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Impacts of Shipping on Air Pollutant Emissions, Air Quality, and Health in the Yangtze River Delta and Shanghai, China

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EXECUTIVE SUMMARY

Health Effects Institute

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EXECUTIVE SUMMARY

Impacts of Shipping on Air Pollutant Emissions, Air Quality, and Health in the Yangtze River Delta and Shanghai, China

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INTRODUCTION AND BACKGROUND

Air pollution has posed a major challenge in China. Although there has been recent progress, many sources continue to contribute to air pollution in quantities that vary geographically. Some are more important than others; several previous studies have identified substantial contributions from the industrial, power generation, transportation, agricultural biomass burning, and residential sectors (Ding et al. 2019; GBD MAPS Working Group 2016). Although China's first Action Plan for Air Pollution Prevention and Control, which was initiated in 2013 to improve air quality, led to reductions of 25% or more in the levels of $PM_{2.5}$ in 2017, the annual average concentrations of $PM_{2.5}$ in China were still estimated at about 53 µg/m^3, well above the World Health Organization's guidelines for healthy air (Health Effects Institute 2019). The potential implications for public health are substantial. In 2015, air pollution from all sources contributed to an estimated 1.1 million deaths in China (Cohen et al. 2017).

What This Study Adds

- This study provides a comprehensive and detailed spatial analysis of the impacts of shipping and related activities on air quality and health of the populations of the Yangtze River Delta (9-km resolution) and the city of Shanghai (1-km resolution).
- It examines emissions and health effects in a baseline year (2015, before implementation of China's domestic emissions control areas [DECAs]*) and under three future emissions control scenarios (2030).
- Both the baseline and future analyses showed the importance for air quality and human health of controlling emissions from shipping and related activities that occur close to population centers, in particular from coastal or international ships entering inland waterways of Shanghai.
- In the Yangtze River Delta in 2015, shipping-related exposures to $PM_{2.5}$ contributed to about 3,600 premature deaths from stroke, chronic obstructive pulmonary disease, ischemic heart disease, and lung cancer combined, and to 270,000 hospital admissions from all causes. About a third of these deaths were in Shanghai.
- The analysis of the current policy scenario identified clear health benefits of full compliance with the current China DECA policies; the number of premature deaths relative to 2015 would be cut by half in 2030. Implementation of stricter and aspirational policy scenarios could reduce the 2015 mortality burden by substantially more (by a total of 62% and 77%, respectively). Requiring use of marine fuels with 0.1% sulfur content out to an extended emissions control area boundary of 100 nautical miles (NM) would provide the most benefit of the shipping emissions controls.

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* A list of abbreviations and other terms appears at the end of this summary.

Although such national studies have typically not included the shipping sector in their analyses, a number of other studies have examined the global impacts of shipping and, more recently, their specific implications for China. Globally, air pollution from ship emissions has been estimated to contribute around 18,300 to 147,900 premature deaths primarily from the contributions to $PM_{2.5}$ of large ships traveling on international routes (Corbett et al. 2007; Partanen et al. 2013; Winebrake et al. 2009). Liu and colleagues (2016) estimated that shipping contributed 5,560 to 25,500 premature deaths in 2013 in East Asia of which about 18,000 were in mainland China. A recent global analysis estimated that 137,000 cardiovascular and lung cancer deaths globally related *to ship emissions* — 80% of them in Asia — could be avoided by more stringent controls, specifically by decreasing the sulfur content of marine fuel from approximately 2.7% (mass/mass) to less than 0.5% by 2020 (Sofiev et al. 2018).

The overall goal of this project was to conduct a comprehensive assessment of the current and potential future air quality and health impacts of shipping and related activities at finer spatial scales in the city of Shanghai and the broader Yangtze River Delta region than have been conducted to date (Figure ES-1). We sought to estimate the impacts of shipping prior to the implementation of Chinese DECAs, using 2015 as a baseline year, as well as the future impacts (2030) of implementing both the latest DECA and more ambitious policies related to ships and green ports initiatives.

SCIENTIFIC APPROACH

The flow chart in Figure ES-2 provides an overview of the steps taken and the related data inputs necessary to assess the impact of ships and shipping-related sources on air pollutant emissions, ambient air quality levels, population exposures, and health burden in this study. The main steps were to:

- Develop emissions inventories for shipping and shipping-related sources in the Yangtze River Delta and Shanghai for the baseline year 2015 and projected for the year 2030 under alternative control scenarios. Emissions from non-shipping sources were obtained from existing national and regional emissions inventories.
- Simulate the impact of total and shipping-specific emissions on ambient pollutant and population-weighted $PM_{2.5}$ concentrations in the Yangtze River Delta and Shanghai using the Weather Research and Forecasting (WRF version 3.3) and Community Multiscale Air Quality (CMAQ version 4.6) modeling system (WRF-CMAQ). Simulations were conducted for 2015 and for 2030 under three alternative emissions control policies, described below.
- Estimate the health burden, defined in terms of excess numbers of deaths and hospital admissions in a given year, using the Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE version 1.4), an open-source software developed by the U.S. Environmental Protection Agency (U.S. EPA 2015). We worked with Chinese scientists to identify the most appropriate studies with which to characterize the risks associated with exposures to $PM_{2.5}$ for China and to obtain the appropriate mortality and hospital admissions rates for Shanghai and the Yangtze River Delta.

EVALUATION OF ALTERNATIVE CONTROL POLICIES

We examined potential air quality and health benefits of controlling ship emissions for the Yangtze River Delta in 2030 under three alternative policy scenarios (Table ES-1). The "current" policy scenario was intended to examine the benefits of full implementation of China's second domestic emissions control policies (DECA 2.0), first proposed in July 2018. The 0.5% sulfur fuel requirement for cruising ships under this scenario is the same as the International Maritime Organization (IMO) sulfur fuel content limit set to be implemented globally in 2020. However, to estimate the benefits of the China policy alone, we assumed that the sulfur fuel content used by vessels beyond 12 NM of shore would remain the same as it was in 2015. The second, "stricter" policy scenario assumed lower fuel sulfur content and tighter NO_x controls than the current policy, but still extended to vessels only 12 NM from shore. The third, "aspirational" policy scenario extended these stricter policies to vessels 100 NM from shore; this policy scenario was more aspirational because implementation would require agreement of the IMO. Although not included in our future policy analyses, emissions from cargo transport and from port machinery were expected to decrease in the future because of upcoming low-sulfur fuel and electrification requirements.

MAIN FINDINGS

BASELINE (2015)

Our assessment of the relative contributions of total ship emissions and their impacts on average $PM_{2.5}$ concentrations in the Yangtze River Delta region at varying distances from shore emphasizes the importance of shipping activities close to shore and to population centers. We found that between about 48% and 75% of pollutant emissions from ships are released within 12 NM of shore, depending on the pollutant; over 90% are released within 96 NM. Ship emissions within 12 NM accounted for between 53% and 83% of estimated human exposure to $PM_{2.5}$ in the core cities, represented in this analysis as population-weighted $PM_{2.5}$ concentrations.

Annual population-weighted $PM_{2.5}$ concentrations from shipping sources in individual core cities of the Yangtze River Delta region ranged from 0.5 $\mu g/m^3$ to 2.5 $\mu g/m^3$ (average 0.93 $\mu g/m^3$) (Figure ES-3), accounting for 1% to 6% of population-weighted $PM_{2.5}$ concentrations from all pollution sources. The four cities in the Yangtze River Delta with the largest contributions of population-weighted $PM_{2.5}$ from shipping sources were all coastal cities. Of these, Shanghai had the highest average ship-related population-weighted $PM_{2.5}$ concentration (2.5 $\mu g/m^3$).

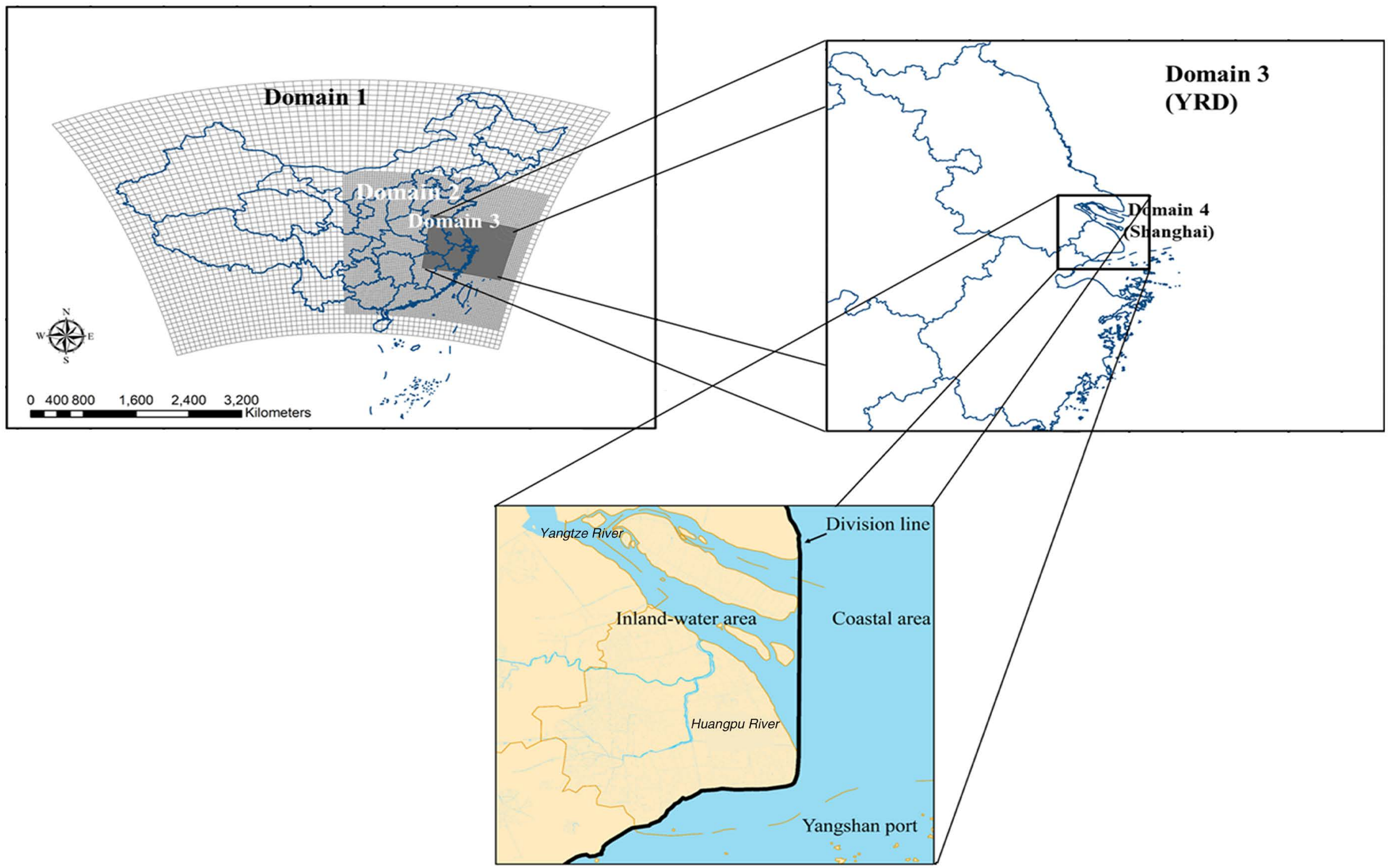


Figure ES-1. Map of nested study areas and delineation of inland-water area in Shanghai. Spatial resolutions for main analyses were 9 km in the Yangtze River Delta (YRD) (Domain 3) and 1 km in Shanghai (Domain 4). The inland-water area was defined by the black line shown above at the mouth of the Yangtze River; inland-water ships are defined as river ships, coastal ships, and ocean-going vessels that enter this area. (Adapted from Feng et al. 2019 [supplement]; distributed under Creative Commons Attribution 4.0 License.)

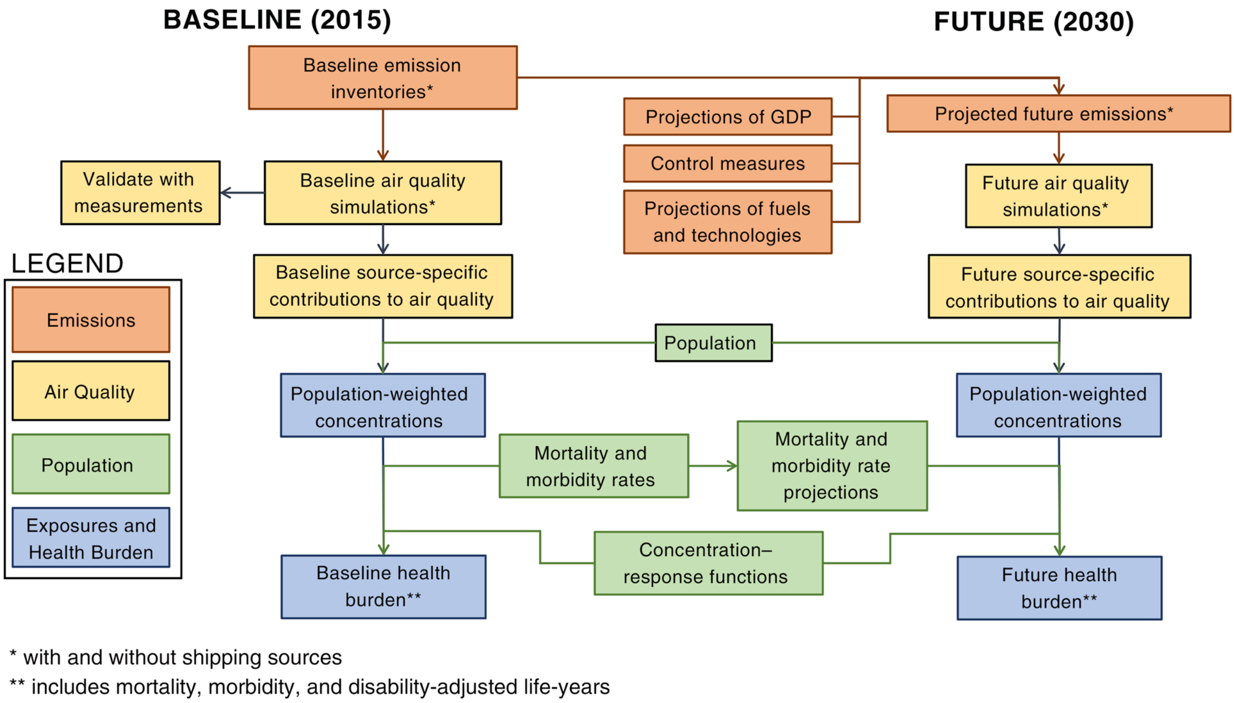


Figure ES-2. Process flowchart for estimating the impacts of emissions on air quality and health.

Table ES-1. Future Policy Scenarios

Scenario	Control Area	Sulfur Controls	NO_x Controls
Base year (2015)	12 NM	All vessels change over to 0.5% sulfur fuel prior to entering the DECA	No controls on ships built before 2000 Tier I for ships constructed on or after Jan 1, 2000 Tier II for ships constructed on or after Jan 1, 2011
Current policy scenario, year 2030	12 NM	0.1% sulfur fuel at berth 0.5% sulfur fuel while cruising	China II for Chinese inland vessels Tier II for foreign ships
Stricter policy scenario, year 2030	12 NM	0.1% sulfur fuel	Tier III engines for all ships
Aspirational scenario, year 2030	100 NM	0.1% sulfur fuel	Tier III engines for all ships

NM = nautical miles

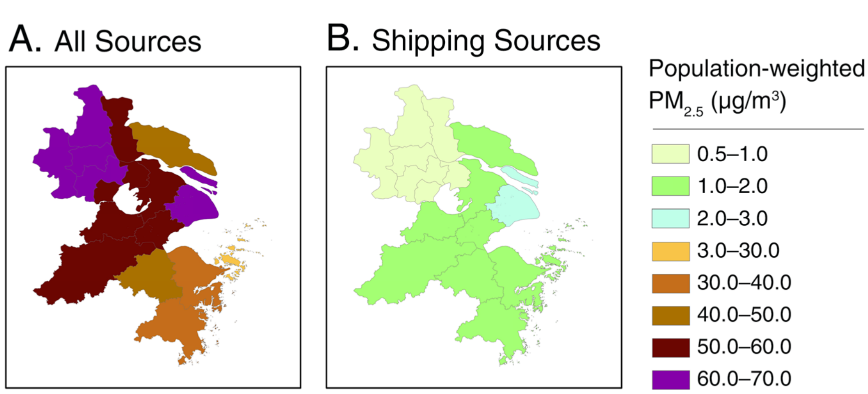


Figure ES-3. Annual average population-weighted $PM_{2.5}$ concentrations (μg/m³) in core cities in the Yangtze River Delta from (A) all air pollution sources and (B) ships. (From Feng et al. 2019; distributed under Creative Commons Attribution 4.0 License.)

The detailed analysis of ship and related emissions within the Shanghai port area (Domain 4) found that inland-water ships contributed the most to average annual population-weighted $PM_{2.5}$ concentrations (0.48 μg/m³), followed by coastal ships (0.18 μg/m³), and trucks and port machinery (0.15 μg/m³), but varied spatially (Figure ES-4). Inland-water ship contributions to population-weighted $PM_{2.5}$ concentrations were highest in Shanghai due to the combination of dense population and close proximity to the Huangpu and Yangtze rivers.

Our study finds that emissions from shipping contribute meaningfully to the burden of disease from long-term exposures to $PM_{2.5}$ (particulate matter ≤ 2.5 μm in aerodynamic diameter) in the Yangtze River Delta and in Shanghai. We estimated that in 2015 there were about 3,600 premature deaths from stroke, chronic obstructive pulmonary disease, ischemic heart disease, and lung cancer attributable to long-term exposures to air pollution from ship emissions in the Yangtze River Delta region (Figure ES-5). When considering the impact of shipping emissions from across the entire Yangtze River Delta modeling domain, long-term exposures to $PM_{2.5}$ from ships contributed to about 1,100 premature deaths in Shanghai. As the figure indicates, the results are broadly consistent with, and in proportion to, the results presented for other regions and ports, despite differences in underlying data and methods.

Short-term, daily exposures to shipping-related $PM_{2.5}$ also contribute to the health burden. In the Yangtze River Delta, these exposures contributed to an estimated 1,000 additional deaths and to over 270,000 additional hospital admissions from all causes. Within the Shanghai port domain, we estimated that about 73 additional deaths and 16,000 hospital admissions were attributable to short-term exposures to $PM_{2.5}$ from all shipping sources. The largest impacts were from ships traveling on inland waterways, with additional contributions from coastal ships, container-cargo trucks, and in-port machinery.

ANALYSIS OF FUTURE POLICY SCENARIOS

Our analysis projected that existing Chinese air quality policies for all sources are likely to reduce population exposures to $PM_{2.5}$ levels substantially in the Yangtze River Delta — from 48 μg/m³ in 2015 to about 32 μg/m³ by 2030. Only a small fraction of that change was attributable to reductions in shipping emissions. The projected contributions from shipping to population-weighted annual average $PM_{2.5}$ was 0.36 μg/m³ in the current scenario, 0.26 μg/m³ in the more stringent scenario, and 0.16 μg/m³ in the aspirational scenario (accounting for 1.1%, 0.8%, and 0.5%, respectively, of $PM_{2.5}$ from all sources).

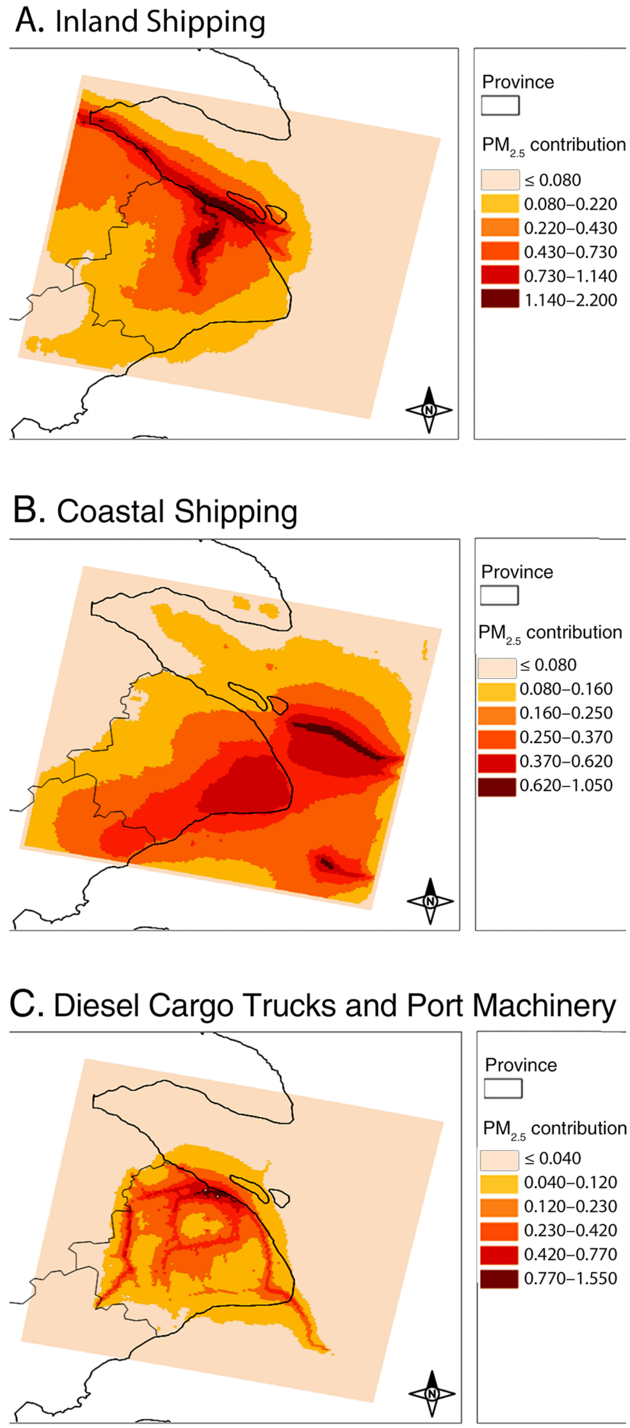
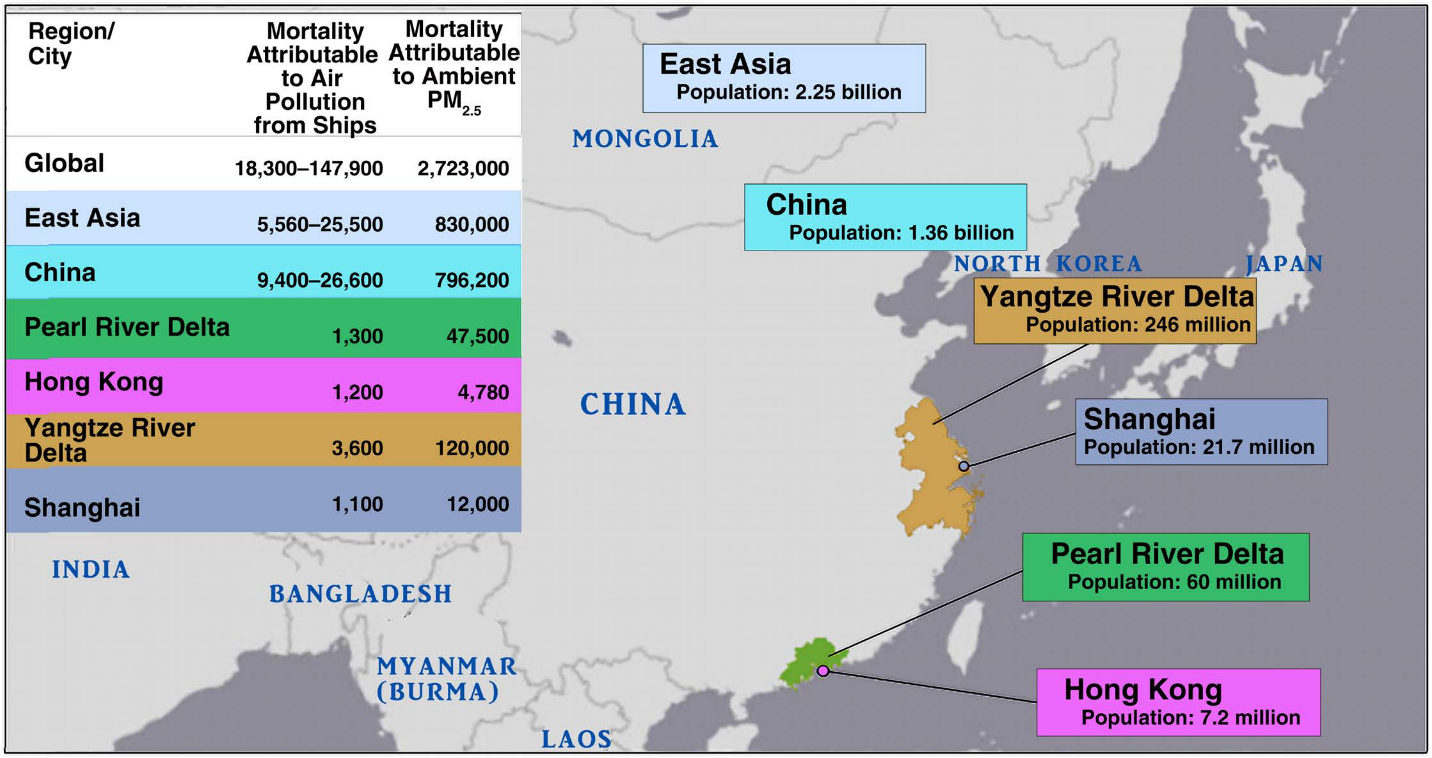


Figure ES-4. Contribution of (A) inland shipping, (B) coastal shipping, and (C) diesel cargo trucks and port machinery to annual average -population-weighted $PM_{2.5}$ in Shanghai in the baseline year 2015.

Despite these small changes in exposure, we estimated that each of these policies could contribute to important reductions in the numbers of premature deaths attributable to shipping and related emissions in 2030 (Figure ES-6), reflecting the large numbers of people potentially exposed. The current policies were projected to reduce the health burden from stroke, chronic obstructive pulmonary disease, ischemic heart disease, and lung cancer by about half (~1,800) relative to the numbers of estimated deaths attributable to $PM_{2.5}$ in 2015. The stricter and aspirational policies were projected to reduce mortality burden further to 1,400 and 830 deaths, respectively. Ships close to shore contributed more to $PM_{2.5}$ concentrations than those farther from shore, so most of the marginal benefit to air quality and health was obtained by more stringent regulations close to shore. However, the aspirational scenario of 0.1% sulfur fuel within a 100 NM DECA would be even more effective in reducing $PM_{2.5}$ pollution and associated health impacts than maintaining the 12 NM DECA area.



Region/ City	Mortality Attributable to Air Pollution from Ships	Mortality Attributable to Ambient $PM_{2.5}$
Global	18,300–147,900	2,723,000
East Asia	5,560–25,500	830,000
China	9,400–26,600	796,200
Pearl River Delta	1,300	47,500
Hong Kong	1,200	4,780
Yangtze River Delta	3,600	120,000
Shanghai	1,100	12,000

Figure ES-5. Estimated mortality attributable to exposure to air pollution from ships and all sources, including the results for this study. Pollutant is $PM_{2.5}$ and year is 2013 unless otherwise specified for regions outside this study. See figures in the full report for data sources.

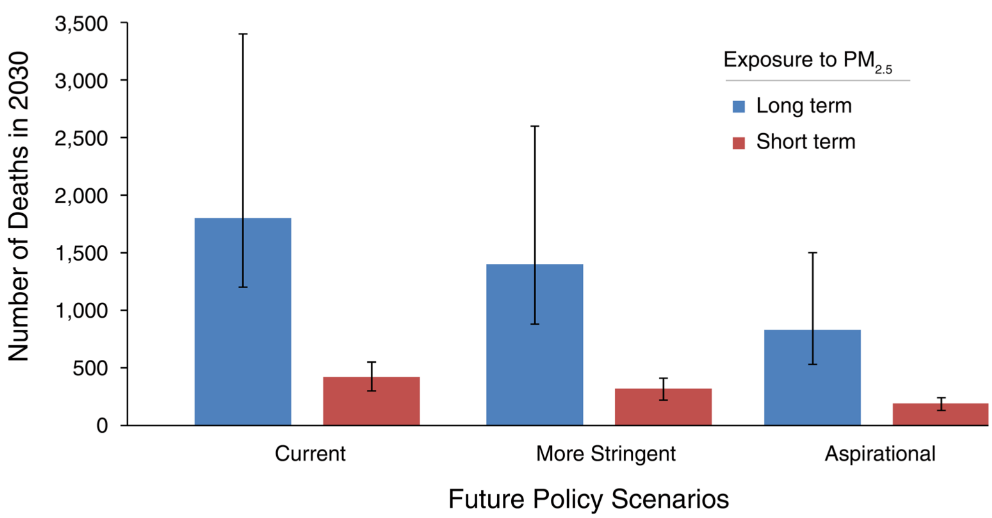


Figure ES-6. Numbers of premature deaths attributable to long- and short-term exposures to shipping-related $PM_{2.5}$ in the Yangtze River Delta in 2030 under alternative future policy scenarios for control of ship emissions.

CONCLUSIONS AND RECOMMENDATIONS

This study provides a comprehensive and detailed spatial analysis of the impacts of shipping and related activities on air quality and health of the populations of Shanghai and the Yangtze River Delta in a pre-DECA baseline year (2015) and under three future scenarios designed to inform decisions about the efficacy of alternative emissions control policies by 2030. It corroborates previous work and provides additional scientific evidence relevant to controlling future shipping emissions and to improving air quality in China.

Both the baseline and future analyses showed the importance of controlling emissions from shipping and related activities close to population centers. The baseline analysis indicated that 61% of

SO_2 emissions and 48% of $PM_{2.5}$ emissions from ships in the Yangtze River Delta occur within 12 NM of shore, the current demarcation for the DECA in China. However, over 90% of emissions of these pollutants from ships traveling within 200 NM of shore are released within 96 NM. Due to long distance transport and transformation of primary emissions to $PM_{2.5}$, the influence of ship emissions on air quality and health extends far inland from the coastal cities.

Our analysis of the baseline year 2015 scenario suggested substantial air quality and health benefits of full implementation of the current DECA requirements within 12 NM of shore. The greatest benefits are expected from the more aspirational scenario which, similar to what might be required under an IMO agreement, would require the most stringent fuel sulfur requirements out to 100 NM. Further detailed evaluation of the relative contributions to air quality and health burden of inland ships — that is, ships travelling into the inland waterways of Shanghai — reinforces the importance of controlling emissions that occur in close proximity to high-density population centers like Shanghai.

Our analysis of the contributions of cargo-transport trucks and in-port activities (including ships at berth) to air quality was limited and may underestimate the impacts both for the city of Shanghai and for the Yangtze River Delta. More data are needed to more completely identify and characterize the contributions of these sources.

As our analysis assumed 100% compliance with existing and proposed regulations, the air quality and health benefits are likely to be overstated. Consequently, compliance monitoring and enforcement are a critical component of any ongoing and future policies.

Confidence in the benefits of implementing and enforcing strong regulations will come from demonstrable improvements in air quality. See for example the studies that have evaluated the effectiveness of shipping emissions regulations by measuring $PM_{2.5}$ concentrations at nearby air quality monitoring stations (e.g., Mason et al. 2019; Zhang et al. 2019). As the estimated contributions of ships to $PM_{2.5}$ exposures are small in both absolute and relative terms compared with other major sources of $PM_{2.5}$, it would be advisable to ensure ongoing monitoring of air pollution components that are more reliable indicators of ship emissions (e.g., vanadium and nickel) in order to detect and evaluate the impact of any regulations. We recommend that such studies be done in Shanghai and the Yangtze River Delta to evaluate the effectiveness of the regulations at reducing air pollution over time.

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ABBREVIATIONS AND OTHER TERMS

DECA	Domestic Emissions Control Area (China)
GBD MAPS	Global Burden of Disease from Major Air Pollution Sources (initiative)
IMO	International Maritime Organization
NM	nautical miles
$PM_{2.5}$	particulate matter ≤ 2.5 µm in aerodynamic diameter
U.S. EPA	U.S. Environmental Protection Agency
WRF-CMAQ	Weather Research and Forecasting–Community Multiscale Air Quality modeling system
YRD	Yangtze River Delta

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