



## Review article

## Health impact assessments of shipping and port-sourced air pollution on a global scale: A scoping literature review

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## ABSTRACT

**Background:** Globalisation has led to international trade expand rapidly. Seaborne transport moves 80% of traded goods across the globe, producing around 3% of greenhouse gases and other hazardous pollutants, such as PM, NO<sub>x</sub> and SO<sub>x</sub>, known to be harmful to health.

**Methods:** A scoping literature review was conducted reviewing peer-reviewed studies on health impact assessments (HIA) of global shipping and port-sourced air pollution. For review inclusion, studies had to (1) use a HIA methodology; (2) quantify the air pollution concentration attributable to at least one shipping or port activity scenario; (3) assess at least one health outcome (i.e. epidemiological measure or monetization); (4) quantify the attributable health burden of the respective scenario.

**Results:** Thirty-two studies were included, studying predominantly European Sea shipping/ port-sourced emissions with health impacts for global or respective European populations. Also, Global, Asian, North American and Australian Sea shipping/ port-sourced emissions were studied, with attributable health impacts for global or respective populations. The health outcome predominantly studied was mortality (all-cause, cause-specific, loss in life expectancy, years of life lost (YLLs)), but also morbidity (disease cases, hospital admissions, years lived with disability (YLDs)), disability-adjusted life-years (DALYs), restricted activity days and work loss days. The highest air pollution concentrations were identified along major shipping routes and ports, and the strongest health impacts occurred among respective riparian populations. Globally, ~265,000 premature deaths were projected for 2020 (~0.5% of global mortality) attributable to global shipping-sourced emissions. Emission control scenarios studied were predominantly sulphur fuel content caps and NO<sub>x</sub> emission reduction scenarios, consisting of technological interventions, cleaner fuels or fuel switches, and were assessed as effective in reducing shipping-sourced emissions, and hence, health burdens.

**Conclusions:** Our review positions maritime transport an important source of air pollution and health risk factor, which needs more research and policy attention and rigorous emission control efforts, as shipping-sourced emissions are projected to increase with increases in global trade and shipping volumes.

## 1. Introduction

The rapid growth of international trade goes back to the early 1960s, when due to economic growth and technological advances goods became rapidly available from all over the world. World trade volume today is roughly 4000% the volume of 1960 (WTO, 2022). The demands for transport have increased simultaneously. Maritime transport allows for considerably larger volumes to be transported than alternative air, rail or road transport, and advances in naval engineering have led to fast expansion of the shipping sector. Sea transport accounts for 80% of

goods transported worldwide, moving 10 billion (bn) tonnes of cargo annually (Schnurr and Walker, 2019). Across the world seas, strongly-trafficked shipping routes have evolved and ports have expanded likewise (Fig. 1), which link the world economies and have allowed for the ongoing rapid expansion of international trade and demands for maritime transport. Recent estimates foresee a demand growth of almost 40% for seaborne trade by 2050 (Serra and Fancello, 2020).

While maritime transport enables mass movement of goods, it comes at the high costs of pollution of water and air. Maritime transport accounts for about 3% of global greenhouse gases (GHG), as well as 13% of

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**List of Abbreviations**

BAU	Business as usual	LLE	Loss in life expectancy
BA	Benefit analysis	LNG	Liquefied natural gas
BC	Black carbon	LT	Lithuania
BD	Bangladesh	LV	Latvia
BDA	Burden of disease assessment	MARPOL	International Convention for the Prevention of Pollution from Ships
BE	Belgium	MDO	Marine diesel oil
Bn	billion	MGO	Marine gas oil
CA	Cost analysis	Mio	Million
CBA	Cost-benefit analysis	MM	Myanmar
CH	China	MT	Malta
CH <sub>4</sub>	Methane	NCEAS	National Centre for Ecological Analysis and Synthesis
CM	City model	NECA	Nitrogen emission control area
CO	Carbon monoxide	N <sub>i</sub>	Nickel
COPD	Chronic obstructive pulmonary disease	NL	Netherlands
CO <sub>2</sub>	Carbon dioxide	Nm	Nautical miles
CP	Cardiopulmonary	NO	Norway
CRA	Comparative risk assessment	NO <sub>x</sub>	Nitrogen oxide
CVD	Cardiovascular disease	NO <sub>2</sub>	Nitrogen dioxide
CY	Cyprus	O <sub>3</sub>	Ozone
DALY	Disability-adjusted life-year	PH	Philippines
DD	Difference-in-difference model	PM	Particulate matter
DE	Germany	PL	Poland
DECA	Domestic emission control area (China)	PRD	Pearl River Delta (China)
DK	Denmark	PT	Portugal
EBD	Environmental Burden of Disease	RA	Risk assessment
EC	European Commission	RAD	Restricted activity days
EE	Estonia	RD	Respiratory disease
EEDI	Energy Efficiency Design Index	RM	Regional model
EGR	Exhaust-gas recirculation	RR	Relative risk
ER	Emergency room	S	Sulphur
ERF	Exposure-response function	(S)	Scenario
ES	Spain	SEEMP	Ship Energy Efficiency Management Plan
EU	European Union	SCR	Selective Catalytic Reduction
FI	Finland	SE	Sweden
FR	France	SECA	Sulphur emission control area
FIN	Finland	SO <sub>x</sub>	Sulphur oxide
GB	Great Britain	SO <sub>2</sub>	Sulphur dioxide
GBD	Global burden of disease	UK	United Kingdom
GR	Greece	TEN-T	Trans-European Transport Network
GT	Gross tonnage	TH	Thailand
HIA	Health impact assessment	TSA	Time-series analysis
HFO	Heavy fuel oil	US	United States
Hosp. adm.	Hospital admissions	V	Vanadium
IHD	Ischemic heart disease	VOLY	Value of a life year
IMO	International Maritime Organisation	VSL	Value of a statistical life
IN	India	VT	Vietnam
IQR	Interquartile range	WLD	Work loss days
IT	Italy	WASP	Wind-assisted shipping propulsion
JJJ	Jing-Jin-Ji (China)	WIF	Water in fuel
JP	Japan	WHO	World Health Organisation
KR	South Korea	YLD	Years lived with disability
LC	Lung cancer	YLL	Years of life lost
		YRD	Yangzi River Delta (China)

nitrogen oxide (NO<sub>x</sub>) and 12% of sulphur oxide (SO<sub>x</sub>) emissions, but also emits other pollutants, including particles (PM), black carbon (BC) and methane (CH<sub>4</sub>), all known to be harmful to human health (IMO, 2015; Liu et al., 2016; Serra and Fancello, 2020).

There is a substantial amount of evidence on the wide range of health effects of air pollution, which include respiratory (RD), cardiovascular (CVD) and metabolic diseases, stroke, lung cancer (LC), impaired fertility outcomes, preterm birth, reduced birth weight and premature

mortality (Cesaroni et al., 2014; Chen and Hoek, 2020; Eze et al., 2015; Hamra et al., 2014; Nieuwenhuijsen et al., 2014; Pedersen et al., 2013; Sapkota et al., 2010; Stafoggia et al., 2014). For 2019, it was estimated that around 4.1 million deaths, or 7% of premature mortality worldwide, were attributable to ambient air pollution, ranking air pollution as a leading risk factor in the Global Burden of Disease (GBD) Study (IHME, 2019).

### 1.1. Emission control regulations

The International Maritime Organisation (IMO) is the key player in engaging United Nation (UN) member states in reducing shipping emissions. UN member states are accountable for their own shipping industries, but have an obligation to comply with the laws and regulations imposed by the IMO. The International Convention for the Prevention of Pollution from Ships (MARPOL) by the IMO, first entered into force in 2005, provides in Annex VI the regulations for reducing shipping-sourced air pollution (IMO, 2019a). Under MARPOL Annex VI, the IMO has established emission control areas (ECA) for sulphur oxides ( $\text{SO}_x$ ) (i.e. SECA) and nitrogen oxides ( $\text{NO}_x$ ) (i.e. NECA), forcing shipping companies to lower  $\text{SO}_x$  and  $\text{NO}_x$  emissions, respectively. MARPOL Annex VI was revised several times, lowering in 2010 the sulphur (S) fuel content from 1.5% to 1% and in 2015 to 0.1% inside established SECAs. In non-SECA waters, the S fuel content was lowered in 2012 from 4.5% to 3.5% and from 2020 onwards to 0.5% (IMO, 2019b). Until recently, the cheapest and most-widely used fuel was heavy fuel oil (HFO), a residual fuel with high sulphur (S) and nitrogen content, leading to high air pollution levels during the combustion process. However, IMO S fuel content limits imply a movement from residual fuel oil to distillate fuels, such as marine diesel oil (MDO), marine gas oil (MGO) and liquefied natural gas (LNG) that are expected to reduce air pollution levels considerably (Jonson et al., 2015; Ramacher et al., 2020; Winebrake et al., 2009). NECA regulations target primarily marine diesel engines that depending on engine age have different emission control levels (i.e. Tier I, II or III) (Table 1). Ships built from 2016 onwards must comply with Tier III limits within established NECAs (IMO, 2019c).

Until now, there are four ECAs implemented by the IMO (Fig. 2): The North American ECA, including most of the US and Canadian coast, the US Caribbean ECA, including Puerto Rico and the Virgin Islands, the North Sea ECA, and the Baltic Sea ECA (IMO, 2019d). The North American ECA extends as far the Economic Exclusion Zone (EEZ), i.e. 200 nautical miles (nm) into the respective territorial sea. The North American and US Caribbean ECAs apply SECA and NECA limits. The North and Baltic Sea ECAs applied exclusively SECA limits until 2021, when also NECA limits came into force. A Domestic Emission Control Area (DECA) is also established along the Chinese coastline within 12 nm (Mao et al., 2019). The Chinese DECA control requirements follow

**Table 1**

IMO ECA limits to reduce  $\text{NO}_x$  and  $\text{SO}_x$  emissions.

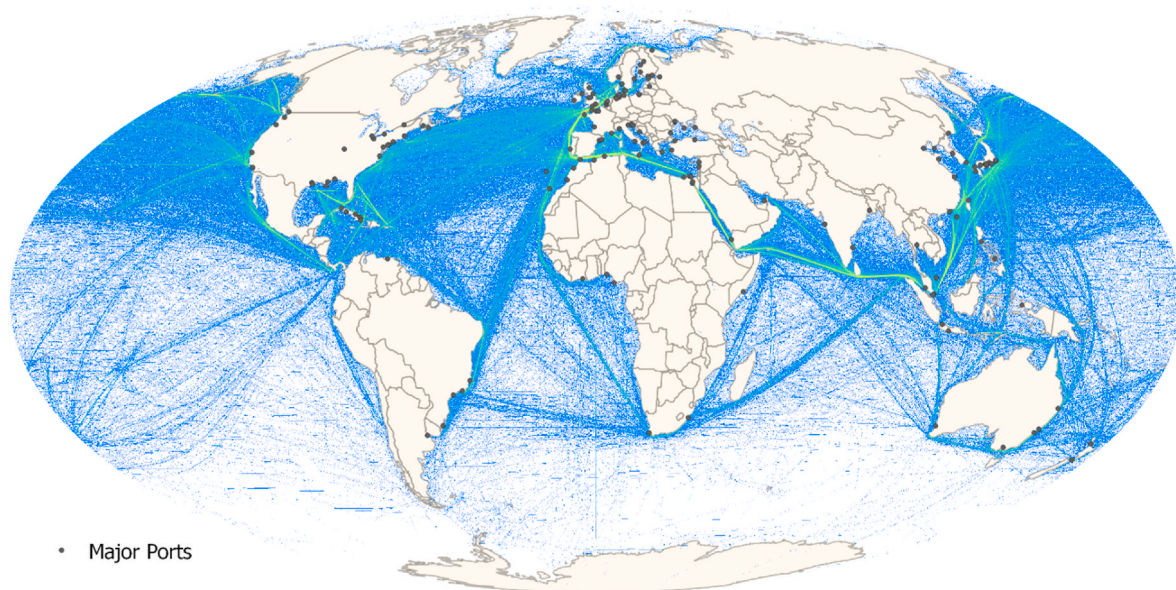
	Tier (construction year)	Limits inside ECA	Limits outside ECA
NECA	Tier I (2000)		9.8–17.0 g $\text{NO}_x$ /kWh
	Tier II (2011)		7.7–14.4 g $\text{NO}_x$ /kWh
	Tier III (2016)	2.0–3.4 g $\text{NO}_x$ /kWh	
SECA		0.1% S in fuel (2015)	0.5% S in fuel (2020)

$\text{NO}_x$  total weighted cycle emission limit (g/kWh) depend on ship engine's rated speed. IMO  $\text{NO}_x$  Tier III emission standards are 80% less than  $\text{NO}_x$  Tier I emission requirements. Outside NECA, Tier II limits are applicable.

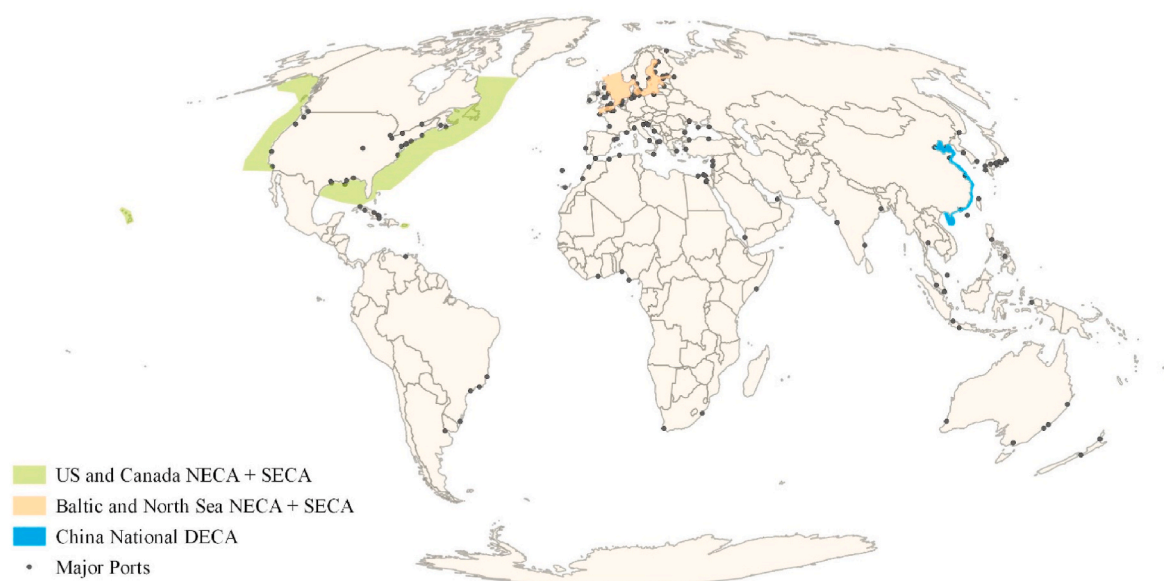
that of the MARPOL convention, however the Chinese DECA is not yet IMO regulated (Mao et al., 2019). At the European level, the EU has adopted directives for lowering the S fuel content to 0.1% for ships at berth for more than 2 h in all Union ports (Directive (EU) 2016/802), and from 2025 will require LNG refueling points and provision of shoreside electricity in all Trans-European Transport Network (TEN-T) ports (Directive, 2014/94/EU), compromising all major Union ports (Serra and Fancello, 2020).

Moreover, under IMO MARPOL Annex VI, since 2013, new ships must comply with the Energy Efficiency Design Index (EEDI) aimed at promoting the use of more energy efficient ship equipment and engines. The EEDI particularly aims at reducing  $\text{CO}_2$  emissions by providing an energy efficiency index for ship design, expressed in grams of  $\text{CO}_2$  per ship capacity-mile (IMO, 2019e). Also, all ships must comply with the Ship Energy Efficiency Management Plan (SEEMP), an IMO operational measure that sets the mechanisms to improve the energy efficiency of ships (e.g. speed management) in a cost-effective way (IMO, 2019e). The EEDI and SEEMP both work towards the IMO's commitment to tackle climate change and reduce total annual GHG emissions by at least 50% by 2050 compared to 2008 (IMO, 2018). Despite EEDI and SEEMP being aimed at GHG emission reductions, it is expected that these measures will also reduce other air pollutants, bringing co-benefits for air quality and ultimately human health (West et al., 2013).

Although the established IMO emission control measures contribute to reducing shipping-sourced air pollution, there are still vast amounts of emissions from shipping, ships at berth and port activities, which expose populations to high levels of air pollution that pose a threat to health. While numerous studies looked especially at the health effects related to road transport-sourced air pollution, relatively less research



**Fig. 1.** Global map with shipping routes and major ports indicated by black dots; data from 2008 (National Centre for Ecological Analysis and Synthesis (NCEAS), 2008).



**Fig. 2.** IMO ECAs indicated in green and orange, Chinese DECA indicated in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

attention has been given to shipping and port-sourced air pollution and attributable health burdens. Therefore, the objective of this study was to provide a scoping overview of the scientific literature assessing the health burden of air pollution from shipping and port activities globally. The review aims to create awareness of this particular source of pollution, understand how its associated health burden has been assessed until now, and what possible implications for policy and research might look like.

## 2. Methods

The review was done following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews (PRISMA-ScR) guidelines for the reporting of scoping literature reviews (Tricco et al., 2018). Scoping literature reviews are of great utility for synthesizing research evidence on a specific or novel topic. To our knowledge, no comprehensive overview exists yet on the health burden of shipping-sourced air pollution. Therefore, we considered a scoping literature review to be the most appropriate method to assess the size and scope of the available literature, gain insight into how and for whom health impacts have been assessed, understand applied health impact assessment (HIA) methodologies and attributable health burdens.

### 2.1. Search strategy

Database searches of PubMed, Web of Science, Science Direct and Google Scholar, were conducted between June 2019 and February 2022. Keyword combinations of “shipping”, “vessels”, “port”, “air pollution”, “health”, “mortality” and “morbidity” were used in various orders and combined with Boolean operators (“AND”, “OR”, and “NOT”) to optimize the search strategy (Appendix A). The search strategy was complemented by the snowballing method, reference screening and expert consultation. All levels of screening and review were conducted by two independent researchers (NM and MW) and discrepancies were resolved by discussion and consensus.

### 2.2. Eligibility criteria

Peer-reviewed articles, published in scientific journals in English

language between January 2000 up to February 2022 were reviewed. For review inclusion, studies had to meet following eligibility criteria: (1) use a HIA methodology; (2) quantify the air pollution concentration attributable to at least one shipping or port activity scenario; (3) assess at least one health outcome, which could either be an epidemiological (e.g. mortality, morbidity, disability-adjusted life-years (DALYs), activity restriction, etc.) or health economic measure (e.g. value of statistical life (VSL), value of a life year (VOLY), costs of illness, etc.); and (4) quantify the attributable health burden of the respective shipping or port activity scenario (e.g. attributable deaths, cases of morbidity, number of years of life lost (YLLs), DALYs, etc.).

### 2.3. Data extraction and synthesis

A data extraction tool was developed for summary and analytical synthesis of the selected studies (Table 2). The data extraction tool summarizes the (1) health impact assessment (HIA) method; (2) shipping-routes/ ports assessed; (3) emission source; (4) scenario assessed; (5) impacted population; (6) scenario attributable air pollution contribution; (7) health outcome; (8) health risk/ impact estimate applied; and (9) the attributable health impact.

## 3. Results

### 3.1. Search results

A total of 1101 articles were identified with the initial search strategy. Title screening identified 84 candidate studies, abstract screening identified 48 candidate studies and final full text reading resulted in 32 studies that met the eligibility criteria (Fig. 3).

### 3.2. Study settings

The included studies provided either a global or a region-specific overview of health impacts of shipping and port-related air pollution. Five studies examined the global health impact of international shipping (Corbett et al., 2007; Crippa et al., 2019; Partanen et al., 2013; Sofiev et al., 2018; Winebrake et al., 2009). One study assessed health effects of shipping-sourced air pollution in the Northern Hemisphere (Brandt et al., 2013). Fourteen studies examined the health effects of air



**Table 2**  
Summary of studies on the health burden of shipping and port-sourced air pollution.

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
<b>Global</b>									
Corbett et al. (2007) Environ. Sci. Technol.	BDA	Global; North America; Europe/Mediterranean; East Asia; South Asia; East South America	Shipping-sourced emissions	(S1) <i>Inventory A, Case 1a-1c</i> 2002 PM <sub>2.5</sub> with/without ship emissions; (S2) <i>Inventory B, Case 2a-2b</i> 2001 PM <sub>2.5</sub> with/without ship missions; (S3) <i>Inventory C, Case 3</i> 2012 PM <sub>2.5</sub> with/without ship emissions	Global adults ≥30 years	Ship PM <sub>2.5</sub> 0–2 µg/m <sup>3</sup> , mainly along major ship routes + coasts	Mortality (CP, LC)	CP mortality RR = 1.06 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> , LC mortality RR = 1.08 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Pope et al., 2002)	(S1) Global 18,920–64,180 deaths: 430 deaths (East South America) - 26,710 deaths (Europe/Mediterranean); (S2) Global 40,190–61,840 deaths: 1280 deaths (East South America) - 16,530 deaths (Europe/Mediterranean); (S3) Global 27,020 deaths: 650 deaths (East South America) - 9870 deaths (Europe/Mediterranean)
Winebrake et al. (2009) Environ. Sci. Technol.	CRA	Global	Shipping-sourced emissions	(S1) <i>No control</i> 2012 PM <sub>2.5</sub> of 2.7% S fuel content; (S2) <i>Coastal 0.5</i> 2012 PM <sub>2.5</sub> of 0.5% S fuel content at coast (200 nm); (S3) <i>Coastal 0.1</i> 2012 PM <sub>2.5</sub> of 0.1% S fuel content at coast (200 nm); (S4) <i>Global 0.5</i> 2012 PM <sub>2.5</sub> of 0.5% S fuel content global	Global adults 30–99 years	Ship PM <sub>2.5</sub> 0–2.9 µg/m <sup>3</sup> , mainly along major ship routes + coasts	Mortality (CP, LC)	CP mortality RR = 1.06 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> , LC mortality RR = 1.08 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Pope et al., 2002) CP mortality β = 0.15515 PM <sub>2.5</sub> , LC mortality β = 0.23218 PM <sub>2.5</sub> (Ostro, 2004)	(S1) CP 80000 deaths, LC 7050 deaths; (S2) CP 49150 deaths, LC 4400 deaths; (S3) CP 39850 deaths, LC 3650 deaths; (S4) CP 42300 deaths, LC 3800 deaths
Partanen et al. (2013) Atmos. Chem. Phys.	CRA	Global; Africa; Americas; South East Asia; Europe; Eastern Mediterranean; Western Pacific	Shipping-sourced emissions	(S1) <i>Ships-2010</i> 2010 PM <sub>2.5</sub> of 2.7% S fuel content at coast & ocean; (S2) <i>Geo-narrow</i> 2010 PM <sub>2.5</sub> of 0.1% S fuel content at coast (200–300 km) & 5.4% at ocean; (S3) <i>Geo-wide</i> 2010 PM <sub>2.5</sub> of 0.1% S fuel content at coast (400–600 km) & 5.4% at ocean; (S4) <i>Ships-2020</i> 2020 PM <sub>2.5</sub> of 0.1% S fuel content at coast & 0.5% at ocean	Global adults ≥30 years	Ship PM <sub>2.5</sub> 0–3.3 µg/m <sup>3</sup> , mainly along major ship routes + coasts	Mortality (CP, LC)	CP β = 0.15515 PM <sub>2.5</sub> , LC β = 0.23218 PM <sub>2.5</sub> (Ostro, 2004)	(S1) CP Global 45,100 deaths: 1150 deaths (Africa) – 24,420 deaths (Europe), LC Global 5100 deaths: 20 deaths (Africa) – 2850 deaths (Europe); (S2) CP Global 31,200 deaths: 950 (Africa) – 13,940 (Europe) deaths, LC Global 3600 deaths: 20 (Africa) – 1630 (Europe) deaths; (S3) CP Global 13,800 deaths: 340 deaths (Africa) – 6720 deaths (Europe), LC Global 1600 deaths: 10 deaths (Africa) – 790 deaths (Europe); (S4) CP Global 1800 deaths: 0 deaths (Africa) – 1180 deaths (Europe) deaths, LC Global 200 deaths: 0 deaths (Africa) – 140 deaths (Europe)
Sofiev et al. (2018) Nat. Commun.	CRA	Global	Shipping-sourced emissions	(S1) <i>BAU 2020</i> PM <sub>2.5</sub> of fuel with no low S content; (S2) <i>Action 2020</i>	Global adults ≥30 years; children ≤14 years	Ship PM <sub>2.5</sub> 0–2 µg/m <sup>3</sup> , mainly along major ship routes + coasts	Mortality (CVD, LC), childhood asthma	CVD mortality RR = 1.26 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> , LC mortality RR = 1.37 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Lepeule	(S1) CVD 349000 deaths, LC 54300 deaths, 14 mio. childhood asthma cases; (S2) CVD 226800 deaths, LC

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
				PM <sub>2.5</sub> of 0.5% S fuel content				et al., 2012); childhood asthma RR = 1.023 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Zheng et al., 2015)	39500 deaths, 6.4 mio. childhood asthmas cases
Crippa et al. (2019) Atmos. Chem. Phys.	BDA	Global	Shipping-sourced emissions	(S1) 2010 PM <sub>2.5</sub> for 6 emission sectors, including shipping	Global population	Ship of total PM <sub>2.5</sub> Europe 4.4%, South East Asia 3.4%, China 0.3%, India 0.2%, Africa 7.4%, Middle East 1.8%, North America 4.2%, Russia 0.8%, South America 2.6%, Oceania 21.8%	Mortality (IHD, stroke, COPD, LC, acute lower respiratory infections)	(Burnett et al., 2014) Integrated Exposure-Response (IER) model incorporating 1000 risk functions per cause for IHD, stroke, COPD, LC and acute lower respiratory infections in children mortality	(S1) Europe 11,566 deaths, Asia 4496 deaths, Africa + Middle East 972 deaths, North America 1757 deaths, Russia + former USSR 981 deaths, South America 493 deaths, Australia + Oceania 7 deaths
<b>European Seas</b>									
Brandt et al. (2013) Atmos. Chem. Phys.	CA	Northern Hemisphere, Baltic Sea and North Sea	Shipping-sourced emissions	(S1) All/15 2000 PM <sub>2.5</sub> from ship traffic in Northern Hemisphere with 2.7% S fuel content; (S2) All/15 2007 with 1.5% S fuel content in Baltic & North Seas; (S3) All/15 2011 with 1% S fuel content in Baltic & North Seas; (S4) All/15 2020 with 0.1% S fuel content in Baltic & North Seas; (S5) BaS-NoS/15 2000 PM <sub>2.5</sub> from ship traffic in Baltic & North Seas with 2.7% S fuel content; (S6) BaS-NoS/15 2007 with 1.5% S fuel content in Baltic & North Seas; (S7) BaS-NoS/15 2011 with 1% S fuel content in Baltic & North Seas; (S8) BaS-NoS/15 2020 with 0.1% S fuel content in Baltic & North Seas	European population; DK population	(S1–S4) Ship PM <sub>2.5</sub> 0–1 µg/m <sup>3</sup> , highest in Mediterranean between Strait of Gibraltar & Sea of Crete; (S5–S8) ship PM <sub>2.5</sub> 0–0.4 µg/m <sup>3</sup> , highest in North Sea between English Channel & Kattegat	All-cause mortality; external health costs € (VSL + VOLY), [CVD, LC, RD & stroke hosp. adm., asthma, bronchitis, RAD]	Economic Valuation of Air pollution (EVA) model (ERFs not indicated) VSL = 1.4 mio € (EC, 2001), adjusted for DK VOLY = 54,000 € (Alberini et al., 2006), adjusted for DK	(S1) Europe 49,530 deaths, 58.4 bn €; DK 700 deaths, 805 mio €; (S2) Europe 48,300 deaths, 56.9 bn €; DK 550 deaths, 623 mio €; (S3) Europe 46,040 deaths, 54.3 bn €; DK 500 deaths, 558 mio €; (S4) Europe 53,400 deaths, 64.1 bn €; DK 430 deaths, 484 mio €; (S5) Europe 20,380 deaths, 22.0 bn €; DK 560 deaths, 627 mio €; (S6) Europe 16,230 deaths, 17.2 bn €; DK 440 deaths, 474 mio €; (S7) Europe 14,060 deaths, 14.7 bn €; DK 390 deaths, 414 mio €; (S8) Europe 13,200 deaths, 14.1 bn €; DK 340 deaths, 357 mio €
Jonson et al. (2015) Atmos. Chem. Phys.	CRA	Baltic and North Sea	Shipping-and port-(berthing) sourced emissions	(S1) Baseline YLLs 2010 from all sources; (S2) YLLs from ships 2009 with 1.5% S fuel content in SECA; (S3) YLLs from ships 2011 with 1% S fuel content in SECA & 0.1% S fuel content in harbor areas; (S4) YLLs from ships 2030 No NECA with 0.1% S fuel content in SECA & no NECA; (S5) YLLs from ships 2030 with	Populations of BE, NL, DE, GB, DK, NO, SE, FI, PL, LV, LT, EE ≥ 30 years	Ship PM <sub>2.5</sub> 0–1 µg/m <sup>3</sup> , with contribution ranging 0–15% of total PM <sub>2.5</sub> , highest contribution in North Sea along major ship routes	YLLs	Mortality RR = 1.06 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (WHO, 2006)	(S1) Baseline 69,189,000 YLLs; (S2) 3,032,648 YLLs (4.4%), range: 1.6% PL to 11.7% DK; (S3) 2,785,432 YLLs (4%), range: 1.4% PL to 9.5% DK; (S4) 2,691,129 YLLs (3.9%), range: 1.4% PL to 9.2% DK; (S5) 2,113,793 YLLs (3.1%), range: 1.1% PL to 7.5% DK

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
Viana et al. (2015) Environ. Sci. Technol.	CRA	Marmara Sea, including Turkish Straits	Shipping-sourced emissions	NECA with 0.1% S fuel content in SECA & with NECA (transition to Tier III engines) (S1) Baseline 2013 PM <sub>2.5</sub> , PM <sub>10</sub> , SO <sub>2</sub> (S2) 2013 PM <sub>2.5</sub> , PM <sub>10</sub> , SO <sub>2</sub> ECA with 0.1% S fuel content	Population of Marmara region (23 mio. persons, 0–99 years)	(S1) 1.2 µg/m <sup>3</sup> PM <sub>2.5</sub> , 1.6 µg/m <sup>3</sup> PM <sub>10</sub> , 1.5 µg/m <sup>3</sup> SO <sub>2</sub> (S2) 0.4 µg/m <sup>3</sup> PM <sub>2.5</sub> (↓67%), 0.5 µg/m <sup>3</sup> PM <sub>10</sub> (↓67%), 0.1 µg/m <sup>3</sup> SO <sub>2</sub> (↓96%)	All-cause mortality, RD & CVD hops. adm.	Mortality RR = 1.07 per 5 µg/m <sup>3</sup> PM <sub>2.5</sub> (Beelen et al., 2014); RR = 1.32 per 10 µg/m <sup>3</sup> PM <sub>10</sub> (Samoli et al., 2013); RR = 1.05 per 50 µg/m <sup>3</sup> SO <sub>2</sub> (Samoli et al., 2001); RD hosp. adm. RR = 1.096 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Atkinson et al., 2014), RR = 1.136 per 14.4 µg/m <sup>3</sup> PM <sub>10</sub> (Stafoggia et al., 2014); CVD hosp. adm. RR = 1.09 per per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Atkinson et al., 2014), RR = 1.053 per 14.4 µg/m <sup>3</sup> PM <sub>10</sub> (Stafoggia et al., 2014), RR = 1.07 per 10 µg/m <sup>3</sup> SO <sub>2</sub> (Sunyer et al., 2003)	(S2 vs S1) PM <sub>2.5</sub> ↓15 deaths (↓1–2%), ↓347 RD hosp. adm. (↓1–2%), ↓111 CVD hosp. adm. (↓1–2%), PM <sub>10</sub> ↓1 death (↓1%), ↓158 RD hosp. adm. (↓1%), ↓52 CVD hosp. adm. (↓1%), SO <sub>2</sub> ↓2 deaths (↓2–10%), ↓185 RD hosp. adm. (↓1–14%), ↓205 CVD hosp. adm. (↓2–12%)
Antturi et al. (2016) J. Environ. Manage.	CBA	Baltic Sea	Shipping-sourced emissions	(S1) Baseline 2015 PM <sub>2.5</sub> with 1% S fuel content; (S2) Sulphur Directive Scenario (SECA) switch to 0.1% S fuel content or installation of S scrubbers	Populations of DK, EE, FI, DE, LV, LI, PL, SE, all ages	DK ↓1%; EE ↓1.3%; FI ↓1.3%; DE ↓0.1%; LV ↓0.6%; LI ↓0.4%; PL ↓0.1%; SE ↓1.4%	DALYs (CP, LC, COPD, RAD), health benefits € (DALY * VOLY) vs costs € (shipowner abatement costs for fleet adjustment)	EBD approach for PM <sub>2.5</sub> (Hänninen et al., 2014) YLL <sub>CP</sub> + YLD <sub>CP</sub> RR = 1.0077 per 1 µg/m <sup>3</sup> PM <sub>2.5</sub> YLL <sub>LC</sub> + YLD <sub>LC</sub> RR = 1.012 per 1 µg/m <sup>3</sup> PM <sub>2.5</sub> YLD <sub>COPD</sub> UR = 1.0000533 per 1 µg/m <sup>3</sup> PM <sub>2.5</sub> YLD <sub>RAD</sub> UR = 0.0902 per 1 µg/m <sup>3</sup> PM <sub>2.5</sub> VOLY = 40,000 € (Desaigues et al., 2011)	(S2 vs S1) DK ↓308 DALYs, ↓14.5 mio €; EE ↓107 DALYs, ↓5 mio €; FI ↓223 DALYs, ↓10.5 mio €; DE ↓373 DALYs, ↓17.5 mio €; LV ↓125 DALYs, ↓5.9 mio €; LI ↓107 DALYs, ↓5 mio €; PL ↓587 DALYs, ↓27.6 mio €; SE ↓399 DALYs, ↓18.7 mio €; total ↓2229 DALYs, ↓104.7 mio €; Health benefits 105 mio € < costs 465 mio €
Ballini et al. (2017) Ocean Eng.	CBA	Baltic Sea; North Sea; English Channel; Kattegat	Shipping-sourced emissions	(S1) Baseline 2013 emissions; (S2) SAIL1 all bulk carriers equipped with WASP; (S3) SAIL2 all transport vessels size 3000 < gross tonnage (GT) < 10,000 equipped with WASP	Populations of Central Europe, DK	(S2 vs S1) ↓3.9% ship emissions; (S3 vs S1) ↓3.5% ship emissions	All-cause mortality, YLLs, RD & stroke hosp. adm., CVD, LC, RAD, [bronchitis, asthma, lower respiratory symptoms], health benefits € (VSL + VOLY + costs of illness) vs costs € (WASP installation)	Economic Valuation of Air pollution (EVA) model Mortality β = 0.001138 YLL per 1 µg/m <sup>3</sup> PM; RD hosp. adm β = 0.00000346 cases per 1 µg/m <sup>3</sup> PM, β = 0.00000204 cases per 1 µg/m <sup>3</sup> SO <sub>2</sub> ; stroke hosp. adm. β = 0.00000842 cases per 1 µg/m <sup>3</sup> PM; CVD β = 0.0000309 cases per 1 µg/m <sup>3</sup> PM, β = 0.000000564 cases per 1 µg/m <sup>3</sup> CO; LC β = 0.0000125 cases per 1 µg/m <sup>3</sup> PM; RAD β = 0.00084	(S2 vs S1) Central Europe ↓3 deaths, ↓1532 YLLs, ↓8 RD hosp. adm., ↓17 stroke hosp. adm., ↓8 CVD, ↓21 LC, ↓137,984 RAD, ↓0.03% health costs; DK 0 deaths, ↓101 YLLs, ↓1 RD hosp. adm., ↓1 stroke hosp. adm., ↓1 CVD, ↓2 LC, ↓9696 RAD, ↓0.15% health costs; (S3 vs S1) Central Europe ↓2 deaths, ↓1153 YLLs, ↓6 RD hosp. adm., ↓13 stroke hosp. adm., ↓6 CVD, ↓15 LC, ↓103,680 RAD, ↓0.026% health costs; DK 0 deaths,

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
								cases per 1 $\mu\text{g}/\text{m}^3$ PM VSL/VOLY not specified	↓90 YLLs, ↓1 RD hosp. adm., ↓1 stroke hosp. adm., ↓1 CVD, ↓1 LC, ↓8588 RAD, ↓0.13% health costs; Short-term health benefits < costs; long-term health benefits > costs
Åström et al. (2018) Transp. Res. D	CBA	Baltic Sea; North Sea; including English Channel	Shipping-sourced emissions	(S1) Baseline 2030 $\text{NO}_x$ ( $\text{SO}_2$ , $\text{PM}_{2.5}$ $\text{CO}_2$ and $\text{CH}_4$ ) emissions with SECA implemented (low S fuel content and $\text{SO}_x$ scrubbers); (S2) NECA-BAS as baseline with NECA in Baltic Sea (2021) through use of Selective Catalytic Reduction (SCR) or Exhaust-Gas Recirculation & Water in Fuel (EGR + WIF) technologies; (S3) NECA-NSE as S1 with NECA in North Sea; (S4) NECA-BAS + NSE as S1 with NECA in Baltic and North Sea; (S5) NECA-LNG as S1 with NECA in Baltic and North Sea with LNG propulsion engines on new ships	Population of Europe	(S1) Baltic Sea $\text{NO}_x$ 241 kt, North Sea $\text{NO}_x$ 507 kt; (S2) Baltic Sea $\text{NO}_x$ ↓26%; (S3) North Sea $\text{NO}_x$ ↓26%; (S4) Baltic Sea + North Sea $\text{NO}_x$ ↓26%; (S5) Baltic Sea + North Sea $\text{NO}_x$ ↓39%	Control costs € (technology + fuels) vs benefits € [mortality, CVD + RD hosp. adm., asthma, bronchitis, LWD, RAD] (VSL + VOLY + avoided crop damage + avoided climate impact)	Mortality RR = 1.06 per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (WHO, 2013) CVD hosp adm. RR = 1.125 per per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (WHO, 2013) RD hosp. adm. RR = 1.043 per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (WHO, 2013) Asthma RR = 1.28 per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{10}$ (WHO, 2013) Bronchitis RR = 1.14 per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (WHO, 2013) RAD RR = 1.47 per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (WHO, 2013) WLD RR = 1.46 per 10 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (WHO, 2013) VSL = 1.2–3.1 mio € (Holland et al., 2014) VOLY = 45,000–155,000 € (Holland et al., 2005)	(S2) costs 111 mio € < benefits 139 mio €; (S3) costs 181 mio € < benefits 869 mio €; (S4) costs 230 mio € < benefits 1 bn €; (S5) costs 153 mio € < benefits 1.5 bn €
Barregard et al. (2019) Env. Res. Pub. Health	CRA	Baltic Sea	Shipping-sourced emissions	(S1) 2014 high S fuel content 1%, (S2) 2016 low S fuel content 0.1% (SECA)	Populations of SE, NO, DK, FI, DE, PL, EE, LV, LI, European Russia	Ship emissions account for >50% of $\text{NO}_2$ in central parts of the Baltic Sea and for 20–50% in adjacent coastal zones	All-cause mortality, YLLs, [IHD, stroke]	Mortality RR = 1.0062 per 1 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (Héroux et al., 2015) Mortality RR = 1.014 per 1 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (Beelen et al., 2014) [IHD RR = 1.026 per 1 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (Cesaroni et al., 2014) Stroke RR = 1.038 per 1 $\mu\text{g}/\text{m}^3$ $\text{PM}_{2.5}$ (Stafoggia et al., 2014)]	(S1) SE 187 deaths, 1812 YLLs; NO 12 deaths, 127 YLLs; DK 173 deaths, 1901 YLLs; FI 75 deaths, 775 YLLs; DE 471 deaths, 4940 YLLs; PL 236 deaths, 2868 YLLs; EE 30 deaths, 346 YLLs; LV 37 deaths, 414 YLLs; LI 47 deaths, 514 YLLs; Russia 245 deaths, 2977 YLLs; SUM 1511 deaths, 16,674 YLLs; (S2) SE 120 deaths (↓35%), 1167 YLLs; NO 8 deaths (↓39%), 78 YLLs; DK 130 deaths (↓25%), 1431 YLLs; FI 40 deaths (↓47%), 414 YLLs; DE 342 deaths (↓27%), 3634 YLLs; PL 158 deaths (↓33%), 1922 YLLs; EE 17 deaths (↓45%), 191 YLLs; LV 22 deaths (↓40%), 249 YLLs; LI 30 deaths (↓36%), 1625

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
Mwase et al. (2020) Env. Res. Pub. Health	CRA	Baltic Sea and domain around Gothenburg area (North Sea)	Shipping-sourced emissions	(S1) High S fuel content 1%, (S2) Low S fuel content 0.1% (SECA)	Population of SE, Gothenburg	(S1) PM <sub>2.5</sub> SE 0.35 µg/m <sup>3</sup> regional model (RM), Gothenburg 1.6 µg/m <sup>3</sup> city model (CM), 0.5 µg/m <sup>3</sup> RM (S2) SE 0.23 µg/m <sup>3</sup> RM; Gothenburg 1.5 µg/m <sup>3</sup> CM, 0.3 µg/m <sup>3</sup> RM	All-cause mortality, YLLs, DALYs, [MI, stroke]	Mortality RR = 1.07 per 5 µg/m <sup>3</sup> PM <sub>2.5</sub> (Beelen et al., 2014) Mortality RR = 1.062 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Héroux et al., 2015) [MI RR = 1.13 per 5 µg/m <sup>3</sup> PM <sub>2.5</sub> (Cesaroni et al., 2014) Stroke RR = 1.19 per 5 µg/m <sup>3</sup> PM <sub>2.5</sub> (Stafoggia et al., 2014)]	YLLs; Russia 134 deaths (↓45%), 1625 YLLs; SUM 1011 deaths (↓37%), 11,041 YLLs (S1) SE 410 deaths, 4161 YLLs; 5700 DALYs; Gothenburg 97 deaths CM, 32 deaths RM, 1294 YLLs CM, 433 YLLs RM; 1374 DALYs CM, 513 DALYs RM; (S2) SE 264 deaths (↓36%), 2680 YLLs (↓36%), 4200 DALYs (↓26%); Gothenburg 90 deaths (↓7%) CM, 21 deaths RM (↓34%), 1206 YLLs CM (↓7%), 283 YLLs RM (↓35%), 1268 DALYs CM (↓8%), 363 DALYs RM (↓29%)
Tang et al. (2020) Atm. Chem. Phys.	CRA	Baltic Sea and North Sea (Gothenburg area)	Shipping-and port-(berthing) sourced emissions	(S1) BAU 2012 complete emission inventory with S fuel content 1% inside SECA, 0.1% for ships at berth in EU ports; (S2) 2012 no local shipping emission inventory without local shipping emissions; (S3) 2012 no local and regional shipping emission inventory without local and regional shipping emissions	Population of Gothenburg	(S1) BAU 2012 mean PM <sub>2.5</sub> 4 µg/m <sup>3</sup> ; NO <sub>2</sub> 3.7 ppb (S2) local shipping PM <sub>2.5</sub> 0.1 µg/m <sup>3</sup> (3%); NO <sub>2</sub> 0.05 ppb (14%); O <sub>3</sub> -0.5 ppb (-2%) (S3) regional shipping PM <sub>2.5</sub> 0.4 µg/m <sup>3</sup> (11%); NO <sub>2</sub> 1 ppb (26%); O <sub>3</sub> 2 ppb (7%)	All-cause mortality (acute, chronic), YLLs	Mortality RR = 1.062 per 10 per µg/m <sup>3</sup> PM <sub>2.5</sub> (WHO, 2013) Mortality RR = 1.029 per 10 µg/m <sup>3</sup> O <sub>3</sub> (WHO, 2013) Mortality RR = 1.027 per 10 µg/m <sup>3</sup> NO <sub>2</sub> (WHO, 2013)	(S1) PM <sub>2.5</sub> all shipping 174 YLLs (12% of mortality relative to total exposure), NO <sub>2</sub> all shipping 2.59 acute deaths, O <sub>3</sub> all shipping -0.4 acute deaths; (S2) PM <sub>2.5</sub> 31 YLLs, NO <sub>2</sub> 1.06 acute deaths, O <sub>3</sub> -0.5 acute deaths; (S3) PM <sub>2.5</sub> 143 YLLs, NO <sub>2</sub> 1.53 acute deaths, O <sub>3</sub> 0.03 acute deaths
Ramacher et al. (2020) Atmos. Chem. Phys.	CRA	Baltic Sea and North Sea (Gothenburg area)	Shipping-and port-(berthing) sourced emissions	(S1) BAU 2040 (SECA + NECA + trends in ship traffic and transport volumes, different ship types, changes in fuel mixtures (10% LNG), use of abatement measures and technologies to reduce emissions (20% scrubbers), regulations influencing emission and fuel consumption) (S2) BAU240LP as BAU2040 with additional shoreside electricity; (S3) EEDI2040 fuel efficiency just follows the Energy Efficiency Design Index regulation of IMO; (S4) EEDI2040LP as	Population of Gothenburg (0.6 million residents)	(S1) PM <sub>2.5</sub> 2.80 µg/m <sup>3</sup> , NO <sub>2</sub> 1.16 ppb, O <sub>3</sub> 18,723 ppb/h; (S2) PM <sub>2.5</sub> ↓0.01 µg/m <sup>3</sup> , NO <sub>2</sub> ↓0.12 ppb, O <sub>3</sub> ↑241 ppb/h; (S3) PM <sub>2.5</sub> 2.83 µg/m <sup>3</sup> , NO <sub>2</sub> 1.39 ppb, O <sub>3</sub> 18,434 ppb/h; (S4) PM <sub>2.5</sub> ↓0.01, NO <sub>2</sub> ↓0.18 ppb, O <sub>3</sub> ↑267 ppb/h	All-cause mortality, YLLs	Mortality RR = 1.062 per 10 per µg/m <sup>3</sup> PM <sub>2.5</sub> (WHO, 2013) Mortality RR = 1.029 per 10 µg/m <sup>3</sup> O <sub>3</sub> (WHO, 2013) Mortality RR = 1.027 per 10 µg/m <sup>3</sup> NO <sub>2</sub> (WHO, 2013)	(S1) PM <sub>2.5</sub> 13 deaths (0.8 deaths due to local shipping), 106 YLLs, 0.009 YLLs/per person, NO <sub>2</sub> 0.36 deaths, O <sub>3</sub> 0.02 deaths; (S2) PM <sub>2.5</sub> ↓0.3 deaths, ↓2.7 YLLs, ↓0.0002 YLLs/per person, NO <sub>2</sub> ↓0.23 acute deaths, O <sub>3</sub> ↑0.1 acute deaths; (S3) PM <sub>2.5</sub> local shipping 0.6 deaths, 4.8 YLLs, 0.0004 YLLs/per person, NO <sub>2</sub> 0.55 acute deaths, O <sub>3</sub> -0.4 acute deaths; (S4) PM <sub>2.5</sub> ↓0.5 deaths, ↓3.9 YLLs, ↓0.0004 YLLs/per person, NO <sub>2</sub> ↓0.35 acute deaths, O <sub>3</sub> ↑0.1 acute deaths

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
Viana et al. (2020) Environ. Int.	CRA	Mediterranean Sea	Shipping-sourced emissions	EEDI2040 with additional shoreside electricity (S1) BAU (2007–2017) high S fuel content 3.5%, (S2) 2020 low S fuel content 0.5%	Populations of 8 European cities: Nicosia (CY), Brindisi (IT), Genoa (IT), Venice (IT), Msida (MT), Barcelona (ES), Melilla (ES), Athens (GR)	(S1) PM <sub>2.5</sub> Nicosia 1.2 µg/m <sup>3</sup> (8%); Brindisi 2.3 µg/m <sup>3</sup> (15%); Genoa 0.3 µg/m <sup>3</sup> (15%); Venice 0.4 (5%); Msida 0.8 µg/m <sup>3</sup> (5%); Barcelona 1 µg/m <sup>3</sup> (6%); Melilla 2.6 µg/m <sup>3</sup> (14%); Athens 1 µg/m <sup>3</sup> (6%)	All-cause mortality, [CVD & RD hosp. adm.]	Mortality β = 0.0117 (Beelen et al., 2014) Mortality β = 0.003922 (Hoek et al., 2013) [CVD hosp. adm. β = 0.005827 (Hoek et al., 2013) RD hosp. adm. B = 0.002956 (Hoek et al., 2013)]	(S1) Nicosia 22–66 deaths (0.5–1.4%), Brindisi 7–22 deaths (0.9–2.7%), Genoa 8–25 deaths (0.1–0.3%), Venice 7–22 deaths (0.1–0.5%), Msida 0.2–0.7 deaths (0.3–1%), Barcelona 60–177 deaths (0.4–1.2%); Melilla 13–37 deaths (1–3%), Athens 102–302 deaths (0.4–1.2%); (S2) Nicosia ↓9.9 deaths (↓23%), Brindisi ↓0.1 deaths (↓1%), Genoa ↓1.3 deaths (↓8%), Venice ↓0.4 deaths (↓8%), Msida ↓0.1 deaths (↓26%), Barcelona ↓8.3 deaths (↓7%); Melilla ↓10.7 deaths (↓45%), Athens ↓16.2 deaths (↓8%)
Velders et al. (2020) Atmos. Env.	CRA	North Sea (International Seas)	Shipping-sourced emissions	(S1) Baseline reported emissions 1980–2015 in Europe from different emission sectors considering air quality policy measures, including IMO shipping emission regulations; (S2) World Avoided emissions assuming NO implementation of air quality policies	Population of NL (17 million)	(S2 vs S1) Foreign shipping-sourced PM <sub>2.5</sub> ↓0.7 µg/m <sup>3</sup> , NO <sub>2</sub> ↑1.1 µg/m <sup>3</sup>	All-cause mortality, YLLs, LLE, DALYs, health costs € (VOLY), [morbidity impacts]	Mortality RR = 1.06 per 10 per µg/m <sup>3</sup> PM <sub>2.5</sub> (WHO, 2013) Mortality RR = 1.02 per 10 µg/m <sup>3</sup> NO <sub>2</sub> (Fischer et al., 2015) VOLY = 50,000–110,000 (De Bruyn et al., 2017)	(S2 vs S1) (PM <sub>2.5</sub> and NO <sub>2</sub> combined): ↓ 100 deaths, ↓1200 YLLs, ↓0 LLEs (months), ↓1200 DALYs; ↓100 mio €
Nunes et al. (2021) Env. Intern.	CRA	Mediterranean; Atlantic Ocean	Shipping-sourced emissions	(S1) Baseline B–SCN all emissions, no shipping 2015; (S2) S–SCN all emissions including shipping 2015; (S3) CAP2020-SCN all emissions and shipping 2015 with S CAP2020 regulations (0.5% S fuel content)	Population of Iberian Peninsula (PT, ES); adults and children	(S2) mean 2015 concentrations, including shipping, for all grids of Iberian Peninsula NO <sub>2</sub> 1.8 µg/m <sup>3</sup> ; PM <sub>2.5</sub> 8.2 µg/m <sup>3</sup> ; PM <sub>10</sub> 22 µg/m <sup>3</sup>	Mortality (all-cause, cause-specific, post-neonatal), YLLs, costs € (VSL + VOLY + costs of illness), [RD & CVD hosp. adm., WLD, RAD, bronchitis, asthma]	(Burnett et al., 2014) Integrated Exposure-Response (IER) model incorporating 1000 risk functions per cause VSL = 3.6 mio € EU27 (adjusted to Spain and Portugal) (OECD, 2014) VOLY = 40,000 € (Desaigues et al., 2011)	(S2 vs S1) PT PM <sub>2.5</sub> 349 deaths, 2645 YLLs, 639 mio €, PM <sub>10</sub> 6 post-neonatal deaths; ES PM <sub>2.5</sub> 1595 deaths, 11,815 YLLs, 3998 mio €, PM <sub>10</sub> 37 post-neonatal deaths; (S3 vs S2) PM <sub>2.5</sub> ↓ 6% deaths, PM <sub>10</sub> ↓10% post-neonatal deaths
Lindgren (2021) Transp. Res. Part D	DD model	North Sea and English Channel	Shipping-sourced emissions	(S1) BAU 2010–2015 (S2) Effect of SECA 2015 S fuel content reduction from 1% to 0.1% in coastal (within 35 km from coast) and inland areas	Newborns in England and Wales	(S2 vs S1) ↓ 0.58 µg/m <sup>3</sup> (22%) SO <sub>2</sub> ; ↓ 0.8 µg/m <sup>3</sup> (6%) PM <sub>2.5</sub> in coastal compared to inland areas	Low birthweight (<2500 g), costs of neonatal care US\$	Regression model: each 1 µg/m <sup>3</sup> PM <sub>2.5</sub> increases probability of low birthweight by 0.61 percentage points, or 9%. Costs of low birthweight = 11,463\$–36,000\$	(S2 vs S1) ↓7% risk of low birthweight in coastal areas ↓576 cases of low birthweight newborns in coastal areas, neonatal care savings ↓6.6–20.1 mio \$

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
<b>Asian Seas</b>									
Tian et al. (2013) Atmos. Environ.	TSA	Port of Hong Kong, China	Port- (berthing) sourced emissions	(S1) Effect of Ni and V in PM <sub>10</sub> as indices of shipping emission on CVD hosp. adm. in Hong Kong from 1998 to 2007.	Hong Kong population	Mean 4.7 ng/m <sup>3</sup> Ni in PM <sub>10</sub> ; Mean 9.7 ng/m <sup>3</sup> V in PM <sub>10</sub>	CVD hosp. adm.	TSA model (GAM)	(S1) IQR ↑ of lag <sub>0</sub> Ni in PM <sub>10</sub> ↑1.25% (0.81–1.68%) CVD hosp. adm.; IQR ↑ of lag <sub>0</sub> V in PM <sub>10</sub> ↑0.95% (0.55–1.35%) CVD hosp. adm.
Liu et al. (2016) Nat. Clim. Change	BDA	East Asian Seas (East China Sea, South China Sea, Yangzi River Delta, Taiwan Strait, Bohai Sea, Yellow Sea, Sea of Japan, Western Pacific)	Shipping-sourced emissions	(S1) 2013 East Asian Seas shipping emission-derived PM <sub>2.5</sub> , O <sub>3</sub>	East Asian populations; global	Contribution of shipping in East Asian Seas is 16% to global shipping CO <sub>2</sub> , 16% to global shipping NO <sub>x</sub> and 19% to global shipping SO <sub>2</sub> emissions	Mortality [IHD, stroke, COPD, LC, acute lower respiratory infections]	(Burnett et al., 2014) Integrated Exposure-Response (IER) model incorporating 1000 risk functions per cause for IHD, stroke, COPD, LC and acute lower respiratory infections in children mortality	(S1) East Asia 24,000 deaths (CH, 18000 ± 8600 deaths, JP 3600 ± 1200 deaths, Taiwan + Hong Kong + Macau 1100 ± 400 deaths, KR 800 ± 300 deaths, VT 600 ± 200 deaths); Global 17,000 ± 8400 deaths PM <sub>2.5</sub> , 8900 ± 3100 deaths O <sub>3</sub>
Lin et al. (2018) Environ. Pollut.	TSA	Port of Guangzhou, China	Port- (berthing) sourced emissions	(S1) Effect of Ni and V in PM <sub>2.5</sub> as indices of shipping emission on mortality in Guangzhou in 2014	Guangzhou population	Mean Ni in PM <sub>2.5</sub> 4.5 ng/m <sup>3</sup> ; mean V in PM <sub>2.5</sub> 9.3 ng/m <sup>3</sup> ; shipping emissions 1.0 µg/m <sup>3</sup>	Mortality (CVD, stroke)	TSA model (GAM)	(S1) IQR ↑ of lag <sub>2</sub> Ni in PM <sub>2.5</sub> ↑4.6% (0.1–9.3%) CVD mortality, ↑13.4% (5.5–21.8%) stroke mortality; IQR ↑ of lag <sub>0</sub> V in PM <sub>2.5</sub> ↑6.6% (1.8–10.4%) ↑ CVD mortality, 11% (3.2–19.5%) stroke mortality; IQR ↑ of lag <sub>1</sub> shipping emissions ↑5.6% (0.8–10.5%) CVD mortality, ↑10.4% (1.4–20.1%) stroke mortality
Liu et al. (2018) Environ. Pollut.	CBA	Jing-Jin-Ji (JJJ; Beijing, Tianjin, Heibei province), Yangtze River Delta (YRD), Pearl River Delta (PRD), China	Shipping- and port- (berthing) sourced emissions	(S1) BAU 2020 shipping emissions with 2.43% S fuel content; (S2/S3) P1/P2 2020 0.5% S fuel content in core ports/all ports in DECAs (JJJ, YRD, PRD); (S4–S9) R1–R6 YRD + PRD 2020 0.5%/0.1% S fuel content and varying distances (12 nm, 50 nm, 100 nm) to DECAs; (S9/S10) R1/R2 JJJ 2020 0.5%/0.1% S fuel content in DECA	Populations of JJJ, YRD, PRD	JJJ, YRD, PRD port emissions will rise between 2013 and 2020 by 61%, 15% and 34%, respectively, without control measures	Social costs US\$ (health (cause-specific mortality (VSL), CVD & RD hosp. adm.) + environment + climate) vs costs US\$ (fuel price premium for fuel switch), all-cause mortality, CVD & RD hosp. adm.	Burnett et al., (2014) Integrated Exposure-Response (IER) model incorporating 1000 risk functions per cause for IHD, stroke, COPD, LC mortality CVD hosp. adm. β = 0.001882 (WHO, 2013) RD hosp. adm. β = 0.0009059 (WHO, 2013) VSL = 163,351 (2020) US\$ (Wang and Mauzerall, 2006)	(S2 vs S1) JJJ benefits 0.17 bn US\$ > costs 0.05 bn US\$ (ratio 3.8:1); YRD benefits 0.65 bn US\$ > costs 0.16 bn US\$ (ratio 3.9:1); PRD benefits 0.21 bn US\$ > costs 0.06 bn US\$ (ratio 3.9:1); (S3 vs S1) JJJ benefits 0.61 bn US\$ > costs 0.16 bn US\$ (ratio 3.9:1); YRD benefits 0.68 bn US\$ > costs 0.17 bn US\$ (ratio 3.7:1); PRD benefits 0.32 bn US\$ > costs 0.09 bn US\$ (ration 3.8:1); (S9) JJJ ↓ 600 annual deaths, ↓ 500 annual CVD + RD hosp. adm.
Mason et al. (2019) Chemosph.	TSA/RA	Port of Hong Kong, China	Port- (berthing) sourced emissions	(S1) BAU January 1st 2010–June 30th 2015; (S2) S fuel content of 0.5% at berth as of July 1st 2015, study period January 1st 2010 to June 30th 2017	Population of Hong Kong	(S1) mean SO <sub>2</sub> 21 µg/m <sup>3</sup> , PM <sub>10</sub> 42 µg/m <sup>3</sup> , NO <sub>2</sub> 68 µg/m <sup>3</sup> , O <sub>3</sub> 33 µg/m <sup>3</sup> ; (S2) mean SO <sub>2</sub> 11 µg/m <sup>3</sup> (↓50%), PM <sub>10</sub> 34 µg/m <sup>3</sup> (↓20%), NO <sub>2</sub>	Mortality (all-causes, CVD, RD)	All-cause mortality excess risk 0.71% per 10 per µg/m <sup>3</sup> SO <sub>2</sub> , 1.4% per 10 per µg/m <sup>3</sup> NO <sub>2</sub> , 0.42% per 10 per µg/m <sup>3</sup> O <sub>3</sub> ; 0.31% per 10 per µg/m <sup>3</sup> PM <sub>10</sub> (Lai et al., 2013) CVD mortality excess risk	(S1 vs S2) SO <sub>2</sub> , PM <sub>10</sub> , NO <sub>2</sub> , O <sub>3</sub> impacts combined ↓379 all-cause deaths; ↓172 CVD deaths; 30 RD deaths

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
Chen et al. (2019) GeoHealth	CRA	Pearl River Delta (PRD), China	Shipping- and port- (berthing) sourced emissions	(S1) 2015 BAU Without Ship emissions; (S2) 2015 BAU With Ship emissions; (S3) 2030 BAU constant ship emissions of 0.5% S fuel content and constant 2015 land source emissions; (S4) 2030 ECA Constant ship emissions of 0.1% S fuel content within 200 nm and constant 2015 land source emission; (S5) 2030 BAU Projected ship emissions of 0.5% S fuel content and 2030 projected land source emissions; (S6) 2030 ECA Projected ship emissions of 0.1% S fuel content within 200 nm and projected 2030 land source emission	Population of PRD (58 mio people)	58 µg/m <sup>3</sup> (↓14%), O <sub>3</sub> 27 µg/m <sup>3</sup> (↓10%)  (S2 vs S1) ship-emitted PM <sub>2.5</sub> 3.75 µg/m <sup>3</sup> (7%), O <sub>3</sub> 6.01 µg/m <sup>3</sup> (12%); (S4) PM <sub>2.5</sub> ↓57%, SO <sub>x</sub> ↓76%, NO <sub>x</sub> ↓13%	Mortality (all-causes, CVD), [respiratory infections, IHD, COPD, stroke, LC]	0.72% per 10 per µg/m <sup>3</sup> SO <sub>2</sub> RD mortality excess risk 1.29% per 10 per µg/m <sup>3</sup> SO <sub>2</sub> (Burnett et al., 2014) Integrated Exposure-Response (IER) model incorporating 1000 risk functions per cause for IHD, stroke, COPD, LC mortality for PM <sub>2.5</sub> RD mortality RR = 1.009 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> , (Tao et al., 2011) RR = 1.029 per 10 ppb O <sub>3</sub> (Jerrett et al., 2009) IHD mortality RR = 1.015 per 10 ppb O <sub>3</sub> (Jerrett et al., 2009) CVD mortality RR = 1.011 per 10 ppb O <sub>3</sub> (Jerrett et al., 2009)	(S3) PM <sub>2.5</sub> 3019 deaths, O <sub>3</sub> 957 deaths; (S4) PM <sub>2.5</sub> ↓811 deaths (↓27%), O <sub>3</sub> ↓108 deaths (↓11%); (S5) PM <sub>2.5</sub> 4033 deaths, O <sub>3</sub> 1736 deaths; (S6) PM <sub>2.5</sub> ↓1194 deaths (↓30%), O <sub>3</sub> ↓160 deaths (↓9%)
Dasadzhikari et al. (2019) Atmos. Environ.	BDA	Asian-Pacific Seas	Shipping-sourced emissions	(S1) 2015 sectoral contributions to annual PM <sub>2.5</sub> in Asia-Pacific country, including shipping	Populations of BD, CH, IN, ID, JP, MM, PH, KR, TH, VT,		Mortality (IHD, stroke, COPD, LC, acute lower respiratory infections)	(Burnett et al., 2014) Integrated Exposure-Response (IER) model incorporating 1000 risk functions per cause for IHD, stroke, COPD, LC and acute lower respiratory infections in children mortality	(S1) BD 900 deaths, CH 20000 deaths, IN 2700 deaths, ID 770 deaths, JP 2800 deaths, MM 90 deaths, PH 730 deaths, KR 250 deaths, TH260 deaths, VT 590 deaths,

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
<b>North American Seas</b>									
Fann et al. (2012) Environ. Int.	BA	United States	Shipping-sourced emissions	(S1) BAU 2005 emissions for 17 emission sectors, including ocean-going vessels; (S2) 2016 emissions for 17 emission sectors, including ocean-going vessels	US population	(S1) PM <sub>2.5</sub> 89,325 t/year, NO <sub>x</sub> 1,169,907 t/year, SO <sub>2</sub> 740,998 t/year; (S2) PM <sub>2.5</sub> 63,030 t/year (129%), NO <sub>x</sub> 1,534,234 t/year (131%), SO <sub>2</sub> 439,987 t/year (141%)	Health benefits US\$ (mortality (VSL) + costs of illness (non-fatal heart attacks, CVD + RD hosp. adm., asthma ER visits, respiratory symptoms, bronchitis, WLD, RAD)/1-ton emissions	Mortality RR = 1.06 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Krewski et al., 2009) Infant mortality RR = 1.04 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Woodruff et al., 1997) Non-fatal heart attacks OR = 1.62 per 20 µg/m <sup>3</sup> PM <sub>2.5</sub> CVD hosp. adm. β = 0.00189 24-h PM <sub>2.5</sub> avg (Zanobetti et al., 2009) RD hosp. adm. β = 0.00207 24-h PM <sub>2.5</sub> avg (Zanobetti et al., 2009) Asthma ER-vistis RR = 1.04 per 7 µg/m <sup>3</sup> PM <sub>2.5</sub> (Mar et al., 2004) Acute bronchitis OR = 1.5 per 14.9 µg/m <sup>3</sup> PM <sub>2.5</sub> (Dockery et al., 1996) WLD β = 0.0046 24-h PM <sub>2.5</sub> avg (Ostro, 1987) RAD β = 0.00220 24-h PM <sub>2.5</sub> avg (Ostro and Rothschild, 1989) VSL = 8.1–8.9 mio US\$ All-cause mortality decrease of 1% (0.4–1.8%) for a 1 µg/m <sup>3</sup> PM <sub>2.5</sub> decrease (U.S. EPA, 2011) RD mortality RR = 1.04 per 10 ppb O <sub>3</sub> (Jerrett et al., 2009)	(S1) 96,000 US\$/1-ton PM <sub>2.5</sub> , 1300 US\$/1-ton NO <sub>x</sub> , 29,000 US\$/1-ton SO <sub>2</sub> ; (S2) 46,000 US\$/1-ton PM <sub>2.5</sub> (152%), 1900 US\$/1-ton NO <sub>x</sub> (146%), 12,000 US\$/1-ton SO <sub>2</sub> (159%)
Caiazzo et al. (2013) Atmos. Environ.	BDA	United States	Shipping-sourced emissions	(S1) 2005 emissions for 6 emission sectors, including maritime transportation within the EEZ 200 nm off coastline	US population, adults ≥30 years	(S1) PM <sub>2.5</sub> annual mean 0.36 µg/m <sup>3</sup> , O <sub>3</sub> daily max mean 0.39 ppb, Southern California exhibits largest PM <sub>2.5</sub> marine emission impact	Mortality (CP. LC, RD)	All-cause mortality decrease of 1% (0.4–1.8%) for a 1 µg/m <sup>3</sup> PM <sub>2.5</sub> decrease (U.S. EPA, 2011) RD mortality RR = 1.04 per 10 ppb O <sub>3</sub> (Jerrett et al., 2009)	(S1) PM <sub>2.5</sub> 8300 (3700–15000) deaths (4.1% of total PM <sub>2.5</sub> deaths); O <sub>3</sub> 530 (-50-110) deaths (5.2% of total O <sub>3</sub> deaths)
Rowangould et al. (2018) Transp. Res. Rec.	CRA	Ports of New York and New Jersey, United States	Truck-sourced emissions from port terminals + truck routes	(S1) BAU emissions from original Clean Trucks Program (remove old trucks from service); (S2) emissions from revised and rolled back Clean Trucks Program 2017/2018	Adults ≥25 years of 8 New Jersey counties	(S1 vs S2) PM <sub>2.5</sub> 10.01–1.00 µg/m <sup>3</sup> , depending on county, with 3 counties closest to port being exposed to highest concentrations	All-cause mortality	Mortality RR = 1.06 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Krewski et al., 2009) Mortality RR = 1.13 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Lepeule et al., 2012)	(S1 vs S2) 400,000 - 700,000 adults mortality risk of 1/1 mio persons; 5000 - 40,000 adults mortality risk of 10/1 mio persons; 600 - 3000 adults mortality risk of 25/1 mio persons; 3 counties closest to port exhibit greatest risk (Essex, Hudson, Union)
Wolfe et al. (2019) Sci. Total Environ.	BA	United States	Shipping-sourced emissions	(S1) 2025 emissions for 17 mobile sources, including marine vessels within the EEZ (diesel engines above 800 hp with <30 l/cylinder = C1+C2, engines >30 l/cylinder = C3)	US population 0–99 years	Population-weighted mean contribution PM <sub>2.5</sub> C1+C2 0.01 µg/m <sup>3</sup> , C3 0.002 µg/m <sup>3</sup> ; SO <sub>2</sub> C1+C2 0.001 µg/m <sup>3</sup> ; C3 0.012 µg/m <sup>3</sup> ; NO <sub>x</sub> C1+C2 0.001 µg/m <sup>3</sup> , C3 0.01 µg/m <sup>3</sup>	Health benefits US\$ (mortality (VSL) + costs of illness (non-fatal heart attacks, CVD + RD hosp. adm., asthma ER visits, respiratory symptoms, bronchitis, WLD, RAD)/1-ton emissions	Mortality RR = 1.06 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Krewski et al., 2009) Mortality RR = 1.13 per 10 µg/m <sup>3</sup> PM <sub>2.5</sub> (Lepeule et al., 2012) Non-fatal heart attacks OR = 1.62 per 20 µg/m <sup>3</sup> PM <sub>2.5</sub> CVD hosp. adm. β = 0.00189 24-h PM <sub>2.5</sub> avg (Zanobetti et al., 2009)	(S1) 610,000–1370,000 US \$/1-ton PM <sub>2.5</sub> ; 208,000-47000 US\$/1-ton SO <sub>2</sub> ; 5000–11300 US\$/1-ton NO <sub>x</sub>

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Table 2 (continued)

Publication	HIA method	Shipping routes/ ports	Emission source	Scenario	Impacted population	Air pollution contribution	Health outcome	Health risk/impact estimates	Health impact
RD hosp. adm. $\beta = 0.00207$ 24-h $PM_{2.5}$ avg (Zanobetti et al., 2009) Asthma ER-visits RR = 1.04 per $7 \mu g/m^3$ $PM_{2.5}$ (Mar et al., 2004) Acute bronchitis OR = 1.5 per $14.9 \mu g/m^3$ $PM_{2.5}$ (Dockery et al., 1996) WLD $\beta = 0.0046$ 24-h $PM_{2.5}$ avg (Ostro, 1987) RAD $\beta = 0.00220$ 24-h $PM_{2.5}$ avg (Ostro and Rothschild, 1989) VSL = 10.4 mio. US\$									
<b>Australian Seas</b>									
Broome et al. (2016) Environ. Int.	CRA	Ports of Sydney, Australia	Shipping- and port- (berthing) -sourced emissions	(S1) BAU 2010/11 shipping $PM_{2.5}$ with 2.7% S fuel content; (S2) shipping $PM_{2.5}$ with 0.1% S fuel content at berth; (S3) shipping $PM_{2.5}$ with 0.1% S fuel content within 300 km of Sydney	Population of 5.4 mio of Sydney's Greater Metropolitan Region	Mean ship-related $PM_{2.5}$ (S1) $0.085 \mu g/m^3$ ; (S2) $0.064 \mu g/m^3$ ( $\downarrow 25\%$ ); (S3) $0.037 \mu g/m^3$ ( $\downarrow 56\%$ )	All-cause mortality, YLLs, life-years gained	Mortality $\beta = 0.006$ (RR = 1.062 per $10 \mu g/m^3$ $PM_{2.5}$ ) (Hoek et al., 2013)	(S1) 17 (11–22) deaths, 220 (140–290) YLLs; (S2) $\uparrow 390$ (260–520) life years; (S3) $\uparrow 920$ (600–1200) life years
Broome et al. (2020) Environ. Int.	BDA	East Australian Sea, adjacent to Greater Metropolitan Region of Sydney	Shipping- and port- (berthing) sourced emissions	(S1) 2010/11 $PM_{2.5}$ emissions for 8 emissions sources, including ships	Population of 5.6 mio of Sydney's Greater Metropolitan Region	Mean ship $PM_{2.5}$ $0.12 \mu g/m^3$ (5.7%), highest at coast decreasing towards inland	All-cause mortality, YLLs, LLE	Mortality $\beta = 0.006$ (RR = 1.062 per $10 \mu g/m^3$ $PM_{2.5}$ ) (Hoek et al., 2013) Mortality $\beta = 0.01$ (Roman et al., 2008)	(S1) 25 deaths, 340 YLLs, 3 days LLE

**HIA method:** BA = benefit analysis; BDA = burden of disease assessment; CA = cost analysis; CBA = cost-benefit analysis; CRA = comparative risk assessment; RA = risk assessment; TSA = time-series analysis.

**Abbreviations:** BAU = business as usual; BD=Bangladesh; BE=Belgium; bn = billion; CH=China; CH<sub>4</sub> = methane; CM = city model; CP = cardio-pulmonary; CO<sub>2</sub> = carbon dioxide; COPD = chronic obstructive pulmonary disease; CVD = cardiovascular disease; CY=Cyprus; DALY = disability-adjusted life-year; DD = difference-in-differences model; DE = Germany; DK = Denmark; EBD = Environmental Burden of Disease; EC = European Commission; EE = Estonia; EEDI = Energy Efficiency Design Index; EEZ = Economic Exclusion Zone; EGR = exhaust-gas recirculation; ER = emergency room; ES = Spain; FI=Finland; FR=France; GB = Great Britain; GR = Greece; GT = gross tonnage; hosp. adm. = hospital admissions; IHD = ischemic heart disease; IN=India; IQR = interquartile range; IT=Italy; JJJ = Jing-Jin-Ji; JP = Japan; KR=South Korea; LC = lung cancer; LLE = loss in life expectancy; LNG = liquefied natural gas; LT = Lithuania; LV = Latvia; mio = million; MM = Myanmar; MT = Malta; NECA = nitrogen emission control area; Ni = nickel; NL=Netherlands; nm = nautical miles, NO=Norway; NO<sub>x</sub> = nitrogen oxides; NO<sub>2</sub> = nitrogen dioxide; O<sub>3</sub> = ozone; PH=Philippines; PM<sub>2.5</sub> = particulate matter <2.5  $\mu m$ ; PL=Poland; PRD=Pearl River Delta; PT=Portugal; RAD = restricted activity days; RD = respiratory disease; RM = regional model; RR = relative risk; S = sulphur; (S) = scenario; SCR = selective catalytic reduction; SE=Sweden; SECA = sulphur emission control area; SO<sub>2</sub> = sulphur dioxide; TH = Thailand; US=United States; V = vanadium; VOLY = value of a life year; VSL = value of statistical life; VT=Vietnam; WLD = work loss days; WASP = wind assisted ship propulsion; WIF = water in fuel; YLD = years lived with disability; YLL = years of life lost; YRD=Yangtze River Delta

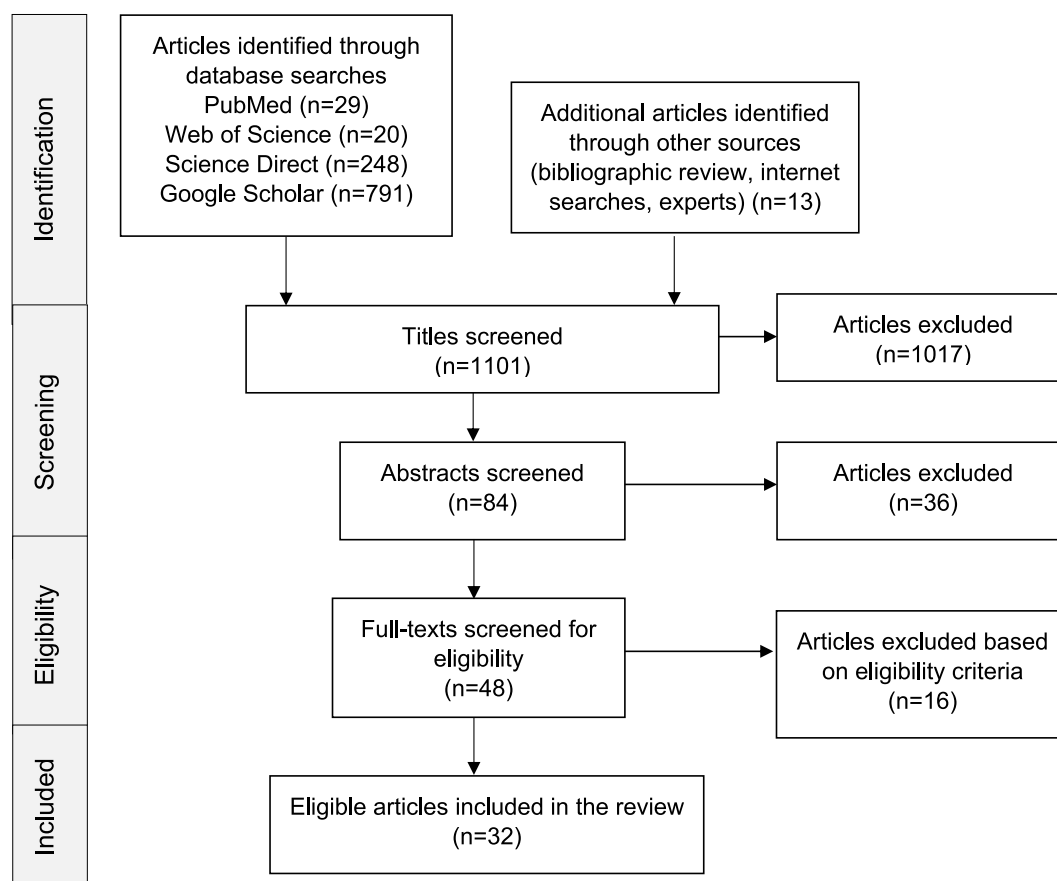


Fig. 3. Flow diagram for study selection.

pollution from maritime transport in European Seas, predominantly the Baltic and North Seas, including the English Channel, Kattegat and the Gothenburg area, but also the Mediterranean Sea and Atlantic Ocean, and the Marmara Sea, including the Turkish Straits (Antturi et al., 2016; Åström et al., 2018; Ballini et al., 2017; Barregard et al., 2019; Brandt et al., 2013; Jonson et al., 2015; Lindgren, 2021; Mwase et al., 2020; Nunes et al., 2021; Ramacher et al., 2020; Tang et al., 2020; Velders et al., 2020; Viana et al., 2020, 2015). Seven studies looked at Asian seas and ports, including the Asian-Pacific and East Asian Seas (East China Sea, South China Sea, Yangzi River Delta (YRD), Taiwan Strait, Bohai Sea, Yellow Sea, Sea of Japan and the Western Pacific), the Chinese Jing-Jin-Ji (JJJ), YRD and Pearl River Delta (PRA), as well as the Chinese ports of Hong Kong and Guangzhou (Chen et al., 2019; Dasadhikari et al., 2019; Lin et al., 2018; Liu et al., 2018, 2016; Mason et al., 2019; Tian et al., 2013). Four studies looked at air pollution along the coasts of North America, extending as far as the North American EEZ, i.e. 200 nm off the coast, and the United States (US) ports of New York and New Jersey (Caiazzo et al., 2013; Fann et al., 2012; Rowangould et al., 2018; Wolfe et al., 2019). Finally, two study looked at the air pollution associated health burden of the ports of Sydney and East Australian Sea, adjacent to the Greater Metropolitan Region of Sydney, Australia (Broome et al., 2020, 2016).

While 21 studies looked at shipping-sourced air pollution generated by ships in transit (even though these studies might have implicitly included port-sourced (berthing) air pollution without explicitly quantifying it); three studies exclusively considered the air pollution of ships at berth in the ports of Hong Kong (Mason et al., 2019; Tian et al., 2013) and Guangzhou (Lin et al., 2018), while seven studies explicitly studied both, shipping-sourced and port-sourced (berthing) air pollution (Broome et al., 2020, 2016; Chen et al., 2019; Jonson et al., 2015; Liu et al., 2018; Ramacher et al., 2020; Tang et al., 2020). Finally, one study

looked specifically at port-related air pollution sourced from heavy-duty trucks in the US ports of New York and New Jersey (Rowangould et al., 2018).

### 3.3. HIA method

In order to assess the health burden of shipping and port-sourced air pollution, various HIA methods were applied (Table 2). Fifteen studies used comparative risk assessment (CRA) frameworks, comparing a reference with one or multiple counterfactual scenarios and estimated attributable mortality, cases of disease or monetized impacts, using value of a statistical life (VSL), value of a life year (VOLY) or costs of illness approaches (Barregard et al., 2019; Broome et al., 2016; Chen et al., 2019; Jonson et al., 2015; Mwase et al., 2020; Nunes et al., 2021; Partanen et al., 2013; Ramacher et al., 2020; Rowangould et al., 2018; Sofiev et al., 2018; Tang et al., 2020; Velders et al., 2020; Viana et al., 2020, 2015; Winebrake et al., 2009). Six studies used a burden of disease assessment (BDA), assessing the total attributable mortality burden associated with past or projected shipping-sourced air pollution levels (Broome et al., 2020; Caiazzo et al., 2013; Corbett et al., 2007; Crippa et al., 2019; Dasadhikari et al., 2019; Liu et al., 2016). Four studies used a cost-benefit analysis (CBA), assessing costs and health benefits of different shipping-sourced emission scenarios, whereas costs considered ship fleet adjustment costs, such as emission control technologies (e.g. wind-assisted ship propulsion (WASP)) and fuel switches, and health benefits were monetized using VSL, VOLY, costs of illness or social costs approaches, including health costs (Antturi et al., 2016; Åström et al., 2018; Ballini et al., 2017; Liu et al., 2018). Two studies used a benefit analysis (BA) approach, assessing exclusively the economic health benefits of avoided air pollution, using VSL and costs of illness approaches, and expressed health benefits per 1-ton emission reduction

(Fann et al., 2012; Wolfe et al., 2019). One study used a cost-analysis (CA), assessing exclusively the attributable deaths and health-related external costs, using VSL, VOLY, and cost of illness approaches, under different shipping-sourced emission reduction scenarios (Brandt et al., 2013). Three studies used time-series analysis (TSA) to estimate based on historic data the attributable health burden of port-sourced (berthing) air pollution in the ports of Hong Kong and Guangzhou, China (Lin et al., 2018; Mason et al., 2019; Tian et al., 2013), of which one study additionally included a risk assessment (RA) to quantify attributable mortality impacts based on available risk estimates (Mason et al., 2019). Finally, one study used a difference-in-difference (DD) model to compare the risk and monetized impacts, using a costs of illness approach, for low birth weight outcomes in coastal and inland areas before and after the studied S fuel content cap scenario (Lindgren, 2021).

### 3.4. Health risk/ impact estimates

All studies, except two TSA (Lin et al., 2018; Tian et al., 2013) and the DD model (Lindgren, 2021), used standard HIA methods (Murray et al., 2004) to forecast health impacts, by a) retrieving risk estimates (e. g. relative risks (RRs)) and exposure-response functions (ERFs) from the literature that quantify the association between air pollution and health outcomes, b) extrapolating risks to study populations, and c) combining exposure, risk and health data to quantify the association between shipping-sourced air pollution levels and associated health outcomes, and d) finally estimate attributable health burdens.

For the different pollutants, all-cause or cause-specific mortality risk estimates were frequently retrieved (besides others, see Table 2) from Hoek et al. (2013); Jerrett et al. (2009); Krewski et al. (2009); Laden et al. (2006); Lepeule et al. (2012); Ostro (2004); Pope et al. (2002); WHO, 2006, indicating mortality risks ranging between 4 and 26% per 10  $\mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{2.5}$ ; the European Study of Cohort for Air Pollution Effects (ESCAPE) project mortality estimate by Beelen et al. (2014) (RR 1.07 per 5  $\mu\text{g}/\text{m}^3$   $\text{PM}_{2.5}$ ); the integrated exposure-response (IER) functions by Burnett et al. (2014) that incorporate 1000 risk functions per mortality cause from ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), LC and acute lower respiratory infections in children; as well as Health Risks of Air Pollution in Europe (HRAPIE) project-recommended ERFs for all-cause mortality and cause-specific mortality, but also CVD and RD hospital admissions, bronchitis, asthma, restricted activity days (RADs) and work loss days (WLDs) (Héroux et al., 2015; WHO, 2013).

Moreover, for disease-specific outcomes, besides or already being part of the ESCAPE and HRAPIE projects-recommended ERFs, available risk estimates for CVD (Cesaroni et al., 2014), stroke (Stafoggia et al., 2014), CVD and RD hospital admissions (Atkinson et al., 2014; Hoek et al., 2013; Stafoggia et al., 2014; Sunyer et al., 2003; Zanobetti et al., 2009), asthma (Mar et al., 2004; WHO, 2013; Zheng et al., 2015), bronchitis (Dockery et al., 1996; WHO, 2013), WLD and RAD (Ostro, 1987; Ostro and Rothschild, 1989; WHO, 2013) were used. Some studies followed the Environmental Burden of Disease (EBD) approach, as recommended by Hänninen et al. (2014), to calculate air pollution attributable DALYs, and components of YLLs and YLDs.

To monetize mortality effects, VSL or VOLY approaches were commonly used, with applied VSL values ranging between 163,351 US\$ for China (Liu et al., 2018; Wang and Mauzerall, 2006), 1.2 mio € to 3.6 mio € for Europe (Åström et al., 2018; Holland, 2014; Nunes et al., 2021), to 8.1 mio US\$ to 10.4 mio US\$ for the US (Fann et al., 2012; U.S. EPA, 2010; Wolfe et al., 2019). VOLY values, exclusively applied in European studies, ranged between 40,000 € to 155,000 € (Antturi et al., 2016; Desaiques et al., 2011; Holland et al., 2005). To monetize morbidity impacts, different costs of illness approaches and values were used.

### 3.5. Scenarios studied

Nineteen studies estimated health impacts under different S emission control scenarios, reducing  $\text{SO}_x$  emissions through varying S fuel content reductions, mostly towards 0.5% S fuel content in non-SECA waters and 0.1% in established SECAs, and/or S scrubber installation that reduce  $\text{SO}_x$  to equivalent levels, to comply with IMO SECA regulations (Antturi et al., 2016; Åström et al., 2018; Barregard et al., 2019; Brandt et al., 2013; Broome et al., 2016; Chen et al., 2019; Jonson et al., 2015; Lindgren, 2021; Liu et al., 2018; Mason et al., 2019; Mwase et al., 2020; Nunes et al., 2021; Partanen et al., 2013; Ramacher et al., 2020; Sofiev et al., 2018; Tang et al., 2020; Viana et al., 2020, 2015; Winebrake et al., 2009). Three studies assessed NECA limits to reduce  $\text{NO}_x$  emissions, considering ship engine transitions towards Tier III standards (e.g. LNG propulsion engines) and other  $\text{NO}_x$  reduction technologies, such as Selective Catalytic Reduction (SCR) or Exhaust-Gas Recirculation (EGR) and Water in Fuel (WIF) technologies (Åström et al., 2018; Jonson et al., 2015; Ramacher et al., 2020). Two studies investigated further emission reduction technologies, consisting of WASP installation (Ballini et al., 2017), different ship types, changes in fuel mixtures, shoreside electricity, and other abatement measures and technologies to reduce emissions (Ramacher et al., 2020).

Seven studies studied multiple emission sectors, including maritime transport (Broome et al., 2020; Caiazzo et al., 2013; Crippa et al., 2019; Dasadhikari et al., 2019; Fann et al., 2012; Velders et al., 2020; Wolfe et al., 2019). Four studies used different emissions inventories and projection years to study emissions with and without shipping emissions, partially considering different emission reduction measures (Chen et al., 2019; Corbett et al., 2007; Nunes et al., 2021; Tang et al., 2020). One study estimated East Asian Sea shipping emissions for 2013 (Liu et al., 2016). Two studies, using time series data and source apportionment methods, studied nickel (Ni) and vanadium (V) in PM as toxic constituents and indices of shipping emissions to be responsible for health effects in the two Chinese ports of Hong Kong and Guangzhou (Lin et al., 2018; Tian et al., 2013). Finally, one study looked at a clean truck program in the US ports of New York and New Jersey that was meant to remove old trucks from service in order to reduce emissions (Rowangould et al., 2018).

### 3.6. Impacted populations

Shipping-sourced air pollution impacted populations were populations of cities (Lin et al., 2018; Mason et al., 2019; Mwase et al., 2020; Ramacher et al., 2020; Tang et al., 2020; Tian et al., 2013; Viana et al., 2020), regions (Broome et al., 2020, 2016; Chen et al., 2019; Liu et al., 2018; Rowangould et al., 2018; Viana et al., 2015), and countries adjacent to studied sea areas, except for the five global studies that included the global population (Corbett et al., 2007; Crippa et al., 2019; Partanen et al., 2013; Sofiev et al., 2018; Winebrake et al., 2009). One study estimated in addition to Asian populations the impact for the global population of East Asian Sea shipping-sourced emissions (Liu et al., 2016). Most studies included all population age groups, however, six studies restricted the HIA to adults only (Caiazzo et al., 2013; Corbett et al., 2007; Partanen et al., 2013; Rowangould et al., 2018; Sofiev et al., 2018; Winebrake et al., 2009), one study additionally included children until age 14 (Sofiev et al., 2018), and finally, one study was restricted to impacts for newborns in England and Wales (Lindgren, 2021).

### 3.7. Air pollution contribution

Shipping-sourced air pollution contributed considerably to total global air pollution levels. The highest contributions were commonly found along major shipping routes and adjacent coastal cities or regions, and the reported absolute shipping-sourced  $\text{PM}_{2.5}$  contributions ranged between 0 and 5.1  $\mu\text{g}/\text{m}^3$  annual mean (Brandt et al., 2013; Broome et al., 2020, 2016; Caiazzo et al., 2013; Chen et al., 2019; Corbett et al.,

2007; Jonson et al., 2015; Lin et al., 2018; Mwase et al., 2020; Nunes et al., 2021; Partanen et al., 2013; Ramacher et al., 2020; Rowangould et al., 2018; Sofiev et al., 2018; Tang et al., 2020; Viana et al., 2020, 2015; Winebrake et al., 2009; Wolfe et al., 2019).

In terms of percentage contributions of shipping emissions to total emissions, Crippa et al. (2019) estimated that shipping accounted for 0.2% and 0.3% of Indian and Chinese total emissions, respectively, 7.4% of African total emissions, 4.2% of North American total emissions, 2.6% of South American total emissions, 4.4% of European total emissions, and 21.8% of Oceanian total emissions. Jonson et al. (2015) estimated that shipping PM<sub>2.5</sub> contributions to total PM<sub>2.5</sub> ranged between 0 and 15% for 12 European countries. Barregard et al. (2019) estimated that shipping emissions accounted for over 50% of NO<sub>2</sub> in central parts of the Baltic Sea and for 20–50% in adjacent coastal areas. Tang et al. (2020) estimated that regional shipping accounted for 11% of total PM<sub>2.5</sub> and 26% of total NO<sub>2</sub> in Gothenburg. Viana et al. (2020) estimated that Mediterranean Sea shipping accounted for 5% of total PM<sub>2.5</sub> in Venice and Msida, 6% in Barcelona and Athens, 8% in Nicosia, 14% in Melilla, and 15% in Brindisi and Genoa. Liu et al. (2016) estimated that East Asian Sea shipping contributed 16% to global shipping CO<sub>2</sub> and NO<sub>x</sub>, respectively, and 19% to SO<sub>2</sub>. Chen et al. (2019) estimated shipping-emitted PM<sub>2.5</sub> and O<sub>3</sub> to contribute 7% and 12%, respectively, to total PM<sub>2.5</sub> and O<sub>3</sub> of the PRD region in China. Broome et al. (2020) estimated East Australian Sea shipping to contribute 5.7% of total PM<sub>2.5</sub> in the Sydney Greater Metropolitan Region.

Of the studied sea areas, particularly affected by high ship traffic volumes and hence emissions were the Mediterranean Sea, between the Strait of Gibraltar and the Sea of Crete (Brandt et al., 2013), the Baltic and North Sea, especially between the English Channel and Kattegat (Antturi et al., 2016; Åström et al., 2018; Barregard et al., 2019; Brandt et al., 2013; Jonson et al., 2015), East Asian Seas and ports along the JJJ, YRD and PRD regions (Chen et al., 2019; Liu et al., 2018, 2016), and the Western US, especially Southern California (Caiazzo et al., 2013; Wolfe et al., 2019).

Air pollution levels were considerably reduced with studied emission control measure scenarios (Antturi et al., 2016; Åström et al., 2018; Ballini et al., 2017; Broome et al., 2016; Chen et al., 2019; Fann et al., 2012; Lindgren, 2021; Mason et al., 2019; Mwase et al., 2020; Ramacher et al., 2020; Viana et al., 2015), with populations closer to intervened sea regions benefiting the most in terms of air pollution reductions and related health impacts (Antturi et al., 2016; Brandt et al., 2013; Chen et al., 2019; Jonson et al., 2015; Lindgren, 2021; Liu et al., 2018; Mason et al., 2019; Mwase et al., 2020; Ramacher et al., 2020). However, shipping-sourced air pollution levels were projected to increase in the future, due to anticipated increases in global trade, maritime transport and ship traffic demands (Brandt et al., 2013; Liu et al., 2018; Sofiev et al., 2018).

### 3.8. Health outcomes

The majority of studies estimated shipping-sourced attributable mortality impacts. Mortality referred to the attributable number of deaths from all causes (Åström et al., 2018; Ballini et al., 2017; Barregard et al., 2019; Brandt et al., 2013; Broome et al., 2020, 2016; Chen et al., 2019; Fann et al., 2012; Liu et al., 2018; Mason et al., 2019; Mwase et al., 2020; Nunes et al., 2021; Ramacher et al., 2020; Tang et al., 2020; Velders et al., 2020; Viana et al., 2020, 2015), a normalized all-cause mortality risk (Rowangould et al., 2018), cause-specific deaths such as CVD, cardiopulmonary (CP), COPD, LC, stroke, RD or post-neonatal mortality (Caiazzo et al., 2013; Chen et al., 2019; Corbett et al., 2007; Crippa et al., 2019; Dasadhikari et al., 2019; Lin et al., 2018; Liu et al., 2018, 2016; Mason et al., 2019; Nunes et al., 2021; Partanen et al., 2013; Sofiev et al., 2018; Winebrake et al., 2009), CVD and stroke mortality risk per interquartile range (IQR) pollution concentrations (Lin et al., 2018), loss in life expectancy (LLE) (Broome et al., 2020; Velders et al., 2020), YLLs (Ballini et al., 2017; Barregard et al., 2019; Brandt et al.,

2013; Broome et al., 2020, 2016; Jonson et al., 2015; Mwase et al., 2020; Nunes et al., 2021; Ramacher et al., 2020; Tang et al., 2020; Velders et al., 2020), DALYs that combine YLLs and YLDs (Antturi et al., 2016; Mwase et al., 2020; Velders et al., 2020), life-years gained (Broome et al., 2016), economic mortality evaluation approaches, such as VSL (Åström et al., 2018; Ballini et al., 2017; Brandt et al., 2013; Fann et al., 2012; Liu et al., 2018; Nunes et al., 2021; Wolfe et al., 2019) and VOLY approaches (Antturi et al., 2016; Åström et al., 2018; Ballini et al., 2017; Brandt et al., 2013; Nunes et al., 2021; Velders et al., 2020).

Various studies directly or indirectly included morbidity outcomes as cases of disease and/or hospital admissions (including emergency room (ER) visits), such as childhood asthma, RD, CVD, and stroke, respiratory symptoms, bronchitis, COPD, RADs and WLDs (Åström et al., 2018; Ballini et al., 2017; Barregard et al., 2019; Chen et al., 2019; Fann et al., 2012; Liu et al., 2018; Mwase et al., 2020; Nunes et al., 2021; Sofiev et al., 2018; Viana et al., 2015, 2020). One study assessed the risk for CVD hospital admissions per IQR pollutant concentrations (Tian et al., 2013). One study investigated exclusively the impact on low birthweight and avoidable neonatal care costs (Lindgren, 2021). Seven studies included costs of illness approaches for respiratory, CVD and stroke hospital admissions, ER visits, lung cancer and CVD cases, respiratory symptoms and medication use, bronchitis, asthma, RADs, WLDs, neonatal care costs, and DALY costs (Antturi et al., 2016; Ballini et al., 2017; Brandt et al., 2013; Fann et al., 2012; Lindgren, 2021; Nunes et al., 2021; Wolfe et al., 2019).

### 3.9. Health impacts

The shipping and port-sourced air pollution was estimated to have considerable effects on mortality, morbidity and health economic impacts. The health impacts are presented by geographic region.

### 3.10. Global

Five studies provided a global assessment of the health impacts of air pollution from shipping and ports. Corbett et al., (2007) estimated ~60,000 CP and LC deaths attributable to shipping-sourced air pollution for 2001/2 (S1, S2), most of which occurred along major shipping routes in the European/Mediterranean region and East Asia, and least affected South East America. Similarly, Partanen et al., (2013), using data for 2010, estimated ~50,000 CP and LC deaths attributable to shipping-sourced air pollution (S1), most of which occurred in Europe and the fewest in Africa. Projections for 2020, under the assumption of global SECA implementation with 0.1% S fuel content in coastal areas and 0.5% S fuel content at ocean (S4), reduced CP and LC deaths to 2000 (i.e. 96% reduction). Crippa et al., (2019) estimated for 2010 most shipping-sourced attributable all-cause deaths for the European and Asian regions, and the least attributable deaths for South America, Australia and Oceania. The magnitude of impact in Crippa et al., (2019) was with 7 (Australia and Oceania) to ~11,600 (Europe) all-cause deaths comparably smaller than in the other global assessments. Winebrake et al., (2009) estimated for 2012, ~87,000 attributable CP and LC deaths, without IMO emission control measures (S1). A projected implementation of a 2012 coastal 0.1% S fuel standard (S3) was estimated to reduce CP and LC deaths to ~44,000 (i.e. 50% reduction). Sofiev et al., (2018) projected for 2020 ~400,000 CVD and LC deaths and ~14 mio childhood asthma cases without the implementation of the global IMO 0.5% S fuel standard coming into force that year (S1). In contrast, the 2020 implementation of the global IMO 0.5% S fuel standard, was estimated to reduce CVD and LC deaths to ~265,000 (i.e. 33% reduction), and childhood asthma cases to ~6.4 mio (i.e. 54% reduction) (S2). Both latter studies did not specify where geographically those health impacts would occur. Generally, the more restrictive the emission control scenario studied, the greater were the health benefits estimated.



### 3.11. Europe

Brandt et al. (2013) attributed for 2000 shipping emissions in the Northern Hemisphere 49,500 all-cause deaths and 58 bn € health-related external costs for Europe, and 700 all-cause deaths and 800 mio € health-related external costs for Denmark (DK) (S1). Emission projections for 2020, with SECA of 0.1% S fuel content implemented in the Baltic and North Seas (S4), showed particularly health benefits for DK of reduced attributable all-cause deaths to 430 (i.e. 39% reduction) and health-related external costs to 480 mio € (i.e. 40% reduction). On the other hand, 53,400 all-cause deaths (i.e. 8% increase) and 64 bn € health-related external costs (i.e. 10% increase) were estimated for Europe, due to expected overall increases in maritime transport. Jonson et al., (2015) attributed to 2009 shipping-sourced emissions (S2) over 3 mio YLLs for 12 European countries adjacent to the North and Baltic Seas, of which Poland (PL) was the least affected with representing 1.6% of YLLs and DK the most, with representing 11.7% of YLLs. Projected emissions for 2030, with SECA of 0.1% S fuel content, and NECA transition to Tier III engine standards, implemented (S5), reduced shipping-sourced emission attributable YLLs to 2.1 mio (i.e. 30% reduction), of which PL represented 1.1% of YLLs and DK 7.5%. Antturi et al., (2016) estimated DALY reductions associated with SECA implementation (S2 vs S1), through 0.1% S fuel content or S scrubber installation, exclusively in the Baltic Sea, for eight adjacent European countries, and estimated a reduction of over 2200 attributable DALYs. PL benefited the most in absolute terms (i.e. −587 DALYs) and Estonia (EE) and Lithuania (LT) the least (i.e. −107 DALYs each). Annual health benefits amounted to 105 mio €, which were estimated to not outweigh abatement costs of 465 mio € for ship fleet adjustment to SECA standards, with a negative cost-benefit ratio of 4.4:1, which was attributed to generally low population density of Baltic Sea neighbouring countries (Antturi et al., 2016). The two latter studies, Jonson et al., (2015) and Antturi et al., (2016), consistently found European countries, with dense population centres at coastal areas and closest to heavy trafficked shipping routes in the North (and Baltic) Seas, to benefit the most from emission control measures in terms of improved health outcomes. Similarly, Barregard et al., (2019) studied (S2) 2016 data with SECA implemented with 0.1% S fuel content in the Baltic Sea compared to (S1) 2014 data with 1% S fuel content allowance for 10 Northern and Eastern European countries and regions. Shipping emission attributable deaths and YLLs were considerably reduced in S2 with an overall 37% mortality reduction, ranging between 25% in DK (173 deaths (S1) vs 130 deaths (S2)) and 47% in FI (75 deaths (S1) vs 40 deaths (S2)). Ballini et al., (2017) studied shipping-sourced emissions in the Baltic and North Sea under the assumption that all bulk carriers and smaller transport vessels were equipped with WASP technologies (S2, S3 vs S1). Results for Central Europe were per year 2–3 avoidable all-cause deaths, 1150–1530 avoidable YLLs and a reduction of external health costs of 120–150 mio €. Results for DK were per year 90–100 avoidable YLLs and a reduction of external health costs of 9–10 mio € for DKs. External health benefits were estimated to not outweigh initial WASP installation costs (approx. 6 mio € per vessel), but the long-term health benefit-cost trade-off was estimated to be positive, once investment costs were offset (Ballini et al., 2017). Åström et al., (2018), assuming SECA implemented, studied shipping-sourced emissions for 2030 in the Baltic and North Seas of NECA implementation through different NO<sub>x</sub> reduction technologies (i.e. SCR, EGR, WIF, LNG propulsion engines) (S2–S5 vs S1). Monetized benefits for the European population, including avoided health, crop damage and climate impacts, were estimated to outweigh studied emission control costs (i.e. technology and fuel costs) throughout all scenarios, with positive cost-benefit ratios of 1:1.3–10.1 (S2–S5 vs S1) (Åström et al., 2018). Mwase et al., (2020) compared a 1% S fuel content scenario (S1) with a 0.1% S fuel content scenario (SECA) (S2) in the Baltic Sea for the Swedish and Gothenburg populations and found, under the low S fuel content scenario (S2 vs S1), a 36% mortality reduction for the Swedish population, and 7–34% mortality, 7–35%

YLLs and 8–29% DALY reductions for the Gothenburg population, based on whether a city (CM) or regional (RM) dispersion model was used. Similarly, Tang et al., (2020) and Ramacher et al., (2020) studied shipping and berthing-sourced emissions for the Gothenburg population. Tang et al., (2020) compared a 2012 complete emission inventory (S1), assuming a S fuel content of 1% inside SECA, 3.5% outside SECA and 0.1% for ships at berth in EU ports, with 2012 emission inventories (S2) excluding local shipping emissions and (S3) excluding local and regional shipping emissions, and estimated (S1) 2012 shipping PM<sub>2.5</sub> to have caused 174 YLLs and 2.59 acute NO<sub>2</sub> deaths among the Gothenburg population of 0.6 mio residents, of which local shipping emissions (S2) caused 31 PM<sub>2.5</sub> YLLs and 1.06 acute NO<sub>2</sub> deaths, and regional shipping emissions (S3) caused 143 PM<sub>2.5</sub> YLLs and 1.53 acute NO<sub>2</sub> deaths. Ramacher et al., (2020) ambitiously studied the impacts for the Gothenburg population of a 2040 implementation of (S1) different emission control measures, including SECA and NECA implementation, different ship types, changes in fuel mixtures with 10% LNG use, 20% scrubber use, and other abatement measures and technologies (i.e. EEDI and SEEMP) in the Baltic and North Seas, as well as (S2) additional shoreside electricity, and found for S1 13 PM<sub>2.5</sub> shipping attributable deaths, 106 shipping attributable PM<sub>2.5</sub> YLLs and 0.36 shipping NO<sub>2</sub> attributable deaths, which is considerably less than estimated by Tang et al., (2020) for the same population. Additional shoreside electricity (S2) was additionally reducing PM<sub>2.5</sub> shipping attributable deaths by 0.3, shipping attributable PM<sub>2.5</sub> YLLs by 2.7 and shipping attributable NO<sub>2</sub> deaths by 0.23 (Ramacher et al., 2020). Viana et al., (2015) studied (S2) 2013 shipping-sourced emissions, assuming a SECA of 0.1% S fuel content in the Marmara Sea, compared to no SECA (S1). Associated emission reductions (S2 vs S1) were estimate to reduce all-cause deaths by 1–2%, RD hosp. adm. by 1–14% and CVD hosp. adm. by 1–12% for the 23 mio persons living in the Marmara region (Viana et al., 2015). Moreover, Viana et al., (2020) compared a (S1) 3.5% S fuel content scenario (2007–2017) with a (S2) 2020 0.5% S fuel content scenario for the Mediterranean Sea and estimated mortality impacts for eight Mediterranean cities. The high S fuel content scenario (S1) was estimated to cause 0.3% (Genoa) to 3% (Melilla) of total mortality in the eight cities, while the low S fuel content scenario (S2) was estimated to reduce shipping attributable mortality, ranging between 1% (Brindisi) to 23% (Nicosia) in the eight cities. Nunes et al., (2021) studied health impacts for the Spanish and Portuguese populations of the 2020 S fuel content cap of 0.5% for the Mediterranean and Atlantic Ocean (S3) and compared the impact to a 2015 total emission inventory (S2), including shipping emissions. Estimations showed that (S3 vs S2) the 2020 S fuel content cap of 0.5% might have reduced shipping PM<sub>2.5</sub> attributable mortality by 6% and shipping PM<sub>10</sub> attributable post-neonatal deaths by 10% among the Spanish and Portuguese populations. Velders et al. (2020) compared (S1) 1980–2015 emissions in Europe from different emission sectors, considering implemented air quality policy measures, particularly targeting shipping emissions in the North and International Seas, with (S2) expected emissions assuming no implementation of air quality policies, and estimated impacts for the Dutch population. Estimations showed that shipping emission regulations, and resulting PM<sub>2.5</sub> and NO<sub>2</sub> reductions, had probably led to 100 avoided deaths, 1200 avoided YLLs and savings of 100 mio. € among the Dutch population (Velders et al., 2020). Finally, Lindgren, 2021, estimated impacts on low birthweight in England and Wales of the S fuel content reduction from 1% (S1) to (S2) 0.1% (SECA) in 2015 in the North Sea and English Channel and estimated 576 prevented cases of low birthweight newborns in English and Welsh coastal areas, a corresponding 7% risk reduction of low birthweight for 2015, and avoidable neonatal care costs ranging between 6.6 and 20.1 mio US\$.

### 3.12. Asia

Tian et al., (2013) and Lin et al., (2018) estimated the health impacts of N<sub>i</sub> and V in PM as indices of port (berthing)-sourced emissions in the



Chinese ports of Hong Kong and Guangzhou, respectively. Tian et al., (2013) found a 1.3% and 1% increase in CVD hosp. adm. for each IQR increase of  $\text{lag}_0 N_i$  in  $\text{PM}_{10}$  and  $\text{lag}_0 V$  in  $\text{PM}_{10}$ , respectively, while results for Lin et al., (2018) were even more pronounced. An increase in IQR of  $\text{lag}_2 N_i$  in  $\text{PM}_{2.5}$  resulted in a 4.6% increase in CVD mortality and 13.45% stroke mortality, while  $\text{lag}_0 V$  in  $\text{PM}_{2.5}$  was associated with a 6% increase in CVD mortality and 11% increase in stroke mortality. Also, Mason et al., 2019 estimated mortality impacts for the Hong Kong population, of a (S2) 0.5% S fuel content cap for ships at berth in the Hong Kong Port as of July 1, 2015 compared to (S1) years 2010–2015. Combined  $\text{SO}_2$ ,  $\text{PM}_{10}$ ,  $\text{NO}_2$  and  $\text{O}_3$  reductions were estimated to have prevented 379 all-cause deaths, 72 CVD and 30 RD deaths from June 2015 to July 2017 among the Hong Kong population. Liu et al., (2016) estimated 24,000 premature all-cause deaths in East Asia attributable to 2013 East Asian Sea shipping-sourced emissions, with China (CH) being most affected with 18,000 attributable deaths, followed by Japan (JP) (i.e. 3600 deaths), combined Taiwan, Hong Kong and Macau (i.e. 1100 deaths), South Korea (KR) (i.e. 800 deaths) and finally Vietnam (VT) (i.e. 600 deaths). Additionally, 17,000 premature deaths due to  $\text{PM}_{2.5}$  and 8000 deaths due to  $\text{O}_3$  were estimated for other parts of the world attributable to East Asian shipping emissions (Liu et al., 2016). Liu et al., (2018) studied (S2–S9) 0.5% and 0.1% S fuel content limits for the ports of JJJ, YRD and PRD and found social benefits, including health, environmental and climate impacts, to outweigh costs of fuel price premiums for required fuel switches across all scenarios with positive cost-benefit ratios of 1:3.7–3.9. Moreover, 600 premature deaths and 500 CVD and RD hosp. adm. were estimated to be preventable for the JJJ region (Liu et al., 2018) (S8). Chen et al., (2019), using either constant or projected ship emissions, compared impacts (S4 and S6) of a 2030 0.1% S fuel content cap with impacts of a (S3 and S5) 0.5% S fuel content cap in the PRD for ships in transit and at berth, and estimated shipping attributable  $\text{PM}_{2.5}$  deaths to be reduced by 27% (S4 vs S3) and 30% (S6 vs S5), and  $\text{O}_3$  deaths to be reduced by 9% and 11% (S4). Finally, Dasadhihari et al., 2019 estimated 2015 sectorial contributions, including shipping in Asian-Pacific Seas, to annual  $\text{PM}_{2.5}$  in 10 Asian-Pacific countries, and estimated shipping emission attributable deaths to range between 90 deaths in Myanmar to 20,000 deaths in China.

### 3.13. North America

Caiazzo et al., (2013) estimated for the US 8300 and 530 premature deaths attributable to 2005  $\text{PM}_{2.5}$  and  $\text{O}_3$ , respectively, emitted by ships traveling along the US coastlines and in the EEZ (Caiazzo et al., 2013). Fann et al., (2012) and Wolfe et al., (2019) estimated the US\$-value of health per reduced 1-ton of shipping-sourced air pollution. Fann et al., (2012) compared 2005 (S1) with 2016 (S2) emissions and estimated shipping-sourced emissions of  $\text{PM}_{2.5}$  and  $\text{SO}_2$  to have reduced by 29% and 41%, respectively, while  $\text{NO}_x$  emissions were estimated to have increased by 31% (S2 versus S1). Accordingly, the US\$-value of health per 1-ton decreased by 52% from 96,000 US\$ to 46,000 US\$ for  $\text{PM}_{2.5}$ , by 59% from 29,000 US\$ to 12,000 US\$ for  $\text{SO}_2$ , but increased by 46% from 1300 US\$ to 1900 US\$ for  $\text{NO}_x$  (Fann et al., 2012). Values by Wolfe et al., (2019) were considerably larger than the values derived by Fann et al., (2012). Wolfe et al., (2019) estimated for 2025 the US\$ to be 610, 000–1,370,000 US\$ per 1-ton  $\text{PM}_{2.5}$ , 208,000–470,000 US\$ per 1-ton  $\text{SO}_2$ , and 5000–11,300 US\$ per 1-ton  $\text{NO}_2$  from marine vessels. Benefit estimates of reduced emissions were substantially larger for the West US than for the East US, due to especially the Californian coast being heavily ship-trafficked and large population centres in close proximity being at increased health risk, therefore, benefiting especially from emission reductions (Wolfe et al., 2019). Rowangould et al., (2018) estimated the increased mortality risk for eight New Jersey counties due to the rolled back Clean Trucks Program in the Ports of New York and New Jersey (S2 vs S1). The three counties closest to the port exhibited the greatest mortality risk of up to 25 expected deaths per 1 mio persons, attributable to projected increases in  $\text{PM}_{2.5}$  exposure (Rowangould et al.,

2018).

### 3.14. Australia

Broome et al. (2016) found that for the Ports of Sydney and the 5.4 mio population of the Sydney's Greater Metropolitan Region, a SECA implementation of 0.1% S fuel content at berth (S2) and within 300 km of coast (S3) could prevent 17 deaths annually (S1) and lead to a gain of up to 920 life years. Furthermore, Broome et al., (2020) studied mortality impacts of 2010/11  $\text{PM}_{2.5}$  emissions for eight emission sources, including shipping, and found East Australian Sea shipping and berthing-sourced emissions to have caused 25 all-cause deaths, 340 YLLs and 3 days in LLE among the 5.6 mio residents of Sydney's Greater Metropolitan Region.

## 4. Discussion

This scoping review identified 32 studies assessing the health burden of shipping-sourced air pollution. The literature indicates that an extensive health burden might be caused by shipping and port-sourced air pollution positioning maritime transport as an important source of global air pollution and health risk factor. For years up to 2012, before IMO imposed more restrictive emission control measures, up to ~87,000 deaths globally could be attributed to shipping-sourced air pollution (Corbett et al., 2007; Partanen et al., 2013; Winebrake et al., 2009). Despite emission control measures, the health burden was estimated to have further increased and ~265,000 global premature deaths were projected for 2020 (i.e. 0.5% of global mortality) (Sofiev et al., 2018), due to rapid increases in global trade, maritime transport volumes and associated emission levels. Studied emission control measures, such ECA implementation, consisting of S fuel content caps and  $\text{SO}_x$ ,  $\text{NO}_x$  and other emission control measures (e.g. cleaner fuels, fuel switches, scrubbers, WASP installation, offshore electricity, other technological innovations, EEDI and SEEMP compliance, etc.), were generally assessed to be effective in reducing shipping-sourced emissions, and hence adverse health impacts. Cost-benefit ratios were generally positive, with long-term benefits outweighing costs up to 10 times, except for one study that found a negative cost-benefit trade-off for the SECA implementation in the Baltic Sea alone, which was attributed to low population density (Antturi et al., 2016). Nevertheless, despite demonstrated effectiveness of emission control measures and associated health benefits, projected increases in global trade and hence shipping demands (by up to 40% by 2050 (Serra and Fancello, 2020)), and associated emissions, can potentially offset health benefits or at least reduce their magnitude (Brandt et al., 2013; Sofiev et al., 2018).

Comparing by geographic region, until now, most research has been done for European Seas, particularly for the North and Baltic Seas and adjacent European countries. The Mediterranean Sea has been subject in two recent studies for European populations (Nunes et al., 2021; Viana et al., 2020), despite being highly ship-trafficked, being a major global shipping route and equally affecting African and Middle Eastern populations. Viana et al., (2015) studied health impacts for the Turkish population of the Marmara Sea region, and is the only study for a Middle Eastern population. East Asian Seas were studied, with considering especially the health impacts for the Chinese population, and particularly populations of the PRD (including Hong Kong and Guangzhou) (Chen et al., 2019; Lin et al., 2018; Liu et al., 2018; Mason et al., 2019; Tian et al., 2013). For North America, shipping-sourced emissions within the EEZ were studied and attributable health impacts were estimated exclusively for the US population. The two Australian studies focused on the health impacts for Sydney's Greater Metropolitan Region. Limited evidence exists so far on health impacts of shipping-sourced emissions for South American, African, further Middle Eastern and other populations along major ship-traffic routes, as they were included only as sub-populations in the five global studies.

Riparian populations, closest to heavy ship traffic routes, were

commonly found to receive the highest shipping-sourced air pollution concentrations and thus exhibited the highest attributable health burdens. Consequently, emission control measures especially benefited those populations. Especially European populations were estimated to be exposed to high shipping-sourced air pollution concentrations and attributable health burdens, as in Europe dense population centres and close proximity to major shipping routes coincide (Corbett et al., 2007; Partanen et al., 2013). Shipping routes in the North (and Baltic) Seas, the Atlantic Ocean and Mediterranean Sea, are located in direct coastal proximity to European population centres, whereas shipping routes in Asia are located further away from shore (Fig. 1) (Partanen et al., 2013).

Interestingly, no HIA studies were identified targeting the cruise ship tourism industry, quantifying associated emissions and health impacts, even though this sector has experienced a strong increase in activity since 1970. The most popular cruise ship destinations are found in the Caribbean, Asian and Mediterranean Seas, which are already highly ship-trafficked, and therefore, attributable emissions and related health impacts are expected to be considerable. Also remarkable, only one study assessed port pollution from trucks, whereas emissions from trucks (and cargo-loading machinery, heavy-duty vehicles and trains, etc.) in ports are believed to be substantial (Rowangould et al., 2018), but appear to be overlooked.

Generally, heterogeneous study objectives, emission assessments, inventories and projections, emission control scenarios, study populations, and HIA methods and models made the comparison of shipping-sourced attributable health burdens challenging, particularly when considering that air pollution dispersion disrespects territorial boundaries.

#### 4.1. Emission reduction strategies

Until now, most research focused on the health gains associated with implementing S fuel content reductions and the effectiveness of ECAs (Antturi et al., 2016; Åström et al., 2018; Brandt et al., 2013; Broome et al., 2016; Jonson et al., 2015; Liu et al., 2018; Partanen et al., 2013; Sofiev et al., 2018; Viana et al., 2015; Winebrake et al., 2009). According to the IMO, shipping SO<sub>x</sub> emissions were expected to have decreased by over 75% with the global 2020 0.5% S fuel content cap implementation (IMO, 2020), which should have reduced attributable health impacts considerably. To this point it is uncertain how well IMO 0.5% S fuel content regulations have been complied with from 2020 onwards, also partly due to the Covid-19 pandemic and resulting shutdowns of global economies and disruptions of global trade (and cruise ship tourism), and how it translates in terms of emissions and related health impacts.

Generally though, the global requirement to switch to low S fuels (from 3.5% S fuel content to 0.5% in non-SECA waters and 0.1% in SECAs) is thought to imply certain challenges: Due to increased demands, and also exacerbated by the current energy crisis, prices for cleaner fuels, such as MGO or LNG, are expected to increase (Åström et al., 2018; Lähteenmäki-Uutela et al., 2019), which in return might encourage ship owners to install S scrubbers on their ships instead. Scrubbers, on the one hand, are effective in reducing air pollution levels to low S fuel content equivalent levels, but on the other hand, the released wastewater contains S and PM that causes marine pollution instead (Åström et al., 2018). IMO emission control limits and implied increases in costs for ship owning companies (e.g. ship fleet renewal, fuel costs, technological upgrades, etc.), might lead to increases in land-based transport (Jonson et al., 2015; Serra and Fancello, 2020), which would intensify road traffic and shift the problem from ship-sourced to road traffic-sourced emissions. A recent estimate for a hypothetical designation of the Mediterranean Sea as an ECA showed an expected increase in modal shift from ship to road by over 5% (Serra and Fancello, 2020). Moreover, NECA requirement of compliance with Tier III engine standards affects exclusively ships built after 2016, hence, there persists the risk that older ships are particularly assigned to established NECAs in the North American and North and Baltic Seas, bypassing stricter NO<sub>x</sub> control measures (Åström et al., 2018). WASP

installation was considered as another measure to reduce shipping-sourced emissions and despite being efficient and using less or no fossil fuels, and thus causing less or zero pollution, not all ships and their cargo are suited for wind propulsion devices, which implies dependence on wind conditions (Ballini et al., 2017).

As mentioned above, the IMO committed to tackling climate change and reducing GHG emissions by 50% by 2050 compared to 2008 (IMO, 2018), which will also improve air quality and ultimately health. However, the EEDI and SEEMP are the only measures working towards this ambitious IMO goal and achievement is currently assessed as impossible without significant shipowner investment in improved and more efficient ship design and operational measures (e.g. lower speeds), wide adoption of LNG and biofuel use, wind power and electrification, including use of shoreside electricity (i.e. cold ironing, meaning turning-off main engines while at berth) (Jonson et al., 2015; Ramacher et al., 2020). Compliance and oversight of IMO regulations and switching to cleaner fuels in designated ECAs are questionable, because compliance costs for shipowners are rather high and penalties for non-compliance are rather low, probabilities for on-ship inspections remain low, and outside territorial waters no authority exists to monitor compliance (Lähteenmäki-Uutela et al., 2019). Therefore, improved IMO oversight and enforcement of established rules and attractive incentives for shipowner investments and compliance are desirable to shift the shipping industry on a more sustainable, low carbon, and thus healthy trajectory.

#### 4.2. Methodological considerations

##### 4.2.1. Air pollution assessment

Authors frequently stated to probably have underestimated shipping-sourced air pollution and thus associated health burdens (Ballini et al., 2017; Caiazzo et al., 2013; Corbett et al., 2007; Crippa et al., 2019; Fann et al., 2012; Liu et al., 2018; Viana et al., 2015; Wolfe et al., 2019). Reasons for the believed underestimation were various: Most studies focused on one or a few pollutants only. Not considering other pollutants with established links to health might have led to underestimation of total health impacts. Furthermore, there is a lack of appropriate on- and offshore air pollution measurement stations, in order to assess shipping and port-sourced air pollution more accurately (Broome et al., 2016; Caiazzo et al., 2013; Corbett et al., 2007). In the studies including port/berthing-sourced air pollution, it was not always clear whether emissions from non-ship activities were included, such as cargo-loading machinery, heavy-duty vehicles or trains, etc., as emissions and pollution from these kinds of activities can also be considerable, as demonstrated in the study by Rowangould et al., (2018). Related to the lack of measurement stations, more routine source apportionment assessments would be important to better understand what proportion of air pollution is actually shipping-sourced. Moreover, source apportionment can help disentangle the chemical composition of PM, a commonly assessed pollutant, which is important because different toxic compounds of PM were shown to have varying health effects (Caiazzo et al., 2013; Lin et al., 2018; Tian et al., 2013). Tracing N<sub>i</sub> and V in PM are good markers for residual oil combustion with high S content, until recently typical for ocean-going vessels (Tian et al., 2013). N<sub>i</sub> and V in PM were shown to be very toxic and port (berthing)-sourced N<sub>i</sub> and V in PM were associated with increased CVD and stroke hospitalisation and mortality in Hong Kong and Guangzhou (Lin et al., 2018; Tian et al., 2013). Generally, better track records of types of fuels used, ship design and operational performance (considering EEDI and SEEMP and also how GHG reductions lead to reductions in other air pollutants), and clarity and standardization of modelling assumptions made, can help establish more complete ship emission inventories. Inventories for non-road emission sources, including maritime transport, are known to be less certain and complete than road-transport (Wolfe et al., 2019). Inaccurate geospatial models, e.g. due to transboundary emissions or regional inventories being incomplete, contribute to inaccurate estimations of

shipping-sourced air pollution, and hence the associated health burden (Åström et al., 2018; Crippa et al., 2019; Liu et al., 2018; Tian et al., 2013). Furthermore, still the most common approach in HIA studies for population air pollution exposure assignment is to consider residential address or some kind of census unit, disrespecting real-life spatiotemporal variability in exposure according to population activity, leading to considerable underestimations in population exposure (Ramacher and Karl, 2020). There are calls for better population time activity considerations (e.g. through GPS tracking, agent-based modelling or time-microenvironment-activity (TMA) models) for improved air pollution exposure assignment (Ramacher and Karl, 2020; Soares et al., 2014).

All these exposure assessment uncertainties can probably to some extent explain (besides different HIA methods and varying underlying health impact modelling assumptions) the large discrepancy in shipping-sourced air pollution attributable health impacts. For instance, attributable deaths ranged from ~45,000 deaths (Crippa et al., 2019) to ~87,000 deaths in older global studies (Corbett et al., 2007; Partanen et al., 2013; Winebrake et al., 2009) to ~265,000 deaths in the most recent global study (Sofiev et al., 2018).

#### 4.2.2. Health impact modelling

Generally, estimated health impacts are very sensitive to the health impact methods and underlying modelling assumptions applied, e.g. the applied health risk functions, considered susceptible populations, monetized estimates, etc. All studies, but the two TSA and the DD models, extrapolated health risks from existing studies, assuming external validity and generalizability of health risks in the studied populations. However, populations are generally heterogenous and varying demographic, socio-economic and health characteristics make their susceptibility to adverse health effects of air pollution exposure vary.

Similar to the air pollutants, only certain health outcomes were assessed, which likely has led to an underestimation and incomplete assessment of the total health burden of shipping-sourced air pollution (Åström et al., 2018; Rowangould et al., 2018; Winebrake et al., 2009). Most commonly premature all-cause or cause-specific mortality impacts (mostly CP and LC mortality), CVD and RD morbidity outcomes were assessed. However, air pollution epidemiology has a long tradition and other associated health outcomes with a strong evidence-base, such as type 2 diabetes, dementia, cognition, preterm birth or reproductive health (Eze et al., 2015; Fu et al., 2019; Lafuente et al., 2016; Rivas et al., 2019; Schifano et al., 2016), were not assessed, resulting in likely underestimations of the total shipping-sourced air pollution attributable health burden.

The two BA studies, expressing monetized health benefits per 1-ton emission reduction, both found PM per unit reductions to be the most beneficial for health, followed by SO<sub>2</sub> and NO<sub>x</sub> reductions (Fann et al., 2012; Wolfe et al., 2019). This is in line with previous findings, indicating PM<sub>2.5</sub> to be more strongly associated with adverse health effects than other pollutants (U.S. EPA, 2009). Wolfe et al., (2019) found health benefits per 1-ton emission reduction to be 3–17 fold the benefits estimated by Fann et al., (2012), which were attributed to US population growth and increases in personal income, leading to increases in willingness to pay (i.e. VSL) to reduce mortality risks from exposure to air pollution (Wolfe et al., 2019).

#### 4.3. Policy and research implications

Generally, progress has been made in reducing air pollution from the transport sector and policy actions to address transport-related air pollution have increased globally over the last three decades. Reductions in emission from road transport account for the largest part. Data for Europe shows that since 1990, CO from road transport decreased by 88%, NO<sub>x</sub> by 60%, and SO<sub>x</sub> by 99% (European Environment Agency, 2019). In contrast, since 1990, aviation and shipping are the two

transport sub-sectors for which emissions have actually increased. For Europe for 2017, it was estimated that the shipping sector was responsible for 23% of total NO<sub>x</sub> and 12% of total SO<sub>x</sub> emissions, respectively (European Environment Agency, 2019). By 2050, the global demand for seaborne trade is expected to grow by 40% and IMO predictions for 2050 foresee that 15% of global CO<sub>2</sub> emission will be attributable to maritime transport (Serra and Fancello, 2020), positioning maritime transport as an important source of air pollution and climate change driver.

UN member states have an obligation to comply with the laws and regulations imposed by the IMO, but nevertheless, they are accountable for their own shipping industries (IMO, 2019f). Shipping-sourced air pollution, however, does not respect national boundaries. European countries appear to be disproportionately affected by high shipping-sourced emission levels and attributable health burdens, but these countries have also been studied more frequently due to availability of detailed routine environmental monitoring data and strong research traditions. As seen in Fig. 2, South American, African and Middle Eastern countries have fewer major ports that are major shipping destinations. Nevertheless, especially North and Eastern African countries, as well as countries in the Middle East, are adjacent to the major shipping route connecting Asia with Europe, with passage through the Red Sea, Suez Canal, Mediterranean and Strait of Gibraltar, and hence are emission receiver countries. Not much is known about how these regions are being affected in terms of shipping-sourced air pollution levels and associated health outcomes. Hence, better environmental monitoring, complete emission inventories, routine health data collection and more research attention are needed to guarantee a more accurate and complete assessment of shipping-sourced air pollution levels and the association health burden in these countries.

With growing international trade and shipping demand, the 2020 S fuel content cap and ECA limits seemed timely. However, more restrictive measures and extension of ECAs to other sea regions (e.g. the Mediterranean Sea, Red Sea, Arabian Sea, South and East Chinese Seas and Sea of Japan, etc.) should be considered. The prohibition of heavy fuel use anywhere where ships are near ports and population centres, as well as global SECA limits within 200 nm from coasts have been proposed (Lin et al., 2018). Also, the benefit of implementing more restrictive regulations for ships at berth was pointed out, which is in control of national government legislations (Broome et al., 2016). As a positive trend, increased shoreside electrification can be notified, with major EU ports, for instance, being required to provide shoreside electricity by the end of 2025 (Serra and Fancello, 2020). Study results show considerable reductions in emissions and air pollution levels with ships at berth switching from fuel-powered engines to shoreside electricity (i.e. cold ironing) for un- and onloading of cargo, hoteling functions, and providing heat and steam to maintain essential functions of the ship (Stolz et al., 2021).

#### 4.4. Strengths and limitations

This is the first scoping literature review of studies assessing the health impact of shipping-sourced air pollution, which revealed that adverse health impacts attributable to this specific source of air pollution are considerable. The data extraction tool developed and used (Table 2) ensures reproducibility and adds robustness to the findings of this review and enables study comparison. The detailed search strategy and study eligibility criteria applied ensure study selection bias to be limited.

However, as only articles published between 2000 and 2022 were included, we might have missed relevant literature published before 2000. Additionally, assessing risk of bias and quality was difficult as studies were heterogenous and had different objectives. As such, providing a pooled effect (i.e. meta-analysis) was not possible due to the differences in study objectives, exposure assessments, HIA methods, health data, and study populations. Furthermore, the review is susceptible to publication bias as only peer-reviewed articles were reviewed



and grey literature (e.g. policy and public agency reports, national/local maritime and port authority studies and reports, etc.) were not included. Moreover, reports published in any other language than English were not included, but might be relevant in the discussion.

## 5. Conclusions

A considerable health burden can be attributed to shipping and port-sourced emissions worldwide (up to 0.5% of global mortality). IMO imposed emission control measures are important to counteract and were generally assessed to be effective in reducing emissions and associated health burdens. However, expected increases in global trade and shipping volumes will likely exacerbate shipping-sourced emissions and attributable health burdens in the near future, and in light of the IMO's goal to reduce GHG emissions by 50% by 2050 compared to 2008, even more ambitious emission control efforts are needed to not fail this climate goal. Therefore, significant shipowner investment and commitment to improved and more efficient ship design and operational performance, wide adoption of LNG and biofuel use, wind power and electrification are needed, as well as improved IMO oversight and enforcement of established rules. Furthermore, more routine environmental and health monitoring, complete emission inventories (including port activity-sourced pollution from e.g. trucks), and research focus on understudied geographic world regions (i.e. African, Middle Eastern and South American countries) are needed, as not much is known about their shipping-sourced air pollution levels and associated health burdens.

Finally, and in summary, our review positions maritime transport as an important source of global air pollution and health risk factor, which needs more policy and research attention and even more rigorous emission control efforts.

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## Author contributions

Conceptualization: NM, MW, MN; Data curation: NM, MW; Formal analysis: NM, MW; Funding acquisition: Not applicable; Investigation: NM, MW; Methodology: NM, MW, MN; Project administration: NM, MW; Resources: NM, MN; Software: NM, MW; Supervision: NM, MN; Validation: NM, MW; Visualization: NM, MW; Roles/Writing - original draft: NM, MW, MN; Writing - review & editing: NM; MW, MN.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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## Appendix A. Supplementary data

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## References

- Alberini, A., Hunt, A., Markandya, A., 2006. Willingness to pay to reduce mortality risks: evidence from a three-country contingent valuation study. *Environ. Res. Econom.* 33, 251–264. <https://doi.org/10.2139/ssrn.593661>.
- Antturi, J., Hänninen, O., Jalkanen, J.P., Johansson, L., Prank, M., Sofiev, M., Ollikainen, M., 2016. Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping. *J. Environ. Manag.* 184, 431–440. <https://doi.org/10.1016/j.jenvman.2016.09.064>.
- Åström, S., Yaramenka, K., Winnes, H., Fridell, E., Holland, M., 2018. The costs and benefits of a nitrogen emission control area in the Baltic and North Seas. *Transport. Res. Transport Environ.* 59, 223–236. <https://doi.org/10.1016/j.trd.2017.12.014>.
- Atkinson, R.W., Kang, S., Anderson, H.R., Mills, I.C., Walton, H.A., 2014. Epidemiological time series studies of PM<sub>2.5</sub> and daily mortality and hospital admissions: a systematic review and meta-analysis. *Thorax* 69, 660–665. <https://doi.org/10.1136/thoraxjnl-2013-204492>.
- Ballini, F., Ölger, A.L., Brandt, J., Neumann, D., 2017. Health costs and economic impact of wind assisted ship propulsion. *Ocean Eng.* 146, 477–485. <https://doi.org/10.1016/j.oceaneng.2017.09.014>.
- Barregard, L., Molnr, P., Jonson, J.E., Stockfelt, L., 2019. Impact on population health of baltic shipping emissions. *Int. J. Environ. Res. Publ. Health* 16. <https://doi.org/10.3390/ijerph16111954>.
- Beelen, R., Stafoggia, M., Raaschou-Nielsen, O., Andersen, Z.J., Xun, W.W., Katsouyanni, K., Dimakopoulou, K., Brunekreef, B., Weinmayr, G., Hoffmann, B., Wolf, K., Samoli, E., Houthuijs, D., Nieuwenhuijsen, M., Oudin, A., Forsberg, B., Olsson, D., Salomaa, V., Lanki, T., Yli-Tuomi, T., Oftedal, B., Aamodt, G., Nafstad, P., De Faire, U., Pedersen, N.L., Östenson, C.G., Fratiglioni, L., Penell, J., Korek, M., Pyko, A., Eriksen, K.T., Tjønneland, A., Becker, T., Eeftens, M., Bots, M., Meliester, K., Wang, M., Bueno-De-Mesquita, B., Sugiri, D., Krämer, U., Heinrich, J., De Hoogh, K., Key, T., Peters, A., Cyrys, J., Concin, H., Nagel, G., Ineichen, A., Schaffner, E., Probst-Hensch, N., Dratva, J., Ducret-Stich, R., Vilier, A., Clavel-Chapelon, F., Stempfelet, M., Grioni, S., Krogh, V., Tsai, M.Y., Marcon, A., Ricceri, F., Sacerdote, C., Galassi, C., Migliore, E., Ranzì, A., Cesaroni, G., Badaloni, C., Forastiere, F., Tamayo, I., Amiano, P., Dorronsoro, M., Katsoulis, M., Trichopoulos, A., Vineis, P., Hoek, G., 2014. Long-term exposure to air pollution and cardiovascular mortality: an analysis of 22 European cohorts. *Epidemiology* 25, 368–378. <https://doi.org/10.1097/EDE.0000000000000076>.
- Brandt, J., Silver, J.D., Christensen, J.H., Andersen, M.S., Bønløkke, J.H., Sigsgaard, T., Geels, C., Gross, A., Hansen, A.B., Hansen, K.M., Hedegaard, G.B., Kaas, E., Frohn, L. M., 2013. Assessment of past, present and future health-cost externalities of air pollution in Europe and the contribution from international ship traffic using the EVA model system. *Atmos. Chem. Phys.* 13, 7747–7764. <https://doi.org/10.5194/acp-13-7747-2013>.
- Broome, R.A., Cope, M.E., Goldsworthy, B., Goldsworthy, L., Emmerson, K., Jegasothy, E., Morgan, G.G., 2016. The mortality effect of ship-related fine particulate matter in the Sydney greater metropolitan region of NSW, Australia. *Environ. Int.* 87, 85–93. <https://doi.org/10.1016/j.envint.2015.11.012>.
- Broome, R.A., Powell, J., Cope, M.E., Morgan, G.G., 2020. The mortality effect of PM<sub>2.5</sub> sources in the greater metropolitan region of Sydney, Australia. *Environ. Int.* 137. <https://doi.org/10.1016/j.envint.2019.105429>.
- Burnett, R., Pope, C., Ezzati, M., Olives, C., Lim, S., Mehta, S., Shin, H., Singh, G., Hubbell, B., Brauer, M., Anderson, H., Smith, K., Balmes, J., Bruce, N., Kan, H., Laden, F., Prüss-Ustün, A., Turner, M., Gapstur, S., Diver, W., Cohen, A., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* 122, 397–403. <https://doi.org/10.1289/ehp.1307049>.
- Caiazzo, F., Ashok, A., Waitz, I.A., Yim, S.H.L., Barrett, S.R.H., 2013. Air pollution and early deaths in the United States. Part I: quantifying the impact of major sectors in 2005. *Atmos. Environ.* 79, 198–208. <https://doi.org/10.1016/j.atmosenv.2013.05.081>.
- Cesaroni, G., Forastiere, F., Stafoggia, M., Andersen, Z.J., Badaloni, C., Beelen, R., Caracciolo, B., Faire, U. De, Erbel, R., Eriksen, K.T., Fratiglioni, L., Galassi, C., Hampel, R., Heier, M., Hennig, F., Hilding, A., Hoffmann, B., Houthuijs, D., Korek, M., Lanki, T., Leander, K., Magnusson, P.K.E., Migliore, E., Overvad, K., Pedersen, N.L., Penell, J., Pyko, A., Raaschou-Nielsen, O., Ranzì, A., Ricceri, F., Sacerdote, C., Salomaa, V., Turunen, A.W., Vineis, P., Weinmayr, G., Wolf, K., Hoogh, K. De, Hoek, G., Brunekreef, B., Peters, A., 2014. Long term exposure to ambient air pollution and incidence of acute coronary events: prospective cohort study and meta-analysis in 11 European cohorts from the ESCAPE Project. *BMJ* 348, 1–16. <https://doi.org/10.1136/bmj.f7412>.
- Chen, C., Saikawa, E., Comer, B., Mao, X., Rutherford, D., 2019. Ship emission impacts on air quality and human health in the Pearl River Delta (PRD) region, China, in 2015, with projections to 2030. *GeoHealth* 3, 284–306. <https://doi.org/10.1029/2019GH000183>.
- Chen, J., Hoek, G., 2020. Long-term exposure to PM and all-cause and cause-specific mortality: a systematic review and meta-analysis. *Environ. Int.* 143, 105974. <https://doi.org/10.1016/j.envint.2020.105974>.
- Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V., Lauer, A., 2007. Mortality from ship emissions: a global assessment. *Environ. Sci. Technol.* 41, 8512–8518. <https://doi.org/10.1021/es071686z>.
- Crippa, M., Janssens-Maenhout, G., Guizzardi, D., Dingenen, R. Van, Dentener, F., 2019. Contribution and uncertainty of sectorial and regional emissions to regional and global PM<sub>2.5</sub> health impacts. *Atmos. Chem. Phys.* 19, 5165–5186. <https://doi.org/10.5194/acp-19-5165-2019>.
- Dasadhikari, K., Eastham, S.D., Allroggen, F., Speth, R.L., Barrett, S.R.H., 2019. Evolution of sectoral emissions and contributions to mortality from particulate

- matter exposure in the Asia-Pacific region between 2010 and 2015. *Atmos. Environ.* 216, 116916 <https://doi.org/10.1016/j.atmosenv.2019.116916>.
- De Bruyn, S., Blom, M., Schep, E., Warringa, G., 2017. *Werkwijzer Voor MKBA's Op Het Gebied Van Milieu*. Report 7.7A76.48, CE-Delft, Delft, the Netherlands.
- Desaigues, B., Ami, D., Bartczak, a., Braun-Kohlová, M., Chilton, S., Czajkowski, M., Farreras, V., Hunt, a., Hutchison, M., Jeanrenaud, C., Kaderjak, P., MácA, V., Markiewicz, O., Markowska, a., Metcalf, H., Navrud, S., Nielsen, J.S., Ortiz, R., Pellegrini, S., Rabl, a., Riera, R., Scasny, M., Stoeckel, M.E., Szántó, R., Urban, J., 2011. Economic valuation of air pollution mortality: a 9-country contingent valuation survey of value of a life year (VOLY). *Ecol. Indic.* 11, 902–910. <https://doi.org/10.1016/j.ecolind.2010.12.006>.
- Dockery, D., Cunningham, J., Damokosh, A., Neas, L., Spengler, J., Koutrakis, P., Ware, J., Raizenne, M., Speizer, F., 1996. Health effects of acid aerosols on North American children: respiratory symptoms. *Environ. Health Perspect.* 104, 506–514. <https://doi.org/10.1289/ehp.96104506>.
- European Environment Agency, 2019. Emissions of air pollutants from transport. Indicator assessment. <https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-8>.
- Eze, I.C., Hemkens, L.G., Bucher, H.C., Hoffmann, B., Schindler, C., Kunzli, N., Schikowski, T., Probst-Hensch, N.M., 2015. Association between ambient air pollution and diabetes mellitus in Europe and North America: systematic review and meta-analysis. *Environ. Health Perspect.* 123, 381–389. <https://doi.org/10.1289/ehp.1307823>.
- Fann, N., Baker, K.R., Fulcher, C.M., 2012. Characterizing the PM<sub>2.5</sub>-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S. *Environ. Int.* 49, 141–151. <https://doi.org/10.1016/j.envint.2012.08.017>.
- Fischer, P.H., Marra, M., Ameling, C.B., Hoek, G., Beelen, R., de Hoogh, K., Breugelmans, O., Kruize, H., Janssen, N.A.H., 2015. Air Pollution and mortality in seven million adults: the Dutch environmental longitudinal study (DUELS). *Environ. Health Perspect.* 123, 697–704. <https://doi.org/10.1289/ehp.1408254>.
- Fu, P., Guo, X., Cheung, F.M.H., Yung, K.K.L., 2019. The association between PM<sub>2.5</sub> exposure and neurological disorders: a systematic review and meta-analysis. *Sci. Total Environ.* 655, 1240–1248. <https://doi.org/10.1016/j.scitotenv.2018.11.218>.
- Hamra, G.B., Guha, N., Cohen, A., Laden, F., Raaschou-Nielsen, O., Samet, J.M., Vineis, P., Forastiere, F., Saldiva, P., Yorifuji, T., Loomis, D., 2014. Outdoor particulate matter exposure and lung cancer: a systematic review and meta-analysis. *Environ. Health Perspect.* 122, 906–911. <https://doi.org/10.1289/ehp.1408092>.
- Hänninen, O., Knol, A.B., Jantunen, M., Lim, T.-A., Conrad, A., Rappolder, M., Carrer, P., Fanetti, A.-C., Kim, R., Buekers, J., Torfs, R., Iavarone, I., Classen, T., Hornberg, C., Mekel, O.C.L., 2014. Environmental burden of disease in Europe: assessing nine risk factors in six countries. *Environ. Health Perspect.* 122, 439–446. <https://doi.org/10.1289/ehp.1206154>.
- Héroux, M.E., Anderson, H.R., Atkinson, R., Brunekreef, B., Cohen, A., Forastiere, F., Hurley, F., Katsouyanni, K., Krewski, D., Krzyzanowski, M., Kunzli, N., Mills, I., Querol, X., Ostro, B., Walton, H., 2015. Quantifying the health impacts of ambient air pollutants: recommendations of a WHO/Europe project. *Int. J. Publ. Health* 60, 619–627. <https://doi.org/10.1007/s00038-015-0690-y>.
- Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio-respiratory mortality: a review. *Environ. Health* 12, 43. <https://doi.org/10.1186/1476-069X-12-43>.
- Holland, M., 2014. Cost-benefit analysis of final policy scenarios for the EU clean air package version. Version 2. DG - Environ. Eur. Comm. Version 2, 68.
- Holland, M., Hunt, A., Hurley, F., Navrud, S., Watkiss, P., 2005. Title Final Methodology Paper (Volume 1) for Service Contract for carrying out cost-benefit analysis of air quality related issues, in Particular in the Clean Air for Europe (CAFE) Programme 1. IHME, 2019. GBD Results Tool. - <https://ghdx.healthdata.org/gbd-2019>.
- IMO, 2020. Cutting Sulphur Oxide Emissions. - <https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx>.
- IMO, 2019a. Prevention of air pollution from ships. <https://www.imo.org/en/OurWork/Environment/Pages/Air-Pollution.aspx>.
- IMO, 2019b. Sulphur Oxides (SOx) and Particulate Matter (PM) – Regulation 14. URL. [https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-\(SOx\)-%5fRegulation-14.aspx](https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)-%5fRegulation-14.aspx).
- IMO, 2019c. Nitrogen oxides (NOx) – regulation 13. [https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-\(SOx\)—Regulation-14.aspx](https://www.imo.org/en/OurWork/Environment/Pages/Sulphur-oxides-(SOx)—Regulation-14.aspx).
- IMO, 2019d. Emission control areas (ECAs) designated under MARPOL Annex VI. [https://www.imo.org/en/OurWork/Environment/Pages/Emission-Control-Areas-\(ECAs\)-designated-under-regulation-13-of-MARPOL-Annex-VI-\(NOx-emission-control\).aspx](https://www.imo.org/en/OurWork/Environment/Pages/Emission-Control-Areas-(ECAs)-designated-under-regulation-13-of-MARPOL-Annex-VI-(NOx-emission-control).aspx).
- IMO, 2019e. Energy Efficiency Measures. <https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx>.
- IMO, 2019f. International Convention for the Prevention of Pollution from Ships (MARPOL). [https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-\(MARPOL\).aspx#:~:text=The%20International%20Convention%20for%20the,2%20November%201973%20at%20IMO.](https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx#:~:text=The%20International%20Convention%20for%20the,2%20November%201973%20at%20IMO.)
- IMO, 2018. Resolution MEPC.304(72). Initial IMO strategy on reduction of GHG emissions from ships. - [https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304\(72\).pdf](https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf).
- IMO, 2015. Third IMO Greenhouse Gas Study 2014. Executive Summary and Final Report, London. <https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf>.
- Jerrett, M., Burnett, R., Pope, A., Ito, K., Thurston, G., Krewski, D., Shi, Y., Calle, E., Thun, M., 2009. Long-term ozone exposure and mortality. *N. Engl. J. Med.* 360, 1085–1095. <https://doi.org/10.1056/NEJMoa0803894>. Long-Term.
- Jonson, J.E., Jalkanen, J.P., Johansson, L., Gauss, M., Van Der Gon, H.A.C.D., 2015. Model calculations of the effects of present and future emissions of air pollutants from shipping in the Baltic Sea and the North Sea. *Atmos. Chem. Phys.* 15, 783–798. <https://doi.org/10.5194/acp-15-783-2015>.
- Krewski, D., Jerrett, M., Burnett, R., Ma, R., Hughes, E., Shi, Y., Turner, M., Pope, C., Thurston, G., Calle, E., Thun, M., Beckerman, B., DeLuca, P., Finkelstein, N., Ito, K., Moore, D., Newbold, K., Ramsay, T., Ross, Z., Shin, H., Tempalski, B., 2009. Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. *Res. Rep. Health Eff. Inst.* 140, 5–114.
- Laden, F., Schwartz, J., Speizer, F.E., Dockery, D.W., 2006. Reduction in fine particulate air pollution and mortality: extended follow-up of the Harvard Six Cities study. *Am. J. Respir. Crit. Care Med.* 173, 667–672. <https://doi.org/10.1164/rccm.200503-4430C>.
- Lafuente, R., García-Blàquez, N., Jacquemin, B., Checa, M.A., 2016. Outdoor air pollution and sperm quality. *Fertil. Steril.* 106, 880–896. <https://doi.org/10.1016/j.fertnstert.2016.08.022>.
- Lähtenmäki-Uutela, A., Yliskylä-Peuralahti, J., Repka, S., Mellqvist, J., 2019. What explains SECA compliance: rational calculation or moral judgment? *WMU J. Marit. Aff.* 18, 61–78. <https://doi.org/10.1007/s13437-019-00163-1>.
- Lai, H.K., Tsang, H., Chau, J., Lee, C.H., McGhee, S.M., Hedley, A.J., Wong, C.M., 2013. Health impact assessment of marine emissions in Pearl River Delta region. *Mar. Pollut. Bull.* 66, 158–163. <https://doi.org/10.1016/j.marpolbul.2012.09.029>.
- Lepeule, J., Laden, F., Dockery, D., Schwartz, J., 2012. Chronic exposure to fine particles and mortality: an extended follow-up of the Harvard six cities study from 1974 to 2009. *Environ. Health Perspect.* 120, 965–970. <https://doi.org/10.1289/ehp.1104660>.
- Lin, H., Tao, J., Qian, Z., Min, Ruan, Z., Xu, Y., Hang, J., Xu, X., Liu, T., Guo, Y., Zeng, W., Xiao, J., Guo, L., Li, X., Ma, W., 2018. Shipping pollution emission associated with increased cardiovascular mortality: a time series study in Guangzhou, China. *Environ. Pollut.* 241, 862–868. <https://doi.org/10.1016/j.envpol.2018.06.027>.
- Lindgren, S., 2021. The coast is clear: shipping emission standards, air quality and infant health. *Transport. Res. Transport Environ.* 100 <https://doi.org/10.1016/j.trd.2021.103067>.
- Liu, H., Fu, M., Jin, X., Shang, Y., Shindell, D., Faluvegi, G., Shindell, C., He, K., 2016. Health and climate impacts of ocean-going vessels in East Asia. *Nat. Clim. Change* 6, 1037–1041. <https://doi.org/10.1038/nclimate3083>.
- Liu, H., Meng, Z.H., Shang, Y., Lv, Z.F., Jin, X.X., Fu, M.L., He, K. Bin, 2018. Shipping emission forecasts and cost-benefit analysis of China ports and key regions' control. *Environ. Pollut.* 236, 49–59. <https://doi.org/10.1016/j.envpol.2018.01.018>.
- Mao, X., Chen, C., Comer, B., Rutherford, D., (QCCT), I.C. on C.T., 2019. Cost and Benefits of a Pearl River Delta Emission Control Area. Washington DC.
- Mar, T.F., Larson, T.V., Stier, R.A., Claiborn, C., Koenig, J.Q., 2004. An analysis of the association between respiratory symptoms in subjects with asthma and daily air pollution in Spokane, Washington. *Inhal. Toxicol.* 16, 809–815. <https://doi.org/10.1080/08958370490506646>.
- Mason, T.G., Chan, K.P., Schooling, C.M., Sun, S., Yang, A., Yang, Y., Barratt, B., Tian, L., 2019. Air quality changes after Hong Kong shipping emission policy: an accountability study. *Chemosphere* 226, 616–624. <https://doi.org/10.1016/j.chemosphere.2019.03.173>.
- Murray, C., Ezzati, M., Lopez, A., Rodgers, A., Vander Hoorn, S., 2004. Comparative quantification of health risks: conceptual framework and methodological issues, comparative quantification of health risks. Global and Regional Burden of Disease Attributable to Selected Major Risk Factors. WHO, Geneva.
- Mwase, N.S., Ekström, A., Jonson, J.E., Svensson, E., Jalkanen, J.P., Wichmann, J., Molnár, P., Stockfelt, L., 2020. Health impact of air pollution from shipping in the Baltic sea: effects of different spatial resolutions in Sweden. *Int. J. Environ. Res. Publ. Health* 17, 1–16. <https://doi.org/10.3390/ijerph17217963>.
- Nieuwenhuijsen, M.J., Basagaña, X., Dadvand, P., Martínez, D., Cirach, M., Beelen, R., Jacquemin, B., 2014. Air pollution and human fertility rates. *Environ. Int.* 70, 9–14. <https://doi.org/10.1016/j.envint.2014.05.005>.
- Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Peñuelas, A.L., Durán-Grados, V., Moreno-Gutiérrez, J., Jalkanen, J.P., Hannuniemi, H., Sousa, S.I.V., 2021. Estimating the health and economic burden of shipping related air pollution in the Iberian Peninsula. *Environ. Int.* 156 <https://doi.org/10.1016/j.envint.2021.106763>.
- Ostro, B., 2004. *Outdoor Air Pollution: Assessing the Environmental Burden of Disease at National and Local Levels*. Geneva.
- OECD, 2014. The Cost of Air Pollution. Health Impacts of Road Transport. <https://doi.org/10.1787/9789264210448-en>.
- Ostro, B., 1987. Air pollution and morbidity revisited: a specification test. *J. Environ. Econ. Manag.* 14, 87–98. [https://doi.org/10.1016/0095-0696\(87\)90008-8](https://doi.org/10.1016/0095-0696(87)90008-8).
- Ostro, B.D., Rothschild, S., 1989. Air pollution and acute respiratory morbidity: an observational study of multiple pollutants. *Environ. Res.* 50, 238–247. [https://doi.org/10.1016/S0013-9351\(89\)80004-0](https://doi.org/10.1016/S0013-9351(89)80004-0).
- Partanen, A.I., Laakso, A., Schmidt, A., Kakkola, H., Kuokkanen, T., Pietikäinen, J.-P., Kerminen, V.-M., Lehtinen, K.E.J., Laakso, L., Korhonen, H., 2013. Climate and air quality trade-offs in altering ship fuel sulfur content. *Atmos. Chem. Phys.* 13, 12059–12071. <https://doi.org/10.5194/acp-13-12059-2013>.
- Pedersen, M., Giorgis-Allemand, L., Bernard, C., Aguilera, I., Andersen, A.-M.N., Ballester, F., Beelen, R.M.J., Chatzi, L., Cirach, M., Danileviciute, A., Dedele, A., Eijdsen, M. van, Estarlich, M., Fernández-Somoano, A., Fernández, M.F., Forastiere, F., Gehring, U., Grazuleviciene, R., Gruzjeva, O., Heude, B., Hoek, G., Hoogh, K.de, van den Hooven, E.H., Häberg, S.E., Jaddoe, V.W.V., Klümper, C.,



- Korek, M., Krämer, U., Lerchundi, A., Lepeule, J., Nafstad, P., Nystad, W., Patelarou, E., Porta, D., Postma, D., Raaschou-Nielsen, O., Rudnai, P., Sunyer, J., Stephanou, E., Sørensen, M., Thiering, E., Tuffnell, D., Varró, M.J., Vrijkotte, T.G.M., Wijga, A., Wilhelm, M., Wright, J., Nieuwenhuijsen, M.J., Pershagen, G., Brunekreef, B., Kogevinas, M., Slama, R., 2013. Ambient air pollution and low birthweight: a European cohort study (ESCAPE). *Lancet Respir. Med.* 1, 695–704. [https://doi.org/10.1016/S2213-2600\(13\)70192-9](https://doi.org/10.1016/S2213-2600(13)70192-9).
- Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA* 287, 1132–1141.
- Ramacher, M.O.P., Karl, M., 2020. Integrating modes of transport in a dynamic modelling approach to evaluate population exposure to ambient NO<sub>2</sub> and PM<sub>2.5</sub> pollution in urban areas. *Int. J. Environ. Res. Publ. Health* 17, 1–35. <https://doi.org/10.3390/ijerph17062099>.
- Ramacher, M.O.P., Tang, L., Moldanová, J., Matthias, V., Karl, M., Fridell, E., Johansson, L., 2020. The impact of ship emissions on air quality and human health in the Gothenburg area - Part II: scenarios for 2040. *Atmos. Chem. Phys.* 20, 10667–10686. <https://doi.org/10.5194/acp-20-10667-2020>.
- Rivas, I., Basagaña, X., Cirach, M., López-Vicente, M., Suades-González, E., Garcia-Esteban, R., Álvarez-Pedrerol, M., Dadvand, P., Sunyer, J., 2019. Association between early life exposure to air pollution and working memory and attention. *Environ. Health Perspect.* 127, 1–11. <https://doi.org/10.1289/EHP3169>.
- Roman, H., Walker, K., Walsh, T., Conner, L., Richmond, H., Hubbell, B., Kinney, P., 2008. Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the U.S. *Environ. Sci. Technol.* 42, 2268–2274. <https://doi.org/10.1021/es0713882>.
- Rowangould, D., Rowangould, G., Niemeier, D., 2018. Evaluation of the health impacts of rolling back a port clean trucks program. *Transport. Res. Rec.* 2672, 53–64. <https://doi.org/10.1177/0361198118793328>.
- Samoli, E., Schwartz, J., Wojtyniak, B., Touloumi, G., Spix, C., Balducci, F., Medina, S., Rossi, G., Sunyer, J., Bacharova, L., Anderson, H.R., Katsouyanni, K., 2001. Investigating Regional Differences in Short-Term Effects of Air Pollution on Daily Mortality in the APHEA Project: A Sensitivity Analysis for Controlling Long-Term Trends and Seasonality. *Environ. Health Perspect.* 109, 349–353. <https://doi.org/10.1289/ehp.01109349>.
- Samoli, E., Stafoggia, M., Rodopoulou, S., Ostro, B., Declercq, C., Alessandrini, E., Diaz, J., Karanasiou, A., Kelessis, A.G., Le Tertre, A., Pandolfi, P., Randi, G., Scarinzi, C., Zauli-Sajani, S., Katsouyanni, K., Forastiere, F., MED-PARTICLES Study Group, 2013. Associations between Fine and Coarse Particles and Mortality in Mediterranean Cities: Results from the MED-PARTICLES Project. *Environ. Health Perspect.* 121, 932–938. <https://doi.org/10.1289/ehp.1206124>.
- Sapkota, A., Chelikowsky, A.P., Nachman, K.E., Cohen, A.J., Ritz, B., 2010. Exposure to particulate matter and adverse birth outcomes: a comprehensive review and meta-analysis. *Air Qual. Atmos. Heal.* 5, 369–381. <https://doi.org/10.1007/s11869-010-0106-3>.
- Schifano, P., Asta, F., Dadvand, P., Davoli, M., Basagaña, X., Michelozzi, P., 2016. Heat and air pollution exposure as triggers of delivery: a survival analysis of population-based pregnancy cohorts in Rome and Barcelona. *Environ. Int.* 88, 153–159. <https://doi.org/10.1016/j.envint.2015.12.013>.
- Schnurr, R.E.J., Walker, T.R., 2019. Marine transportation and energy use. *Ref. Modul. Earth Syst. Environ. Sci.* <https://doi.org/10.1016/b978-0-12-409548-9.09270-8>.
- Serra, P., Fancello, G., 2020. Towards the IMO's GHG goals: a critical overview of the perspectives and challenges of the main options for decarbonizing international shipping. *Sustain. Times* 12. <https://doi.org/10.3390/su12083220>.
- Soares, J., Kousa, A., Kukkonen, J., Matilainen, L., Kangas, L., Kauhaniemi, M., Riikonen, K., Jalkanen, J.P., Rasilta, T., Hänninen, O., Koskentalo, T., Aarnio, M., Hendriks, C., Karppinen, A., 2014. Refinement of a model for evaluating the population exposure in an urban area. *Geosci. Model Dev. (GMD)* 7, 1855–1872. <https://doi.org/10.5194/gmd-7-1855-2014>.
- Sofiev, M., Winebrake, J.J., Johansson, L., Carr, E.W., Prank, M., Soares, J., Vira, J., Kouznetsov, R., Jalkanen, J.P., Corbett, J.J., 2018. Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nat. Commun.* 9, 1–12. <https://doi.org/10.1038/s41467-017-02774-9>.
- Stafoggia, M., Cesaroni, G., Peters, A., Andersen, Z.J., Badaloni, C., Beelen, R., Caracciolo, B., Cyrys, J., de Faire, U., de Hoogh, K., Eriksen, K.T., Fratiglioni, L., Galassi, C., Gigante, B., Havulinna, A.S., Hennig, F., Hilding, A., Hoek, G., Hoffmann, B., Houthuijs, D., Korek, M., Lanki, T., Leander, K., Magnusson, P.K., Meisinger, C., Migliore, E., Overvad, K., Ostenson, C.-G., Pedersen, N.L., Pekkanen, J., Penell, J., Pershagen, G., Pundt, N., Pyko, A., Raaschou-Nielsen, O., Ranzi, A., Ricceri, F., Sacerdote, C., Swart, W.J.R., Turunen, A.W., Vineis, P., Weimar, C., Weinmayr, G., Wolf, K., Brunekreef, B., Forastiere, F., 2014. Long-term exposure to ambient air pollution and incidence of cerebrovascular events: results from 11 European cohorts within the ESCAPE project. *Environ. Health Perspect.* 122, 919–925. <https://doi.org/10.1289/ehp.1307301>.
- Stolz, B., Held, M., Georges, G., Boulouchos, K., 2021. The CO<sub>2</sub> reduction potential of shore-side electricity in Europe. *Appl. Energy* 285, 116425. <https://doi.org/10.1016/j.apenergy.2020.116425>.
- Sunyer, J., Ballester, F., Le Tertre, A., Atkinson, R., Ayres, J.G., Forastiere, F., Forsberg, B., Vonk, J.M., Bisanti, L., Tenías, J.M., Medina, S., Schwartz, J., Katsouyanni, K., 2003. The association of daily sulfur dioxide air pollution levels with hospital admissions for cardiovascular diseases in Europe (the Apha-II study). *Eur. Heart J.* 24, 752–760. [https://doi.org/10.1016/S0195-668X\(02\)00808-4](https://doi.org/10.1016/S0195-668X(02)00808-4).
- Tang, L., Ramacher, M.O.P., Moldanová, J., Matthias, V., Karl, M., Johansson, L., Jalkanen, J.P., Yaramenka, K., Aulinger, A., Gustafsson, M., 2020. The impact of ship emissions on air quality and human health in the Gothenburg area-Part 1: 2012 emissions. *Atmos. Chem. Phys.* 20, 7509–7530. <https://doi.org/10.5194/acp-20-7509-2020>.
- Tao, Y., Huang, W., Huang, X., Zhong, L., Lu, S.-E., Li, Y., Dai, L., Zhang, Y., Zhu, T., 2011. Estimated acute effects of ambient ozone and nitrogen dioxide on mortality in the Pearl River Delta of Southern China. *Environ. Health Perspect.* 120 (3), 393–398. <https://doi.org/10.1289/ehp.1103715>.
- Tian, L., Ho, K., Louie, P.K., Qiu, H., Pun, V.C., Kan, H., Ignatius, T.S., Wong, T.W., 2013. Shipping emissions associated with increased cardiovascular hospitalizations. *Atmos. Environ.* 74, 320–325. <https://doi.org/10.1016/j.atmosenv.2013.04.014>.
- Tricco, A.C., Lillie, E., Zarin, W., O'Brien, K.K., Colquhoun, H., Levac, D., Moher, D., Peters, M.D.J., Horsley, T., Weeks, L., Hempel, S., Akl, E.A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M.G., Garritty, C., Lewin, S., Godfrey, C.M., MacDonald, M.T., Langlois, E.V., Soares-Weiser, K., Moriarty, J., Clifford, T., Tunçalp, Ö., Straus, S.E., 2018. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann. Intern. Med.* 169, 467–473. <https://doi.org/10.7326/M18-0850>.
- U.S. EPA, 2009. Integrated Science Assessment for Particulate Matter. Final Report, Washington, DC. EPA/600/R-08/139F.
- U.S. EPA, 2010. Guidelines for preparing economic analyses, National Center for Environmental Economics Office of Policy - U.S. Environmental Protection Agency. Natl. Cent. Environ. Econ. Off. Pol. - U.S. Environ. Prot. Agency 1–302, 2010.
- U.S. EPA, 2011. The benefits and costs of the Clean Air Act from 1990 to 2020. Final Report - Rev. A. U.S. Environmental Protection Agency Office of Air and Radiation. [https://www.epa.gov/sites/default/files/2015-07/documents/fullreport\\_rev\\_a.pdf](https://www.epa.gov/sites/default/files/2015-07/documents/fullreport_rev_a.pdf).
- Velders, G.J.M., Maas, R.J.M., Geilenkirchen, G.P., de Leeuw, F.A.A.M., Ligterink, N.E., Ruysenaars, P., de Vries, W.J., Wesseling, J., 2020. Effects of European emission reductions on air quality in The Netherlands and the associated health effects. *Atmos. Environ.* 221, 117109. <https://doi.org/10.1016/j.atmosenv.2019.117109>.
- Viana, M., Fann, N., Tobías, A., Querol, X., Rojas-Rueda, D., Plaza, A., Aynon, G., Conde, J.A., Fernández, L., Fernández, C., 2015. Environmental and health benefits from designating the marmara sea and the Turkish straits as an emission control area (ECA). *Environ. Sci. Technol.* 49, 3304–3313. <https://doi.org/10.1021/es5049946>.
- Viana, M., Rizza, V., Tobías, A., Carr, E., Corbett, J., Sofiev, M., Karanasiou, A., Buonanno, G., Fann, N., 2020. Estimated health impacts from maritime transport in the Mediterranean region and benefits from the use of cleaner fuels. *Environ. Int.* 138. <https://doi.org/10.1016/j.envint.2020.105670>.
- Wang, X., Mauzerall, D.L., 2006. Evaluating impacts of air pollution in China on public health: implications for future air pollution and energy policies. *Atmos. Environ.* 40, 1706–1721. <https://doi.org/10.1016/j.atmosenv.2005.10.066>.
- West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., Fry, M.M., Anenberg, S., Horowitz, L.W., Lamarque, J.F., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nat. Clim. Change* 3, 885–889. <https://doi.org/10.1038/nclimate2009>.
- WHO, 2013. Health Risks of Air Pollution in Europe – HRAPIE Project. WHO. Copenhagen.
- WHO, 2006. Health Risks of Particulate Matter from Long-Range Transboundary Air Pollution. WHO. Copenhagen.
- Winebrake, J.J., Corbett, J.J., Green, E.H., Lauer, A., Eyring, V., 2009. Mitigating the health impacts of pollution from oceangoing shipping: an assessment of low-sulfur fuel mandates. *Environ. Sci. Technol.* 43, 4776–4782. <https://doi.org/10.1021/es803224q>.
- Wolfe, P., Davidson, K., Fulcher, C., Fann, N., Zawacki, M., Baker, K.R., 2019. Monetized health benefits attributable to mobile source emission reductions across the United States in 2025. *Sci. Total Environ.* 650, 2490–2498. <https://doi.org/10.1016/j.scitotenv.2018.09.273>.
- Woodruff, T.J., Grillo, J., Schoendorf, K.C., 1997. The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. *Environ. Health Perspect.* 105 (6), 608–612. <https://doi.org/10.1289/ehp.97105608>.
- WTO, 2022. Evolution of trade under the WTO: handy statistics. [https://www.wto.org/english/res/e/statistics/e/evolution\\_trade\\_wto\\_e.htm](https://www.wto.org/english/res/e/statistics/e/evolution_trade_wto_e.htm).
- Zanobetti, A., Franklin, M., Koutrakis, P., Schwartz, J., 2009. Fine particulate air pollution and its components in association with cause-specific emergency admissions. *Environ. Heal. A Glob. Access Sci. Source* 8. <https://doi.org/10.1186/1476-069X-8-58>.
- Zheng, X.Y., Ding, H., Jiang, L.N., Chen, S.W., Zheng, J.P., Qiu, M., Zhou, Y.X., Chen, Q., Guan, W.J., 2015. Association between Air pollutants and asthma emergency room visits and hospital admissions in time series studies: a systematic review and meta-analysis. *PLoS One* 10. <https://doi.org/10.1371/journal.pone.0138146>.