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BLACK CARBON EMISSIONS AND FUEL USE IN GLOBAL SHIPPING

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ABBREVIATIONS

AC	Arctic Council
AE	Auxiliary engine
AIS	Automatic Identification System
BC	Black carbon
BO	Boiler
CCAC	Climate and Clean Air Coalition
CCTS	Clean Cam Technology System
CH_4	Methane
CO_2	Carbon dioxide
DECA	Domestic Emission Control Area
DPF	Diesel particulate filter
DPM	Diesel particulate matter
dwt	Deadweight tonnage
ECA	Emission Control Area
EF	Emission factor
EGCS	Exhaust gas cleaning system
EGR	Exhaust gas recirculation
EMF	Emulsified fuel
EUROMOT	European Association of Internal Combustion Engine Manufacturers
FSN	Filter smoke number
GT	Gas turbine
gt	Gross tonnage
HDDI	Heavy-Duty Diesel Initiative
HFO	Heavy fuel oil
HSD	High speed diesel
IEA	International Energy Agency
IFO	Intermediate fuel oil
IMO	International Maritime Organization
kt	Kilotonnes
LNG	Liquefied natural gas
ME	Main engine
MEPC	Marine Environment Protection Committee
MSD	Medium speed diesel
Mt	Million tonnes
N_2O	Nitrous oxide
NaOH	Sodium hydroxide
NO_x	Nitrogen oxides
PAME	Protection of the Arctic Marine Environment
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter
PPR	Pollution Prevention and Response
S	Sulfur
SO_2	Sulfur dioxide
SOG	Speed over ground
SO_x	Sulfur oxides
SFOC	Specific fuel oil consumption
SSD	Slow speed diesel
ST	Steam turbine
SWS	Seawater scrubbers
U.S. EPA	United States Environmental Protection Agency
UCR	University of California, Riverside
WiFE	Water-in-fuel emulsions

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Ships are an efficient way to move cargo, transporting approximately 80% of the world's goods by volume, but ships also threaten human health, ecosystems, and the climate. This report focuses on the air and climate pollutant black carbon (BC). As one component of fine particulate matter ($PM_{2.5}$), BC 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. Ship emissions account for a substantial and growing share of BC from diesel engines used in transportation. Additionally, the widespread use of residual fuels, mainly heavy fuel oil (HFO), in international shipping exacerbates the problem 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 both the scale of impacts of BC emissions as well as the potential effectiveness of BC control policies.

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 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), carbon monoxide (CO), 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 BC emissions impacts of six policy alternatives are discussed: 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 ship greenhouse gas (GHG) reduction strategies; promoting vessel scrappage; and promoting shore power. The report ends with an ambitious BC reduction policy recommendation. 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.

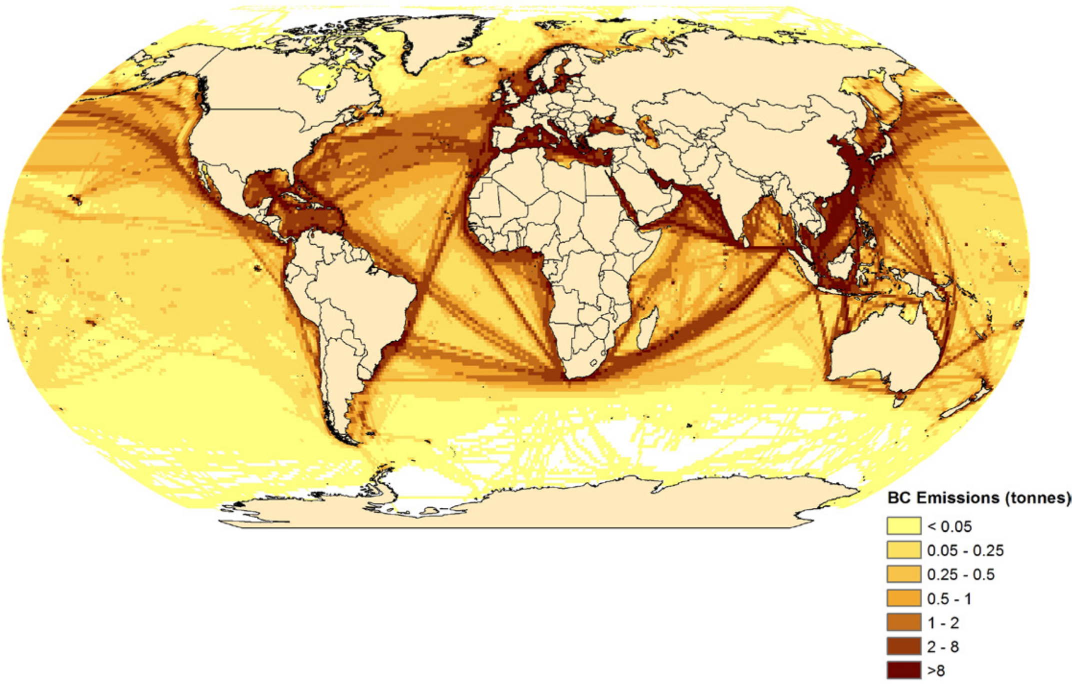
BLACK CARBON

Ships emitted approximately 67 kilotonnes (kt, or thousand tonnes) of BC in 2015, with a lower and upper range between 53 kt and 80 kt, respectively, corresponding to a fleet-wide average BC emission factor (EF) of 0.25 g/kg fuel with a range of 0.20 to 0.30 g/kg fuel. Accounting for BC's global warming potential, ship BC emissions were responsible for 5% to 8% (100-year timescale) and 16% to 23% (20-year timescale) of the CO_2-equivalent climate warming impact from shipping in 2015.

Klimont et al. (2017) estimated total anthropogenic BC emissions of 7,264 kt in 2010. Assuming 2015 anthropogenic emissions are similar to 2010, our results suggest that ship BC emissions were responsible for 0.7% to 1.1% of anthropogenic BC emissions in 2015. Similarly, based on Bond et al. (2013), who estimated diesel source BC emissions at 1,420 kt in 2000, if diesel source emissions have remained similar, we estimate that ship BC emissions were responsible for 3.9% to 5.7% of diesel source BC emissions in 2015. However, it is important to understand that this inventory may underestimate global BC emissions from ships.

The BC EFs developed for this report rely on BC emissions from 27 engine measurements. Twenty of these (74%) are modern, well-maintained Tier II (2011-2015) and Tier III (2016+) engines. Evidence presented in this report and by the University of California, Riverside (Johnson et al., 2016) suggests that modern, electronically controlled engines emit much less BC than older engines. Given that 84% of the global fleet has Tier 0 (pre-2000) or Tier I (2000-2010) engines, BC measured from new, well-maintained Tier II and Tier III engines is not representative of what we would expect from engines in the 2015 fleet. We attempted to account for this by taking the BC EFs derived from the raw testing data and increasing them to a range that might more reasonably estimate BC emissions from the current fleet (see Appendix G for full details). The BC EFs presented here can be updated as more testing data become available. In particular, data from in-use Tier 0 and Tier I engines, which would be more representative of the current fleet, could substantially improve our understanding of BC EFs from ships. While the exact amount of BC emitted from ships can be further refined, this inventory yields interesting, policy-relevant results.

BC is emitted nearly everywhere, even in the Arctic and Antarctic, where it accelerates warming and melting, and the majority of BC from ships is emitted in the northern hemisphere (Figure ES-1), some of which is transported to the Arctic. Furthermore, a substantial portion of BC is 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 83% of BC from ships, while ships powered with 2-stroke slow speed diesel main engines were responsible for two-thirds of global BC emissions. Further, just six flag states—Panama, China, Liberia, Marshall Islands, Singapore, and Malta—accounted for more than half of BC emissions.

Larger ships are responsible for the most BC emissions. Container ships, bulk carriers, and oil tankers together emitted 60% of BC emissions, while accounting for 30% of ships and 81% of deadweight tonnage (dwt) in the global fleet in 2015. Within that group, container ships, which make up 7% of ships and 14% of dwt in the global fleet, emitted the most BC (26%) compared with other ship classes. Outside that group, cruise ships accounted for a disproportionately large amount of BC, emitting 6% of BC emissions despite accounting for only 1% of ships and less than 1% of dwt in the global fleet. In fact, as shown in Figure ES-2, cruise ships emitted 10 t per ship per year, or nearly triple that of a typical container ship. On average, one cruise ship emits as much black carbon as 4,200 Euro V heavy-duty trucks operating 100,000 km over one year. Further, cruise ships emit the most BC per unit of fuel they burn: the average cruise ship emits 0.34 kg of BC for every tonne of fuel, compared with 0.26 kg/t for a container ship. Thus, policies that aim to reduce BC emissions from ships must address container ships, which emit the most BC in total of any ship class (17.4 kt BC/year), and from cruise ships, which emit the most BC per tonne of fuel (0.34 kg BC/t fuel) and per ship per year (10 t BC/ship/year).

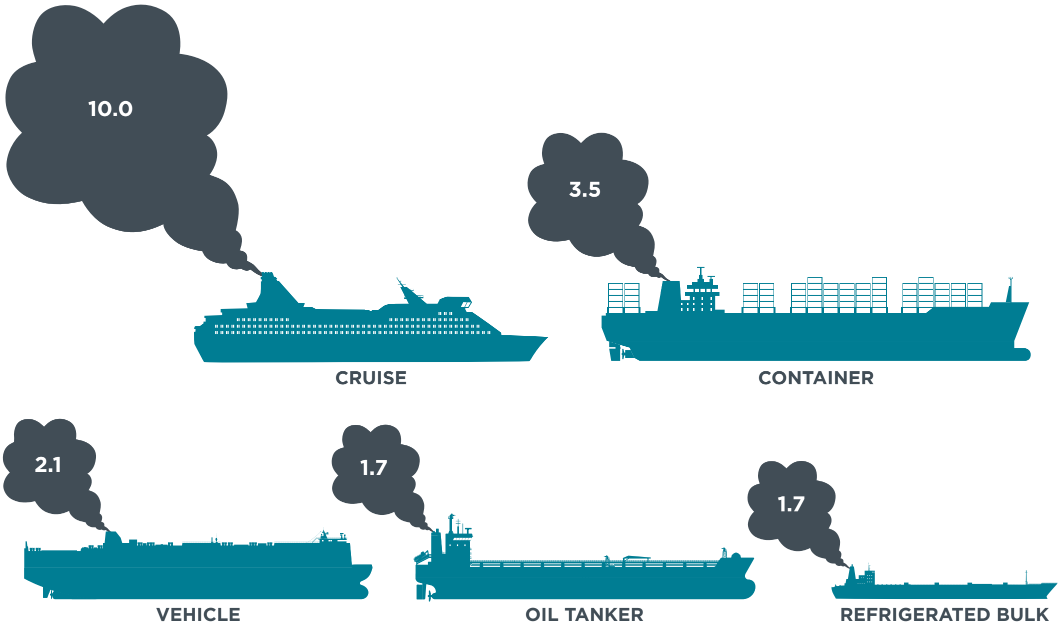


Figure ES-2: Tonnes of black carbon emissions per ship per year, 2015

FUEL USE AND CARRIAGE

The global fleet consumed 266 Mt of fuel in 2015, consisting of 210 Mt of residual fuel, 50 Mt of distillate, and 6 Mt of LNG. As such, residual fuel represented 79% 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. Residual fuels, such as HFO, are essentially prohibited in the North American, U.S. Caribbean Sea, Baltic Sea, and North Sea SECA regions, due to the 0.1% sulfur (S) limit for marine fuels in these areas.

Most residual fuel (86%) was consumed by ships with 2-stroke slow speed diesel main engines, and container ships were responsible for 30% of residual fuel consumption, more than any other ship class. Five flag states accounted for 59% of residual fuel consumption by ships in 2015: Panama (40 Mt), China (25 Mt), Liberia (25 Mt), Marshall Islands (18 Mt), and Singapore (16 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 "what-if" BC reduction scenarios were analyzed.

Scenario 1: All ships operating on residual fuel switch to distillate fuel. Under this scenario, BC emissions in 2015 would have dropped from 67 kt to 30 kt, meaning that if all ships operated on distillate fuel, total BC emissions could be reduced by more than 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 (66%–69%), as most of these ships operate on residual fuel. The actual fuel switch to distillate will be driven largely by fuel quality regulations. The 0.5% global fuel sulfur limit, which begins in 2020, will encourage a shift to distillates, but ship operators may use residual fuel blends or desulfurized residual fuels that may not reduce BC much, if at all, compared with high sulfur residual fuels.

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. As an example, a 50% switchover from oil-based fuels (residual and distillate) to LNG would cut BC emissions roughly in half (-47%). The actual fuel switch potential to LNG will depend on future regulatory and economic conditions.

Scenario 3: Some ships install exhaust gas cleaning systems. Exhaust gas cleaning systems (EGCSs), otherwise known as SO_x scrubbers, can be installed by ship operators hoping to continue to operate on less expensive high S residual fuels such as HFO. For instance, if scrubbers were installed on ships representing 20% of 2015 residual fuel consumption, BC from these ships would have dropped 6%, equivalent to a reduction of 5% of total 2015 BC emissions. If all ships operating on residual fuel installed scrubbers, BC could be reduced by 17.8 kt, representing a 30% reduction in BC from residual fuel-powered ships and a net 27% reduction in BC from the global shipping fleet. The actual uptake of scrubbers will depend on future regulatory and economic conditions.

Scenario 4: Some ships install DPFs. Some ships operating on distillate fuel are suitable candidates for DPF retrofits. If 50% of distillate fuel consumption was treated with a DPF, BC would fall by 42% for that fuel, but total BC emissions from ships would decline only 5%, as distillate makes up only 19% of total fuel consumption for ships in the global fleet. The actual uptake of DPFs may be limited to harbor craft, ferries, and other domestic ships in the near-term, as there is currently no regulatory driver to encourage DPFs for international shipping.

Some parts of these scenarios are likely to happen in the future. Some ships will switch from residual to distillate fuels to comply with the International Maritime Organization'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 with 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, especially harbor craft and smaller vessels that operate on distillate fuels, will install DPFs 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. It includes the following elements:

» **Retrofit cruise ships with diesel particulate filters or scrubbers**
Cruise ships emit the most BC per ship, on average. Ideally, these ships would be retrofitted with DPFs, 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 DPFs 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 35% to 80% less BC than residual fuels, according to this study. Sulfur ECAs reduce emissions quickly because they apply to all vessels in the existing fleet, whereas policies such as emission standards affect only new-build vessels. 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 (ro-ro) 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 DPFs 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 that is 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. If cruise ships operating in the Arctic are retrofitted with DPFs, this would help protect the Arctic that the ships' customers are paying to see. Progressive flag states could also retrofit their fishing vessels with DPFs. Fishing vessels are the largest source of BC from ships in the Arctic (Comer, Olmer, Mao, Roy, & Rutherford, 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 and the costs of such an approach could be estimated in future work. However, the net effect would be fewer premature deaths and diseases from ship emissions, lower risks of economically and ecologically damaging residual fuel spills, and less climate warming impacts from ships.

1. INTRODUCTION

Ships are an efficient way to move cargo, transporting approximately 80% of the world's goods by volume (UNCTAD, 2017), but ships also threaten human health, ecosystems, and the climate. This report focuses on the air and climate pollutant black carbon (BC). As one component of fine particulate matter ($PM_{2.5}$), BC contributes to heart and lung disease and early death. For instance, BC emitted by ships 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 in transportation. The wide use of residual fuels, mainly heavy fuel oil (HFO), in the international maritime shipping sector exacerbates the problem. 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 BC 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 United States and Canada have committed to phase down the use of HFO in their portions of the Arctic.[1] Finally, intergovernmental organizations such as the Climate and Clean Air Coalition (CCAC) are actively funding research on approaches to reduce emissions of BC and PM from diesel engines, as the CCAC is doing under its Heavy-Duty Diesel Initiative (HDDI).

In recent years, there has been 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. 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.

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 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), carbon monoxide (CO), methane (CH_4), nitrous oxide

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[1] Read 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

(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 the following four scenarios are analyzed in detail: 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: 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 ship greenhouse gas (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% to 13% of BC emissions from diesel sources (Azzara, Minjares, & Rutherford, 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, Berntsen, Seland, and Kristjánsson (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 et al., 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 (Johansen, 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 EFs used in these studies range from 0.18 to 1.33 g BC/kg fuel. Because studies vary so dramatically, it is difficult to understand how much BC is emitted from ships. Additionally, several factors may influence BC formation.[2] Indeed, researchers have found that BC EFs are influenced by several factors, including fuel type (e.g., residual, distillate, LNG), engine stroke type (e.g., 2-stroke, 4-stroke), and engine load (Johnson et al., 2016). In this work, we develop new main engine (ME) BC EFs that change as a function of fuel type, engine stroke type, and engine load. These EFs are based on the latest research presented to IMO.

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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 by 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, third, and fourth workshops on marine BC emissions held in Utrecht (2015), Vancouver (2016), and Washington, DC (2017). For more information on the ICCT black carbon workshops, visit http://www.theicct.org/events/30.

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

Study	Inventory Year	BC (kt)	Fuel consumption (Mt)	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, Berntsen, Myhre, Rypdal, & Skeie (2008)	2000	197	182	1.08
Eyring, Köhler, van Aardenne, & Lauer (2005)	2001	50	280	0.18
Lack, Thuesen, & Elliot (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]
EDGAR (2016)	2010	283	213	1.33[e]
Klimont et al. (2017)	2010	120	322[f]	0.37[f]
BC in the Arctic				
Corbett, Lack, et al. (2010)	2004	1.25	3.5	0.35
Peters et al. (2011)	2004	1.15	3.3	0.35
Det Norske Veritas (2013)[g]	2012	0.052	0.3	0.18
Winther et al. (2014)	2012	1.58	4.5	0.35
Comer, Olmer, Mao, Roy, & Rutherford (2017)	2015	1.45	4.4	0.30-0.56 (0.34 avg.)

[a] A combination of BC EFs from Petzold et al. (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 emission 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] We derived this emission factor. EDGAR v4.3.1 estimated that international shipping emitted 283 kt of BC, based on International Energy Agency (IEA) energy statistics. In 2010, IEA World Energy Statistics estimated that international shipping consumed 213 million t of fuel, implying a BC EF of 1.33 g BC/ kg fuel. [f] We estimated fuel consumption and derived the BC EF based on Klimont et al. (2017), which states that their 2010 fuel consumption was approximately 10% higher than Smith et al. (2015) for the same year. Smith et al. (2015) estimated 293 Mt fuel consumption in 2010. [g] 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 emissions from ships. This section describes the 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 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 PM emissions.

A synthesis report by the National Research Council (NRC) 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, the only technologies that are readily commercially available are slide valves, the use of low sulfur fuels, water in fuel emulsions (WiFE), dual fuel power systems, and wet scrubbers.

Another report by Lack, Thuesen, & Elliot (2012), submitted to the IMO, identifies six abatement options for BC mitigation from international shipping: LNG, WiFE, scrubbers, diesel particulate filters (DPFs), fuel switching (HFO to distillate), and slow steaming with derating. Other important studies include Corbett, Winebrake, and Green (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), which 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 at least 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 superheating to the auto-ignition temperature of the emulsified fuel. In previous work, the SFOC penalty at 30% added water is estimated to be approximately 2% when considering evaporation and superheating 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 & Nyggard, 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 SO_x. 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). 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 sulfur dioxide (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 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% to 92% have been reported when paired with heavy oil (1% max sulfur content) (Lack et al., 2012; 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, and using finer fuel filters. 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: 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. Average fuel oil cost savings of approximately 42% are possible without a derated engine and 45% with a derated engine (Lack et al., 2012). 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% to 3.5% per day.[3] To counterbalance the potential of increasing BC emissions when operating a vessel at lower load (slow steaming), the engine should be

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

retuned or derated. 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 NO_X and PM (Ritchie, Jonge, Hugi, & Cooper, 2005). Slide valves are reported to reduce PM emissions by approximately 25% (Henningsen, 2004; Marine Shipping Retrofit Project, 2009). Although estimates of 50% PM control have been presented, BC control performance estimates have not been reported (California Air Resources Board, 2002); it is assumed that slide valves will reduce PM and BC similarly. Today, most ship engines have slide valves, and ship owners can retrofit old engines with slide valves if other fuel saving options, like de-rating, are impossible (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 PM and SO_X, cooled, then reintroduced into the combustion chamber. The lower oxygen content of the recirculated exhaust gases decreases the amount of 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 and BC emissions through the process. EGR is estimated to reduce up to 20% of BC emissions (Lack et al. 2012), although in some cases it is possible for EGR to increase BC emissions; thus, EGR is not recommended to be used primarily to reduce BC emissions.

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 found that slide valves emit over 90% less hydrocarbons compared with other conventional valve configurations[4]. Lack et al. (2008) 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, Winebrake, 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% to 80%, as verified in a demonstration project that showed 57% reductions in PM (Ritchie et al., 2005; Kircher, 2008). Research indicates that SWS may reduce $PM_{2.5}$ (of which BC is a component) by 75%. (IMO, 2009; Marine Exhaust Solutions, 2006). Based on the ICCT testing of a Hamworthy/Krystallon seawater scrubber onboard a container vessel, total PM reductions ranged from 40% to 50% and averaged 45% across the scrubber, but varied

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

from 10% to 80% for BC depending on load. The results suggest BC reductions for scrubbers are strongly related to engine load.

Corbett, Winebrake, et al. (2010) estimate reductions for several other technologies. Emulsified fuels (EMFs), which are stable mixtures of fuel, water, and additives for emulsification and stabilization, reportedly reduce PM emissions by up to 63%. Additionally, WiFE reportedly reduces PM emissions by two to three times the water content, so a 10% water emulsion would equate to 20% to 30% PM reductions, while 30% emulsion would result in 60% to 90%. Corbett, Winebrake, et al. (2010) and Lack et al. (2012) both list DPF systems as possible technology options. DPF systems are effective in controlling PM (achieving 70% to 95% total PM reductions), and are particularly effective at controlling BC emissions; achieving 95% to 99% BC reductions by mass (Liu, Berg, & Schauer, 2009; Majewski, 2005). The Manufacturers of Emission Controls Association (2014) produced a report presenting the results of testing on harbor craft and ferries. They explored combination technologies of Clean Cam Technology System (CCTS)[5] retrofit engine control technology and the Rypos active DPF system with demonstrations aboard harbor craft reducing PM between 43% and 90%.

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 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 that affect BC emissions, including fuel type, engine stroke type, engine load, engine tier, and exhaust gas cleaning system (EGCS, or scrubber). The results of this research shed light on the ways that BC can be controlled from marine engines, as summarized next.

Fuel type: Researchers have found that (a) distillate fuels emit less BC than HFO; (b) desulfurized residual fuels emit more BC than HFO at typical engine operating loads; and (c) with few exceptions, 0.5% sulfur residual fuel blends seem to emit as much or more BC as HFO. Specifically, Johnson et al. (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 of 25% to 75%, higher even than HFO. Johnson et al. (2016) also included information on three fuel switching studies UCR had previously conducted. In those studies, only minor BC emission factor changes were observed when switching from HFO to distillate. However,

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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 NO_x emissions. The Rypos active-regeneration diesel DPF traps and incinerates PM in the exhaust system.

the highest BC reduction occurred when switching from an 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 kilogram of fuel than similar engine stroke 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.

Finnish researchers found that a 0.5% sulfur (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 et al., 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 stroke 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 10 times more BC per kilogram of fuel than 2-stroke engines when operating on the same kind of fuel under typical marine engine operating loads (25% to 75% engine load).

Engine load: Results from UCR (Johnson et al., 2016), 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 few operating hours (most fewer 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 an approximate 30% reduction in BC emissions across the scrubber. This suggests that EGCSs that are designed to reduce sulfur emissions may have some BC reduction co-benefits. This topic deserves more study.

2.3. POLICY CONTEXT

BC 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.

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[6] Document number PPR 4/9

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

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 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 in May 2017 signed the Fairbanks Declaration[8], 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 EUROMOT in 2015 was subsequently endorsed by PPR 3. Recommendations for appropriate marine BC measurement methods and promising control technologies were submitted by IMO delegations to PPR 4. When PPR completes its BC work plan by recommending appropriate measurement method(s) 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% S cap for marine fuels starting in 2020. Reducing the allowable S content of marine fuels will reduce total PM emissions, saving up to 200,000 premature deaths over 5 years, according to a study submitted to the IMO's 70th session of MEPC.[9] However, 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 (Johnson et al., 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; Johnson et al., 2016).

2.3.3 National governments

National governments in the United States, 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 g/kWh and 0.4 g/kWh for Category 1 engines[10] and between 0.27 g/kWh and 0.5 g/kWh for Category 2 engines.[11] The European Commission

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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

[10] Category 1, or C1, engines refer to marine diesel engines with greater than 37 kW rated power and less than 5 liters of displacement per cylinder. Category 2, or C2, engines refer to marine diesel engines with greater than 37 kW 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

(1997) 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. As noted by the International Council on Clean Transportation (2016), 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).

Additionally, the United States and Canada, in a March 2016 joint statement from President Obama and Prime Minister Trudeau,[12] 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 United States and Canada announced plans to "phase down" the use of HFO in their portions of the Arctic.[13]

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[12] 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

[13] See the United States-Canada Joint Arctic Leaders' Statement at https://pm.gc.ca/eng/news/2016/12/20/united-states-canada-joint-arctic-leaders-statement

3. METHODOLOGY

This report presents a global inventory of BC emissions from ships for the year 2015 using exactEarth 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, CO, CH_4, 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.

3.1.1. Datasets

Two main datasets were utilized in this study: (a) fused terrestrial and satellite AIS data from exactEarth that provides information about ship location and speed and (b) 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; and
- Draught, instantaneous draught associated with each AIS point, in decimeters.

3.1.2.1. Removing invalid data

Data points with an IMO number or MMSI number that did not match any ship in the IHS ShipData database were excluded from this inventory. Roughly 240 million of the 530 million records, or 45%, were excluded because they did not match any ship in the IHS ShipData database. Records with latitudes outside the normal range of -90 to 90 degrees, longitudes outside the normal range of -180 to 180, and ships with an SOG greater than 1.5 times the rated speed of the ship were also excluded. However, only the invalid field (LAT, LON, 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 290 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 transponder or the signals were not successfully picked up by a satellite. In the case of these gaps, the missing hours, ship position, and SOGs 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 SOG 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 traveled 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.

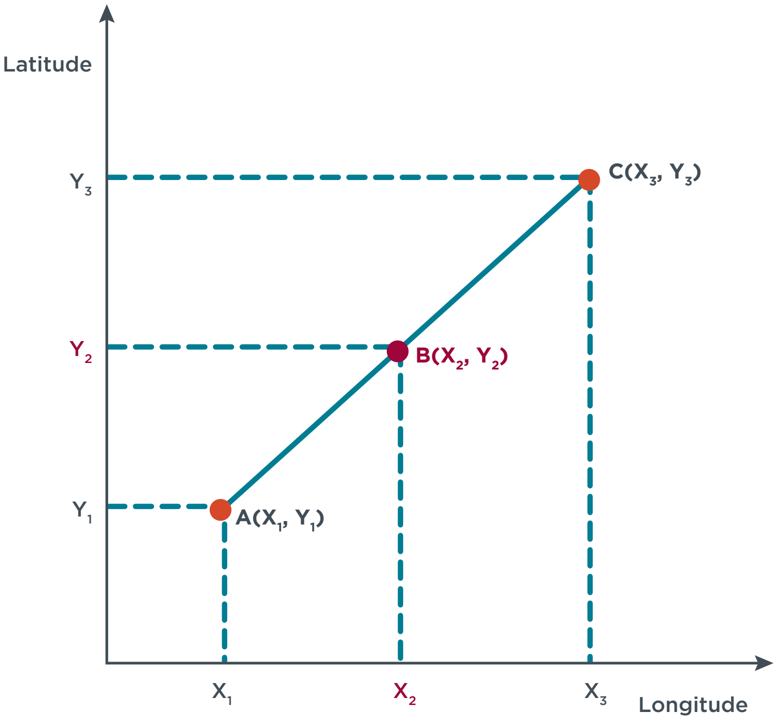

Figure 1. Illustration of linear interpolation procedure where the speed over ground at point B is interpolated

3.1.3. IHS data processing

The IHS ShipData database is continuously updated with newly built ships and, at the time of purchase for this study (August 2016), it contained ship characteristics for 180,530 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 were over 165,000 ships flagged to mainland China in 2015, whereas the IHS ShipData database reports less than 6,000. The database contains 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 recategorized into one of 22 “ship classes” according to the process used in the Third IMO GHG Study 2014 (Smith et al., 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. The International Convention for the Prevention of Pollution from Ships (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 3. The percentage of the fleet by IMO NO_x Tier, as of August 2016, is also shown in Table 3. Note that because this inventory estimates 2015 emissions, no ships with Tier III engines are represented in this analysis. See Table 16 for IMO NO_x Tier statistics for the 2015 fleet.

Table 3. IMO NO_x tier for ships in the global fleet, mid-2016

Tier	Year of construction	IHS Global Fleet	
		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 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 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 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 less than 600 are assigned to residual fuel, while ships with a main engine RPM greater than or equal to 600 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, the average RPM by ship class and capacity bin is used.

3.1.3.4. Fuel capacity

The IHS ShipData database includes fields for fuel capacity (m^3) for up to two fuels: 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 dwt and 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. Twenty-seven percent of the global fleet had missing average maximum vessel speed, 6% 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 emission factors, each vessel is classified into one of seven engine types: steam turbine (ST), gas turbine (GT), slow speed diesel (SSD), medium speed diesel (MSD), high speed diesel (HSD), LNG-fueled Diesel-cycle engine (LNG-Diesel), or LNG-fueled Otto-cycle engine (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 were assigned an engine type based on the procedures in (4).

Table 4 details 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 AND CARRIAGE

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 is calculated as follows:

$$FC_{i,y,f} = \sum_{f} \left(\frac{CO_{2_{i,y,f}}}{CI_f} \right)$$

where

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

Fuel carriage (t) is calculated using its main fuel type capacity (m^3) as derived from the IHS ShipData database and the assumed density of the fuel (Table 6). When estimating the amount of fuel onboard each vessel, this study assumes that each ship's fuel tanks are 65% full at all times, consistent with Det Norske Veritas (Det Norske Veritas, 2013). Note that it is assumed that gas boil-off is the same density as LNG, because the fuel source for gas boil-off is LNG until it is converted to compressed natural gas.

Table 6. Assumed fuel density by fuel type

Fuel type	Density (t/m^3)
Residual[a]	0.985
Distillate[b]	0.860
LNG[c]	0.456
Gas boil-off	0.456

[a] *International Organization for Standardization (2014).*
[b] *Chevron (2014).* [c] *U.S. Department of Energy (2005).*

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 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 auxiliary engine (AE) and boiler (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 7 and Table 8 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 7. Phase assignment decision matrix for all ship classes except liquid tankers

	Distance from port/coast				
Speed over ground	**<=1 nm from port**	**<= 1 nm from coast**	**1-5 nm from coast**	**>=5nm from coast**	**In a river**
< 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 8. Phase assignment decision matrix for liquid tankers

	Distance from port/coast					
Speed over ground	**<=1 nm from port**	**<=1 nm from coast**	**1-5 nm from port**	**1-5 nm from coast**	**>=5nm from coast**	**In a river**
< 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 each varies depending on the phase in which the ship is operating (Table 9). 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 shoreside electrical power to allow ships to switch off their auxiliary engines at berth, this analysis assumes auxiliary engines are always on at berth.

Table 9. 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. Emission factors

3.3.2.1. 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 stroke 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, 2-stroke engines operating on distillate fuel, 4-stroke engines operating on residual fuel, and 4-stroke engines operating on distillate fuel, 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 35% to 50% lower than residual for 4-stroke engines and approximately 75% to 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.

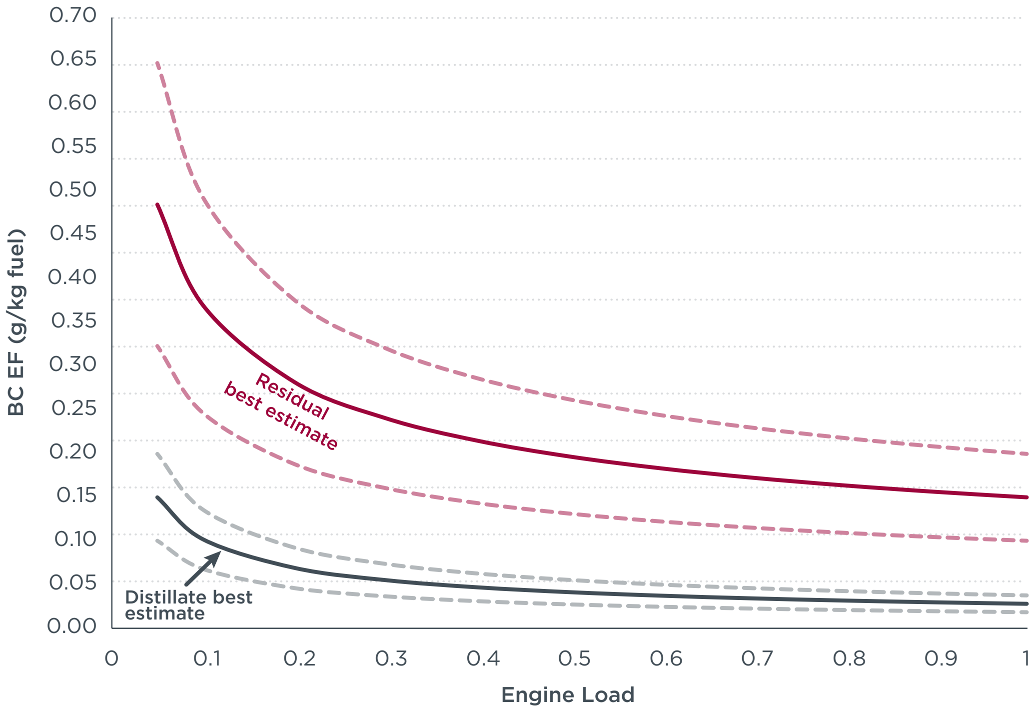

Figure 2. Black carbon emission factors for 2-stroke engines by fuel type

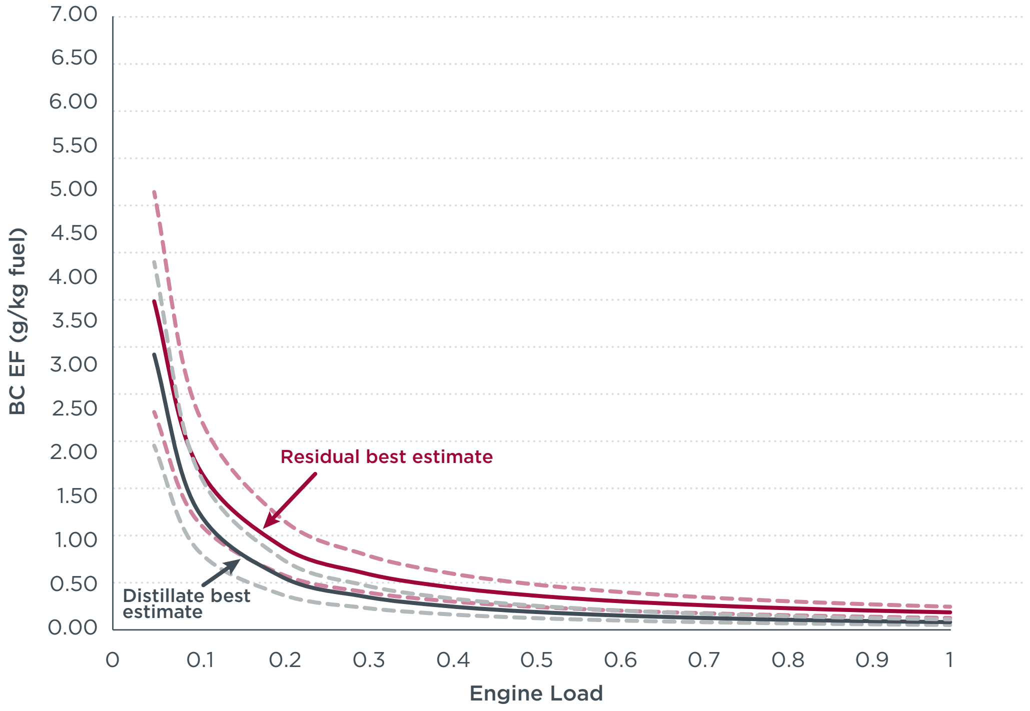

Figure 3. Black carbon emission factors for 4-stroke engines by fuel type

Black carbon EFs for other engine types (GT, ST, LNG-Otto cycle, LNG-Diesel cycle) were estimated due to a lack of experimental data. Comer et al. (2017) assumed that BC from MSDs and HSDs operating on HFO was 0.12 g/kWh. They also assumed that PM from these engines operating on HFO was 1.42 g/kWh. Therefore, BC accounted for approximately 8.4% of PM emissions by mass in this case. Thus, we assume that BC emissions from GT and ST engines are equivalent to 8.4% of those engines' PM EFs when operating on HFO. When operating on distillate and ECA-compliant fuel, we assume that the BC EFs for these engines are 25% lower than when operating on HFO. For LNG-Otto cycle and LNG-Diesel cycle engines, we assume that their BC EFs are 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 with 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 1% of the engines on ships in the global fleet. BC EFs for all engines, including GT, ST, LNG-Otto, and LNG-Diesel, are presented in Appendix G.

3.3.2.2. Other emission factors

This analysis uses main engine emission factors for all other air emissions from the Third IMO GHG Study 2014, with a few exceptions (see Appendix F for all EFs except BC EFs, which are found in Appendix G). 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 emission 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 emission factors used in this study are presented in Appendix H and boiler emission factors are presented in Appendix I. The Third IMO GHG Study 2014 assumes identical emission factors for AEs and BOs (auxiliary machinery). However, BOs are typically steam turbines. As such, this study uses the same AE emission factors as the Third IMO GHG Study 2014, but BO emission factors are set to equal to steam turbine emission factors according to the United States Environmental Protection Agency (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 BC EFs, AEs are assumed to perform the same as medium-speed diesel engines, and BOs are assumed to perform the same as steam turbines.

Emission 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 J.

3.3.2.3. Estimating emissions of all pollutants except black carbon

Emissions from ships come from MEs, AEs, and BOs. In the following equations, ME power demand is a function of installed ME power and ME load factor; AE and BO power demand depends on the ship class and capacity bin and the phase in which the ship is operating—cruise, maneuver, anchor, or berth. AE and BO power demand assumptions are the same as those in the Third IMO GHG Study 2014 (Smith et al., 2015), as found in Appendices C and D. Emissions for all air pollutants except BC are estimated according to the following equation:

$$E_{i,j} = \sum_{t=0}^{t=n} \left((P_{ME_i} \times \mathrm{LF}_{i,t} \times EF_{ME_{j,k,l,m}} + D_{AE_{p,i,t}} \times EF_{AE_{j,k,l,m}} + D_{BO_{p,i,t}} \times EF_{BO_{j,m}}) \times 1\ \text{hour} \right)$$

where:

i = ship
j = pollutant
t = time (operating hour, h)
k = engine type
l = engine tier
m = fuel type
p = phase (cruise, maneuvering, anchor, berth)
l = fuel type
$E_{i,j}$ = emissions (g) for ship i and pollutant j
P_{ME_i} = main engine power (kW) for ship i
$\mathrm{LF}_{i,t}$ = main engine load factor for ship i at time t, defined by the equation below
$EF_{ME_{j,k,l,m}}$ = main engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m
$D_{AE_{p,i,t}}$ = auxiliary engine power demand (kW) in phase p for ship i at time t
$EF_{AE_{j,k,l,m}}$ = auxiliary engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m
$D_{BO_{p,i,t}}$ = boiler power demand (kW) in phase p for ship i at time t
$EF_{BO_{j,m}}$ = boiler emission factor (g/kWh) for pollutant j and fuel type m

Load factor (LF) is a function of the SOG at time *t* modified by a speed adjustment factor that corrects for underestimating SOG for interpolated AIS signals, a hull fouling factor that accounts for increasing hydrodynamic resistance due to hull fouling as the ship ages and as biofouling builds up between drydock, a weather factor that accounts for increased main engine power demand when the ship encounters bad weather, and a draught adjustment factor that reduces the load factor when the ship is lightly loaded. A description of how we developed each adjustment factor can be found in the subsections immediately below the equation.

The equation for calculating the ME LF for a ship at any given time is as follows:

$$LF_{i,t} = \left(\frac{SOG_t \times SAF_{i,t}}{V_{max}} \right)^3 \times HFF_i \times W_t \times DAF_i$$

where

i = ship
t = time (operating hour, h)
$LF_{i,t}$ = main engine load factor for ship *i* at time *t*
SOG_t = vessel speed over ground at time *t*
$SAF_{i,t}$ = speed adjustment factor for ship *i* at time *t*
V_{max} = maximum ship speed
HFF_i = hull fouling factor for ship *i*
W_t = weather factor at time *t*
DAF_i = draught adjustment factor for ship *i*

There are some instances where the ship's SOG is greater than its maximum design speed. In these instances, SOG is replaced with the ship's average SOG for that phase and the load factor is recalculated. In case of an invalid average SOG phase value of a ship, the average SOG for similar ship type, capacity bin, and phase is used. The load factor is then recalculated with the replaced SOG. If, after applying the SAF, the LF exceeds 1, the LF is assumed to be 0.98, because ships do not typically operate above 98% of maximum continuous rating (MCR).

3.3.2.4. Speed adjustment factors

Although linearly interpolating missing AIS signals allows us to estimate emissions from missing data, it simplifies the path a ship takes. Because a linear interpolation takes the most direct path between the first and last signals, it does not take into account maneuvering around coastal geography, islands, or bends in rivers. As a result, linearly interpolated SOGs tend to be lower than the SOGs actually reported, leading to underestimated emissions and activity. To rectify this discrepancy, we determine an average ratio between interpolated cruising and reported cruising speeds and between interpolated maneuvering speeds and reported maneuvering speeds for each individual ship. We call these ratios speed adjustment factors (SAF). When a ship is cruising and its SOG is interpolated, the interpolated SOG is multiplied by the ship's cruising SAF. Similarly, when a ship is maneuvering and its SOG is interpolated, we apply its maneuvering SAF. When a ship is cruising or maneuvering and its SOG is not interpolated, we set the SAF equal to 1. Table 10 describes the average speed adjustment factors applied for the interpolated cruising and maneuvering SOGs for 2013, 2014, and 2015, showing that interpolating SOGs underestimates actual cruising and maneuvering SOGs by 7%–12% and 43%–70%, respectively; thus, SAFs are needed. Each individual ship has its own cruising and maneuvering SAF that represents the ratio of its reported SOG to its interpolated SOG in those phases.

Table 10. Average speed adjustment factors for cruising and maneuvering phases, 2013–2015

Year	Average speed adjustment factor, cruising	Average speed adjustment factor, maneuvering
2013	1.12	1.70
2014	1.10	1.69
2015	1.07	1.43

Because missing SOGs for ferries, tugs, and fishing vessels are backfilled by a random sample of their reported SOGs, we did not apply speed adjustment factors to these ship classes.

If after applying the SAF, the LF exceeds 1, the LF is assumed to be 0.98, because ships do not typically operate above 98% of MCR.

3.3.2.5. Hull fouling factors

As a ship travels, biological growth accumulates on its hull in a process known as hull fouling. Because hull fouling reduces the smoothness of the hull, it increases the friction between the ship and the surrounding water, causing an increase in the ship's instantaneous power demand. On average, hull fouling increased the power demanded by an individual ship by about 7%, and ranges from 2%–11% depending on the ship's age and maintenance schedule.

The hull roughness of a ship is determined by its age and the extent of biofouling on its hull. It is measured by method Rt_{50}, which provides an Average Hull Roughness (AHR) in µm. The AHR for a new ship is approximately 120µm, with an average increase of 30µm per year (Doulgeris, Korakianitis, Pilidis, & Tsoudis, 2012), due to biofouling. However, irrespective of drydocking, the hull surface deteriorates with age, with an increase in its AHR. Based on Townsin (2000, 2003), and Willsher (2007), Table 11 shows the variation of AHR according to the vessel's age.

Table 11. Average hull roughness based on the age of a ship

Age of ship	AHR
0 – 1 year	120 µm
2 – 5 years	150 µm
6 – 10 years	200 µm
11 – 15 years	300 µm
16 – 20 years	400 µm
> 20 years	500 µm

Based on Townsin (2000, 2003), the increase in total hull resistance can be calculated as shown in the formula below:

$$\frac{\Delta P_B}{P_B} - 0.02 = \frac{\Delta R}{R_T} = \frac{\Delta C_F}{C_T} = \frac{\left[0.044\left[\left(\frac{k_2}{L}\right)^{1/3} - \left(\frac{k_1}{L}\right)^{1/3}\right]\right]}{C_T}$$

where

ΔP_B = increase in brake power due to hull fouling (to maintain the same speed)
P_B = brake power without hull fouling
ΔR = increase in ship resistance due to hull fouling
R_T = total resistance of the ship without hull fouling
ΔC_F = increase in coefficient of frictional resistance due to hull fouling
C_T = coefficient of total resistance without hull fouling, which can be approximated as $0.018 \times L^{-1/3}$
k_1 = initial roughness of a new ship (120 µm)
k_2 = final hull roughness depending on ship's age, based on values from Table 11, and number of years after drydocking (assuming 5-yearly dry docking from the date of delivery, and a 30µm annual increase in hull roughness due to biofouling).
L = length between the perpendiculars (L_{BP})

The above formula provides a ratio of the increase in brake power due to hull resistance to the original brake power. Rearranging the terms, HFF can be estimated as follows:

$$\textit{Hull Fouling Factor (HFF)} = 1.02 + \left[0.044\left\{\left(\frac{k_2}{L}\right)^{1/3} - \left(\frac{k_1}{L}\right)^{1/3}\right\}\right] \times \frac{1}{0.018 \times L^{-1/3}}$$

3.3.2.6. Weather factors

Local weather conditions also affect power demand. High winds and waves moving against the direction of travel increase the resistive force, thereby increasing the overall power demand, while a favorable sea can assist in propulsion, significantly reducing the power demand.[14]

Following the lead of the Third IMO GHG Study 2014 (Smith et al., 2015), we assume an increase in power demand of 10% for coastal shipping, which we define as less than or equal to 5 nautical miles from the nearest shore, and an increase in power demand of 15% for international shipping, defined as greater than 5 nautical miles from the nearest shore.

3.3.2.7. Draught adjustment factors

The hydrodynamic resistance of a vessel depends on its wetted surface area, which is related to the vessel's draught. Based on the admiralty coefficient and assuming a constant length (L), breadth (B), block coefficient (C_b) and seawater density (Psw), the relationship between a vessel's power requirement and draught (t) is:

$$\textit{Power} \propto (\Delta)^{2/3} \propto (LBtC_{b}\rho_{sw})^{2/3} \propto (t)^{2/3}$$

---

[14] A following sea is commonly used in weather rerouting, an operational practice to reduce fuel consumption by taking advantage of favorable weather conditions.

Therefore, by reducing the wetted surface area of a ship, a smaller draught reduces overall power requirements of the ship. During loaded conditions, most vessels operate below their design summer load line draughts. Moreover, vessels like bulk carriers, tankers, and general cargo vessels have a well-defined ballast voyage with a significantly lesser draught than the loaded voyage, further reducing the power requirement.

Based on the above principles, this study incorporates an annual average draught correction factor for individual ships, including different loaded and ballast correction factors for the specific ship types. We assume any draught greater than 75% of the design draught is considered as loaded voyage. Draughts less than or equal to 75% of the design draught are considered ballasted voyages. Vessels with fewer than 30 reported draughts are assumed to have draught ratios equal to the average draught ratio by either ship type and capacity bin, when available, or ship class and capacity bin. The annual average draught ratios by ship class are provided in Appendix L.

Furthermore, the annual operation for ballasted ships is unequally divided between their ballast and loaded voyages. The proportion can vary due to several factors such as the cargo, market conditions, geographical location, etc. Therefore, for each ship with dedicated loaded and ballast voyages, we also calculate the annual percentage of ballast and loaded voyages. Similar to annual average draught ratio, vessels with insufficient draught data, which is to say less than 30 records, were backfilled with annual average percentage of ballast and loaded voyage by ship type and capacity bin or ship class and capacity bin. Table 12 displays the average percentage of ballast and loaded voyages by ship class.

Table 12. Share of ballast and loaded voyages by ship class

Ship class	2015	
	Ballast	**Loaded**
Bulk carrier	56%	44%
Chemical tanker	44%	56%
General cargo	46%	54%
Liquefied gas tanker	29%	71%
Oil tanker	48%	52%
Other liquid tankers	34%	66%
Refrigerated bulk	28%	72%

Using the draught ratio and the percent of time spent in ballasted and loaded voyages, we can calculate a draught adjustment factor (DAF) for each unique ship:

$$DAF_{nbs} = (DR_{nbs})^{2/3}$$

$$DAF_{bs} = \left((DR_b)^{2/3} \times P_b\right) + \left((DR_l)^{2/3} \times P_l\right)$$

where

DAF_{nbs} = draught adjustment factor for non-ballasted ships
DR_{nbs} = draught ratio for non-ballasted ships
DAF_{bs} = draught adjustment factor for ballasted ships
DR_b = draught ratio for ballasted ships during ballast condition
DR_l = draught ratio for ballasted ships during loaded condition
P_b = percentage of ballast voyage annually for ballasted ships
P_l = percentage of loaded voyage annually for ballasted ships.

Table 13 shows the average annual DAF by ship class.

Table 13. Average annual draught adjustment factors (DAF) by ship class, 2013–2015

Ship Class	2015
Bulk carrier	0.7982
Chemical tanker	0.8483
General cargo	0.8448
Liquefied gas tanker	0.8740
Oil tanker	0.8226
Other liquid tankers	0.8756
Refrigerated bulk	0.8777
Container	0.8689
Cruise	0.9799
Ferry pax Only	0.9322
Ferry ro-pax	0.9459
Miscellaneous - fishing	0.8903
Miscellaneous - others	0.6045
Naval ship	0.8761
Non-propelled	0.8328
Non-ship	0.9664
Offshore	0.8832
Ro-ro	0.9113
Service other	0.9043
Service tug	0.9253
Vehicle	0.9113
Yacht	0.9459

3.3.2.8. 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:

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

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

$FC_{ME_{i,t}}$ = main engine fuel consumption (kg) for ship i at time t, 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
$EF_{ME_{k,m,n,t}}$ = 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 at time t
$D_{AE_{p,i,t}}$ = auxiliary engine power demand (kW) in phase p for ship i at time t
$EF_{AE_{k,m}}$ = auxiliary engine black carbon emission factor (g/kWh) for engine type k and main fuel type m
$D_{BO_{p,i,t}}$ = boiler power demand (kW) in phase p for ship i at time t
$EF_{BO_{m}}$ = 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.

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 "what-if" 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 emissions 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 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 14.

Table 14. 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:

$$BC_X = \left(BC_{R_{2015}} \times (1 - x_R)\right) + \left(BC_{D_{2015}} \times (1 - x_D)\right) + \left(BC_{LNG_{2015}} + \left(BC_{R_{2015}} \times x_R \times \frac{EF_{LNG_{2015}}}{EF_{R_{2015}}} \times \frac{EC_{LNG}}{EC_{PF}}\right) + \left(BC_{D_{2015}} \times x_D \times \frac{EF_{LNG_{2015}}}{EF_{D_{2015}}} \times \frac{EC_{LNG}}{EC_{PF}}\right)\right)$$

where

x_R = percentage of residual fuel changed over to LNG
x_D = percentage of distillate fuel changed over to LNG
BC_X = total BC emissions (g) on switching over x% of residual and distillate fuel to LNG
$BC_{R_{2015}}$ = BC emissions (g) from residual fuel consumption in 2015
$BC_{D_{2015}}$ = BC emissions (g) from distillate fuel consumption in 2015
$BC_{LNG_{2015}}$ = BC emissions (g) from LNG fuel consumption in 2015
$EF_{R_{2015}}$ = emission factor (gBC/kg-fuel) for residual fuel
$EF_{D_{2015}}$ = emission factor (gBC/kg-fuel) for distillate fuel
$EF_{LNG_{2015}}$ = emission factor (gBC/kg-fuel) for LNG
EC_{LNG} = energy content of LNG fuel (in this case 50 MJ/kg)
EC_{PF} = energy content of petroleum-based 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:

$$BC_X = BC_O\left(1 - \frac{0.3x}{100}\right)$$

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_O = residual BC emissions when 0% of residual BC emissions are treated with scrubbers

This assumes that EGCS reduce BC by 30%, per research by Johnson et al. (2016).

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:

$$BC_X = BC_O\left(1 - \frac{0.85x}{100}\right)$$

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_O = distillate BC emissions when 0% of distillate BC emissions are treated with DPFs

We assume that DPFs cannot be effectively used with HFO, as diesel fuel with low sulfur content is required to prevent frequent plugging. Thus, Scenario 4 considers application of DPFs only for distillate fuel oils and assumes an average DPF BC reduction potential of 85%. This analysis assumes that DPFs could treat and remove BC from all distillate exhaust. In practice, DPFs may only be suitable for ships using very high-quality distillate fuels, similar in quality to on-road diesel fuel. This what-if analysis shows the BC reduction potential of treating distillate exhaust at varying levels of DPF uptake.

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 among 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 EFs 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. EFs used to calculate emissions from ships, including the EFs in this study, typically do not take these nuances into account, leading to some uncertainty in emissions estimates. The exception in this study is the BC EF, which corrects for engine type and fuel type.

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 the general category, such as residual fuel, distillate fuel, and LNG. 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 to match ships to emission 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 or within a river, or if the time gap is large. 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. We have attempted to correct for underestimated SOG and emissions by applying a speed adjustment factor to interpolated data points; however, 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 knots) that are 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, BO, or both on to provide auxiliary power. However, some ports provide onshore electrical power so that ships can switch off their AE and BO 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, and potential air emissions, 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. Heavy fuel oil use in Emission Control Areas

This report makes a simplifying assumption that no ships use HFO while in ECAs. In reality, a handful of ships are allowed to use HFO in ECAs because they use EGCS (scrubbers) to comply with ECA SO_x regulations. The authors are aware that several cruise ships and a few cargo ships are outfitted with EGCSs and use HFO in ECAs; however, a complete list of these ships was not available. These ships, moreover, represent a small fraction of the number of ships and fuel consumption in ECAs. Thus, for the sake of simplicity, this analysis assumes no HFO was used in ECAs in 2015.

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 fuel type and engine type is presented in Table 15. The vast majority of ships are powered by diesel engines (HSD, MSD, and SSD). Most SSDs are 2-stroke and almost all operate on residual fuel; most MSDs are 4-stroke with slightly more operating on distillate fuel than residual fuel; and 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 five 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 15. Number of ships in the global fleet by main fuel type and engine type, 2015

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.

The IMO NO_X Tier of main engines in the 2015 global fleet is shown in Table 16. Note that 85% of main engines represented in this inventory are Tier 0 or Tier I.

Table 16. Number of ships in the global fleet by main engine tier, 2015

Tier	Year of Construction	Vessel Count	Share of Fleet
Tier 0	Pre-2000	29,409	42%
Tier I	2000-2010	30,053	43%
Tier II	2011-2015	10,834	15%
Unknown tier	—	64	<1%
Total	**All**	**70,360**	**100%**

4.2. TIME IN PHASE

Ships tend to split their time between cruising and waiting (berth and anchorage). Time at berth and anchorage seems related to cargo value. Container ships spend most of their time cruising and have the lowest turnaround time due to 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 loading and unloading operations. Liquid tankers such as 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 AEs are on when a ship is at anchor. Thus, ME emissions from fishing vessels may be underestimated.

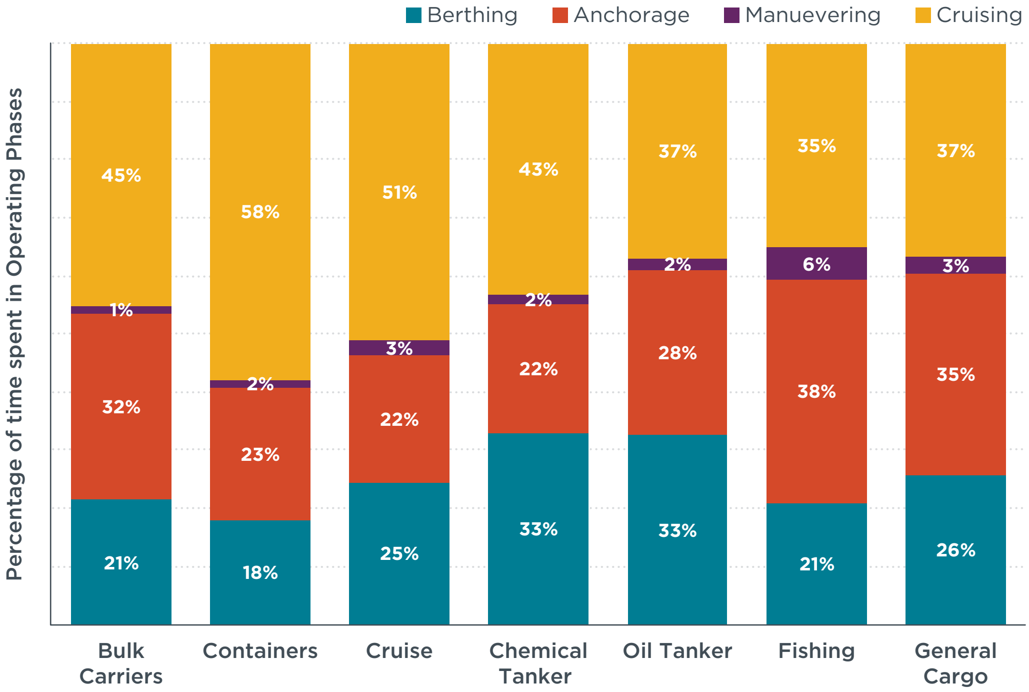

Figure 4. Time spent in each operating phase for major ship classes

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 17.

Overall, the global shipping fleet consumed 1.3 trillion kWh of energy in 2015, which is enough to power California for 6 years.[15] The fleet operated for about 560 million hours, equivalent to 64,000 years, and traveled 2.2 billion nautical miles, equivalent to circling the globe more than 100,000 times.

Container ships, bulk carriers, and oil tankers made up 30% of the global fleet, but accounted for 49% of distance traveled and 62% of fuel consumption. About 5,000

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[15] 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.

container ships, 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 sixth out of 22 ship classes in terms of energy use (6%) and fuel consumption (5%), despite making up a small proportion of the fleet in terms of number (2%). 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 uncombusted 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 1% of energy use and 2% of fuel consumption due to the relatively small size of their engines. A similar pattern is observed for tugs and other service vessels (service-tug and service-other).

Table 17. 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 (t)[a]	Percent of fuel cons.	Energy use (million kWh)	Percent of energy use
Container	5,008	7%	42,658,000	8%	368,851,000	17%	66,861,000	25%	332,000	26%
Bulk carrier	10,572	15%	87,713,000	16%	505,403,000	23%	55,529,000	21%	278,000	21%
Oil tanker	5,733	8%	47,001,000	8%	203,355,000	9%	39,229,000	15%	183,000	14%
Chemical tanker	4,568	6%	38,156,000	7%	189,608,000	9%	17,754,000	7%	85,000	7%
General cargo	9,183	13%	74,085,000	13%	272,662,000	12%	15,548,000	6%	74,000	6%
Liquefied gas tanker	1,675	2%	13,736,000	2%	91,072,000	4%	14,365,000	5%	76,000	6%
Cruise	406	1%	3,318,000	1%	22,236,000	1%	11,955,000	4%	54,000	4%
Ferry-ro-pax	2,062	3%	16,614,000	3%	52,208,000	2%	9,370,000	4%	45,000	3%
Vehicle	820	1%	7,017,000	1%	72,937,000	3%	8,113,000	3%	41,000	3%
Ro-ro	1,055	1%	8,263,000	1%	33,790,000	2%	5,534,000	2%	26,000	2%
Service-other	6,865	10%	52,353,000	9%	54,525,000	2%	4,899,000	2%	23,000	2%
Fishing vessel	7,030	10%	51,803,000	9%	151,453,000	7%	4,307,000	2%	20,000	2%
Offshore	4,447	6%	33,906,000	6%	29,156,000	1%	4,202,000	2%	20,000	1%
Refrigerated bulk	703	1%	5,812,000	1%	36,390,000	2%	4,071,000	2%	19,000	1%
Service - tug	6,941	10%	53,194,000	10%	87,525,000	4%	2,129,000	1%	10,000	1%
Ferry-pax-only	1,424	2%	10,409,000	2%	18,159,000	1%	1,520,000	1%	7,000	1%
Yacht	1,530	2%	10,928,000	2%	9,621,000	<1%	551,000	<1%	3,000	<1%
Other liquid tanker	61	<1%	434,000	<1%	596,000	<1%	193,000	<1%	740	<1%
Naval ship	80	<1%	596,000	<1%	567,000	<1%	82,000	<1%	330	<1%
Others	139	<1%	1,117,000	<1%	1,574,000	<1%	63,000	<1%	300	<1%
Non-propelled	49	<1%	313,000	<1%	72,000	<1%	3,000	<1%	10	<1%
Non-ship	9	<1%	52,000	<1%	41,000	<1%	400	<1%	2	<1%
Total[b]	**70,360**	**100%**	**559,489,000**	**100%**	**2,201,808,000**	**100%**	**266,275,000**	**100%**	**1,297,000**	**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

Total global BC emissions from ships were estimated to be between 53 kt and 80 kt in 2015, with a best estimate of approximately 67 kt. This corresponds to a BC EF of 0.25 g/kg fuel with a range of 0.20 to 0.30 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 cruise ships is 0.34 g/kg fuel, with a range of 0.28 to 0.40 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 5% to 8% (100-year timescale) and 16% to 23% (20-year timescale) of the CO_2-equivalent climate warming impact from shipping in 2015.[16]

It is important to understand that this inventory may underestimate global BC emissions from ships. The BC EFs developed for this report rely on BC emissions from 27 engine measurements. Twenty of these (74%) were modern, well-maintained Tier II (2011-2015) and Tier III (2016+) engines. Evidence presented in this report and by Johnson et al. (2016) suggests that modern, electronically controlled engines emit much less BC than older engines. Given that 85% of the global fleet has Tier 0 (pre-2000) or Tier I (2000-2010) engines, BC measured from new, well-maintained Tier II and Tier III engines is not representative of what we would expect from engines in the 2015 fleet. We attempted to account for this by taking the BC EFs derived from the raw testing data and increasing them to a range that might more reasonably estimate BC emissions from the current fleet (see Appendix G for full details). The BC EFs presented here can be updated as more testing data become available. In particular, data from in-use Tier 0 and Tier I engines, which would be more representative of the current fleet, could substantially improve our understanding of BC EFs from ships.

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 t are shaded darkest. Because of intense ship traffic in the Baltic Sea and North Sea, BC emissions exceed 8 t in most areas.

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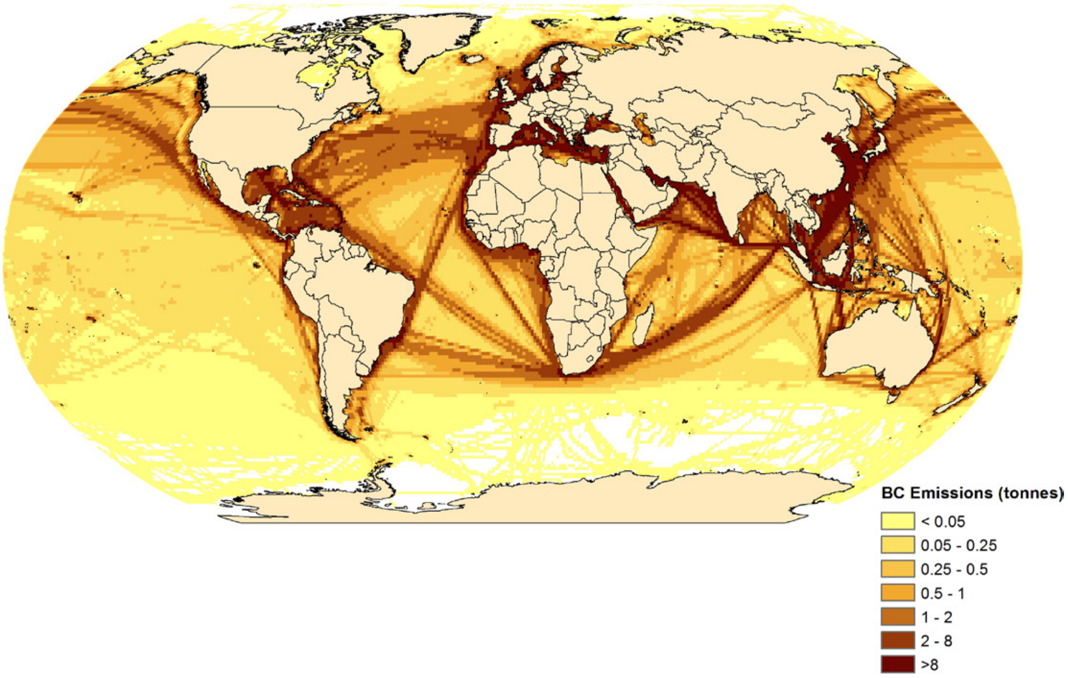
[16] Assumes that, in 2015, ships emitted 53 to 80 kt of BC with GWPs of 900 (100-year) and 3,200 (20-year); 831,000 kt of CO_2 with GWP of 1; 41.5 kt of N_2O with GWPs of 298 (100-year) and 289 (20-year); and 361 kt of CH_4 emissions with GWPs of 25 (100-year) and 72 (20-year), per the results of this study.



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 in 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).

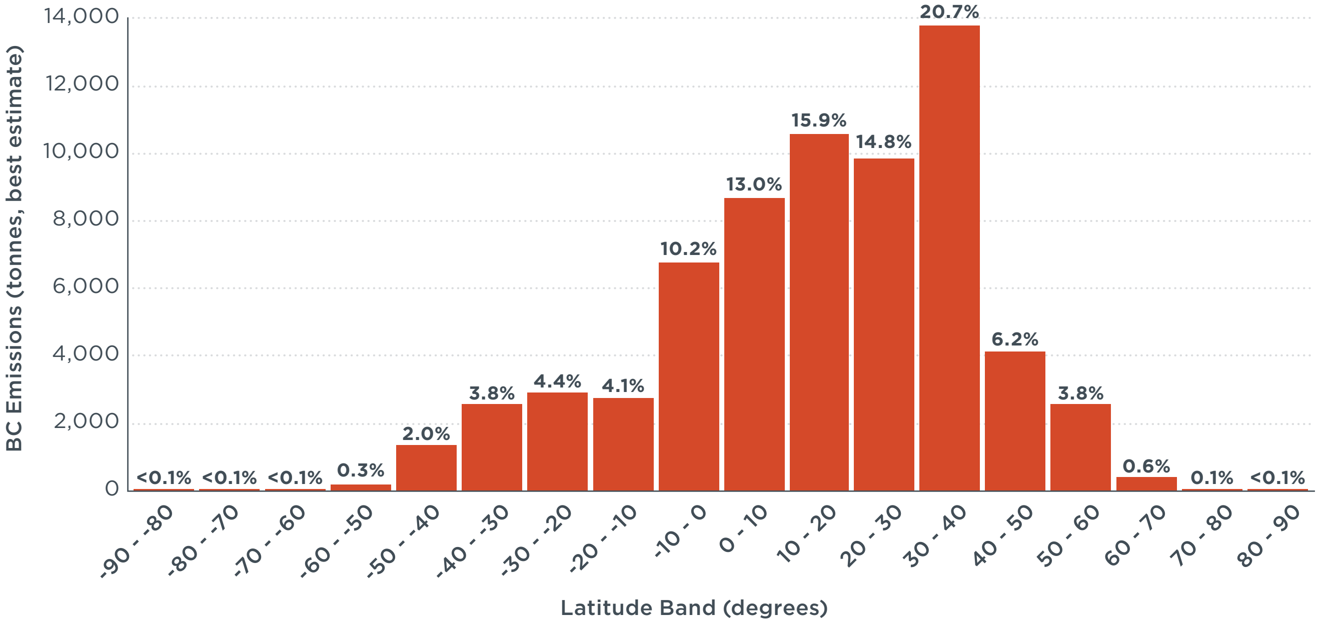


Figure 6. Distribution of BC emissions by latitude

Table 18 shows BC emissions by ship class and Figure 7 shows the proportion of BC emissions (best estimate) by ship class.

Larger ships are responsible for the most BC emissions. Container ships, bulk carriers, and oil tankers together emit 60% of BC emissions, while accounting for 30% 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 (26%) compared with other ship classes. Outside that group, cruise ships account for a disproportionately large amount of BC, emitting 6% of BC emissions despite accounting for only 1% 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 from ships in the IMO-defined 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 18. Black carbon emissions, number of ships, and deadweight tonnage by ship class, 2015

Ship class	BC emissions (t)[a]	% of BC emissions	BC EF (g/kg fuel)[a]	Number of ships	% of Total fleet	Deadweight tonnage	% of total deadweight tonnage
Container	17,384 (13,469 – 21,298)	26.1%	0.26 (0.20 - 0.32)	5,008	7%	242,659,796	14%
Bulk carrier	12,358 (9,467 – 15,250)	18.6%	0.22 (0.17 - 0.27)	10,572	15%	755,457,667	42%
Oil tanker	10,014 (8,509 - 11,519)	15.0%	0.26 (0.22 - 0.29)	5,733	8%	446,535,445	25%
Chemical tanker	4,368 (3,618 - 5,119)	6.6%	0.25 (0.20 - 0.29)	4,568	7%	100,549,218	6%
General cargo	4,301 (3,438 - 5,165)	6.5%	0.28 (0.22 - 0.33)	9,183	13%	71,569,718	4%
Cruise	4,050 (3,330 – 4,771)	6.1%	0.34 (0.28 - 0.40)	406	<1%	1,975,639	<1%
Ferry-ro-pax	2,418 (1,801 - 3,035)	3.6%	0.26 (0.19 - 0.32)	2,062	3%	3,715,807	<1%
Liquefied gas tanker	1,998 (1,687 - 2,309)	3.0%	0.14 (0.12 - 0.16)	1,675	2%	55,411,731	3%
Vehicle	1,724 (1,317 - 2,130)	2.6%	0.21 (0.16 - 0.26)	820	1%	13,108,259	1%
Service-other	1,561 (1,290 – 1,833)	2.3%	0.32 (0.26 - 0.37)	6,865	10%	50,856,202	3%
Ro-ro	1,465 (1,221 - 1,710)	2.2%	0.26 (0.22 - 0.31)	1,055	1%	6,129,121	<1%
Fishing vessel	1,348 (1,135 - 1,562)	2.0%	0.31 (0.26 - 0.36)	7,030	10%	2,834,440	<1%
Refrigerated bulk	1,176 (1,039 - 1,312)	1.8%	0.29 (0.26 - 0.32)	703	1%	4,807,714	<1%
Offshore	1,158 (995 - 1,320)	1.7%	0.28 (0.24 - 0.31)	4,447	6%	21,807,535	1%
Service-tug	694 (517 - 871)	1.0%	0.33 (0.24 - 0.41)	6,941	10%	1,296,198	<1%
Ferry-pax only	333 (266 - 400)	0.5%	0.22 (0.18 - 0.26)	1,424	2%	203,137	<1%
Yacht	143 (124 - 163)	0.2%	0.26 (0.22 - 0.30)	1,530	2%	199,234	<1%
Other liquid tanker	38 (36 - 40)	0.1%	0.20 (0.19 - 0.21)	61	<1%	326,023	<1%
Naval ship	26 (19 - 34)	<0.1%	0.32 (0.28 - 0.36)	80	<1%	1,492,026	<1%
Others	20 (17 - 23)	<0.1%	0.32 (0.28 - 0.36)	139	<1%	328,263	<1%
Non-propelled	1 (<1-<2)	<0.1%	0.33 (0.22 - 0.43)	49	<1%	296,089	<1%
Non-ship	<1	<0.1%	0.40 (0.27 - 0.54)	9	<1%	422	<1%
Total	**66,581 (53,296 - 79,856)**	**100%**	**0.25 (0.20 - 0.30)[b]**	**70,360**	**100%**	**1,781,559,684**	**100%**

[a]Best estimate, with low-high range in parentheses. [b]Best estimate for BC EF and range (in parenthesis), based on the quotient of the range of total BC emissions and total fuel consumption.

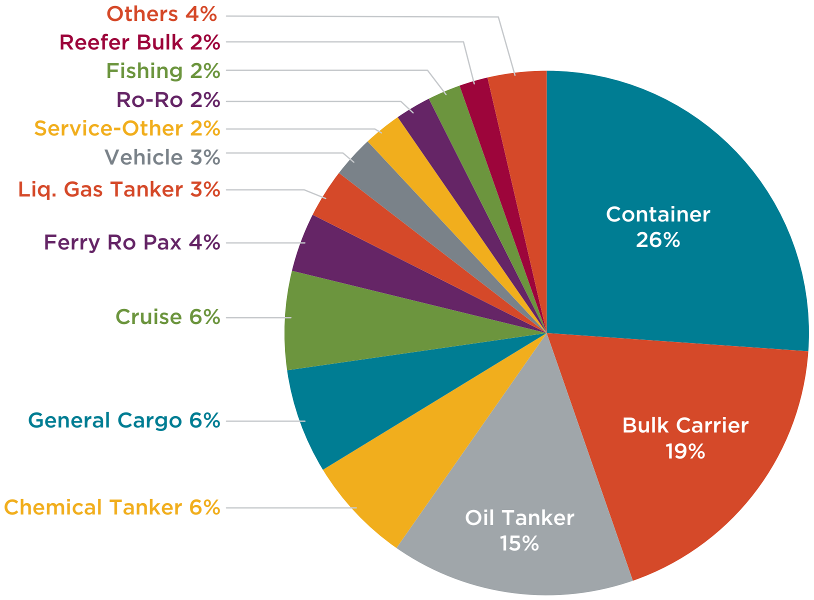


Figure 7. Share of global BC emissions by ship class

Figure 8 shows BC emissions by source (ME, AE, and BO) for the top six emitting ship classes, plus fishing vessels. In total, most BC emissions for all ships comes from MEs (61%), followed by AEs (35%), and BOs (4%). Oil tankers have higher BC emissions from AEs and BOs compared with 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 require 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.

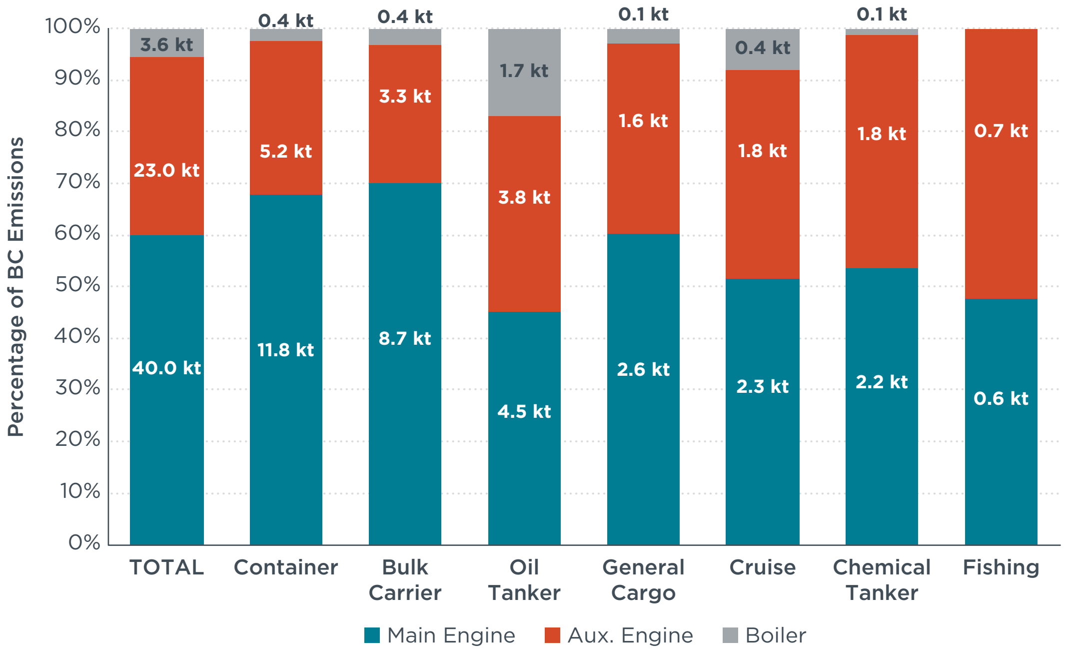


Figure 8. Proportion of black carbon emissions from main engines, auxiliary engines, and boilers for select ship classes

Table 19 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 (28 kt) of ME BC is emitted by SSD engines, roughly 70% 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 70% of total ME BC emissions from ships. MSD and HSD engines together account for approximately 11 kt of BC emissions, which is 28% 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 19. 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	3	5	23	1,684	6	1,732	4	21	3,479
Residual	84	5	1	138	28	7,425	28,419	372	36,472
LNG	52	<1	—	—	—	30[b]	<1[c]	—	83
Total	**140**	**10**	**24**	**1,822**	**34**	**9,157**	**28,423**	**393**	**40,034**

[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 (69%) 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 50% of BC emissions from fishing vessels are from ships with 4-stroke HSD MEs, since small ships are often powered by such engines.

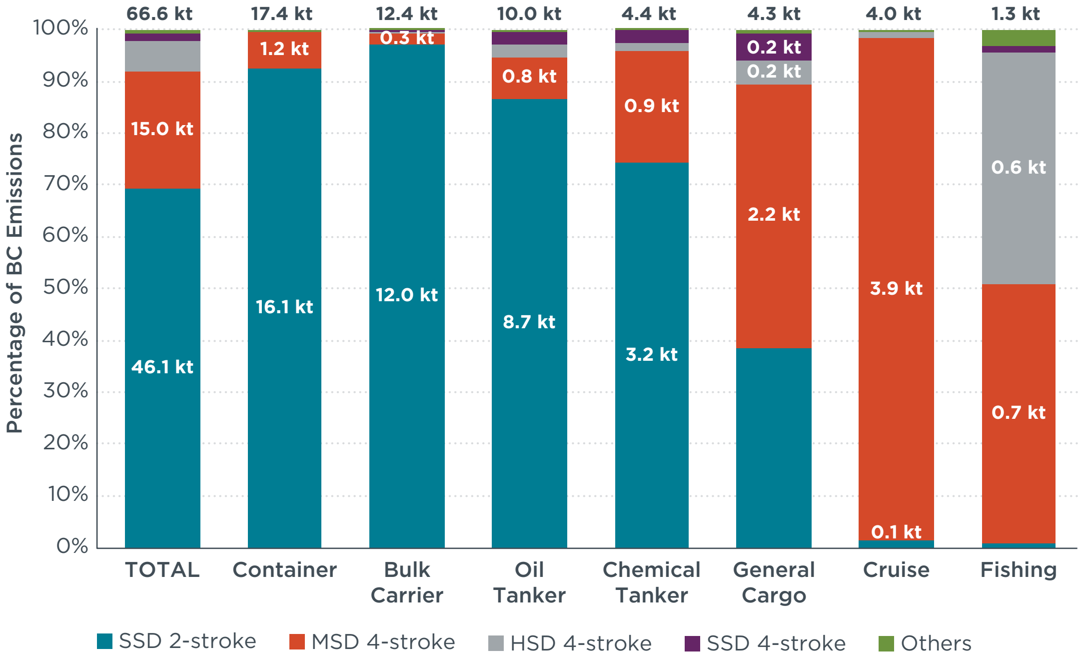


Figure 9. Black carbon emissions by main engine type and ship class, summarized by ship classes emitting the most BC, plus fishing vessels

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” column includes BC from LNG emissions, but the amount is too small to be visible on the graph. Approximately 89% of BC emissions from the global fleet are from ships whose main fuel type is residual. In reality, some proportion of the BC emissions that are emitted from ships with main fuel type “residual” are actually from burning distillate fuel when these ships switch to distillates when operating in ECAs. For ship classes that emit the most BC, 82% to 99% of BC is emitted from ships whose main fuel type is residual fuel. In contrast, more than 70% of BC from fishing vessels comes from ships whose main fuel type is distillate fuel.

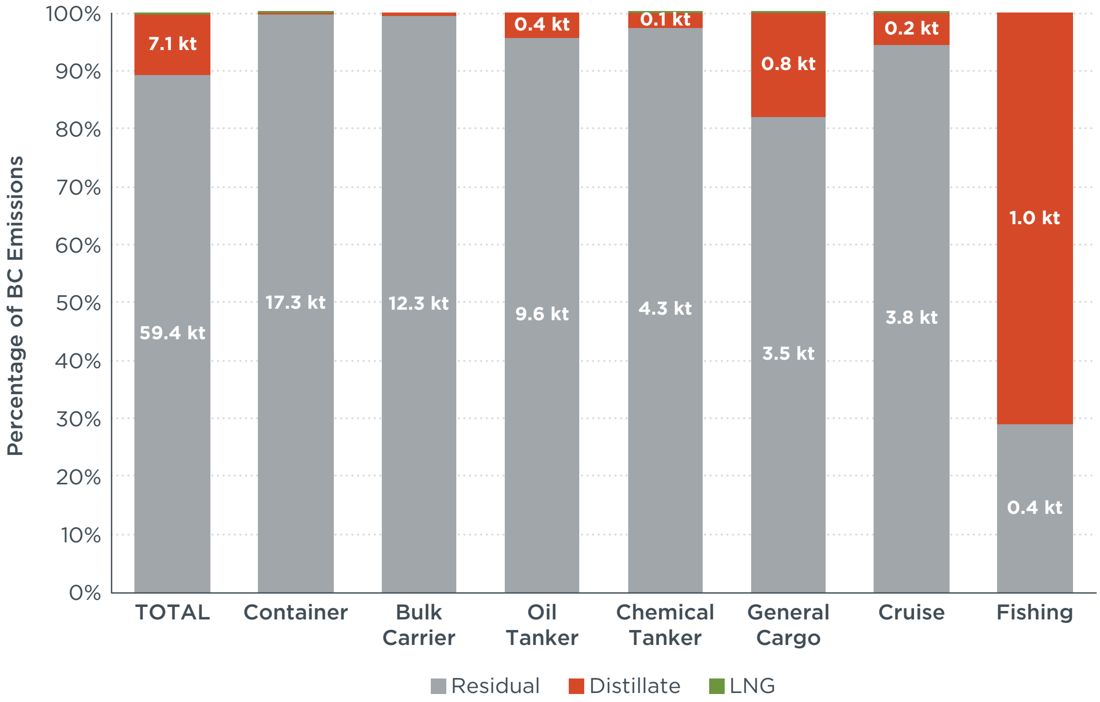


Figure 10. Black carbon emissions by main fuel type for the highest emitting ship classes and fishing vessels

Figure 11 shows total BC emissions by flag state. Just six of 178 flag states—Panama; China, Liberia; Marshall Islands; Singapore; and Malta—accounted for 55% of marine BC emissions in 2015. Panama-flagged ships emit more BC than ships registered to any other flag state, accounting for more than 10,500 t of BC emissions, equivalent to 16% of global emissions from ships.

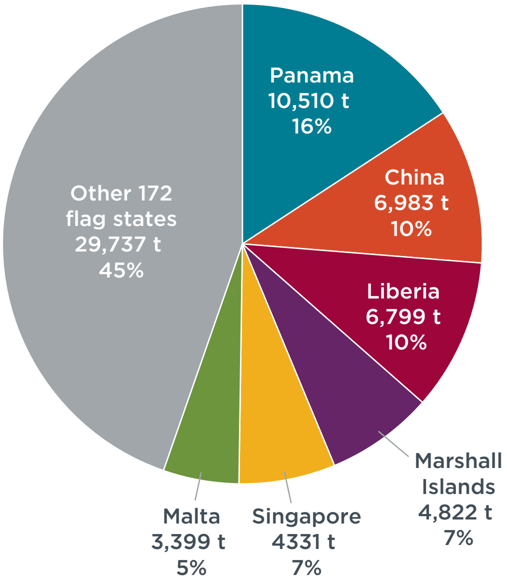


Figure 11. Black carbon emissions by top emitting flag states

BC intensity, measured as BC emissions per ship per year, for the highest emitting ship classes in 2015 is shown in Figure 12. Cruise ships emit 10 t per ship per year, about three times greater than container ships and equal to about 4,200 Euro V heavy-duty trucks operating 100,000 km over one year.[17] Further, cruise ships emit the most BC per unit of fuel they burn: The average cruise ship emits 0.34 kg of BC for every tonne of fuel, compared with 0.26 kg/t for a container ship. Thus, policies that aim to reduce BC emissions from ships must address container ships, which emit the most BC in total of any ship class (17.4 kt BC/year), and from cruise ships, which emit the most BC per tonne of fuel (0.34 kg BC/t) and per ship per year (10 t BC/ship/year).

The ships in Figure 12 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. Assuming DPFs reduce BC emissions by 85%, retrofitting all 400 or so cruise ships with DPFs would reduce BC by 8.5 t per ship and 3,443 t in total, or 5.2% of total BC emissions from ships. If it were possible to retrofit all 5,000 or so container ships with DPFs, it would reduce BC by 3 t per ship per year on average, with a total reduction of 14,776 t, or 22% of total BC emissions from ships.

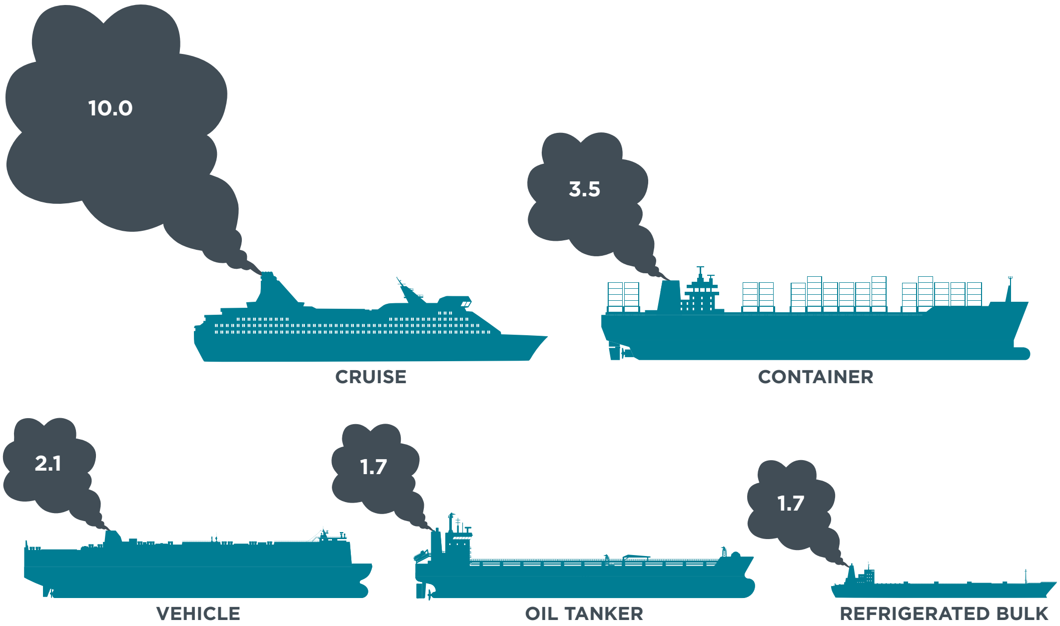


Figure 12. Tonnes of black carbon per ship per year for the highest emitting ship classes, 2015

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[17] 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.

4.4.2 Other air and climate pollutants

Table 20 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 71% of SO_x, 67% of NO_x, 59% of CO, 60% of BC, 70% of PM, 61% of CO_2, 62% 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 (29%), CO (26%), BC (26%), PM (30%), CO_2 (25%), and N_2O (26%).

Table 20. Emissions of other air and climate pollutants, 2015

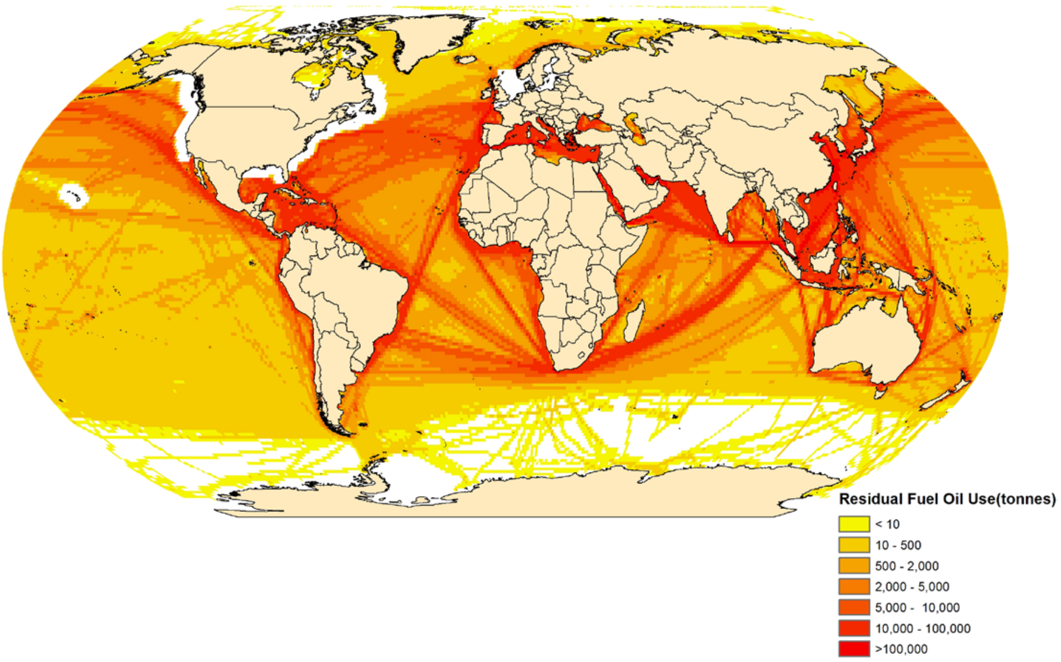
Ship class	SO_x[a] (t)	NO_x (t)	CO (t)	BC (best; t)	PM (t)	CO_2 (t)	N_2O (t)	CH_4 (t)
Container	3,059,940	5,017,821	189,773	17,384	436,333	208,636,855	10,735	4,176
Bulk carrier	2,594,275	4,233,241	150,653	12,358	362,997	173,174,287	8,819	3,258
Oil tanker	1,706,872	2,471,699	92,769	10,014	218,817	122,587,368	6,189	1,892
Chemical tanker	726,303	1,112,704	45,260	4,368	97,983	55,565,225	2,775	1,583
General cargo	543,728	944,910	40,489	4,301	75,475	48,845,745	2,390	1,022
Cruise	412,703	616,221	28,732	4,050	53,507	37,566,907	1,838	802
Vehicle	362,080	619,896	22,202	1,724	51,151	25,333,394	1,282	480
Liquefied gas tanker	354,861	570,211	69,471	1,998	47,111	42,560,357	1,962	332,919
Ferry-ro-pax	223,372	446,559	25,409	2,418	32,297	29,557,328	1,386	10,264
Refrigerated bulk	172,168	282,444	10,286	1,176	22,961	12,730,853	637	201
Ro-ro	143,801	267,006	13,673	1,465	20,213	17,480,822	827	566
Fishing vessel	46,506	256,507	12,121	1,348	8,717	13,738,353	635	226
Service-other	40,812	265,772	13,997	1,561	8,414	15,647,751	720	491
Offshore	21,684	209,765	11,701	1,158	5,345	13,426,454	599	3,102
Ferry-pax only	11,981	77,440	3,718	333	2,269	4,854,676	217	205
Service tug	10,831	93,529	6,493	694	2,947	6,814,082	314	150
Other liquid tanker	1,837	5,149	264	38	218	614,496	28	4
Yacht	1,620	29,586	1,454	143	547	1,767,140	77	25
Naval ship	880	2,739	154	26	140	261,887	13	3
Others	137	2,912	179	20	59	200,269	9	78
Non-propelled	64	136	9	1	10	9,420	0	0
Non-ship	1	26	1	0	0	1,201	0	0
Total	**10,436,459**	**17,526,274**	**738,810**	**66,581**	**1,447,509**	**831,374,870**	**41,453**	**361,448**

[a] *Ranked by SO_x emissions.*

4.5. FUEL USE AND CARRIAGE

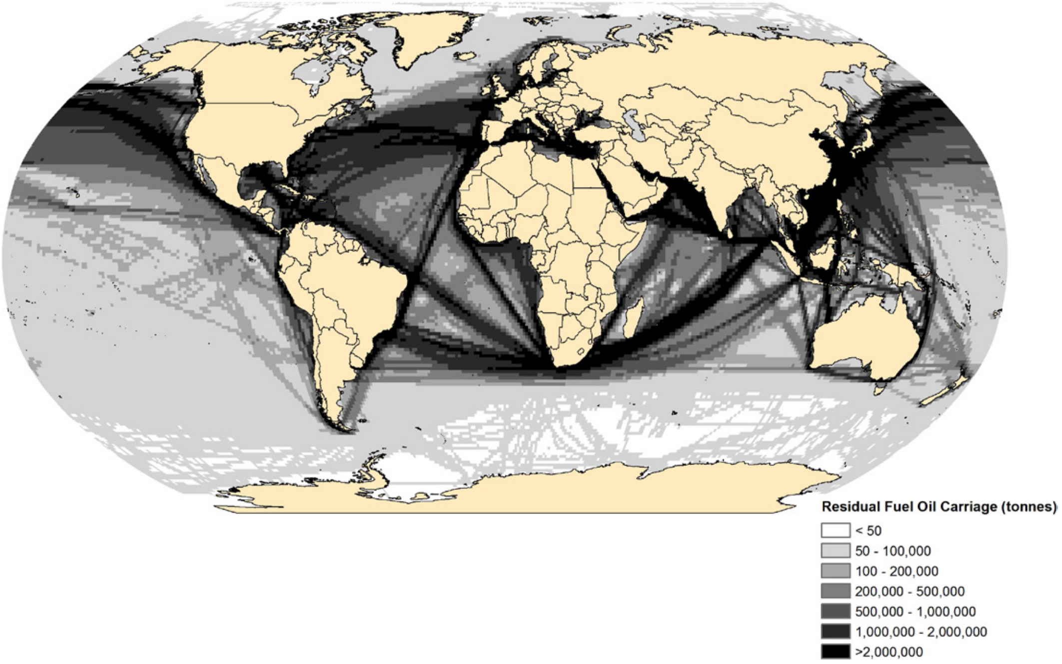
The geographic distribution of residual fuel use and residual fuel carriage (as bunker fuel, not cargo) for the global fleet in 2015 are presented in Figure 13 and Figure 14, respectively. Residual fuel use and carriage occurs across the globe, including the polar regions. In general, residual fuel use 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. Residual fuels, such as HFO, are essentially prohibited in the North American, U.S. Caribbean Sea, Baltic Sea, and North Sea SECA regions; the impact of which is evident in Figure 13, showing no HFO use in these areas. 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% S standard by using EGCS (scrubbers) that remove most of the sulfur from the ships' exhaust. Also, a small number of steam powered ships (fewer than 10) operating on the North American Great Lakes are exempt from the North American ECA fuel S 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 United States 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 with other marine fuels (Roy & Comer, 2017).



Data sources: exactEarth; IHS; ArcGIS

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



Data sources: exactEarth; IHS; ArcGIS

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

Table 21 summarizes fuel consumption by main engine type. The global fleet consumed 210 Mt of residual fuel in 2015, compared with 50 Mt of distillate, and approximately 6 Mt of LNG. Residual fuel consumption represents 79% of fuel use by ships; distillate represents roughly 19% of fuel consumption; and LNG makes up the rest (a bit more than 2%). Ships with 2-stroke SSD MEs consume the majority (86%) 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 21. Fuel consumption by main engine type

Fuel consumption (t)	SSD		MSD		HSD		ST	GT	Total
	2-stroke	4-stroke	2-stroke	4-stroke	2-stroke	4-stroke			
Residual	180,481,833	2,326,172	261,803	26,186,769	8,684	535,707	213,790	256,678	210,271,436
Distillate[a]	12,228,505	425,155	467,794	20,692,897	1,081,383	13,663,260	204,729	752,190	49,515,912
LNG	27,619[b]	—	—	2,315,902[c]	—	—	4,123,776	20,560	6,487,856
Total	**192,710,338**	**2,751,326**	**729,597**	**48,879,666**	**1,090,067**	**14,198,966**	**4,542,295**	**1,029,427**	**266,275,204**

[a] Distillate fuel includes Distillate-ECA Fuel with slightly lower % S content than typical distillate fuel. [b] LNG SSD 2-stroke contains only LNG-Diesel cycle dual fuel engines. [c] LNG MSD 4-stroke contains LNG-Otto cycle and LNG-Diesel cycle dual fuel engines.

Table 22 shows fuel consumption by ship class in 2015. 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 61% of total fuel use and 71% 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, representing 21% of total fuel consumption and 25% of residual fuel consumption.

Table 22. Fuel consumption by ship class, 2015

Ship class	Residual fuel use (t)	%Residual fuel use	Distillate fuel use (t)	%Distillate fuel use	LNG use (t)	%LNG use	Total fuel use (t)	%total fuel use
Container	62,141,484	30%	4,716,152	10%	3,015	<1%	66,860,651	25%
Bulk carrier	52,727,822	25%	2,800,881	6%	82	<1%	55,528,785	21%
Oil tanker	34,557,116	16%	4,671,401	9%	—	—	39,228,516	15%
Chemical tanker	14,666,112	7%	3,075,522	6%	12,665	<1%	17,754,299	7%
General cargo	10,847,499	5%	4,695,807	9%	4,319	<1%	15,547,625	6%
Liquefied gas tanker	7,181,244	3%	969,740	2%	6,214,173	96%	14,365,157	5%
Cruise	8,247,257	4%	3,702,240	7%	5,661	<1%	11,955,158	4%
Ferry-ro-pax	4,323,260	2%	4,860,870	10%	185,726	3%	9,369,856	4%
Vehicle	7,344,227	3%	768,387	2%	9	<1%	8,112,622	3%
Ro-ro	2,803,925	1%	2,723,861	6%	6,074	<1%	5,533,859	2%
Service -other	606,375	<1%	4,289,110	9%	3,133	<1%	4,898,617	2%
Fishing vessel	761,646	<1%	3,545,411	7%	—	—	4,307,057	2%
Offshore	242,156	<1%	3,910,668	8%	49,011	1%	4,201,835	2%
Refrigerated bulk	3,479,499	2%	591,296	1%	—	—	4,070,794	2%
Service- tug	120,881	<1%	2,007,727	4%	321	<1%	2,128,930	1%
Ferry- pax only	172,505	<1%	1,344,378	3%	2,697	<1%	1,519,581	1%
Yacht	3,477	<1%	547,820	1%	—	—	551,298	<1%
Other liquid tanker	29,104	<1%	163,401	<1%	—	—	192,506	<1%
Naval ship	14,453	<1%	67,648	<1%	—	—	82,101	<1%
Others	174	<1%	61,463	<1%	972	<1%	62,610	<1%
Non-propelled	1,217	<1%	1,756	<1%	—	—	2,973	<1%
Non-ship	—	—	375	<1%	—	—	375	<1%
Total	**210,271,436**	**100%**	**49,515,912**	**100%**	**6,487,856**	**100%**	**266,275,204**	**100%**

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

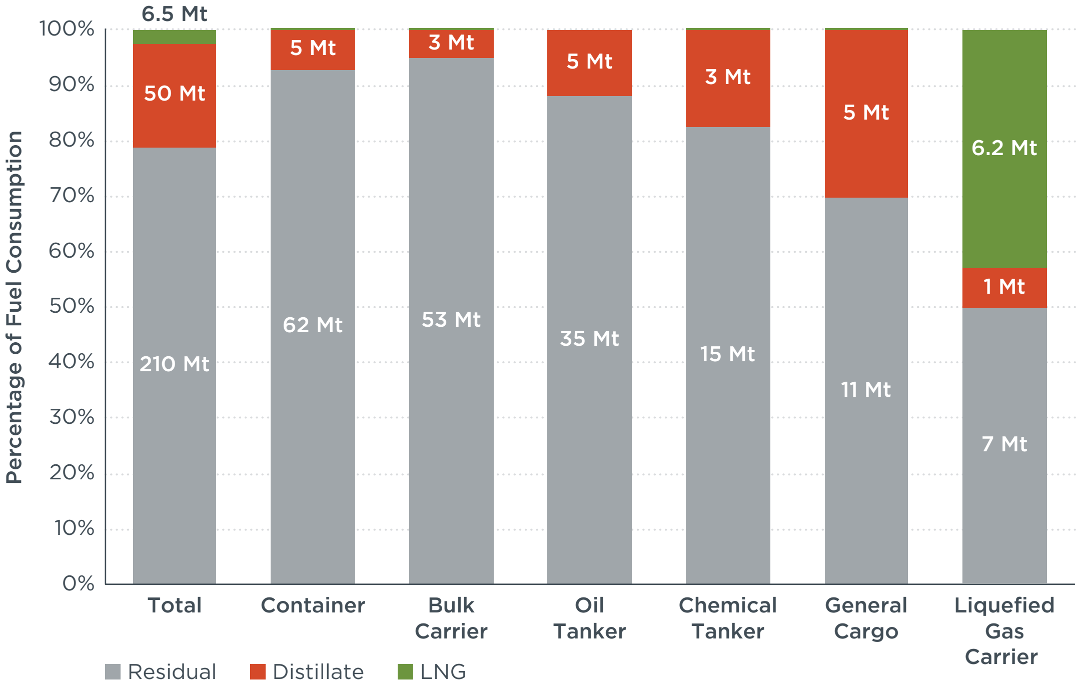


Figure 15. Percentage of different fuel burned, summarized by ship class

Figure 16 shows total fuel consumption by major ship class for the flag states that consumed the most fuel. Five flag states (Panama, China, Liberia, Marshall Islands, and Singapore) consumed 137 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.

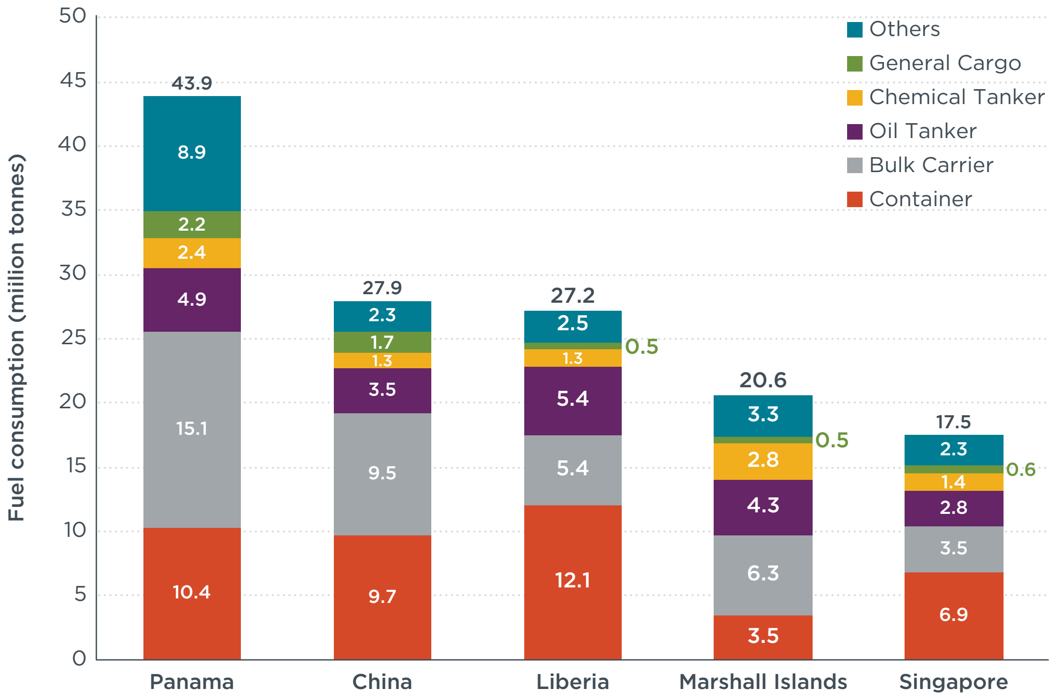


Figure 16. Total fuel consumption by top 5 fuel-consuming flag states, summarized by ship class, 2015

Figure 17 shows residual fuel use by flag state. Panama-flagged ships used the most residual fuel (40 Mt), followed by China (25 Mt), Liberia (25 Mt), Marshall Islands (18 Mt), and Singapore (16 Mt). Given that the global fleet consumed 210 Mt of residual fuel, ships registered to these five flag states account for more than 59% of residual fuel consumption by ships in 2015. A full list of BC emissions by flag state is presented in Appendix K.

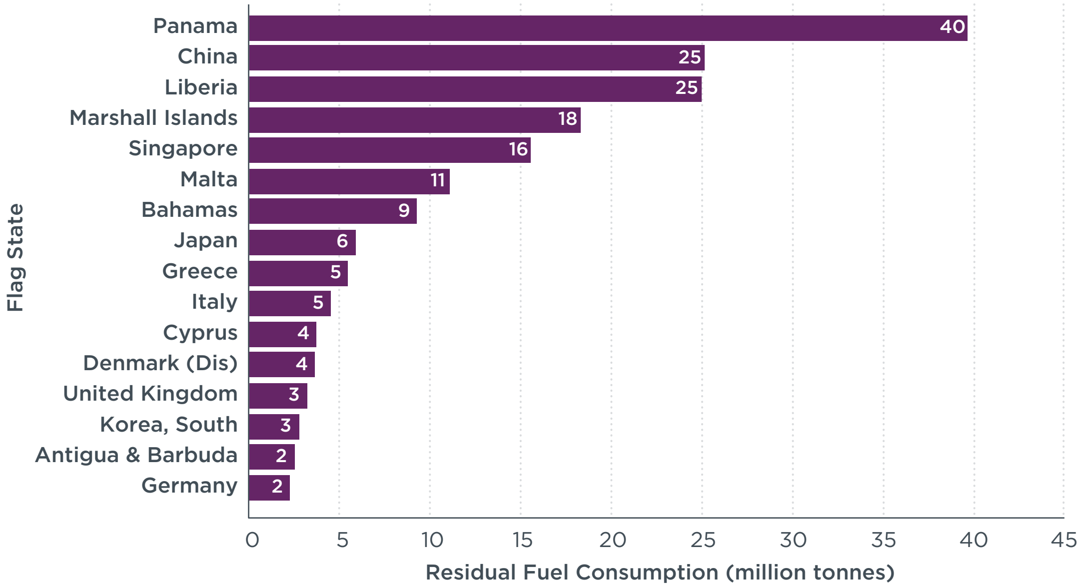


Figure 17. Residual fuel oil use by top consuming flag states, 2015

5. COMPARISON WITH OTHER STUDIES

This section compares the results of this global BC inventory study with those of other researchers (Table 23): Bond et al. (2013); Dentener et al. (2006); Fuglestvedt et al. (2008); Eyring et al. (2005); Eyring et al. (2010); Lack et al. (2008); Dalsøren et al. (2009); Buhaug et al. (2009); EDGAR (2016); and Klimont et al. (2017). These studies estimate a wide range of BC emissions from ships from 2000 to 2010, with a low of 39 kt (Dalsøren et al., 2009) and a high of 283 kt (EDGAR, 2016). BC EFs also range widely, with two studies assuming 0.18 g/kg fuel (Dalsøren et al., 2009; Eyring et al., 2005) and two studies with BC EFs greater than one: Fuglestvedt et al. (2008) and EDGAR (2016).

We estimate total global BC emissions from ships to be 53 kt to 80 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 23). Differences in BC estimates are due to variations in both 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 the Lack et al. (2008) 2001 inventory, but about half of the BC emissions because the Lack et al. weighted BC EF was 0.53 g/kg fuel, more than twice as high as our best estimate of 0.25 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 and Appendix G; that said, BC EFs and ship BC inventories will continue to change in the future as researchers gather more data.

Klimont et al. (2017) estimated total anthropogenic BC emissions of 7,264 kt in 2010 and estimated that international shipping emitted 120 kt of BC, about 1.7% of total anthropogenic BC emissions. Assuming 2015 anthropogenic emissions are similar to 2010, our results suggest that ship BC emissions were responsible for 0.7% to 1.1% of anthropogenic BC emissions. Similarly, based on Bond et al. (2013), who estimated diesel source BC emissions at 1,420 kt in 2000, if diesel source emissions have remained similar, we estimate that ship BC emissions were responsible for 3.9% to 5.7% of diesel source BC emissions in 2015. However, it is important to understand that this inventory may underestimate global BC emissions from ships.

As an example of how BC EFs can influence our understanding of shipping's contribution to global BC, consider the following: Bond et al. (2013) estimated BC emissions from diesel sources at 1,420 kt in the year 2000.[18] They also estimated shipping BC emissions at 100 kt in 2000. As such, shipping represented 7% of diesel sources of BC in 2000, according to Bond and colleagues. Our inventory estimates 53 to 80 kt BC from ships in the year 2015. To our knowledge, Bond et al. provide the most recent peer-reviewed global BC inventory that includes estimates for diesel source BC. Ideally, to contextualize our results, we would like to compare our shipping BC inventory to a recent inventory of BC from other diesel sources. Unfortunately, the Bond et al. inventory reflects year 2000 estimates, 15 years older than our ship BC inventory. If we assume that diesel sources of BC have remained relatively constant from 2000 to 2015, ships represent 3.9% to 5.7% of global diesel source BC emissions, based on our estimated range of 53 to 80 kt BC. However, this estimate is sensitive to not only the actual 2015 diesel source BC

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[18] See Bond et al. (2013) Table 8, SPEW inventory results, which shows total diesel BC emissions at 1320 Gg/yr (same as kt/yr), plus 100 Gg/yr for shipping, for a total of 1420 Gg/yr for all diesel sources.

inventory, but also the BC EFs developed for this analysis. One recent comprehensive review of BC emission testing (Johnson et al., 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." Taking that range, and applying it to the fuel consumption we estimated (266 Mt), 2015 BC emissions could be between 26.6 and 266 kt. In this case, BC from ships could represent between 2% and 17% of global diesel source BC emissions, assuming that 2015 diesel source BC emissions are similar to those in the Bond et al. year 2000 estimates. Similarly, this range (26.6 kt to 266 kt), suggests that ships could be responsible for 0.4 to 3.5% of total global anthropogenic BC emissions, based on Klimont et al. (2017).

Table 23. Comparing this study with other global ship BC inventories

Study	Inventory Year	BC (kt)	Fuel consumption (Mt)	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. (2008)	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]
EDGAR (2016)	2010	283	213	1.33[e]
Klimont et al. (2017)	2010	120	322[f]	0.37[f]
Comer et al. (this study)	2015	67	266	0.25[g]

[a] A combination of BC EFs from Petzold et al. (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 emission factor from Sinha 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] We derived this emission factor. EDGAR v4.3.1 estimated that international shipping emitted 283 kt of BC, based on IEA energy statistics. In 2010, IEA World Energy Statistics estimated that international shipping consumed 213 million t of fuel, implying a BC EF of 1.33 g BC/ kg fuel. [f] We estimated fuel consumption and derived the BC EF based on Klimont et al. (2017), which states that their 2010 fuel consumption was approximately 10% higher than Smith et al. (2015) for the same year. Smith et al. (2015) estimated 293 Mt fuel consumption in 2010. [g] This study predicts a range of BC EFs of 0.20 g/kg fuel to 0.30 g/kg fuel with a best estimate of 0.25 g/kg fuel, resulting in a range of 53 kt BC to 80 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 "what-if" scenarios:

1. All ships switch from residual to distillate fuels
2. Some ships switch to LNG from residual or distillate
3. Some ships install scrubbers
4. Some ships use DPFs

6.1. SCENARIO 1: ALL SHIPS OPERATING ON RESIDUAL FUEL SWITCH TO DISTILLATE FUEL

As described earlier, evidence suggests that burning distillate fuel emits less BC than residual fuel. If all ships that use residual fuel had switched to distillate fuel, total BC emissions from ships in 2015 would have decreased from 67 kt to 30 kt, a reduction of 55%. This suggests that simply switching all ships operating on residual fuel to distillate fuel can more than 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 highest emitting ship class, could be brought from 17.4 kt to 6.0 kt by operating exclusively on distillate fuel, a reduction of 66%. Similarly, bulk carrier emissions could drop from 12.4 kt to 3.9 kt, a 69% 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. The actual fuel switch to distillate will be driven largely by fuel quality regulations. The 0.5% global fuel sulfur limit, which enters into force in 2020, will encourage a shift to distillates, but ship operators may use residual fuel blends or desulfurized residual fuels that may not reduce BC much, if at all, compared with high sulfur residual fuels.

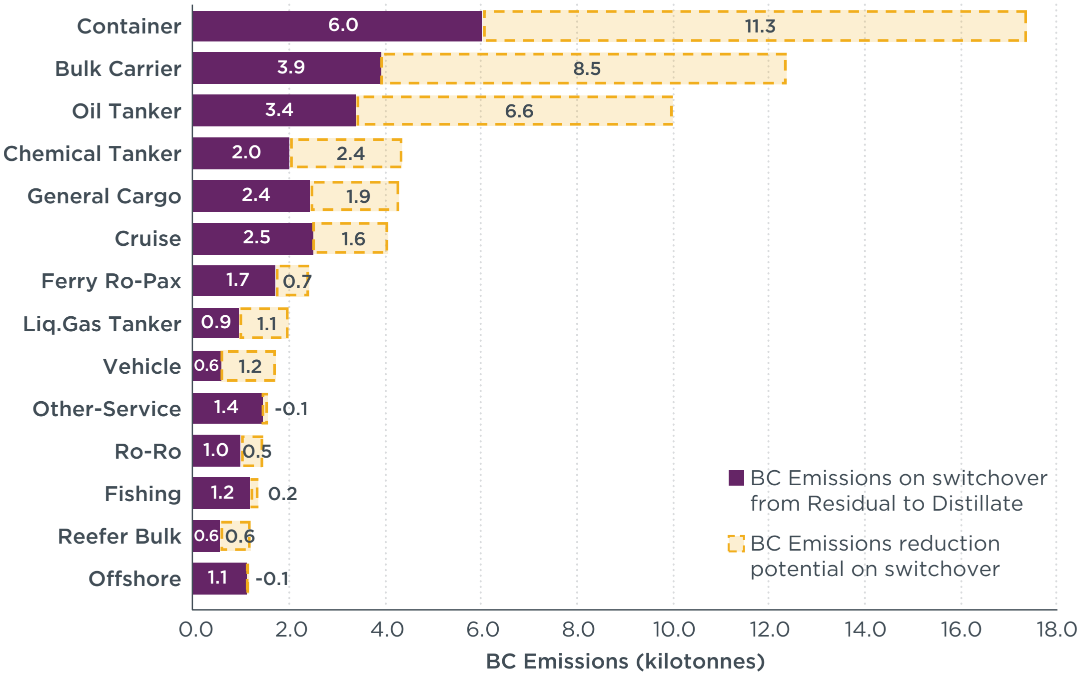


Figure 18. Black carbon reduction potential for fuel switching (residual to distillate) by ship class

6.2. 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 to operate on LNG. However, as ship air pollution regulations become more stringent, and if the price of LNG remains low compared with 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 50% of fuel (based on energy use) in 2015 had switched to LNG, BC emissions would have dropped from 67 kt to 35 kt, a 47% 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%. The actual fuel switch potential to LNG will depend on future regulatory and economic conditions. 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.

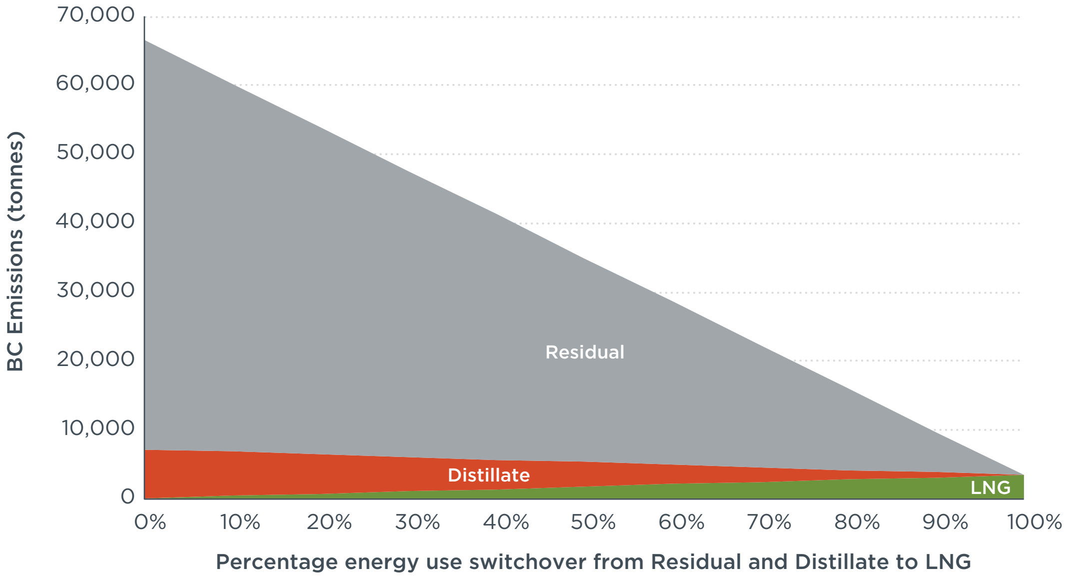
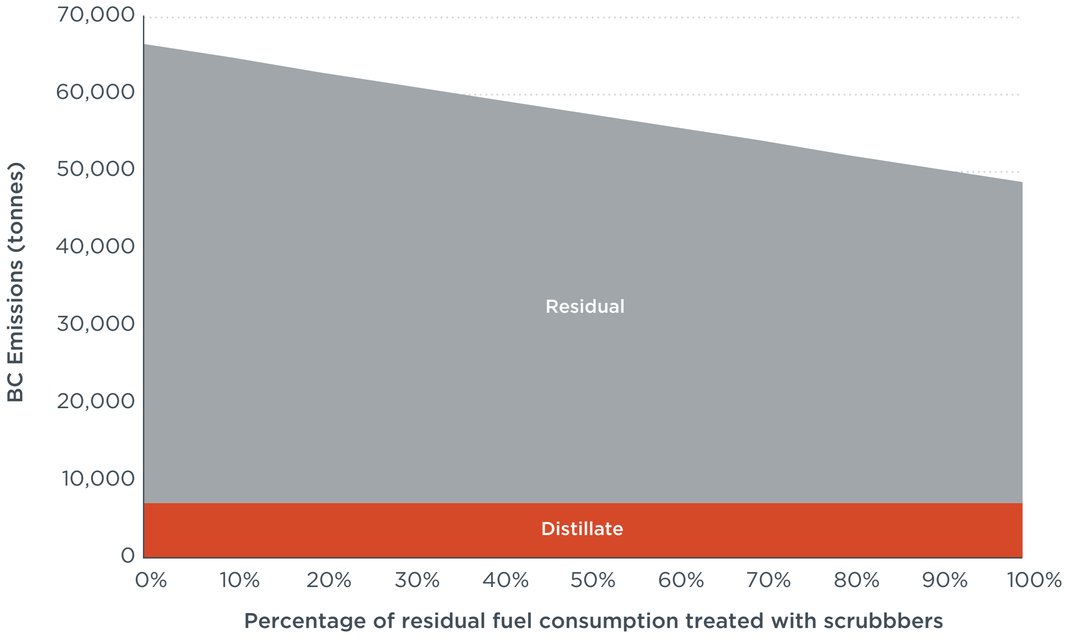


Figure 19. Black carbon reduction potential on switching over to LNG from residual or distillate fuel

6.3. SCENARIO 3: SOME SHIPS INSTALL EXHAUST GAS CLEANING SYSTEMS

Recent research (Johnson et al., 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 HFO, 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 3.6 kt, representing a 6% reduction from residual fuel-powered ships and a total BC reduction of 5%. If all ships operating on residual fuel installed scrubbers, BC could be reduced by 17,800 t, representing a 30% reduction in BC from residual fuel-powered ships and a total reduction in BC of 27% for all ships, based on 2015 residual fuel consumption and BC emissions. The actual uptake of scrubbers will depend on future regulatory and economic conditions.



**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

6.4. SCENARIO 4: SOME SHIPS INSTALL DIESEL PARTICULATE FILTERS

DPFs can drastically reduce BC emissions. NRC Canada estimates that DPFs can reduce BC by 70% to 90%; Johansen (2015) showed that catalyzed DPFs with reverse pulse flow (for ash removal) can reduce PM by 80% to 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 3 kt – a 42% reduction in distillate BC emissions and a 5% reduction in total BC emissions. The actual uptake of DPFs may be limited to harbor craft, ferries, and other domestic ships in the near-term, as there is currently no regulatory driver to encourage DPFs for international shipping.

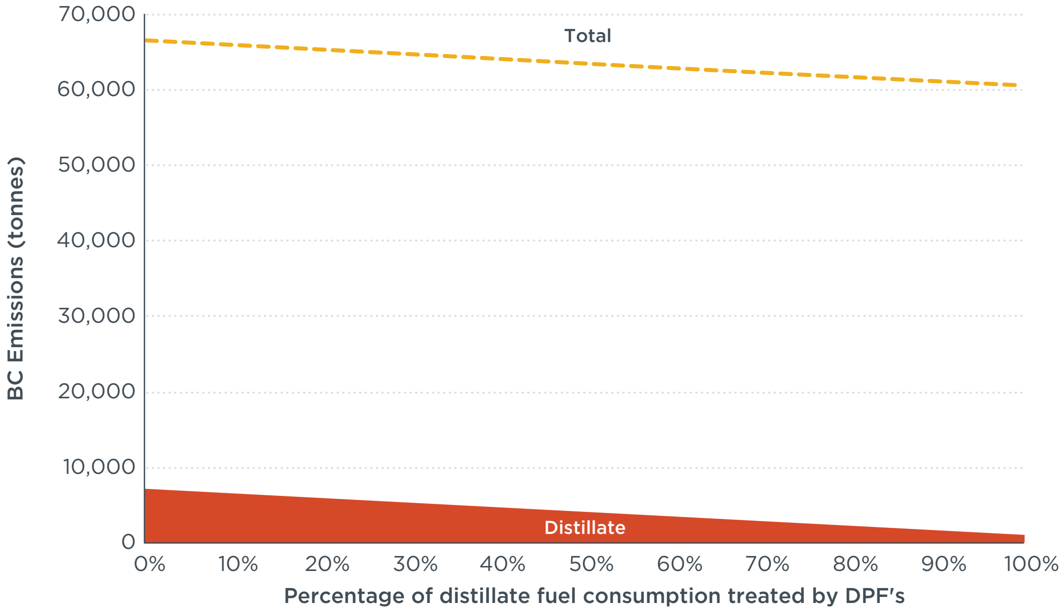


Figure 21. Black carbon reduction potential for installing DPFs on ships operating on distillate fuel

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. The 0.5% global fuel sulfur cap will be implemented in 2020, but even 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. 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 35% to 50% reduction in BC and ships powered by 2-stroke engines could achieve a 75% to 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).

7.2. 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. 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 they HFO, residual fuel blends, or desulfurized residual fuel, would offer the best chance for BC reductions. Ships powered by 4-stroke engines could achieve a 35% to 50% reduction in BC, and ships powered by 2-stroke engines could achieve a 75% to 80% reduction in BC, by switching from HFO to distillate fuels. 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).

7.3. ALTERNATIVE 3: ESTABLISH A BLACK CARBON EMISSION STANDARD FOR SHIPS

Individual nations and the IMO have already established SO_x, NO_x, and PM standards as pollution control strategies. Similarly, the IMO or a member state could also set a BC emission standard. A BC emission standard could apply to sensitive ecological regions (like the Arctic or coastal waterways), or even extend to all ships. For example, the United States, the European Union, and China have promulgated PM limits for all but the largest domestic ships. As a next step, these nations could also set BC limits. If so, ship operators could reduce BC emissions using an EGCS, a DPF, or by switching to low- or zero-BC fuels such as LNG or hydrogen. Governments could use taxes, grants, subsidies, or financing tools to reward ship owners and operators that adopt BC control technologies or cleaner fuels. Additionally, governments could promote the shift toward cleaner technologies by investing in alternative fuel infrastructure.

7.4. 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 an initial strategy expected in 2018 and a revised strategy in 2023. This strategy will certainly focus on reducing CO_2 emissions from ships but could also include other climate pollutants, including CH_4 and BC. Fuel consumption data will be collected from most commercial ships (5,000 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.

7.5. 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 to 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,[19] or by exercising Port State control, restricting access to their ports to newer ships.

7.6. 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 with burning HFO and distillate; the level of reduction 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

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[19] 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.

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.

8. CONCLUSIONS

Shipping poses largely unregulated risks to the global environment. The fuels that ships use, especially residual fuels such as 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 1.3 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 (53 to 80) kt of BC in 2015, corresponding to a fleet-wide average BC EF of 0.25 (0.20 to 0.30) g/kg fuel. Accounting for BC's global warming potential, ship BC emissions were responsible for 5% to 8% (100-year timescale) and 18% to 23% (20-year timescale) of the CO_2-equivalent climate warming impact from shipping in 2015.

Eighty-nine percent of BC emissions from the global fleet are from ships whose main fuel type is residual fuel, and ships with 2-stroke SSD MEs are responsible for 69% of global BC emissions. Further, just six flag states—Panama, China, Liberia, Marshall Islands, 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 60% of BC emissions, while accounting for 30% 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 (26%) than other ship classes. Outside that group, cruise ships account for a disproportionately large amount of BC, emitting 6% 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 10 t per ship in 2015, or nearly three times a typical container ship (3.5 t) and equal to about 4,200 Euro V heavy-duty trucks operating 100,000 kilometers over one year. Further, cruise ships emit the most BC per unit of fuel they burn: The average cruise ship emits 0.34 kg of BC for every tonne of fuel, compared with 0.26 kg/t for a container ship. Thus, policies that aim to reduce BC emissions from ships must address container ships, which emit the most BC in total of any ship class (17.4 kt BC/year), and from cruise ships, which emit the most BC per tonne of fuel (0.34 kg BC/t) and per ship per year (10 t BC/ship/year).

Residual fuel use and carriage occurs across the globe, including the polar regions. The global fleet consumed an estimated 266 Mt of fuel in 2015, consisting of 210 Mt of residual fuel, 50 Mt of distillate, and 6 Mt 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 residual fuel (86%) 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 59% of residual fuel consumption by ships in 2015: Panama (40 Mt), China (25 Mt), Liberia (25 Mt), Marshall Islands (18 Mt), and Singapore (16 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 30 kt in 2015. This means that if all ships operated on distillate fuel, total BC emissions could be reduced by more than 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 47%. 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 16,700 t, representing a 30% reduction in BC from residual fuel-powered ships and a total reduction in BC of 27% 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 42% for that fuel, but total BC emissions from ships would decline only 5%, as distillate makes up only 19% 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 with 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 business as usual 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 55%, 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 for the purposes of this work that no residual fuel is consumed. Thus, the next step could be to establish a BC emission 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 new builds 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 42% for that fuel, but total BC emissions from ships would decline only 5% 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 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.[20] Including BC in the comprehensive IMO strategy to reduce GHG emissions may be justified, given that BC represents 5% to 23% of the CO_2-equivalent 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 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

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[20] 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 55%, leaving 45 units. A DPF is expected to reduce BC by 85%, leaving approximately 7 units of BC from ships, for a total reduction of approximately 93%.

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 35% to 80% less BC than residual fuels. In contrast to requirements for new 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 along the Norwegian coast, 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 ro-ro 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 DPFs for some ships**
  While BC from ships contributes to a changing climate globally, 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 retrofitted with DPFs to protect the Arctic that their customers are paying to see. Progressive flag states could also retrofit their fishing vessels with DPFs. These fishing vessels are the largest source of BC from ships in the Arctic, as defined by the IMO (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 and the costs 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. APPENDICES

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		

APPENDIX B

Ship capacity bin by ship class

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

APPENDIX C

Linear regression used to determine the main fuel capacity

Main fuel capacity (m^3) = dwt*dwt Beta + dwt Intercept, or Main fuel capacity (m^3) = 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 meters	**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
Bulk carrier	<10000	0	50	50	50	dwt
Bulk carrier	10000-35000	0	50	50	50	
Bulk carrier	35000-60000	0	100	100	100	
Bulk carrier	60000-100000	0	200	200	200	
Bulk carrier	100000-200000	0	200	200	200	
Bulk carrier	>200000	0	200	200	200	
Chemical tanker	<5000	0	125	125	125	dwt
Chemical tanker	5000-10000	0	250	250	250	
Chemical tanker	10000-20000	0	250	250	250	
Chemical tanker	>20000	0	250	250	250	
Container	<1000	0	120	120	120	teu
Container	1000-2000	0	290	290	290	
Container	2000-3000	0	350	350	350	
Container	3000-5000	0	450	450	450	
Container	5000-8000	0	450	450	450	
Container	8000-12000	0	520	520	520	
Container	12000-14500	0	630	630	630	
Container	>14500	0	700	700	700	
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 meters
Liquefied gas tanker	50000-200000	150	300	1500	300	
Liquefied gas tanker	>200000	300	600	3000	600	

ship class	ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	capacity unit
Oil tanker	<5000	0	100	500	100	dwt
Oil tanker	5000-10000	0	150	750	150	
Oil tanker	10000-20000	0	250	1250	250	
Oil tanker	20000-60000	150	300	1500	300	
Oil tanker	60000-80000	150	300	1500	300	
Oil tanker	80000-120000	200	400	2000	400	
Oil tanker	120000-200000	250	500	2500	500	
Oil tanker	>200000	300	600	3000	600	
Other liquid tankers	-	100	200	1000	200	dwt
Ferry-pax only	<2000	0	0	0	0	gt
Ferry-pax only	>2000	0	0	0	0	
Cruise	<2000	0	250	250	250	gt
Cruise	2000-10000	0	250	250	250	
Cruise	10000-60000	0	1000	1000	1000	
Cruise	60000-100000	0	500	500	500	
Cruise	>100000	0	500	500	500	
Ferry-ro-pax	<2000	0	0	0	0	gt
Ferry-ro-pax	>2000	0	0	0	0	
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	All	SSD	607	593	593	—
		MSD/HSD	670	658	658	—
		GT/ST	950	962	962	—
		LNG-Otto	—	—	—	457
		LNG-Diesel	—	—	—	366
NO_x	Tier 0	0-130 rpm	18.10	17.01	17.01	—
		>130 rpm	14.00	13.16	13.16	—
	Tier I	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	—
	Tier II	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	—
	All	GT	6.10	5.92	5.92	—
		ST	2.10	2.00	2.00	—
		LNG-Otto	—	—	—	1.3
		LNG-Diesel	—	—	—	5
SO_x	All	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	All	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	All	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	All	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	All	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 for main engines

The main engine BC EFs used in this study are presented in Table G-3. 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 1.33 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 stroke type, fuel type, and engine load. One recent comprehensive review of BC emission testing (Johnson et al., 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 stroke type, fuel type, and engine load are described herein.

We based our BC EFs on measurement data from UCR, Finland, and EUROMOT. UCR measured BC from two marine engines installed on two container ships. One engine was Tier II, the other was Tier 0 and was retrofitted with an EGCS. Finland measured BC from one Tier 0 test marine engine in the laboratory. EUROMOT tested 35 marine engines in the lab; 5 of those engines operated on residual fuels (i.e., HFO, RME, RMG), 20 operated on marine distillate fuels (i.e., MGO, DMA, DMB, DMX), 6 operated on ultra-low-sulfur diesel (ULSD), and 4 operated on LNG. When developing marine BC EFs, we focused on residual and marine distillate fuels and excluded ULSD and LNG to focus on the fuels most commonly used in international shipping. ULSD is used in some small ships, including some harbor craft, but is more expensive than marine distillate fuels such as MGO and is unlikely to be used in large ocean-going vessels. LNG is used in a very small fraction of the international fleet and LNG emits very low amounts of BC; thus, we decided to use the same LNG BC EF assumptions as Comer et al. (2017), as reported in Table G-3. Excluding the engines that operated on ULSD and LNG, we are left with 25 engine test results. BC from all but one of these engines was measured using the FSN method, the other was tested using the PAS method. We decided to exclude the BC EFs from the engine tested using the PAS method in order maintain a consistent measurement method. Thus, we were left with results from 24 engine tests; of these, none were Tier 0, 5 were Tier I, 13 were Tier II, and 6 were Tier III. All together, we were left with results from 27 engine tests (24 EUROMOT + 2 UCR + 1 Finland), with 20 out of 27 (74%) Tier II or Tier III. The raw BC EFs from the UCR, Finland, and EUROMOT tests are shown in Table G-2

The last column of Table G-2 reports emission factors in terms of g BC/kg fuel. UCR and Finland reported their BC EF results in both FSN units and in g/kg fuel. EUROMOT only reported in FSN units, requiring us to convert from FSN units to g/kg fuel. We did so as follows:

$$EF_{BC\_mass} = \frac{AF \times EF_{BC\_vol}}{P_{ME,l} \times SFOC_l \times D}$$

where

EF_{BC_mass} = black carbon emission factor in mgBC/g fuel (equivalent to gBC/kg fuel)
FSN = filter smoke number
AF = air flow in kg/h
EF_{BC_vol} = black carbon emission factor in mgBC/m^3
$P_{ME,l}$ = main engine power at engine load l in kW
$SFOC_l$ = specific fuel oil consumption at load l in g fuel/kWh
D = air density in kg/m^3

Specifically, the EF_{BC_vol} is derived from on an equation from a presentation given by MAN,[21] as follows:

$$EF_{BC\_vol} = \left(\frac{1}{0.405}\right) \times 5.23 \times FSN \times e^{(0.3062 \times FSN)}$$

where

EF_{BC_vol} = black carbon emission factor in mgBC/m^3
FSN = filter smoke number

Note that the EF_{BC_vol} assumes that the sample was taken using a heated sample line. There is a different EF_{BC_vol} when using an unheated sample line,[22] which we applied to the FSN measurement for engine 29.

$SFOC_l$ is based on Smith et al. (2015), as follows:

$$SFOC_l = SFOC_{base} \times (0.455 \times l^2 - 0.71 \times l + 1.28)$$

where

$SFOC_l$ = specific fuel oil consumption at load l in g fuel/kWh
$SFOC_{base}$ = the baseline SFOC in g fuel/kWh, which is assumed to be 185 for SSD using distillate, 195 for SSD using residual, 205 for MSD using distillate, and 215 for MSD using residual
l = main engine load factor

Lastly, the D is calculated as follows:

$$D = \frac{P}{R \times T}$$

where

D = air density in kg/m^3
P = standard air pressure in kg/m/s^2, equal to 101,325 Pa
R = specific gas content for dry air, equal to 287.05 m^2/s^2/K
T = temperature, equal to 298.15 K

Figure G-1 and Figure G-2 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

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[21] Lauer, P. (2016). Challenges of black carbon determination for marine diesel engines. Available at: http://www.theicct.org/sites/default/files/05-Challenges%20of%20Black%20Carbon%20Determination%20for%20Marine%20Diesel%20Engines%20-%20Peter%20Lauer%2C%20MAN%20Diesel%20and%20Turbo.pdf

[22] EF_{BC_vol} = (1/0.405)*4.95*FSN*e^(0.38*FSN)

for 4-stroke engines operating on residual fuel or distillate fuel, respectively. The open circles represent raw data from EUROMOT, UCR, and Finnish research. Table G-2 summarizes the data in these two figures, identifying the data source, engine type (including engine stroke type), fuel type, engine load, and measured BC EF. All BC EFs in these figures and tables were measured using the FSN method with AVL 415S or AVL 415SE smoke meters.

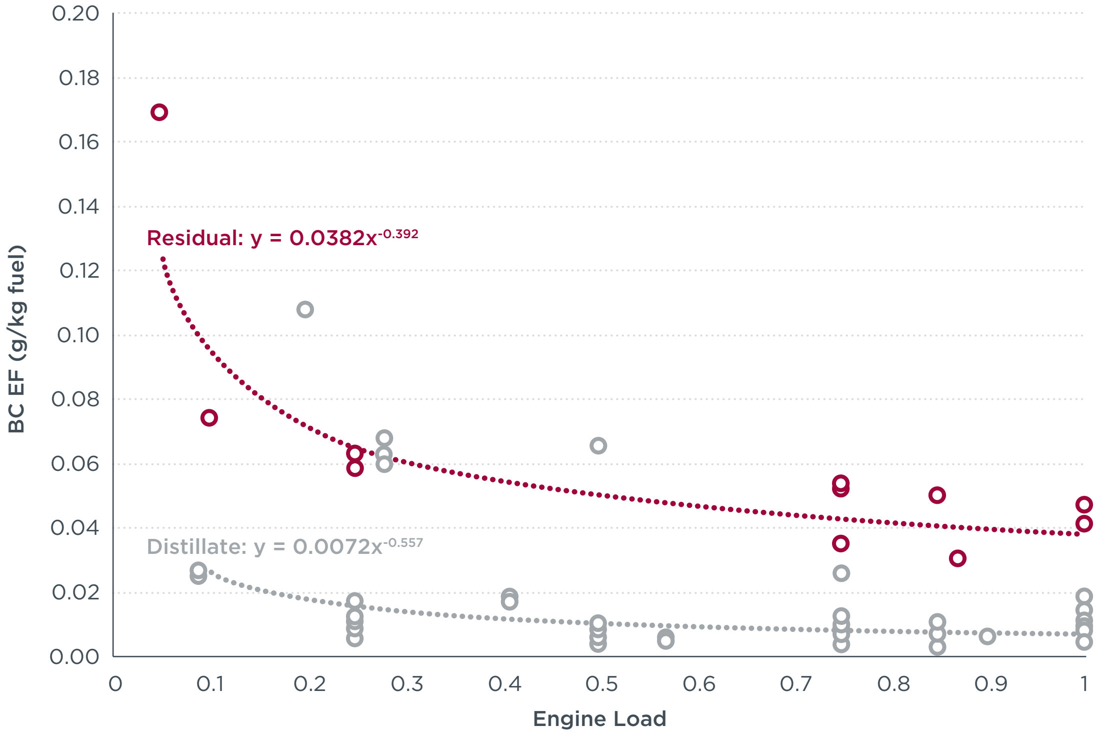

Figure G-1. Raw black carbon emission factors for 2-stroke main engines using residual fuel and distillate fuel

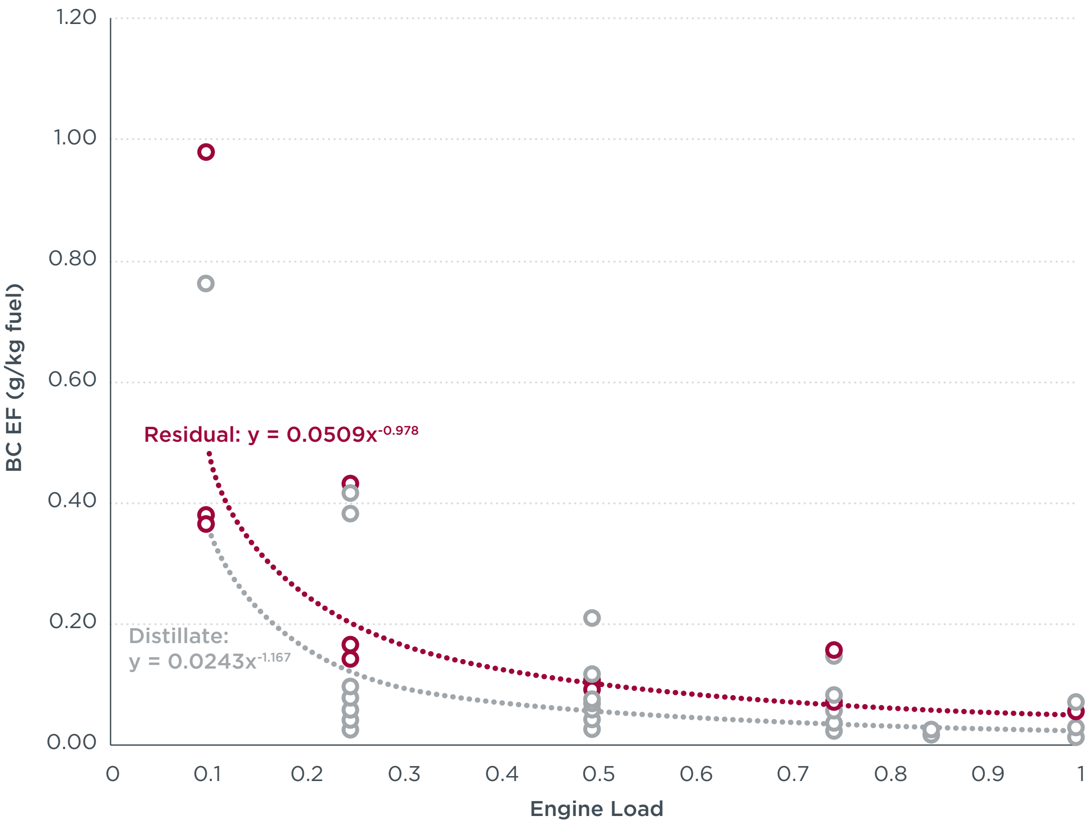

Figure G-2. Raw black carbon emission factors for 4-stroke main engines using residual fuel and distillate fuel

The raw data suggest emission factors well below those recommended by Johnson et al. (2016) for use in global inventories. For example, as shown in Figure G-2, the best fit line to the raw data for two stroke engines using residual fuel indicates a BC EF of 0.066 g/kg fuel at 25% load and 0.043 g/kg fuel at 75% load. EFs for 2-strokes operating on distillate fuel are roughly 75% to 80% lower: 0.016 g/kg fuel at 25% load and 0.008 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 from 6 Tier III engines, 14 Tier II engines, 5 low-hour Tier I engines, and only 2 Tier 0 engines. Thus, 20 out of the 27 engines (74%) were modern Tier II or Tier III engines. Evidence presented in this report and by Johnson et al. (2016) suggests that modern, electronically controlled engines emit less BC than older engines. Given that 85% of the fleet has Tier 0 or Tier I engines (Table 16), 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.

Reflecting these factors, the Johnson et al. (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 21, 2-stroke engines operating on residual fuel accounted for the majority (68%) 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 stroke 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:

$$y = 0.0382 \times (x^{-0.392})$$

Note that when $x = 1$, which is equivalent to 100% engine load, an emission factor of 0.0382 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:

$$y = 0.1 \times (x^{-0.392})$$

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 stroke type/fuel type combinations, as described next.

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

$$\gamma = \alpha \times (x^{\beta})$$

where

γ = 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:

$$2R_0: y = 0.0382 \times (x^{-0.392})$$

$$2D_0: y = 0.0072 \times (x^{-0.557})$$

$$4R_0: y = 0.0509 \times (x^{-0.978})$$

$$4D_0: y = 0.0243 \times (x^{-1.167})$$

To maintain the relationship between the BC EFs for 2R, 2D, 4R, and 4D, the coefficients (a) must be modified based on the new coefficient for 2R. See row 2 in Table G-1 for the new coefficients that correspond to a 2R coefficient of 0.1. The last row of Table G-1 describes the method for deriving the new coefficients based on the relationship between the original 2R, 2D, 4R, and 4D coefficients.

Table G-1. Black carbon emission factor coefficients for lower bound curves

		A	B	C	D
		2R*	**2D**	**4R**	**4D**
1	Old Coefficient	0.0382	0.0072	0.0509	0.0243
2	**New Coefficient**	**0.100**	**0.0188**	**0.1332**	**0.0636**
	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 (Row 2 in Table G-1) are used to develop the lower bound emission factor equations for each engine stroke type/fuel type pair, denoted by sub-script “L” as follows:

$$2R_L: y = 0.1000 \times (x^{-0.392})$$

$$2D_L: y = 0.0188 \times (x^{-0.557})$$

$$4R_L: y = 0.1332 \times (x^{-0.978})$$

$$4D_L: y = 0.0636 \times (x^{-1.167})$$

Recognizing the uncertainty of developing BC EFs, we developed an upper bound BC EF for each engine stroke 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.[23] 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 G-3. The same is shown for 4-stroke engines in Figure G-4.

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[23] 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.

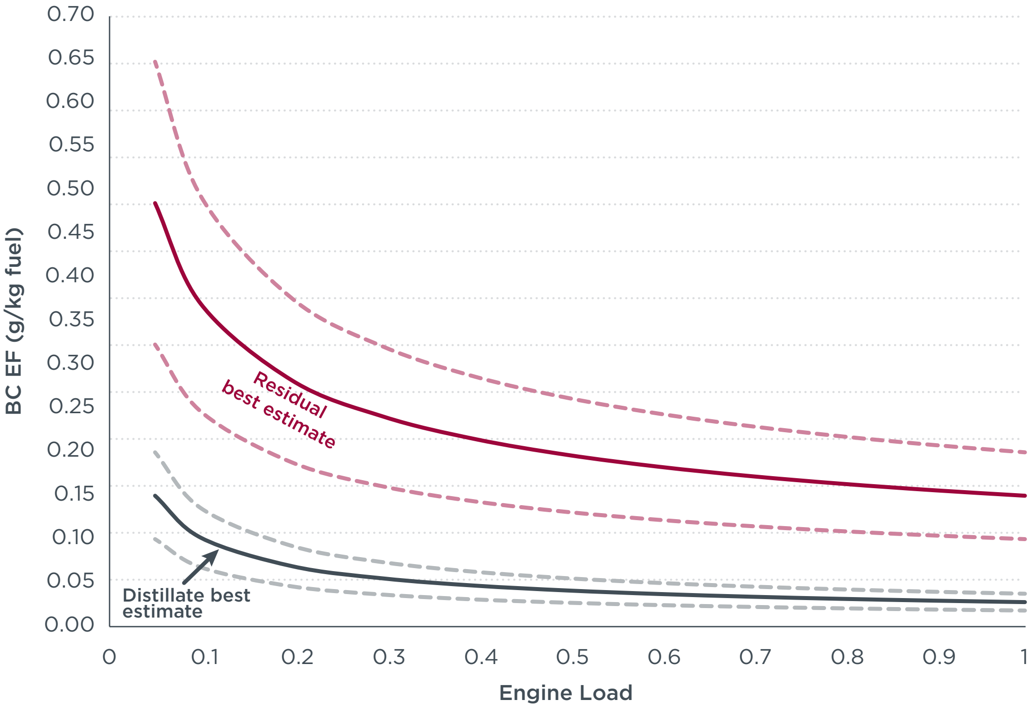

Figure G-3. Black carbon emission factors for 2-stroke main engines used in the analysis

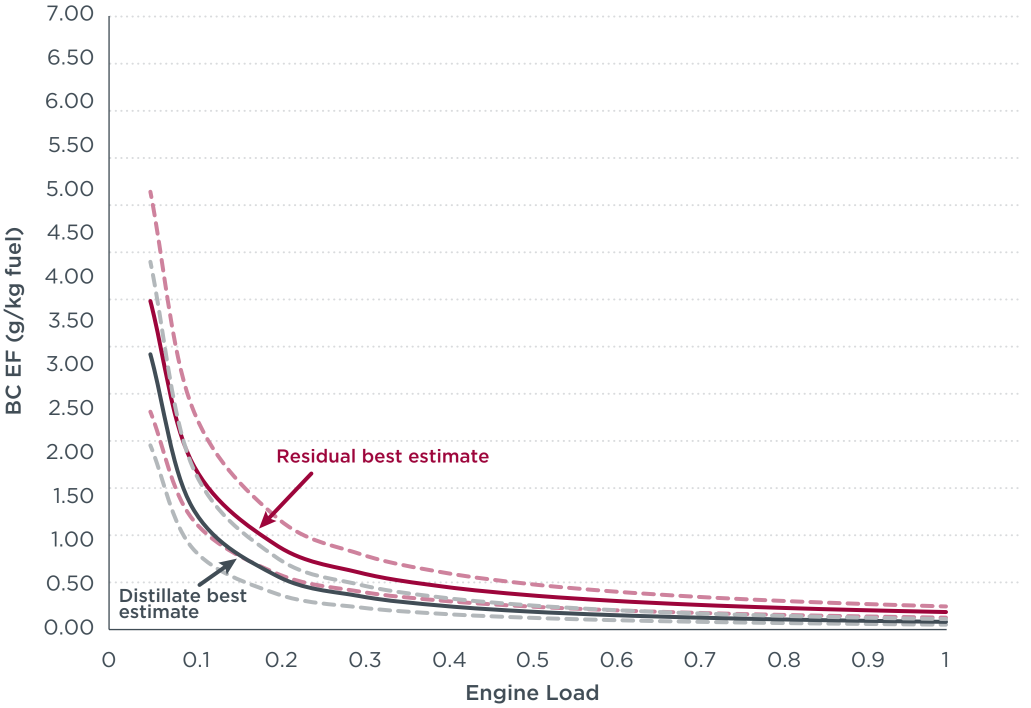

Figure G-4. Black carbon emission factors for 4-stroke main engines used in the analysis

Table G-2. Raw data used to develop the black carbon emission factors in this study

Engine ID	Source	Engine Stroke Type (2-stroke or 4-stroke)	Tier	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	II	70,000	MGO	Distillate	0.09	N/A	0.0259
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.09	N/A	0.0252
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.09	N/A	0.0247
8	EUROMOT	2	II	5,450	DMA	Distillate	0.2	0.133	0.1078
1	EUROMOT	2	I	6,513	DMA	Distillate	0.25	0.024	0.0119
3	EUROMOT	2	III	13,450	DMX	Distillate	0.25	0.024	0.0169
4	EUROMOT	2	I	6,513	DMA	Distillate	0.25	0.024	0.0119
6	EUROMOT	2	III	13,450	DMX	Distillate	0.25	0.015	0.0114
10	EUROMOT	2	II	11,335	DMB	Distillate	0.25	0.015	0.0082
11	EUROMOT	2	II	28,310	DMA	Distillate	0.25	0.017	0.0048
12	EUROMOT	2	II	6,100	DMA	Distillate	0.25	0.009	0.0052
13	EUROMOT	2	II	11,080	DMB	Distillate	0.25	0.016	0.0102
14	EUROMOT	2	II	11,080	DMB	Distillate	0.25	0.016	0.0100
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.28	N/A	0.0592
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.28	N/A	0.0629
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.28	N/A	0.0676
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.41	N/A	0.0184
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.41	N/A	0.0175
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.41	N/A	0.0174
1	EUROMOT	2	I	6,513	DMA	Distillate	0.5	0.016	0.0082
3	EUROMOT	2	III	13,450	DMX	Distillate	0.5	0.016	0.0100
4	EUROMOT	2	I	6,513	DMA	Distillate	0.5	0.016	0.0082
6	EUROMOT	2	III	13,450	DMX	Distillate	0.5	0.014	0.0093
8	EUROMOT	2	II	5,450	DMA	Distillate	0.5	0.086	0.0653
10	EUROMOT	2	II	11,335	DMB	Distillate	0.5	0.017	0.0084
11	EUROMOT	2	II	28,310	DMA	Distillate	0.5	0.013	0.0033
12	EUROMOT	2	II	6,100	DMA	Distillate	0.5	0.016	0.0078
13	EUROMOT	2	II	11,080	DMB	Distillate	0.5	0.01	0.0056
14	EUROMOT	2	II	11,080	DMB	Distillate	0.5	0.01	0.0055
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.57	N/A	0.0058
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.57	N/A	0.0048
UCRT2	UCR	2	II	70,000	MGO	Distillate	0.57	N/A	0.0049
1	EUROMOT	2	I	6,513	DMA	Distillate	0.75	0.025	0.0125
3	EUROMOT	2	III	13,450	DMX	Distillate	0.75	0.02	0.0116
4	EUROMOT	2	I	6,513	DMA	Distillate	0.75	0.025	0.0125
6	EUROMOT	2	III	13,450	DMX	Distillate	0.75	0.015	0.0092
8	EUROMOT	2	II	5,450	DMA	Distillate	0.75	0.036	0.0258

Engine ID	Source	Engine Stroke Type (2-stroke or 4-stroke)	Tier	Rated Power (kW)	Detailed Fuel type	Main Fuel Type	Engine Load	Raw BC EF (FSN units)	Raw BC EF (g/kg fuel)
10	EUROMOT	2	II	11,335	DMB	Distillate	0.75	0.02	0.0094
11	EUROMOT	2	II	28,310	DMA	Distillate	0.75	0.013	0.0033
12	EUROMOT	2	II	6,100	DMA	Distillate	0.75	0.025	0.0118
13	EUROMOT	2	II	11,080	DMB	Distillate	0.75	0.013	0.0065
14	EUROMOT	2	II	11,080	DMB	Distillate	0.75	0.012	0.0059
1	EUROMOT	2	I	6,513	DMA	Distillate	0.85	0.015	0.0070
4	EUROMOT	2	I	6,513	DMA	Distillate	0.85	0.015	0.0070
10	EUROMOT	2	II	11,335	DMB	Distillate	0.85	0.023	0.0102
11	EUROMOT	2	II	28,310	DMA	Distillate	0.85	0.011	0.0026
12	EUROMOT	2	II	6,100	DMA	Distillate	0.85	0.016	0.0074
13	EUROMOT	2	II	11,080	DMB	Distillate	0.85	0.012	0.0056
14	EUROMOT	2	II	11,080	DMB	Distillate	0.85	0.014	0.0065
6	EUROMOT	2	III	13,450	DMX	Distillate	0.9	0.011	0.0059
1	EUROMOT	2	I	6,513	DMA	Distillate	1	0.018	0.0078
3	EUROMOT	2	III	13,450	DMX	Distillate	1	0.016	0.0080
4	EUROMOT	2	I	6,513	DMA	Distillate	1	0.018	0.0078
6	EUROMOT	2	III	13,450	DMX	Distillate	1	0.014	0.0074
8	EUROMOT	2	II	5,450	DMA	Distillate	1	0.03	0.0182
10	EUROMOT	2	II	11,335	DMB	Distillate	1	0.025	0.0098
11	EUROMOT	2	II	28,310	DMA	Distillate	1	0.018	0.0038
12	EUROMOT	2	II	6,100	DMA	Distillate	1	0.032	0.0139
13	EUROMOT	2	II	11,080	DMB	Distillate	1	0.022	0.0097
14	EUROMOT	2	II	11,080	DMB	Distillate	1	0.028	0.0126
UCRT0pre	UCR	2	0	16,600	HFO	Residual	0.05	N/A	0.1690
15	EUROMOT	2	I	10,201	RMG	Residual	0.1	0.179	0.0740
9	EUROMOT	2	I	6,509	RMG	Residual	0.25	0.12	0.0585
15	EUROMOT	2	I	10,201	RMG	Residual	0.25	0.132	0.0626
9	EUROMOT	2	I	6,509	RMG	Residual	0.5	0.099	0.0487
15	EUROMOT	2	I	10,201	RMG	Residual	0.5	0.087	0.0464
UCRT0pre	UCR	2	0	16,600	HFO	Residual	0.5	N/A	0.0420
9	EUROMOT	2	I	6,509	RMG	Residual	0.75	0.112	0.0518
15	EUROMOT	2	I	10,201	RMG	Residual	0.75	0.105	0.0531
UCRT0pre	UCR	2	0	16,600	HFO	Residual	0.75	N/A	0.0350
15	EUROMOT	2	I	10,201	RMG	Residual	0.85	0.105	0.0499
UCRT0pre	UCR	2	0	16,600	HFO	Residual	0.87	N/A	0.0300
9	EUROMOT	2	I	6,509	RMG	Residual	1	0.097	0.0407
15	EUROMOT	2	I	10,201	RMG	Residual	1	0.106	0.0471

Engine ID	Source	Engine Stroke Type (2-stroke or 4-stroke)	Tier	Rated Power (kW)	Detailed Fuel type	Main Fuel Type	Engine Load	Raw BC EF (FSN units)	Raw BC EF (g/kg fuel)
25	EUROMOT	4	III	3,960	DMA	Distillate	0.1	0.76	0.7615 [outlier; removed]
17	EUROMOT	4	II	10,800	DMA	Distillate	0.25	0.07	0.0269
18	EUROMOT	4	II	10,800	DMA	Distillate	0.25	0.1	0.0412
19	EUROMOT	4	II	10,350	DMA	Distillate	0.25	0.15	0.0820
20	EUROMOT	4	II	5,000	DMA	Distillate	0.25	0.13	0.0641
21	EUROMOT	4	II	6,000	DMA	Distillate	0.25	0.12	0.0534
27	EUROMOT	4	III	8,000	DMA	Distillate	0.25	0.216	0.0966
16	EUROMOT	4	III	7,200	DMA	Distillate	0.5	0.11	0.0525
17	EUROMOT	4	II	10,800	DMA	Distillate	0.5	0.05	0.0225
18	EUROMOT	4	II	10,800	DMA	Distillate	0.5	0.16	0.0666
19	EUROMOT	4	II	10,350	DMA	Distillate	0.5	0.07	0.0374
20	EUROMOT	4	II	5,000	DMA	Distillate	0.5	0.12	0.0531
21	EUROMOT	4	II	6,000	DMA	Distillate	0.5	0.13	0.0608
24	EUROMOT	4	III	3,960	DMA	Distillate	0.5	0.404	0.2091
25	EUROMOT	4	III	3,960	DMA	Distillate	0.5	0.226	0.1141
27	EUROMOT	4	III	8,000	DMA	Distillate	0.5	0.175	0.0828
16	EUROMOT	4	III	7,200	DMA	Distillate	0.75	0.07	0.0271
17	EUROMOT	4	II	10,800	DMA	Distillate	0.75	0.06	0.0240
18	EUROMOT	4	II	10,800	DMA	Distillate	0.75	0.18	0.0809
19	EUROMOT	4	II	10,350	DMA	Distillate	0.75	0.05	0.0258
20	EUROMOT	4	II	5,000	DMA	Distillate	0.75	0.07	0.0307
21	EUROMOT	4	II	6,000	DMA	Distillate	0.75	0.14	0.0586
24	EUROMOT	4	III	3,960	DMA	Distillate	0.75	0.264	0.1455
25	EUROMOT	4	III	3,960	DMA	Distillate	0.75	0.1	0.0504
27	EUROMOT	4	III	8,000	DMA	Distillate	0.75	0.079	0.0374
16	EUROMOT	4	III	7,200	DMA	Distillate	0.85	0.05	0.0191
17	EUROMOT	4	II	10,800	DMA	Distillate	0.85	0.04	0.0156
18	EUROMOT	4	II	10,800	DMA	Distillate	0.85	0.05	0.0195
19	EUROMOT	4	II	10,350	DMA	Distillate	0.85	0.03	0.0140
21	EUROMOT	4	II	6,000	DMA	Distillate	0.85	0.06	0.0220
16	EUROMOT	4	III	7,200	DMA	Distillate	1	0.05	0.0181
17	EUROMOT	4	II	10,800	DMA	Distillate	1	0.05	0.0197
18	EUROMOT	4	II	10,800	DMA	Distillate	1	0.08	0.0317
19	EUROMOT	4	II	10,350	DMA	Distillate	1	0.03	0.0128
20	EUROMOT	4	II	5,000	DMA	Distillate	1	0.04	0.0154
21	EUROMOT	4	II	6,000	DMA	Distillate	1	0.06	0.0210
24	EUROMOT	4	III	3,960	DMA	Distillate	1	0.135	0.0710

Engine ID	Source	Engine Stroke Type (2-stroke or 4-stroke)	Tier	Rated Power (kW)	Detailed Fuel type	Main Fuel Type	Engine Load	Raw BC EF (FSN units)	Raw BC EF (g/kg fuel)
25	EUROMOT	4	III	3,960	DMA	Distillate	1	0.048	0.0213
27	EUROMOT	4	III	8,000	DMA	Distillate	1	0.056	0.0226
16	EUROMOT	4	III	7,200	DMA	Distillate	1	0.07	0.0240
Finland_D	Finland	4	0	1,640	MGO	Distillate	0.25	N/A	0.4110
Finland_D	Finland	4	0	1,640	MGO	Distillate	0.25	N/A	0.3800
Finland_D	Finland	4	0	1,640	MGO	Distillate	0.75	N/A	0.0560
Finland_D	Finland	4	0	1,640	MGO	Distillate	0.75	N/A	0.0500
22	EUROMOT	4	II	3,498	HFO	Residual	0.1	0.497	0.3630
23	EUROMOT	4	II	3,498	HFO	Residual	0.1	0.499	0.3793
29	EUROMOT	4	I	3,480	RME	Residual	0.1	1.2	0.9759
22	EUROMOT	4	II	3,498	HFO	Residual	0.25	0.34	0.1443
23	EUROMOT	4	II	3,498	HFO	Residual	0.25	0.32	0.1407
29	EUROMOT	4	I	3,480	RME	Residual	0.25	0.35	0.1641
22	EUROMOT	4	II	3,498	HFO	Residual	0.5	0.235	0.0920
23	EUROMOT	4	II	3,498	HFO	Residual	0.5	0.254	0.1032
29	EUROMOT	4	I	3,480	RME	Residual	0.5	0.13	0.0548
22	EUROMOT	4	II	3,498	HFO	Residual	0.75	0.163	0.0623
23	EUROMOT	4	II	3,498	HFO	Residual	0.75	0.163	0.0635
29	EUROMOT	4	I	3,480	RME	Residual	0.75	0.14	0.0526
22	EUROMOT	4	II	3,498	HFO	Residual	1	0.153	0.0531
23	EUROMOT	4	II	3,498	HFO	Residual	1	0.146	0.0513
29	EUROMOT	4	I	3,480	RME	Residual	1	0.15	0.0526
Finland_R	Finland	4	0	1,640	HFO	Residual	0.25	N/A	0.4300
Finland_R	Finland	4	0	1,640	HFO	Residual	0.75	N/A	0.1550

Table G-3. Black carbon main engine emission factors

Engine Load (%)	Engine Type	Unit	HFO		Distillate		LNG
			2-stroke	4-stroke	2-stroke	4-stroke	
≤ 5	SSD/MSD/HSD	g/kg fuel	0.49 (0.32-0.65)	3.74 (2.49-4.99)	0.15 (0.10-0.20)	3.15 (2.10-4.20)	—
10	SSD/MSD/HSD	g/kg fuel	0.37 (0.25-0.49)	1.90 (1.27-2.53)	0.10 (0.07-0.14)	1.40 (0.93-1.87)	—
15	SSD/MSD/HSD	g/kg fuel	0.32 (0.21-0.42)	1.28 (0.85-1.70)	0.08 (0.05-0.11)	0.87 (0.58-1.16)	—
20	SSD/MSD/HSD	g/kg fuel	0.28 (0.19-0.38)	0.96 (0.64-1.29)	0.07 (0.05-0.09)	0.62 (0.42-0.83)	—
25	SSD/MSD/HSD	g/kg fuel	0.26 (0.17-0.34)	0.78 (0.52-1.03)	0.06 (0.04-0.08)	0.48 (0.32-0.64)	—
30	SSD/MSD/HSD	g/kg fuel	0.24 (0.16-0.32)	0.65 (0.43-0.86)	0.06 (0.04-0.07)	0.39 (0.26-0.52)	—
35	SSD/MSD/HSD	g/kg fuel	0.23 (0.15-0.30)	0.56 (0.37-0.74)	0.05 (0.03-0.06)	0.32 (0.22-0.43)	—
40	SSD/MSD/HSD	g/kg fuel	0.21 (0.14-0.29)	0.49 (0.33-0.65)	0.05 (0.03-0.06)	0.28 (0.19-0.37)	—
45	SSD/MSD/HSD	g/kg fuel	0.21 (0.14-0.27)	0.44 (0.29-0.58)	0.04 (0.03-0.06)	0.24 (0.16-0.32)	—
50	SSD/MSD/HSD	g/kg fuel	0.20 (0.13-0.26)	0.39 (0.26-0.52)	0.04 (0.03-0.06)	0.21 (0.14-0.29)	—
55	SSD/MSD/HSD	g/kg fuel	0.19 (0.13-0.25)	0.36 (0.24-0.48)	0.04 (0.03-0.05)	0.19 (0.13-0.26)	—
60	SSD/MSD/HSD	g/kg fuel	0.18 (0.12-0.24)	0.33 (0.22-0.44)	0.04 (0.02-0.05)	0.17 (0.12-0.23)	—
65	SSD/MSD/HSD	g/kg fuel	0.18 (0.12-0.24)	0.30 (0.20-0.41)	0.04 (0.02-0.05)	0.16 (0.11-0.21)	—
70	SSD/MSD/HSD	g/kg fuel	0.17 (0.12-0.23)	0.28 (0.19-0.38)	0.03 (0.02-0.05)	0.14 (0.10-0.19)	—
75	SSD/MSD/HSD	g/kg fuel	0.17 (0.11-0.22)	0.26 (0.18-0.35)	0.03 (0.02-0.04)	0.13 (0.09-0.18)	—
80	SSD/MSD/HSD	g/kg fuel	0.16 (0.11-0.22)	0.25 (0.17-0.33)	0.03 (0.02-0.04)	0.12 (0.08-0.17)	—
85	SSD/MSD/HSD	g/kg fuel	0.16 (0.11-0.21)	0.23 (0.16-0.31)	0.03 (0.02-0.04)	0.12 (0.08-0.15)	—
90	SSD/MSD/HSD	g/kg fuel	0.16 (0.10-0.21)	0.22 (0.15-0.30)	0.03 (0.02-0.04)	0.11 (0.07-0.14)	—
95	SSD/MSD/HSD	g/kg fuel	0.15 (0.10-0.20)	0.21 (0.14-0.28)	0.03 (0.02-0.04)	0.10 (0.07-0.14)	—
100	SSD/MSD/HSD	g/kg fuel	0.15 (0.10-0.20)	0.20 (0.13-0.27)	0.03 (0.02-0.04)	0.10 (0.06-0.13)	—
All	ST	g/kWh	0.08	0.08	0.06	0.06	—
All	GT	g/kWh	0.005	0.005	0.004	0.004	—
All	LNG-Otto	g/kWh	—	—	—	—	0.003
All	LNG-Diesel	g/kWh	—	—	—	—	0.002

APPENDIX H

Auxiliary engine emission factors (g/kWh)

Pollutant	Engine Tier	Engine Type	HFO (2.5% S)	Distillate (0.14% S)	ECA fuel (0.1% S)	LNG
CO_2	All	SSD/MSD/HSD	707	696	696	—
		LNG-Otto	—	—	—	457
		LNG-Diesel	—	—	—	366
NO_x	Tier 0	All RPMs	14.70	13.82	13.82	—
	Tier I	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	—	—	—	—
	Tier II	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	All	SSD/MSD/HSD	11.98	0.60	0.43	—
		LNG-Otto	—	—	—	0.0027
		LNG-Diesel	—	—	—	0.0022
PM	All	SSD/MSD/HSD	1.44	0.20	0.19	—
		LNG-Otto	—	—	—	0.03
		LNG-Diesel	—	—	—	0.02
CO	All	SSD/MSD/HSD	0.54	0.54	0.54	—
		LNG-Otto	—	—	—	1.30
		LNG-Diesel	—	—	—	1.04
CH_4	All	SSD/MSD/HSD	0.01	0.01	0.01	—
		LNG-Otto	—	—	—	8.50
		LNG-Diesel	—	—	—	0.94
N_2O	All	SSD/MSD/HSD	0.04	0.03	0.03	—
		LNG-Otto	—	—	—	0.02
		LNG-Diesel	—	—	—	0.01
BC	All	SSD/MSD/HSD	0.12	0.06	0.06	—
		LNG-Otto	—	—	—	0.003
		LNG-Diesel	—	—	—	0.002

APPENDIX I

Boiler emission factors (g/kWh)

Pollutant	HFO (2.5% S)	Distillate (0.14% S)	ECA fuel (0.1% S)	LNG-Otto	LNG-Diesel
CO_2	950	962	962	457	366
NO_x	2.10	2.00	2.00	1.3	5
SO_x	16.10	0.81	0.57	0.0027	0.0022
PM	0.93	0.11	0.10	0.03	0.02
CO	0.20	0.20	0.20	1.30	1.04
CH_4	0.002	0.002	0.002	8.5	0.94
N_2O	0.05	0.04	0.04	0.02	0.01
BC	0.08	0.06	0.06	0.003	0.002

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

APPENDIX K

Black carbon emissions by flag state

	Flag Name	BC (t)		Flag Name	BC (t)		Flag Name	BC (t)		Flag Name	BC (t)
1	Panama	10,510	**19**	Korea, South	851	**40**	St Vincent & The Grenadines	194	**61**	Curacao	71
2	China	6,983	**20**	Germany	744	**41**	Canada	184	**62**	Cook Islands	70
	Hong Kong, China	4,579	**21**	Bermuda	670	**42**	Finland	180	**63**	Argentina	69
	China, People's Republic	2,146	**22**	Portugal (MAR)	667	**43**	Luxembourg	180	**64**	Venezuela	69
	Chinese Taipei	258	**23**	Norway (NIS)	630	**44**	Spain (CSR)	176	**65**	Croatia	66
3	Liberia	6,799	**24**	Isle Of Man	613	**45**	Mexico	154	**66**	Egypt	61
4	Marshall Islands	4,822	**25**	Turkey	520	**46**	Belgium	147	**67**	Comoros	60
5	Singapore	4,331	**26**	India	478	**47**	Vanuatu	146	**68**	Palau	55
6	Malta	3,399	**27**	Norway	339	**48**	Kuwait	131	**69**	Switzerland	50
7	Bahamas	3,203	**28**	Malaysia	329	**49**	Belize	129	**70**	Bahrain	49
8	Japan	1,745	**29**	France (FIS)	290	**50**	United Arab Emirates	117	**71**	Barbados	49
9	Italy	1,643	**30**	Cayman Islands	276	**51**	Australia	106	**72**	Qatar	47
10	Greece	1,555	**31**	Vietnam	269	**52**	Spain	100	**73**	Kiribati	47
11	Cyprus	1,213	**32**	Gibraltar	247	**53**	Chile	98	**74**	Denmark	45
12	United Kingdom	1,186	**33**	Iran	238	**54**	Togo	96	**75**	Tuvalu	44
13	United States of America	1,099	**34**	Philippines	236	**55**	Sierra Leone	92	**76**	Lithuania	41
14	Denmark (DIS)	1,044	**35**	Thailand	224	**56**	St Kitts & Nevis	90	**77**	Iceland	41
15	Antigua & Barbuda	1,025	**36**	Brazil	220	**57**	Unknown	85	**78**	Cambodia	39
16	Indonesia	988	**37**	France	208	**58**	Azerbaijan	85	**79**	Tanzania (Zanzibar)	39
17	Netherlands	966	**38**	Saudi Arabia	205	**59**	Nigeria	81	**80**	Faeroe Islands	39
18	Russia	878	**39**	Sweden	202	**60**	Mongolia	74	**81**	Estonia	39

	Flag Name	BC (t)		Flag Name	BC (t)		Flag Name	BC (t)		Flag Name	BC (t)
82	Moldova	38	**102**	Lebanon	21	**122**	Myanmar	9	**142**	Mozambique	2
83	Ecuador	36	**103**	Sri Lanka	20	**123**	Namibia	8	**143**	Cuba	2
84	New Zealand	36	**104**	Latvia	19	**124**	Brunei	7	**144**	French Antarctic Territory	2
85	Irish Republic	36	**105**	Ukraine	19	**125**	Maldive Islands	7	**145**	El Salvador	2
86	Portugal	35	**106**	Pakistan	17	**126**	Congo (Democratic Republic)	7	**146**	Georgia	2
87	Libya	35	**107**	Honduras	17	**127**	Iraq	6	**147**	Guyana	2
88	Peru	33	**108**	Seychelles	16	**128**	Ghana	6	**148**	Djibouti	2
89	Jamaica	33	**109**	Ethiopia	16	**129**	Fiji	5	**149**	Sao Tome & Principe	2
90	Tunisia	30	**110**	Tanzania	15	**130**	Cape Verde	5	**150**	Tonga	1
91	Israel	28	**111**	Uruguay	15	**131**	Niue	5	**151**	Sudan	1
92	Algeria	28	**112**	Poland	15	**132**	Angola	5	**152**	Guatemala	1
93	Bangladesh	27	**113**	Bulgaria	14	**133**	Equatorial Guinea	4	**153**	Somalia	1
94	Micronesia	27	**114**	Turkmenistan	13	**134**	Senegal	3	**154**	Cameroon	1
95	Kazakhstan	26	**115**	Colombia	11	**135**	Montenegro	3	**155**	Flag Not Required	1
96	Papua New Guinea	26	**116**	Jordan	10	**136**	Bolivia	3	**156**	Dominican Republic	1
97	South Africa	25	**117**	Trinidad & Tobago	10	**137**	Romania	3	**157**	Jersey	1
98	Korea, North	25	**118**	Falkland Islands	9	**138**	Albania	3	**158**	Madagascar	1
99	Faeroes (FAS)	23	**119**	Paraguay	9	**139**	Syria	3	**159**	Slovenia	1
100	Morocco	21	**120**	Mauritius	9	**140**	Virgin Islands, British	2	**160**	Guernsey	<1
101	Dominica	21	**121**	Oman	9	**141**	Gabon	2	**161**	St Helena	<1

Rank	Flag Name	BC (t)
162	Kenya	<1
163	Mauritania	<1
164	Turks & Caicos Islands	<1
165	Solomon Islands	<1
166	Guinea	<1
167	Samoa	<1
168	Yemen	<1
169	Grenada	<1
170	Cote D'Ivoire	<1
171	Congo	<1
172	Tanzania (Sumatra)	<1
173	Monaco	<1
174	Gambia	<1
175	Benin	<1
176	Niger	<1
177	Haiti	<1
178	Nicaragua	<1

APPENDIX L

Average draught ratio by ship class

	Ship Class	2015	
		Ballast	Loaded
Ships with ballast-only voyages	Bulk carrier	0.57	0.91
	Chemical tanker	0.65	0.89
	General cargo	0.65	0.89
	Liquefied gas tanker	0.67	0.88
	Oil tanker	0.60	0.89
	Other liquid tankers	0.67	0.90
	Refrigerated bulk	0.68	0.88
Ships that typically do not have ballast-only voyages	Container	0.81	
	Cruise	0.97	
	Ferry pax only	0.90	
	Ferry ro-pax	0.92	
	Miscellaneous – fishing	0.84	
	Miscellaneous - others	0.47	
	Naval ship	0.82	
	Non-propelled	0.76	
	Non-Ship	0.95	
	Offshore	0.83	
	Ro-ro	0.87	
	Service other	0.86	
	Service tug	0.89	
	Vehicle	0.87	
	Yacht	0.92	