



SIMULATE AIR POLLUTION TO PROPOSE EMISSION CONTROL AREA AT HO CHI MINH CITY SEAPORT IN 2030

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ABSTRACT

This study investigates the potential for a localised Emission Control Area (ECA) in the Ho Chi Minh City seaport, Vietnam, using the FVM-TAPOM model to simulate air pollution from shipping activities, including SO₂, PM₁₀, PM_{2.5}, and NO₂. The simulation used 2022 emission inventory data for shipping activities and accounted for meteorological conditions, revealing that the Cat Lai port area has the highest pollution concentration. Three ECA options were evaluated based on their cost implications and potential impact on port competitiveness, using a cost-benefit analysis. Option No. 1, encompassing the upstream of the Binh Khanh intersection is viable and selected for its balance of emission reduction and economic feasibility. Post-ECA implementation simulations demonstrated significant reductions in SO₂ and NO₂ concentrations in the Cat Lai port area. Maximum 1-hour average concentrations of SO₂ and NO₂ are expected to decrease from 360 µg/m³ to 260 µg/m³ and from 120 µg/m³ to 64 µg/m³ in the dry season, and from 340 µg/m³ to 320 µg/m³ and from 115 µg/m³ to 80 µg/m³ in the rainy season, respectively. The study concludes that while the selected ECA effectively reduces pollution to meet air quality standards, the forecast shows that by 2030, air pollution is expected to decrease by 171% for NO₂, 70% for SO₂, 39% for PM₁₀, and 37% for PM_{2.5} compared to current levels.

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Introduction

Over the years, the volume of goods and vessels passing through the Ho Chi Minh City seaport has increased significantly. In the period from 2022 to 2023, the growth rate of cargo passing through the seaport of Ho Chi Minh City was 3.5% (from 161 million tonnes to 167 million tonnes), which meets the expected average growth rate for 2050 of the Vietnam seaport group No. 4 (Prime Minister, 2021; Maritime Administration of Ho Chi Minh City, 2023). This seaport group is assessed as having the largest market share in terms of goods throughput, accounting for 39% of the total national seaport cargo market share (Vietnam Maritime Administration, 2022). The growing economic and social development

activities are increasingly putting significant pressure on the air quality in Ho Chi Minh City. Therefore, the proposal to establish an Emission Control Area (ECA), requiring vessels operating within the area to use fuel with a sulphur content below 0.10% mass/mass (i.e., 0.1 g of sulphur per 100 g of fuel), should be taken into consideration. According to the International Maritime Organisation (IMO), the designation of ECA plays a crucial role in reducing air pollution and its harmful effects on human health and the environment, in accordance with the provisions of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 2023).

Recent research on the design of extreme ECA, considering the ship's evasion strategy, was conducted for the first time to assess the expansion of ECA beyond the exclusive economic zone (200 nautical miles from the baselines) in North America (Lingyue Li *et al.*, 2022). The novelty of this study lies in examining the establishment of localised ECA within internal waters (at the provincial or port-level), where ship evasion is practically impossible. One effective tool for studying and investigating potential ECA is the use of air quality simulation models, which are mathematical tools that describe the processes of pollutant transport, diffusion, and transformation in the atmosphere. Meteorological simulation models are indispensable for air quality simulations, as their outputs serve as input to air quality models.

Currently, several popular meteorological models include Mesoscale Model 5 (MM5), Weather Research and Forecasting (WRF), developed by the United State National Center for Atmospheric Research (NCAR), and Finite Volume Model (FVM), developed by LPAS-EPFL, Switzerland. The FVM model is a three-dimensional Eulerian model (Clappier *et al.*, 1996) that has been applied in numerous studies, including those in Bogotá, Colombia (Sajjad *et al.*, 2023) and several in Vietnam (Dung *et al.*, 2021; Quynh *et al.*, 2023). While the MM5 was discontinued, the WRF model has undergone numerous improvements to simulate mesoscale physical processes better and can be applied to various user needs. The WRF model can be used in conjunction with the Community Multiscale Air Quality (CMAQ) model to simulate air pollution dispersion (Yongfan Wu *et al.*, 2024).

Some of the widely used air quality models today include CMAQ, developed by the United State Environmental Protection Agency. CMAQ can simulate atmospheric processes that affect the chemical transformation, dispersion, and deposition of pollutants. The CMAQ model has been applied to air quality

simulations and to regional-scale emissions forecasting from shipping (Meng Wang *et al.*, 2024). The Transport and Air Pollution Model (TAPOM) developed by the Laboratory of Air and Soil Pollution (LPAS) and Lausanne Federal Polytechnic University (EPFL), simulates the transport, diffusion, and chemical transformation processes of pollutants in the atmosphere. The TAPOM model has been widely used in European countries and in developing countries such as Vietnam (Ho *et al.*, 2024). The Air Pollution Model (TAPM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, is used to forecast three-dimensional meteorological conditions and air pollution concentrations. The TAPM model has also been applied in meteorological simulations as input for air quality modelling in Vietnam (Ho *et al.*, 2022; Ho Minh Dung, 2023).

Currently, there are quite a few modelling systems available for simulating air pollution dispersion. These modelling tools are widely used in air quality research and management. Among air quality models, the TAPOM model has a distinct advantage: It is an Eulerian model that provides high accuracy and is commonly used in local-scale air quality simulation studies, particularly in research conducted in Vietnam. However, due to its high accuracy, the model requires many input parameters and a high-performance computer, and it takes considerable time to simulate and run on a Linux platform, which limits its widespread use. In recent studies, good results have been reported at Sai Gon port in 2013 (Ho *et al.*, 2013) and Tra Vinh province in 2024 (Thang & Dung, 2024).

In this study, the research team continues to use the FVM-TAPOM modelling system to identify and propose the establishment of ECA in the Ho Chi Minh City seaport. The emission reduction of air pollution from SO₂, PM₁₀, PM_{2.5}, and NO₂ will be discussed after localised ECA establishment in scenario 2030.

Materials and Methods

Study Site

Ho Chi Minh City served as a hub for economics, finance, commerce, and services. It is the central city of the Southern Economic Region, one of the three major economic zones in the country. Despite covering just 0.6% of the nation’s land area and housing 8.3% of its population, the city has contributed 20.2% to the country’s gross domestic product (The People’s Committee of Ho Chi Minh City, nd). The distribution of the population and the role of seaport development are discussed below.

Population distribution: Ho Chi Minh City is a special-class urban area. According to the General Statistics Office of Vietnam, Ho Chi Minh City has the highest population (General Statistics Office of Vietnam, 2022). The human population in the Vietnam seaport group No. 4 in 2022 is described in Figure 1.

Figure 1 shows that the Dong Nai River area has the highest population density in Ho Chi Minh City. This area is located within the administrative boundaries of Thu Duc City, experiencing the fastest development in Ho Chi

Minh City in all aspects. In contrast, the Go Gia River area, located within the administrative boundaries of Thanh An commune (in Can Gio district) has the lowest population due to the lack of road infrastructure and connectivity. According to a 2022 study, air pollution in Ho Chi Minh City has a severe impact on public health, contributing to approximately 1,397 deaths from lung cancer, cardio-pulmonary diseases, and ischemic heart disease as a result of exposure to PM_{2.5}, NO₂, and SO₂; The number of pollution-related deaths is notably higher in the city centre, where the population density is significantly greater than in suburban areas (Nguyen Van Phuoc *et al.*, 2022).

Seaport development: Ho Chi Minh City seaport is classified as a potential special seaport with the highest vessel traffic density, serving as a national general port and a regional hub for the southern key economic region, including the South Central Coast and the Mekong Delta (Prime Minister, 2021). Figure 2 shows the research area of the study.

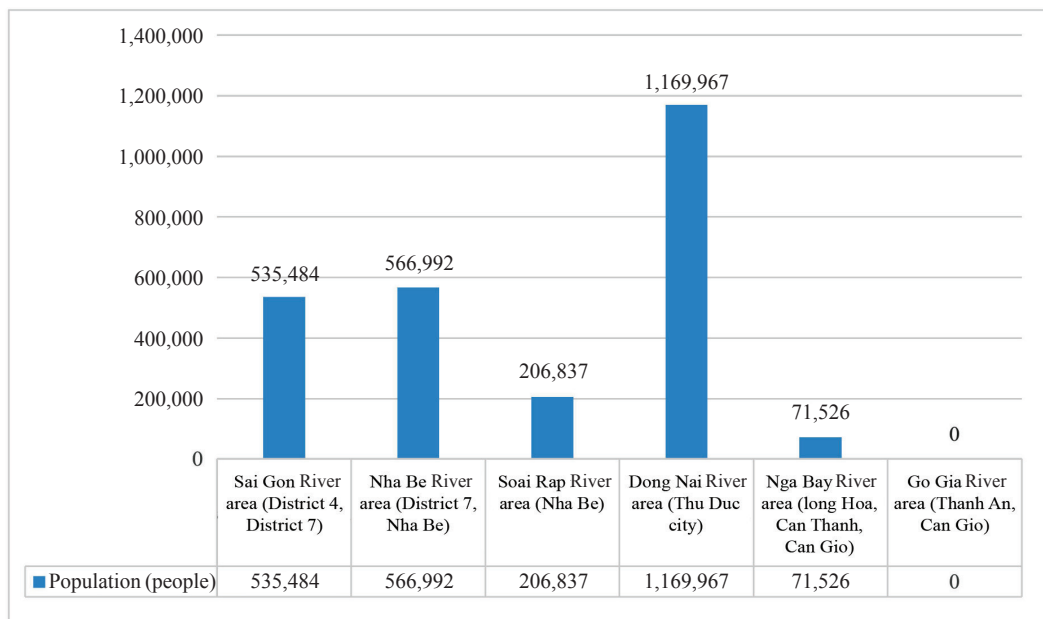


Figure 1: Ho Chi Minh City population distribution



Figure 2: Study site

Based on the Table 1, there are 38 berths in Ho Chi Minh City seaport with a total quay length of nearly 14 km, including 94 operational quays that can accommodate vessels up to 60,000 DWT with suitable draft; along the entire managed area, 67 mooring buoys, transshipment anchorage area, and 6 anchorage zones, with more than 50 anchorage points are established to accommodate vessels with a maximum capacity of up to 150,000 DWT (Maritime Administration of Ho Chi Minh City, 2023).

According to a study by Ho Quoc Bang, which conducted an emissions inventory in Ho Chi Minh City in 2019, seaports accounted for

16% of SO₂ emissions and 8% of NO₂ emissions, making them one of the city’s primary sources of emissions (Ho *et al.*, 2019).

Methods

The research method is conducted as shown in Figure 3. To select localised ECA, the research will evaluate air pollution simulations based on emission inventory results.

Emission Inventory Method

The two primary methodologies applied in emission inventories are bottom-up and top-down. The top-down approach, which relies

Table 1: Ho Chi Minh City seaport infrastructure

River	Number of Berths	Number of Buoys	Number of Anchorage Areas	Maximum Deadweight (DWT)
Sai Gon	10	8	0	60,000
Nha Be	10	17	1	40,000
Dong Nai	7	9	0	60,000
Soai Rap	11	15	1	50,000
Go Gia	0	10	1	150,000
Nga Bay	0	8	1	80,000

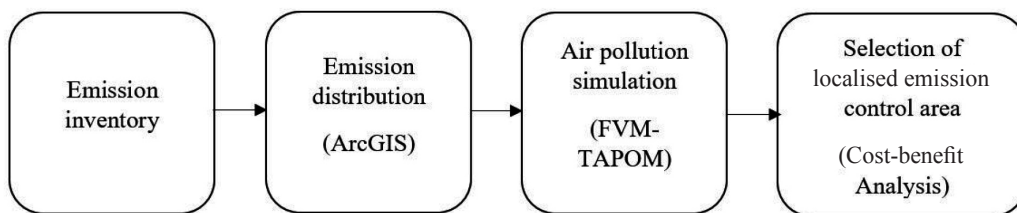


Figure 3: Research method

on fuel consumption data reported by the vehicle’s owners or operators, and the bottom-up approach, which uses vehicle technical specifications and operational data. According to Yongbum Kwon *et al.* (2019), the bottom-up approach has higher accuracy. The air pollution emission inventory results for the seaport in this study will inherit the calculation data from the research conducted by Pham Thanh Tuan for the Ho Chi Minh City seaport in 2023 and forecast results to 2030. The inventory subjects include Oceangoing Vessel (OGV), Harbour Craft (HBC), Heavy Duty Vehicle (HDV), and Cargo Handling Equipment (CHE).

Air Pollution Distribution Method

Based on the previously calculated emission data, a Geographic Information Systems (GIS) database will be developed to manage emissions from maritime activities and to create digital maps of current air pollution levels. ArcGIS Desktop, a product of the Environmental Systems Research Institute (ESRI) is one of the most advanced GIS platforms. To distribute emissions spatially, the objects will be categorised into two types: Point (for on-site type emissions) and polygon (for underway type emissions), since OGV emissions are divided into four phases (cruise, reduce speed zone, manoeuvre, and hotel).

Therefore, in the survey of sources, it is necessary to collect data through direct surveys to obtain specific information on the coordinates, emission levels, etc., of seaport facilities and floating docks, and to compile a list to be represented spatially as points, corresponding to their locations. In addition to the point data, an emission database will be built for each river area

within the Ho Chi Minh City seaport to support polygon distribution. Here, the total emissions for each river area will be calculated for each pollutant, along with the total navigation channel area for each river section. Emissions for each river area will be evenly distributed based on the location of the corresponding navigation channel. The emissions, when displayed on the map, will be shown as the average emissions per grid cell (tonne per year).

On-site type emission: The total emission of OGV in hotel mode (the vessel is anchoring or mooring and operating auxiliary engines for all on-board power) and in manoeuvre mode (the ship turns around before the dock to berth alongside), with emission of CHE, emission of HDV in a specific port.

$$E_{\text{on-site}} = (E_{\text{OGV hotel}} + E_{\text{OGV manoeuvre}}) + E_{\text{CHE}} + E_{\text{HDV}} \quad (1)$$

where:

- $E_{\text{on-site}}$ On-site type emission
- $E_{\text{OGV hotel}}$ Emission from an oceangoing vessel during the hotel
- $E_{\text{OGV manoeuvre}}$ Emission from an oceangoing vessel during manoeuvre
- E_{CHE} Emission from cargo handling equipment
- E_{HDV} Emission from heavy-duty vehicle

Underway type emission: The total emission of OGV in underway mode (the vessel travels with maximum speed) and in reduced speed zone mode (the vessel travels within a reduced speed zone with speed less than cruise and greater than manoeuvring), with emission of CHE, emission of HDV in a specific area.

$$E_{\text{underway}} = (E_{\text{OGV cruise}} + E_{\text{OGV RSZ}}) + E_{\text{HBC}} \quad (2)$$

where:

- E_{underway} Underway type emission
- $E_{\text{OGV cruise}}$ Emission from an oceangoing vessel during a cruise
- $E_{\text{OGV RSZ}}$ Emission from an oceangoing vessel in a reduced speed zone
- E_{HBC} Emission from harbor craft

Air Pollution Simulation Method

Air pollution simulation progress is conducted as shown in Figure 4.

Concentration distribution maps of each pollutant will be used to assess the effectiveness of the selected localised ECA.

FVM Model

The FVM model is a three-dimensional Eulerian model that uses grid-based terrain with limited volume resolution. The model’s outputs include meteorological fields such as temperature, humidity, pressure, heat and moisture flux, and turbulence characteristics at multiple levels. It is designed to accurately reflect the detailed

influence of the urban surface on meteorological factors in the boundary layer and on the dispersion of pollutants.

Simulation area: Five different-sized domains (ranging from D1 to D5) are simulated by the FVM model as shown in Figure 5.

The dimensions of the areas are: 400 km x 400 km (D1), 260 km x 260 km (D2), 170 km x 170 km (D3), 115 km x 115 km (D4), and 75 km x 75 km (D5). In the horizontal direction, the grid cell sizes are: 20 km x 20 km, 7 km x 7 km, 5 km x 5 km, 3 km x 3 km, and 2 km x 2 km in both the X and Y directions. The nesting technique is used to run grid nesting from larger to smaller grid cells, where the wind and temperature results from the D1 area are used as initial and boundary conditions for the D2 area.

The input data for the FVM model include: The required input data include the starting corner coordinates of the domain and the simulation time: Domain characteristics, including size, position, and grid cell dimensions; boundary and initial conditions (<http://www.cdc.noaa.gov>, from U.S Geological Survey); topography data is collected as GTOPO30 (<http://edc.usgs.gov>); land use data (land use type, roughness,

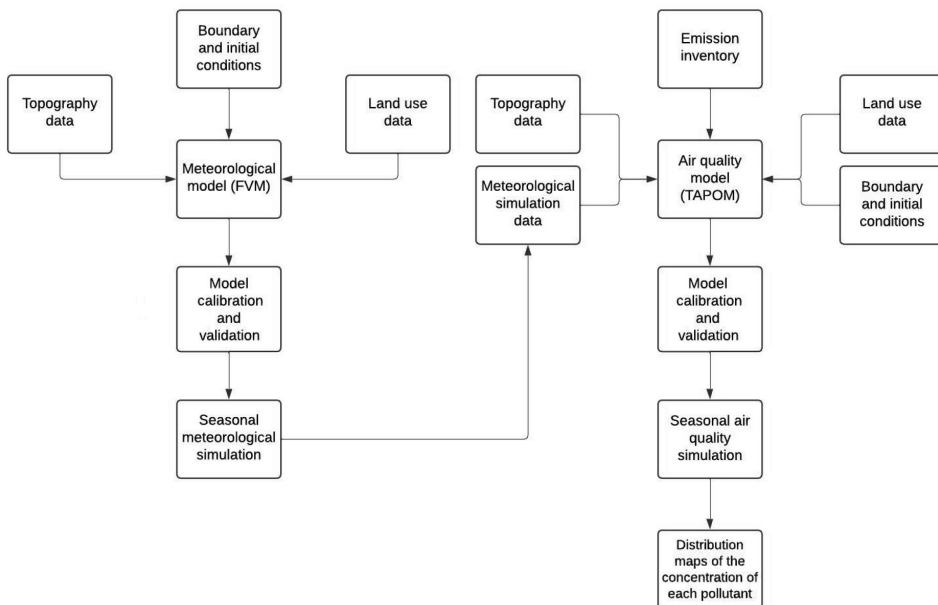


Figure 4: Air pollution simulation progress

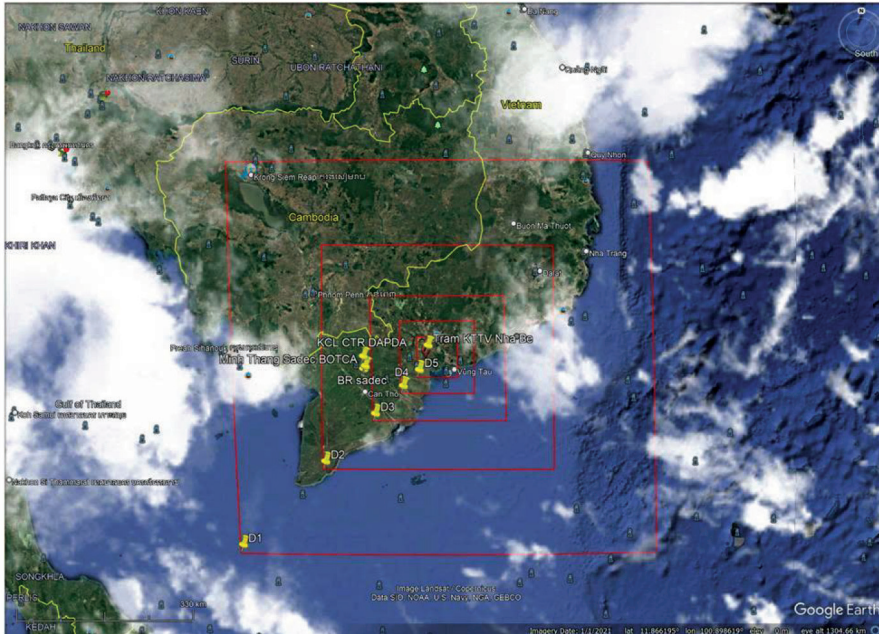


Figure 5: Simulation area

moisture, and temperature) is collected from global land cover database for the year 2000 (Bartholomé *et al.*, 2005).

Selection of simulation period: Based on meteorological conditions, particularly the prevailing wind direction in the study area and climate observation data, two periods within the year were selected for simulation: March and September 2022, corresponding to two seasons and two dominant wind regimes.

The output results of the FVM model include the following data: Distribution maps of each meteorological parameter (wind direction, wind speed, temperature, humidity, pressure, solar radiation, etc.) within the simulated domain; hourly average values of each parameter by grid cell and at different heights (layers): Temperature, wind direction, wind speed, and humidity.

TAPOM Model

Referencing the baseline results from Ho Quoc Bang’s study (Ho Quoc Bang, 2010), the input data for the TAPOM model includes: The location of the computational domain

and simulation period, the domain size and resolution, meteorological simulation results, emission load distribution data from various sources, topographical and land use data of the study area, and baseline concentrations of pollutants.

Output results: The TAPOM model outputs include the following: Distribution maps of pollutant concentrations within the simulated computational domain, hourly average pollutant concentrations for each grid cell.

Model Calibration and Validation

The quality of the simulation results (meteorology and air quality) is evaluated based on measurement data from monitoring stations within the computational domain D5 (the innermost domain). Air quality monitoring data from the east of Cat Lai New Port on 6 July 2024 are used to validate the TAPOM model. Additionally, meteorological observation data from the Nha Be monitoring station are utilised to validate the meteorological model, including temperature, humidity, wind direction, and wind speed. Statistical indices used to assess the

model’s accuracy, with P_i as the simulated value and O_i as the observed value, include $R^2 \approx 1$ is accepted.

Cost-benefit Analysis

Cost-benefit Analysis (CBA) is a decision-making process used to evaluate the total anticipated costs versus the total benefits of a project, policy, or investment (O’Mahony, 2021; Afzal Husain Khan et al., 2022). It helps determine whether a project or decision is worthwhile by comparing its benefits to its costs.

In this study, CBA is determined to support decision-making in selecting the area for establishing an ECA. The Benefit-cost Ratio (BCR) expresses the outcome of a CBA.

$$BCR = \frac{\text{Total Benefits}}{\text{Total Costs}} \quad (3)$$

where:

Total benefits : Reduce treatment costs for respiratory diseases (assuming costs are determined by expenses for treating flu-related illnesses, at approximately 400,000 VND per person)

Total costs : Apply low sulphur fuel for a round turn (assumption is that the vessel travels a distance of 10 km to the port, consuming 4 tonnes of fuel, with the price of MDO 0.50% m/m fuel being 20,190,000 VND per tonne, MDO 0.10% m/m fuel being 20,430,000 VND per tonne)

$BCR > 1$, the project or decision is considered viable.

Results and Discussions

Emission Inventory

After collecting emission inventory results from shipping activities in different river areas, on-site type and underway type emission inventory are summarised in Tables 2 and 3.

Oceangoing vessel is the primary emission source, with the most significant emissions in the Cat Lai port area (Thanh Tuan Pham et al., 2025). During operations, the emissions generated from hotelling are the largest, accounting for 80% (Ho Quoc Bang et al., 2013).

Because the majority of vessels operating in the Cat Lai port area navigate through Long Tau River, emissions from activities in this area are the highest (Thanh Tuan Pham et al., 2025).

Air Pollution Distribution

Distributed on-site type emission and underway type emission are merged in Figures 6 and 7.

SO₂ and NO₂ distribution: Cat Lai port area (on the Dong Nai River) and the port area on the Nha Be River have the most significant SO₂ and NO₂ distributions, ranging from 825 to 4,497 tonnes per year and from 3,661 to 14,887 tonnes per year, respectively. The second area is the ports on the Nha Be River (Binh Khanh intersection area), with SO₂ distribution ranging from 272 to 824 tonnes per year and NO₂ distribution ranging from 2,432 to 3,660 tonnes per year. The third area is the port on the Sai Gon River, with SO₂ distribution ranging from

Table 2: On-site type emission

Port Area	NO ₂ (tonne)	PM ₁₀ (tonne)	PM _{2.5} (tonne)	SO ₂ (tonne)
Dong Nai River	17,066.54	804.15	742.63	5,072.11
Sai Gon River	5,886.66	310.58	289.83	1,664.34
Soai Rap River	3,442.97	436.67	399.60	3,437.31
Thieng Lieng River	5.19	0.28	0.25	1.93
Nha Be River	3,084.55	304.95	279.10	2,343.89
Go Gia River	110.57	5.45	5.00	37.26

Table 3: Underway type emission

Area	NO ₂ (tonne)	PM ₁₀ (tonne)	PM _{2.5} (tonne)	SO ₂ (tonne)	Distance (km)
Entrance to the intersection of Go Gia – Thi Vai	44.98	2.32	2.20	11.37	16.00
Thieng Lieng River	3,075.85	177.48	169.01	846.47	24.40
Long Tau River	4,088.04	236.03	224.77	1,125.40	32.60
Nha Be River	1,213.85	67.92	64.61	325.17	9.00
Dong Nai River	1,092.42	63.09	60.08	301.58	9.50
Sai Gon River	186.49	7.57	7.07	38.89	14.00
Dong Tranh River	13.37	0.97	0.94	4.21	14.50
Tat Cua	5.53	0.40	0.39	1.74	6.00
Go Gia River	59.57	3.17	3.02	15.26	7.00
Soai Rap River	500.72	25.88	24.48	124.24	66.60
Ganh Rai Bay	1,809.78	104.16	99.17	497.05	14.00

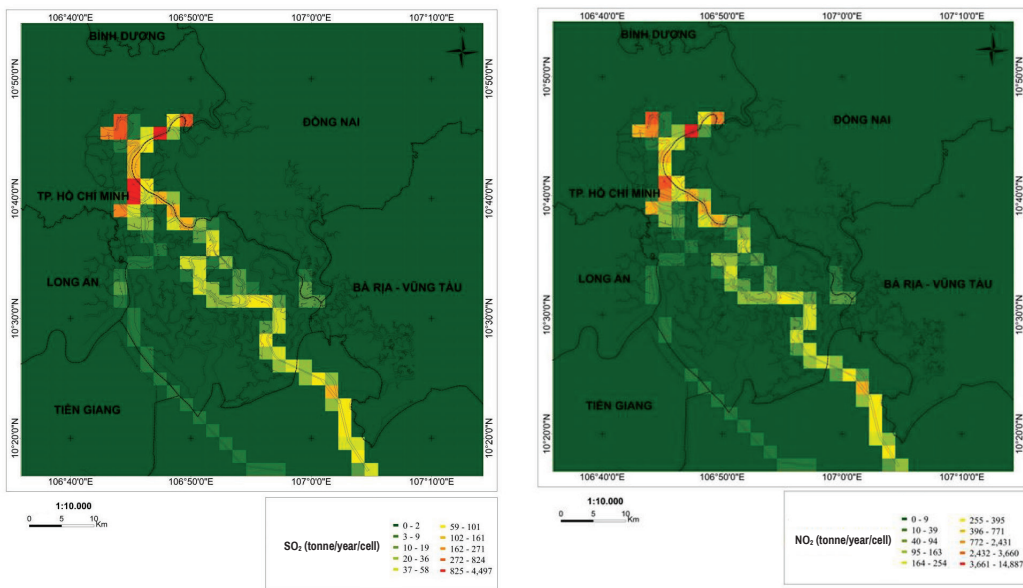


Figure 6: SO₂ and NO₂ distribution map

162 to 271 tonnes per year and NO₂ distribution ranging from 772 to 2,431 tonnes per year.

PM_{2.5} and PM₁₀ distribution: Cat Lai port area (on the Dong Nai River) has the largest PM_{2.5} distribution, ranging from 355 to 652 tonnes per year, and the most extensive PM₁₀ distribution, ranging from 388 to 707 tonnes per year. The second area is the ports on the

Nha Be River (Binh Khanh intersection area), with PM_{2.5} distribution ranging from 173 to 354 tonnes per year and PM₁₀ distribution ranging from 184 to 387 tonnes per year. The third area is the ports on the Sai Gon River, with PM_{2.5} distribution ranging from 37 to 172 tonnes per year and PM₁₀ distribution ranging from 40 to 183 tonnes per year.

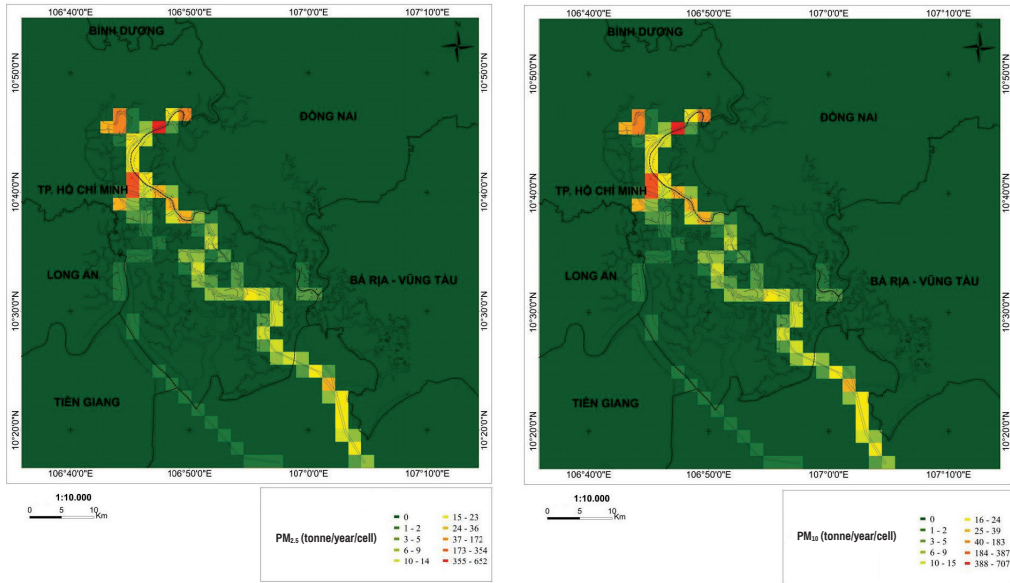


Figure 7: PM_{2.5} and PM₁₀ distribution map

Throughout the emission distribution in Figures 6 and 7, there are three areas with high emissions in order: Cat Lai port area (in the Dong Nai River), Binh Khanh intersection area (in the Nha Be River), and Sai Gon port area (in the Sai Gon River). The emission distribution results are almost identical to the study by Ho Quoc Bang *et al.* (2019), which calculated emissions in Ho Chi Minh City. An essential contribution of the study lies in its identification of pollutant distribution patterns, which reflect the main shipping routes through underway type emissions. The findings indicate that the majority of vessels use the Sai Gon–Vung Tau channel to access the port area and return via the same route.

Calibration and Validation Result

FVM–Meteorological Model: The model was run one day ahead of the scheduled calibration and validation date to eliminate numerical errors. The calibration data for the model included land surface temperature and surface air humidity. The study conducted meteorological simulations for 2022 using the FVM model, with the results subsequently calibrated and validated for the dry

season (March) and the rainy season (September) at the Nha Be meteorological station. The calibrated dataset of the FVM model was then used to simulate meteorology for 2022, and the resulting meteorological data served as input to the TAPOM dispersion simulation model. The simulated temperature results and the observed data at Nha Be station during the periods from 4 to 6 March 2022, and from 1 to 3 September 2022, were found to be similar. Based on the Figure 8, the correlation between the simulation results and the actual measurements at the Nha Be station was relatively good, with $R^2 \approx 1$ ($R^2 = 0.84$ for the dry season and $R^2 = 0.66$ for the rainy season).

The FVM model effectively simulates daytime and nighttime temperatures in the study area. The simulation results show that the highest temperatures occur between 11:00 a.m. to 01:00 p.m., ranging from approximately 35°C to 37°C in March and from 34°C to 36°C in September. This period also corresponds to the highest recorded temperatures at the Nha Be station. The simulated wind direction aligns well with observed data, varying from east to southeast during the dry season and from west to southwest during the rainy season.

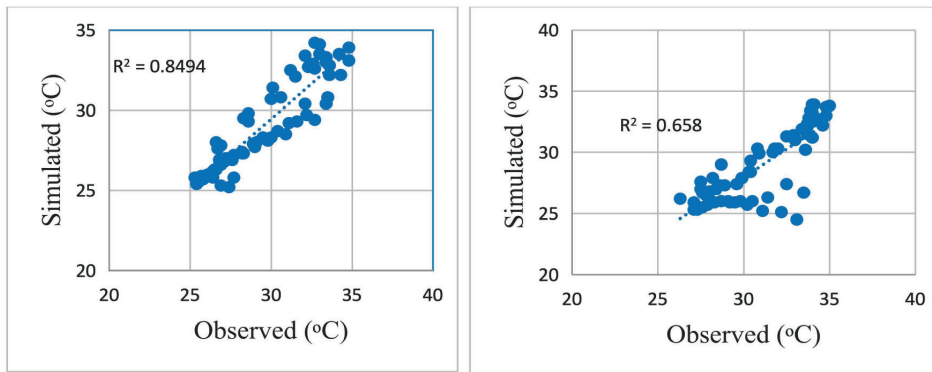


Figure 8: Temperature correlation between simulation and observation at Nha Be station

TAPOM–Air Pollution Dispersion Model: Due to the lack of automatic monitoring data for calibration and validation of the TAPOM model, the study conducted ambient air quality sampling at CL7 berth (east of Cat Lai New Port) on 6 July 2024, for SO₂ and NO₂ parameters to support the calibration and validation of the air pollution dispersion model. As a result, the 2022 meteorological calibration and validation dataset was used to simulate meteorological conditions in the study area for July 2024. The meteorological simulation results for July 2024 were then used to model air pollutant dispersion for calibration and validation of the TAPOM model.

The simulation and observations at CL7 berth, as shown in Figure 9, indicate that the TAPOM model effectively simulates air pollutant concentrations in the study area. It is evident that the simulated SO₂ concentrations

tend to be higher than the observed values, whereas the opposite trend holds for NO₂.

The comparison results of ambient air pollutant concentrations between the simulation and observations at CL7 berth, as shown in Figure 10, indicate that the TAPOM model performs reasonably well in simulating pollutant concentrations in the study area, with coefficients of determination (R²) of 0.7 for NO₂ and 0.65 for SO₂.

Air Pollution Simulation

Southern Vietnam is located in a region characterised by a tropical monsoon climate and near the equator. The climate is shaped by two main seasons: The dry and rainy seasons. The rainy season is influenced by the southwest monsoon from May to November, while the dry season is affected by the northeast monsoon from December to April (Mayhew, 1965). Due

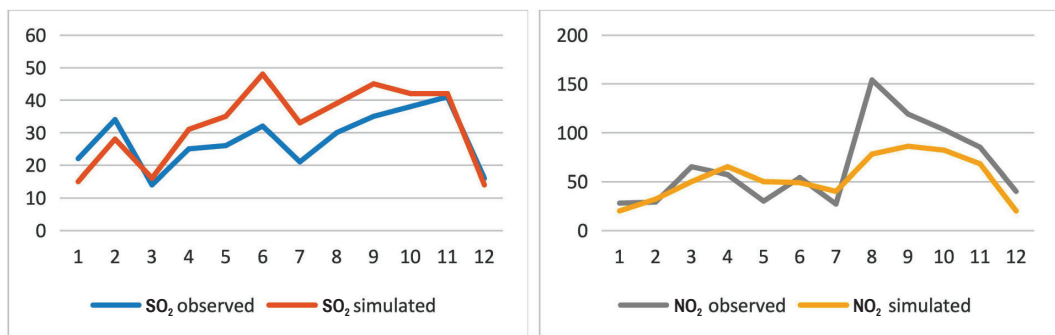


Figure 9: Correlation comparison of SO₂ and NO₂ concentrations between observations and TAPOM model simulations

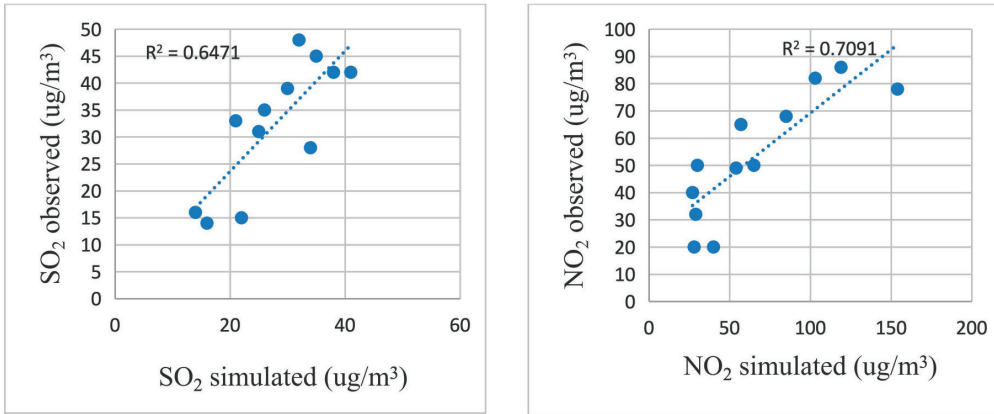


Figure 10: Comparison results of the correlation between simulation and observation at CL7 berth

to meteorological conditions during the dry season, with the prevailing wind direction from the northeast, pollutants tend to spread towards the southwest of Ho Chi Minh City. In contrast, the main direction of pollutant dispersion is toward the northeast of Ho Chi Minh City during the rainy season, influenced by prevailing meteorological conditions with the southwest wind direction.

As shown in Figure 11, the area with the highest pollution concentration is Cat Lai port area (on Dong Nai River), where the maximum 1-hour average SO₂ concentration reaches 340 µg/m³ in rainy season and 360 µg/m³ in dry season, exceeding the air quality standard of 350 µg/m³ (Minister of Natural Resources

and Environment, 2023). The second-highest pollution concentration is the Nha Be port area in the Nha Be River, with maximum SO₂ average 1-hour levels in both the rainy and dry seasons, which are lower than the air quality standard (Minister of Natural Resources and Environment, 2023).

As shown in Figure 12, the area with the highest pollution concentration is Cat Lai port area (on Dong Nai River), where maximum 1-hour average NO₂ concentration is 115 µg/m³ in rainy season and 120 µg/m³ in dry season, both of which are below the air quality standard of 200 µg/m³ (Minister of Natural Resources and Environment, 2023).

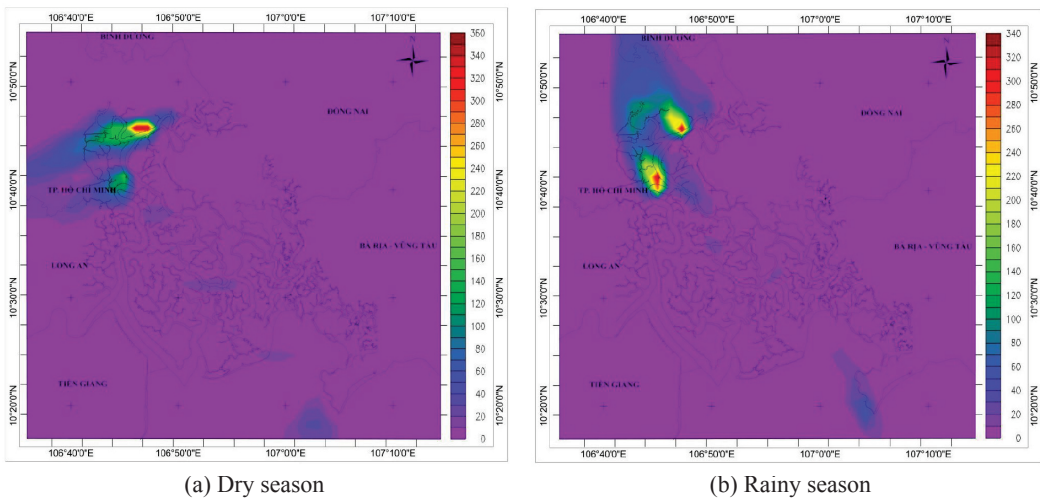


Figure 11: SO₂ average 1-hour (µg/m³) distribution map

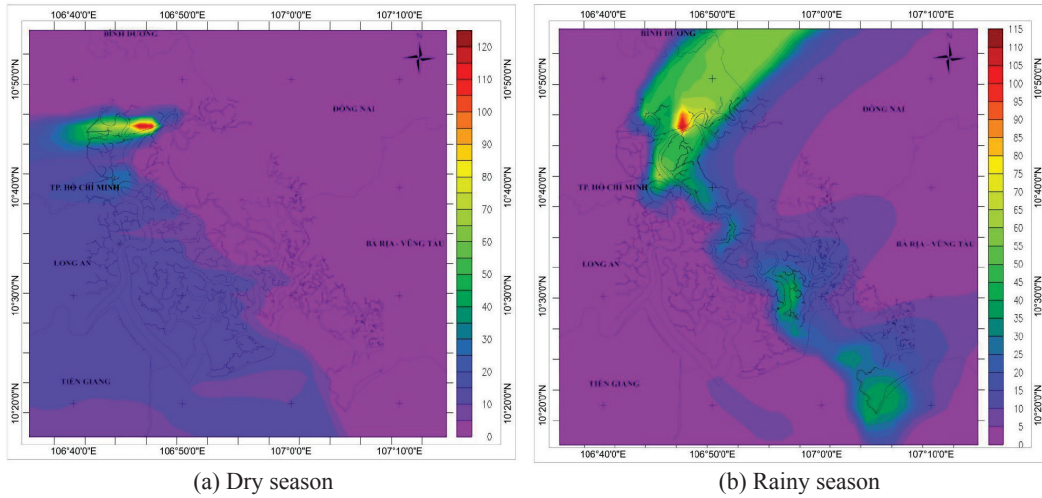


Figure 12: NO₂ average 1-hour (µg/m³) distribution map

As shown in Figure 13, the area with the highest pollution concentration is Cat Lai port area (on Dong Nai River), where maximum 24-hour average PM_{2.5} concentration is 26 µg/m³ in rainy season and 24 µg/m³ in dry season, both of which are below the air quality standard of 50 µg/m³ (Minister of Natural Resources and Environment, 2023). The second-highest pollution concentration is in the Nha Be port area (on the Nha Be River), where the maximum 24-hour average PM_{2.5} concentration in both rainy and dry seasons is also below the air quality standard (Minister of Natural Resources and Environment, 2023).

As shown in Figure 14, the area with the highest pollution concentration is Cat Lai port area (on Dong Nai River), where maximum 24-hour average PM₁₀ concentration is 52 µg/m³ in rainy season and 56 µg/m³ in dry season, both of which are below the air quality standard of 100 µg/m³ (Minister of Natural Resources and Environment, 2023). The second-highest pollution concentration is in the Nha Be port area (on the Nha Be River), where the maximum 24-hour average PM₁₀ concentration in both rainy and dry seasons is also below the air quality standard (Minister of Natural Resources and Environment, 2023).

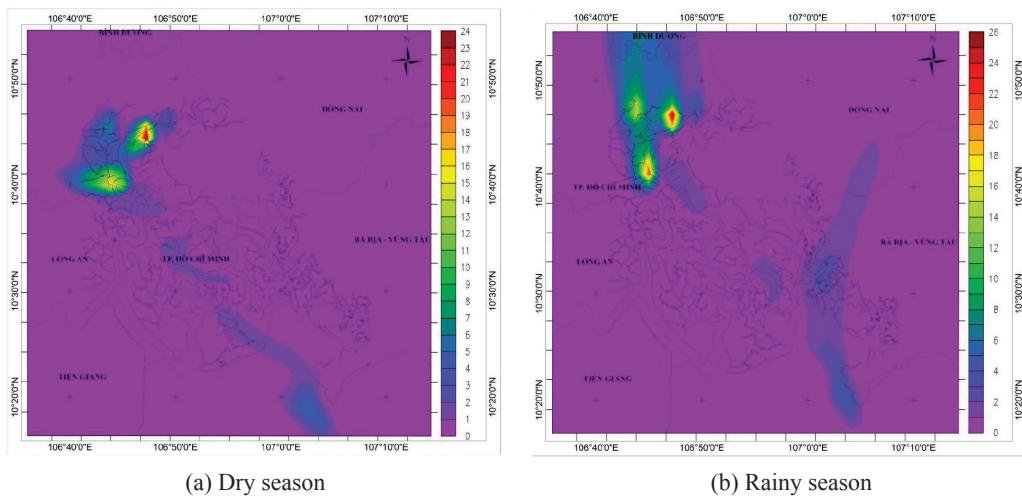


Figure 13: PM_{2.5} average 24-hour (µg/m³) distribution map

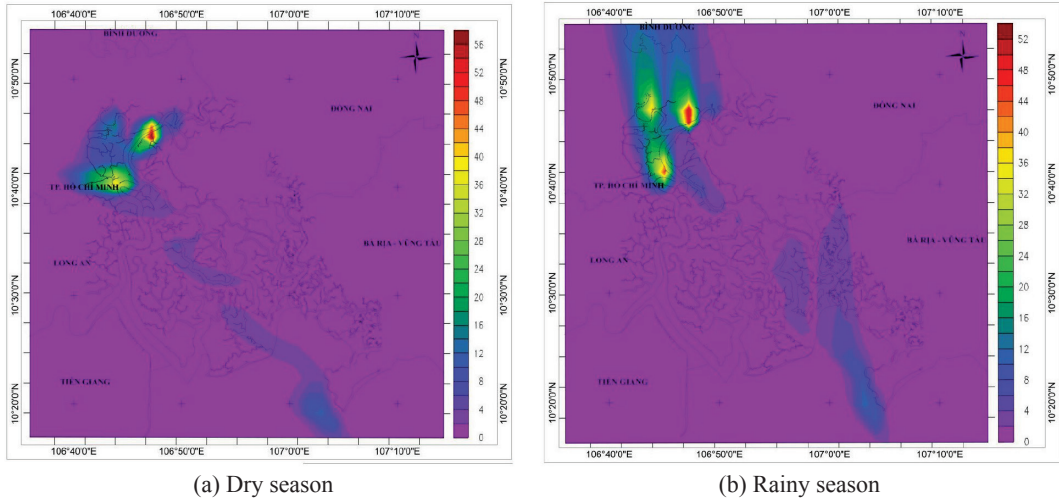


Figure 14: PM₁₀ average 24-hour (µg/m³) distribution map

Propose the Establishment of a Localised Emission Control Area

According to the air pollution simulation results, the further discussion to propose an air quality management solution shall focus on SO₂, since the distribution meets the standard. Establishing ECA to enforce vessels operating on low-sulphur fuel below 0.10% m/m, as instructed by IMO, is the most effective way to cut down emissions (especially SO₂), which has been adopted by many countries (IMO, 2023).

There are five ECA areas (including the Baltic Sea, North Sea, North America, the United States Caribbean Sea, and the Mediterranean Sea) that have entered into force officially. In general, most ECA are established either in a specific sea area (such as the Baltic Sea, North Sea, or Mediterranean Sea) or across the entire exclusive economic zone, as in North America. ECA can differ in terms of size and shape, but it should contribute to reducing pollution from shipping activities (IMO, 2023). In order to establish an effective localised ECA, the study focuses on evaluating the three options shown in Figure 15, based on a balance between socioeconomic development and environmental protection.

The first option is the Cat Lai port area, the second is upstream of the Binh Khanh

intersection, and the last is the entire study site. The evaluation of the localised ECA proposal is based on its potential impact on port competitiveness and the cost implications of fuel conversion and emission reduction efficiency.

Potential impact on port competitiveness and qualitative assessment of emission reduction efficiency are discussed in Table 4.

Cost implications for fuel conversion: Through a fuel consumption survey, it was recorded that the vessel consumed approximately 4 tonnes of MDO while traveling 90 km along the Sai Gon–Vung Tau channel, as detailed in Table 5.

Benefit-cost ratio: With the total benefit being the savings in treatment costs for respiratory diseases of the population in ECA, the BCR of options is calculated in Table 6.

In descending order, the BCR of option No. 3 is greater than that of option No. 1, which is greater than that of option No. 2. While option No. 3 is suitable for application at the regional scale (provincial level), option No. 1 should be the priority option in case of implementing ECA at the local scale (port area level).

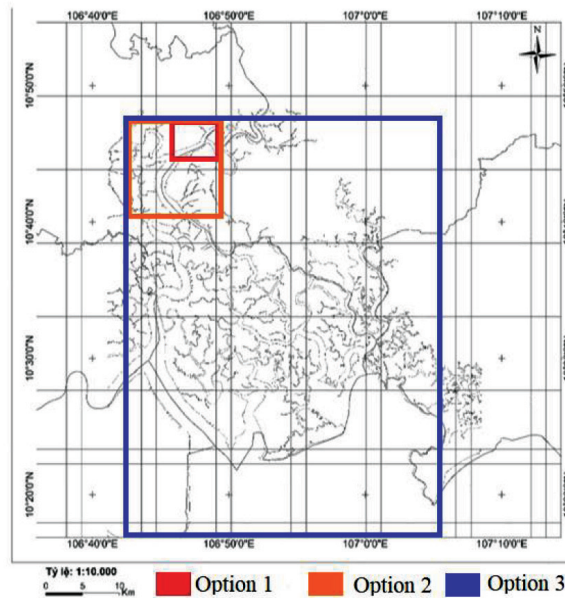


Figure 15: Selection of emission control area

Table 4: Proposal of ECA establishment

Option	Propose ECA	Advantage	Disadvantage	Solutions for Improvement
No. 1	The area encompasses three priority zones for establishing the ECA, including Dong Nai, Nha Be, and Sai Gon River (approximately 19 km in length).	Average emission reduction efficiency. The cost difference for fuel conversion per voyage is not too high.		<ul style="list-style-type: none"> - Applying an environmental protection fee of 3,000,000 VND per year for port enterprises to reduce the cost burden on dedicated-route shipping companies and to encourage ships to return to Ho Chi Minh City's seaports multiple times a year. - Coordinating vessels to underway via Soai Rap channel to reduce the concentration of underway type of emission on Long Tau River.
No. 2	The area covers the Dong Nai River region, prioritised for ECA establishment (approximately 9.5 km in length).	The cost difference for fuel conversion per voyage is relatively low.	<ul style="list-style-type: none"> - Low emission reduction efficiency. - Establishing an ECA in this area will reduce the competitiveness of Cat Lai port. 	ECA should be extended as fuel conversion requires preparation time.

No. 3	The area covers four priority zones for ECA establishment, including the Dong Nai, Nha Be, Soai Rap, and Sai Gon River (approximately 51.6 km in length).	High emission reduction efficiency.	The cost difference for fuel conversion per voyage is relatively high.	ECA should be reduced as the Long Tau River, Thieng Lieng River, and Go Gia River (in Can Gio District) have limited port operations.
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Table 5: Cost implications for fuel conversion

	Cost of Usage MDO 0.1 (VND)	Cost of Usage MDO 0.5 (VND)	Total (VND)	Cost Difference (VND)
Current scenario plan	-	80,760,000	80,760,000	-
Option No. 1	16,344,000	64,608,000	80,952,000	192,000
Option No. 2	8,172,000	72,684,000	80,856,000	96,000
Option No. 3	81,720,000	-	81,720,000	960,000

Table 6: Cost-benefit analysis for the implementation of ECA

Option	Total Benefit (thousand VND)	Total Costs (thousand VND)	BCR
No. 1	908,977,200	161,904	5,614.3
No. 2	467,986,800	161,712	2,894.0
No. 3	1,020,322,400	163,440	6,242.8

Emission reduction: After reviewing and evaluating, the research team selected option No. 1 for the pilot implementation, which yielded the following results as shown in Table 7.

The air pollution reduction efficiency increases when applying the 2030 scenario (establishing ECA according to option No. 1), with reductions of 171% for NO₂, 70% for SO₂, 39% for PM₁₀, and 37% for PM_{2.5}. The establishment of ECA has achieved the goal of effectively controlling emissions from transportation activities by 2030 (with 83% reduction in NO₂) according to the Environmental Pollution Reduction Program for the period from 2020 to 2030 approved by the People's Committee of Ho Chi Minh City in Decision No.1055/QD-UBND dated 29 March 2021.

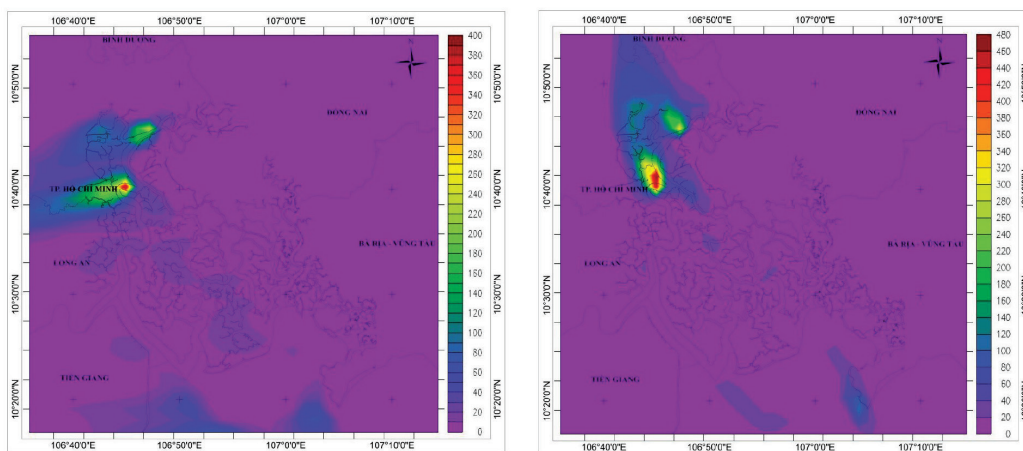
Air Pollution Simulation in 2030 (After Establishing ECA)

Apply the new on-site emission and underway emission in 2030, the air pollution simulation is described in Figures 16 to 19.

According to the simulation results, air pollution is still increasing due to the increasing number of vessels. However, after the establishment of the ECA, emissions in the Cat Lai port area were significantly reduced, especially SO₂ and NO₂, as shown in Figures 16 to 19. During the dry season, the maximum 1-hour average SO₂ concentration will decrease from 360 µg/m³ to 260 µg/m³, and the maximum 1-hour average NO₂ concentration will decrease from 120 µg/m³ to 64 µg/m³. During the rainy season, the maximum 1-hour average SO₂ concentration will decrease from 340 µg/m³ to

Table 7: Additional air pollution reduction effectiveness after ECA establishment

Emission	NO ₂ (tonne)	PM ₁₀ (tonne)	PM _{2.5} (tonne)	SO ₂ (tonne)	Note
Result in 2022 (without ECA)	28,335.02	1,818.25	1,667.07	13,185.79	(1)
Predict in 2030 (without ECA)	39,952.37	2,563.73	2,350.56	18,591.96	(2) = (1) x 1.41
Result in 2022 (with ECA)	14,216.33	1,610.01	1,488.30	10,493.38	(3)
Predict in 2030 (with ECA)	20,045.03	2,270.11	2,098.50	14,795.67	(4) = (3) x 1.41
Difference period 2022-2030 (without ECA)	↑ 11,617.36	↑ 745.48	↑ 683.50	↑ 5,406.17	(5) = (2) – (1)
Difference period 2022-2030 (with ECA)	↓ -8,289.99	↑ 451.87	↑ 431.43	↑ 1,609.88	(6) = (4) – (3)
Difference in 2030 (with and without ECA)	↓ 19,907.35	↓ 293.61	↓ 252.07	↓ 3,796.29	(7) = (2) – (4)
Additional air pollution reduction effectiveness	-71%	61%	63%	30%	(8) = (5) / (6)
	↓ 171%	↓ 39%	↓ 37%	↓ 70%	(9) = 1 – (8)



(a) Dry season (b) Rainy season

Figure 16: SO₂ average 1-hour (µg/m³) distribution map in 2030

320 µg/m³, and the maximum 1-hour average NO₂ concentration will decrease from 115 µg/m³ to 80 µg/m³. Pollutants meet the regulatory standards in the Cat Lai port area (Minister of Natural Resources and Environment, 2023).

After ECA establishment, the effectiveness in reducing additional air pollution by 2030 is shown in Table 8.

In general, under the 2030 scenario, with a substantial increase in maritime activities, maximum 1-hour average SO₂ concentration will increase at the edge of ECA (rising by 40 µg/m³ in dry season, 140 µg/m³ in rainy season) but significantly reduce inside ECA (dropping by 100 µg/m³ in dry season, 20 µg/m³ in rainy season); maximum 1-hour average NO₂ concentration will decrease 56 µg/m³ in

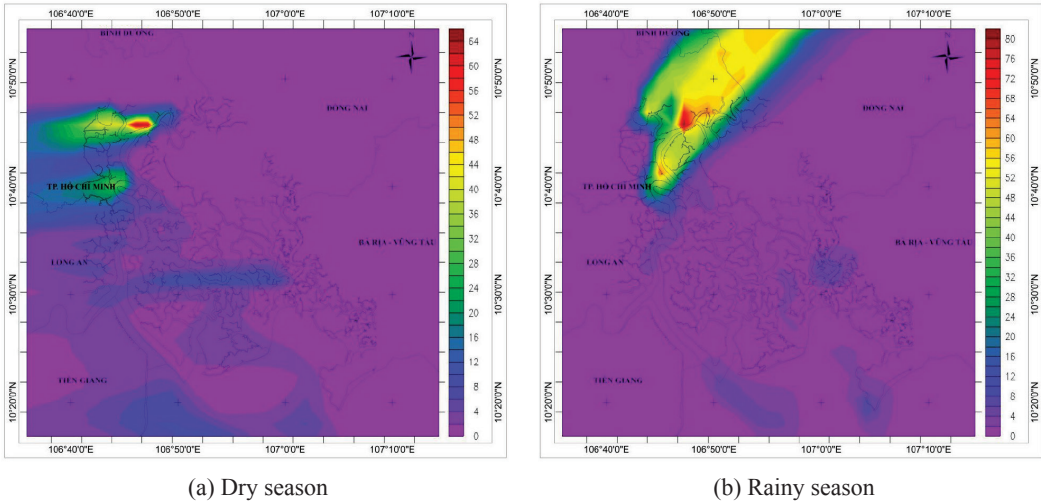


Figure 17: NO₂ average 1-hour (µg/m³) distribution map

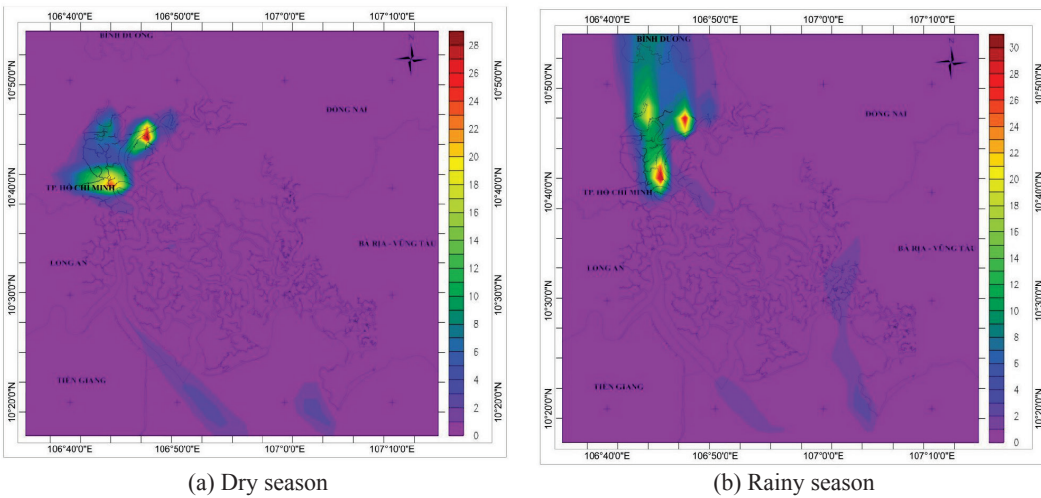
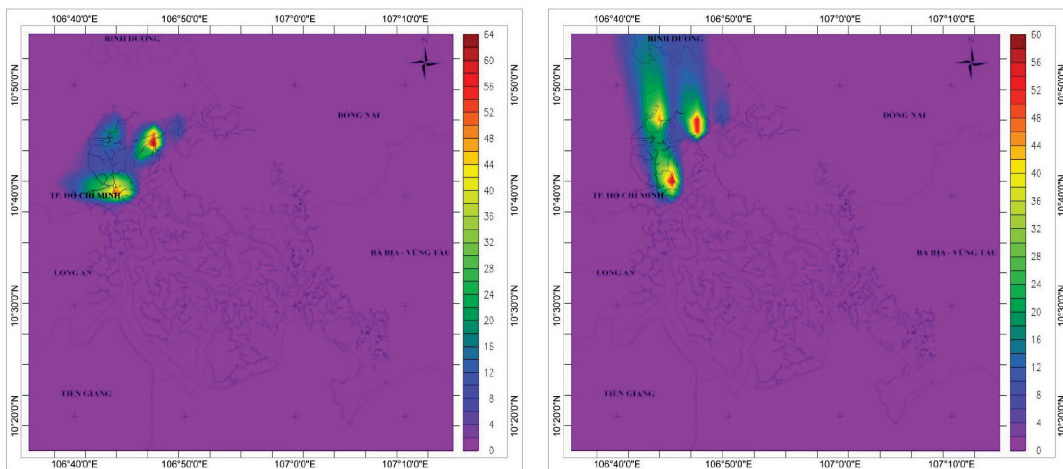


Figure 18: PM_{2.5} average 24-hour (µg/m³) distribution map

dry season, 35 µg/m³ in rainy season; maximum 24-hour average PM_{2.5} and PM₁₀ concentration will slow growth. Only the maximum 1-hour average SO₂ concentration meets the Vietnam air quality standard, which is 350 µg/m³ (Minister of Natural Resources and Environment, 2023). Compared with the interim targets recommended by the World Health Organisation (WHO), the pollutant levels fall within interim target 4 (PM_{2.5} average 24-hour: 25 µg/m³; PM₁₀ average 24-hour: 50 µg/m³), which could potentially reduce premature deaths caused by air pollution

by 56.8% compared to the air pollution level in 2016 (WHO, 2021).

The study’s goal is achieved through this ECA selection. The establishment of a localised ECA (at port-area level) in option No. 1 is a regulatory solution for managing the transition of vessels to low-sulphur fuel, which has proven to be highly effective in reducing emissions during vessel operations. However, it is also necessary to consider integrating additional measures to more effectively mitigate air pollution from other related emission sources in the distant



(a) Dry season (b) Rainy season

Figure 19: PM_{2.5} average 24-hour (µg/m³) distribution map

Table 8: Comparison of air pollution simulation results after ECA establishment

		Max. SO ₂		Max. NO ₂		Max. PM ₁₀		Max. PM _{2.5}	
		Average		Average		Average		Average	
		1-hour (µg/m ³)		1-hour (µg/m ³)		24-hour (µg/m ³)		24-hour (µg/m ³)	
		Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy
Current scenario		360	340	120	115	56	52	24	26
Scenario in 2030 (after establish ECA)	Inside ECA	260	320	64	80	64	60	28	30
	Outside ECA	400	480	64	80	64	60	28	30
Different	Inside ECA	↓ 100	↓ 20	↓ 56	↓ 35	↑ 8	↑ 8	↑ 4	↑ 4
	Outside ECA	↑ 40	↑ 140	↓ 56	↓ 35	↑ 8	↑ 8	↑ 4	↑ 4

future, especially on-site type emissions. In addition to the emission inventory and air pollution simulation, it is necessary to evaluate relevant criteria as outlined in MARPOL Annex VI (IMO, 2022). Criteria such as seaport development, environmental sensitivity, vessel traffic density, human health, and population density are taken into consideration in the designation of an ECA for Ho Chi Minh City seaport in 2025 (Thanh Tuan Pham *et al.*, 2025). The additional strength of this study lies in demonstrating the feasibility of reducing air pollution in specific port areas, based on the results of emission distribution analyses. This provides a foundation for formulating port-

specific air quality management plans with clearly defined objectives.

Conclusions

This study simulated air pollution dispersion in the Ho Chi Minh City seaport using the FVM-TAPOM modelling system, focusing on emissions from shipping activities and their impact on air quality. The air pollution simulation results for the current scenario show that NO₂ and particulate matter concentrations remain low, whereas SO₂ levels exceeded the specified regulatory limits. The chosen localised ECA option balances port competitiveness

with economic feasibility and demonstrates its viability using the CBA method. The implementation of localised ECA from Binh Khanh intersection to the inner urban area showed a significant reduction in SO₂ and NO₂ concentrations, effectively bringing SO₂ levels into compliance with Vietnam's air quality standards.

Maximum 1-hour average concentrations of SO₂ are expected to decrease from 360 µg/m³ to 260 µg/m³ in the dry season, and from 340 µg/m³ to 320 µg/m³ in the rainy season, respectively. In addition, the maximum 24-hour average concentrations of particulate matter also meet the WHO interim target 4, which aims to reduce mortality associated with air pollution. However, the ongoing growth in vessel traffic necessitates continuing monitoring and management. Future research should consider additional factors, such as seaport development, environmental sensitivity, and human distribution, to support comprehensive localised ECA planning and sustainable air quality management, as instructed by MARPOL Annex VI (IMO, 2022).

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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