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DOI:
10.1016/j.fmre.2024.02.013

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Document Version
Version created as part of publication process; publisher's layout; not normally made publicly available

Citation for published version (Harvard):
Liu, H, Yi, W, Jalkanen, J-P, Luo, Z, Majamäki, E, Matthias, V, Moldanová, J, Shi, Z & He, K 2024, 'Atmospheric impacts and regulation framework of shipping emissions: achievements, challenges and frontiers', *Fundamental Research*. https://doi.org/10.1016/j.fmre.2024.02.013

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PII: S2667-3258(24)00109-2
DOI: https://doi.org/10.1016/j.fmre.2024.02.013
Reference: FMRE 753

To appear in: *Fundamental Research*

Received date: 15 December 2023
Revised date: 8 January 2024
Accepted date: 25 February 2024

Please cite this article as: Huan Liu , Wen Yi , Jukka-Pekka Jalkanen , Zhenyu Luo , Elisa Majamäki , Volker Matthias , Jana Moldanová , Zongbo Shi , Kebin He , Atmospheric impacts and regulation framework of shipping emissions: achievements, challenges and frontiers, *Fundamental Research* (2024), doi: https://doi.org/10.1016/j.fmre.2024.02.013

Atmospheric impacts and regulation framework of shipping emissions: achievements, challenges and frontiers

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Abstract: Currently, over 80% of the international trade volume is carried by sea. Marked by persistent growth, evident atmospheric impacts, intricate mitigation challenges, international shipping has been recognized as one of the most "hard-to-abate" sectors gathering increasing attention from both academic community and governmental sectors in recent years. Against the backdrop of the ambitious climate and clean air objectives, the quantitative shipping emission characterization, impact assessment and policy effectiveness research are not only fundamental to understand the status quo and ramifications of shipping emissions but also beneficial for future emission regulations. Here, we summarized the achievements in shipping emission modelling and impact research in the past two decades, and identified the challenges lying in the transition pathway towards a clean and carbon-neutral shipping. To address the pressing demand for this, we proposed an innovative framework which aims to facilitate emission abatement. Finally, promising directions for future work were delineated, including the indirect effects of shipping emitted aerosols on the climate, the emissions and impacts of novel contaminants, synergies and conflicts among different emission reduction measures, projections on future shipping emission inventories, Arctic shipping emissions, etc.

Keywords: shipping emissions, atmospheric impacts, trade-based framework, models, challenges, future directions

1 Introduction

Shipping exhibits characteristics of higher efficiency and lower costs relative to other modes of transportation. Over 80% of the volume of international trade is carried by sea [1]. However, greenhouse gas (GHG) and air pollutant emissions from international shipping should not be overlooked, accounting for approximately 3% for CO_2, 9% for SO_x, 17% for NO_x, 4% for primary $PM_{2.5}$ and 4% for NMVOC emissions from all anthropogenic sources in 2018 [3]. Previous studies have underscored the significance of the clean and carbon-neutral transition of shipping in achieving objectives related to clean air and climate targets [2]. Yet as the transition unfolds, new concerns inevitably arise. At this point of time, it is urgent for us to recap our knowledge on shipping emissions and their impacts, identify the major obstacles and challenges in the way, as well as identify the emerging scientific inquiries for future research. Therefore, aims of this perspective include: 1) review the progress and achievements in quantifying shipping emissions and unveiling their atmospheric impacts; 2) recognize challenges in shipping emission mitigations; 3) propose a trade-based framework to reduce shipping emissions; 4) identify future directions in the general fields of shipping emission, impacts and regulations.

2 Outstanding progress in shipping emission and impact research

There has been a sustained evolution for shipping emission modelling methods, generally following the course of archiving detailed fleet information, high resolution, and even real-time feasibility currently. In the 1990s, shipping emission modelling was based on statistical data of fuel consumption and voluntary reporting of harbor arrivals/departures. During the last 15 years, with the advent of mandatory reporting systems, such as Automatic Identification System (AIS), and big data processing technology, near real-time tracking of ship movements and emission simulations have become prevalent. Several research groups have established shipping emission inventories with high spatiotemporal resolution by developing bottom-up models based on AIS data, unlocking new insights into dynamics of shipping emissions nowadays. Several typical shipping emission models include STEAM developed by Finnish Meteorological Institute [4], SEIM developed by Tsinghua University [5], MariTEAM developed by Norwegian University of Science and Technology [6], etc.

The spatiotemporally resolved shipping emission inventories are well adapted to various chemical transport models and climate models, therefore providing fundamental data for modelling their environmental impacts on various scales from local to global. Interactions between air pollutants emitted from shipping and other sources such as on-road traffic or agriculture are also stressed in a number of studies. Generally, indicated by chemical transport models, shipping emissions could be the major contributors to air pollution as well as premature deaths in coastal and riverside areas. From the perspective of climate impacts, it is recognized that black carbon from ships had warmed the lower atmosphere, but shipping emissions primarily affect climate through aerosol indirect effects on clouds, with model estimates ranging from negligible to moderate (-0.18 W m^{-2}), and large (-0.19 to -0.60 W m^{-2}) [3]. There remain large uncertainties, however, with more recent studies suggesting that previous estimates of the indirect effects from shipping emissions may be underestimated as they produce “invisible” ship tracks [7].

In addition, top-down satellite data observations can support bottom-up studies by filling in the gaps of ship activity, providing measurements of air pollutants in the atmospheric column and offering additional datasets of ambient conditions in various parts of the planet. Fig. 1 shows a scheme of shipping emission modelling and atmospheric impacts. The combination of observations, emissions and modelling has made it increasingly complete and multifaceted for shipping emission modelling and impact research fields [8].

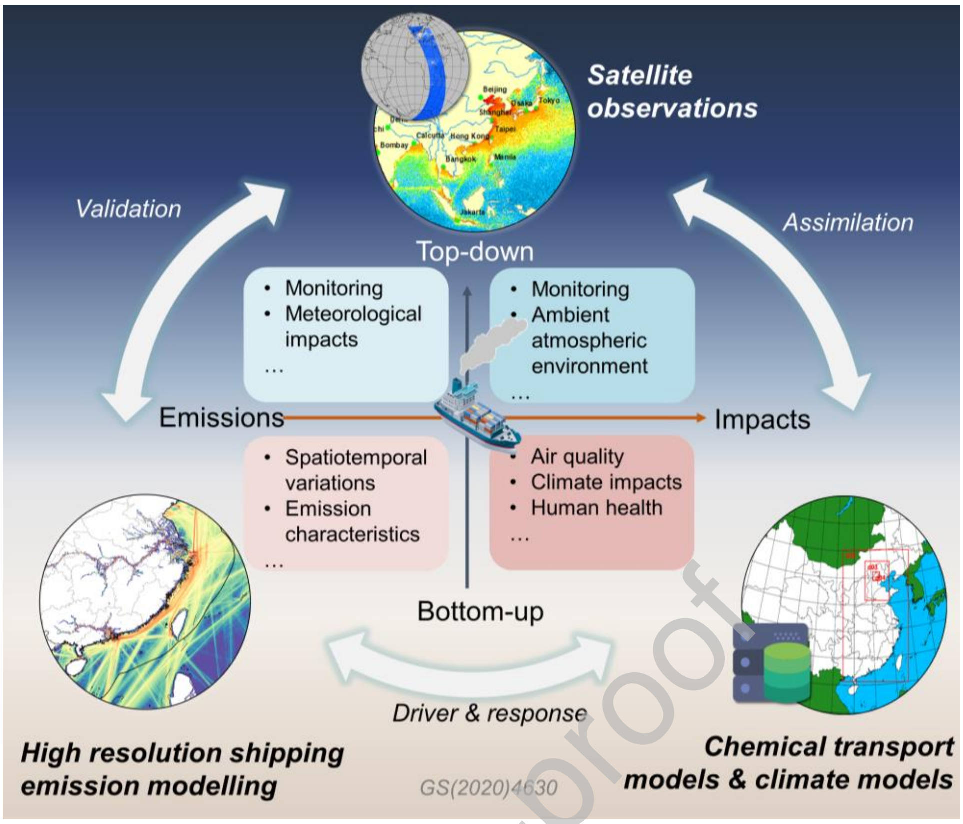

Fig. 1. A scheme of shipping emission modelling and atmospheric impact research [8].

3 Challenges to achieve carbon-neutral and clean shipping

The significant achievements in the field of shipping emission characterization have enhanced our understanding of the characteristics and variations of shipping emissions. However, practical challenges persist in controlling and mitigating shipping emissions. IMO plays a pivotal role in mitigating shipping GHGs and air pollutants. Since 1 January, 2020, the IMO limits of fuel sulfur content have decreased from 3.5% to 0.5% m/m, drastically cutting shipping SO_x emissions impacts on air quality. However, the possibility to continue use of high-sulfur fuels in combination with scrubbers endangers marine environment by release of toxic and acidifying species to the sea. Ships play a major role in NO_x emissions. The IMO NO_x emission limits (Tier system) are in place, however, they only apply to the newly-built. As ships have a long lifetime, these emissions are expected to continue until the next decade. Policy compliance is another problem. European coasts have recently revealed that the Tier II vessels, supposedly emitting ~20% less than Tier I vessels, are actually emitting more and there is a high level of non-compliance of the few sailing Tier III ships [9].

International shipping has been recognized as one of the most difficult sectors to decarbonize. Shown in Fig. 2. a), the control of CO_2 emissions from international shipping has been slow and iterative historically. CO_2 emissions from international shipping as measured by the IMO in 2018 are almost at the same level as in 2008 and have been predicted to rise by 4-50% in 2050 compared to 2018 [10]. If future ship emissions are well controlled under the 2023 IMO Strategy framework, i.e., net zero around 2050, international shipping will at least be in line with the 2°C target, but still face considerable challenges in striving for the 1.5°C target, as shown in Fig. 2. b).

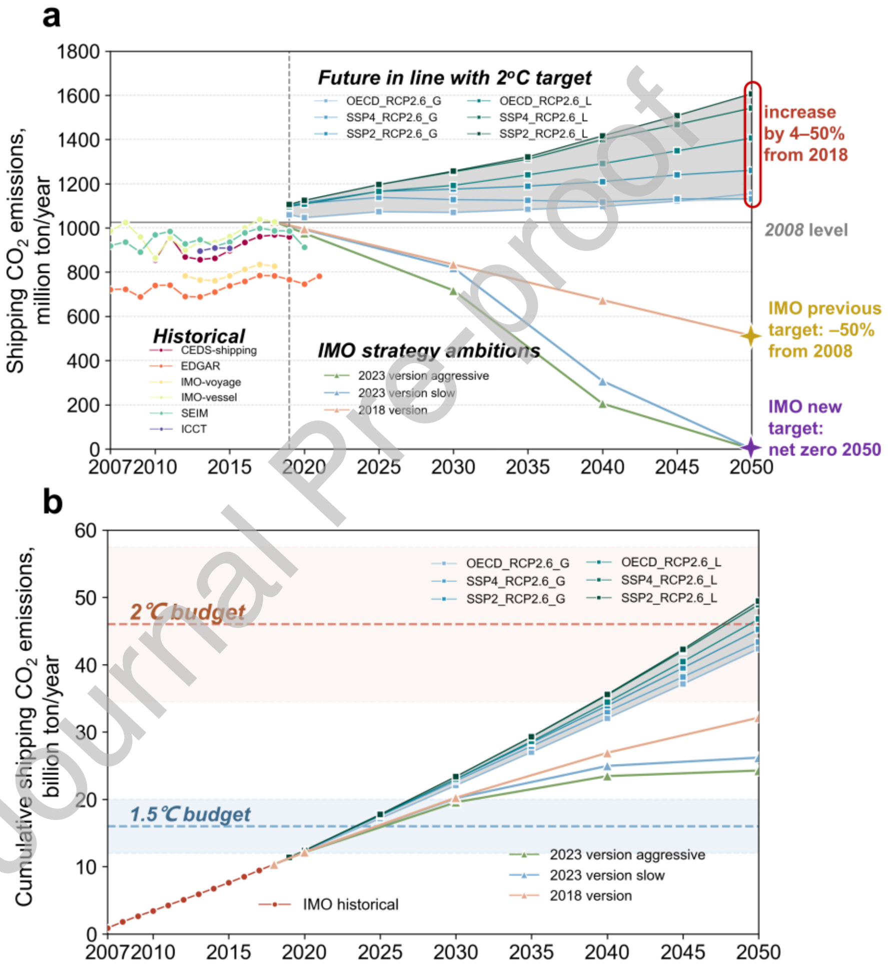

Fig. 2. Historical, future and pathways of 2023 IMO Strategy in terms of a) annual and b) cumulative tank-to-wake CO_2 emissions from international shipping. The legends are basically divided into 3 sections. For the "Historical" part, legends represent various data sources, i.e., CEDS [11], EDGAR [12], IMO [10], SEIM [13], ICCT [14]. For the "Future in line with 2°C target" part, we

gathered projection data under RCP2.6-based scenarios by Fourth IMO GHG Study (Faber et al., 2020). For the “IMO strategy ambitions” part, “2018 version” represents what the pathway of international shipping will look like assuming the 2018 version of IMO initiatives will be adopted. “2023 version” complies with 2023 IMO Strategy. By “aggressive” we assume that the higher rate of CO_2 emission reduction envisioned by the indicative checkpoints is achieved. By “slow” the lower.

The 2023 IMO Strategy will bring measures like energy efficiency improvement and climate-friendly fuels employment which along with GHG will also cut emissions of air pollutants. However, close attention needs to be paid to trade-offs such as emissions of ammonia and N_2O from use of ammonia fuel or emissions of aldehydes, other toxic organic species or CH_4 from carbonaceous fuels. Stringent emission limits should be called for pollutants not covered by current IMO regulations. Studies have combined current or upcoming regulations with shipping emission models and chemistry transport models to assess the future shipping emissions’ impacts, providing insights for policy making. However, description of technical properties of the fleet and knowledge of the ambient conditions are still lacking to create a credible prediction for emissions and their impacts.

4 Trade-based mitigation framework

In order to address the obstacles and motivate the international shipping to reduce CO_2 emissions as soon as possible, we have proposed an innovative trade-based framework for international shipping CO_2 emission reduction, based on the analysis of millions of shipping voyage energy efficiency and trade-related characteristics of international shipping (VoySEIM-GTEMS model chain) [15], as illustrated in Fig. 3. The framework aims at motivating Importer, Carrier and Exporter (ICE community), to reduce shipping emissions cooperatively, by rewarding them with credits for emission reduction through technological promotion and route optimization. The left penal of Fig. 3 displays the trade emission efficiency index matrix based VoySEIM-GTEMS, forming the basis for quantifying emission reduction credits for ICE community. The right panel of Fig. 3 illustrates the prospects of emission reductions under optimal conditions brought about by trade optimization. The specific mechanisms of incentives of the framework are as follows. On the one hand, when carriers apply carbon-neutral technology or operation improvement, the credits are generated and allocated to the corresponding importing and exporting countries, thereby stimulating their motivation to purchase advanced carbon-neutral technology and energy. On the other hand, the emissions saved by choosing adjacent trade partners instead of distant ones would also be recorded as extra credits for importers and exporters. Trade optimization, if exploited to its maximum potential, could reduce emissions from international shipping by 38% compared with the status quo, representing a huge short- and mid-term breakthrough in shipping emission reductions. Compared to existing measures, the distinctive feature of this framework lies in its ability to stimulate nations to accelerate shipping emission reduction processes by altering shipping costs. The inherent trade structure may pose a great challenge in implementation, yet the transformation of trade structures, however, could potentially be encouraged through the augmentation of credits. Although the framework is still in a theoretical stage, it harbors significant potential for emission reductions and can serve as a robust reference for IMO in formulating mid-term techno-economic measures.

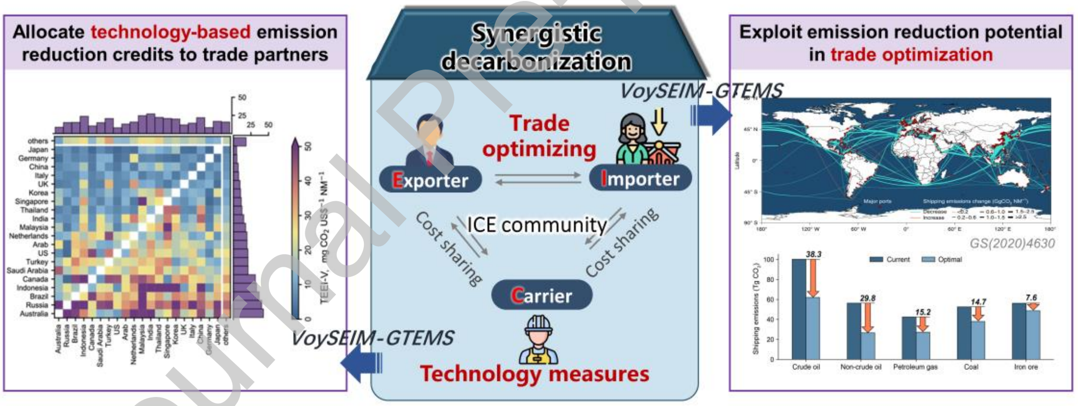

Fig. 3. A scheme of the ICE framework for international shipping to reduce CO_2 emissions by motivating new technologies and route optimization.

5 Towards a climate-friendly and health-harmless shipping

Overall, existing research models and tools for shipping emission modelling and impacts assessment, including air quality and climate impacts, have been gradually maturing and extensively employed in academic research and policy-making. The future directions in this area lie in the impact of indirect effects of shipping emitted aerosols on the climate and the emissions and impacts of VOCs and other non-CO_2 GHGs, where large uncertainties still remain.

The mitigation of GHG and air pollutant emissions from ships has been progressing slowly. On the one hand, the lagging replacement of the global fleet hindered the effectiveness of NOx Tier standard upgrade and adaptation of alternative fuel. On the other hand, the imperfection of the IMO policy system is also hindering the process. Several policy weaknesses summarized above include the employment of scrubbers, insufficient NO_x limitations, non-compliance to policies, and lack of coverage on non-CO_2 GHGs. Besides, the synergies and conflicts among different measures still lack comprehensive evaluation. For example, if CCS was installed on ships to address the carbon border adjustment mechanism by Europe, the utilization of shipping capacity was reduced. Is this a right solution when the whole planet needs to rely on efficiency to cut every gram of non-necessary carbon emission? The optimization of such a complex system remains a challenge.

Looking forward, continuous growth of maritime transport, ambitions to reduce the emissions of GHGs and air pollutants from shipping and initiatives to limit the effects of shipping on the environment will shape the future for international shipping. Future emission inventories will have to take emission factors for alternative fuels, emerging Arctic routes, fleet structure variations, etc. into account. Particularly, research on life cycle assessment of alternative fuels should also be addressed, with attention to the impact of new species such as NH_3 and aldehyde.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

Acknowledgements

This research has been supported by National Natural Science Foundation of China (42325505 and U2233203 to H.L.) and National Key Research and Development Program of China (2022YFC3704200)

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Wen Yi is a Ph.D. student at the School of Environment, Tsinghua University. She received her Bachelor degree of Engineering in Environmental Engineering from Renmin University. Her work is mainly related to international shipping decarbonization pathways, Arctic shipping emission projections and associated atmospheric impacts. She has published articles on *PNAS Nexus*, *Atmospheric Chemistry and Physics*, *Environmental Science & Technology* as a co-author.

Declaration of interests

☒ 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.

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