Distribution of air pollution from oceangoing vessels in the Greater Pearl River Delta, 2015

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1. Executive summary

China is the world's second largest economy[1] and the largest trading nation in the world.[2] Its coastline is visited by thousands of cargo-carrying ships on a daily basis. The Greater Pearl River Delta (GPRD),[3] which sits in southern China facing the South China Sea, is a heavily populated and prosperous region with heavy ship traffic. Because this traffic contributes to poor local air quality, the Chinese government has identified the GPRD region as a key target for steps to control emissions from ships. Upon establishment of the Pearl River Delta Domestic Emission Control Area (DECA), ships operating within approximately 12 nautical miles [nm] beyond China's coastal baseline must gradually switch to cleaner marine fuels (Mao, 2016). Upon evaluation of the effectiveness of the current DECA, China may consider taking additional actions as soon as 2020.

We used Automatic Identification System (AIS) ship operations data to compile a high-resolution ship emissions inventory in this region. The purpose of this work is threefold:

- To quantify the magnitude of major air pollutants from oceangoing vessels (OGVs);
- To identify the top contributing ship classes in this region; and
- To understand the distribution of at-sea emissions from OGVs, from at berth to 200 nm offshore as a first step to identifying control polices.

Our results showed that:

- In 2015, OGVs emitted 104 thousand tonnes (kilotonnes [kt]) of sulfur oxides (SO_X), 14 kt of particulate matter (PM), and 150 kt of nitrogen oxides (NO_X). This is approximately 24%, 3%, and 17% of respective emissions from all sources in the PRD region.[4]
- Container ships alone emitted about 60% of all air pollution from OGVs in 2015, making them a clear target of future air pollution control policies. Bulk carriers and oil tankers were also important contributors to total emissions.
- In our study region, about 9% of total emissions were emitted at berth. This share increased to 63% at the 12-nm boundary and then continued to increase mildly moving further away. The 96-nm boundary captured about 82% of total emissions. Expanding the current DECA regulations to 12 nm would reduce emissions roughly 7 fold. Further expansion, for example via an international emission control area (ECA) out to 100 nm, would provide even greater benefits.

2. Background

2.1 OGVS IN THE GREATER PEARL RIVER DELTA REGION

The GPRD region is home to 11 major port cities in China, together handling roughly 39% of all outbound trade in China as of 2015.[5] With Shenzhen (3rd largest), Hong Kong (5th), and Guangzhou (7th) among the top 10

1 Ranking is from World Bank: http://data.worldbank.org/data-catalog/GDP-ranking-table

2 Ranking is from World Trade Organization 2016 report: https://www.wto.org/english/res_e/statis_e/wts2016_e/wts2016_e.pdf

3 Greater Pearl River Delta region includes 11 cities: Guangzhou, Shenzhen, Zhuhai, Dongguan, Zhongshan, Jiangmen, Huizhou, Foshan, Zhaoqing, Hong Kong, and Macau.

4 The number of total source emissions we used here to calculate the contribution ratios of OGVs is from: Li, C., Yuan, Z., Ou, J., Fan, X., Ye, S., Xiao, T., ... & Zheng, J. (2016). An AIS-based high-resolution ship emission inventory and its uncertainty in Pearl River Delta region, China. *Science of The Total Environment, 573,* 1–10. However, this should be interpreted with caution since the number of total source emissions are based on 2012 data.

5 Data source: China Port Year Book 2016

largest container ports worldwide, this port-clustered region contributes the largest cargo throughput in the world. The Port of Shenzhen, which is equipped with 39 deep-water berths to service some of the world's largest ships, alone handled 24 million twenty-foot equivalent units (TEUs) of containers in 2015 according to the China Ports Year Book 2016 (Yearbook 2016). A total of 254 international liner routes serve this port, and "super" ships greater than 300 m in length paid 8,953 visits to this port in 2015. Table 1 presents information for ports in this region.

Table 1. Overview of port cities in the GPRD region[a]

Port	Type	Cargo throughput (million tonnes)	Container throughput (million TEUs)	International liner routes[b]	Major berths[c]	Annual OGV arrivals[d]
Guangzhou	Sea port, river port	413	17.6	67	71	4,825
Hong Kong	Sea port, river port	257	20.1	340	24	29,011
Shenzhen	Sea port	217	24.2	254	69	25,325
Dongguan	Sea port	131	3.36	N/A	28	1,250
Zhuhai	Sea port	112	1.14	23	27	888
Jiangmen	River port	75	1.09	N/A	3	6,668
Zhongshan	River port, Sea port	73	1.36	0	N/A	0
Huizhou	Sea port, river port	70	0.27	N/A	22	653
Foshan	River port	61	3.02	N/A	N/A	11,493
Zhaoqing	River port	29	0.70	N/A	0	2,070
Macau	Sea port	0.21[e]	0.15	N/A	N/A	N/A

[a] Data were collected from multiple sources, including the China Ports Year Book 2016, Hong Kong Port and Maritime Statistics (http://www.mardep.gov.hk/en/publication/portstat.html), and internal communication with China's Ministry of Transport.
[b] This column lists the number of international liner routes that serve these ports.
[c] Major berths are berths that can handle over 10,000 tonnes of cargo annually.
[d] This column only summarizes OGV arrivals from five major ship classes, which together account for 90% of all OGV arrivals.
[e] Due to data availability, this number only captures containerized cargo throughput in Macau.

OGVs, a major transportation mode for international trade, frequent the GPRD region to load and unload cargo and passengers. Among them, container ships, bulk carriers, chemical tankers, general cargo vessels, and roll-on/roll-off (Ro/Ro) ships carrying vehicles represent over 90% of the total gross tonnage (2,712 million gross tonnage) of ships visiting this region in 2015.[6] Table 2 compares annual OGV arrivals by major ship class in the GPRD region with the San Pedro Bay Ports (Los Angeles and Long Beach) and the Port of Singapore.

Table 2. 2015 OGV arrivals by ship class for representative ports[a]

Ship class	2015 arrivals		
	GPRD	San Pedro Bay Ports (LA/LB)	Singapore[b]
Container ships	57,260	4,891	17,722
Bulk carriers	7,954	857	16,560
Tankers	2,849	2,502	22,062
General cargo ships	8,845	283	4,143
Ro/Ro ships	516	52	NA

[a] The numbers are collected from multiple sources, including Port of Long Beach 2015 Air Emissions Inventory, Port of Los Angeles Inventory of Air Emissions 2015, Hong Kong Port and Maritime Statistics (http://www.mardep.gov.hk/en/publication/portstat.html), Port of Singapore Port Statistics (http://www.mpa.gov.sg/web/portal/home/port-of-singapore/port-statistics), and internal communication with China's Ministry of Transport.
[b] Due to data availability, this column lists ship arrivals in Port of Singapore for both OGVs and non-OGVs.

2.2 AIR POLLUTION FROM OGVS

Long-term exposure to $PM_{2.5}$ has been linked to adverse public health outcomes, including increased premature deaths from heart and pulmonary diseases and worsened respiratory diseases (Friedrich, Heinen, Kamakate, & Kodjak, 2007). Emissions of NO_x, SO_x, and PM from OGVs can significantly impact the air quality of major port cities and coastlines along important shipping corridors. SO_x and NO_x irritate the respiratory system, and they react with ammonia to form sulfates and nitrates, two important components of ambient $PM_{2.5}$.[7] NO_x is also an important precursor for ground-level ozone, an air pollutant that causes decreased lung function, respiratory symptoms, aggravation of asthma, increased hospital and

6 According to electronic communications with China's Waterborne Research Institute

7 Information from the U.S. Environmental Protection Agency: https://www.epa.gov/sites/production/files/2016-09/documents/420r09007.pdf

emergency room visits, and various other respiratory effects.

Liu et al. (2016) found that shipping traffic in East Asia has doubled since 2005 and accounts for 16% of global shipping carbon dioxide (CO_2) emissions. Liu (2016) estimated that air pollution causes between 14,500 and 37,500 premature deaths annually in the region. A study by Kwok, Fung, Lau, & Wang (2012) indicated that shipping was responsible for 25% of $PM_{2.5}$ emissions in the Pearl River Delta (PRD) region.[8] Ships are even larger contributors to air quality problems in Hong Kong and Shenzhen, two of the most important port cities in the GPRD. A 2015 Hong Kong emissions inventory showed that ships were the single largest source of SO_x, NO_x, and PM emissions.[9] Yau, Lee, Corbett, Wang, Cheng, & Ho (2012) estimated that shipping is responsible for 17%, 11%, and 16% of total NO_x, SO_2 and PM_{10} emitted in Hong Kong. Similarly, an internal study on Shenzhen's port emissions estimated that oceangoing vessels contributed 12% NO_x emissions and 54% SO_x emissions, respectively, in 2014.[10] More detailed studies, including ship plume dispersion modeling, are needed to accurately estimate the health and environmental impacts of ship emissions, especially in regions adjacent to major ports in mainland China.

In addition to conventional air pollutants, OGVs produce greenhouse gases (GHGs), including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and black carbon (BC), which contribute to climate change. Liu et al. (2016) estimated that GHG emissions from OGVs in East Asia would have a long-term warming impact if no control measures are in place.

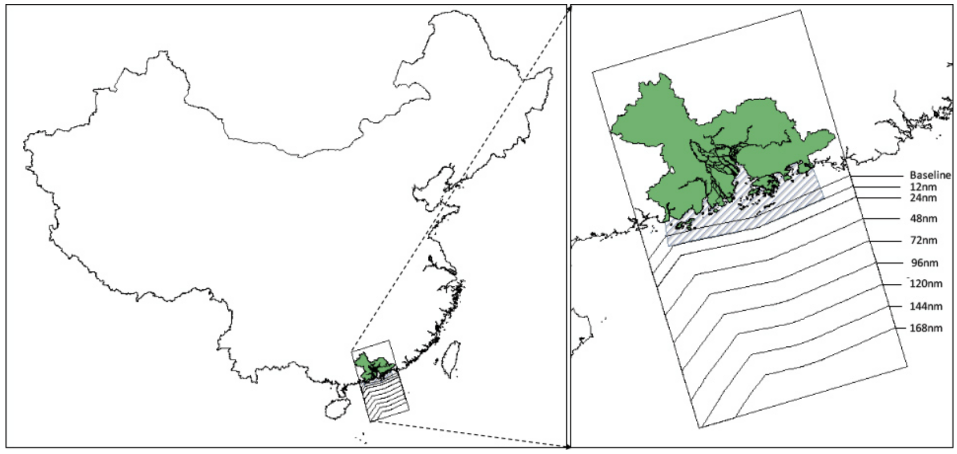

Figure 1. Study region and geographic boundaries analyzed

Realizing the negative impact of ship traffic, the Chinese government has taken steps to curb their emissions. One of the control measures is the enactment of three Domestic Emission Control Areas (DECAs), in the Bo Sea, the Yangtze River Delta, and the Pearl River Delta. Within these DECA regions (approximately 12 nm from coastal baseline), all ships are mandated to gradually switch to cleaner fuels (less than 0.5% m/m of sulfur content) starting from January 1, 2017 (Mao, 2016). Prior to designation of the DECAs, the International Maritime Organization (IMO) designated four international emission control areas (ECAs), which are larger in scale and require more ambitious air pollution control measures. For example, the North America ECA extends to about 200 nm offshore, and the current allowable fuel sulfur content for all ships operating in this region is 0.1% m/m.[11] In addition, Tier III NO_x requirements took effect on January 1, 2016, requiring 80% reductions in NO_x emissions from new build vessels operating off of the North American coast.[12]

3. Study region

Figure 1 shows the region covered in this study. The GPRD region summarized in Table 1, including the nine port cities in Guangdong province, plus Hong Kong and Macau, is indicated in green. The shaded area shows the current Pearl River Delta DECA. Several seaside boundaries are drawn based on the 1982 United Nations Convention on the Law of the Sea (UNCLOS).[13] The first line, referred to as the "baseline," denotes the boundary of Chinese mainland

8 The Pearl River Delta (PRD) region differs from the GPRD region in that it excludes Hong Kong and Macau.

9 Information from Hong Kong Environmental Protection Bureau's official website: http://www.epd.gov.hk/epd/english/environmentinhk/air/data/emission_inve.html

10 Electronic communications with Shenzhen Human Habitat and Environment Commissions.

11 U.S. Environmental Protection Agency. (n.d.). Designation of the North American Emission Control Area for Marine Vessels. Retrieved from https://www.epa.gov/regulations-emissions-vehicles-and-engines/designation-north-american-emission-control-area-marine

12 International Maritime Organization. (n.d.). Nitrogen oxides (NO_x)–Regulation 13. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

13 For a detailed description of this convention, see http://www.un.org/Depts/los/convention_agreements/texts/unclos/part2.htm

internal waters.[14] The second line extends 12 nm (about 22 km) from the baseline, defined under UNCLOS as the boundary of a country's territorial sea. The third line extends 24 nm from the baseline. The next several lines are theoretical boundaries extending further out into the ocean, up to 168 nm. The rectangular boundary extending approximately 200 nm from the mouth of GPRD delineates the limit of this analysis.

4. Methodology

For this inventory, we used AIS data provided by exactEarth, along with ship characteristics data from IHS Fairplay. AIS data provides a ship's instantaneous activity—most importantly, its location and speed over ground at a specific timestamp, as well as information such as the Maritime Mobile Service Identity (MMSI) number and IMO number to identify the ship. IHS Fairplay provides a ship's technical specifications, including power, fuel type, and design speed, which can be linked with the AIS data to estimate a ship's instantaneous emissions.

Emissions of PM, SO_x, NO_x, non-methane volatile organic compounds (NMVOCs), CH_4, N_2O, BC, and CO_2 were estimated for year 2015 based on Equation 1.

Most of the emission factors were taken from the IMO's 3rd Greenhouse Gas Study (Smith et al., 2014), except for BC emission factors, which are taken as the "best estimate" from an upcoming ICCT study.[15] A detailed description of methodologies and assumptions are included in the Methodology section of the same report.

$$E_{i,j} = \Sigma_{t=0}^{t=n}\left(\left(P_{ME_i} * \left(\frac{SOG_{i,t}}{V_{max_i}}\right)^3 * EF_{ME_{j,k,l,m}} + D_{AE_{p,i}} * EF_{AE_{j,k,l,m}} + D_{BO_{p,i}} * EF_{BO_{j,m}}\right) * 1\text{ hour}\right)$$

(Equation 1)

Where:

i = ship	P_{ME_i} = main engine power (kW) for ship i
j = pollutant	$SOG_{i,t}$ = speed over ground (knots) for ship i at time t
t = time (operating hour, h)	V_{MAX_i} = maximum speed (knots) for ship i
k = engine type	$EF_{ME_{j,k,l,m}}$ = main engine emission facor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m
l = engine tier	$D_{AE_{p,i}}$ = auxiliary engine power demand (kW) in phase p for ship i
m = fuel type	$EF_{AE_{j,k,lm}}$ = auxiliary engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m
p = phase	$D_{BO_{p,i}}$ = boiler power demand (kW) in phase p for ship i
$E_{i,j}$ = emissions (g) for ship i and pollutant j	$EF_{BO_{j,m}}$ = boiler emission factor (g/kWh) for pollutant j and fuel type m

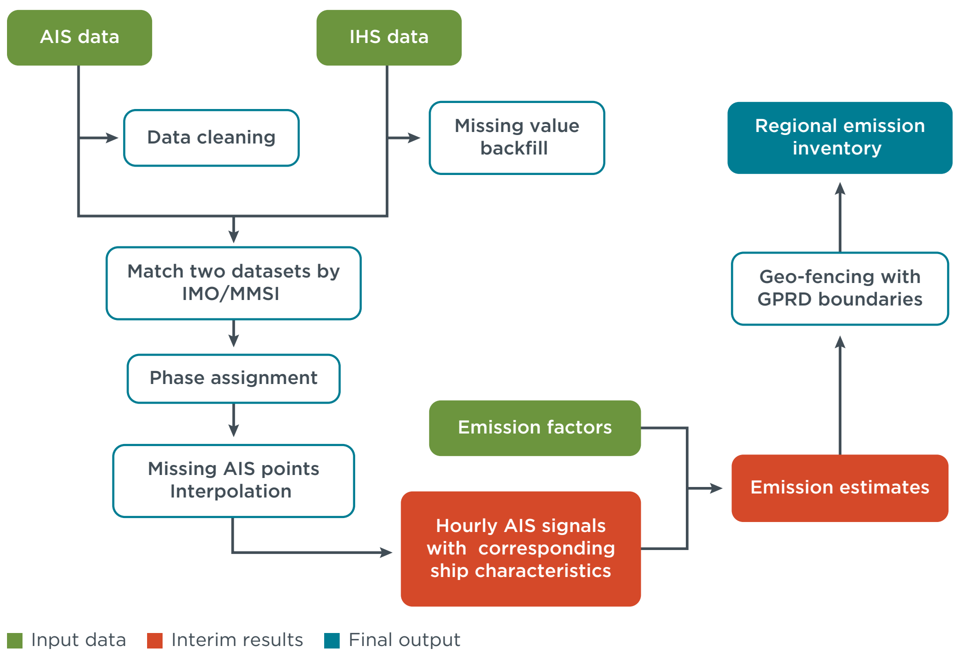

Figure 2. Bottom-up emissions inventory compilation process

Figure 2 shows the process of the bottom-up compilation of the emissions inventory.

Emissions were first calculated for the whole study region (tilted rectangular boundary). Then, the different seaside boundaries were used to geo-fence the data according to its geographical location identified in AIS. Because the AIS data also includes river and coastal

14 For simplicity, we only included the baseline points for mainland China.

15 *Black carbon emissions and fuel use in global shipping, 2015.*

Table 3. 2015 OGV emissions inventory in the study region

Ship class	Count	Tonnes emitted								CO_2 emitted (milllion tonnes)
		SO_x	PM	NO_x	CO	CH_4	N_2O	BC	NMVOCs	
Container ship	2,400	64,000	9,000	95,000	3,800	84	220	420	4,000	4.05
Bulk carrier	4,400	15,000	2,000	22,000	810	17	50	88	840	0.97
Oil tanker	970	9,300	1,000	10,000	440	7.8	39	77	380	0.79
General cargo vessel	1,500	4,500	610	6,800	270	5.4	16	36	260	0.32
Chemical tanker	1,000	4,200	520	5,400	220	4.2	15	32	210	0.29
Cruise ship	44	3,100	370	3,800	150	2.5	11	35	120	0.21
Liquefied gas tanker	350	2,200	250	2,600	150	340	8.7	17	97	0.18
Vehicle carrier	400	1,800	240	2,700	96	2	6	11	97	0.12
RoPax ferry	19	340	47	530	22	0.41	1.3	5.4	20	0.02
Refrigerated bulk carrier	52	57	7.1	75	2.9	0.052	0.19	0.5	2.6	0
Other liquid tankers	2	21	2.3	21	0.87	0.015	0.067	0.18	0.74	0
Ro/Ro ship	8	7.1	0.92	11	0.51	0.009	0.031	0.076	0.45	0
Passenger ferry	1	2.9	0.37	3.9	0.15	0.0025	0.0095	0.038	0.12	0
Total	**11,200**	**104,000**	**14,000**	**150,000**	**5,930**	**466**	**363**	**721**	**6,070**	**6.96**

Note: All figures are rounded to 2 or 3 significant digits.

vessels, only data from OGVs were retained for this study, as defined by having a valid IMO number and being a ship class deemed to be engaged in international shipping in the 3rd IMO GHG report (e.g., major cargo-carrying ship classes, cruise ships, large ferries).

5. Results and discussion

5.1 OGV EMISSIONS IN THE GPRD REGION

The 2015 baseline OGV emissions inventory for the GPRD region aggregated instantaneous emissions from 11,169 OGVs (more than 4 million AIS signals observed) in the study region (Table 3). These OGVs consumed about 2 million tonnes of marine fuels, predominately heavy fuel oil with an average sulfur content of about 2.5% m/m.

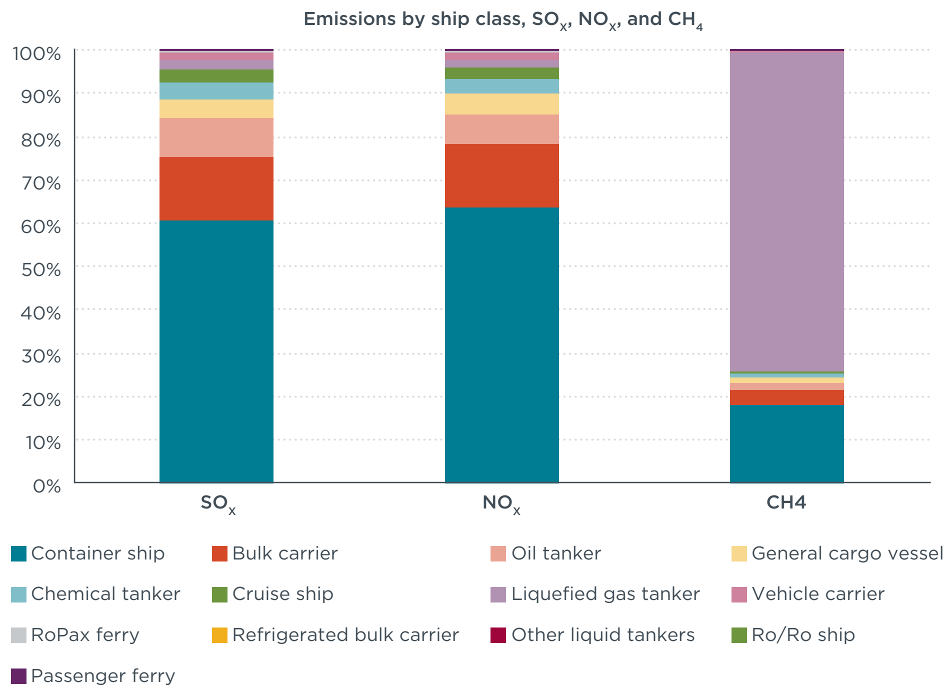

Figure 3. Air pollutants by ship class

Different classes of OGVs contribute to air pollution in different amounts. As shown in Table 3 and Figure 3, container ships, bulk carriers, and oil tankers are the top three contributors for all pollutants other than CH_4. This is mainly because of their large number of port visits, high operational hours, large engines, and use of dirty (but cheap) residual fuel oil. More strikingly, container ships alone account for 60% of all emissions, making them a clear target for emission-control policies. Container ships are some of the largest ships operating in the GPRD region and thus require enormous propulsion engines, which burn tonnes of fuel per day. Additionally, they require large auxiliary engines to meet the constant electrical power demand of ship operations. On average, a container ship that visits the GPRD operates 605 hours per year in the region—the highest of all ship classes considered. Bulk carriers, which transport raw materials like grains, coal, ore, and cement, are frequent visitors to the GPRD region, representing almost 40% of the OGVs observed. On average, an oil tanker consumes 430 MWh of auxiliary electrical power annually in this region when loading and unloading products, equivalent to the annual demand of approximately 40 U.S. homes. [16] Their total operational hours in the GPRD region are also relatively high, third only to container ships and bulk carriers.

Together, container ships, bulk carriers, and oil tankers emitted almost 84% of all air pollution in the GPRD region in 2015, excluding CH_4. Liquefied gas tankers, most of which are carriers of liquefied natural gas (LNG), are the dominant contributor to CH_4 emissions as a result of "methane slip"; methane slip occurs when LNG fuel escapes an engine or fueling system unburned and enters the atmosphere as methane.

In addition to the absolute level of emissions within the GPRD region, we also analyzed the cumulative emissions within different geographical delineations to shed light on the benefits of expanding the DECA requirements to cover a wider geographic area. Figure 4 shows that about 82% of air pollution from OGVs occurred within the 96-nm boundary, about half of the furthest extent analyzed. Surprisingly, only about 9% of the total emissions took place at berth. This suggests that portside regulations, although often easier to implement, only cover a small portion of the total emissions. Cumulative emissions increased dramatically from at berth to the 12-nm boundary and then increased more or less linearly with distance away from shore. This is because ship traffic tends to intensify closer to shore, leading to a higher collective activity level within the 12-nm boundary. The distribution of CH_4 emissions follows a somewhat different pattern, increasingly more gradually to 12 nm linearly from there. This is because CH_4 emissions are dominated by liquefied gas tankers, which have less concentrated activity within the 12-nm boundary.

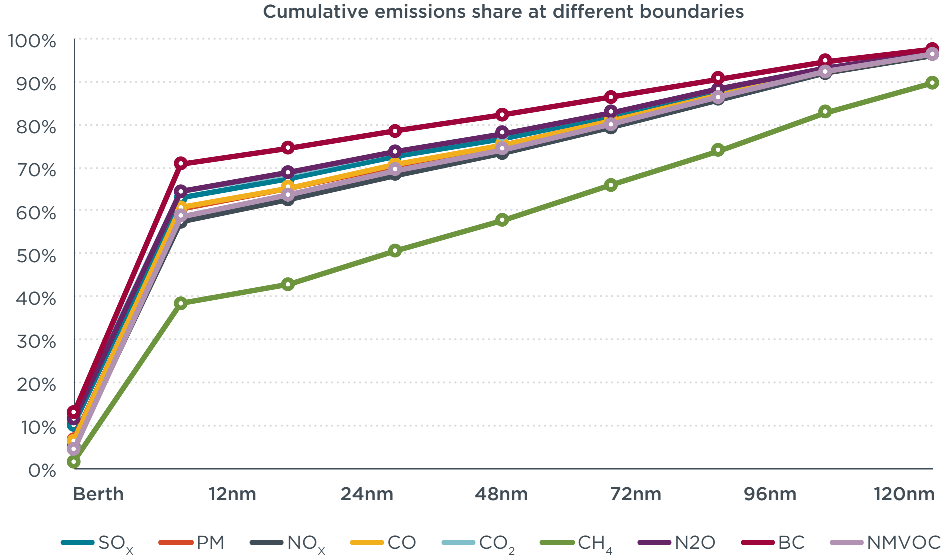

Figure 4. Cumulative emissions share at different boundaries

The current regulations under China's DECA framework require the use of marine fuels with less than 0.5% m/m sulfur content when ships are at berth. However, we estimate that at-berth requirements exclude over 90% of total emissions in the area. Enormous emission-reduction benefits would be achieved if the mandatory requirement expands to 12 nm, which will not take effect until 2019 under the current schedule. Moving faster would provide significant, early reductions in air pollution. Beyond that, the additional 37%[17] of emissions occurring outside of the DECA extent (12 nm) should also be considered, because these emissions are close enough to shore to likely have a negative impact on the air quality and human health in China coastal and even inland communities (Corbett et al., 2007). A potential solution is for China to apply for an IMO ECA, which would make emission-control measures enforceable on foreign-flagged ships, even if these emissions occur far out at sea.

5.2 POTENTIAL AREAS FOR FUTURE RESEARCH

5.2.1 Estimating emissions from river and coastal vessels

This report only considers air pollution from OGVs. To capture all of the entire emission sources from water navigation, ships that mostly engage in coastal waters and inland waterways should also be included.

16 In 2015, the average annual electricity consumption for a U.S. residential utility customer was 10,812 kWh. Data source: https://www.eia.gov/tools/faqs/faq.php?id=97&t=3

17 Emissions share at the 12-nm boundary was 63%; therefore, the remaining emissions are 100%–63% = 37% of the total emissions.

This report does not include emissions from China's domestic transport fleet[18] and the fishing fleet (referred to hereafter as "the missing fleet") operating within the GPRD region. On a global scale, emissions from these ships are relatively small. The IMO's 3rd Greenhouse Gas Study found that fishing vessels contributed negligibly to CO_2 emissions (less than 1%) from global shipping in 2012, with domestic shipping responsible for 14% of emissions (Smith et al., 2014). On a regional scale, emissions from these ships could be significantly larger. China's huge domestic (coastal plus river) shipping and fishing fleets are likely a significant contributor to regional air quality problems (Mao, 2017).

exactEarth data report signals from all vessels that are equipped with an AIS transmitting device. Nearly half of all AIS signals from the study region are not matched with vessels in the IHS Fairplay dataset, suggesting that these signals were probably emitted by domestic vessels not holding an IMO number and registered for international voyages. An estimate of emissions from this missing fleet is needed to create a comprehensive GPRD ship emissions inventory.[19] Further work is needed to match these signals to domestic vessels and to identify reliable sources of ship technical data. In addition, because China's domestic transport fleet and fishing fleet are expected to be different from the international shipping fleet mechanically, localized emission factors should be used to estimate emissions. China's Ministry of Environment does have recommended emission factors for their domestic transport fleet and fishing fleet, but these values are based on emission tests on a very limited number of vessels.[20]

In future work, we will estimate emissions from river and coastal vessels via the following steps:

- Find additional data sources for ship characteristics of the missing fleet,
- Develop a machine-learning algorithm to identify more ship characteristics based on routing,
- Collect appropriate emission factors through literature review and communicating with key partners in China, and
- Validate results via previous emission estimates (both top-down and bottom-up) in a similar study area.

5.2.2 Evaluating costs and benefits of policy alternatives

Baseline emission inventories can help choose regulatory targets (pollutants, ship classes, geographical areas, etc.). However, they cannot provide the whole picture for sound policy decisions. A cost–benefit analysis improves policy decision making. In general terms, a cost–benefit analysis needs to identify policy options and scenarios for comparison, define "costs" and "benefits" and how to measure them, and choose a proper baseline and a target year for policy evaluation. Fundamentally, air pollution control policies aim to provide health benefits by reducing $PM_{2.5}$- and ozone-induced premature deaths and morbidities.

A four-step approach could be used to evaluate the health benefits of a potential vessel emission control policy scenario:

1. Model emissions of criteria pollutants from vessels and other emission sources under policy and business-as-usual (BAU) scenarios, respectively;
2. Model ambient $PM_{2.5}$ and ozone concentrations under these scenarios using chemical transport models (e.g., CMAQ) together with corresponding meteorological data;
3. Estimate health impacts in terms of premature death and morbidities using exposure–response functions for specific health outcomes in combination with demographic and health incidence data; and
4. Determine the health benefits of policy action by comparing results of the BAU and policy scenarios.

18 Although China's domestic transport fleet that are ocean-going were included in this study.

19 Smaller vessels under 300 gross tonnes (gt) are not required by IMO to install AIS devices. Nonetheless, the China Maritime Safety Administration released regulations in 2010 to promote AIS installation on domestic fleet. Those regulations can be retrieved from http://210.73.66.144:4601/law?fn=chl376s035.txt

20 Technical guidance on developing non-road mobile source emission inventory, retrieved from http://www.zhb.gov.cn/gkml/hbb/bgg/201501/W020150107594587960717.pdf

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