Black Carbon Emissions and Fuel Use in Global Shipping, 2015

By:

The International Council on Clean Transportation
Bryan Comer, Ph.D.
Naya Olmer
Xiaoli Mao
Biswajoy Roy
Dan Rutherford, Ph.D.

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For additional information:

International Council on Clean Transportation
1225 I Street NW, Suite 900
Washington DC 20005 USA

Table of Contents

Figures

Tables

Executive Summary

Emissions of black carbon (BC) and the use of residual fuels pose risks to human health, ecosystems, and the climate. As one component of fine particulate matter ($PM_{2.5}$), BC exposure contributes to heart and lung disease and is also a danger to the environment. Globally, BC from all sources is the second largest cause of human-induced climate change and is contributing to the rapid decline in Arctic sea ice. Ships contribute a substantial and growing share of BC from diesel engines used in transportation. Additionally, the wide-spread use of residual fuels, mainly heavy fuel oil (HFO), in international shipping exacerbates the problem of BC emissions from ships because ships using residual fuels emit more BC than if they operated on cleaner distillate fuels.

International forums have recognized the need to address the risks of BC and residual fuel (specifically HFO), resulting in a push in recent years for researchers to find ways to define, measure, and control BC emissions from ships. An updated ship emissions and fuel use inventory is needed to assess the potential effectiveness of marine BC control policies on reducing the risks from BC and residual fuel. While ship BC emissions have been estimated by other researchers, the most recent global inventory year is 2007 (Buhaug et al., 2009), using BC EFs from a 2009 study (Eyring et al., 2009). International interest on how to address the risks of BC and HFO, combined with new research on BC EFs and BC reduction strategies, suggests that a detailed inventory of BC emissions, residual fuel use, and residual fuel carriage from the global shipping fleet is needed.

This report presents a bottom-up, activity-based global inventory of BC emissions, residual fuel use, and residual fuel carriage from commercial ships in the global fleet for the year 2015. Ship activity is based on exactEarth satellite Automatic Identification System (AIS) data paired with ship characteristic data from IHS Fairplay. The inventory is geospatially aggregated at a 1° x 1° resolution. Global emissions of other air and climate pollutants and the use and carriage of other fuels (distillate and liquefied natural gas [LNG]) are also estimated for the year 2015. Emissions include particulate matter (PM), sulfur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2).

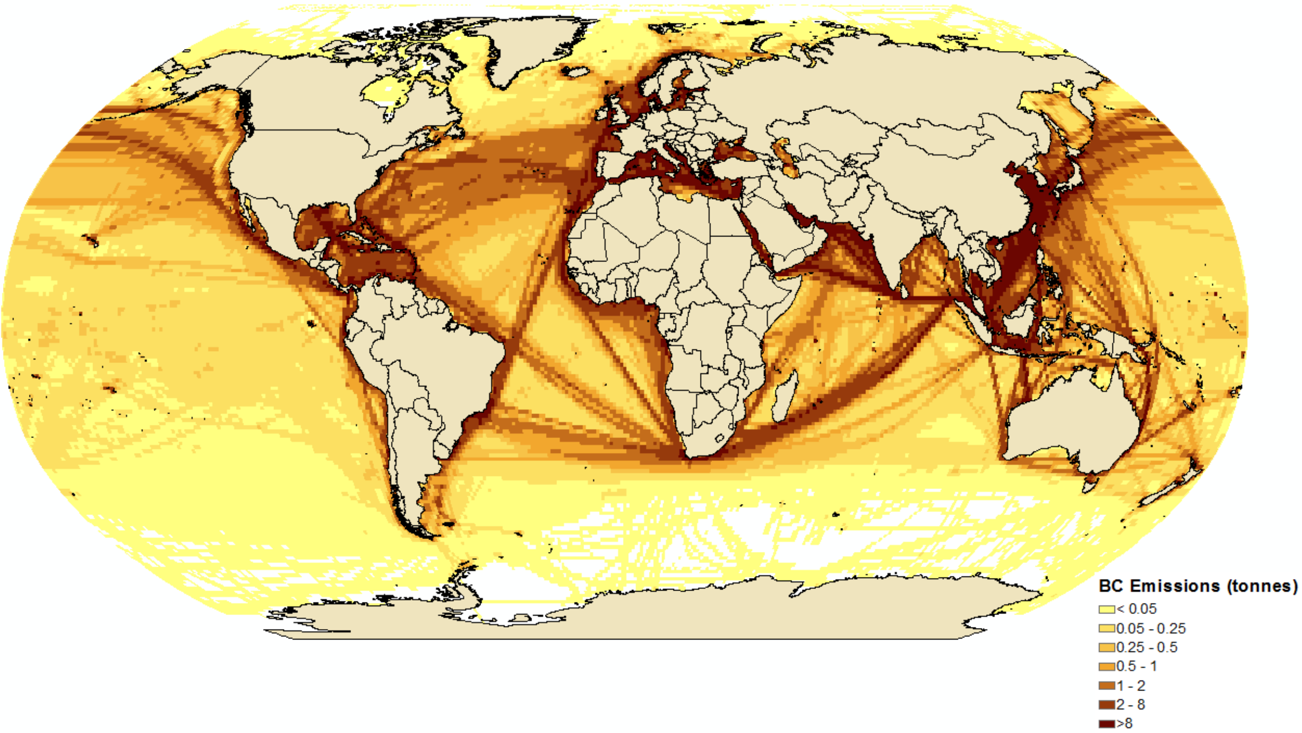
In addition, the report analyzes the BC reduction potential of four technology scenarios: switching all ships from residual to distillate fuels; switching some ships from residual or distillate fuel to LNG; installing exhaust gas cleaning systems on ships; and installing diesel particulate filters (DPFs). The impacts of six policy alternatives are discussed, including expanding or establishing more Emission Control Areas (ECAs), prohibiting the use of residual fuel; establishing a BC emissions standard for ships; including BC in global ships GHG reduction strategies; promoting vessel scrappage; and promoting shore power. The report ends with an ambitious BC reduction policy recommendation that decision-makers can consider. It includes retrofitting cruise ships with DPFs or scrubbers; establishing ECAs in heavily trafficked and sensitive areas; increasing the use of shore power; and lowering the risks of BC and residual fuel in the Arctic.

This summary highlights the key takeaways of the report.

Black carbon

Ships emitted approximately 67 kilotonnes (kt, or thousand tonnes) of BC in 2015, with a lower and upper range between 54 kt and 81 kt, respectively, corresponding to a fleet-wide average BC EF of 0.27 g/kg fuel with a range of 0.22 to 0.33 g/kg fuel. Accounting for BC's global warming potential, ship BC emissions were responsible for 6-8% (100-year timescale) and 18-24% (20-year timescale) of the CO_{2eq} climate warming impact from shipping in 2015.

BC is emitted nearly everywhere throughout the globe, even in the Arctic and Antarctic, and 74% of BC from ships is emitted in the northern hemisphere (Figure ES-1). Furthermore, a substantial portion of BC appears to be emitted near the coast, where it can degrade local air quality.



Data sources: exactEarth; IHS; ArcGIS

Figure ES-1: Black carbon emissions from ships in 2015 (1° x 1° resolution)

Residual fuels such as HFO accounted for an estimated eighty-three percent (83%) of BC from ships, while ships powered with 2-stroke slow speed diesel (SSD) main engines were responsible for two-thirds (66%) of global BC emissions. Further, just six flag states - Panama, Liberia, China, Marshall Island, Singapore, and Malta - accounted for more half of BC emissions.

Larger ships are responsible for the most BC emissions. Container ships, bulk carriers, and oil tankers together emit 58% of BC emissions, while accounting for 20% of the ships and 81% of deadweight tonnage (DWT) in the global fleet. Within that group, container ships, which make up 7% of ships and 14% of DWT in the global fleet, emit the most BC (25%) compared to other ship classes. Outside that group, cruise ships account for a disproportionately large amount of BC, emitting 7% of BC emissions despite accounting for only 1% of the number of ships and less than 1% of DWT in the global fleet. In fact, as shown in Figure ES-2 cruise ships emitted about 11 t per ship per year, or more than triple that of a typical container ship. On average, one container ship emits as much black carbon as 4,600 Euro V heavy-duty trucks operating 100,000 kilometers over one year.

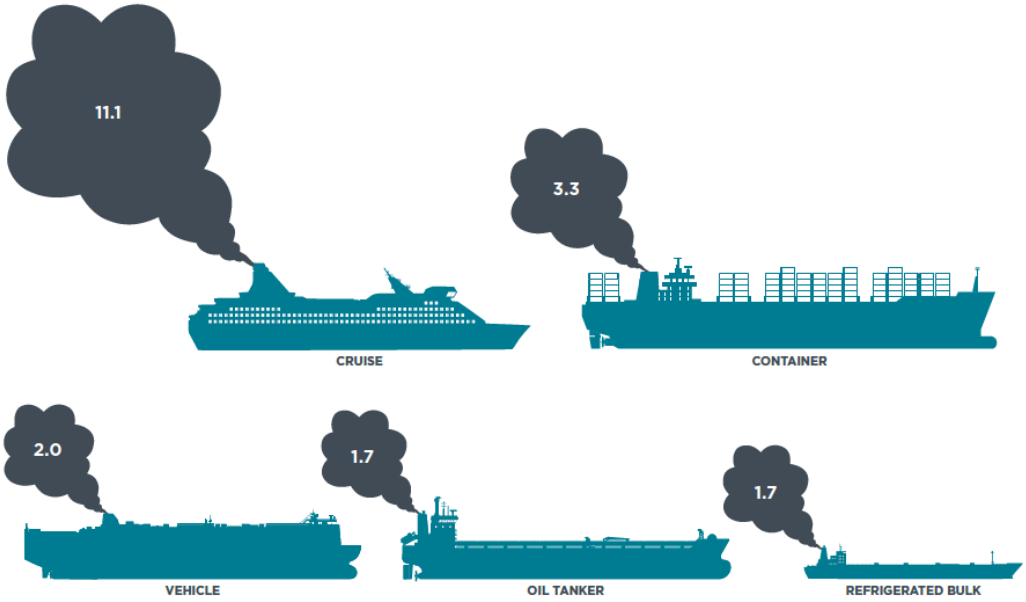


Figure ES-2: 2015 black carbon emissions per ship in tonnes by top emitting ship classes

Fuel use and carriage

The global fleet consumed 247 million tonnes of fuel in 2015, consisting of 196 million tonnes of residual fuel, 45 million tonnes of distillate, and less than 6 million tonnes of LNG. As such, residual fuel represented 80% of the fuel used by ships in 2015. In general, residual fuel use and carriage is most heavily concentrated along major trade routes and coastal areas. For instance, East Asia, along the Chinese coast down to the Singapore straits, has very high residual fuel use and carriage. The 0.1% sulfur limit for marine fuels in these areas means that residual fuels, such as HFO, are essentially prohibited in the North American, U.S. Caribbean Sea, Baltic Sea, and North Sea SECA regions.

Most of residual fuel (74%) was consumed by ships with 2-stroke SSD MEs, and container ships were responsible for 30% of residual fuel consumption, more than any other ship class. Five flag states accounted for more than 57% of residual fuel consumption by ships in 2015: Panama (37 Mt), Liberia (24 Mt), China (24 Mt), Marshall Islands (17 Mt) and Singapore (15 Mt). The use and carriage of residual fuels, such as HFO, poses risks from not only fuel oil spills, but also from air and climate pollution.

BC reduction scenarios

Given the need to reduce climate pollutants from shipping, four BC reduction scenarios were analyzed.

Scenario 1: all ships operating on residual fuel switch to distillate fuel. Under this scenario, BC emissions would have dropped from 67 kt to 33 kt in 2015, meaning that if all ships operated on distillate fuel, total BC emissions could be cut in half. The reduction potential is greater for ship classes that favor residual fuels. For instance, BC emissions from container ships and bulk carriers could be reduced by about two-thirds (65%-67%), as most of these ships operate on residual fuel.

Scenario 2: some ships switch from residual or distillate fuel to LNG. While using LNG emits climate pollutants, including CO_2 and CH_4 (especially when used in Otto-cycle engines), BC emissions are miniscule and other air pollutants, such as SO_x and NO_x are greatly reduced as well. A 50% switchover from oil-based fuels (residual and distillate) to LNG would cut BC emissions roughly in half (-48%).

Scenario 3: some ships install exhaust gas cleaning systems. Exhaust gas cleaning systems (EGCS), otherwise know as SO_x scrubbers, can be installed by ship operators hoping to continue operating on high sulfur residual fuels, such as HFO within ECAs. If scrubbers were installed on ships consuming 20% of 2015 residual fuel consumption, BC from these ships would have dropped 6%, equivalent to a total reduction of 5% across all ships. If all ships operating on residual fuel installed scrubbers, BC could be reduced by 16.7 kt, representing a 30% reduction in BC from residual fuel-powered ships and a total reduction in BC of 25% for all ships.

Scenario 4: some ships install DPFs. Some ships operating on distillate fuel are suitable candidates for diesel particulate filter (DPF) retrofits. If 50% of distillate fuel consumption was treated with a DPF, BC would fall by 58% for that fuel, but total BC emissions from ships would decline only 7%, as distillate makes up only 18% of total fuel consumption for ships in the global fleet.

Some parts of these scenarios is likely to happen in the future. Some ships will switch from residual to distillate fuels to comply with IMO's new 0.5% global fuel sulfur cap in 2020 to avoid the maintenance and safety risks of newly formulated fuels. Newly built or retrofit LNG ships will enter the fleet to take advantage of the low price of LNG fuels compared to traditional bunker fuels and to meet increasingly stringent air pollution regulations. Ships that wish to take advantage of cheap HFO will install scrubbers rather than switching to 0.5% sulfur fuel. Some ships will install DPFs, especially harbor craft and smaller vessels that operate on distillate fuels, as a way to reduce PM pollution in ports and near shore. Cruise ships may also start to install DPFs to please ports, residents, customers, and governments.

An ambitious BC reduction policy recommendation

An ambitious, yet reasonable, BC reduction scenario was developed based on the results of the four BC reduction scenarios and potential effectiveness of several policy alternatives. In all, an effective BC reduction scenario that decision-makers could consider includes the following elements:

- Retrofit cruise ships with diesel particulate filters or scrubbers
    - Cruise ships emit the most BC per ship, on average. Ideally, a ship would be retrofitted with a DPF, which can reduce BC by 85%. Unlike most large ships, cruise ships tend to use 4-stroke engines that may be easier to retrofit with a DPF than the large 2-stroke main engines of cargo ships. Alternatively, cruise ships could be outfitted with scrubbers which can reduce BC emissions by 30%. The cruise industry has taken the lead in retrofitting their ships with scrubbers to meet regional fuel sulfur standards. Thus, it may be reasonable to retrofit the majority of the cruise ship fleet with either a DPF or scrubber in the near term.
- Establish ECAs in heavily trafficked and sensitive areas
    - ECAs encourage the use of distillate fuels, which emit 40-80% less BC than residual fuels. In contrast to policies like emission standards affecting only new-build vessels, sulfur ECAs reduce emissions quickly because they apply to all vessels in the existing fleet. New ECAs in East and Southeast Asia, the Red Sea, and the Mediterranean Sea would seem to offer the greatest BC reduction benefits. Extending the North American ECA and the North Sea ECA to the Arctic and establishing ECAs around Iceland, Greenland, and Russia would offer additional protections to the Arctic.
- Make shore power the norm for major ports and major ship classes
    - Shore power can greatly reduce air pollution, including BC, in port. Several major ports have shore power connections for container, cruise, and roll-on roll-off (roro) vessels, but the use of shore power is limited by the number of berths with shore-side connections and the number of ships with ship-side connections. Ports worldwide could follow California's lead, which requires that most passenger ships (including cruise ships), container ships, and refrigerated cargo ships connect to shore power when at berth in their ports.
- Prohibit the use of residual fuels in the Arctic and require diesel particulate filters for some ships
    - While BC from ships warms the entire planet, the worst damage is sustained in the Arctic. Prohibiting the use of residual fuel in the Arctic would immediately reduce BC emissions in a region warming twice as fast as the rest of the planet and would have the added benefit of reducing the risks of HFO spills in sensitive Arctic ecosystems. Requiring some ships to use DPFs would reduce the deposition of BC from ships to Arctic snow and ice, where it lowers albedo, increases melt, and accelerates warming. Cruise ships operating in the Arctic are one ship class that could be retrofit with DPFs, this would help protect the Arctic that their customers are paying to see. Progressive flag states could also retrofit their fishing vessels with DPFs. This would reduce emissions from the largest source of BC in the IMO Arctic: fishing vessels.

Implementing these strategies would not only reduce climate warming BC emissions, but would also reduce emissions of other air and climate pollutants. The net effect would be fewer premature mortalities and morbidities from ship emissions, lower risks of economically and ecologically damaging residual fuel spills, and less climate warming impacts from ships

1 INTRODUCTION

Emissions of black carbon (BC) and the use of residual fuels pose risks to human health, ecosystems, and the climate. As one component of fine particulate matter ($PM_{2.5}$), BC exposure contributes to heart and lung disease. BC emitted at and above 40°N latitude causes approximately 6,200 premature cardiopulmonary and lung cancer mortalities per year (Green, Silberman, Comer, Winebrake, & Corbett, 2011). BC is also a danger to the environment. Globally, BC from all sources is the second largest cause of human-induced climate change and is contributing to the rapid decline in Arctic sea ice. Ships are responsible for a substantial and growing share of BC from diesel engines used transportation. The wide use of residual fuels, mainly heavy fuel oil (HFO), in the international maritime shipping sector exacerbates the problem of BC emissions from ships. As will be explained in this study, ships using residual fuels emit many times more BC than if they operated on cleaner, but more expensive, distillate fuels.

Recognizing the threat of BC and HFO to the Arctic, the International Maritime Organization (IMO) Pollution Prevention and Response (PPR) Sub-Committee is investigating measures to control black carbon from ships and the IMO Marine Environment Protection Committee (MEPC) is discussing how to address the risks of HFO to the Arctic. Other international forums, including the Arctic Council (AC) Protection of the Arctic Marine Environment (PAME) working group are seeking to understand the impacts of BC and HFO on the Arctic. Further, the U.S. and Canada have committed to phase down the use of HFO in their portions of the Arctic.[1] Finally, intergovernmental organizations like the Climate and Clean Air Coalition (CCAC) are actively funding research on approaches to reduce emissions of BC and PM from diesel engines under its Heavy-Duty Diesel Initiative (HDDI).

Recent years have seen a dramatic increase in scientific research to define, measure, and control BC from ships, including new data on marine BC emission factors (EFs) and the effectiveness of operational and technical measures that can reduce BC. While ship BC emissions have been estimated by other researchers, the most recent global inventory year is 2007 (Buhaug et al., 2009), using BC EFs from a 2009 study (Eyring et al., 2009). International interest on how to address the risks of BC and residual fuel (especially HFO), combined with new research on BC EFs and BC reduction strategies, suggests that a detailed inventory of BC emissions, residual fuel use, and residual fuel carriage from the global shipping fleet is needed. An updated inventory provides a baseline to assess the potential effectiveness of marine BC control policies on reducing the risks from BC and residual fuel.

This report presents a bottom-up, activity-based global inventory of BC emissions, residual fuel use, and residual fuel carriage from commercial ships in the global fleet for the year 2015. Ship

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[1] See the United States-Canada Joint Arctic Leader's statement at https://obamawhitehouse.archives.gov/the-press-office/2016/12/20/united-states-canada-joint-arctic-leaders-statement

activity is based on exactEarth satellite Automatic Identification System (AIS) data paired with ship characteristic data from IHS Fairplay. The inventory is geospatially aggregated at a 1° x 1° resolution. Global emissions of other air and climate pollutants and the use and carriage of other fuels (distillate and liquefied natural gas [LNG]) are also estimated for the year 2015. Emissions include particulate matter (PM), sulfur oxides (SO_x), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The year 2015 was chosen because it is the most recent year for which complete AIS ship position data were available.

The BC reduction potential of four scenarios are analyzed in detail, including: switching all ships from residual to distillate fuels; switching some ships from residual or distillate fuel to LNG; installing exhaust gas cleaning systems on ships; and installing diesel particulate filters (DPFs). The impacts of six policy alternatives are discussed, including expanding or establishing more Emission Control Areas (ECAs), prohibiting the use of residual fuel; establishing a BC emissions standard for ships; including BC in global ships GHG reduction strategies; promoting vessel scrappage; and promoting shore power. The report ends with an ambitious BC reduction scenario for consideration by decision-makers. It includes retrofitting cruise ships with DPFs or scrubbers; establishing ECAs in heavily trafficked and sensitive areas; increasing the use of shore power; and lowering the risks of BC and residual fuel in the Arctic.

2 BACKGROUND

2.1 Black Carbon

Black carbon (BC) is a small dark particle emitted following the incomplete combustion of fuel. BC from all sources is the second largest contributor to human-induced climate change, after CO_2 (Bond et al., 2013). In 2010, BC from ships accounted for 8-13% of BC emissions from diesel sources (Azzara, et al., 2015). As a result of its dark color, BC absorbs a high proportion of incoming solar radiation and directly warms the atmosphere. BC has a relatively short atmospheric lifetime, depositing on the earth's surface a few days up to a few weeks after emission. However, when BC deposits onto light covered surfaces, such as snow or ice, it reduces the albedo of the surface and continues to have a warming effect (AMAP, 2015). In fact, Sand et al. (2013) found that BC emitted in the Arctic (60-90°N) warms Arctic surface temperatures nearly five times more than BC emitted in mid latitudes (28-60°N). Unfortunately, ship BC emissions are expected to increase; one widely cited study (Corbett, Lack, & Winebrake, 2010) estimated that, barring additional controls, global BC emissions from marine vessels will nearly triple from 2004 to 2050 due to increased shipping demand, with a growing share emitted in the Arctic region due to vessel diversion. At the same time, emissions from land-based sources are expected to fall due to stricter controls (Johnson et al., 2015), increasing the relative importance of shipping emissions. In addition to its climate impacts, exposure to PM and BC emissions has been linked to negative human health impacts including cardiopulmonary disease, respiratory illness, and lung cancer.

Several studies have estimated BC emissions from ships globally and in the Arctic (defined geographically in various ways) as shown in Table 1. The BC emission factors (EFs) used in these studies range from 0.18 to 1.08 g BC/kg fuel. Uncertainty in marine BC EFs is a barrier to understanding how much BC is emitted from ships and what factors influence BC formation.[2] Differences in BC EFs drive the differences between global ship BC emissions estimates. Researchers have found that BC EFs are influenced by several factors, including fuel type (e.g., residual, distillate, LNG), engine type (e.g., 2-stroke, 4-stroke), and engine load (UCR, 2016). In this work, we develop new main engine (ME) BC EFs that change as a function of fuel type, engine type, and engine load based on the latest research presented to IMO.

Table 1. Summary of marine black carbon inventory results from other studies.

Study	Inventory Year	BC (kilotonnes)	Fuel consumption (million tonnes)	BC EF (g/kg fuel)
Global BC Inventory				
Bond et al. (2013)	2000	100	-	0.17-0.85[a]
Dentener et al. (2006)	2000	130	182	0.69
Fuglestvedt et al. (2010)	2000	197	182	1.08
Eyring et al. (2005)	2001	50	280	0.18
Lack et al. (2008)	2001	133	254	0.53[b]
Dalsøren et al. (2009)	2004	39	216	0.18[c]
Eyring et al. (2010)	2005	160	300	0.53
Buhaug et al. (2009)	2007	120	333	0.36[d]
BC in the Arctic				
Corbett et al. (2010)	2004	1.25	3.5	0.35
Peters et al. (2011)	2004	1.15	3.3	0.35
DNV (2013)[e]	2012	0.052	0.3	0.18
Winther et al. (2014)	2012	1.58	4.5	0.35
Comer et al. (2017)	2015	1.45	4.4	0.30-0.56 (0.34 avg.)

[a] A combination of BC EFs from Petzold et a. (2008), Sinha et al. (2003), and Lack et al. (2008) that are used in the SPEW model, as described in Lamarque et al. (2010). [b] Weighted average. [c] BC emissions factor from Shina et al. (2003). [d] Buhaug et al. did not estimate BC emissions directly, but cited an estimate of BC emissions in 2007 from an In Press version of Eyring et al. (2010); the BC emissions estimate was the same in the In Press and published version. [e] Only includes the Arctic as defined in the IMO Polar Code, an area much smaller than the Arctic as described in other Arctic BC studies.

2.2 Black Carbon Control Strategies

Researchers have investigated ways to reduce BC emission from ships. This section describes the

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[2] To address this uncertainty, the IMO is undertaking a process to define, measure, and potentially control BC emissions from ships. A definition of BC has been achieved, with help from research from Bond et al. (2013), participants of the ICCT's first workshop on marine BC emissions in Ottawa in 2014, and delegates to the IMO's Pollution Prevention and Response (PPR) Sub-Committee. To tackle questions on how best to measure marine BC emissions, researchers have systematically measured marine BC emissions in the lab and on ships to improve marine BC EFs, discussing their approaches and findings at the ICCT's second and third workshops on marine BC emissions in Utrecht (2015) and Vancouver (2016).

current state of knowledge on BC control technologies and operational practices based on the existing literature and new research from UCR, the European Association of Internal Combustion Engine Manufacturers (EUROMOT), Finland, and Japan.

Several studies have tested available technologies for controlling particulate matter (PM) emissions. While ranges of effectiveness have been established for PM, few studies have specifically addressed the reduction of black carbon as a PM component. Most BC reduction estimates are derived from PM measures and the estimated percent component of BC. To better understand actual BC emissions from vessels, specific measures of black carbon are needed (along with PM) to better estimate the percent or portion of black carbon in particulate matter emissions.

A draft synthesis report by the National Research Council Canada (McWha, 2012) lists the following ranges for BC reductions by technology (Table 2).

Table 2. Expected black carbon emissions reductions from various technologies from National Research Council Canada.

Emission Reduction Technology	Expected Emissions Reductions (%)	
	Low	High
Slide valves	25	50
Low sulphur fuels	30	80
Water in fuel emulsions	45	50
Dual fuel power systems	50	85
Alternative fuels	67	84
Exhaust gas recirculation	0	20
Seawater scrubbers	25	70
Diesel particulate filters	70	90

According to the report, of the presented technologies, only slide valves, the use of low sulfur fuels, water in fuel emulsions, dual fuel power systems and wet scrubbers are readily commercially available.

Another synthesis report, titled “Investigation of appropriate control measures (abatement technologies) to reduce Black Carbon emissions from international shipping” prepared by Lack et al. (2012) and submitted to IMO identifies six abatement options for black carbon mitigation from international shipping: Liquefied natural gas (LNG), Water-in-Fuel Emulsion, Scrubbers, Diesel Particulate Filters (DPFs), Fuel Switching (HFO – Distillate), and Slow Steaming – De-Rating. Other important studies include Corbett et al. (2010), which assessed a variety of technologies for reducing short-lived climate forcers from ships impacting the Arctic region, and the National Research Council Canada (McWha, 2012) have identified Slide Valves and Exhaust Gas Recirculation (EGR) as important control technologies.

Based upon these studies the following key control measures for marine black carbon were identified:

Liquefied natural gas: LNG is natural gas stored as liquid at -162°C. The predominant component is methane with some ethane and small amounts of heavy hydrocarbons. LNG is used as a fuel for marine propulsion and power generation with steam turbine engines or dual fuel diesel engines. Most LNG powered ships in service today are LNG tankers. LNG is estimated to provide a 90% reduction in BC emissions.

Water-in-fuel emulsions: In WiFE, water is added continuously to the fuel supply and a homogeneous mixture is achieved by mechanical measures. When WiFE is used, the specific fuel oil consumption (SFOC) generally increases as larger amounts of water are added. This is due to the energy required to heat up the injected water to its saturation temperature, subsequent evaporation at the saturation temperature, and further super-heating to the auto-ignition temperature of the emulsified fuel. In previous work, the SFOC penalty at 30% vol. added water is estimated to be approximately 2% when considering evaporation and super heating only. It should be noted that the water may contribute with work in the expansion process, thereby reducing the actual SFOC penalty, and that little is known about the corrosive effects from the water on the fuel system and other machinery related to the fuel system (Andreasen et al., 2011). WiFE is estimated to provide 45 to 50% reductions in marine black carbon emissions.

Exhaust gas scrubbers: Trials of exhaust gas scrubbers have been conducted since 2006. Exhaust scrubbers expose exhaust gases to a water spray, or by other means of physical contact (bubbler, etc.), to decrease the emissions of SOx. The scrubbing systems can be either open-loop (seawater scrubbers) or closed-loop (freshwater systems). In a closed loop, freshwater is recycled, into which sodium hydroxide (NaOH) is continuously added in order to balance pH to a slightly alkaline value (required for optimal scrubbing operation). The closed loop is used for special areas or coastal waters where discharge water is restricted. For an open-loop seawater scrubber, seawater is sufficiently alkaline to achieve the removal of acid sulfur compounds. Dry exhaust gas scrubbers are also in commercial production, and remove SO_2 via chemical absorption to calcium hydroxide (Lack et al., 2012). Scrubbers are estimated to provide 25 to 70% reductions in marine black carbon emissions.

Diesel particulate filters: DPF systems are comprised of silicon carbide ceramic fibers with a self- cleaning mechanism. The filter efficiently removes particulate matter (PM) and BC from exhaust gas forced through it. Passively regenerating filters rely upon catalytic activity and the latent heat of the exhaust gas to periodically removed accumulated material, while actively generated filters typically involve periodic fuel injection or external heating to combust PM buildup in the filter. The use of particle filters in inland waterway vessels and highway trucks has been very successful but requires access to low sulfur fuels. DPFs are estimated to provide 80 to 90% reductions in marine black carbon emissions with low sulfur fuel. There has been limited success with DPF and high sulfur fuels. Reductions of 80%-92% have been reported when paired with heavy oil (1% max sulfur content) (Lack et al., 2012 and Johansen, 2015). Arranging DPFs in series may reduce the need for regeneration (McWha, 2012).

Fuel switching: Switching to distillate fuel from residual fuel is a straightforward alternative to reduce BC in conjunction with current and forthcoming IMO emissions regulations on maximum allowable sulfur content in the fuel oil. Switching to distillate fuels requires minor changes for the ship operator such as switching to fuel pumps with reduced plunger clearance, replacing fuel valves, alternating the fuel injection timing to correspond to the altered calorific value of the fuel, using finer fuel filters, and other small alterations. These changes require minimal capital expenditures. Switching to low sulfur fuel is estimated to provide 30 to 80% reductions in marine black carbon emissions (Lack et al., 2012).

Slow steaming/derating*:* Slow steaming became popular within the shipping industry at the end of 2007, mainly with container vessel owners and operators, as a consequence of increased fuel costs and reduced demand. Vessels were instructed by owners to reduce main engine load to approximately 40% MCR, which decreased the speed by approximately 20%. Average fuel oil cost (FOC) savings of approximately 42% are possible without a de-rated engine and 45% with a de-rated engine. Derating is a process by which the maximum power of a ship engine is artificially limited to provide better fuel efficiency at lower speeds, at the sacrifice of some flexibility in operations (e.g. slower maximum ship speeds). For example, Wärtsilä has marketed engines with a constant engine power but an extra cylinder providing fuel savings of 2-3.5% per day.[3] To counter balance the potential of increasing BC emissions when operating a vessel at lower load (slow steaming) the engine should be retuned or re-rated. The combined use of the two techniques provides fuel savings in coordination with reduced emissions (Lack et al., 2012).

Slide Valves: Slide valves replace conventional fuel valves, facilitating more complete combustion at lower peak-flame temperatures and thus reducing NOx and PM (Ritchie et al., 2005). Slide valves are reported to reduce PM emissions by approximately 25%, (Henningsen, 2004 and MSRP, 2009). Although estimates of 50% PM control have been presented, BC control performance estimates have not been reported (CARB, 2002); it is assumed that slide valves will reduce PM and BC similarly. Slide valves are already in use in a good portion of the shipping fleet in order to meet IMO Tier 2 NOx requirements and are often a retrofit option for vessels unable to de-rate (MAN Diesel and Turbo, 2012). Slide valves are estimated to provide 25 to 50% reductions in marine black carbon emissions (Lack et al. 2012).

Exhaust Gas Recirculation*:* EGR is used to lower the oxygen content of the charge air entering the combustion chamber. A portion of the exhaust gases are diverted from the engine exhaust, scrubbed to remove particulate matter and SO_X, cooled, then reintroduced into the combustion chamber. The lower oxygen content of the re-circulated exhaust gases decreases the amount of

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[3] http://www.wartsila.com/file/Wartsila/1278512639967a1267106724867-Wartsila-SP-Tech-2008-Derating.pdf

free oxygen available for the creation of NO_X, thereby reducing NO_X emissions. Also, the specific heat capacities of the products of combustion are higher than fresh air and fuel mixtures. This results in a lower peak combustion temperature, additionally limiting the formation of NO_X. It has the additional advantage of reducing PM/BC emissions through the process. EGR is estimated to reduce up to 20% of black carbon emissions (Lack et al. 2012).

A few other studies have directly tested the effectiveness of specific technologies. A study for the Port of Long Beach and Los Angeles testing the effectiveness of slide valves at low loads found a reduction in emissions of diesel particulate matter (DPM) by up to 50% and that overall, slide valves emit over 90% less hydrocarbons compared with other conventional valve configurations[4]. Lack et al. (2009) performed measurements on ship exhaust, including the benefits of fuel switching. Their measurements suggest that a change from fuel with an average fuel sulfur content of more than 0.5% to fuel with less than 0.5% will give a reduction of the sulfur mass fraction of total PM mass from 50 % down to 3%. The PM emission factor will also be reduced from 4.2 kg/ton to 2.1 kg/ton. Even though there are uncertainties attached with these numbers, they still provide a clue on how PM emissions will change following the switch to lower sulfur fuels. While the BC emission factor may not change, as was pointed out by Corbett et al. (2010), the ratio of black carbon to sulfate mass would, which has its own potential climate implications.

Seawater scrubbers (SWS) can reduce PM emissions by 25–80%, as verified in a recent demonstration project that showed 57% reductions in PM (Ritchie et al., 2005 and Kircher, 2008). Recent research indicates that SWS may reduce $PM_{2.5}$ (of which BC is a component) by 75%. (IMO 2nd GHG study, 2009 and Marine Exhaust Solutions, 2006). Based on the ICCT testing of a Hamworthy/Krystallon seawater scrubber on board a container vessel, total PM reductions ranged from 40 to 50% and averaged 45% across the scrubber, but varied from 10% to 80% for BC depending on load. The results suggest BC reductions for scrubbers are a strongly related to engine load.

Corbett et al. (2010) estimate reductions for several other technologies. Emulsified fuels (EMFs) are stable mixtures of fuel, water and additives for emulsification and stabilization; EMFs reportedly reduce PM emissions by up to 50–63%. Additionally, WiFE reportedly reduces PM emissions by two- to three-times the water content – so a 10% water emulsion would equate to 20–30% PM reductions, while 30% emulsion would result in 60–90%. Corbett et. al. 2010 and the Litehauz report both list diesel particulate filter systems as possible technology options. DPF systems are effective in controlling PM (achieving 70–95% total PM reductions), and are particularly effective at controlling BC emissions; achieving 95–99% BC reductions by mass (Liz et al., 2009 and Majewski, 2005). MECA produced a report presenting the results of testing on harbor craft and ferries. They explored combination technologies of Clean Cam Technology

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[4] MAN slide valve low-load emissions test final report
http://www.cleanairactionplan.org/civica/filebank/blobdload.asp?BlobID=2571

System (CCTS)[5] retrofit engine control technology and the Rypos active DPF system with demonstrations aboard harbor craft reducing PM between 43 and 90%. (MECA, 2014)

The major issue with many of these estimates is that they are often based on PM measurement and not direct BC measurement. In addition, they are not necessarily conducted uniformly with a standard protocol for engine load conditions. The large variation in equipment effectiveness across conditions and studies indicates that there is likely a need to develop a standard approach for testing the effectiveness of mitigation technologies as well as a need to measure black carbon emissions directly, or at the least develop a conversion from PM to BC under more controlled conditions. In addition, not all measurements used the same instruments or protocols for the actual PM or BC measurement, introducing uncertainty for BC emissions and inter-study comparisons. These discontinuities in methodology need to be addressed to better characterize technology efficacy as well as emissions estimates. Fortunately, recent research on BC emissions has started to use a standardized measurement reporting protocol and has systematically tested several BC measuring instruments, as discussed next.

Recently, researchers have measured marine BC EFs in the lab and on ships at sea, exploring the factors the affect BC emissions, including fuel type, engine type, engine load, engine tier, and exhaust gas cleaning systems (EGCS, or scrubbers). The results of this research shed light on the ways that BC can be controlled from marine engines, as summarized next.

<u>Fuel type</u>: Researchers have found that (1) distillate fuels emit less BC than HFO; (2) desulfurized residual fuels emit more BC than HFO at typical engine operating loads; and (3) with few exceptions, 0.5% sulfur residual fuel blends seem to emit as much or more BC as HFO. Specifically, researchers at the University of California Riverside (UCR, 2016) tested the effects of fuel switching on BC emissions and found that distillate fuel had the lowest BC EF and that a desulfurized residual fuel (RMB-30) had the highest BC EF at typical engine operating loads (25% to 75%), higher even than HFO. UCR also included information on three fuel switching studies they had previously conducted. In those studies, only minor BC emission factor changes were observed when switching from HFO to distillate. However, the highest BC reduction occurred when switching from a HFO residual fuel to an MGO distillate fuel.

EUROMOT submitted BC emissions testing results from 35 marine engines tested in the lab using a filter smoke number (FSN) to IMO's Pollution Prevention and Response's (PPR) fourth meeting in 2017.[6] EUROMOT data suggests that engines using residual fuel emitted approximately two to five times more BC per kg of fuel than similar engine types operating on distillate fuel under typical marine engine operating loads. Lastly, LNG was found to emit a negligible amount of BC, demonstrating the fuel's BC reduction potential.

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[5] The Clean Cam Technology System combines turbo-charging the original naturally-aspirated engine with in-cylinder changes to effect internal EGR, with the goal of reducing PM and NOx emissions. The Rypos active- regeneration diesel DPF traps and incinerates PM in the exhaust system.

[6] Document number PPR 4/9

Finnish researchers found that a 0.5% S residual fuel blend emitted less BC than HFO at 75% load but more than HFO at 25% load, perhaps due to higher metallic compounds in HFO that facilitate more complete combustion at lower loads compared to the 0.5% S fuel (Aakko-Saksa, 2016). However, distillate fuel emitted less BC than HFO and a 0.5% S residual fuel blend at both engine loads. The evidence to-date suggests, therefore, that switching from HFO to distillate fuel will reduce BC emissions.

Engine type: Results from the 35 EUROMOT tests showed that 4-stroke engines emitted more BC than 2-stroke engines operating on similar fuels. Specifically, 4-stroke engines emitted two to ten times more BC per kg of fuel than 2-stroke engines when operating on the same kind of fuel under typical marine engine operating loads (25-75% engine load).

Engine load: Results from UCR, EUROMOT, Finland, and Japan show a clear trend of decreasing BC EFs with increasing engine loads.

Engine tier: UCR observed extremely low BC EFs from the Tier II engine onboard the ship they tested. Similarly, EUROMOT's testing of newly manufactured Tier II and Tier III engines[7] with very low operating hours (most less than 100 hours), using the FSN method generated emission factors lower than those typically found in the literature. These EFs may be biased low due to several factors, including the maintenance status of the engine, steady state testing approach, choice of instrument and sampling duration. Nevertheless, these results are consistent with the hypothesis that newer, electronically controlled engines with improved combustion control may emit less BC than older engines.

Exhaust gas cleaning systems: There has been limited testing on how scrubbers might affect BC emissions, despite their main objective of reducing SO_x emissions. UCR measured BC EFs before and after a scrubber on a Tier 0 engine installed on a container ship while operating at sea. They found a ~30% reduction in BC emissions across the scrubber. This suggests that EGCS that are designed to reduce sulfur emissions may have some BC reduction co-benefits. This topic deserves more study.

2.3 Policy Context

Black carbon emissions from ships are not directly controlled by any IMO regulation today. However, both the Arctic Council (AC) and the IMO are actively considering the impacts of BC on the Arctic.

2.3.1 The Arctic Council

The AC is an intergovernmental forum for Arctic governments and peoples. On the issue of BC, the AC established an Expert Group on Black Carbon and Methane in 2015. The group

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[7] See Table 3 for a description of how engine tiers are designated.

periodically assesses progress on the AC Framework for Enhanced Black Carbon and Methane Emissions Reductions (Arctic Council, 2015). This framework requires AC member states to conduct and submit biennial national reports that summarize BC and methane emissions from all sources. The reports highlight emission reduction actions, best practices, and lessons learned. In addition to these reports, AC governments signed the Fairbanks Declaration[8] in May 2017 which commits AC member states to reducing their BC emissions. However, the AC does not have the authority to establish binding BC reduction requirements for member states.

2.3.2 IMO

The IMO is the specialized United Nations Agency responsible for regulating ship safety and environmental issues. The IMO's Marine Environment Protection Committee (MEPC) has tasked its Sub-Committee on Pollution Prevention and Response (PPR) to determine how to define, measure, and control marine BC emissions. A definition of BC suitable for research purposes that was developed by Bond et al. (2013) was adopted by PPR 2. A marine BC measurement reporting protocol for voluntary marine BC emissions testing campaigns developed by the European Association of Internal Combustion Engine Manufacturers (EUROMOT) in 2015 (Utrecht, 2015) was subsequently endorsed by PPR 3. Recommendations for appropriate marine BC measurement methods and promising control technologies (Vancouver, 2016) were submitted by IMO delegations to PPR 4. When PPR completes its BC workplan by recommending appropriate measurement approach(es) and control strategies, MEPC may take up the issue of appropriate international marine BC control policies.

The IMO recently agreed to implement a 0.5% sulfur (S) cap for marine fuels starting in 2020. While reducing the allowable S content of marine fuels will reduce total PM emissions, saving up to 200,000 premature deaths over five years, according to a study submitted to the IMO's 70th session of MEPC[9], the policy's impacts on BC emissions are less clear. If ships switch to distillate fuel, BC emissions should decrease, as recent research suggests that switching from residual fuel to distillate results in lower BC emissions (UCR, 2016). However, if ships comply by using desulfurized residual fuel or residual fuel blends, BC emissions will remain the same, or even increase (Aakko-Saksa, 2016; UCR, 2016).

2.3.3 National Governments

National governments in the U.S., Canada, and China have set PM standards for smaller marine engines that likely control BC emissions indirectly. The United States Environmental Protection Agency (U.S. EPA) has Tier 2 standards for marine diesel engines with PM limits between 0.2

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[8] The Fairbanks Declaration can be found on the Arctic Council website: https://oaarchive.arctic-council.org/handle/11374/1910

[9] The report is not public, but The Guardian ran a story outlining the report's findings: https://www.theguardian.com/environment/2016/oct/07/delay-to-curbs-on-toxic-shipping-emissions-would-cause-200000-extra-premature-deaths

g/kW-hr and 0.4 g/kW-hr for Category 1 engines[10] and between 0.27 g/kWh and 0.5 g/kWh for Category 2 engines. [11] The European Commission has stage III A standards under Directive 97/68/EC as amended, which set limits on PM between 0.2 g/kWh and 0.5 g/kWh, and starting from stage III B it caps the PM emissions at 0.025 g/kWh, on inland waterway vessels.[12] China has just released its first marine engine standards for C1 and C2 engines. In Phase I (from 7/1/2018), PM emission limits are between 0.2 g/kWh and 0.5 g/kWh, tightening to between 0.12 g/kWh and 0.5 g/kWh in Phase II (from 7/1/2021). [13]

Additionally, the U.S. and Canada, in a March 2016 joint statement from President Obama and Prime Minister Trudeau,[14] resolved to work with other Arctic partners to determine "how best to address the risks posed by heavy fuel oil use and black carbon emissions from Arctic shipping." Further, in December 2016, the U.S. and Canada announced plans to "phase down" the use of HFO in their portions of the Arctic.[15]

3 METHODOLOGY

This report presents a global inventory of BC emissions from ships for the year 2015 using exactEarth satellite Automatic Identification System (AIS) data along with ship characteristic data from IHS Fairplay. The inventory covers ships operating at sea and on major lakes and rivers across the globe. The inventory is geospatially aggregated at a 1° x 1° resolution. Global emissions of other air and climate pollutants from ships are also estimated for the year 2015. These emissions include PM, SO_x, NO_x,, methane (CH_4), nitrous oxide (N_2O), and CO_2. Fuel consumption by fuel type (residual, distillate, LNG, coal, methanol, and nuclear) is also calculated. Details of the methodology are found in this section.

3.1 Emissions Inventory

This section describes how an emissions inventory was developed for ships operating in 2015.

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[10] Category 1, or C1 engines, refer to marine diesel engines with greater than 37kW rated power and less than 5 liters of displacement per cylinder. Catetory2, or C2 engines, refer to marine diesel engines with greater than 37kW rated power and between 5 and 20 liters of displacement per cylinder.

[11] U.S. Environmental Protection Agency. (2004). Overview of EPA's emission standards for marine engines. Retrieved from: https://nepis.epa.gov/Exe/ZyPDF.cgi/P1002K40.PDF?Dockey=P1002K40.PDF

[12] Directive 97/68/EC of the European Parliament and of the Council of 16 December 1997 on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery, 1997 O.J. L27/02/1998 P. 0001–0086. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1997L0068:20130110:EN:PDF

[13] International Council on Clean Transportation. (2016). Marine Engine Emission Standards For China's Domestic Vessels. http://www.theicct.org/marine-engine-emission-standards-chinas-domestic-vessels.

[14] See the U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership at https://obamawhitehouse.archives.gov/the-press-office/2016/03/10/us-canada-joint-statement-climate-energy-and-arctic-leadership.

[15]See the United States-Canada Joint Arctic Leader's statement at https://obamawhitehouse.archives.gov/the-press-office/2016/12/20/united-states-canada-joint-arctic-leaders-statement

3.1.1 Datasets

Two main datasets were utilized in this study: (1) fused terrestrial and satellite Automatic Identification System (AIS) data from exactEarth that provides information about ship location and speed and (2) IHS ship registry data (IHS ShipData) that includes information on ship specific design characteristics such as engine type, fuel type, maximum ship speed, and main engine power. Both datasets include the ship's unique identification number (IMO number) and the unique identification number of its AIS transponder (MMSI number). The AIS ship activity data can be matched with the IHS ship characteristics data by either its IMO number or MMSI number. This merged dataset is used to estimate ship activity, emissions, and fuel consumption for ships in 2015.

3.1.2 AIS data

Hourly-aggregated AIS data were obtained from exactEarth for all ships with a registered AIS transponder for calendar year 2015. There were over 530 million AIS data points in the raw data set, representing roughly 373,600 unique vessels, covering ship movements in the open sea as well as lakes and inland waterways. Information associated with each AIS point include the following:

- MMSI number: a unique identification number associated with each AIS transmitting device;
- IMO number: a unique identification number associated with each registered vessel;
- TIME: the timestamp associated with each AIS point, formatted as Year-Month-Date-Hour;
- LAT: latitude associated with each AIS point, in decimal degrees;
- LON: longitude associated with each AIS point, in decimal degrees;
- COG: course-over-ground associated with each AIS point;
- SOG: speed-over-ground associated with each AIS point, in knots;
- HEADING: actual heading associated with each AIS point:
- NAV_STATUS: navigational status associated with each AIS point, a 1-15 code set by the crew;
- Draught: instantaneous draught associated with each AIS point, in decimeters.

3.1.2.1 Removing invalid data

Data points without a valid IMO number or MMSI number were excluded from the dataset. Roughly 220 million of the 530 million records, or 41%, were excluded as a result of invalid IMO or MMSI numbers. Records with latitudes outside the normal range of -90 to 90 degrees, longitudes outside the normal range of -180 to 180, and ships with a SOG greater than 1.5 times the rated speed of the ship were also excluded. However, only the invalid field (latitude, longitude, or sog) is excluded from the record, with the remaining valid fields are kept in the record. These missing fields are then interpolated. Within the 310 million matched records, 0.5% had an invalid latitude, 3% had an invalid longitude, and 0.3% had an invalid SOG.

3.1.2.2 Interpolating missing AIS data points

Although AIS signals may be transmitted by ships every six seconds, the AIS dataset used in this report has been aggregated to hourly averages to reduce the total size of the dataset. Some gaps in transmitted AIS data exist, either because the ship turned off the AIS transmitter or the signals were not successfully picked up by a satellite. In the case of these gaps, the missing hours, ship position, and speed over ground were linearly interpolated for most ship classes. For example, if a ship was traveling from point A at "timestamp 1" to point C at "timestamp 3," but the position and speed over ground were unknown for "timestamp 2," the interpolated point B would situate at the center of segment AC (see Figure 1). The interpolated SOG would equal to distance between point A and C divided by time elapsed in between. Linearly interpolated data points represent 48% of total hours in the inventory.

For ferries, tugs, and fishing vessels, the SOG was not linearly interpolated, but taken as a random sample of all valid SOGs for each individual ship. These ship classes were treated differently for several reasons. Ferries and tugs tend to operate within small geographic regions, so although they may appear to travel very little distance (resulting in an interpolated SOG of close to 0), they may actually have travelled at higher speeds. Similarly, fishing vessels often travel in a circular path as they fish. In this case, the start and end latitude and longitude may be very similar, implying close to 0 SOG, even though these ships did travel at speeds greater than 0. For these reasons, a simple linear interpolation for these ship classes was not appropriate. Therefore, missing SOGs for these ship classes are taken as a random sample of all valid SOGs for each individual ship.

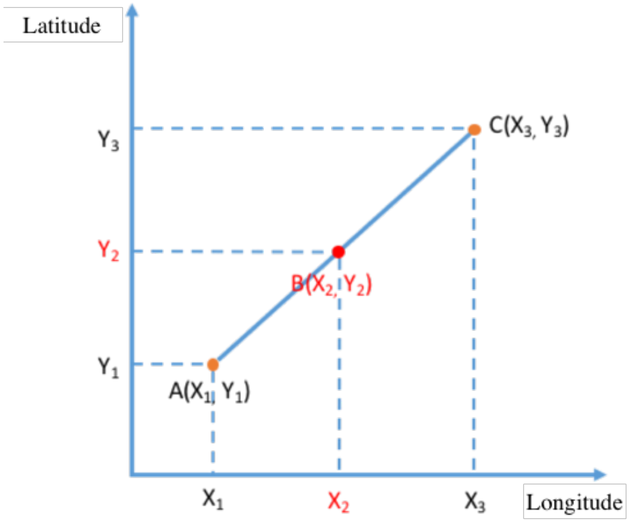

Figure 1. Illustration of linear interpolation procedure where the speed over ground at point B is interpolated.

3.1.3 IHS data processing

The IHS ShipData database contains ship characteristics for 180,530 ships at the time of purchase and is continuously expanding with newly-built ships. The IMO number is 100% populated for the IHS ShipData. The ships included in the ShipData range from small fishing vessels up to the largest cargo ships in the world. Ships that engage in international as well as domestic activities are included in the database. However, many small domestic ships are not included. For example, there are over 165,000 ships flagged to mainland China in 2015, whereas the IHS ShipData database reports less than 6,000. The IHS ShipData contain a variety of fields that are useful for estimating fuel consumption and emissions from ships. Data pulled directly from or derived from the IHS ShipData for analysis are described in the subsections that follow. In some cases, missing data needed to be filled in, per the methods described below.

3.1.3.1 **Ship class and capacity bin**

The IHS ShipData classifies each vessel as one of 256 unique "ship types" via the StatCode5 field. From the StatCode5 field, each ship was re-categorized into one of the twenty-two "ship classes" according to the process used in the Third IMO GHG Study 2014 (IMO, 2015). Each ship is also assigned a "capacity bin" according to its cargo or passenger capacity. The capacity bin categories are the same as those used in the Third IMO GHG Study 2014. The combined ship class and capacity bin categorizations resulted in a total of 55 unique ship groups. Complete tables describing which ship types and capacities fall into different ship classes and capacity bins are presented in Appendix A and Appendix B. The main purpose of reclassifying each ship from its "ship type" to its "ship class" is to estimate each ship's auxiliary engine and boiler power demand under different operating modes (cruise, maneuvering, and at anchor/berth).

3.1.3.2 Tier level

Because newer marine engines are subject to more stringent NO_x emissions standards, a ship's year of construction influences its NO_x emissions. MARPOL Annex VI Regulation 13 defines tiered NO_X emissions standards based on a vessel's year of construction, as defined in the leftmost two columns of Table 1. The percentage of the fleet by IMO NO_x Tier is also shown in Table 1.

Table 3. IMO NO_x tier for ships in the global fleet

		IHS Global Fleet	
Tier	**Year of construction**	**Vessel Count**	**Share of Fleet**
Tier 0	Pre-2000	69,360	54%
Tier I	2000-2010	38,084	30%
Tier II	2011-2015	18,082	14%
Tier III	2016 or later	2,741	2%
Total	**All**	**128,267**	**100%**

3.1.3.3 Main fuel type

The IHS ShipData database includes fields that indicate the types of fuel each ship uses. The fuel type for ships that operate on oil-based marine fuels (as opposed to LNG, gas boil off, or nuclear) is categorized as "residual fuel" or "distillate fuel." There are two fuel type fields in the IHS database: FuelType1First and FuelType2Second. FuelType1First records the "lightest" fuel onboard (distillate is considered a lighter fuel than residual, for example); FuelType2Second records the "heaviest" fuel onboard. A main fuel type (i.e., the type of fuel - residual or distillate - on which the ship primarily operates) was assigned to each vessel based on the fuels specified in FuelType1First and FuelType2Second. If either fuel type is listed as residual fuel, residual fuel is recorded as its main fuel type. Since HFO is the most common residual fuel used in marine ships and is less expensive than distillate fuels, it is assumed that ships operating on "residual fuel" were operating on HFO in 2015. Ships could potentially bunker with an intermediate fuel oil (IFO) that contains some small fraction of distillate fuel, but such a fuel is more expensive than HFO and is predominately composed of HFO. If the ship only carries "distillate" onboard, the ship is assumed to operate on distillate fuel. Ships that do not operate on oil-based fuels are either classified as using LNG or nuclear. If a ship's FuelType1First or FuelType2Second is indicated to be "LNG" or "gas boil-off", the main fuel type is assumed to be LNG. If a ship's FuelType1First or FuelType2Second is recorded as "Nuclear", the ship is assumed to operate on nuclear power.

Fifty-nine percent (59%) of ships in the IHS ShipData database lacked a fuel type designation, with fuel type more available for larger ships than smaller vessels. In these cases, ships with a main engine RPM of <600 RPM are assigned to residual fuel, while ships with a main engine RPM of ≥ 600 RPM are assigned to distillate. If the main engine RPM is missing, the average main engine RPM for that ship by ship type and capacity bin is used. If there is no valid average main engine RPM by ship type and capacity bin, then the average RPM by ship class and capacity bin is used instead.

3.1.3.4 Fuel capacity

The IHS ShipData database includes fields for the capacity of FuelType1First and

FuelType2Second, called FuelType1Capacity and FuelType2Capacity. A main fuel type capacity, representing the fuel capacity for the main propulsion fuel, was assigned to each vessel, recording the fuel capacity of the larger of the two fuel type capacities, assuming that the larger fuel tank is carrying the main fuel type. Both fuel capacity fields were empty for 42% of vessels operating on residual fuel and 74% of vessels operating on distillate. In such cases, missing fuel capacity data were filled via a regression analysis of existing main fuel type capacity data and either deadweight tonnage (dwt) or gross tonnage (gt) of similar ships, as follows:

- A linear regression analysis between main fuel type capacity and both deadweight tonnage (dwt) and gross tonnage (gt) resulted in two sets of linear equations (main fuel type capacity vs. dwt and main fuel type capacity vs. gt) for each ship class. A separate linear regression was completed for LNG-fueled ships, regardless of class.
- The R^2 values ranged from 0.22 and 0.96, with the best correlation between fuel capacity and either dwt or gt observed for oil tankers (0.96), bulk carriers (0.91), liquid tankers (0.90), and container ships (0.90).
- For some ship classes, fuel capacity correlated better with dwt; in others, fuel capacity correlated better with gt.
- For each ship class, the linear regression equation with a higher R^2 value was chosen to estimate the missing main fuel type capacity.

R^2, Beta, and intercept values for each ship class are provided in Appendix C.

3.1.3.5 Speed, power, and rpm

IHS ShipData includes fields for each ship's maximum vessel speed, main engine (ME) power, and ME RPM. Where missing, these data were backfilled by considering the characteristics of similar ships. For each ship class, average maximum vessel speed, ME power, and ME RPM were calculated within each ship capacity bin. Vessels with missing data were assigned the mean value for their ship class and capacity bin. 27% of the global fleet had missing average maximum vessel speed, 6% of the fleet had missing ME power values, and 24% had missing ME RPM values.

3.1.3.6 Engine Type

This report applies emission factors from the Third IMO GHG Study 2014, which specifies emission factors by engine type. To match the AIS and IHS data to these emissions factors, each vessel is classified into one of seven engine types: steam turbines (ST), gas turbines (GT), slow speed diesel (SSD), medium speed diesel (MSD), high speed diesel (HSD), LNG-fueled Diesel-cycle engines (LNG-Diesel), and LNG-fueled Otto-cycle engines (LNG-Otto). Each ship was classified to an engine type as follows:

1. Any ship with an ST propulsion system was classified as ST
2. Any ship with a GT propulsion system was classified as GT
3. Remaining ships with a main fuel type of LNG have engine types assigned either LNG-Diesel or LNG-Otto based on the following:

    a. LNG ships with ME model numbers ending in either “GI”, “GIE” or “LGIM” or with Propulsion Type as “Oil Engine(s), Direct Drive” were classified as LNG-Diesel
    b. All other LNG-fueled ships were classified as LNG-Otto
4. Remaining ships are assumed to be motor propelled ships. For ships with valid main engine RPMs, the following rules are applied:
    a. < 300 RPM were classified as SSD
    b. ≥ 300 RPM and < 900 RPM were classified as MSD
    c. ≥ 900 RPM were classified as HSD
5. Ships without a valid main engine RPM that have 2-stroke engines were classified as SSD
6. Remaining ships were assigned an ME RPM based on the average ME RPM for the ship’s class and capacity bin. These ships then have an engine type assigned based on the procedures in (4).

Table 4 describes the total count of vessels and percent of the global fleet (in-service vessels as of mid-2016) within each engine type class.

Table 4. Vessels by engine type in the global fleet for in-service vessels as of mid-2016.

Engine type[a]	**IHS Global Fleet**	
	Vessel Count	**Share of Fleet**
SSD	33,047	26%
MSD	37,964	30%
HSD	56,153	44%
ST	543	0.4%
GT	109	0.08%
LNG-Otto	318	0.2%
LNG-Diesel	133	0.1%
Total	**128,267**	**100%**

[a] SSD = slow-speed diesel (<300 rpm); MSD = medium-speed diesel (300-900 rpm); HSD = high-speed diesel (>900 rpm); ST = steam turbine; GT = gas turbine; LNG-Otto = dual fuel engine operating on the Otto cycle; LNG-Diesel = dual fuel engine operating on the Diesel cycle.

3.2 Estimating 2015 Fuel Consumption

Fuel consumption was estimated on a ship-by-ship basis based on the amount of CO_2 that ship emitted and its main fuel type. Marine fuels emit varying amounts of CO_2 when burned; this is called the “CO_2 intensity of the fuel” and is reported in units of g CO_2/g fuel (Table 5).

Table 5. Carbon dioxide intensity by fuel type.

Fuel type	CO_2 intensity of fuel (g CO_2/g fuel)
Residual	3.114
Distillate	3.206
LNG	2.75
Gas Boil Off	2.75

Fuel consumption from ships operating in 2015 is calculated as follows:

$$FC_{i,2015} = \frac{CO_{2_{i,2015}}}{CI_f}$$

where

i = ship
f = main fuel type of ship i
$FC_{i,2015}$ = fuel consumption (g) for ship i in 2015
$CO_{2i,2015}$ = total CO_2 emissions (g) for ship i in 2015
CI_f = CO_2 intensity for fuel f in g CO_2/g fuel

3.3 Estimating 2015 Vessel Emissions

As explained earlier, SOG data for each ship for every hour of the year were provided by exactEarth or interpolated by the authors. Combining that information with ship characteristics data from IHS, emissions for each ship can be calculated for every hour of the year. Emissions are influenced by a ship's operating phase, power demand, and emission factors for each pollutant.

3.3.1 Phase

While in service, a ship is operating in one of four "phases": at berth, at anchor, maneuvering, or cruising. A ship's operating phase is used to estimate AE and BO power demand, crucial information for estimating emissions from those engines. A ship's phase is determined by its proximity to land or port and its SOG. Table 6 and Table 7 present the way these two features define the ship's phase. The tables are split between ships that are not liquid tankers and ships that are liquid tankers. Liquid tankers represent a special case as they can be considered to be "at berth" within 5 nautical miles from a port due to the common practice of lightering these vessels offshore.

Table 6. Phase assignment decision matrix for all ship classes except liquid tankers

		Distance from port/coast				
		<=1 nm from port	<= 1 nm from coast	1-5 nm from coast	>=5nm from coast	In a river
Speed over ground	< 1 knots	Berth	Anchor	Anchor	Anchor	Berth
	1- 3 knots	Anchor	Anchor	Anchor	Anchor	Man
	3-5 knots	Man*	Man	Man	Cruising	Man
	> 5 knots	Man	Cruising	Cruising	Cruising	Cruising
*"Man" is short for "maneuvering"						

Table 7. Phase assignment decision matrix for liquid tankers.

		Distance from port/coast					
		<=1 nm from port	<=1 nm from coast	1-5 nm from port	1-5 nm from coast	>=5nm from coast	In a river
Speed over ground	< 1 knots	Berth	Anchor	Berth	Anchor	Anchor	Berth
	1-3 knots	Anchor	Anchor	Anchor	Anchor	Anchor	Man
	3-5 knots	Man*	Man	Man	Man	Cruising	Man
	> 5 knots	Man	Cruising	Cruising	Cruising	Cruising	Cruising
*"Man" is short for "maneuvering"							

Ships typically have three types of engines: main engines (mainly for propulsion purposes), auxiliary engines (normally for electricity generation), and boilers (for steam generation). The power demanded from these machineries varies depending on the phase in which the ship is operating (Table 8). Main engines are turned off at berth and at anchor. Auxiliary engines are usually always on and boilers are normally turned on for low load maneuvering, berthing and anchoring. While some ports offer shore-side electrical power to allow ships to switch off their auxiliary engines at berth, this analysis assumes auxiliary engines are always on at berth.

Table 8. Assumed vessel engine state by phase.

Phase	Main Engine State	Auxiliary Engine State	Boiler State*
Berth	Off	On	On
Anchor	Off	On	On
Maneuvering	On	On	On
Cruising	On	On	Off

*Boiler states are not assumed to be the same for all ship classes. See Appendix E for more details

3.3.2 Power Demand

The power demand of auxiliary engines and boilers for each ship class and capacity bin is determined by the phase. A full table listing the auxiliary and boiler power demands as referenced from the Third IMO GHG Study 2014 can be found in Appendix E.

The main engine power demand varies as the ship speed over ground changes:

$$D_{ME_t} = P_{ME} * \left(\frac{SOG_t}{V_{max}}\right)^3$$

where

D_{MEt} = Main engine power demand at time t
P_{ME} = Main engine power at 100% maximum continuous rating (MCR)
SOG_t = vessel speed over ground at time t
V_{max} = maximum ship speed

There are some instances where the ship's speed over ground is larger than its maximum designed speed. In these instances, SOG is replaced with the ship's average SOG for that phase and the load factor is recalculated. When there is no valid average SOG value for the phase for a particular ship, the average SOG for ships of the same ship type, capacity bin, and phase is used. The load factor is then recalculated with the replaced SOG.

3.3.3 Emissions factors

3.3.3.1 Black carbon

This analysis uses ME BC EFs for SSD, MSD, and HSD engines estimated based on the latest marine BC testing data and BC EFs from the literature, as introduced in this section and described in detail in Appendix G.
A range of ME BC EFs for SSD, MSD, and HSD engines were developed for this study, representing a lower bound, a best estimate, and an upper bound for reasonable BC EFs, based on marine BC measurement data from UCR, EUROMOT, Finland, and the literature. The evidence to date suggests that marine BC EFs are primarily a function of engine type (2-stroke or 4-stroke), fuel type (residual or distillate), and engine load (%). Figure 2 and Figure 3 show the relationship between BC EF (g BC/kg fuel) and engine load (%) for 2-stroke engines operating on residual fuel (2R), 2-stroke engines operating on distillate fuel (2D), 4-stroke engines operating on residual fuel (4R), and 4-stroke engines operating on distillate fuel (4D), respectively. A range of BC EFs are used in this analysis to account for uncertainty. Note that BC EFs are higher for 4-stroke engines compared with 2-stroke engines across all ME loads. Additionally, residual fuels emit more BC than distillate across ME load factors. Distillate BC EFs are 40-50% lower than residual for 4-stroke engines and approximately 80% lower than

residual for 2-stroke engines at typical engine loads (25% to 75%). Appendix G provides a detailed description of how these ME BC EFs were developed.

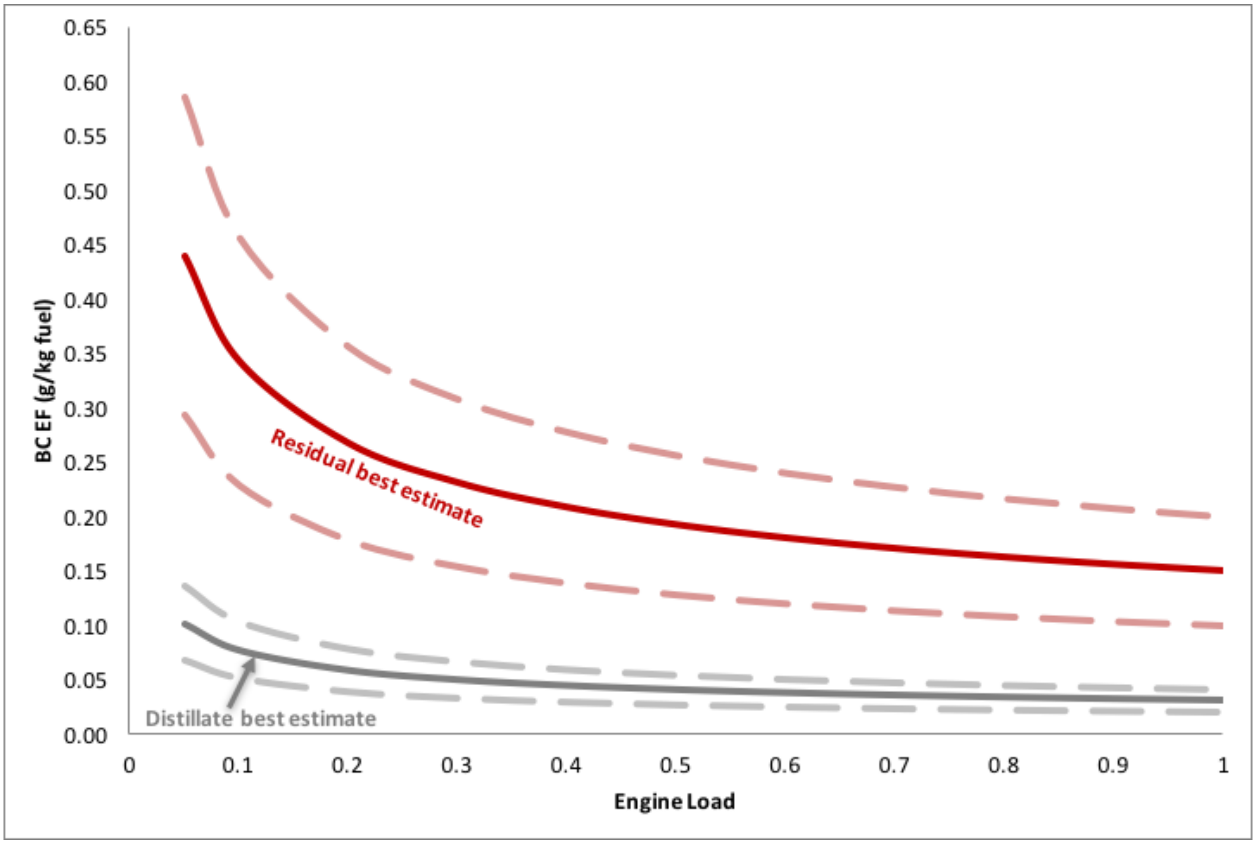

Figure 2. Black carbon emission factors for 2-stroke engines by fuel type.

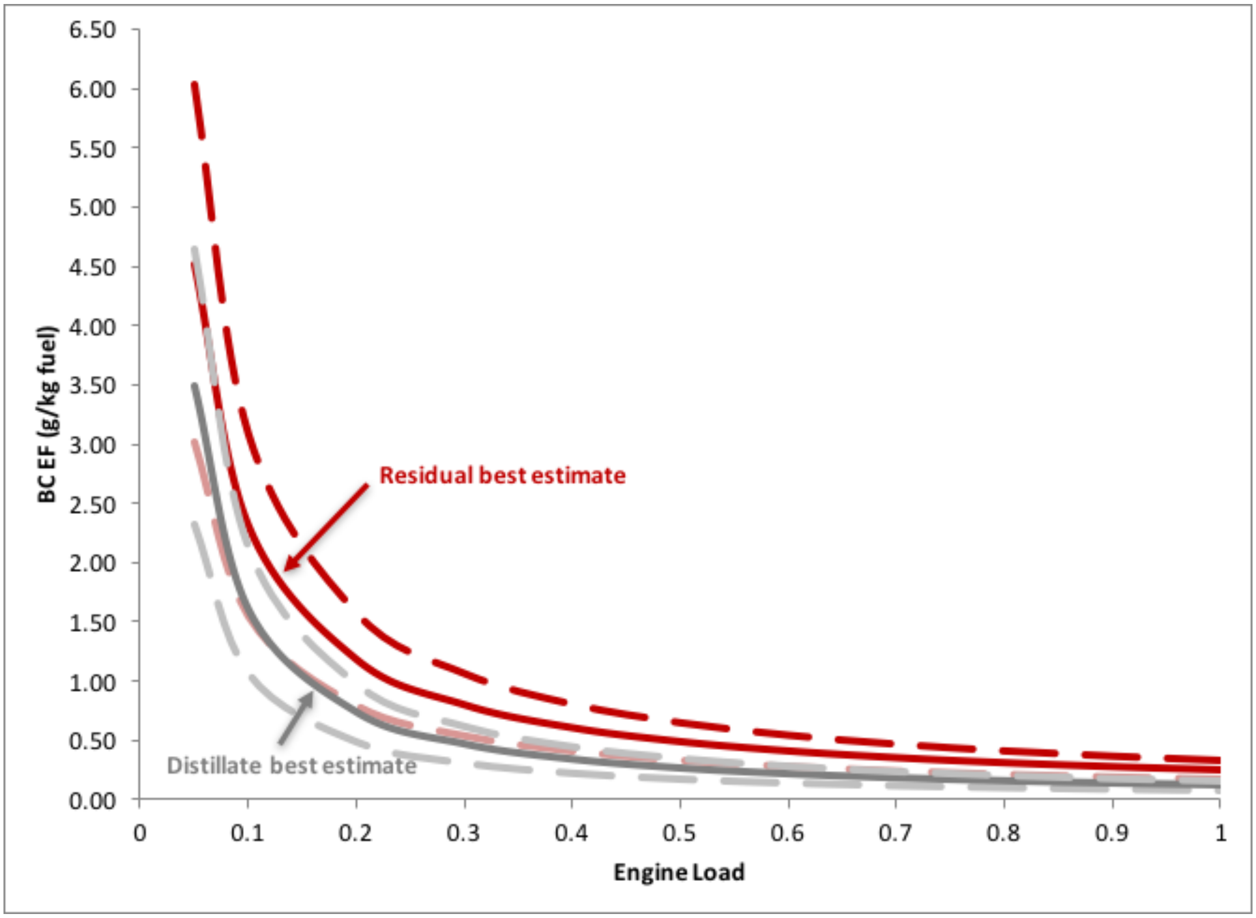

Figure 3. Black carbon emission factors for 4-stroke engines by fuel type.

Black carbon EFs for other engine types were estimated due to a lack of experimental data. Based on the PM and BC EFs for MSD and HSD engines in the Netherlands Organization for Applied Scientific Research (TNO) POSEIDON model,[16] BC accounts for approximately 8.4% of PM emissions by mass. Thus, BC emissions from GT, ST, LNG-Otto cycle, and LNG-Diesel cycle engines are estimated as about 8.4% of these engines' corresponding PM EFs. The actual BC-to-PM ratio may be different, but BC emissions from these engine sources are expected to be relatively small compared to BC from SSD, MSD, and HSD engines, as LNG emits very low PM emissions (and thus low BC emissions) and LNG-Otto, LNG-Diesel, GT and ST engines combined represent less than one percent of the engines on ships in the global fleet.

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[16] These emission factors were presented by Dr. Jan Hulskotte at the ICCT's 3rd Workshop on Marine Black Carbon Emissions held in Vancouver, British Columbia, Canada in September 2016. Dr. Hulskotte's presentation can be found on the ICCT website at the following link: http://www.theicct.org/events/3rd-workshop-marine-black-carbon-emissions

3.3.3.2 Other emission factors

This analysis uses main engine emissions factors for all other air emissions from the Third IMO GHG Study 2014, with a few exceptions (Appendix F). For instance, the Third IMO GHG Study 2014 assumed that all ship engines powered by LNG were Otto cycle. Today, there are several Diesel-cycle engines powered by LNG, which have different emissions factors than those with Otto cycle. Diesel-cycle engines powered by LNG are assumed to be approximately 20% more efficient than those with Otto-cycle and to have higher NO_x emissions due to higher combustion temperatures; however Diesel-cycle engines powered by LNG are assumed to have much less CH_4 slip than Otto-cycle ones, owing to more complete LNG combustion with the Diesel cycle. The Third IMO GHG Study 2014 did not estimate BC emissions.

Auxiliary engine emissions factors used in this study are presented in Appendix G and boiler emissions factors are presented in Appendix H. The Third IMO Greenhouse Gas Study assumes identical emissions factors for auxiliary engines and auxiliary boilers (auxiliary machinery). However, boilers are typically steam turbines. As such, this study uses the same auxiliary emissions factors as the Third IMO GHG Study 2014, but boiler emissions factors are set to equal to steam turbine emission factors according to the US EPA (2009) *Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories*. In cases where the propulsion type is found to be steam or gas turbines, neither auxiliary engines nor auxiliary boilers are assumed to be onboard the ships, as steam and gas turbines also provide auxiliary power and heat. Regarding black carbon emissions factors, auxiliary engines are assumed to perform the same as medium-speed diesel engines, and boilers are assumed to perform the same as steam turbines.

Emissions factors tend to increase at low loads. Low load adjustment factors from the Third IMO GHG Study 2014 were applied when estimated main engine load fell below 20% for all pollutants except BC, which is not estimated in the IMO study. In this case, BC EFs are determined from power curves described in the previous section, which already account for changes in BC EFs as a function of engine load. Low load adjustment factors are presented in Appendix I.

3.3.3.3 Estimating emissions of all pollutants except black carbon

Emissions from ships come from MEs, AEs, and BOs. Emissions for all air pollutants *except* BC are estimated according to the following equation:

$$E_{i,j} = \sum_{t=0}^{t=n}\left(\left(P_{ME_i} * \left(\frac{SOG_{i,t}}{V_{max_i}}\right)^3 * EF_{ME_{j,k,l,m}} + D_{AE_{p,i}} * EF_{AE_{j,k,l,m}} + D_{BO_{p,i}} * EF_{BO_{j,m}}\right) * 1 \text{ hour}\right)$$

where:

i = ship
j = pollutant
t = time (operating hour, h)
k = engine type
l = engine tier
m = fuel type
p = phase
$E_{i,j}$ = emissions (g) for ship i and pollutant j
P_{ME_i} = main engine power (kW) for ship i

$SOG_{i,t}$ = speed over ground (knots) for ship i at time t

V_{max_i}= maximum speed (knots) for ship i

$EF_{ME_{j,k,l,m}}$ = main engine emission facor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m
$D_{AE_{p,i}}$ = auxiliary engine power demand (kW) in phase p for ship i
$EF_{AE_{j,k,l,m}}$ = auxiliary engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m
$D_{BO_{p,i}}$ = boiler power demand (kW) in phase p for ship i

$EF_{BO_{j,m}}$ = boiler emission factor (g/kWh) for pollutant j and fuel type m

3.3.3.4 Estimating emissions of black carbon

BC emissions were estimated as a function of main engine type, main fuel type, and main engine load according to the following equation:

$$BC_i = \sum_{t=0}^{t=n}((FC_{i,ME} * EF_{ME_{k,m,n}} + D_{AE_{p,i}} * EF_{AE_{k,m}} + D_{BO_{p,i}} * EF_{BO_m}) * 1 \text{ hour})$$

Where:

i = ship
t = time (operating hour, h)
k = engine type
m = main fuel type
n = main engine load factor
p = phase
BC_i = black carbon emissions (g) for ship i
$FC_{i,ME}$ = main engine fuel consumption (kg) for ship i, equivalent to the quotient of main engine

CO_2 emissions and the CO_2 intensity for the ship's main fuel type m, as found in Table 5
$EF_{ME_{k,m,n}}$ = main engine black carbon emission factor (g/kg fuel), which is a function of engine type k, fuel type m, and main engine load factor n
$D_{AE_{p,i}}$ = auxiliary engine power demand (kW) in phase p for ship i
$EF_{AE_{k,,m}}$ = auxiliary engine black carbon emission factor (g/kWh) for engine type k and main fuel type m
$D_{BO_{p,i}}$ = boiler power demand (kW) in phase p for ship i
EF_{BO_m} = boiler black carbon emission factor (g/kWh) for main fuel type m

Emissions of all pollutants were calculated on a ship-by-ship basis and aggregated to the ship class level, as reported in the Results section. A more detailed description of some of the key variables or their modifiers in the above equation is presented next.

3.4 Estimating Black Carbon Reduction Potential

Several technological and operational means of reducing BC from ships are available. This study estimates the BC reduction potential under four scenarios: (1) all ships switch from residual fuel to distillate; (2) some ships switch to LNG from residual or distillate fuel; (3) some ships install exhaust gas cleaning systems (scrubbers); and (4) some ships install DPFs. This section describes how BC reduction potential was estimated under these scenarios.

3.4.1 Scenario 1 – All ships switch from residual to distillate fuels

The BC emission reduction potential of switching over all ships that operate on residual fuel to distillate was estimated on a ship by ship basis per the methodology. In this exercise, all ships that had been operating on residual fuel were assumed to operate instead on distillate, with the lower BC EF for distillate fuel applied to all ships.

3.4.2 Scenario 2 – Some ships switch from residual or distillate fuel to LNG

Scenario 2 analyzes the impact of switching a certain percentage of petroleum based fuels (residual fuel or distillate) to LNG. It compares the potential reduction in BC emissions for a 2015 equivalent fuel demand based on energy content of the fuel types. The energy content (EC) of the three fuel types are provided in Table 9.

Table 9: Energy content of major fuel types

Fuel Type	Energy Content
Residual	40 MJ/kg
Distillate	40 MJ/kg
LNG	50 MJ/kg

The BC reduction potential of switching some ships to LNG in 2015 was estimated as follows:

$$\Delta BC = \left(\frac{BC_{R_{2015}}}{FC_{R_{2015}}} \times \Delta FC_R\right) + \left(\frac{BC_{D_{2015}}}{FC_{D_{2015}}} \times \Delta FC_D\right) - \left(\frac{BC_{LNG_{2015}}}{FC_{LNG_{2015}}} \times (\Delta FC_R + \Delta FC_D) \times \frac{EC_{LNG}}{EC_{PF}}\right)$$

where

ΔBC = change in BC emissions
$BC_{R_{2015}}$= BC emissions (g) from residual fuel consumption in 2015
$FC_{R_{2015}}$= Residual fuel consumption (kg) in 2015
ΔFC_R = change in residual fuel consumption (kg) in 2015
$BC_{D_{2015}}$= BC emissions (g) from distillate fuel consumption in 2015
$FC_{D_{2015}}$= distillate fuel consumption (kg) in 2015
ΔFC_D = change in distillate fuel consumption (kg) in 2015
$BC_{LNG_{2015}}$= BC emissions (g) from LNG fuel consumption in 2015
$FC_{LNG_{2015}}$= LNG fuel consumption (kg) in 2015
EC_{LNG} = energy content (MJ/kg) of LNG fuel
EC_{PF} = energy content (MJ/kg) of petroleum fuel (residual or distillate fuel; in this case 40 MJ/kg)

3.4.3 Scenario 3 – Some ships install exhaust gas cleaning systems

The BC reduction potential of installing exhaust gas cleaning systems (scrubbers) on some ships was estimated as follows:

$$BC_x = BC_0\left(1 - \frac{0.3x}{100}\right)$$

where

x = percentage of residual fuel BC emissions treated with scrubbers
BC_x = residual BC emissions when x% of residual BC emissions are treated with scrubbers
BC_0 = residual BC emissions when 0% of residual BC emissions are treated with scrubbers

Application of exhaust gas cleaning systems like scrubbers reduces marine BC emission approximately 30% (UCR, 2016). The scenario estimates the total BC emissions at every 10% increase in residual fuel BC emissions begin treated with scrubbers, up to 100%.

3.4.4 Scenario 4 – Some ships install diesel particulate filters

The BC reduction potential of installing diesel particulate filters on some ships was estimated as follows:

$$BC_x = BC_0\left(1 - \frac{0.85x}{100}\right)$$

where

x = percentage of distillate BC emissions treated with DPFs
BC_x = distillate BC emissions when x% of distillate BC emissions are treated with DPFs
BC_0 = distillate BC emissions when 0% of distillate BC emissions are treated with DPFs

Application of DPF's is fuel specific, and it has very limited application for heavy fuel oils. The scenario 4 considers application of DPF's only for distillate fuel oils (which generally has less than 1 sulfur %), with an average 85% BC reduction potential. It analyses the distillate and total BC emissions at every 10% increase in distillate fuel oil emissions being treated with DPF's. However, the current scenario does not take into consideration various grades of distillate fuel, as DPF's might not be applicable to all of them.

3.5 Uncertainties

Factors that introduce uncertainty into the results are discussed in this section.

3.5.1 Emission Factors

The international marine industry is one of the least regulated transportation modes in terms of emissions. Consequently, quality data on EFs across all engines and fuel types currently in use is generally lacking. While CO_2 and GHG emission factors are fairly robust, BC EFs are less certain. Ship emissions can vary based on several factors, including engine load, engine age, rated power, fuel type, and time since last maintenance. Emissions factors used to calculate emissions from ships, including the EFs in this study, except for the BC EF which corrects for engine type and fuel type, typically do not take these nuances into account, leading to some uncertainty in emissions estimates.

3.5.2 Fuel Quality

The chemical and physical properties of marine fuels vary greatly in ways that can influence their pollutant emissions. The IHS ShipData does not indicate fuel quality beyond "residual fuel"; "distillate fuel"; "LNG"; etc. As a result, this report assumes that a single emission factor is representative of each fuel type. Given the importance of fuel quality on emissions, future work should try to relate emissions from various fuels to key fuel quality characteristics, including sulfur, aromatic, and asphaltene contents.

3.5.3 Missing Data

Although both the AIS and IHS data sets were predominantly complete, assumptions were made where needed to fill in missing data. Within the IHS ShipData database, ship specifications such as main fuel type, fuel capacity, rated speed, rated power, and main engine RPM had missing values that had to be estimated. The backfilling process, detailed in the methodology section, assumes ships within similar classes, types, and sizes, behave similarly and have similar specifications. Vessels were also classified based on information within the IHS ShipData database in order to match ships to the correct emissions factors. Emissions vary by ship specifications, so extrapolating and interpolating missing fields further introduces uncertainty in the emissions calculations. Future iterations of the IHS ShipData database should endeavor to fill missing data gaps to enable more confidence in marine emissions inventory results.

The AIS data for each individual ship were sometimes incomplete. In cases where activity was missing from the AIS data set for specific ships, the position and speed of the ship during missing hours were linearly interpolated using the start and end points of the gap in coverage. Although this is relatively accurate for very small gaps, linearly interpolating ship locations can result in inaccuracies when the ship is operating close to shore, within a river, or the time gap is large (>24 hours). Since the missing data are interpolated linearly, the ship is assumed to operate in a straight line from start to finish. However, this procedure does not consider navigational obstacles such as bends in rivers, coastal geography, or islands. Linear interpolation likely results in an underestimation of emissions, as it can result in shorter estimated distances, lower speeds, and lower power demand. Future work should strive to more accurately interpolate ship position and speed, which will improve confidence in ship emissions inventories and will better reflect the geospatial distribution of ship emissions, which could have an especially large impact when analyzing the impacts of regional policies to reduce ship emissions.

3.5.4 Phase Assignment

The amount of power demanded by a ship is determined by its SOG and its proximity to a port or the coast. This report assumes that ships operating at slow speeds (0-3 kts) and far from port, and not in a river, are at anchor, in which case their main engine is assumed to be turned off. However, ships may significantly reduce their speeds in the presence of environmental hazards such as sea ice, icebergs, poor visibility, or rough seas. If vessels are operating at low speeds due to environmental hazards but are not at anchor, their main engines may continue to run. For example, ice breakers moving slowly through ice may operate at low speeds, but require a large amount of power to move. Assuming vessels at slow speeds are at anchor may result in an underestimate of main engine emissions. Future work could include a sensitivity analysis to estimate the potential impacts on ship emissions inventories by altering the phase assignment classification scheme.

3.5.5 Shore power

When a vessel's phase is "at-berth," the vessel is assumed to switch off its main engine, but is assumed to leave its AE, boiler, or both on to provide auxiliary power. However, some ports provide onshore electrical power so that ships can switch off their AE and boiler to reduce fuel use and emissions close to coastal communities. That said, several ports only offer shore-side power to smaller vessels such as ferries, and shore-side power may not be used even when it is available. Future work could explore the characteristics of existing shore power facilities, including the number of electrified berths, power supply, electricity source, potential air emissions, and so forth to estimate the emissions impacts of using shore power. Additional work could also explore the emissions impacts of expanding the use of shore power.

3.5.6 Weather and Hull Condition

This report does not attempt to estimate the impact of weather or hull conditions (e.g., if the hull coating is damaged or fouled) on fuel consumption or emissions. The *Third IMO GHG Study 2014* included a simple correction factor for these influences in their global inventory; however, there is uncertainty surrounding the influence of these factors on fuel use and emissions. Thus, this report excludes the potential influence of these factors. Future work could focus on modeling the potential fuel consumption and emissions impacts of weather and hull conditions.

4 RESULTS AND DISCUSSION

This section presents fleet characteristics, emissions of BC and other pollutants, and fuel consumption for ships in 2015. Results are summarized by ship class and flag state.

4.1 Fleet characteristics

A summary of ships in the global fleet by main engine type and main fuel type is presented in Table 10. The vast majority of ships are powered by diesel engines (HSD + MSD + SSD). Most SSDs are 2-stroke and almost all operate on residual fuel, while most MSDs are 4-stroke with slightly more operating on distillate fuel compared with residual fuel; over 90% of HSDs are 4-stroke engines that operate on distillate fuel. STs make up a very small percentage of engines installed on ships, and most ST engines are installed on LNG carriers that use their cargo for fuel; hence the large share of STs that are LNG powered. Nuclear powers only 5 commercial ships, and all of them are Russian flagged and operate in the Arctic, where eliminating the need for refueling offers a considerable advantage. Naval ships, which may operate on nuclear power, are not included in the dataset.

Table 10. Number of ships in the global fleet by main fuel type and engine type

Fuel type	**ST**[a]	**GT**	**HSD**		**MSD**		**SSD**		**Total**
			2-stroke	**4-stroke**	**2-stroke**	**4-stroke**	**2-stroke**	**4-stroke**	
Residual	79	9	20	569	191	8,699	24,063	1459	**35,089**
Distillate	9	53	1,832	21,693	379	10,494	97	222	**34,779**
LNG	254	1	--	--	--	221[b]	6[c]	--	**482**
Methanol	--	--	--	--	--	1	2	--	**3**
Coal	2	--	--	--	--	--	--	--	**2**
Nuclear	5	--	--	--	--	--	--	--	**5**
Total	**349**	**63**	**1,852**	**22,262**	**570**	**19,415**	**24,168**	**1,681**	**70,360**

[a]ST = steam turbine; GT = gas turbine; HSD = high-speed diesel (>900 rpm); MSD = medium-speed diesel (300-900 rpm); SSD = slow-speed diesel (<300 rpm). [b]LNG MSD 4-stroke contains LNG-Otto cycle and LNG-Diesel cycle dual fuel engines. [c]LNG SSD 2-stroke contains only LNG-Diesel cycle dual fuel engines.

4.2 Time in phase

Ships tend to split their time between cruising and waiting (berth/anchorage). Time at berth/anchorage seems related to cargo value. Container ships spend most of their time cruising and have the lowest turnaround time due the high value of cargo. In contrast, general cargo ships, which have relatively lower freight rates than container ships, have the longest turnaround time, which may reflect slower load/unloading operations. Liquid tankers like oil and chemical tankers require slightly higher port stay due to inerting and purging operations. Fishing vessels spend only about one-third of their time cruising, with most of their time at anchor. It is possible that some activity labeled as “anchorage” is really time spent setting or hauling fishing gear. During this time, in the real world, the ME load may fluctuate as the master positions the ship; however, this study assumes that only the AE are on when a ship is at anchor. Thus, ME emissions from fishing vessels may be underestimated.

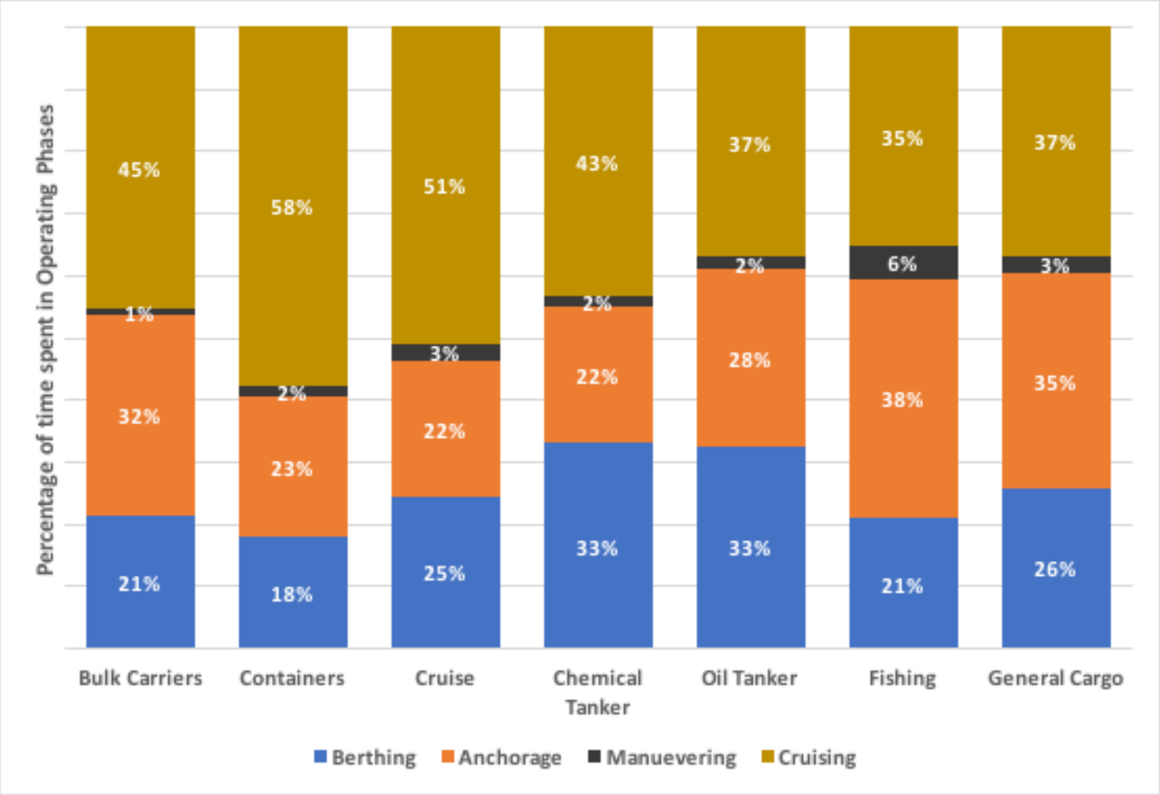

Figure 4: Frequency of time spent in each operating phase for major ship classes

4.3 Fleet activity and fuel use

A summary of the number of ships, operating hours (h), distance traveled (nm), fuel consumption (t) and energy use (kWh) for the global fleet by ship class is presented in Table 11.

Overall, the global shipping fleet consumed 1.2 trillion kWh of energy in 2015, enough to power California for 6 years[17] while operating for about 560 million hours (equivalent to 64,000 years) and traveling 2.2 billion nautical miles, equivalent to circling the globe more than 100,000 times.

Container ships, bulk carriers, and oil tankers numbered 30% of the global fleet, but accounted for 49% of distance traveled and 62% of fuel consumption. About 5,000 container ships, while making up roughly 7% of the global fleet, consumed the most energy (26%) and fuel (25%) of any ship class. Cruise ships have disproportionately high energy use and fuel consumption. While cruise ships make up 1% of the world fleet, they consume 4% of its energy and fuel.

Liquefied gas tankers rank 6th out of 22 ship classes in terms of energy use (5%) and fuel consumption (6%), despite making up a small proportion of the fleet in terms of number (2%).

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[17] The state of California consumed approximately 200 billion kWh of electricity in 2015 according to the U.S. Energy Information Administration (https://www.eia.gov/electricity/state/california/index.php), or about one-sixth of the energy use of ships in 2015.

Many liquefied gas tankers are LNG carriers, which tend to use their cargo (LNG) as their main propulsion fuel. While LNG is a relatively clean fuel in terms of BC emissions and other air pollutants, it can be an important source of GHG emissions, particularly if some of the fuel is emitted as un-combusted methane.

Fishing vessels represent 10% of the world fleet, account for 9% of ship operating hours and 7% of distance traveled, but are responsible for only 2% of energy use and fuel consumption due to the relatively small size of their engines. A similar pattern is observed for tugs and other service vessels (service-tugs and service-other).

Table 11. Number of ships, operating hours, distance traveled, fuel consumption, and energy use for the global fleet by ship class.

Ship Class	**No. of Ships**	**Percent of ships**	**Operating hours**	**Percent of op. hours**	**Distance traveled (nm)**	**Percent of dist. traveled**	**Fuel consumption (tonnes)**[a]	**Percent of fuel cons.**	**Energy use (10^6 kWh)**	**Percent of energy use.**
Container	5,008	7%	42,658,000	8%	368,851,000	17%	62,153,000	25%	308,000	26%
Bulk Carrier	10,572	15%	87,713,000	16%	505,403,000	23%	53,425,000	22%	266,000	22%
Oil Tanker	5,733	8%	47,001,000	8%	203,355,000	9%	38,060,000	15%	176,000	15%
Chemical Tanker	4,568	6%	38,156,000	7%	189,608,000	9%	16,160,000	7%	77,000	6%
General Cargo	9,183	13%	74,085,000	13%	272,662,000	12%	13,689,000	6%	65,000	5%
Liquefied Gas Tanker	1,675	2%	13,736,000	2%	91,072,000	4%	12,858,000	5%	67,000	6%
Cruise	406	1%	3,318,000	1%	22,236,000	1%	10,034,000	4%	45,000	4%
Ferry-Ro-Pax	2,062	3%	16,614,000	3%	52,208,000	2%	8,153,000	3%	38,000	3%
Vehicle	820	1%	7,017,000	1%	72,937,000	3%	7,237,000	3%	36,000	3%
Ro-Ro	1,055	1%	8,263,000	1%	33,790,000	2%	4,927,000	2%	22,000	2%
Service-Other	6,865	10%	52,353,000	9%	54,525,000	2%	4,309,000	2%	20,000	2%
Fishing Vessels	7,030	10%	51,803,000	9%	151,453,000	7%	3,977,000	2%	18,000	2%
Refrigerated Bulk	703	1%	5,812,000	1%	36,390,000	2%	3,759,000	2%	17,000	1%
Offshore	4,447	6%	33,906,000	6%	29,156,000	1%	3,752,000	2%	17,000	1%
Service - Tugs	6,941	10%	53,194,000	10%	87,525,000	4%	1,907,000	1%	9,000	1%
Ferry-Pax-Only	1,424	2%	10,409,000	2%	18,159,000	1%	1,393,000	1%	6,000	1%
Yacht	1,530	2%	10,928,000	2%	9,621,000	<1%	480,000	<1%	2,000	<1%
Other Liquid Tankers	61	<1%	434,000	<1%	596,000	<1%	176,000	<1%	670	<1%
Others	139	<1%	1,117,000	<1%	1,574,000	<1%	64,000	<1%	300	<1%
Naval Ship	80	<1%	596,000	<1%	567,000	<1%	60,000	<1%	240	<1%
Non-Propelled	49	<1%	313,000	<1%	72,000	<1%	2,000	<1%	10	<1%
Non-Ship	9	<1%	52,000	<1%	41,000	<1%	260	<1%	1	<1%
Total[b]	**70,360**	**100%**	**559,489,000**	**100%**	**2,201,808,000**	**100%**	**246,587,000**	**100%**	**1,198,000**	**100%**

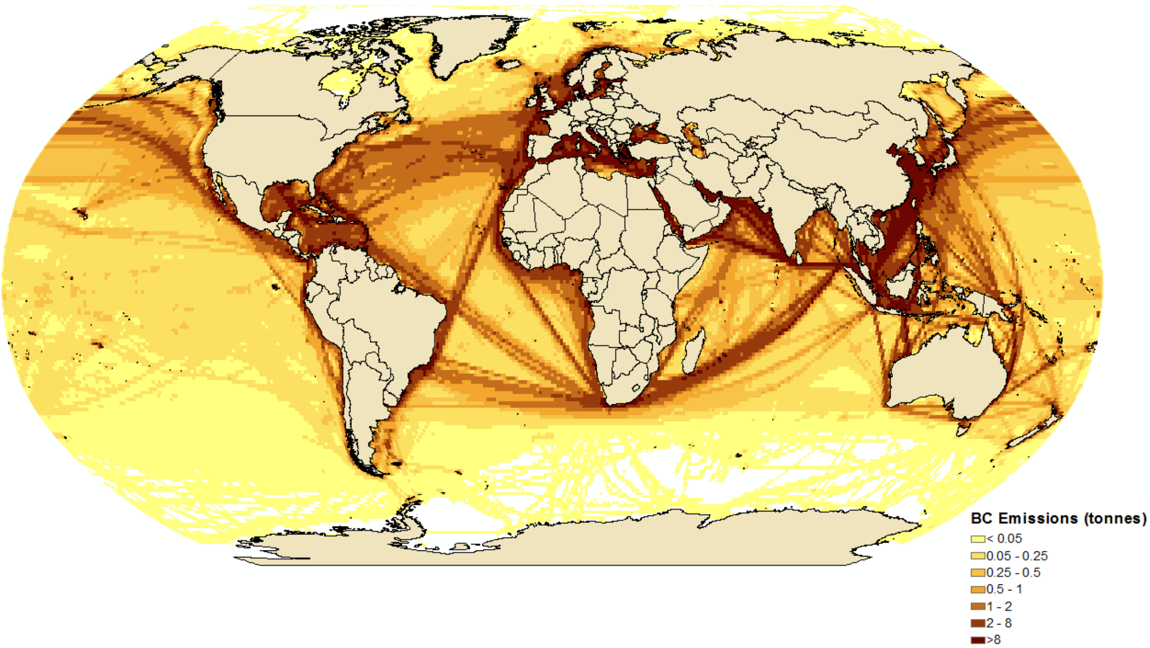
[a] Ranked by fuel consumption. [b] May not sum, due to rounding.

4.4 Emissions

This section describes global emissions of BC and other air and climate pollutants from ships in 2015.

4.4.1 Black Carbon

The geographic distribution of BC emissions from the global fleet in 2015 is presented in Figure 5. As shown on the map, BC is emitted nearly everywhere throughout the globe, even in the Arctic and Antarctic. The heaviest BC emissions are concentrated along major trade routes, particularly along the Asia to Europe route, including the straits of Malacca and Singapore. Additionally, BC appears to be mainly emitted near the coast, where it can degrade local air quality, even in ECAs. For example, the North American ECA reduces BC emissions offshore, but BC emissions near shore, especially in the Gulf of Mexico, are still high, because of highly concentrated coastal traffic. The Baltic and North Sea ECAs reduce BC emissions in western Europe, but their effect is masked by how BC emissions are portrayed on the map. Specifically, grid cells where BC emissions exceed 8 tonnes are shaded darkest. Because of intense ship traffic in the Baltic Sea and North Sea, BC emissions exceed 8 tonnes in most areas.



Data sources: exactEarth; IHS; ArcGIS

Figure 5. Black carbon emissions from ships in 2015 (1° x 1° resolution)

Figure 6 shows the distribution of BC emissions by latitude band. Ships emit 74% of BC the northern hemisphere. One percent (1%) of BC is emitted at 60°N latitude and above. While BC emitted at all latitudes has a climate warming effect, BC emitted in the Arctic has a nearly five times greater Arctic surface warming effect than BC emitted in mid latitudes (Sand et al., 2013). However, 11% of BC is emitted from ships in the Arctic Front (40°N latitude and above), an area where BC emissions may have a direct impact on the Arctic through atmospheric transport (Green et al., 2011).

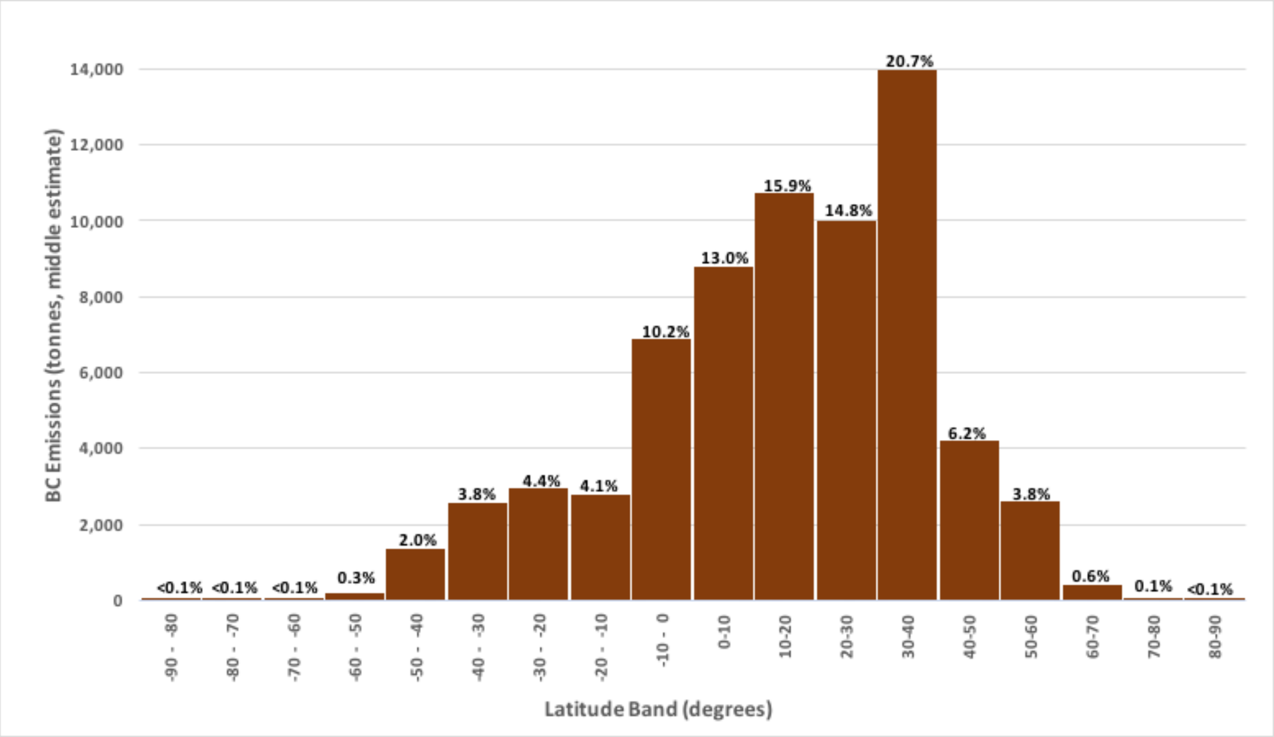


Figure 6: Distribution of BC emissions by latitude band

Table 12 shows BC emission by ship class and Figure 7 shows the proportion of BC emissions (best estimate) by ship class.

Total global BC emissions from ships were estimated to be between 54 kt to 81 kt in 2015, with a best estimate of approximately 67 kt. This corresponds to a BC EF of 0.27 g/kg fuel with a range of 0.22 to 0.33 g/kg fuel. However, depending on the ship class, the BC EF can be higher or lower than this range. For example, the best estimate of BC EF for fishing vessels is 0.38 g/kg fuel, with a range of 0.31 to 0.45 g/kg fuel.

Assuming a BC global warming potential of 900 and 3,200 on a 100 and 20-year timescale, respectively, ship BC emissions were responsible for 6-8% (100-year timescale) and 18-24% (20-year timescale) of the CO_{2eq} climate warming impact from shipping in 2015.[18]

Larger ships are responsible for the most BC emissions. Container ships, bulk carriers, and oil

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[18] Assumes that, in 2015, ships emitted 54 to 81 kt of BC; 770,000 kt of CO_2; 38.5 kt of N_2O with GWPs of 298 (100-year) and 289 (20-year); and 322 kt of CH_4 emissions with GWPs of 25 (100-year) and 72 (20-year), per the results of this study.

tankers together emit 58% of BC emissions, while accounting for 20% of the ships and 81% of DWT in the global fleet. Within that group, container ships, which make up 7% of ships and 14% of DWT in the global fleet, emit the most BC (25%) compared to other ship classes. Outside that group, cruise ships account for a disproportionately large amount of BC, emitting 7% of BC emissions despite accounting for only 1% of the number of ships and less than 1% of DWT in the global fleet. Some ship classes that have large numbers of (albeit relatively small) ships in the global fleet emit disproportionately less; for example, fishing vessels emit only 2% of BC emissions, despite representing 10% of the global fleet by number. However, Comer et al. (2017) found that fishing vessels were responsible for 25% of BC emissions in the IMO Arctic and 13% in the Geographic Arctic (roughly 59°N latitude and above), an area where BC has a five-times greater warming impact than in mid-latitudes (Sand et al., 2013). Thus, certain ship classes may have an outsized influence on regional BC emissions.

Table 12. Black carbon emissions, number of ships, and deadweight tonnage by ship class, 2015

Ship Class	**No. of Vessels**	**% of total fleet**	**Deadweight Tonnage**	**% of Global Deadweight**	**Low BC emissions (tonnes)**	**Best BC emissions (tonnes)**	**High BC emissions (tonnes)** [a]	**% of best BC emissions**	**Fuel consumption (tonnes)**	**BC EF Low (g/kg)**	**BC EF Best (g/kg)**	**BC EF High (g/kg)**
Container	5,008	7%	242,659,796	14%	12,997	16,680	20,363	24.7%	62,153,000	0.21	0.27	0.33
Bulk Carrier	10,572	15%	755,457,667	42%	9,254	12,039	14,825	17.9%	53,425,000	0.17	0.23	0.28
Oil Tanker	5,733	8%	446,535,445	25%	8,442	9,914	11,386	14.7%	38,060,000	0.22	0.26	0.30
General Cargo	9,183	13%	71,569,718	4%	3,655	4,627	5,599	6.9%	13,689,000	0.27	0.34	0.41
Cruise	406	<1%	1,975,639	<1%	3,628	4,500	5,371	6.7%	10,034,000	0.36	0.45	0.54
Chemical Tanker	4,568	7%	100,549,218	6%	3,626	4,381	5,136	6.5%	16,160,000	0.22	0.27	0.32
Ferry-Ro-Pax	2,062	3%	3,715,807	<1%	2,136	2,921	3,706	4.3%	8,153,000	0.26	0.36	0.45
Liquefied Gas Tanker	1,675	2%	55,411,731	3%	1,646	1,943	2,239	2.9%	12,858,000	0.13	0.15	0.17
Service-Others	6,865	10%	50,856,202	3%	1,402	1,729	2,057	2.6%	4,309,000	0.33	0.40	0.48
Vehicle	820	1%	13,108,259	1%	1,257	1,634	2,010	2.4%	7,237,000	0.17	0.23	0.28
Ro-Ro	1,055	1%	6,129,121	<1%	1,303	1,591	1,878	2.4%	4,927,000	0.26	0.32	0.38
Fishing Vessels	7,030	10%	2,834,440	<1%	1,247	1,517	1,787	2.3%	3,977,000	0.31	0.38	0.45
Offshore	4,447	6%	21,807,535	1%	1,081	1,288	1,494	1.9%	3,752,000	0.29	0.34	0.40
Refrigerated Bulk	703	1%	4,807,714	<1%	1,027	1,158	1,289	1.7%	3,759,000	0.27	0.31	0.34
Service-Tugs	6,941	10%	1,296,198	<1%	614	838	1,063	1.2%	1,907,000	0.32	0.44	0.56
Ferry-Pax Only	1,424	2%	203,137	<1%	307	394	482	0.6%	1,393,000	0.22	0.28	0.35
Yacht	1,530	2%	199,234	<1%	133	157	181	0.2%	480,000	0.28	0.33	0.38
Other Liquid Tankers	61	<1%	326,023	<1%	36	38	40	0.1%	176,000	0.21	0.22	0.23
Naval Ship	80	<1%	1,492,026	<1%	20	29	37	<0.1%	60,000	0.34	0.48	0.62
Others	139	<1%	328,263	<1%	19	22	25	<0.1%	64,000	0.29	0.34	0.39
Non-Propelled	49	<1%	296,089	<1%	1	1	2	<0.1%	2,000	0.40	0.59	0.79
Non-Ship	9	<1%	422	<1%	<1	<1	<1	<0.1%	260	0.43	0.65	0.87
Total	**70,360**	**100%**	**1,781,559,684**	**100%**	**53,832**	**67,401**	**80,970**	**100%**	**246,587,000**	**0.22**	**0.27**	**0.33**

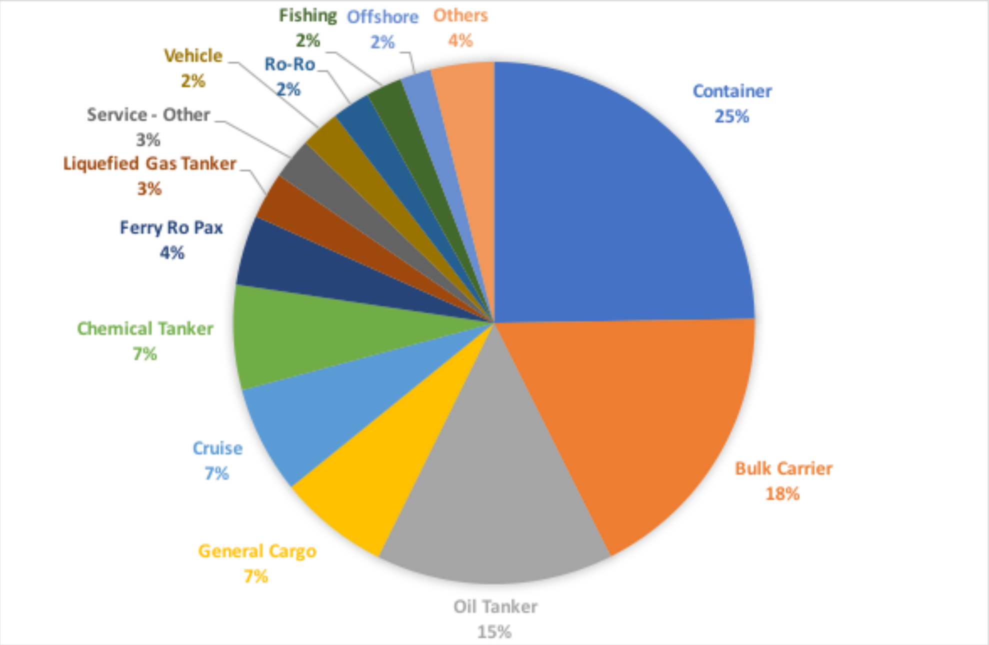

Figure 7: Share of global BC emissions by ship class

Figure 8 shows BC emissions by source (ME, AE, and BO) for the top 6 emitting ship classes, plus fishing vessels. In total, most BC emissions for all ships comes from MEs (61%), followed by AEs (34%), and BOs (5%). Oil tankers have higher BC emissions from AEs and BOs compared to other ship classes. These ships demand more AE and BO power than many other ship classes because the cargo is discharged either by steam-turbine driven pumps requiring higher steam demand from BOs (crude oil tankers) or hydraulic/electric driven pumps which requires higher power demand from AE (product tankers). Fishing vessel BC emissions are split nearly evenly between ME and AE, with slightly more BC emitted from their MEs. This is likely because our model estimates that fishing vessels spend more time at berth and anchor compared with other ships (Figure 4). As explained earlier, it is possible that some activity labeled as “at anchor” is really time spent setting or hauling fishing gear. During this time, in the real world, the ME load may fluctuate as the master positions the ship; however, this study assumes that only the AE are on when a ship is at anchor. Thus, ME emissions from fishing vessels may be underestimated.

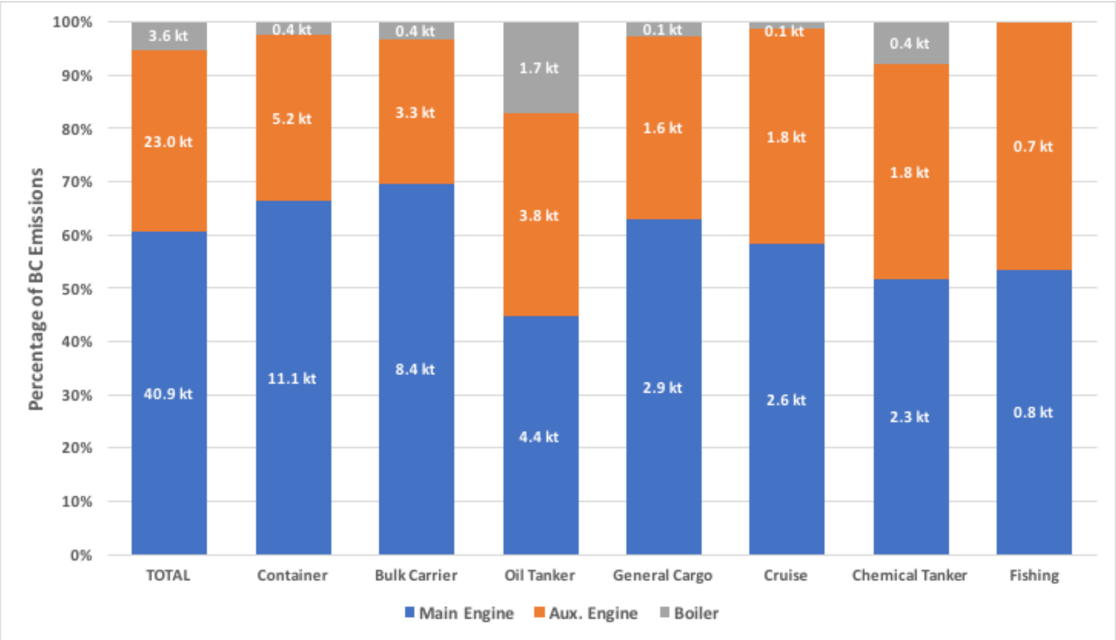

Figure 8. Proportion of black carbon emissions from main engines, auxiliary engines, and boilers for select ship classes.

Table 13 summarizes ME BC emissions by main fuel type and main engine type excluding AE and BO emissions. More than 99% of ME BC from ships is emitted from diesel engines (SSD, MSD, and HSD). Most (27 kt) of ME BC is emitted by SSD engines, roughly two-thirds of the total. Because nearly all SSDs are 2-stroke, and because most other engine types are 4-stroke, 2-stroke engines also account for approximately two-thirds of total ME BC emissions from ships. MSD and HSD engines together account for approximately 14 kt of BC emissions: about one-third of total ME BC emitted from ships. ST and GT MEs emit less than 0.2 kt, or much less than 1% of ME BC emissions from ships.

Table 13. Summary of main engine black carbon emissions by main fuel type and main engine type

Fuel type	**Main Engine Type**[a]								**Total**
	ST	**GT**	**HSD**		**MSD**		**SSD**		
			2-stroke	**4-stroke**	**2-stroke**	**4-stroke**	**2-stroke**	**4-stroke**	
Distillate	31	6	20	2,169	9	3,784	341	35	**6,396**
Residual	41	2	1	135	20	7,553	26,195	439	**34,387**
LNG	45	0.23	--	--	--	26[b]	0.35[c]	--	**72**
Total	**117**	**9**	**21**	**2,303**	**29**	**11,364**	**26,537**	**474**	**40,854**

[a]ST = steam turbine; GT = gas turbine; HSD = high-speed diesel (>900 rpm); MSD = medium-speed diesel (300-900 rpm); SSD = slow-speed diesel (<300 rpm). [b]LNG MSD 4-stroke contains LNG-Otto cycle and LNG-Diesel cycle dual fuel engines. [c]LNG SSD 2-stroke contains only LNG-Diesel cycle dual fuel engines.

Figure 9 summarizes the proportion of BC by ship class and main engine type in 2015 for the top six emitting ship classes, plus fishing vessels, which rank 12th. Note that these BC emissions are grouped by the ME type, but some proportion of the emissions will be from AEs and BOs, which could be a different engine type. For example, a container ship may have a 2-stroke SSD ME, one or more 4-stroke MSD AEs, and one or more ST BOs.

Ships with SSD, MSD, and HSD MEs account for nearly all BC (>99%) emissions, and most BC (66%) is emitted by ships with 2-stroke, SSD MEs. The vast majority of BC emitted by container ships, bulk carriers, oil tankers, and chemical tankers is from ships with 2-stroke MEs, whereas most BC emitted by general cargo vessels is from ships with 4-stroke MEs. Nearly all BC emitted from cruise ships is from medium speed 4-stroke engines. This is because cruise ships are usually powered by a series of smaller, 4-stroke diesel generator sets that enable greater flexibility in power output for propulsion and hoteling. More than 40% of BC emissions from fishing vessels are from ships with 4-stroke HSD MEs, since small ships are often powered by such engines.

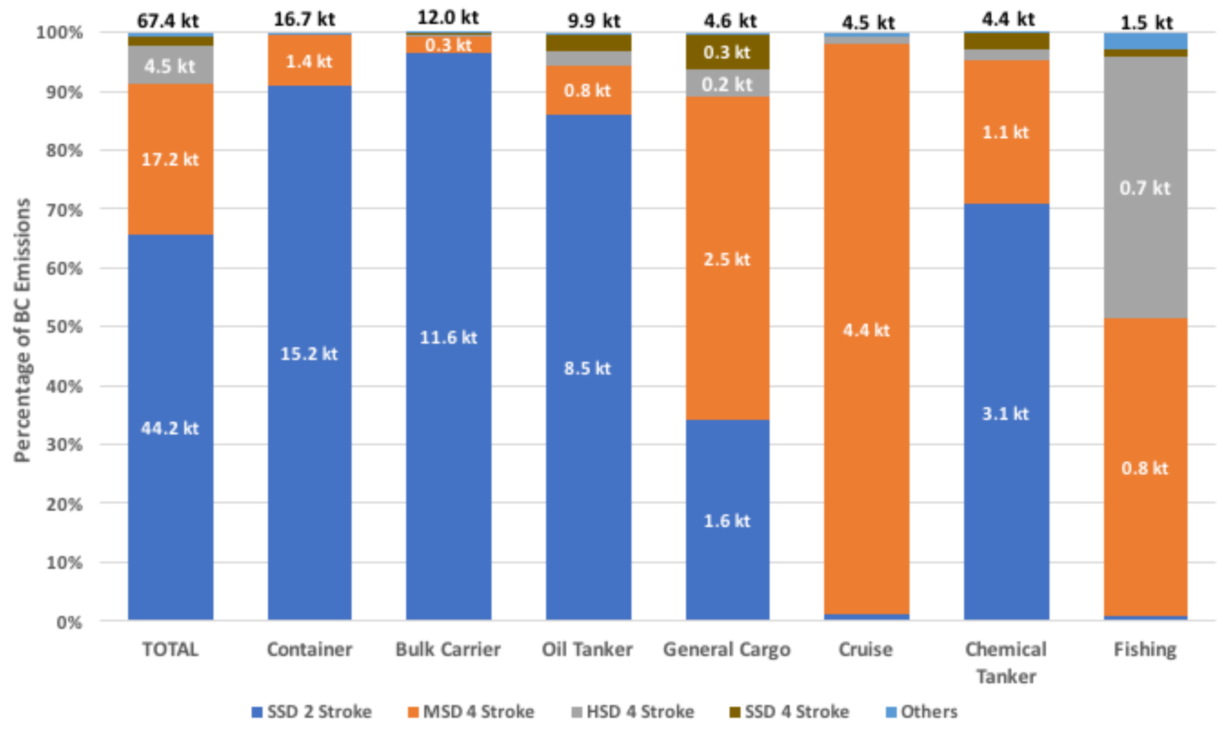

Figure 9: Black carbon emissions by main engine type and ship class, summarized by ship classes emitting the most BC, plus fishing vessels.

Figure 10 summarizes BC emissions by main fuel type for all ships and for ship classes that emit the most BC, plus fishing vessels. The Total BC emissions column includes BC from LNG emissions, but the amount is too small to be visible on the graph. Approximately 83% of BC emissions from the global fleet are from using residual fuels, such as HFO. For ship classes that emit the most BC, 75-97% of BC is emitted from using residual fuel. In contrast, more than 73% of BC from fishing vessels comes from using distillate fuel.

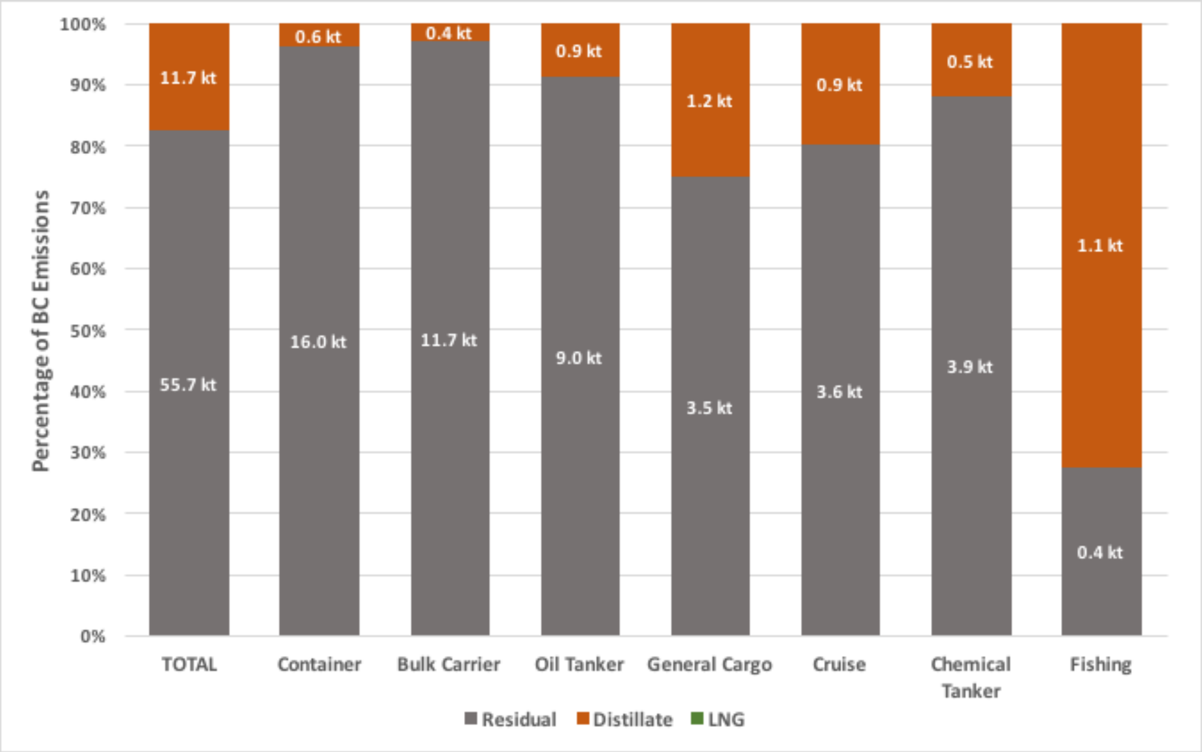

Figure 10: Black carbon emissions by fuel type for the highest emitting ship classes and fishing vessels

Figure 11 shows total BC emissions by flag state. Just 6 of the 180 flag states - Panama, Liberia, China, Marshall Island, Singapore, and Malta - accounted for more than 53% of marine BC in 2015. Panama-flagged ships emit more BC than ships registered to any other flag state, accounting for more than 10 kt of BC emissions, equivalent to more than 15% of global emissions from ships. Liberia and China follow, each accounting for about 10% of total global BC emissions from ships.

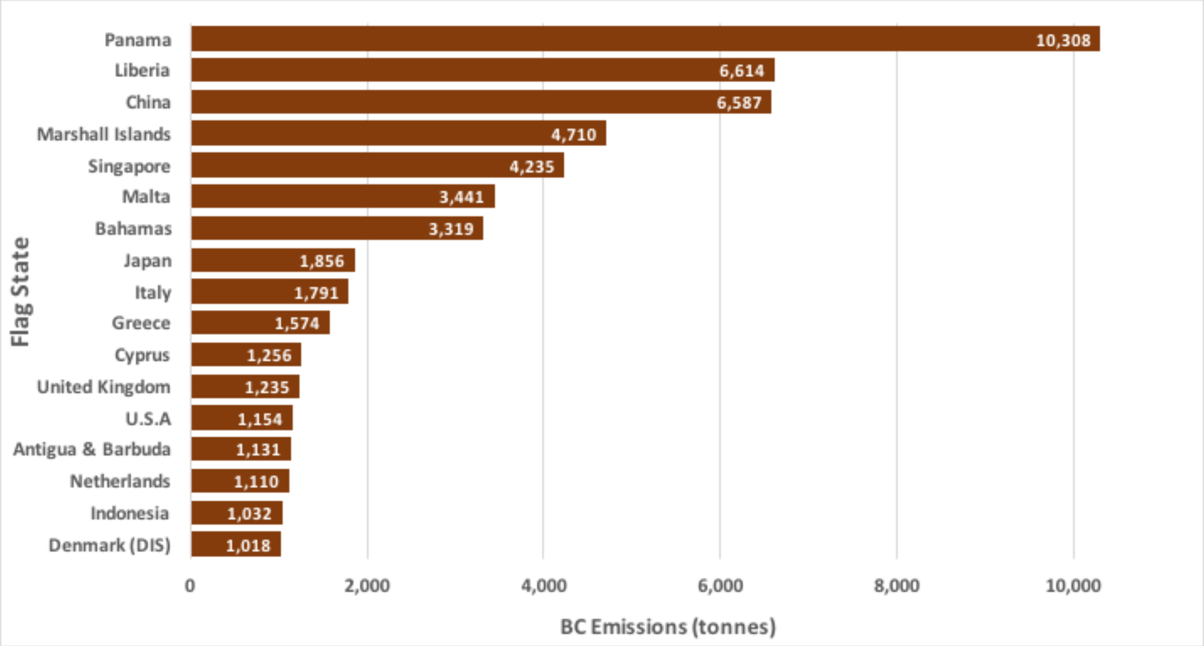

Figure 11: Black carbon emissions by top emitting flag states

BC intensity, measured as BC emissions per ship per year, for the most polluting ship classes in 2015 is shown in Figure 12. Cruise ships emit more than 11 t per ship per year, more than three times greater than container ships and equal to about 4,600 Euro V heavy-duty trucks operating 100,000 kilometers over one year.[19] The ships on this graph may be good candidates to test BC reduction technologies, such as DPFs, or other BC reduction strategies Cruise ships typically use 4-stroke diesel generator sets that can readily operate on distillate fuels, providing an opportunity to retrofit with DPFs, as DPFs operate best when treating exhaust from high quality, low sulfur, and low ash fuels.. Reducing BC from cruise ships can help improve local air quality in ports of call and, for cruise ships in and near the Arctic, reduce the climate warming impacts of these ships. Reducing BC from container ships would greatly reduce BC from global shipping, as container ships emit the most BC of any ship class. Installing DPFs on the cruise ship fleet would result in the most BC reduction per ship, on average, but installing DPFs on the container ship fleet would result in the most BC reduction overall. To take an extreme case, retrofitting all 400 or so cruise ships with DPFs would reduce BC by 9.4 t per ship and 3,825 t in total, or 5.7% of total BC emissions from ships. Whereas retrofitting all 5,000 or so container ships with DPFs would reduce BC by 2.8 t per ship per year on average, but a total reduction of 14,180 t, or 21% of total BC emissions from ships.

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[19] According to the ICCT's Roadmap Model, one Euro V heavy-duty truck, operating 100,000 km/yr, emits roughly 2.4 kg of BC.

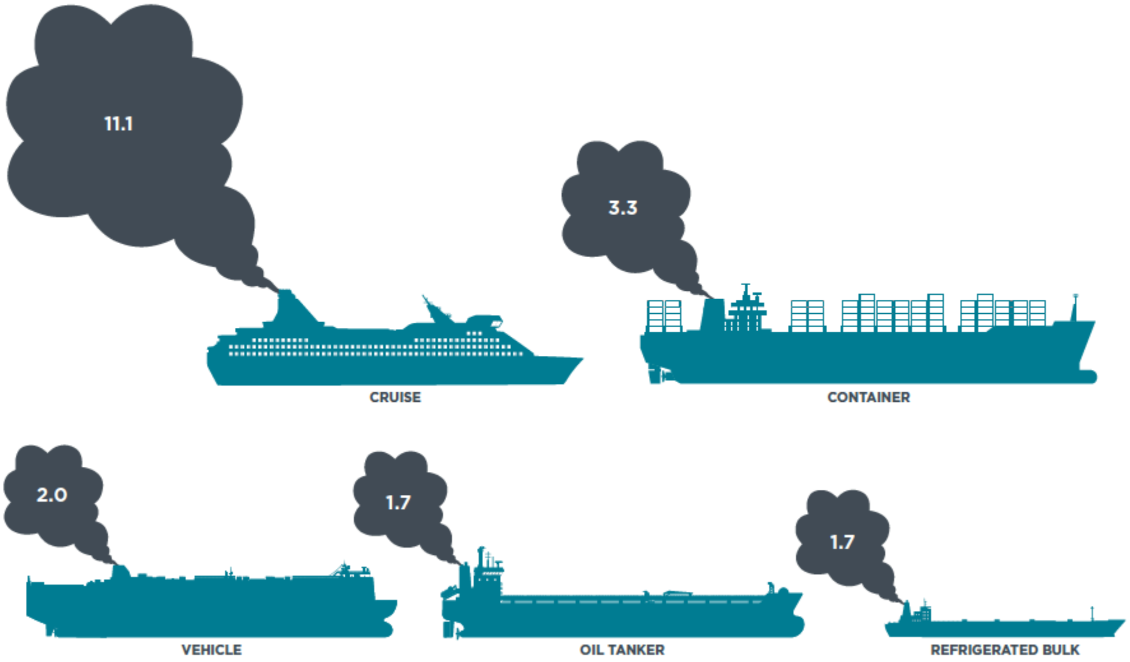


Figure 12: Tonnes of black carbon per ship for the most polluting ship classes in 2015.

4.4.2 Other air and climate pollutants

Table 14 shows emissions of other air and climate pollutants by ship class; the best BC estimate is included for reference. Container ships emit the most across all pollutants, except for CH_4, which, due to methane slip, is dominated by liquefied gas carriers. Container ships, bulk carriers, and oil tankers together emit approximately 72% of SO_x, 68% of NO_x, 60% of CO, 57% of BC, 72% of PM, 62% of CO_2, 63% of N_2O, and 3% of CH_4, while representing 30% of ships and 81% of DWT. Within that group, container ships emit disproportionately high amounts of air pollution. For example, the roughly 5,000 container ships operating in 2015, which represent 7% of ships and 14% of DWT in the world fleet, were responsible for a quarter or more of all pollutants except CH_4, including SO_x (29%), NO_x (28%), CO (26%), BC (25%), PM (30%), CO_2 (25%), and N_2O (26%).

Table 14. Emissions of other air and climate pollutants, 2015

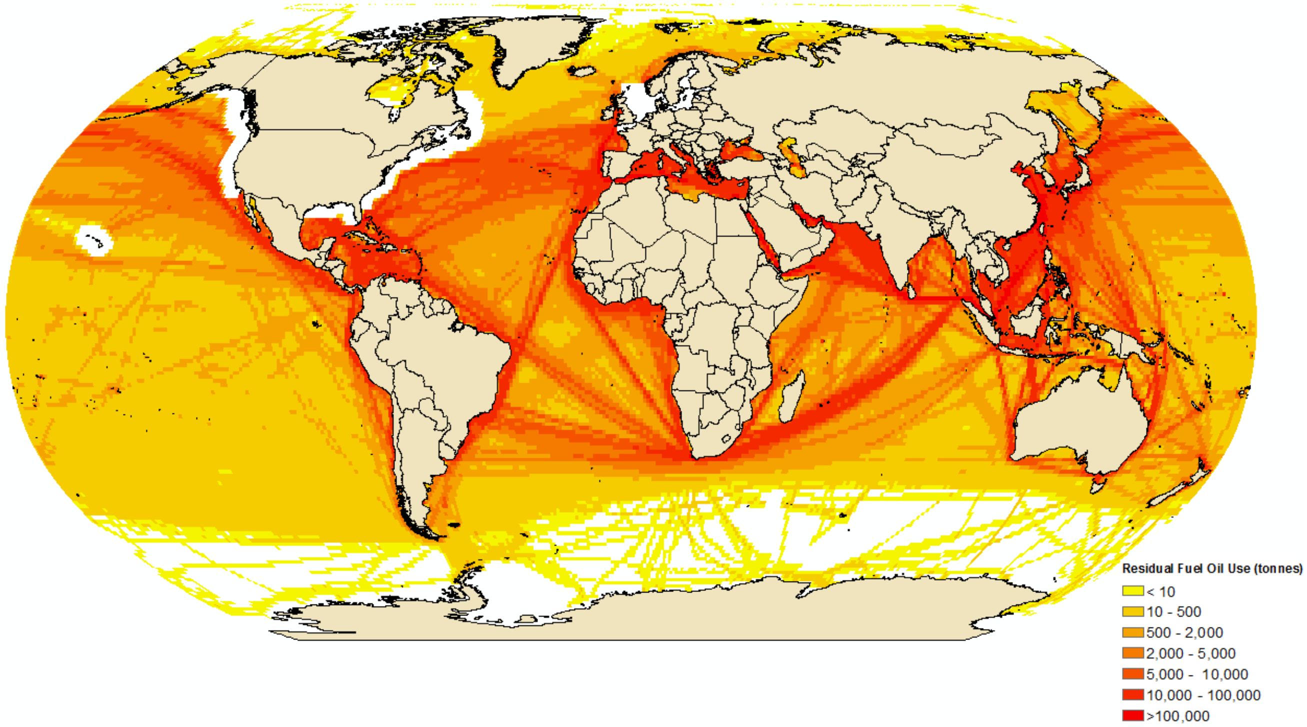
Ship Class	**SO$_X$[a] (tonnes, t)**	**NO$_X$ (t)**	**CO (t)**	**BC (best; t)**	**PM (t)**	**CO$_2$ (t)**	**N$_2$O (t)**	**CH$_4$ (t)**
Container	2,845,000	4,660,000	178,000	16,680	406,000	193,947,000	10,000	3,900
Bulk Carrier	2,499,000	4,065,000	145,000	12,039	349,000	166,610,000	8,500	3,100
Oil Tanker	1,657,000	2,381,000	89,000	9,914	211,000	118,935,000	6,000	1,800
Chemical Tanker	661,000	1,004,000	41,000	4,381	89,000	50,579,000	2,500	1,400
General Cargo	482,000	832,000	36,000	4,627	67,000	43,003,000	2,100	900
Cruise	343,000	522,000	24,000	4,500	45,000	31,538,000	1,500	700
Vehicle	323,000	550,000	20,000	1,634	45,000	22,603,000	1,100	400
Liquefied Gas Tanker	321,000	505,000	62,000	1,943	42,000	38,155,000	1,800	296,000
Ferry-Ro-Pax	192,000	393,000	22,000	2,921	28,000	25,772,000	1,200	9,300
Refrigerated Bulk	159,000	258,000	9,000	1,158	21,000	11,760,000	600	180
Ro-Ro	126,000	238,000	12,000	1,591	18,000	15,572,000	700	490
Fishing Vessel	43,000	239,000	11,000	1,517	8,000	12,689,000	600	200
Service Other	36,000	238,000	12,000	1,729	7,400	13,768,000	600	420
Offshore	19,000	193,000	10,000	1,288	4,700	12,003,000	500	3,000
Ferry-Pax Only	11,000	71,000	3,400	394	2,000	4,454,000	200	190
Service Tug	10,000	85,000	5,800	838	2,600	6,104,000	300	130
Other Liquid Tankers	1,700	4,700	240	38	200	564,000	30	4
Yacht	1,400	26,000	1,300	157	480	1,540,000	100	20
Naval Ship	800	2,200	130	29	120	191,000	10	3
Others	140	2,900	180	22	60	207,000	9	80
Non-Propelled	50	0	6	1	7	6,900	0	0
Non-Ship	1	0	1	0	0	900	0	0
Total[b]	**9,730,000**	**16,272,000**	**682,000**	**67,401**	**1,346,000**	**769,999,000**	**38,500**	**322,000**

[a]Ranked by SO$_x$ emissions. [b]May not sum due to rounding.

4.5 Fuel Use and Carriage

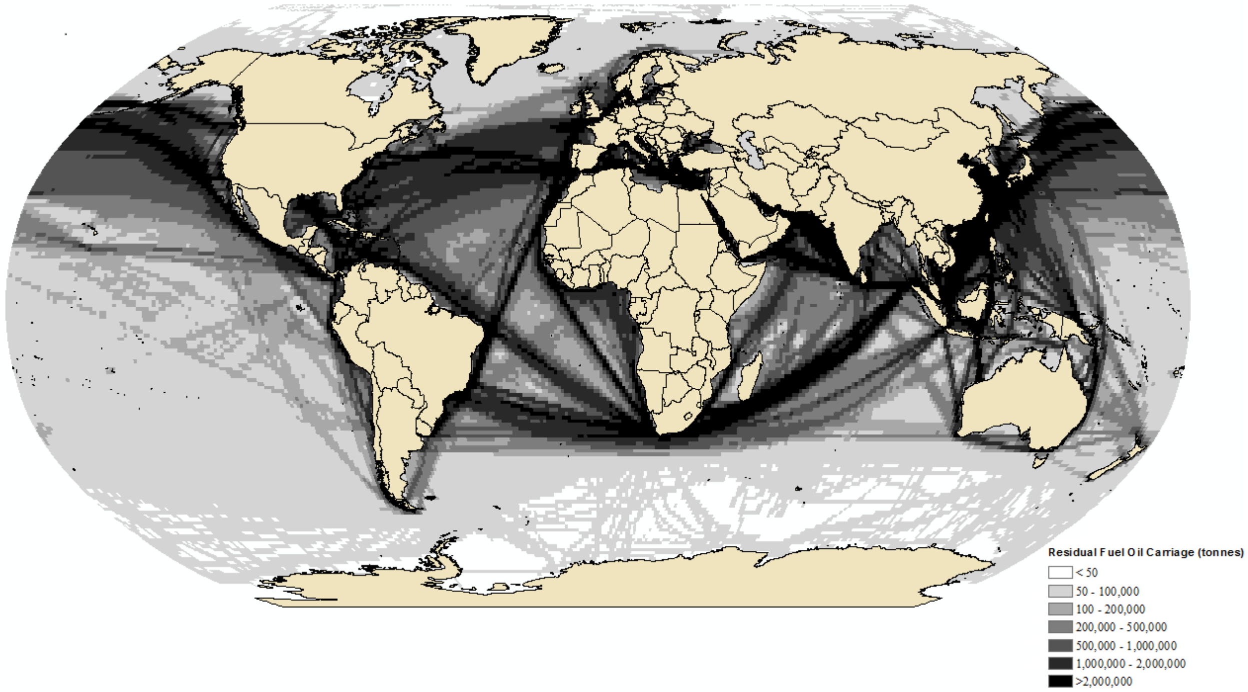
The geographic distribution of residual fuel use and residual fuel carriage (as bunker fuel; not cargo) for the global fleet in 2015 are presented in Figure 13 and Figure 14, respectively. Residual fuel use and carriage occurs across the globe, including the polar regions. In general, residual fuel use and carriage is most heavily concentrated along major trade routes and coastal areas. For instance, East Asia, along the Chinese coast down to the Singapore straits, has very high residual fuel use and carriage. The 0.1% sulfur limit for marine fuels in these areas means that residual fuels, such as HFO, are essentially prohibited in the North American, U.S. Caribbean Sea, Baltic Sea, and North Sea SECA regions, as shown in Figure 13; ships will typically operate on distillate fuels instead of HFO in SECAs. Note that some HFO use does happen in SECAs, as ships can comply with the 0.1% sulfur standard by using exhaust gas cleaning systems (scrubbers) that remove most of the sulfur from the ships' exhaust. Also, a small number of steam powered ships (less than ten) operating on the North American Great Lakes are exempt from the North American ECA fuel sulfur rules. However, the prevalence of HFO use in SECAs in 2015 was low and limited to a small number of ships (mainly cruise ships); as such, residual fuel use in SECAs is not included on the map.

One major distinction between residual fuel carriage and residual fuel use can be seen in the North American ECA along the Pacific Coast of the USA and in the Baltic and North Sea ECAs in Europe. The use of residual fuel in both areas is essentially nil, as shown in Figure 13; however, the carriage of residual fuel is higher in the Baltic and North Sea ECAs and along the Atlantic and Gulf coasts within the North American ECA than along the Pacific Coast. This could be due to more intense ship traffic in these areas. The carriage of residual fuels, such as HFO, poses additional economic and environmental risks from fuel oil spills compared to other marine fuels (Roy & Comer, 2017).



Data sources: exactEarth; IHS; ArcGIS

Figure 13. Residual fuel use by ships in 2015 (1º x 1º resolution)



Data sources: exactEarth; IHS; ArcGIS

Figure 14. Residual fuel carriage by ships in 2015 (1º x 1º resolution)

Table 15 summarizes fuel consumption by main engine type. The global fleet consumed 196 million tonnes of residual fuel in 2015, compared to 45 million tonnes of distillate, and less than 6 million tonnes of LNG. Residual fuel consumption represents 80% of fuel use by ships; distillate represents roughly 18% of fuel consumption and LNG makes up the rest (a bit more than 2%). Ships with 2-stroke SSD MEs consume the majority (74%) of residual fuel. Ships with MSD and HSD MEs together account for most distillate fuel consumption, although ships with SSD MEs consume approximately one-quarter of distillate fuel.

Table 15: Summary of fuel consumption by main engine type

Fuel consumption (tonnes)	**ST**	**GT**	**HSD**		**MSD**		**SSD**		**Total**
			2-stroke	**4-stroke**	**2-stroke**	**4-stroke**	**2-stroke**	**4-stroke**	
Residual	181,000	215,000	7,000	496,000	235,000	22,563,000	170,359,000	2,046,000	196,105,000
Distillate[a]	177,000	655,000	982,000	12,517,000	420,000	18,107,000	11,539,000	386,000	44,788,000
LNG	3,617,000	16,000	--	--	--	2,031,000[b]	27,000[c]	--	5,692,000
TOTAL[d]	**3,976,000**	**887,000**	**990,000**	**13,013,000**	**656,000**	**42,703,000**	**181,926,000**	**2,433,000**	**246,586,000**

[a] Distillate Fuel includes Distillate-ECA Fuel with slightly lower %S content than normal Distillate Fuel [b] LNG MSD 4-stroke contains LNG-Otto cycle and LNG-Diesel cycle dual fuel engines. [c] LNG SSD 2-stroke contains only LNG-Diesel cycle dual fuel engines. [d] May not sum due to rounding.

Table 16 shows fuel consumption by ship class in 2015. As with emissions, container ships, bulk carriers, and oil tankers dominate fuel consumption in the global fleet, especially with respect to residual fuel use. These ship classes account for 62% of total fuel use and 72% of residual fuel use. Within this group, container ships use the most fuel, representing 25% of total fuel consumption and 30% of residual fuel consumption in 2015. Bulk carriers follow closely behind, representing 22% of total fuel consumption and 26% of residual fuel consumption.

Table 16: Fuel consumption by ship class, 2015

Ship Class	**Residual fuel use (tonnes)**	**%Residual fuel use**	**Distillate fuel use (tonnes)**	**%Distillate fue use**	**LNG use (tonnes)**	**%LNG use**	**Total fuel use (tonnes)**	**%Total Fuel Use**
Container	57,777,000	29%	4,373,000	10%	3,300	<1%	62,153,000	25%
Bulk Carrier	50,803,000	26%	2,623,000	6%	100	<1%	53,426,000	22%
Oil Tanker	33,551,000	17%	4,510,000	10%	--	--	38,060,000	15%
Chemical Tanker	13,347,000	7%	2,802,000	6%	10,600	<1%	16,160,000	7%
General Cargo	9,619,000	5%	4,067,000	9%	3,300	<1%	13,690,000	6%
Cruise	6,854,000	3%	3,175,000	7%	5,500	<1%	10,035,000	4%
Vehicle	6,544,000	3%	693,600	2%	10	<1%	7,238,000	3%
Liquefied Gas Tanker	6,487,000	3%	900,700	2%	5,471,000	96%	12,859,000	5%
Ferry – Ro – Pax	3,717,000	2%	4,283,000	10%	152,800	3%	8,153,000	3%
Refrigerated Bulk	3,206,000	2%	554,100	1%	--	--	3,760,000	2%
Ro-Ro	2,447,000	1%	2,476,000	6%	4,800	<1%	4,928,000	2%
Fishing Vessel	703,000	<1%	3,275,000	7%	--	--	3,978,000	2%
Service – Others	532,000	<1%	3,775,000	8%	2,500	<1%	4,310,000	2%
Offshore	214,000	<1%	3,503,000	8%	35,100	1%	3,753,000	2%
Ferry – Pax only	152,000	<1%	1,239,000	3%	2,200	<1%	1,394,000	1%
Service – Tug	108,000	<1%	1,799,000	4%	270	<1%	1,907,000	1%
Other Liquid Tankers	27,300	<1%	149,000	<1%	--	--	176,700	<1%
Naval Ship	13,000	<1%	47,100	<1%	--	--	60,100	<1%
Yacht	2,800	<1%	478,000	1%	--	--	480,300	<1%
Non – Propelled	960	<1%	1,200	<1%	--	--	2,200	<1%
Others	160	<1%	63,400	<1%	1,000	<1%	64,600	<1%
Non – Ship	--	--	270	<1%	--	--	270	<1%
TOTAL [a]	**196,105,000**	**100%**	**44,788,000**	**100%**	**5,692,000**	**100%**	**246,586,000**	**100%**

[a] May not sum, due to rounding

Figure 15 summarizes fuel use by ship class and main fuel type for the top consuming ship classes in 2015. Residual fuel is the fuel of choice for the top fuel consuming ship classes. The fuel consumption for the top five fuel consuming ship classes is 70 to 95% residual fuel. Liquefied gas tankers, which rank 6th in total fuel consumption, are split between residual fuel consumption and LNG consumption, as many LNG carriers use their cargo as fuel.

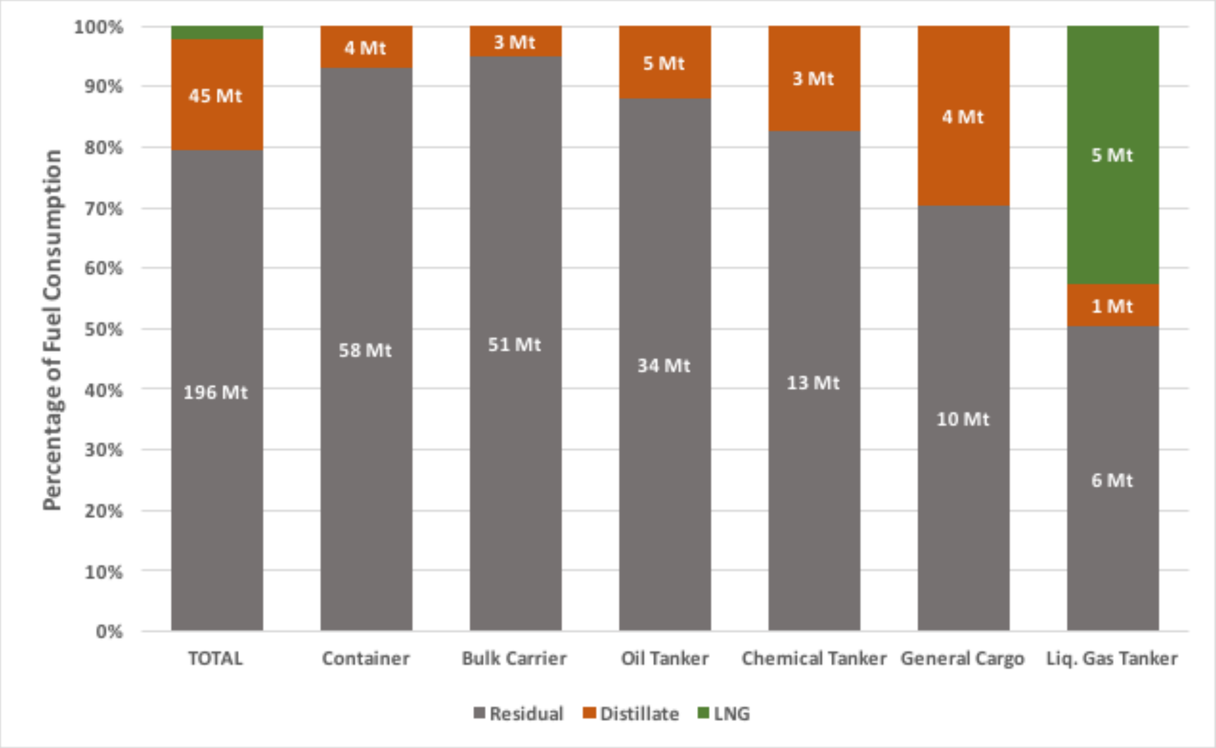


Figure 15: Percentage of different fuel burned, summarized by ship class

Figure 16 shows total fuel consumption by major ship class for the largest flag states. Five flag states (Panama, Liberia, China, Marshall Islands, and Singapore) consumed 129 Mt of fuel, equivalent to 52% of total fuel consumption by ships in 2015. Of these flag states, ships flagged to Panama consumed the most fuel, with most fuel consumption attributable to bulk carriers, container ships, and oil tankers.

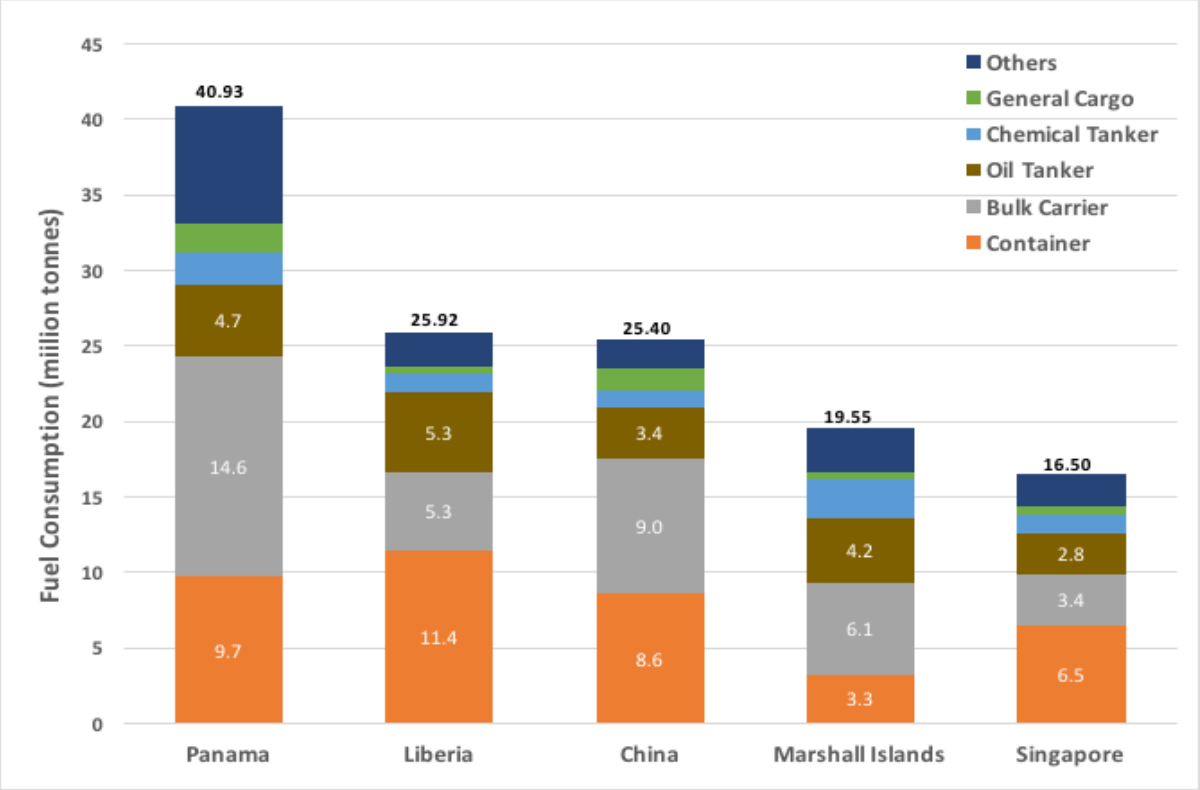


Figure 16: Total fuel consumption by top 5 fuel consuming flag states, summarized by ship class, 2015.

Figure 17 shows residual fuel use by flag state. Panama-flagged ships used the most residual fuel (37 Mt), followed by Liberia (24 Mt), China (24 Mt), Marshall Islands (17 Mt) and Singapore (15 Mt). Given that the global fleet consumed 196 Mt of residual fuel, ships registered to these five flag states account for more than 57% of residual fuel consumption by ships in 2015.

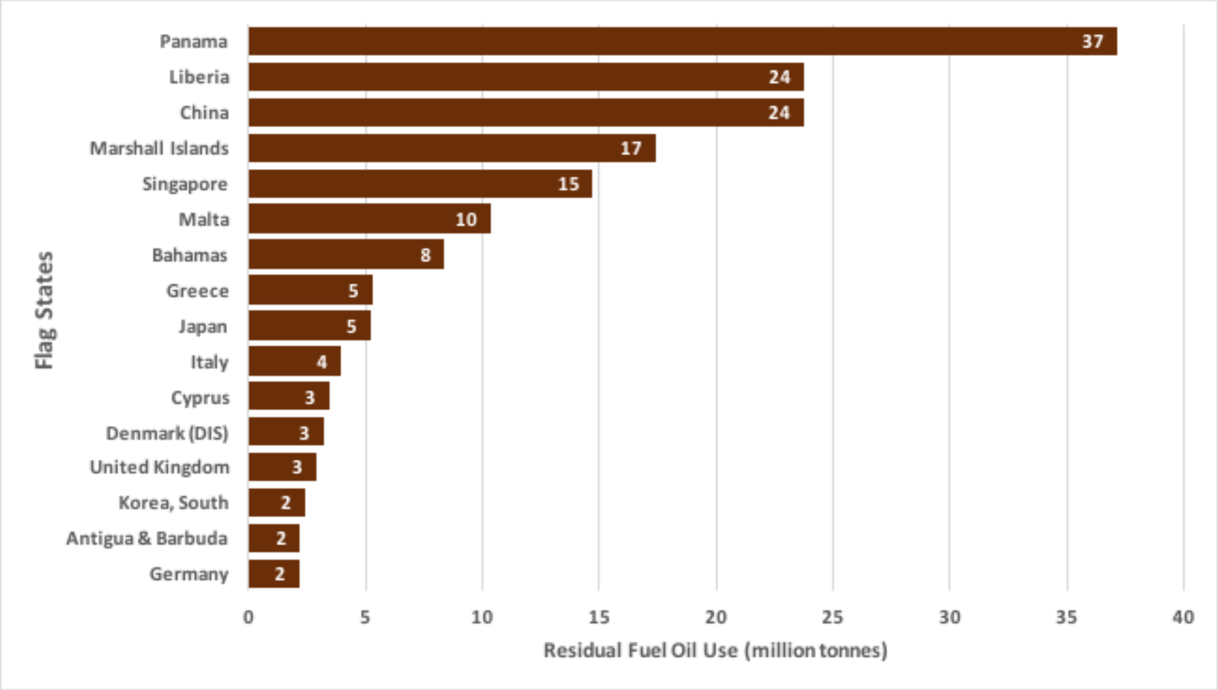


Figure 17. Residual fuel oil use by top consuming flag states, 2015

5 COMPARISON TO OTHER STUDIES

This section compares the results of this global BC inventory study with those of previous researchers: Bond et al (2013); Dentener et al. (2006); Fuglestvedt et al. (2010); Eyring et al. (2005, 2010); Lack et al. (2008); Dalsøren et al. (2009); and Buhaug et al. (2009).

In this study, total global BC emissions from ships are estimated at 54 kt to 81 kt, with a best estimate of approximately 67 kt. These results are somewhat lower but within the range of other researchers' estimates for global BC emissions from ships (Table 17). Differences in BC estimates are driven by both variations in fuel consumption estimates and BC EFs. Assumptions on BC EFs greatly affect the results of BC inventories. For example, this study found nearly the same amount of fuel consumption from ships as Lack et al.'s (2008) 2001 inventory, but about half of the BC emissions because Lack et al.'s weighted BC EF was 0.53 g/kg fuel, twice as high as our best estimate of 0.27 g/kg fuel. The BC EFs used in this study are based on the most recent emissions testing results and expert analysis on the range of likely BC EFs as described in the Methodology; that being said, BC EFs and ship BC inventories may continue to change in the future as researchers gather more data.

Table 17. Comparing this study to other global ship BC inventories

Study	Inventory Year	BC (kt)	Fuel consumption (million t)	BC EF (g/kg fuel)
Bond et al. (2013)	2000	100	-	0.17-0.85[a]
Dentener et al. (2006)	2000	130	182	0.69
Fuglestvedt et al. (2010)	2000	197	182	1.08
Eyring et al. (2005)	2001	50	280	0.18
Lack et al. (2008)	2001	133	254	0.53[b]
Dalsøren et al. (2009)	2004	39	216	0.18[c]
Eyring et al. (2010)	2005	160	300	0.53
Buhaug et al. (2009)	2007	120	333	0.36[d]
Comer et al. (this study)	**2015**	**67**	**247**	**0.27**[e]

[a] A combination of BC EFs from Petzold et a. (2008), Sinha et al. (2003), and Lack et al. (2008) that are used in the SPEW model, as described in Lamarque et al. (2010). [b] Weighted average. [c] BC emissions factor from Shina et al. (2003). [d]Buhaug et al. did not estimate BC emissions directly, but cited an estimate of BC emissions in 2007 from an In Press version of Eyring et al. (2010); the BC emissions estimate was the same in the In Press and published version. [e]This study predicts a range of BC EFs of 0.22 g/kg fuel to 0.33 g/kg fuel with a middle estimate of 0.27 g/kg fuel, resulting in a range of 54 kt BC to 81 kt BC and a best estimate of 67 kt BC.

6 BLACK CARBON EMISSION REDUCTION SCENARIOS

Several technologies and operational practices can reduce BC emissions from ships. This section explores the BC reduction potential of four scenarios:

1. All ships switched from residual fuel to distillate
2. Some ships switch to LNG from residual fuel or distillate
3. Some ships install scrubbers

4. Some ships use DPFs

6.1.1 *Scenario 1 – All ships switch from residual to distillate fuels*

As described earlier, evidence suggests that burning distillate fuel emits less BC than residual fuel. If all ships that use residual fuel switched to distillate fuel, total BC emissions from ships would have decreased from 67 kt to 33 kt in 2015. This suggests that simply switching all ships operating on residual fuel to distillate fuel can halve global BC emissions from ships. Figure 18 shows the BC reduction potential of switching from residual fuel to distillate for the top 14 emitting ship classes. BC emissions from container ships, the most polluting ship class, could be brought from 16.7 kt to 5.9 kt by operating exclusively on distillate fuel, a reduction of nearly 65%. Similarly, bulk carrier emissions could drop from 12 kt to less than 4 kt, a 67% reduction. The opportunities for BC reduction under this scenario are limited to ship classes that primarily use residual fuel, which tend to be larger ships; smaller ships, such as fishing vessels, service vessels, and offshore supply vessels would see modest BC reductions, as most operate on distillate already.

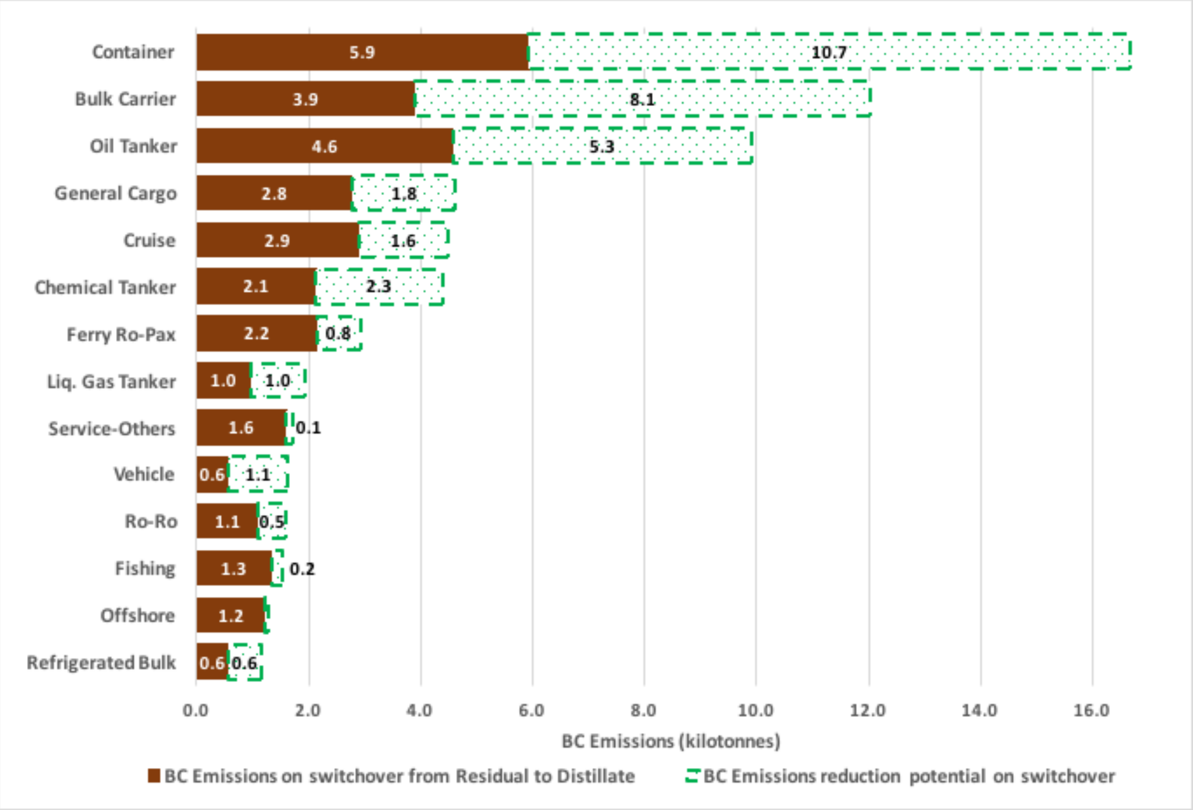


Figure 18: Black carbon reduction potential for fuel switching (residual to distillate) by major ship class

6.1.2 *Scenario 2 – Some ships switch to LNG from Residual or Distillate fuel oil*

LNG fuel emits very little BC. As such, switching from residual or distillate fuels to LNG offers substantial BC reduction potential. Converting to LNG is challenging, since most ships would need to convert their engine and fuel systems in order to operate on LNG. However, as ship air pollution regulations become more stringent, and if the price of LNG remains low compared to other fuels, some ships will convert to LNG. Figure 19 shows the BC reduction potential of ships switching to LNG from residual fuel or distillate. Note that as the proportion of ships operating on LNG increases, BC emissions decrease. If 20% of fuel (based on energy use) in 2015 had switched to LNG, BC emissions would have dropped from 67.4 kt to 54.5 kt, a 19% decrease. In fact, because LNG emits such small amounts of BC, every 10% replacement of residual fuel or distillate with LNG reduces BC by nearly 10%. While switching to LNG can reduce BC emissions and other air pollutants, care must be taken to minimize methane slip throughout the LNG fuel lifecycle, as methane is a potent climate warming pollutant. One way to minimize methane slip is to use marine dual fuel engines that operate on the Diesel-cycle rather than the Otto-cycle.

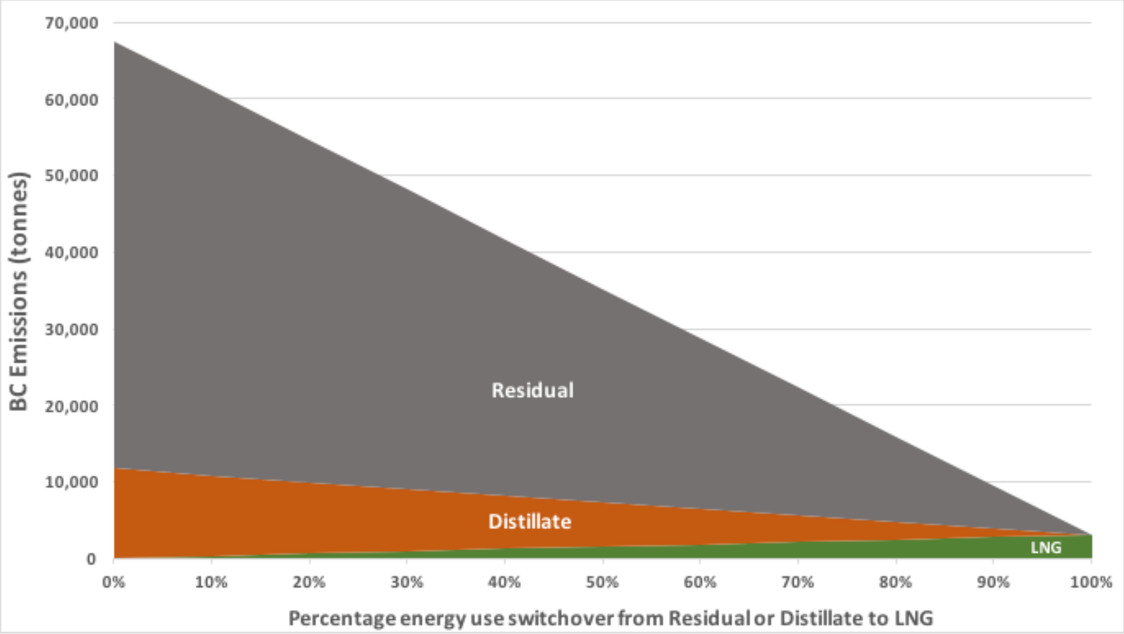
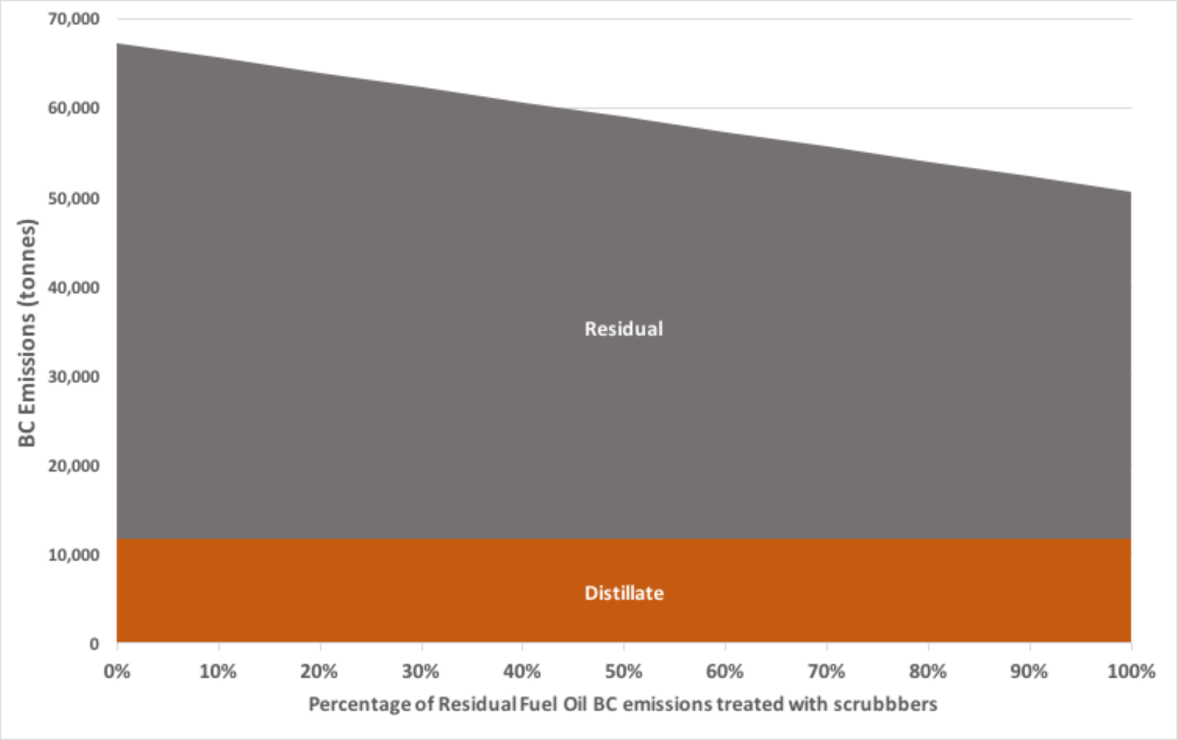


Figure 19: Black carbon reduction potential on switching over to LNG from Residual or Distillate fuel

6.1.3 Scenario 3 – Some ships install exhaust gas cleaning systems

Recent research (UCR, 2016) suggests that exhaust gas cleaning systems, such as scrubbers, can reduce marine BC emissions by roughly 30%. Some ships, primarily cruise ships, have installed scrubbers to comply with ECA sulfur emissions standards. Other ships are expected to install scrubbers to comply with new 2020 global 0.5% fuel sulfur standards,. Note that only ships operating on high-sulfur residual fuel, such as residual fuel, will use scrubbers. Assuming scrubbers reduce BC emissions by 30% on average, Figure 20 shows the BC reduction potential as a function of scrubber uptake. For example, in 2015, if scrubbers were installed on ships that represented 20% of residual fuel consumption, BC from residual fuel-powered ships would fall by 3.3 kt, representing a 6% reduction from residual fuel-powered ships and a total reduction of

5% for all ships. If all ships operating on residual fuel installed scrubbers, BC could be reduced by 16,700 t, representing a 30% reduction in BC from residual fuel-powered ships and a total reduction in BC of 25% for all ships, based on 2015 residual fuel consumption and BC emissions.



*LNG BC emissions, although included, are too small to be visible

Figure 20: Black carbon reduction potential for installing scrubbers on ships operating on Residual fuel

6.1.4 Scenario 4 – Some ships install diesel particulate filters

DPFs can drastically reduce BC emissions. NRC Canada estimates that DPFs can reduce BC 70-90%; Johansen showed that catalyzed DPFs with reverse pulse flow (for ash removal) can reduce PM by 80-92%, even when operating on HFO (1% S), evidenced by DPF performance on the *Queen Victoria* cruise ship's 8.6 MW 4-stroke engine. For this scenario, we assume that DPFs reduce BC emissions by 85% and that only ships operating on distillate fuel are suitable candidates for DPF retrofits, as suggested by the literature. While DPFs can work with HFO in some cases, DPFs are more likely to operate well when paired with higher quality distillate fuel, which have lower sulfur and ash contents and fewer impurities that can damage the filters. Figure 21 shows BC reduction as a function of DPF uptake for ships operating on distillate fuel. If 50% of distillate fuel consumption was treated with a DPF, BC would fall by 5 kt – a 58% reduction in distillate BC emissions and a 7% reduction in total BC emissions from all fuels.

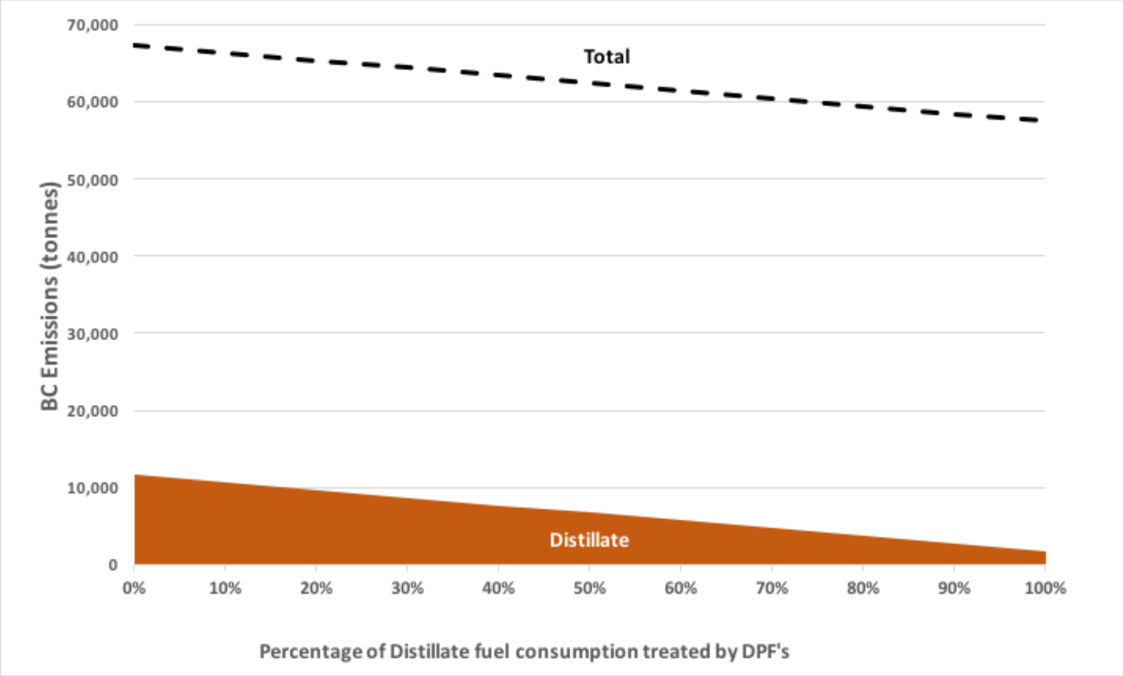


Figure 21: Black carbon reduction potential for installing DPFs on ships operating on distillate fuel

7 POLICY ALTERNATIVES TO REDUCE BLACK CARBON EMISSIONS

Left unregulated, BC will continue to be emitted unabated from ships, threatening not only the climate but also human health. Despite the implementation of the 0.5% global fuel sulfur cap in 2020, 0.5% sulfur compliant fuels may be blends of residual fuel and lower sulfur distillate fuels that are just as harmful to the environment as residual fuel. Several policy alternatives to reduce the damage from ship BC emissions are possible.

7.1.1 Alternative 1 – Expanding or establishing more Emission Control Areas

Expanding existing ECAs or establishing new ECAs could reduce BC emissions. To comply with an ECA, many ships would switch to distillate fuels, which emit less BC than residual fuels. According to recent data, as analyzed in this study, ships powered by 4-stroke engines could achieve a 40-50% reduction in BC and ships powered by 2-stroke engines could achieve an 80% reduction in BC from fuel switching. Some ships would comply with the ECA fuel sulfur standards by using scrubbers, which may yield BC reductions of 30%; however, the BC reduction potential of scrubbers deserves more study. This study showed the BC reduction potential of ECAs, as shown off the Pacific Coast of North America (Figure 5). However, intense near-coast ship traffic will still result in elevated BC emissions, as seen by high BC emissions in the Baltic Sea and North Sea, despite the Baltic and North Sea SECA. Nevertheless, ECAs are expected to reduce BC emissions compared to emissions in non-ECA areas. The North American ECA currently excludes the Arctic and could be expanded, which would reduce BC emissions in the Arctic. An ECA for China or perhaps all or most of Southeast Asia could greatly reduce BC emissions in this heavily trafficked area of the world. Other areas that would benefit from an ECA include the Mediterranean Sea, the Arabian Sea, the Red Sea (to include the Suez Canal), Mexico, and Central America (to include the Panama Canal).

7.1.2 Alternative 2 – Prohibit the use of residual fuel

Residual fuels, including HFO, residual fuel blends, and desulfurized residual fuel, could be banned globally or in sensitive ecological areas. For example, HFO use and carriage is already banned in the Antarctic and in some of Norway's national park waters surrounding Svalbard in the Arctic Ocean. The risks of HFO in the Arctic are being discussed at the IMO, which could indicate the future prohibition of HFO use in the Arctic. Prohibiting the use of HFO in the entire Arctic would require an international agreement through the IMO, but other regions or governments, such as the European Union or individual countries, could ban HFO in their waters. Researchers have also found that residual fuel blends and desulfurized residual fuel can emit as much or more BC than HFO; thus, prohibiting the use of any residual fuels whatsoever, be them HFO, residual fuel blends, or desulfurized residual fuel, would offer the best chance for BC reductions. If the use *and* carriage of residual fuels were prohibited, one co-benefit would be a reduced economic and environmental risk of residual fuel spills in addition to the climate benefits of lower BC emissions (Comer et al., 2017).

7.1.3 Alternative 3 – Establish a black carbon emissions standard for ships

Following the lead of SO_X, NO_X, and PM standards, a specific BC emission limit could be set forth by the IMO or by individual nations. This regulation could apply to sensitive ecological regions (like the Arctic or coastal waterways), or even extend to all ships. Typically, policies set emissions limits and leave it up to the regulated party to decide how to comply, rather than mandating the use of a particular control technology. For example, the U.S., the EU, and China have promulgated PM limits for all but the smallest and largest domestic ships which will also reduce BC emissions; however, one could envision a standard that specifically targets BC and standards that apply to all domestic ships. In this case, BC emissions could be reduced using BC control technologies, such as DPFs, or by using low- or zero-BC fuels (e.g., LNG, hydrogen, etc.). Governments could use taxes, grants, subsidies, or financing tools (e.g., provide or guarantee loans) to reward ship owners and operators that adopt BC control technologies, cleaner fuels, or novel auxiliary power or propulsion technologies (e.g., fuel cells). Governments could also invest in alternative fuel infrastructure that private companies may be unwilling to undertake, as often a shift toward cleaner technologies is a "chicken-and-egg" problem.

7.1.4 Alternative 4 – Include BC in GHG reduction strategies

The IMO has begun a process to develop a comprehensive strategy to reduce GHG emissions from ships, with a initial strategy expected in 2018 and a final strategy in 2023. This strategy will certainly focus on reducing CO_2 emissions from ships but could also include other climate pollutants, including BC and CH_4 and BC. Fuel consumption data will be collected from most commercial ships (ships 5000 gt or more) beginning in 2019 to estimate CO_2 emissions from those ships; BC emissions could also be estimated and used to inform the IMO GHG reduction strategy for ships. Including BC in this strategy would drive the adoption of BC reduction technologies over time.

7.1.5 Alternative 5 – Promote vessel scrappage

Newer ships, with newer engines, likely emit less BC than older ships. Ships have a long useful life, but to date most new emissions regulations have applied to new ships, sparing the existing fleet. One ship, operating in the fresh waters of the North American Great Lakes, recently retired after more than 100 years in service, but more common ship lifetimes for "salties" (ships that operate on the ocean) are in the range of 25-35 years. While the long life of ships is good from a business perspective, fleet turnover can delay the effectiveness of regulations that reduce pollution from ships, improve environmental quality and protect human health. Governments can encourage fleet turnover and retirement of the oldest ships in the fleet by promoting vessel scrappage, as China is doing[20], or by exercising Port State control, restricting access to their ports to newer ships.

7.1.6 Alternative 6 – Promote shore power

Shore power can greatly reduce air emissions in port, improving local air quality. In nearly all cases, shore power reduces total air and climate pollutant emissions compared to burning HFO and distillate; the level of emissions reductions depends on the source of electricity. Connecting to shore power in port can greatly reduce BC emissions from ships at berth. Shore power connections are becoming increasingly common on cruise ships, container ships, ro-ro, and ro-pax ships. Shore power is available at several ports throughout the world, including large ports such as the Port of Shenzhen in China and the Ports of Long Beach and Oakland in California. Additionally, California requires a portion of ships calling on its ports to connect to shore power at berth. China is actively promoting shore power in its three Domestic Emission Control Areas (DECAs) as one alternative to comply with a low sulfur fuel requirement in those areas (Mao, 2016). Other governments could implement similar measures to promote shore power.

The policy alternatives presented above could be applied at the global, regional, national, or subnational scales. Global policies tend to deliver the greatest benefits to the marine environment; however, in some cases, it may be prudent to implement policies at the national or regional level to protect sensitive areas and to serve as a model for international policy actions. Unilateral or multilateral actions to control international shipping emissions can catalyze global IMO regulations to maintain a level playing field in the global shipping industry.

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[20] Ministry of Finance of the People's Republic of China, Regulations of providing subsidies for ship's early scrappage or demolition and the standardization of ship types, Retrieved on May 8, 2017 from: http://www.mof.gov.cn/zhengwuxinxi/caizhengwengao/wg2015/wg201512/201604/t20160421_1960412.html.

8 CONCLUSIONS

Shipping poses largely unregulated risks to the global environment. The fuels ships use, especially residual fuels like HFO, endanger ocean and coastal ecosystems not only through the threat of oil spills, but also because burning these fuels emits harmful air and climate pollutants. Understanding the quantity of residual fuel that is used and carried along with how much BC is emitted can inform international policy discussions on ways to address the risks of shipping to the environment, especially risks to sensitive ecological areas such as the Arctic. This study produced a geospatially allocated global inventory of ship BC emissions, residual fuel use, and residual fuel carriage in 2015. Emissions of other air and climate pollutants and the use and carriage of other marine fuels were also estimated.

The global shipping fleet consumed 1.2 trillion kWh of energy in 2015, enough to power California for 6 years. This energy consumption results in air and climate pollution emissions, including BC. BC is emitted nearly everywhere throughout the globe, even in the Arctic and Antarctic, and 74% of BC from ships is emitted in the northern hemisphere. Furthermore, BC is mainly emitted near the coast, where it can degrade local air quality.
Ships emitted approximately 67 (54 to 81) kt of BC in 2015, corresponding to a fleet-wide average BC EF of 0.27 (0.22 to 0.33) g/kg fuel. Accounting for BC's global warming potential, ship BC emissions were responsible for 6-8% (100-year timescale) and 18-24% (20-year timescale) of the CO_{2eq} climate warming impact from shipping in 2015.

Eighty-three percent (83%) of BC from ships came from burning residual fuels, such as HFO, and ships with 2-stroke SSD MEs are responsible for two-thirds (66%) of global BC emissions. Further, just six flag states - Panama, Liberia, China, Marshall Island, Singapore, and Malta - accounted for more than half of BC emissions from global shipping. Larger ships are responsible for the most BC emissions. Container ships, bulk carriers, and oil tankers together emit 58% of BC emissions, while accounting for 20% of the ships and 81% of DWT in the global fleet. Within that group, container ships, which make up 7% of ships and 14% of DWT in the global fleet, emit more BC (25%) than other ship classes. Outside that group, cruise ships account for a disproportionately large amount of BC, emitting 7% of BC emissions despite accounting for only 1% of the number of ships and less than 1% of DWT in the global fleet. On average, a cruise ship emitted more than 11 t per ship in 2015, or greater than three times a typical container ship (3.3 t) and equal to about 4,600 Euro V heavy-duty trucks operating 100,000 kilometers over one year.

Regarding fuels, residual fuel use and carriage occurs across the globe, including the polar regions. The global fleet consumed an estimated 247 million tonnes of fuel in 2015, consisting of 196 million tonnes of residual fuel, 45 million tonnes of distillate, and less than 6 million tonnes of LNG. In general, residual fuel use and carriage is most heavily concentrated along major trade routes and coastal areas such as the Chinese coast down to the Singapore straits. The 0.1% sulfur limit for marine fuels in these areas means that residual fuels, such as HFO, are essentially prohibited in the North American, U.S. Caribbean Sea, Baltic Sea, and North Sea SECA regions.

Most of residual fuel (74%) was consumed by ships with 2-stroke SSD MEs, and container ships were responsible for 30% of residual fuel consumption, more than any other ship class. Five flag states accounted for more than 57% of residual fuel consumption by ships in 2015: Panama (37 Mt), Liberia (24 Mt), China (24 Mt), Marshall Islands (17 Mt) and Singapore (15 Mt). The use and carriage of residual fuels, such as HFO, poses risks from not only fuel oil spills, but also from air and climate pollution.

Given the need to reduce climate pollutants from shipping, four BC reduction scenarios were analyzed. The first scenario presented that all ships operating on residual fuel switched to distillate fuel. Under this scenario, BC emissions would drop from 67 kt to 33 kt in 2015. This means that if all ships operated on distillate fuel, total BC emissions could be cut in half. The second scenario assumed that some ships switched to LNG instead of operating on residual fuel or distillate. While using LNG emits climate pollutants, including CO_2 and CH_4, BC emissions are miniscule and other air pollutants, such as SO_x and NO_x are greatly reduced as well. Because LNG emits such small amounts of BC, every 10% replacement of oil-based fuels with LNG reduces BC by nearly 10%. Therefore, a 50% switchover from oil-based fuels to LNG reduces BC by 48%. Scenario 3 explored the BC reduction potential of exhaust gas cleaning systems, such as scrubbers, that are designed to reduce the sulfur emissions from ship exhaust. BC could be reduced by 16,700t, representing a 30% reduction in BC from residual fuel-powered ships and a total reduction in BC of 25% for all ships, based on 2015 residual fuel consumption and BC emissions. The final scenario considers the impact of installing DPFs, which reduce BC by approximately 85%. If 50% of distillate fuel consumption was treated with a DPF, BC would fall by 58% for that fuel, but total BC emissions from ships would decline only 7%, as distillate makes up only 18% of total fuel consumption for ships in the global fleet.

Parts of these scenarios are likely to happen in the future even without policy action. Some ships will switch from HFO to distillate fuels to comply with the 2020 0.5% global fuel sulfur cap instead of taking their chances with newly formulated fuels that could potentially damage their equipment or pose a safety hazard. Other ships will switch to LNG and newly built LNG ships will enter the fleet to take advantage of the low price of LNG fuels compared to traditional bunker fuels and to meet increasingly stringent air pollution regulations. Ships that wish to take advantage of cheap HFO fuel will install scrubbers rather than switching to 0.5% sulfur fuel. Some ships will install DPFs, especially harbor craft and smaller vessels that operate on distillate fuels, if governments insist on finding ways to reduce PM pollution in ports and near shore. Cruise ships may also start to install DPFs to please residents and governments at ports of call and to please their customers. The total impact on BC emissions under BAU is yet to be seen, and the best way to ensure BC reductions from ships is through policy action.

Several policy alternatives that can reduce the impacts of BC emissions and residual fuel use and carriage on human health and the environment can be considered. These include expanding or establishing ECAs, prohibiting the use of residual fuel, establishing a BC emissions standard for ships, including BC in GHG reduction strategies, promoting vessel scrappage, and promoting shore power. While all can reduce BC emissions from ships, some are more likely to meaningfully reduce these emissions. Based on the results presented here, three policy alternatives, if implemented together, could offer greater BC reduction potential. These include: prohibiting the use of residual fuels, establishing a BC emissions standard for ships, and including BC in GHG reduction strategies.

Let us consider the larger BC reductions that could be achieved by prohibiting the use of residual fuels, establishing a BC emissions standard for ships, and including BC in GHG reduction strategies. Prohibiting the use of residual fuel would immediately reduce BC emissions from the existing fleet by more than 50%, as evidenced in the first BC reduction scenario. However, BC emissions would still threaten human health and the environment. This is evident when one considers that elevated BC emissions persist in ECAs, areas where we assume no residual fuel is consumed for the purposes of this work. Thus, the next step could be to establish a BC emissions standard for engines on new, and perhaps existing, ships to encourage a switch to near zero BC fuels or the use of control technologies such as DPFs. Emissions limits for ships in the existing fleet could encourage operational practices, such as slow steaming with engine derating, to reduce BC. Emissions limits for newbuilds could be set at a level that strongly encourages ships that continue to use oil-based fuels, such as distillate, to treat their exhaust with DPFs. One could also envision BC emissions limits for ships operating in ECAs or other special areas to protect human health and the environment. The fourth scenario showed that if 50% of distillate fuel consumption was treated with a DPF, BC emissions would fall 58% for that fuel, but total BC emissions from ships would decline only 7% because distillate represents less than one-fifth of fuel consumption from ships. However, if the use of residual fuels was already prohibited, one barrier to retrofitting ships (fuel quality) with DPFs would be reduced, as DPFs work best when paired with distillate fuels that have much lower levels of contaminants than HFO, including substantially lower ash content, lessening the frequency of clogging and increasing the lifetime of the filters. As DPFs are expected to reduce BC emissions by approximately 85%, total BC emissions would be reduced by nearly 93% from 2015 levels from a combination of prohibiting the use of residual fuels and establishing a BC emissions standard that limits BC at a level that would require the use of DPFs.[21] Including BC in the comprehensive IMO strategy to reduce GHG emissions may be justified, given that BC represents 6-24% of the $CO_{2\text{-eq}}$ warming impact from shipping in 2015. This would provide a policy driver to implement these alternatives and would ensure that BC, a climate warming pollutant, is not left out of a plan to reduce the climate warming impacts of ships.

An ambitious, but perhaps more reasonable BC policy recommendation could include some combination of the following solutions:

- **Retrofit cruise ships with diesel particulate filters or scrubbers**
    - Cruise ships emit the most BC per ship, on average. Ideally, a ship would be retrofitted with a DPF, which can reduce BC by 85%. Some smaller ships have tested out DPFs with some success; however, few larger ships have tried to

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[21] To take a simple example, assume BC emissions were 100 units in 2015. Switching all ships that operate on residual fuel to distillate reduces BC by 51%, leaving 49 units. A DPF is expected to reduce BC by 85%, leaving a bit more than 7 units of BC from ships, for a total reduction of approximately 97%.

retrofit with a DPF, likely because there is no incentive or regulatory driver to do so. Unlike most large ships, cruise ships tend to use 4-stroke MSD engine sets, engines similar to those used on smaller vessels. Thus, cruise ships may be a good ship class to test DPFs on larger ships. Scrubbers for marine vessels, which reduce BC emissions on the order of 30%, are commercially available for passenger and cargo ships and will become increasingly affordable as the 0.5% global fuel sulfur standard in 2020 increasing the cost of baseline fuels. The cruise industry has taken the lead in retrofitting their ships with scrubbers to comply with ECA sulfur emissions standards and more cruise ships are expected to retrofit with scrubbers to comply with the 0.5% global fuel sulfur standard. Thus, it may be reasonable to retrofit the majority of the global cruise fleet with either a DPF or scrubber in the near term.

- **Establish ECAs in heavily trafficked and sensitive areas**
    - ECAs encourage the use of distillate fuels, which emit 40-80% less BC than residual fuels. In contrast to requirements for newbuild vessels, ECAs reduce emissions from the existing fleet immediately upon entering into force. Based on this research, ECAs in East and Southeast Asia, the Red Sea, and the Mediterranean Sea would seem to offer the greatest BC reduction benefits. Extending the North American ECA and the North Sea ECA to the Arctic and establishing ECAs around Iceland, Greenland, and Russia would offer additional protections to the Arctic.
- **Make shore power the norm for major ports and major ship classes**
    - Shore power can greatly reduce air pollution, including BC, in port. Several major ports have shore power connections for container, cruise, and roro vessels, but the use of shore power is limited by the number of berths with shore-side connections and the number of ships with ship-side connections. Exercising port state control, California requires that most passenger ships (including cruise ships), container ships, and refrigerated cargo ships connect to shore power when at berth in their ports. Ports in other regions could follow suit. This would encourage more ships to adopt ship-side shore power connections and could have a cascading effect of increasing demand for shore power in ports around the world, with concomitant reductions in BC and other air and climate pollutants.
- **Prohibit the use of residual fuels in the Arctic and require diesel particulate filters for some ships**
    - While BC from ships warms the entire planet, the worst damage is sustained in the Arctic. Prohibiting the use of residual fuel in the Arctic would immediately reduce BC emissions in a region warming twice as fast as the rest of the planet and would have the added benefit of reducing the risks of HFO spills in sensitive Arctic ecosystems. Requiring some ships to use DPFs would reduce the deposition of BC from ships to Arctic snow and ice, where it reduces albedo, increases melt, and accelerates warming. Several ship types could be targeted for maximum benefit. Cruise ships operating in the Arctic could be retrofit with DPFs to protect the Arctic that their customers are paying to see. Progressive flag states could also retrofit their fishing vessels with DPFs, which are the largest

source of BC in the IMO Arctic (Comer et al. 2017).

Implementing these strategies would not only reduce climate warming BC emissions, but would also reduce emissions of other air and climate pollutants. The exact BC reduction potential, in tonnes and percent, of such an approach could be estimated in future work. However, the net effect would be fewer premature mortalities and morbidities from ship emissions, lower risks of economically and ecologically damaging residual fuel spills, and less climate warming impacts from ships.

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10 APPENDIXES

Appendix A. Ship types represented

Ship class	Ship type	Ship class	Ship type	Ship class	Ship type
Bulk carrier	Aggregates carrier	General Cargo continued	Open hatch cargo ship	Naval ship	Aircraft carrier
	Bulk carrier		Palletized cargo ship		Command vessel
	Bulk carrier, Laker only		Pipe carrier		Corvette
	Bulk carrier, self-discharging		Replenishment dry cargo vessel		Frigate
	Bulk carrier, self-discharging, Laker		Stone carrier		Helicopter carrier
	Bulk cement storage ship		Yacht carrier, semi submersible		Infantry landing craft
	Bulk/caustic soda carrier (cabu)	Liquefied gas tanker	CNG tanker		Landing ship (dock type)
	Bulk/oil carrier (obo)		CO_2 tanker		Logistics vessel (naval Ro-Ro cargo)
	Cement carrier		Combination gas tanker (LNG/LPG)		Mine hunter
	Limestone carrier		LNG tanker		Tank landing craft
	Ore carrier		LPG tanker		Unknown function, naval/naval auxiliary
	Ore/oil carrier		LPG/chemical tanker		Weapons trials vessel
	Powder carrier	Miscellaneous-fishing	Factory stern trawler	Non propelled	Bitumen tank barge, non propelled
	Refined sugar carrier		Fish carrier		Bulk cement barge, non propelled
	Urea carrier		Fish factory ship		Cement storage barge, non propelled
	Wood chips carrier		Fish farm support vessel		Chemical tank barge, non propelled
Chemical tanker	Bulk/sulfuric acid carrier		Fishery patrol vessel		Covered bulk cargo barge, non propelled
	Chemical tanker		Fishery research vessel		Crane vessel, non propelled
	Chemical/products tanker		Fishery support vessel		Deck cargo pontoon, non propelled
	Edible oil tanker		Fishing vessel		Deck cargo pontoon, semi submersible
	Latex tanker		Kelp dredger		Desalination pontoon, non propelled
	Molten sulfur tanker		Live fish carrier (well boat)		General cargo barge, non propelled
	Vegetable oil tanker		Seal catcher		Hopper barge, non propelled
	Wine tanker		Stern trawler		Jacket launching pontoon, semi submersible
Container	Container ship (fully cellular)		Trawler		Linkspan/jetty
	Container ship (fully cellular/Ro-Ro facility)		Whale catcher		LPG tank barge, non propelled
	Passenger/container ship	Miscellaneous-other	Chemical tanker, inland waterways		Mechanical lift dock
Cruise	Passenger/cruise		Chemical/products tanker, inland waterways		Mooring buoy
Ferry-pax only	Passenger ship		Container ship (fully cellular), inland waterways		Museum, stationary
Ferry-ro-pax	Passenger/landing craft		Cruise ship, inland waterways		Pontoon (function unknown)
	Passenger/Ro-Ro ship (vehicles)		Dredging, inland waterways		Power station pontoon, non propelled
	Passenger/Ro-Ro ship (vehicles/rail)		Exhibition vessel		Products tank barge, non propelled
General cargo	Barge carrier		General cargo, inland waterways		Restaurant vessel, stationary
	Deck cargo ship		Incinerator		Sheerlegs pontoon
	General cargo ship		Lighthouse tender		Steam supply pontoon, non propelled
	General cargo ship (with Ro-Ro facility)		Mission ship		Trans shipment barge, non propelled
	General cargo ship, self-discharging		Oil tanker, inland waterways		Water tank barge, non propelled

	General cargo/passenger ship		Other activities, inland waterways		Work/maintenance pontoon, non propelled
	General cargo/tanker		Passenger ship, inland waterways	Non-ship structure	Air cushion vehicle passenger
	Heavy load carrier		Passenger/Ro-Ro ship (vehicles), inland waterways		Air cushion vehicle passenger/Ro-Ro (vehicles)
	Heavy load carrier, semi submersible		Pearl shells carrier		Car park
	Livestock carrier		Ro-Ro cargo ship, inland waterways		Floating dock
	Nuclear fuel carrier		Shopping complex		Wing in ground effect vessel
	Nuclear fuel carrier (with Ro-Ro facility)		Towing/pushing, inland waterways		

Ship class	Ship type
Offshore	Accommodation platform, jack up
	Accommodation platform, semi submersible
	Accommodation ship
	Accommodation vessel, stationary
	Crane platform, jack up
	Crane vessel
	Diving support platform, semi submersible
	Drilling rig, jack up
	Drilling rig, semi submersible
	Drilling ship
	Gas processing vessel
	Maintenance platform, semi submersible
	Offshore construction vessel, jack up
	Offshore support vessel
	Offshore tug/supply ship
	Pile driving vessel
	Pipe burying vessel
	Pipe layer
	Pipe layer crane vessel
	Pipe layer platform, semi submersible
	Platform supply ship
	Production testing vessel
	Standby safety vessel
	Supply platform, jack up
	Support platform, jack up
	Trenching support vessel
	Well stimulation vessel
Oil tanker	Asphalt/bitumen tanker
	Coal/oil mixture tanker
	Crude oil tanker
	Crude/oil products tanker
	Products tanker
	Shuttle tanker
	Tanker (unspecified)
Other liquid tankers	Alcohol tanker
	Caprolactam tanker
	Molasses tanker
Service-other	Anchor handling tug supply
	Anchor handling vessel
	Backhoe dredger
	Bucket ladder dredger
	Bucket wheel suction dredger
	Bunkering tanker
	Buoy & lighthouse tender
	Buoy tender
	Cable layer
	Crew boat
	Crew/supply vessel
	Cutter suction dredger
	Diving support vessel
	Dredger (unspecified)
	Dredging pontoon, unknown dredging type
	Effluent carrier
	Fire fighting vessel
	FPSO, oil
	FSO, oil
	Grab dredger
	Grab dredger pontoon
	Grab hopper dredger
	Hopper, motor
	Hopper/dredger (unspecified)
	Hospital vessel
	Icebreaker
	Icebreaker/research
	Mining vessel
	Mooring vessel
	Patrol vessel
	Pilot vessel
	Pollution control vessel
	Power station vessel
	Research survey vessel
	Sailing vessel
	Salvage ship
	Search & rescue vessel
Service-other continued	Utility vessel
	Vessel (function unknown)
	Waste disposal vessel
	Water-injection dredging pontoon
	Work/repair vessel
Service-tug	Articulated pusher tug
	Pusher tug
	Tug
Vehicle	Vehicles carrier
Yacht	Sail training ship
	Theatre vessel
	Yacht
	Yacht (sailing)

	Replenishment tanker		Suction dredger
	Water tanker		Suction dredger pontoon
Refrigerated bulk	Fruit juice carrier, refrigerated		Suction hopper dredger
	Refrigerated cargo ship		Supply tender
Ro-Ro	Container/Ro-Ro cargo ship		Tank cleaning vessel
	Landing craft		Trailing suction hopper dredger
	Rail vehicles carrier		Training ship
	Ro-Ro cargo ship		Trans shipment vessel

Appendix B. Ship capacity bin by ship class.

Ship class	Capacity bin	Capacity	Unit	Ship class	Capacity bin	Capacity	Unit
Bulk carrier	1	<10000	dwt	Other liquid tankers	1	All	dwt
	2	10000-35000		Ferry-pax only	1	<2000	gt
	3	35000-60000			2	>2000	
	4	60000-100000		Cruise	1	<2000	gt
	5	100000-200000			2	2000-10000	
	6	>200000			3	10000-60000	
Chemical tanker	1	<5000	dwt		4	60000-100000	
	2	5000-10000			5	>100000	
	3	10000-20000		Ferry-ro-pax	1	<2000	gt
	4	>20000			2	>2000	
Container	1	<1000	teu	Refrigerated bulk	1	<2000	dwt
	2	1000-2000		Ro-Ro	1	<5000	gt
	3	2000-3000			2	>5000	
	4	3000-5000		Vehicle	1	All	gt
	5	5000-8000		Yacht	1	All	gt
	6	8000-12000		Service-tug	1	All	gt
	7	12000-14500		Miscellaneous-fishing	1	All	gt
	8	>14500		Offshore	1	All	Gt
General cargo	1	<5000	dwt	Service-other	1	All	gt
	2	5000-10000		Miscellaneous-other	1	All	gt
	3	>10000					
Liquefied gas tanker	1	<50000	Cubic meters				
	2	50000-200000					
	3	>200000					
Oil tanker	1	<5000	dwt				
	2	5000-10000					
	3	10000-20000					
	4	20000-60000					
	5	60000-80000					
	6	80000-120000					
	7	120000-200000					

	8	>200000	

Appendix C. Linear regression used to determine the main fuel capacity

Main Fuel Capacity = DWT*DWT Beta + DWT Intercept or = GT*GT Beta + GT Intercept

Ship Class	DWT R^2	GT R^2	DWT Intercept	DWT Beta	GT Intercept	GT Beta	All Ships Intercept (corresponds with GT)	All Ships Beta (corresponds with GT)
Offshore	0.35	0.38	315.71	0.124	214.75	0.118	233.53	0.059
Naval ship	0.47	0.72	1329.89	0.114	285.15	0.098	233.53	0.059
Service-other	0.69	0.70	387.72	0.027	336.41	0.049	233.53	0.059
Miscellaneous-other	0.22	0.33	33.28	0.043	5.50	0.069	233.53	0.059
Fishing	0.57	0.65	92.19	0.234	64.76	0.170	233.53	0.059
Non propelled	0.36	0.72	77.01	0.054	-23.70	0.086	233.53	0.059
Other liquid tankers	0.85	0.90	37.55	0.045	20.46	0.064	233.53	0.059
Service-tug	0.67	0.73	53.45	0.586	-6.91	0.490	233.53	0.059
Yacht	0.26	0.62	59.91	0.208	28.32	0.091	233.53	0.059
Bulk carrier	0.90	0.91	683.89	0.024	510.39	0.047	233.53	0.059
General cargo	0.66	0.73	53.45	0.056	20.35	0.083	233.53	0.059
Chemical tanker	0.81	0.81	223.34	0.029	195.68	0.049	233.53	0.059
Container	0.90	0.89	212.55	0.091	664.68	0.093	233.53	0.059
Cruise	0.83	0.81	203.67	0.275	385.10	0.026	233.53	0.059
Ferry-pax only	0.55	0.48	-36.92	0.707	-58.05	0.204	233.53	0.059
Ferry-ro-pax	0.66	0.69	54.72	0.130	61.20	0.030	233.53	0.059
Liquefied gas tanker	0.77	0.76	170.76	0.062	397.44	0.049	233.53	0.059
Oil tanker	0.96	0.96	250.30	0.025	144.86	0.049	233.53	0.059
Ro-Ro	0.72	0.69	207.76	0.088	238.34	0.051	233.53	0.059
Non ship	0.92	0.00	11.06	0.039	13.72	0.000	233.53	0.059
Refrigerated bulk	0.57	0.61	230.13	0.117	211.54	0.130	233.53	0.059

Appendix D. Auxiliary engine power demand (kW) by phase, ship class and capacity bin

ship class	ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	capacity unit	ship class	ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	capacity unit
Bulk carrier	<10000	190	310	280	190	dwt	Oil tanker	<5000	250	375	250	250	dwt
Bulk carrier	10000-35000	190	310	280	190		Oil tanker	5000-10000	375	563	375	375	
Bulk carrier	35000-60000	260	420	370	260		Oil tanker	10000-20000	625	938	625	625	
Bulk carrier	60000-100000	420	680	600	420		Oil tanker	20000-60000	750	1125	750	750	
Bulk carrier	100000-200000	420	680	600	420		Oil tanker	60000-80000	750	1125	750	750	
Bulk carrier	>200000	420	680	600	420		Oil tanker	80000-120000	1000	1500	1000	1000	
Chemical tanker	<5000	80	110	160	80	dwt	Oil tanker	120000-200000	1250	1875	1250	1250	
Chemical tanker	5000-10000	230	330	490	230		Oil tanker	>200000	1500	2250	1500	1500	
Chemical tanker	10000-20000	230	330	490	230		Other liquid tankers	~	500	750	500	500	dwt
Chemical tanker	>20000	550	780	1170	550		Ferry-pax only	<2000	186	186	186	186	gt
Container	<1000	300	550	340	300	teu	Ferry-pax only	>2000	524	524	524	524	
Container	1000-2000	820	1320	600	820		Cruise	<2000	450	580	450	450	gt
Container	2000-3000	1230	1800	700	1230		Cruise	2000-10000	450	580	450	450	
Container	3000-5000	1390	2470	940	1390		Cruise	10000-60000	3500	5460	3500	3500	
Container	5000-8000	1420	2600	970	1420		Cruise	60000-100000	11480	14900	11480	11480	
Container	8000-12000	1630	2780	1000	1630		Cruise	>100000	11480	14900	11480	11480	
Container	12000-14500	1960	3330	1200	1960		Ferry-ro-pax	<2000	105	105	105	105	gt
Container	>14500	2160	3670	1320	2160		Ferry-ro-pax	>2000	710	710	710	710	
General cargo	<5000	60	90	120	60	dwt	Refrigerated bulk	<2000	1170	1150	1080	1080	dwt
General cargo	5000-10000	170	250	330	170		RoRo	<5000	600	1700	800	800	gt
General cargo	>10000	490	730	970	490		RoRo	>5000	950	2720	1200	1200	
Liquefied gas tanker	<50000	240	360	240	240	cubic metres	Vehicle	~	500	1125	800	800	gt
Liquefied gas tanker	50000-200000	1710	2565	1710	1710		Yacht	~	130	130	130	130	gt

Liquefied gas tanker	>200000	1710	2565	1710	1710		Service-tug	~	50	50	50	50	gt
							Miscellaneous-fishing	~	200	200	200	200	gt
							Offshore	~	320	320	320	320	gt
							Service-other	~	220	220	220	220	gt
							Miscellaneous-other	~	190	190	190	190	Gt

Appendix E. Boiler power demand (kW) by phase by ship class and capacity bin

ship class	ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	capacity unit	ship class	ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	capacity unit
Bulk carrier	<10000	0	50	50	50	dwt	Oil tanker	<5000	0	100	500	100	dwt
Bulk carrier	10000-35000	0	50	50	50		Oil tanker	5000-10000	0	150	750	150	
Bulk carrier	35000-60000	0	100	100	100		Oil tanker	10000-20000	0	250	1250	250	
Bulk carrier	60000-100000	0	200	200	200		Oil tanker	20000-60000	150	300	1500	300	
Bulk carrier	100000-200000	0	200	200	200		Oil tanker	60000-80000	150	300	1500	300	
Bulk carrier	>200000	0	200	200	200		Oil tanker	80000-120000	200	400	2000	400	
Chemical tanker	<5000	0	125	125	125	dwt	Oil tanker	120000-200000	250	500	2500	500	
Chemical tanker	5000-10000	0	250	250	250		Oil tanker	>200000	300	600	3000	600	
Chemical tanker	10000-20000	0	250	250	250		Other liquid tankers	~	100	200	1000	200	dwt
Chemical tanker	>20000	0	250	250	250		Ferry-pax only	<2000	0	0	0	0	gt
Container	<1000	0	120	120	120	teu	Ferry-pax only	>2000	0	0	0	0	
Container	1000-2000	0	290	290	290		Cruise	<2000	0	250	250	250	gt
Container	2000-3000	0	350	350	350		Cruise	2000-10000	0	250	250	250	
Container	3000-5000	0	450	450	450		Cruise	10000-60000	0	1000	1000	1000	
Container	5000-8000	0	450	450	450		Cruise	60000-100000	0	500	500	500	
Container	8000-12000	0	520	520	520		Cruise	>100000	0	500	500	500	
Container	12000-14500	0	630	630	630		Ferry-ro-pax	<2000	0	0	0	0	gt
Container	>14500	0	700	700	700		Ferry-ro-pax	>2000	0	0	0	0	

General cargo	<5000	0	0	0	0	dwt
General cargo	5000-10000	0	75	75	75	
General cargo	>10000	0	100	100	100	
Liquefied gas tanker	<50000	100	200	1000	200	cubic metres
Liquefied gas tanker	50000-200000	150	300	1500	300	
Liquefied gas tanker	>200000	300	600	3000	600	
Refrigerated bulk	<2000	0	270	270	270	dwt
RoRo	<5000	0	200	200	200	gt
RoRo	>5000	0	300	300	300	
Vehicle	~	0	268	268	268	gt
Yacht	~	0	0	0	0	gt
Service-tug	~	0	0	0	0	gt
Miscellaneous-fishing	~	0	0	0	0	gt
Offshore	~	0	0	0	0	gt
Service-other	~	0	0	0	0	gt
Miscellaneous-other	~	0	0	0	0	gt

Appendix F. Main engine emission factors for all pollutants except BC (g/kWh)

Pollutant	Engine Tier	Engine Type	HFO (2.5% S)	Distillate (0.14% S)	ECA fuel (0.1% S)	LNG
CO_2		SSD	607	593	593	--
		MSD/HSD	670	658	658	--
		GT/ST	950	962	962	--
		LNG-otto	--	--	--	457
		LNG-diesel	--	--	--	366
NO_X		0-130 rpm	18.10	17.01	17.01	--
		>130 rpm	14.00	13.16	13.16	--
		0-130 rpm	17.00	15.98	15.98	--
		130-1999 rpm	0.94*45*rpm^(-0.2)	0.94*45*rpm^(-0.2)	0.94*45*rpm^(-0.2)	--
		2000+ rpm	9.80	9.21	9.21	--
		0-130 rpm	14.40	13.54	13.54	--
		130-1999 rpm	0.94*44*rpm^(-0.23)	0.94*44*rpm^(-0.23)	0.94*44*rpm^(-0.23)	--
		2000+ rpm	7.70	7.24	7.24	--
		GT	6.10	5.92	5.92	--
		ST	2.10	2.00	2.00	--
		LNG-otto	--	--	--	1.3
		LNG-diesel	--	--	--	5
SO_X		SSD	10.29	0.51	0.37	--
		MSD/HSD	11.35	0.57	0.41	--
		GT/ST	16.10	0.81	0.57	--
		LNG-otto	--	--	--	0.0027
		LNG-diesel	--	--	--	0.0022
PM		SSD	1.42	0.20	0.19	--
		MSD/HSD	1.43	0.20	0.19	--
		GT	0.06	0.01	0.01	--
		ST	0.93	0.11	0.10	--
		LNG-otto	--	--	--	0.03
		LNG-diesel	--	--	--	0.02
CO		SSD/MSD/HSD	0.54	0.54	0.54	--

		GT	0.10	0.10	0.10	--
		ST	0.20	0.20	0.20	--
		LNG-otto	--	--	--	1.30
		LNG-diesel	--	--	--	1.04
CH_4		SSD/MSD/HSD	0.01	0.01	0.01	--
		GT/ST	0.00	0.00	0.00	--
		LNG-otto	--	--	--	8.50
		LNG-diesel	--	--	--	0.94
N_2O		SSD/MSD/HSD	0.03	0.03	0.03	--
		GT/ST	0.05	0.04	0.04	--
		LNG-otto	--	--	--	0.02
		LNG-diesel	--	--	--	0.01

Appendix G. Black carbon emission factors

As noted in in the introduction to this report, BC emission factors from marine engines vary greatly in the literature. Those EFs are based on laboratory and on-board vessels tests measured from different sources using different methods. The BC EFs used to compile global inventories are typically in the range of 0.18 to 1.08 g/kg fuel (See Table 1), with several prominent studies applying a 0.35 g BC/kg fuel emission factor for all fuel types and operating conditions. The evidence presented here suggests that a static BC EF fails to account for differences in engine type, fuel type, and engine load. One recent comprehensive review of BC emission testing (UCR, 2016) assessed the compiled evidence and concluded that "BC emission factors near the lower end of the 0.1 to 1.0 g/kg of fuel range found in the literature likely provide the best estimate for the more prevalent larger marine engines during at sea operation." An approach to develop reasonable assumptions for EFs as a function of engine type, fuel type, and engine load are described herein.

Figure 22 and Figure 23 show the relationship between BC EF (g BC/kg fuel) and engine load (%) for 2-stroke engines operating on residual fuel or distillate fuel and for 4-stroke engines operating on residual fuel or distillate fuel, respectively. All BC EFs were measured using the FSN method with AVL 415S or AVL 415SE smoke meters and converted from FSN units to gBC/kg fuel. The open circles represent raw data from EUROMOT, UCR, and Finnish research. The EUROMOT BC EF data are converted from FSN measurement results to units of gBC/kg fuel using a method advised by EUROMOT (personal communication, MAN Diesel, 17 Nov. 2016) which accounts for exhaust temperature and air flow rate. Table 19 summarizes the data in these two figures, identifying the data source, engine type, fuel type, engine load, and measured BC EF.

The raw data collected on modern, well-maintained marine engines in a laboratory setting points suggests emission factors well below those recommended by UCR (2016) for use in global inventories. For example, as shown in Figure 22, the best fit line to the raw data for two stroke engines using residual fuel indicates a BC EF of 0.09 g/kg fuel at 25% load and 0.06 g/kg fuel at 75% load. EFs for 2-strokes operating on distillate fuel are roughly 80% lower: 0.02 g/kg fuel at 25% load and 0.013 g/kg fuel at 75% load. While we believe the general relationship of increasing BC EFs with decreasing engine load is correct, the BC EFs generated from these raw data may be biased low and therefore not representative of the global fleet, for the following reasons:

- Emissions from generally new, well-maintained engines were tested. Emissions from older in-service engines that may not be as well-maintained are expected to be higher.
- Laboratory testing was completed under steady-state conditions with constant, well-controlled engine speeds. In contrast, emissions may be higher for real marine engines under transient conditions with continual changing wind and wave conditions.
- Emissions from modern Tier II and Tier III engines do not likely represent emissions from ships in the global fleet. The raw BC EF curves represent emissions mainly from Tier II and Tier III engines and a handful of low-hour Tier I engines, and evidence suggests that modern, electronically controlled engines emit less BC than older engines.

Given that 84% of the fleet has Tier 0 or Tier I engines (Table 3), EFs measured from new, well-maintained Tier II and Tier III engines are likely to be lower than those from engines in the global fleet.

- Variations in fuel quality can influence BC EFs in the global fleet. In general, poorer quality fuels emit more BC than higher quality fuels. The test fuels available in Europe and North America may be of higher quality than fuels from other regions.
- The FSN measurement method may report low BC EFs if the sampling period is too short. Japanese researchers using FSN with a longer sampling interval have found higher BC EFs than others, including EUROMOT, that use shorter sampling intervals. It appears that the smoke meters used to measure BC are set to a shorter sampling interval in some regions and a longer sampling interval in others, meaning that while researchers may use the same model of smoke meter, the testing parameters may vary.

Reflecting these factors, the UCR (2016) report recommended BC EFs toward the lower end of the 0.1 to 1.0 g/kg fuel range for global inventory development. We take this to mean that a representative BC EF for fuel consumed in diesel engine powered ships in the global fleet falls somewhere in this range. As shown in Table 15, 2-stroke engines operating on residual fuel accounted for the majority (71%) of fuel oil consumption in 2015. It is reasonable to limit BC EFs to a minimum of 0.1 g/kg fuel for 2-stroke engines operating on residual fuel and to adjust the BC EFs derived from the raw data for other engine type and fuel type combinations accordingly.

First, we took the best fit line for the raw BC EF for a 2-stroke engine operating on residual fuel, represented by the following equation:

$y = 0.0574*(x^{-0.359})$

Note that when $x = 1$, which is equivalent to 100% engine load, an emission factor of 0.0574 g BC per kg of fuel is estimated. To set the minimum BC EF for a 2-stroke engine operating on residual fuel to equal 0.1 g/kg fuel, the equation is modified as follows:

$y = 0.1*(x^{-0.359})$

Now, when $x = 1$, a ship using a 2-stroke engine operating on residual fuel is estimated to emit 0.1 g BC per kg fuel. The equation above defines the "lower bound" for BC EFs for 2-stroke engines operating on residual fuel.

This lower bound equation for the 2-stroke engine operating on residual fuel is subsequently used as a reference to set the BC EF curves for other engine type/fuel type combinations, as described next.

The equations describing the best fit to the raw data take the following form:

$$y = \alpha * (x^{\beta})$$

where

y = black carbon emission factor (gBC/kg fuel)

α = coefficient; equivalent to the black carbon emission factor when engine load equals 100%

x = engine load

β = exponent derived from the best fit power curve

Original best fit equations were as follows:

$2R_0 = 0.0574*(x^{-0.359})$

$2D_0 = 0.0119*(x^{-0.397})$

$4R_0 = 0.0953*(x^{-0.968})$

$4D_0 = 0.0460*(x^{-1.124})$

To maintain the relationship between the BC EFs for 2R, 2D, 4R, and 4D, the coefficients (α) must be modified based on the new coefficient for 2R. See row 2 in Table 18 for the new coefficients that correspond to a 2R coefficient of 0.1. The last row of Table 18 describes the method for deriving the new coefficients based on the relationship between the original 2R, 2D, 4R, and 4D coefficients.

Table 18. Black carbon emission factor coefficients for lower bound curves

		A	B	C	D
		2R*	**2D**	**4R**	**4D**
1	Old Coefficient	0.0574	0.0119	0.0953	0.0460
2	**New Coefficient**	**0.100**	**0.0207**	**0.1660**	**0.0801**
	Equation	--	(B1/A1)*A2	(C1/A1)*A2	(D1/A1)*A2

*2R = 2-stroke engine operating on residual; 2D = 2-stroke engine operating on distillate; 4R = 4-stroke engine operating on residual; 4D = 4-stroke engine operating on distillate

The new coefficients (Table 18) are used to develop the lower bound emission factor equations for each engine type/fuel type pair, denoted by sub-script “L” as follows:

$2R_L = 0.1000*(x^{-0.359})$

$2D_L = 0.0207*(x^{-0.397})$

$4R_L = 0.1660*(x^{-0.968})$

$4D_L = 0.0801*(x^{-1.124})$

Recognizing the uncertainty of developing BC EFs, we developed an upper bound BC EF for each engine type/fuel type pair. Buffaloe et al. (2014) found that on average BC EFs doubled with one positive standard deviation from the mean across three plume intercept studies from ships at sea.[22] The BC EFs here are based on direct, in-stack measurements, but nearly all of the data were from laboratory tests under carefully controlled conditions, and could be biased low, as previously discussed. Thus, we believe doubling the lower bound estimates provides a reasonable range of uncertainty in actual BC emissions from the in-use global fleet. Our best BC EF estimate is the midpoint between the lower and upper bounds at a given engine load. The lower, upper, and best estimate BC EF curves for 2-stroke engines operating on residual or distillate fuels are shown in Figure 24. The same is shown for 4-stroke engines in Figure 25.

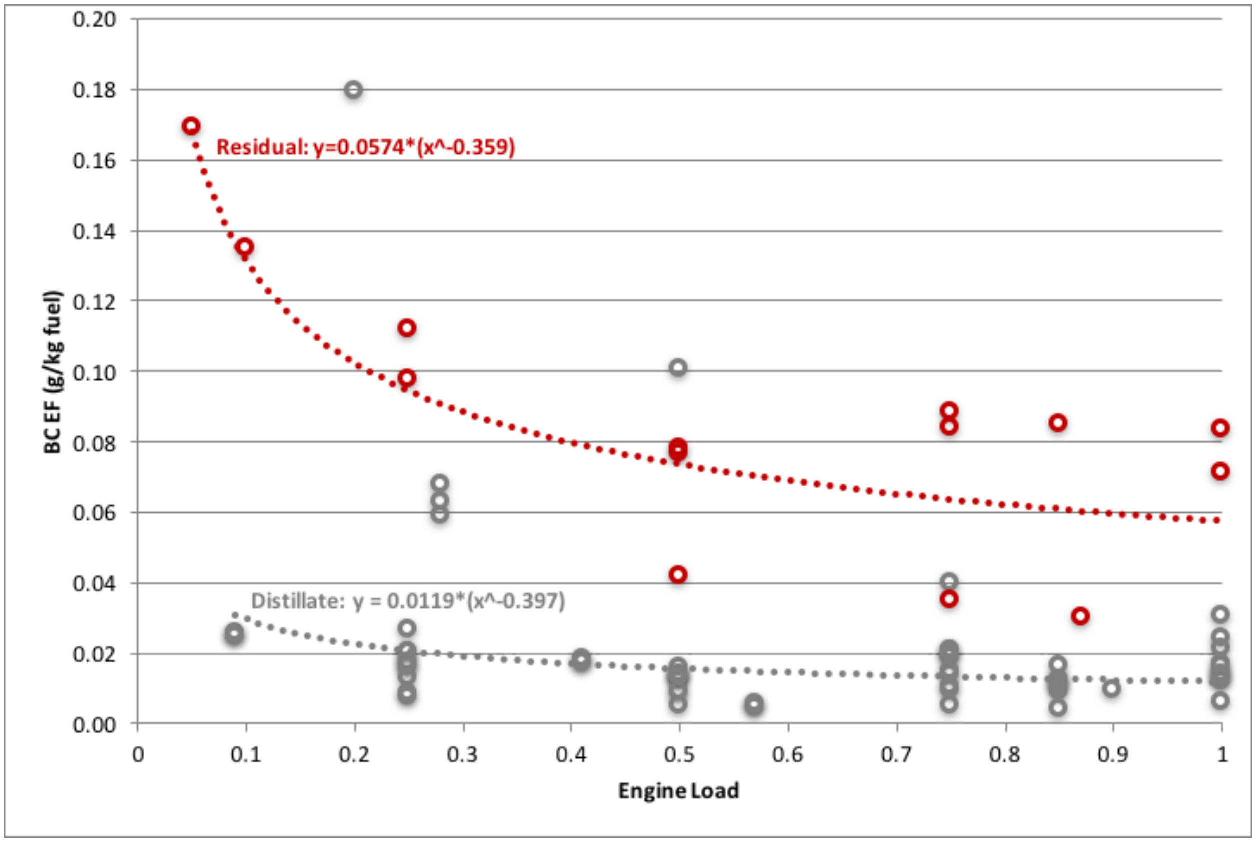

Figure 22. Raw black carbon emission factors for 2-stroke main engines using residual fuel and distillate fuel

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[22] See "Average EF_{BC} g BC (kg fuel)$^{-1}$" column in Table 2 on p. 1890 in Buffaloe et al. (2014) which shows "All Ships" BC EFs can roughly double at 1 positive standard deviation from the mean.

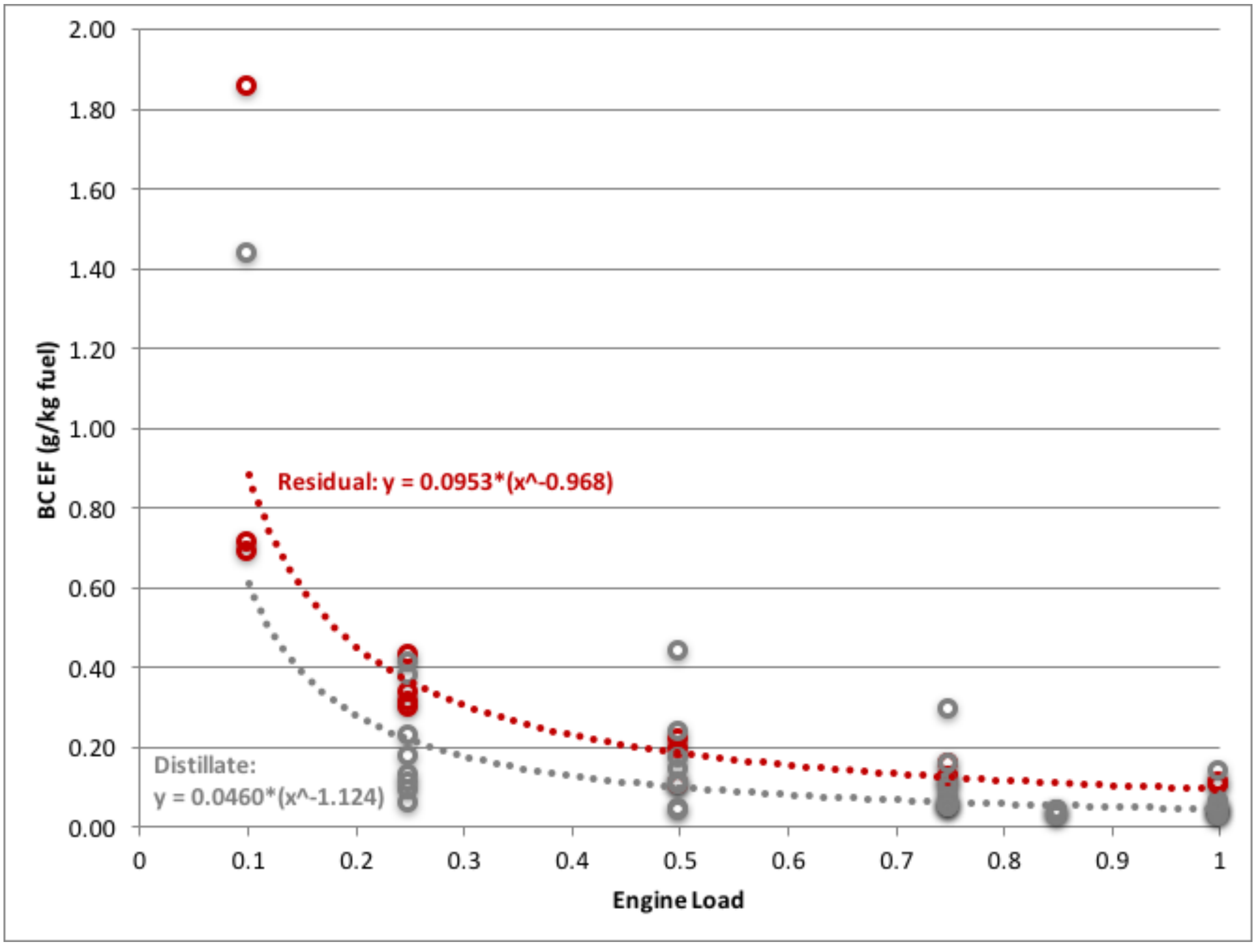

Figure 23. Raw black carbon emission factors for 2-stroke main engines using residual fuel and distillate fuel

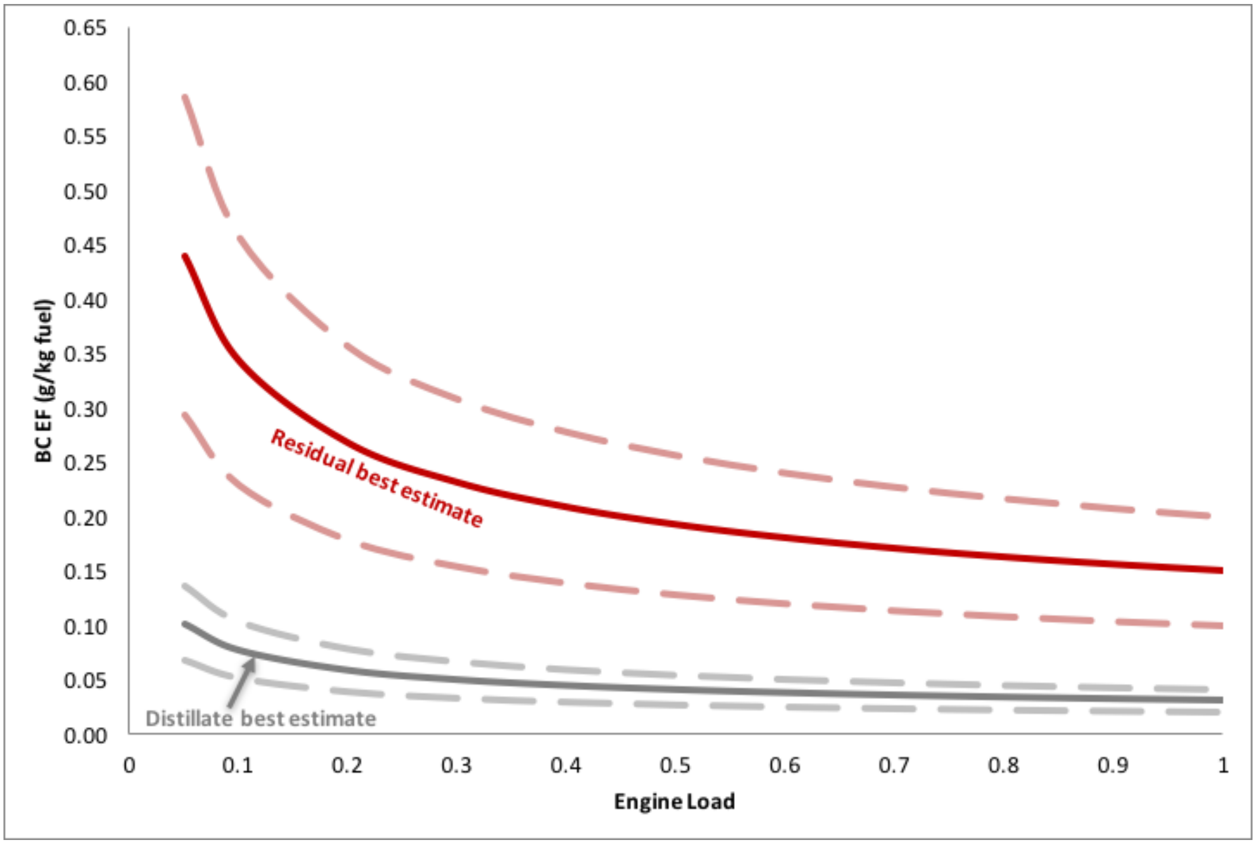

Figure 24. Black carbon emission factors for 2-stroke main engines used in the analysis

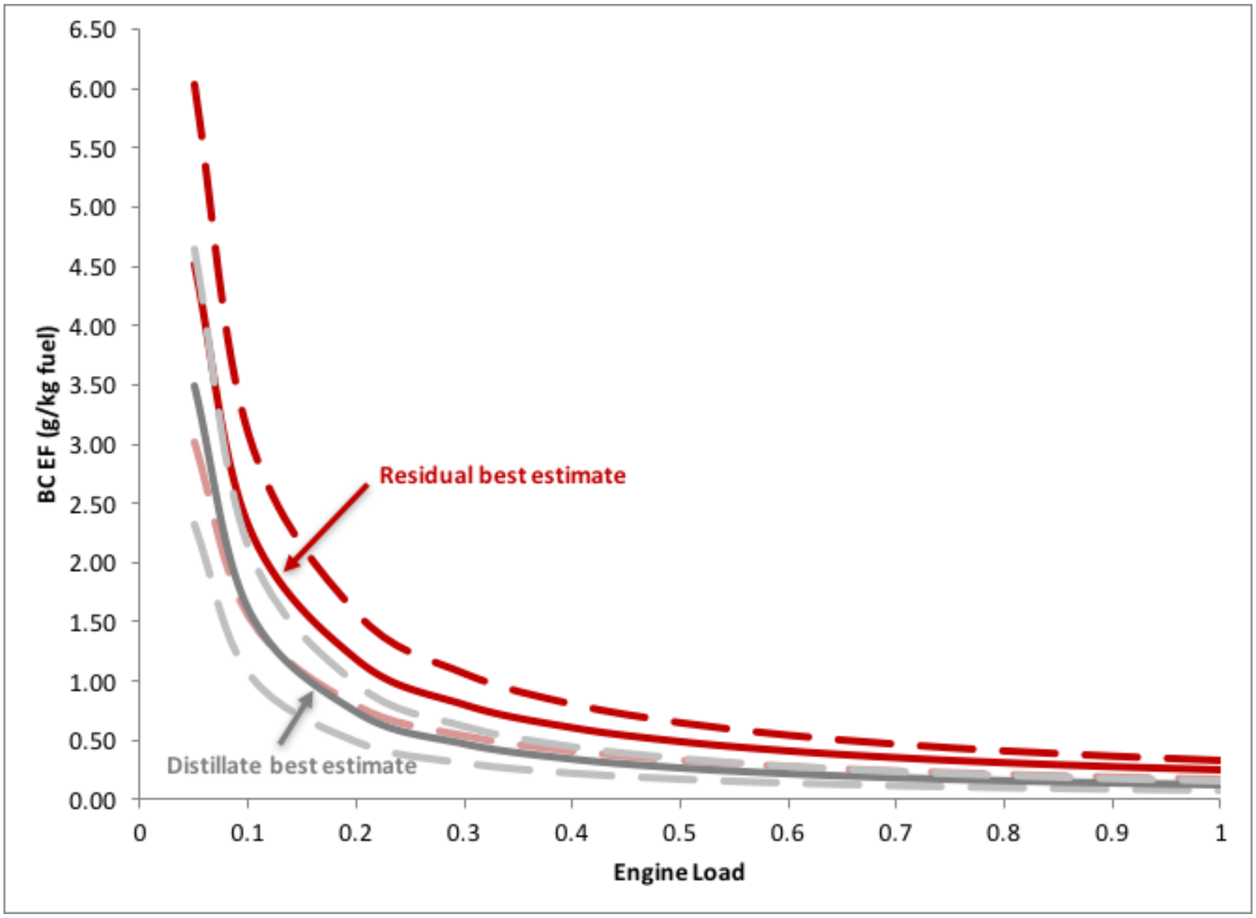

Figure 25. Black carbon emission factors for 4-stroke main engines used in the analysis

Table 19. Raw data used to develop the black carbon emission factors in this study

Engine ID	Source	Engine Type (2-stroke or 4-stroke)	Rated Power (kW)	Detailed Fuel type	Main Fuel Type	Engine Load	Raw BC EF (FSN units)	Raw BC EF (g/kg fuel)
UCRT2	UCR	2	70,000	MGO	Distillate	0.09	N/A	0.0259
UCRT2	UCR	2	70,000	MGO	Distillate	0.09	N/A	0.0252
UCRT2	UCR	2	70,000	MGO	Distillate	0.09	N/A	0.0247
8	EUROMOT	2	5,450	DMA	Distillate	0.2	0.133	0.1795
1	EUROMOT	2	6,513	DMA	Distillate	0.25	0.024	0.0201
3	EUROMOT	2	13,450	DMX	Distillate	0.25	0.024	0.0266
4	EUROMOT	2	6,513	DMA	Distillate	0.25	0.024	0.0201
6	EUROMOT	2	13,450	DMX	Distillate	0.25	0.015	0.0175
10	EUROMOT	2	11,335	DMB	Distillate	0.25	0.015	0.0128
11	EUROMOT	2	28,310	DMA	Distillate	0.25	0.017	0.0075
12	EUROMOT	2	6,100	DMA	Distillate	0.25	0.009	0.0084
13	EUROMOT	2	11,080	DMB	Distillate	0.25	0.016	0.0165
14	EUROMOT	2	11,080	DMB	Distillate	0.25	0.016	0.0162
UCRT2	UCR	2	70,000	MGO	Distillate	0.28	N/A	0.0592
UCRT2	UCR	2	70,000	MGO	Distillate	0.28	N/A	0.0629
UCRT2	UCR	2	70,000	MGO	Distillate	0.28	N/A	0.0676
UCRT2	UCR	2	70,000	MGO	Distillate	0.41	N/A	0.0184
UCRT2	UCR	2	70,000	MGO	Distillate	0.41	N/A	0.0175
UCRT2	UCR	2	70,000	MGO	Distillate	0.41	N/A	0.0174
1	EUROMOT	2	6,513	DMA	Distillate	0.5	0.016	0.0134
3	EUROMOT	2	13,450	DMX	Distillate	0.5	0.016	0.0159
4	EUROMOT	2	6,513	DMA	Distillate	0.5	0.016	0.0134
6	EUROMOT	2	13,450	DMX	Distillate	0.5	0.014	0.0141

8	EUROMOT	2	5,450	DMA	Distillate	0.5	0.086	0.1008
10	EUROMOT	2	11,335	DMB	Distillate	0.5	0.017	0.0132
11	EUROMOT	2	28,310	DMA	Distillate	0.5	0.013	0.0051
12	EUROMOT	2	6,100	DMA	Distillate	0.5	0.016	0.0131
13	EUROMOT	2	11,080	DMB	Distillate	0.5	0.01	0.0090
14	EUROMOT	2	11,080	DMB	Distillate	0.5	0.01	0.0088
UCRT2	UCR	2	70,000	MGO	Distillate	0.57	N/A	0.0058
UCRT2	UCR	2	70,000	MGO	Distillate	0.57	N/A	0.0048
UCRT2	UCR	2	70,000	MGO	Distillate	0.57	N/A	0.0049
1	EUROMOT	2	6,513	DMA	Distillate	0.75	0.025	0.0205
3	EUROMOT	2	13,450	DMX	Distillate	0.75	0.02	0.0187
4	EUROMOT	2	6,513	DMA	Distillate	0.75	0.025	0.0205
6	EUROMOT	2	13,450	DMX	Distillate	0.75	0.015	0.0141
8	EUROMOT	2	5,450	DMA	Distillate	0.75	0.036	0.0398
10	EUROMOT	2	11,335	DMB	Distillate	0.75	0.02	0.0149
11	EUROMOT	2	28,310	DMA	Distillate	0.75	0.013	0.0049
12	EUROMOT	2	6,100	DMA	Distillate	0.75	0.025	0.0195
13	EUROMOT	2	11,080	DMB	Distillate	0.75	0.013	0.0105
14	EUROMOT	2	11,080	DMB	Distillate	0.75	0.012	0.0096
1	EUROMOT	2	6,513	DMA	Distillate	0.85	0.015	0.0119
4	EUROMOT	2	6,513	DMA	Distillate	0.85	0.015	0.0119
10	EUROMOT	2	11,335	DMB	Distillate	0.85	0.023	0.0163
11	EUROMOT	2	28,310	DMA	Distillate	0.85	0.011	0.0040
12	EUROMOT	2	6,100	DMA	Distillate	0.85	0.016	0.0123
13	EUROMOT	2	11,080	DMB	Distillate	0.85	0.012	0.0092
14	EUROMOT	2	11,080	DMB	Distillate	0.85	0.014	0.0106

6	EUROMOT	2	13,450	DMX	Distillate	0.9	0.011	0.0093
1	EUROMOT	2	6,513	DMA	Distillate	1	0.018	0.0136
3	EUROMOT	2	13,450	DMX	Distillate	1	0.016	0.0139
4	EUROMOT	2	6,513	DMA	Distillate	1	0.018	0.0136
6	EUROMOT	2	13,450	DMX	Distillate	1	0.014	0.0122
8	EUROMOT	2	5,450	DMA	Distillate	1	0.03	0.0304
10	EUROMOT	2	11,335	DMB	Distillate	1	0.025	0.0167
11	EUROMOT	2	28,310	DMA	Distillate	1	0.018	0.0062
12	EUROMOT	2	6,100	DMA	Distillate	1	0.032	0.0241
13	EUROMOT	2	11,080	DMB	Distillate	1	0.022	0.0164
14	EUROMOT	2	11,080	DMB	Distillate	1	0.028	0.0214
UCRT0pre	UCR	2	16,600	HFO	Residual	0.05	N/A	0.1690
15	EUROMOT	2	10,201	RMG	Residual	0.1	0.179	0.1350
9	EUROMOT	2	6,509	RMG	Residual	0.25	0.12	0.0977
15	EUROMOT	2	10,201	RMG	Residual	0.25	0.132	0.1119
9	EUROMOT	2	6,509	RMG	Residual	0.5	0.099	0.0780
15	EUROMOT	2	10,201	RMG	Residual	0.5	0.087	0.0764
UCRT0pre	UCR	2	16,600	HFO	Residual	0.5	N/A	0.0420
9	EUROMOT	2	6,509	RMG	Residual	0.75	0.112	0.0841
15	EUROMOT	2	10,201	RMG	Residual	0.75	0.105	0.0882
UCRT0pre	UCR	2	16,600	HFO	Residual	0.75	N/A	0.0350
15	EUROMOT	2	10,201	RMG	Residual	0.85	0.105	0.0848
UCRT0pre	UCR	2	16,600	HFO	Residual	0.87	N/A	0.0300
9	EUROMOT	2	6,509	RMG	Residual	1	0.097	0.0710
15	EUROMOT	2	10,201	RMG	Residual	1	0.106	0.0837
25	EUROMOT	4	3,960	DMA	Distillate	0.1	0.76	1.4346

17	EUROMOT	4	10,800	DMA	Distillate	0.25	0.07	0.0579
18	EUROMOT	4	10,800	DMA	Distillate	0.25	0.1	0.0910
19	EUROMOT	4	10,350	DMA	Distillate	0.25	0.15	0.1761
20	EUROMOT	4	5,000	DMA	Distillate	0.25	0.13	0.1275
21	EUROMOT	4	6,000	DMA	Distillate	0.25	0.12	0.1082
27	EUROMOT	4	8,000	DMA	Distillate	0.25	0.216	0.2258
16	EUROMOT	4	7,200	DMA	Distillate	0.5	0.11	0.1062
17	EUROMOT	4	10,800	DMA	Distillate	0.5	0.05	0.0432
18	EUROMOT	4	10,800	DMA	Distillate	0.5	0.16	0.1412
19	EUROMOT	4	10,350	DMA	Distillate	0.5	0.07	0.0385
20	EUROMOT	4	5,000	DMA	Distillate	0.5	0.12	0.1051
21	EUROMOT	4	6,000	DMA	Distillate	0.5	0.13	0.1108
24	EUROMOT	4	3,960	DMA	Distillate	0.5	0.404	0.4382
25	EUROMOT	4	3,960	DMA	Distillate	0.5	0.226	0.2391
27	EUROMOT	4	8,000	DMA	Distillate	0.5	0.175	0.1706
16	EUROMOT	4	7,200	DMA	Distillate	0.75	0.07	0.0574
17	EUROMOT	4	10,800	DMA	Distillate	0.75	0.06	0.0469
18	EUROMOT	4	10,800	DMA	Distillate	0.75	0.18	0.1593
19	EUROMOT	4	10,350	DMA	Distillate	0.75	0.05	0.0471
20	EUROMOT	4	5,000	DMA	Distillate	0.75	0.07	0.0573
21	EUROMOT	4	6,000	DMA	Distillate	0.75	0.14	0.1113
24	EUROMOT	4	3,960	DMA	Distillate	0.75	0.264	0.2947
25	EUROMOT	4	3,960	DMA	Distillate	0.75	0.1	0.0977
27	EUROMOT	4	8,000	DMA	Distillate	0.75	0.079	0.0720
16	EUROMOT	4	7,200	DMA	Distillate	0.85	0.05	0.0402
17	EUROMOT	4	10,800	DMA	Distillate	0.85	0.04	0.0302

18	EUROMOT	4	10,800	DMA	Distillate	0.85	0.05	0.0384
19	EUROMOT	4	10,350	DMA	Distillate	0.85	0.03	0.0258
21	EUROMOT	4	6,000	DMA	Distillate	0.85	0.06	0.0419
16	EUROMOT	4	7,200	DMA	Distillate	1	0.05	0.0390
17	EUROMOT	4	10,800	DMA	Distillate	1	0.05	0.0389
18	EUROMOT	4	10,800	DMA	Distillate	1	0.08	0.0638
19	EUROMOT	4	10,350	DMA	Distillate	1	0.03	0.0249
20	EUROMOT	4	5,000	DMA	Distillate	1	0.04	0.0290
21	EUROMOT	4	6,000	DMA	Distillate	1	0.06	0.0412
24	EUROMOT	4	3,960	DMA	Distillate	1	0.135	0.1375
25	EUROMOT	4	3,960	DMA	Distillate	1	0.048	0.0410
27	EUROMOT	4	8,000	DMA	Distillate	1	0.056	0.0447
16	EUROMOT	4	7,200	DMA	Distillate	1	0.07	0.0542
Finland_D	Finland	4	1,640	MGO	Distillate	0.25	N/A	0.4110
Finland_D	Finland	4	1,640	MGO	Distillate	0.25	N/A	0.3800
Finland_D	Finland	4	1,640	MGO	Distillate	0.75	N/A	0.0560
Finland_D	Finland	4	1,640	MGO	Distillate	0.75	N/A	0.0500
22	EUROMOT	4	3,498	HFO	Residual	0.1	0.497	0.6887
23	EUROMOT	4	3,498	HFO	Residual	0.1	0.499	0.7134
29	EUROMOT	4	3,480	RME	Residual	0.1	1.2	1.8530
22	EUROMOT	4	3,498	HFO	Residual	0.25	0.34	0.3107
23	EUROMOT	4	3,498	HFO	Residual	0.25	0.32	0.2982
29	EUROMOT	4	3,480	RME	Residual	0.25	0.35	0.3355
22	EUROMOT	4	3,498	HFO	Residual	0.5	0.235	0.1961
23	EUROMOT	4	3,498	HFO	Residual	0.5	0.254	0.2160
29	EUROMOT	4	3,480	RME	Residual	0.5	0.13	0.1069

22	EUROMOT	4	3,498	HFO	Residual	0.75	0.163	0.1252
23	EUROMOT	4	3,498	HFO	Residual	0.75	0.163	0.1260
29	EUROMOT	4	3,480	RME	Residual	0.75	0.14	0.1062
22	EUROMOT	4	3,498	HFO	Residual	1	0.153	0.1076
23	EUROMOT	4	3,498	HFO	Residual	1	0.146	0.1032
29	EUROMOT	4	3,480	RME	Residual	1	0.15	0.1086
Finland_R	Finland	4	1,640	HFO	Residual	0.25	N/A	0.4300
Finland_R	Finland	4	1,640	HFO	Residual	0.75	N/A	0.1550

Appendix H. Auxiliary engine emission factors (g/kWh) used.

Pollutant	Engine Tier	Engine Type	HFO (2.5% S)	Distillate (0.14% S)	ECA fuel (0.1% S)	LNG
CO_2		SSD/MSD/HSD	707	696	696	--
		LNG-otto	--	--	--	457
		LNG-diesel	--	--	--	366
NO_X	Tier 0	All RPMs	14.70	13.82	13.82	--
		0-130 rpm	13.00	12.22	12.22	--
		130-1999 rpm	0.94*45*rpm^(-0.2)	0.94*45*rpm^(-0.2)	0.94*45*rpm^(-0.2)	--
		2000+ rpm	13.00	12.22	12.22	--
		LNG-otto	--	--	--	1.3
		LNG-diesel	--	--	--	--
		0-130 rpm	11.20	10.53	10.53	--
		130-1999 rpm	0.94*44*rpm^(-0.23)	0.94*44*rpm^(-0.23)	0.94*44*rpm^(-0.23)	--
		2000+ rpm	11.20	10.53	10.53	--
		LNG-otto	--	--	--	1.3
		LNG-diesel	--	--	--	5
SO_X		SSD/MSD/HSD	11.98	0.60	0.43	11.98
		LNG-otto/LNG-diesel	--	--	--	0.00
PM		SSD/MSD/HSD	1.44	0.20	0.19	1.44
		LNG-otto	--	--	--	0.03
		LNG-diesel	--	--	--	0.02
CO		SSD/MSD/HSD	0.54	0.54	0.54	0.54
		LNG-otto	--	--	--	1.30
		LNG-diesel	--	--	--	1.04
CH_4		SSD/MSD/HSD	0.01	0.01	0.01	0.01

		LNG-otto	--	--	--	8.50
		LNG-diesel	--	--	--	0.94
N_2O		SSD/MSD/HSD	0.04	0.03	0.03	0.04
		LNG-otto	--	--	--	0.02
		LNG-diesel	--	--	--	0.01
BC		SSD/MSD/HSD	0.12	0.06	0.06	0.12
		LNG-otto	--	--	--	0.003
		LNG-diesel	--	--	--	0.002

Appendix I. Boiler emission factors (g/kWh) used.

Pollutant	**HFO (2.5% S)**	**Distillate (0.14% S)**	**ECA fuel (0.1% S)**
CO_2	950	962	962
NO_X	2.10	2.00	2.00
SO_X	16.10	0.81	0.57
PM	0.93	0.11	0.10
CO	0.20	0.20	0.20
CH_4	0.002	0.002	0.002
N_2O	0.05	0.04	0.04
BC	0.08	0.06	0.06

Appendix J. Low load adjustment factors for main propulsion engines

Load factor	PM	NO_X	SO_X	CO_2	CO	CH_4	N_2O
≤2%	7.29	4.63	1	1	9.7	21.18	4.63
3%	4.33	2.92	1	1	6.49	11.68	2.92
4%	3.09	2.21	1	1	4.86	7.71	2.21
5%	2.44	1.83	1	1	3.9	5.61	1.83
6%	2.04	1.6	1	1	3.26	4.35	1.6
7%	1.79	1.45	1	1	2.8	3.52	1.45
8%	1.61	1.35	1	1	2.45	2.95	1.35
9%	1.48	1.27	1	1	2.18	2.52	1.27
10%	1.38	1.22	1	1	1.97	2.18	1.22
11%	1.3	1.17	1	1	1.79	1.96	1.17
12%	1.24	1.14	1	1	1.64	1.76	1.14
13%	1.19	1.11	1	1	1.52	1.6	1.11
14%	1.15	1.08	1	1	1.41	1.47	1.08
15%	1.11	1.06	1	1	1.32	1.36	1.06
16%	1.08	1.05	1	1	1.24	1.26	1.05
17%	1.06	1.03	1	1	1.17	1.18	1.03
18%	1.04	1.02	1	1	1.11	1.11	1.02
19%	1.02	1.01	1	1	1.05	1.05	1.01
≥20%	1	1	1	1	1	1	1