

Review

Review of Top-Down Method to Determine Atmospheric Emissions in Port. Case of Study: Port of Veracruz, Mexico

Gilberto Fuentes García ^{1,*} , Rodolfo Sosa Echeverría ¹ , José María Baldasano Recio ^{2,3} , Jonathan D. W. Kahl ⁴
and Rafael Esteban Antonio Durán ⁵ 

- ¹ Sección de Contaminación Ambiental, Ciudad Universitaria, Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico; rodsosa@unam.mx
- ² Barcelona Supercomputing Center-Centro Nacional de Supercomputación (BSC-CNS), Department of Earth Sciences, Nexus II Building, Jordi Girona 29, 08034 Barcelona, Spain; jose.baldasano@upc.edu
- ³ Department of Engineering Design, Universitat Politècnica de Catalunya (UPC), Av. Diagonal 647, Planta 10, 08028 Barcelona, Spain
- ⁴ School of Freshwater Science, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA; kahl@uwm.edu
- ⁵ Facultad de Ingeniería, Ciudad Universitaria, Universidad Nacional Autónoma de México, Mexico City 04510, Mexico; RafaelEAD@outlook.com
- * Correspondence: fuenbeto@me.com

Abstract: Indicators of environmental policies in force in Mexico, fossil fuels will continue to be used in industrial sectors, especially marine fuels, such as marine diesel oil, in port systems for some time. Considering this, we have evaluated several methods corresponding to a top-down system for determining fuel consumption and sulfur dioxide atmospheric emissions for the port of Veracruz in 2020 by type of ship on a daily resolution, considering a sulfur content of 0.5% mass by mass in marine fuel. After analyzing seven methods for determining sulfur dioxide atmospheric emission levels, Goldsworthy's method was found to be the best option to characterize this port. The port system has two maritime zones, one of which is in expansion, which represented 55.66% of fuel consumption and 23.05% of atmospheric emissions according to the typology of vessels. We found that higher fuel consumption corresponded to container vessels, and tanker vessels represented higher atmospheric emission levels in the berthing position. The main differences that we found in the analysis of the seven methods of the top-down system corresponded to the load factor parameter, main and auxiliary engine power, and estimation of fuel consumption by type of vessel.

Keywords: fuel consumption; berthing position; marine fuel; gross tonnage; emission factor; sulphur content



Citation: Fuentes García, G.; Sosa Echeverría, R.; Baldasano Recio, J.M.; W. Kahl, J.D.; Antonio Durán, R.E. Review of Top-Down Method to Determine Atmospheric Emissions in Port. Case of Study: Port of Veracruz, Mexico. *J. Mar. Sci. Eng.* **2022**, *10*, 96. <https://doi.org/10.3390/jmse10010096>

Academic Editor: Hong Yang

Received: 19 November 2021

Accepted: 7 January 2022

Published: 11 January 2022

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1. Introduction

Two traditional approaches, the bottom-up and top-down methods, have been widely used for generating atmospheric emission inventories in ports (Corbett and Koehler [1,2], Browning and Bailey [3], and Brown and Aldridge [4]). The bottom-up method is commonly used for estimating atmospheric emissions, due to this method considering the time of operation and power of the main engine (ME) and auxiliary engine (AE), load factor (LF), maximum continuous rating (MCR), specific fuel consumption (SFC), the emission factor of each engine in each navigation phase, and the Gross Tonnage (GT) by type of vessel. Currently, the United States Environmental Protection Agency (USEPA) [5] has been carrying out a state-of-the-art assessment corresponding to the traditional bottom-up method to determine atmospheric emissions from ocean-going vessels (OGV). However, this study does not reflect the top-down method.

The top-down method is based primarily on the consumption of marine fuel by type of ship, engine type, navigation phase, emission factors, and SFC, but exhibits some

inconsistencies in its calculation methodology, according to Saputra et al. [6,7] and Knezevic et al. [8].

This study in essence consists of a review of the top-down system to estimate atmospheric emissions by sulfur dioxide (SO₂) due to the movement of ships in port (berthing and maneuvering positions), with application to the Port of Veracruz, one of the most important ports in Mexico due to its ongoing expansion and location in the Gulf of Mexico.

This area is very important to consider, since the level of industrial sector activity is very interesting to evaluate (Muriel-García et al. [9]).

According to the literature, we have found seven methods based on the top-down system to identify fuel consumption and atmospheric emission by type of ship. Studies carried out by [7], Knezevic et al. [8], Johansson et al. [10], and Toscano and Murena [11] indicate that the top-down method is not as widely used as the bottom-up system to characterize port systems or for the creation of atmospheric emission inventories in maritime areas.

Therefore, this study aims to identify why there are discrepancies in the top-down method, and what the limitations are for its use in determining fuel consumption and atmospheric emissions. For the application of the top-down system of this study, we considered official and detailed information of the port of Veracruz corresponding to typology of ships, *GT* data, and time spent in port in berthing and maneuvering positions. The information for estimating the power of the ME and AE, as well as the emission factors in the docking stage, *LF*, sulfur content in marine fuel, fuel consumption level, and atmospheric emissions were based on Trozzi and Vaccaro [12,13], Schrooten et al. [14], Van der Gon and Hulskotte [15], Goldsworthy and Goldsworthy [16], and Gusti and Semin [17].

The objective of the development of this study is to characterize the port of Veracruz with respect to fuel consumption and atmospheric emissions by type of ship, as it promises greater port activity for the next few years. Some studies carried out by [18,19], and Fuentes et al. [20,21] have promoted the development of atmospheric emission inventories of the main pollutants that are emitted due to the movement of ships in port, using the bottom-up system at the national level in Mexico. However, it is necessary to identify fuel consumption with consideration to the type of ships that arrive at the port of Veracruz, because the country's environmental policies are committed to the use of fossil fuels for the next few years.

Therefore, this study tries to reflect the current situation of the movement of ships in port using algorithms to estimate the level of fuel consumption and atmospheric emissions by SO₂ during 2020 with daily resolution. The results of atmospheric emissions of this study with daily resolution will strengthen the use of air quality models as there is no detailed information about this in Mexico, which is an important factor in decision making regarding the application of air quality models when the emission source (ship at berthing position) is considered as a punctual source, according to Fuentes et al. [22], Jagangiri et al. [23], Murena et al. [24], Bai et al. [25], Mocerino et al. [26], and Pan et al. [27].

2. Background

2.1. International Maritime Organization and Marine Pollution Regulations for SO₂

In accordance with the rule implemented by the International Maritime Organization (IMO), sulfur content in marine fuels was reduced from 3.5% to 0.5% mass by mass (m/m) globally, beginning 1 January 2020 [28]. Consequently, atmospheric emissions of sulfur compounds are expected to decrease by 77% (8.5 million tons) globally. The IMO rule is expected to reinforce the Marine Pollution (MARPOL) Agreement, Annex VI, which focuses on reducing atmospheric emissions in port to improve or maintain air quality for port city populations. The IMO has further suggested that an enforcement measure is needed to determine whether the 0.5% m/m reduction in marine fuel sulfur content has been achieved [28].

The strategy of reducing sulfur content in marine fuels to 0.5% m/m worldwide is intended to improve air quality by reducing emissions from the movement of ships. This reduction has been adopted by the IMO, effective 1 January 2020. The signatory countries

of the MARPOL agreement will be responsible for implementing this control measure, which is mainly intended to reduce emissions of sulfur compounds.

Ship movement consists of three navigation stages: cruising, maneuvering, and berthing. Atmospheric emissions are generally highest during the cruising stage. When ships are in port, however, emissions are highest during the berthing stage. Maintaining satisfactory air quality within the port system, in light of the MARPOL initiatives, thus requires consideration of ship emissions as a function of ship type for berthing, the non-cruising navigation stage.

Acquiring marine fuels that meet the quality criteria of 0.5% m/m sulfur content may be challenging for some countries depending on their socioeconomic level, political and environmental situation, and geographical region. It will be necessary to analyze marine fuels to ensure that the established quality criteria are maintained [28]. It is expected that developed countries will have fewer obstacles in adapting to the IMO and MARPOL regulatory measures. It should be noted that the COVID-19 health emergency also forced adjustments in social and economic spheres within developing countries, indicating that despite the effective date of 1 January 2020, the regulation has not yet been fully adopted. This situation occurred in Mexico due to it being a developing country, COVID-19 affecting their socioeconomic and political level, and being unable to acquire fuels with low sulfur content, according to information from the captaincy of the Port of Veracruz.

During the global COVID-19 health crisis, maritime activity has been one of the main sectors that did not experience interruptions. Maritime transport complied with health protocols and responsibilities in the movement of merchandise and was not affected by the state of alarm [29]. Therefore, the global growth of marine activity has continued, mainly due to the movement of gas carrier vessels. According to [29], gas carrier vessels have experienced a growth of 6.5% from 2019 to 2020, followed by oil tankers at 5.8%, bulk carriers at 3.9%, container ships at 3.3%, and chemical tankers at 2.9%. Bulk carriers, oil tankers, and container ships represented the highest demand worldwide, with 19.6%, 17.3% and 17.1%, respectively. It is therefore necessary to monitor compliance in the reduction in sulfur content in marine fuels and to identify the level of atmospheric SO₂ emissions in port. Viana et al. [30], Prati et al. [31], Xiao et al. [32], and Wang et al. [33] indicate that atmospheric emissions from the combustion of marine fuel taking place inside the ME and AE of ships in the berthing position impact the air quality for the surrounding population. In addition, Corbett et al. [34], Muller et al. [35], Sofiev et al. [36], and Mwase et al. [37] indicate some direct health effects of these emissions.

According to [38] the sulfur content of marine fuels varies from 3.5% to 0.5% m/m. Marine Residual Oil (MRO) has the largest content (3.5%), while Marine Diesel Oil (MDO, 1.0%) and Marine Gas Oil (MGO, 0.5%) are cleaner with respect to sulfur. Unfortunately, little information is available at the international level regarding sulfur content in marine fuels. In many cases the information is confidential. It is therefore important to obtain representative samples of each fuel type to determine chemical speciation. Cooper and Gustafsson [39] reported the trace metals content in MDO fuel, and indicated that sulfur content from 1990 to 2002 was 1.0 to 0.2% m/m. This type of information needs to be updated for each region and/or country. In Mexico, the sampling of marine fuel for the determination of its chemical speciation has not yet been considered; therefore, it is necessary to promote this initiative at the national level for the next few years.

2.2. SO₂ Emission Factor

The sulfur content in marine fuel is widely used for the determination of atmospheric SO₂ emissions by traditional methods. The SO₂ emission factor in the three navigation stages by ship type depends on the sulfur content in the fuel (20 s) where “s” indicates the % of sulfur in the fuel. In this case, the emission factor (20 s) indicates that all of the sulfur is converted to sulfur dioxide through combustion process in ME and AE and the chemical reaction corresponds to 100%, considering one ton of marine fuel according to Equation (1):



Considering that 1 ton of fuel and all sulfur is converted to sulfur dioxide, then according to the stoichiometry of reaction, 1 mol of SO₂ is formed by 1 mol of S. In terms of mass corresponding to 64 kg SO₂ formed by 32 kg S, the factor is 2, when the reaction corresponds to 100%.

$$\%S = \frac{1 \text{ kgS}}{100 \text{ kg}_{fuel}} * \frac{1000 \text{ kg}_{fuel}}{1 \text{ ton}_{fuel}} * \frac{64 \text{ kg SO}_2}{32 \text{ kg S}} = 20 * s$$

The 20 s emission factor for sulfur dioxide is supported by Trozzi and Vaccaro [12,13,38], and Cooper and Gustafsson [39–42]. However, Johansson et al. [10] and Jalkanen et al. [43–45] indicate that when the AIS information is considered, SO₂ emission factors can be generated more precisely as functions of engine operation, specifically the engine power, MCR, LF and SFC, and fuel demand in the different stages of ship navigation.

2.3. Top-Down Method to Determine Atmospheric Emissions

The top-down and bottom-up methods for estimating atmospheric emissions from ships are important tools for generating international emission inventories due to the movement of ships within different geographic regions (Brown and Aldridge [4]). The bottom-up method is most commonly used because it is based primarily on the time of operation of the ME and AE by ship type, as well as the power of both engines in the different stages of navigation, and time spent in port [46]. Gutiérrez et al. [47,48] compared several methods based on the bottom-up system and found minimal variability (20%), indicating that the method is applicable for most port systems.

The top-down method has shown little applicability for estimating atmospheric emissions in port. This method has been considered unreliable, especially on the global scale, due to inconsistent information on the quantity of fuel consumed, according to [8,49].

The method requires detailed data on routing, engine workload, ship speed, location, and duration by [7]. It is necessary to analyze and compare the methods found within the top-down system to determine why they present inconsistent information. Toscano and Murena [11] indicate that methodologies for the assessment of ship emissions go from a full top-down approach to a full bottom-up approach. In the full top-down approach, total emissions are calculated at a large scale, generally national, and then geographically reduced at a smaller scale (regional or urban) using proxy variables.

The main advantage of such bottom-up emission inventories, compared to the top-down ones, is that these can describe the emitters in a more realistic manner, while maintaining the connection between single emitters and large-scale inventories. In addition, it is possible to construct sophisticated emission scenarios and analyze in detail the spatial-temporal variation of emissions (Johansson et al. [10]).

Each method within the top-down system is based mainly on the estimation of fuel consumption (Trozzi and Vaccaro [12,13]). These estimates consider the ship navigation stage, as well as the GT by ship and cargo type, engine type, and time in port. Schrooten et al. [14] provide an expression for estimating fuel consumption, based on the energy expenditure by ship type and navigation stage. Their method utilizes the power of the AE in port, SFC, and the duration of stay for each ship type to obtain the fuel consumption.

The methodology of Van der Gon and Hulskotte [15] determined fuel consumption based on GT and time spent in the berthing situation by ship type. Goldsworthy and Goldsworthy [16] determined fuel consumption based on the power of the machine type, LF for each position of the ship, time spent in each navigation phase, and the SFC. Gusti and Semin [17] described a method nearly identical to that of Goldsworthy and Goldsworthy [16], except that the Gusti and Semin method does not consider the LF by ship type.

The fuel consumption determination methods of Schrooten et al. [14], Goldsworthy and Goldsworthy [16], and Gusti and Semin [17], each utilize the information of [38,41], specifically data from *SFC*, as well as power of the AE in berthing stage and *LF*.

Other methods have been described but are inappropriate for use in the present study. Bialystocki and Konovertis [50] included more detailed data, such as ship speed and factors of weather force, weather direction, and date of the forthcoming voyage. This information is not available for the port of Veracruz. Simonsen et al. [51] developed a model to estimate the fuel consumption of cruise ships based on AIS and specified *GT* levels of approximately 25,000. This model has a specific application for cruise ships and may not be generalized to the typology of ships from other port systems.

3. Case Study: Port of Veracruz

The location of the port of Veracruz is shown in Figure 1. It is in the State of Veracruz, Mexico, on the Gulf of Mexico. The port of Veracruz is under expansion, with construction estimated to end in 2030. Its new expansion, “Bahía Norte” (BN), will have 35 new berthing positions, while the “Bahía Sur” (BS), the current port, has 18 berthing positions. BN received its first container ship on 1 July 2019. The purpose of the new expansion is to reduce the stay times of the ships that arrive at the port, thus improving efficiency and reducing maritime traffic [52]. Currently, container ships and bulk agricultural and bulk mineral ships arrive at BN, while general cargo, RoRo cargo, bulk agricultural and mineral, tankers, and chemicals arrive at the BS.

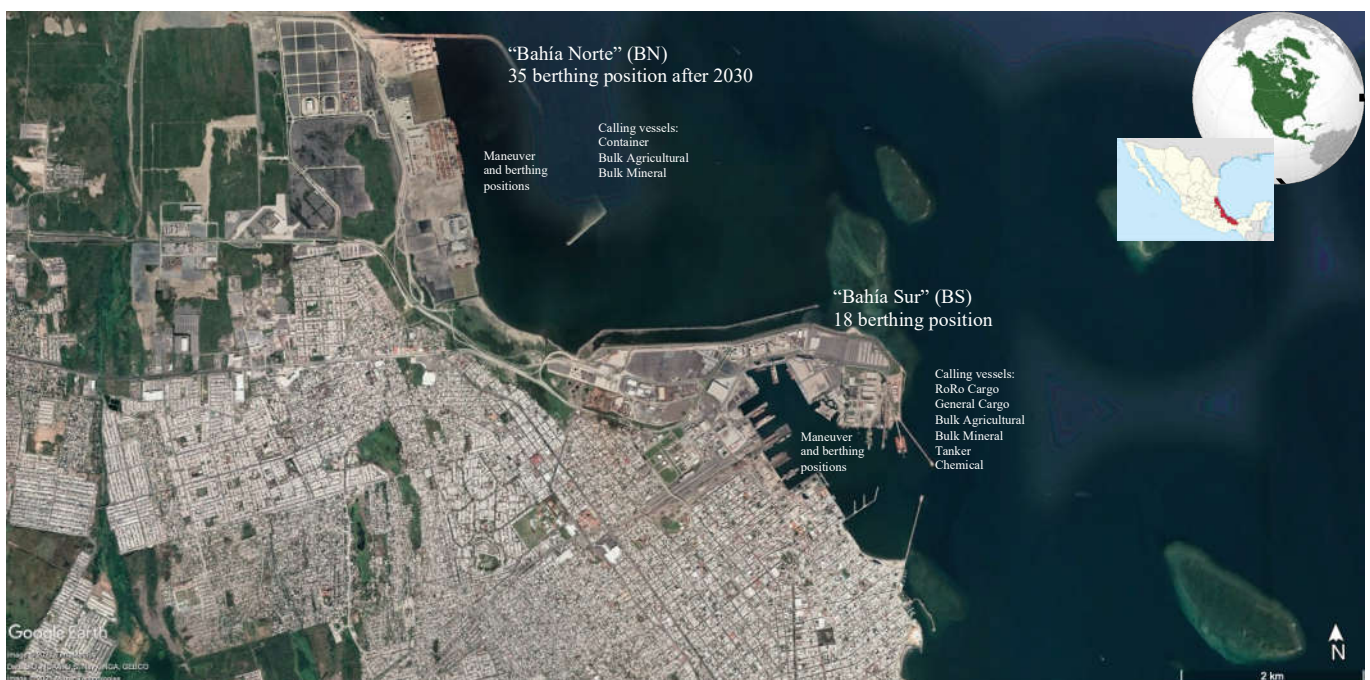


Figure 1. The port of Veracruz.

The types of ships that arrive at the port are shown in Table 1 and consist mainly of general cargo, RoRo cargo, container ships, bulk mineral and agricultural, tanker, and chemicals [53]. In 2020 the length of stay decreased relative to 2019, indicating an increase in efficiency in the movement of merchandise within the Veracruz port system.

Table 1. Typology of ships in the port of Veracruz [53].

Type of Vessel	Ships		GT Average		Tonnage Average/Ship		Stay at Port Average/Ship, h	
	2019	2020	2019	2020	2019	2020	2019	2020
General Cargo	358	296	28,979	30,672	5020	4487	87.6	74.7
RoRo Cargo	230	178	57,407	57,329	6800	6766	44.6	42.0
Container No Specialized	168	110	27,031	22,486	7509	6240	20.5	16.1
Container Specialized	494	532	60,435	59,153	20,031	16,887	21.1	17.1
Bulk Agricultural	236	223	24,589	25,284	31,482	31,138	154.6	158.4
Bulk Mineral	125	148	20,314	19,182	19,255	19,275	92.4	93.8
Tanker	208	188	28,367	26,839	12,708	12,489	88.3	94.0
Chemical	177	186	13,807	14,479	7206	9958	54.3	60.7
	1996	1861	32,616.13	31,928.00	13,751.38	13,405.00	70.4	69.6

The projection of merchandise growth (million tons) from 2016 to 2035 is shown in Figure 2. The port authority indicates that the base trend (annual average) in the growth of general cargo will be 4.1%, container 3.2%, bulk agricultural −0.3%, bulk mineral 1.3%, tanker 2.6%, and chemical 0.6%. The growth of the movement of general cargo and containers is implied in accordance with the port authority’s projection. From 2016 to 2035 a total combined tonnage of 582,249,448 is obtained, with 45% corresponding to containers, 22% bulk agricultural, 13% general cargo, 9% bulk mineral, 8% tanker and 3% chemical [52]. Given this projected growth in ship traffic at the expanding port, there is a need to determine the level of atmospheric emissions at this port system, especially considering that MDO will continue to be used.

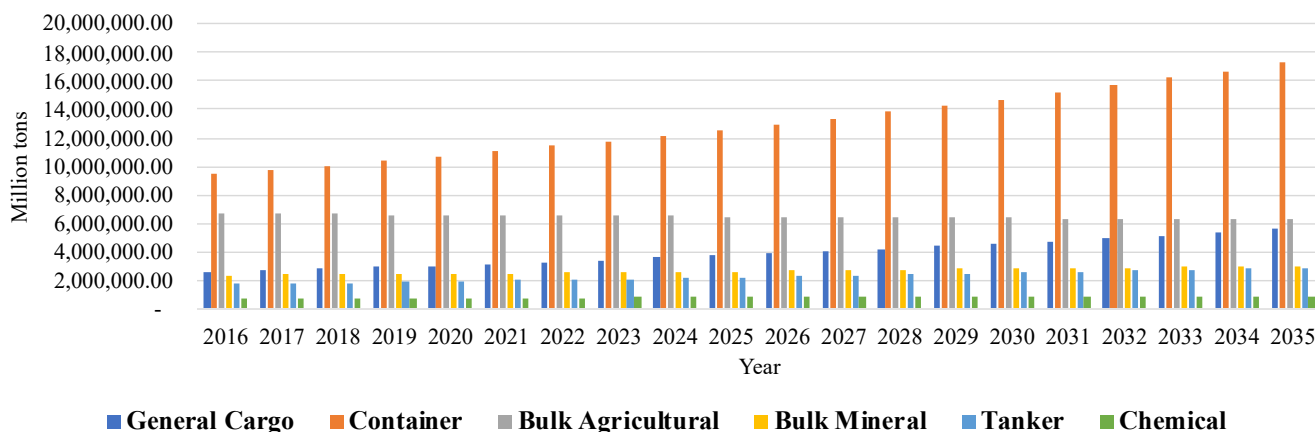


Figure 2. Projection of merchandise growth (million tons) in the port of Veracruz.

Because the port system considers the movement of different types of goods, the port of Veracruz does not have a specific classification in cargo movement in the same way that other port systems do both nationally and internationally. However, the movement of containers is one of the main goods within the port system of Veracruz [52,53].

The temporal distribution of container movement (thousands of TEUs) from 2008 to 2020 is shown in Figure 3. An increase in container movement through the Veracruz port system was observed until 2018, while in 2019 and 2020 a clear decrease was observed. The COVID-19 health emergency and resulting adjustment in the economy are factors towards the reduction in container movement in 2020.

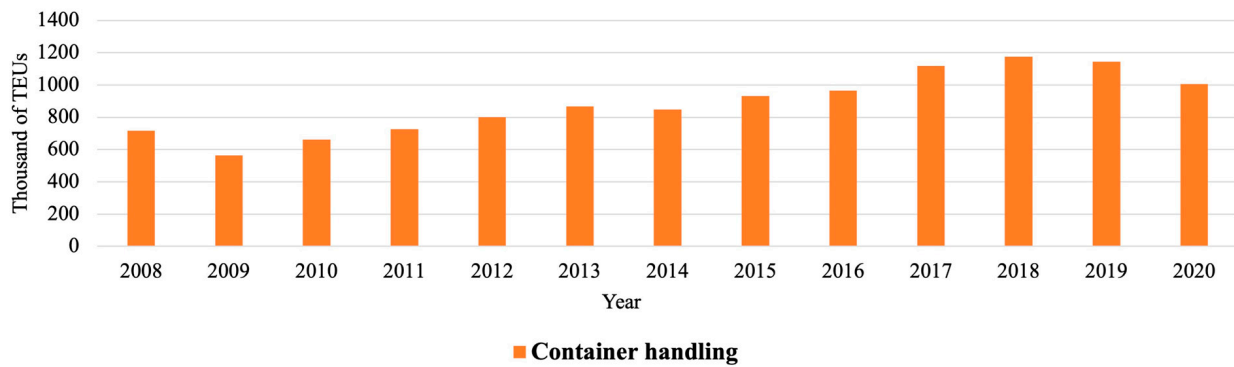


Figure 3. Container handling from 2008 to 2020.

Motivated by the maritime development in the State of Veracruz and the associated need to identify atmospheric emissions due to the Veracruz port system, Fuentes et al. [20,21] recently studied atmospheric emissions in the port due to the movement of ships in the maneuvering and berthing phase. Results indicate that atmospheric emissions were higher due to the movement of ships in the BS (87%) compared to BN (13%) during 2018 and 2019. However, the fuel consumption by ship type has yet to be identified, despite the Veracruz port’s status as one of the most important port systems in the Gulf of Mexico [54].

4. Methodology

4.1. Database

To estimate atmospheric emissions using the top-down method, we used the official information of the port of Veracruz for the year 2020 [53]. This database includes daily ship arrivals and detailed information on technical aspects of ship typology.

4.2. Applying to Top-Down Method

The expression to determine the daily atmospheric emissions of sulfur dioxide is shown in Equation (2). The equation was applied in the berthing and maneuvering situation. In addition, the highest atmospheric emissions in the port of Veracruz occurred in berthing phase, according to Fuentes et al. [20,21].

According to Equation (2), the fuel consumption by ship and type of cargo must first be determined in both positions.

$$E_{i,j} = FC_{i,j} * EF_{SO_2} * t_{i,j} \tag{2}$$

where:

i, j : Berthing and maneuvering position, respectively;

$E_{i,j}$: Atmospheric Emissions, $kg_{\text{pollutant}}$;

$FC_{i,j}$: Fuel Consumption, $\frac{\text{ton}_{\text{fuel}}}{\text{h}}$, according to vessel type;

EF_{SO_2} : Emission Factor for SO_2 , $\frac{kg_{SO_2}}{\text{ton}_{\text{fuel}}}$;

$t_{i,j}$: Time spent, h, according to vessel type.

We use seven methods based on the top-down system for estimating fuel consumption and SO_2 atmospheric emissions daily for each ship type in the berthing and maneuvering situation. The methods utilized are shown in Table 2. It should be noted that the fuel consumption estimation methods of Trozzi and Vaccaro [12,13] do not include consideration of the SFC, LF , or AE power.

Table 2. Methods used in this study for estimating fuel consumption and atmospheric SO₂ emissions.

Method	FC by Type of Ship	GT	SFC	Power of ME (P_{ME}) and AE (P_{AE})	LF	Time Spent in Berthing Position	Emission Factor
Trozzi and Vaccaro [12]	Table 3	Yes	-	-	-	Yes	Yes
Trozzi and Vaccaro [13]	Table 4	Yes	-	-	-	Yes	Yes
Schrooten et al. [14]	Table 5	Yes	Yes	Yes	Yes	Yes	Yes
Goldsworthy and Goldsworthy [16]		Yes	Yes	Yes	Yes	Yes	Yes
Gusti and Semin [17]		Yes	Yes	Yes	-	Yes	Yes
Van der Gon and Hulskotte [15]	Table 6	Yes	-	-	-	Yes	Yes
Considering Heat Value for MDO	Table 7	Yes	Yes	Yes	Yes	Yes	Yes

Table 3. Fuel consumption by type of ship (Trozzi and Vaccaro [12]).

Type of Vessel	FC ($\frac{Mg_{fuel}}{day}$)	Adjustment of the FC
General Cargo	$9.8197 + 0.00143 * GT$	Berthing: 0.2 Maneuvering: 0.4
RoRo Cargo	$12.834 + 0.00156 * GT$	
Container	$8.0552 + 0.00235 * GT$	
Bulk Agricultural	$20.186 + 0.00049 * GT$	
Bulk Mineral		
Tanker	$14.685 + 0.00079 * GT$	
Chemical		

Table 4. Fuel consumption by type of ship/adjustment (Trozzi and Vaccaro [13]).

Type of Vessel	FC ($\frac{Mg_{fuel}}{day}$)	Adjustment of the FC
General Cargo	$2.2602 + 0.0049 * GT - 1.6401 \times 10^{-7} * GT^2 + 1.7394 \times 10^{-12} * GT^3$	Berthing: 0.2 Maneuvering: 0.4
RoRo Cargo	$6.3501 + 0.0013 * GT + 1.6852 \times 10^{-7} * GT^2 - 6.2691 \times 10^{-12} * GT^3 + 5.6990 \times 10^{-17} * GT^4$	
Container	$0.0919 + 0.0038 * GT - 6.1565 \times 10^{-8} * GT^2 + 6.7917 \times 10^{-13} * GT^3$	
Bulk Agricultural	$12.0724 + 0.0012 * GT - 1.1501 \times 10^{-8} * GT^2 + 4.6484 \times 10^{-14} * GT^3$	
Bulk Mineral		
Tanker	$7.2194 + 0.0015 * GT - 9.1885 \times 10^{-9} * GT^2 + 2.6803 \times 10^{-14} * GT^3$	
Chemical		

We determine the fuel consumption according to the procedures of each method (Tables 3–8), which depend on the GT parameter by ship type and the AE power in the berthing situation. To determine AE power, it is necessary to determine the power of the ME by vessel type and multiply it by the average vessel ratio [46].

For all methods we used an atmospheric SO₂ emission factor of 20 s. We assumed a sulfur content of 0.5% m/m according to IMO Regulations. Data on time spent in berthing and maneuvering positions by ship and cargo type was obtained from [53], Table 8.

Table 5. Fuel consumption by type of ship, case of berthing situation (Schrooten et al. [14], Goldsworthy and Goldsworthy [16], and Gusti and Semin [17]).

Type of Vessel	Schrooten et al. [14]: $FC\left(\frac{g_{fuel}}{h}\right) = \left(SFC, \frac{g_{fuel}}{kWh}\right) * (LF) * (P_{AE}, kW)$					
	To Obtain $\left(\frac{Mg_{fuel}}{h}\right)$ Divided by 1.1×10^{-6}					
	Goldsworthy and Goldsworthy [16]: $FC\left(\frac{g_{fuel}}{h}\right) = \left(SFC, \frac{g_{fuel}}{kWh}\right) * (LF) * (P_{AE}, kW)$					
	Gusti and Semin [17]: $FC\left(\frac{g_{fuel}}{h}\right) = \left(SFC, \frac{g_{fuel}}{kWh}\right) * (P_{AE}, kW)$					
						To Obtain $\left(\frac{Mg_{fuel}}{h}\right)$ Divided by 1.0×10^{-6}
	SFC at berth $\frac{g_{fuel}}{kWh}$ [38]	LF [38]	P_{ME}, kW [46]	Average Gross Tonne, [53]	Average Vessel Ratio [46]	P_{AE}, kW
General Cargo	225	0.2	$5.5648 * GT^{0.7425}$	30,672	0.23	2745
RoRo Cargo	227	0.2	$164.58 * GT^{0.435}$	57,329	0.24	4640
Container	223	0.2	$2.9165 * GT^{0.8719}$	40,820	0.25	7639
Bulk Agricultural	222	0.2	$35.912 * GT^{0.5276}$	22,233	0.30	2118
Bulk Mineral						
Tanker	222	0.4	$14.775 * GT^{0.6082}$	20,659	0.30	1867
Chemical						

Table 6. Fuel consumption by type of ship in berthing position (Van der Gon and Hulskotte [15]).

Type of Vessel	$FC\left(\frac{kg_{fuel}}{1000GTh}\right)$
General Cargo	5.4
RoRo Cargo	6.9
Container	5.0
Bulk Agricultural	2.4
Bulk Mineral	
Tanker	19.3
Chemical	

Table 7. Fuel consumption by type of ship considering the Heat Value method for Marine Diesel Oil in berthing position.

Type of Vessel	Heat Value $42.19 \frac{MJ}{kg_{fuel}} = \frac{1 kg_{fuel}}{11.719 kWh}$					
	$FC\left(\frac{kg_{fuel}}{h}\right) = \left(\frac{1kg_{fuel}}{11.719 kWh}\right) * (LF) * (P_{AE}, kW)$					
	Consumption	LF [38]	P_{ME}, kW [46]	Average GT, [53]	Average Vessel Ratio [46]	P_{AE}, kW
General Cargo	$\frac{1kg_{fuel}}{11.719kWh}$	0.2	$5.5648 * GT^{0.7425}$	30,672	0.23	2745
RoRo Cargo		0.2	$164.58 * GT^{0.435}$	57,329	0.24	4640
Container		0.2	$2.9165 * GT^{0.8719}$	40,820	0.25	7639
Bulk Agricultural		0.2	$35.912 * GT^{0.5276}$	22,233	0.30	2118
Bulk Mineral						
Tanker		0.4	$14.775 * GT^{0.6082}$	20,659	0.30	1867
Chemical						

Table 8. Time spent in berthing position (h) by type of vessel in the port of Veracruz.

Type of Vessel	Time Spent in Berthing Position Average/Vessel, h [53]	Time Spent in Maneuver Position Average/Vessel, h [53]
General Cargo	74.7	1.0
RoRo Cargo	42.0	1.0
Container	16.6	1.0
Bulk Agricultural	158.4	1.0
Bulk Mineral	93.8	1.0
Tanker	94.0	1.0
Chemical	60.7	1.0

5. Results and Analysis

Atmospheric emissions in berthing and maneuvering positions for each method are shown in Figure 4. The level of atmospheric emissions in berthing position is higher than in maneuvering position since the time spent in berthing position is higher than the time spent in maneuvering position. In addition, the ME and AE’s time spent in operation in maneuvering position is low compared to the AE’s time spent in operation in berthing position. The Trozzi and Vaccaro methods represented a difference of 95% between berthing and maneuvering positions. For the Schrooten method we found a difference of 86%; for Goldsworthy, the difference was 80%; for Gusti and Semin, 82%; and for the Heat Value method, 80%.

In other words, 95.4% corresponded to berthing position and 4.6% in maneuvering position for the Trozzi and Vaccaro methods. For the Schrooten method the figures were 87.6% berthing and 12.4% maneuvering; for Goldsworthy, 83.2% in berthing and 16.8% in maneuvering; for Gusti and Semin, 85.0% in berthing and 15.0% in maneuver; and for the Heat Value method, 83.2% in berthing and 16.8% in maneuver.

For the Van der Gon and Hulskotte method, we only show the level of atmospheric emissions in berthing position since their information corresponds to this position, i.e., the emission factor that determines the level of fuel consumption and atmospheric emissions corresponds to berthing position.

Daily total atmospheric SO₂ emissions (berthing and maneuvering positions) estimated by seven top-down methods are shown in Figure 5. The method of Gusti and Semin [17] presented the highest levels of atmospheric emissions, followed by the methods of Trozzi and Vaccaro [12,13] and Van der Gon and Hulskotte [15]. The methods of Schrooten et al. [14] and Goldsworthy and Goldsworthy [16] presented a similar atmospheric emission level, while the Heat Value method presented the lowest levels of atmospheric emissions. The variability in emissions estimates among the different methods is due to differences in how vessel operation information, mainly the GT and AE power, are considered.

Boxplots for each method of estimating atmospheric emissions are shown in Figure 6. The Trozzi and Vaccaro [12,13] methods presented similar behavior in the atmospheric emissions estimates, as did the methods of Schrooten et al. [14], Van de Gon and Hulskotte [15], and Goldsworthy and Goldsworthy [16]. The method of Gusti and Semin [17] is outside the range of the aforementioned methods, with a 25th percentile corresponding to the maximum value (75th percentile) of Trozzi and Vaccaro [12,13]. The Heat Value method consistently estimates the minimum atmospheric emission level among the models tested. Considering the results of Trozzi and Vaccaro [12,13] we find an average difference of 3.5%, while for the Schrooten and Goldsworthy methods we find an average difference of 10%. Considering the results of Trozzi and Vaccaro [13] and Goldsworthy, we obtained a difference of 64%. These differences mainly lie in key parameters for determining fuel consumption and atmospheric emission. Finally, if we consider the results of the Trozzi and

Vaccaro [13] and Gusti and Semin methods there is a 35% difference, and a 77% difference considering Goldsworthy and Gusti and Semin.

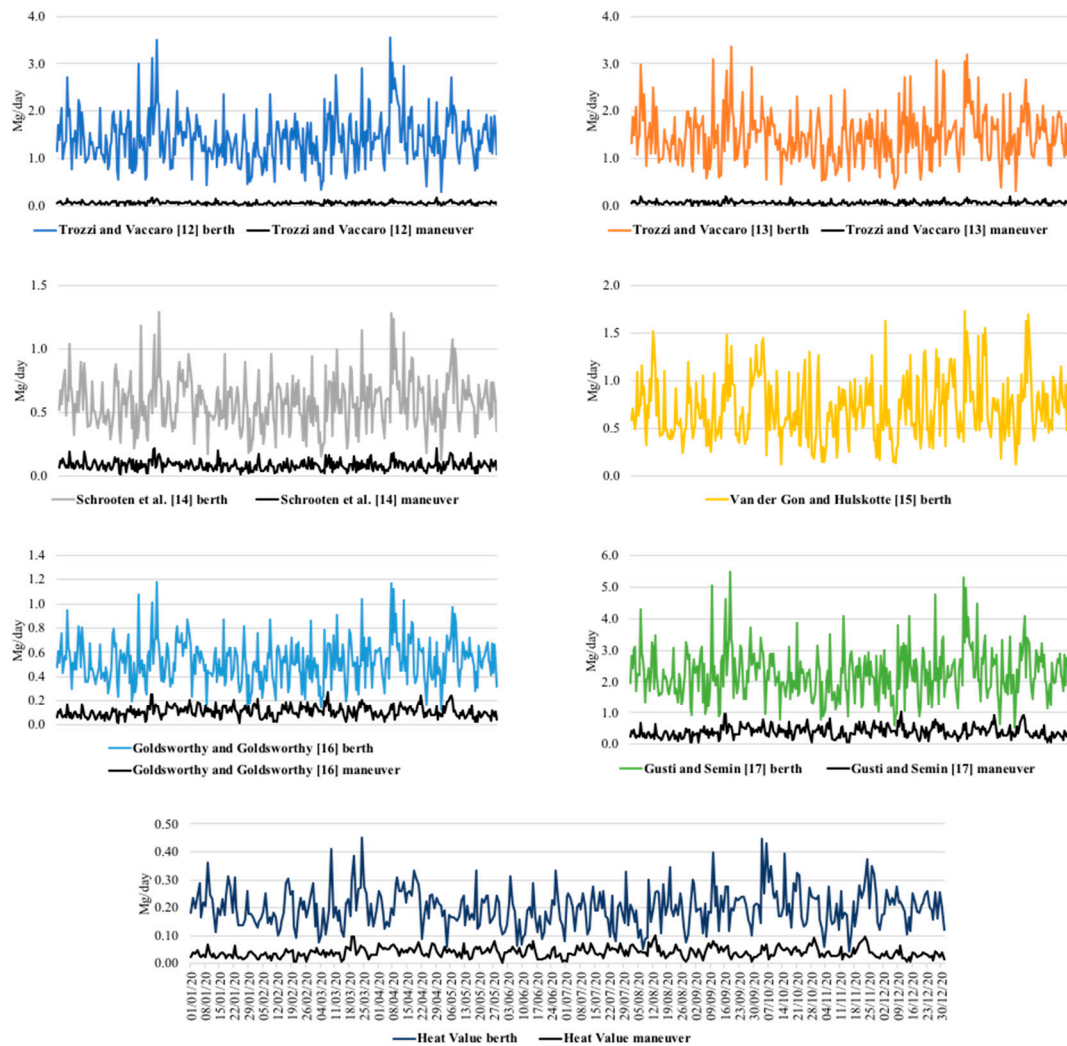


Figure 4. Atmospheric SO₂ emissions (Mg/day) in berthing and maneuvering positions for each method.

The correlation factor for each method according to Pearson tests is shown in Table 9. The Van der Gon and Hulskotte method presented low correlation coefficient, due to the algorithm to determine the level of fuel consumption and atmospheric emission depending on *GT* and not the power of *ME* and *AE*. The Trozzi and Vaccaro methods have a good correlation coefficient due to being based on the level of *GT* to determine fuel consumption; these methods do not consider the power of *ME* and *AE*. We found that the major correlation coefficient is shown for the Goldsworthy method and Schrooten, as well as the Goldsworthy method and Heat Value method, due to the algorithm being the same, i.e., the parameters to determine the level of fuel consumption and atmospheric emissions are the same.

Here we examine the relationship between daily total emissions and the number of ships that arrived in port during the study period (Figure 7). There is no clear relationship between the number of ships and atmospheric emissions determined by any of the methods tested. This is problematic, since the *GT*, number of arrivals, and berthing time by ship type are factors that would be expected to influence atmospheric emission levels. The Trozzi and Vaccaro emissions estimates are higher because they do not consider technical aspects of *AE* operation by ship type in the berthing situation.

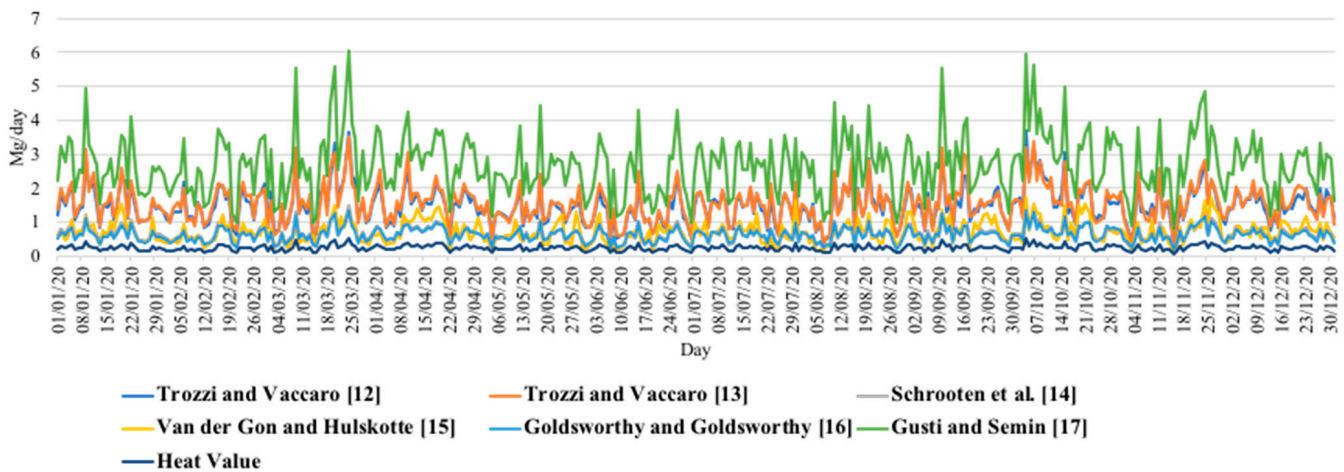


Figure 5. Total atmospheric SO₂ emissions (Mg/day), berthing + maneuvering position, for each method.

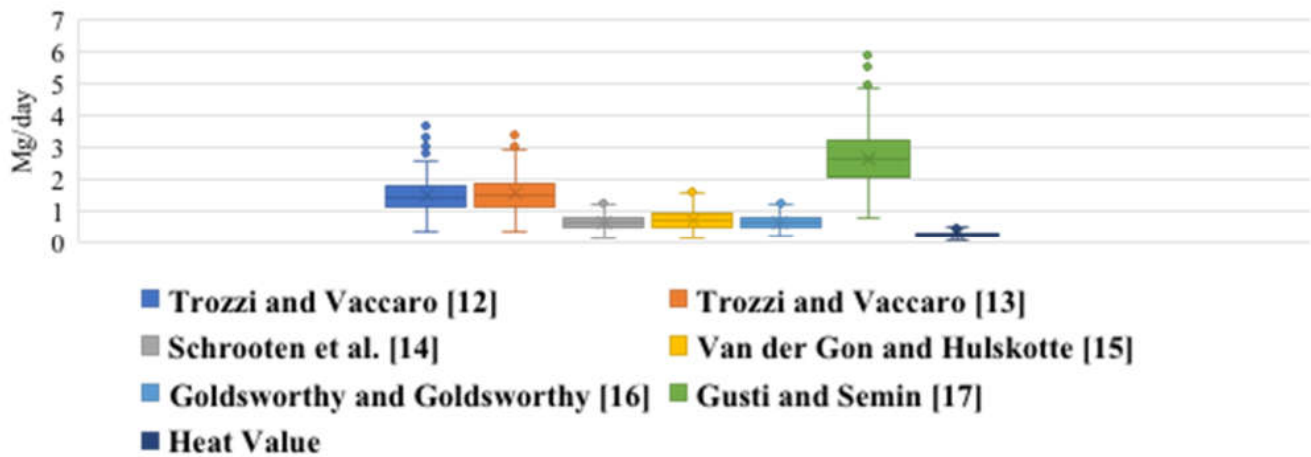


Figure 6. Boxplot of atmospheric emissions (Mg/day) for each method.

Table 9. Correlation Coefficient (R²) according to Pearson test.

Method	Trozzi and Vaccaro [12]	Trozzi and Vaccaro [13]	Schrooten et al. [14]	Van der Gon and Hulskotte [15]	Goldsworthy and Goldsworthy [16]	Gusti and Semin [17]	Heat Value
Trozzi and Vaccaro [12]	1.00000	0.93027	0.90468	0.55793	0.86807	0.92246	0.86493
Trozzi and Vaccaro [13]	0.93027	1.00000	0.89452	0.49810	0.86388	0.91322	0.86230
Schrooten et al. [14]	0.90468	0.89452	1.00000	0.67816	0.97557	0.92957	0.97518
Van der Gon and Hulskotte [15]	0.55793	0.49810	0.67816	1.00000	0.65994	0.47072	0.65812
Goldsworthy and Goldsworthy [16]	0.86807	0.86388	0.97557	0.65994	1.00000	0.94481	0.99995
Gusti and Semin [17]	0.92246	0.91322	0.92957	0.47072	0.94481	1.00000	0.94399
Heat Value	0.86493	0.86230	0.97518	0.65812	0.99995	0.94399	1.00000

The correlation coefficient (R²) between atmospheric emissions and the number of vessels was 0.38 for all methods except for the Van der Gon and Hulskotte method, which presented a correlation coefficient of 0.24.

These levels of correlation coefficients are low, since the typology of ships that arrive at the port of Veracruz is different for each day. For example, in one day, the number of calling vessels may be low and the level of atmospheric emissions may be very high, indicating that in such days, vessels arrived with very high levels of GT, such as container and/or

RoRo cargo vessels. Considering this, it is complicated to understand why the correlation coefficient is low because different factors directly affect the calculations to determine fuel consumption and atmospheric emissions.

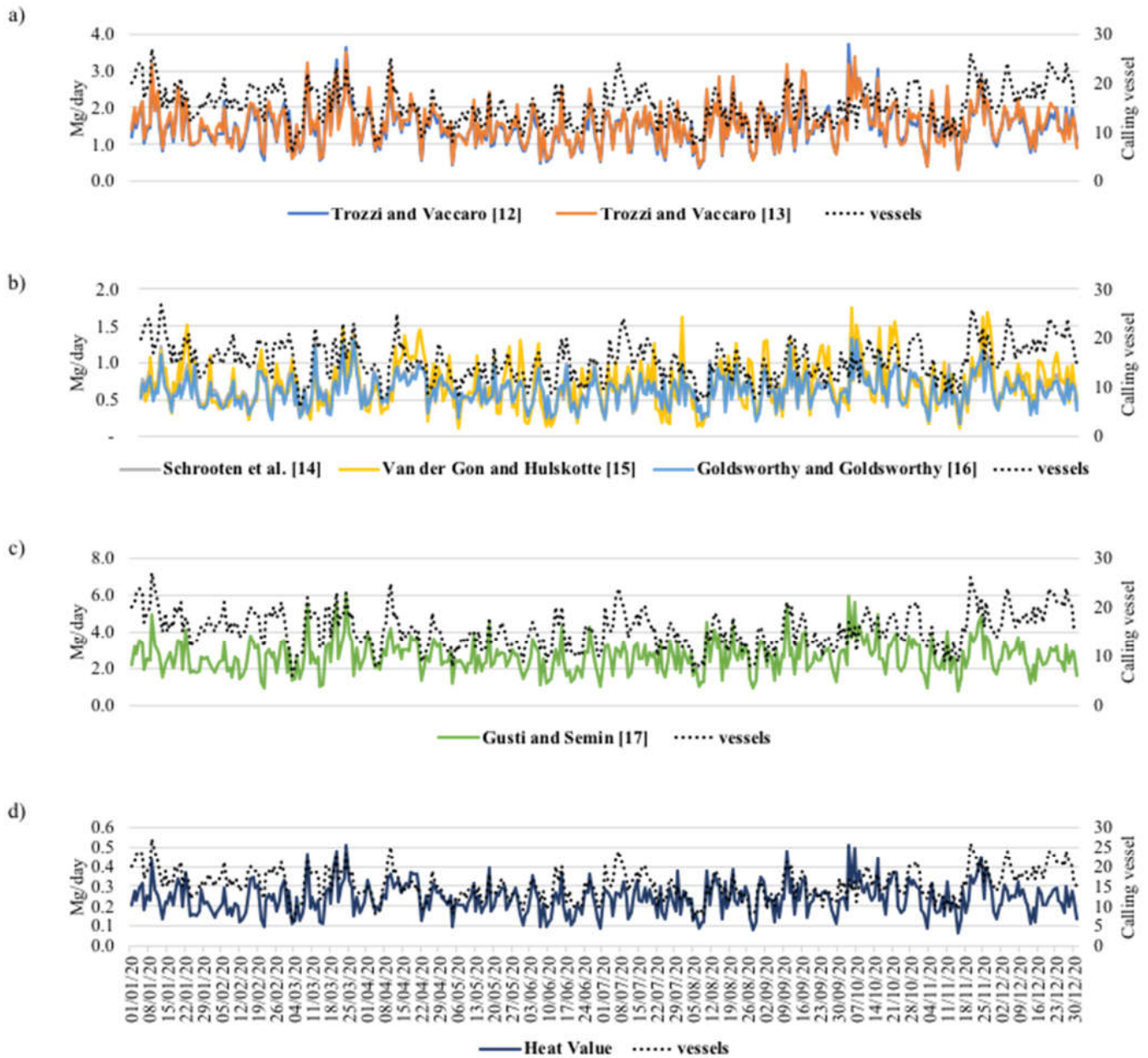


Figure 7. Atmospheric emissions according to the methods of (a) Trozzi and Vaccaro [12,13], (b) Schrooten et al. [14], Van der Gon and Hulskotte [15], Goldsworthy and Goldsworthy [16], (c) Gusti and Semin [17], and (d) Heat Value.

The annual average fuel consumption by ship type for each method is shown in Figure 8 for (a) berthing and (b) maneuvering position. For (a), the method of Gusti and Semin [17] presented the highest fuel consumption levels for all ship types except tanker, for which the Van der Gon and Hulskotte [15] method presented the highest levels. Fuel consumption levels were below $0.5 \text{ Mg}_{fuel}/\text{h}$ for each method for general cargo, agricultural, mineral, tanker, and chemical ship types. Values for the RoRo cargo and container ships were larger, due to their higher GT relative to the other types. The Trozzi and Vaccaro methods do not consider the energy used by the AE, unlike the Schrooten et al. [14], Van der Gon and Hulskotte [15], Goldsworthy and Goldsworthy [16], and Heat Value

methods. These methods presented the lowest levels of fuel consumption because the methods utilized information on *GT*, *SFC*, *AE* power, and *LF*. The Trozzi and Vaccaro [12,13] methods presented similar and considerable levels of fuel consumption.

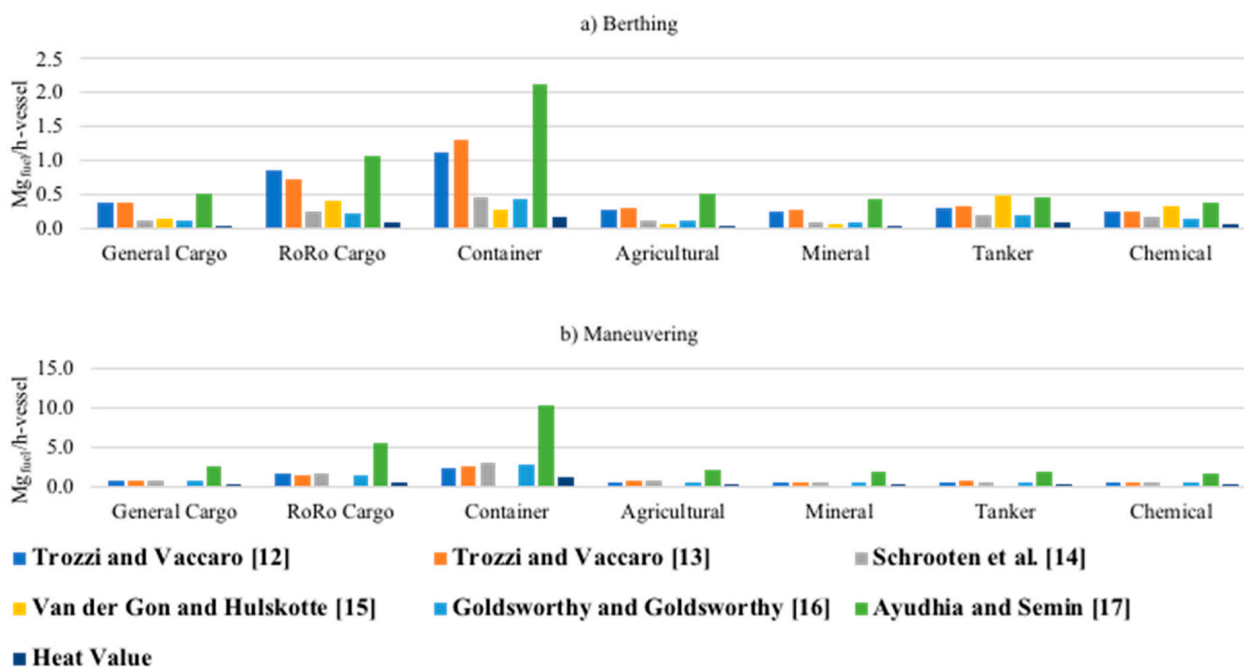


Figure 8. Annual average fuel consumption ($Mg_{fuel}/h-vessel$) for each method in (a) berthing and (b) maneuvering position.

For (b) it is evident that the level of fuel consumption is higher than (a), because in maneuvering position ME and AE are operating for an average of 1 h, and the ME gives propulsion to the vessel to start the maneuvering position. In addition, the *LF* parameter in maneuvering position is important to consider, since both engines are operating; in this case, the *LF* corresponds 0.2 for ME and 0.5 for AE, increasing the level of fuel consumption. RoRo cargo and container vessels represented the highest fuel consumption for each method considered.

The annual average of SO_2 emissions by type of ship and for each method are shown in Figure 9 in (a) berthing and (b) maneuvering position. For (a), the Heat Value method presented the lowest emission levels. The Gusti and Semin [17] method presented the highest atmospheric emission levels for each type of ship except for the tanker type. This method, as with Schrooten et al. [14] and Goldsworthy and Goldsworthy [16], utilizes the same technical parameters—the energy consumption of the AE by ship type. However, the Gusti and Semin [17] method does not consider the *LF*. This creates the difference in estimated emission level; otherwise, the three methods would produce approximately the same result. Given this consideration, the Trozzi and Vaccaro [12,13] methods would represent the maximum level of atmospheric emission as it is based exclusively on the *GT* by ship type, adjusting the fuel consumption in berthing position.

In (b) the level of atmospheric emissions were very low compared with (a), according to the typology of ships. The time spent in maneuvering position is key to producing low levels of atmospheric emissions. RoRo cargo and container vessels represented the highest level of atmospheric emissions for each method. Agricultural, mineral, tanker and chemical vessels represented atmospheric emissions which were lower than 0.05 $Mg/year$.

The results for monthly average fuel consumption for each vessel type and method are shown in Figure 10, in berthing position only. Fuel consumption was higher for container and RoRo cargo vessels in berthing position for nearly all methods used. The exception was the Van der Gon and Hulskotte [15] method, which indicated higher fuel consumption for

tanker and RoRo cargo ships. The two methods that do not consider energy expenditure of the AE in the berthing stage, Trozzi and Vaccaro [12,13], indicated the highest fuel consumption for container ships and RoRo cargo ships, respectively. The Trozzi and Vaccaro method [13] is the preferable of the two, as it incorporates adjustments to the earlier method of Trozzi and Vaccaro [12]. The methods that consider the energy expenditure for AE operation indicate lower fuel consumption levels than the Trozzi and Vaccaro methods. The lowest and highest fuel consumption levels were presented by the Heat Value and Gusti and Semin [17] methods, respectively. The Schrooten et al. [14] and Goldsworthy and Goldsworthy [16] methods, both of which consider the use of the *LF*, fall in between.

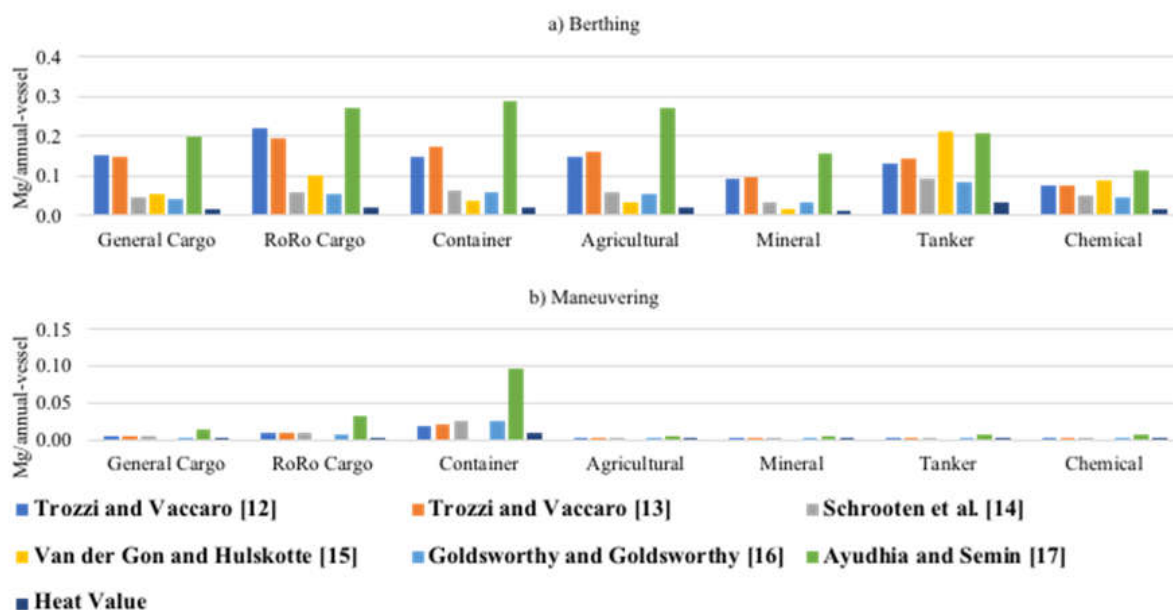


Figure 9. Distribution of atmospheric emission (Mg/annual-vessel) of SO₂ for each method in (a) berthing and (b) maneuvering position.

The monthly distribution of daily average SO₂ emissions by ship type and method is shown in Figure 11, only in berthing situation. Despite the fact that container ships presented a higher fuel consumption, its emission levels were not higher. RoRo cargo ships presented the highest emission levels using the Trozzi and Vaccaro method. This model was a pioneering method for the determination of fuel consumption by ship and cargo type, used very widely in Europe for the estimation of atmospheric emissions, according to Baldasano et al. [55]. Monthly emissions determined by this method were often similar across different ship types to those determined by the Trozzi and Vaccaro [12] and Gusti and Semin [17] methods. The other methods indicate the highest emissions for tanker ships, due mainly to higher *LF* values for this ship type. The Van der Gon and Hulskotte [15] method presents clear evidence of higher SO₂ emissions from tanker ships due to the higher value of the emission factor for this method, while the Heat Value method presented minimum levels of atmospheric emission.

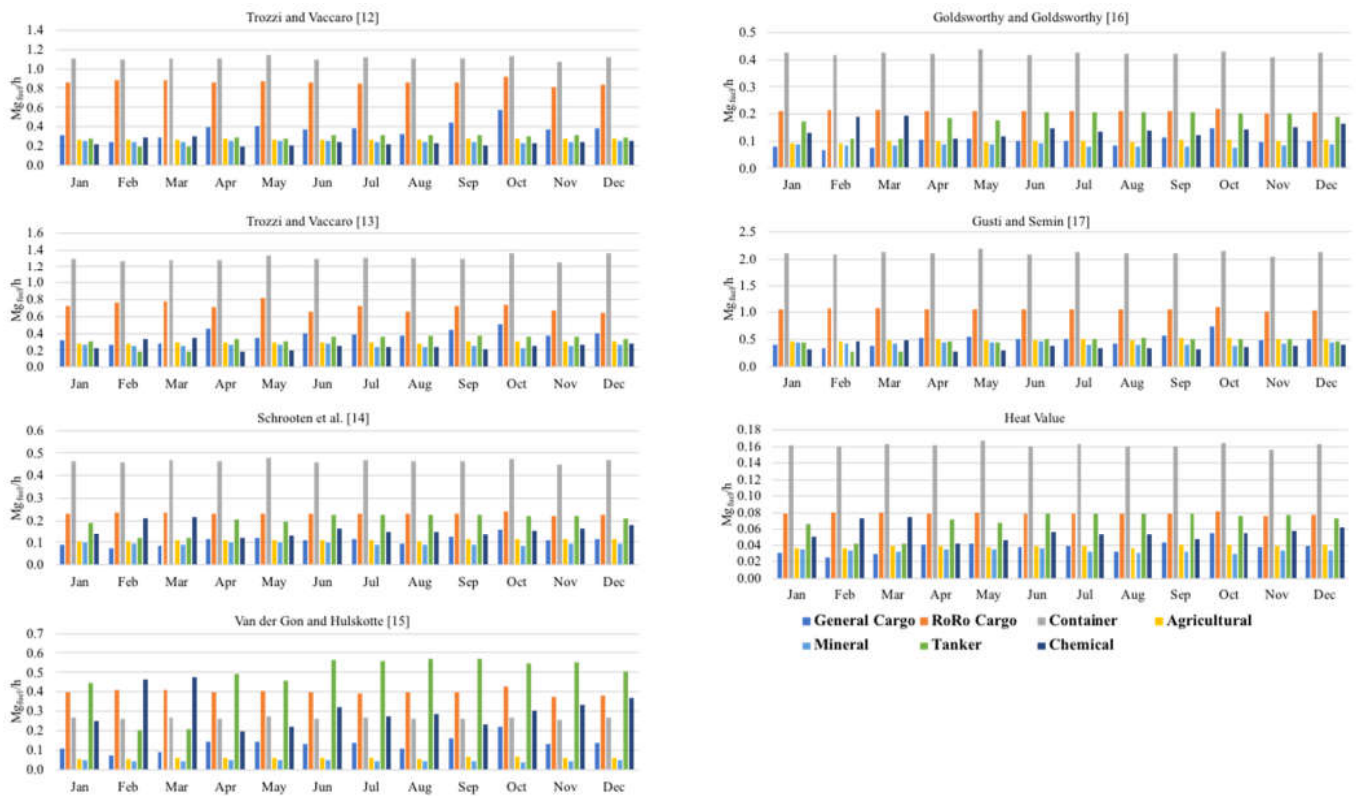


Figure 10. Monthly average fuel consumption (Mg_{fuel}/h) for each type of vessel and method.

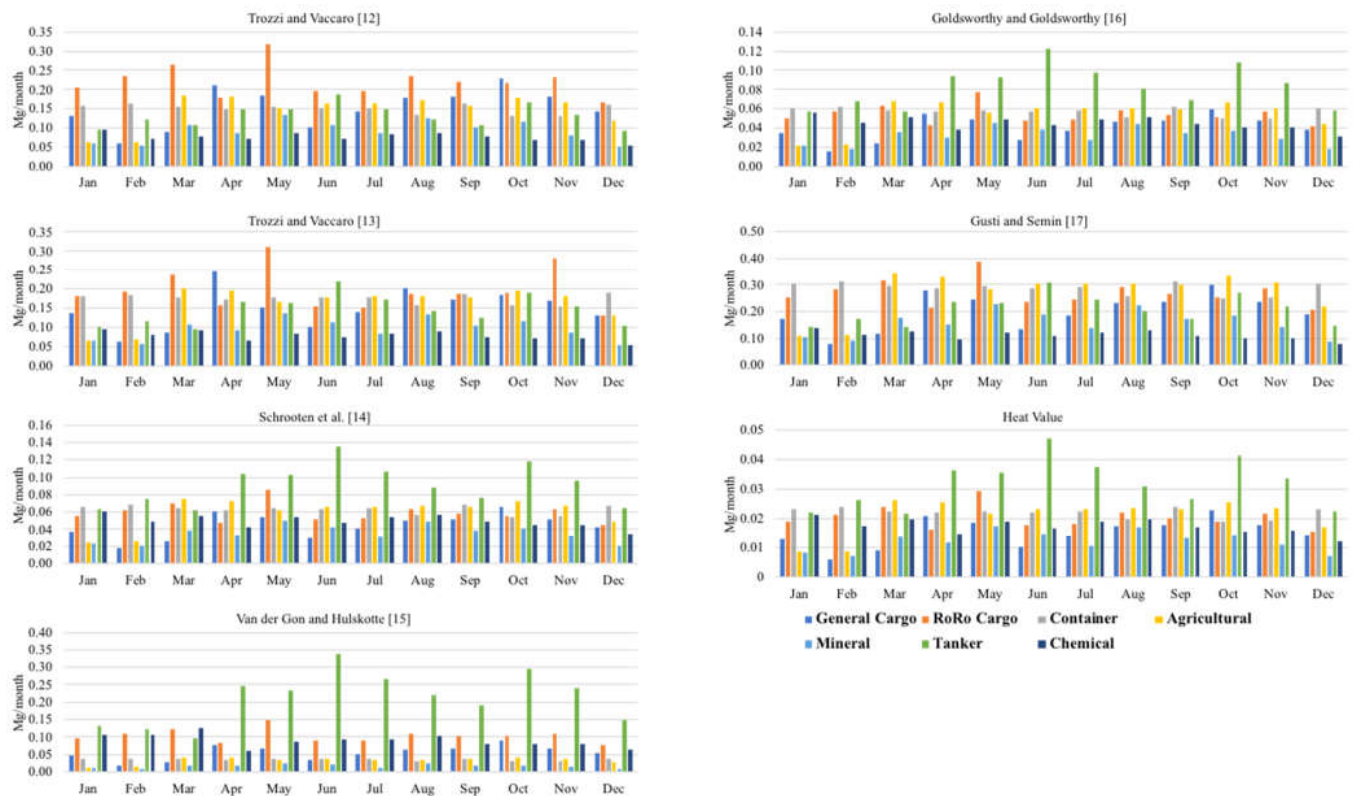


Figure 11. Monthly distribution of average SO_2 emissions (Mg) by type of vessel and method.

6. Conclusions

Our main conclusions reached indicate that:

The Trozzi and Vaccaro methods represented a first scenario for the characterization of fuel consumption and atmospheric emission by type of ship for the port of Veracruz, considering *GT* only. The Van der Gon and Hulskotte method did not represent a good analysis because the method considers vessels with *GT* of 1000 as local vessels. Gusti and Semin presented the highest level of fuel consumption and atmospheric emission for the port of interest because the method does not integrate the *LF* as in other methods based on the technical information of the ships.

The Goldsworthy method, which incorporates detailed technical information, represented the best option to characterize and determine fuel consumption and atmospheric SO_2 emissions by ship and cargo type in the port of Veracruz, according to the official information.

GT is a principal control on atmospheric SO_2 emissions. An average monthly *GT* of 222,674 was found for the port of Veracruz during the study period, with 26.0% corresponding to the RoRo cargo vessel type, 23.9% to container, 11.4% to bulk agricultural, 11.1% to general cargo, 11.0% to tanker, 8.6% to bulk mineral, and 8.0% to chemical.

The Goldsworthy method indicated that the monthly average fuel consumption for the port of Veracruz was 1.24 $\text{Mg}_{\text{fuel}}/\text{h}$ considering berthing position, with 34% attributed to container-type vessels, 17.0% to RoRo cargo, 14.5% to tanker, 11.7% to chemical, 8.0% to bulk agricultural, 7.9% to general cargo, and 6.8% to bulk mineral. The monthly average sulfur dioxide emissions were 365.50 kg/day in berthing position, with 22.7% corresponding to tanker-type vessels, 15.7% to container, 14.8% to bulk agricultural, 14.8% to RoRo cargo, 12.3% to chemical, 11.0% to general cargo, and 8.8% to bulk mineral vessels.

The limitation to our study consisted of not using the automatic identification system generated in the port, because the information is confidential and restricted by the captaincy of the port of Veracruz.

7. Recommendations

Analyzing the sulfur content of marine fuel through analytical methods with respect to the sampling of the type of fuel for all ship types arriving at the port of Veracruz, according to international protocols (American Society for Testing and Materials, ASTM), and comparing to the results of this study with respect to the new sulfur content in fuel from the analytical method.

Generating emission factors based on fuel consumption by type of ship in the docking stage through continuous emission monitoring in the field due to the configuration of the boiler and number of chimneys; this is an important factor for levels of fuel consumption and atmospheric emissions. This activity will be important to evaluate the operations of the Main Engine, Auxiliary Engine and Boiler for both engines.

8. Future Work

To identify trends in fuel consumption in the Mexican port system over the next few years as fossil fuels will continue to be used in Mexico, and the port authority project's continued maritime growth.

To determine fuel consumption and atmospheric SO_2 emissions in the anchoring stage, because adverse weather conditions—frequent in the port of Veracruz—cause ships to remain at anchor for extended periods.

Author Contributions: Conceptualization, J.D.W.K., and R.E.A.D.; Data curation, R.S.E.; Formal analysis, J.M.B.R.; Investigation, G.F.G., R.S.E., and R.E.A.D.; Methodology, G.F.G., R.S.E., and J.M.B.R.; Resources, G.F.G., and R.E.A.D.; Supervision, R.S.E., and J.M.B.R.; Validation, G.F.G., R.S.E., J.M.B.R., and J.D.W.K.; Writing-review and editing, J.D.W.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors of this study are grateful to the Contaminación Ambiental Group at Instituto de Ciencias de la Atmósfera y Cambio Climático of UNAM, especially Ana Luisa Alarcón Jiménez, Elizabeth Vega Rangel, Elías Granados Hernández, Pablo Sánchez Álvarez, José Hernández Téllez, and Humberto Bravo Witt. Instituto de Geografía de la UNAM: Víctor Magaña Rueda and Gustavo Vázquez Cruz. Participation of the staff of the Administración Portuaria Integral de Veracruz (APIVER): Francisco Liaño C., Socaris de la Luz, and David Augusto de la O N. Finally, we acknowledge Universidad Nacional Autónoma de México, Instituto de Ciencias de la Atmósfera y Cambio Climático (ICAYCC) for supporting the lead author's postdoctoral appointment, and Agreement between APIVER and UNAM: "Evaluación de la calidad del aire, depósito atmosférico y meteorología para desarrollar el programa para la prevención y minimización del posible deterioro ambiental significativo en el Recinto Portuario de Veracruz y en las zonas de interés".

Conflicts of Interest: The authors declare no conflict of interest.

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