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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 quanitfy 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 μm 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 (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, Skjolsvik *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 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 NO_x standard to new ships constructed on or after 1 January 2025 (MOT 2018). The 0.1% sulphur cap and Tier III NO_x 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 NO_x and SO_x 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 CO_2 emissions with and without interpolation.

We estimate emissions of CO_2, sulphur dioxide (SO_2), sulphate (SO_4), nitrogen dioxide (NO_2), carbon monoxide (CO), black carbon (BC), organic carbon (OC), ammonia (NH_3), 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, Starcrest 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 NO_x 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 NO_x 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 ($\geqslant$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 $K^+ - Ca^{2+} - Mg^{2+} - NH_4^+ - Na^+ - SO_4^{2-} - NO_3^- - Cl^- - H_2O$ aerosol system (Fountoukis and Nenes 2007). NO_x 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 SO_2, SO_4, NO_2, CO, BC, OC, NH_3, 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. $PM_{2.5}$ 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 $\mu g\ m^{-3}$, as follows:

$$
\begin{aligned}
PM_{2.5} = {} & 1.33 \times (SO4 + NIT + NH_4) + BCPI \\
& + BCPO + 2.1 \times (1.16 \times OCPI + OCPO) \\
& + 1.16 \times SOAS + 1.86 \times SALA) \\
& + DST1 + 0.38 \times DST2
\end{aligned}
$$

where SO4, NIT, and NH4 represent SO_4, 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 $PM_{2.5}$ at 35% RH. The $PM_{2.5}$ 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 $PM_{2.5}$ 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 $PM_{2.5}$ in each grid cell are estimated as:

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

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 $PM_{2.5}$ 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:

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

where $z = \max(0, C_{cf})$ represents the simulated $PM_{2.5}$ concentration, and C_{cf} is the counterfactual concentration (2.4 $\mu g\ m^{-3}$) below which there is no additional risk. θ and its standard error are estimated using standard computer software that fits the Cox proportional hazard model (Cox 1972). α is an additional parameter controlling the amount of curvature, μ is a parameter controlling the shape, $\nu = \tau r$ in which *r* represents the range in the pollutant concentration and τ controls the amount of curvature. We use the set of parameters (θ, α, μ, ν) 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 θ 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 NO_x 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_2, 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_2, 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_x 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
CO_2	866 000	704 000	81.3%	162 000	18.7%
SO_2	10 000	9910	99.0%	98.4	1.0%
SO_4	340	338	99.3%	2.52	0.7%
NO_x	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%
NH_3	3.81	3.11	81.6%	0.703	18.4%

Figure 1. Geographical distribution of CO_2 emissions from maritime shipping in 2015, from international vessels (a) and domestic vessels (b).
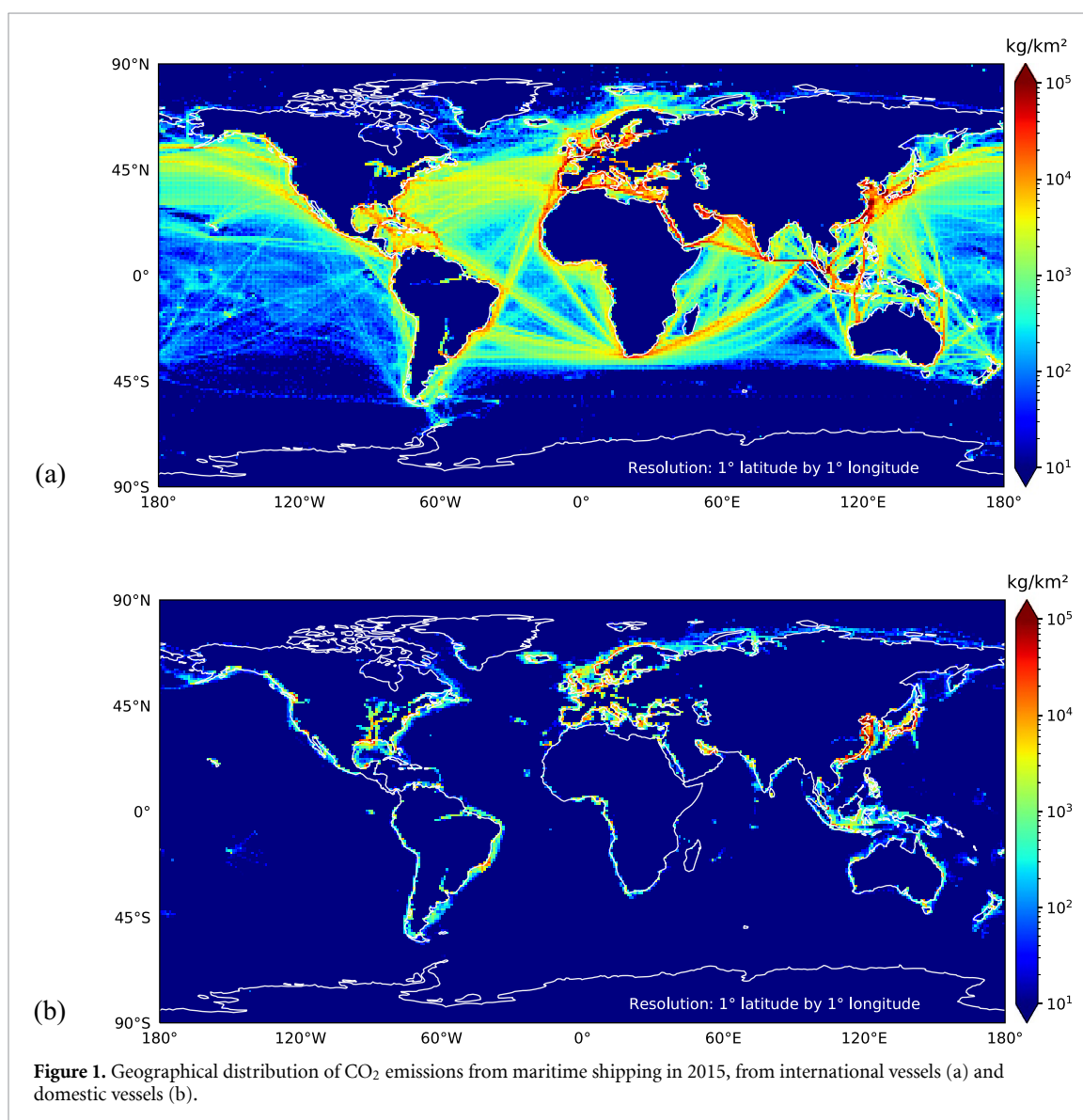
Figure 2 compares simulated annual-mean $PM_{2.5}$ concentrations resulting from emissions from international vessels versus domestic vessels under the baseline scenario. The $PM_{2.5}$ contributions from the international vessels are mainly in the open sea and over busy sea-lanes, with the highest grid value of 6.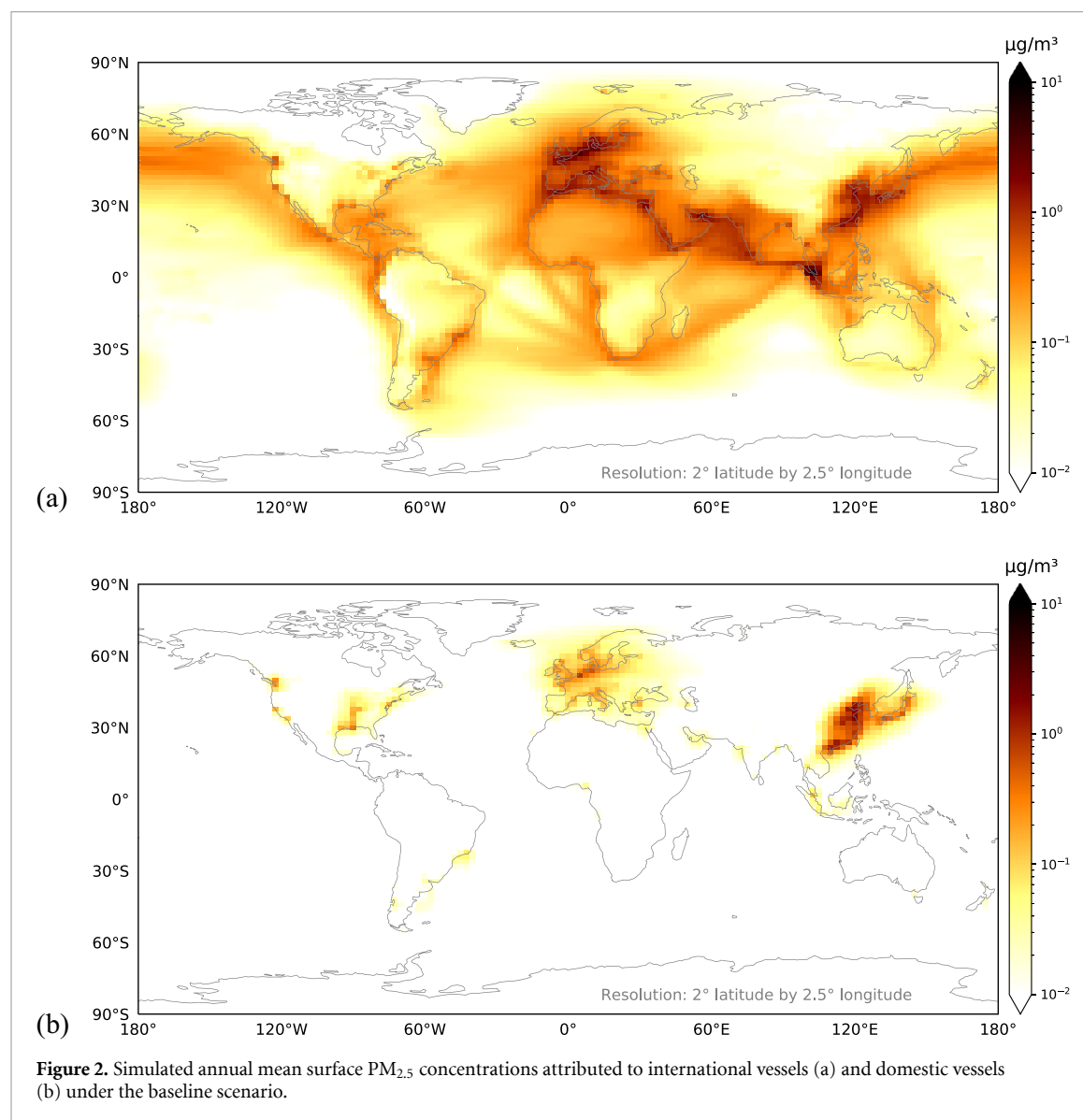7 μg m^{-3} in the Malacca Strait. In contrast, $PM_{2.5}$ contributions from domestic vessels are elevated in China, with the grid value as high as 2.0 μg m^{-3} in the Yangtze River Delta. Gridded $PM_{2.5}$ concentration data for each scenario can be acquired as described in the Data Availability 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		0.5% sulphur cap		0.1% sulphur cap		Tier III NO$_x$ standard	
	IV	DV	IV	DV	IV	DV	IV	DV
CO_2	704 000	162 000	672 000	162 000	672 000	162 000	672 000	162 000
SO_2	9910	98.4	1780	98.4	408	98.4	1780	98.4
NO_x	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

NO$_x$ 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 NO$_x$ 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.
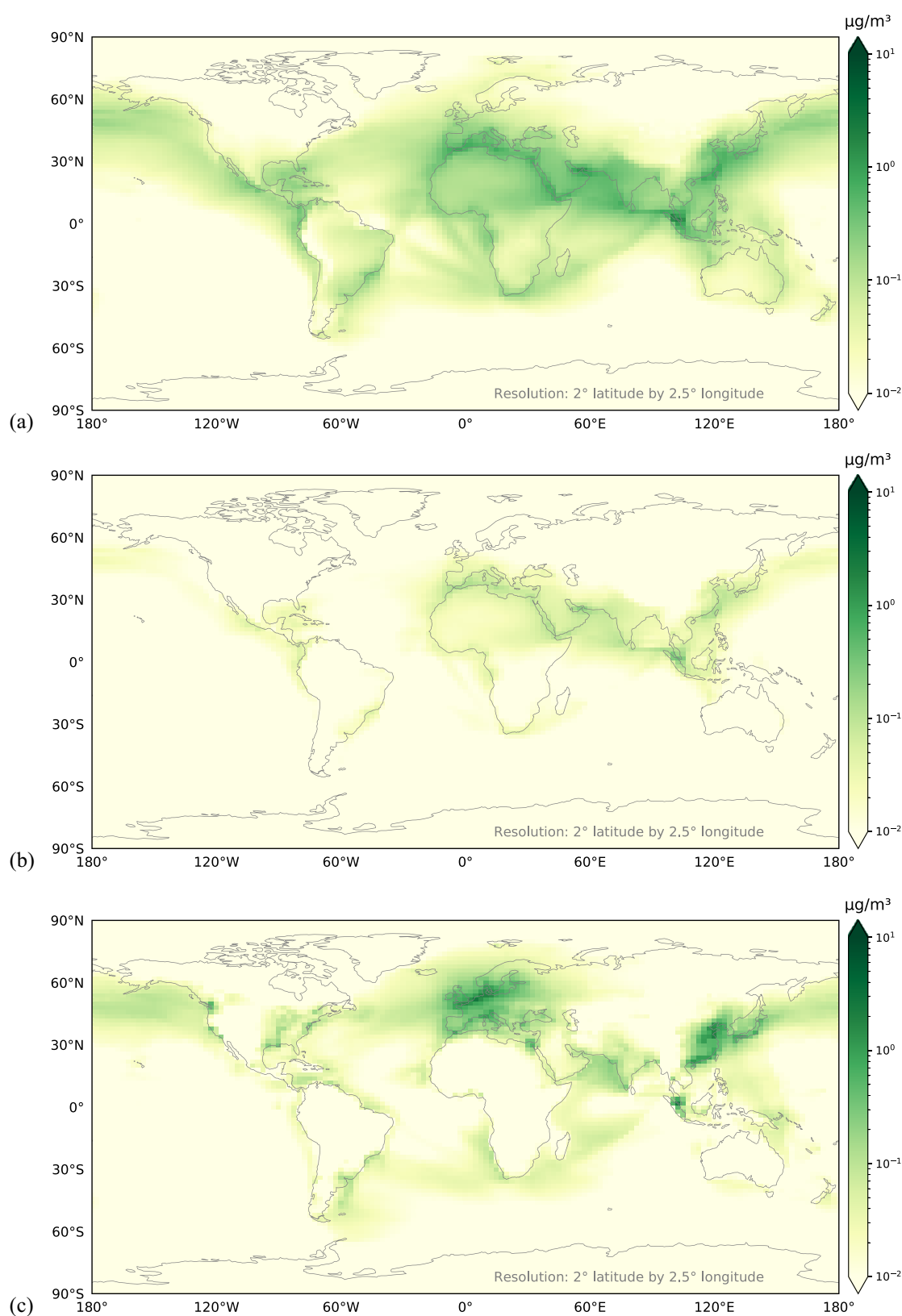
Figure 3. Reduction in annual mean PM$_{2.5}$ concentration under control scenarios: (a) baseline—0.5% sulphur cap; (b) 0.5% sulphur cap—0.1% sulphur cap; and (c) 0.5% sulphur cap—Tier III NO$_x$ standard.

Table 3. Premature deaths caused by ship-related PM$_{2.5}$ in the baseline scenario and avoided premature deaths under control scenarios.

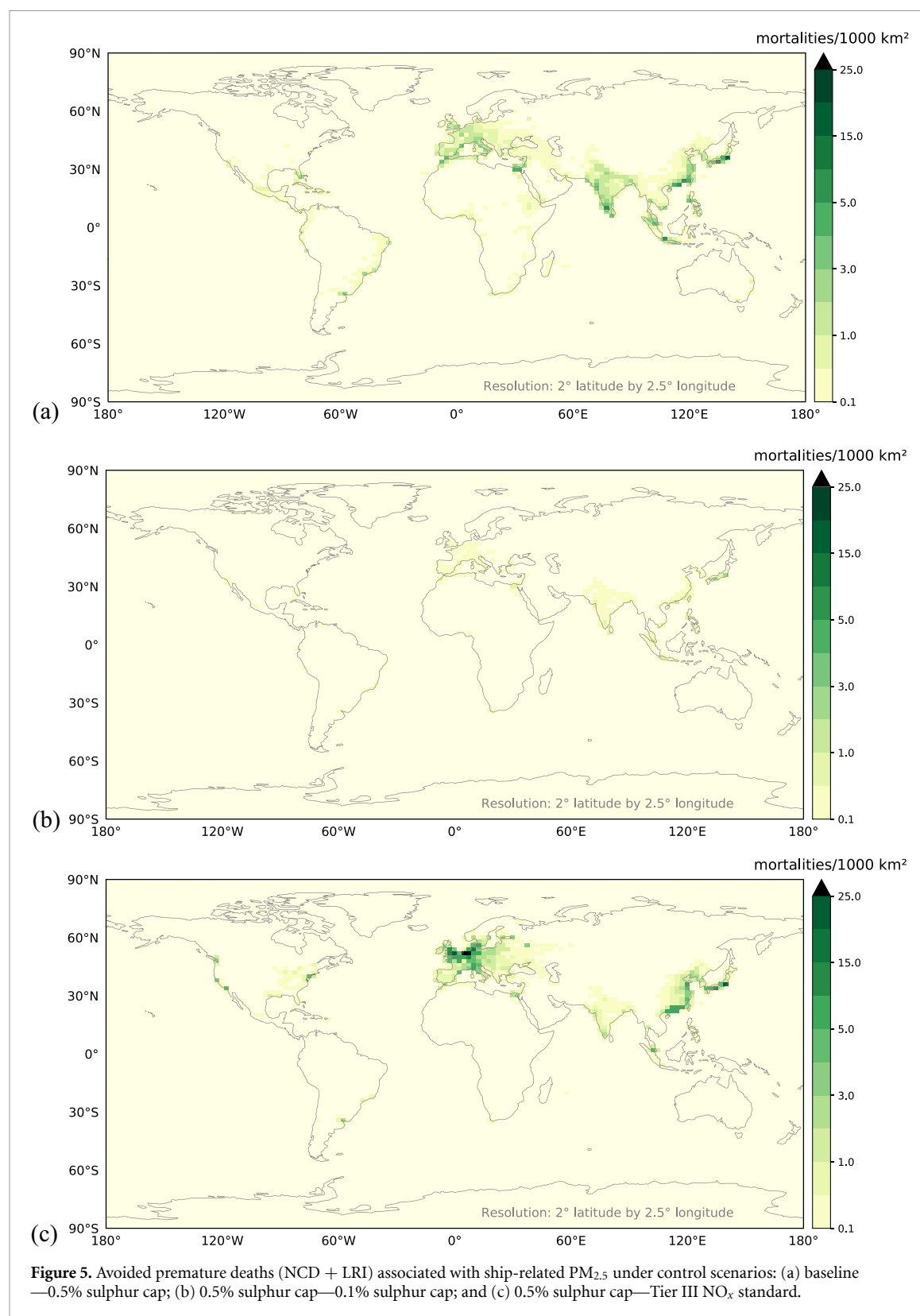| No.	Impact to be quantified	Calculation
1	Impact of international shipping in baseline scenario	78 000 (70 100–85 400)
2	Impact of domestic shipping in baseline scenario	16 200 (14 700–17 500)
3	Total impact of maritime shipping in baseline scenario	94 200 (84 800–103 000)
4	Impact of 0.5% sulphur 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)
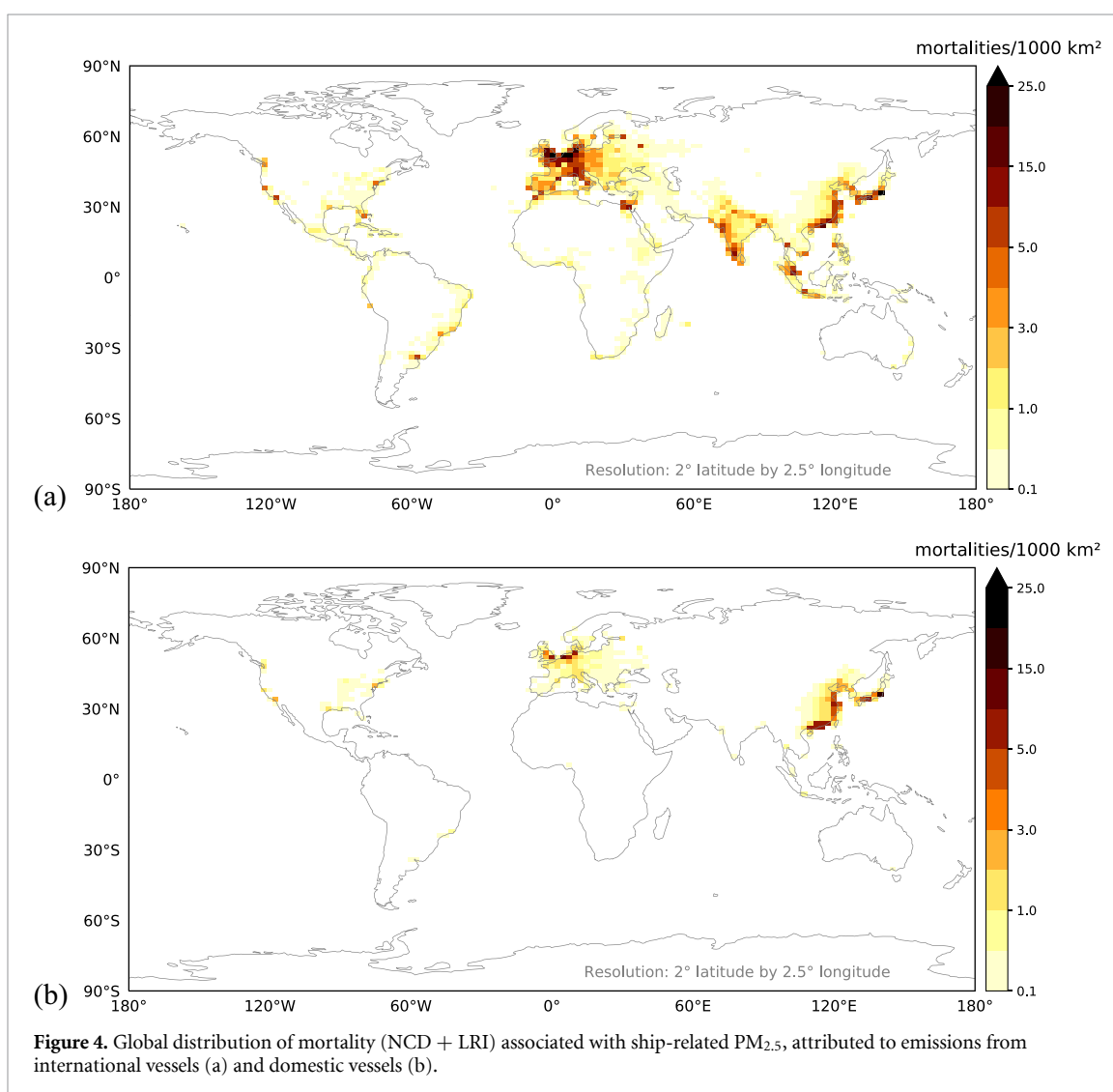
Figure 4. Global distribution of mortality (NCD + LRI) associated with ship-related PM$_{2.5}$, attributed to emissions from international vessels (a) and domestic vessels (b).

3.3. Health outcomes

Table 3 summarizes 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

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.

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.

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_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 the 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_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 $PM_{2.5}$ 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 $PM_{2.5}$ 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_x-based controls are all the result of SO_x 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_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_x standard has fewer NO_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_x-based control policy would have a larger impact on mitigating shipping-related health burden than the SO_x-based approach for countries that with existing SO_x 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_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_x standard on new marine diesel engines. If these NO_x-based control measures were to be applied globally, they could reduce a much larger number of mortalities than SO_x-based control. However, implementing a Tier III NO_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_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_x and NO_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_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_2 emission comes from international vessels. With respect to air quality, we compared the simulated $PM_{2.5}$ concentration from the GEOS-Chem modelling with observational air quality data. Overall, GEOS-Chem reproduces the observed spatial distribution of $PM_{2.5}$ 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 $PM_{2.5}$ concentrations to premature mortality. The 95% CI due to these parameters is provided above. Based on total $PM_{2.5}$ in GEOS-Chem, we estimate using our methods that 9.4 (8.2–10.1) million premature deaths are attributable to outdoor $PM_{2.5}$ 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_x-based control policies, but could achieve further mortality reductions under a NO_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_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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