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REVIEW

Perspectives on shipping emissions and their impacts on the surface ocean and lower atmosphere: An environmental-social-economic dimension

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Shipping is the cornerstone of international trade and thus a critical economic sector. However, ships predominantly use fossil fuels for propulsion and electricity generation, which emit greenhouse gases such as carbon dioxide and methane, and air pollutants such as particulate matter, sulfur oxides, nitrogen oxides, and volatile organic compounds. The availability of Automatic Information System (AIS) data has helped to improve the emission inventories of air pollutants from ship stacks. Recent laboratory, shipborne, satellite and modeling studies provided convincing evidence that ship-emitted air pollutants have significant impacts on atmospheric chemistry, clouds, and ocean biogeochemistry. The need to improve air quality to protect human health and to mitigate climate change has driven a series of regulations at international, national, and local levels, leading to rapid energy and technology transitions. This resulted in major changes in air emissions from shipping with implications on their environmental impacts, but observational studies remain limited. Growth in shipping in polar areas is expected to have distinct impacts on these pristine and sensitive environments. The transition to more sustainable shipping is also expected to cause further changes in fuels and technologies, and thus in air emissions. However, major uncertainties remain on how future shipping emissions may affect atmospheric composition, clouds, climate, and ocean biogeochemistry, under the rapidly changing policy (e.g., targeting decarbonization), socioeconomic, and climate contexts.

Keywords: Shipping, Aerosol, Clouds, Climate, Decarbonization, Scrubber

1. Introduction

The shipping industry (including fishing vessels) is an important player in the global economy. Currently, around 90% of all international trade is carried out using shipping; it has been predicted that trade by sea will triple from 2019 to 2050 (OECD, 2023). But the benefits of the shipping industry come at an environmental cost. In this perspective article, we focus on propulsion-related emissions into air and water. Other types of environmental impacts of shipping, including wastewater, ballast water, noise, and sewage are not included here but we suggest further reading, for example, Moldanová et al. (2022) and Ytreberg et al. (2021).

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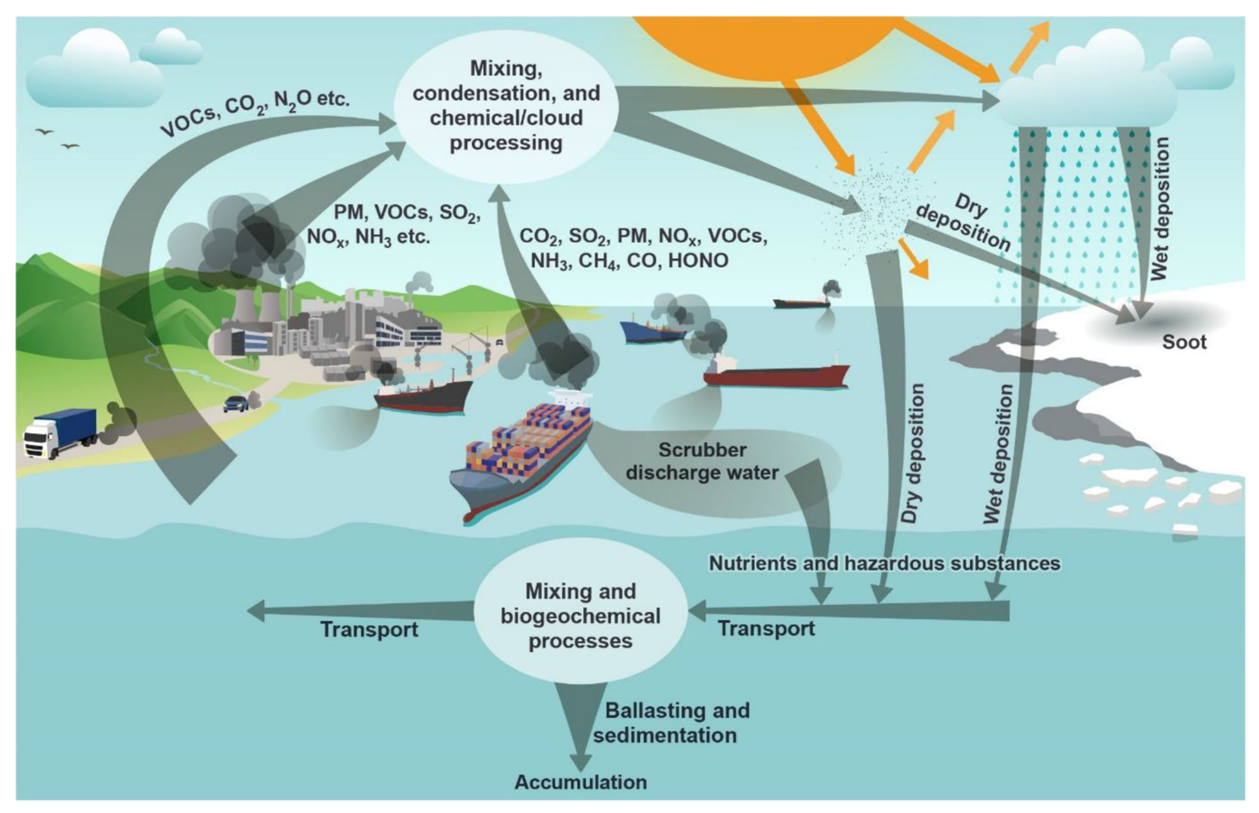

Figure 1. An overview of the emissions, processes, and impacts of shipping. Ship-emitted air pollutants (primary) are mixed in the atmosphere with other pollutants and undergo complex chemical and physical processing, leading to formation of secondary pollutants such as particulate matter; the primary and secondary pollutants interact with radiation to cause light absorption and scattering, affecting the climate; particulate matter can also interact with clouds to further affect the climate (indirectly); once deposited on the snow, the black carbon can accelerate melting; once deposited to the surface ocean, the nutrients and hazardous substance from the particles can then affect ocean biogeochemistry, with indirect impacts on the climate.

Figure 1 provides an overview of shipping emissions and their environmental impacts. Ship stacks emit greenhouse gases (GHGs) such as carbon dioxide (CO_2), and air pollutants, including $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 µm), sulfur oxides (SO_x), nitrogen oxides (NO_x), and volatile organic compounds (VOCs). The formation and sources of these pollutants are described in detail elsewhere, for example, Salo et al. (2016). Air pollutants from ship stacks interact with natural and anthropogenic gases and particles in the atmosphere and cause changes in air composition (Kivekäs et al., 2014; Viana et al., 2014; Becagli et al., 2017; Monteiro et al., 2018), including formation of secondary aerosol particles comprised of sulfate, nitrate, and organic compounds downwind of ship plumes (Sofiev et al., 2018). Aerosol particles reflect sunlight back to space and a small fraction of the ship plumes cause "ship tracks" (clouds) visible in satellite images (Conover, 1966). Both processes cool the atmosphere. And a more recent study showed that shipping emissions substantially change cloud properties (called "invisible ship tracks") even hundreds of kilometers away from the ship routes (Manshausen et al., 2022). This indicates that the impacts of shipping emissions on clouds and radiation may be larger than we previously thought.

Furthermore, once aerosol particles associated with ship emissions are deposited to the surface ocean, they can stimulate phytoplankton growth, initiating changes in biogeochemical processes, including potentially carbon storage (Zhang et al., 2021). In case of exhaust aftertreatment deploying scrubbers, pollutants are transferred to scrubber effluents and released directly to the seawater (Turner et al., 2017; Endres et al., 2018). Shipping emissions thus not only affect atmospheric composition and physics but also ocean biogeochemistry.

Currently, the maritime industry is challenged by the need for rapid energy and technology transition to reduce GHG and air pollutants emissions. This is enforced mainly by international regulations such as the International Maritime Organization global ship fuel sulfur limit (International Maritime Organization [IMO], 2020a) and the IMO Greenhouse Gas Strategy. The long-term goal is to increase the use of carbon-neutral fuels. However, they are not yet available at a competitive price. Growth in shipping activities and the establishment of new shipping routes, particularly in the Arctic, are expected to have distinct impacts on these pristine environments.

Considering the enormous impacts of shipping emissions on both the lower atmosphere and upper ocean, interdisciplinary knowledge on upper ocean and lower atmosphere processes is required, both from a natural science perspective (strongly linked to SOLAS science; Brévière et al., 2015), but also including economic and legal frameworks, as shipping is a rapidly developing economic sector.

2. Impacts on ocean and atmosphere

2.1. Ship stack emissions

Emission inventories form the basis of environmental impact assessments and management strategies. Shipping emission inventories have been iteratively updated over the past decade, with significant improvement in spatial resolution from the proxy-ship-lane-based to real-GPS-based approaches (Ng et al., 2013; Fan et al., 2016; Liu et al., 2016; Chen et al., 2017; Johansson et al., 2017; Faber et al., 2020). The bottom-up mathematical emission simulation model based on Automatic Information System (AIS) data has become the state-of-the-art calculation method for global ship emissions (Jalkanen et al., 2009; Winther et al., 2014; Liu et al., 2016; Nunes et al., 2017; Lv et al., 2018; Schwarzkopf et al., 2021) and policy assessment (Matthias et al., 2016; Sofiev et al., 2018; Karl et al., 2019; Wang et al., 2021).

Primary aerosols from shipping (i.e., those emitted at the source) consist mainly of sulfate, black carbon, and organics. SO_x and primary aerosol emissions are strongly dependent on the ship's fuel quality and sulfur content (Alföldy et al., 2013), while NO_x emission is largely independent of fuel type. Historical NO_x, SO_x, and CO_2 emissions from global shipping, based on various data sources, including Community Emissions Data System (CEDS; McDuffie et al., 2020), Emissions Database for Global Atmospheric Research (EDGAR; Crippa et al., 2021), IMO (Faber et al., 2020), Shipping Emission Inventory Model (SEIM; Wang et al., 2021), and International Council on Clean Transportation (ICCT; Olmer et al., 2017), are shown in **Figure 2a**, **c**, and **e**. They all showed a similar trend but the magnitude of emissions differed by up to around 40%. For the state-of-art power-based ship emission calculation model utilizing AIS data, the main uncertainties come from shipping activity characterization and emission factors. NO_x is a combustion-based pollutant, which is dependent on many factors such as ship type, size, energy efficiency stage, ship operation conditions, and combustion temperature, while the emissions of SO_x are mainly affected by the sulfur content of the fuel. Compliance to fuel regulations and the installation of gas purification equipment such as selective catalytic reduction and scrubbers add to the uncertainty of NO_x and SO_x emission factors. Beecken et al. (2015) estimated that the uncertainty of NO_x and SO_x emission factors is between 20% and 30%. Furthermore, the quality of ships' activity data and the processing method for AIS data and static technical ship data also introduce additional uncertainty into the inventory results.

Based on McDuffie et al. (2020), global shipping emitted 9.6–10.9 Mt SO_x, 16.7–20.0 Mt NO_x, 1.4–1.9 Mt $PM_{2.5}$, and approximately 5.3 Mt non-methane VOC (NMVOC) into the atmosphere in 2018, which accounted for about 9.2% SO_x,16.8% NO_x, 4% $PM_{2.5}$, and 4% NMVOC emissions from all anthropogenic sources. **Figure 2b**, **d**, and **f** showed that the spatial distribution of SO_2, NO_x, and CO_2 emissions in the SEIM inventory from shipping are concentrated along the main shipping routes, as expected.

NO_x emission from shipping has been subject to less regulation and consequently has not decreased over recent years. Currently, only the North and Baltic Seas and parts of the North American coastline are designated nitrogen emission control areas (NECA). Ship emissions of NO_x are estimated to be comparable to terrestrial NO_x sources in Europe in 2020 (European Environment Agency, 2013; Karl et al., 2019). About 70% of ship activity and thus emissions occur within 400 km of the coast, with particularly high ship density in main shipping lanes and near major ports (**Figure 2b**, **d**, and **f**) (Liu et al., 2016; Contini and Merico, 2021).

2.2. Impact on atmospheric composition

Ship stack emissions directly affect atmospheric composition by emitting air pollutants. Primary particles provide surfaces for the condensation of oxidation products of inorganic and organic compounds emitted from natural oceanic sources, including dimethyl-sulfide, isoprene, and ammonia. Most of gaseous NO_x and SO_x from shipping are also oxidized in the atmosphere to form secondary aerosols (e.g., nitrate and sulfate) on a timescale of hours to days. These processes contribute to an enhanced number and mass of particles in the air. Kivekäs et al. (2014) estimated from a coastal site in Denmark that ship emissions contribute 11%–19% of the aerosol number concentration (diameter between 12 and 490 m) when air arrived from a shipping lane. Viana et al. (2014) estimated that shipping is responsible for 1%–14% of $PM_{2.5}$ at different European cities and approximately 11% of PM_1 in coastal areas. Monteiro et al. (2018) and Becagli et al. (2017) estimated <5% contribution to PM_{10} at the coast of Portugal and about 10% in the central Mediterranean Sea (Lampedusa), but they contribute much more to NO_2 in Portugal (Monteiro et al., 2018) and at the Norwegian coast (Marelle et al., 2016). China, which hosts 7 out of 10 of the busiest container ports in the world, was severely impacted by shipping emissions, which contribute to an increase of $PM_{2.5}$ concentration up to 5.2 $\mu g\ m^{-3}$ in eastern China in 2015 (Lv et al., 2018). NO_x from shipping also leads to ozone reduction (due to titration by NO) near the emission sources, but over a longer distance may result in production of ozone. HONO emissions may enhance marine atmospheric oxidation processes (Sun et al., 2020). The impacts of ship stack emissions on atmospheric composition have a major impact on public health, with annual premature deaths estimated to about 400,000 from lung cancer and cardiovascular disease prior to implementing the IMO (2020a) low-sulfur fuel policy (Sofiev et al., 2018).

As more emission control areas (ECA) come into effect, ships are required to switch to low-sulfur fuel. It is expected that the global shipping emissions of SO_x and PM will decrease by 78% and 49% owing to the implementation of IMO low-sulfur fuel policy (Sofiev et al., 2018), but the actual effects of this policy still need to be confirmed in observations. Furthermore, there is evidence that NMVOC emissions from ships increase despite

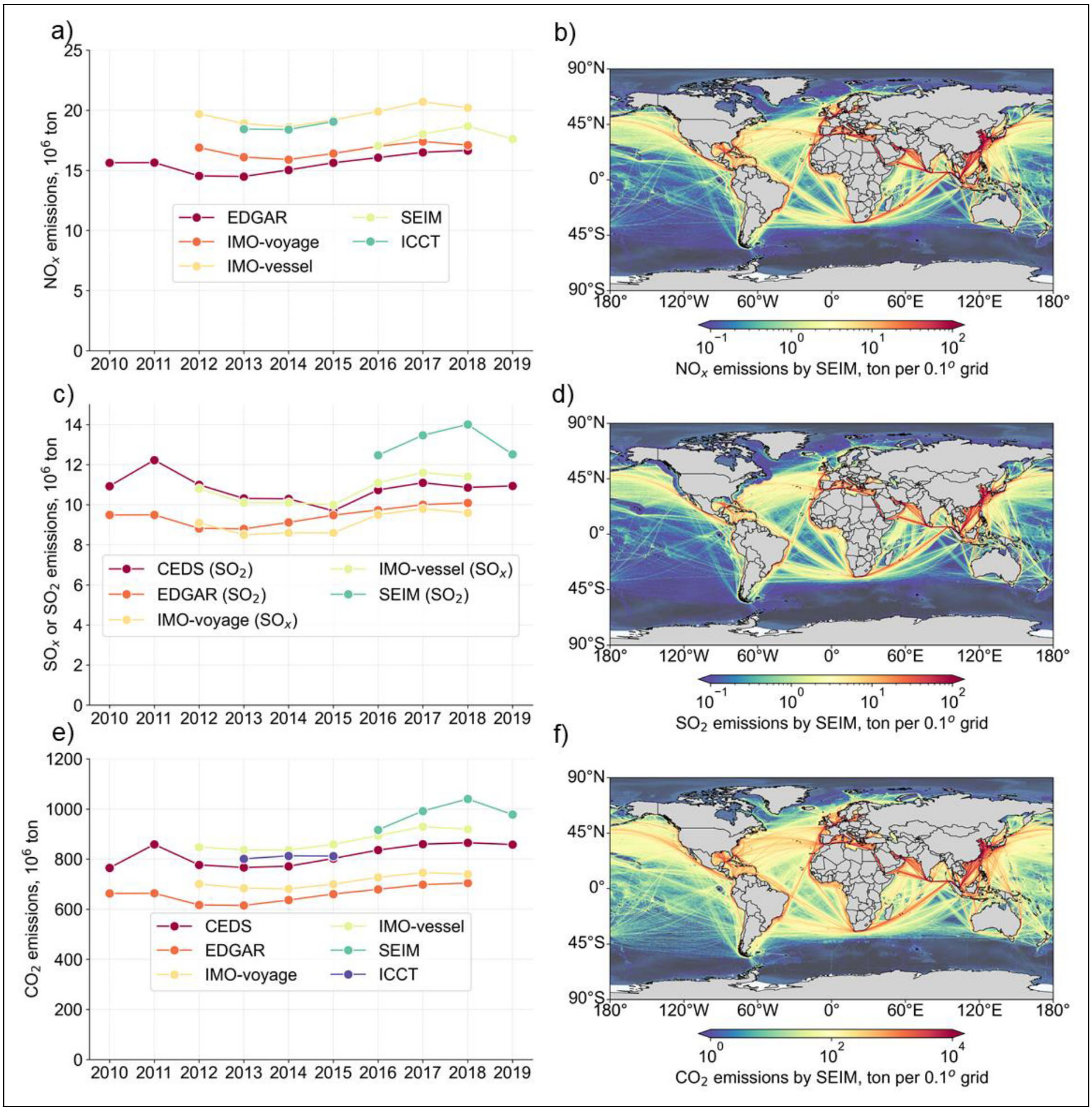

Figure 2. Annual shipping emissions of NO_x, SO_x or SO_2, CO_2 and their spatial distributions. (a) NO_x, (c) SO_x or SO_2, and (e) CO_2 emissions (2010–2019); (b) NO_x, (d) SO_x or SO, and (f) CO_2 spatial distributions in 2017 (from SEIM ; Wang et al., 2021). Note that "SO_x" is a collective term for sulfur oxides, which is dominated by SO_2. CEDS (McDuffie et al., 2020); EDGAR (Crippa et al., 2021); IMO-voyage and IMO-vessel (Faber et al., 2020); and ICCT (Olmer et al., 2017). IMO-voyage and IMO-vessel are calculated slightly differently; both are from the IMO Greenhouse Study 2020 (Faber et al., 2020).

major SO_x and PM emission reductions, especially in the domestic ECA of China (Wu et al., 2020). Liquified Natural Gas (LNG) is emerging to be a feasible and cheap low-carbon energy. However, using LNG causes methane (CH_4) leakage into the atmosphere (Balcombe et al., 2019; Lindstad et al., 2020), which should not be ignored due to its high warming potential (20 to 30 times that of CO_2).

2.3. Impact on clouds and radiation

Aerosols influence the Earth's radiative balance directly by scattering/absorbing light (the aerosol direct effect) and indirectly through their impact on clouds (the aerosol indirect effect). Aerosol particles from shipping emissions, whether directly emitted or formed in the atmosphere, along with background conditions (e.g., meteorology, non-shipping-aerosol concentration) affect clouds and radiation.

Most of the direct radiative effect from ship emissions is due to scattering of sulfate aerosols, estimated to cause a cooling of -0.012 to -0.047 W m^{-2} (Eyring et al., 2010). Black carbon from shipping could cause a warming effect, which however is about an order of magnitude smaller

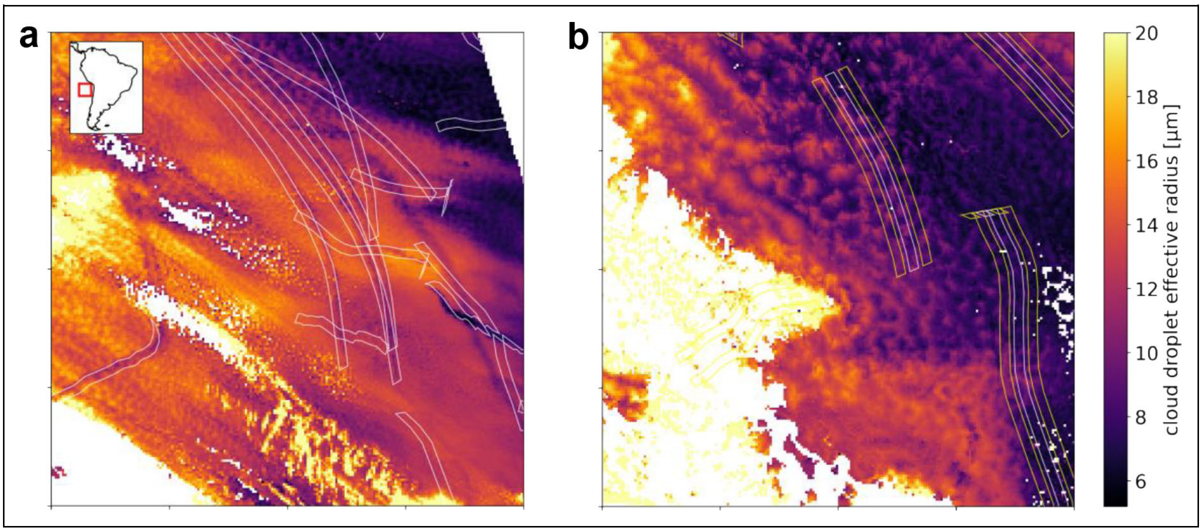

Figure 3. Visible and invisible ship tracks. Color indicates the size of the cloud droplets. Ship tracks are visible in panel (a) as the darker lines where aerosols have caused a reduction in droplet sizes. White boxes indicate the location where ship emissions are advected by wind. Panel (b) shows the example of a day with no visible ship tracks, even though ships have polluted some regions (white boxes). Cloud droplet size in these white boxes is smaller than the nearby regions (yellow boxes). Reproduced from Manshausen et al. (2022) under CC-BY license.

than the direct cooling effect from sulfate (Eyring et al., 2010). Studies generally agree that, on short timescales, ship emissions influence radiation and climate predominantly through the aerosol indirect effect. Earlier studies on aerosol indirect effects due to shipping emissions tended to focus on the highly reflective streaks of clouds (known as "ship tracks"), which are often several kilometers wide and several hundred kilometers long, and are visible in satellite images (**Figure 3a**). Such clouds not only reduce light reaching the surface but also suppress precipitation. Generally, only a very small fraction (ca. 1%) of ship emissions result in visible ship tracks that are distinctly different from the background. High sulfur emission favors ship track formation and the impact of ship emissions on clouds tends to be more pronounced in regions of low ambient aerosol loading (Gryspeerdt et al., 2019).

Most of ship emissions do not result in visible ship tracks, but the radiative impact may still be significant (**Figure 3b**) (Manshausen et al., 2022). This is linked to the perturbation of cloud properties due to secondary aerosol formation, which may occur far away from the emitting ships. For example, it takes at least several hours to convert SO_2 from ship emissions to sulfate aerosols under clear sky condition (e.g., Yu et al., 2020), when ship plumes may have traveled for tens or hundreds of kilometers. Gryspeerdt et al. (2021) found that the strongest cloud droplet number enhancement due to ships occurs not instantly after emission, but about 3-h later. Given the weeklong residence time of small aerosols (in the absence of precipitation), it seems highly likely that ship plumes will affect clouds for many days after emission by contributing to the background aerosol loading in addition to the formation of ship tracks.

The radiative impact of ship emissions remains highly uncertain, with model estimates ranging from negligible (Sofiev et al., 2018) to moderate (-0.18 W m^{-2}; Righi et al., 2015), and large (-0.19 to -0.60 W m^{-2}; Lauer et al., 2007). Most model studies predict a reduction in the magnitude of cooling post-2020 (by a factor of 2 to 4), emphasizing the importance of sulfur emissions. The radiative impact of ship emissions has also been estimated using satellite observations. Diamond et al. (2020) estimated a total anthropogenic aerosol indirect forcing of -1.0 W m^{-2} in the southeast Atlantic shipping corridor, which approximately scales to -0.1 W m^{-2} from global shipping alone (M. Diamond, personal communications, 11/05/2022). Based on machine learning analysis of ship tracks from satellite cloud images from 2003 to 2020, Yuan et al. (2022) arrived at a similar magnitude. However, focusing on visible ship tracks only may underestimate the overall radiative impact of ship emissions (Manshausen et al., 2022).

2.4. Impacts on surface ocean processes

Like other substances deposited to the ocean, such as dust and anthropogenic particles (Ito et al., 2021; Hamilton et al., n.d.), particles associated with shipping emissions are characterized by high nitrogen (N) and low phosphorus (P) (Zhang et al., 2019a; Zhang et al., 2021), which is complementary with general oceanic biological requirements, that is, N deficiency relative to P (Moore et al., 2013). The N fertilization of air emissions from shipping on marine phytoplankton has been documented through in situ experiments (Zhang et al., 2021) and numerical modeling (Raudsepp et al., 2019). On a global scale, the contribution of shipping N to total N emissions are small relative to other sources including terrestrial anthropogenic activities, agriculture, natural soil, and lightning. However, apart from the direct ship emissions (oxidized N deposition), if we consider the indirectly enhanced deposition efficiency of reduced-N (primarily refers to NH_4^+) already

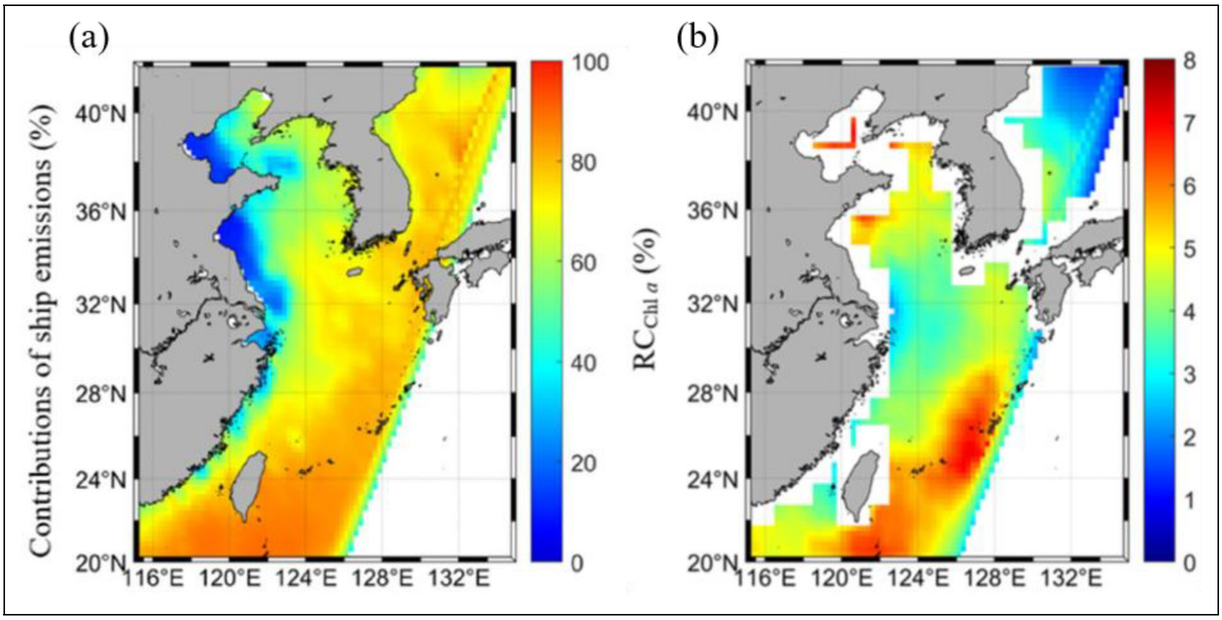

Figure 4. Impact of shipping emissions on total N deposition and chlorophyll *a* concentrations. (a) Contribution of shipping emissions to total annual N (including oxidized N and reduced N) deposition fluxes in the NW Pacific Ocean; (b) relative % change in chlorophyll *a* ($RC_{Chl\ a}$) in surface seawater due to ship-induced N deposition. $RC_{Chl\ a}$ was based on an empirical equation obtained from the incubation experiments. The area where N:P ratios in the surface seawater exceeded 16:1 according to the World Ocean Atlas 2013 nutrient dataset was excluded. Reproduced from Zhang et al. (2021) with rights permission from Elsevier (5443111364528).

present in the atmosphere due to the release of acidic gases from shipping, the contribution of ship stack emissions to total anthropogenic N deposition reaches over approximately 50% in some specific regions of the Western Pacific Ocean (**Figure 4a**) (Zhang et al., 2021). Shipping-related N deposition was predicted to cause up to an 8% increase in Chl *a* concentration in the northwest Pacific Ocean (**Figure 4b**) (Zhang et al., 2021) and up to 10% in the Baltic Sea (Raudsepp et al., 2019).

Apart from N, anthropogenic iron (Fe) has been found to contribute a considerable proportion (21%–59%) to the Fe stock in the North Pacific Ocean (Pinedo-González et al., 2020). Shipping emissions are an important source of anthropogenic dissolved Fe because they are highly soluble and efficiently deposited to the ocean (Ito, 2013). Nonetheless, there is a poor understanding of Fe sources and cycling processes (Ito et al., 2021), which makes it complicated to quantify the role of shipping in contributing to the soluble Fe stock and the subsequent effect on marine biogeochemical cycles, especially in high nutrient-low chlorophyll regions indicated by iron deficiency.

Besides macronutrients, shipping emitted particles also contain other soluble metals, such as copper, as well as organic material including polycyclic aromatic hydrocarbons (Zhang et al., 2021). Atmospheric input of certain trace metals such as Fe can benefit plankton growth, but some metals could cause a toxic effect if in high concentration (Paytan et al., 2009). However, at present, there is no in situ evidence of the toxic effect of ship plumes, possibly due to the natural ocean-atmosphere system diluting concentrations below the toxic threshold in realistic ocean conditions (Zhang et al., 2019a; Thor et al., 2021).

Exhaust gas cleaning systems (scrubbers) concentrate ship stack emissions and the most common type, open loop scrubbers, discharges large volumes, typically 91 ± 13 m^3 MW h^{-1} of acidic (pH = 3) and polluted water (Hermansson et al., 2021). Wide scale use of scrubber technology may cause problems for sensitive ecosystems (e.g., Turner et al., 2018). For instance, metals and organic pollutants cause a toxic effect on phytoplankton such as *Nodularia spumigena* (Ytreberg et al., 2019) and zooplankton such as copepods at different life stages (Thor et al., 2021). At present, however, what substances in scrubber discharge water cause the toxic effect is still elusive (Thor et al., 2021). Moreover, possible synergetic effects of 2 or more substances (Zhang et al., 2022), or the possible formation of new toxic material, that is, the effect of "Witch's Cauldrons" (Thor et al., 2021), need to be further studied with the help of new techniques or methods.

3. The science-social-economic dimension

The potential impacts of shipping emissions on the environment and climate have promoted the implementation of control measures from local to international scales. These measures are linked to the environmental impacts and need to be evaluated from various perspectives. In this section, we will introduce various policy and economic measures to reduce shipping emissions, with a focus on post-2018. Readers are directed to Christodoulou et al. (2018) for a comprehensive review of policies, incentives, and measures targeting the air pollutant emissions from shipping before 2018.

3.1. Legal framework for emission regulations

The legal framework involves basically 3 different levels: international (such as the IMO and the EU), national, and port authorities (Christodoulou et al., 2018). The IMO is the leading intergovernmental administration for the shipping industry. The IMO aims for a 40% reduction in GHG emissions per transport work (ton miles) by 2030 and 70% by 2050 compared to 2008. The EU goes further by targeting a 55% GHG reduction by 2030 compared to 1990 levels and climate neutrality by 2050 (COM, 2019, 2020). The IMO established ECA to curb SO_x, NO_x, and PM emissions, which include the Baltic Sea, the North Sea, North America (the United States and Canada except the Arctic), and the U.S. Caribbean Sea (Puerto and U.S. Virgin Islands). China has implemented increasingly more stringent ship sulfur emission standards for coastal ECAs since 2016. Seas and oceans that fall outside the abovementioned areas come under non-emission control areas (non-ECA). The EU adopted the IMO regulations and incorporated them within its directive prior to 2019. In 2020, IMO further restricted the maximum allowed sulfur content in marine fuels in the global low sulfur fuel policy, which was first adopted in 2008.

Regulations led to the use of compliant low-sulfur fuels, but the IMO also allows abatement technologies such as scrubbers as an equivalent compliance option as it reduces SO_x emissions to the atmosphere by the same proportion as compliant fuels. Scrubbers require a separate legal framework. The Marine Environment Protection Committee (MEPC) published a new scrubber guideline in 2021 under the remit of the IMO (MEPC, 2021). IMO guidelines state that scrubber air emissions should comply with the respective compliant fuels, as shown in **Table 1** (Comer et al., 2020). In 2022, additional guidelines for risk and impact assessments of the discharge water from scrubbers (MEPC.1/Circ.899) was adopted (MEPC, 2022). Although the guidelines have been stepwise improved, they are still only recommendatory in nature. However, IMO invites administrations and governments to use the guidelines as basis for relevant legislation (MEPC, 2021, 2022).

Since January 1, 2020, only 0.50% fuel oil sulfur content for non-ECA and 0.1% for ECA and their corresponding SO_x/CO_2 values, as given in **Table 1**, are relevant. Although the sulfur' air emissions are consistent with the limits set in the guidelines, there is a major uncertainty regarding national regulations on the scrubbers' wash water (discharge) in the sea. Most countries do not adopt consistent or semi-consistent regulations, as in the case of sulfur limits.

Table 1. Air emissions limits for ships with scrubbers (Comer et al., 2020)

Fuel Oil Sulfur Content (% m/m)	SO_2 (ppm)/CO_2 (%v/v)
4.50	195.0
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10 (emission control areas)	4.3

3.2. Current and potential economic measures to reduce ship emissions

Pollution is a well-known negative "externality." Economic theories suggest that externalities associated with transport can be managed with various policy measures, including market-based instruments such as charges, taxes, and tradable permits. Many economists favor emission taxes following the idea of the "Pigovial tax" that companies tend to reduce their emissions by charging for every unit of emissions released. In emission trading, incentives are provided to reduce carbon footprints (Lagouvardou and Psaraftis, 2022). Although companies prefer taxes as their costs are comparatively stable, there are cases of successful implementation of emission trading schemes at local and regional levels. One such program is the U.S. Acid Rain Program, implemented to reduce SO_x and NO_x emissions in the power sector through allowance trading (Chan et al., 2018). Other regulatory measures such as the Energy Efficiency Design Index (EEDI) to strengthen incentives for improved energy efficiency, and the Ship Energy Efficiency Management Plan (SEEMP) for monitoring of energy efficiency were introduced by IMO in 2011. However, these are considered as "soft measures" because of the applicability to newbuilt vessels and excluding existing fleets (Gilbert and Bows, 2012; Stalmokaitė and Hassler, 2020).

3.2.1. International and regional measures

Although several market-based measures (MBM) are proposed, such as Emissions Trading System (ETS) and Rebate Mechanism (RM), none of the MBMs has been adopted to cover maritime transport so far. The EU plans to introduce ETS in shipping (Wissner and Cames, 2022) as part of the EU "FIT for 55" package, which is aiming for a 55% reduction of GHG emissions by 2030 compared to 1990 levels. Although it is supported by the European Community Shipowners Association (ECSA), the global characteristic of shipping raises concerns about the effectiveness of EU ETS.

3.2.2. Port and government authority incentives

Ports play a crucial role in proposing port-differentiated fees, which are expected to reduce up to 4% of CO_2 and NO_x emissions in ports' vicinities (Styhre and Winnes, 2019). Regarding ship plumes, these incentives are based on the fuel type to support alternative fuels such as shore power and low sulfur fuels (LNG and methanol). Considering the role of the ports in environmental upgrading, zero-emission shipping and supply chains, they could be instrumental in mitigating shipping GHG emissions (Styhre and Winnes, 2019; Alamoush et al., 2022).

3.2.3. National sanctions

Sanctions for noncompliance with emissions regulations are various and are country-dependent. Main compliance controls are done during port inspections, but the development of drones or sniffers under bridges increases. Noncompliant ships are exposed to financial sanctions, ship detention, and even criminal charges (International Transport Forum, 2018). At the Baltic and North Sea ECA scale, 4.79% of ships failed to comply with regulations in 2018 (Zis and Cullinane, 2020).

Several obstacles limit the effectiveness of national sanctions (Sys et al., 2016; Zis and Cullinane, 2020). First, the probability of detecting noncompliant ships is low due to the lack of sufficient means (Zis and Cullinane, 2020) and the complexity of the procedure which gives the owners the opportunity to find ways to avoid fines and sanctions. Second, sanctions such as ship detention can easily be undone (Sys et al., 2016). Third, the heterogeneity in financial penalties is a weakness of the current enforcement regime (Sys et al., 2016).

3.3. Impact of legal and economic measures

Evaluating the impacts of different policies on emissions is a key process in the policy cycle, to inform future legislation. This could be done by observations, followed by causal inference data analysis, or by modeling. Reduced SO_2 concentrations have been detected in several regions. Grange and Carslaw (2018) showed a dramatic drop in a port city of England after the implementation of the 2006 and 2010 ship fuel sulfur limits in a port by using time series data with machine learning. Using ground observation, large decreases in atmospheric SO_2 have been seen in both Europe and North America after the ECA implementation (Yang et al., 2016; Anastasopolos et al., 2021). Zhang et al. (2019a, 2019b), Yu et al. (2021), and Zhou et al. (2022) also found large changes in air quality and/or particle composition before and during the implementation of the domestic emission control areas (DECA). It appears that none of these studies considered weather variations (Shi et al., 2021) or quantified the impacts of respective policies in a causal framework (e.g., Song et al., 2023). Yang et al. (2016) and Kattner et al. (2015) showed a high degree of compliance ($\sim$95%) by ships with respect to sulfur emission after the 2015 transition within the European ECA.

The IMO (2020a) fuel sulfur regulations have been predicted to contribute to a decline of SO_2 emissions from global ships in 2020 (Sofiev et al., 2018; Chu Van et al., 2019), which led to a reduction in sulfate aerosol concentrations. This will not only reduce the radiative cooling from sulfate aerosols (Sofiev et al., 2018) but also affect cloud properties (Watson-Parris et al., 2022; Yuan et al., 2022). Overall, this will cause an unintended consequence of global warming. The magnitude of such impact remains uncertain. More observations on atmospheric chemistry and clouds in the remote atmosphere are needed to validate model estimates of cloud and climatic impacts of different policies. Impact assessments can be done at a range of complexities. It is possible to set up scenarios to evaluate the changed environmental pressure from shipping following different legal and economic measures. Moldanová et al. (2022) proposed to use the ecosystem services concept to link the pollution to degradation of ecosystem services, and thereby allowing for an assessment of the ship emissions' impact in socioeconomic terms. Ytreberg et al. (2021) studied the damage costs associated with ship emissions in the Baltic Sea and the results showed that the shipping related damage costs on the marine environment were in the same range as the combined damage costs for reduced air quality and climate change. While antifouling paints were the single largest source of ecotoxicity related impacts (545M€$_{2010}$), scrubber discharge was the largest contributor of the liquid waste streams (33.3M€$_{2010}$).

Studies of different scenarios could utilize Drivers-(Activities)-Pressure-State-Impact-Response (D(A)PSIR), consisting of a range of qualitative and quantitative models to assess the impact of shipping as one of a complex system of anthropogenic drivers and activities on the environment and human well-being (e.g., Moldanová et al., 2022 for the Baltic Sea). The use of AIS data is fundamental for the more recent assessment studies. AIS data is used in combination with emission factors for individual ships, for example, the Ship Traffic Emission Assessment Model (STEAM), originally developed for emissions to air, and later expanded to underwater noise, direct discharges of onboard generated liquid waste streams, and leakage of antifouling paints (Jalkanen et al., 2021). However, the single most polluting type of liquid waste stream from ships is scrubber wash water (Jalkanen et al., 2021; Ytreberg et al., 2022). Assessment frameworks for air pollutants are in general well advanced, but assessment frameworks for marine pollution have higher uncertainties and often include only qualitative assessments.

4. Transformation toward sustainable shipping

Currently, shipping accounts for approximately 3% of total anthropogenic GHG emissions (IMO, 2020b). In line with the IMO's ambition to reduce CO_2 emissions from shipping, the industry is starting to move from traditional fuel oil to cleaner alternative fuels that not only reduce their carbon footprint but also emit less air pollutants. Considering the average lifetime of a ship around 20–25 years, there is an urgent need to move forward.

Decarbonization of ships is challenging and key barriers to the utilization of low or zero-carbon fuels include high investment costs, limited fuel availability, lack of global bunkering infrastructure, high fuel prices, safety concerns, the lack of safety regulations, and the additional demand for onboard storage space (DNV, 2022).

Reducing vessel GHG emissions by up to 100% by 2050 can only be achieved with carbon-neutral fuels. However, several recent studies have shown that emissions of certain GHGs and short-lived climate forcers (SLCFs) from ships increase with the substitution of cleaner fuels. For example, using LNG has increased CH_4 emissions (Balcombe et al., 2019; Lindstad et al., 2020); introducing fuels with lower sulfur content has increased NMVOC (Wu et al., 2020) and potentially black carbon. These complicate the actual GHG reduction process of shipping. The consequences of alternative fuel use need to be studied in advance to avoid unanticipated effects, such as those potentially introduced using exhaust gas cleaning systems (e.g., scrubber bleed-off) and those related to fuel shifts (e.g., methane slip). For the decarbonization of the maritime sector, future marine fuels need to be climate neutral from a well-to-wake perspective and assessed on an equivalent CO_2 ($CO_{2\ eq}$) basis.

A wide variety of energy carriers are currently under evaluation in terms of their advantages, such as reducing GHG emissions, and barriers, such as costs, availability, and acceptability. The most important ones are methane/LNG, methanol, ammonia, hydrogen, and electricity (**Table 2**). A diverse range of more complex molecules, such as different biodiesels, are also a possibility. Renewable pathways for these energy carriers are from biomass (biofuels) or from renewable electricity (e-fuels). Fuels synthesized from hydrogen and CO_2, CO, or nitrogen, using renewable energy are typically called e-fuels or power-to-X. If the carbon and electricity source is renewable, the overall CO_2 footprint of the fuel can be very low (Grahn et al., 2022), and they are considered to be "green fuels." Promising e-fuels that might be widely used in shipping are methanol and ammonia. Biofuels made from biomass such as plants or waste as carbon source and are usually blended with fossil fuels to reduce net CO_2 emissions of an existing vessel with conventional diesel propulsion. Emissions over the whole lifecycle and emission reduction potential of e-fuels and biofuels depend largely on the type of fuel and the primary energy source used for production (**Table 2**).

Table 2 shows the comparison of different energy carriers if used in an internal combustion engine and one fuel used in fuel cell, based on key emission criteria. The comparison is based on literature and expert judgment.

The green energy carriers described above could contribute significantly to decarbonization of shipping (Willis et al., 2023). Air emissions from ships running on future fuels depend heavily on the types of propulsion system setups (e.g., 2-stroke or 4-stroke combustion engine, proton-exchange membrane, or soli oxide fuel cells). Additionally, factors in ship design can enhance ship propulsion efficiency and thereby reduce emissions (e.g., propulsor type and characteristics, hull form design, hull coatings) (Brynolf et al., 2023). The application of exhaust gas after-treatment systems seems to be a promising solution to further reduce NO_x and PM emissions. A small fraction of additives as lubricants or ignition improver in internal combustion engines can drastically reduce the emissions of PM including black carbon. However, the impacts of these new fuels or measures on air emissions and the consequential environmental impacts need to be quantified. Assuming that 40% of the fuel used will be ammonia, Schwarzkopf et al. (2023) estimated an ammonia emission of up to 930 Gg in 2050 in the North and Baltic Seas if shipping activities grow considerably and no exhaust gas cleaning will be applied. This would imply significant additional secondary PM formation in the atmosphere. Furthermore, the effects of possible additives in some of the new fuels (e.g., methanol), in case of accidents and release of these fuels to the ocean, need to be investigated. On the other hand, wind power has no air pollutant issue and is being considered by some freight carriers as a potential source of power.

As several of the studied fuel and propulsion system are in the development phase, their actual emissions of GHGs and air pollutants in the future are still largely uncertain. Some of these fuels may have drawbacks such as the emissions of other potent GHGs (e.g., N_2O and CH_4). Additionally, the whole lifecycle of each fuel should also be considered as all steps including production, storage, and use result in energy use and emissions to air and sea. It is not yet clear which of the potential options is the most appropriate post-fossil fuel—a quantitative update should be performed as soon as the fuels and propulsion options are further developed, tested, and monitored on board of vessels.

5. Arctic shipping and climate change

Arctic shipping is already on the rise (Ng and Song, 2018) with concerns over the potential impact this increased traffic may have on the fragile Arctic ecosystem. Black carbon from shipping could darken ice sheets, accelerating their melting (**Figure 1**). Ship stack emissions could also affect aerosol chemistry and clouds. Ship plumes may also amplify the background levels of ice nucleating particles, especially in regions with low background levels such as the Arctic (Thompson et al., 2018). However, studies of the climate impacts of Arctic shipping have been unable to provide a consensus on the magnitude of impacts (Ødemark et al., 2012; Gilgen et al., 2018).

Climate change has affected the Arctic ecosystems and climate more profoundly than the rest of the world. One of the main outcomes of Arctic warming is the reduction in sea ice in the Arctic Ocean during summer. This would open up the Northwest Passage, enabling large ships to pass (Melia et al., 2016). However, future Arctic shipping may depend on political regulations, economic aspects such as infrastructure and reliability of the routes, but also societal trends, demographics, and tourism demand (Dawson et al., 2017). Currently, there is no binding international legal regime that regulates Arctic water. The most dominant form of legal regulation is the domestic laws of the Arctic coastal states.

It is predicted that Arctic ship emissions in 2050 could be about twice as high as in 2020 (Winther et al., 2014). Stephenson et al. (2018) suggested that future Arctic shipping could have an important impact on the climate of the Arctic (e.g., by reducing warming), while Gilgen et al. (2018) indicated that the impact is small. Clearly, there are still large uncertainties about future Arctic shipping and their climate impact (Goldstein et al., 2022), including (1) the uncertainties in shipping emissions (Winther et al., 2014; Gilgen et al., 2018), (2) a lack of understanding of the natural sources and their interaction with shipping emissions, that is, the present-day aerosol baseline from which predictions are made (Browse et al., 2013), and (3) aerosol–cloud interaction and feedback processes (Possner et al., 2017). We here focus on Arctic shipping, but increased shipping and associated environmental impacts is also becoming an issue in the Antarctic.

Table 2. Expected impacts of energy carriers on shipping emissions, calculated as if used in an internal combustion engine or fuel cell, based on key emission criteria (compared to marine diesel oil [MDO])

Fuel Type (Engine Type)	Description	CO_2	NO_x	SO_x	PM		Relevant Emission Types, Comments	Perspectives
MDO		3.21 kg per tonne fuel (IMO, 2020b)	56.71 kg per tonne fuel (IMO, 2020b)	1.37 kg per tonne fuel (IMO, 2020b)	0.90 kg per tonne fuel (IMO, 2020b)		Reduction in GHG and pollutants emissions is possible through operational measures: improving the engine efficiency, decreasing the vessel hull resistance, slow steaming within certain limits, better weather routing, etc. (DNV, 2022).	At the moment, 98.8% of the world's fleet run on conventional fuel exclusively. The global order book as of June 2022 shows that 3,921 out of 4,967 ships ordered will be still running on conventional (fossil) fuel (DNV, 2022).
		Reduction in … Emissions Compared to MDO				Life Cycle GHG Emissions—Renewable Pathway		
Fuel Type (Engine Type)	Description	CO_2	NO_x	SO_x	PM		Relevant Emission Types, Comments	Perspectives
Methane (Internal Combustion Engine, ICE)	Renewable methane (biomethane) produced from biomass or as an e-fuel will have a similar low emission profile for most air pollutants in an ICE as fossil methane (LNG) (Jiven et al., 2022).	Lower (minus 15%, IMO, 2020b)	Much lower (minus 75%, IMO, 2020b)	Very low to zero (minus 98%, IMO 2020b)	Much lower (minus 88%, IMO, 2020b)	Lower (but high risk of CH_4 emissions)	CH_4 emissions occur upstream during extraction, production, and transportation (methane slip) and downstream (11.96 kg per tonne fuel, IMO GHG study 2020) due to incomplete combustion and methane boil-off on board (ICCT, 2020). The downstream emissions are highly dependent of type of engine, combustion strategies, and operational pattern (Ushakov et al., 2019). CH_4 is a GHG.	LNG is categorized as not harmful to the marine environment if spilled. The trend of larger ships being ordered with alternative fuel propulsion is continuing, with LNG as the dominant fuel. In 2022, 923 ships are in operation with LNG fuel, and 334 more are ordered (DNV, 2022).

Methanol (ICE)	Methanol is an alternative fuel that can lower GHG emissions from shipping if produced from biogenic feedstocks or as an e-fuel (Brynolf et al., 2014; Malmgren et al., 2021).	Not much gain (about 10%) (Brynolf et al., 2014)	Lower	Very low to zero	Much lower	Much lower	NO_x emissions expected to be lower than for traditional fuels (depends strongly on engine load). Exhaust gas cleaning would be needed to reach Tier III levels (Fridell et al., 2021). Emissions of SO_2, PM and BC will be significantly lower compared to traditional fossil fuels. Formaldehyde emissions have been reported. Additives (approximately 3%–4%) are necessary to improve combustion on board.	A major advantage of methanol is that it is liquid in ambient conditions and less hazardous for humans as well as marine organisms when spilled. The handling onboard a vessel is therefore much easier compared to gaseous fuels or ammonia. Methanol as fuel has been taken up recently in the container segment (DNV, 2022).
Ammonia (ICE)	The e-fuel ammonia can be produced from atmospheric nitrogen and regenerative (green) hydrogen.	Very low to zero	Not much gain	Very low to zero	Much lower	Much lower	NO_x emissions similar to MDO (de Vries, 2019). Ammonia engines have a certain ammonia slip, and they also emit nitrogen oxides and nitrous oxide (DNV, 2020), the latter being a very potent greenhouse gas. Emissions of NO_x and NH_3 at the same time might lead to efficient secondary particle formation (Mao et al., 2021). Emissions from ammonia engines and effects of ammonia as a fuel remain poorly studied. Additives are necessary to improve combustion on board.	Ammonia is toxic and needs to be handle with care.Production of ammonia as a shipping fuel will further increase the amount of reactive nitrogen in the environment and therefore counteract attempts to reduce eutrophication of coastal waters. The use of ammonia as ship fuel is currently restricted to pilot studies (DNV, 2022).

(continued)

Table 2. *(continued)*

Fuel Type (Engine Type)	Description	CO_2	NO_x	SO_x	PM		Relevant Emission Types, Comments	Perspectives
Hydrogen (fuel cells)	Hydrogen fuel, produced using renewable energy, has the potential to power ships emitting zero GHG emissions and other pollutants.	Very low to zero	Very low to zero	Very low to zero	Very low to zero	Much lower	If cryogenic, hydrogen boil-off possible. Hydrogen leakages is suggested to contribute to indirect climate effects (Warwick et al., 2022). Burning H_2 in ICE has the potential increase NO_x emissions, which with subsequent impacts on air quality and climate (Lewis, 2021).	The challenges related to hydrogen are its very low density and the requirement to store large volumes at either high pressure or very low temperatures on board. Hydrogen is expected to be used first in short-sea shipping (DNV, 2022).
Green electric power/ batteries	Battery-powered ships are emission-free; however, overall emissions depend on the lifecycle-emissions of the batteries as well as the electrical power used.	Very low to zero	Very low to zero	Very low to zero	Very low to zero	Much lower	Today, still high CO_2 emissions during battery production, but more production are starting in Europe with a better electricity mix.	Due to relatively high weight and limited range, 100% utilization of battery-electric propulsion are only practical for a limited type of ships, such as urban or coastal ferries, that can charge on a regular basis. In the short-sea segment there is a clear trend toward electrification, with some looking toward hydrogen and fuel-cell technology to increase range (DNV, 2022).

Reduction by	Label
0%–10%	Not much gain
10%–50%	Lower
50%–90%	Much lower
90%–100%	Very low to zero

Abbreviations: ICE = internal combustion engine; LNG = liquified natural gas; GHG = greenhouse gas; MDO = marine diesel oil.

The comparison is based on literature and expert judgment. *Source*: Authors' own compilation.

6. Summary and future research directions

The following provides a summary of the main points within this article:

1) New data, such as AIS combined with emission factors, enabled a more accurate quantification of shipping emissions but there are significant differences in the emission estimates of CO_2, SO_2, and NO_x from different inventories. SO_2 emissions from shipping reduced significantly after 2020 but NO_x from shipping remains an important source globally.
2) Shipping emissions interact with natural and anthropogenic pollutants to cause changes in atmospheric composition. The impacts of ship emissions on air quality and human health are significant near the coast, primarily due to SO_x, NO_x, and small aerosols. There appears to be somewhat of a convergence in more recent estimates of the climatic impact of ship emissions from both satellite and modeling perspectives, amounting to a cooling effect of on the order of -0.1 W m^{-2} for pre-2020. However, this may be underestimated due to the presence of "invisible" ship tracks.
3) Substances emitted from shipping emissions, directly via atmospheric deposition, or indirectly via discharge from scrubbers used to remove air pollutants, contain both nutrients such as nitrogen and phosphorus and toxic metals such as vanadium and copper. Atmospheric deposition is more likely to stimulate primary production but impacts of scrubber water discharge is uncertain.
4) Impacts of shipping emissions on the environment and climate have promoted the implementation of control measures from local to international scales. Regulations of air pollutants are generally more advanced, compared to marine pollution. Economic measures to regulate shipping emissions range from taxes, and various permits, to sanctions.
5) The decarbonization of the shipping sector ultimately requires the switch to alternative fuels that can be used in internal combustion engines or fuel cells. Methane, ammonia, hydrogen, and green electric power are potential fuels of the future. While these fuels aim to reduce the CO_2 footprint, there are concerns about high emissions of other pollutants or additional environmental or health risks.
6) Arctic shipping is increasing, which may have a potential impact on the sensitive environment.

Despite the recent progress, there are still major uncertainties in quantifying the impacts of shipping emissions on the environmental systems. To reduce such uncertainties, we need to:

1) Improve emission inventories and future projections: to comprehensively assess the health and climate impacts of shipping emissions in the Anthropocene, shipping emissions inventories should include more chemical species such as VOCs. Furthermore, more shipping-related data sources should be integrated to reduce the uncertainties of the inventory. The shipping industry is undergoing rapid changes both in terms of fleets and decarbonization. Research on the chemical composition of exhaust gas emissions of alternative energy ships and their emission inventories is needed. Projections on global shipping emissions in the context of increasing trade and tourism demand (e.g., in the Arctic) as well as emissions reduction measures are urgently needed in the short- and mid-term.
2) Establish 3-dimensional monitoring systems of ship plumes and impacts: Comprehensive atmospheric and ocean observational systems, including satellite, airborne (aircraft and UAVs), and long-term ground (e.g., ports and sites close to shipping lanes) and ocean (research cruises, and commercial ships) observations will provide the data needed to improve models and to better quantify shipping emissions and their impacts on the surface ocean and lower atmosphere.
3) Apply advanced data science and modeling techniques in understanding impacts of shipping emissions: quantifying the impact of shipping emission not only requires more observations (see above point 2) but also calls for the application of advanced modeling systems as well as data science techniques including artificial intelligence, with the potential to uncover patterns and trends that are not possible with traditional methods, both from satellite, ground and mobile observations.
4) Co-design policy and economic interventions: the development of a particular policy or economic intervention requires the collaboration of social and physical scientists and all stakeholders including the policymakers. Before the implementation of a new policy, an evaluation plan should be put in place to enable the pre- and post-intervention observations to evaluate the effectiveness of such interventions to inform future interventions. The wider environmental-socio-economic impacts, including those related to the air–sea interface (van Doorn et al., 2023), should also be considered.
5) Carry out a full lifetime cycle analysis of alternative fuels: Here a transdisciplinary approach is needed, with economic and policy-related factors feeding into the technologies, and with iterations between economic viability, technological innovation, and environmental standards.
6) Quantify the impacts of shipping emissions, both now and in the future, on polar aerosols, clouds, and oceans: the impact of increasing shipping emissions on the highly sensitive Arctic ecosystems and the climate needs to be better understood.

Data accessibility statement

All data used have been shown in this article. No additional data are available.

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