Global air quality and health impacts of domestic and international shipping

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Abstract

Shipping activities contribute to degraded air quality and premature mortalities worldwide, but previous assessments of their health impact have not yet differentiated contributions from domestic and international shipping at the global level. The impacts of domestic shipping can affect different populations, and domestic and international shipping emissions are governed under different regulatory systems. Thus, a consistent global analysis comparing the health impacts from domestic and international shipping could inform policy making in attempts to coordinate policies across multiple scales to address the health burden of shipping emissions. In this study, we create bottom-up global ship emission inventories based on ship activity records from the automatic identification system, and then apply the GEOS-Chem atmospheric model and global exposure mortality model to quantify shipping-related PM$_{2.5}$-concentrations and associated mortalities. We also quantify the public health benefits under different control scenarios including the 2020 0.5% sulphur cap, a post-2020 0.1% sulphur cap, and a post-2020 Tier III NO$_x$ standard. We find that 94 200 (95% confidence interval: 84 800–103 000) premature deaths were associated with PM$_{2.5}$ exposure due to maritime shipping in 2015, of which 83% were associated with international shipping activities and 17% with domestic shipping. Although the global health burdens of ship emissions are dominated by international shipping, the fraction varies by region: 44% of shipping-related premature deaths in China come from domestic shipping activities. We estimate about 30 200 (27 200–33 000) avoided premature deaths per year under a scenario consistent with a 2020 0.5% sulphur cap. We find that a post-2020 Tier III NO$_x$ standard would have greater benefits than a post-2020 0.1% sulphur cap, with the two policies reducing annual shipping-attributable PM$_{2.5}$-related premature deaths by 33 300 (30 100–36 400) and 5070 (4560–5540), respectively.

1. Introduction

Large diesel engines burning heavy fuel oil (HFO) have dominated maritime shipping’s energy system for decades. These engines generate air pollutants including sulphur oxides (SO$_x$) and nitrogen oxides (NO$_x$), causing air quality degradation over coastal areas (Eyring et al 2010). SO$_x$ and NO$_x$ contribute to the formation of PM$_{2.5}$, atmospheric particulate matter less than or equal to 2.5 $\mu$m in diameter. Exposure to PM$_{2.5}$ is harmful to human health, and is causally related to respiratory diseases, cardiovascular diseases, and total mortality (USEPA 2009). Previous studies estimated that PM due to shipping emissions...
was responsible for around 60 000 cardiopulmonary and lung cancer deaths globally per year, with most deaths occurring near coastlines in Europe, East Asia, and South Asia (Corbett et al 2008), and more than 24 000 premature deaths annually in East Asia (Liu et al 2016). It was recently estimated that the 2020 0.5% sulphur cap, a policy which limits the sulphur content of global marine bunker fuel starting in 2020, could decrease PM concentrations by an annual average of 2–4 µg m$^{-3}$ globally and related premature mortality by 34% (Sofiev et al 2018).

However, previous studies have not compared the air pollution-related health impacts of domestic shipping with those from international shipping at either the local or global level. This gap stems from data limitations in emission inventories. Domestic shipping refers to shipping activities between ports of the same country, and international shipping refers to shipping between ports of different countries (International Maritime Organization 2015). Global inventories of ship emissions have historically focused exclusively on international shipping because of the methodologies by which they have been constructed. Although total fuel consumption and emissions of carbon dioxide ($\text{CO}_2$) for international and domestic shipping can be estimated from national-level fuel statistics (Corbett and Fischbeck 1997, Corbett et al 1999, International Maritime Organization 2015), this does not provide information on emissions such as NO$_x$ or the spatial distribution of emissions. In contrast, global spatial characterizations of ship emissions use year-long proxies from ship activity density, which include only a limited number of ships engaged in international shipping and do not include any domestic ships. (Corbett et al 1999, 2008, Skjølsvik et al 2000, Corbett and Koehler 2003, Endresen et al 2003, Eyring et al 2005, Wang et al 2008, Dalsøren et al 2009, Paxian et al 2010).

The spatial characterization of ship emissions at the global level has been improved through inventories based on marine traffic data from the automatic identification system (AIS), a global vessel tracking system that provides data on ships’ real-time location. By combining information from AIS records with corresponding engine parameters, recent studies have estimated emissions of shipping activities and associated spatio-temporal patterns, ranging from local ports to global shipping (Fan et al 2016, Jalkanen et al 2016, Li et al 2016, Johansson et al 2017, Chen et al 2019, Zhang et al 2019). In addition to shipping activities along coastal areas and the open sea, studies have identified AIS-based emission tracks in inland waterways (Zhang et al 2019) and applied AIS data to estimate emissions from inland vessels and coastal vessels (Zhang et al 2017). However, existing AIS-based emissions inventories have nevertheless not yet well-distinguished international shipping from domestic shipping. Although ‘international vessels’ and ‘ocean-going vessels’ are commonly seen in published AIS-based estimates (Li et al 2016, Johansson et al 2017, Feng et al 2019), these previous studies determined this category based on whether the vessels have an identified IMO number, a unique international registered number that is generally used to link ship parameters to AIS records. However, domestic vessels can also register for an IMO number, and evidence has shown that some IMO-identified vessels have been used for domestic shipping (Corbett and Koehler 2003). A few AIS-based emission inventories exclude domestic shipping from emissions of IMO-identified ships according to ship group and size (International Maritime Organization 2015, Olmer et al 2017); however, such an approach is not appropriate for countries with extensive coastlines, since these countries also use large vessels for domestic shipping along their coastal waters. Recently, the IMO published emission inventories for $\text{CO}_2$ using a voyage-based allocation method in which emissions from international and domestic shipping were identified according to departure and arrival ports of shipping activities (International Maritime Organization 2021).

As a result of these limitations in emission inventories, previous studies have not differentiated or compared the air quality and health impact contributions from domestic and international shipping in a consistent analysis. Domestic emission sources can be controlled by national policies, while emissions from international shipping are governed through international conventions (Selin et al 2021). For policy-makers interested in mitigating shipping-related impacts, it is thus relevant to quantify the relative impact on air quality and related health outcomes of domestic versus international shipping.

Here, we quantify the impact of domestic versus international shipping on PM$_{2.5}$ concentration and public health on a global scale using consistent data sources and calculations. We first create bottom-up global emission inventories for international vessels and domestic vessels using AIS data, based on global marine traffic and policy context of the year 2015. In contrast to other AIS-based estimates, we differentiate international vessels from domestic vessels by the geographical range of their shipping activities. We then use the GEOS-Chem atmospheric chemistry and transport model to compute pollutant concentrations, and apply the global exposure mortality model (GEMM) to estimate health burdens attributable to outdoor PM$_{2.5}$ exposure. In addition to calculating the overall impact of international and domestic shipping, we quantify potential public health benefits under different control scenarios designed to identify the impact of policy choices. Starting from 1 January 2020, the global sulphur limit for shipping was reduced to 0.5% m/m (mass by mass). Stricter regulations including a 0.1% sulphur limit and a Tier III NO$_x$ standard are being phased in at IMO-designated emission control areas (ECAs) in the North America,
Caribbean Sea, Baltic Sea and North Sea (International Maritime Organization 2017a, 2017b). Apart from the four IMO-designated ECAs, China has established domestic ECAs, and is planning to tighten the sulphur limit to 0.1% from the year 2025 and to mandate Tier III NO₂ standard to new ships constructed on or after 1 January 2025 (MOT 2018). The 0.1% sulphur cap and Tier III NO₂ standard are thus existing policy strategies that are currently in place and proposed by various jurisdictions, and have the potential to be further applied in other regions. Here, we examine the impacts of the 2020 0.5% sulphur cap as well as the potential impact of applying these stricter regulations on NOₓ and SO₂ globally.

2. Methods

2.1. AIS-based ship emission inventory

We create the global ship emission inventory by applying power-based calculations and AIS data, following the emission modeling described in (Zhang et al 2019) but with several updates. The computational process of AIS-based emission modelling is attached as figure S1 in supplementary information (available online at stacks.iop.org/ERL/16/084055/mmedia). First, we differentiate international vessels from domestic vessels based on vessels’ geographical range of activities. Considering that the power of enforcement relies on coastal states to which pollution control and prevention rights are granted in their contiguous zone and the exclusive economic zones (EEZ) (Stopford 2009), we used the EEZ to differentiate domestic and international shipping for the purposes of our study. If a vessel has more than 99% of its AIS signals within one specific EEZ for the entire study year, it is defined as a Domestic Vessel; otherwise, it is an International Vessel. This is consistent with the IPCC 2006 guideline (Sánchez et al 2006), though we assume that the purpose of a vessel did not change during the study year. Second, we fill in missing hours in the ship activity records by interpolation. For each ship, missing values of speed and coordinates between two AIS records for the same day were interpolated to an hourly frequency, using linear interpolation and nearest neighbour methods, respectively. The interpolated data points represent 32% of total hours in the inventory for international shipping, and 37% for domestic shipping. Figure S2 shows CO₂ emissions with and without interpolation.

We estimate emissions of CO₂, sulphur dioxide (SO₂), sulphate (SO₄²⁻), nitrogen dioxide (NO₂), carbon monoxide (CO), black carbon (BC), organic carbon (OC), ammonia (NH₃), and non-methane volatile organic compounds (NMVOC). For emission factors, we first identify or calculate baseline emission factors based on literature and regulations (IVL 2004, International Maritime Organization 2008, 2012, 2015, Jalkanen et al 2012, Starcres 2013), and then adjust them by engine loads using low load adjustment factors or specific fuel oil consumption engine curves (Jalkanen et al 2012, International Maritime Organization 2015). The emission factor for NOₓ is also associated with the build year of the engine following IMO requirements (International Maritime Organization 2017a), assuming that all engines are emitting the maximum permissible NOₓ per unit of fuel burn. For vessels without build year information, we assume that vessels use pre-2000 engines. Emission factors are listed in the supporting materials. International vessels are assumed to use HFO with 2.7% sulphur content, except those with high-speed main engines (>960 rpm) that use marine diesel oil (MDO) (Kuiken 2012) with 0.5% sulphur content (Lloyd’s Register 1995, EEA 2013). For domestic vessels, the fuel quality is determined by local regulations. International vessels switch to compliant fuel with the 0.1% sulphur limit when they operate within ECAs of the North Sea, Baltic Sea, North America, and the United States Caribbean Sea. We also account for the EU Sulphur Directive (Directive (EU) 2016/802) which mandates a 0.1% sulphur limit when ships are berthing at European ports (European Parliament 2003); ships bound by this directive operating among EU countries use MDO with 0.1% sulphur content. Given the prevalence of these requirements in several of these ECAs, we choose to apply a sulphur limit for domestic vessels that corresponds to the strictest regulation for international shipping applied currently—the 0.1% sulphur limit. This provides a conservative assumption in our calculation of the total air quality and health burden of domestic shipping relative to international shipping.

AIS raw data is used for the year 2015, and ship parameters from the World Register of Ship (WRS) database are from IHS Markit (https://ihsmarkit.com). The data fields provided by the AIS or WRS database are summarized in table S1 in supplementary information. Auxiliary engine and boiler engine loads follow the Third IMO GHG study (International Maritime Organization 2015). Geographical shapefiles of EEZs, ECAs, and world countries are from the Flanders Marine Institute (Flanders Marine Institute 2014, 2020).

2.2. GEOS-Chem modelling

GEOS-Chem is a global 3D model of atmospheric chemistry and transport driven by assimilated meteorological observations from the Goddard Earth Observing System (GEOS) of the NASA Global Modelling Assimilation Office (www.geos-chem.org). Inorganic aerosol formation is simulated using the ISORROPIA II module, which treats the thermodynamics of the K⁺ – Ca²⁺ – Mg²⁺ – NH₄⁺ – Na⁺ – SO₄²⁻ – NO₃⁻ – Cl⁻ – H₂O aerosol system (Fountoulakis and Nenes 2007). NOₓ emissions from the shipping sector are processed by the PARANOX module, a Gaussian plume model with a plume-in-grid parameterization added (Holmes et al 2014). We use
GEOS-Chem version 12.4 with a horizontal resolution of 2° latitude × 2.5° longitude globally. The temporal resolution for the GEOS-Chem simulation is a 10 min time step for transport calculations, and a 20 min time step for chemistry and emissions. Each scenario is simulated for 14 months from November 2014 to December 2015. We discard the first two months as ‘spin-up’, and average all data from 2015 to provide our results.

We estimate hourly ship emissions of SO₂, NO₂, CO₂, BC, OC, NH₄, and hydrocarbon species according to the outputs from the AIS-based ship emission inventory described above. All emissions are gridded at a global spatial resolution of 0.1° latitude × 0.1° longitude. Hydrocarbon speciation (alkanes, ethylene, acetylene, benzene, toluene, and xylene) is from Eyring et al (2005). Apart from ship emissions, other emissions are GEOS-Chem default inputs and are kept constant in all simulations. PM₂.₅ concentrations are calculated under standard conditions of 35% relative humidity (RH). The calculation is performed using the dry (0% RH) concentrations of all aerosol species, in µg m⁻³, as follows:

\[
PM_{2.5} = 1.33 \times (SO_4 + NIT + NH_4) + BCPI + BCPO + 2.1 \times (1.16 \times OCPI + OCPO) + 1.16 \times SOAS + 1.86 \times SALA + DST1 + 0.38 \times DST2
\]

where SO₄, NIT, and NH₄ represent SO₄, nitrate, and ammonium mass in aerosols, respectively, BCPI and BCPO hydrophilic and hydrophobic BC, OCPI and OCPO represent hydrophilic and hydrophobic OC, SALA represents accumulation mode sea salt, and SOAS refers to secondary organic aerosol. DST1 and DST2 represent dust with size bins of 0.2–2.0 and 2.0–3.6 µm in diameter, respectively, and 38% of the mass in the DST2 bin is assumed to be in particles which have a diameter of less than 2.5 µm. Scaling factors of 1.33, 1.16, and 1.86 are used for SO₄-NIT-NH₄, OCPI-SOAS, and SALA to convert dry aerosol concentrations to PM₂.₅ at 35% RH. The PM₂.₅ concentration is estimated every 20 min and averaged to the annual means presented here. The equation above is the sum of the constituents. Growth factors are based on the default hygroscopic growth tables in GEOS-Chem, and more discussion is available in Latimer and Martin (2019). We use 35% RH because that is the standard used by the EPA when preparing samples (Chow and Watson 1998). More details about the PM calculation in the GEOS-Chem model are provided on the wiki page (http://wiki.seas.harvard.edu/geos-chem/index.php/Particulate_matter_in_GEOS-Chem).

### 2.3. Health impact quantification

Premature deaths from exposure to ambient PM₂.₅ are estimated by the GEMM (Burnett et al 2014, 2018). The GEMM model extends a log-linear model by including non-linear responses defined by transformations of concentration (Burnett et al 2014, 2018). It is based on cohort studies of outdoor air pollution covering the entire global exposure range. Here, we estimate premature deaths due to non-communicable diseases (NCDs) and lower respiratory infections (LRIs), denoted as GEMM NCD + LRI. Premature deaths attributed to PM₂.₅ in each grid cell are estimated as:

\[
Mort = P_i \times y_i \times \left(1 - \frac{1}{R_i}\right)
\]

where \(i\) represents each of the diseases, \(P\) is the population of adults older than 25 years, \(y\) is the baseline mortality rate of a certain disease, \((1 - 1/R)\) is the attributable fraction of deaths due to outdoor PM₂.₅ exposure, and \(R\) is the hazard ratio defined as the ratio of incidence rates between exposed and unexposed populations. Hazard ratios in each grid cell are estimated from:

\[
R(z) = \exp \left\{ \theta \log \left(1 + \frac{z - \mu}{\alpha} \right) \times \left\{ 1/(1 + \exp \left[-\frac{(z - \mu)}{\nu}\right]) \right\} \right\}
\]

where \(z = \max (0, C_{ci})\) represents the simulated PM₂.₅ concentration, and \(C_{ci}\) is the counterfactual concentration (2.4 µg m⁻³) below which there is no additional risk. \(\theta\) and its standard error are estimated using standard computer software that fits the Cox proportional hazard model (Cox 1972). \(\alpha\) is an additional parameter controlling the amount of curvature, \(\mu\) is a parameter controlling the shape, \(\nu = \tau r\) in which \(r\) represents the range in the pollutant concentration and \(\tau\) controls the amount of curvature. We use the set of parameters \((\theta, \alpha, \mu, \nu)\) estimated by cause of death, including the Chinese Male Cohort, as provided by Burnett et al (2018). Uncertainties in the GEMM for health impact analysis are represented by uncertainty in the GEMM parameters; we use the \(\theta\) standard error to estimate the 95% confidence interval (CI).

Data on population count and age profile are from the Gridded Population of the World collection, the fourth version (GPW v4). We use the gridded population from the UN WPP-Adjusted Population Count, v4.11 for the year 2015, and the age profile for the year 2010 (CIESIN 2018). Both datasets have 30 arc-minute resolution. Country-specific baseline mortality rates for different age groups and diseases for the year 2015 are from the Global Health Dataset (IHME 2018, Roth et al 2018). For countries without available baseline mortality rates, the global baseline mortality rate is applied.
2.4. Impact analysis
To calculate the impact of maritime shipping, we conduct three GEOS-Chem-GEMM simulations under a baseline scenario (for year 2015) with emissions from (a) all sectors; (b) non-ship sectors and international shipping; and (c) non-ship sectors and domestic shipping. To estimate potential impact of emissions controls, we conduct three additional GEOS-Chem-GEMM simulations with input emissions of all sectors: (d) 2020 0.5% sulphur cap; (e) post-2020 0.1% sulphur cap; and (f) post-2020 Tier III NOx standard (the 0.5% sulphur cap continues, and all existing non-Tier II marine engines are upgraded to Tier III standard). We keep shipping activity constant at 2015 levels in all scenarios. We calculate the difference in PM$_{2.5}$ concentrations and resulting premature deaths between the scenarios (see table S2 and S3 in supplementary information).

3. Results

3.1. Ship emission inventory
Annual global ship emissions under the baseline scenario are presented in table 1. We estimate that in 2015, 866 million tonnes of CO$_2$ were generated from maritime shipping, accounting for 2.7% of global energy-related CO$_2$ emissions of 32 400 million tonnes in 2015 (IEA 2020). We also estimate that maritime shipping contributed 10.0 million tonnes of SO$_x$ (SO$_2$ and SO$_4^-$) emissions, and 18.0 million tonnes of NO$_x$ emissions. Globally, emissions from international vessels dominate the total for all species, with 81% of CO$_2$, 99% of SO$_x$, 84% of NO$_x$, 83% of CO, 82% of BC, 81% of OC, 83% of NMVOC, and 82% of NH$_3$ emissions. As shown in figure 1, emissions from international vessels occur along tracks in the open sea and on busy shipping lanes. In contrast, emissions from domestic navigation are largest in coastal areas of China and Japan; sea areas in south-eastern Asia; the Persian Gulf in the Middle East; Mediterranean Sea; the North Sea, the Baltic Sea and the North Atlantic around European coastal areas; the Gulf of Mexico; the eastern coast, south-eastern inland areas, and the western coast of North America; and the eastern coast of South America.

Compared with CO$_2$ emissions estimated for maritime shipping by the International Energy Agency (IEA)’s fuel sale statistics (IEA 2020), the total CO$_2$ emissions for 2015 estimated here are 7% higher for international vessels and 16% for domestic vessels. Consistent with IEA fuel sale statistics, we calculate that around 81% of CO$_2$ emitted from maritime shipping comes from international vessels. A recently published study by the IMO (2021), using an allocation method that classifies emissions as international vs. domestic based on ports of arrival and departure, estimates that 71% of CO$_2$ emissions are from international shipping, 10% less than that of our estimates. Our larger estimate is likely a result of the difference in our division methods. See table S4 in supplementary information for more detailed comparison with previous global CO$_2$ emissions estimates. Differentiating domestic and international shipping based on whether the ports they operate between are in the same jurisdiction is more consistent with IPCC guidelines and definitions (Sánchez et al. 2006). Our approach is designed instead to better capture the emissions standards these voyages must comply with: for example, voyages involving long-distance operation in the open sea between ports of the same country would be subject to regulations for international shipping. In addition, domestic vessels identified by our method are used exclusively for domestic shipping, and thus provide a conservative estimation of the potential for reducing shipping emissions using domestic control policies. However, we assume that a certain vessel operates exclusively for either international shipping or domestic shipping during the study year, which may underestimate the domestic contribution of some vessels such as small dry bulk carriers and oil tankers which have been shown to shift range within a given year (International Maritime Organization 2021).

Table 2 presents annual ship emissions of CO$_2$, SO$_x$, and NO$_x$ for the different scenarios. Under the 0.5% sulphur cap, SO$_2$ emissions from international shipping are 1.78 million tonnes, 82% lower than the 9.91 million tonnes in the baseline scenario. Emissions of CO$_2$ and NO$_x$ are 32.0 million tonnes and 0.70 million tonnes lower, respectively, under the 0.5% sulphur cap, due to the transition from HFO to MDO/MGO. Under the 0.1% sulphur cap, a further 1 million tonnes of SO$_2$ emissions from international vessels are avoided compared to the emissions with the 2020 0.5% sulphur cap. Because all domestic vessels already use fuel with only 0.1% sulphur content in our baseline scenario, the global 0.5% sulphur cap scenario shows an increased relative contribution of domestic shipping to global SO$_2$ from shipping. Under the Tier III NO$_x$ standard scenario (which includes the 0.5% sulphur cap), there are 9.53 million fewer tonnes of emitted NO$_x$ from international vessels and 2.28 million fewer tonnes from domestic vessels compared with emissions when only the 0.5% sulphur cap is imposed.

3.2. PM$_{2.5}$ concentrations
We compare our simulated PM$_{2.5}$ concentrations under the baseline scenario with observational data collected from monitoring stations in China and Europe (Hjellbrekke 2015, HKUST 2020). Overall, GEOS-Chem can reproduce the observed spatial distribution of PM$_{2.5}$, with Pearson’s correlation coefficients ($r$) of 0.82 in China (1224 data pairs) and 0.76 in Europe (53 data pairs), respectively (see figure S3 in supplementary information).
Table 1. Estimated global ship emissions in 2015 under the baseline scenario, for international vs. domestic vessels.

| Emissions | Total \(10^6\) kg | International vessels \(10^6\) kg | Proportion | Domestic vessels \(10^6\) kg | Proportion |
|-----------|----------------|----------------|-----------|----------------|-----------|
| CO₂       | 866 000        | 704 000        | 81.3%     | 162 000        | 18.7%     |
| SO₂       | 10 000         | 9910           | 99.0%     | 98.4           | 1.0%      |
| SO₄       | 340            | 338            | 99.3%     | 2.52           | 0.7%      |
| NOₓ       | 18 000         | 15 000         | 83.5%     | 2970           | 16.5%     |
| CO        | 1600           | 1330           | 83.1%     | 269            | 16.9%     |
| BC        | 103            | 84.4           | 81.7%     | 18.9           | 18.3%     |
| OC        | 283            | 230            | 81.2%     | 53.3           | 18.8%     |
| NMVOC     | 689            | 574            | 83.3%     | 115            | 16.7%     |
| NH₃       | 3.81           | 3.11           | 81.6%     | 0.703          | 18.4%     |

Figure 1. Geographical distribution of CO₂ emissions from maritime shipping in 2015, from international vessels (a) and domestic vessels (b).

Figure 2 compares simulated annual-mean PM\(_{2.5}\) concentrations resulting from emissions from international vessels versus domestic vessels under the baseline scenario. The PM\(_{2.5}\) contributions from the international vessels are mainly in the open sea and over busy sea-lanes, with the highest grid value of 6.7 \(\mu\)g m\(^{-3}\) in the Malacca Strait. In contrast, PM\(_{2.5}\) contributions from domestic vessels are elevated in China, with the grid value as high as 2.0 \(\mu\)g m\(^{-3}\) in the Yangtze River Delta. Gridded PM\(_{2.5}\) concentration data for each scenario can be acquired as described in the Data Availability Statement.

Figure 3 presents the reduction in PM\(_{2.5}\) concentrations when comparing different scenarios. In the
Table 2. Estimated global ship emissions for control scenarios.

| Emissions (10^6 kg) | Baseline (IV) | Baseline (DV) | 0.5% sulphur cap (IV) | 0.5% sulphur cap (DV) | 0.1% sulphur cap (IV) | 0.1% sulphur cap (DV) | Tier III NOx standard (IV) | Tier III NOx standard (DV) |
|---------------------|---------------|---------------|----------------------|----------------------|----------------------|----------------------|---------------------------|---------------------------|
| CO2                 | 704 000       | 162 000       | 672 000              | 162 000              | 672 000              | 162 000              | 672 000                    | 162 000                    |
| SO2                 | 9910          | 98.4          | 1780                 | 98.4                 | 408                  | 98.4                 | 1780                      | 98.4                      |
| NOx                 | 15 000        | 2970          | 14 300               | 2970                 | 14 300               | 2970                 | 4770                      | 692                       |

IV: international vessels; DV: domestic vessels

Figure 2. Simulated annual mean surface PM$_{2.5}$ concentrations attributed to international vessels (a) and domestic vessels (b) under the baseline scenario.

0.5% sulphur cap scenario (figure 3(a)), PM$_{2.5}$ concentrations from shipping are lower over busy sea-lanes compared to the baseline scenario, with the greatest reduction of 2.0 μg m$^{-3}$ in the grid cell located at the Malacca Strait. When the sulphur cap is further reduced to 0.1% (figure 3(b)), the PM$_{2.5}$ concentration attributable to shipping in busy sea-lanes is reduced by a smaller amount relative to the effect of the 0.5% sulphur cap, with a maximum difference of 0.3 μg m$^{-3}$ around the Malacca Strait. The Tier III NOx standard scenario, which includes a 0.5% sulphur cap, has the lowest PM$_{2.5}$ concentration attributable to shipping. The greatest difference compared to the 0.5% sulphur cap scenario is a reduction of 2.6 μg m$^{-3}$ at the Malacca Strait. Compared with the two sulphur cap-only control scenarios, the Tier III NOx standard scenario has lower PM$_{2.5}$ concentrations over the North Sea, the English Channel, and the coastal areas in China as well as their associated inland rivers.
Figure 3. Reduction in annual mean PM$_{2.5}$ concentration under control scenarios: (a) baseline—0.5% sulphur cap; (b) 0.5% sulphur cap—0.1% sulphur cap; and (c) 0.5% sulphur cap—Tier III NO$_x$ standard.
Table 3. Premature deaths caused by ship-related PM$_{2.5}$ in the baseline scenario and avoided premature deaths under control scenarios.

| No. | Impact to be quantified                                      | Calculation              |
|-----|-------------------------------------------------------------|--------------------------|
| 1   | Impact of international shipping in baseline scenario       | 78 000 (70 100–85 400)   |
| 2   | Impact of domestic shipping in baseline scenario            | 16 200 (14 700–17 500)   |
| 3   | Total impact of maritime shipping in baseline scenario      | 94 200 (84 800–103 000)  |
| 4   | Impact of 0.5% sulphur cap entering into force in 2020     | 30 200 (27 200–33 000)   |
| 5   | Impact of post-2020 0.1% sulphur cap                        | 5070 (4560–5540)         |
| 6   | Impact of post-2020 Tier III NO$_x$ standard (with 0.5% sulphur cap) | 33 300 (30 100–36 400)   |

Figure 4. Global distribution of mortality (NCD + LRI) associated with ship-related PM$_{2.5}$, attributed to emissions from international vessels (a) and domestic vessels (b).

3.3. Health outcomes
Table 3 summarises premature deaths associated with ship-related PM$_{2.5}$ in the baseline scenario and avoided premature mortality under the three control scenarios. Globally, international and domestic shipping in 2015 contributed to 94 200 (95% CI: 84 800–103 000) premature deaths. Total premature deaths by cause of death for each simulation are provided in table S5 in supplementary information. Emissions from international vessels result in 78 000 (70 100–85 400) premature deaths, or 83% of total deaths attributed to shipping, while emissions from domestic vessels lead to the remaining 17%, or 16 200 (14 700–17 500).

Figure 4 shows the geographical distribution of premature deaths due to international and domestic shipping in the baseline scenario. China, India, and Japan are the top three EEZs in terms of overall premature mortalities attributed to PM$_{2.5}$ due to shipping in the baseline scenario, with 15 500, 8890, and 7820, respectively. Whereas in India 98% of this health burden is from international vessels, China
and Japan have a relatively large proportion from domestic vessels, reaching 44% and 29%, respectively. China has the largest number (around 6820) of premature deaths attributed to domestic shipping. Other EEZs where domestic shipping contributes to more than 20% of premature deaths due to shipping include the United States (27%), South Korea (28%), North Korea (40%), Canada (25%), and Norway (23%). More details are provided in table S6 in supplementary information. Small coastal countries such as Singapore, however, are not well resolved in our study, which simulates atmospheric chemistry and concentrations at a grid resolution of 2° latitude × 2.5° longitude.

Figure 5. Avoided premature deaths (NCD + LRI) associated with ship-related PM$_{2.5}$ under control scenarios: (a) baseline —0.5% sulphur cap; (b) 0.5% sulphur cap—0.1% sulphur cap; and (c) 0.5% sulphur cap—Tier III NO$_x$ standard.
The 0.5% sulphur cap scenario has 32% fewer shipping-attributable premature mortalities annually (a difference of 30 200 (27 200–33 000) mortalities), relative to the baseline scenario. The post-2020 0.1% sulphur cap scenario avoids an additional 5070 (4560–5540) premature mortalities, while a post-2020 Tier III NO\textsubscript{x} standard avoids a further 33 300 (30 100–36 400) annually (both relative to the 2020 0.5% sulphur cap scenario only). Figure 5 shows the geographical distribution of avoided mortalities under different scenarios compared with the Baseline or the 0.5% sulphur cap scenario. The global 0.5% sulphur cap scenario has less PM exposure due to shipping relative to the Baseline, especially in areas with intensive international shipping activity: India has the largest difference (resulting 5010 avoided deaths, 56% fewer shipping-attributable premature mortalities relative to the Baseline), followed by China (3520, 23% fewer) and Japan (2200, 28% fewer). We do not observe a large difference in our 0.5% sulphur cap scenario for countries already associated with sulphur ECAs (SECAs), compared with the Baseline. This is because a 0.1% sulphur limit has already been applied in our scenarios to the SECAs before 2020 which required all international vessels switch to low sulphur fuel when operating in these areas. For example, for North America, Canada has 5% fewer premature mortalities relative to the Baseline, and the United States has 18% fewer. For Europe, in addition to SECAs in the North Sea and Baltic Sea, there is an existing European sulphur directive applying to all EU ports which requires all vessels must use clean fuel with a 0.1% sulphur limit when berthing at the port. As such, European countries including Germany, UK, Netherlands, Belgium, Poland, Sweden, Denmark, Norway, and Belarus, have very small reductions of 2%–9% under the 0.5% sulphur cap relative to the Baseline, due to the combined effects of SECAs and the European sulphur directive, while countries such as Italy, France, Spain, Turkey, Romania, Portugal, Hungary, and Greece, have reductions of 16%–43% since parts of their territorial waters are out of the SECAs. The areas of largest avoided mortality under 0.1% sulphur cap scenario are generally consistent with changes under the 0.5% sulphur cap, but with much smaller values. The Tier III NO\textsubscript{x} standard is associated with fewer mortalities in China, Japan, Indonesia, India, European countries around the North Sea, the English Channel, and the Mediterranean Sea, and countries around the canal linking the Red Sea and the Mediterranean Sea.

4. Discussion

The impact of domestic relative to international shipping on PM\textsubscript{2.5} concentrations and associated mortalities varies geographically. International shipping is the dominant contributor to health burden due to shipping globally, but domestic vessels lead to elevated mortalities in East Asia, especially in China. Our estimate of premature mortality due to shipping in East Asia of 25 600 (23 400–27 600)—sum of mainland China, Hong Kong, Macao, Taiwan, Japan, South Korea, North Korea—is larger than the 8700–25 500 found in an earlier study for the health impact of ocean-going vessels in East Asia (Liu et al 2016). This is because more ships are included in our estimate, and the updated exposure-response model used in this study estimates a larger impact of PM\textsubscript{2.5} concentrations on health. Different from other global AIS-based emissions estimates (IMO 2015, Olmer et al 2017), this study distinguished domestic and international vessels by their geographical range of activities, more accurately allocating emissions and related mortalities due to each type of activity.

Our results suggest that a 0.1% sulphur cap would have a relatively small additional impact on mitigating health burden from shipping relative to the impacts of the 0.5% sulphur cap implemented in 2020. Our 2020 0.5% sulphur cap scenario has 32% fewer premature deaths attributed to shipping emissions than the Baseline. This estimate is similar to that of an earlier study suggesting that this policy would lead to a 34% reduction in premature mortality (Sofiev et al 2018). The scenario that implements a post-2020 0.1% sulphur cap, however, mitigates only an additional 5070 premature deaths, an 8% reduction compared to the 0.5% sulphur cap scenario. Avoided mortalities from these SO\textsubscript{x}-based controls are all the result of SO\textsubscript{2} reduction from international vessels, since, consistent with domestic policies, the Baseline assumes that all domestic vessels already use fuel oil with the 0.1% sulphur limit.

Post-2020 NO\textsubscript{x}-based controls, in contrast, could bring substantial benefits to air quality and avoided mortality from maritime shipping. Our scenario including a Tier III NO\textsubscript{x} standard has fewer NO\textsubscript{x} emissions from shipping from both domestic vessels (2.28 million tonnes) and international vessels (9.53 million tonnes) compared with the 0.5% sulphur cap. At the national level, a NO\textsubscript{x}-based control policy would have a larger impact on mitigating shipping-related health burden than the SO\textsubscript{2}-based approach for countries that with existing SO\textsubscript{2} ECAs (i.e. USA, Canada, and European countries), and countries that have a large amount of domestic shipping (e.g. China, Japan). This is because a NO\textsubscript{x} standard could further reduce emissions for both international vessels and domestic vessels beyond existing controls.

While international-level regulation on shipping is moving forward and additional controls are being gradually phased in, domestic authorities in some regions have a substantial opportunity to further mitigate health burdens from shipping. Globally,
the 0.5% sulphur limit is to be imposed starting from 2020. Regionally, by 2015 the IMO-designated ECAs of North America and Europe implemented a 0.1% sulphur cap and released a timeline to phase in a Tier III NO\textsubscript{x} standard on new marine diesel engines. If these NO\textsubscript{x}-based control measures were to be applied globally, they could reduce a much larger number of mortalities than SO\textsubscript{x}-based control. However, implementing a Tier III NO\textsubscript{x} standard globally would require substantial long-term capital investments as well as international consensus. If areas where domestic shipping is a large relative contributor to health impacts, such as China and Japan, implemented stringent emission control measures such as a Tier III NO\textsubscript{x} standard for domestic vessels, our results suggest that they would achieve improved air quality and reduced mortalities. This paper focuses on impacts of domestic versus international shipping, and potential impacts of prevalent control practice. In addition to SO\textsubscript{x} and NO\textsubscript{x}, other emissions from maritime shipping, such as BC, also lead to adverse impacts on human health (Lelieveld et al 2015, Li et al 2021). Their contribution to health burden and potential to be mitigated could be addressed in future studies using a similar approach to that elaborated here.

Uncertainty in our estimates comes from AIS-based ship emission inventories, GEOS-Chem modelling, and GEMM model. We validate our emission inventory by comparing the amount of estimated CO\textsubscript{2} emissions with the IEA fuel consumption of international marine bunker fuel and domestic fuel sale. The estimates in this study are consistent with IEA fuel statistics, and both this study and IEA statistics suggest that around 81% of CO\textsubscript{2} emission comes from international vessels. With respect to air quality, we compared the simulated PM\textsubscript{2.5} concentration from the GEOS-Chem modelling with observational air quality data. Overall, GEOS-Chem reproduces the observed spatial distribution of PM\textsubscript{2.5} as discussed above, but the global resolution of the model may underestimate high concentrations in locations very near to ports, providing a conservative estimate of the impacts. Uncertainties in using the GEMM for health impact analysis result from parameters of the ensemble function for linking a given amount of PM\textsubscript{2.5} concentrations to premature mortality. The 95% CI due to these parameters is provided above. Based on total PM\textsubscript{2.5} in GEOS-Chem, we estimate using our methods that 9.4 (8.2–10.1) million premature deaths are attributable to outdoor PM\textsubscript{2.5} exposure in 2015, consistent with prior global estimates of 8.9 million (7.5–10.3) (Burnett et al 2018). Applying a 0.1% sulphur limit for domestic shipping—the strictest regulation for international shipping that is currently applied—simplifies diverse effects of local control policies, but provides us with a conservative estimate of the total air quality and health burden of domestic shipping relative to international shipping.

5. Conclusions

This study quantifies global and location-specific environmental and health impacts associated with maritime shipping, distinguishing between the contributions of international and domestic shipping activities. We do this by using consistent bottom-up calculation methods and high-resolution input datasets. Globally, international shipping dominates shipping emissions and associated health impacts, contributing to 83% of premature mortality associated with maritime shipping. However, domestic vessels are greater contributors to shipping-related mortality in East Asia, especially in China where they contribute 44% of the health burden from shipping. Areas associated with existing sulphur ECAs that have already mandated the 0.1% sulphur limit, including the United States, Canada, and most European countries, have limited potential benefits under emerging global SO\textsubscript{x}-based control policies, but could achieve further mortality reductions under a NO\textsubscript{x}-based control strategy.

Differentiating impacts of domestic shipping from international shipping provides further information on potential policy options for addressing impacts. Areas with high proportions of mortalities contributed by domestic shipping could effectively use domestic regulations to implement controls. For example, our results suggest that China could substantially mitigate its ship-related health burden by introducing the Tier III NO\textsubscript{x} standard to domestic vessels. However, for other regions where much damage comes from international vessels, further international cooperation is required to mitigate impacts. The regional variation in the relative importance of domestic and international shipping illustrates the potential for new policy options to address impacts, especially for regions with extensive coastlines and inland water networks such as China.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

The modelling results and data are either attached in this article as supplementary material or uploaded to the online database (http://envf.ust.hk/dataview/ship_emission/).

The code for data analysis and plotting are uploaded to the GitHub repository (https://github.com/yzhangen/Paper_ERL2021_ShippingImpact).

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**References**

Burnett R T et al 2014 An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure Environ. Health Perspect. 122 397–403

Burnett R T et al 2018 Global estimates of mortality associated with long term exposure to outdoor fine particulate matter rich—supplementary information Proc. Natl Acad. Sci. USA 115 9592–7

Center for International Earth Science Information Network—CIESIN—Columbia University 2018 Gridded population of the world, version 4 (GPWv4); population count adjusted to match 2015 revision of UN wpp country totals, revision 11 [https://doi.org/10.7297/H4PN93PB](https://doi.org/10.7297/H4PN93PB)

Chen D, Tian X, Lang J, Zhou Y, Li Y, Guo X, Wang W and Liu B 2019 The impact of ship emissions on PM2.5 and the deposition of nitrogen and sulfur in Yangtze River Delta, China Sci. Total Environ. 649 1609–19

Chow J C and Watson J G 1998 Guideline on specified particulate monitoring (available at: www3.epa.gov/ttnamti1/files/ambient/pm25/spec/drispec.pdf) (accessed June 2021)

Corbett J, Fischbeck P S and Pandis S N 1999 Global nitrogen and sulfur inventories for oceangoing ships J. Geophys. Res. Atmos. 104 3457–70

Corbett J and Fischbeck P 1997 Emissions from ships Science 278 823–4

Corbett J and Koehler H W 2003 Updated emissions from ocean shipping J. Geophys. Res. 108 D20, 4650

Corbett J, Winebrake J J and Lauer A 2008 Mortality from ship emissions: a global assessment CoX D R 1972 Regression models and life-tables J. R. Stat. Soc. B 34 187–220

Dalsoren S B, Eidle M S, Endresen O, Mjelde A, Gravir G and Isaksen I S A 2009 Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports Atmos. Chem. Phys. 9 2171–94

Endresen Ø, Særgård E, Sundet J K, Dalsoren S B, Isaksen I S A, Berglen T F and Gravir G 2003 Emission from international sea transportation and environmental impact J. Geophys. Res. Atmos. 108 D17, 4560

European Environment Agency 2013 EMEP/EEA air pollutant emission inventory guidebook (International Maritime Navigation)

European Parliament the C of E U 2003 Directive 2003/17/EC of the European parliament and of the council of 3 march amending directive 98/70/EC relating to the quality of petrol and diesel fuels (available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32003L0017) (accessed November 2020)

Eyring V, Ilyasen I S A, Berntsen T, Collins W J, Corbett J J, Endresen O, Grainger R G, Moldanova J, Schläger H and Stevenson D S 2010 Transport impacts on atmosphere and climate: shipping Atmos. Environ. 44 4735–71

Eyring V, Köhler H W, Van Aardenne J and Lauer A 2005 Emissions from international shipping: 1. The last 50 years J. Geophys. Res. Atmos. 110 171–82

Fan Q, Zhang Y, Ma W, Ma H, Feng J, Yu Q, Yang X, Ng S K W, Fu Q and Chen L 2016 Spatial and seasonal dynamics of ship emissions over the Yangtze River Delta and East China sea and their potential environmental influence Environ. Sci. Technol. 50 1322–9

Feng J et al 2019 The influence of spatiality on shipping emissions, air quality and potential human exposure in the Yangtze River Delta/ Shanghai,China Atmos. Chem. Phys. 19 6167–83

Flanders Marine Institute 2014 Union of the ESRI country shapefile and the exclusive economic zones (version 2) (available at: www.marineregions.org/) (accessed May 2020)

Flanders Marine Institute 2020 Emission control areas (ECAs) designated under MARPOL annex VI (available at: www.marineregions.org/downloads.php?eca) (accessed May 2020)

Fountoukis C and Nenes A 2007 ISORROPIA II: a computationally efficient thermodynamic equilibrium model for K+–Ca2+–Mg2+–NH4+–Na+–SO42−–NO3− Atmos. Chem. Phys. 7 4639–59

Hjelbrekke A 2015 EMEP data report 2015 particulate matter, carbonaceous and inorganic compounds HKUST 2020 ENVF atmospheric and environmental database (available at: https://enfv.ust.hk/dataview/iet/current/) (accessed May 2020)

Holmes C D, Prather M J and Vinken G C M 2014 The climate impact of ship NOx emissions: an improved estimate accounting for plume chemistry Atmos. Chem. Phys. 14 6001–12

IEA 2020 CO2 emissions from fuel combustion (available at: www.iea.org/reports/co2-emissions-from-fuel-combustion-overview/) (retrieved March 2021)

IMO 2015 Third IMO greenhouse gas study 2014 pp 1–26 Institute for Health Metrics and Evaluation (IHME) 2018 Global Burden of disease collaborative network. Global burden of disease study 2017 (GBD 2017) results (available at: http://ghdx.healthdata.org/gbd-results-tool) (accessed March 2020)

International Maritime Organization 2008 Amendments to the technical code on control of emission of nitrogen oxides from marine diesel engines (available at: www.imo.org/en/KnowledgeCentre/IndexofIMOResolutions/Shipping/EnvironmentProtectionCommittee-(MEPC)/Documents/MEPC.177(58).pdf%0A) (accessed January 2020)

International Maritime Organization 2012 Report of the marine environment protection committee on its sixty-third session (available at: www.crs.hr/Portals/0/MEPC63-23.pdf) (accessed January 2020)

International Maritime Organization 2015 Third IMO greenhouse gas study 2014 1–26

International Maritime Organization 2017a Nitrogen oxides (NOx)—regulation 13 (available at: www.imo.org/en/OurWork/environment/pollutionprevention/airpollution/pages/nitrogen-oxides-(nox)—regulation-13.aspx) (accessed January 2020)

International Maritime Organization 2017b Sulphur oxides (SOx)—regulation 14 (available at: www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)—Regulation-14.aspx) (accessed January 2020)
International Maritime Organization 2021 Forth IMO greenhouse gas study vol 6 (available at: www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx) (retrieved June 2021)

IVL C 2004 Methodology for calculating emissions from ships: 2. Emission factors for 2004 reporting

Jalkanen J P, Johansson L and Kukkonen J 2016 A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011 Atmos. Chem. Phys. 16 71–84

Jalkanen J P, Johansson L, Kukkonen J, Brink A, Kalli J and Stips T 2012 Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide Atmos. Chem. Phys. 12 2641–59

Johansson L, Jalkanen J P and Kukkonen J 2017 Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution Atmos. Environ. 167 403–15

Kuiken K 2012 Diesel engines for ship propulsion and power plants

Latimer R N C and Martin R V 2019 Interpretation of measured aerosol mass scattering efficiency over North America using a chemical transport model Atmos. Chem. Phys. 19 2633–53

Lelieveld J, Evans J S, Fain M, Giannadaki D and Pozzer A 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale Nature 525 367–71

Li C et al 2016 An AIS-based high-resolution ship emission inventory and its uncertainty in Pearl River Delta region, China Sci. Total Environ. 573 1–10

Li X, Lynch A H, Bailey D A, Stephenson S R and Veland S 2021 The impact of black carbon emissions from projected Arctic shipping on regional ice transport Clim. Dyn. 14

Liu H, Fu M, Jin X, Shang Y, Shindell D, Faluvegi G, Shindell D and He K 2016 Health and climate impacts of ocean-going vessels in East Asia Nat. Clim. Change 6 1037–41

Lloyd’s Register 1995 Marine exhaust emissions research programme

Ministry of Transport of the People’s Republic of China 2018 Implementation scheme of the domestic emission control areas for atmospheric pollution from vessels (available at: www.msa.gov.cn/public/documents/document/mtex/mzm1/~emisp/20181219111335546.pdf) (accessed March 2020)

Olmer N, Comer B, Roy B, Mao X and Rutherford D 2017 Greenhouse gas emissions from global shipping, 2013–2015 The International Council on Clean Transportation

Paxian A, Eyring V, Beer W, Sausen R and Wright C 2010 Present-day and future global bottom-up ship emission inventories including polar routes Environ. Sci. Technol. 44 1333–9

Roth G A et al 2018 Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: a systematic analysis for the global burden of disease study 2017 Lancet 392 1776–88

Sánchez M J S, Bhattacharya S and Mareckova K 2006 2006 IPCC guidelines for national greenhouse gas inventories chapter 8 reporting guidance and tables (available at: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/1_Volume1/V1_8_Ch8_Reporting_Guidance.pdf) (accessed January 2020)

Selin H, Zhang Y, Dunn R, Selin N and Lau A 2021 Mitigation of CO₂ emissions from international shipping through national allocation Environ. Res. Lett. 16 045909

Skjoldvik K, Andersen A, Corbett J and Skjelvik J 2000 Study of greenhouse gas emissions from ships (report to international maritime organization on the outcome of the IMO study on greenhouse gas emissions from ships), MEPC 45/8

Sofiev M, Winebrake J J, Johansson L, Carr E W, Prank M, Soares J, Vira J, Kouznetsov R, Jalkanen J P and Corbett J J 2018 Cleaner fuels for ships provide public health benefits with climate tradeoffs Nat. Commun. 9 1–12

Starcrest 2013 Port of Los Angeles inventory of air emissions for calendar year 2012 ADP#121011-529 Starcrest Consulting Group

Stopford M 2009 Maritime Economics (Oxon: Routledge)

United States Environmental Protection Agency (USEPA) 2009 Integrated science assessment for particulate matter (available at: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=21654) (accessed November 2020)

Wang C, Corbett J J and Firestone J 2008 Improving spatial representation of global ship emissions inventories Environ. Sci. Technol. 42 193–9

Zhang Y, Fung J C H, Chan J W M and Lau A K H 2019 The significance of incorporating unidentified vessels into AIS-based ship emission inventory Atmos. Environ. 203 102–13

Zhang Y, Gu J, Wang W, Peng Y, Wu X and Feng X 2017 Inland port vessel emissions inventory based on ship traffic emission assessment model-automatic identification system Adv. Mech. Eng. 9 1–9