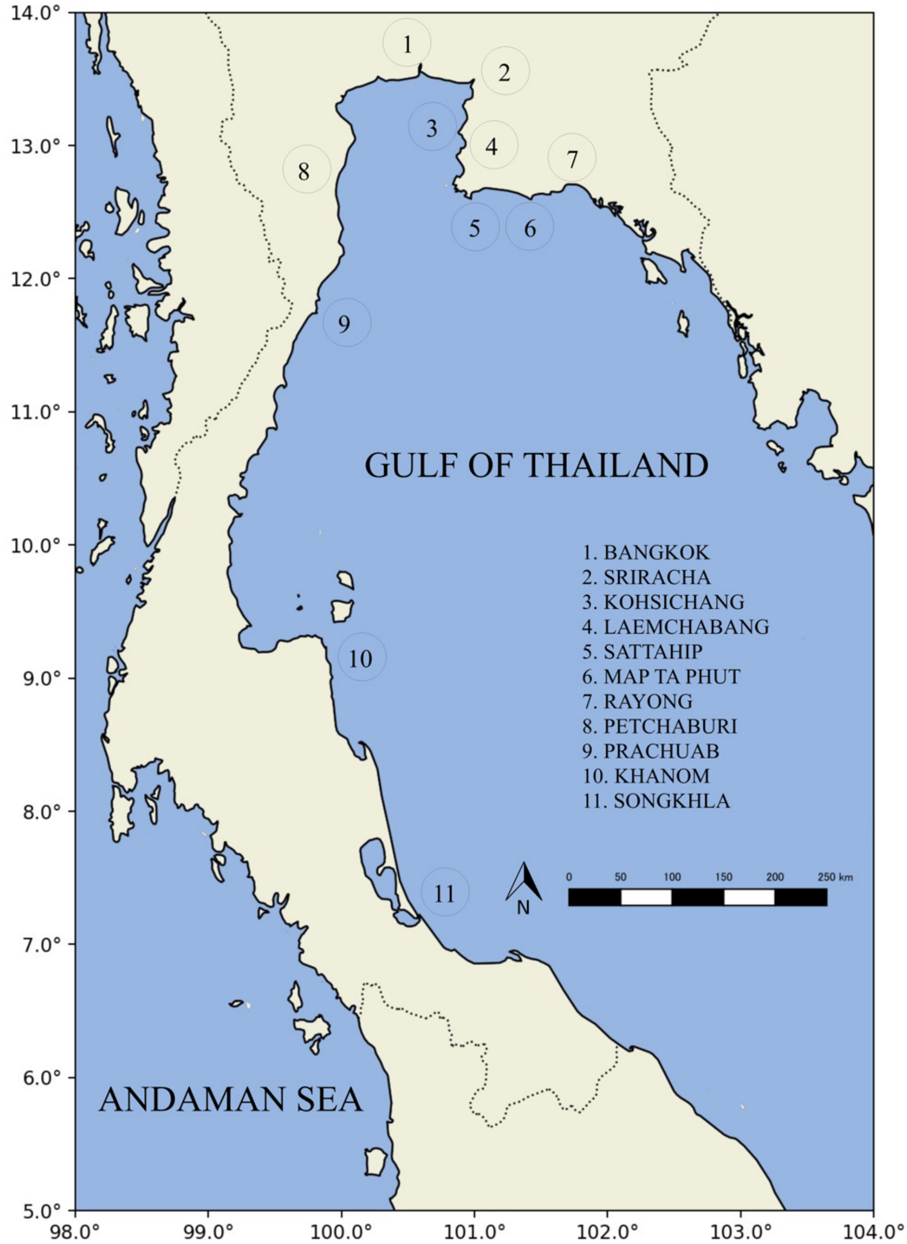

Figure 2 The Gulf of Thailand and Ports in the Gulf of Thailand.

Table 1 Auxiliary engine operating loads by mode.

Ship Type	Sub Type	Normal Cruising (kW)	Slow Steaming (kW)	Maneuvering (kW)	Hoteling (kW)
Bulk Carrier	Small	190	190	310	280
	Handysize	190	190	310	280
	Handymax	260	260	420	370
	Panamax	420	420	680	600
Container	1,000 TEU	300	300	550	340
	2,000 TEU	820	820	1,320	600
	3,000 TEU	1,230	1,230	1,800	700
General	5,000 DWT	60	60	90	120
	10,000 DWT	170	170	250	330
	Largest	490	490	730	970
Reefer	All Reefer	1,170	1,170	1,150	1,080
Ro-Ro / Passenger	20,000 Ton	105	105	105	105
	Largest	710	710	710	710
Oil Tanker	Smallest	250	250	375	250
	Small	375	375	563	375
	Handysize	625	625	938	625
	Handymax	750	750	1,125	750
	Panamax	750	750	1,125	750
	Aframax	1,000	1,000	1,500	1,000
Gas Tanker	50,000 DWT	240	240	360	240
Chemical Tanker	Smallest	80	80	110	160

Source: U.S. Environmental Protection Agency (2022).

Table 2 Boiler operating loads by mode.

Ship Type	Sub Type	Normal Cruising (kW)	Slow Steaming (kW)	Maneuvering (kW)	Hoteling (kW)
Bulk Carrier	Small	0	0	50	50
	Handysize	0	0	50	50
	Handymax	0	0	100	100
	Panamax	0	0	200	200
Container	1,000 TEU	0	0	120	120
	2,000 TEU	0	0	290	290
	3,000 TEU	0	0	350	350
General	5,000 DWT	0	0	0	0
	10,000 DWT	0	0	75	75
	Largest	0	0	100	100
Reefer	All Reefer	0	0	270	270
Ro-Ro / Passenger	20,000 Ton	0	0	0	0
	Largest	0	0	0	0
Oil Tanker	Smallest	0	0	100	500
	Small	0	0	150	750
	Handysize	0	0	250	1,250
	Handymax	150	150	300	1,500
	Panamax	150	150	300	1,500
	Aframax	200	200	400	2,000
Gas Tanker	50,000 DWT	100	100	200	1,000
Chemical Tanker	Smallest	0	0	125	125

Source: U.S. Environmental Protection Agency (2022).

The operational performance of a ship can be categorized into various modes, each characterized by specific speed ranges and machinery status (Wan et al., 2019), as shown in **Table 3**.

Table 3 Basic for determining the operation mode.

Operation Mode	**Speed**	**Machine Operation Status**
Normal cruising	> 12 knots	ME, AE
Slow steaming	8 - 12 knots	ME, AE
Maneuvering	1 - 8 knots	ME, AE, Boiler
Hotelling	< 1 knot	AE, Boiler

Source: Wan et al. (2019).

For emission factors, NO_x emission factors vary based on the engine group, fuel type, keel-laid year, and engine type (Buhaug et al., 2009; Smith et al., 2015; Starcrest Consulting Group, LLC., 2021; U.S. Environmental Protection Agency, 2009), as shown in **Table 4**. In this study, the actual sulfur content in the fuel (weight ratio) is assumed to be 0.0185, based on a local survey. $PM_{2.5}$ emission factors are calculated as 92 % of the PM_{10} factors. The sulfur content used in calculating SO_2 emission factors is assumed to be the same as that used for Particulate Matter (PM), as shown in **Table 5**.

Table 4 NO_x emission factors.

Engine Group	**Fuel Type**	**Keel Laid Year**	**Engine Type**	**NO_xEmission Factor (g/kWh)**
Propulsion	MGO/MDO	≤ 1999	SSD	17.0
			MSD	13.2
		2000 - 2010	SSD	16.0
			MSD	12.2
		2011 - 2015	SSD	14.4
			MSD	10.5
		≥ 2016	SSD	3.4
			MSD	2.6
	RM/HFO	≤ 1999	SSD	18.1
			MSD	14.0
		2000 - 2010	SSD	17.0
			MSD	13.0
		2011 - 2015	SSD	15.3
			MSD	11.2
		≥ 2016	SSD	3.6
			MSD	2.8
Auxiliary	MGO/MDO	≤ 1999	SSD	13.8
			MSD	10.9
		2000 - 2010	SSD	12.2
			MSD	9.8
		2011 - 2015	SSD	10.5
			MSD	7.7
		≥ 2016	SSD	2.6
			MSD	2.0
Boiler	RM/HFO		Boiler	2.1

Source: U.S. Environmental Protection Agency (2022).

Table 5 PM_{10}, $PM_{2.5}$, and SO_2 emission factors.

Engine Group	Fuel Type	Engine Type	PM_{10} Emission Factor (g/kWh)	$PM_{2.5}$ Emission Factor (g/kWh)	SO_2 Emission Factor (g/kWh)
Propulsion	MGO/MDO	SSD	0.69	0.63	6.69
		MSD	0.75	0.69	7.41
	RM/HFO	SSD	1.14	1.05	7.05
		MSD	1.20	1.10	7.78
Auxiliary	MGO/MDO	SSD	0.79	0.73	7.85
		MSD	0.79	0.73	7.85
Boiler	RM/HFO	Boiler	1.46	1.34	7.85

Source: U.S. Environmental Protection Agency (2022).

The emission factors for propulsion engines assume a propulsion load of less than 20 % of total power. Low load adjustment factors (LLAFs) should be applied in formula. **Table 6** provides LLAFs by load and pollutant. Specific LLAFs for NO_x, PM_{10}, and $PM_{2.5}$ are detailed, with SO_2 factors depending on fuel sulfur content.

Table 6 Low Load Adjustment Factors.

Propulsion Engine Load Factor	NO_x	PM	SO_2 (1.85 % fuel sulfur content)
≤ 2 %	4.63	7.29	3.39
3 %	2.92	4.33	2.51
4 %	2.21	3.09	2.06
5 %	1.83	2.44	1.80
6 %	1.60	2.04	1.62
7 %	1.45	1.79	1.49
8 %	1.35	1.61	1.40
9 %	1.27	1.48	1.33
10 %	1.22	1.38	1.27
11 %	1.17	1.30	1.22
12 %	1.14	1.24	1.18
13 %	1.11	1.19	1.14
14 %	1.08	1.15	1.11
15 %	1.06	1.11	1.09
16 %	1.05	1.08	1.07
17 %	1.03	1.06	1.05
18 %	1.02	1.04	1.03
19 %	1.01	1.02	1.01
20 %	1.00	1.00	1.00

Source: U.S. Environmental Protection Agency (2022).

To assess the potential reductions that could be achieved through the implementation of an Emission Control Area (ECA) policy in the Gulf of Thailand, a comparative analysis was conducted with existing ECAs, particularly with those in the Baltic Sea (Jalkanen et al., 2023) and ASEAN regions (DNV GL, 2018). The models used in studies of the Baltic Sea and ASEAN are categorized as bottom-up models (Miola & Ciuffo, 2011). Therefore, the results of this study can be compared, as they share similarities in their methodologies. The percentage difference is calculated as follows;

$$\%\,difference = \frac{\text{Emissions from ships in Gulf of Thailand} - \text{Emission from ships in Baltic Sea}}{\text{Emissions from ships in Gulf of Thailand}} \times 100 \quad (4)$$

6. Results and discussions

Figure 3 illustrates the process for calculating emissions from ships, in which data from the Automatic Identification System (AIS) plays a crucial role in the assessment. The analysis considers several key variables, such as engine operating power, measured in kilowatts (kW), operating activity in hours, and emission factors (EF), expressed in grams per kilowatt-hour (g/kWh). Additionally, it includes the Low Load Adjustment Factor (LLAF), a critical variable used to adjust emission values during low-load operations (excluding auxiliary engines and boilers).

The analysis process begins with data cleaning to eliminate erroneous or incomplete AIS records. Temporal gaps in ship activity are then filled in cases where AIS signals are missing. Subsequently, AIS data is linked with ship characteristics, such as engine type and size. Each AIS record is categorized based on operational modes, including normal cruising, slow steaming, maneuvering, and hoteling. Engine power and load factors are calculated next to estimate emissions by source type, such as propulsion engines, auxiliary engines, and boilers. The results of the analysis provide estimated emissions in grams for various pollutants, including NO_x, SO_2, and PM. These emissions can be aggregated over specific geographical areas or time periods as needed.

Ship classification also plays an essential role in the process, as the characteristics of each ship type affect emissions differently. Engine categories are typically determined by analyzing ships with similar usage patterns or sizes. Alternative data sources are also employed to classify engine types based on ship type and size. By leveraging AIS data and the above analytical process, accurate results can be achieved, allowing emissions to be evaluated based on the operational characteristics of each ship. This approach supports effective planning and the development of strategies to reduce emissions from ships efficiently.

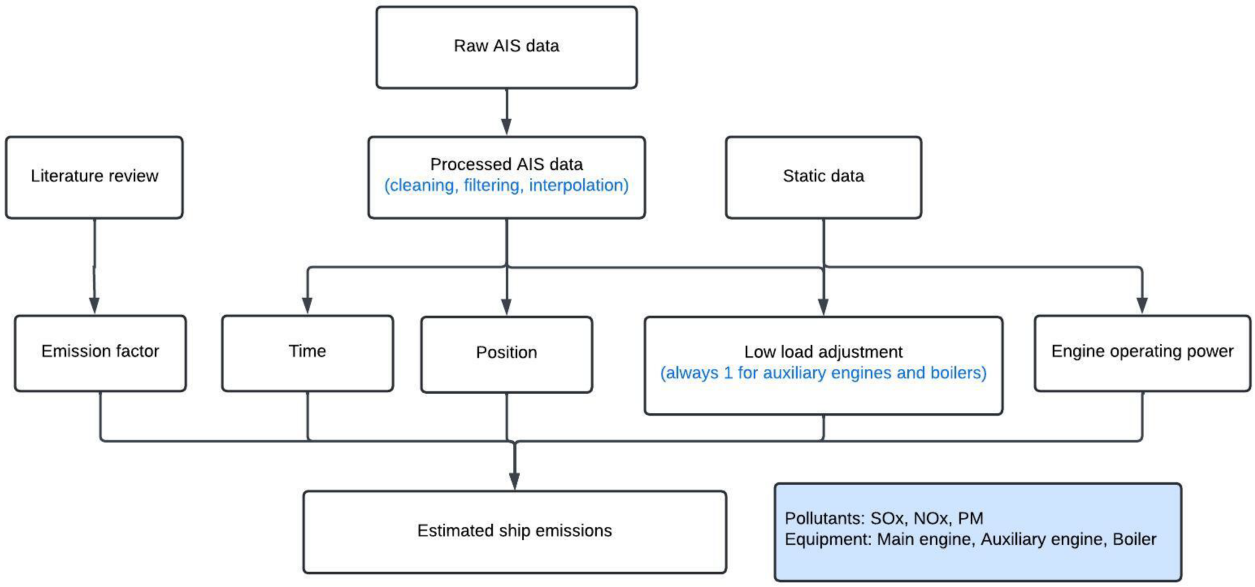

Figure 3 Flowchart of estimating ship emissions.

The emissions of each pollutant by ship type based on AIS data and ship characteristics were calculated, with the results shown in **Table 7** and **Figure 4**. It can be concluded that, according to statistical data and AIS records, Thailand has the largest fleet of oil tankers. This is due to the country's significant reliance on fossil fuels, particularly crude oil and petroleum products. As a major producer and importer, Thailand extensively utilizes oil tankers to transport fuel between refineries, ports, and storage facilities. Key ports such as the Map Ta Phut Port, the largest oil terminal in the country, play a critical role in this process.

As a result, oil tankers account for 75 % of total emissions, with 122 ships in operation. These findings support the hypothesis that oil tankers are the main contributors to emissions in the region, highlighting the necessity for targeted emission reduction strategies for this ship type. Additionally, gas tankers, although fewer in number, contribute 8.10 % of emissions, while container ships account for 7.10 %.

Table 7 Ship emissions by ship type for different pollutants from January 1 to 31, 2023 (tons).

Ship Type	NO_x	SO_2	PM_{10}	$PM_{2.5}$	Total
Container	17.9	16.7	2.4	2.2	39.2
Bulk carrier	1.6	0.8	0.1	0.1	2.6
General cargo	6.2	4.1	0.5	0.5	11.3
Oil tanker	237.5	138.9	20.6	18.9	415.9
Gas tanker	19.8	19.9	2.6	2.4	44.7
Chemical tanker	6.5	3.5	0.5	0.4	10.9
Reefer ship	5.2	3.1	0.4	0.3	9.0
RoRo/Passenger	10.7	7.2	1.0	0.9	19.8
Total	305.4	194.2	28.1	25.7	553.4

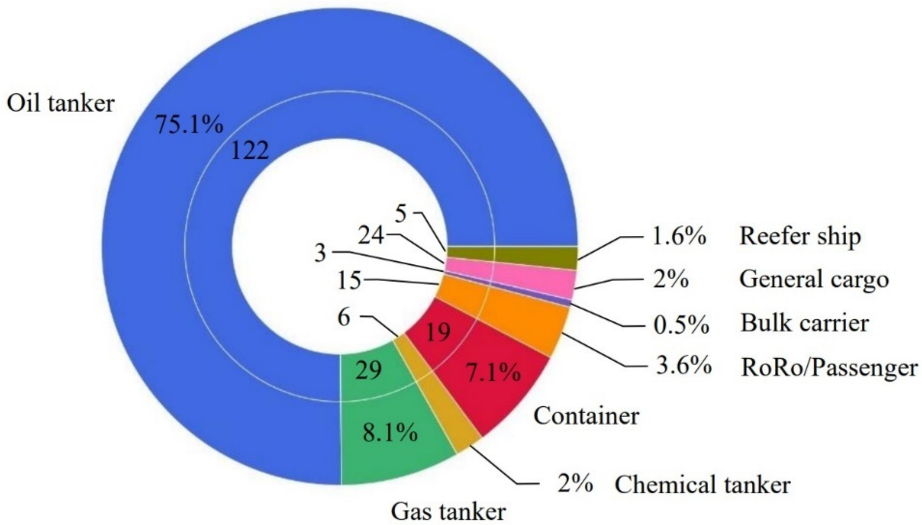

Figure 4 Contribution of each ship type to total emissions from 223 ships.

Figure 5 illustrates the proportional contribution of various ship types to different pollutants (NO_x, SO_2, PM_{10}, and $PM_{2.5}$). The percentages shown represent the relative contributions within each pollutant category, with the total proportion of each pollutant equaling 100 % for each ship type. The pattern of pollutants is consistent with the findings from previous research (Shi et al., 2020; Yau et al., 2012). When comparing the emissions of each pollutant, nitrogen oxides (NO_x) have the highest values, followed by sulfur dioxide (SO_2), particulate matter (PM_{10}), and fine particulate matter ($PM_{2.5}$), respectively. This alignment with prior studies supports the validity and reliability of the results. NO_x emissions total 305.4 tons, representing approximately 55.2 % of the total ship emissions. Emissions of 194.2 tons of SO_2, 28.1 tons of PM_{10}, and 25.7 tons of $PM_{2.5}$ account for 35.1, 5.1, and 4.6 % of the total emissions, respectively.

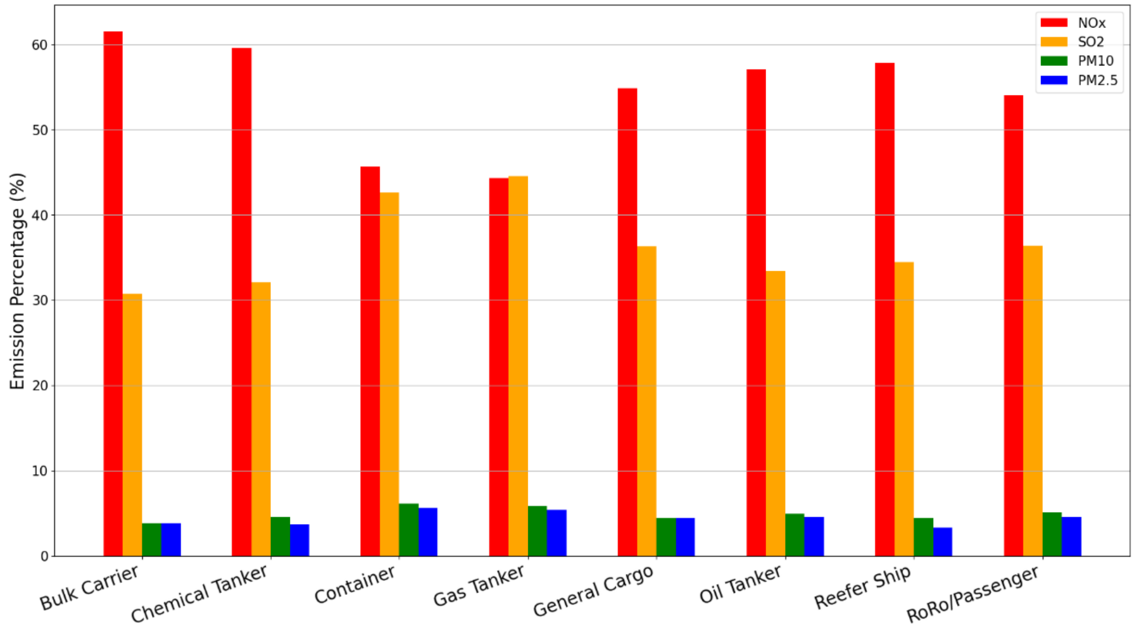

Figure 5 Proportion of each pollutant by ship type.

When considering emissions by operational mode for different ship types, categorized by speed, it is evident that operational modes significantly influence emission patterns. As shown in **Figure 6**, the Slow Steaming mode accounts for the highest proportion of emissions across many ship types, such as Oil Tankers (61.09 %) and General Cargo Ships (44.14 %). Meanwhile, emissions from the Hoteling mode are significant across all ship types, especially for Gas Tankers (48.77 %) and Chemical Tanker Ships (39.81 %). For the Normal Cruising mode, Bulk Carriers (57.69 %) and Container Ships (44.25 %) show a high proportion of emissions. In contrast, the Maneuvering mode plays an important role in emissions for Container Ships (39.13 %) and General Cargo Ships (34.24 %). This data highlights the variations in sailing patterns and fuel consumption across operational modes, which significantly impact emission levels. These insights can serve as a foundation for developing effective strategies to reduce emissions in the future.

Additionally, **Figure 7** highlights that the Main Engine is the predominant source of emissions, contributing significantly to the total emissions across most ship types. For instance, the Main Engine accounts for 79.51 % of emissions for Oil Tankers, 69.23 % for Bulk Carriers, and 65.47 % for Container Ships. This underscores the critical role of propulsion systems in the overall emission profile of ships and suggests that advancements in propulsion technology could lead to substantial emission reductions. However, the substantial contribution of Auxiliary Engines cannot be overlooked, particularly in energy-intensive operations like cargo handling and onboard systems. For example, Reefer Ships (62.22 %) and Chemical Tankers (44.04 %) exhibit high emissions from their Auxiliary Engines, reflecting their unique operational demands. Even though the Boiler contributes a relatively small share of total emissions, ranging from 1.01 % for RoRo/Passenger Ships to 38.34 % for Gas Tankers, it remains a key component of ship emissions. This suggests that boiler efficiency and alternative energy sources should also be considered in emission reduction strategies. These insights emphasize the need for a comprehensive approach to emission control, addressing not only propulsion systems, but also auxiliary operations and boilers, to achieve significant environmental benefits.

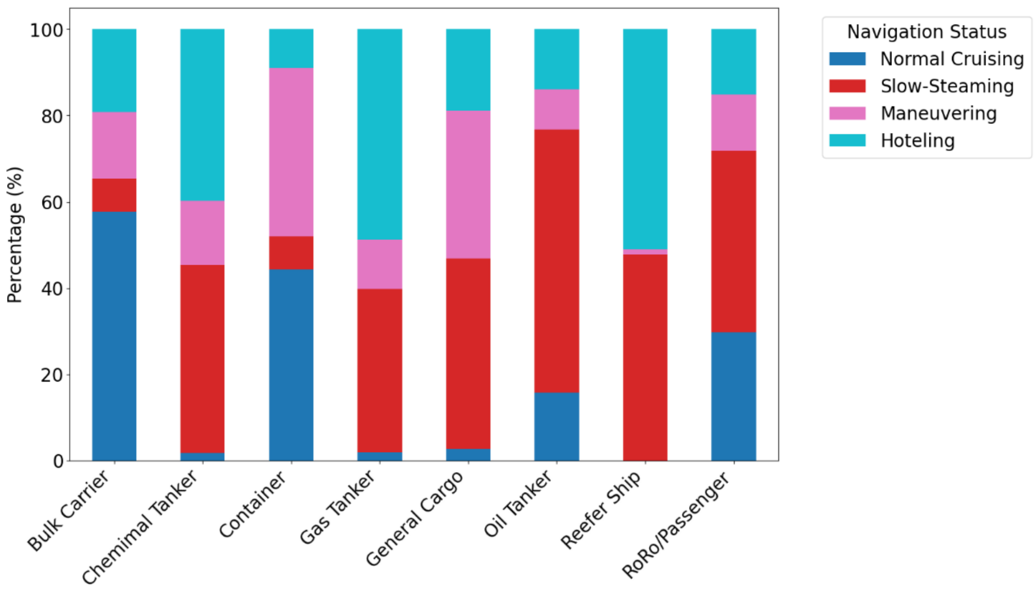

Figure 6 Emissions proportion of each operating mode by ship type.

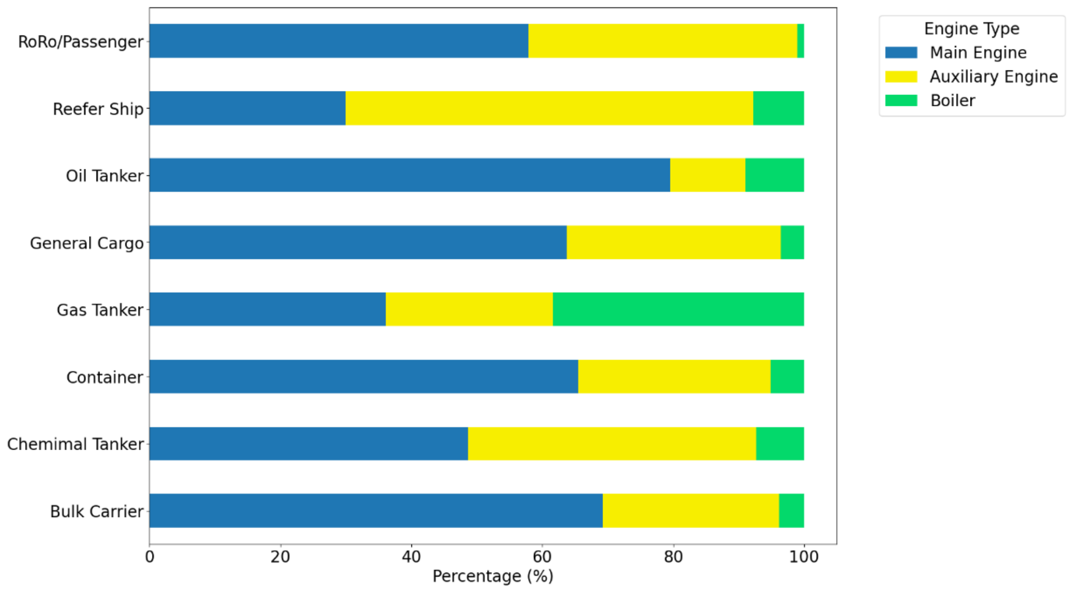

Figure 7 Emissions proportion of each engine type by ship type.

Based on all the results above, emissions at each location were calculated using AIS data, then the emissions were aggregated by grid cell and the spatial distribution was plotted, as shown in **Figure 8**. **Figure 8** illustrates the spatial distribution of emissions in the Gulf of Thailand, measured in tons per 0.05° × 0.05° grid, which shows significant emission levels concentrated in areas with high ship traffic density. This indicates that regions with higher ship traffic density also experience higher emissions. The data depicts an increase in emissions around key port areas, including Bangkok Port, Laem Chabang Port, Maptaphut Port, Khanom Port, and Songkhla Port. These areas, characterized by high ship density, particularly in anchorage zones, exhibit elevated emission levels. Therefore, optimizing ship schedules and reducing port congestion can play a key role in mitigating emissions.

Additionally, the increase in emissions is associated with major shipping routes in the Gulf of Thailand. The data shows that emissions are widely distributed in the central parts of the gulf, where oil drilling platforms are located. Most ships using these routes are non-cargo ships, and emissions rise along coastal and international routes. Consequently, optimizing ship schedules and routes for various types of ships, along with reducing port congestion through the use of statistical data from each port authority, could enhance transportation efficiency and reduce emissions. These findings highlight the need for additional regulation and monitoring, particularly in regions with heavy ship traffic and near critical environmental zones along the gulf's coastline.

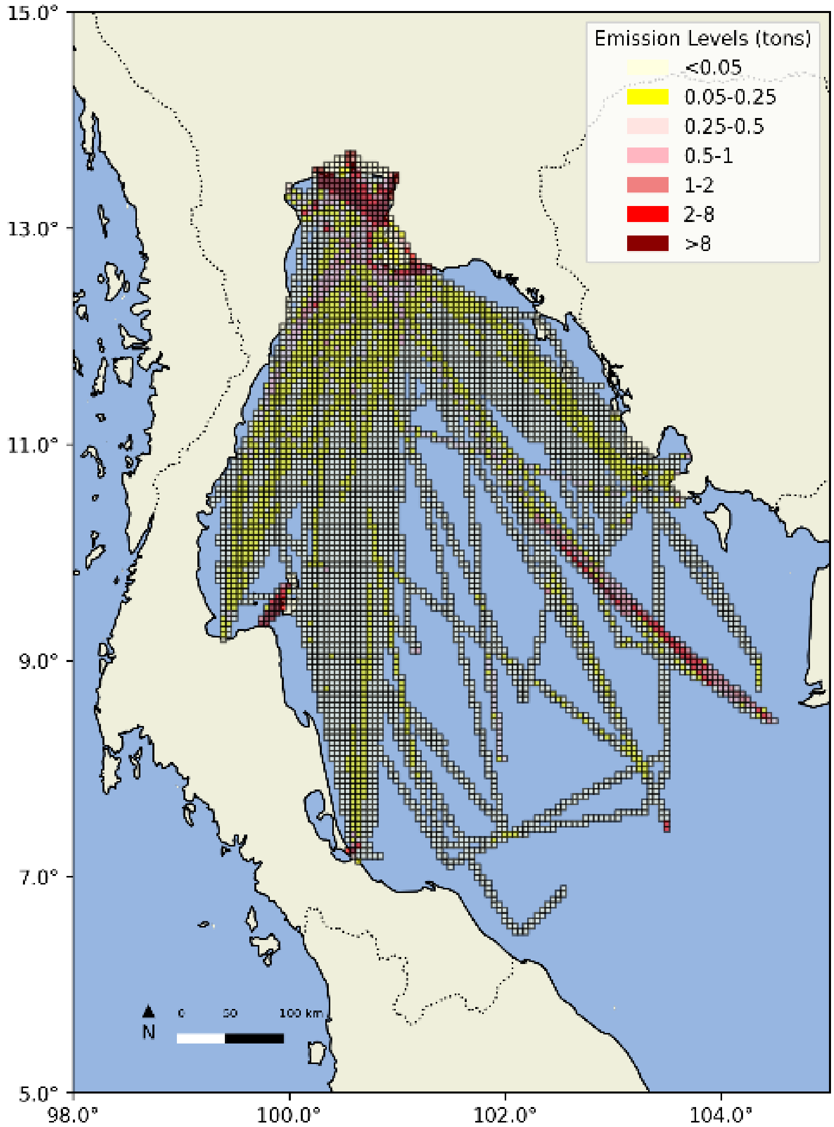

Figure 8 Ship emissions map of the Gulf of Thailand.

By using the Gulf of Thailand as a baseline, the comparative analysis with the Baltic Sea (Jalkanen et al., 2023) and ASEAN regions (DNV GL, 2018) in **Table 7** reveals a stark contrast. Positive percentage differences indicate that emissions in the Gulf of Thailand are substantially higher than those in established ECAs like the Baltic Sea, while negative percentage differences show that emissions in the Gulf of Thailand are significantly lower than in the ASEAN region. This suggests that the implementation of ECA policies in the Gulf of Thailand could lead to substantial reductions in emissions, similar to the reductions observed in the Baltic Sea following the adoption of stricter sulfur regulations. These findings emphasize the importance of adopting low-sulfur fuels and advanced emission control technologies, as well as the potential environmental and public health benefits of implementing ECA or similar policies in the Gulf of Thailand.

The bottom-up approach employed in this study, integrating AIS data with detailed ship emissions modeling, provides a granular understanding of the spatial distribution of emissions in the

Gulf of Thailand. This method enables the identification of emission hotspots and the differentiation of emissions by ship type and operational mode. When ships operate in a particular location for extended periods, or frequently pass through the same area, their energy consumption and emissions increase, leading to higher pollution levels in those specific areas.

Drawing from previous studies, such as Li et al. (2016) in the Pearl River Delta, which utilized AIS data for localized emission inventories, this research reaffirms the effectiveness of bottom-up models in delivering precise spatial and temporal insights into ship emissions. For instance, Jalkanen et al. (2023) highlighted the importance of detailed emission inventories in regions like the Baltic Sea, where ECA policies have been effectively implemented. Similarly, the Gulf of Thailand exhibits significant potential for targeted policy interventions, as emissions are concentrated around ports and major shipping lanes.

Studies on the effectiveness of ECA regulations, such as those by Weng et al. (2022) and Wan et al. (2019), emphasize the substantial reductions in NO_x, SO_x, and PM achieved in established ECAs. These findings underscore the potential benefits of implementing similar measures in the Gulf of Thailand. The high contribution of oil tankers, which account for 75 % of total emissions in this region, further emphasizes the need for targeted interventions to address pollution from this sector.

The results also align with the work of Shi et al. (2020), who demonstrated the role of reduced sulfur fuel content and optimized operational modes in lowering ship emissions. The spatial distribution of emissions in this study reveals elevated levels in high-density ship traffic areas, reinforcing the necessity for port congestion management strategies and optimized routing to mitigate emissions.

In conclusion, this study contributes to the growing body of evidence supporting the implementation of ECA or similar localized policies. By demonstrating the accuracy of the bottom-up approach in capturing detailed emission profiles and comparing these results with established ECAs, the research lays a strong foundation for future policy development in the Gulf of Thailand.

Table 7 Comparison of emission percentages between the Gulf of Thailand, ASEAN region, and the Baltic Sea (tons).

The percentage difference in emissions			
Area	NO_x **(tons)**	SO_2 **(tons)**	$PM_{2.5}$ **(tons)**
Gulf of Thailand VS. ASEAN	-460.72	-570.90	-443.97
Gulf of Thailand VS. Baltic Proper	95.89	93.53	50.86
Gulf of Thailand VS. Kattegat	98.53	97.69	81.03
Gulf of Thailand VS. Gulf of Finland	99.12	98.61	89.66
Gulf of Thailand VS. Gulf of Bothnia	99.56	99.19	93.97
Gulf of Thailand VS. Gulf of Riga	99.93	99.88	99.14

The baseline sulfur content in ship fuel outside ECAs ranges from 0.5 to 2.7 % (Wan et al., 2019), with an average of 1.85 % (assumed in this study). This is a decrease from the previous year's 3.5 % sulfur concentration ceiling. The potential for emission reductions, as shown in **Figure 9**, highlights the effectiveness of ECA policies. The Baltic Sea, with a sulfur limit of 0.1 %, has seen significant reductions in ship emissions, suggesting that similar policies could benefit the Gulf of Thailand. Implementing ECA policies could reduce NO_x, SO_x, and $PM_{2.5}$ emissions by about 96.3 % for ships using high-sulfur fuel (2.7 %), 94.59 % for those using average sulfur fuel (1.85 %), and approximately 80 % for ships using low-sulfur fuel (0.5 %).

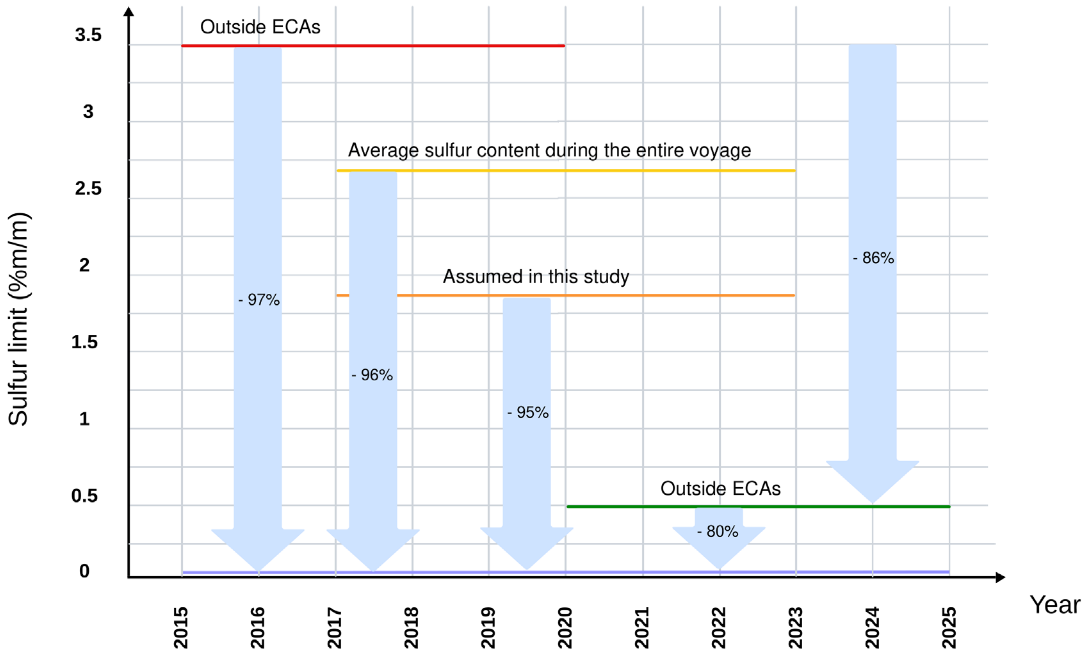

Figure 9 Sulfur content limits in marine fuels and potential emission reductions over time.

7. Conclusions

This study leverages AIS data, which indicates ship status, to assess the emissions of cargo ships in the Gulf of Thailand using a bottom-up approach. It examines pollutants associated with ECA policies, including NO_x, SO_x, and PM. The spatial distribution results reveal high emissions correlated with ship traffic density, port locations, particularly around anchorage areas, and major shipping lanes in the Gulf of Thailand. Oil tankers are the primary emitters, followed by gas tankers and container ships. This highlights the reliability of the data used in the study, as the types of ships emitting pollutants align with the primary ship types in the Gulf of Thailand. Although access to specific ship data, such as ship characteristics, engine details, or fuel types, is limited, this study is based on statistical data. Incorporating direct ship data from the study area and AIS data provided by local authorities would improve the scope and accuracy of the results.

Comparing emissions between the Gulf of Thailand, the ASEAN region, and the Baltic Sea, an established ECA, demonstrates a stark difference in emission levels. Ships in the Baltic Sea must comply with stringent regulations mandating low-sulfur fuels and advanced emission reduction technologies, resulting in significantly lower emission levels. In contrast, higher sulfur content in fuels used by ships in Thailand and the ASEAN region leads to greater emissions in these areas. This comparison suggests that implementing ECA or similar policies in the Gulf of Thailand and, more broadly, across ASEAN could significantly reduce emissions, improve air pollution, and protect public health, particularly in coastal and urban areas with concentrated transport activities. This aligns with previous studies indicating that reducing sulfur content in fuels can help reduce pollution. However, this does not imply that all ASEAN countries must immediately reduce emissions. As countries adopt green technologies, prioritize environmental sustainability, and work to improve citizens' quality of life by reducing pollution, ECA regulations can play a crucial role in supporting these efforts.

The findings from this study suggest that significant emission reductions can be achieved in the Gulf of Thailand and the ASEAN region through better management of maritime traffic and the implementation of stricter emission regulations. It is recommended that the scheduling of different types of ships be optimized to reduce shipping emissions, ensure optimal sailing times, and minimize port congestion by utilizing statistical data from each port authority. Additionally, optimizing shipping routes and speeds can further contribute to minimizing fuel consumption and emissions, particularly in high-emission areas. Using larger ships could also help reduce ship emissions.

Implementing ECA policies or similar regulations in the Gulf of Thailand poses significant economic challenges and costs for local maritime authorities and stakeholders. These include substantial investments in infrastructure upgrades to accommodate cleaner fuels and advanced pollution reduction technologies, and high retrofit costs for existing ships to install scrubbers and selective catalytic reduction systems. Operational expenses will also rise due to the use of more expensive low-sulfur fuels. Additionally, complying with ECA regulations could affect the competitiveness of the Gulf of Thailand as a shipping hub, potentially leading to higher shipping costs and freight rates, which could impact local businesses and the overall economy. To address these challenges, financial support from the government, including grants, tax incentives, and funding for infrastructure upgrades, will be essential. Despite the initial costs, long-term economic benefits include improved air pollution, reduced health costs, and enhanced economic resilience by positioning the Gulf of Thailand as an environmentally responsible shipping hub.

Due to seasonal variations and fluctuating demand for different goods, data from a single month may not fully represent ship emissions in the Gulf of Thailand. Collecting additional data, particularly across multiple seasons, would enhance the reliability and generalizability of these findings. Such an approach would help address potential seasonal variations in ship movements and emissions, offering a more comprehensive understanding of their impact in this region. This study not only sheds light on the current state of ship emissions in Thailand, but also provides a roadmap for achieving significant environmental and health benefits through the adoption of stricter emission controls. The lessons learned from established ECAs serve as valuable guides for future policy development in the region.

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