

Article

Ship Air Emission and Their Air Quality Impacts in the Panama Canal Area: An Integrated AIS-Based Estimation During Hotelling Mode in Anchorage Zone

Yongchan Lee ^{1,2}, Youngil Park ^{1,2}, Gaeul Kim ³, Jiye Yoo ² , Cesar Pinzon-Acosta ^{4,5} ,
Franchesca Gonzalez-Olivardia ⁴ , Edmanuel Cruz ^{4,6}  and Heekwan Lee ^{1,3,*}

¹ Graduate Department of Environmental and Energy Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea; jehun1108_m@inu.ac.kr (Y.L.); 01park@inu.ac.kr (Y.P.)

² Institute for Environmental Convergence Technology, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea; jiyeeyoo@inu.ac.kr

³ Department of Environmental Engineering, Incheon National University, 119 Academy-ro, Yeonsu-gu, Incheon 22012, Republic of Korea; a92443110@gmail.com

⁴ AirES Research Group, CINEMI, Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama; cesar.pinzon1@utp.ac.pa (C.P.-A.); francesca.gonzalez@utp.ac.pa (F.G.-O.); edmanuel.cruz@utp.ac.pa (E.C.)

⁵ Facultad de Ingeniería Mecánica, Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama

⁶ Centro Regional de Veraguas, Universidad Tecnológica de Panamá, Atalaya 0901, Panama

* Correspondence: airgroup@inu.ac.kr; Tel.: +82-32-835-8468; Fax: +82-32-777-8468

Abstract

This study presents an integrated assessment of anchorage-related emissions and air quality impacts in the Panama Canal region through Automatic Identification System (AIS) data, bottom-up emission estimation, and atmospheric dispersion modeling. One year of terrestrial AIS observations (July 2024–June 2025) captured 4641 vessels with highly variable waiting times: mean 15.0 h, median 4.9 h, with maximum episodes exceeding 1000 h. Annual emissions totaled 1,390,000 tons of CO₂, 20,500 tons of NO_x, 4250 tons of SO₂, 656 tons of PM₁₀, and 603 tons of PM_{2.5}, with anchorage activities contributing 497,000 tons of CO₂, 7010 tons of NO_x, 1520 tons of SO₂, 232 tons of PM₁₀, and 214 tons of PM_{2.5}. Despite the main engines being shut down during anchorage, these activities consistently accounted for 34–36% of the total emissions across all pollutants. High-resolution emission mapping revealed hotspots concentrated in anchorage zones, port berths, and canal approaches. Dispersion simulations revealed strong meteorological control: northwesterly flows transported emissions offshore, sea–land breezes produced afternoon fumigation peaks affecting Panama City, and southerly winds generated widespread onshore impacts. These findings demonstrate that anchorage operations constitute a major source of shipping-related pollution, highlighting the need for operational efficiency improvements and meteorologically informed mitigation strategies.

Keywords: Panama Canal; AIS-based ship air emission inventory; anchorage air pollution; air dispersion modeling



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1. Introduction

1.1. Maritime Emissions and Global Context

Maritime transport underpins global trade and supply chains [1,2], and its atmospheric impacts extend from open-ocean climate forcing to near-shore air quality. Beyond

the aggregate contribution of shipping to anthropogenic NO_x and SO_x [3,4], port-proximate activities—including maneuvering, hotelling, and prolonged anchorage—can concentrate emissions immediately adjacent to densely populated coastlines [5], where many monitoring studies have reported elevated $\text{PM}_{2.5}$ and co-pollutants during periods of intense port activity [6–8]. Situating the inquiry within this broader context of coastal chokepoints allows the present work to address both local exposure and generalizable mechanisms.

Fine particulate matter ($\text{PM}_{2.5}$) is of particular concern due to its adverse health effects, including cardiopulmonary diseases and premature mortality [9,10]. Previous work has shown that reductions in marine fuel sulfur content can significantly decrease PM emissions [11,12]. However, emission inventories often rely on average port call times and generalized vessel activity factors [13,14], which may underestimate localized contributions from ships at anchor. These global dynamics highlight the urgency of port- and chokepoint-specific assessments, where local exposures may far exceed global averages.

1.2. AIS-Based Methodologies: Current State and Limitations

The integration of Automatic Identification System (AIS) data has enabled the development of high-resolution, bottom-up emission inventories [4,15], allowing for more accurate estimation of spatially and temporally explicit emissions. Furthermore, the application of atmospheric dispersion models has proven effective in linking shipping-related $\text{PM}_{2.5}$ emissions to population exposure in nearby cities [16,17].

Terrestrial AIS offers superior temporal resolution compared to satellite AIS, capturing anchorage, maneuvering, and short-term operations with updates every few seconds [18–20]. Still, anchorage-specific contributions remain underrepresented in most AIS-based assessments, which frequently apply generalized emission factors without validation against real fuel-consumption records.

Prior port-city studies have leveraged AIS to construct bottom-up ship emission inventories and, in several cases, to simulate near-surface concentrations with regulatory dispersion models. For example, studies at Tianjin developed AIS-based inventories and used localized emission factors with AERMOD to map port-proximate $\text{NO}_x/\text{SO}_2/\text{PM}$ impacts [21,22], while a Bandırma case combined inventory and AERMOD over a $10 \text{ km} \times 10 \text{ km}$ urban domain to identify meteorology-driven variability in ground-level response [23]. Methodological advances have also addressed plume physics and source representation—e.g., parameterizing cruise-ship near-field vertical dispersion [24] and integrating moving ship point sources into urban chemistry–transport systems [25]. Meteorological controls are repeatedly emphasized: port city exchanges during sea–land–breeze conditions have been documented in Kaohsiung and other coastal conurbations, with afternoon sea-breeze enhancing on-shore $\text{PM}_{2.5}$ transport under specific regimes [26,27]. Despite these advances, few studies at maritime chokepoints explicitly isolate anchorage versus underway contributions under representative meteorological classes using continuous, terrestrial AIS in conjunction with high-resolution dispersion.

1.3. Panama Canal as a Case Study

The Panama Canal represents a strategic maritime corridor linking the Atlantic and Pacific, with bidirectional traffic funneled through narrow approaches and lock systems. Queueing, pilotage, and lock-transit schedules can lead vessels to spend extended periods in designated anchorage areas, operating auxiliary and, at times, boiler systems while awaiting passage [28]. These operational realities, together with demand fluctuations and fleet dynamics [2], shape the temporal distribution of emissions and potential on-shore impacts along the metropolitan coastline of Panama City, where more than one million inhabitants may experience exposure [29].

Prior studies have shown that shipping emissions (notably NO_x , SO_2 , and $\text{PM}_{2.5}$) materially degrade air quality in port and coastal urban areas [30]. Although the IMO 2020 sulfur cap has reduced sulfur emissions, residual health burdens remain [12]. Given the proximity of intense shipping activity to densely populated districts along the Panama City shoreline, quantifying onshore impacts from ship emissions is therefore necessary [31].

Existing research has focused primarily on port-related or transit emissions [31], while anchorage-specific contributions remain poorly characterized. This gap is critical given the Canal's tropical meteorology, where sea–land breeze cycles and synoptic southerly flows can transport emissions inland, amplifying exposure risks. Moreover, Panama's context as a developing country underscores the relevance of this case for broader policy transfer: many nations with major maritime facilities face similar constraints in emission monitoring and management.

1.4. Research Objectives and Contributions

Against this background, the present study aims to quantify and assess the impacts of $\text{PM}_{2.5}$ emissions from vessels waiting to transit the Panama Canal. Specifically, we (i) analyze vessel waiting times using AIS data to characterize anchorage behavior, (ii) develop a bottom-up $\text{PM}_{2.5}$ emission inventory distinguishing between underway and anchorage phases, and (iii) evaluate the contribution of ship-sourced $\text{PM}_{2.5}$ to ambient concentrations in Panama City under different meteorological scenarios through atmospheric dispersion modeling. By combining real-world vessel activity data with high-resolution modeling, this study provides the first systematic assessment of the air quality implications of anchorage emissions in the Panama Canal region.

Methodologically, this study advances emission accounting by coupling terrestrial AIS with validated bottom-up estimation and dispersion modeling. Substantively, it provides the first anchorage-specific quantification for the Panama Canal, thereby addressing a critical research gap. From a policy perspective, our findings are expected to inform both national policy and international maritime environmental governance by highlighting the need for targeted emission control strategies in critical chokepoints of global trade.

2. Materials and Methods

2.1. Study Domain

As delineated in Figure 1, the study domain encompasses a 70 km (E–W) $\times$ 50 km (N–S) rectangle centered on the southern entrance of the Panama Canal and the Port of Balboa (8.95° N, 79.57° W). Panama City—the principal population center within the domain—lies along the Pacific coastline (Gulf of Panama) at the foot of low, rolling hills. The local winds are governed by the diurnal sea–land breeze (SLB), background flows, and terrain effects [32,33].

Panama exhibits a tropical savanna climate (Aw, Köppen classification). The seasonal migration of the Intertropical Convergence Zone (ITCZ) delineates dry and wet seasons [34,35]. During the dry season (December–April), the Caribbean Low-Level Jet (CLLJ) accelerates through the low divide of the isthmus, establishing the predominantly northerly Panama Low-Level Jet (PLLJ). In the wet season (April–December), a pronounced diurnal cycle emerges from the coupling between the SLB and the background winds [36–38]. This seasonality modulates dispersion patterns for ship emissions in and around the canal and adjacent ports [39].

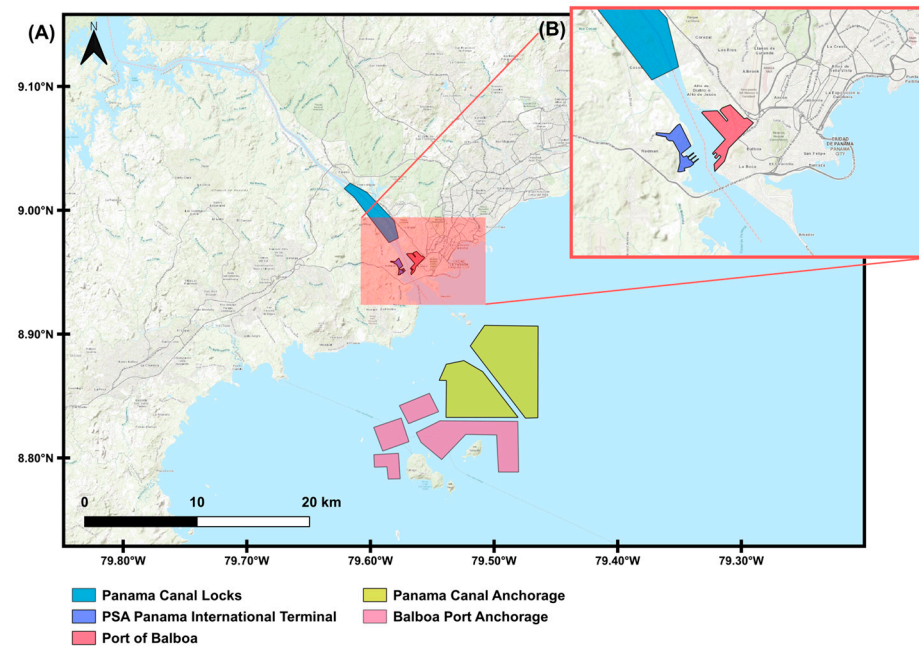


Figure 1. (A) Study area (70 km × 50 km domain), (B) Panama Canal and major densely populated areas.

West of the city center, the canal is flanked by two major terminals—the Port of Balboa and the PSA Panama International Terminal. Previous studies have established that shipping emissions (notably NO_x , SO_2 , and $\text{PM}_{2.5}$) markedly deteriorate air quality in port and coastal urban areas [6]. Although the IMO 2020 sulfur cap has reduced sulfur emissions, residual health burdens persist [12]. Given the proximity of intense shipping activity to densely populated districts along the Panama City shoreline, quantifying onshore impacts from ship emissions remains essential [40].

2.2. Automatic Identification System Data and Processing

The Automatic Identification System (AIS) is a vessel-tracking technology that broadcasts dynamic and static information, including Maritime Mobile Service Identity (MMSI), timestamp, position (latitude, longitude), speed over ground (SOG), course over ground (COG), heading, and navigational status. AIS was originally mandated by the International Maritime Organization (IMO) for safety and collision avoidance purposes but has since become an indispensable data source for shipping emission inventories and marine traffic analysis [41–43].

In this study, AIS data were directly collected using a shore-based receiving system installed and operated by the research team near the Pacific entrance of the Panama Canal, ensuring continuous, high-resolution coverage of vessel activity. The receiving station was established at the Universidad Tecnológica de Panamá, offering reliable coverage within approximately a 40 km radius that included the Pacific anchorage zone. The dataset spanned the period from July 2024 to June 2025, providing complete annual vessel activity data for both anchorage and transit domains. Compared to satellite-based AIS, terrestrial AIS signals offer superior temporal resolution and data density, typically providing updates at intervals shorter than 5 s when vessels are underway and at several minutes when vessels are at anchor. This high-frequency resolution makes shore-based AIS particularly well-suited for port and nearshore studies, where detailed records are necessary to accurately capture anchorage times, maneuvering events, and short-term variations in vessel operations [18,44,45].

The collected dataset contained key variables including the Maritime Mobile Service Identity (MMSI), geographic coordinates (longitude and latitude), speed over ground,

course over ground (COG), navigational status, and timestamps. Quality control procedures were applied to remove erroneous or incomplete records, including duplicated signals, implausible positions on land, speeds exceeding 50 knots, and missing vessel specifications, which were subsequently imputed through regression analysis against gross tonnage [46,47]. The cleaned AIS dataset was resampled to uniform intervals and merged with vessel specifications for emission estimation. In this study, the AIS data were applied to two main analyses: (i) anchorage-time estimation, by tracking vessel position and navigational status, and (ii) emission calculation, by using MMSI-linked specifications, vessel speed, and positional data to determine engine load factors, operational modes, and activity times. In particular, the high-resolution AIS coordinates allowed the generation of detailed spatial emission maps across the Canal region, thereby strengthening the transparency and reproducibility of the emission inventory.

2.3. AIS-Based Approach for Vessel Waiting Time Estimation in Panama

This study focused on vessels anchoring south of the Panama Canal while awaiting Canal transit clearance or port cargo handling operations, rather than simply stationary ships. To extract these waiting events from the AIS dataset, a combined filter of navigational status (*nav_status*) and speed over ground (SOG) was applied. While *nav_status* = 1 (“At anchor”) generally denotes anchorage, this field is manually set by crew members and is frequently inconsistent. Thus, records with *nav_status* $\in$ {0, 8, 15} were also classified as waiting whenever $\text{SOG} \leq 0.7$ kn, reflecting minimal motion typical of anchorage conditions [41,48,49].

To ensure that only vessels anchored for operational reasons were included, a polygonal anchorage boundary was delineated around the designated waiting zones south of the Canal, slightly extended based on repeated observations of ships queuing outside the official limits. Only AIS records within this polygon and satisfying the status–speed criteria were retained, thereby excluding through-passing traffic [43].

Waiting times were computed on a voyage-call basis, grouping AIS records by MMSI, sorting chronologically, and linking them into waiting periods until Canal entry or port operations commenced. If the time gap between consecutive AIS messages exceeded two hours, the previous call was closed and a new call was defined [49,50]. For each voyage call, waiting duration was measured as the difference between the first and last AIS timestamp. Ship-level (total waiting time, number of calls) and temporal (monthly) statistics were then derived. Data cleaning removed duplicates, implausible speeds, and position jumps before calculation, following AIS best-practice protocols [51].

Through this integrated spatial–behavioral filtering and voyage-based segmentation, a robust dataset of waiting vessels was established. This dataset forms the foundation for assessing anchorage-related emissions and their subsequent air quality impacts in the Panama Canal region.

2.4. AIS-Based Ship Emission Estimation

Ship emissions were estimated using a bottom-up, activity-based (Tier 3) methodology consistent with IMO and U.S. EPA guidance, which integrates AIS-derived activity data, vessel technical specifications, engine load estimation, and pollutant-specific emission factors (EFs). The computational framework (Figure 2) was implemented using the Portal Air Quality Management (PAQman©) system, a comprehensive maritime emission inventory platform developed by the Air/Climate Group at Incheon National University. The PAQman© system has been applied and validated across multiple port environments, including comparative studies that have demonstrated substantial discrepancies between fuel-based and activity-based inventories [21,52]. Through adopting standardized IMO/EPA proce-

dures while accommodating region-specific parameters, the PAQman© framework ensures transparent and reproducible emission estimates that are suitable for high-resolution dispersion modeling and policy applications. The pollutants considered were PM₁₀, PM_{2.5}, SO₂, NO_x, and CO₂. Emissions were calculated for main engines (ME) and auxiliary engines (AE), while boilers were excluded due to the absence of standardized methodologies and operational data [53]. AIS data were collected between July 2024 and June 2025 and included MMSI, timestamp, vessel position, and speed over ground (SOG). Vessel specifications, such as rated engine power, maximum design speed, and engine type, were obtained from the S&P Global Marine Database.

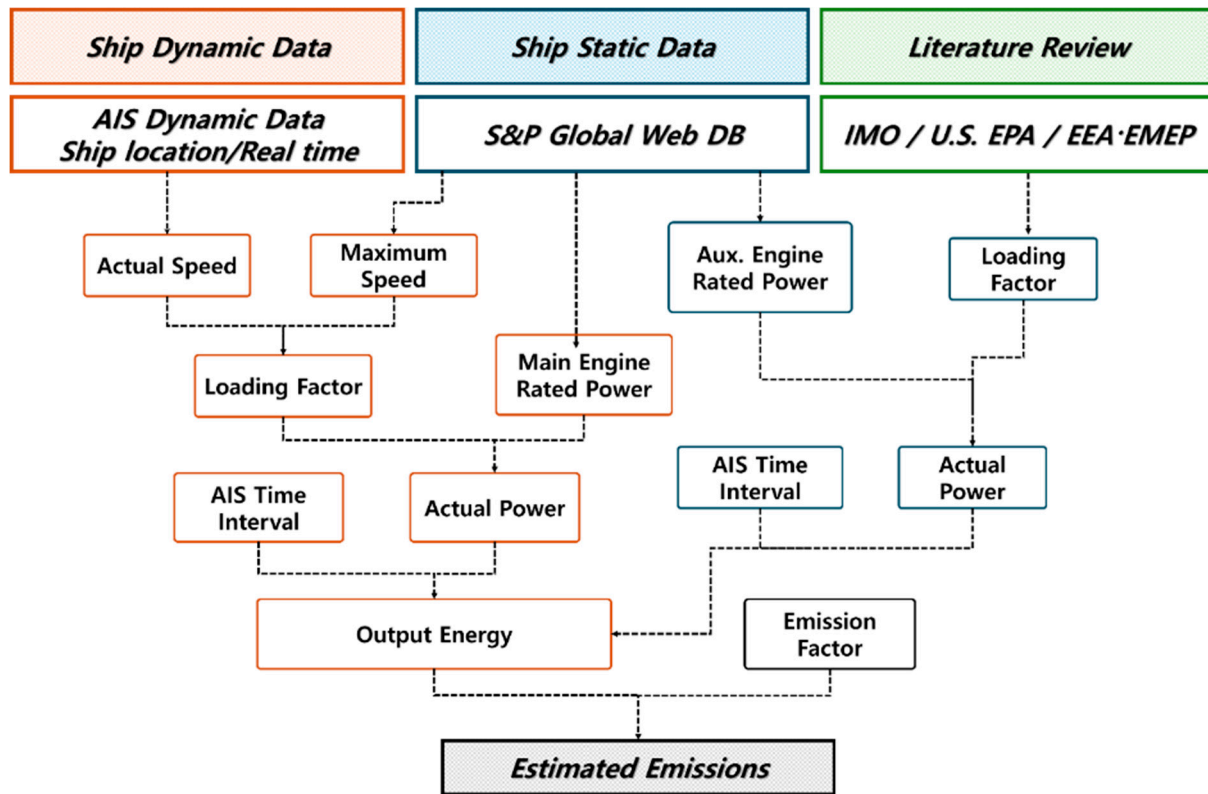


Figure 2. Flow diagram illustrating AIS-based methodology for ship emission estimation.

Main engine (ME) load and emissions

For main engines, load factors (LF) were calculated as a cubic function of vessel speed relative to design speed [54,55]:

$$LF_t = \left(\frac{V_t}{V_{max}} \right)^3 \quad (1)$$

$$P_{ME,t} = P_{rated,ME} \times LF_t \quad (2)$$

Fuel consumption of the main engine was then derived as:

$$FC_{ME,t} = P_{ME,t} \times SFC_{ME} \quad (3)$$

Emissions from the main engine were calculated as:

$$E_{i,ME,t} = P_{ME,t} \times EF_{i,ME/(g/kWh)} \times \Delta t \quad (4)$$

or alternatively,

$$E_{i,ME,t} = FC_{ME,t} \times EF_{i,ME/(g/kg \text{ fuel})} \times \Delta t \quad (5)$$

Parameters:

V_t : vessel speed at time t (kn);
 V_{max} : vessel maximum speed (kn);
 LF_t : main-engine loading factor (unitless);
 $P_{rated,ME}$: rated main-engine power (kW);
 $P_{ME,t}$: main-engine operating power at time t (kW);
 SFC_{ME} : specific fuel consumption of ME (g/kWh);
 FC_{ME} : fuel consumption (g);
 $EF_{i,ME}$: emission factor for pollutant i (g/kWh or g/g fuel);
 Δt : time interval between consecutive AIS records (h);
 $E_{i,ME,t}$: emissions of pollutant i from ME over Δt (g).
 Depending on whether energy-based or fuel-based factors were applied.

Auxiliary engine (AE) load and emissions

Auxiliary engines were assumed to operate at constant loads depending on vessel operational mode (anchorage, maneuvering, cruise). To clarify, the parameters used in the emission equations were derived from established guidelines. For main engines, specific fuel consumption (SFC) values were obtained from IMO technical references, with 185–195 g/kWh for two-stroke slow-speed engines and 200–210 g/kWh for four-stroke medium-speed engines [56]. For auxiliary engines, SFC values of 215–225 g/kWh were applied based on IMO defaults [56]. Load factors (LF) were assigned by operational mode following international guidelines: anchorage (hotelling) at 0.20–0.40, consistent with IMO and EMEP/EEA recommendations [56,57]; maneuvering at 0.50; and cruising at 0.80, both from EMEP/EEA [57]. These values are summarized in Table 1, and were directly applied in the calculation of engine loads and subsequent emissions for each vessel activity mode. The auxiliary engine power demand was expressed as:

$$P_{AE,t} = P_{rated,AE} \times LF_{AE, mode} \quad (6)$$

where $LF_{AE, mode}$ is the mode-specific load factor (e.g., hotelling/anchorage, maneuvering, cruising).

The corresponding fuel consumption was estimated as:

$$FC_{AE,t} = P_{AE,t} \times SFC_{AE} \quad (7)$$

Auxiliary engine emissions were then calculated as:

$$E_{i,AE,t} = P_{AE,t} \times EF_{i,AE}/(\text{g/kWh}) \times \Delta t \quad (8)$$

or alternatively,

$$E_{i,AE,t} = FC_{AE,t} \times EF_{i,AE}/(\text{g/kg fuel}) \times \Delta t \quad (9)$$

Parameters:

$P_{rated,AE}$: rated auxiliary-engine power (kW);
 $LF_{AE, mode}$: mode-specific AE loading factor (unitless);
 $P_{AE,t}$: auxiliary-engine power at time t (kW);
 SFC_{AE} : specific fuel consumption of AE (g/kWh);
 $FC_{AE,t}$: fuel consumption (g);
 $EF_{i,AE}$: emission factor for pollutant i (g/kWh or g/g fuel);
 Δt : time interval between consecutive AIS records (h);
 $E_{i,AE,t}$: emissions of pollutant i from AE over Δt (g).

Aggregation

Total annual emissions for pollutant i were obtained as the sum of ME and AE contributions across all vessels and time steps:

$$E_{i,annual} = \sum_{j=1}^N \sum_{t=1}^T (E_{i,ME,j,t} + E_{i,AE,j,t}) \quad (10)$$

In this study, pollutant-specific emission factors (EFs) were applied for both main and auxiliary engines, as summarized in Table 2. For nitrogen oxides (NO_x), a range of 2.6–17.0 g/kWh for main engines and 2.0–13.8 g/kWh for auxiliary engines was adopted, reflecting the variation across engine types and operating conditions reported in IMO and EPA guidelines. Sulfur dioxide (SO₂) factors were adjusted to reflect the IMO 2020 global sulfur cap of 0.5% m/m fuel sulfur content, expressed as a function of specific fuel consumption (SFC), sulfur fraction (FSC), and molecular weight ratio (MWR) [12]. For particulate matter, baseline values were scaled by engine-specific activity factors, with PM_{2.5} assumed to constitute 92% of PM₁₀ in line with international recommendations. Carbon dioxide (CO₂) was calculated using a fuel-based factor of 3.206 g-emission/g-fuel, consistent with stoichiometric carbon oxidation [56,58].

Table 1. Specific fuel consumption (SFC) and auxiliary engine load factors applied in this study [56,57].

Engine Type/Mode	Fuel Type	SFC (g/kWh)	Loading Factor (LF)
Main engine (2-stroke, slow-speed)	HFO	185–195	$LF_t = \left(\frac{V_t}{V_{max}}\right)^3$
Main engine (4-stroke, medium-speed)	HFO/MDO	200–210	
Auxiliary engine— Anchorage (hotelling)	MDO/MGO	215–225	0.20–0.40 [IMO, EMEP/EEA]
Auxiliary engine— Maneuvering	MDO/MGO	215–225	0.50 [EMEP/EEA]
Auxiliary engine— Cruising	MDO/MGO	215–225	0.80 [EMEP/EEA]

Table 2. Emission factors (EFs) applied in this study [56–58].

Pollutant	EF (g/kWh) Main Engine	EF (g/kWh) Auxiliary Engine	EF (g/kg Fuel)
NO _x	2.6–17.0	2.0–13.8	
PM ₁₀	$PM_{base} + (S_{act} \times SFC \times FSC \times MWR)$		
PM _{2.5}	$EF_{PM_{10}} \times 0.92$		
SO ₂	$SFC \times S_{act} \times FSC \times MWR$		
CO ₂			3.206

The final emission inventory is reported as a comprehensive dataset that describes pollutant-specific totals, distinguishes emissions generated by vessels at anchor from those during active transit, and provides an overall annual total for all operational phases in the Panama Canal region.

2.5. Atmospheric Dispersion Modeling

2.5.1. Meteorology Analysis

We analyzed hourly 10-m winds at Albrook International Airport (ICAO: MPMG; 8.967° N, 79.550° W) from 1 July 2024 to 30 June 2025 (local time, LT) to identify meteorological regimes that modulate onshore dispersion of ship-derived pollutants [59].

MPMG is situated on relatively open terrain; while a roadway passes nearby, the anemometer's open exposure and our use of multi-hour directional coherence (MRL) reduce sensitivity to short-lived micro-scale perturbations. For geographic context, straight-line distances from MPMG to key maritime nodes in our domain are ≈ 2.0 km to the Balboa berths (port area), ≈ 5.5 km to the Miraflores Locks, and ≈ 10.2 km to the primary Pacific anchorage centroid.

Under typical 10 m wind speeds of $2\text{--}6\text{ m s}^{-1}$, these separations imply advection time scales on the order of 15–85 min, which guided our interpretation of phase locked peaks at coastal receptors under SLB and SW.

After filling in missing values using linear interpolation, wind vectors were decomposed into zonal (u) and meridional (v) components.

$$u(t) = -W_s(t) \sin\theta_{\text{from}}(t), \quad v(t) = -W_s(t) \cos\theta_{\text{from}}(t) \quad (11)$$

To emphasize diurnal variability, a 24-h moving mean (denoted by an overbar) was removed from each component,

$$uu_B(t) = u(t) - \bar{u}(t; 24\text{ h}), \quad vv_B(t) = v(t) - \bar{v}(t; 24\text{ h}), \quad (12)$$

Yielding the band-pass amplitude and direction

$$W_{s,B}(t) = \sqrt{u_B^2(t) + v_B^2(t)}, \quad \theta_{\text{from}, B}(t) = \text{atan2}(-u_B(t), -v_B(t)) \text{ (deg)}. \quad (13)$$

We classified days into three regimes:

- (i) sea–land breeze (SLB)
- (ii) ensemble-like (EL; the canonical year-round pattern)
- (iii) southerly wind (SW).

For SLB detection, following Kim & Kang (2020)'s methodology [60], we removed the 24 h moving mean to isolate diurnal variability (u_B, v_B). A day was labeled SLB when daytime sea-breeze conditions (southerly sector; 11–17 LT) persisted for ≥ 3 h and nighttime land-breeze conditions (northerly sector; 23–05 LT) persisted for ≥ 3 h.

$$\text{Sea breeze : } 11 - 17 \text{ LT, } \theta_{\text{from}, B} \in [90^\circ, 210^\circ]$$

$$\text{Land breeze : } 23 - 05 \text{ LT, } \theta_{\text{from}, B} \in [270^\circ, 30^\circ]$$

$$\text{Wind speed : } W_{s,B} \geq 0.5 \text{ m s}^{-1}$$

The EL regime captures the canonical Panama pattern. We first constructed a 'reference ensemble' by averaging wind vectors by hour of day over the full year. A day was labeled EL when the cosine similarity between its diurnal vector sequence and the reference exceeded 0.8 and the circular RMSE was $\leq 45^\circ$. These thresholds follow established practice and were selected empirically [61–63].

$$\cos(x, y) = \frac{x \cdot y}{||x|| ||y||}, \quad \text{RMSE}_O = \sqrt{\frac{1}{n} \sum_{i=1}^n [((\alpha_i - \beta_i + 180) \bmod 360) - 180]^2} \quad (14)$$

The SW regime, expected to yield the strongest onshore transport, was defined by a daily-mean wind direction between 135° and 225° and a mean resultant length (MRL) ≥ 0.4 , indicating directional coherence.

Regime labels are used (i) to construct ensemble diurnal cycles and quiver plots for interpretation, (ii) as meteorology classes to drive GRAMM/GRAL dispersion runs, and (iii) to anticipate on-shore vs. off-shore transport and receptor-point peaks (e.g., afternoon

fumigation during SLB) [39,64]. For each regime, all assigned days were ensemble-averaged to build a representative 96 h sequence for dispersion modeling.

Parameters:

$W_s(t)$: 10 m wind speed (m/s);
 $\theta_{\text{from}}(t)$: meteorological “from” direction (degrees, range 0–360°);
 $u(t), v(t)$: wind-vector components (m/s);
 $\bar{u}(t; 24 \text{ h}), \bar{v}(t; 24 \text{ h})$: 24 h moving averages of wind-vector components;
 $u_B(t), v_B(t)$: band-pass-like (detrended) components emphasizing diurnal variability;
 x, y : diurnal vector sequences (e.g., concatenated hourly $[u_B, v_B]$ vectors over a single day);
 α_i, β_i : paired directional angles (degrees) derived from both sequences at hour i ;
 n : number of hourly samples in the diurnal sequence;
 $\text{MRL} = \sqrt{[(\sum \cos\theta)^2 + (\sum \sin\theta)^2]/n} \in [0,1]$, quantifying directional coherence (higher values indicate greater coherence).

All trigonometric functions utilize angles in degrees, consistent with established directional conventions.

2.5.2. Air Dispersion Modeling

We used the GRAMM/GRAL modeling system (GRAMM: Graz Mesoscale Model; GRAL: Graz Lagrangian Model) developed at Graz University of Technology to simulate mesoscale flow and pollutant dispersion over complex coastal/urban terrain. GRAMM/GRAL resolves local wind-field variations induced by complex coastlines and urban structures, and GRAL’s Lagrangian particle dispersion capabilities in complex topography have been validated in several studies [65–69].

GRAMM is a prognostic, non-hydrostatic mesoscale model that solves the Reynolds-averaged conservation equations for momentum, mass, potential temperature, and humidity, with turbulence parameterization (standard k – ϵ or algebraic forms) on terrain-following grids. Lower-boundary fluxes follow Monin–Obukhov similarity (uses friction velocity u_* and Obukhov length L), and a radiation/surface energy module represents short/longwave fluxes and soil heat exchange. GRAMM is typically run in quasi-steady “categorized” meteorology and can be initialized from a single surface station with stability class or from profile/point observations; large-scale forcing is introduced via geostrophic winds and boundary nudging. These steps are iterated with pressure-correction to enforce mass continuity, producing 3D wind fields for dispersion.

GRAL is a 3D Lagrangian particle model that advances many fictitious particles along trajectories composed of the mean wind ($\bar{u}_i$) plus a stochastic turbulent fluctuation (u'_i) at each time step; it supports steady/transient runs across all stability regimes and very low wind speeds. Micro-scale effects from buildings and vegetation (downwash, flow blockage) are handled by an embedded micro-flow module; dry/wet deposition and sedimentation are available, while atmospheric chemistry is not treated. Typical horizontal grid spacing is meters to tens of meters.

For complex terrain without buildings, 3D winds and stability fields computed by GRAMM are interpolated onto GRAL’s Cartesian grid with an internal mass conserving procedure, ensuring zero net flux through each control volume; when coupled, GRAL directly imports GRAMM’s flow fields for dispersion.

For the 70 km $\times$ 50 km domain, both GRAMM and GRAL used a 500 m horizontal grid. For each meteorological regime (SLB, EL, SW), we generated a regime-specific wind field and ran two emission scenarios: (i) all-sailing (all AIS-attributed vessel emissions) and (ii) anchorage-only (vessels identified as at anchor). This design isolates the onshore contribution of anchorage emissions relative to total shipping. Following prior applications

and STEAM3 vertical profiles, we used an effective emission height of 36 m for ship sources [53,70].

Terrain was represented by SRTM 1-arc-second DEM [71] and land cover by the 2021 national dataset [72]. Given the 500 m grid resolution, building and vegetation heights were not explicitly represented.

The emission inventory was derived from PAQman, our AIS-based bottom-up system developed at Incheon National University (details in Section 2.4).

For this study, we focused on emissions from vessels within the canal approaches whether underway or at anchor and simulated dispersion for primary $PM_{2.5}$, analyzing ground-level (5 m) concentrations. Each regime simulation covered 96 h; to minimize spin-up effects, we excluded the first 24 h and analyzed the subsequent 72 h. We performed six model runs in total (3 regimes $\times$ 2 scenarios). The end-to-end workflow is illustrated in Figure 3.

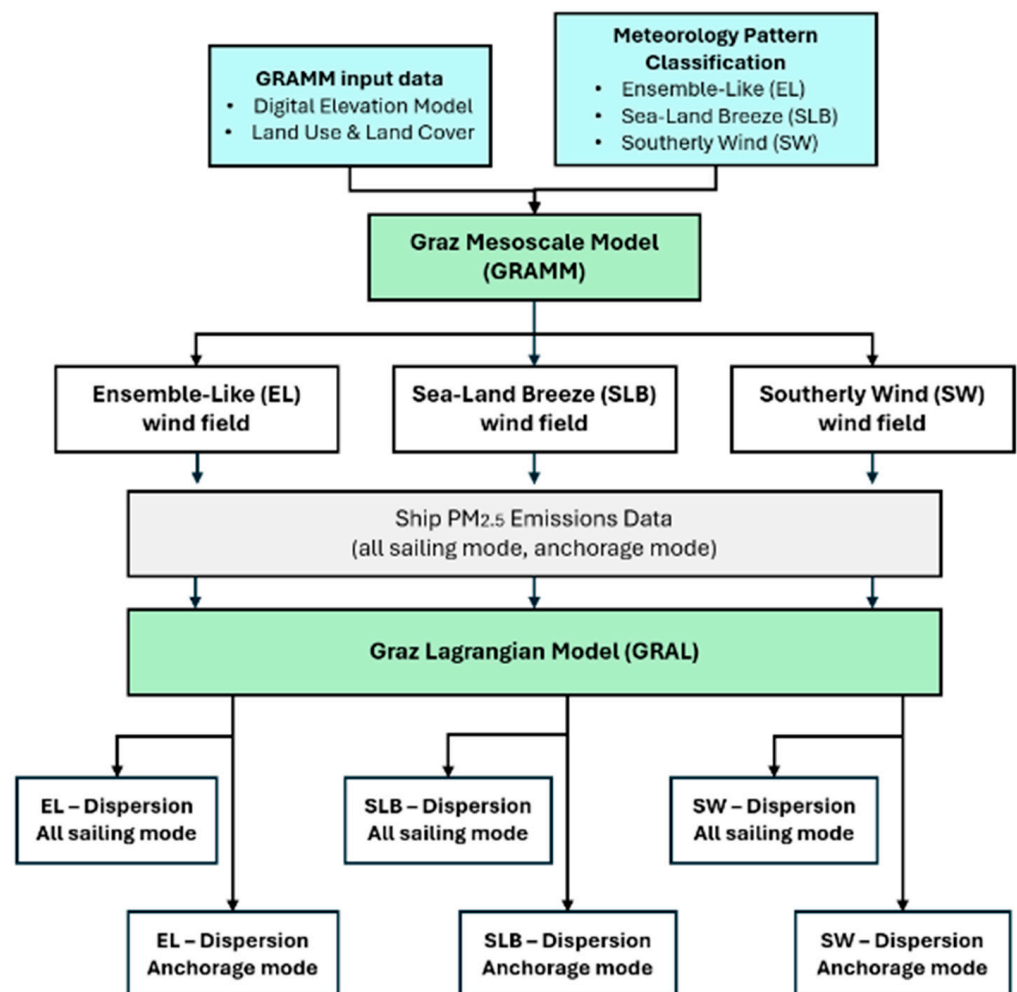


Figure 3. Modeling Pipeline Flowchart.

3. Results

3.1. AIS Data Collection and Processing

To collect AIS data of vessels navigating the Pacific side of Panama, a terrestrial AIS receiving system was installed at the Panama Technological University in Panama City. This system enabled the acquisition of high spatiotemporal resolution AIS signals, which were directly utilized in this study. The monitoring campaign covered a full year, from July 2024 to June 2025, yielding a total of 50,353,520 AIS records. Using the in-house algorithm

described in Section 2.3, we identified and extracted records associated with vessels at anchorage, resulting in 9,718,703 data points. The geospatial information (latitude and longitude) embedded in the AIS messages was processed and visualized in QGIS. To further examine vessel traffic density, a kernel density estimation (KDE) function was applied to generate density maps. As illustrated in Figure 4a–d, both raw AIS positions and KDE density maps cluster at designated anchorages, port berths, and Canal approaches;

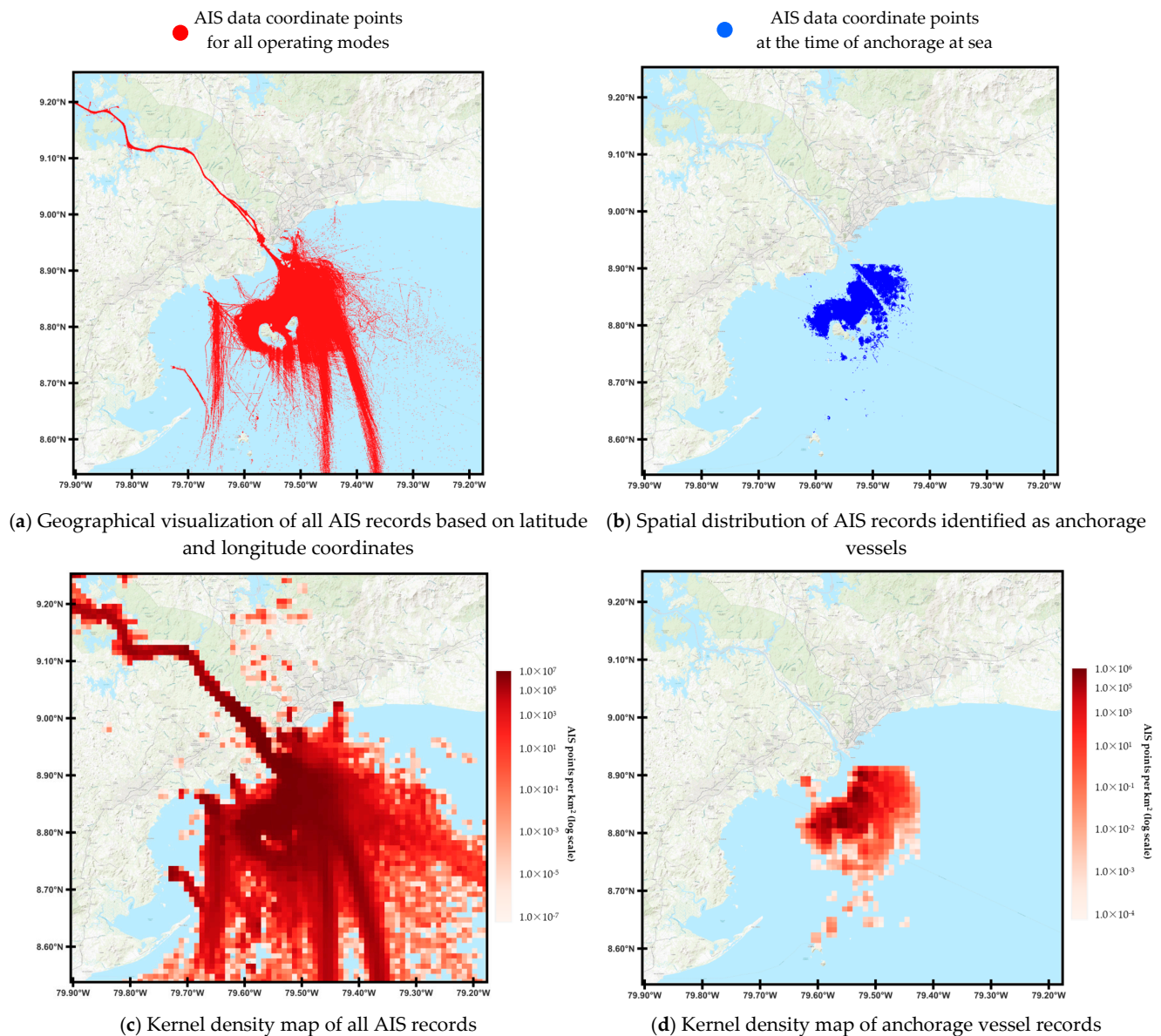


Figure 4. Spatial distribution and density of AIS data collected in the Pacific side of Panama. Density values are displayed on a logarithmic color scale. Darker shades correspond to disproportionately higher vessel densities concentrated at anchorage zones, port berths, and Canal approaches.

3.2. Vessel Waiting Time Analysis in Panama

Although the initial objective of this study was to quantify the waiting times of vessels queuing for Panama Canal transit, the Automatic Identification System (AIS) data did not allow clear separation between canal-related waiting and anchorage associated with port entry. Therefore, the analysis was conducted for all vessels observed within the defined anchorage domain, encompassing both canal users and vessels calling at nearby ports. To identify anchorage episodes, we applied an in-house AIS algorithm that combined navigational status codes with speed-over-ground thresholds (≤ 0.7 kn)

within the predefined anchorage polygon. Consecutive stationary records were grouped into episodes using a 2 h continuity rule, from which episode durations were calculated. This approach enabled consistent estimation of anchorage times despite occasional gaps, reporting noise, or misclassified status codes.

A total of 4725 vessels were recorded during the one-year observation period, of which 4641 remained after quality control and error removal. Aggregating all waiting episodes, the mean annual waiting time was calculated as 15.01 h, whereas the median value was only 4.94 h. This discrepancy underscores the asymmetric nature of the distribution, with a large number of short waiting periods and a small number of extremely long events that disproportionately elevate the mean.

The distribution of waiting times confirms that short events dominate in terms of frequency. Episodes lasting less than 6 h represented nearly half of the dataset, while those shorter than 24 h accounted for over 80% of all events. Nevertheless, their cumulative contribution was limited to only 30.5% of total waiting time. Conversely, the 19.7% of episodes that extended beyond 24 h were responsible for 69.5% of the accumulated time, illustrating the decisive influence of relatively rare but prolonged delays.

As detailed in Table 3, short events dominate by frequency: episodes < 6 h account for nearly half of all cases, whereas the ≥ 48 h class is only 7.2% yet contributes 46.8% of total waiting hours.

Table 3. Frequency and contribution of waiting episodes by duration class.

Duration Class (h)	Share of Events (%)	Share of Waiting Time (%)
0–6	46.7	5.6
6–24	33.6	24.9
24–48	12.5	22.7
48–72	4.5	18.5
>120	2.7	28.3

The longest individual episode exceeded 1000 h, and the top ten events all lasted more than 500 h. Such cases were largely associated with tankers and bulk carriers, often remaining at anchorage while awaiting canal slots, conducting bunkering operations, or completing paperwork and inspections. These activities generated extended waiting episodes lasting several hundred hours.

When considering cumulative waiting time by vessel, the inequality becomes even more apparent. The top five vessels each accumulated more than 6000 h of waiting during the year, equivalent to over 200 days. While these vessels also experienced numerous short episodes, their overall burden was driven by repeated multi-day delays. Once again, tankers and bulk carriers were the dominant contributors.

The distribution can also be examined through percentile thresholds. As summarized in Table 4, the 90th percentile corresponded to 38.48 h, meaning that 90% of all episodes were resolved within that duration. Yet, this upper decile alone accounted for 54.85% of total waiting time. The 95th percentile was 60.92 h, representing 39.01% of cumulative hours, while the longest 1% of episodes (≥ 142.52 h) still accounted for 15.81% of total waiting time. These statistics underscore that system-level waiting time is largely determined by a small set of extreme events.

Table 4. Statistical summary of waiting times.

Indicator	Value (h)	Share of Total Waiting Time (%)
Mean	15.01	–
Median	4.94	–
90th percentile	38.48	54.85
95th percentile	60.92	39.01
99th percentile	142.52	15.81

Finally, we evaluated vessel-type differences by aggregating average and total waiting times per ship category (Table 5); the overall distribution of waiting durations, including tail behavior, is summarized in Table 4. Tankers and bulk carriers not only exhibited the longest waiting times and the highest cumulative total consistent with their reliance on bunkering, cargo handling, and canal transit but also frequently remained at anchorage for extended periods due to offshore cargo transfer or transshipment operations. These maritime activities commonly occur at anchorage, where shoreside electrical power is unavailable. The absence of shore power necessitates the use of onboard generators, which complicates both energy management and emissions control, thereby increasing vulnerability in operational oversight and environmental impact mitigation [73,74].

Table 5. Average and total annual waiting times by vessel type in the Panama Canal anchorage area.

Ship Type Group	Total_Wait_Hours	Avg_Episode_Hours
Bulk Carrier	54,685	35.40
Chemical Tanker	74,394	29.01
Container Ship	44,507	11.80
Cruise	1.76	1.76
Dredging	5537	17.41
Fishing	7448	20.64
General Cargo	15,875	21.07
Liquefied Gas Tanker	39,854	22.24
Oil Tanker	122,632	19.18
Other	10,409	17.49
Other Tanker	14,238	29.49
Passenger	507	6.03
Refrigerated	8283	16.63
RoRo	12,218	50.49
Tugs	15,274	23.05
Yacht	4289	22.70

Overall, the analysis reveals a dual structure in waiting patterns: a majority of short episodes with negligible cumulative effect, and a small number of extreme cases that dominate total waiting time. This duality suggests that average values alone cannot capture the operational reality; instead, management strategies should specifically identify and target long-duration events and high burden vessels. Such an approach is essential not only for improving traffic efficiency but also for mitigating the environmental impacts associated with extended anchorage periods.

3.3. AIS-Based Ship Emission in Panama

The estimated annual emissions for the study period are summarized in Table 6; waiting (anchorage) activities contributed a considerable share across pollutants 34–36% despite lower engine loads than during transit.

Table 6. Annual ship emissions in the Panama Canal (July 2024–June 2025) by pollutant and operational mode.

Pollutant	All Sailing Emissions (kg)	Waiting Emissions (kg)	Waiting Contribution (%)
CO ₂	1.39×10^9	4.97×10^8	36
NO _x	2.05×10^7	7.01×10^6	34
SO ₂	4.25×10^6	1.52×10^6	36
PM ₁₀	6.56×10^5	2.32×10^5	35
PM _{2.5}	6.03×10^5	2.14×10^5	35

Consistent with Table 6, CO₂ dominates the inventory (1.39×10^9 kg while sailing and 4.97×10^8 kg while waiting; 36% waiting share), with similar one-third contributions from waiting for NO_x, SO₂, and PM species. Nitrogen oxides (NO_x) amounted to 2.05×10^7 kg in sailing and 7.01×10^6 kg in waiting mode, with the waiting share reaching 34%. Sulfur dioxide (SO₂) exhibited a similar pattern, with annual totals of 4.25×10^6 kg (sailing) and 1.52×10^6 kg (waiting), corresponding to a 36% waiting contribution. For particulate matter, the emissions were 6.56×10^5 kg and 2.32×10^5 kg for PM₁₀, and 6.03×10^5 kg and 2.14×10^5 kg for PM_{2.5}, with waiting shares of 35% in both cases.

These results underscore that, despite the lower engine loads compared with sailing, waiting activities represent a considerable fraction of annual emissions. The relatively consistent contribution of waiting mode across pollutants (approximately one-third of the total) emphasizes the importance of anchorage-related operations in shaping the overall emission profile of the Panama Canal region.

To generate spatial emission distributions, vessel-level emissions calculated from PAQ-man© were mapped to a 1 km × 1 km grid covering a 45 km radius from the receiving station at Universidad Tecnológica de Panamá. This spatial domain encompassed the Canal entrance and approaches, major anchorage points, and adjacent port areas of Panama City. Each AIS message contained a vessel position, and emissions computed for that time step were directly assigned to the corresponding grid cell. Annual emission totals were then aggregated for the full observation period (July 2024–June 2025). Hotspot grids were identified by ranking all non-empty cells and extracting the top 10%, 5%, and 1% by total emissions out of 6480 populated cells. The algorithm was implemented using in-house Python 3.8 scripts for data processing and QGIS for visualization. This procedure ensured that the reported hotspot patterns directly reflect the high-resolution spatiotemporal dynamics of vessel operations captured by the AIS dataset. Figure 5 summarizes PM_{2.5} as a representative pollutant: (a) highlights the top 1% high-emission grids in all-sailing mode, (b) shows the waiting-mode PM_{2.5} map, and (c–d) depict cumulative shares from the top 5% and 10% grids; CO₂, NO_x, SO₂, and PM₁₀ show similar spatial patterns

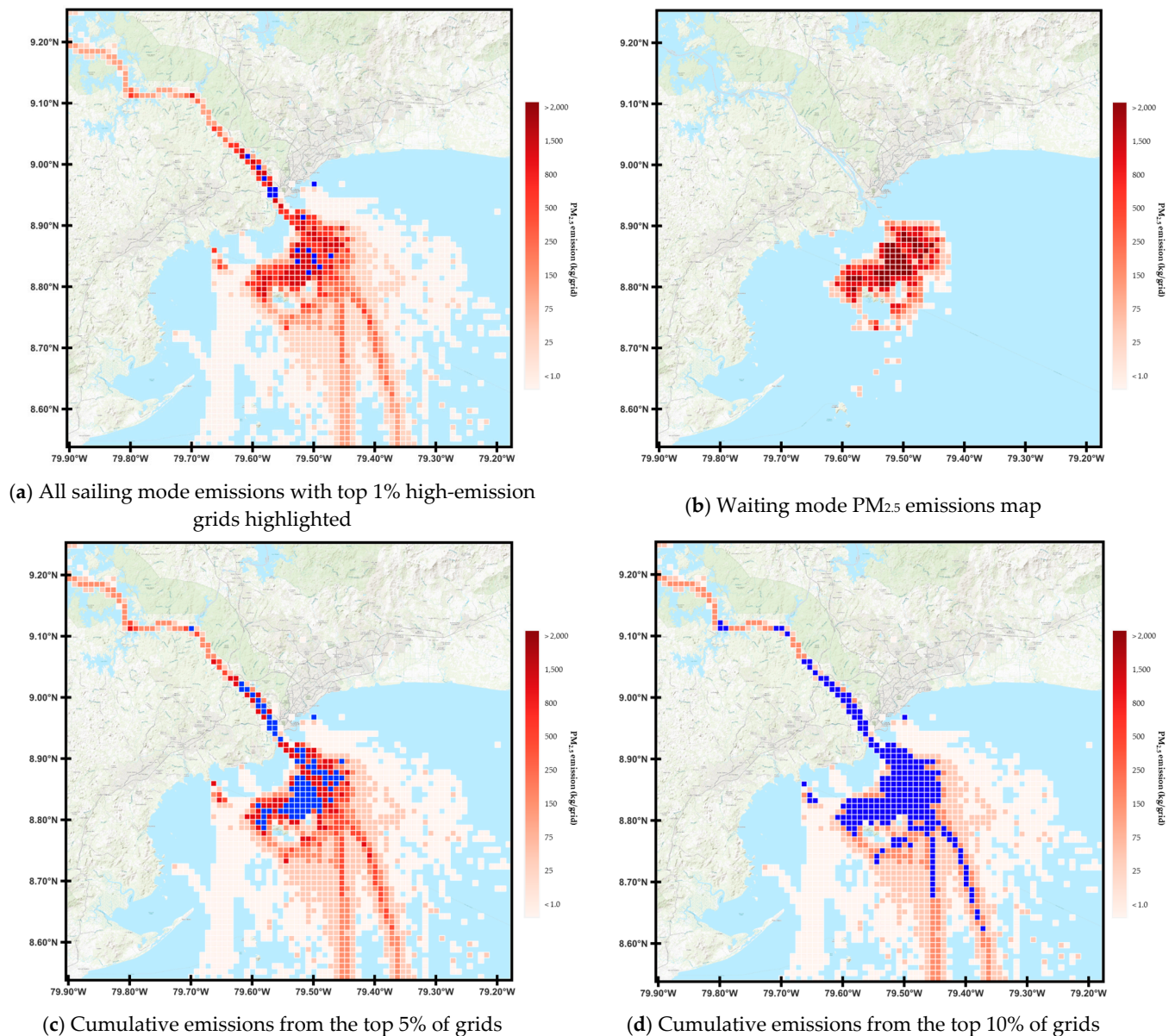


Figure 5. Concentration of annual PM_{2.5} emissions within high-emission grids in the Panama Canal (July 2024–June 2025). Blue grids highlight the top 1%, 5%, and 10% of emission grids, respectively, indicating the most concentrated hotspots of vessel-related emissions.

The total annual PM_{2.5} emissions amounted to 6.03×10^5 kg. However, the distribution was markedly uneven, with a limited number of cells dominating the total burden. The top 5% of emission grids accounted for 4.41×10^5 kg, representing 75% of the total PM_{2.5} emissions, while the top 10% of grids contributed approximately 90%. This pronounced spatial concentration was consistently observed across all pollutants.

The high-emission grids were predominantly located in (i) offshore anchorage zones near the Pacific entrance (Balboa Anchorage Area), where vessels frequently remain at anchor awaiting Canal transit; (ii) alongside berthing terminals in Balboa and Cristóbal Ports, where cargo handling operations are conducted; and (iii) the immediate vicinity of the Gatun and Miraflores Locks, where vessels must decelerate or remain stationary during lockage procedures. A common operational feature of these hotspots is that ships operate at very low speeds or remain in a stationary condition for prolonged periods. Under such conditions, propulsion engines are either idled or shut down, and the majority of emissions

originate from auxiliary engines supplying onboard electrical and hotelling demands. Consequently, emissions from these localized operating modes disproportionately shape the overall spatial profile of the Canal.

This quantile-based analysis establishes that, despite the continuous fuel consumption during transit, the greatest share of emissions is concentrated in grid cells associated with low-speed or stationary operations. The pronounced contribution of anchorage and lock-related activities suggests that potential exposure risks are geographically localized, particularly around the Pacific entrance and urbanized areas adjacent to Balboa, whereas sailing activities yield a more diffuse but less concentrated emission footprint along the navigational channel.

3.4. Analysis of Meteorological Characteristics and Dispersion Modeling

Prevailing winds are northwesterly under the influence of the PLLJ. Following the classification in Section 2.5.1, we computed ensemble-mean quiver plots for each regime (Figures 6 and 7: wind-rose and EL/SLB/SW quiver patterns).

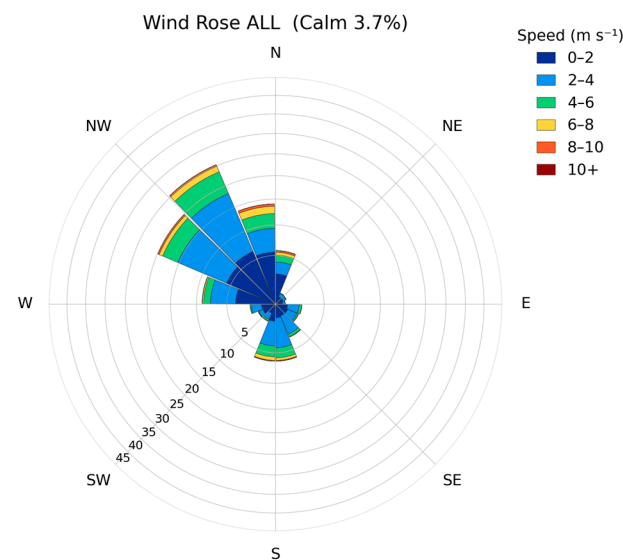


Figure 6. Yearly ensemble averaged wind rose (1 July 2024 to 30 June 2025).

Based on one year of observations, we classified three representative patterns for Panama City: Ensemble-Like (EL, 31.0%), Sea–Land Breeze (SLB, 32.1%), and Southerly Wind (SW, 8.8%). We then applied these representative meteorological conditions in GRAMM/GRAL to simulate the spatiotemporal dispersion of ship-emitted $PM_{2.5}$ near the canal and quantify onshore impacts, under both anchorage-only and all-sailing scenarios.

The regime shares are not mutually exclusive because the SLB is a diurnal circulation superimposed on the larger-scale background flow. For instance, a day classified as EL (characterized by a dominant northwesterly background flow) can simultaneously exhibit the distinct diurnal patterns of an SLB cycle. This reflects the high frequency of SLB embedded within the dominant NW flow, consistent with previous sea-breeze literature and canal-vicinity wind analyses [39,75].

Under EL (the most frequent regime), the NW-mean flow driven by the PLLJ transports most anchorage emissions southwestward over the Gulf, yielding negligible direct impacts across central Panama City (Figure 8). In contrast, in the all-sailing case (Figure 9), emissions along the canal approach/berthing channels produce localized coastal peaks near Balboa–Ancón—suggesting persistent exposure potential in port-adjacent neighborhoods even when the prevailing flow points seaward [76–78].

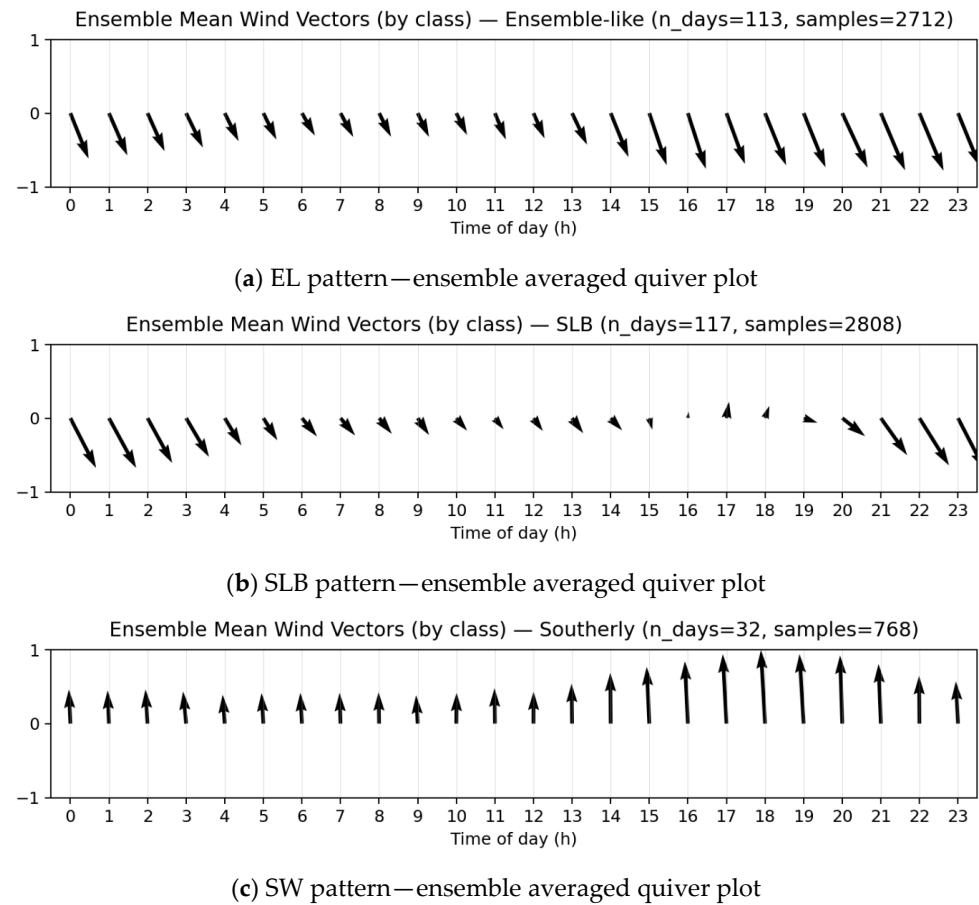


Figure 7. Ensemble-averaged quiver plots illustrating EL, SLB, and SW wind field patterns in Panama. The direction of the arrow indicates the wind direction, and the length of the arrow indicates the relative wind speed.

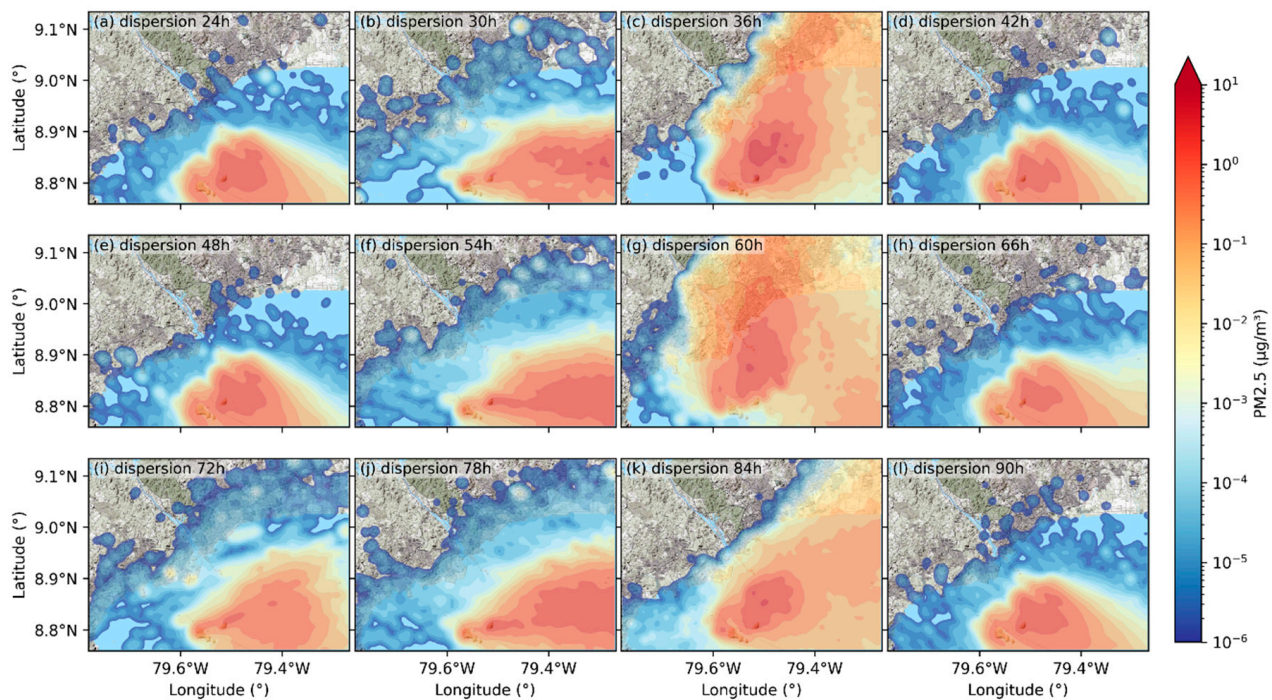


Figure 8. EL pattern—PM_{2.5} Emission Dispersion (anchorage mode).

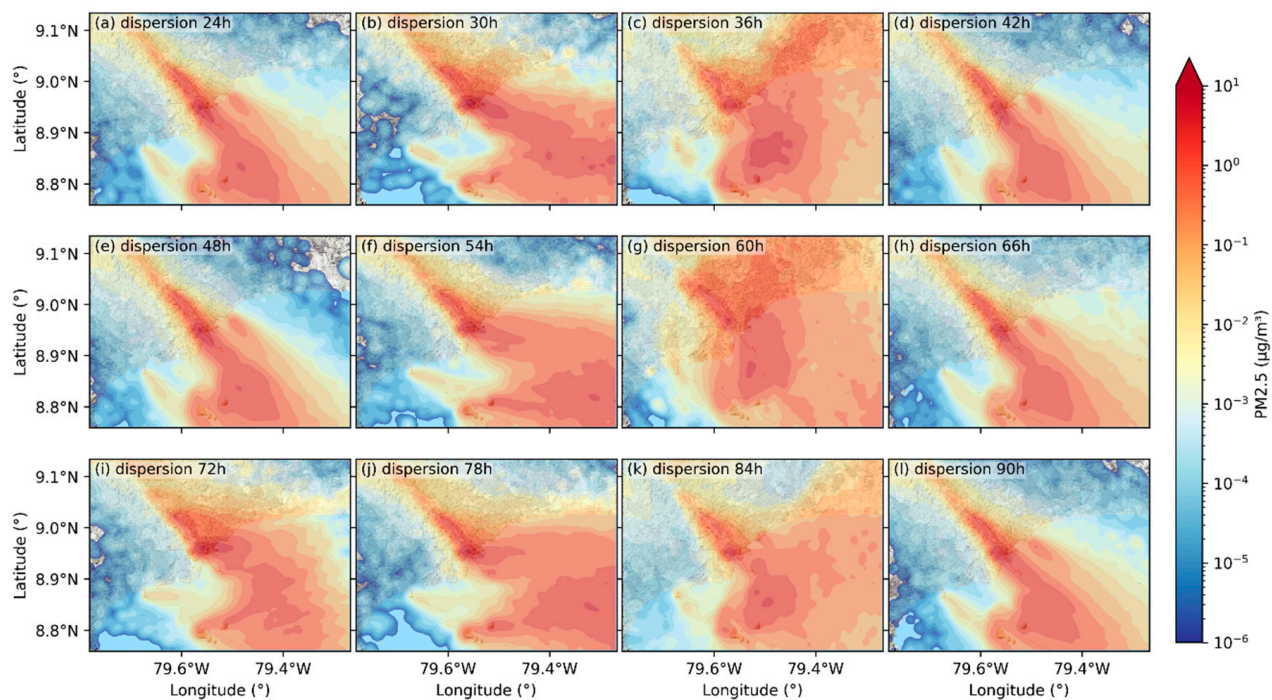


Figure 9. EL pattern—PM_{2.5} Emission Dispersion (all sailing mode).

We selected six receptor points (major hospitals, government offices, high-footfall sites near the shoreline) and computed mean and maximum PM_{2.5} for each regime and scenario.

Under EL, most PM_{2.5} from ships is transported offshore; receptor concentrations are generally low, with peaks during sea-breeze stagnation episodes (e.g., 36 h, 60 h). While the mean anchorage share is modest at the Port of Balboa (0.2%) (Table 7), maximum-based shares exceed 60% at Multiplaza Panama, Panama City Hall, and San Fernando (Table 8), indicating that EL-regime incursions can still be anchorage-dominated at peak hours.

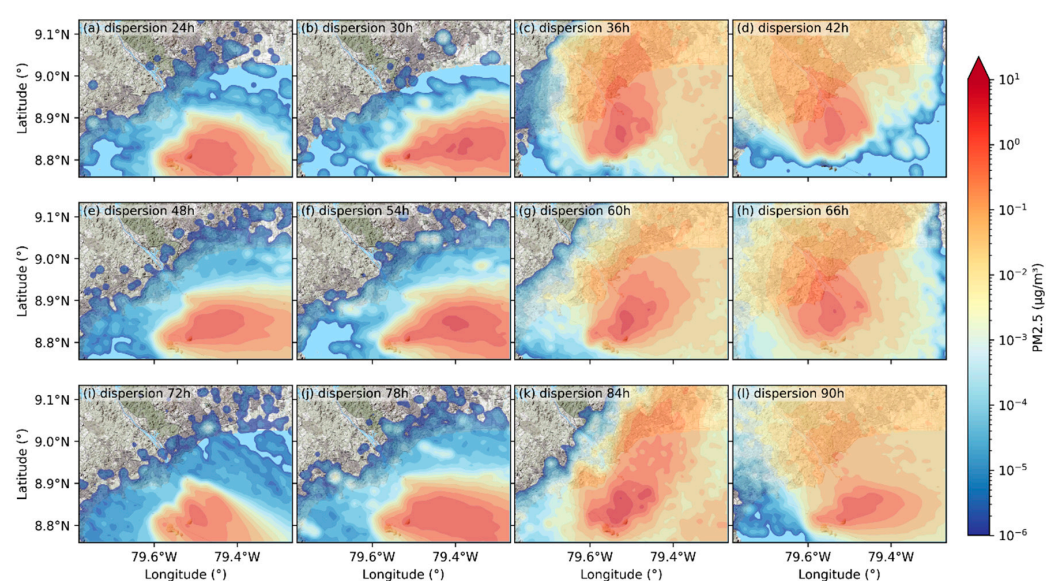
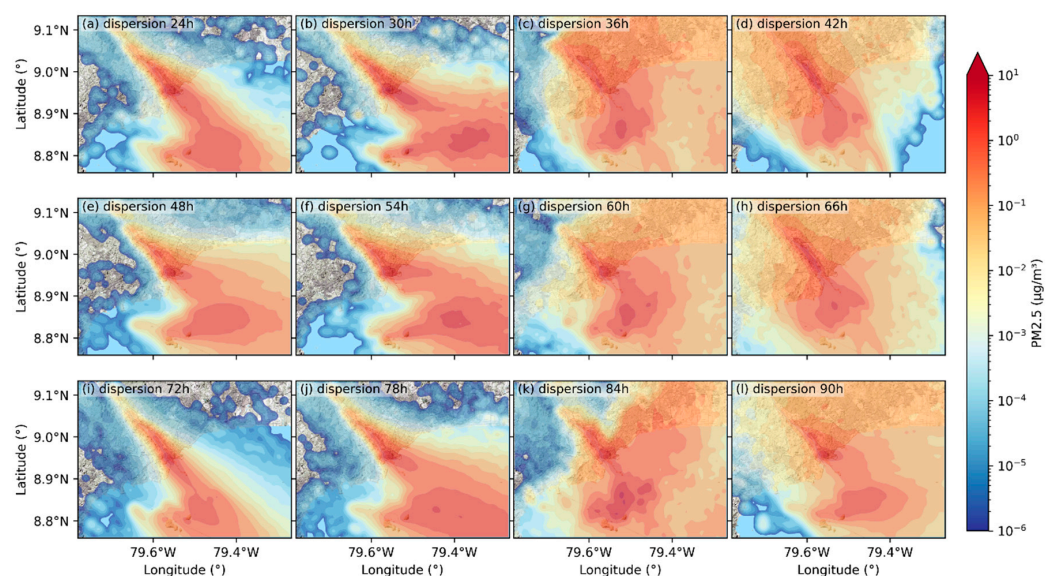
Table 7. Mean Concentrations at Major Receptor Points at EL pattern (µg/m³).

Point Name	Mean Conc. (All Sail.)	Mean Conc. (Anch.)	Contribution of Anch. (Mean)
Port of Balboa Office (8.960° N, 79.561° W)	4.72	0.01	0.2%
Panama Convention Center (8.938° N, 79.548° W)	1.04	0.04	3.8%
Panama City Hall (8.971° N, 79.535° W)	0.33	0.04	12.1%
Multiplaza Panama (8.986° N, 79.511° W)	0.27	0.08	29.6%
Embassy of the United States (8.999° N, 79.562° W)	0.33	0.01	3.0%
San Fernando Hospital Clinic (9.004° N, 79.517° W)	0.12	0.03	25.0%

SLB yields highly dynamic dispersion night/morning land-breeze export followed by post-noon sea-breeze inland fumigation producing shoreline spikes across the city (Figures 10 and 11); [79]. In the all-sailing case, emissions from both anchorage and channel sources combine to drive deeper penetration into the urban interior.

Table 8. Max Concentrations at Major Receptor Points at EL pattern ($\mu\text{g}/\text{m}^3$).

Point Name	Max Conc. (All Sail.)	Max Conc. (Anch.)	Contribution of Anch. (Max)
Port of Balboa Office (8.960° N, 79.561° W)	10.7	0.29	2.7%
Panama Convention Center (8.938° N, 79.548° W)	2.99	0.82	27.4%
Panama City Hall (8.971° N, 79.535° W)	1.37	0.86	62.8%
Multiplaza Panama (8.986° N, 79.511° W)	3.61	2.34	64.8%
Embassy of the United States (8.999° N, 79.562° W)	2.59	0.13	5.0%
San Fernando Hospital Clinic (9.004° N, 79.517° W)	1.1	0.76	69.1%

**Figure 10.** SLB pattern—PM_{2.5} Emission Dispersion (anchorage mode).**Figure 11.** SLB pattern—PM_{2.5} Emission Dispersion (all sailing mode).

In SLB, as shown in Tables 9 and 10, port-adjacent receptors (e.g., Port of Balboa Office) can exceed $22 \mu\text{g}/\text{m}^3$ ($22.03 \mu\text{g}/\text{m}^3$ under all-sailing), consistent with SLB fumigation peaks; frequent low-wind recirculation under SLB can cause local accumulation, explaining elevated mean and maximum values here than under EL or SW. Notably, anchorage contributions are larger on the city's eastern side (Multiplaza, San Fernando) than the west-consistent with afternoon onshore flow steering plumes eastward into the urban core.

Table 9. Mean Concentrations at Major Receptor Points at SLB pattern ($\mu\text{g}/\text{m}^3$).

Point Name	Mean Conc. (All Sail.)	Mean Conc. (Anch.)	Contribution of Anch. (Mean)
Port of Balboa Office (8.960° N, 79.561° W)	6.84	0.11	1.6%
Panama Convention Center (8.938° N, 79.548° W)	1.78	0.21	11.8%
Panama City Hall (8.971° N, 79.535° W)	0.71	0.14	19.7%
Multiplaza Panama (8.986° N, 79.511° W)	0.32	0.11	34.4%
Embassy of the United States (8.999° N, 79.562° W)	0.49	0.05	10.2%
San Fernando Hospital Clinic (9.004° N, 79.517° W)	0.22	0.07	31.8%

Table 10. Max Concentrations at Major Receptor Points at SLB pattern ($\mu\text{g}/\text{m}^3$).

Point Name	Max Conc. (All Sail.)	Max Conc. (Anch.)	Contribution of Anch. (Max)
Port of Balboa Office (8.960° N, 79.561° W)	22.03	0.63	2.9%
Panama Convention Center (8.938° N, 79.548° W)	5.52	1.36	24.6%
Panama City Hall (8.971° N, 79.535° W)	3.09	0.79	25.6%
Multiplaza Panama (8.986° N, 79.511° W)	1.54	0.68	44.2%
Embassy of the United States (8.999° N, 79.562° W)	3.65	0.48	13.2%
San Fernando Hospital Clinic (9.004° N, 79.517° W)	0.92	0.47	51.1%

SW (persistent southerly) occurs less frequently but exerts the most severe urban impacts (Figures 12 and 13) [80]. Continuous southerly flow advects emissions from both anchorage and channel sources onshore throughout the day; unlike SLB, there is no nocturnal land-breeze “relief,” so the influence extends beyond the coastal core to the broader metropolitan area and farther inland. The plume centerline often aligns along the canal corridor between hills, implying key exposure hotspots and potential guidance for future position of fixed/roving monitors.

Under SW, as shown in Tables 11 and 12, continuous southerlies produce the maximum mean and peak concentrations at nearly all receptors (except Port of Balboa Office), with wide, elongated plumes extending inland. Although annual frequency is modest (8.8%), SW episodes commonly persist through November, emphasizing the need for seasonal, targeted controls. Anchorage contributions of 30–50% are observed at most sites (except Balboa Office), consistent with direct, linear plume advection across the city. Interestingly,

the Port of Balboa Office shows elevated mean/maximum concentrations under SLB than under SW, likely due to low-wind recirculation and local accumulation during SLB periods.

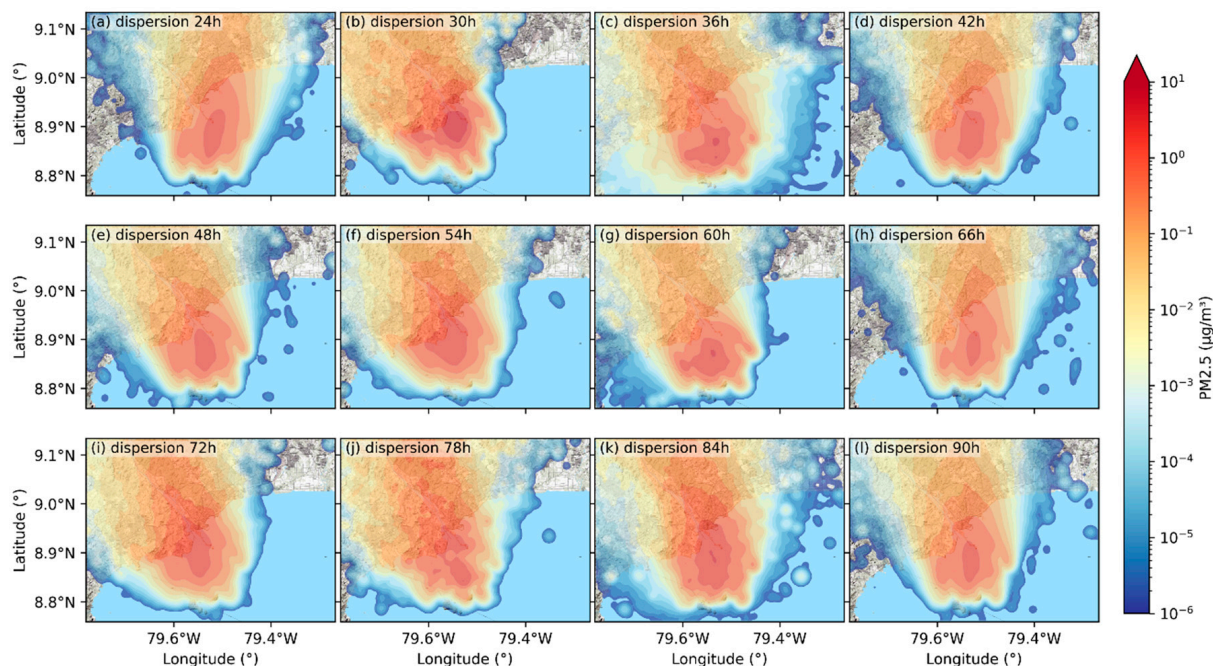


Figure 12. SW pattern—PM_{2.5} Emission Dispersion (anchorage mode).

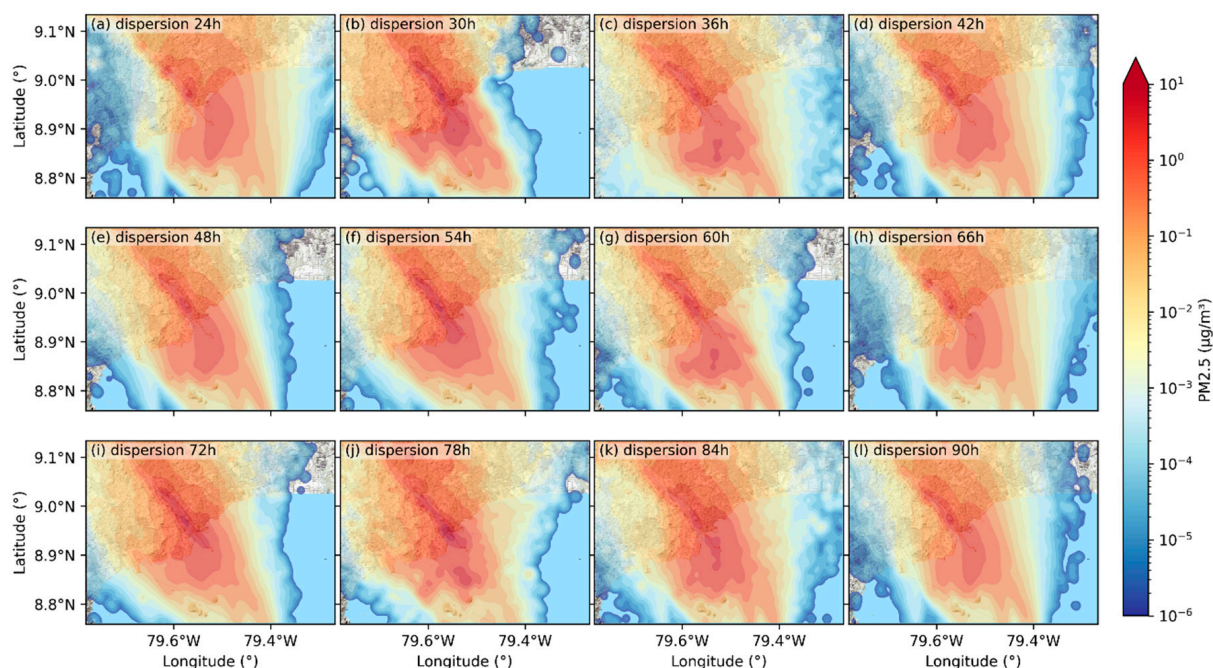


Figure 13. SW pattern—PM_{2.5} Emission Dispersion (all sailing mode).

Synthesis across regimes: (i) Anchorage contributions are generally larger to the east of the urban core, indicating that managing anchorage emissions and/or reducing anchorage time would help suppress PM_{2.5} peaks there. (ii) SW is a low-frequency, high-impact regime with broad spatial reach and amplified maximum concentrations, motivating seasonal/event-based targeted controls. (iii) Even under EL, port/approach-adjacent neighborhoods face persistent local peaks and potential health risks, motivating continuous mitigation measures for near-port communities [81].

Table 11. Mean Concentrations at Major Receptor Points at SW pattern ($\mu\text{g}/\text{m}^3$).

Point Name	Mean Conc. (All Sail.)	Mean Conc. (Anch.)	Contribution of Anch. (Mean)
Port of Balboa Office (8.960° N, 79.561° W)	2.38	0.55	23.1%
Panama Convention Center (8.938° N, 79.548° W)	2.47	0.98	39.7%
Panama City Hall (8.971° N, 79.535° W)	1.05	0.51	48.6%
Mutiplaza Panama (8.986° N, 79.511° W)	0.7	0.27	38.6%
Embassy of the United States (8.999° N, 79.562° W)	0.89	0.26	29.2%
San Fernando Hospital Clinic (9.004° N, 79.517° W)	0.44	0.2	45.5%

Table 12. Max Concentrations at Major Receptor Points at SW pattern ($\mu\text{g}/\text{m}^3$).

Point Name	Max Conc. (All Sail.)	Max Conc. (Anch.)	Contribution of Anch. (Max)
Port of Balboa Office (8.960° N, 79.561° W)	14.92	2.77	18.6%
Panama Convention Center (8.938° N, 79.548° W)	9.83	4.02	40.9%
Panama City Hall (8.971° N, 79.535° W)	3.74	1.9	50.8%
Mutiplaza Panama (8.986° N, 79.511° W)	1.88	0.91	48.4%
Embassy of the United States (8.999° N, 79.562° W)	2.3	0.91	39.6%
San Fernando Hospital Clinic (9.004° N, 79.517° W)	1.43	0.54	37.8%

4. Discussion

The results of this study underscore the notable role of anchorage activities in shaping the air pollution burden associated with shipping at one of the world's busiest maritime chokepoints. Through integrating AIS-based vessel activity with a bottom-up emission estimation framework, we established that emissions from vessels waiting to transit the Panama Canal are not negligible but rather constitute a considerable share of total shipping-related emissions in the region (Tables 8, 10 and 12). This finding is consistent with previous studies in other port environments, where anchorage-related emissions have been shown to account for a disproportionate fraction of local air pollution compared to underway operations [82–84].

A key determinant of anchorage emissions is waiting time, which reflects congestion and operational inefficiencies. Our analysis establishes that ships often remain at anchor for extended periods before transiting the Canal or engaging in cargo operations, leading to sustained auxiliary engine use. Similar patterns have been reported in studies of major ports in Asia and Europe, where prolonged waiting contributes notably to NO_x and PM emissions [85,86]. The use of AIS data allowed us to overcome limitations in self-reported navigational status and accurately capture waiting periods, a methodological advancement over earlier inventory approaches that relied on average port-call statistics [87].

From an air-quality perspective, fine particulate matter ($\text{PM}_{2.5}$) merits particular attention due to its established health impacts [88]. The anchorage-related emissions

estimated here indicate that waiting vessels contribute considerably to the local $\text{PM}_{2.5}$ burden in Panama City. Given that the metropolitan area lies near the Canal's southern anchorage, the dispersion modeling suggests that even moderate waiting times can translate into noticeable increments in ground-level concentrations. This aligns with findings from other major port cities, where ship emissions can contribute approx. 50% of urban $\text{PM}_{2.5}$ levels under certain conditions [6,7,89].

The results also emphasize the importance of distinguishing operational phases when designing control strategies. While underway emissions dominate regional-scale pollutant loads, anchorage emissions are temporally concentrated and spatially close to densely populated areas, amplifying their health relevance. Recent international measures, such as the IMO 2020 global sulfur cap and the establishment of Emission Control Areas (ECAs), have markedly reduced SO_2 and associated PM emissions [12,27,44,90]. However, NO_x and CO_2 emissions remain largely unregulated at anchorage, despite their established contribution to both air quality degradation and climate forcing [53,54].

Policy implications emerge from these findings. Reducing waiting-related emissions could be approached through multiple pathways: (i) operational efficiency improvements that minimize queuing times, such as optimized Canal scheduling; (ii) application of cleaner fuels and onboard abatement technologies, including low-sulfur fuels, scrubbers, and selective catalytic reduction (SCR) systems, to reduce auxiliary engine emissions while at anchor; and (iii) regional monitoring frameworks that explicitly account for anchorage contributions in emission inventories. Evidence from the Pearl River Delta, Yangtze River delta and the Port of Los Angeles establishes that targeted measures addressing waiting-related emissions can yield local air-quality benefits [85,91,92]. For the Panama Canal, such interventions are particularly relevant given its dual role as a critical global trade artery and as a near-urban emission hotspot.

Finally, this study makes a methodological contribution through its demonstration of how high-resolution AIS data can be integrated with the PAQman inventory system to generate detailed bottom-up emission estimates for ships at anchor. This combined framework improves upon conventional inventory approaches, which often rely on aggregated port statistics and thus underestimate emissions from waiting ships. Through linking vessel activity profiles with engine-specific emission factors, the approach reduces uncertainties in estimating pollutant loads during anchorage operations. Nevertheless, limitations persist. Boilers were excluded from the analysis due to the absence of standardized methodologies, which may result in conservative estimates of total emissions. Furthermore, uncertainties in emission factors, fuel consumption rates, and auxiliary engine load assumptions persist, particularly for older or less-documented vessels.

An additional source of uncertainty stems from the inability to fully distinguish Canal transit waiting vessels from those anchoring for port entry at nearby terminals. Canal related waiting episodes are generally much longer, often extending to several days, whereas port-related anchorage is typically less than six hours. Aggregating these categories inevitably blends different operational behaviors, but the observed heavy tailed distribution where a minority of very long episodes dominate the total waiting time can still be attributed primarily to Canal-transit delays [28,49].

Uncertainties are also inherent in the emission estimation parameters, including assumptions on auxiliary engine load factors, fuel consumption rates, and pollutant emission factors. While these parameters follow internationally accepted defaults (IMO, EMEP/EEA), they may not fully capture the diversity of vessel types and operating conditions in the Canal region, which introduces variability into the absolute emission estimates [21,56,57,93].

Finally, boilers were excluded from this study because standardized calculation methods are not yet well established. In practice, however, ship boilers are operated during low-speed or stationary phases for purposes such as fuel heating, even though their role is often supplemented by waste heat recovery when the main engine is running. As a result, the anchorage-related emissions reported here are likely conservative, and actual emissions during extended waiting may be higher than estimated [28,53].

In addition, several modeling-related limitations should be noted. First, the wind regimes were derived from a single surface meteorological site, which may not capture the full spatial variability of wind fields across the domain. Second, our simulations focused on primary PM_{2.5} and did not account for the formation of secondary aerosols. Third, the 500 m grid resolution does not resolve fine-scale effects of complex terrain and urban structures like buildings. Finally, the lack of an official air quality monitoring network in the immediate study area prevented independent model validation.

The assumed 36 m effective emission height is consistent with STEAM-type inventories, but actual plume rise can vary by vessel class and operation. Future work should therefore include comparison against regulatory monitoring networks or continuous PM_{2.5} observations, incorporate secondary aerosol formation and background fields, and resolve high-resolution terrain and urban morphology. Further refinement could also disaggregate anchorage emissions by ship type and destination to support waiting-time management strategies. Establishing fixed or mobile monitoring stations along densely populated stretches near the Canal would additionally enable cumulative exposure assessments under varying meteorological regimes and facilitate evaluation of policy interventions.

These findings carry broader implications for international maritime regulatory frameworks beyond their local relevance. Given that anchorage emissions are predominantly driven by auxiliary engine operations, effective mitigation strategies must specifically target these sources. While Alternative Maritime Power (AMP) has demonstrated efficacy at berth facilities, it is structurally unavailable for offshore anchorage areas where vessels await Canal transit. Current regulatory measures therefore inadequately address waiting-related emissions at open anchorages. In this regulatory gap, the establishment of Emission Control Areas (ECAs) represents the most viable international framework, as ECAs enforce stricter fuel quality standards and emission limits regardless of operational mode—whether underway, maneuvering, or at anchor.

However, the most immediate and cost-effective intervention for Panama involves operational optimization through enhanced Canal scheduling efficiency to reduce queuing times. Such measures would directly support MARPOL Annex VI objectives and align with the IMO's strategy for greenhouse gas reduction from international shipping, while simultaneously delivering tangible co-benefits for regional air quality and public health in the Panama City metropolitan area.

In summary, the findings emphasize that anchorage emissions south of the Panama Canal constitute a notable source of local air pollution, with direct implications for urban exposure and policy. Addressing these emissions through both operational and technological measures represents an opportunity for Panama to align local air-quality management with global decarbonization and pollution control efforts.

5. Conclusions

This study presents the first integrated assessment of vessel waiting times, shipping-related emissions, and air quality impacts in the Panama Canal region using high-resolution AIS data and dispersion modeling. The findings can be summarized as follows:

1. Vessel waiting time—Analysis of over 4600 ships during July 2024—June 2025 revealed that the mean waiting time at anchorage was 15.0 h, with an asymmetrically

distributed pattern dominated by a small number of extreme events. Episodes longer than 48 h accounted for less than 10% of cases but nearly half of the cumulative waiting time, with tankers and bulk carriers as the primary contributors. This dual structure emphasizes the need for targeted management of prolonged anchorage events rather than reliance on average statistics.

2. Emission inventory—AIS-based, bottom-up estimates established that anchorage emissions represented a considerable share of total shipping-related emissions in the Canal. Across all pollutants, waiting activities contributed approximately one-third of annual totals (34–36%), despite lower engine loads compared to transit. Spatial analysis revealed that emissions were markedly concentrated in anchorage zones, port berths, and lock vicinities, where vessels remain stationary or at very low speed and rely primarily on auxiliary engines. These hotspots overlap with densely populated areas near Panama City, emphasizing the health relevance of anchorage emissions.

3. Dispersion modeling—GRAMM/GRAL simulations under three characteristic meteorological regimes (Ensemble-Like, Sea–Land Breeze, and Southerly winds) established that dispersion patterns markedly modulate onshore exposure. Under the prevailing northwesterly flow (EL), most emissions were advected offshore, though persistent local peaks occurred near port approaches. Sea–land breeze (SLB) cycles produced sharp afternoon fumigation spikes (Figures 10 and 11), with inland receptor maxima detailed in Tables 8–12, while persistent southerly flow (SW), though infrequent, generated the most severe and widespread urban impacts, with anchorage contributions reaching 30–50% at inland receptors.

Taken together, the results confirm that anchorage operations south of the Panama Canal constitute a notable source of air pollution with direct implications for Panama City. Effective mitigation will require a dual strategy: (i) operational measures to reduce queuing times and manage prolonged anchorage events, and (ii) technological and regulatory interventions, such as low-sulfur fuels, exhaust after-treatment, and provision of shore power where feasible. The pronounced influence of meteorology suggests that seasonal or event-based controls targeting sea-breeze and southerly wind conditions could markedly reduce population exposure.

Through combining AIS-based vessel activity, bottom-up emission inventories, and high-resolution dispersion modeling, this study advances the understanding of shipping-related air quality impacts in one of the world's most critical maritime chokepoints. The approach presented here can be applied to other port–city systems to inform evidence-based policy, improve emission inventories, and guide sustainable maritime–urban coexistence.

Within the context of evolving international maritime governance, these results highlight the critical need to incorporate anchorage emissions into both global and regional regulatory frameworks. Since these emissions stem primarily from auxiliary engine operations during extended waiting periods, policy instruments must explicitly acknowledge their significance and operational constraints. While AMP deployment remains limited to berthed vessels, the strategic expansion of ECA designations offers a pragmatic regulatory pathway for controlling offshore anchorage emissions. For Panama specifically, operational reforms aimed at minimizing Canal transit delays, combined with potential ECA designation in adjacent waters, constitute the most feasible approach to address anchorage-related environmental impacts. Through connecting local operational improvements with the IMO's broader regulatory evolution, this study demonstrates how scientific evidence can inform practical maritime policy solutions at critical global chokepoints.

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Abbreviations

AE	Auxiliary Engine
AIS	Automatic Identification System
AMP	Alternative Maritime Power
CO	Carbon Monoxide
ECA	Emission Control Area
EF	Emission Factor
EPA (U.S. EPA)	United States Environmental Protection Agency
FSC	Fraction of Sulfur in fuel that is Converted to direct sulfate PM
GHG/GHG _s	Greenhouse Gas/Greenhouse Gases
GT	Gross Tonnage
IMO	International Maritime Organization
LF	Load Factor
ME	Main Engine
MEPC	Marine Environment Protection Committee (IMO)
MWR	Molecular Weight Ratio
NO _x	Nitrogen Oxides
OGV(s)	Ocean-Going Vessel(s)
PAH(s)	Polycyclic Aromatic Hydrocarbon(s)
PAQman©	Portal Air Quality Management system
PM	Particulate Matter
PM ₁₀	Particulate Matter ≤ 10 µm
PM _{2.5}	Particulate Matter ≤ 2.5 µm
S	Sulfur (fuel sulfur content, % m/m)
SFC	Specific Fuel Consumption
SO ₂	Sulfur Dioxide
TSP	Total Suspended Particles
UNCTAD	United Nations Conference on Trade and Development
VOCs	Volatile Organic Compounds

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