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EXPORTING EMISSIONS: MARINE FUEL SALES AT THE PORT OF SINGAPORE

Xiaoli Mao, Dan Rutherford, Ph.D., Liudmila Osipova, Ph.D., and Elise Georgeff

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

Maritime shipping is a major contributor to global air pollution and anthropogenic climate change. About 60,000 people die prematurely each year due to exposure to shipping air pollution, and global shipping emits about 1 gigatonne (Gt) of greenhouse gases (GHGs) each year. Heavy fuel oil (HFO), a viscous, residual fuel that remains after higher-value fuels are distilled off crude oil, continues to be burned in marine engines. A related fuel, very low sulfur fuel oil (VLSFO), is also gaining favor as a means to comply with international marine fuel standards that took effect in 2020.

Burning HFO in marine engines emits fine particulate matter ($PM_{2.5}$), sulfur oxides (SO_x), and nitrogen oxides (NO_x) that drive premature mortality and morbidity in coastal communities. Earlier work found that most early deaths occur in Asia, and Singapore, the world's largest seller of marine bunker fuel, suffers the world's highest per-capita premature death rate from shipping emissions. Singapore sells about one-fifth of the world's marine fuel and more than three times that of any other country. Accounting for GHG emissions from marine fuel sales would quadruple Singapore's domestic inventory and increase emissions per capita to six times the global average if they were attributed to the country.

A shift away from residual fuels like HFO and VLSFO to low- or zero-carbon marine fuels is crucial to improve public health and meet climate goals. But this shift could risk Singapore's dominance in marine fuel markets. Currently, a handful of ports sell most of the world's marine fuels, and this is possible because the high energy density of fossil marine fuels allows oceangoing vessels to operate over long distances without refueling. Renewable marine fuels, in contrast, have lower energy density and thus their deployment implies more widespread and diverse bunkering, particularly if the fuels are generated using distributed renewable electricity.

Using a new research method, we identify ships that bunker (i.e., purchase and load) residual fuels in Singapore, and we quantify and map the distribution of air and water pollution that is generated when the fuel is burned. Water pollution occurs from ships that use high-sulfur HFO in combination with exhaust gas cleaning systems, also called scrubbers, as these spray the exhaust with seawater to cut air pollution and dump discharge overboard. We estimate both the absolute and relative share of air and water pollution by sea region, country, and port. This knowledge can inform efforts to shift to low- and zero-carbon marine fuels throughout the globe, and we consider policy implications and areas ripe for future research.

We estimate that Singapore sells 35 million tonnes (Mt) of marine residual fuels to large cargo ships each year. The consequence is significant air and water pollution. While Singapore's marine fuel sales exert a global environmental footprint, much of the pollution is concentrated in seas and coastal areas neighboring the country. Figure ES-1 shows the distribution of $PM_{2.5}$ pollution from marine fuels sold in Singapore. In the seas surrounding Southeast Asia, marine residual fuel sold in Singapore accounts for more than 42% of all shipping $PM_{2.5}$, as shown in the darkest blue color. Hot spots are also seen in the South China Sea, the Indian Ocean, and throughout Oceania, including along the western and southern coasts of Australia.

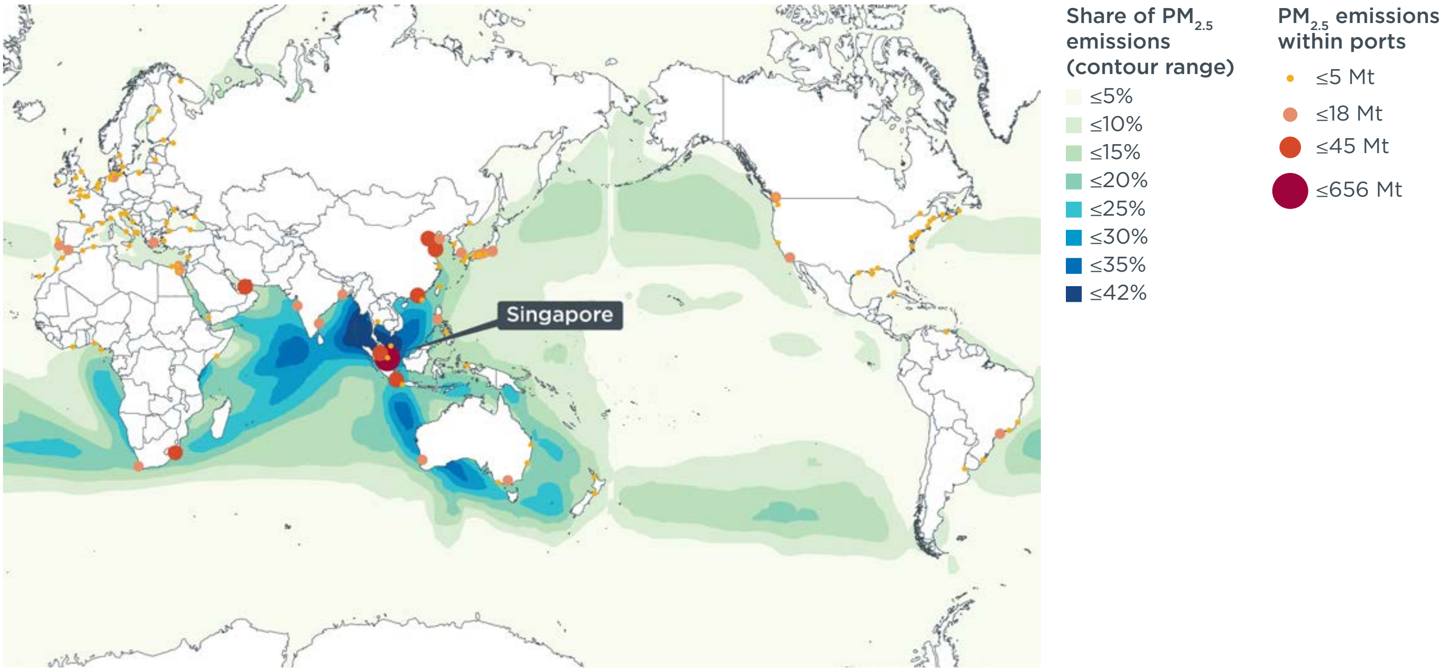

Figure ES-1. Share and mass of shipping $PM_{2.5}$ emitted by ships burning residual fuel sold in Singapore.

Lower shares are seen in transpacific voyages to North America and voyages to South America in the Southern Hemisphere. In contrast, residual fuel bunkered in Singapore contributes less to air pollution in Europe, where other bunkering options, such as Rotterdam in the Netherlands, are available.

Table ES-1 summarizes the share of shipping emissions within the Exclusive Economic Zones (EEZs) of select countries from ships burning residual fuel bunkered in Singapore. Emissions are ranked in order of absolute tonnes of $PM_{2.5}$; data for the regional share of NO_x and scrubber washwater emissions are also presented. Countries where fuel bunkered in Singapore is responsible for more than 30% of $PM_{2.5}$ within their EEZ are highlighted in dark blue; countries with between 20 and 29% are highlighted in light blue. Singapore ranks low in terms of absolute emissions, owing to the small size of its EEZ, but high in terms of relative contribution of $PM_{2.5}$ (35%) and NO_x (29%) from ships burning residual fuel bunkered in Singapore. Other neighboring countries, including Malaysia (37% of shipping $PM_{2.5}$), Vietnam (30%), Sri Lanka (25%), Indonesia (23%), and India (22%), are also heavily impacted by Singapore marine fuel sales.

Table ES-1. Share of shipping emissions in Exclusive Economic Zones of select countries from ships burning residual fuel bunkered in Singapore

Exclusive Economic Zone	$PM_{2.5}$		NO_x		Scrubber washwater	
	Thousand tonnes (kt)	Share of shipping total	Thousand tonnes (kt)	Share of shipping total	Million tonnes (Mt)	Share of shipping total
Indonesia	9.13	23%	215	19%	187	37%
China	8.24	14%	195	13%	181	40%
Malaysia	4.42	37%	100	31%	33.6	43%
Vietnam	4.37	30%	104	25%	98.1	45%
India	4.05	22%	94.8	20%	132	41%
Australia	2.42	18%	54.1	14%	50.2	29%
Japan	2.32	7%	52.4	5%	59.0	19%
Sri Lanka	2.05	25%	49.6	23%	56.1	42%
Taiwan	1.85	18%	43.9	14%	52.9	32%
Philippines	1.78	11%	40.9	8%	43.8	22%
Singapore	0.752	35%	12.6	29%	4.68	44%

Singapore's marine fuel sales contribute even more heavily to scrubber washwater discharges than for $PM_{2.5}$ and NO_x. For the most heavily impacted regions – Vietnam, Malaysia, Sri Lanka, India, China, and Singapore itself – marine fuel bunkered in Singapore is responsible for at least 40% of all scrubber discharges in their EEZs despite scrubber washwater discharge bans in some countries. For example, Singapore banned discharges at port, but that covers only a small portion of their EEZ. Other countries like China ban discharges within 12 nautical miles (nm) of shore, but all EEZs extend up to 200 nm from shore.

These findings hold several implications. First, air pollution and water pollution could be mitigated by transitioning away from residual fuels to renewable fuels. This transition may result in a more distributed bunkering network, whereby other countries in the region will produce and sell marine fuels that might otherwise be bunkered in Singapore. Countries like China, Malaysia, Indonesia, and Australia have an opportunity to both produce and sell renewable marine fuels to ships calling on their ports. Using renewable marine fuels instead of residual fuels will reduce air and water pollution, protect public health, and provide economic benefits to the countries that sell them.

Second, Singapore would need to increase efforts to supply renewable fuels in order to remain an important bunkering port. In addition to its current initiatives, Singapore could consider further efforts to transition away from fossil bunkering and reconsider any further investments in liquefied natural gas (LNG), which provides limited, if any, life cycle GHG reduction relative to conventional marine fuels. Integrating shipping into Singapore's domestic GHG inventory and Nationally Determined Contribution would further demonstrate the country's commitment to decarbonizing its marine fuel sales.

Lastly, Singapore could lead regional and global efforts to advance regional and international green shipping corridors under agreements like the 2021 Clydebank Declaration. Relevant international green shipping corridors could link Singapore to Asian countries, the Middle East, Europe, and North America.

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INTRODUCTION

Maritime shipping contributes significantly to global air pollution and anthropogenic climate change. At least 60,000 people die prematurely each year due to exposure to shipping air pollution (Rutherford & Miller, 2019; Sofiev et al., 2018) and global shipping emitted more than 1 gigatonne (Gt) of greenhouse gases (GHGs) in 2018 (Faber et al., 2020). But less is known about the global distribution of marine fuel bunkering and fuel supply, and how the resulting emissions impact air quality and public health.

Heavy fuel oil (HFO) is a dense, viscous residual fuel that remains after higher-value fuels are distilled off crude oil. Due to high concentrations of aromatics and other impurities, including sulfur and heavy metals, HFO emits substantial air pollution when burned. In January 2020, the International Maritime Organization (IMO) lowered the maximum allowable level of sulfur in fuel oils globally from 3.5% to 0.5% by mass. To comply, many ships switched to a new residual fuel called very low sulfur fuel oil (VLSFO). Burning HFO and VLSFO in marine engines harms public health by emitting fine particulate matter ($PM_{2.5}$),[1] sulfur oxides (SO_x), and nitrogen oxides (NO_x), the latter of which contribute to ground-level ozone and secondary particulate formation.

There are several other means of complying with IMO's fuel sulfur limit. Oceangoing vessels can burn distillate fuel, which is a cleaner burning alternative that is used when ships enter Emission Control Areas (ECAs) around North America and Europe; it is also used in a variety of other transport applications, including smaller ships, heavy-duty road vehicles, and aircraft.[2] Ships can also comply with the sulfur limit by using exhaust gas cleaning systems, or "scrubbers." Scrubbers remove sulfur oxides from the exhaust but discharge polluted washwater into the sea. Scrubbers are generally optimized to reduce sulfur dioxide (SO_2) and are less effective at controlling other air pollution.[3] Singapore is the world's largest seller of marine bunker fuel, and an estimated one-quarter of its fuel sales today remain HFO due to scrubbers (Ship & Bunker, 2021b).

Fossil fuels burned in shipping produce air pollution that contributes to premature mortality and morbidity. Table 1 lists the top 20 countries in terms of absolute and per capita premature mortality in 2015 from shipping PM and NO_x.

1 Defined as fine particulate matter with an aerodynamic diameter of 2.5 micrometers or less.

2 The most common marine distillate fuel is marine gas oil (MGO), which contains less than 0.1% sulfur by mass. Many smaller ships run solely on MGO, whereas larger ships may switch between VLSFO and MGO in Emission Control Areas, places where the maximum allowable fuel sulfur content is 0.1%, unless the ship uses a scrubber to comply.

3 For example, Comer et al. (2020) found that while scrubbers reduce SO_2 by 30% more than ships using 0.07% sulfur MGO, ships with scrubbers emit nearly 70% more PM compared with MGO and 81% to 353% more black carbon, depending on the engine. Scrubbers also discharge acidic and turbid washwater that contains nitrates, polycyclic aromatic hydrocarbons, and heavy metals that worsen water quality, threaten marine life, and potentially impact humans that interact with the water or consume seafood (Comer et al., 2020; Georgeff et al., 2019; Osipova et al., 2021).

Table 1. Premature mortality linked to shipping air pollution, 2015 (Rutherford & Miller, 2019)

Top 20 countries by early deaths from shipping emissions, 2015			
Rank	Country	2015 shipping deaths	Share of shipping deaths
1	China	22,400	37%
2	Japan	4,100	7%
3	India	3,400	6%
4	United Kingdom	3,200	5%
5	Indonesia	1,900	3%
6	Germany	1,900	3%
7	Brazil	1,400	2%
8	Vietnam	1,400	2%
9	Italy	1,300	2%
10	United States	1,200	2%
11	France	1,100	2%
12	Egypt	1,100	2%
13	Malaysia	1,000	2%
14	Netherlands	880	1%
15	Spain	880	1%
16	Philippines	730	1%
17	Turkey	730	1%
18	South Korea	690	1%
19	Russian Federation	600	1%
20	Morocco	590	1%
	Top 20	50,500	84%
	Other	9,200	16%
	Total	**59,700**	**100%**

Source: Anenberg et al. 2019. https://www.theicct.org/publications/health-impacts-transport-emissions-2010-2015

Top 20 countries by per capita early deaths from shipping emissions, 2015		
Rank	Country	Shipping deaths per 100,000 population[a]
1	Singapore	7.9
2	Denmark	5.5
3	Netherlands	5.3
4	United Kingdom	5.1
5	Belgium	4.7
6	Ireland	4.0
7	Malaysia	3.6
8	Japan	3.4
9	Mauritius	3.2
10	Portugal	2.4
11	Germany	2.4
12	Italy	2.3
13	Spain	1.9
14	Cuba	1.9
15	Morocco	1.8
16	France	1.8
17	China	1.6
18	Sri Lanka	1.6
19	Sweden	1.6
20	Vietnam	1.5
	Top 20	2.0
	Other	0.4
	Total	**0.8**

[a] Not age adjusted; excludes countries with fewer than 10 total deaths attributable to shipping.

As shown in Table 1, eight of the top 20 countries in terms of absolute premature mortality from shipping air pollution in 2015, and six of the top 20 in terms of per capita mortality that year, were in Asia. Moreover, Singapore was the most heavily impacted country in terms of premature deaths per capita at 10 times the global average. These impacts are directly related to the large volume of shipping traffic off Asia's shores and the strategic position of Singapore along major shipping routes.

SINGAPORE'S DOMINANCE IN MARINE BUNKERING

Marine fuel bunkering is highly concentrated and dominated by a relatively small number of ports (Figure 1). More than half of globally tracked fuel sales in 2019 occurred in the 16 busiest ports (Ship & Bunker, 2021a). Of these, Singapore is by far the most important, responsible for about one-fifth of sales, or three times that of the next largest, which is the Amsterdam, Rotterdam, Antwerp port cluster in the Netherlands. This concentrated fossil fuel infrastructure is enabled by HFO's high energy density, which allows oceangoing vessels to operate long distances and refuel infrequently at a handful of ports with large economies of scale.

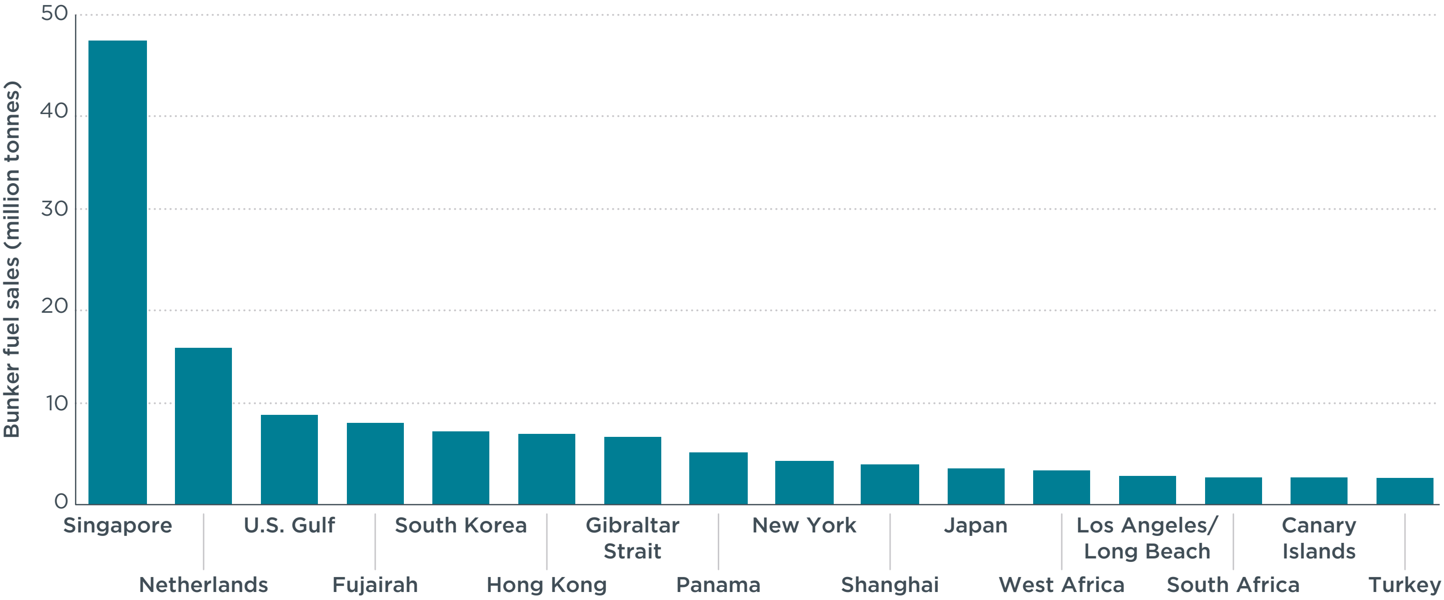

Figure 1. Marine bunker fuel sales in the world's top 16 bunker ports in 2019

Figure 2 shows the breakdown of marine fuels bunkered annually in Singapore from 2011 to 2021 (year to date through September). In 2019, Singapore sold about 47 million tonnes (Mt) of marine bunker fuel, or about one-fifth of tracked sales globally.[4] These sales are supported by a rigorous bunkering license system to safeguard bunker fuel quality and deter malpractice (Maritime Port Authority of Singapore, 2021d). As shown, residual fuel—HFO and 0.5% sulfur VLSFO—account for about 90% of all fuel sales at port; cleaner-burning distillates like marine gas oil (MGO), marine distillate oil (MDO), and low sulfur marine gas oil (LSMGO) account for the bulk of the rest. Starting in 2019, sales shifted dramatically away from HFO and to VLSFO to comply with IMO's 2020 limit, and the latter now accounts for two-thirds of all marine fuel sales in Singapore. Given their prominence and excess emissions when burned, this report focused on emissions from HFO and VLSFO.

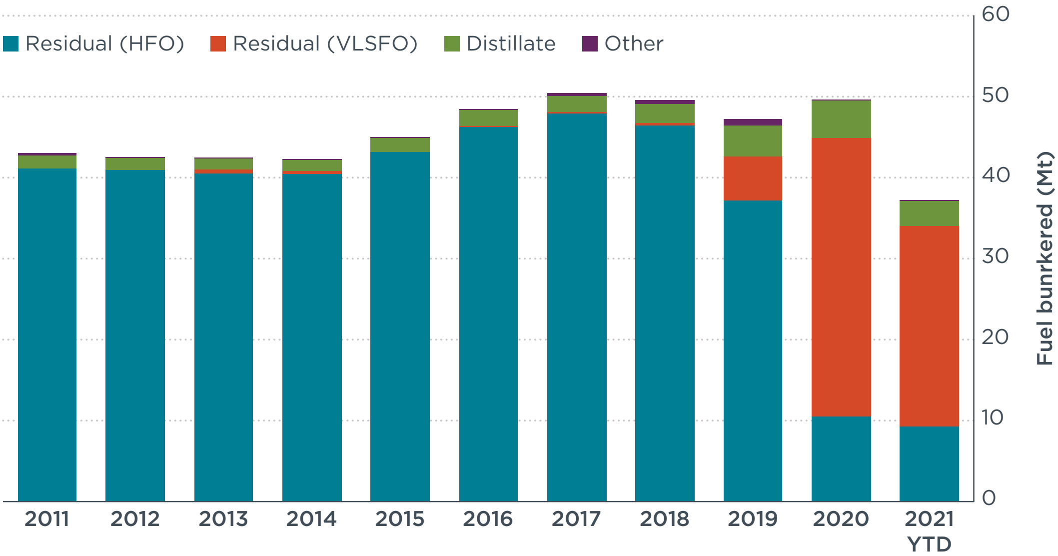

Figure 2. Marine fuel mass bunkered in Singapore, 2011 to 2021 (through September).
Source: Maritime Port Authority of Singapore (2021b)

4 There remains uncertainty about both the volume and location of marine fuel sales globally. According to IMO's (2020) Data Collection System (DCS), which covers an estimated 93% of global gross tonnage, maritime shipping consumed 213 Mt of fuel in 2019. The International Energy Agency estimates that 219 Mt of bunker fuel was sold in 2019 after correcting for apparent double counting of OECD countries (IEA, n.d.). In contrast, Faber et al. (2020) estimates that international shipping emitted 919 Mt CO_2 in 2018, which corresponds to about 300 Mt of fuel sales.

Greenhouse gas emissions from marine bunker fuel sales in Singapore dwarf those from its domestic economy. As shown in Figure 3, from 2000 to 2019, GHG emissions from Singapore's domestic economy increased by 32%, from 39 to 52 million tonnes of CO_2 equivalent (CO_2e, using 100-year global warming potentials). By our estimates, over the same period GHG emissions from marine fuel sales more than doubled, from 58 Mt to 148 Mt CO_2e. Put another way, GHG emissions from marine fuel sales would quadruple Singapore's GHG inventory and increase per capita emissions to six times the global average (Ritchie & Roser, 2020) if they were attributed to that country.[5]

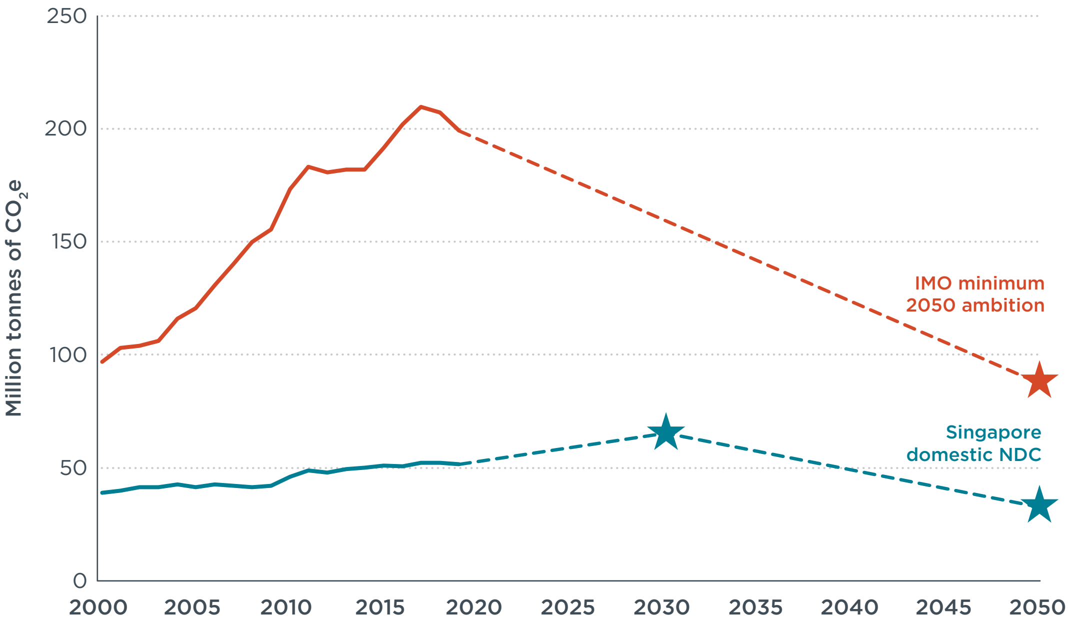

Figure 3. GHG emissions from Singapore's domestic economy (blue) and marine fuel sales (red), 2000 to 2019, with projections to 2050 (dashed lines) and absolute emissions targets from Singapore's NDC (blue stars) and IMO's initial GHG Strategy (red star).
Source: ICCT analysis of Singapore Department Of Statistics (n.d.)

To contribute proportionately to IMO's goal of reducing shipping pollution by at least 50% from 2008 levels, Singapore would need to reduce the GHG intensity of its marine fuel sales by two-thirds by 2050, or below 2000 levels. Cuts to domestic emissions will also be needed under its National Determined Contribution (NDC) under the Paris Agreement.[6] Possible emissions trajectories toward those goals are shown in dotted lines on Figure 3.

LOW-CARBON MARINE FUELS

Interest is growing in low- and zero-carbon alternative marine fuels.[7] Vessels fueled by hydrogen, ammonia, and methanol have the potential to power large oceangoing

5 While a few countries, including the United Kingdom, integrate international aviation and shipping (IAS) emissions into their national inventories and carbon budgets, most countries do not. The question of how international transport emissions could be allocated to individual countries has been a topic of international discussion under the UNFCCC's Subsidiary Body for Scientific and Technical Advice (SBSTA) since 1995. In 1997, SBSTA outlined five options for attributing international transport emissions to countries for future refinement: (1) no allocation; (2) allocation by fuel sales; (3) allocation by where a plane or ship, or operator is registered; (4) allocation by country of departure or destination of the plane or ship; or (5) allocation by country of departure or destination of payload (passengers or cargo). See SBSTA (1997); and Murphy (2018). The attribution issue remains unsettled; for this paper we apply option 2.

6 In February 2022, Singapore announced a new goal to transition to a net zero economy "by or around 2050" and an increasing carbon tax to support that goal (NCCS, 2022). This target is yet to be codified under a revised NDC.

7 Throughout this paper, we use the term "low- and zero-carbon marine fuels" to indicate alternative fuels that have low or near-zero GHG emissions on a life-cycle basis. Not all alternatives to fossil residual fuels will have a lower GHG intensity. For example, Pavlenko et al. (2020) found that using liquefied natural gas (LNG) could worsen shipping's climate impacts due to methane slip from marine engines.

vessels with low life-cycle emissions if made using additional renewable electricity. Hydrogen, which historically has been used in space programs, can be used in fuel cells or burned in internal combustion engines. Hydrogen can be stored as a pressurized gas or cryogenic liquid in insulated tanks but has a much lower (about one-eighth) the volumetric energy density than HFO. Ammonia is denser and more easily stored than hydrogen, but it is toxic and will produce NO_x and nitrous oxide (N_2O) emissions if burned. Methanol, if sourced and produced responsibly, has the potential to be less emitting than liquefied natural gas (LNG) and safer than ammonia. However, methanol contains carbon and many current sources of methanol do not have sustainable feedstocks (Zhou et al., 2020).

Operating ships on hydrogen, ammonia, or methanol will reduce air pollution compared to residual fuels but given the less energy per unit volume, such ships would have shorter operational ranges for a given fuel tank size. Shifting from residual fuels to renewable fuels thus could challenge the current concentrated HFO bunkering system and open up new opportunities for the distributed production and sale of marine fuels (Georgeff et al., 2020).[8]

In today's bunkering system, the largest ships refuel as infrequently as once every three months (90-day endurance range) at a handful of large ports. Figure 4 shows the estimated operational ranges of ships that bunkered residual fuel in Singapore compared to if they were retrofitted to use alternative fuels. Details about how these ranges were calculated are provided in Appendix A. Representative distances ranging from about 9,000 km (Long Beach to Tokyo) up to approximately 40,000 km (the equatorial circumference of the Earth) are shown as dotted horizontal lines.

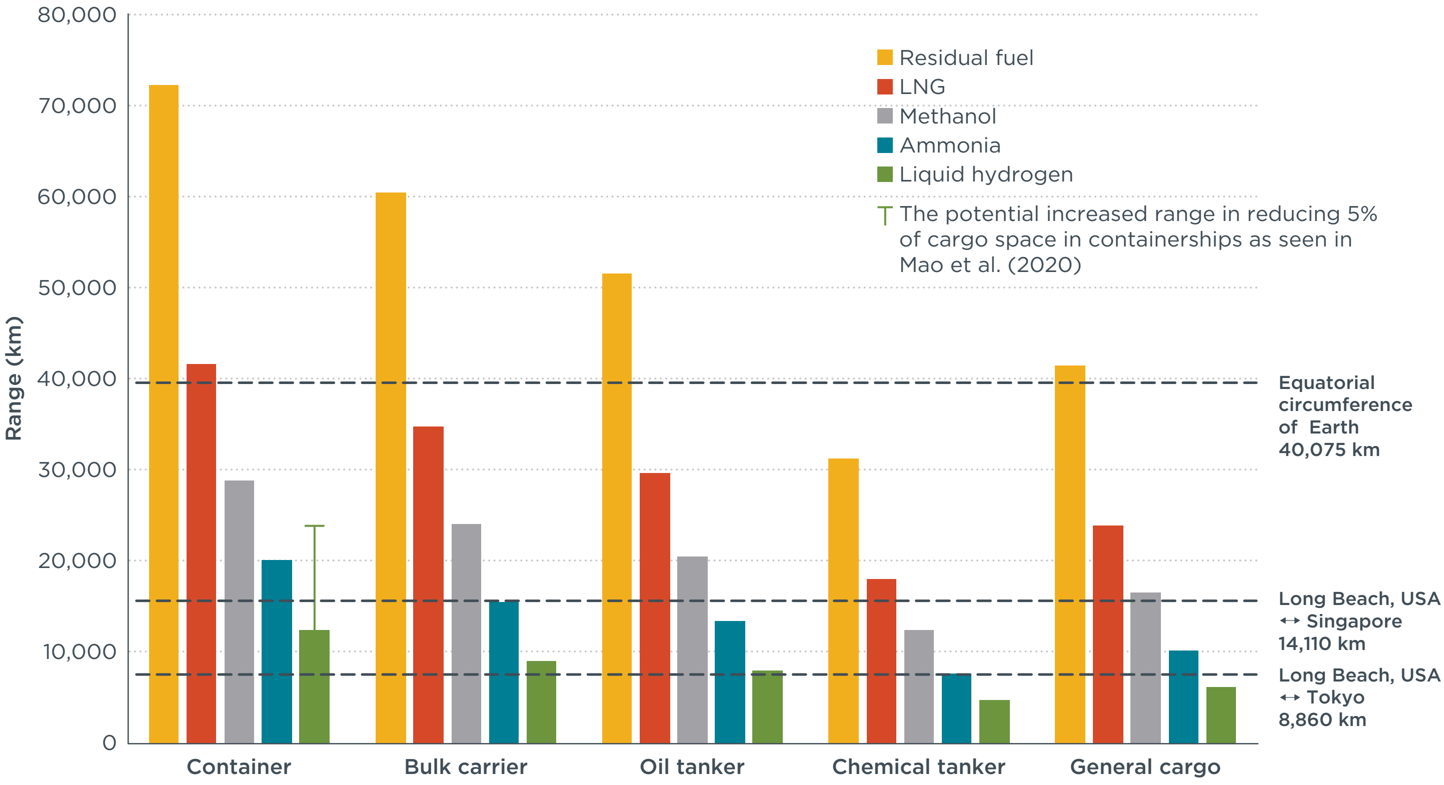

Figure 4. Potential operational ranges for retrofitted ships that bunker in Singapore, by ship type and fuel type

8 Liquid biofuels, in contrast, contain about as much energy per unit volume and mass as residual fuels and can also reduce air pollution from ships, but require careful accounting to ensure that they actually reduce GHGs on a life-cycle basis by accounting for direct and indirect land use change (Zhou et al., 2020).

As shown, many ship types that bunker in Singapore can carry enough residual fuel to circumnavigate the globe at least once before refueling, and can navigate a one-way, 14,000 km voyage between Singapore and Long Beach, California two or three times. Alternative fuels, in contrast, provide shorter ranges for the same engine plus fuel tank volume. Some ships operating on lower density marine fuels, notably liquid hydrogen, would need to make at least one refueling stop between Singapore and California. Previous work (Mao et al., 2020) showed that less than half (43%) of container voyages between China's Pearl River Delta and California's San Pedro Bay Ports could be achieved using liquid hydrogen without operational or design changes. Ninety-nine percent of those voyages, however, could be attained by adding an additional refueling stop.

Figure 4 assumes a simple retrofit of a vessel's fuel tank and engine while maintaining all existing cargo carrying capacity. For newbuild liquid hydrogen ships in particular, it is likely that additional fuel storage would be provided. Ship range could be boosted by reducing the cargo capacity of a ship modestly in order to increase fuel carriage. Mao et al. (2020) found that 99% of transpacific voyages could be met by supplementing fuel volume by reducing cargo volume by 5%. The resulting operational range is shown as the whisker on the green liquid hydrogen bar for container ships. Thus, the ranges outlined in Figure 4 should be considered conservative for newbuild vessels operating on less-energy-dense fuels.

Singapore has begun investing in low-carbon marine fuels. Its 2030 R&D roadmap (Singapore Maritime Institute, 2021) established a goal to develop alternative energy solutions and the related supporting infrastructure for marine applications. It has also joined the Castor Initiative, a joint project with five companies and Lloyd's Register to develop an ammonia-fueled tanker (Maritime Port Authority of Singapore, 2021a). The Maritime Singapore Decarbonisation Blueprint 2050 Consultation Document (Maritime Port Authority of Singapore, 2021c) includes a focus area to develop Singapore as an Asian hub for maritime decarbonization R&D. The final reported released in March 2022 included several concrete climate goals, including to achieve net zero emissions from port terminal operations, to reduce absolute emissions from harbor craft by 50% below 2021 levels in 2050, and to support the transition to future marine fuels through R&D, infrastructure investments, and international engagement at IMO (Maritime Port Authority of Singapore, 2022). Finally, the government of Singapore has signed agreements with Australia (Six, 2021) to support the adoption of low-carbon marine fuels and with the United States and to improve the sustainability of ports and shipping (United States Government, 2021).

The pace at which Singapore transitions away from fossil marine fuels will help determine how quickly maritime shipping decarbonizes. Given its central role in fossil fuel bunkering, the associated air and GHG pollution from those fuels, and the large public health impacts of shipping air pollution in Asia, a better understanding of pollution from marine fuels bunkered in Singapore is needed. To help, this paper quantifies the geographic distribution of air and water pollution from marine fuels sold in Singapore. It provides a better understanding of the stakes involved in accelerating the transition to renewable marine fuels and can inform efforts to shift to such fuels in Singapore, in Asia and Oceania, and throughout the globe.

The balance of this paper is structured as follows. The next section introduces how we identified which ships bunker in Singapore and how we estimated the air and water pollution from those fuel sales. Next, we summarize our key findings, including the magnitude (absolute and relative) of air and water pollution that can be traced back to Singapore residual marine fuel sales by traffic lane, sea region, country, and port. We close by discussing policy implications and areas for future work. Supplemental data is provided in three appendices.

METHODS

This section summarizes how we estimated the air pollution and scrubber washwater impacts of Singapore's marine fuel sales. First, we outline how we used ship Automatic Information System (AIS) data to identify bunkering events and to estimate the volume of residual fuel bunkered at the Port of Singapore. We then outline how we used the Systematic Assessment of Vessel Emissions (SAVE) model to estimate air emissions and scrubber washwater discharges from those fuel sales globally and regionally.

IDENTIFYING BUNKERING EVENTS AND AMOUNTS

Step one of the main analysis was to identify bunkering events in Singapore. Bunkering may take place offshore, at anchor, or alongside the port. It may be pumped from road tanker, bunker barge, or another tanker or ship. Whatever the provider, the procedures followed are similar. The choice of method depends on the quantity of fuel needed, available space at port, density of fuel, and time available for bunkering. Bunker barges are a popular choice at ports due to the flexibility of capacity and the option to be fueled anywhere both ships can anchor. A vessel can unload its cargo shoreside while being fueled by a bunker barge on the other side. Or, for ships anchored at nearby ports, barges can travel to their anchored locations for refueling.

Barge-to-ship bunkering is prevalent at the Port of Singapore. There are 41 accredited bunker barge operators at the Port of Singapore providing over 200 licensed bunker barges to vessels seeking refuel. A barge-to-ship bunkering event involves two parties: a receiving vessel which purchases fuel and a supplier which usually delivers fuel via a bunker barge (Aarsnes, 2018). These bunkering operations take place at designated berths or anchorages. Figure 5 shows the location of bunkering events we identified in the Port of Singapore in 2019.

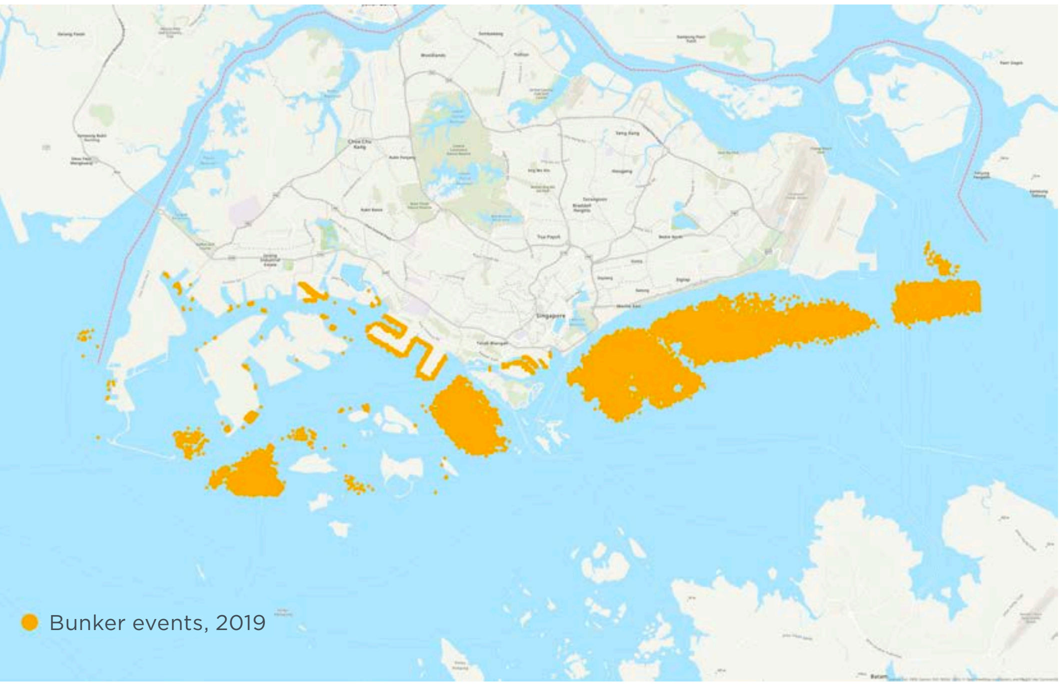

Figure 5. Location of bunker events in Singapore, 2019

During a barge-to-ship bunkering operation, a bunker barge approaches the receiving vessel, connects its hose to the fuel tank manifold, measures the baseline bunker quantities on both vessel tanks, and transfers fuel while monitoring both quantities (Aarsnes, 2018). A bunkering event can be defined based on the time and duration that a bunker barge and receiving vessel remain in close proximity. AIS transponders onboard most oceangoing vessels broadcast ships' positions, speeds, and other identifying information every few seconds and can be used to identify bunkering operations and estimate the mass of fuel bunkered.

The process is as follows. First, we identified bunker barges active at the Port of Singapore using public data.[9] As of July 2020, there were 41 licensed bunker barge operators in Singapore operating a total of 210 bunker barges. Of these, we matched 197 with the IHS Markit ship characteristics database that were also active in 2019, the base year of this study. The remaining 13 vessels might not have been used for bunkering in 2019 and so were excluded from the analysis.

Next, we identified ships that berthed or anchored at the Port of Singapore in 2019 that can operate on residual fuels using our SAVE model. Analyzed ship types included containers, bulk carriers, oil tankers, chemical tankers, general cargo ships, vehicle carriers, roll-on/roll-off ships, refrigerated bulk carriers, and other liquid tankers. Collectively, these ship types accounted for nearly 80% of global shipping fuel use in 2018, according to the *Fourth IMO Greenhouse Gas Study* (Faber et al., 2020).

Using the bunker barge and ship databases, we then identified bunkering events based on when both a ship and bunker barge were at berth or anchor at the same time and at a distance of less than 100 meters for at least 2 hours. The period of time when the receiving vessel and bunker barge were within 100 meters of each other was deemed the bunker duration of that event. If more than one bunker barge was found to meet this criterion, they were counted as separate bunker events. If a bunker barge was found to meet our criteria for multiple cargo ships, then the one with the longest bunker duration was selected as the receiving vessel for that bunker event. In other words, multiple barges could bunker the same receiving vessel, but each barge was assumed to only fuel one ship at a time.

Once a bunker event was identified, we estimated the mass of fuel bunkered. That could not be estimated from the duration of the bunkering event because the rate at which fuel is transferred varies (BIMCO & IBIA, 2018). Instead, we took the following approach. First, we aggregated multiple bunker events (if identified) that supplied the same receiving vessel at the same time into one bunker event. From there, two different approaches were evaluated to estimate the mass of fuel that was bunkered. The first was to assume that 65% of a receiving vessels' fuel tank was filled during each bunker event. As shown below, this approach estimated larger amounts than actual fuel sales; for that reason, we refer to it as the high estimate.

The second approach was voyage-based. We used a voyage identification method (Mao et al., 2021) with the SAVE model to determine where each ship was operated after receiving fuel in Singapore. Voyages that aggregately consumed less than 65% of the receiving vessel's fuel tank capacity were deemed enabled by bunkering from Singapore. Additional voyages that would have exceeded 65% of a ship's capacity were assumed to require bunkering at a subsequent port. This method estimated bunkered amounts somewhat less than public sales statistics, so we refer to it as the low estimate.

Calendar year 2019 served as the base analysis year and was chosen instead of 2020 to avoid the impacts of COVID-19. Because our AIS data and ship voyages terminated at the end of December 2019, the low estimate likely missed some voyages that took place in early 2020 but were fueled in 2019. To re-capture fuel consumed for those voyages, we first investigated the duration of all voyages sustained by one bunker

9 The detailed bunker barge information can be accessed here: https://www.mpa.gov.sg/web/wcm/connect/www/5e78a58e-7ce1-4237-a275-86a11ff8fa1f/Bunker+Tankers.pdf?MOD=AJPERES&attachment=true&id=1614910238998.

event. We found that more than 73% of bunker events sustained voyages longer than 1 month, and around 47% sustained two-month voyages. This indicates that we likely underestimated the amount of fuel bunkered in November and December. Similarly, the ratio between the actual fuel sales and our low estimate remained relatively stable until abruptly rising in November and December, indicating fuel bunkered in calendar year 2019 but consumed the following year. To compensate, we adjusted the low estimates of bunker sales for November and December by finding the average ratio between actual fuel sales versus our low estimate in the first 10 months of the year and applying that to the November and December estimates.

This approach identified about 28,500 bunker events distributed among 9,454 vessels in 2019 and between 35 (low estimate) and 61 (high estimate) million tonnes of residual fuel bunkered by major cargo ships in 2019. Figure 6 compares the estimated monthly fuel sales delivered with the Port of Singapore's public fuel sales data. The low estimate equals about 80% of 2019 fuel bunkered for all ships; that is reasonable because we modeled residual fuel delivered to select ship types by bunker barges registered in Singapore that had an IMO number. The high estimate, on the other hand, is much higher than the sales records. In addition, the low estimate tracks fuel sales variation from month to month better than the high estimate. As a result, we adopted the low estimate results for further analysis.

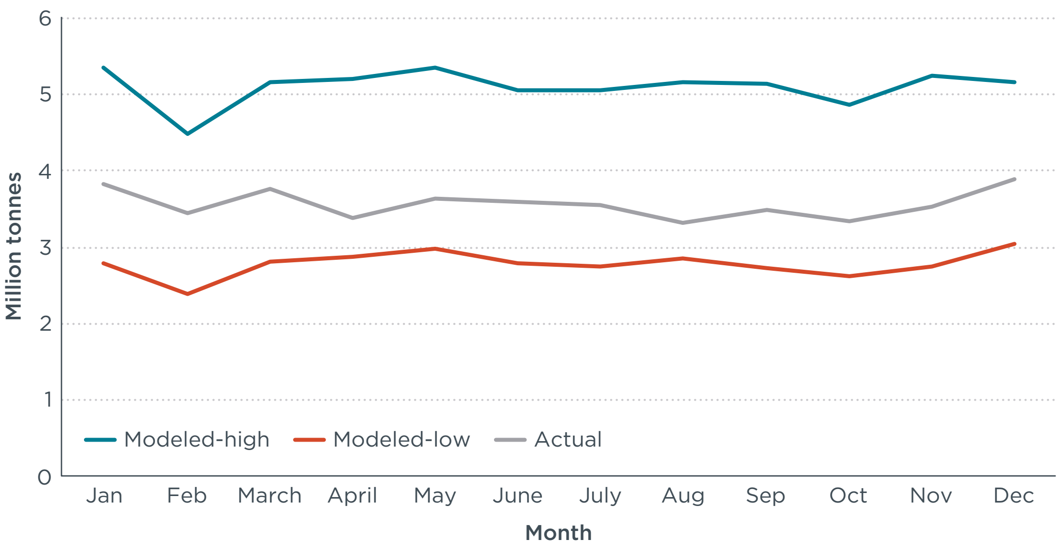

Figure 6. Actual versus modeled residual fuel sales in Singapore, 2019

Figure 7 presents the estimated HFO mass bunkered by key ship types, in million tonnes on the left axis and cumulative percent on the right axis. Container ships accounted for half of all identified bunker fuel sales in 2019, with bulk carriers, oil tankers, chemical tankers, and general cargo ships accounting for almost all (49%) of remaining sales. Other ship types were responsible for an insignificant amount of fuel bunkered.

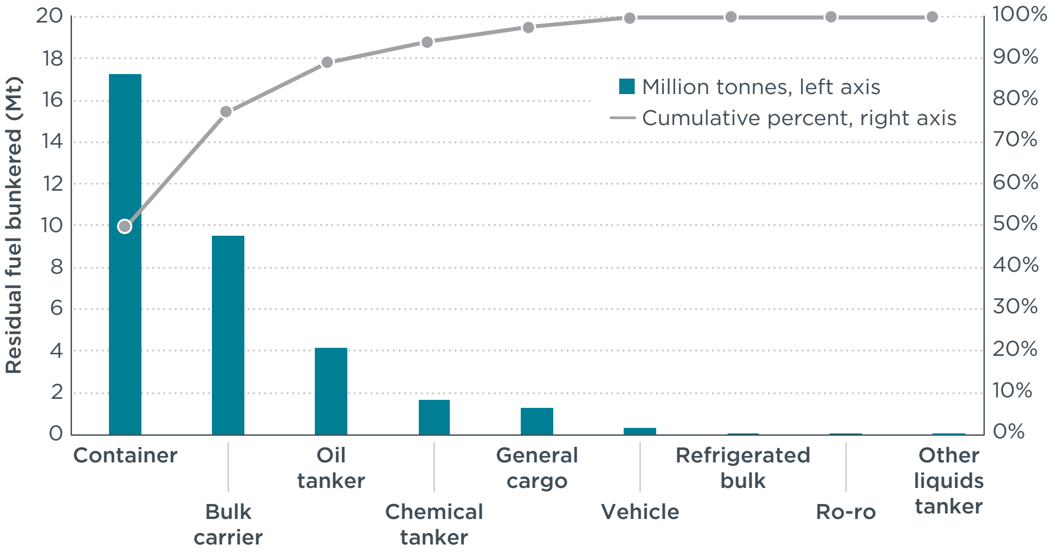

Figure 7. Modeled residual fuel bunkered in Singapore by ship type, 2019

These results were validated against fuel sample testing data purchased from Veritas Petroleum Services (VPS),[10] a leading fuel sample testing service provider. VPS's database allows comparison to a sample of actual bunker events and mass by ship type. Data from VPS showed a total of 14.3 million tonnes of HFO sold in Singapore in 2019 to the ship types included in this study, compared to our estimated 35 million tonnes. This corresponds to around one-third of the port's total fuel sales share and is consistent with VPS's own estimation of their overall market share.

Overall, we estimated two to four times more bunkering events than VPS records for eight of the nine ship types studied, consistent with VPS's market share estimate. Estimated bunker mass was also two to four times higher than VPS's records for the top five ship types (container, bulk carrier, oil tanker, chemical tanker, and general cargo). There were larger variations for ship types that contributed little to total amounts. Detailed validation results are provided in Appendix B.

ESTIMATING AIR AND WATER POLLUTION

Air pollution in the form of $PM_{2.5}$, NO_x, and SO_x, and water pollution in the form of scrubber washwater associated with ship voyages after bunkering in Singapore, were estimated and then mapped using ArcGIS. Even though 2019 was the base year, to remain relevant today, fuel quality was adjusted to reflect the global fuel sulfur limit of 0.5% m/m that took effect on January 1, 2020. That reduced SO_x and $PM_{2.5}$ emissions by requiring the use of VLSFO or scrubbers.

To reflect the new limit, we assumed that all ships burning HFO as their main fuel type in 2019 instead burned VLSFO to comply with IMO's 2020 global sulfur limit. This has the effect of cutting estimated SO_X and $PM_{2.5}$ emissions by reducing the fuel sulfur fraction in the SAVE model. For ships installed with scrubbers in 2019, we assumed emissions consistent with Comer et al. (2020). These updates cut emissions of SO_X, $PM_{2.5}$, and black carbon relative to VLSFO when they are outside of ECAs, but increased $PM_{2.5}$ and black carbon emissions within ECAs relative to MGO. This assumes that ships with scrubbers use them instead of low-sulfur fuels like MGO to comply with fuel sulfur regulations.

10 Veritas Petroleum Services offers customized data and analytics services, including analytics for marine fuel quality. For more details, see https://www.vpsveritas.com/analytics-whatwedo.html.

Discharges of scrubber washwater were also estimated. First, we determined which of the ships bunkering in Singapore had scrubbers installed using Clarksons World Fleet Register dataset (WFR, 2020). Scrubber washwater discharges were estimated using the methods outlined in Osipova, Georgeff, & Comer (2021). Energy demand for each hour was estimated using the SAVE model. Washwater mass is equal to total energy demand multiplied by the scrubber washwater flow rate. Following IMO guidelines for exhaust gas cleaning systems (MEPC.259(68)), we assumed a normalized flow rate equal to 45 t/MWh for open-loop scrubbers and 0.1 t/MWh for closed-loop scrubbers. We assumed zero discharges within prohibited areas as of June 2020, consistent with Osipova, Georgeff, and Comer (2021). This includes a ban on scrubber discharges in the Port of Singapore, but not within Singapore's larger EEZ.

We estimated emissions of $PM_{2.5}$, $NO_{x,}$ $SO_{x,}$ and washwater in 1° by 1° grid cells for the entire global fleet of ships and again just for the ships that bunkered residual fuel in Singapore. We merged the two datasets by geographical coordinates and then calculated the relative contribution of pollution from ships that bunkered residual fuels in Singapore. Emissions were allocated to major ports using a 5 nautical mile (about 9 km) buffer around a ports shapefile from the World Port Index (National Geospatial-Intelligence Agency, 2019). Three maps were generated: absolute mass using point density visualization, relative (percent) values using contour visualization, and absolute mass in port using a graduated color scale and icon size.

RESULTS

The following sections present our main findings. First, we show the global distribution of key shipping pollutants—$PM_{2.5}$, NO_x, SO_x, and scrubber washwater—linked to residual fuel sales in Singapore. We then summarize results at the regional, country, and port levels.

We used the methods outlined above to map air and water pollution linked to residual fuel sales in Singapore to shipping lanes, regions, nations, and ports. Below we present gridded maps of $PM_{2.5}$. Results are presented in both absolute mass (Mt) and relative share of the global shipping fleet's total. We also present tabulated results for two other air pollutants, NO_x and SO_x. We close with a discussion of scrubber washwater discharges. Maps of NO_x and SO_x emissions are provided in Appendix C.

GLOBAL EMISSIONS

The 35 million tonnes of marine residual fuels sold to oceangoing vessels in Singapore generate significant air pollution, much of it concentrated in seas neighboring Singapore. At the same time, emissions are seen worldwide. Figure 8 shows the distribution of $PM_{2.5}$ globally due to residual fuels bunkered in Singapore.

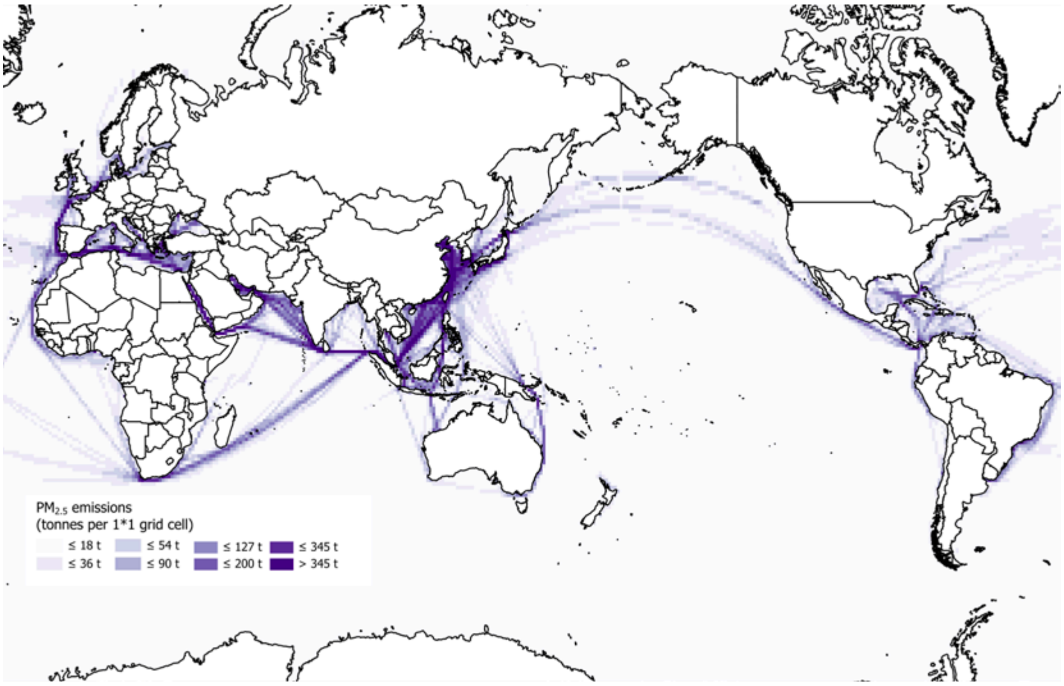

Figure 8. $PM_{2.5}$ emissions from residual fuel sold in Singapore

As shown, the associated $PM_{2.5}$ is emitted primarily on key shipping lanes, including from Singapore to China, in the Indian Ocean en route to the Suez Canal and ultimately Europe, and on voyages through Malaysia, Indonesia, and Australia. Significant, but more dispersed, emissions can be seen on transpacific routes to the United States and Canada. Only Iceland, Greenland, Antarctica, and the North American ECA are essentially unaffected.[11]

Another way to understand the environmental impact of Singaporean fuel sales is through their relative contribution to overall shipping air pollution. Figure 9 is a contour map of the distribution of $PM_{2.5}$ pollution from marine fuels sold in Singapore. In shipping lanes near Singapore, the relative contribution reaches above 42% of air

11 Limited emissions are seen within the 200 nm North American ECA for two reasons: either affected ships reroute outside of the ECA, or they switch fuels while inside.

pollution from maritime shipping (darkest blue color). Particularly intense hot spots are seen in the South China Sea, the Indian Ocean, and throughout Oceania, including along the western and southern coasts of Australia.

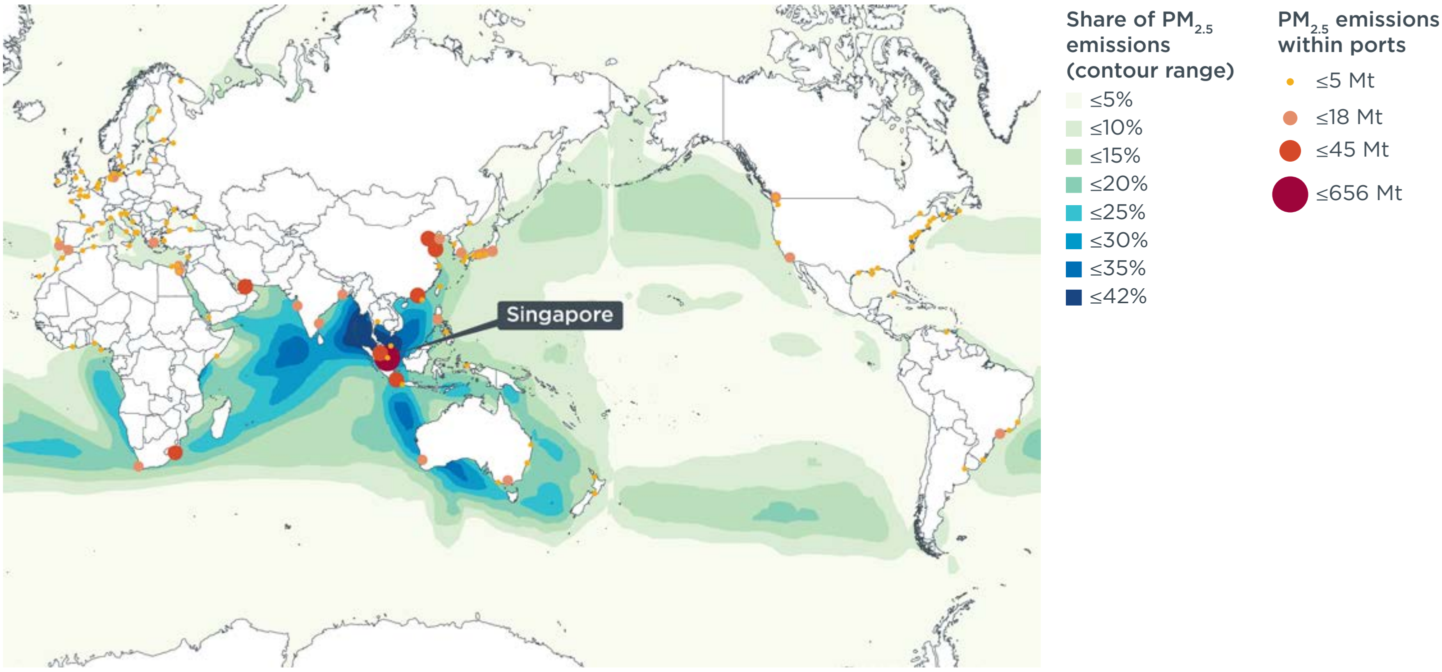

Figure 9. Share and mass of shipping $PM_{2.5}$ emitted by ships burning residual fuel sold in Singapore.

Lesser hot spots include transpacific voyages to North America and voyages to South America using either the South Pacific or South Atlantic. In contrast, Singapore's marine residual fuel sales cause relatively little air pollution in Europe, where other bunkering options, such as Rotterdam in the Netherlands, are available.

The dots on Figure 9 summarize the air pollution impacts of Singapore's fuel sales at the port level. As demonstrated, ports predominately in Oceania, China, the United Arab Emirates (Mina Jabal Ali), and South Africa (Durban) see large absolute mass of $PM_{2.5}$. Smaller impacts are seen at ports in Japan, Korea, West Coast ports in the United States and Canada, and a few ports in Southern Europe. We return to this list later.

Figure 10 shows the global distribution of scrubber washwater from residual fuel sold in Singapore, along with the key ship types involved. Container ships are responsible for half of all washwater discharges, followed by oil tankers (21%) and bulk carriers (19%). Other ship types were responsible for less than 10% of scrubber discharges. Washwater discharges are concentrated along the same global trading routes highlighted in Figure 8 and Figure 9. Note that, while HFO sold in Singapore creates a global water pollution footprint, open-loop scrubber operations are banned in the Port of Singapore.

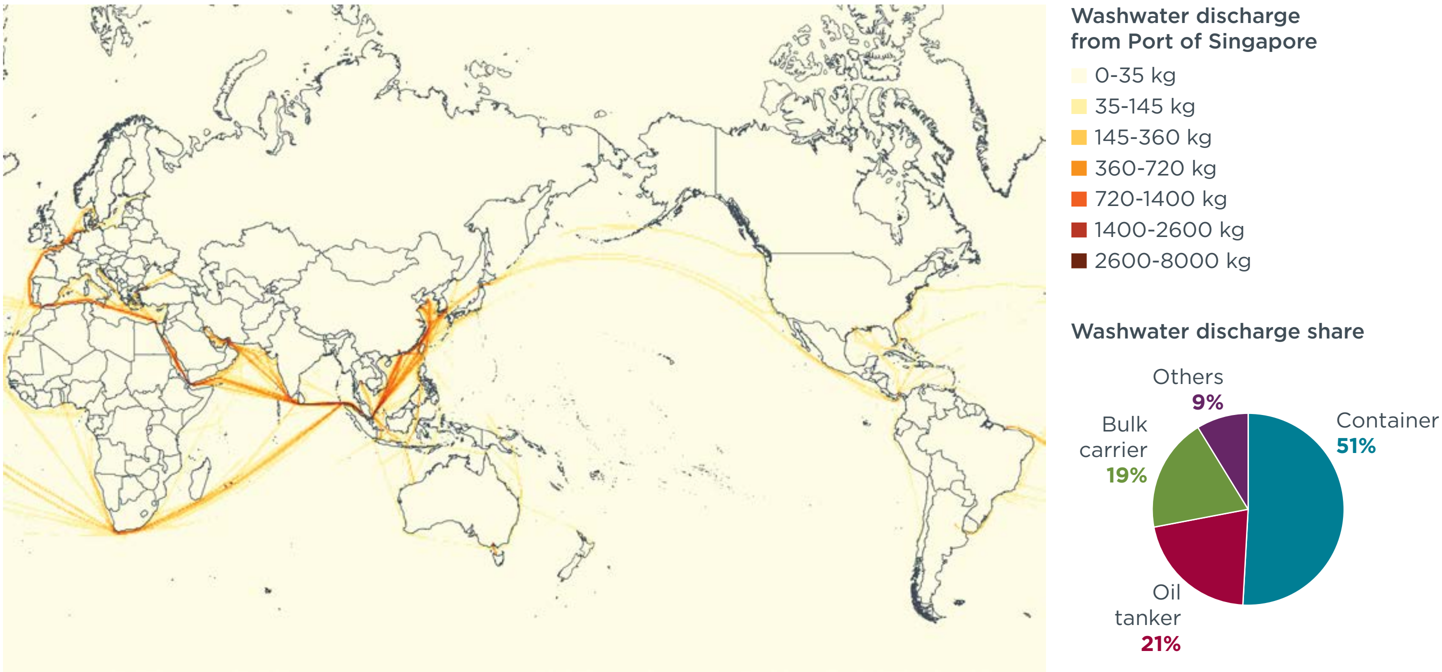

Figure 10. Wastewater discharge associated with residual fuel sold in Singapore

REGIONAL IMPACTS

The above maps highlight the relative contribution of Singapore's residual fuel sales to regional shipping air and water pollution. Table 2 lists the absolute and relative (%) shares of $PM_{2.5}$, NO_x, SO_x, and scrubber washwater compared to all shipping emissions by sea region (Flanders Marine Institute, 2021). Regions where Singapore fuel sales account for more than 30% of shipping $PM_{2.5}$ share are highlighted in dark blue, while regions where it accounts for between 20% and 29% are highlighted in light blue.

Table 2. $PM_{2.5}$, NO_x, and SO_x emissions and washwater discharges by select sea regions from residual fuel sold in Singapore, absolute mass and share of total shipping emissions

Hemisphere	Region	$PM_{2.5}$		NO_x		SO_x		Washwater	
		Thousand tonnes (kt)	Share of total	Thousand tonnes (kt)	Share of total	Thousand tonnes (kt)	Share of total	Million tonnes	Share of total
North	South China Sea	18.5	23%	45.8	27%	427	27%	336.6	41%
	Arabian Sea	5.18	18%	12.0	20%	125	20%	174.7	42%
	Bay of Bengal	5.02	27%	11.8	30%	120	29%	74.0	45%
	North Pacific Ocean	4.89	7%	11.5	8%	116	8%	190.3	19%
	Eastern China Sea	4.45	12%	10.6	13%	104	14%	91.9	32%
	Malacca Strait	4.27	30%	10.3	36%	100	35%	64.1	42%
	Laccadive Sea	2.91	25%	6.812	27%	70.4	27%	76.8	41%
	North Atlantic Ocean	2.81	4%	6.32	4%	75.6	4%	208.4	18%
	Philippine Sea	2.04	7%	4.88	10%	46.4	9%	43.5	20%
	Red Sea	2.05	18%	4.67	18%	50.7	19%	92.5	46%
	Northern total	**66.5**	**14%**	**161**	**13%**	**1,580**	**11%**	**1,912**	**25%**
South	Indian Ocean	9.98	17%	22.9	20%	249	20%	360.4	38%
	South Atlantic Ocean	4.75	12%	10.7	12%	122	12%	211.3	37%
	Java Sea	1.38	19%	3.37	23%	31.2	23%	18.7	41%
	Coral Sea	0.798	11%	1.90	13%	18.4	13%	17.8	25%
	South Pacific Ocean	0.663	4%	1.59	5%	15.1	5%	26.1	18%
	Great Australian Bight	0.490	32%	1.21	36%	10.9	36%	6.0	50%
	Arafura Sea	0.311	26%	0.738	28%	7.18	28%	4.2	60%
	Mozambique Channel	0.268	11%	0.663	13%	6.14	13%	8.0	33%
	Tasman Sea	0.256	13%	0.618	15%	5.79	15%	6.2	15%
	Banda Sea	0.238	13%	0.579	17%	5.46	17%	3.2	27%
	Southern total	**20.0**	**16%**	**46.5**	**15%**	**492**	**14%**	**701**	**35%**

As seen, the largest regional shares of shipping pollution are seen in regions abutting Singapore, including the Malacca Strait and off the southern coast of Australia (the Great Australian Bight). Other areas with shares exceeding 20% include the South China Sea, the Bay of Bengal, waters surrounding Sri Lanka (the Laccadive Sea), and the Arafura Sea between Australia and New Guinea. The Arabian Sea, the Indian Ocean, and the Java Sea have shares of shipping $PM_{2.5}$ that exceed the Northern (14%) and Southern (16%) Hemisphere averages.

Even higher percentages are seen for the share of scrubber discharges linked to fuel sales in Singapore. Those surpass 40% in key regions such as the South China Sea, Arabian Sea, Bay of Bengal, the Laccadive Sea, and the Java Sea. Singapore's fuel sales also account for 50% to 60% of scrubber discharges off the coast of Australia (Great Australian Bight and the Arafura Sea). Overall, Singapore HFO sales are responsible for an estimated one-quarter (25%) of shipping scrubber discharges in the Northern Hemisphere and over one-third (35%) in the Southern Hemisphere.

Table 3 breaks down absolute emissions of $PM_{2.5,}$ NO_x, and SO_x and discharges of scrubber washwater within the EEZs of select countries from ships that bunkered residual fuel in Singapore. The share of those emissions and discharges compared to totals from all shipping in that area are included. Emissions are ranked in order of absolute tonnes of $PM_{2.5}$. Countries where fuel bunkered in Singapore is responsible for more than 30% of $PM_{2.5}$ within their EEZ are highlighted in dark blue; countries with between 20% and 29% are highlighted in light blue. Singapore is low in terms of absolute emissions due to its small EEZ, but high in terms of relative contribution of $PM_{2.5}$ (35%). Other neighboring countries, including Malaysia (37%), Vietnam (30%), Indonesia (23%), Sri Lanka (25%), and India (22%), are also heavily impacted by Singapore's marine fuel sales. Combined, shipping air pollution was linked an estimated 8,500 premature deaths in these countries in 2015, or 14% of the global total (Rutherford & Miller, 2019).

Table 3. Share of shipping emissions in Exclusive Economic Zones of select countries from ships burning residual fuel bunkered in Singapore

Exclusive Economic Zone	$PM_{2.5}$		NO_x		Scrubber washwater	
	Thousand tonnes (kt)	Share of shipping total	Thousand tonnes (kt)	Share of shipping total	Million tonnes (Mt)	Share of shipping total
Indonesia	9.13	23%	215	19%	187	37%
China	8.24	14%	195	13%	181	40%
Malaysia	4.42	37%	100	31%	33.6	43%
Vietnam	4.37	30%	104	25%	98.1	45%
India	4.05	22%	94.8	20%	132	41%
Australia	2.42	18%	54.1	14%	50.2	29%
Japan	2.32	7%	52.4	5%	59.0	19%
Sri Lanka	2.05	25%	49.6	23%	56.1	42%
Taiwan	1.85	18%	43.9	14%	52.9	32%
Philippines	1.78	11%	40.9	8%	43.8	22%
Singapore	0.752	35%	12.6	29%	4.68	44%

Singapore's marine fuel sales contribute even more heavily to scrubber washwater discharges in the countries shown in Table 3. For the most heavily impacted regions—Vietnam, Malaysia, Sri Lanka, India, China, and Singapore itself—marine fuel sales in Singapore are responsible for at least 40% of all scrubber discharges. This in spite of the fact that discharges are banned at port in countries like Singapore, and in other areas such as China's Domestic Emission Control Area (DECA; Ministry of Transport of the People's Republic of China, 2019), where they are banned within 12 nautical miles of the shore. Discharges throughout the wider EEZs of countries can be significant.

Table 4 summarizes the distribution of $PM_{2.5}$ and NO_x pollution by port. Singapore itself is the most heavily impacted port from its own fuel sales, with more than 650 tonnes of $PM_{2.5}$ and more than 10,000 tonnes of NO_x emitted at home. The second most impacted port, Jakarta in Indonesia, received less than a tenth as much $PM_{2.5}$ and NO_x as Singapore on a mass basis. Still, relative shares could still be quite high, and for example, 35% of $PM_{2.5}$ and 28% of NO_x at Port Klang in Malaysia comes from fuels sold in Singapore. Of the remaining top 10 impacted ports, three are located in China, two in the Middle East, one in South Africa (Durban) and one in Australia (Melbourne).

Table 4. Top 10 ports by $PM_{2.5}$ and NO_x emissions from residual fuel sold in Singapore

Country	Port	$PM_{2.5}$		NO_x	
		Tonnes	Share of total	Tonnes	Share of total
Singapore	Singapore	655	41%	10,233	34%
Indonesia	Jakarta	45	17%	713	13%
China	Qingdao Gang	41	14%	834	13%
Malaysia	Port Klang	30	35%	475	28%
China	Hong Kong	28	27%	607	21%
South Africa	Durban	25	17%	437	17%
United Arab Emirates	Mina Jabal Ali	24	14%	424	14%
China	Tianjin	22	13%	448	13%
Australia	Melbourne	18	23%	262	21%
Egypt	Port Said	17	15%	330	14%

Figure 11 shows where scrubber wastewater discharges from Singapore's residual fuel sales are emitted in ports globally using a 5 nautical mile buffer around each port. Units are in million tonnes of discharge and the top 10 ports by scrubber discharges are indicated by name. A large concentration of impacted ports can be seen in East Asia (three ports) outside of the Chinese DECA, and high amounts of scrubber washwater are also seen at European ports. The remaining ports in the top 10 are Pulau Sambu in Indonesia, Port Louis in Mauritius, and the Port of Lagos in Nigeria. In-port scrubber discharges can also be seen in India, the Caribbean, the Middle East, Japan, and Australia. Open-loop scrubber discharges are banned at the Port of Singapore, so the port of Singapore is not displayed on the map.

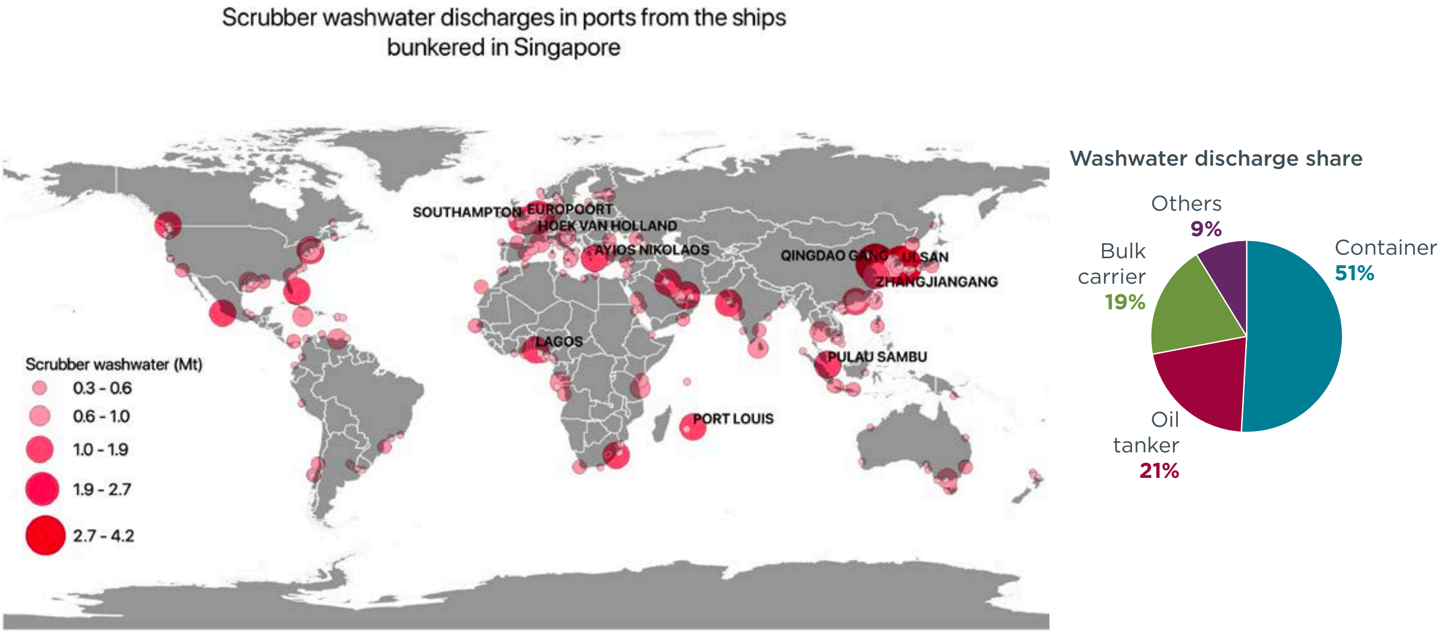

Figure 11. Top 10 ports by scrubber washwater discharged from residual fuel sold in Singapore

CONCLUSIONS

This study investigated the GHG, air, and water pollution linked to marine fuel sales at the Port of Singapore, the world's largest bunkering hub, in calendar year 2019. We developed a new method to identify how and where bunkering occurs, and to track the resulting pollution worldwide. In doing so, we improved our understanding of the magnitude and distribution of emissions from international shipping. This better understanding of present bunkering practices can help guide decisions about how to transition to alternative marine fuels.

Residual marine fuel sales in Singapore leave a global air, water, and climate pollution footprint. Singapore accounted for about one-fifth of reported marine fuel sales globally in 2019; if Singapore accounted for GHG emissions associated with the residual fuel it sells, its total climate impact would be four times higher than its national inventory implies, resulting in per-capita emissions six times greater than the global average. Regarding water pollution, scrubber washwater discharges linked to residual fuel sold in Singapore pollutes its own EEZ, neighboring countries, and even ports in Europe.

We draw three main conclusions from this work. First, because port and coastal communities in Asia are exposed to substantial air and water pollution from fuel sold in Singapore, countries like China, Malaysia, Indonesia, and Australia could win twice by producing and selling renewable marine fuels at their ports: first by reducing local air and water pollution and second by capturing the economic benefits of new renewable marine fuel markets. Countries and ports that develop policies to support such fuels will reduce pollution, improve public health, and contribute to IMO's GHG reduction targets for international shipping.

Second, as the preeminent seller of bunker fuel globally, Singapore will need to transition to low-carbon bunkering if it wants to remain an important bunkering port. Singapore itself is heavily impacted by shipping pollution and can improve public health and confront climate change by transitioning from fossil fuel to low-carbon fuel bunkering. Several steps should be considered. Singapore could halt further investment in fossil fuel bunkering infrastructure, for example by no longer registering new fossil fuel bunker barges. In particular, any investments in bunkering infrastructure for LNG, which provides limited, if any, life-cycle GHG reduction relative to fossil bunker fuel, should be reviewed (Pavlenko et al., 2020). Singapore could expand investments into "green" marine fuel development and support international efforts to transition away from fossil fuels, including continued work on a global carbon tax for marine fuels (Walia, 2021) and the development of a Low GHG Fuel Standard (LGFS). Integrating shipping into Singapore's domestic GHG inventory and Nationally Determined Contribution would further demonstrate Singapore's resolve.

Third, Singapore could lead regional and international efforts to advance green shipping corridors. Relevant corridors may be along northward along coastal China and then extending to East Asia; westward to India, the Middle East, and then Europe; and throughout the ASEAN region to Australia (IAP, 2021). International agreements like the 2021 Clydebank Declaration could help structure that involvement. Coordinated investments will be needed at the route level. Previous ICCT studies (Georgeff et al., 2020; Mao et al., 2020) evaluated the feasibility of a transpacific container shipping corridor supported by hydrogen bunkering infrastructure and found that a distributed refueling network will be needed, and that small and mid-sized ports with hydrogen infrastructure may attract new refueling calls and therefore trade opportunities.

Whether by Singapore or a new entrant, a comprehensive package of public investments, infrastructure development, and supportive policies will be needed to start generating, transporting, and distributing new fuels like hydrogen, ammonia, and methanol. Governments will also need to implement fuel certification schemes that are supported by proper well-to-wake accounting practices to ensure that renewable fuels reduce emissions on a life-cycle basis, including direct and indirect land use change. Policies that mandate the use of renewable marine fuels, reduce the price gap between fossil and renewable marine fuels, or both will be needed. Targeted policies to promote the use of clean fuels at port, such as the zero emissions "at berth" mandate in the European Union's Fit-for-55 legislative package for shipping, could help scale up supply chains. Finally, proactive investments in renewable energy (wind, solar, and geothermal) and local bunkering infrastructure are needed to support renewable marine fuels.

This paper focused on residual fuel sales at a single, albeit the world's busiest, marine bunkering port. Future work could analyze other fuels such as MGO and LNG to better understand the local, regional, and global implications of those marine fuels. Ports other than Singapore should be analyzed, for example the Port of Rotterdam and other major bunkering ports. Future work could estimate renewable marine fuel demand at ports near Singapore to determine if these ports could begin to sell renewable fuels as the sector transitions to zero-emission vessels. Such studies could include a detailed infrastructure and techno-economic assessments for renewable fuels.

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APPENDICES

APPENDIX A. ESTIMATING RETROFITTED SHIP RANGE

The Systematic Assessment of Vehicle Emissions (SAVE) model (Olmer et al., 2017) was used to estimate the range of different alternative fuels using engine volume and fuel tank specifications from ships in the IHS Markit ShipData database. Ships were assumed to be retrofitted from existing engines powered by fossil fuels to engines and/or fuel cells that can utilize liquefied natural gas (LNG), methanol, ammonia, or liquid hydrogen (LH_2). For each calculation, the existing engine room and fuel tank volumes were conserved. The fuel assumptions used to derive ship ranges are shown in Table A1.

Table A1. Assumptions used to estimate ship operational ranges

Fuel type	Volumetric energy density (GJ/m³)	Density (kg/m³)	Propulsion		Storage pressure (bar)	Storage temperature (°C)	Source
			Technology	Thermal efficiency			
Heavy fuel oil	39.6	991	ICE	0.50	1	20	Comer (2019)
Distillate	37.5	890	ICE	0.50	1	20	Comer (2019)
VLSFO (0.5% s)	38.0	910	ICE	0.50	1	20	Comer (2019)
LNG	22.8	456	ICE	0.50	1	-162	Comer (2019)
Methanol	15.8	794	ICE	0.50	1	20	Faber et al. (2020) de Vries (2019)
Liquid ammonia	11.2[a]	683	Ammonia breaker, PEM fuel cell	0.45[b]	1 or 10	20 or -34	de Vries (2019)
Liquid hydrogen	4.8[c]	40.0[c]	PEM fuel cell	0.54	1	-253	Comer (2019) Minnehan and Pratt (2017)

[a] This is calculated as liquid ammonia fuel system volumetric density. The fuel tank is assumed to hold 5 lbs. of ammonia per gallon of capacity, and we assumed the tank to be at maximum 85% filled.
[b] This is calculated as system-level efficiency which combines energy conversion efficiency of an ammonia breaker and a liquid hydrogen fuel cell system.
[c] System-level density assumptions from Comer (2019).

Using the fuel specifications in Table A1, we estimated the maximum volume of alternative fuel in cubic meters that can be stored in the existing space dedicated to the engine and fuel tanks. From that volume of each fuel, we estimated the maximum range in kilometers (km) for each transoceanic ship that refuels in Singapore based upon its mean 2019 cruising speed over ground. This provides an estimate of operational ranges for existing ships if retrofitted to run on alternative fuels. Note that newbuild ships, which presumably would be designed to store larger volumes of less-energy-dense fuels, are thus expected to have longer ranges than retrofitted ships.[12]

12 See Mao et al. (2020) for a discussion of how modest (5%) reductions in cargo capacity could enable nonstop container ship voyages between China and California. Estimated ranges for this approach for container ships are shown as a whisker chart on Figure 8.

APPENDIX B. BUNKERING VOLUME VALIDATION

This appendix shows the detailed comparison of our modeled results versus Veritas Petroleum Services (VPS) database records. Figure B1 compares modeled (black bar) vs. VPS-recorded (red bar) bunker events by ship type.

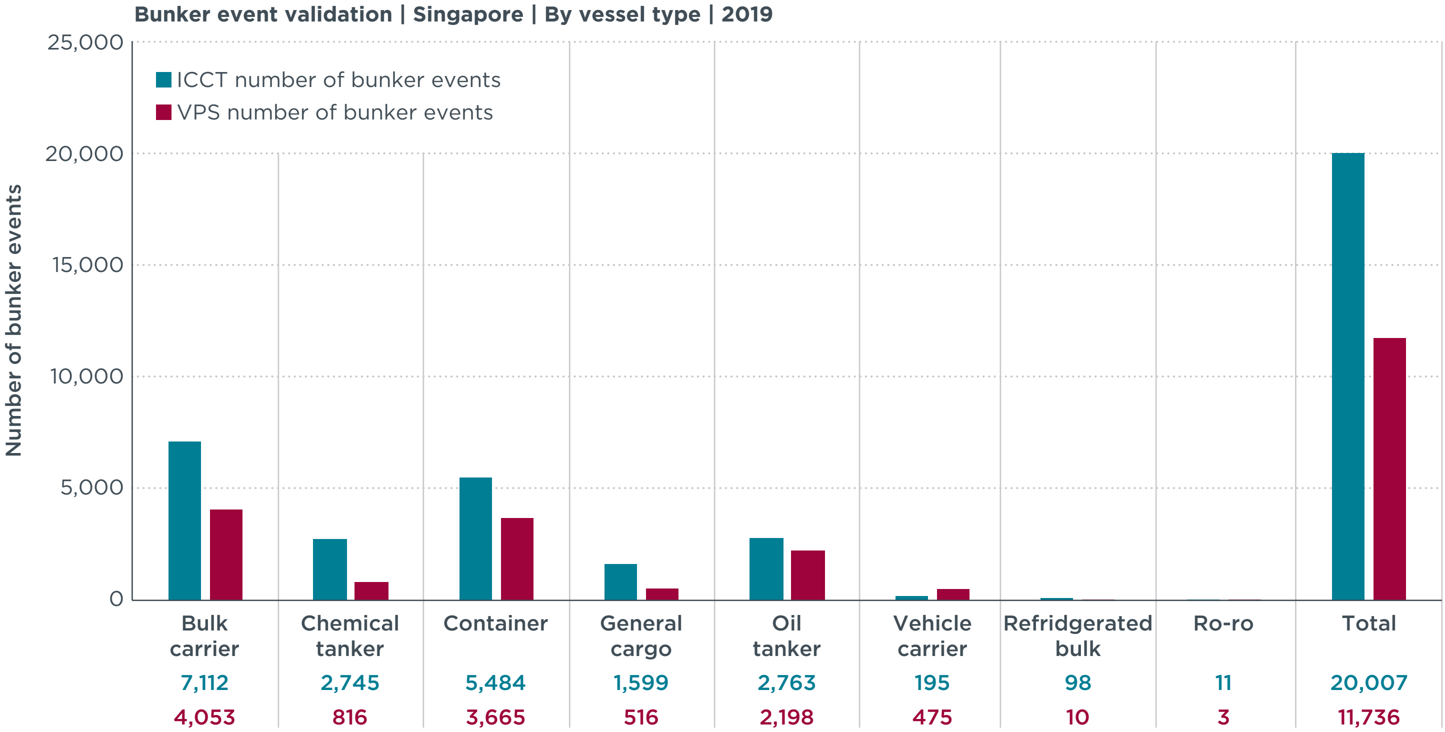

Figure B1. Modeled versus recorded bunkering events by vessel type, 2019

Overall, we model roughly twice as many bunkering events as VPS records indicate, with some variation by ship type. For example, the modeled number of bunker events for chemical tankers outnumber VPS records by twofold but are only modestly higher for oil tankers. While we do not have an estimate of VPS records' coverage of bunkering at the Port of Singapore for each individual ship type, the overall trend fits the understanding that VPS tests about one-third of bunker events there. Vehicle carriers, while accounting for a small number of events, are the notable exception, as we modeled fewer bunker events than VPS records. This could be because some vehicle carriers bunkered for less than 2 hours (the cut-off criterion for identifying bunker events in our analysis), or because some were serviced by bunker barges that were not identified in the study.

A similar trend is observed for bunker mass validation. Figure B2 compares our high (blue) and low (grey) modeled mass results against VPS records (red) by ship type. Both approaches estimated bunker volumes higher than VPS records, which is reasonable because VPS represents roughly one-third of the total Singapore fuel sampling market.

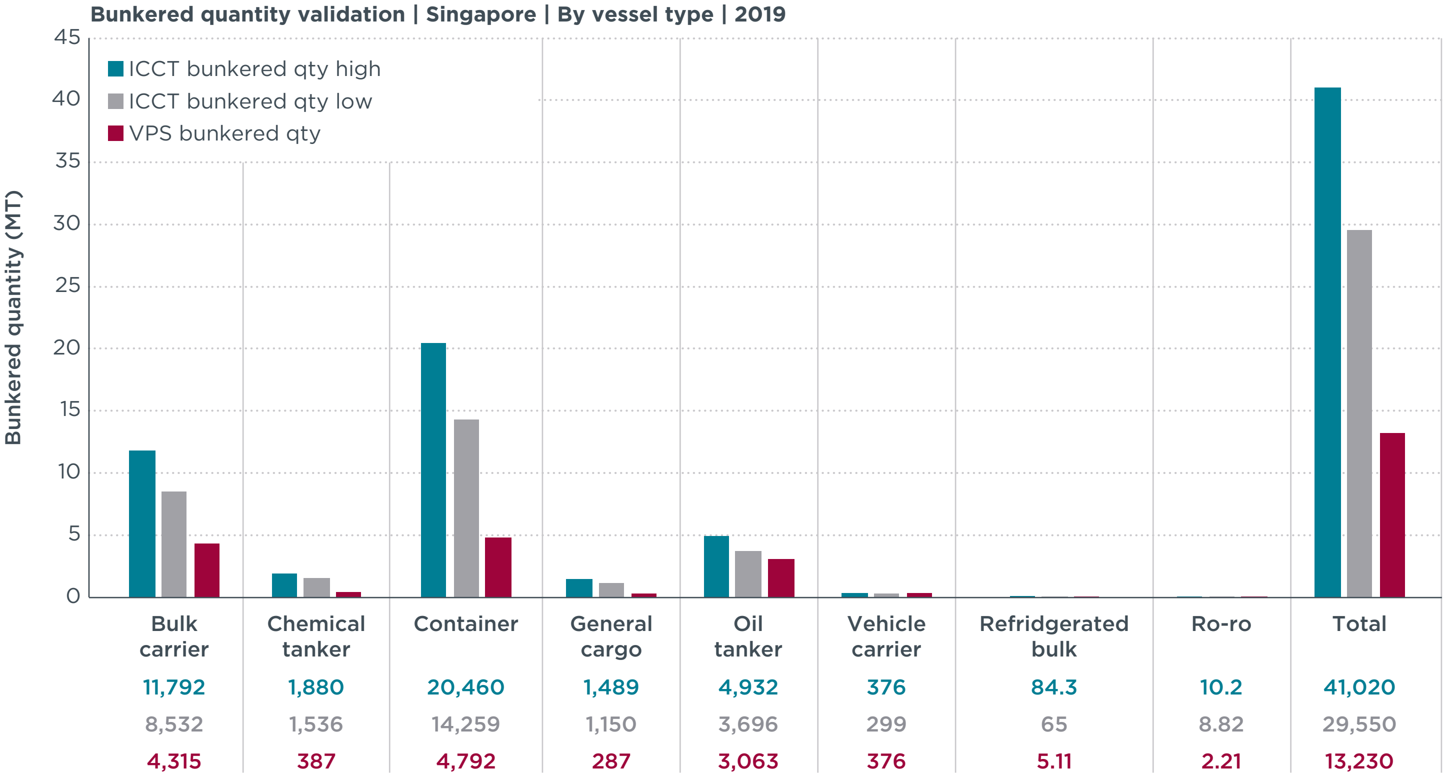

Figure B2. Modeled versus recorded bunkering mass by vessel type, 2019

Our low estimate was a little more than twice that of the VPS records and our high estimate was more than three times higher; this is consistent with our conclusion that our low estimate is a conservative estimate. Variations are seen by ship type, but the overall trend is consistent with VPS's expected market share in Singapore. Although we identified fewer vehicle carrier bunker events than VPS, our modeled results were higher than the VPS record, albeit only slightly. This might be because the bunker events identified were for larger-size vehicle carriers, whereas we missed bunkering events for some smaller ships.

APPENDIX C. SUPPLEMENTAL RESULTS

This appendix provides supplemental details concerning other pollutants investigated in the study, namely nitrogen oxides (NO_x) and sulfur oxides (SO_x). We also provide detail on other metrics of how Singaporean fuel sales drive global shipping emissions, including by fuel type.

Figure C1 shows the monthly trend of modeled residual fuel bunkered. The overall amount of fuel was relatively stable over time, varying from a minimum of 2.4 million tonnes in February to maximums of 3 million tonnes in the peak months of May and December.

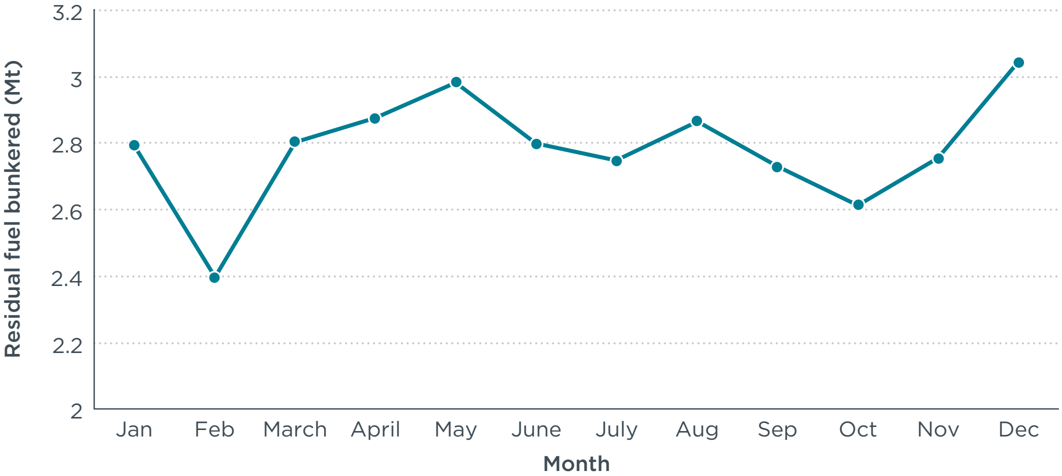

Figure C1. Mass of marine residual fuels bunkered by cargo carrying ships in Singapore by month in 2019

Figure C2 provides a map of the distribution of NO_x emissions from residual fuel bunkered in Singapore in 2019 in 1° by 1° grid cells. The overall distribution is similar to that of $PM_{2.5}$, with emissions concentrated in the South and East China Seas, the Strait of Malacca, and in trade routes to Europe through the Suez Canal and around the Cape of Good Hope in southern Africa.

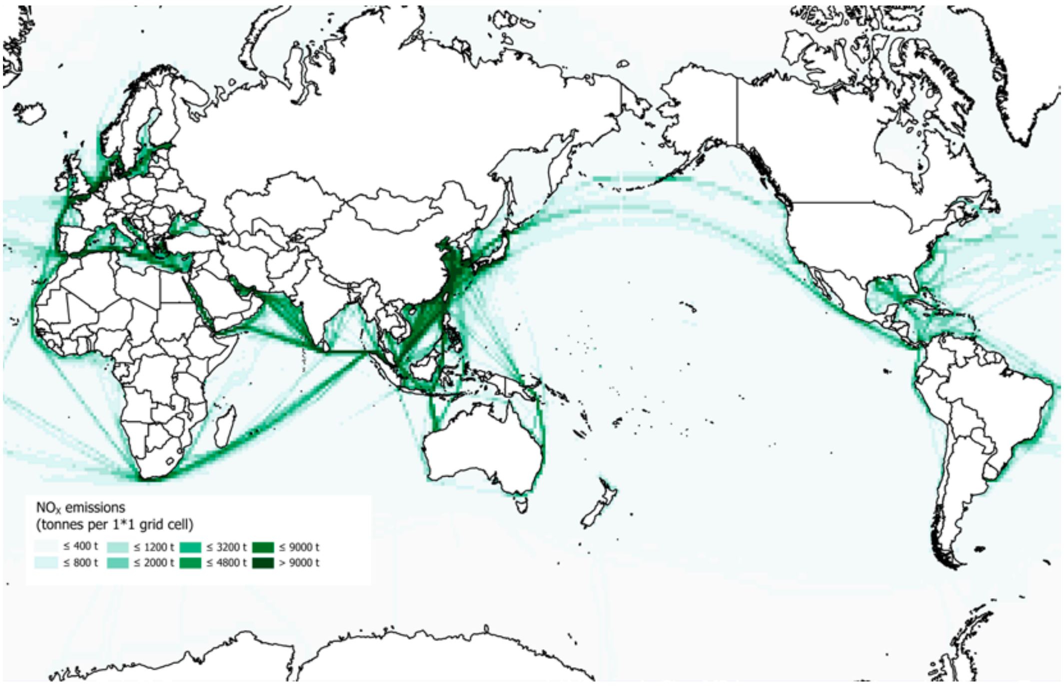

Figure C2. NO_x emissions from marine residual fuels sold in Singapore in 2019

Figure C3 shows the relative distribution of NO_x emissions by region. Similar to the relative contribution map for $PM_{2.5}$, hot spots surrounding Vietnam, Thailand, Indonesia, Singapore, Malaysia, Sri Lanka, and Australia are evident.

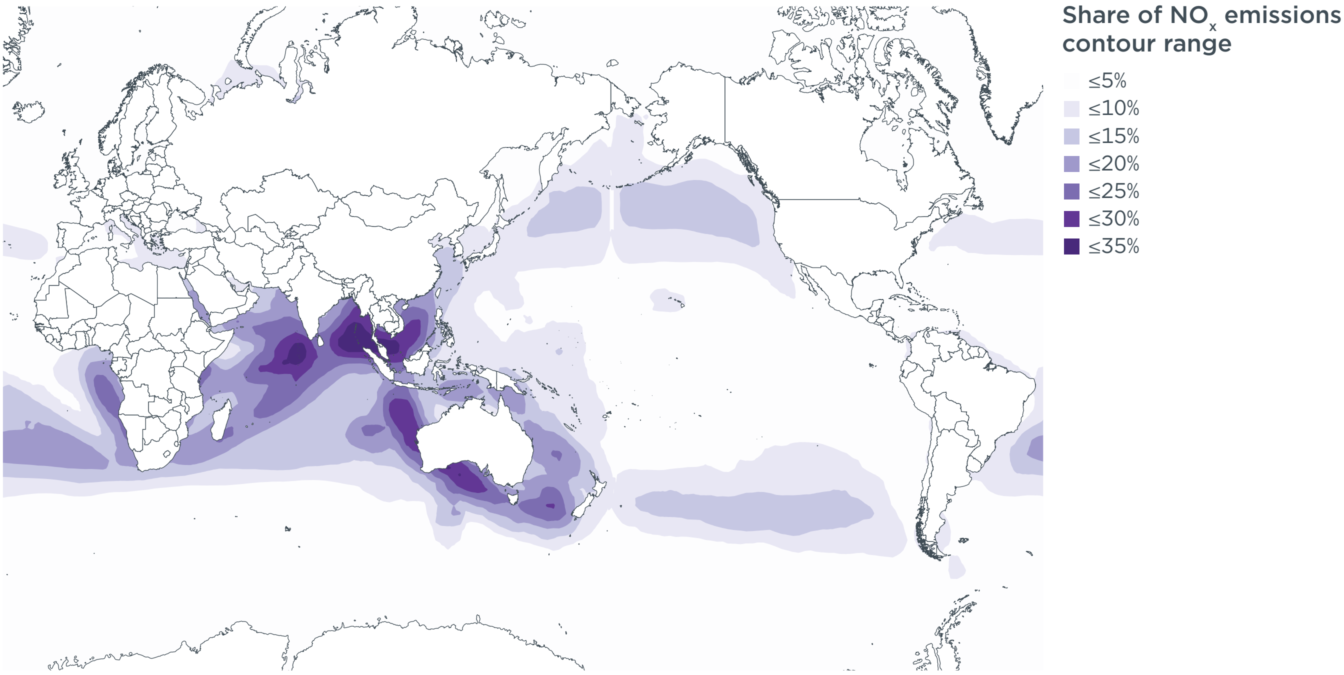

Figure C3. Share of shipping NO_x emissions from marine residual fuels sold in Singapore in 2019

Figures C4 and C5 provide a graphical illustration of the same data for SO_x, a key precursor of $PM_{2.5}$.

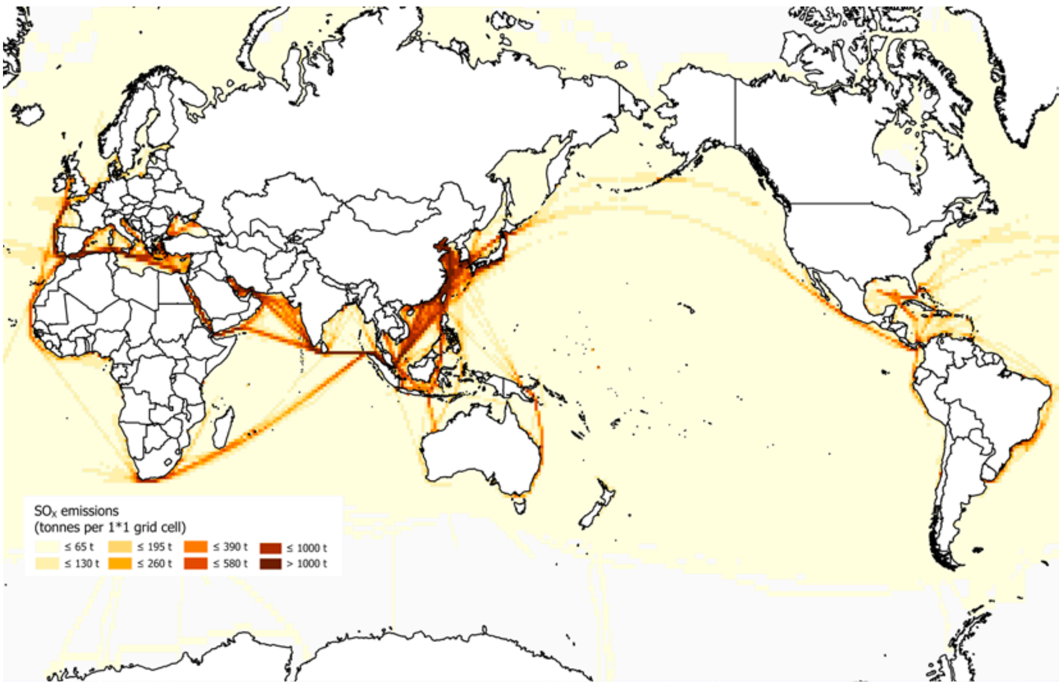

Figure C4. SO_x emissions from marine residual fuels sold in Singapore in 2019

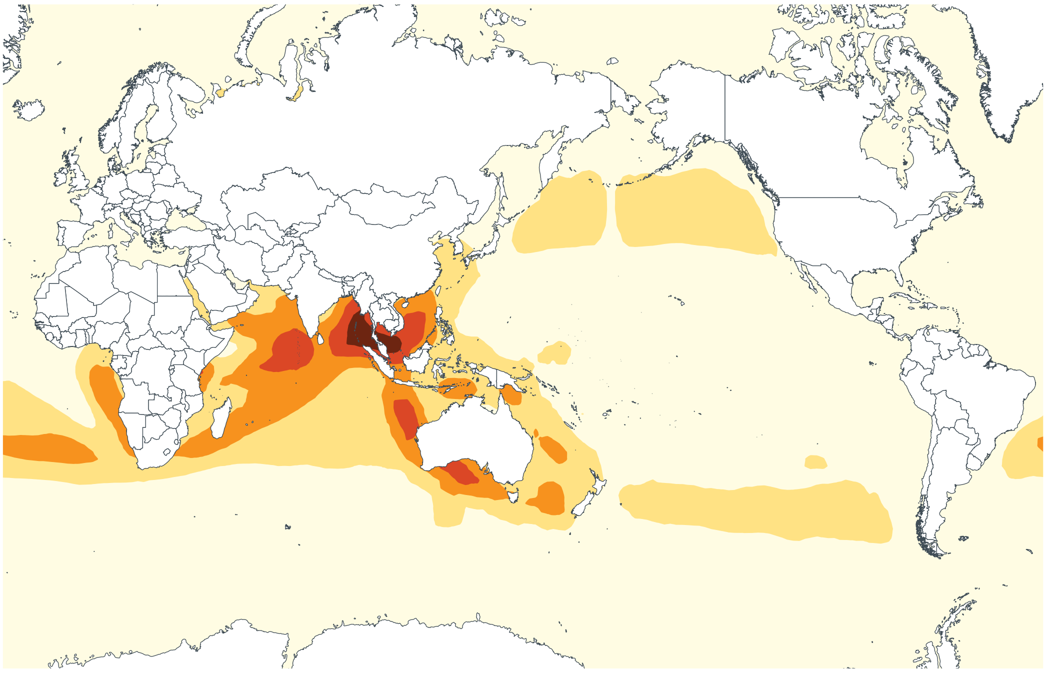

Figure C5. Share of shipping SO_x emissions from marine residual fuels sold in Singapore in 2019

Table C1 summarizes emissions by ship type for ships that bunkered residual fuel in Singapore in 2019. Both in absolute and relative terms, container ships drive the majority of air pollution linked to residual fuel sales in Singapore, with almost 50,000 tonnes of $PM_{2.5}$ and more than 1.1 million tonnes of NO_x emitted by those ships. More than 20% of global container ship emissions, and more than 40% of scrubber washwater discharges, were driven by fuel sold in Singapore.

Table C1. $PM_{2.5}$, NO_x, and SO_x emissions plus scrubber washwater discharges from marine residual fuels sold in Singapore

	$PM_{2.5}$		NO_x		SO_x		Washwater	
Ship type	**Mass (thousand tonnes)**	**Share of global emissions**	**Mass (thousand tonnes)**	**Share of global emissions**	**Mass (thousand tonnes)**	**Share of global emissions**	**Mass (million tonnes)**	**Share of global emissions**
Container	48.8	23%	1,190	20%	114	23%	1,360	42%
Bulk carrier	17.7	10%	420	8%	41.5	9%	512	25%
Oil tanker	11.0	11%	259	11%	29.2	11%	563	32%
Chemical tanker	5.20	9%	112	7%	13.8	9%	118	38%
General cargo	4.27	11%	89.8	8%	10.9	10%	32.2	35%
Vehicle	1.15	5%	27.3	5%	2.70	5%	21.6	13%
Refrigerated bulk	0.215	2%	4.35	2%	0.617	2%	1.68	4%
Ro-ro	0.022	0%	0.700	0%	.044	0%	15.4	4%
Other liquids tanker	0.010	2%	0.245	2%	0.028	2%	44.5	24%