Thirteenth Meeting of the Focal Points of the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC)

REMPEC/WG.45/INF.9
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Agenda Item 11

TECHNICAL AND FEASIBILITY STUDY TO EXAMINE THE POSSIBILITY OF DESIGNATING THE MEDITERRANEAN SEA, OR PARTS THEREOF, AS SOX ECA(S) UNDER MARPOL ANNEX VI

Note by the Secretariat

SUMMARY

Executive Summary: This document presents the technical and feasibility study to examine the possibility of designating the Mediterranean Sea, or parts thereof, as SOx ECA(s) under MARPOL Annex VI, as prepared pursuant to Specific Objective 15 of the Regional Strategy (2016-2021).

Action to be taken: Paragraph 3

Related documents: UNEP(DEPI)/MED IG.22/28, REMPEC/WG.45/11

Background

1. As presented in document REMPEC/WG.45/11, the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) prepared the technical and feasibility study to examine the possibility of designating the Mediterranean Sea, or parts thereof, as sulphur oxides (SOx) emission control area(s) (ECA(s)) under Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL), hereinafter referred to as "the Technical and Feasibility Study", pursuant to Specific Objective 15 of the Regional Strategy for Prevention of and Response to Marine Pollution from Ships (2016-2021)[1], which was adopted by the Nineteenth Ordinary Meeting of the Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean ("the Barcelona Convention") and its Protocols (COP 19) (Athens, Greece, 9-12 February 2016).

2. The Technical and Feasibility Study is presented in the **Appendix** to the present document.

Action requested by the Meeting

3. **The Meeting is invited to take note** of the information provided in the present document.

[1] UNEP(DEPI)/MED IG.22/28, Decision IG.22/4.

APPENDIX

Technical and feasibility study to examine the possibility of designating the Mediterranean Sea, or parts thereof, as SOx ECA(s) under MARPOL Annex VI

Table of Contents

Table of Tables

Table of Figures

List of Acronyms and Abbreviations

CO_2	Carbon Dioxide
ECA	Emission Control Area
EERA	Energy and Environmental Research Associates, LLC
EGCS	Exhaust Gas Cleaning System (mainly termed in this study as “scrubber”)
FMI	Finnish Meteorological Institute
GHG3	Third IMO Greenhouse Gas Study 2014
GHO	Global Health Observatory
HFO	Heavy Fuel Oil (residual fuel by-product and or blends including IFO 380, IFO 180, etc.)
IER	Integrated Exposure Response
IHO	International Hydrographic Organization
IMO	International Maritime Organization
k	Thousands (as in Thousands of Dollars)
kW	Kilowatt
kWh	Kilowatt-hour
LNG	Liquefied Natural Gas
M	Millions (as in Millions of Dollars)
MARPOL	International Convention for the Prevention of Pollution from Ships
MARPOL VI	MARPOL Annex VI (global fuel-sulphur limit of 0.5% S)
MDO	Marine Distillate Oil (including blended or refined products meeting MARPOL VI 0.5% S)
Med ECA	Mediterranean Emission Control Area for Sulphur Oxides and Particulate Matter (regional fuel-sulphur limit of 0.1% S)
MGO	Marine Gas Oil (including refined products meeting SECA fuel limits of 0.1% S)
MMT	Million Metric Tonnes
MT	Metric Tonnes
NO_x	Nitrogen Oxides
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter 2.5µm or smaller
REMPEC	Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea
S	Sulphur
SECA	SO_x Emission Control Area
SO_x	Sulphur Oxides
STEAM	Ship Traffic Emissions Assessment Model
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
VSL	Value of a statistical life (or monetary value to reduce statistical risk of premature death)
WHO	World Health Organization

1 Executive Summary

This report presents the technical and feasibility study to examine the possibility of designating the Mediterranean Sea, or parts thereof, as sulphur oxides (SO_x) emission control area(s) (ECA(s)) under Annex VI to the International Convention for the Prevention of Pollution from Ships (MARPOL), hereinafter referred to as this study, conducted for the Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) by a collaborative team from Energy and Environmental Research Associates (EERA) and the Finnish Meteorological Institute (FMI). We find that compliance with 0.1% sulphur (S) fuel limits would produce additional reductions of emissions over a global 0.5% S fuel standard in 2020. We quantify these reductions and expected increased costs for fleet compliance through fuel switching or alternate compliance approaches including exhaust gas cleaning systems (scrubbers). We evaluate potential benefits of additional emissions reductions to Mediterranean coastal States in avoided human health and environmental impacts. Technical and economic feasibility results indicate positive net benefits with a Mediterranean Sea SOx ECA.

1.1 Overview of Project

REMPEC tasked EERA to examine the possibility of designating the Mediterranean Sea, or parts thereof, as SO_x ECA(s) under MARPOL Annex VI. EERA teamed with FMI to collaborate on activity-based modeling of ship fuel consumption, combustion emissions, and regional pollution fate and transport. FMI provided activity-based shipping emissions fuel consumption estimates and emissions estimates for a base year of 2016 and for future years 2020, 2030, 2040, and 2050. Vessel modeling was informed by 2016 direct vessel observations using Automated Identification System (AIS) data, used the state-of-art Ship Traffic Emissions Assessment Model (STEAM), which was the model chosen for the Third IMO Greenhouse Gas Study 2015 (GHG3) and updated for current research including a 2018 peer-reviewed journal publication evaluating potential impact of global implementation of MARPOL VI fuel-sulphur limits on health and environment. EERA used pollutant exposure and deposition data from the FMI fate and transport model to estimate changes in health outcomes, namely premature mortality and childhood asthma morbidity. EERA also evaluated the fuel and emissions summaries to consider technical and economic feasibility, to quantify compliance costs, and to describe the cost-effectiveness of a SO_x Emission Control Area. Work products are intended to provide decision-support information regarding whether and how to mitigate ship emissions in service of regional environmental and human health and maritime stewardship in the Mediterranean Sea.

1.1.1 Description of Mediterranean Sea Area Domain and Shipping Activity

The Mediterranean Sea area is an important region for international shipping and commercial navigation. The Mediterranean Sea represents approximately 0.7% of navigable seas and oceans, and Mediterranean ship traffic accounts for about 7% of global shipping activity, energy use, and emissions. Based on AIS observations, more than 30,000 vessels are observed to operate annually in the Mediterranean Sea area. Based on this work, shipping CO_2 emissions represent about 10% of Mediterranean coastal States' CO_2 inventories, as reported to the United Nations Framework Convention on Climate Change (UNFCCC).

The proposed area of application for the designation of the Mediterranean Sea area, as an ECA for SO_x and Particulate Matter (PM), hereinafter referred to as the proposed Med ECA, as modeled in this study, is illustrated in Figure 1. The proposed area of application follows the International Hydrographic Organization (IHO) definition of the Mediterranean Sea[1] as being bounded on the southeast by the entrance to the Suez Canal, on the northeast by the entrance to the Dardanelles, delineated as a line joining Mehmetcik and Kumkale lighthouses, and to the west by the meridian passing through Cap Spartel lighthouse, also defining the western boundary of the Straits of Gibraltar. The waters of the proposed Med ECA involve the 22 Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (the Barcelona Convention), namely Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, France, Greece, Israel, Italy, Lebanon, Libya, Malta, Monaco, Montenegro, Morocco, Slovenia, Spain, Syrian Arab Republic, Tunisia, Turkey and the European Union.

[1] https://www.iho.int/iho_pubs/standard/S-23/S-23_Ed3_1953_EN.pdf.

Figure 1. Contracting Parties to the Barcelona Convention and proposed Med ECA

1.1.2 Background and Overview of Regulatory Compliance Prospects

International ship power systems currently consume mainly petroleum-based fuel products and by-products, with limited use of liquefied natural gas (LNG). Most of the fleet consumes residual fuel, also known as heavy fuel oil (HFO), which includes several grades of blended petroleum by-products of refining (*1*). Current regulations prescribed under MARPOL VI will require marine vessels to adopt fuels meeting a global limit of 0.5% S in 2020. This study models default compliance with MARPOL VI to result from a switch from non-compliant fuel (average 2.4% S) to MARPOL VI compliant (0.5% S) fuel. All future year scenarios consider technical and economic feasibility of the proposed Med ECA to be compared with conditions defined using MARPOL VI compliant fuel.

In considering the proposed Med ECA, compliance alternatives modeled in this study begin by assuming a switch from MARPOL VI compliant fuel to SECA compliant fuel. In other words, the proposed Med ECA would result in a shift from 0.5% S to 0.1% S marine fuel. Recognizing that SECA compliance can be achieved through alternative compliance mechanisms, this study considers these mainly as part of their economic feasibility; fleet operators would be expected to adopt compliance alternatives to fuel switching where the long-run costs of SECA compliance were reduced. Alternative approaches to SECA compliance consider adoption of exhaust abatement technology or advanced fuel alternatives. This study models onboard exhaust gas cleaning systems (EGCS), also termed sulphur scrubbers, as the primary exhaust abatement technology to meet lower-sulphur limits of the proposed Med ECA. This study models LNG as the advanced fuel alternative to meet lower-sulphur limits of the proposed Med ECA[2]. Acknowledging that other technologies and fuels may be specified, this study utilizes an analytical framework that can be applied to more specifically investigate other compliance strategies (e.g., various scrubber designs, biodiesel, bio-ethanol, methanol, hydrogen fuel cells, ammonia, or other marine fuel-power combinations).

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[2] EU Directive on the 'Deployment of an Alternative Fuel Infrastructure' (2014/94/EU) requires Member States to put in place the necessary infrastructure, like refueling stations, to ensure availability of LNG for road and maritime transport.

This study uses the STEAM model to estimate the activity-based fuel consumption and emissions of over 30,000 vessels operating annually in the Mediterranean Sea. Informed by Ship Automated Identification System (AIS) for the year 2016, the STEAM model integrates vessel activity, technology and design characteristics, and fuel type inputs to estimate vessel-specific energy requirements, fuel consumption, and emissions. These estimates are aggregated by vessel type and within the Mediterranean geographic domain to produce annual fuel and emissions estimates for a base year 2016. STEAM also produces a set of future-year estimates for 2020, 2030, 2040, and 2050, employing assumptions about future fleet demand, vessel economies of scale, improvements in fuel economy, and fleet replacement rates.

1.1.3 Study Organization

This study is organized in the following sections. Section 1 provides an executive summary. Section 2 presents an overview of the project. Section 3 presents fuel and emissions modeling results. Section 4 presents an assessment of health and environmental benefits. Section 5 presents the economic and technical feasibility assessment. Section 6 performs a cost-effectiveness comparison of prior studies proposing SECA regions with combined actions (MARPOL VI + SECA compliance) in the Mediterranean Sea area. Section 7 presents detailed methodologies and data supporting the analysis. Section 8 presents references.

1.2 Primary Findings and Results

This study evaluates the case for the proposed Med ECA, as defined by the International Hydrographic Organization (*2*). Vessels operating in this region use 19 million metric tons (MMT) fuel annually at an estimated cost in 2016 of $9.9 Billion. Costs to adopt fuels meeting MARPOL VI Global standards in 2020 are estimated to amount to approximately $4 Billion more per year. Additional costs to adopt fuels meeting potential SECA standards in 2020 are estimated to be $1.8 Billion per year over compliance costs for the MARPOL VI global. When considering the economic adoption of exhaust gas cleaning systems (scrubbers), compliance costs with SECA standards may be lower, estimated to be $1.2 Billion more than MARPOL VI global compliance costs.

The associated benefits of implementing SECA standards include but may not be limited to reduced health impacts (mortality and morbidity), reduced deposition/discharge of acidifying combustion products, and improved visibility (less haze) in some locations. Geospatial distribution of impacts with no action and the benefits of the proposed Med ECA vary according to the distribution of shipping activity, fate and transport of pollution/discharges, and distribution of exposed populations or vulnerable ecosystems. Reduced health impacts evaluated here include 1,100 avoided premature deaths annually, 2,300 fewer children impacted by pollution-related asthma annually, reductions in acidifying deposition, and reductions in aerosol optical depth related to haze effects. Primary findings are reported briefly with tables and charts that follow in this section. A detailed presentation of results is found in the main report.

1.2.1 Meeting MARPOL VI global and SECA standards increases fuel/technology costs

Fuels compliant with SECA standards are expected to be more expensive than fuels compliant with the global MARPOL VI standards, and both fuels are more expensive than the current dominant residual fuels used by ships. Table 1 and Figure 2 summarize the estimated compliance costs related to adopting cleaner, compliant marine fuels. Also shown are compliance costs estimated to include investment and adoption of scrubber technologies where abating emissions while using higher-sulphur residual oil can offer cost savings over adopting fuels compliant with 0.1% S limits.

Table 1. Estimated fuel-related costs in 2020 under different Mediterranean regulatory and compliance scenarios for ships

$ Billion/y / Policy Scenario	Total Cost	Compliance Cost
No Action (base fuel cost)	$9.884	N/A
MARPOL VI (0.5% S)	$13.849	$3.965
Proposed Med ECA (0.1% S)	$15.614	$1.766
Proposed Med ECA (with scrubbers)	$15.005	$1.157

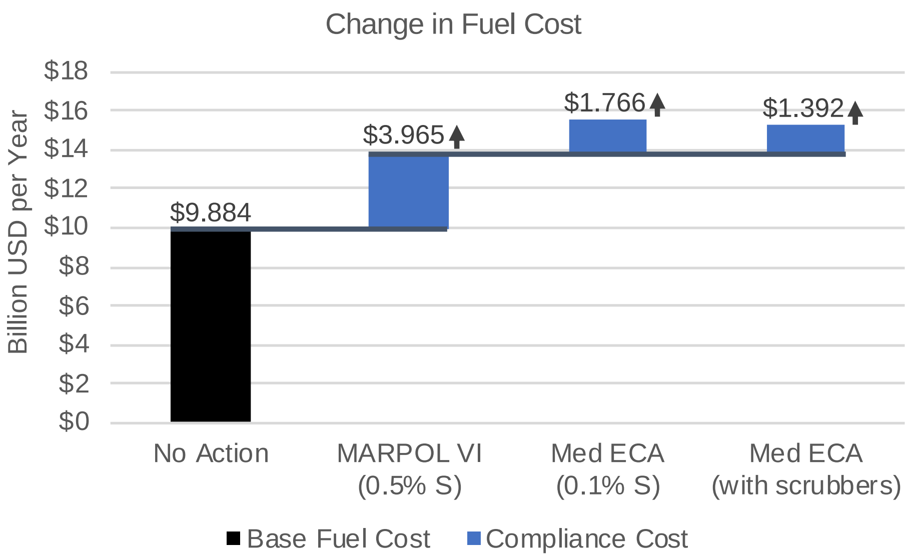


Figure 2. Fuel-related costs in 2020 under different Mediterranean regulatory compliance scenarios

1.2.2 The proposed Med ECA Provides Reductions in SO_x and $PM_{2.5}$ Emissions

Lower-sulphur fuels that would be required under the proposed Med ECA will result in lower emissions than current practices, and lower emissions compared with global MARPOL VI 2020 limits. SO_x reductions are directly proportion to the shift from 0.5% to 0.1% fuel. PM reductions depend primarily on the fraction of ship-emitted PM that results from fuel-sulphur content.

MARPOL VI standards will reduce SO_x emissions by approximately 75% from typical operations using residual fuels. Implementing SECA standards will achieve about a 95% reduction in SO_x emissions from ships compared with current operations. PM reductions of about 51% are associated with MARPOL VI, and SECA standards would increase that to about 62% reduction in emissions. These results are shown in Table 2 and Figure 3.

Table 2. Estimated SO_x and $PM_{2.5}$ emissions under different Mediterranean regulatory and compliance scenarios

MT per year / Policy Scenario	SO_x		$PM_{2.5}$	
	Emissions	**Reduction**	**Emissions**	**Reduction**
No Action	681,000	N/A	97,500	N/A
MARPOL VI (0.5% S)	168,000	513,000	48,100	49,400
Proposed Med ECA (0.1% S)	35,800	132,200	36,700	11,400
Proposed Med ECA (with scrubbers)	35,800	132,200	36,700	11,400

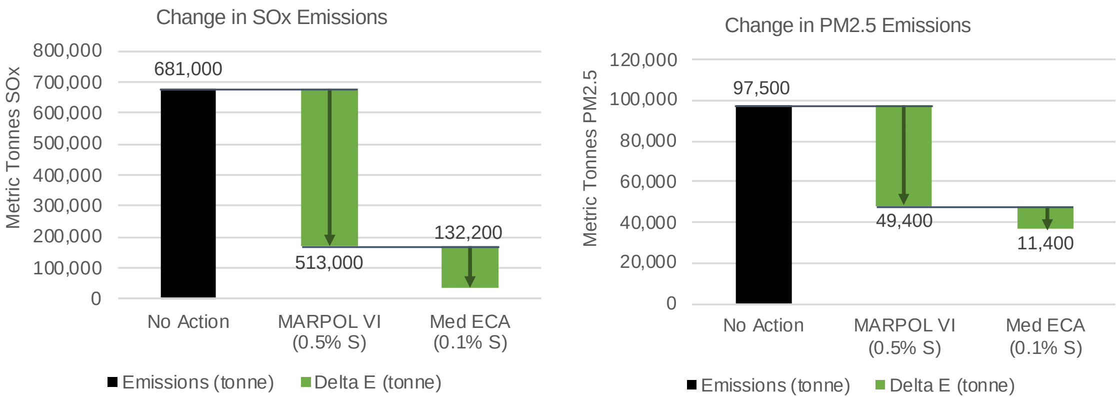


Figure 3. Change in SO_x and $PM_{2.5}$ emissions under different Mediterranean regulatory scenarios

1.2.3 The proposed Med ECA Provides Additional Health Benefits Beyond MARPOL VI Global

Emissions reductions by ships operating in the Mediterranean Sea area will reduce concentrations of ambient air pollution and reduce exposure of $PM_{2.5}$ for communities of people living in Mediterranean coastal States. These improved exposure conditions are associated with additional health benefits, namely reduced risk of premature cardiovascular and lung cancer mortality and reduced risk of childhood asthma. Health benefits from SECA implementation are smaller than the avoided mortality and morbidity from adopting global MARPOL VI standards; this is expected given the emissions reduction from 0.5% S to 0.1% S is smaller than the first step to SECA conditions. This is a condition that will be likely for all SECA proposals considered after 2020 implementation of MARPOL VI.

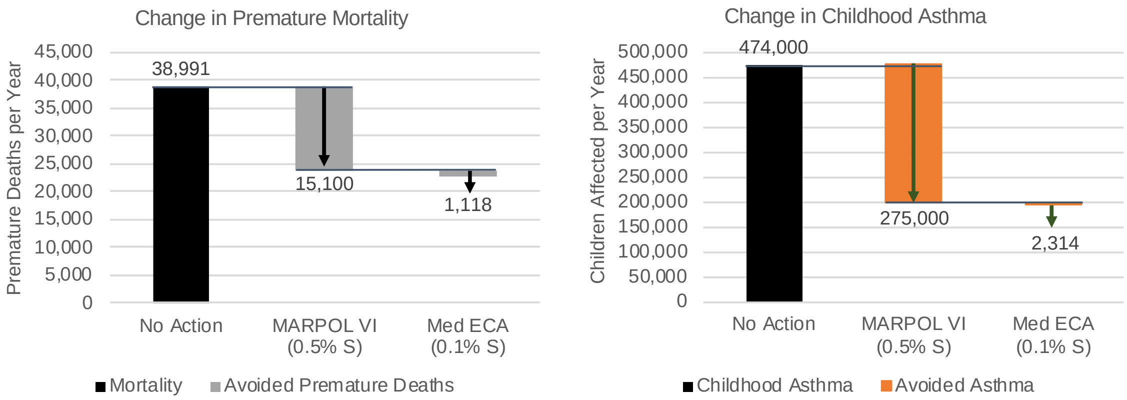


Figure 4. Change in lung cancer and cardiovascular mortality, and childhood asthma morbidity

1.2.4 Med ECA Cost-effectiveness for Ships Is Reported by Control Target and Health Outcome

Estimated compliance costs and abated emissions provide the necessary data to calculate the cost-effectiveness of emissions control through MARPOL VI global standards and SECA limits (assuming fuel switch and including feasible scrubber adoption). These are presented in Table 3 and Figure 5. Estimated health benefits results can also be presented in terms of cost-effectiveness. These are presented in Table 3 and Figure 6.

Table 3. Cost-effectiveness of quantified benefits

Benefit Type	MARPOL VI	Proposed Med ECA	Proposed Med ECA with Scrubbers
Control Target			
Abated SO_x emissions	\$7,730 /MT SO_x	\$13,400 /MT SO_x	\$8,750 /MT SO_x
Abated $PM_{2.5}$ emissions	\$80,300 /MT $PM_{2.5}$	\$155,000 /MT $PM_{2.5}$	\$101,000 /MT $PM_{2.5}$
Health Outcome			
Avoided mortality	\$0.263 M/Δ Mortality	\$1.580 M/Δ Mortality	\$1.035 M/Δ Mortality
Avoided childhood asthma	\$14 k/Δ Morbidity	\$763 k /Δ Morbidity	\$500 k/Δ Morbidity

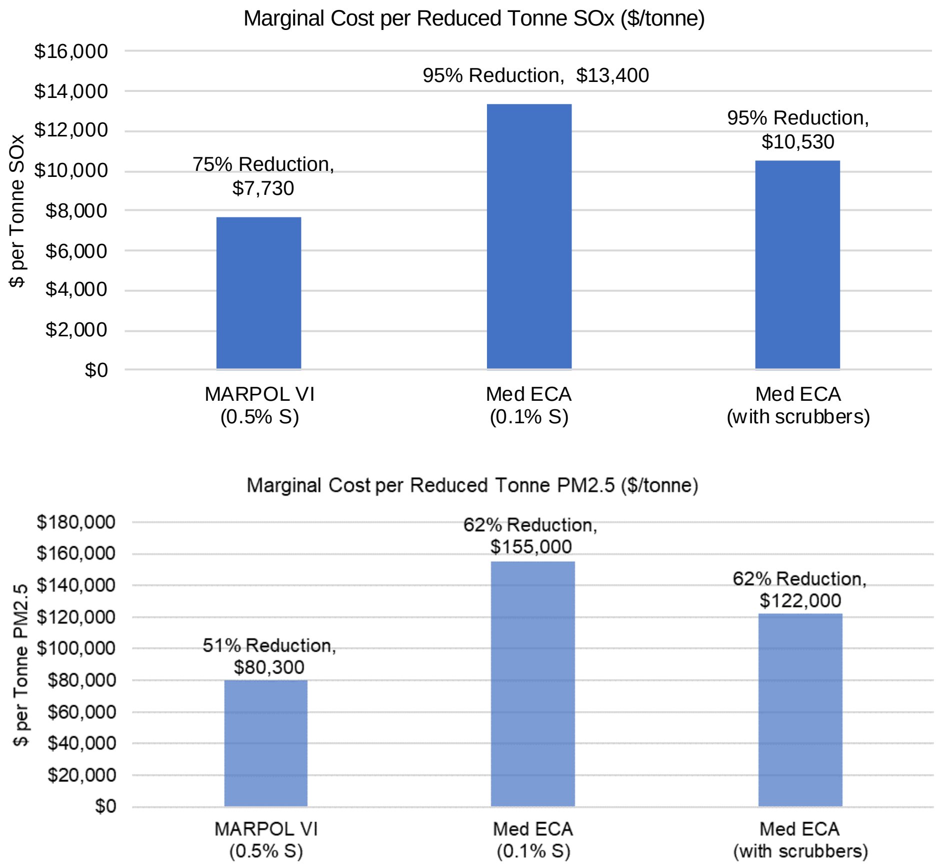


Figure 5. Control cost-effectiveness of SO_x and $PM_{2.5}$ reductions based on prices in this study

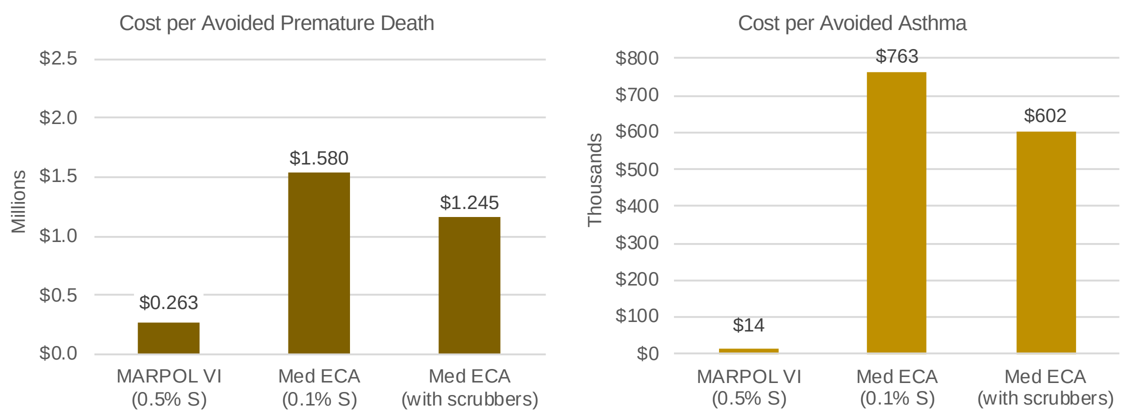


Figure 6. Cost-effectiveness of health outcomes in terms of avoided premature mortality and avoided childhood asthma

1.2.5 Combined MARPOL VI and Proposed Med ECA Cost-effectiveness Appears Similar to Prior SECAs

Costs to achieve SECA performance, considered by combining the MARPOL VI to the proposed Med ECA scenarios into one step, are very similar to the costs to achieve SECA performance in previously designated SECAs. Figure 7 illustrated this, as discussed in Section 0. This provides validating insight for this analysis. More generally, the agreement between prior SECA proposal cost-effectiveness and the cost-effectiveness of the combined MARPOL VI and SECA actions in the Mediterranean offer a decision support element regarding the potential designation of SECA regions after 2020.

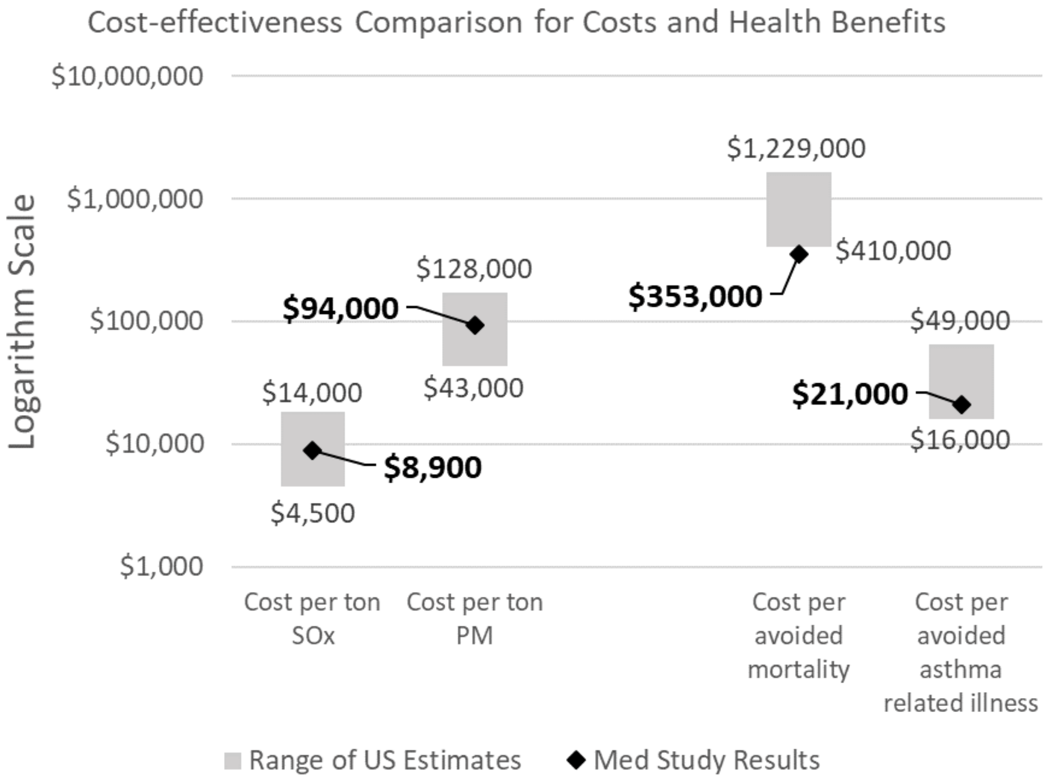


Figure 7. Summary comparison of cost-effectiveness metrics for this study (combining MARPOL VI and SECA measures) with U.S. SO_x and PM data from the Proposal to Designate an Emission Control Area for North America

2 Motivation and Project Summary

The Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea (REMPEC) tasked Energy and Environment Research Associates (EERA) to examine the possibility of designating the Mediterranean Sea, or parts thereof, as SO_x Emission Control Area(s) under Annex VI of the International Convention for the Prevention of Pollution from Ships. EERA has teamed with the Finnish Meteorological Institute (FMI) to collaborate on activity-based modeling of ship fuel consumption, combustion emissions, and regional pollution fate and transport. EERA evaluated the fuel and emissions summaries to consider technical and economic feasibility, to quantify compliance costs, and to describe benefits of a SO_x Emission Control Area. Work products are intended to provide decision-support information regarding whether and how to mitigate ship emissions in service of regional environmental and human health and maritime stewardship in the Mediterranean Sea.

2.1 Study Area

The proposed area of application follows the International Hydrographic Organization (IHO) definition of the Mediterranean Sea[3] as being bounded on the southeast by the entrance to the Suez Canal, on the northeast by the entrance to the Dardanelles, delineated as a line joining Mehmetcik and Kumkale lighthouses, and to the west by the meridian passing through Cap Spartel lighthouse, also defining the western boundary of the Straits of Gibraltar. The proposed area of application for the designation of the proposed Med ECA, and subsequently modeled in this study, is illustrated in Figure 8[4].

The waters of the proposed Med ECA involve the 22 Contracting Parties to the Barcelona Convention, namely Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, France, Greece, Israel, Italy, Lebanon, Libya, Malta, Monaco, Montenegro, Morocco, Slovenia, Spain, Syrian Arab Republic, Tunisia, Turkey and the European Union.

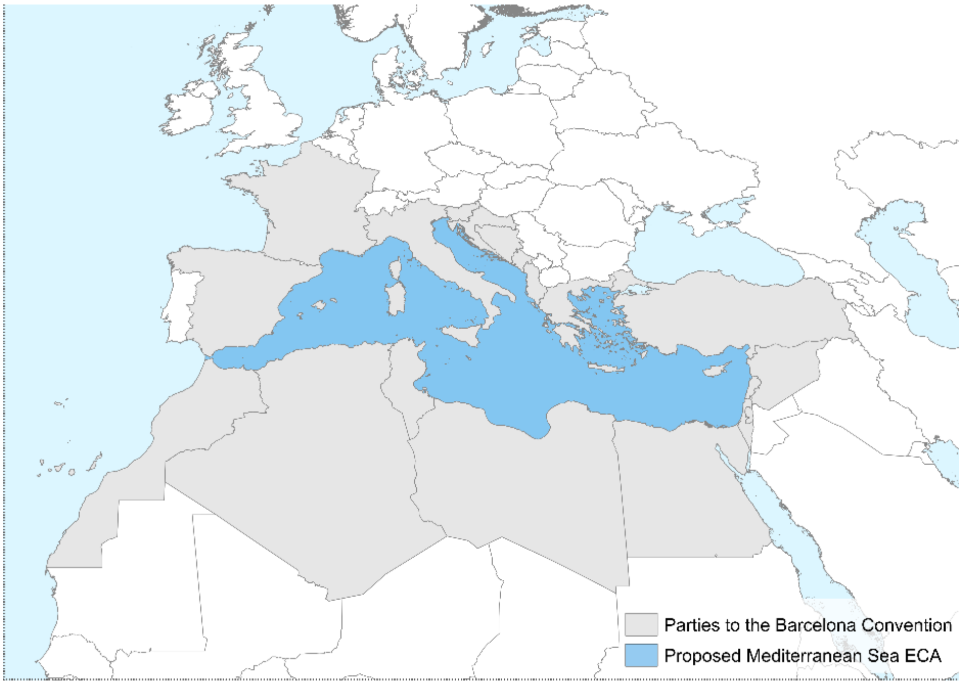


Figure 8. Contracting Parties to the Barcelona Convention and proposed Med ECA

[3] https://www.iho.int/iho_pubs/standard/S-23/S-23_Ed3_1953_EN.pdf.
[4] The proposed Med ECA emissions modeling domain is identical to the geographic area described in Article 1.1 of the Barcelona Convention. See section 7.2 for additional discussion on the air quality modeling domain.

2.2 Background and Overview of Regulatory Compliance Prospects

International ship power systems currently consume mainly petroleum-based fuel products and by-products, with limited use of liquefied natural gas. Most of the fleet consumes residual fuel, also known as heavy fuel oil (HFO), which includes several grades of blended petroleum by-products of refining (*1*) with a permissible sulphur limit of 3.5%. Current limits prescribed under MARPOL VI will require marine vessels to adopt fuels meeting a global limit of 0.5% Sulphur (0.5% S) in 2020. This study models default compliance with MARPOL VI to result from a switch from non-compliant fuel (average 2.4% S) to MARPOL VI compliant (0.5% S) fuel. All future year scenarios consider technical and economic feasibility of the proposed Med ECA to be compared with conditions defined using MARPOL VI compliant fuel.

In considering the proposed Med ECA, compliance alternatives modeled in this study begin by assuming a switch from MARPOL VI compliant fuel to SECA compliant fuel. In other words, the proposed Med ECA would result in a shift from 0.5% S to 0.1% S marine fuel. Recognizing that SECA compliance can be achieved through alternative compliance mechanisms, this study considers these mainly as part of the economic feasibility; fleet operators would be expected to adopt compliance alternatives to fuel switching where the long-run costs of SECA compliance were reduced. Alternative approaches to SECA compliance consider adoption of exhaust abatement technology or advanced fuel alternatives. This study models onboard exhaust gas cleaning systems (EGCS), also termed sulphur scrubbers, as the primary exhaust abatement technology to meet lower-sulphur limits of the proposed Med ECA. This study models liquefied natural gas (LNG) as the advance fuel alternative to meet lower-sulphur limits of the proposed Med ECA. Acknowledging that other technologies and fuels may be specified, this study utilizes an analytical framework that can be applied to more specifically investigate other compliance strategies (e.g., various scrubber designs, methanol, hydrogen or other marine fuel-power combinations).

This study uses the Ship Traffic Emission Assessment Model (STEAM) to model the activity-based fuel consumption and emissions of over 30,000 vessels operating annually in the Mediterranean Sea. Informed by Ship Automated Identification System (AIS) for the year 2016, the STEAM model integrates vessel activity, technology and design characteristics, and fuel type inputs to estimate vessel-specific energy requirements, fuel consumption, and emissions. These estimates are aggregated by vessel type and within the Mediterranean geographic domain to produce annual fuel and emissions estimates for a base year 2016. The STEAM Model also produces a set of future-year estimates for 2020, 2030, 2040, and 2050, employing assumptions about future fleet demand, vessel economies of scale, improvements in fuel economy, and fleet replacement rates.

3 Fuel and Emissions Modeling and Fate and Transport Analysis

3.1 Fuel Use in the Mediterranean Sea (2016 and 2020)

Baseline (2016) fuel use inventories show total fuel use of 19.16 million tonnes in the Mediterranean Sea area (Table 4). STEAM modeling outputs indicate that improvements in power system fuel economy and vessel economies of scale result in 10.8% overall fuel consumption decreases in 2020 from 2016, accompanied by fuel switching.

The dominant fuel used in 2016 was HFO (78.8%). MDO was the next most commonly used fuel (17.2%), and MGO and LNG comprised a small fraction of overall fuel usage (2.8% and 1.3%, respectively). The STEAM model predicts that under MARPOL VI the Mediterranean Sea area overall fuel mix will switch to 95.5% MDO and 3.1% MGO, and 0.8% LNG. HFO fuel use falls to 0.6% under MARPOL VI conditions, and continues to be used by a small number of vessels currently equipped with exhaust gas cleaning systems (scrubbers).

Under the proposed Med ECA scenario, the STEAM model estimates total fuel use equivalent to the MARPOL VI scenario, but changes to 97.7% MGO and 1% MDO fuel mix. HFO and LNG fuel usage is unchanged in the proposed Med ECA scenarios compared to the MARPOL VI fuel consumption.

Table 4. Baseline year (2016) fuel usage and projected 2020 fuel usage under MARPOL VI and the proposed Med ECA scenarios

MT	MED 2016 Baseline	MARPOL VI 2020	Proposed Med ECA 2020
Total Fuel	19,160,000	17,100,000	17,100,000
MGO	542,000	522,000	16,700,000
MDO	3,290,000	16,340,000	164,000
HFO	15,090,000	99,900	94,700
LNG	243,000	141,000	138,000

Table 5. Fuel mix percentages for the Mediterranean Sea area in 2016 and under MARPOL VI and the proposed Med ECA scenarios

Fuel Allocation	Pre-MARPOL VI Baseline Fuel Mix	MARPOL VI Fuel Mix	Proposed Med ECA Fuel Mix
MGO	2.8%	3.1%	97.7%
MDO	17.2%	95.5%	1.0%
HFO	78.8%	0.6%	0.6%
LNG	1.3%	0.8%	0.8%

Geographically, fuel consumption is driven by regional shipping patterns. The highest fuel consumption is observed at the western end of the Mediterranean Sea at the entrance to the Straits of Gibraltar, in the central Mediterranean Sea off of the north coast of Tunisia, and at the eastern end of the Mediterranean Sea at the entrance to the Suez Canal. Relative fuel consumption patterns are unchanged in the various scenario years.

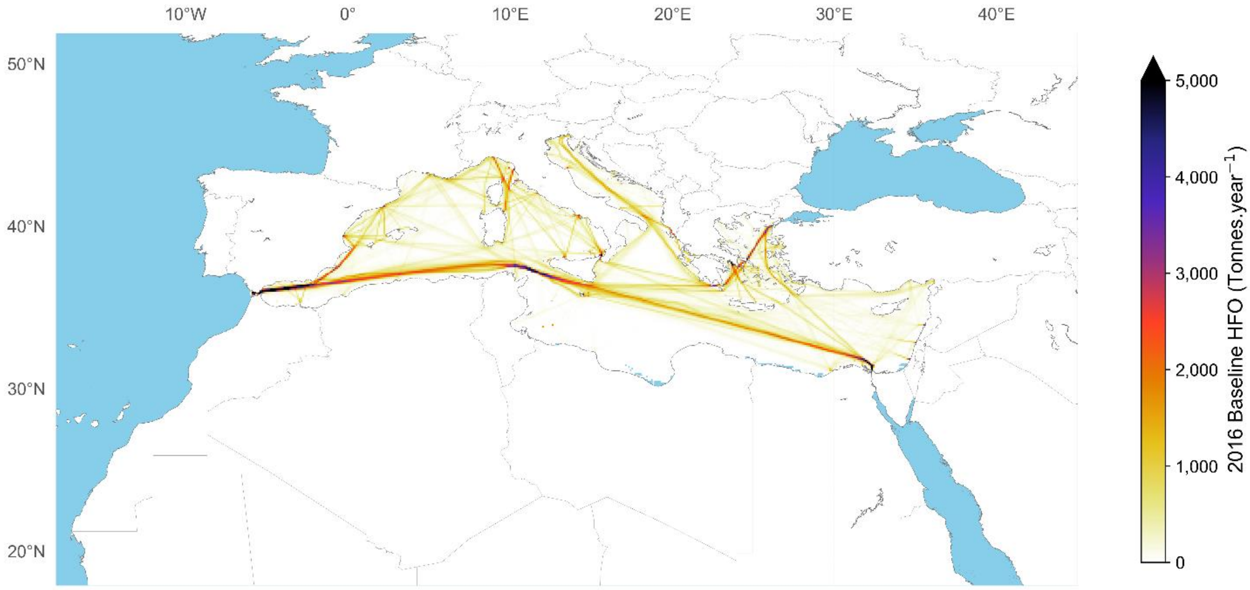


Figure 9. Baseline 2016 HFO fuel use

3.2 Criteria and CO_2 Pollution Emissions in the Mediterranean Sea (2016 and 2020)

Baseline SO_x and $PM_{2.5}$ emissions are estimated to be 681,000 and 97,500 MT in 2016. Under the MARPOL VI scenario emissions of these species fall by 75.3% and 50.7% respectively. Emission inventory results under the proposed Med ECA 2020 scenario for SO_x and $PM_{2.5}$ species are reduced by a further 78.7% and 23.7% compared to MARPOL VI 2020 (Table 6).

Table 6. Baseline and 2020 scenario criteria and GHG pollution emissions

MT	MED 2016 Baseline	MARPOL VI 2020	Proposed Med ECA 2020
Total SO_x	681,000	168,000	35,800
Total $PM_{2.5}$	97,500	48,100	36,700
Total NO_x	1,330,000	1,160,000	1,170,000
Total CO_2	58,070,000	51,700,000	51,880,000

3.2.1 Geographic Distribution of Shipping Emissions in the Mediterranean Sea Area

The geographic distribution of shipping emissions for a 2016 non-MARPOL VI baseline case, the MARPOL VI 2020 case, and the proposed Med ECA 2020 case is shown in Figure 10. Figure 11 shows the avoided PM emissions (in kg) in the region under the proposed Med ECA 2020 case (0.1% S), compared to the MARPOL VI 2020 base case (0.5% S). Lastly, Figure 12 and Table 7 show the impacts of the proposed Med ECA on emissions and fuel consumption numerically.

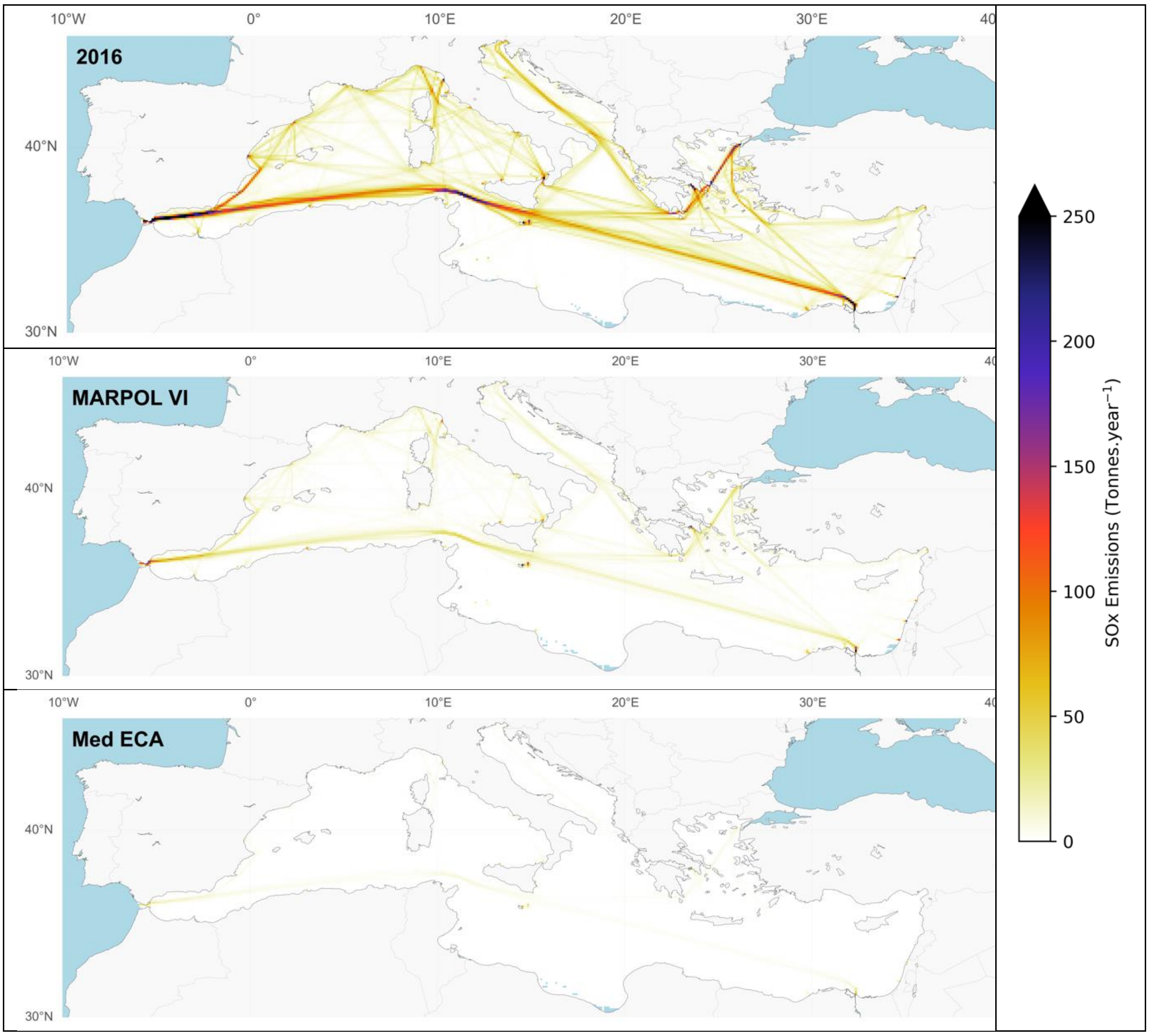


Figure 10. SO_x emissions under 2016 baseline, 2020 MARPOL VI, and the 2020 proposed Med ECA scenarios

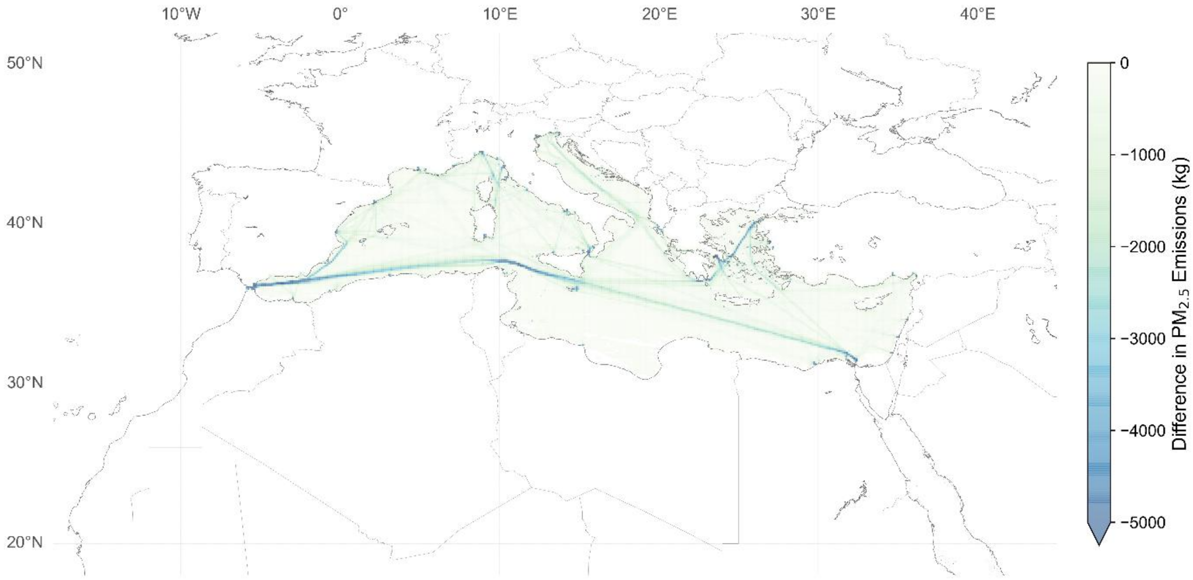


Figure 11. Geographic distribution of reduction in $PM_{2.5}$ emissions (in kg) between MARPOL VI 2020 fuels (0.5% S) and proposed Med ECA 2020 fuels (0.1% S)

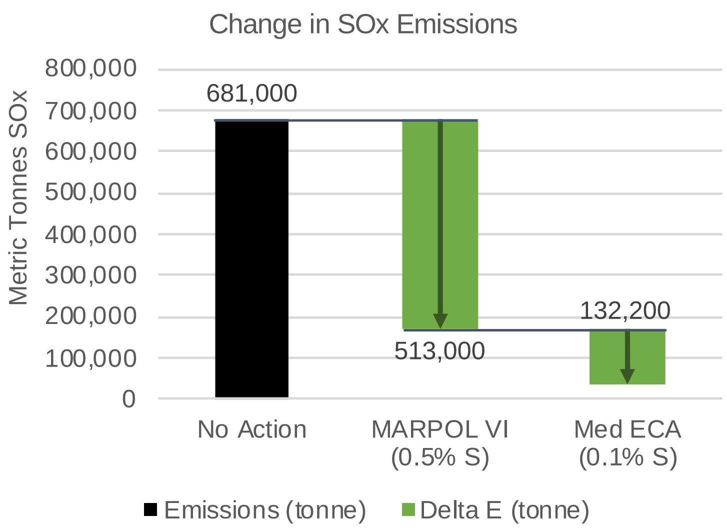


Figure 12. STEAM modeled reduction in total SO_x emissions in the Mediterranean Sea from 2016 baseline, to MARPOL VI (0.5% S) and the proposed Med ECA (0.1% S) scenarios

Table 7. Summary of total fuel usage and criteria and GHG emissions for the 2016 baseline, MARPOL VI, and the proposed Med ECA scenarios

	Current Inventory		
	2016	**2020 Marpol VI**	**2020 ECA**
Fuel Usage	19,160	17,100	17,100
SOx	681	168	36
PM	98	48	37
NOx	1,330	1,160	1,170
CO_2	58,070	51,700	51,880

3.2.2 National Allocation of Emissions in the Mediterranean Sea Area

National allocation of emissions is performed using gridded emissions results and land+water area designations determined by the Flanders Marine Institute (http://www.marineregions.org/eez.php) based on international treaties and geospatial attribution of water areas to the nearest country. It is important to note that many Mediterranean coastal States have not formally defined exclusive economic zones, and that the areas to which emissions are attributed here do not necessarily reflect any official territorial claims. Table 8 through Table 11 present ship emissions allocated to country by water area in the Mediterranean Sea area.

Table 8. National allocation by marine regions of shipping SO_x emissions in Mediterranean Sea area

Country	2016 Baseline SO_x 680,780 MT	Percent	2020 MARPOL VI SO_x 167,740 MT	Percent	2020 proposed Med ECA SO_x 35,830 MT	Percent
Albania	1,180	0.2%	400	0.2%	90	0.3%
Bosnia and Herzegovina*	0	0.0%	0	0.0%	0	0.0%
Cyprus	8,930	1.3%	2,420	1.4%	520	1.5%
Algeria	74,920	11.0%	15,690	9.4%	3,200	8.9%
Egypt	51,060	7.5%	11,710	7.0%	2,700	7.5%
Spain	113,080	16.6%	28,030	16.7%	5,980	16.7%
France	20,170	3.0%	6,450	3.8%	1,390	3.9%
Greece	155,110	22.8%	36,620	21.8%	7,670	21.4%
Croatia	11,720	1.7%	3,190	1.9%	670	1.9%
Israel	5,160	0.8%	1,820	1.1%	380	1.1%
Italy	159,440	23.4%	41,350	24.7%	8,820	24.6%
Lebanon	1,650	0.2%	570	0.3%	120	0.3%
Libya	13,240	1.9%	3,360	2.0%	770	2.1%
Morocco	2,130	0.3%	820	0.5%	180	0.5%
Monaco*	0	0.0%	0	0.0%	0	0.0%
Malta	10,990	1.6%	3,230	1.9%	750	2.1%
Montenegro	470	0.1%	200	0.1%	40	0.1%
Slovenia	70	0.0%	30	0.0%	10	0.0%
Syrian Arab Republic	530	0.1%	170	0.1%	40	0.1%
Tunisia	34,960	5.1%	7,230	4.3%	1,490	4.2%
Turkey	15,970	2.3%	4,450	2.7%	1,010	2.8%

* Bosnia and Herzegovina as well as Monaco do not show any counts of emissions in their EEZs because of an artifact of the resolution used to model emissions

Table 9. National allocation by marine regions of shipping $PM_{2.5}$ emissions in Mediterranean Sea area

Country	2016 Baseline $PM_{2.5}$ 97,490 MT	Percent	2020 MARPOL VI $PM_{2.5}$ 48,110 MT	Percent	2020 proposed Med ECA $PM_{2.5}$ 36,740 MT	Percent
Albania	180	0.2%	110	0.2%	90	0.2%
Bosnia and Herzegovina*	0	0.0%	0	0.0%	0	0.0%
Cyprus	1,290	1.3%	690	1.4%	530	1.4%
Algeria	10,310	10.6%	4,480	9.3%	3,380	9.2%
Egypt	7,240	7.4%	3,380	7.0%	2,600	7.1%
Spain	16,360	16.8%	8,100	16.8%	6,200	16.9%
France	3,120	3.2%	1,850	3.8%	1,410	3.8%
Greece	21,820	22.4%	10,440	21.7%	7,960	21.7%
Croatia	1,690	1.7%	900	1.9%	690	1.9%
Israel	820	0.8%	510	1.1%	390	1.1%
Italy	23,140	23.7%	11,910	24.8%	9,100	24.8%
Lebanon	260	0.3%	160	0.3%	120	0.3%
Libya	1,850	1.9%	960	2.0%	740	2.0%
Morocco	340	0.3%	230	0.5%	170	0.5%
Monaco*	0	0.0%	0	0.0%	0	0.0%
Malta	1,770	1.8%	970	2.0%	760	2.1%
Montenegro	80	0.1%	60	0.1%	40	0.1%
Slovenia	10	0.0%	10	0.0%	10	0.0%
Syrian Arab Republic	80	0.1%	50	0.1%	40	0.1%
Tunisia	4,800	4.9%	2,060	4.3%	1,560	4.2%
Turkey	2,330	2.4%	1,240	2.6%	950	2.6%

* Bosnia and Herzegovina as well as Monaco do not show any counts of emissions in their EEZ's because of an artifact of the resolution used to model emissions

Table 10. National allocation by marine regions of shipping NO_x emissions in Mediterranean Sea area

	2016 Baseline NO_x		2020 MARPOL VI NO_x		2020 proposed Med ECA NO_x	
Country	**1,332,800 MT**	**Percent**	**1,161,780 MT**	**Percent**	**1,165,900 MT**	**Percent**
Albania	3,050	0.2%	2,890	0.2%	2,870	0.2%
Bosnia and Herzegovina*	0	0.0%	0	0.0%	0	0.0%
Cyprus	18,420	1.4%	16,680	1.4%	16,850	1.4%
Algeria	133,750	10.0%	112,420	9.7%	112,680	9.7%
Egypt	92,300	6.9%	79,420	6.8%	79,840	6.8%
Spain	223,870	16.8%	192,840	16.6%	193,580	16.6%
France	46,650	3.5%	42,410	3.7%	42,360	3.6%
Greece	298,410	22.4%	259,900	22.4%	261,450	22.4%
Croatia	24,020	1.8%	21,680	1.9%	21,710	1.9%
Israel	11,800	0.9%	10,630	0.9%	10,780	0.9%
Italy	323,430	24.3%	286,630	24.7%	287,040	24.6%
Lebanon	3,780	0.3%	3,410	0.3%	3,440	0.3%
Libya	24,790	1.9%	23,610	2.0%	23,810	2.0%
Morocco	4,760	0.4%	4,530	0.4%	4,580	0.4%
Monaco*	0	0.0%	0	0.0%	0	0.0%
Malta	25,590	1.9%	21,050	1.8%	21,020	1.8%
Montenegro	1,360	0.1%	1,320	0.1%	1,300	0.1%
Slovenia	230	0.0%	200	0.0%	210	0.0%
Syrian Arab Republic	1,200	0.1%	1,120	0.1%	1,110	0.1%
Tunisia	62,250	4.7%	51,700	4.5%	51,800	4.4%
Turkey	33,140	2.5%	29,340	2.5%	29,470	2.5%

* Bosnia and Herzegovina as well as Monaco do not show any counts of emissions in their EEZ's because of an artifact of the resolution used to model emissions

Table 11. National allocation by marine regions of shipping CO_2 emissions in Mediterranean Sea area

	2016 Baseline CO_2		2020 MARPOL VI CO_2		2020 proposed Med ECA CO_2	
Country	**58,074,560 MT**	**Percent**	**51,889,720 MT**	**Percent**	**51,879,130 MT**	**Percent**
Albania	136,030	0.2%	128,700	0.2%	127,630	0.2%
Bosnia and Herzegovina*	0	0.0%	0	0.0%	10	0.0%
Cyprus	802,110	1.4%	748,390	1.4%	753,230	1.5%
Algeria	5,563,940	9.6%	4,742,040	9.1%	4,733,790	9.1%
Egypt	4,063,640	7.0%	3,553,590	6.8%	3,558,600	6.9%
Spain	9,864,660	17.0%	8,731,260	16.8%	8,733,440	16.8%
France	2,193,300	3.8%	2,047,780	3.9%	2,037,780	3.9%
Greece	12,643,060	21.8%	11,255,350	21.7%	11,279,680	21.7%
Croatia	1,077,100	1.9%	1,002,830	1.9%	1,000,830	1.9%
Israel	579,260	1.0%	543,760	1.0%	549,310	1.1%
Italy	14,257,030	24.5%	12,985,330	25.0%	12,957,330	25.0%
Lebanon	181,710	0.3%	170,220	0.3%	170,830	0.3%
Libya	1,032,640	1.8%	1,013,680	2.0%	1,018,060	2.0%
Morocco	249,630	0.4%	244,930	0.5%	246,980	0.5%
Monaco*	0	0.0%	0	0.0%	0	0.0%
Malta	1,258,570	2.2%	1,084,220	2.1%	1,079,080	2.1%
Montenegro	67,000	0.1%	66,080	0.1%	65,080	0.1%
Slovenia	12,680	0.0%	11,800	0.0%	12,060	0.0%
Syrian Arab Republic	54,200	0.1%	51,810	0.1%	51,560	0.1%
Tunisia	2,593,310	4.5%	2,181,020	4.2%	2,176,600	4.2%
Turkey	1,444,690	2.5%	1,326,930	2.6%	1,327,250	2.6%

* Bosnia and Herzegovina as well as Monaco do not show any counts of emissions in their EEZ's because of an artifact of the resolution used to model emissions.

3.3 Comparison with Previous Emission Inventories

As part of our validation process, EERA compared our results with previous emissions estimates for the region. That comparison is shown in Table 12, which shows consistency of this work with previous studies (*3*).

Table 12. Comparison of current inventory with IMO GHG3 and previous inventories

	Current Inventory			IMO	"Cleaner fuels for ships" article (*3*)	
	2016	2020			2020	
		MARPOL VI	Proposed Med ECA	GHG3	no IMO	MARPOL VI
Fuel Use	19,160	17,100	17,100	20,100	18,559	18,400
SO_x	681	168	36	680	737	170
PM	98	48	37	90	101	50
NO_x	1,330	1,160	1,170	1,270	1,427	1,430
CO_2	58,070	51,700	51,880	62,846	57,620	58,290

3.4 Multi-Year Scenarios Fuel Use and Emissions (2020, 2030, 2040, 2050)

3.4.1 Total Fuel Consumption

A key part of our work was to project expected fuel consumption and emissions impacts for the future years 2020, 2030, 2040, and 2050. Table 13, Table 14, and Figure 13 through Figure 15 provide these projections. We estimate fuel consumption to decrease over time due to efficiency (BTU/ton-mile) improvements in the vessel fleet. Along with this fuel reduction will come a concomitant reduction in GHGs and criteria pollutants (Table 14). These shifts will occur under both a MARPOL VI policy regime and the proposed Med ECA policy regime, with the proposed Med ECA also demonstrating significant reductions in SO_x and PM compared to MARPOL VI.

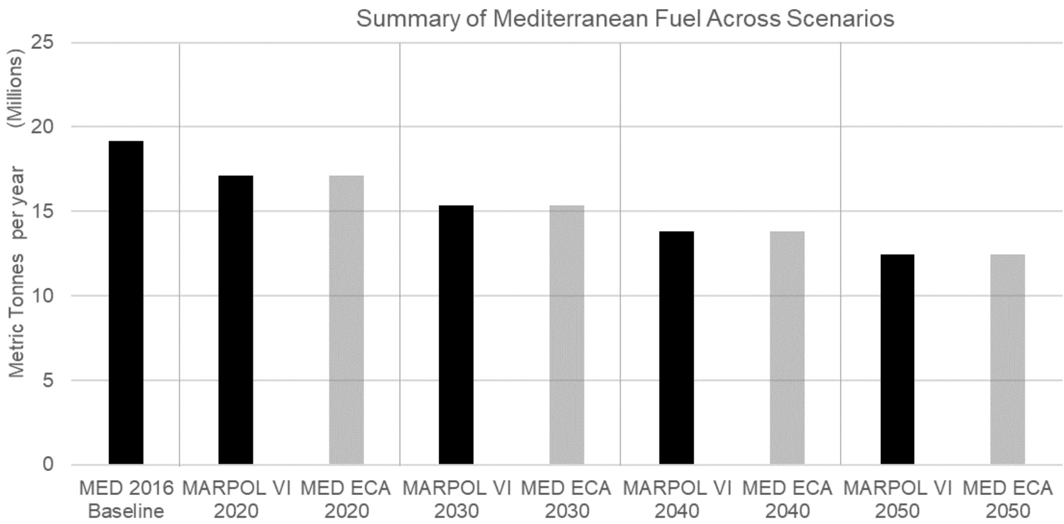


Figure 13. Multi-year estimates of annual fuel consumption in the Mediterranean Sea area

Table 13. Summary of future year estimated fuel consumption in the Mediterranean Sea area, by scenario and fuel type

MT	2030		2040		2050	
	MARPOL VI	Proposed Med ECA	MARPOL VI	Proposed Med ECA	MARPOL VI	Proposed Med ECA
Total Fuel	15,350,000	15,350,000	13,810,000	13,810,000	12,450,000	12,450,000
MGO	480,000	15,000,000	436,000	13,490,000	400,000	12,160,000
MDO	14,680,000	148,000	13,200,000	133,000	11,910,000	120,000
HFO	86,300	85,000	67,900	76,500	63,200	68,900
LNG	107,000	124,000	103,000	112,000	72,500	101,000

3.4.2 Criteria and GHG Pollution Emissions

Table 14. Summary of future year estimated fuel use and pollutant emissions in the Mediterranean Sea area, by scenario

MT	2030		2040		2050	
	MARPOL VI	Proposed Med ECA	MARPOL VI	Proposed Med ECA	MARPOL VI	Proposed Med ECA
Total Fuel	15,350,000	15,350,000	13,810,000	13,810,000	12,450,000	12,450,000
Total SO_x	151,000	33,600	136,000	30,100	122,000	25,900
Total $PM_{2.5}$	43,400	34,500	39,100	30,900	35,200	26,800
Total NO_x	986,000	1,030,000	875,000	908,000	785,000	785,000
Total CO_2	46,600,000	48,520,000	41,910,000	43,530,000	37,790,000	37,650,000

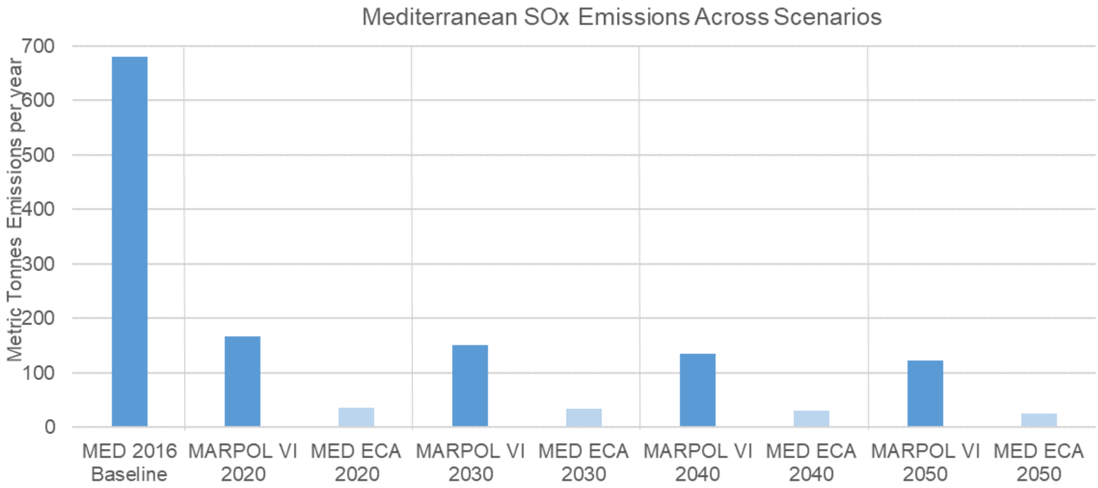


Figure 14. Multi-year estimates of SO_x emissions under future compliance scenarios for the Mediterranean Sea area

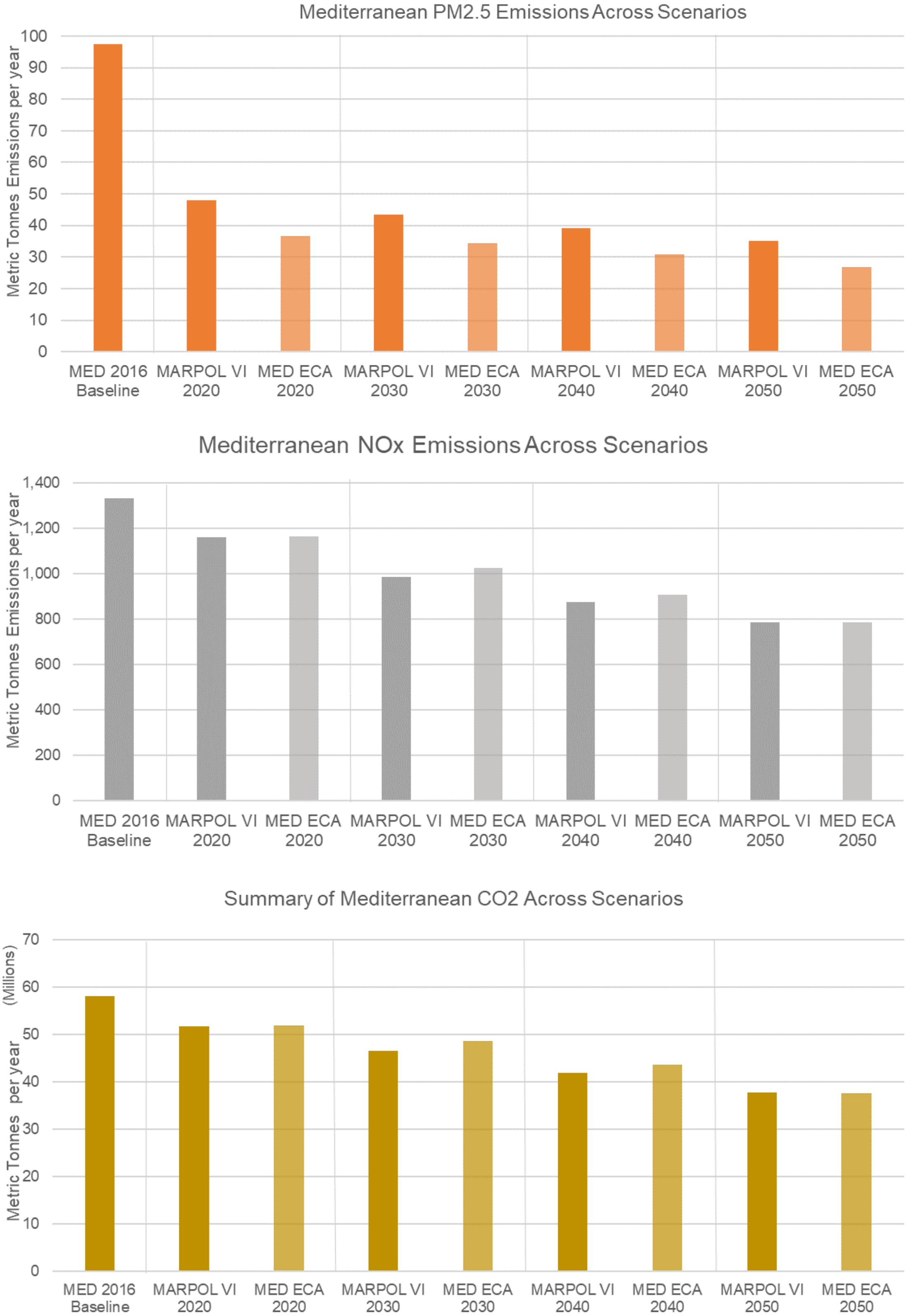


Figure 15. Multi-year estimates for $PM_{2.5}$, NO_x, and CO_2 from shipping in Mediterranean Sea area

3.5 Fate and Transport for 2020 Regulatory Scenarios

3.5.1 Change in Particulate Matter ($PM_{2.5}$) Concentration

Figure 16 shows the geospatially-modeled annual average difference in $PM_{2.5}$ concentration due to implementation of the proposed Med ECA compared to the MARPOL VI 2020 baseline. Areas in blue show places where $PM_{2.5}$ under MARPOL VI is greater than for the proposed Med ECA scenario, i.e. where the proposed Med ECA leads to a reduction in $PM_{2.5}$. As shown, all water areas of the Mediterranean Sea experience reductions in $PM_{2.5}$ concentration, with coastal land benefits being realized primarily along the North African coastline, Spain, France, Italy, Malta, and Greece. Areas with the greatest expected reductions in $PM_{2.5}$ concentrations attributable to ships are at the western Mediterranean Sea, along the coastlines of Spain and Morocco, in the central Mediterranean Sea to the south of Sicily and over Malta, to the south and east of Greece, and along the north coast of Egypt approaching the entrance to the Suez Canal.

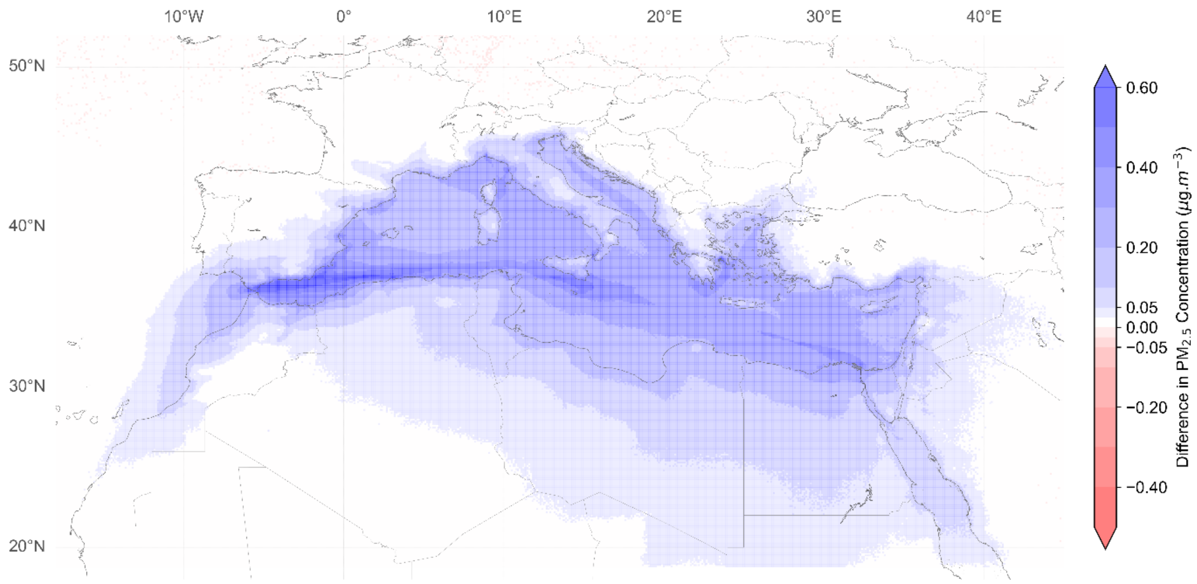


Figure 16. Difference in $PM_{2.5}$ concentration between MARPOL VI and the proposed Med ECA scenarios

3.5.2 Change in Wet and Dry Deposition

3.5.2.1 Sulphate deposition (SO_4)

Decreases in wet (Figure 17) and dry (Figure 19) sulphate (SO_4) deposition associated with the proposed Med ECA show similar orders of magnitude, but follow different patterns. Decreases in wet sulphate deposition are largest in the western and northern Mediterranean and show reductions in SO_4 deposition occurring far inland. Reductions in dry sulphate deposition are more closely correlated to the high traffic shipping lanes. Taking this study area as a whole, the average reduction in wet sulphate deposition is 43.3 $g.ha^{-1}.yr^{-1}$, and the maximum observed reduction is 3,127.8 $g.ha^{-1}.yr^{-1}$. The maximum percent decrease in wet sulphate deposition observed is 14.23% (Figure 18), which occurred over the Straits of Gibraltar. The average percent decrease in wet sulphate deposition estimated for the whole study area is 1.16%.

The maximum percent decrease in dry sulphate deposition observed is 48.13% (Figure 20), which occurred over the Straits of Gibraltar and extending eastwards towards Algiers. The average percent decrease in dry sulphate deposition estimated for the whole study area is 1.95%.

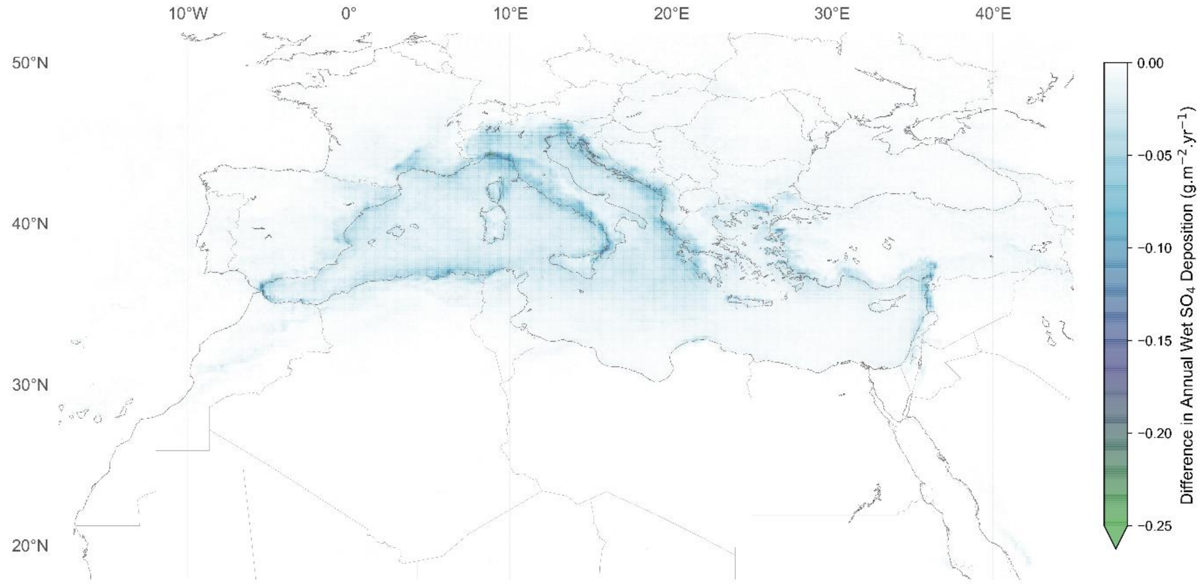


Figure 17. Decrease in annual wet sulphate deposition between MARPOL VI and the proposed Med ECA

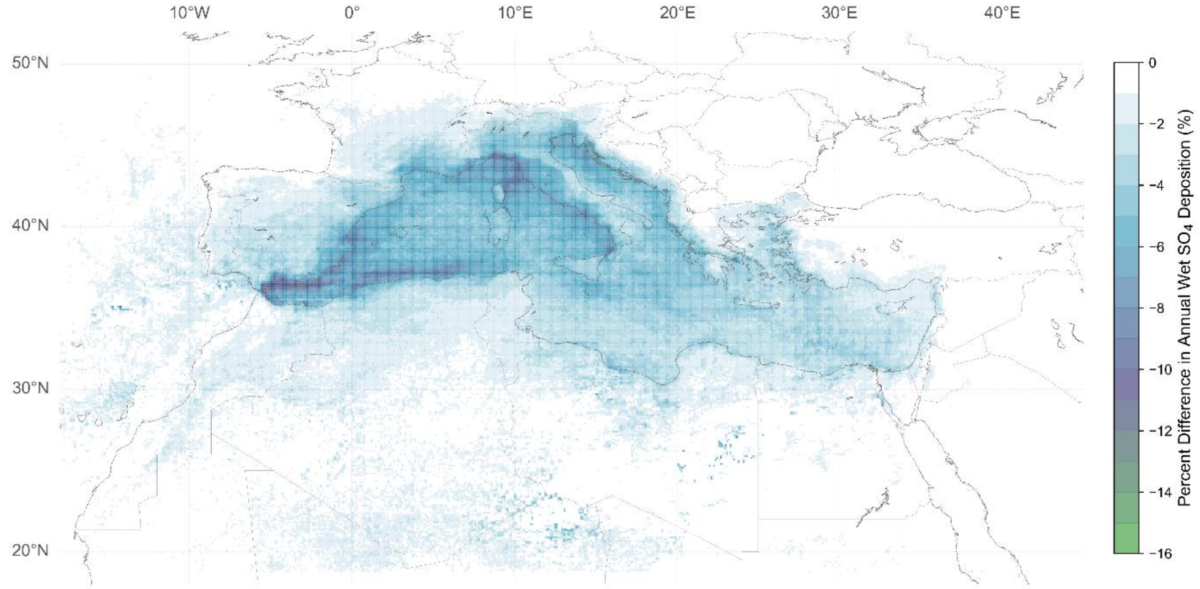


Figure 18. Percent decrease in annual wet sulphate deposition between MARPOL VI and the proposed Med ECA

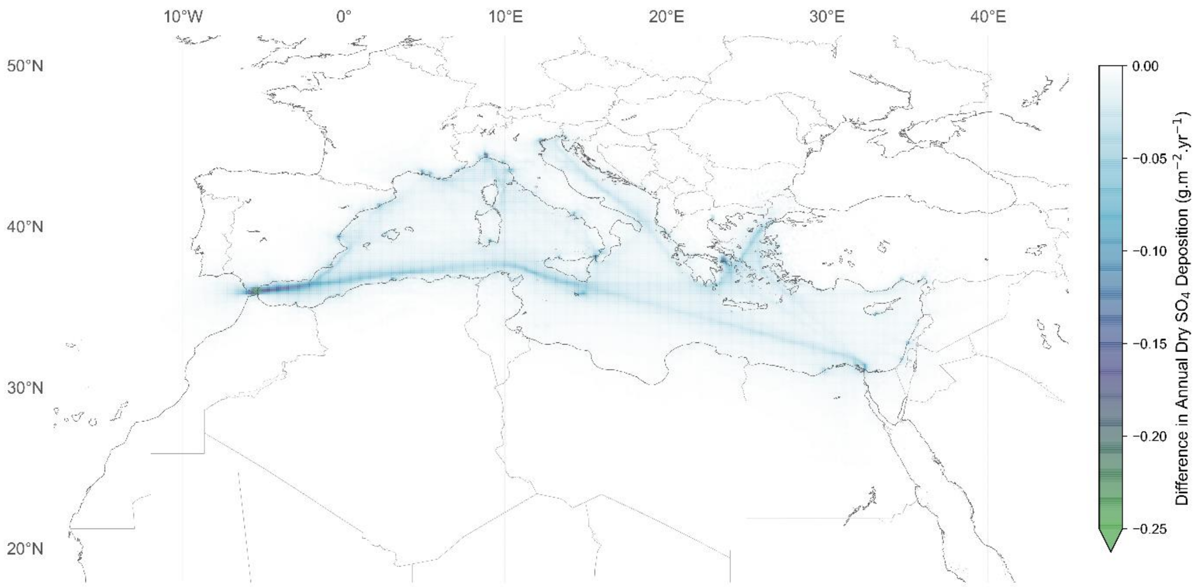


Figure 19. Decrease in annual dry sulphate deposition between MARPOL VI and the proposed Med ECA

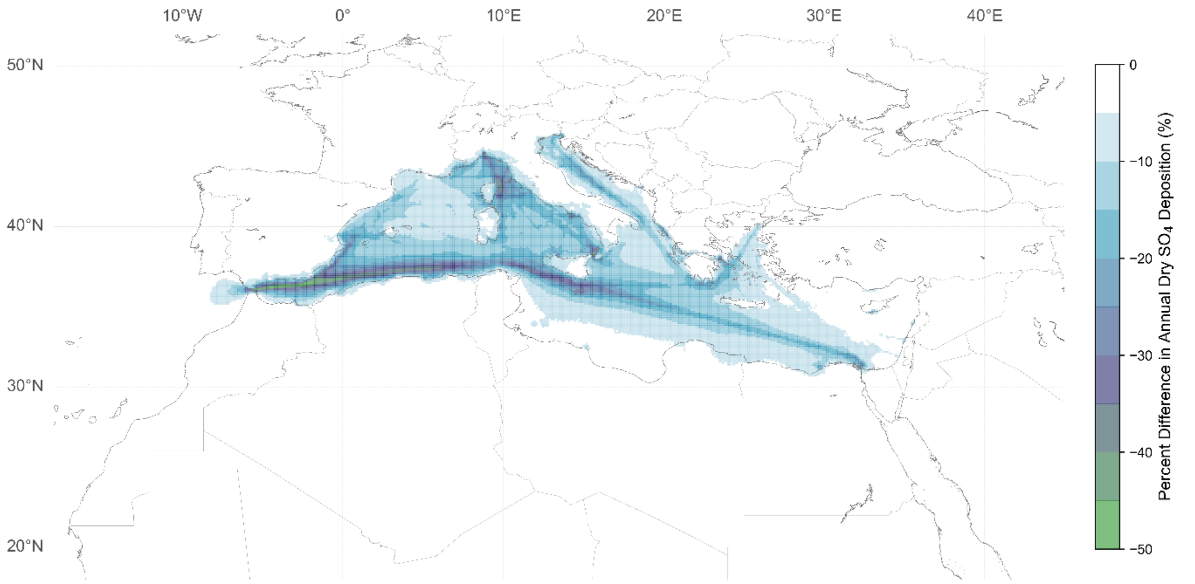


Figure 20. Percent decrease in annual dry sulphate deposition between MARPOL VI and the proposed Med ECA

3.5.2.2 PM_{Total} Deposition

Changes in wet (Figure 21) PM_{Total} deposition associated with the proposed Med ECA are two orders of magnitude greater than decreases in dry deposition, and follow different geographic distributions. Decreases in wet PM_{Total} deposition are largest in the western and northern Mediterranean and show reductions in PM_{Total} deposition far inland. Reductions in dry PM_{Total} deposition (Figure 23) are more geographically limited to western Spain, northern Algeria, the Alps, and isolated areas in Greece, and dry PM_{Total} deposition actually increases over water along the main shipping lane through the Straits of Gibraltar, past Malta and over towards the Suez.

The maximum percent decrease in wet PM_{Total} deposition observed is 4.58% (Figure 22), which occurred over the Straits of Gibraltar. The average percent decrease in wet PM_{Total} deposition estimated for the whole study area is 0.25%.

The maximum percent increase in dry PM_{Total} deposition observed is 8.45% (Figure 23), which occurred over the Straits of Gibraltar and extending eastwards towards Algiers. The average percent change in dry sulphate deposition estimated for the whole study area is 0.66%, indicating that dry PM_{Total} deposition increases overall when going from MARPOL VI to the proposed Med ECA, but shows significant geographic variation.

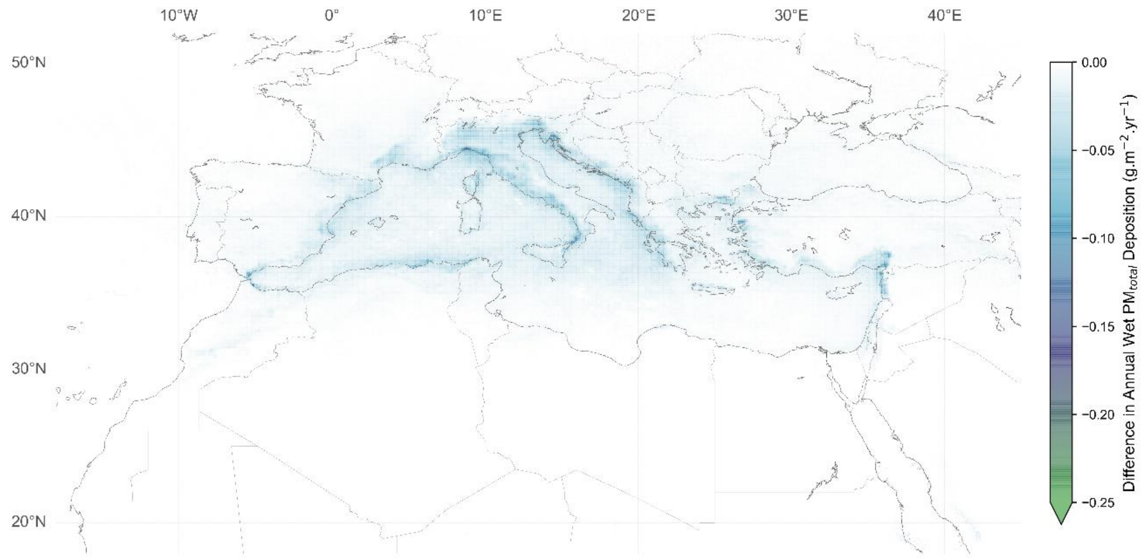


Figure 21. Decrease in annual wet PM_{Total} deposition between MARPOL VI and the proposed Med ECA

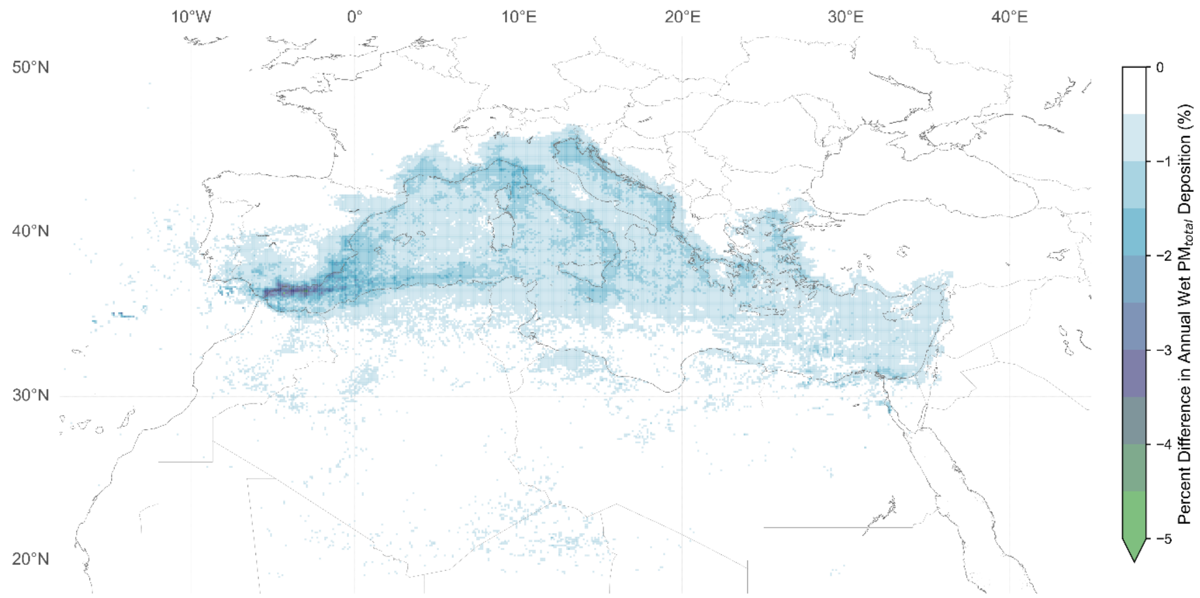


Figure 22. Percent decrease in annual wet PM_{Total} deposition between MARPOL VI and the proposed Med ECA

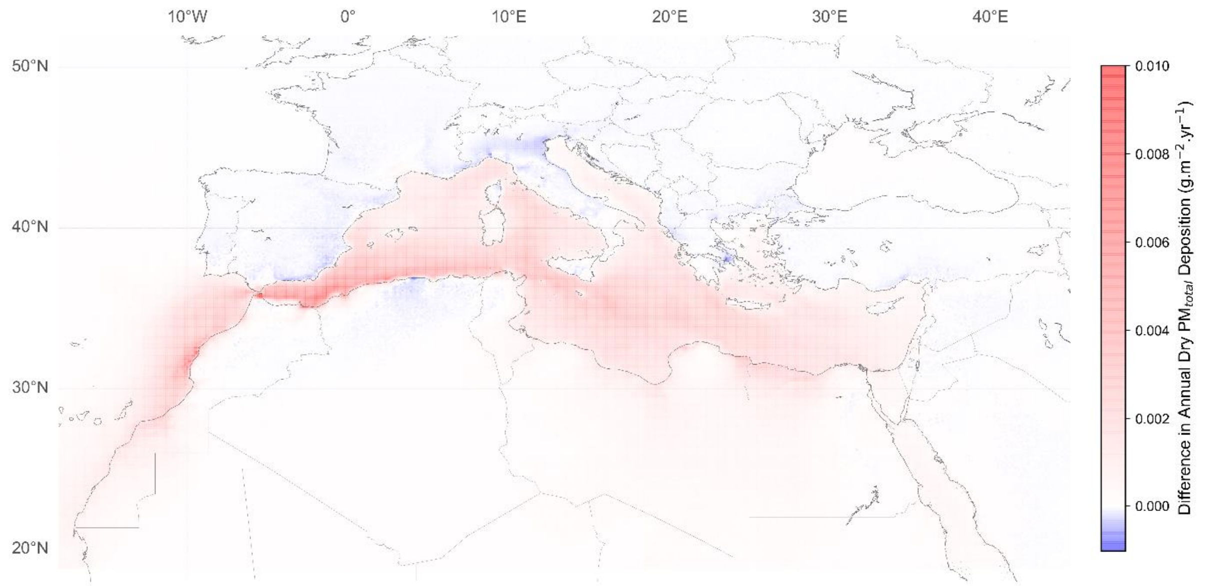


Figure 23. Change in annual dry PM_{Total} deposition between MARPOL VI and the proposed Med ECA

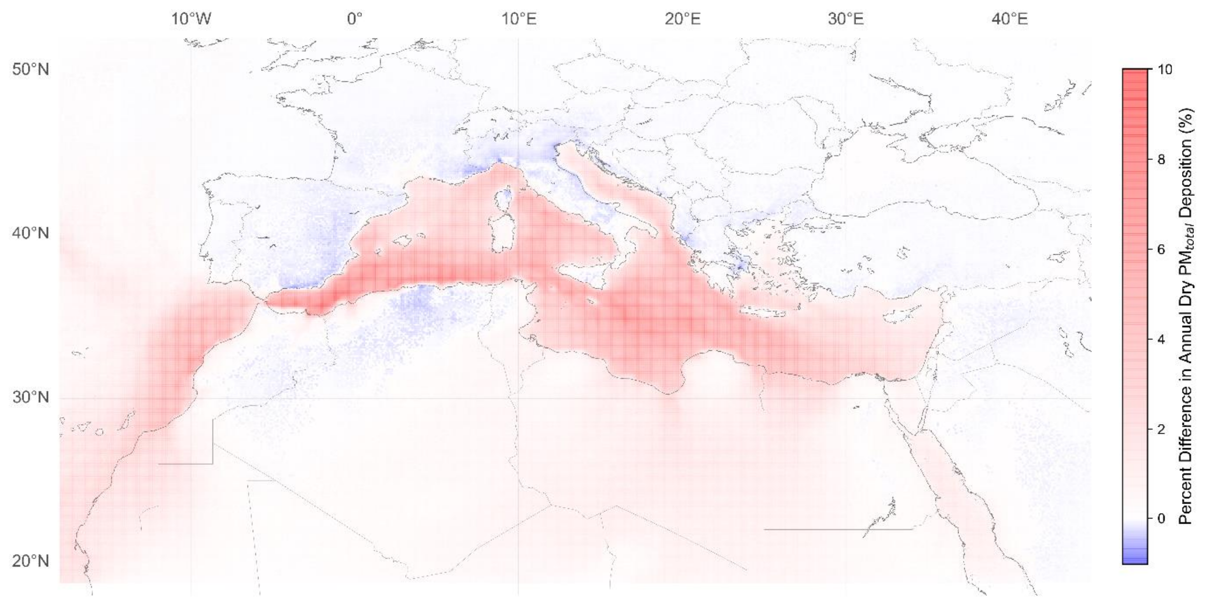


Figure 24. Percent change in annual dry PM_{Total} deposition between MARPOL VI and the proposed Med ECA

3.5.3 Change in Aerosol Optical Depth

The estimated percent increase in PM aerosol optical depth is shown in Figure 25. Increases in aerosol optical depth are associated with reduced haze and increased visibility. This figure shows a widespread increase in aerosol optical depth over water areas of the Mediterranean Sea and extending far inland over North Africa. That greatest increases in PM aerosol optical depth occur over the Straits of Gibraltar and northern Morocco and Algeria, and along the main shipping lane connecting the Straits of Gibraltar, Malta, and towards the Suez Canal.

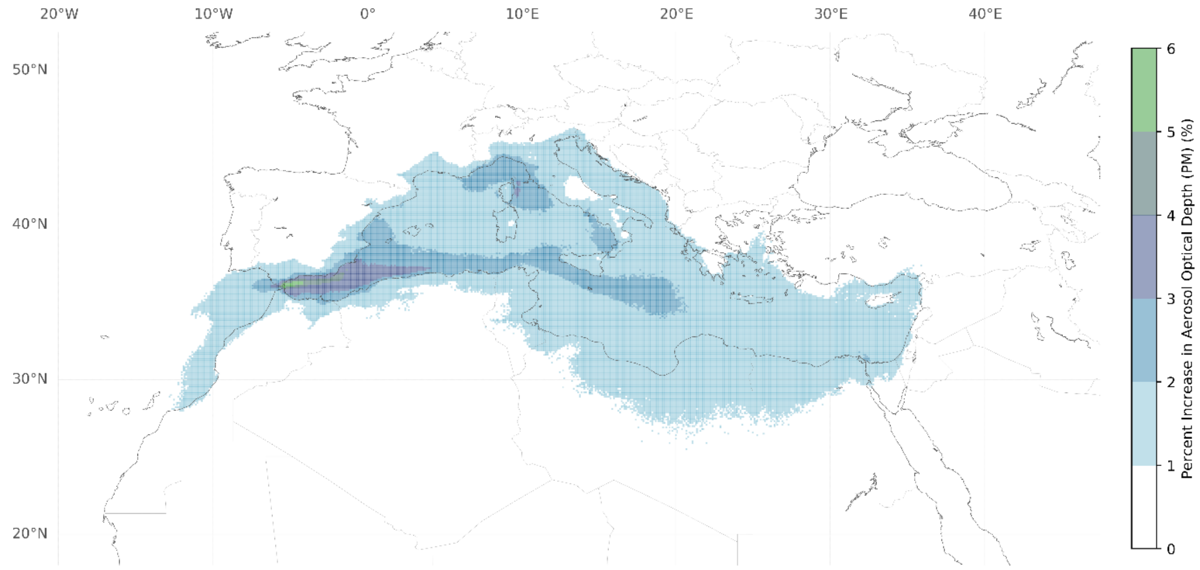


Figure 25. Percent Change in aerosol optical depth (PM species) between MARPOL VI and the proposed Med ECA

4 Assessment of Health and Environmental Mitigation Benefits

4.1 Health Benefits Assessment for 2020 Scenarios

We estimate the expected avoided lung cancer and cardiovascular disease mortality, and childhood asthma morbidity, associated with the proposed Med ECA using our state-of-the-art health model, recently published in *Nature Communications* (*3*), and referenced in document MEPC 70/INF.34. Our model produces high resolution (10km x 10km) mortality and morbidity estimates, corresponding to the resolution of underlying concentration grids provided by SILAM. Our high-resolution modeling approach reduces under and over estimation of mortality and morbidity inherent with coarser (50km x 50km) models of emissions and population. Our model outputs include high resolution gridded estimates of mortality and morbidity, and country-specific burdens of disease for the countries shown in Figure 8. We use country-specific population growth estimates, disease incidence rates, and age structures, and global gridded population and socioeconomic data from the Socioeconomic Data and Applications Center (SEDAC) (*4*).

4.1.1 Avoided Cardiovascular and Lung Cancer Mortality

Health outcomes are improved in all coastal areas of all countries bordering the Mediterranean Sea. Figure 26 shows the combined avoided lung cancer and cardiovascular mortality associated with implementing the proposed Med ECA. In many cases, health outcomes are improved hundreds of miles inland. Modeling results show a reduction in cardiovascular disease mortality of ~970 deaths/year and a reduction in lung cancer mortality of ~150 deaths/year. Due to the interaction between air quality improvements, population centers, and country-specific incidence rates, we see hotspots where avoided mortality from reduced ship emissions is greater. Clusters of these hotspots can be seen in north Africa as well as areas of the Eastern Mediterranean. Detailed country-specific results of improved cardiovascular and lung cancer disease outcomes are discussed in Section 4.1.4.

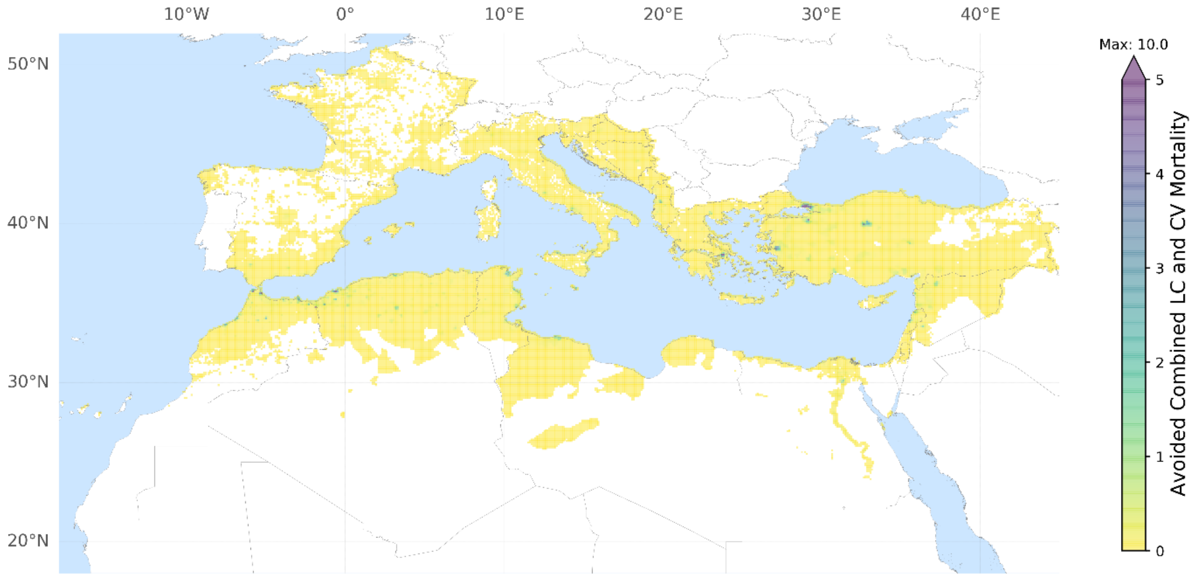


Figure 26. Combined avoided lung cancer and cardiovascular mortality with the proposed Med ECA

4.1.2 Childhood Asthma Morbidity

Childhood asthma health outcomes are improved in all countries bordering the Mediterranean Sea. Figure 27 shows the avoided childhood asthma morbidity associated with implementing the proposed Med ECA. Avoided morbidity in this case refers to the number of children experiencing one or more ship-pollution induced asthma events each year. In many instances, improved health outcomes are observed hundreds of miles inland, and in many Mediterranean countries experience the benefits of the proposed Med ECA over the entirety of their land area. Modeling results show a reduction in childhood asthma morbidity of ~2,300 children experiencing one or more ship-pollution induced asthma events per year. As for morbidity, we see improved health outcomes across large areas of the Mediterranean countries, with a hotspots of avoided asthma morbidity seen in north Africa and the eastern Mediterranean. Country-specific results are discussed in Section 4.1.4.

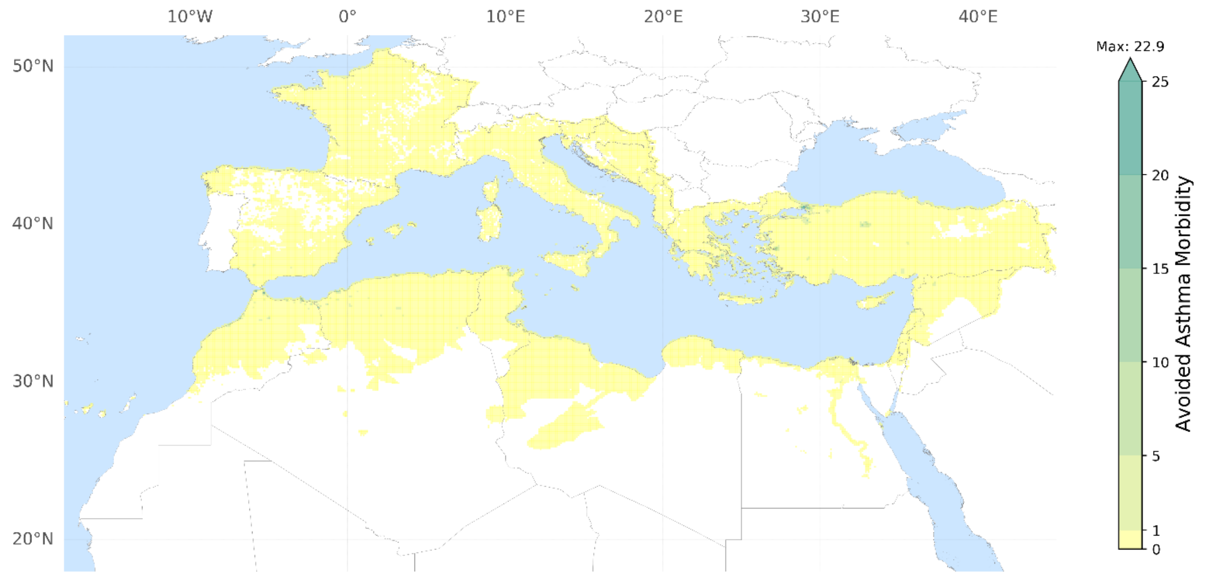


Figure 27. Avoided childhood asthma morbidity with the proposed Med ECA

4.1.3 Summary of Evaluated Health Benefits

The health effects estimated in this study are shown in Table 15, along with 95% confidence intervals.

Table 15. Summary of health benefits evaluated for the proposed Med ECA (model year 2020)

Scenario Results (Linear C-R Model)	Reduced Mortality (annual premature adult deaths)		Avoided Childhood Asthma (annual avoided incidents)	
Health benefits of the proposed Med ECA	**Reduced Mortality**		**Reduced Asthma Morbidity**	
	CV Mortality Avoided	969 (CI 95% 551; 1412)	**Avoided Childhood Asthma**	**2314 (CI 95% 1211; 3406)**
	LC Mortality Avoided	149 (CI 95% 32; 270)		
	Combined Avoided Mortality	**1,118 (CI 95% 583; 1682)**		

4.1.4 Country-Specific Estimates of Health Benefits

We also estimated mortality and morbidity impacts of the proposed Med ECA by Mediterranean coastal States. These results, along with their 95% confidence intervals, are shown in Table 16. Note that Monaco shows zero health benefits because the sampling resolution of our model exceeds the geographic area of Monaco.

Table 16. Regional allocation of estimates for health benefits

REMPEC Results by Country	Reduced Mortality (CI 95% Low; High)		Avoided Childhood Asthma (CI 95% Low; High)	
Albania	19	(CI 95% 10; 28)	6	(CI 95% 3; 9)
Algeria	162	(CI 95% 90; 240)	338	(CI 95% 177; 497)
Bosnia and Herzegovina	8	(CI 95% 4; 12)	6	(CI 95% 3; 9)
Croatia	7	(CI 95% 4; 11)	4	(CI 95% 2; 6)
Cyprus	2	(CI 95% 1; 4)	4	(CI 95% 2; 6)
Egypt	32	(CI 95% 17; 46)	34	(CI 95% 18; 50)
France	17	(CI 95% 7; 27)	61	(CI 95% 32; 90)
Greece	62	(CI 95% 30; 96)	76	(CI 95% 40; 112)
Israel	1	(CI 95% 0; 2)	7	(CI 95% 4; 10)
Italy	82	(CI 95% 40; 126)	143	(CI 95% 75; 210)
Lebanon	17	(CI 95% 9; 26)	35	(CI 95% 18; 52)
Libya	39	(CI 95% 22; 58)	76	(CI 95% 40; 112)
Malta	4	(CI 95% 2; 5)	7	(CI 95% 4; 10)
Monaco	0	(CI 95% 0; 0)	0	(CI 95% 0; 0)
Montenegro	3	(CI 95% 2; 6)	3	(CI 95% 2; 5)
Morocco	114	(CI 95% 63; 169)	350	(CI 95% 183; 516)
Slovenia	2	(CI 95% 1; 3)	3	(CI 95% 1; 4)
Spain	43	(CI 95% 20; 67)	118	(CI 95% 62; 173)
Syrian Arab Republic	48	(CI 95% 26; 70)	71	(CI 95% 37; 105)
Tunisia	70	(CI 95% 38; 104)	107	(CI 95% 56; 158)
Turkey	386	(CI 95% 197; 582)	865	(CI 95% 452; 1272)

4.1.5 Comparison with other health studies

This study estimates two mortality endpoints, cardiovascular and lung cancer mortality. Viana et al. (2015) assume a much smaller SECA in only the Marmara Sea and use independent AIS data, dispersion modeling, health modeling, all-cause mortality endpoints compared to this study (*5*). Viana et al. estimate total disease burden of 670 all-cause mortalities related to $PM_{2.5}$ exposure in Turkey, which is 42% higher than our estimate. Considering the different end points, all-cause mortality vs. cardiovascular and lung cancer mortality, we find these two studies to be in good agreement.

An independent study completed by IIASA in 2018 (*6*) looking at all-cause mortality estimated around 3,500 avoided premature deaths resulting from the proposed Med ECA in 2030. This study applied independent air quality dispersion and health models, using a different methodology to that described in this study. The IIASA estimate is 3.13x larger than the estimate provided by this study for 2020. Given differences in the disease endpoints (all-cause vs. cardiovascular and lung cancer) and projected population growth in the region these estimates align with the findings reported in Section 4.1.3.

4.2 Other Benefits Associated with the proposed Med ECA

Environmental benefits associated with the proposed Med ECA besides mortality and morbidity include reduced acidification impacts on aquatic systems and reduced aerosol related haze. Although this report focuses primarily on the human health impacts of the proposed Med ECA, the acidification and aerosol effects are important as well. Proxy indicators for these are presented in Section 3.5 and summarized in Table 17.

Sulphate deposition reductions are a proxy indicator for potential change in pH acidification to aquatic and terrestrial ecosystems. PM_{Total} deposition reductions are a proxy indicator for potential change in other particle and nutrient effects. Note that Dry PM_{Total} deposition indicated some regions with small increases in deposition, due to non-linear PM formation responses with the reduction of sulphates, consistent with findings reported in science literature. Aerosol optical depth is a proxy for increased suspended particles affecting regional haze and visibility impairment, an increase in aerosol optical depth indicates an improvement in visibility.

We also note that while this analysis focuses on benefits to Mediterranean coastal States, human health and environmental benefits may extend to countries outside the domain of this study.

Table 17. Summary of proxies for other benefits associated with the proposed Med ECA

Environmental Benefit Proxy	Relative Range of Change (%)	Areas of greater benefit shown:
Wet sulphate deposition	1 to 15% reduction	Figure 18. Percent decrease in annual wet sulphate deposition between MARPOL VI and the proposed Med ECA
Dry sulphate deposition	1 to 50% reduction	Figure 20. Percent decrease in annual dry sulphate deposition between MARPOL VI and the proposed Med ECA
Wet PM_{Total} deposition	0.5 to 5% reduction	Figure 22. Percent decrease in annual wet PMTotal deposition between MARPOL VI and the proposed Med ECA
Dry PM_{Total} deposition	0 to 10% reduction	Figure 24. Percent change in annual dry PMTotal deposition between MARPOL VI and the proposed Med ECA
Aerosol optical depth (PM-related)	1% to 6% increase	Figure 25. Percent Change in aerosol optical depth (PM species) between MARPOL VI and the proposed Med ECA

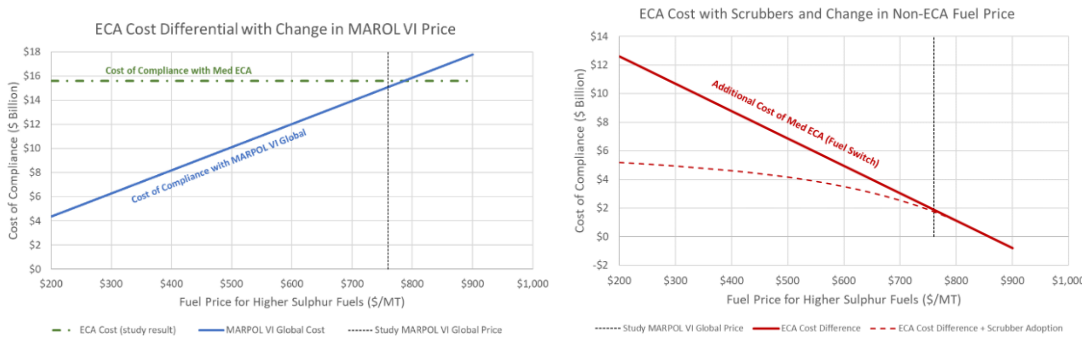
5 Economic and Technical Feasibility Assessment

5.1 Estimated Compliance Costs for 2020 Mediterranean Policy Scenarios

This study estimated compliance costs for the proposed Med ECA policy scenario using best available data along with conservative assumptions regarding fuel prices and scrubber costs, as described in later sections. The results of our cost analysis is shown in Table 18, which demonstrates that a movement to the proposed Med ECA using fuel switching would add $1.766 billion/year in 2020 ($2016) compared to simply meeting the MARPOL standard. Using scrubbers would add $1.157 billion/year. These values are highly depending on the assumed price differential between HFO, MDO, and MGO. Price differentials are described in Section 7.4.1. Figure 28 shows the sensitivity of the cost impacts given a fixed MDO and MGO price, and a change in HFO (x-axis). As HFO price increases (i.e., as the difference between HFO price and MDO/MGO price decreases), the cost of compliance with MARPOL increases, and therefore the incremental cost of compliance with the proposed Med ECA decreases. These graphs demonstrate to decision makers the importance of fuel costs in determining overall compliance costs.

Table 18. Estimated costs under different Mediterranean regulatory and compliance scenarios

$ Billion/y / Policy Scenario	Total Cost	Compliance Cost
No Action	$9.884	N/A
MARPOL VI (0.5% S)	$13.849	$3.965
Proposed Med ECA (0.1% S)	$15.614	$1.766
Proposed Med ECA (with scrubbers)	$15.005	$1.157



(a) (b)

Figure 28. Summary graphs of SECA cost sensitivity to fuel price for non-SECA (higher-sulphur) fuels, and scrubber adoption: (a) cost difference between switching from MARPOL VI global fuel to SECA fuel; and (b) additional cost to comply with the proposed Med ECA including potential economically feasible adoption of scrubber technology

5.2 Exhaust Gas Cleaning Adoption Analysis

Scrubbers represent one possible compliance option for the proposed Med ECA. Following the method describe in Section 7.4.3.1, scrubbers Table 21 indicates that about 5,900 vessels, some 18% of the fleet operating in the Mediterranean Sea area, could adopt scrubbers, under conservative 100-year investment horizon and 15% investment rate. This conservative investment horizon may be considered to describe the least cost investment option, and therefore defines the most favorable conditions for investment in exhaust gas cleaning technology. This finding is consistent with some, but not all, estimates reported in industry media or other studies, fundamentally related to investment horizon conditions assumed. Therefore, we performed some sensitivity analyses to further explore economically feasible conditions.

Table 19. Fleet counts considered for exhaust gas cleaning technology

	Fleet Count	Percent of Total Fleet
Scrubbers	5,915	18%
No Scrubbers	27,248	82%

Table 20 shows the expected scrubber investment rates over a range of investment horizons. Investment decisions are typically confidential business information, and thus we parameterize the decision over a range of investment lifetimes. We identify 39 vessels currently operating with scrubbers in the Mediterranean Sea area, and do not expect this number to change under a 1-year investment horizon. If scrubber costs are amortized over 10 years the results show that scrubber installations would increase by a factor of ten, from 39 to 464. Assuming a 15-year investment horizon, the results indicate that 3.7% of the fleet might invest in a scrubber, and save the fleet over $260 million

Table 20. Cost analysis relating scrubber capital costs and investment years to the percent of the fleet using scrubbers in the proposed Med ECA

Investment years	Feasible Scrubber Use, Capital included		
	Compliance Savings ($Billions)	**Number of Scrubbers**	**Percent of Fleet Using Scrubbers**
None	$0.61	39 in 2020	0.0%
1	$0.00	0	0.0%
5	$0.02	53	0.2%
10	$0.10	464	1.4%
11	$0.13	632	1.9%
12	$0.15	767	2.3%
14	$0.19	1,010	3.0%
15	$0.26	1,226	3.7%
20	$0.37	1,888	5.7%
25	$0.47	2,702	8.1%
30	$0.53	4,155	12.5%
50	$0.60	5,726	17.3%
100	$0.61	5,915	17.8%

Table 21 shows that scrubber may be feasible for vessels that spend a greater amount of time inside the Mediterranean Sea area (and/or other SECA region). Scrubbers require increased capital investment but use lower cost fuels, and economic feasibility increases with more cost-saving operation using lower cost fuels. These results agree with previously published work (*7*). These results indicate that, under and unlimited (100-year) investment horizon scrubber scenario, 5,900 vessels (~18% of the Mediterranean fleet) might be expected to invest in scrubbers, while most of the fleet (82%) may determine that fuel switching remains the least cost option.

Table 21. Use of scrubbers by vessel type under the proposed Med ECA scenario

Vessel Type	No Scrubber Average Operating Hours [h] in Med	No Scrubber Ship Count	Scrubber Adoption Average Operating Hours [h] in Med	Scrubber Adoption Ship Count
Cargo ships	1,356	6,875	5,172	458
Container ships	756	1,146	3,464	915
Cruisers	879	62	4,400	118
Fishing vessels	1,472	1,000	3,683	268
Misc	1,202	6,749	4,148	1,183
Passenger ships	1,513	649	3,457	294
RoPax vessels	2,213	177	6,404	361
Service ships	1,265	652	3,910	207
Tankers	1,049	3,586	5,096	723
Unknown	370	5,875	2,469	1,190
Vehicle carriers	749	477	5,597	198
Grand Total	**1,039**	**27,248**	**4,027**	**5,915**

5.3 Alternative Fuels

Alternative fuels and advanced power systems may offer economically feasible alternatives for SECA compliance, particularly if the net costs of these systems are lower than switching to SECA fuel. Of course, additional reasons beyond cost-savings within a SECA may support investment in vessels using advanced fuels, but this study evaluates only decision criteria for advanced power and fuel technologies within the scope of evaluating SECA compliance costs. Moreover, some alternative fuels may present other environmental tradeoffs beyond SECA compliance through very low sulphur content in the fuel, which merit consideration beyond the scope of this report.

A variety of fuels and power configurations could be considered. These include, but are not limited to: a) liquefied natural gas (LNG); b) methanol marine fuels; c) hydrogen fuel; d) hybrid propulsion systems that may include wind-assist, fuel cells, energy storage technologies, etc. Given that LNG is a fuel currently used on a significant number of vessels, and across many vessel types, data are most available to conduct economic feasibility assessment using LNG as an example.

As described in Section 7.4.3.2, we compare increased installation costs with fuel cost savings based on price differential between MGO and LNG. We apply this analysis to older vessels, selected to be at or beyond typical replacement ages in 2020. Therefore, this analysis is applied to replacement of end of life vessels and new build vessels as they enter the fleet. If a vessel net costs of complying with SECA conditions are lower using LNG, then that vessel is considered to be economically feasible. We evaluate the fraction of the fleet that is replaced or replacement eligible based on age in 2020, and we evaluate the fraction of those vessels for which LNG would be economically feasible. Additional methodology description can be found in Section 7.4.3.2.

The approach may be considered to serve as a screening tool for economic feasibility of LNG conversion, which is known through fleet adoption experience to be technically feasible. Further analyses of infrastructure, energy supply, and regional economic conditions would be required for specific fleet operator or port selection of alternative fuels.

The average fuel cost savings for vessels could be greater than 30%, given the higher costs of MGO fuel and lower costs of LNG used in this study. Where the average LNG installation premium is lower than the present value of the potential capital investment window derived from fuel cost savings, this study identifies approximately 3,900 vessels to be feasible candidates for alternative fuels. Some of these vessels included smaller service vessels, fishing vessels, etc.; we recognize that conversion of these locally operating and networked vessel operations may include infrastructure and co-fleet investment decisions not captured here. Therefore, we present in Table 22 a summary of larger commercial transport and cruise vessels considered to be feasible for alternative fuel operation under the conditions and assumptions applied in this study. Fleet adoption rates shown in Table 22 exclude fishing vessels, passenger ferries, service ships, miscellaneous, and unknown vessel types. Table 23 presents a summary of overall fleet counts combining all ships. Under our base input conditions, about 11%-12% of the fleet operating in the Mediterranean Sea area could feasibly consider alternative fuels for cost-saving compliance with the proposed Med ECA.

Table 22. Summary of alternative fuel economic feasibility analysis for major vessel types in the Mediterranean Sea area

Vessel Type	Count of Feasible Vessels	Percent of Vessel Type	Average Age	Average Fuel Cost Savings (Percent)	Average LNG Installation Premium ($ Million)	Capital Investment Window ($ Million)
Cargo ships	890	12%	33	32%	$1.0	$2.5
Container ships	130	6%	28	33%	$4.0	$11.9
Cruisers	45	25%	37	37%	$5.5	$20.0
RoPax vessels	220	41%	35	40%	$3.9	$19.0
Tankers	260	6%	30	36%	$1.3	$4.1
Vehicle carriers	79	12%	33	39%	$2.6	$12.0
Total[1]	**1,624**	**11%**				

Table 23. Fleet counts considered for alternative fuel replacement, and the number that could reduce SECA compliance costs

Feasibility Category	Fleet Count	Percent of Total Fleet
Salvage age (>20 yrs.) circa 2020	19,700	59.3%
Alternative Fuel-cost Feasible	3,900	11.8%
Other Criteria Necessary	15,800	47.5%

The economic feasibility of alternative fuels will be sensitive to several inputs, primarily to the fuel-price differential between SECA compliant fuel and the alternative fuel (LNG in this analysis). Table 24 illustrates this through sensitivity analysis that exercises the LNG fuel price from no-cost ($0) through a price equal to SECA fuel. As illustrated, fleet adoption rates from nearly 17% to 0% are dependent upon the net savings of installing power systems for and operating alternative fuels. The shaded row represents the results of this analysis using fuel prices described in Section 7.4.1. Regional compliance cost savings with the proposed Med ECA through adoption of economically feasible alternative fuels could be in the range of $1.4 Billion per year.

Table 24. Cost analysis relating LNG price and LNG-MGO price differential to the percent of the fleet (all vessel types) adopting alternative fuel

LNG Price[1]	LNG-MGO Price Δ	Proposed Med ECA Cost with LNG Alternative ($ Billion per year)	Proposed Med ECA Savings with LNG ($ Billion per year)	Fleet Percent Adoption[2]
$0	$858	$13.4	$2.2	16.7%
$50	$808	$13.5	$2.1	16.1%
$100	$758	$13.7	$2.0	15.5%
$200	$658	$13.9	$1.7	14.0%
$300	$558	$14.2	$1.4	12.3%
$327	**$531**	**$14.2**	**$1.4**	**11.8%**
$350	$508	$14.3	$1.3	11.3%
$400	$458	$14.4	$1.2	10.2%
$450	$408	$14.6	$1.1	9.2%
$600	$258	$14.9	$0.7	5.1%
$700	$158	$15.2	$0.4	2.5%
$800	$58	$15.5	$0.2	0.2%
$858	$0	$15.6	$0.0	0.0%

5.4 Comparison of Vessel-Specific Costs

The above analysis allows us to estimate costs of compliance for different types of vessels. Table 25 provides results of these costs for MARPOL VI, the proposed Med ECA, and the proposed Med ECA with scrubbers. Results show that per vessel costs are largest for the biggest most powerful vessels, which include cruise ships, RoPax vessels, containers, and vehicle carriers. The columns represent total costs under each scenario; annual cost increases would be the difference between column prices, e.g., for Cruisers the difference between the proposed Med ECA average cost and MARPOL VI average cost would be about $550k per year.

Table 25. Summary of average annual compliance cost per vessel by type

Vessel Type	Ship Count	2020 MARPOL VI Average Cost	Proposed Med ECA Average Cost	Proposed Med ECA + Scrubber Average Cost
Cargo ships	7,333	$290,000	$327,000	$325,000
Misc	7,932	$48,400	$54,000	$52,200
Passenger ships	943	$70,600	$79,300	$74,100
Tankers	4,309	$681,000	$763,000	$750,000
Unknown	7,065	$24,500	$27,400	$26,300
Service ships	859	$110,000	$123,000	$118,000
Fishing vessels	1,268	$30,500	$34,100	$32,900
Vehicle carriers	675	$1,550,000	$1,760,000	$1,650,000
Cruisers	180	$3,280,000	$3,830,000	$3,540,000
RoPax vessels	538	$2,920,000	$3,280,000	$2,970,000
Container ships	2,061	$2,340,000	$2,640,000	$2,540,000

5.5 Benefit-Cost Analysis

5.5.1 Cost effectiveness analysis

Similar to other SECA analyses, we have assigned the same cost across each of these dimensions, which over-assigns the cost per unit benefit given that the same cost is achieving all these benefits. See Methods and Data Section 0 for further discussion. Table 26, Figure 29, and Figure 30 summarize our results. For example, the proposed Med ECA without scrubbers is shown to cost about $1.58M per avoided annual death, if we assign all the costs of the proposed Med ECA to our avoided mortality estimates. This cost comes down to $1.035M/avoided death under a scrubber scenario.

Table 26. Cost-effectiveness of quantified benefits

Benefit Type	MARPOL VI	Proposed Med ECA	Proposed Med ECA with Scrubbers
Control Target			
Abated SO_x emissions	\$7,730 /MT SO_x	\$13,400 /MT SO_x	\$8,750 /MT SO_x
Abated $PM_{2.5}$ emissions	\$80,300 /MT $PM_{2.5}$	\$155,000 /MT $PM_{2.5}$	\$101,000 /MT $PM_{2.5}$
Health Outcome			
Avoided mortality	\$0.263 M/Δ Mortality	\$1.580 M/Δ Mortality	\$1.035 M/Δ Mortality
Avoided childhood asthma	\$14 k/Δ Morbidity	\$763 k /Δ Morbidity	\$500 k/Δ Morbidity

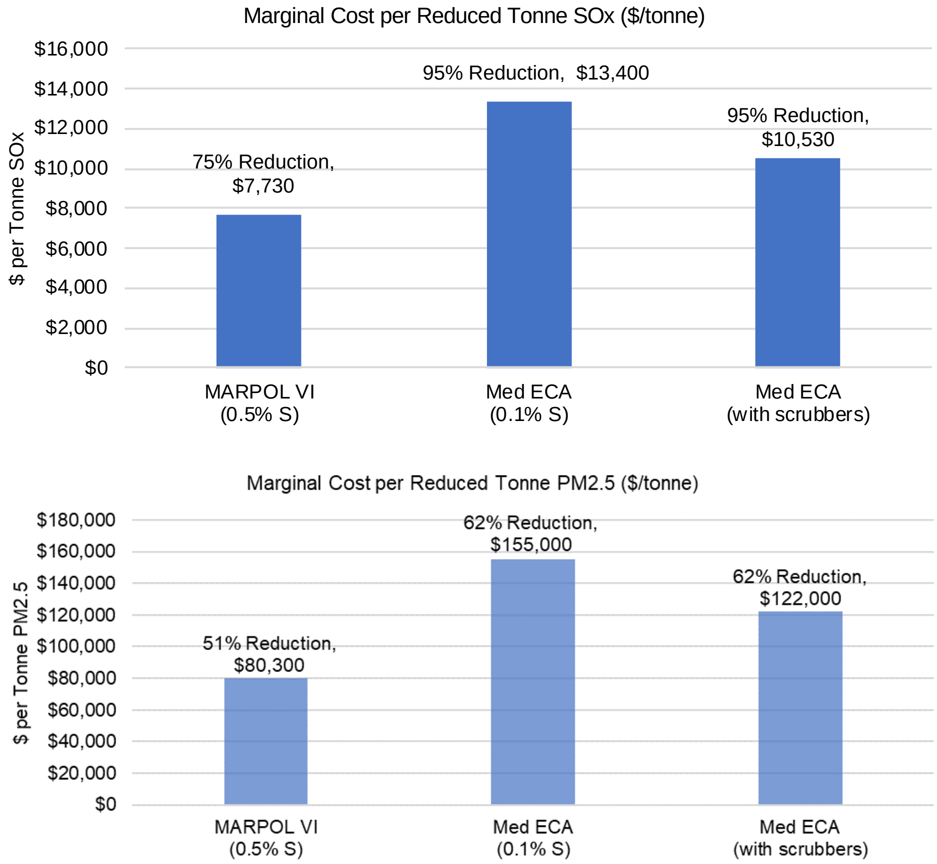


Figure 29. Control cost-effectiveness of SO_x and $PM_{2.5}$ reductions based on prices in this study

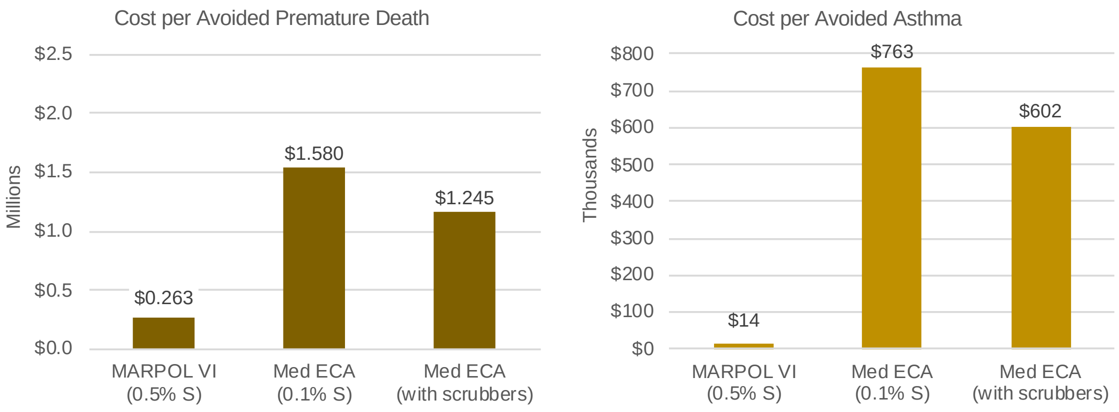


Figure 30. Cost-effectiveness of health outcomes in terms of avoided premature mortality and avoided childhood asthma

5.5.2 Mortality benefit-cost analysis (Lung Cancer and Cardiovascular causes)

A benefit-cost analysis should compare the net monetized benefits for all mitigation and costs for all compliance actions. No prior proposal to designate a SECA under MARPOL VI have presented analyses that monetize all benefits. Prior proposals to designate regional SECAs under IMO MARPOL Annex VI have generally presented cost-effectiveness justifications for benefits of dominant concern or made reference to a concept termed "critical loads", which generally means the maximum tolerable environmental exposure that a region's ecosystem (in whole or part).

The monetary value of small changes in mortality risks using SECA compliant fuels can be considered in terms of an economic term called the "value of a statistical life" or VSL. Formally, VSL is the monetary value of small changes in mortality risks, scaled up to reflect the value associated with one expected fatality in a large population. This project identified a key resource, published in the peer-reviewed literature in 2017, that performs a state-of-practice analysis of VSL that includes nearly all Mediterranean coastal States (*8*).

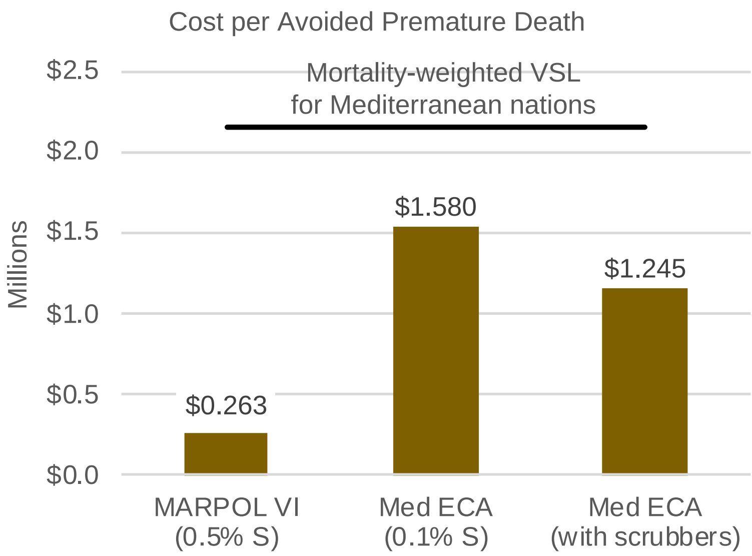


Figure 31. Comparison of the proposed Med ECA cost per avoided mortality and the Mediterranean weighted VSL

6 Comparison with other SECA Assessment and Summary of Other Results

6.1 Comparison with other SECA Assessments

Comparison of these net benefits and net costs with prior SECA proposals for North America and for the Baltic and North Sea and English Channel regions can be qualitatively insightful. However, results reported for the stepwise change from global MARPOL VI fuel-sulphur limits to SECA compliance cannot be directly compared with prior SECA designations that quantified technical and economic feasibility from a base case prior to current global limits defined for 2020 in MARPOL VI. In other words, the environmental and health benefits associated with a shift to SECA-compliant 0.1% S fuel from global fleet average fuel sulphur of ~2.4% or ~2.7% S should be different (and greater than) the benefits of moving from 0.5% S fuel to SECA-compliant fuel limits. Similarly, the costs to achieve net reductions in one policy action, as was the case for all prior SECA proposals, would be expected to yield a lower cost-effectiveness ratio than the cost-effectiveness calculations for the second of two policy actions (global fuel limits and SECA fuel limits) for the Mediterranean.

The benefits estimated in Section 5.5.1 compare a SECA condition with a condition representing a stepwise improvement. Prior SECA proposals estimated benefits and costs from a condition allowing up to 3.5% S fuel to be used and generally used world fleet average fuel sulphur statistics reported by IMO (*9-11*). Fortunately, the project team for this work can reconstruct a set of quantified benefits and costs that offers direct comparison with prior proposals to designate sulphur-related ECAs.

Analyses on fuel consumption and benefits of MARPOL VI published in the peer-reviewed journal Nature Communications in February 2018 provide much of the analytical detail necessary to construct a net benefit assessment for this study's Mediterranean domain (*3*). Moreover, the fuel usage data and global MARPOL VI fuel-based compliance conditions set forth in that prior work are consistent with this study. By applying fuel pricing conditions in this work, a cost to shift in one step from pre-2020 2.4% S fleet-average fuel-sulphur to SECA-compliant 0.1% S fuel can be estimated. This produces the necessary inputs for costs and effectiveness to produce metrics directly comparable with the North American proposal findings for cost-effectiveness.

For clarity, data used for the United States (U.S.) cost-effectiveness estimates in Table 27 and Figure 32 comparisons are from Table 3.2-1, Table 4.2-1 and text in Sections 9.1 and 9.2 of document MEPC 59/6/5. Ship emission reductions for SO_x and $PM_{2.5}$ associated with North American ECA designation are reported in Table 3.2-1 of document MEPC 59/6/5. Avoided mortality and morbidity comparisons use the net differences for estimated $PM_{2.5}$-related health impacts associated with ships, reported in Table 4.2-1 of document MEPC 59/6/5; in order to approximate a direct comparison with this study's childhood asthma estimates, we summed the set of childhood asthma related diseases reported separately for the contiguous 48 U.S. states in document MEPC 59/6/5. Total cost of compliance with the North American ECA reported in 2009 was $3.2 Billion per year (Section 9.1 of document MEPC 59/6/5). These values result in the cost-effectiveness metrics reported below in column 2 of Table 27 and represent the lower values for the gray boxes in Figure 32.

The 2009 proposal to designate a North American ECA assumed fuel production cost increases of $145/MT reported in Section 9.2 of document MEPC 59/6/5. This study is based on fuel prices since 2009 and uses higher values; the net price increase from pre-2020 MARPOL VI fuel to SECA compliant fuel is ~434/MT, as computed from Table 30. Therefore, we also compare our results with adjusted North American ECA cost-effectiveness by multiplying by the ratio of these cost differences; this price-match adjustment assumes no change in estimated abated emissions or morbidity or mortality in the 2009 North American ECA proposal. Column 3 of Table 27 and higher values for the gray boxes in Figure 32 present these comparison values.

Assessment of the benefits of the North Sea and Baltic SECAs shows reductions in mean SO_2 concentrations of between 2.5 to 3 $\mu g.m^{-3}$, which is a 24% to 37% decrease (*12*). No modal shift or change in the number of ship calls observed. As shown in Figure 16, this study finds a PM reduction in much of the Mediterranean Sea area of between 0.1 and 0.6 $\mu g.m^{-3}$ from the switch from MARPOL VI to SECA conditions. The non-linearity of atmospheric fate and transport notwithstanding, the modeled changes in air quality in the proposed Med ECA are proportional to those observed resulting from the North Sea and Baltic SECAs.

The last column of Table 27 and the black diamond markers in Figure 32 present Mediterranean specific cost-effectiveness estimates as if the region were to be designated a SECA from a base case of pre-2020 fleet conditions using 2.4% S fuel-sulphur. One insight from this analysis is that the results presented here are very consistent with prior proposals to designate regional SECA protection. The primary insight across all these metrics is that achieving SECA-compliant performance by ships in the Mediterranean is about as cost-effective as other SECA designations, when compared with current (pre-2020 global MARPOL VI) conditions.

The North American ECA proposal included an economic analysis which estimated that compliance with SECA standards would increase the cost of shipping a container by around 3%, with a similar, small impact on cruise vessels. As such, the North American ECA proposal concluded that the impact on international trade would be modest. Moreover, U.S. and Canadian port traffic and cargo statistics document substantial growth in commerce following ECA implementation, without evidence of negative economic consequence. Given that the results of this study identify similar costs per unit of pollution abated, we suggest that the marginal costs of implementing the proposed Med ECA would be on a similar order of magnitude to the marginal costs for the North American ECA. This analysis is further supported by a report from the European Commission (COM(2018) 188 Final) which describes 93% compliance and no loss of traffic, modal shift, shutdowns, or changes in cargo turnover resulting from the implementation and enforcement of the North Sea and Baltic SECAs. The high compliance rates and minimal disturbances to freight flows indicate that the economic pressure of higher fuels costs resulting from the North Sea and Baltic SECAs indicate that the marginal costs borne initially by shippers were not burdensome to the industry.

Table 27. Cost-effectiveness comparison with North American ECA[1]

Benefit Type	**U.S. estimates for North American ECA**	**North American ECA results with adjusted fuel prices**[2]	**Proposed Med ECA combining MARPOL VI and SECA results**
Control Target			
Abated SO_x emissions	\$4,500 /MT SO_x	\$14,000 /MT SO_x	\$8,900 /MT SO_x
Abated $PM_{2.5}$ emissions	\$43,000 /MT $PM_{2.5}$	\$128,000 /MT $PM_{2.5}$	\$94,000 /MT $PM_{2.5}$
Health Outcome			
Avoided mortality[3]	\$0.410 M/Δ Mortality	\$1.229 M/Δ Mortality	\$0.353 M/Δ Mortality
Avoided asthma illnesses[4]	\$16 k/Δ Morbidity	\$49 k/Δ Morbidity	\$21 k/Δ Morbidity

1 Combined MARPOL VI and the proposed Med ECA costs for this study compared with U.S. NO_x and PM data to reduce ship fuel from pre-MARPOL VI conditions to 0.1% S SECA conditions.

2 Given that the 2009 North American proposal to designate an ECA used a fuel price difference of \$145/MT to shift from HFO to SECA compliant fuel, and this study uses a fuel price difference of ~\$434/MT, we multiply U.S. cost-effectiveness estimates (column 2, above) by the ratio of these price differences to match with fuel price changes used for this study.

3 North American mortality methods are similar to those used here, although they may use a health risk equation similar to the log-linear equation discussed and compared in Sofiev et al, Nature Communications 2018 (*3*).

4 For comparison purposes with this study's childhood asthma illness results, the set of childhood asthma related diseases reported separately by the U.S. was summed.

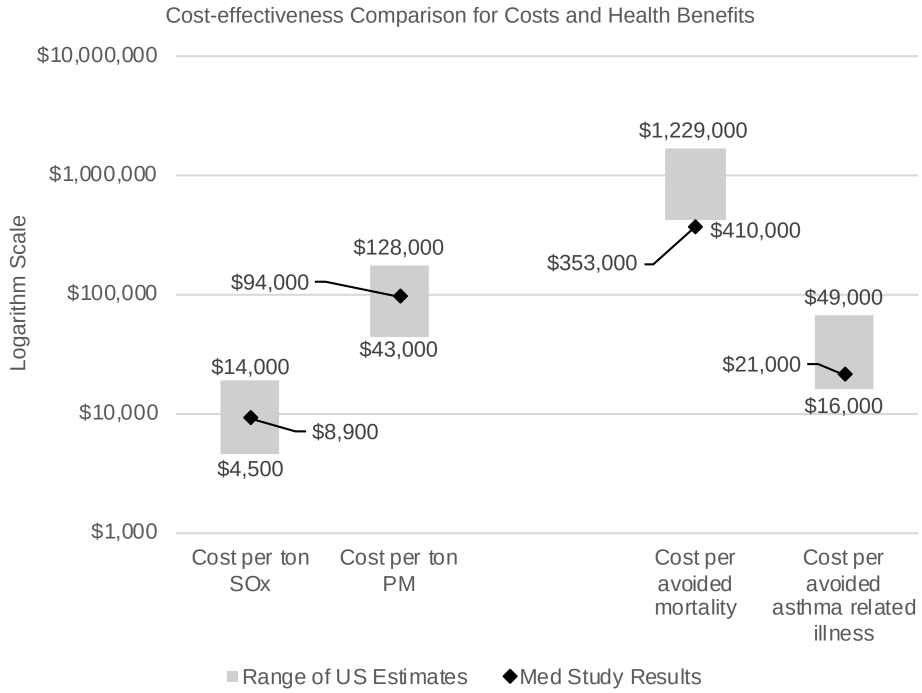


Figure 32. Summary Comparison of cost-effectiveness metrics for this study (combining MARPOL VI and the proposed Med ECA measures) with U.S. SO_x and PM data from the Proposal to Designate an Emission Control Area for North America

6.2 Comparison with Costs of Pollution abatement from Land-Based Sources

The North American ECA application (document MEPC 59/6/5) suggests that the costs of SO_x reductions from land-based sources has ranged from $249 to $7,474 per metric ton (2018 USD). The Shadow Prices Handbook, published by CE Delft (*13*) estimates the costs of SO_x abatement at between €5,645 and €11,308 per metric ton, or $6,461 to $12,943 per metric ton (2018 USD) in the Netherlands based on emissions in 2008. These estimates are supported by another study which found land-based sulphur abatement costs to vary between €600 and €13,000 per metric ton (*14*). The Shadow Prices Handbook finds PM abatement costs of between €2,600 and €56,540 (2018€) per metric ton or $2,976 to $64,717 /MT PM (2018 USD). This analysis finds a central estimate for PM abatement of $94,000/MT PM, which is aligned with the cost-effectiveness of PM abatement for the North American ECA but is greater than the upper end of the Shadow Prices Handbook. This analysis finds a central estimate for SO_x abatement of $8,900/MT SO_x, which is aligned well with the Shadow Prices Handbook, and indicates that SO_x abatement cost-effectiveness from the proposed Med ECA would be comparable to or better than the cost effectiveness of land-based SO_x emission reductions. Note that the costs described above refer to the cost effectiveness of the switch from Baseline fuels in 2016 to SECA compliant fuels in 2020. If only considering the step from MARPOL VI 0.5% S fuels, the cost effectiveness of PM and SO_x abatement becomes $155,000 /MT $PM_{2.5}$ and $13,400 /MT SO_x.

7 Methods and Data

Section 3.1 provides detail on methodologies and data used to assess shipping activity and to estimate shipping emissions and fuel consumption for base year 2016 and future year scenarios with and without SECA compliance performance. Section 3.2 summarizes the employment of FMI's ***System for Integrated modeLing of Atmospheric coMposition (SILAM) model*** to evaluate fate and transport of ship emissions needed to estimate geospatially the increased concentrations of air pollution exposure, change in wet and dry deposition of harmful combustion exhaust particles, and change in suspended aerosols that may contribute to regional haze. Section 3.3 summarizes health risk modeling that is applied to updated country-specific health incident data to estimate premature mortality and asthma impacts that may be avoided if the fleet of ships operating in the Mediterranean were to comply with SECA fuel-sulphur conditions. Section 3.4 presents the fuel prices used to estimate increased costs from adopting SECA compliant fuels, and the potential for alternate technical measures (aftertreatment and advanced fuels) to achieve SECA compliance at lower cost. Section 3.5 discusses key sources of methodological or data uncertainty, and sensitivity to key model input choices.

7.1 Emissions Modeling

We estimate Mediterranean ship emissions and fuel usage using the Ship Traffic Emission Assessment Model (STEAM). The Finnish Meteorological Institute's STEAM model combines vessel activity from Automatic Identification System (AIS) and technical description of the global fleet from IHS Fairplay. The STEAM model incorporates local regulations, such as EU Directive 2016/802, and involves water resistance calculations based on the speeds indicated by the AIS data and it uses engine load dependent functions to describe specific emissions and energy usage of each individual ship at different phases of navigation, including at berth, maneuvering, anchorage, and underway. The STEAM model has undergone extensive peer-review and has formed the basis for multiple HELCOM and IMO submittals (*15-24*)[5]. Used in the Third IMO GHG Study (*25*), and recently used to evaluate the impacts of the 2020 MARPOL VI 0.5% global sulphur cap, we consider STEAM to be the premier model for emissions modeling work.

We incorporate tonnage, power, and vessel count growth rates shown in Table 28 to estimate future scenarios. Our experience preparing forecasts for shipping is extensive. In 2007, EERA developed emissions forecast techniques that recognized the roles of trade activity, energy demand, and technology in estimating future emissions (*26*). STEAM model integrates capacity for vessel-type-specific fleet renewal rate, trade traffic growth rates, fuel-type choices, and technology adoption (*27*).

7.1.1 Fuel Usage

The STEAM model estimates fuel consumption based on observed vessel AIS operating profiles. Fuel usage estimates form the basis for estimating economic costs due to changes in fuel usage and price. Fuel usage is estimated based on the vessel operating mode, speed, installed power, and environmental conditions, such as wave and ocean currents, which affect fuel use. Section 7.5.4 describes fuel prices.

7.1.2 Future Scenarios

STEAM inputs use 2016 high spatiotemporal resolution Automatic Identification System (AIS) data, coupled with fleet growth rates similar to reported in Table 28 2018 IMO Fuel Availability, to estimate air emissions from ships for 2020, 2030, and 2050 (*28, 29*). We present two tabular inventories, allowing for comparison between inventories based on 0.5% sulphur fuels, and with 0.1% sulphur SECA-compliant fuels. We also produced emission inventories for sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), and fuel usage.

[5] Additional annual HELCOM ship emission reporting for the Baltic Sea countries, may include: MARITIME13/4-5/INF, MARITIME11/7-3/INF, MARITIME10/5-1/INF, MARITIME9/Agenda Item 9, MARITIME9/6-2/INF, MARITIME8/6-2/INF, MARITIME8/6-3/INF, MARITIME7/7-1/INF Contribution to the work of AIS expert working group: AIS EWG/15/7-2, AIS EWG/16/5-2, AIS EWG/17/9, AIS EWG/18/6-1.

STEAM model includes vessel-specific and dynamic step changes on an annual basis, assigned stochastically. This differs from the vessel-type category growth rates used in other work, and provides greater detail than some other vessel-specific models we have seen, including the IMO Fuel Availability Study and Sofiev et al. (2018), which used simple categorical growth rates (*3, 28, 29*). The growth rates shown in Table 28 are combined with energy efficiency improvements, described in the Energy Efficiency Design Index, to estimate future fuel use and emissions.

Table 28. STEAM Model vessel power, tonnage, and count growth estimates used for future scenarios

Main Category	Annual Dwt Change (%)	Annual Power Change (%)	Annual Count Change (%)
RoPax vessels	1.25	-2.25	1.1
Vehicle carriers	1.25	-2.25	1.1
Cargo ships	0.4	-1.7	0.2
Container ships	1.2	-2.25	1
Tankers	2	-1.9	1.2
Passenger ships	0.3	-1.3	1
Cruisers	0.3	-1.3	1
Fishing vessels	0.3	-1.3	1
Service ships	0	-1.3	0.5
Unknown	0	-1.3	1
Misc	0	-1.3	0.5

7.2 Emissions Fate and Transport and Exposure Modeling

FMI's System for Integrated modeLing of Atmospheric composition (SILAM) model was used to estimate changes in atmospheric $PM_{2.5}$ concentrations, as well as wet and dry deposition of PM_{total} and SO_4. SILAM is a global-to-mesoscale dispersion model developed for atmospheric composition and air quality modeling. The SILAM Model has been peer-reviewed and applied to a range of air quality studies from global (*3*), to regional (*30*) and local (*31*). The technical description of the SILAM model is available from FMI[6].

The SILAM model is capable of generating high resolution estimates of air quality based on inputs from the STEAM model (Figure 33), and land-based inventories also used by FMI. Recently, we used SILAM in our assessment of the global health benefits of implementing the 0.5% sulphur rule.

The modeling domain for this project is shown in Figure 8, however, due to the transboundary nature of air pollution, we also developed a lower-resolution (0.5 x 0.5 degree) global-scale emissions inventory for marine and land-based sources to model the boundary conditions around our modeling domain, within which we developed high-resolution (0.1 x 0.1 degree) marine and land-based emission profiles.

Using emissions inputs from the STEAM model, we run the SILAM model twice. First, we model air quality under the MARPOL VI 0.5% S fuel baseline assumptions, then we model air quality under the proposed Med ECA 0.1% S fuel assumptions. The land-based emissions between these two runs are equivalent, so the difference between the two modeling outputs describes the air quality benefits resulting from the proposed Med ECA, which we then use to evaluate the health and environmental benefits of the proposed Med ECA.

[6] http://silam.fmi.fi

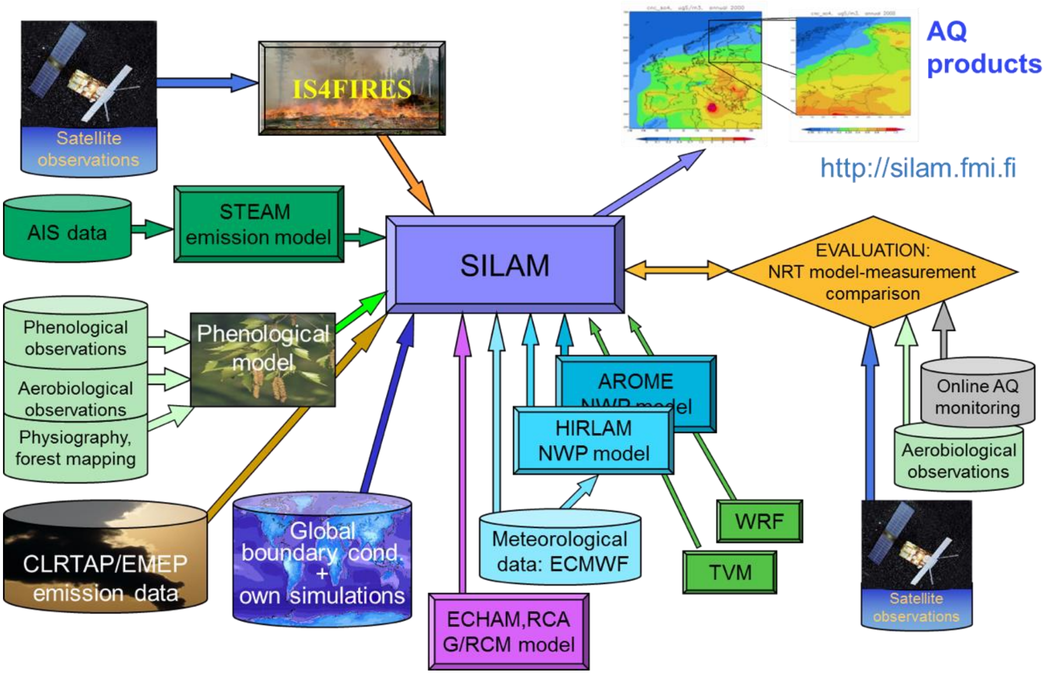


Figure 33. Schematic representation of the STEAM/SILAM system for air quality research problems

7.3 Health Related Impacts Modeling

The methodology for modeling health impacts follows the approach discussed in previous work (*32, 33*). Earlier work applied mortality risk functions identified in Ostro (2004) (*34*), which in turn builds on work developed out of the U.S. Harvard Six Cities study conducted earlier by Pope, et al. (*35-37*).

$PM_{2.5}$ exposure concentrations in this study area are like those in the Harvard Six Cities study, indicating that premature mortality risk functions derived from the Harvard Six Cities study can be applied to this study area.

This health impacts assessment follows work published in *Nature Communications* in 2018 that employs a concentration-response (C-R) function from Lepeule, et al. (2012), which updates epidemiology from the Harvard Six Cities study (*38*). Health outcomes are estimated using a linear C-R function, which reflects updated understanding of the relationship between health and exposure to air pollution and provides improved estimates of health outcomes where ambient concentrations of $PM_{2.5}$ exceed World Health Organization (WHO) guidelines (>20µg m^{-3}). Health outcome estimates focus on cardiovascular and lung cancer mortality responses in populations aged over 30 years old, aligned with Lepeule, et al. (2012). As in earlier work (Sofiev et al., 2018), we include an assessment of childhood (<14 years) asthma morbidity, which uses similar concentration-response equations based on reported asthma incident rates by country (*39*).

Gridded population data for 2020 are from NASA's SocioEconomic Data and Applications Center (SEDAC) Population of the World Version 4.10 (*4*). These data provide gridded population counts, which we resampled to 0.1° x 0.1° resolution (~10km x 10km) to reflect regional differences in population counts. These population data are built upon UN statistics and apply sub-national rates to estimate population change (growth/decline) to estimate population counts in the future. We apply country-level age cohort fractions directly to the population counts for each Member States of the United Nations to determine the age cohort populations by country (*40*). We assume a uniform population age structure across each country, multiplying the population grid by the country-specific fraction of population under the age of 14 and between the ages of 30 and 99. This approach likely does not account for regional differences in age cohorts, but represents the best available practice given the paucity of country-specific age-cohort data.

Country-specific incidence rates for cardiovascular disease and lung cancer are derived from data from the WHO's Global Health Observatory (GHO) (Table 29) (*41, 42*) . To determine overall health outcomes associated with ship emissions and the proposed Med ECA, we calculate avoided mortality based on the change in $PM_{2.5}$ concentration between the 2020 MARPOL VI (0.5% S) scenario and the proposed Med ECA (0.1% S) scenario.

Table 29. WHO cardiovascular and lung cancer disease mortality, and childhood asthma morbidity rates

Country	Cardiovascular (Disease Per 100,000)	Lung Cancer (Disease Per 100,000)	Asthma (Disease Percent, Age <14)
Albania	330.0	26.0	3.6
Algeria	220.3	8.7	7.1
Bosnia And Herzegovina	277.8	29.1	9.9
Croatia	208.0	22.9	5.2
Cyprus	142.3	20.7	9.9
Egypt	412.3	7.6	5.2
France	70.6	27.8	12.6
Greece	135.1	31.8	9.8
Israel	77.1	20.3	10.3
Italy	103.2	22.9	11.4
Lebanon	295.0	17.0	11.6
Libya	324.0	19.0	9.9
Malta	138.5	20.9	14.1
Monaco	70.6	27.8	9.9
Montenegro	329.2	36.6	9.9
Morocco	260.3	12.8	13.3
Slovenia	138.5	28.7	9.9
Spain	82.1	23.8	13.9
Syrian Arab Republic	377.5	17.0	5.1
Tunisia	278.5	15.7	9.3
Turkey	202.6	29.8	9.9

Country-specific incidence rates for childhood asthma are provided in the 2014 Global Asthma Report (*43*). For Asthma disease, we use the "Asthma Ever" data in the 13-14 year old age group reported in the 2014 Global Asthma Report (Table 29), and apply this percentage to the population fraction under the age of 14. Zheng et al (*39*) provide relative risk (RR) factors for childhood asthma from exposure to $PM_{2.5}$ pollution (Table 2 of Zheng), which we convert to β coefficients.

We calculated avoided mortality and morbidity due to changes in total particulate matter concentrations using approaches mentioned above, consistent with other recent work in this area (*33, 44*). The total effect (E) of changes for each grid cell is given as:

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

where *B* represents the incidence rate of the given health effect (Table 29); *P* is the relevant population, weighted by the age cohort; and *AF* is the attributable fraction of disease due to the shipping-related PM pollution, and is given by:

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

For a "linear" C-R model, the response RR is given by the function (*45*):

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

And therefore,

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

which leads to

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

where β = 0.023111 (95% CI = 0.013103, 0.033647) for cardiovascular mortality; β = 0.031481 (95% CI = 0.006766, 0.055962) for lung cancer related mortality (*36, 38, 46*); and where β = 0.002469 (95% CI = 0.001291, 0.003633) for childhood asthma morbidity (*39*).

This approach follows WHO guidelines in the 2016 Global Burden of Disease (*47*) by combining WHO-derived health incidence data with gridded population and ambient air quality data. The functional form of the integrated exposure response (IER) follows a modified, but functionally similar, form of the IER recommended by the WHO.

7.4 Economic Feasibility Assessment

7.4.1 Fuel Prices

The primary data source for fuel prices over the last decade used in this study is BunkerIndex (*48*) coupled with data from the St. Louis Federal Reserve (FRED) on LNG prices (*49*). Figure 34 shows the mean weekly fuel prices ($/MT) for IFO380, IFO180, MDO, MGO, and LNG from 2009 to 2018.

We note two price regimes in the bunker fuels data. 2011-2015 represents a higher price regime, post-recession, while 2015-2018 shows a lower price regime (along with pre-2011). We adopt the most recent price regime for this work, as it includes the global price effects of SECA fuels, which went into effect post-2015. All prices are adjusted to 2015 constant $USD using the CPI index for fuels and fuel oil (*50*) to allow for better comparison between time series prices.

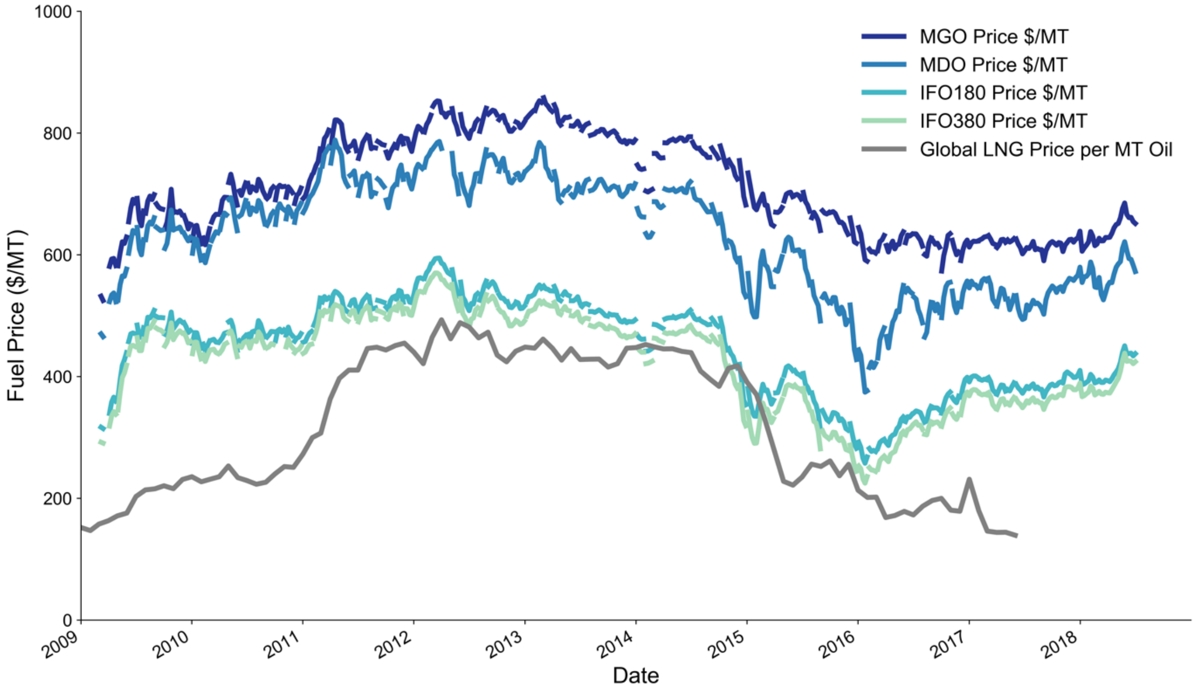


Figure 34. Bunker prices for marine bunker fuels from 2009 to 2018, resampled to mean weekly prices, in 2015 USD/MT

We assume that MDO is compliant with global MARPOL VI standards (0.5% S), and thus use the MDO price to define the fuel price under the MARPOL VI scenario. We note that this price includes fuels that may not fall within compliance of global MARPOL VI. In all weeks observed from 2009 to 2018, MDO prices are lower than SECA-compliant MGO prices.

As shown in both Figure 34 there are periods of volatility in the absolute fuel price time series data, as well as in the ratio of the prices compared to MGO (Figure 35). The primary period of volatility in fuel prices was between September 2014 and July 2016. Prices, and their ratios, are similar before and after this time period. In the period after July 2016, IFO380 prices are 58.5% of MGO prices, and MDO prices are 87.0% of MGO prices. As of August 2018, LSFO (0.5% S compliant) prices at Rotterdam ($635.00/tonne) were priced at 96.2% of MGO prices ($656.50/tonne). Given observed fuel price differentials, our selection of MDO price represents a conservative choice for estimating an upper bound in the fuel price differentials.

Additionally, we recognize that definitions of MGO and MDO fuels vary regionally, and do not always directly map to MARPOL VI and SECA compliant fuels, respectively. We address this issue by selecting the maximum observed spread between HFO, MDO, and MGO in our time series data, in order to reflect the maximum observed price differential, and account for inconsistencies in fuel definitions, while overall providing a robust accounting of fuel prices.

As noted, LNG price data are provided by FRED and do not directly reflect delivered ship bunker prices, but rather global LNG fuel prices. In addition, we convert LNG prices to prices per MT of oil equivalent, but this calculation doesn't account for the fuel consumption penalty associated with using LNG in marine engines, e.g., changes in thermal efficiency and/or energy density, which entail converting LNG prices per volume or mass to prices per kWh.

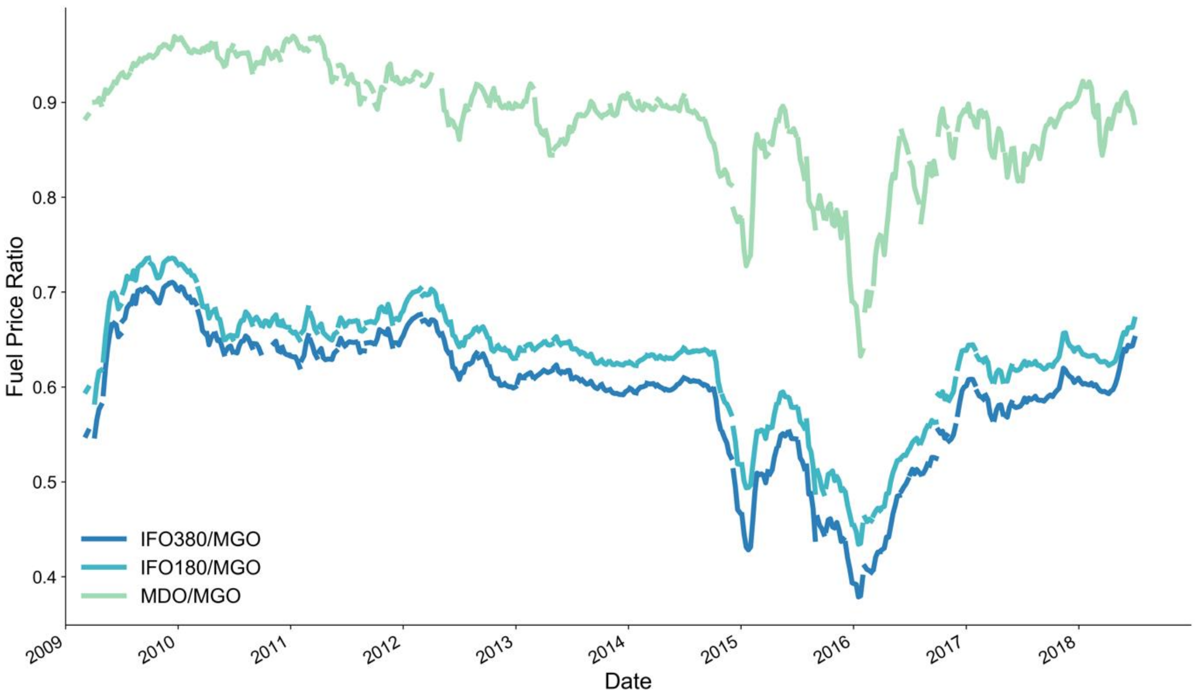


Figure 35. Price ratio of MGO to IFO380, IFO180, and MDO

7.4.2 Cost Methodology for MARPOL VI and the proposed Med ECA Scenarios

Table 30 shows the fuel prices used in this analysis. This study chooses a high SECA-compliant fuel prices and adopts a wide price differential in the available time series data in order to provide a conservatively high estimate of the costs of fuel switching. Specifically the 10-year high MGO price represents this study's SECA-compliant fuel price, an MDO price between the 10-year high and 75th percentile prices is selected to represent MARPOL VI global-compliant fuel price, and the 10-year mean IFO 380 price represents the price of potential use of HFO residual marine fuels (e.g., with scrubbers in Section 7.4.3). An LNG price approximately equal to the 70th percentile of historic LNG price data is applied to LNG consumption (for currently identified LNG vessels, and for advanced fuel consideration in Section 7.4.3).

Table 30. Fuel prices used in this analysis

	LNG Price	MGO Price	MDO Price	HFO Price
Study fuel prices	$327	$858	$760	$424

The change in fuel costs under the MARPOL VI scenario adjusts STEAM estimates of HFO fuel usage in the base 2016 analysis by the HFO-MDO price difference. Given the 2020 MARPOL VI fuel consumption detail from the STEAM model, the cost of compliance with MARPOL VI global 0.5% sulphur limit is directly estimated by multiplying each marine fuel by this study price shown in Table 30. Similarly, each type of fuel consumption provided for the 2020 proposed Med ECA fuel consumption by the STEAM model is multiplied by its characteristic fuel price per Table 30. The increased cost to adopt SECA compliant fuel is therefore the difference in price between the 2020 proposed Med ECA and 2020 MARPOL VI fuel costs.

7.4.3 Cost methodology for evaluating technology and advanced fuels adoption

This section describes the methodology used to estimate compliance costs for vessels using alternative abatement technology in the form of scrubbers, or alternative fuels in the form of LNG to meet proposed Med ECA compliance standards.

7.4.3.1 Exhaust Gas Cleaning (Scrubber) Costs

To estimate scrubber penetration and costs, we took the vessel-specific output from the STEAM model for the 2020 scenarios and identified the installed power on each of the >30,000 vessels and the fuel consumption estimates under the proposed Med ECA scenario condition. The data output from the STEAM model also include annual operating hours in the region.

The economic details for scrubber investment were obtained primarily from a 2018 CARB report (*51*). Scrubber details for capital costs and operating costs are provided in Section 4 (Economics) of that report and include reference to international work from a 2013 presentation by DNV-GL and an *Exhaust Gas Cleaning Systems Selection Guide* prepared by Glosten Associates for the U.S. DOT Maritime Administration. The CARB tech report acknowledged lower adjusted capital costs per kW installed power for larger vessels. We followed the CARB technical reports alignment for lower capital costs for larger vessels, however we applied the same O-M costs, 4% of capital annually, uniformly across all vessel types

Table 31. Summary of cost elements used to evaluate scrubber economic feasibility

Bounds	DNV-GL	MARAD	This study
Capital Cost		$/kWh	
Lo	$152	$147	$147
Hi	$216	$470	$470
Operating Cost	**$/MWh**	**Percent of annual capital costs**	
Lo	$0.4	1%	4%
Hi	$1.0	4%	4%

Following the general methodology published in (Carr and Corbett, 2015, RATES), we applied the annualized cost of capital, annualized cost of maintenance, and annual cost of operations provided in $/kWh. Using the scrubber capital and OM cost inputs, we were able to estimate the annualized additional cost to operate a scrubber. By substituting the lower price for HFO fuels, we were able to estimate the annual savings in fuel costs if a vessel with a scrubber used the least cost non-SECA, non-MARPOL VI heavy fuel oil. The net sum of the additional scrubber cost, and the net savings of scrubber operations using a less costly fuel was compared with the cost of compliance with SECA fuel standards. Our methodology adopts the assumption that a vessel that would install a scrubber would also use the least costly marine fuel, namely HFO. If the cost of operating a scrubber allowed the vessel to comply with SECA conditions at a lower cost than fuel switching, it was identified as an economically feasible investment. Input conditions to which the results were most sensitive included the following

A. Hours of operating within the proposed Med ECA domain

B. The investment horizon (i.e. the years over which the investment cost was amortized), relative to the age of the ship

C. The interest rate at which the fleet was considering this investment

We observe, as expected, that vessels with higher installed power would realize greater annual fuel savings from operating a scrubber, and scrubber technology cost inputs for larger ships were assigned lower capital costs per installed kW.

7.4.3.2 Alternative Fuel Costs

Technology providers and fleet managers have considered alternative fuel technical feasibility with increased attention over the past couple of decades. This includes both liquid and gaseous fuels, ranging from petroleum derived products to natural gas derived products (e.g., methanol) to gaseous products (e.g., LNG). However, limited demonstration or commercial adoption of alternative fuels means that market prices for alternative fuels and costs to convert or build ships using these fuels are not well established. Most information on pricing comes from industry reports by technology providers presenting analyses that help market the feasibility of these technologies, so may be considered preliminary or prospective a priori of broader market adoption. Moreover, full costs for conversion to alternative fuels depends upon other factors beyond ship costs; infrastructure must be provided for handling, delivery, and bunkering of alternative fuels. Lastly, while the fuel-sulphur content of these fuels may be near zero, fully in compliance with the SECA sulphur limit, there are other environmental tradeoffs worth evaluating; a full assessment of alternative fuel feasibility may require consideration of greenhouse gases, engine thermal efficiency and energy density tradeoffs, and life-cycle environmental impacts that consider fuel extraction and processing stages prior operational stages.

This analysis focuses on one alternative fuel in the context of shipboard adoption and use only. LNG is a SECA compliant fuel that is being increasingly employed in the marine transportation sector. We employ a similar methodology to that used for scrubbers to estimate the costs and penetration of LNG in the Mediterranean Sea fleet. Essentially, we use the cost of fuel-based compliance with a SECA as the default from which fuel cost savings may be achieved through use of lower cost LNG fuel. Within the bounds of the higher cost of SECA fuel and lower cost of using LNG fuel, an investment window for capital conversion to alternative fuels can be identified. In other words, a vessel net cost of complying with SECA conditions are lower using LNG, the that alternative fuel conversion for that vessel may be economically feasible. We evaluate the fraction of the fleet that is replacement eligible in 2020, i.e., greater than 20 years since build. We evaluate the fraction of those vessels for which LNG would be economically feasible.

We identify and select a set of candidate replacement vessels [i.e., older vessels nearing typical salvage age for that vessel type] and replacing them with a new LNG powered vessel. We apply a cost premium per installed kW to represent the cost of installation of necessary LNG power systems (*52*). For this study, we expect to apply a price premium of $450/kW to estimate the additional capital costs associated with containership LNG operation. Obtained from an industry report for LNG costs and benefits in the context of containerships, we apply this per-kW cost factor to all vessels eligible for age-related replacement.

We also apply fuel price premiums from Table 30 to determine the price difference between SECA fuel and LNG. Using this estimator of fuel cost savings, we compute the percent change in annual fuel costs. Using a ship financing investment rate of 6% and a financing period of 20 years, we compute the net present value of fuel cost savings. Results are presented in Section 5.3.

7.4.4 Methodology for partial valuation of benefits (avoiding premature death)

This section describes how social benefits such as avoided mortality may be included in a benefit-cost context through rigorous application of economic valuation techniques. This study applies the latest available country-specific study valuing a statistical reduction in the risk of premature mortality to the health mortality results obtained in Section 4.1.

7.4.4.1 Cost-effectiveness Evaluation

This section describes an alternate approach for comparing the costs of achieving benefits when they cannot be fully valued or directly monetized using accepted economic algorithms. These benefits offer substantial value that may require deeper research using social science techniques such as citizen willingness to pay, willingness to accept, risk preference surveys or experiments, etc. One approach that is used in these cases it to evaluate the cost-effectiveness, i.e., the cost to achieve a unit of benefit. Table 32 identifies those outcomes for which this study may consider cost-effectiveness reporting. Providing a metric of cost-effectiveness routinely offers decision makers a convenient way to consider comparative actions and represents a commonly used decision support tool. However, applying total costs of compliance to any one of these beneficial outcomes presents conceptual challenges that need to be transparently revealed.

1. Within a benefit type, allocating total costs to each metric treats them as independent when in fact they are jointly obtained by the same cost of compliance. Therefore, the cost-effectiveness ratio is overstated; in other words, the costs of achieving the set of outcomes is less than suggested. Conceptually, the cost-effectiveness of control might best be applied to the specific pollutants controlled (SO_x), particularly where there are broad benefits (reduced PM exposure, reduced acidification) that would not be associated solely with an alternate pollutant ($PM_{2.5}$).

2. Across benefit types, one cannot combine, or cross compare, the benefits for two primary reasons. First, some benefit types represent nested components of other benefit types; clearly, reducing emissions contributes to reduced exposure which contributes to reduce health outcomes. Second, the numbers are not directly comparable given orthogonal units in the denominators; achieving least-cost compliance per tonne emissions through emission control may appear more or less "cost-effective" than the cost of reducing the percent of acidifying discharge to the environment.

3. Many environmental policy decisions are made using commonly reported cost-effectiveness metrics that are, in fact, proxies for beneficial goals stated in the emission control policy. For example, IMO MARPOL Annex VI "seeks to minimize airborne emissions from ships (SO_x, NO_x, ODS, VOC shipboard incineration) and their contribution to local and global air pollution and environmental problems." In this regard, the two most common metrics types are (a) control cost-effectiveness metrics, and (b) outcome cost-effectiveness metrics. Control cost-effectiveness is generally the most easily quantified and compared across policy measures. For example, the proposal to designate the North American ECA provided control cost-effectiveness estimates (document MEPC 59/6/5, Page 7, Paragraph 14); that proposal does not provide outcome cost-effectiveness estimates, nor benefits monetary valuation. Similarly, the proposal to designate the North Sea SECA sought to "maximize the environmental benefit at least cost" by suggesting a relative cost-effectiveness of controlling ship emissions (document MEPC 44/11/4).

4. The outcome of greater importance often may be considered the dominant outcome for examining cost-effectiveness. Often policy decisions are taken by considering the total costs assigned solely to a primary benefit, which implies that other benefits of pollution control are un-valued co-benefits. For example, the designation of the North Sea SECA in 1999 considered

that "ship emissions in the North Sea area contribute significantly to potentially damaging levels of SO_x deposition in areas with sensitive ecosystems (document MEPC 44/11/4). Technical and feasibility support for designating the North Sea SECA did not include an assessment of air quality benefits for premature mortality from respiratory exposure. Additionally, the designation of the North American ECA included discussion of benefits to "terrestrial and aquatic ecosystems such as visibility, ozone uptake, eutrophication, acidification, loss of forest biomass, and overall forest health … [and] … the reductions in adverse health impacts" (document MEPC 59/INF.13).

Table 32. Summary of quantified benefits that may be evaluated using cost-effectiveness

Benefit Type	Denominator input
Control cost-effectiveness	**Presented in Section 5.5.1**
Abated SO_x emissions	Reduction in annual MT SO_x
Abated $PM_{2.5}$ emissions	Reduction in annual MT $PM_{2.5}$
Exposure cost-effectiveness	**Not quantified: intermediate between control and outcome**
Reduced $PM_{2.5}$ exposure	Annual average reduction in PM concentration µg per m^2
Reduced sulphate deposition (wet/dry)	Percent change (annual average over domain)
Reduced PM deposition (wet/dry)	Percent change (annual average over domain)
Health related cost-effectiveness	**Presented in Section 5.5.1**
Avoided mortality	Avoided annual deaths (lung cancer/cardiovascular)
Avoided childhood asthma	Avoided annual childhood asthma

7.4.4.2 Monetary Value of Reduced Risk of Premature Death from Ship Pollution

In general, a benefit-cost analysis should compare the net monetized benefits for all mitigation and costs for all compliance actions. This could be considered in the following equation:

$$Net\ Benefits \geq Value\ of\ avoided\ impacts - Cost\ to\ achieve\ Med\ ECA$$

Where the value of avoided impacts may be considered to include the monetized sum of

$$\begin{aligned} &Value\ of\ avoided\ impacts \\ &\quad = Avoided\ Mortality\ (\$V_{Mortality}) + Avoided\ Morbidity\ (\$V_{Illness+\ Care}) \\ &\quad + Avoided\ Deposition\ Damages\ (\$V_{Acidification}) + Improved\ Visibility\ (\$V_{Haze}) + etc. \end{aligned}$$

No prior proposal to designate a SECA under MARPOL VI, indeed very few policy proposals if any, have presented analyses that fully monetize all benefits. Prior proposals to designate regional SECAs under IMO MARPOL Annex VI have generally presented cost-effectiveness justifications for benefits of dominant concern. The basis for designation the Baltic Sea SECA in the first ratified version of MARPOL Annex VI was based in part on a concept termed "critical loads", which generally means the maximum tolerable environmental exposure that a region's ecosystem (in whole or part).

Moreover, there are several ambiguities and assumptions that often need to be documented or researched. However, substantial research has been conducted for decades into valuing changes in the risk of premature death, termed by researchers to be the "value of a statistical life" or VSL. Formally, VSL is the monetary value of small changes in mortality risks, scaled up to reflect the value associated with one expected fatality in a large population. VSL can also be illustrated using metrics that allow the researcher to identify the value of risk reductions through revealed or stated preference studies. For example, if an individual were willing to pay $225 for a 1 in 10,000 reduction in their risk of death from a given activity, their implicit VSL would be:

$$\text{VSL} = \frac{\text{Willingness to Pay}}{\text{Risk Reduction}} = \frac{\$225}{1/10000} = \$2{,}250{,}000$$

This project identified a key resource, published in the peer-reviewed literature in 2017 that performs a state-of-practice analysis of VSL:

> "Countries throughout the world use estimates of the value of a statistical life (VSL) to monetize fatality risks in benefit-cost analyses. … This article proposes … the best way to calculate a population average VSL … for all 189 countries for which World Bank income data are available" (*8*).

Viscusi and Masterman include nearly all Mediterranean coastal States as listed in Table 33 (*8*). Given the regionally asymmetric mortality patterns reported in Section 4.1.4, we multiply each country's results for mortality and avoided mortality attributed to ship emissions by that country's respective VLS estimate, producing a single mortality-weighted VSL for the Mediterranean coastal States.

Table 33. International Income-Adjusted Estimates of the VSL for Mediterranean coastal States

Country	VSL in Million 2015 USD	Country (continued)	VSL in Million 2015 USD
Albania	0.736		
Algeria	0.838	Libya	N/A
Bosnia and Herzegovina	0.803	Malta	4.117
Croatia	2.185	Monaco	N/A
Cyprus	4.471	Montenegro	1.242
Egypt	0.575	Morocco	0.521
France	6.975	Slovenia	3.818
Greece	3.496	Spain	4.908
Israel	6.154	Syrian Arab Republic	N/A
Italy	5.645	Tunisia	0.685
Lebanon	1.326	Turkey	1.712

The regionally adjusted VSL is presented in Table 34, and can be applied as a sort of benefit-cost threshold. Estimated compliance costs per avoided mortality that are less than a mortality VSL for the region may be interpreted to provide net benefits regarding health outcomes involving lung cancer or cardiovascular mortality risks. Such a result would imply that additional benefits to morbidity and environmental damage would strengthen the evidence for positive net benefits. Given the other benefits of lower-sulphur ship fuel on morbidity and environmental damages, a case where compliance costs were to exceed this VSL threshold could not independently be used to declare that compliance costs exceeded the sum of total benefits.

Table 34. Mortality-weighted VSL for Mediterranean coastal States

Policy Regime	Mortality-weighted VSL for Mediterranean coastal States ($ Millions)
No Action	2.157
MARPOL VI	1.094
Proposed Med ECA	1.818

Section 5.5.2 applies this VSL methodological approach to evaluate estimated net benefits from reducing premature mortality risk.

7.5 Uncertainty and Limitations

7.5.1 Emissions Modeling

The STEAM model includes dynamic growth and rates of change in fleets. Growth estimates reflect observed changes in the Mediterranean Fleet, and projections assume similar fleet composition and update conditions to those that were observed in the past. The STEAM model also assumes “optimistic” improvements in energy efficiency for new ships. These energy efficiency improvements are governed by projected adoption of EEDI measures in new builds, and continuing behavioral adaptations, such as slow steaming. The emissions estimates also assume no changes in demand for maritime transport of goods. Publications employing the STEAM model have undergone extensive peer review, and the STEAM model represents one of the premier ship emissions models, having been widely applied to international shipping studies.

7.5.2 Air quality modeling

The uncertainty of SILAM model outputs has been evaluated in several studies. These include the comparison over marine areas stressing the performance of the sea salt controlling mechanisms (*53-55*), analysis of European data (*56*), publications of Air Quality Model Intercomparison Initiative (*57, 58*), automatic daily evaluation for Europe (http://www.regional.atmosphere.copernicus.eu/), China (http://www.marcopolo-panda.eu/forecast), and Northern Africa and Southern Europe (https://sds-was.aemet.es). SILAM estimated mean SO_2 concentrations in regions with substantial sulphur emissions are well calibrated to the environment, e.g. in China the bias of SO_2 is -3.3 μg S m^{-3}, in Europe, the SO_2 bias is +0.3 μg m^{-3} while for sulphate it is -0.03 μg S m^{-3}.

Overall, evaluation of the SILAM model performed in several international studies did not show any major deficiencies of the model.

7.5.3 Exposure and Health

We employ mortality and morbidity incidence rates reflecting the best available data from the WHO and Global Asthma Network. However, we note that the country-to-country comparisons indicate some potential discontinuity in underlying incident rates among communities that may be near each other but in adjacent countries. Given the similarity/dissimilarity among adjacent country incident rates, we observe and suggest that our country-to-country comparison of health burden is more directly related to the modeled changes in pollution concentration than could be allocated to country-to-country differences in the quality of incident rate statistics. We employ incidence rates from the most recent, peer-reviewed studies which represent populations similar to those in the Mediterranean Countries. In order to further account for uncertainty, we apply central as well as lower and upper bound relative risk functions, which allow the reader to interpret the 95% confidence interval of our health outcome estimates.

7.5.4 Fuel pricing data

We use time series fuel pricing data for the past 9 years. These data show that fuel prices are generally heavily coupled and proportional to one another. We apply conservative estimates of the maximum observed price spread between MGO (0.1% S) and MDO (0.5% S) and IFO380 (3.5% S). We do not assume any projected fuel prices, as analysis of inflation-adjusted fuel prices over the past 9 years shows little evidence of any trends in the data. We do not assume any dynamic equilibrium market effects, as this level of modeling effort falls outside the scope of this study. By estimating fuel costs using the maximum observed price spread we present a conservative upper bound of the expected maximum fuel costs based on the past 9 year’s fuel pricing data.

7.5.5 Regional Delineation

Ship emissions, air quality, and health model outputs are all produced using a 0.1° x 0.1° gridded resolution. Model outputs are georeferenced with the same origin, resolution, and extents. Model results, including fuel use, air quality concentrations, and health outcomes are estimated using these gridded outputs. As such, gridded results along certain country boundaries may be arbitrarily attributed to one country or the other, on either side of the boundary, which likely follows a finer geographic resolution than our gridded results. This issue does not affect total or regional estimates, but may affect national allocations of emissions, air quality concentrations, and health benefits, especially in regions near national borders. Most notably, the country of Monaco, with a geographic area of 2 km^2 and claims to a 12nm territorial sea, is smaller than an individual grid cell (~11.11 km x 8.5 km), and as such is not individually identified in our model outputs. Similarly, the water area of Bosnia and Herzegovina (10km^2) is below the threshold of our model outputs and aggregation methods, and as such estimates of emissions in the waters of Bosnia and Herzegovina are not individually estimated.

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