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AIR POLLUTION AND ENERGY EFFICIENCY

Study on effects of the entry into force of the global 0.5% fuel oil sulphur content limit on human health

Submitted by Finland

SUMMARY

Executive summary:	At the sixth-ninth session of the Marine Environment Protection Committee (MEPC 69), the Committee agreed in principle that a final decision on the date of implementation of the 0.50% sulphur limit should be taken at MEPC 70, so that maritime Administrations and industry can prepare and plan accordingly. The results of the enclosed study indicate some key findings regarding health impacts due to a delay in the implementation of the IMO's 0.50% global sulphur standard from 1 January 2020 to 1 January 2025. The study focuses on the impacts of fine particulate matter (PM) concentrations on these responses.
Strategic direction:	7.3
High-level action:	7.3.1
Output:	7.3.1.10
Action to be taken:	Paragraph 7
Related document:	MEPC 69/21

Introduction and background

1 At the sixth-ninth session of the Marine Environment Protection Committee (MEPC 69), the Committee agreed in principle that a final decision on the date of implementation of the 0.50% sulphur limit should be taken at MEPC 70, so that maritime Administrations and industry can prepare and plan accordingly.

2 The results of the enclosed study "Health Impacts Associated with Delay of MARPOL Global Sulphur Standards" indicate some key findings to the question: What are the estimated increases in premature mortality due to lung cancer and cardiovascular disease from a delay in the implementation of the IMO's 0.50% global sulphur standard from 1 January 2020 to 1 January 2025? The study focuses on the impacts of fine particulate matter (PM) concentrations on these responses.

3 The study applies a methodology similar to that used in previous global shipping health assessments, whereby geospatial shipping emissions inventories are translated to atmospheric concentrations on land, and then to health impacts based on population exposure and concentration-response (CR) functions. The report uses assumptions made in the Third IMO GHG Study 2014 and in the 2016 IMO Fuel Availability Study (FAS), in combination with highly resolved atmospheric modeling and current CR functions based on more recent analyses of the health effects of PM. The report also incorporates ECAs that have been implemented before 2020 to avoid assigning health impacts to regions that already have benefitted from low-sulphur fuel requirements.

Key findings of the study

4 Sulphur emissions for 2020 through 2024 will be reduced by ~8.5 to ~8.9 million metric tonnes annually (2020 and 2025, respectively), about 77% lower due to the implementation of MARPOL Annex VI standards from 2020 compared to implementation from 2025.

5 The difference in emissions leads to significant reductions in ambient sulphate concentrations in coastal communities. Pollution exposure differences are particularly acute in highly populated coastal areas. The study takes also into account the health benefits afforded by MARPOL Annex VI designated ECAs (North America, Baltic Sea and North Sea) implemented prior to 2020, and legislation such as the European Union Sulphur Directive, which requires that marine fuels meet 0.5% sulphur limits in European waters outside SECA-areas (the territorial seas, exclusive economic zones, and pollution control zones) as of 1 January 2020.

6 Delay in implementation of global sulphur limits from 2020 to 2025 would, according to the study, contribute to more than 570,000 additional premature deaths compared to the implementation from 2020. Health benefits are related to the proximity of coastal communities and major shipping lanes.

Action requested of the Committee

7 The Committee is invited to note the information provided in the study.

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ANNEX

Health Impacts Associated with Delay of MARPOL Global Sulphur Standards

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Acronyms

CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
CR	Concentration Response
CV	Cardiovascular
EERA	Energy and Environmental Research Associates
FAS	Fuel Availability Study
FMI	Finnish Meteorological Institute
HFO	Heavy Fuel Oil
HSD	High-speed Diesel
IMO	International Maritime Organization
LC	Lung Cancer
LL	Log-linear concentration response function
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine Distillate Oil
MGO	Marine Gas Oil
MSD	Medium-speed Diesel
NO_X	Oxides of Nitrogen
PM	Particulate Matter
SFOC	Specific Fuel Oil Consumption
SILAM	FMI Model: System for Integrated modeLling of Atmospheric composition
SO_x	Oxides of Sulphur
SSD	Slow-speed Diesel
STEAM	Ship Traffic Emission Assessment Model
WHO	World Health Organization

Summary

The International Maritime Organization (IMO) has implemented standards to reduce sulphur pollution from ships. These standards require a reduction in sulphur content in fuel oil from maximum 3.50% sulphur by mass (after January 1, 2012) to 0.50% sulphur by mass (after January 1, 2020), in addition to sulphur reductions to 0.1% S content within existing Emission Control Areas (ECAs). This global 2020 standard is subject to deferral to January 1, 2025 based on the outcome of a regulatory review, and this report provides an analysis of the health impacts associated with such a delay. In particular, this report answers the research question: What are the estimated increases in premature mortality due to lung cancer and cardiovascular disease from a delay in the implementation of the IMO's new global sulphur standard? The study focuses on the impacts of fine particulate matter (PM) concentrations on these responses.

The study applies a methodology similar to that used in previous global shipping health assessments, whereby geospatial shipping emissions inventories are translated to atmospheric concentrations on land, and then to health impacts based on population exposure and concentration-response (CR) functions. This report uses assumptions made in the Third IMO GHG Study [1] and in the 2016 IMO Fuel Availability Study (FAS), in combination with highly resolved atmospheric modeling and current CR functions based on more recent analyses of the health effects of PM. The report also incorporates ECAs that have been implemented and will be implemented before 2020 to avoid assigning health impacts to regions that already have benefitted from low-sulphur fuel requirements.

Our results indicate the following key findings:

- Sulphur emissions for 2020 through 2024 will be reduced by ~8.5 to ~8.9 million metric tonnes annually (2020 and 2025, respectively), about 77% lower due to the implementation of the IMO MARPOL Annex VI standards ("on-time" scenario) compared to not implementing MARPOL Annex VI ("delay" scenario).
- The difference in emissions leads to significant reductions in ambient sulphate concentrations in coastal communities. Pollution exposure differences are particularly acute in highly populated coastal areas in Asia Pacific, Africa, and Latin America nations, reflecting reduced exposure afforded by IMO MARPOL ECAs in Europe and North America, and legislation such as the European Union Sulphur Directive, where European States will ensure that "marine fuels meet 0.5% S limits in the territorial seas, exclusive economic zones, and pollution control zones" implemented as of 1 January 2020 [2].
- The delay in implementation from 2020 to 2025 would contribute to more than 570,000 additional premature deaths compared to on-time MARPOL Annex VI implementation. Health benefits are related to the proximity of coastal communities and major shipping lanes.
- The estimated cost of implementation is $30 Billion/yr (with a range of $10 B/yr to $60 B/yr) depending on fuel price assumptions. This estimate is based upon a review of historic price differences between residual and distillate marine fuel oils and is consistent with the expectation that the price premium for the shipping industry to purchase compliant fuel that would reflect increased refining supply costs as estimated from the 2016 IMO FAS.
- Based on this cost and using the best estimates of health impacts, we estimate an average of $277,000 per avoided premature mortality (range of $67,000 to $1.13 Million per avoided

premature death). This cost per avoided mortality is lower than the range of values to avoid a premature death estimated in over sixty studies across more than four dozen nations. Moreover, the costs per avoided death are lowest in regions where population densities are greatest and benefits would be highest.

Introduction

The International Maritime Organization (IMO) has implemented standards to reduce sulphur pollution from ships. These standards require a reduction in sulphur content in fuel oil from 3.50% sulphur by mass (after January 1, 2012) to 0.50% sulphur by mass (after January 1, 2020) [3]. This global 2020 standard is subject to deferral to January 1, 2025 based on the outcome of a regulatory review that is currently ongoing.

As part of the ongoing review, we explore the health impacts associated with such a delay. Without question, a delay in the implementation of the IMO global standard would leave unabated the sulphur emissions and sulphate particulate matter (PM) concentrations above both sea and land. Previous work has shown that these increases in concentrations can lead to global health impacts [4, 5]. These negative health impacts have also been shown in regional work, mainly focused in Europe [6-8], North America [9-11], Australia [12], and East Asia [13].

This report provides high-resolution, global analysis of health impacts associated with a delay in the implementation of IMO's global sulphur fuel oil standard. In particular, this report answers the research question: What are the estimated increases in premature mortality due to lung cancer and cardiovascular disease from a delay in the implementation of the IMO's new global sulphur standard? The study focuses on the impacts of sulphate particulate matter (PM) concentrations on these responses. The study also puts our results in context by comparing the health impacts of regulatory delay with estimates of the costs of regulatory implementation.

Section 3 of the report outlines the methodology used in the study. That section discusses the construction of geospatial emissions inventories; the application of state-of-the-art atmospheric modeling to translate these emissions to land-based concentrations; and the use of current concentration-response (CR) functions to evaluate the health risks associated with these concentrations.   Section 4 of the report discusses our health impact results, both at a global and regional level, and places these results in context vis-à-vis estimated costs of regulatory implementation. Finally, Section 5 of the report presents conclusions and policy implications.

Methodology

Constructing Emissions Inventories

Emission factors and the STEAM model

For this research, we constructed geospatial shipping emissions inventories under two scenarios: (1) an "on-time" implementation case, where it was assumed that the fuel oil standard goes into effect in 2020; and (2) a "delay" implementation case, where it was assumed that the standard is delayed until 2025. The emissions inventory was facilitated by the use of the Ship Traffic Emission Assessment Model (STEAM), which has been used in similar types of work [1, 8, 14-19]. The STEAM model combines 2015 AIS data on shipping routes and volume as well as vessel technical data from IHS Fairplay, with peer-reviewed energy use and emissions equations to construct a geospatial emissions inventory for global shipping. Propulsion energy is evaluated with Hollenbach resistance calculation method, which is based on tank tests [20]. The STEAM model employees a range of emissions factors, specific to fuel types, engine types, and engine load, and *Table 1* presents a range of these values with notes below the table.

Table 1. Emission Factors Used for This Study.

Emission	**Emission Factor (g/kWh), Normal (80%) load**	**Emission Factor (g/kWh), Low (25%) load**
NO_X*		
Tier 1	17 (SSD), 12.9 (MSD)**, 9.8 (HSD)	17 (SSD), 12.9 (MSD)**, 9.8 (HSD)
Tier 2	14.4 (SSD), 10.5 (MSD), 7.7 (HSD)	14.4 (SSD), 10.5 (MSD), 7.7 (HSD)
Tier 3	3.4 (SSD), 2.6 (MSD), 2 (HSD)	3.4 (SSD), 2.6 (MSD), 2 (HSD)
SO_X**		
0.1% S	0.48 (MDO/MGO: SFOC 250 g/kWh)	0.54 (MDO/MGO SFOC 282 g/kWh)
0.5% S	2.40 (MDO/MGO: SFOC 250 g/kWh)	2.7 (MDO/MGO SFOC 282 g/kWh)
2.7% S	8.35 (HFO: SFOC 165 g/kWh)	9.42 (HFO: SFOC 186 g/kWh)
CO	0.54	2.18
PM		
0.1% S	0.38	0.43
0.5% S	0.50	0.57
2.7% S	1.19	1.35
CO_2***		
HFO	515 (SFOC 165 g/kWh)	580 (SFOC 186 g/kWh)
MDO/MGO	803 (SFOC 250 g/kWh)	905 (SFOC 282 g/kWh)

Note: values only indicate the range of values applied on case by case basis because fuel consumption and emissions depend on engine load and specific fuel oil consumption (SFOC), calculated from vessel-specific AIS data, as described in published literature for STEAM [15-19].

* As defined in MARPOL Annex VI, Regulation 13. For MSD, crankshaft rpm of 514 is assumed in this example, but engine specific values are used in each case. For Tier 0 engines, 110% of Tier I value is used.

** Part of sulphur is as gaseous SO_2 and part is in aerosol SO_4. The emission factors listed for SO_X contain the gaseous emission part, the aerosol sulphur has been subtracted to maintain mass balance of sulphur.

*** SFOC changes as a function of engine load. The values listed include this effect and includes the differences in carbon content between HFO and MDO/MGO.

NO_X Emissions Factors

Emission factors for NO_X depend on engine crankshaft speed (rpm) and age. The IMO Tiers are applied for engines, where Tier 0 follows the definitions of the Third IMO GHG study [1], and where Tiers 1-3 follow the functions defined in MARPOL VI.

SO_X Emissions Factors

Emission factors for oxides of sulphur (SO_X) are determined from fuel sulphur content (% by weight) and the amount of fuel consumed at specific engine load. Part of fuel sulphur is emitted as primary PM and the sulphur fraction included in SO_4 is subtracted from sulphur available for SO_X formation in the atmosphere. All gaseous emissions of sulphur are calculated as SO_2. Sulphur content for residual fuel use outside of ECA regions in the "delay" scenario were assigned 2.7% S, similar to the Third IMO GHG Study; in the "on-time" scenario, sulphur content was adjusted to 0.5% S. Where lower fuel limits will be in place in 2020 due to current legislation, the maximum sulphur content was set accordingly: i) the IMO ECA regions (0.1% S) [3]; ii) the regions covered by the European Directive (0.5% S) [2]; iii) China legislation applied to the Pearl River Delta, Yangtze River Delta, and Bohai Sea (0.5% S) [21].

PM Emissions Factors

Particulate matter is modelled as dry PM without the associated water, which normally accompanies the sulphate aerosol. The mass of associated water depends on the ambient conditions (temperature, humidity) and the consecutive chemical transport modelling step takes the hygroscopicity of PM into account.

CO_2 Emissions Factors

The emission factor for CO_2 depends on fuel type and specific fuel oil consumption (SFOC) at a specific load point. The base SFOC (at 80% engine load) depends on engine age, power output and stroke type, as defined in the Second IMO GHG Study 2009 [22]. Table 1 lists the range of values for HFO and MDO/MGO at high and low engine loads. These examples represent the extremes used in the model for diesel engines. This approach necessitates SFOC modelling as a function of engine load and further details can be found in Jalkanen et al. [19] and the Third IMO GHG Study [1].

Base Year Inventory Adjustments for 2020 and 2025

Ship inventories for future years were adjusted for the years 2020 and 2025 using vessel type compound annual growth rates (*Table 2*), which are consistent with energy use base case growth rates used in the 2016 IMO FAS (see MEPC 70/5/6, Table 166). These growth rates produce future year inventories for ship energy demand and emissions that are lower than some other demand estimates submitted to MEPC70 by observer delegations [MEPC 70/5/5]; if higher energy demand estimates were used, the health impact from uncontrolled sulphur levels would be greater.

Table 2. Energy-based Growth Rates derived from Table 166 of 2016 IMO FAS

Ship type	Growth rate
Dry bulk	1.74%
Liquid bulk	-1.90%
Unitized	2.79%
Passenger	-0.55%
Miscellaneous	0.00%
Total Energy	0.95%

Annual totals for emissions from global shipping are collected in *Table 3* together with the results of 2012 described in the Third IMO GHG study. The projected emission results of the global fleet in 2020 and 2025 are similar to those of the Third IMO GHG study. Largest differences are because of reduction of sulphur in marine fuels, which has an impact on SO_X and PM emissions.

Table 3. Summary of Emissions (and Fuel Consumption) from STEAM for 2020, Compared with Third IMO GHG Study 2014.

POLLUTANT (000 TONNES)	**2020**		**2025**		**2012, THIRD IMO GHG STUDY**
	On-Time, With MARPOL VI	Delay, Without MARPOL VI	With MARPOL VI	Without MARPOL VI	
NO_X	21,000		22,500		19,000
SO_X	2,500	10,900	2,700	11,700	10,200
PM	760	1,500	810	1,600	1,400
CO_2	862,000		917,000		938,000
FUEL USED*	272,000		289,000		254,000 (t-d)-300,000 (b-u)

* top-down estimate of Third IMO GHG study is indicated with (t-d) and bottom up with (b-u).

Our results are shown for 2020 in *Figure 1* and *Figure 2*, and for 2025 in *Figure 3* and *Figure 4*, which show geospatially derived emissions inventories under (1) the "delay" scenario; (2) the "on-time" scenario; and (3) the difference between these two scenarios. It is worth noting in *Figure 2* that the North American ECA and the European Directive controls can be clearly identified, where no significant differences in SO_X emissions from ships are observed from 2020 to 2025 because legislation will be in force that is independent of the decision to delay MARPOL VI global fuel sulphur standards. (One also may be able to observe in *Figure 2* the reduced emissions in the Bohai Sea, and near the Yangtze River, where China legislation will be implemented; however, the ship traffic around the Pearl River Delta makes the sulphur emission controls hard to see in that region where China controls will be in place.)

Figure 1. Annual shipping inventories for SO_X *under the delay and on-time scenarios for 2020.*

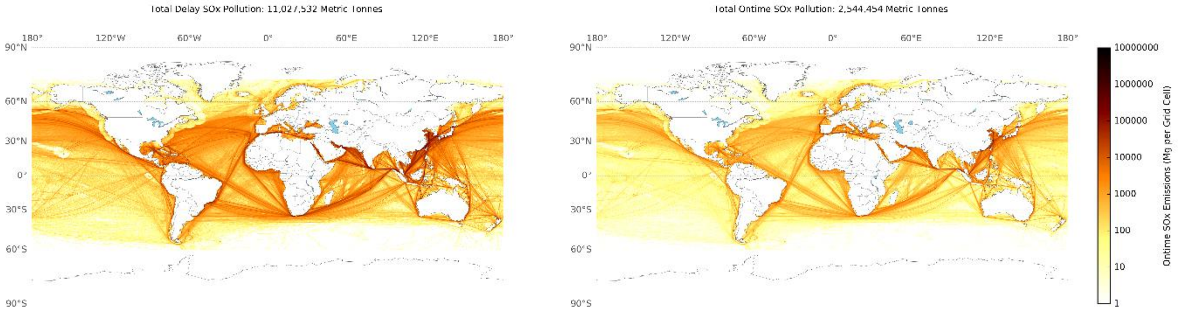


Figure 2. Difference in Shipping Inventories for SO_X for 2020.

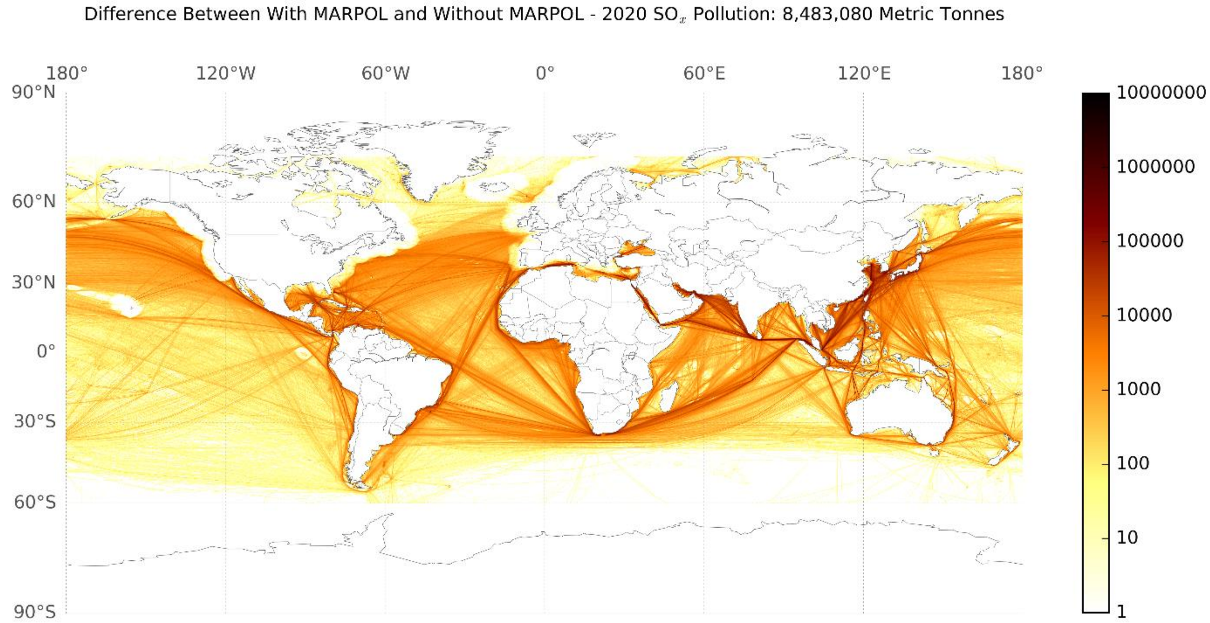


Figure 3. Annual shipping inventories for SOx under the delay and on-time scenarios for 2025.

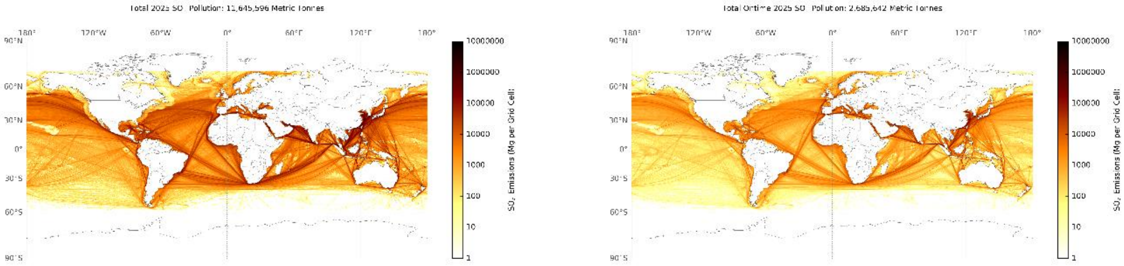
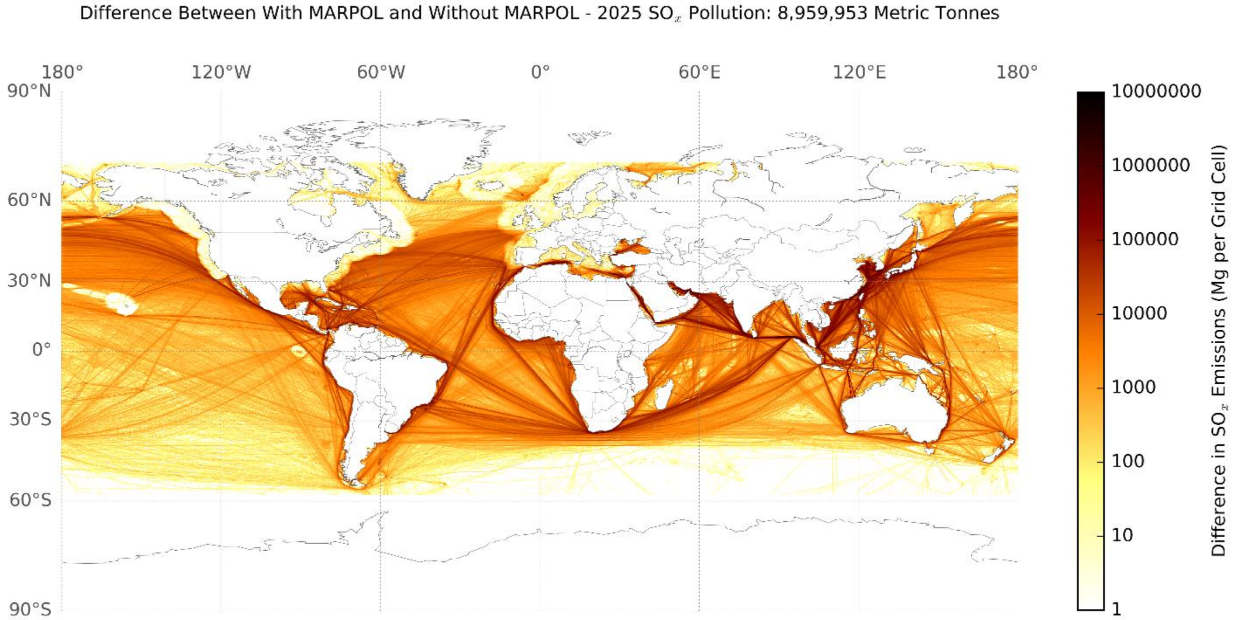


Figure 4. Difference in Shipping Inventories for SO_X *for 2025.*



Modeling Atmospheric Concentrations

These emissions inventories provided input into the System for Integrated modeling of Atmospheric composition (SILAM) model [23-26]. This is an atmospheric chemical transport model that is operated by the Finnish Meteorological Institute (FMI).[1] Atmospheric chemical transport models estimate changes in ambient air pollution exposure resulting from changes in emissions. For this work, SILAM was used to translate emissions inventories under the "delay" and "on-time" scenarios into geospatial concentrations of sulphate PM. *Figure 5* shows the spatial distribution of atmospheric sulphate concentrations at ground level under (1) the "delay" scenario without MARPOL VI; and (2) the "on-time" scenario with MARPOL VI for 2020 and 2025. *Figure 6* show the difference in these scenarios for 2020 and 2025, respectively. All results are shown in micrograms of sulphate per cubic meter. As can be seen in these figures, there are areas of the world where concentrations of sulphates on land may be greatly affected by a delay in regulatory implementation.

FMI SILAM modeling team produced surface-level increase in concentrations for each pollutant on monthly average and annual bases, at 0.1 degree grid size. SILAM team used 20 km ship emission data resolution for ships. The non-shipping gridded emissions inventories prepared by the FMI SILAM modeling team include the following sources:

a. Anthropogenic: HTAPv2 + MEIC (Multi-resolution Emission Inventory for China) + REAS (Regional Emission Inventory in Asia) [27]

b. Fires: IS4FIRES (from FMI, http://is4fires.fmi.fi/, Sofiev et al., ACP, 9 (2009) 6833-6847)

c. Sea salt (from FMI, Sofiev et al., JGR, 116, D21302, 2011)

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[1] More about SILAM can be obtained from http://silam.fmi.fi/.

d. Desert dust (from FMI)

e. Biogenic VOC: MEGAN (Model of Emissions of Gases and Aerosols from Nature, Guenther et al., ACP, 2006)

f. Aircraft emissions: RETRO (http://retro-archive.iek.fz-juelich.de/data/documents/reports/D1-6_final.pdf)

Figure 5. SILAM Model Results for Ship Emissions 2020, MARPOL VI Delay Scenario Compared with On-time Scenario.

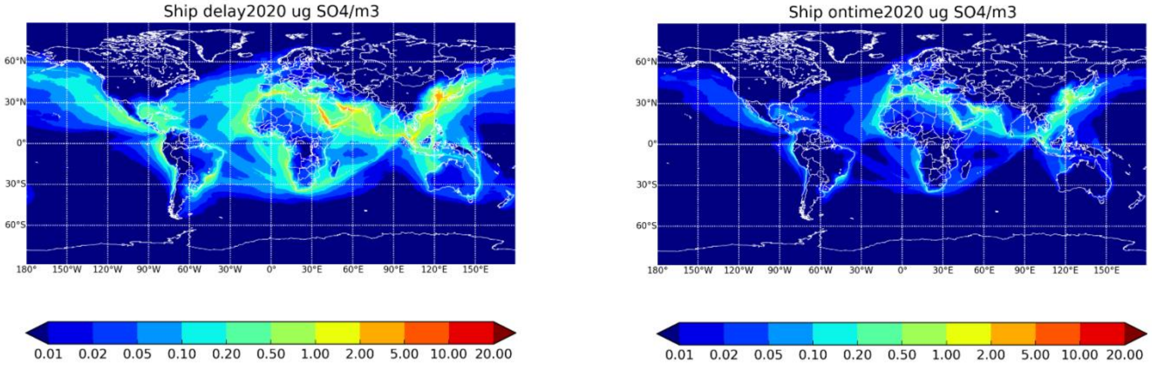
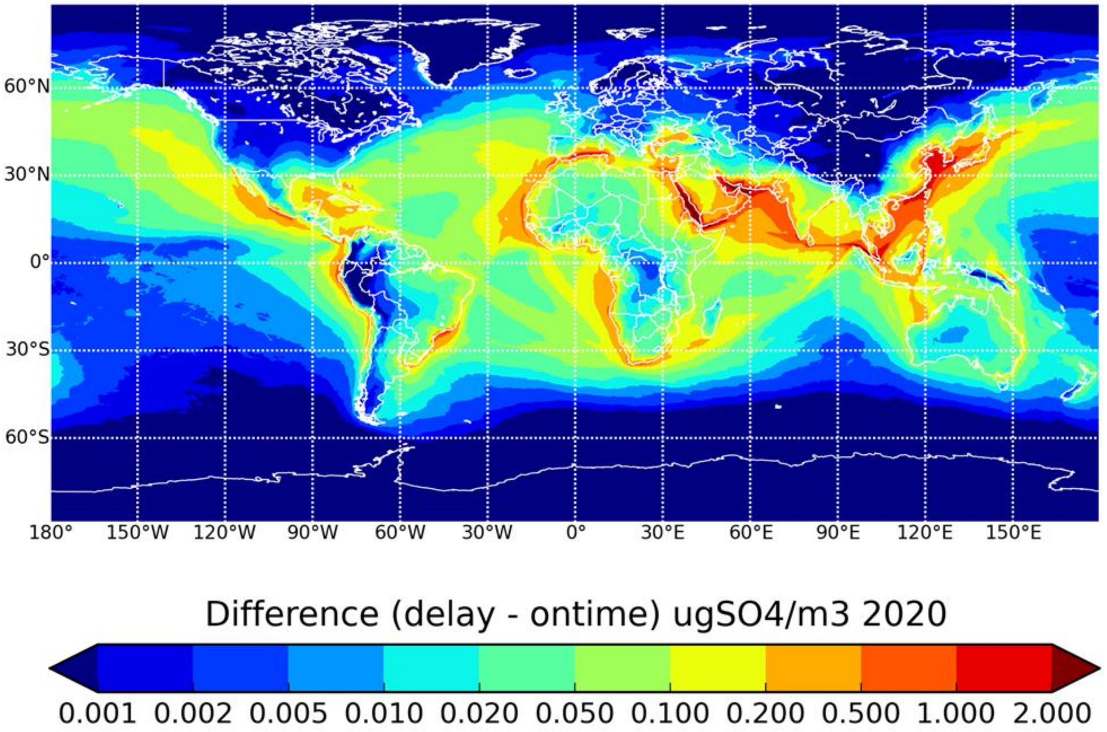


Figure 6. SILAM Model Results for Reduction in Shipping Emissions 2020, Difference of Delay and On-time Scenarios.



Evaluating Health Impacts

The concentrations determined through SILAM were then evaluated from a health standpoint by applying standard health risk assessment approaches discussed in the literature. The key elements of this work includes not only concentrations, but also background incidence rates and populations.

It is well understood that fine particular matter can lead to a host of human health impacts, including lung cancer, cardiovascular disease, COPD, asthma, and stroke, among others [28-46]. This report will not delve into the details of the epidemiological aspects of pollution on human health. Suffice it to say that study upon study has continued to identify PM as a significant contributor to premature mortality and morbidity, and the scientific community is in general agreement about the nature of these effects.

The process of calculating the health impact analysis follows the general approach discussed in previous work [47, 48]. That work applied a log-linear risk analysis discussed in Ostro (2004) [42], which built on work developed out of the United States "six city study" conducted earlier by Pope et al. [43]. In this new work, we conduct a similar assessment (updated with new population data, incidence data, and concentration data) using the log-linear risk function; however, we also apply a more recent CR equation using updated information from Lepuele et al. (2012) [40]. Epidemiological studies have found a relatively consistent association between PM exposure and mortality across several countries and continents—from South America to Western Europe [29, 49, 50], supporting use of this CR function.

The analysis is limited to evaluating premature mortality due to cardiovascular disease and lung cancer[2] attributed to long-term exposure to PM. Concentration-response functions for such exposure correspond to impacts for a population cohort aged 30 years or more using Lepeule (2012) as a guide. Our population data are from NASA's Socioeconomic Data and Applications Center (SEDAC) Population of the World, Version 4 [51]; and age cohort fractions are from the United Nations to determine the population 30 years or greater by country [52]. Country-specific incidence rates for cardiovascular disease and lung cancer were obtained from the World Health Organization's Global Health Observatory (GHO) and GLOBALCAN, respectively [53, 54]. Premature mortality estimates were made using the equations shown in the Appendices.

Results

Health Benefits of On-time Implementation

The results of our analysis for 2020 are shown in *Figure 7* and *Table 4*. *Figure 7* represents the total additional premature mortality expected from a delay in regulatory implementation for the year 2020, using the log-linear (LL) concentration-response functions (see Appendix). The linear concentration-response functions produce very similar mortality estimates. This figure includes both cardiovascular disease and lung cancer, and represents increased premature mortality of 108,000/year due to regulatory delay. *Table 4* includes these results, as well as results of premature mortality associated with each scenario compared to a "no shipping" scenario (where emissions from ships are removed entirely from the analysis). This table allows us to assess the global premature mortality impacts with each scenario individually, and shows total premature

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[2] This is consistent with Lepeule (2012) using WHO's International Classification of Diseases and noting cardiovascular death as *ICD-9 400.0-440.9* and *ICD-10 I10.0-I70.9*; and lung cancer death as *ICD-9 162* and *ICD-10 C33.0-C34.9*.

mortality of 50,400 and 158,200 for the "on-time" and "delay" scenarios, respectively (and using CR function best estimates). *Table 5* shows similar types of results for 2025. The total for all five years is shown in *Table 6* globally and *Table 7* regionally, with a global total of ~570,000 over the five year period 2020-2024. Regional characterizations are in the appendix.

The World Health Organization (WHO) estimates that some 3.7 Million deaths in 2012 are attributed to ambient airpollution (http://www.who.int/phe/health_topics/outdoorair/databases/en/). Recent scientific peer-reviewed journal papers have found similar health burdens due to ambient air pollution of particulate matter (PM), with estimates ranging from 2.2 to 3.3 million deaths annually [55-57]. Using the 2020 "delay" scenario results of this analysis, uncontrolled ship sulphate emissions are estimated to account for about 4-7% of all deaths from ambient air pollution (4.2% with range 1.8% to 6% of WHO deaths from ambient air pollution; 7.1% with range of 5.6% to 7.7% of Silva et al. 2016; and 4.8% with range of 3.6% to 5.3% of Lelieveld et al. 2015). Using the "on-time" scenario results, MARPOL VI controls for sulphur will reduce shipping air pollution health impacts by more than two-thirds (reduction of ~68%), such that shipping would only contribute about 1.3% of WHO estimated deaths from ambient air pollution, and account for between 1.5% to 2.2% of PM related deaths.

Figure 7. 2020 Map of Increased Cardiovascular and Lung Cancer Mortality from Delaying MARPOL VI (Total 108,600).

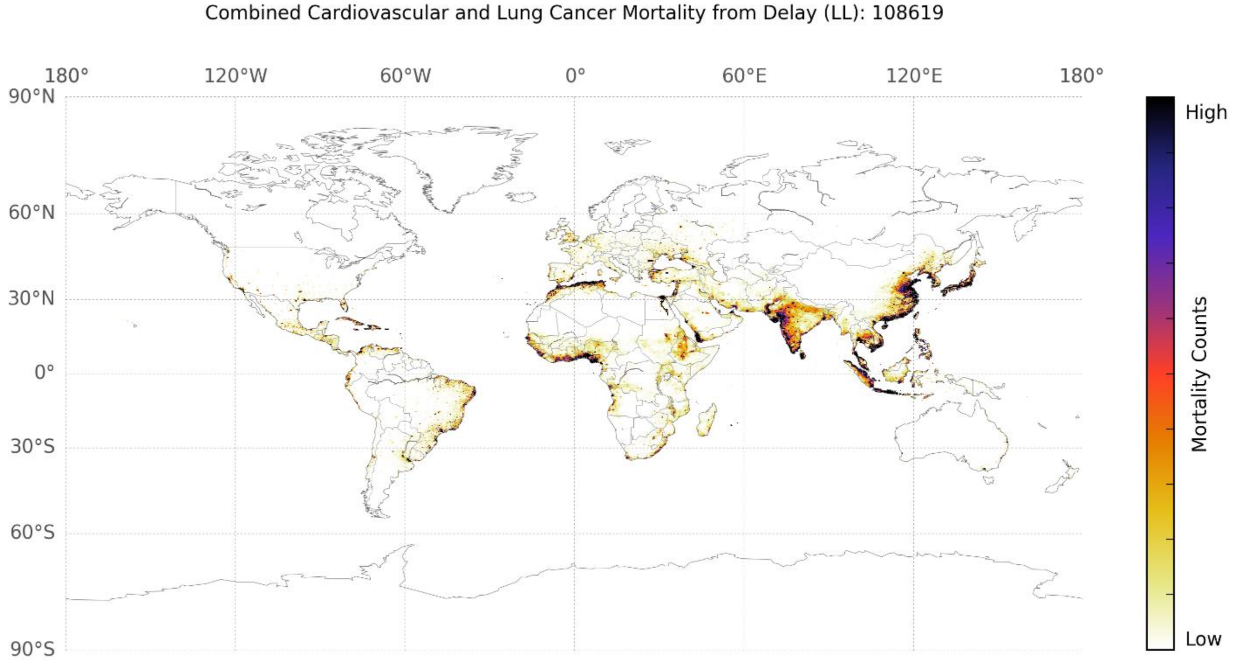

Table 4. Estimated Health Impact in 2020 from a) Mortality Due to Delayed MARPOL VI Action; b) Mortality Due to On-time MARPOL VI Implementation; and c) Available Benefit Due to Avoided Premature Mortality.

Scenario	Health outcome	Mortality Estimate Low	 Best	 High
Absent MARPOL VI 2020	CV LL Mortality	50,700	138,800	225,700
	LC LL Mortality	7,200	19,400	31,300
	Combined Delay Mortality	**57,900**	**158,200**	**257,000**
MARPOL VI 2020	CV LL Mortality	15,700	43,200	70,600
	LC LL Mortality	2,600	7,200	11,600
	Combined On-time Mortality	**18,400**	**50,400**	**82,300**
Available Benefit by On-time Action		Mortality Avoided		
	CV LL Mortality Avoided	35,000	95,600	155,000
	LC LL Mortality Avoided	4,600	12,300	19,700
	Combined Mortality Avoided	**39,600**	**107,800**	**174,800**

Note values rounded to nearest 100; differences between net benefits and scenario differences attributed to rounding. CV = cardiovascular disease; LC = lung cancer; LL = log-linear model.

Table 5. Estimated Health Impact in 2025 from a) Mortality Absent MARPOL VI Action; b) Mortality with MARPOL VI Implementation; and c) Available Benefit Due to Avoided Premature Mortality.

Scenario	Health outcome	Mortality Estimate Low	 Best	 High
Absent MARPOL VI 2025	CV LL Mortality	56,800	155,300	252,400
	LC LL Mortality	7,900	21,200	34,200
	Combined Delay Mortality	**64,700**	**176,500**	**286,600**
MARPOL VI 2025	CV LL Mortality	17,400	47,800	75,200
	LC LL Mortality	2,900	7,700	12,600
	Combined On-time Mortality	**20,200**	**55,600**	**87,700**
Available Benefit by MARPOL VI Action		Mortality Avoided		
	CV LL Mortality Avoided	39,400	107,500	177,200
	LC LL Mortality Avoided	5,100	13,500	21,600
	Combined Mortality Avoided	**44,400**	**120,900**	**198,900**

Note values rounded to nearest 100; differences between net benefits and scenario attributed to rounding.

Table 6. Health Benefit by On-time MAPROL VI Due to Avoided Premature Mortality (Years 2020-2025 inclusive, Best Estimates).

Year	**Combined Mortality (Best-Estimates)** **On-time**	 **Delay**	**Reduced Mortality of On-time Action**
2020	50,400	158,200	**107,800**
2021	51,400	161,900	**110,400**
2022	52,500	165,500	**113,100**
2023	53,500	169,200	**115,700**
2024	54,500	172,800	**118,300**
2025	55,600	55,600	**0***
	Sum of Avoided Mortality		**569,600**

* Policy implemented in either scenario

As shown in *Table 7*, more than 90% of the health benefits from ship emissions reductions will be to 120 nations in the Asia-Pacific Region (58%), Africa (22%), and Latin America (10%). Europe and North America, combined, will receive less than 5% of the health benefits of the 0.5% global sulphur cap. This may be expected, given that most of North America has IMO ECA designation of 0.1% S fuel extending 200 nautical miles from the coasts since 2015, given that the Baltic, North Sea, and English Channel are designated IMO ECAs with 0.1% S fuel, and given that the European Directive will require 0.5% S in territorial seas, exclusive economic zones and pollution control zones fuel by 2020. The Middle East will receive approximately 3% of the benefit from MARPOL VI, partly because that region's nations may benefit indirectly from European Directive controls. Lastly, Russia & CIS region will see about 1.5% of the global health benefit from MARPOL VI implementation.

Table 7. Summary of Regional Health Benefits (Using Best Estimates of Annual Mortality Avoided in 2020).

Region	**Mortality Avoided**		
	Low	**Best**	High
Asia Pacific Region (39 countries)	23,000	**62,600**	101,400
Africa (54 countries and territories)	8,800	**24,000**	38,800
Russia & CIS (12 countries and territories)	600	**1,600**	2,600
Europe (46 countries and territories)	1,300	**3,700**	6,000
Latin America (27 countries and territories)	4,100	**11,200**	18,200
North America (4 countries and territories)	500	**1,300**	2,200
Middle East (13 countries and territories)	1,300	**3,500**	5,600
Total	39,600	**107,800**	174,800

Note: Differences in totals due to rounding.

Estimated Costs of Compliance with Marine Fuel Sulphur Reductions

We also explored our results from a cost per premature mortality avoided context. We estimated the cost of compliance by multiplying the quantity of expected fuel oil burned by the shipping sector over the five year period (2020-2024) times the expected cost differential between heavy fuel oil (high sulphur) and marine diesel oil (low sulphur). STEAM estimates of total fuel oil consumption in 2020 are 272 million tonnes/year, of which HFO totals ~213 million tonnes. The 2016 IMO FAS reports marine fuel demand outside ECAs and not addressed by scrubbers or natural gas fuel to be 233 million tonnes (range 198-289 million tonnes). We estimate low, medium, and high compliance cases using MDO-to-HFO price premiums of $55/tonne (low case), $140/tonne (middle case), and $210/tonne (high case), which represent 2020 dollar conversions of historic ranges of annual average price differences (*Figure 8*).

The annual cost of implementation is about $30 Billion per year, with range of $10 to $60 Billion per year depending on fuel price (*Table 8*). Therefore, we estimate the total cost for on-time MARPOL VI compliance beginning in 2020 to be approximately $150 Billion over the years 2020 to 2024, based on a price premium of USD $140 (see *Table 8*). Given our best-estimate of 570,000 avoided premature mortality during potential delay years 2020-2024, this equates to an average $333,000 per avoided premature mortality *Table 9*. This cost per avoided mortality is lower than the range of values to avoid a premature death estimated in over sixty studies across more than four dozen nations, adjusted to 2020 dollars [58, 59].

Enforcement of MARPOL Annex VI is not estimated here. However, if reported costs for government enforcement and compliance verification in Europe similar enforcement and compliance costs were extended across all port states, enforcement costs would be less than 0.25% of compliance costs. Moreover, the costs reported here would be borne directly by industry, whereas enforcement costs are typically administrative costs borne by governments. Lastly, if use of compliant fuels is less burdensome than dealing with the non-compliant burden of evasion, oversight, and penalty, then the compliance rates may be similarly high to those observed in IMO ECAs.

We recognize that these health benefits do not capture or describe the full set of benefits from on-time implementation of 0.5 % Sulphur regulations of MARPOL Annex VI. Assessing only lung cancer and cardiovascular mortality, this study presents an underestimate by not considering other mortality associated with ambient air pollution, and by ignoring morbidity estimates, which are difficult to estimate given sparse global incident data. Moreover, we do not estimate other impacts to natural and agricultural resources such as eutrophication of vegetation and acidification of coastal waters. Research is ongoing into those benefits of cleaner marine fuels. The implication of attributing the costs of compliance to only two causes of premature mortality is that *Table 9* serves as an upper range for cost-effectiveness of achieving MARPOL Annex VI health benefits.

Figure 8. Historic Marine Distillate and Residual Fuel Price Differential (Average Δ= $210)

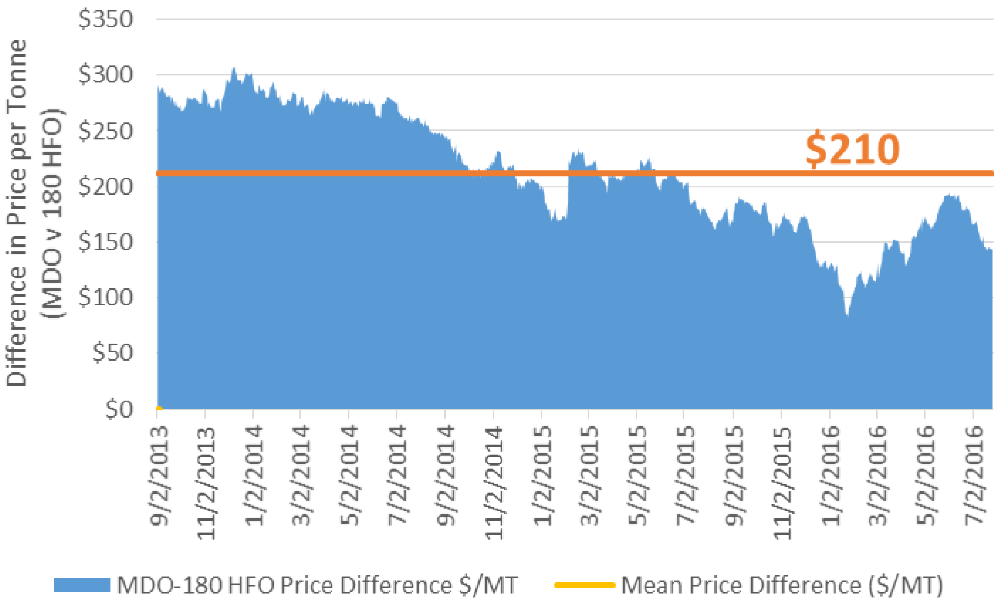

Table 8. Cost to Comply with MARPOL VI Using a Range of Fuel Price Premiums.

Estimate	Fuel to convert (million tonnes in 2020)	Price Premium (USD Billions per Year)		
		USD $55	USD $140	USD $210
		low	middle	high
STEAM HFO	**213**	**$11.7**	**$29.8**	**$44.7**
IMO FAS Low	198	$10.9	$27.7	$41.6
IMO FAS Base case	233	$12.8	$32.6	$48.9
IMO FAS High	289	$15.9	$40.5	$60.7

Table 9. Cost Per Avoided Mortality for MARPOL VI, using Health Best-estimate and using STEAM Fuel Costs.

Health Estimate	Combined 2020 Mortality Avoided by On-time Action	Cost per Avoided Premature Death		
		USD $55	USD $140	USD $211
		low	middle	high
Low	39,600	$296,000	$753,000	$1,130,000
Best	107,800	$109,000	$277,000	$415,000
High	174,800	$67,000	$171,000	$256,000

Conclusion

We conclude that a delay in MARPOL implementation from 2020 to 2025 will impact human health. Implementation of IMO MARPOL Annex VI global sulphur standards in 2020 ("on-time" case) will reduce sulphur emissions by about 77% compared to implementation in 2025 ("delay" case). On-time implementation of MARPOL Annex VI leads to significant reductions in ambient sulphate concentrations in coastal communities. Pollution exposure reductions are largest in highly populated coastal areas closest to major shipping routes.

The delay in implementation of MARPOL Annex VI sulphur regulation from 2020 to 2025 would contribute to more than 570,000 additional premature deaths compared to on-time implementation (based on best estimates reported in *Table 7*. Health benefits are particularly related to the proximity of coastal communities and major shipping lanes near coastal nations in the Asia Pacific, Africa, and Latin America regions.

Implementation of MARPOL Annex VI sulphur regulations will cost approximately $30 Billion per year based on fuel price premiums. This estimate is based upon a review of historic price differences between residual and distillate marine fuel oils and is consistent with the expectation that the price premium for the shipping industry to purchase compliant fuel that would reflect increased refining supply costs, similar to the analysis in 2016 IMO FAS.

This equates to an average $277,000 per avoided premature mortality (range of $67,000 to $1.13 Million per avoided premature death). This cost per avoided mortality is lower than the range of values to avoid a premature death estimated in over sixty studies across more than four dozen nations. Moreover, the costs per avoided death are lowest in the Asia Pacific Region, where population densities are greatest and benefits would be highest.

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Appendices

Health Effects Equations

Region Definitions

Health Effects Equations

Premature mortality effects (E) due to changes in PM concentrations under the "delay" and "on-time" scenarios is given by:

$$E = AF \cdot B \cdot P$$

where *B* represents the incidence of the given health effect; *P* represents the relevant exposed population; and *AF* is the attributable fraction of deaths to the shipping-related PM pollution, given by:

$$AF = \frac{RR - 1}{RR}$$

For the *log-linear* model, relative risk (RR) is given by:

$$RR = \left[\frac{C_1 + 1}{C_0 + 1}\right]^{\beta}$$

and therefore, AF simplifies to:

$$AF = \left\{1 - \left[\frac{C_0 + 1}{C_1 + 1}\right]^{\beta}\right\}$$

which leaves us with the following impact calculation:

$$E = \left\{\left[1 - \left(\frac{1+C_0}{1+C_1}\right)^{\beta_i}\right] \cdot B \cdot P\right\} \qquad (1)$$

where C_0 and C_1 represent pollution concentration for competing scenarios; β = 0.1551 (95% CI = 0.05624, 0.2541) for cardiovascular disease premature mortality; and β = 0.232179 (95% CI = 0.08563, 0.37873) for lung cancer related premature mortality.

For our *linear* model, the response RR is simply given by the linear function [40]:

$$RR = e^{\beta \cdot (C_1 - C_0)}$$

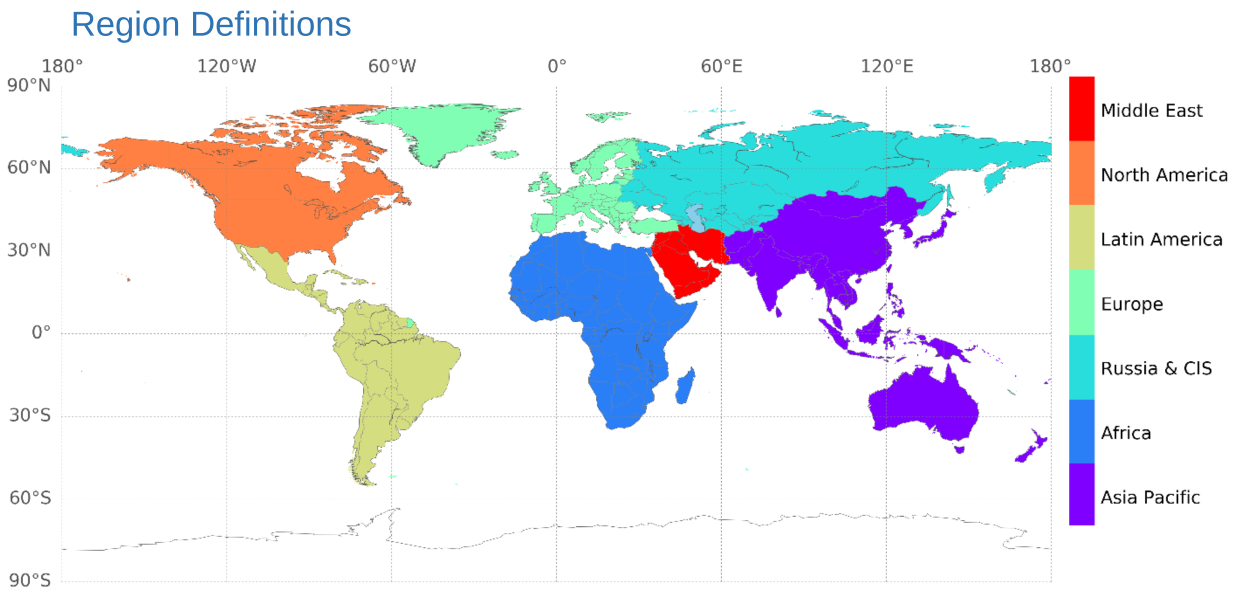
And therefore,

$$AF = 1 - e^{\beta \cdot (C_0 - C_1)}$$

which leads to

$$E = \left[1 - e^{\beta \cdot (C_0 - C_1)}\right] \cdot B \cdot P \qquad (2)$$

where β represents a unit risk associated with a 1 microgram/cubic meter change in PM and is given as β = 0.023111 (95% CI = 0.013103, 0.033647) for cardiovascular disease premature mortality and β = 0.031481 (95% CI = 0.0067659, 0.0559616) for lung cancer related premature mortality [32, 39, 40].



Asia Pacific Region (39 countries): Values represent best estimate (Low, High)

Afghanistan	Australia	Bangladesh	Bhutan
Brunei Darussalam	Cambodia	Cook Islands	Timor-Leste
Fiji	French Polynesia (France)	Hong Kong, China	India
Indonesia	Japan	Kiribati	Lao People's Democratic Republic
Macao, China	Malaysia	Maldives	Mongolia
Myanmar	Nepal	New Caledonia (France)	New Zealand
Democratic People's Republic of Korea	China	Pakistan	Papua New Guinea
Philippines	Samoa	Singapore	Solomon Islands
Republic of Korea	Sri Lanka	Taiwan Province of China	Thailand
Tonga	Vanuatu	Viet Nam	

Africa (54 countries and territories)

Algeria	Angola	Benin	Botswana
Burkina Faso	Burundi	Cameroon	Cabo Verde
Central African Republic	Chad	Comoros	Côte d'Ivoire
Congo	Djibouti	Egypt	Equatorial Guinea
Eritrea	Ethiopia	Gabon	Gambia
Ghana	Guinea	Guinea-Bissau	Kenya
Lesotho	Liberia	Libya	Madagascar
Malawi	Mali	Mauritania	Mauritius
Morocco	Mozambique	Namibia	Niger
Nigeria	Democratic Republic of the Congo	Rwanda	Sao Tome and Principe

Senegal	Seychelles	Sierra Leone	Somalia
South Africa	Sudan	Swaziland	United Republic of Tanzania
Togo	Tunisia	Uganda	Western Sahara
Zambia	Zimbabwe		

Russia & CIS (12 countries and territories)

Armenia	Azerbaijan	Belarus	Georgia
Kazakhstan	Kyrgyzstan	Republic of Moldova	Russian Federation
Tajikistan	Turkmenistan	Ukraine	Uzbekistan

Europe (46 countries and territories)

Albania	Andorra	Austria	Belgium
Bosnia and Herzegovina	Bulgaria	Finland	France
Germany	Gibraltar (United Kingdom)	Greece	Hungary
Lithuania	Luxembourg	Macedonia	Malta
Monaco	Montenegro	San Marino	Serbia
Slovakia	Slovenia	Spain	Sweden
Croatia	Cyprus	Czech Republic	Denmark
Estonia	Finland	Iceland	Ireland
Italy	Latvia	Liechtenstein	Lithuania
Netherlands	Norway	Poland	Portugal
Romania	San Marino	Switzerland	Turkey
United Kingdom	Vatican City State		

Latin America (27 countries and territories)

Argentina	Bahamas	Belize	Bolivia
Brazil	Chile	Colombia	Costa Rica
Cuba	Dominican Republic	Ecuador	El Salvador
French Guiana (France)	Guatemala	Guyana	Haiti
Honduras	Jamaica	Lesser Antilles	Mexico
Nicaragua	Panama	Paraguay	Peru
Suriname	Uruguay	Venezuela	

North America (4 countries and territories)

United States of America	Puerto Rico (United States)	Canada	U.S. Virgin Islands

Middle East (13 countries and territories)

Bahrain	Iran (Islamic Republic of)	Iraq	Israel
Jordan	Kuwait	Lebanon	Oman
Qatar	Saudi Arabia	Syrian Arab Republic	United Arab Emirates
Yemen			

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