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Commentary

Recent Advances in Studying Air Quality and Health Effects of Shipping Emissions

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Abstract: The increase of global commerce and tourism makes the shipping sector an important contributor of atmospheric particles and gaseous pollutants. These have impacts on both health and climate, especially in populated coastal areas. Maritime activities could be an important driver for economic and social development, however, they are also an environmental pressure. Several policies were implemented in the last decades, at local/regional or international levels, mainly focused on reducing the content of sulphur in marine fuels. The last international IMO-2020 regulation was enforced on 1 January 2020. This work reviews some recent studies on this topic delineating current knowledge of the impacts of maritime emissions on air quality and health and the future projections relative to the benefits of the implementation of the new IMO-2020 regulation. In addition, future perspectives for further mitigation strategies are discussed.

Keywords: maritime transport; shipping impacts; health impacts; harbour air quality; mitigation strategies; IMO legislation; low-sulphur fuel; ECA; particulate matter

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1. Introduction

Shipping is a significant atmospheric source of aerosol particles (particulate matter, PM_{10}, $PM_{2.5}$) and gaseous pollutants (SO_2, NO_X, VOCs, CO_X), especially near harbours and surroundings coastal areas, including densely populated harbour cities. Demand for seaborne shipping services is increasing all over the world, so that the number of active ships will be nearly twice as high as in 2016 by the year 2030 [1]. In combination with this trend, the increasing coastal population and the foreseen decrease of important land-based emissions in the near future (e.g., traffic, heating), contribute in keeping high the role of shipping emissions for urban air quality and health. The "green port" concept has been applied to harbours to conciliate economic development and sustainability objectives, reducing pressures on the environment and public health effects. Atmospheric pollution due to ships is one of the main issues within harbour management due to the degradation of local air quality, adverse health effects, and climate implications.

Shipping was recognized within the "Health risks of air pollution in Europe" (HRAPIE) project of the World Health Organization (WHO) as the third among the top-six air pollution emission source categories (of a total of 16), after road transport, heating and air conditioning [2]. This poses an emerging health risk in port cities, reflected in an increase in respiratory diseases such as inflammation, aggravation of asthmatic symptoms, lung cancer, as well as cardiovascular diseases, increase in hospital admissions and respiratory acute mortality.

In the last few decades, many legislative efforts have been made, both at global and local scales, to curb atmospheric pollutants emissions due to the shipping sector. In October 2016, the International Maritime Organization (IMO) introduced the Global Sulphur Cap 2020, enforced on 1 January 2020, according to its Revised International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI rule. It stated that the sulphur content of any fuel oil used on board ships shall not exceed 0.50% m/m (against the previous limit of 3.5% m/m) outside emission control areas (ECAs) and 0.1% m/m remains the standard value (already established in 2015) for the ECAs. Regulation 4 specifies that these limits can be compliant by alternative methods that are 'at least as effective in terms of emissions reductions'. At present, there are two other options: use of alternative fuel such as liquefied natural gas (LNG) or bio-fuel and installation on-board of fitting exhaust gas cleaning (scrubber) units. Since 1 January 2021, a nitrogen emission control area (NECA) will be enforced in the Baltic and North Seas, with a mandatory Tier 3 standard (80% reduction compare to Tier 1) for ships built after 2021 operating in that area. It is expected to reduce NO_X from maritime transport by 80%, in addition to a further reduction of $PM_{2.5}$ of 72%, due to lower NO_X-induced SOA formation, by 2040 [3]. NO_X emissions will decrease gradually because of the slow replacement rate of ships, which could take at least 30 years.

From a climate perspective, the net radiative forcing (RF) of the shipping sector was estimated at -0.4 W/m^2 (cooling effect) on short term [4], due to the combination of negative (SO_2) and positive (CO_2, black carbon) RF of ship-released pollutants. However, the slow removal of $CO_{2,}$ in the long term could turn it to a warming effect [5]. This effect could be amplified by the use of low-sulphur fuels that implies a decrease of secondary sulphate produced in ship-related aerosols [6].

This work briefly reviews the current knowledge on the impact of shipping to local air quality in harbour areas and on public health indicators. The main evidences from health assessment studies will be discussed in order to evaluate the effectiveness of the recent IMO policy regarding the standard of sulphur content in marine fuels, together with the implementation of new ECAs. Finally, future perspectives and mitigation scenarios will be discussed.

2. Discussion

2.1. Contribution of Shipping to Atmospheric Pollutants

The impact of shipping influences both health (through air quality) and climate. Although the contribution of shipping quickly decreases as the distance from the harbour increases [7], important impacts on local air quality, close to harbours and downwind of them, are expected, especially for NO_X, PM and SO_2. These emissions are also related to harbour logistics (i.e., loading/unloading operations, maneuvering, hotelling services), even if emissions from ships are generally larger compared to harbour-related emissions [7]. In medium-size harbour cities, emissions of SO_2 due to ships and harbour activities are larger than those of road traffic, instead, emissions of PM and NO_X could be comparable with those of road traffic [7,8].

Different methodologies have been used to quantify the contributions of maritime activities to PM concentrations, with different uncertainties, pros and cons: from large (global, continental, and/or national) to local scale source-oriented modelling [6,7,9] to receptor-oriented models [10–13]. Some results of the primary contribution to $PM_{2.5}$ and PM_{10} obtained using receptor-oriented approaches, separated by ECA and no-ECA areas, are reported in Table 1. In general terms, it is evident that the contribution to PM_{10} is generally lower (in relative terms) compared to those to $PM_{2.5}$, because ship emissions, being products of a combustion process, are dominated by fine and ultrafine particles. For this reason, contribution to particle number concentration (PNC) in the fine (diameter <0.3 μm) and ultrafine range (diameter <0.1 μm) was found to be 3–4 times larger than those to PM mass concentrations in some Mediterranean harbours [14–16].

Relative contributions to $PM_{2.5}$ range between 3% and 9% in USA sites, with the highest values on the Eastern coasts. In Europe, the contribution is larger in Mediterranean harbours (from 0.2% to 14%), compared to northern Europe (1–5%) where ECAs exist. Worldwide busy harbours in East Asia, especially in China, recorded maxima in $PM_{2.5}$ contributions, between 2.4% and 25%. The combined designation of a SECA and a NECA in European seas could have a $PM_{2.5}$ reduction potential of 50% and 65% in 2030 and 2050, respectively [17]. A similar descending trend (-35–37% of $PM_{2.5}$) was predicted for the

Baltic Sea, between 2012 and 2040, with a consequent reduction of secondary PM, even if not proportional to the reduction of the sulphur emissions [18].

Table 1. Shipping primary contributions (range, expressed as %) to PM concentration estimated using source-apportionment approaches worldwide in ECA and outside ECA.

Location	ECA/no-ECA	PM_{10} (%)	$PM_{2.5}$ (%)	References
North America	SO_X and NO_X ECA		3–9%	[19,20]
East Asia	no-ECA		2.4–25%	[19,21,22]
Mediterranean area	no-ECA	<0.2–16%	0.2–14%	[19,20,23–25]
Baltic and North Sea	SO_X ECA NO_X ECA (from 2021)	2%	1–5%	[20]

The studies regarding contribution of ships to gaseous pollutants concentration are more limited compared to those related to particulate matter, overall, and SO_2 is the most investigated gaseous pollutant, being directly the subject of IMO regulation. Contribution to CO is typically comparable with the contribution to PM [8], while relative contributions to SO_2 and NOx are generally larger compared to those of PM. This could lead to exceedances of legislated standards for NO_2 in sites located near harbour areas, thus representing an important issue that needs to be addressed in future mitigation strategies. At large distances from the emissions, the excess of NO_2 due to ships could enhance the production of O_3 at ground level [26] even if, at local scale, a depletion of O_3 due to NO releases is often observed [12,15]. The use of low-sulphur content fuels will bring a reduction effect not only of SO_2 but also of primary and secondary PM [27–29], instead, no significant changes are expected for total metals and PAHs in gaseous and particulate phase in PM_{10} [30].

2.2. Health Effects of Shipping Emissions

Epidemiological evidences demonstrated that shipping pollutants can lead to negative health effects like asthma, cardiovascular diseases, lung cancer, premature mortality and morbidity [31–36]. The most common exposure estimates are calculated using population-weighted concentrations of ship-related pollutants and specific concentration (or exposure)–response (C/E–R) functions [36–42]. Grid resolution, population density and C/E–R functions used can significantly affect estimates, producing important differences among health assessment studies.

Within the applied models, uncertainties are associated with measured pollutant concentrations, meteorological fields, and boundary conditions as simulation inputs. High-resolution air pollution models could reduce the effect of differences in population density, which is higher along coastlines.

Traditional approaches for exposure estimates are only based on static residency population counts while others are more dynamic, taking into account specific spatial and temporal population activity [43,44]. Population-activity data could vary according to population size, temporal and spatial distribution and infiltration factors of pollutants from outdoor to indoor environments [43]. The C/E–R function used influences health impact estimates. Some studies applied C/E–R functions assuming the same impact of different fractions of PM [32,40], however there are some indications about the different health effects of primary PM compounds (elemental, organic carbon, inorganic PM) with respect to secondary inorganic species (sulphates, nitrates and ammonium). In addition, secondary PM formation (mainly sulphates), which is relevant in specific areas in summer, could be underestimated by global and regional models, thus introducing errors in input boundary conditions [18]. Linear C/E–R functions have been demonstrated to better estimate health impacts when $PM_{2.5}$ concentration was higher (i.e., >20 $\mu g/m^3$) in correspondence of a relevant ship traffic contribution. Instead, alternative log-linear functions [45] reach a saturation level in health risk assessment at high ambient concentrations, which is not evident in other studies using the linear equation. Furthermore, availability, update and accuracy of in-country incidence rates with respect to global incidence rates can affect results, especially asthma morbidity, showing different C/E–R patterns in different countries [46]. Finally, the assumption about age distribution in coastal population can be different from those of hinterland areas, producing large approximations in final estimates. Uncertainties occurring in absolute health effects estimates could be mitigated when different scenarios are evaluated using the same assumptions, like, for example, the effects of the policies on fuel quality [47].

About 60,000 annual premature deaths in 2010 and 90,000 annual premature deaths in 2012 due to cardiopulmonary diseases and lung cancer were attributed to exposure to PM emissions in coastal regions of Europe, eastern Asia and southern Asia [34]. Andersson et al. [32] and Brandt et al. [48] estimated 50,000 and 14,000 annual premature deaths in 2011 in Europe and in the Baltic and North Sea area, respectively. Recent modelling results found 0.1–0.2 YOLLs (years of life lost) per person estimated with 2010 emissions, along the southern coastlines of the Baltic and North Sea regions, with a 24% average reduction in 2030 because of stricter SOx limits in the same area [35]. The decrease in total YOLLs, from 17,000–38,000 in 2014 to 11,000–25,000 in 2016, demonstrated the effectiveness of SECA implementation in the same area, with slight differences between countries due to age specific death rates [49]. Impacts of exposure to NO_2 and $PM_{2.5}$ due to ships accounted for 2.6 premature deaths per year and 0.015 YOLLs per person, respectively, while an opposite trend was recorded for ozone exposure with -0.4 premature deaths per year estimated in 2012 [50]. In Australia, about 1.9% of the region-wide annual average population weighted-mean concentration of all natural and human-made $PM_{2.5}$ was attributable to ship exhaust, and up to 9.4% at suburbs close to harbours for 2010–2011 [33]. From 14,500 to 37,500 premature deaths were estimated worldwide as due to $PM_{2.5}$ related to shipping with the highest values of 24,000 in East Asia [31]. These results were an order of magnitude lower than those obtained applying different C–R functions, and considering all pollutants emissions, which estimated 430,000 premature deaths per year due to shipping, under pre-2020 policies [6]. A health assessment study conducted in eight European Mediterranean coastal cities [47] reported 430 premature death per year attributable to ship-related $PM_{2.5}$ exposure.

Some studies evaluated the effectiveness of the stricter SECA regulations implemented since 2015 in the Baltic area, with a reduction of 35% of $PM_{2.5}$ impact from the regional shipping in the Gothenburg area [51], and a decrease in mortality, morbidity and YOLLs by at least one third from 2014 to 2016 [49]. The introduction of SECA in the Baltic and North Sea produced a decrease up to 40% in observed impacts of 5% and 9% of primary and secondary PM population exposure, respectively [35,49]. Projections indicated that a NECA would reduce total premature deaths in the North Sea countries by nearly 1% by 2030, doubling after 2040 [52]. For the Mediterranean region, the implementation of an ECA could prevent 1730 premature deaths per year [53].

A recent analysis was performed in different cities of the Mediterranean area: Nicosia (Cyprus), Brindisi, Genoa and Venice (Italy), Msida (Malta), Barcelona and Melilla (Spain), and Athens (Greece). Results showed that the implementation of the IMO 2020 policy that limits Sulphur content in marine fuels, could reduce $PM_{2.5}$-attributable premature deaths by 15% considering both primary and secondary $PM_{2.5}$ due to shipping [47]. Percentages varied from 1% in Brindisi to 45% in Melilla evidencing larger health benefits in smaller cities with a higher relative impact of shipping emissions. However, in absolute terms, the total reduction in premature deaths would be larger in cities with larger populations. At global level, enforcement of the IMO-2020 policy could produce a reduction of 34% (range 18–49%) of annual premature deaths due to shipping emissions, while childhood asthma morbidity will be reduced of about 54% (range 24–68%) [6]. This will be accompanied by a reduction of the cooling effect of ships-related aerosol increasing by 3% the radiative forcing due to anthropogenic activities (i.e., a negative drawback for climate). The relationship between climate policies and health was evaluated in a recent report [17], indicating that the $PM_{2.5}$ shipping-related mortality decreased in the "climate scenario" (SECA + NECA) compared to the "no-climate scenario" of about 0.8% and 2% in 2030 and 2050, respectively, in Sweden and 1% and 3.7% in all of Europe. Finally, technical measures introduced by the IMO to control greenhouse gas (GHG) ship-related emissions including the Energy efficiency Design Index (EEDI) determine a small health impact from exposure to $PM_{2.5}$ (1.2%) and an improvement for ozone exposure (−1.6%), with the result being that these are less effective for exposure to NO_2 emissions (+17%). Shore-side electricity in 2040 could determine important reductions of 25–30%, 3% and 12% for NO_2, $PM_{2.5}$ and SO_2, respectively, with limited influence outside the harbour areas [51].

It has to be said that the reduction of emissions obtained using higher-quality fuels could lead to an increase of operational costs with economic feedbacks such as slower fleet replacement rate due to increased ship costs, and modal shift to other transportation routes (roads, railways, and aviation) [54,55]. The latter could be true especially for the smallest vessels that will obtain the largest relative cost increase compared to larger ships [56,57]. Åström et al. [58] concluded that a NECA is less likely to have significant impacts on the transport patterns, compared to a SECA implementation. Results showed that the costs of NECA are around 3% of total marine fuel costs in the Baltic and North Sea region. In comparison, Jonson et al. [35] assessed that a SECA implemented using low sulphur fuel would increase fuel costs in the range 30–80%. The effects of the increase of costs is highly dependent on policies towards fuel prices as well as on additional measures that could be taken for reducing fuel consumptions, like lowering cruising speed of vessels [17,59]. The current situation is very variable since low oil prices have reduced the effects of SECA on transport prices, and the modal shift was expected to be minimal [60]. These aspects need quantitative and exhaustive cost-benefit analysis worldwide such as those conducted for the Northern European areas [56,58,61] and for all European seas, including the Mediterranean Sea [17].

3. Concluding Remarks

Although most shipping emissions take place at sea, a non-negligible fraction of these involve harbour cities and coastal communities, exposing them to PM and gaseous pollutants with negative effects on health.

Ship traffic contribution to PM is found generally to be lower than those to gaseous compounds like NO_X, CO and SO_2. In particular, $PM_{2.5}$ impact ranges typically between 0.2% and 14% in Europe, with lower values in northern Europe compared to the Mediterranean area; between 3% and 9% in North America and from 2.4% to 25% in Asia. Policy actions at international level have been enforced to reduce the content of sulphur in marine fuels as well as the design of specific emission control areas at local level (ECAs, NECAs). The last international IMO regulation was enforced on 1 January 2020 and is expected to produce a reduction of shipping emissions of SO_2 and primary PM and this will also lead to a reduction of secondary sulphate contained in PM. Limited effects are expected on emissions of NO_X, metals, and PAHs contained in PM.

Projections indicated that the implementation of the new IMO-2020 policy will lead to a global decrease of premature deaths and morbidity due to shipping of about 34% and 54%, respectively [6]. The implementation of the new NECA in the North Sea would reduce total premature deaths by 1% by 2030, doubling after 2040. Nevertheless, the estimated ship-related premature deaths will be 250,000 after 2020 policy implementation and, even with the actual reduction efforts, ships could be responsible for about 6.4 million cases of childhood asthma annually in the future [6]. In addition, the reduction of SO_2 emissions due to the implementation of the IMO-2020 regulation will produce an increase of the radiative forcing due to ship-related aerosol. For these reasons, besides the current measures, further mitigation efforts (like, for example, shore-side electricity) should be considered. The simultaneous increase of sea-trade volume, population and urbanization in coastal areas require further efforts in identifying policies and strategies to curb their impacts simultaneously on human health and climate, being two faces of the same coin, from local to global scale in an integrated "green port" vision.

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References

1. Delft, C.E.; Directorate-General for Climate Action (European Commission). *Study on Methods and Considerations for the Determination of Greenhouse Gas Emission Reduction Targets for International Shipping*; Final Report; Publications Office of the European Union: Luxembourg, 2019.
2. Héroux, M.E.; Anderson, H.R.; Atkinson, R.; Brunekreef, B.; Cohen, A.; Forastiere, F.; Hurley, F.; Katsouyanni, K.; Krewski, D.; Krzyanowski, M.; et al. Quantifying the health impacts of ambient air pollutants: Recommendations of a WHO/Europe project. *Int. J. Public Health* **2015**, *60*, 619–627.
3. Karl, M.; Bieser, J.; Geyer, B.; Matthias, V.; Jalkanen, J.-P.; Johansson, L.; Fridell, E. Impact of a nitrogen emission control area (NECA) on the future air quality and nitrogen deposition to seawater in the Baltic Sea region. *Atmos. Chem. Phys.* **2019**, *19*, 1721–1752. [CrossRef]
4. Eyring, V.; Kohler, H.W.; Van Aardenne, J.; Lauer, A. Emissions from international shipping: 1. The last 50 years. *J. Geophys. Res. Atmos.* **2005**, *110*, D17305. [CrossRef]
5. Fuglestvedt, J.; Berntsen, T.; Eyring, V.; Isaksen, I.; Lee, D.S.; Sausen, R. Shipping emissions: From cooling to warming of climates—And reducing impacts on health. *Environ. Sci. Technol.* **2009**, *43*, 9057–9062. [CrossRef] [PubMed]
6. Sofiev, M.; Winebrake, J.J.; Johansson, L.; Carr, E.W.; Prank, M.; Soares, J.; Vira, J.; Kouznetsov, R.; Jalkanen, J.-P.; Corbett, J.J. Cleaner fuels for ships provide public health benefits with climate tradeoffs. *Nat. Commun.* **2018**, *9*, 406. [CrossRef]
7. Merico, E.; Dinoi, A.; Contini, D. Development of an integrated modelling-measurement system for near-real-time estimates of harbour activity impact to atmospheric pollution in coastal cities. *Transp. Res. Part D* **2019**, *73*, 108–119. [CrossRef]
8. Merico, E.; Gambaro, A.; Argiriou, A.; Alebic-Juretic, A.; Barbaro, E.; Cesari, D.; Chasapidis, L.; Dimopoulos, S.; Dinoi, A.; Donateo, A. Atmospheric impact of ship traffic in four Adriatic-Ionian port-cities: Comparison and harmonization of different approaches. *Transp. Res. Part D Transp. Environ.* **2017**, *50*, 431–445. [CrossRef]
9. Monteiro, A.; Russo, M.; Gama, C.; Borrego, C. How important are maritime emissions for the air quality: At European and national scale. *Environ. Pollut.* **2018**, *242*, 565–575. [CrossRef]
10. Contini, D.; Gambaro, A.; Belosi, F.; De Pieri, S.; Cairns, W.R.L.; Donateo, A.; Zanotto, E.; Citron, M. The direct influence of ship traffic on atmospheric $PM_{2.5}$, PM_{10} and PAH in Venice. *J. Environ. Manag.* **2011**, *92*, 2119–2129. [CrossRef]
11. Cesari, D.; Genga, A.; Ielpo, P.; Siciliano, M.; Mascolo, G.; Grasso, F.M.; Contini, D. Source apportionment of $PM_{2.5}$ in the harbor—industrial area of Brindisi (Italy): Identification and estimation of the contribution of in-port ship emissions. *Sci. Total Environ.* **2014**, *497–498*, 392–400. [CrossRef]
12. Ledoux, F.; Roche, C.; Cazier, F.; Beaugard, C.; Courcot, D. Influence of ship emissions on NOx, SO_2, O_3 and PM concentrations in a North-Sea harbour in France. *J. Environ. Sci.* **2018**, *71*, 56–66. [CrossRef] [PubMed]
13. Viana, M.; Amato, F.; Alastuey, A.; Querol, X.; Moreno, T.; Dos Santos, S.G.; Herce, M.D.; Fernández-Patier, R. Chemical tracers of particulate emissions from commercial shipping. *Environ. Sci. Technol.* **2009**, *43*, 7472–7477. [CrossRef] [PubMed]
14. Gregoris, E.; Morabito, E.; Barbaro, E.; Feltracco, M.; Toscano, G.; Merico, E.; Grasso, F.M.; Cesari, D.; Conte, M.; Contini, D.; et al. Chemical characterization and source apportionment of size-segregated aerosol in the port-city of Venice (Italy). *Atmos. Pollut. Res.* **2020**. [CrossRef]
15. Merico, E.; Donateo, A.; Gambaro, A.; Cesari, D.; Gregoris, E.; Barbaro, E.; Dinoi, A.; Giovanelli, G.; Masieri, S.; Contini, D. Influence of in-port ships emissions to gaseous atmospheric pollutants and to particulate matter of different sizes in a Mediterranean harbour in Italy. *Atmos. Environ.* **2016**, *139*, 1–10. [CrossRef]
16. Merico, E.; Conte, M.; Grasso, F.M.; Cesari, D.; Gambaro, A.; Morabito, E.; Gregoris, E.; Orlando, S.; Alebić-Juretić, A.; Zubak, V.; et al. Comparison of the impact of ships to size-segregated particle concentrations in two harbour cities of northern Adriatic Sea. *Environ. Pollut.* **2020**, *266*, 115175. [CrossRef] [PubMed]
17. Cofala, J.; Amann, M.; Borken-Kleefeld, J.; Gomez-Sanabria, A.; Heyes, C.; Kiesewetter, G.; Sander, R.; Schoepp, W.; Holland, M.; Fagerli, H.; et al. *The Potential for Cost-Effective Air Emission Reductions from International Shipping through Designation of Further Emission Control Areas in EU Waters with Focus on the Mediterranean Sea*; IIASA Research Report; IIASA: Laxenburg, Austria, 2018.
18. Karl, M.; Jonson, J.E.; Uppstu, A.; Aulinger, A.; Prank, M.; Sofiev, M.; Jalkanen, J.-P.; Johansson, L.; Quante, M.; Matthias, V. Effects of ship emissions on air quality in the Baltic Sea region simulated with three different chemistry transport models. *Atmos. Chem. Phys.* **2019**, *19*, 7019–7053. [CrossRef]
19. Sorte, S.; Rodrigues, V.; Borrego, C.; Monteiro, A. Impact of harbour activities on local air quality: A review. *Environ. Pollut.* **2020**, *257*, 113542. [CrossRef]

20. Viana, M.; Hammingh, P.; Colette, A.; Querol, X.; Degraeuwe, B.; de Vlieger, I.; Aardennee, J. Impact of maritime transport emissions on coastal air quality in Europe. *Atmos. Environ.* **2014**, *90*, 96–105. [CrossRef]
21. Lang, J.; Zhou, Y.; Chen, D.; Xing, X.; Wei, L.; Wang, X.; Zhao, N.; Zhang, Y.; Guo, X.; Han, L.; et al. Investigating the contribution of shipping emissions to atmospheric PM2.5 using a combined source apportionment approach. *Environ. Pollut.* **2017**, *229*, 557–566. [CrossRef]
22. Nakatsubo, R.; Oshita, Y.; Aikawa, M.; Takimoto, M.; Kubo, T.; Matsumura, C.; Takaishi, Y.; Hiraki, T. Influence of marine vessel emissions on the atmospheric PM2.5 in Japan's around the congested sea areas. *Sci. Total Environ.* **2020**, *702*, 134744. [CrossRef]
23. Donateo, A.; Gregoris, E.; Gambaro, A.; Merico, E.; Giua, R.; Nocioni, A.; Contini, D. Contribution of harbour activities and ship traffic to $PM_{2.5}$, particle number concentrations and PAHs in a port city of the Mediterranean Sea (Italy). Environ. *Sci. Pollut. Res.* **2014**, *21*, 9415–9429. [CrossRef] [PubMed]
24. Saraga, D.E.; Tolis, E.I.; Maggos, T.; Vasilakos, C.; Bartzis, J.G. $PM_{2.5}$ source apportionment for the port city of Thessaloniki, Greece. *Sci. Total Environ.* **2019**, *650*, 2337–2354. [CrossRef] [PubMed]
25. Sarigiannis, D.A.; Handakas, E.J.; Kermenidou, M.; Zarkadas, I.; Gotti, A.; Charisiadis, P.; Makris, K.; Manousakas, M.; Eleftheriadis, K.; Karakitsios, S.P. Monitoring of air pollution levels related to Charilaos Trikoupis Bridge. *Sci. Total Environ.* **2017**, *609*, 1451–1463. [CrossRef] [PubMed]
26. Aksoyoglu, S.; Prévôt, A.S.H.; Baltensperger, U. Contribution of ship emissions to the concentration and deposition of air pollutants in Europe. *Atmos. Chem. Phys.* **2016**, *156*, 1895–1906. [CrossRef]
27. Tao, L.; Fairley, D.; Kleeman, M.J.; Harley, R.A. Effects of switching to lower sulphur marine fuel oil on air quality in the San Francisco Bay area. *Environ. Sci. Technol.* **2013**, *47*, 10171–10178. [CrossRef]
28. Contini, D.; Gambaro, A.; Donateo, A.; Cescon, P.; Cesari, D.; Merico, E.; Belosi, F.; Citron, M. Inter annual trend of the primary contribution of ship emissions to PM2.5 concentrations in Venice (Italy): Efficiency of emissions mitigation strategies. *Atmos. Environ.* **2015**, *102*, 183–190. [CrossRef]
29. Liu, H.; Jin, X.; Wu, L.; Wang, X.; Fu, M.; Lv, Z.; Morawska, L.; Huang, F.; He, K. The impact of marine shipping and its DECA control on air quality in the Pearl River Delta, China. *Sci. Total Environ.* **2018**, *625*, 1476–1485. [CrossRef]
30. Gregoris, E.; Barbaro, E.; Morabito, E.; Toscano, G.; Donateo, A.; Cesari, D.; Contini, D.; Gambaro, A. Impact of maritime traffic on polycyclic aromatic hydrocarbons, metals and particulate matter in Venice air. *Environ. Sci. Pollut. Res.* **2016**, *23*, 6951–6959. [CrossRef]
31. Liu, H.; Fu, M.; Jin, X.; Shang, Y.; Shindell, D.; Faluvegi, G.; Shindell, C.; He, K. Health and climate impacts of ocean-going vessels in East Asia. *Nat. Clim. Chang.* **2016**, *6*, 1037–1041. [CrossRef]
32. Andersson, C.; Bergström, R.; Johansson, C. Population exposure and mortality due to regional background PM in Europe—Long-term simulations of source region and shipping contributions. *Atmos. Environ.* **2009**, *43*, 3614–3620. [CrossRef]
33. Broome, R.A.; Cope, M.E.; Goldsworthy, B.; Goldsworthy, L.; Emmerson, K.; Jegasothy, E.; Morgan, G.G. The mortality effect of ship-related fine particulate matter in the Sydney greater metropolitan region of NSW, Australia. *Environ. Int.* **2016**, *87*, 85–93. [CrossRef] [PubMed]
34. Corbett, J.J.; Winebrake, J.J.; Green, E.H.; Kasibhatla, P.; Eyring, V.; Lauer, A. Mortality from ship emissions: A global assessment. *Environ. Sci. Technol.* **2007**, *41*, 8512–8518. [CrossRef] [PubMed]
35. Jonson, J.; Jalkanen, J.; Johansson, L.; Gauss, M.; Denier van der Gon, H. 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.* **2015**, *15*, 783–798. [CrossRef]
36. Winebrake, J.J.; Corbett, J.J.; Green, E.H.; Lauer, A.; Eyring, V. Mitigating the health impacts of pollution from oceangoing shipping: An assessment of low-sulfur fuel mandates. *Environ. Sci. Technol.* **2009**, *43*, 4776–4782. [CrossRef]
37. Lepeule, J.; Laden, F.; Dockery, D.; Schwartz, J. Chronic exposure to fine particles and mortality: An extended follow-up of the Harvard Six Cities study from 1974 to 2009. *Environ. Health Perspect.* **2012**, *120*, 965. [CrossRef]
38. Zheng, X.-Y.; Ding, H.; Jiang, L.-N.; Chen, S.-W.; Zheng, J.-P.; Qiu, M.; Zhou, Y.-X.; Chen, Q.; Guan, W.-J. Association between air pollutants and asthma emergency room visits and hospital admissions in time series studies: A systematic review and meta-analysis. *PLoS ONE* **2015**, *10*, e0138146. [CrossRef]
39. Pope, C.A., 3rd; Burnett, R.T.; Thun, M.J.; Calle, E.E.; Krewski, D.; Ito, K.; Thurston, G.D. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA* **2002**, *287*, 1132–1141. [CrossRef]
40. WHO. Health Risks of air Pollution in Europe—HRAPIE Project: Recommendations for Concentration—Response Functions for Cost—Benefit Analysis of Particulate Matter, Ozone and Nitrogen Dioxide. 2013. Available online: http://www.euro.who.int/ (accessed on 8 January 2021).
41. Jerrett, M.; Burnett, R.T.; Ma, R.J.; Pope, C.A.; Krewski, D.; Newbold, K.B.; Thurston, G.; Shi, Y.; Finkelstein, N.; Calle, E.E.; et al. Spatial analysis of air pollution and mortality in Los Angeles. *Epidemiology* **2005**, *16*, 727–736. [CrossRef]
42. Beelen, R.; Raaschou-Nielsen, O.; Stafoggia, M.; Andersen, Z.J.; Weinmayr, G.; Hoffmann, B.; Wolf, K.; Samoli, E.; Fischer, P.; Nieuwenhuijsen, M.; et al. Effects of long-term exposure to air pollution on natural-cause mortality: An analysis of 22 European cohorts within the multicentre ESCAPE project. *Lancet* **2014**, *383*, 785–795. [CrossRef]
43. Ramacher, M.O.P.; Karl, M.; Bieser, J.; Jalkanen, J.-P.; Johansson, L. Urban population exposure to NOx emissions from local shipping in three Baltic Sea harbour cities—A generic approach. *Atmos. Chem. Phys.* **2019**, *19*, 9153–9179. [CrossRef]

44. Ramacher, M.O.P.; Karl, M.; Aulinger, A.; Bieser, J. Population Exposure to Emissions from Industry, Traffic, Shipping and Residential Heating in the Urban Area of Hamburg. In *Air Pollution Modeling and Its Application XXVI*; Springer Proceedings in Complexity; Mensink, C., Gong, W., Hakami, A., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 177–183.
45. Burnett, R.T.; Pope, C.A., 3rd; Ezzati, M.; Olives, C.; Lim, S.S.; Mehta, S.; Shin, H.H.; Singh, G.; Hubbell, B.; Brauer, M.; et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ. Health Perspect.* **2014**, *122*, 397403. [CrossRef] [PubMed]
46. Ostro, B. Outdoor air pollution: Assessing the environmental burden of disease at national and local levels. In *Environmental Burden of Disease Series*; OMS: Geneva, Switzerland, 2004; Volume 5.
47. Viana, M.; Rizza, V.; Tobías, A.; Carr, E.; Corbett, J.; Sofiev, M.; Karanasiou, A.; Buonanno, G.; Fann, N. Estimated health impacts from maritime transport in the Mediterranean region and benefits from the use of cleaner fuels. *Environ. Int.* **2020**, *138*, 105670. [CrossRef] [PubMed]
48. 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.; et al. Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system—An integrated modelling approach. *Atmos. Chem. Phys.* **2013**, *13*, 7725–7746. [CrossRef]
49. Barregård, L.; Molnár, P.; Jonson, J.-E.; Stockfelt, L. Impact on population health of Baltic shipping Emissions. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1954. [CrossRef]
50. Tang, L.; Ramacher, M.O.P.; Moldanová, J.; Matthias, V.; Karl, M.; Johansson, L.; Jalkanen, J.-P.; Yaramenka, K.; Aulinger, A.; Gustafsson, M. The impact of ship emissions on air quality and human health in the Gothenburg area—Part 1: 2012 emissions. *Atmos. Chem. Phys.* **2020**, *20*, 7509–7530. [CrossRef]
51. Jonson, J.E.; Gauss, M.; Jalkanen, J.-P.; Johansson, L. Effects of strengthening the Baltic Sea ECA regulations. *Atmos. Chem. Phys.* **2019**, *19*, 13469–13487. [CrossRef]
52. Ramacher, M.O.P.; Tang, L.; Moldanová, J.; Matthias, V.; Karl, M.; Fridell, E.; Johansson, L. The impact of ship emissions on air quality and human health in the Gothenburg area—Part II: Scenarios for 2040. *Atmos. Chem. Phys. Discuss.* **2020**, *20*, 10667–10686. [CrossRef]
53. Rouïl, L.; Ratsivalaka, C.; André, J.M.; Allemand, N. ECAMED: A Technical Feasibility Study for the Implementation of an Emission Control Area (ECA) in the Mediterranean Sea. Synthesis Report—11 January 2019. Available online: https://www.ecologique-solidaire.gouv.fr/ (accessed on 8 January 2021).
54. Lähteenmäki-Uutela, A.; Repka, S.; Haukioja, T.; Pohjola, T. How to recognize and measure the economic impacts of environmental regulation: The Sulphur Emission Control Area case. *J. Clean. Prod.* **2017**, *154*, 553–565. [CrossRef]
55. Johansson, L.; Jalkanen, J.-P.; Kalli, J.; Kukkonen, J. The evolution of shipping emissions and the costs of regulation changes in the northern EU area. *Atmos. Chem. Phys.* **2013**, *13*, 11375–11389. [CrossRef]
56. Lindstad, H.; Sandaas, I.; Strømman, A.H. Assessment of cost as a function of abatement options in maritime emission control areas. *Transp. Res. Part D* **2015**, *38*, 41–48. [CrossRef]
57. Holmgren, J.; Nikopoulou, Z.; Ramstedt, L.; Woxenius, J. Modelling modal choice effects of regulation on low-sulphur marine fuels in Northern Europe. *Transp. Res. Part D* **2014**, *28*, 62–73. [CrossRef]
58. Åström, S.; Yaramenka, K.; Winnes, H.; Fridell, E.; Holland, M. The costs and benefits of a nitrogen emission control area in the Baltic and North Seas. *Transp. Res. Part D* **2018**, *59*, 223–236. [CrossRef]
59. Muntean, M.; Van Dingenen, R.; Monforti-Ferrario, F.; Scarlat, N.; Janssens-Maenhout, G.; Hjorth, J.; Bernabei, C.; Skoniezki, P.; Norcini Pala, A.; Coppola, P.; et al. *Identifying Key Priorities in Support to the EU Macro-Regional Strategies. Implementation. An Ex-Ante Assessment for the Adriatic-Ionian and Alpine Regions Focusing on Clean Growth in Transport and Bioenergy*; Report Number JRC110395; European Commission: Ispra, Italy, 2019.
60. Hämäläinen, E. Estimated impacts of the sulphur directive on the Nordic industry. *Eur. Transp. Res. Rev.* **2015**, *7*, 8. [CrossRef]
61. Antturi, J.; Hänninen, O.; Jalkanen, J.-P.; Johansson, L.; Prank, M.; Sofiev, M.; Ollikainen, M. Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping. *J. Environ. Manag.* **2016**, *184*, 431–440. [CrossRef]