Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025

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EXECUTIVE SUMMARY

Dwindling sea ice is opening new shipping routes through the Arctic, with shipping activity expected to increase with oil and gas development and as ships take advantage of shorter trans-Arctic routes from Asia to Europe and North America. However, with increased shipping comes an increased risk of accidents, oil spills, and air pollution. Potential spills of heavy fuel oil (HFO) and emissions of black carbon (BC) are of particular concern for the Arctic. Heavy fuel oil poses a substantial threat to the Arctic environment because it is extremely difficult to recover once spilled and the combustion of HFO emits BC, a potent air pollutant that accelerates climate change. For these reasons, the Arctic Council (AC) has called HFO "the most significant threat from ships to the Arctic environment" (Arctic Council, 2009). Thus, understanding how much HFO is consumed and carried by ships in the Arctic, and how much BC is emitted by these ships, is critical to assessing the current and future risks of Arctic shipping.

This report uses exactEarth satellite Automatic Identification System (AIS) data along with ship characteristic data from IHS Fairplay to estimate HFO use, HFO carriage, the use and carriage of other fuels, BC emissions, and emissions of other air and climate pollutants for the year 2015, with projections to 2020 and 2025. Results are estimated for ships operating in three Arctic regions: (1) the Geographic Arctic (at or above 58.95°N), (2) the International Maritime Organization's (IMO) Arctic as defined in the Polar Code, and (3) the U.S. Arctic, defined as the portion of the U.S. exclusive economic zone (EEZ) within the IMO Arctic. The risks of HFO and BC in the Arctic are being actively discussed at the AC and the IMO. Because the IMO will likely be the prime decision-making body for international policies that address the environmental risks of Arctic shipping, the Executive Summary focuses primarily on HFO use, HFO carriage, BC emissions, and flag state activity in the IMO Arctic.

Heavy fuel oil was the most consumed marine fuel in the Arctic in 2015. In the IMO Arctic, HFO represented nearly 57% of the nearly half million tonnes (t) of fuel consumed by ships, followed by distillate (43%); almost no liquefied natural gas (LNG) was consumed in this area. General cargo vessels consumed the most HFO in the IMO Arctic, using 66,000 t, followed by oil tankers (43,000 t), and cruise ships (25,000 t). Heavy fuel oil also dominated fuel carriage, in tonnes, and fuel transport, in tonne-nautical miles (t-nm) in the Arctic in 2015. Although only 42% of ships in the IMO Arctic operated on HFO in 2015, these ships accounted for 76% of fuel carried and 56% of fuel transported in this region. Specifically, bulk carriers, container ships, oil tankers, general cargo vessels, and fishing vessels dominated HFO carriage and transport in the IMO Arctic, together accounting for more than 75% of HFO carried and transported in the IMO Arctic in 2015. Considering the quantity of fuel these vessels carry on board and the distances they travel each year, these ships may pose a higher risk for HFO spills than others.

The distribution of HFO use in three Arctic areas is shown in Figure ES-1. The blue outline represents the IMO Arctic boundary. The minimum sea ice extent in 1979 and 2015 are shown as the light blue area and dark black line, respectively. As the figure illustrates, melting sea ice is associated with expanded use and carriage of HFO in the Arctic. Note the 2015 HFO use associated with activity along the northern coast of Russia (part of the Northern Sea Route) and Canada (the Northwest Passage) that would have been ice-locked in 1979.

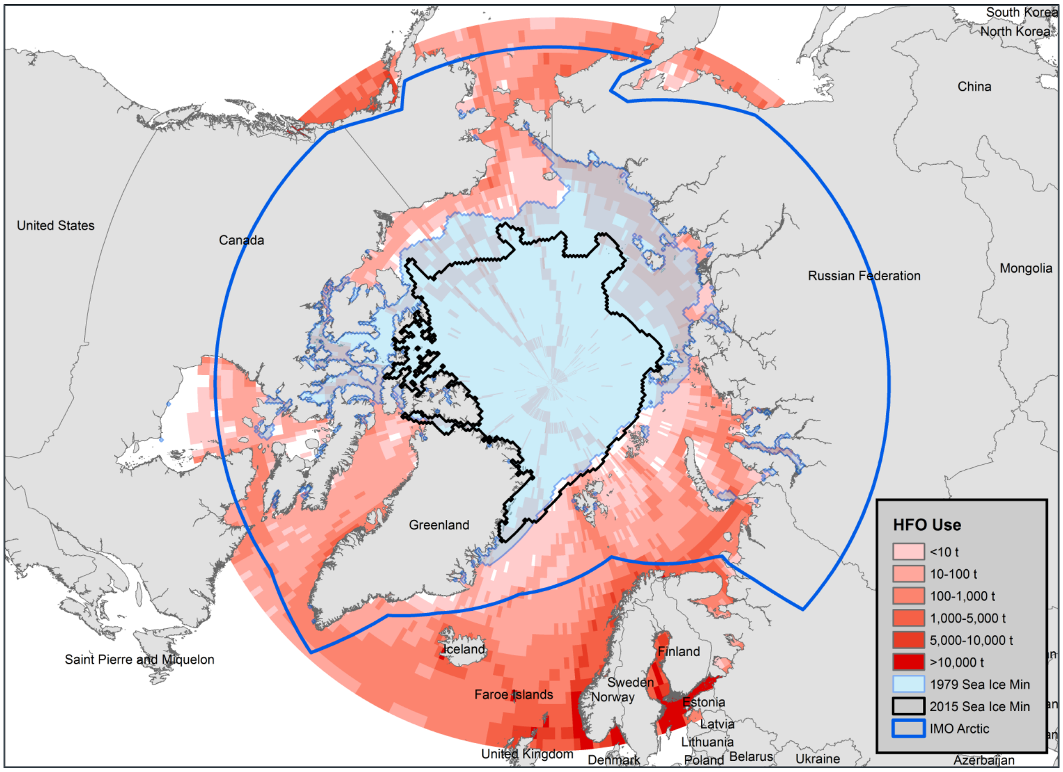

Figure ES-1. Heavy fuel oil use (tonnes) in the Arctic, 2015, with minimum sea extents

Implementing the 0.5% global fuel sulfur cap in 2020 is estimated to reduce the use, carriage, and transport of high-sulfur HFO bunker fuel, which has more than 0.5% sulfur, in all areas of the Arctic by more than 85% from 2015 to 2025 under a business as usual (BAU) scenario. However, the sulfur cap will not eliminate HFO use and carriage in this region, because some ships will comply by using blends of HFO and distillate that comply with the 0.5% sulfur limit. Moreover, the current limited emissions testing that has been performed on those desulfurized and blended residual fuels suggests that they may produce as much or more BC than traditional HFO. Because of the low price of HFO, operators may find it more cost-effective to install scrubbers to meet the 0.5% sulfur limits or use desulfurized HFO or HFO blends in lieu of switching to more expensive distillate fuel. Furthermore, trans-Arctic diversions of large cargo ships from the Suez and Panama canals could dampen the reduction in HFO use and carriage resulting from the sulfur cap by 4 or 5 percentage points. The sulfur cap may reduce the prominence of HFO fuel in the Arctic, but ships will continue to use and carry HFO in Arctic waters, leaving the risk of a major spill of HFO, blended fuels, or desulfurized residual fuels, all of which are more damaging and difficult to clean than a spill of distillate fuel or LNG.

Roughly two thirds of 2015 BC emissions attributable to ships in the Arctic were the consequence of consuming HFO. In the IMO Arctic, the top three emitters of BC were fishing vessels (25%), general cargo vessels (19%), and service vessels (12%). Black carbon emissions are expected to continue to rise in the Arctic, exacerbating Arctic warming, primarily by decreasing the albedo of Arctic snow and ice. Potentially large increases in BC emissions may occur if ships are diverted from the Panama and Suez canals to take advantage of shorter routes to and from Asia, Europe, and North America. Under a BAU scenario without diversions, BC emissions in the IMO Arctic are expected to rise modestly, from 193 t in 2015 to 199 t and 204 t in 2020 and 2025, respectively. However, if even a small percentage (1%–2%) of large cargo vessels are diverted from the Panama and Suez Canals through the Arctic over the next decade, BC emissions could rise dramatically to 271 t and 282 t in 2020 and 2025, respectively—increases of 41% and 46% from 2015.

The distribution of Arctic BC emissions is shown in Figure ES-2. Note that the figure shows where BC was emitted from ships and does not account for atmospheric transport of these emissions. The blue outline represents the IMO Arctic boundary. Black carbon emissions are more intense near Arctic landmasses, but can extend all the way to the North Pole, primarily from icebreaker and research activities. Ship activity off the shores of Iceland, Norway, and south of Anchorage, Alaska, contribute significant BC emissions in the Geographic Arctic that are excluded from the IMO Arctic. If BC emissions from these areas were included in the IMO definition of the Arctic, 2015 emissions would expand by more than 600% from nearly 200 t (IMO Arctic) to more than 1,400 t (Geographic Arctic). This finding highlights that the bulk of vessel traffic north of 60 degrees latitude is excluded from the IMO Arctic.

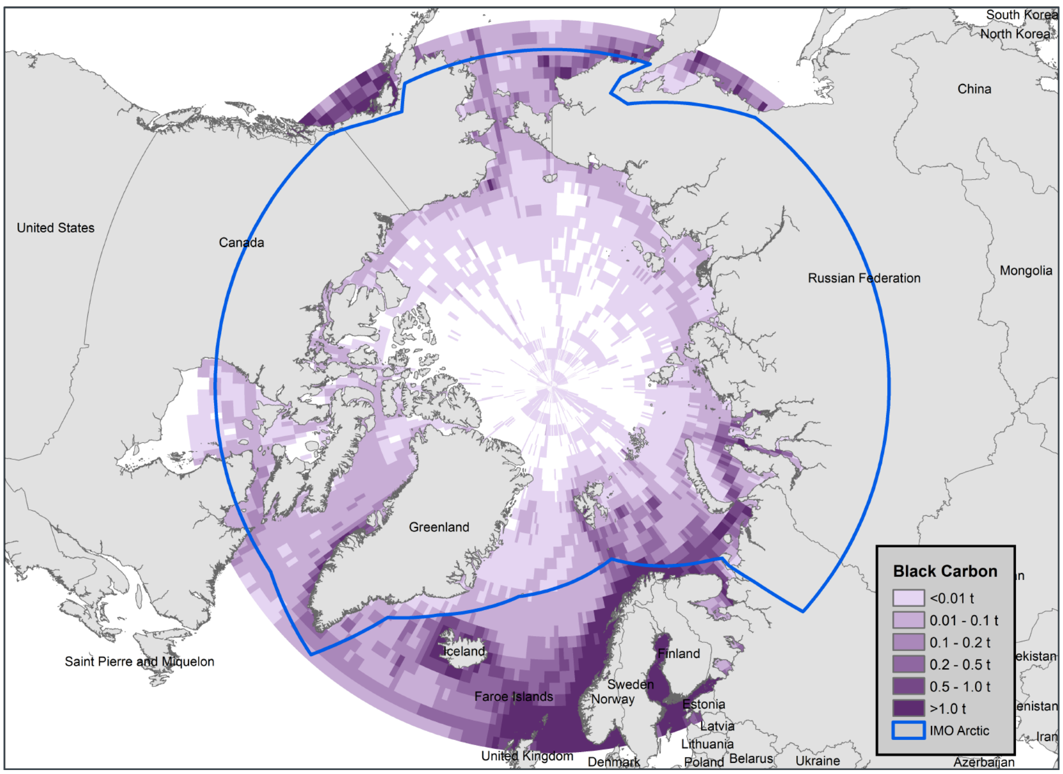

Figure ES-2. Black carbon emissions (tonnes) in the Arctic, 2015

In terms of ship registration status, Russian-flagged ships dominated ship activity, BC emissions, HFO use, and HFO carriage in the IMO Arctic in 2015. Specifically, Russian-flagged vessels accounted for 51% of BC emissions (followed by Canada with 6%), 56% of HFO fuel use (Canada follows with 6%), and 24% of HFO carriage as fuel (followed by Panama with 11%). Figure ES-3 presents the top five BC-emitting flag states in the IMO Arctic in 2015. In general, BC emissions, HFO use, and HFO carriage in the IMO Arctic in 2015 were attributable to activities by vessels flagged in Arctic states and those registered to prominent IMO flag states, such as Panama, Marshall Islands, Liberia, Bahamas, and Singapore.

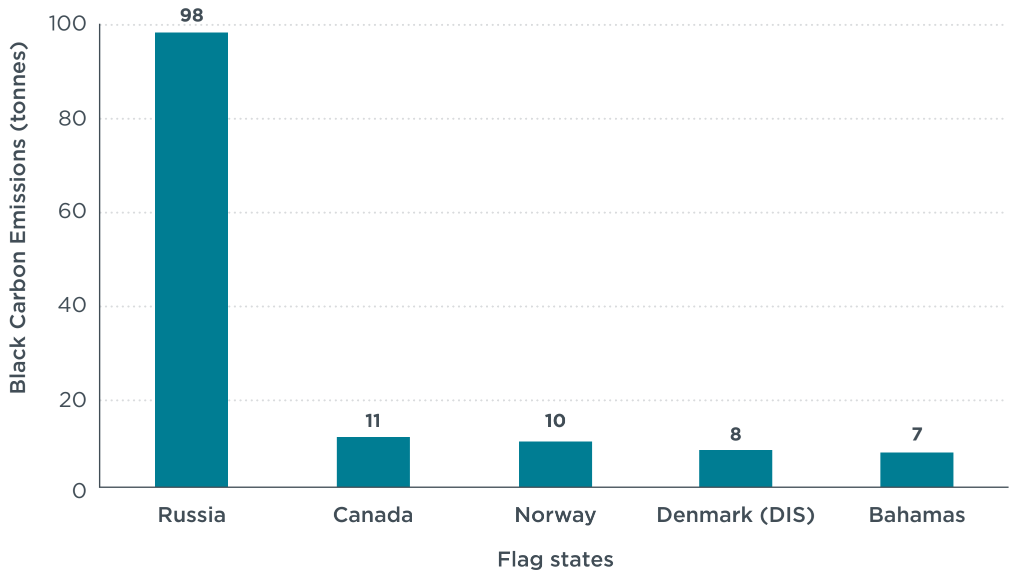

Figure ES-3. Black carbon emissions by top five emitting flag states in the IMO Arctic, 2015

Several policy alternatives could be considered to reduce the dual risks of air pollution and fuel oil spills from ships in the Arctic. These include regional emission control policies; restricting the use of HFO, the carriage of HFO, or both; and regulating BC emissions regionally or globally. Explicitly restricting the use and carriage of HFO in the Arctic would greatly reduce the risks of HFO oil spills and would also reduce air pollution, including BC, provided ships operate on distillate, LNG, or other alternative fuels. An even stronger approach would be to prohibit the use of petroleum-based fuels (e.g., HFO and distillate), which would require a complete shift to cleaner fuels (e.g., LNG, fuel cells), albeit at substantial cost to existing fleets. Finally, Arctic BC emissions could be addressed through regulations that either establish new emission standards for marine engines, require the use of low- or zero-BC fuels, or mandate the use of BC reduction devices such as diesel particulate filters. Such a policy also may encourage a shift toward fuels that are less damaging than HFO when spilled. Other policy options are possible, including market-based approaches such as taxes or fees on HFO use/carriage, BC emissions, or both, but such options are not evaluated here.

Policies could be implemented at the global, regional, national, or subnational scales. Consensus policies that apply specifically to the Arctic region could be effective because ships registered to Arctic states, particularly Russia, account for the majority of HFO use, carriage, and BC emissions in the Arctic. However, because the diversion of ships from traditional trade routes in favor of trans-Arctic routes is likely as the Arctic becomes ice-free for longer periods, policies that apply to the global fleet, or ships intending to sail in the Arctic, are more attractive. Global policies are also desirable given that emissions of BC outside of the IMO Arctic can be, and are, transported northward. Thus, global policies that prohibit the use and carriage of HFO and reduce BC from marine engines will help ensure that the impacts on the Arctic environment from ships are meaningfully reduced.

1. INTRODUCTION AND BACKGROUND

Dwindling sea ice is opening new shipping routes through the Arctic and shipping activity in the Arctic is expected to rise as oil and gas development increases and as ships take advantage of shorter trans-Arctic routes from Asia to Europe and North America. The National Oceanic and Atmospheric Administration (NOAA, 2014a) estimates that 75% of Arctic sea ice volume has been lost since the 1980s. The Northwest Passage (NWP) and Northern Sea Route (NSR), both shown in Figure 1, are the two most economically advantageous routes for trans-Arctic shipping. The trip between Shanghai and Europe is shortened by about a third when the NSR is taken in lieu of the traditional route through the Suez Canal. Similarly, the trip from Shanghai to New York City also is shortened by a third when taking the NWP instead of the path through the Panama Canal. Shorter distances result in fuel, labor, and time savings. However, with expanded Arctic shipping comes the increased risk of accidents, oil spills, and air pollution.

Potential spills of heavy fuel oil (HFO) and emissions of black carbon (BC) are of particular concern for the Arctic. As described in Comer, Olmer, and Mao (2016), HFO poses a substantial threat to the Arctic environment, not only because HFO is extremely difficult to clean up once spilled, but also because burning HFO emits BC, a potent pollutant that accelerates climate change. The Arctic Council (AC) has called HFO "the most significant threat from ships to the Arctic environment" (Arctic Council, 2009). Thus, understanding how much HFO is consumed and carried by ships in the Arctic, along with how much BC is emitted by these ships, is critical to understanding the current and future risks of Arctic shipping.

This report estimates the HFO use, HFO carriage, other fuel use and carriage, BC emissions, and other air pollution in 2015 by ships operating in three Arctic regions: (1) the Geographic Arctic (above 58.95°N), (2) the International Maritime Organization's (IMO) Arctic as defined in the Polar Code, and (3) the U.S. Arctic, defined as the portion of the U.S. exclusive economic zone (EEZ) within the IMO Arctic. These three areas were selected for the following reasons:

- Geographic Arctic (at or above 58.95°N):
    - Ship activities in this area and their associated spills, discharges, and air pollutant emissions reasonably reflect the potential effects of shipping on the Arctic.
    - Other researchers have estimated fuel use and emissions from ships in this area in 2012 with projections to 2020, 2030, and 2050. This report updates those estimates to 2015 for comparison.
- IMO Arctic
    - Ship activities in this area are subject to international Arctic safety and environmental regulations through the IMO's Polar Code.
- U.S. Arctic
    - Ship activities in this area are subject to both international Arctic safety and environmental regulations associated with the IMO's Polar Code, but also to national regulations that could be promulgated by the United States.
        - The United States is a leader in domestic maritime environmental policies and could spearhead Arctic shipping policies within its EEZ.

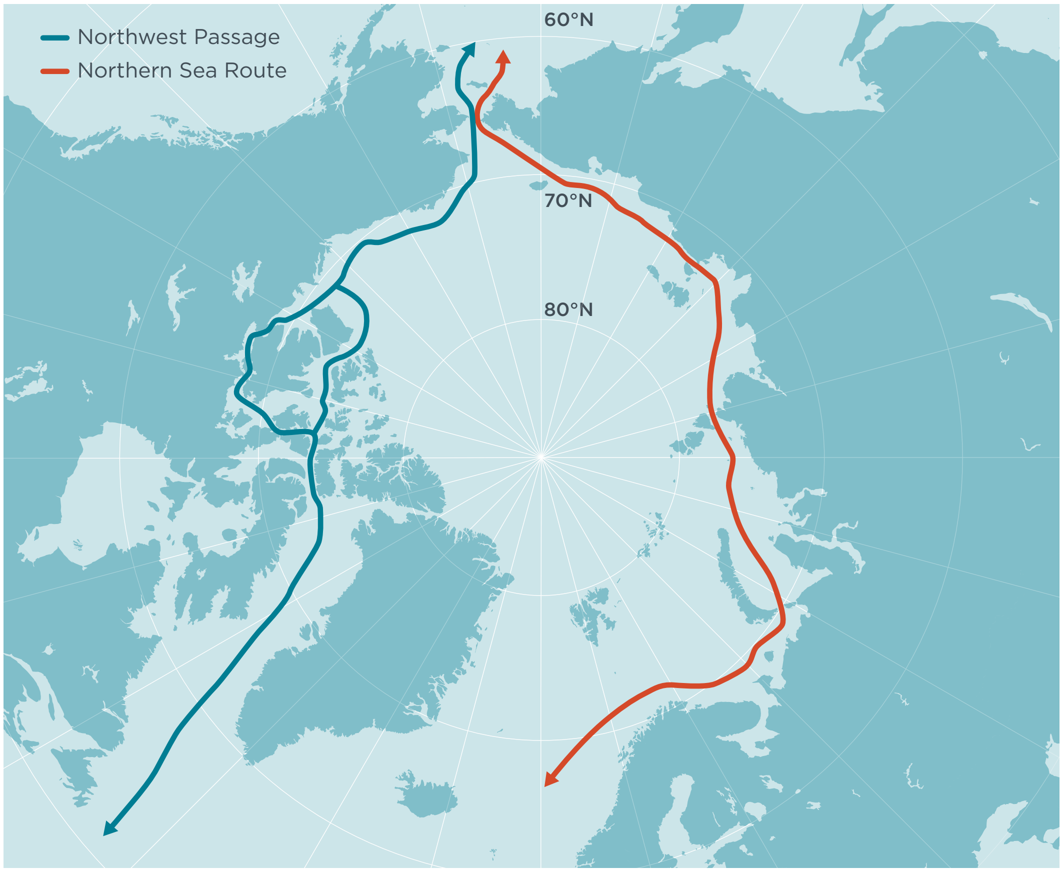

Figure 1. The Northwest Passage and Northern Sea Route

1.1 HEAVY FUEL OIL

Heavy fuel oil, also called residual fuel, consists of the bottom-of-the-barrel leftovers from the oil refining process. It is extremely viscous, so much so that it needs to be heated to around 130°C for it to flow. Heavy fuel oil contains heavy metal impurities and is usually high in sulfur, with an average content around 2.5% by weight, equivalent to 25,000 parts per million (ppm). Consuming HFO emits high levels of air pollutants—for example, sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM)—and climate pollutants, including carbon dioxide (CO_2), nitrous oxide (N_2O), and BC.

In addition to air pollution, a potential spill of HFO poses a serious risk to the marine environment, particularly in the Arctic. Instead of creating a large oil slick and dispersing, HFO spilled in the Arctic tends to emulsify in seawater, creating a material with the consistency of chocolate mousse that can be many times the volume of the original oil spilled (Deere-Jones, 2016). Any emulsion not deposited on shore or ice can sink and resurface once temperatures rise to re-oil sea ice and shorelines. Additionally, a ship leaking HFO in the Arctic may become trapped in ice, preventing rescue workers and spill recovery crews from accessing the spill site. At present, the Arctic region lacks the infrastructure and personnel to adequately respond to an oil spill (NOAA, 2009). Despite its environmental consequences, HFO remains the preferred fuel of the maritime transport industry because of its low cost and widespread availability and because it is the fuel upon which large marine engines have been designed to operate.

Studies have analyzed the amount of HFO used and carried in the Arctic. Between 2011 and 2013, Det Norske Vertitas completed a series of reports for the AC's Protection of the Arctic Marine Environment (PAME) working group to help it understand the use and carriage of HFO in the Arctic (Det Norske Veritas [DNV], 2011, 2013). In these studies, DNV found that only 20% of vessels sailing in the IMO Arctic from August to November 2010, and 28% from January to December 2012, operated on HFO. However, roughly 78%, or 400,000 tonnes, of the bunker fuel *mass* on board vessels in the IMO Arctic was HFO. DNV found that fishing vessels dominated the Arctic fleet in terms number of ships, operating hours, and fuel consumption in the Arctic; however, they assumed that most of these vessels operated on lighter and cleaner distillate fuels, rather than HFO, a reasonable assumption according to the results presented here. Bulk carriers, passenger vessels, and oil tankers had the most HFO fuel on board by mass because of their larger bunker tank capacity.

A recent International Council on Clean Transportation (ICCT) working paper (Comer, Olmer, & Mao, 2016) found that whereas less than half of ships operating in the IMO Arctic used HFO in 2015, the mass of fuel onboard all ships in the IMO Arctic was dominated by HFO (76% HFO; 23% distillate; less than 1% LNG, nuclear, and gas boil off), because ships operating on HFO tend to be larger ships with large bunker fuel tanks. That paper reported that ships in the IMO Arctic in 2015 had more than 830,000 t of HFO onboard, more than twice the amount estimated by DNV for the year 2012. A portion of this substantial increase in fuel carriage is attributable to greater carriage of HFO; however, the bulk of this difference is likely as a result of having more complete ship position and ship characteristics data in the 2016 ICCT study than in the 2013 DNV study. Comer et al. (2016) found that the carriage of HFO as bunker fuel in the IMO Arctic in 2015 was dominated by bulk carriers (247,800 t), container vessels (112,900 t), oil tankers (110,600 t), general cargo vessels (76,600 t), and fishing vessels (76,200 t).

To the authors' knowledge, estimates of the quantity of HFO consumed onboard ships in the Arctic have not been made to date. DNV (2011, 2013) estimated fuel consumption by vessels operating in the IMO Arctic, but did not apportion it by fuel type (e.g., distillate compared to HFO). Similarly, Peters et al. (2011) and Winther et al. (2014) estimated fuel consumption for ships operating in the Arctic in 2004 and 2012, respectively, but did not apportion fuel consumption by fuel type. This study estimates HFO use by ships in the Arctic.

1.2 BLACK CARBON

Black carbon is a small dark particle emitted as a result of incomplete combustion. Black carbon from all sources is the second largest contributor, after CO_2, to human-induced climate change (Bond et al., 2013). In 2010, BC from ships accounted for 8%–13% of BC emissions from diesel sources (Azzara, et al., 2015). Black carbon's dark color allows it to absorb a high proportion of incoming solar radiation. When emitted, BC absorbs solar radiation and warms the atmosphere directly. Black carbon typically falls out of the atmosphere and is deposited on the earth's surface within a few days. When BC forms deposits on light covered surfaces, such as snow or ice, it reduces the albedo of the surface and continues to have a warming effect (AMAP, 2015). This is particularly concerning for the Arctic. Ships operating in the Arctic emit BC that can directly deposit on snow and ice. Thus, emitting BC in the Arctic further amplifies the pollutant's warming effect. In fact, Sand, Berntsen, Seland, and Kristjánsson (2013) found that BC emitted within the Arctic has a surface warming effect nearly five times greater than BC emitted at midlatitudes.

Several studies have estimated BC emissions in the Arctic, although the geographical definitions of the Arctic are inconsistent across studies. Corbett et al. (2010) estimated that ships operating in the AMSA area[1] emitted 0.88 kilotonnes (kt) of BC in 2004,[2] growing to 1.20 kt in 2020, 1.50 kt in 2030, and 2.70 kt in 2050 under a BAU scenario. Similarly, Peters et al. (2011) estimated that ships operating within the AMAP boundary[3] emitted 1.15 kt of BC emissions in 2004, growing to 2.16 kt in 2030 and 2.96 kt in 2050. Both studies assumed a BC emission factor (EF) of 0.35 g/kg fuel. Two more recent studies—DNV (2013) and Winther et al. (2014)—better match the geospatial extents of the Arctic found in this report. DNV (2013) estimated that ships operating within the IMO Arctic emitted 0.052 kt of BC in 2012, assuming a BC EF of 0.18 g/kg fuel. Winther et al. (2014) estimated ships operating at or above 58.95°N emitted 1.585 kt of BC in 2012, assuming a BC EF of 0.35 g/kg fuel.

1.3 POLICY CONTEXT

This report will provide useful information to inform ongoing policy discussions on HFO and BC in the Arctic. The use and carriage of HFO already is prohibited in Antarctic waters per Regulation 43 of the IMO Polar Code. Although Regulation 43 encourages ships not to use HFO in the Arctic, neither the use nor carriage of HFO is prohibited in the Arctic. Black carbon emissions from ships are not directly controlled by any IMO regulation today. However, both the AC and the IMO are actively considering the impacts of HFO and BC on the Arctic.

1.3.1. The Arctic Council

The AC is an intergovernmental forum for Arctic governments and peoples. The AC's PAME working group has been assessing the use and carriage of HFO in the Arctic following the landmark *Arctic Marine Shipping Assessment 2009 Report* that concluded that "the most significant threat from ships to the Arctic marine environment is the release of oil through accidental or illegal discharge" (Arctic Council, 2009).

Recently, PAME invited AC member states, permanent participants, and observers to submit proposals to its Shipping Expert Group by June 1, 2016, for mitigating the risks associated with the use and carriage of HFO by vessels in the Arctic.[4] PAME also instructed the Shipping Expert Group to submit to PAME II-2016, held September 19–21, 2016, in Portland, Maine, a paper that proposed recommendations to mitigate these risks, based on its previous work and any additional information it had received under the request for proposals mentioned above. This paper was not available for review ahead of the publication of this report.

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

1 The Arctic Council Protection of the Arctic Marine Environment (PAME) working group's 2009 Arctic Marine Shipping Assessment (AMSA) report includes areas "defined according to the international policies among Arctic Council member states," which includes considerable sub-Arctic areas.

2 1.23 kt BC in 2004 if fishing vessel emissions are included, although Corbett et al. explain that fishing emissions estimates found in their paper should be considered very uncertain.

3 This is the area that Arctic Council member states have identified as "the Arctic" for the purposes of assessing the impacts of pollution on the Arctic. It is essentially the same as the AMSA boundary.

4 See page 3 of PAME I-2016 report (Protection of the Arctic Marine Environment [PAME], 2016).

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. However, the AC does not have the authority to establish binding BC reduction requirements for member states.

1.3.2. IMO

The use of HFO by vessels in Arctic waters has been debated at the IMO for almost a decade, and its use and carriage in the Antarctic area has been prohibited since August 2011. During the development of a new regulation prohibiting the use and carriage of HFO as fuel, cargo, or ballast in the Antarctic area, the idea of a similar prohibition for the Arctic was raised; however, there was insufficient support to take the discussion forward. At this stage, the subject of HFO use and carriage in the Arctic is not specifically included in the IMO's High Level Action Plan for its 2016/2017 biennium work program.

A group of nongovernmental organizations (NGOs) led by Friends of the Earth International (FOEI) submitted a paper[5] to the Marine Environment Protection Committee's 69th session, held April 18–22, 2016, that implicitly sought member state support for developing an Arctic HFO work plan at MEPC. This same group submitted a paper[6] to MEPC 70 that outlines the risks of HFO in the Arctic. It is possible that a member state will propose such a work plan to assess the risks of the use and carriage of HFO in the Arctic at an upcoming MEPC meeting, perhaps as early as MEPC 71 in 2017.

Separately, MEPC has tasked its Sub-Committee on Pollution Prevention and Response (PPR) to determine how to define, measure, and control marine BC emissions. Under the auspices of the Climate and Clean Air Coalition (CCAC), the ICCT has led a series of workshops designed to bring together stakeholders from industry, government, academia, and NGOs to tackle the questions of how to define, measure, and control marine BC emissions. The outcomes of these workshops have informed IMO member state submissions to the second, third, and fourth sessions of PPR. A definition of BC suitable for research purposes that was developed by Bond et al. (2013) was endorsed by participants at ICCT's first workshop, held in Ottawa in 2014, and adopted by PPR 2. A marine BC measurement reporting protocol for voluntary marine BC emissions testing campaigns developed and presented by the European Association of Internal Combustion Engine Manufacturers (EUROMOT) at ICCT's second workshop, held in Utrecht in 2015, subsequently was endorsed by PPR 3. Recommendations for appropriate marine BC measurement methods and promising control technologies developed at ICCT's third workshop, held in Vancouver in 2016, were submitted by IMO delegations to PPR 4. It is possible that the issue of marine BC emissions will move back to MEPC in the next few sessions, opening up the opportunity to devise and debate appropriate international marine BC control policies.

5 MEPC 69/20/1.

6 MEPC 70/17/4.

2. METHODOLOGY

2.1 ARCTIC DEFINITIONS

The Arctic region has many definitions that often depend upon the geopolitical requirements of various organizations and governments. One definition of the Arctic is the area within the Arctic Circle, an area north of approximately 66.5°N, the latitude above which the sun does not rise on the winter solstice and the sun does not set on the summer solstice (National Geographic, 2016). The Arctic Council, comprising the eight countries that hold territory above 66.5°N,[7] in their PAME working group's *Arctic Marine Shipping Assessment 2009 Report* includes areas of the Arctic as "defined according to the international policies among Arctic Council member states," which includes considerable sub-Arctic areas, because pollutants emitted in sub-Arctic areas often are transported into the Arctic. The IMO definition of the Arctic—the IMO Arctic—as found in the Polar Code consists of the region north of 60°N latitude, but excluding Iceland, Norway, Sweden, and Finland and their respective high seas claims.

This report considers three regions of the Arctic as shown in Figure 2:

- The Geographic Arctic (at or above 58.95°N)
  - Ship activities in this area and their associated spills, discharges, and air emissions reasonably reflect the potential effects of shipping on the Arctic.
  - Provides an opportunity to compare the results of this report to Winther et al. (2014).
- The IMO Arctic (as defined in the Polar Code)
  - Ship activities in this area are subject to international Arctic safety and environmental regulations through the IMO's Polar Code.
- The U.S. Arctic (the U.S. EEZ within the IMO Arctic)
  - Ship activities in this area are subject to both international Arctic safety and environmental regulations associated with the IMO's Polar Code, but also to national regulations that could be promulgated by the United States.

7 The United States, Canada, the Russian Federation, Norway, Denmark (Greenland), Finland, Sweden, and Iceland.

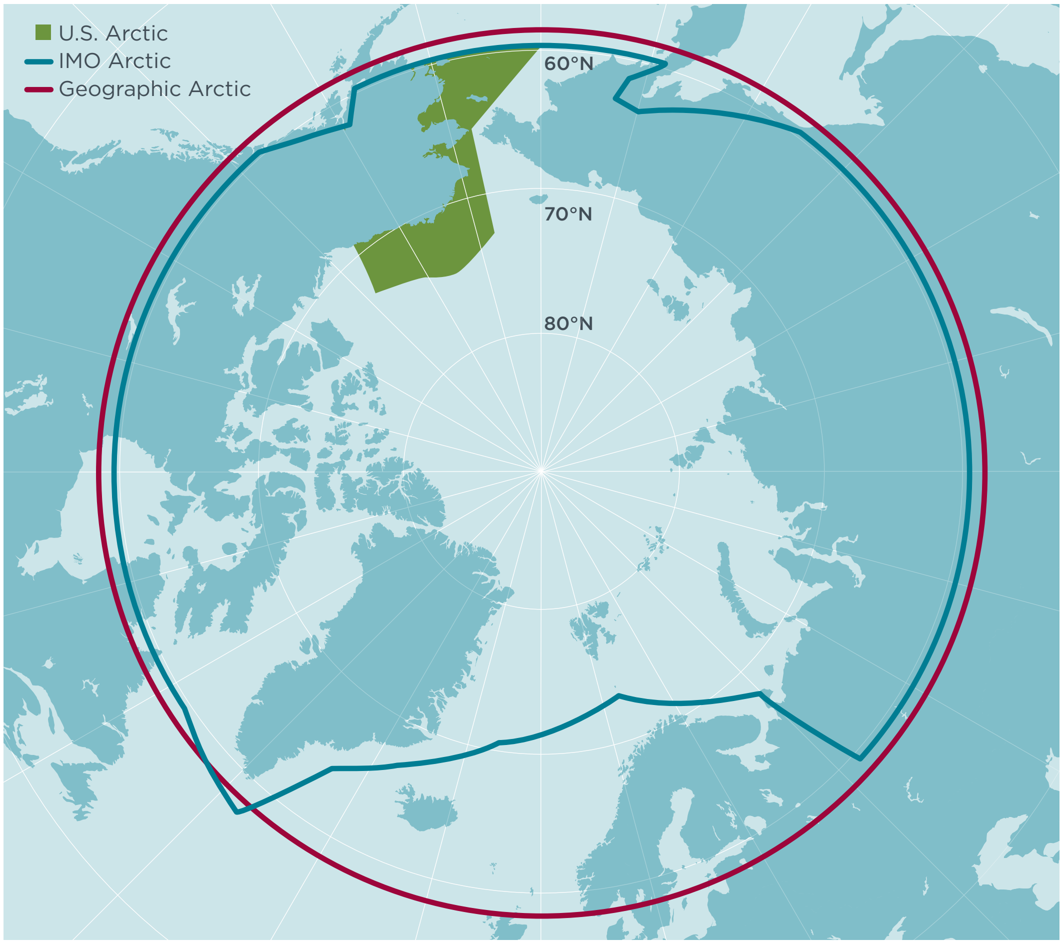

Figure 2. Arctic regions investigated

2.2 EMISSIONS INVENTORY

This section describes how an emissions inventory was developed for ships operating in the Arctic in 2015. In addition to air and climate pollutant emissions, the inventory also estimates fuel consumption (t), mass of fuel onboard (t), and the distance fuel is transported (t-nm), all disaggregated by fuel type (HFO, distillate, LNG, and nuclear).

2.2.1. Datasets

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

2.2.2. AIS data

Hourly-aggregated AIS data were obtained from exactEarth for all ships with a registered AIS transponder for calendar year 2015.

2.2.2.1. Removing invalid data

Data points without a valid IMO number or MMSI number, with invalid longitude or latitude values, or with a course over ground not within 0–359 degrees were excluded from the dataset.

2.2.2.2. Interpolating missing AIS data points

Although AIS signals may be transmitted by ships every 6 seconds, the AIS dataset used in this report has been aggregated to hourly averages to reduce the total size of the dataset. There are some instances where there are gaps in transmitted AIS data, either because the ship left the area, the ship turned off the AIS transmitter, the signals were not registered by a satellite, or the signal was deemed invalid and removed. In the case of gaps of less than 24 hours, the missing hours, ship position, and speed over ground (SOG) were linearly interpolated to fill the missing coordinate locations and speed over ground for the vessel. For example, if a ship was traveling due east at 10 knots at *hour 1* and due east at 12 knots at *hour 3*, but the position and speed were unknown for *hour 2*, the assumption would be that the ship traveled due east at 11 knots at hour 2. Linearly interpolated data points represent 22.3% of total hours within the Geographic Arctic region, 9.7% of hours in the IMO Arctic region, and 6.1% of hours in the U.S. Arctic region.

2.2.3. IHS data processing

IHS ShipData contains a variety of fields that are useful for estimating fuel consumption and emissions from ships. Data pulled directly from or derived from IHS ShipData for analysis are described in the subsections that follow. In cases where missing data needed to be filled in, the methods for doing so are described below.

2.2.3.1. Ship class and capacity bin

IHS ShipData classifies each vessel as one of 256 unique *ship types* via the StatCode5 field. From the StatCode5 field, each ship was re-classified into one of 22 *ship classes* according to the process used in the *Third IMO GHG Study 2014* (International Maritime Organization [IMO], 2015). Each ship is also assigned a *capacity bin* according to its cargo or passenger capacity. The capacity bin categories are the same as those used in the *Third IMO GHG Study 2014*. The combined ship class and capacity bin categorizations resulted in a total of 55 unique ship groups. Complete tables describing which ship types and capacities fall into different ship classes and capacity bins are presented in Appendix A and Appendix B. The main purpose of reclassifying each ship from its ship type to its ship class is to estimate each ship's auxiliary engine (AE) and boiler (BO) power demand under different operating modes, specifically cruise, maneuvering, hoteling, and at anchor/berth; see Appendices D and E for details.

2.2.3.2. Tier level

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

Table 1. In-service and on-order vessels by IMO NO_x tier in the Arctic

Tier	Year of construction	Geo. Arctic fleet		IMO Arctic fleet		U.S. Arctic fleet	
		Vessel count	Share of fleet	Vessel count	Share of fleet	Vessel count	Share of fleet
0	Pre-2000	4914	48.7%	1387	66.5%	105	58.3%
I	2000-2010	4013	39.7%	525	25.2%	52	28.9%
II	2011-2015	1170	11.6%	174	8.3%	23	12.8%
III	2016 or later	2	0.02%	0	0%	0	0%

Source: ICCT analysis of exactEarth AIS data and IHS ShipData.

2.2.3.3. Main fuel type

The IHS ShipData database includes fields that indicate the types of fuel each ship uses. The fuel type for ships that operate on oil-based marine fuels as opposed to LNG, gas boil off, or nuclear is categorized as *residual* fuel or *distillate* fuel. There are two fuel type fields in the IHS database: *FuelType1First* and *FuelType2Second*. FuelType1First records the lightest fuel onboard. For example, distillate is considered a lighter fuel than residual. FuelType2Second records the heaviest fuel onboard. A main fuel type, indicating the type of fuel—residual or distillate—on which the ship primarily operates, was assigned to each vessel based on the fuels specified in FuelType1First and FuelType2Second. If either fuel type was listed as residual fuel, HFO was recorded as its main fuel type. Because HFO is the most common residual fuel used in marine ships and is less expensive than distillate fuels, it was assumed that ships operating on residual fuel were operating on HFO in 2015. Ships potentially could 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 mainly HFO. If the ship carried only distillate onboard, the ship was assumed to operate on distillate fuel. Ships that do not operate on oil-based fuels were classified as using either LNG or nuclear. If LNG was listed as a ship's FuelType1First or FuelType2Second, the main fuel type was assumed to be LNG. Additionally, ships classified as LNG tankers by their ShiptypeLevel5 with main engine (ME) models not ending in ME-C or ME-C8 were also classified as having a main fuel type of LNG. Ships with either FuelType1First or FuelType2Second listed as gas boil off and with neither field classified as residual were classified as LNG. If a ship's FuelType1First or FuelType2Second was recorded as nuclear, the ship was assumed to operate on nuclear power.

Fifty-nine percent of vessels in the IHS ShipData database lacked a fuel type designation, with fuel type more available for larger ships than for smaller ones. In these cases, the following rules were applied to assign the main fuel type to vessels when fuel type data were missing:

- Main fuel type was assumed to be HFO for the following:
  - 2-stroke main engines < 600 rpm
  - 4-stroke main engines < 600 rpm
- Main fuel type was assumed to be distillate fuel for the following:
  - 2-stroke main engines ≥ 600 rpm
  - 4-stroke main engines ≥ 600 rpm

Some ships had neither a main fuel type nor an ME rpm specified. In these cases, the ship was assigned a ME rpm based on the average ME rpm for that ship's ship type and capacity bin. If there was no average ME rpm by ship type and capacity bin, the average rpm for the ship class and capacity bin was used instead. The ships were then classified as above and assigned a main fuel type. In cases where the ME stroke type was missing—about 8,000 of the approximately 123,000 ships in the IHS ShipData database—those ships were assumed to operate on distillate fuel. Of those approximately 8,000 ships, more than 90% had an ME rpm greater than 600, meaning that they would be expected to operate on distillate fuel anyway. Thus, this assumption should not have a significant impact on the results.

2.2.3.4. Fuel capacity

The IHS ShipData database includes fields called *FuelType1Capacity* and *FuelType2Capacity*, which report the bunker tank capacity, in tonnes, for FuelType1First and FuelType2Second. A new field, *MainFuelTypeCapacity,* was created that reports the bunker tank capacity, in tonnes, for the fuel the ship uses for propulsion. The *MainFuelTypeCapacity* field was filled in by assuming that whichever fuel capacity is larger (FuelType1Capacity or FuelType2Capacity) is the main fuel and therefore represents the MainFuelTypeCapacity. For ships operating on HFO, both the FuelType1Capacity and FuelType2Capacity fields were empty for 42% of those ships. For ships operating on distillate fuel, both fuel capacity fields were empty for 74% of those ships. In such cases, missing fuel capacity data were filled in by using the relationship between known MainFuelTypeCapacity and either deadweight tonnage (dwt) or gross tonnage (gt) of similar ships, as follows:

- Scatter plots suggested a linear relationship between MainFuelTypeCapacity and dwt or gt.
- A linear regression analysis between MainFuelTypeCapacity 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 type.
- The R^2 values ranged from 0.32 and 0.96, with the best correlation between fuel capacity and either dwt or gt observed for oil tankers (0.96), bulk carriers (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.
- For ship classes with a poor correlation between main fuel type capacity and both dwt and gt ($R^2 < 0.62$), the relationship between main fuel type capacity and gt for the entire fleet is applied to estimate the missing main fuel type capacity ($R^2 = 0.79$).

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

2.2.3.5. Speed, power, and rpm

IHS ShipData includes fields for each ship's maximum vessel speed, 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 type and capacity bin. For ships missing this value, the average vessel speed, ME power, or ME rpm by ship class and capacity bin was used instead. The amount of data missing for each Arctic region is detailed in Table 2.

Table 2. Missing vessel characteristics for Arctic ships in 2015

Geographic Region	Ships missing max. vessel speed	Ships missing ME power	Ships with ME rpm
Geographic Arctic	14%	1%	13%
IMO Arctic	18%	3%	17%
U.S. Arctic	28%	5%	22%

Source: ICCT analysis of IHS ShipData for ships in the study area.

2.2.3.6. 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 turbines (ST), gas turbines (ST), slow speed diesel (SSD), medium speed diesel (MSD), high speed diesel (HSD), LNG-fueled diesel-cycle engines (LNG-diesel), and LNG-fueled Otto-cycle engines (LNG-Otto). Each ship was classified to an engine type as follows:

1. Any ship with a reciprocating[8] or turbine *MainEngineType* was classified as ST.
2. Any ship with a gas MainEngineType 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 “GI”, “GIE” or “LGIM” were classified as LNG-diesel.
    b. LNG ships with an Oil Engine(s), Direct Drive propulsion type were classified as LNG-diesel
    c. All other LNG-fueled ships were classified as LNG-Otto.
4. Remaining ships are assumed to be motor propelled ships. For ships with valid ME 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. Remaining ships were assigned an ME rpm based on the average ME rpm by either the ship’s ship type and capacity bin or the ship’s ship class and capacity bin. These ships then have an engine type assigned based on the procedures in (4).

Table 3 describes the total count of vessels and portion of the Arctic fleet within each engine type class.

8 Meaning a reciprocating steam engine.

Table 3. Vessels by engine type in the Arctic

Engine type*	Geo. Arctic fleet		IMO Arctic fleet		U.S. Arctic fleet	
	Vessel count	Share of fleet	Vessel count	Share of fleet	Vessel count	Share of fleet
SSD	2,984	29.5%	462	22.1%	45	25.0%
MSD	3,873	38.4%	943	45.2%	28	15.6%
HSD	3.125	30.9%	666	31.9%	106	58.9%
ST	25	0.2%	5	0.2%	1	0.6%
GT	7	0.1%	1	<0.1%	0	0%
LNG-Otto	84	0.8%	9	0.4%	0	0%
LNG-diesel	1	<0.1%	0	0%	0	0%
Total	**10,099**	**100%**	**2,086**	**100%**	**180**	**100%**

SSD = slow speed diesel; MSD = medium speed diesel; HSD = high speed diesel; ST = steam turbine; GT = gas turbine; LNG-Otto = a dual-fuel LNG engine that operates on the Otto cycle in the gas mode; LNG-diesel = a dual-fuel LNG engine that operates on the Diesel cycle in the gas mode. Source: ICCT analysis of IHS ShipData for ships in the Arctic.

2.3 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 from ships in the Arctic come from MEs, AEs, and BOs and are estimated according to the following equation developed by the ICCT for this analysis:

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

Where:

i = ship

j = pollutant

t = time (operating hour, h)

k = engine type

l = engine tier

m = fuel type

p = phase

$E_{i,j}$ = emissions (g) for ship i and pollutant j

P_{ME_i} = main engine power (kW) for ship i

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

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

$EF_{ME_{j,k,l,m}}$ = main engine emission facor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m

$D_{AE_{p,t}}$ = auxiliary engine power demand (kW) in phase p for ship i

$EF_{AE_{j,k,l,m}}$ = auxiliary engine emission factor (g/kWh) for pollutant j, engine type k, engine tier l, and fuel type m

$D_{BO_{p,i}}$ = boiler power demand (kW) in phase p for ship i

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

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

2.3.1. Ship operating phase

While in service, a ship is operating in one of four phases: at berth, at anchor, maneuvering, or cruising. The phase in which the ship is operating is important for estimating AE and BO power demand, crucial information for estimating emissions from those engines. A ship's phase is determined by its proximity to land or port and its SOG. Table 4 and Table 5 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 because they can be considered to be at berth within 5 nautical miles of a port as a result of the common practice of lightering these vessels offshore.

Table 4. Phase assignment decision matrix (all ship classes except liquid tankers)

	Distance from port/coast				
Speed	**≤ 1 nm from port**	**≤ 1 nm from coast**	**1-5 nm from coast**	**≤ 5 nm from coast**	**In a river**
< 1 knots	Berth	Anchor	Anchor	Anchor	Berth
1-3 knots	Anchor	Anchor	Anchor	Anchor	Maneuvering
3-5 knots	Maneuvering	Maneuvering	Maneuvering	Cruising	Maneuvering
> 5 knots	Maneuvering	Cruising	Cruising	Cruising	Cruising

Table 5. Phase assignment decision matrix for liquid tankers

	Distance from port/coast					
Speed	**≤ 1 nm from port**	**≤ 1 nm from coast**	**1-5 nm from port**	**1-5 nm from coast**	**≤ 5 nm from coast**	**In a river**
< 1 knots	Berth	Anchor	Berth	Anchor	Anchor	Berth
1-3 knots	Anchor	Anchor	Anchor	Anchor	Anchor	Maneuvering
3-5 knots	Maneuvering	Maneuvering	Maneuvering	Maneuvering	Cruising	Maneuvering
> 5 knots	Maneuvering	Cruising	Cruising	Cruising	Cruising	Cruising

2.3.2. Engine power demanded

Ships typically have three types of engines: ME, AE, and BO. The power demanded from these engines varies depending on the phase in which the ship is operating (Table 6). MEs are off at berth and at anchor. AEs and BOs are usually always on. Although some ports offer shoreside electrical power to allow ships to switch off their AEs at berth, this analysis assumes AEs are always on at berth. Given the limited use of shore power at ports around the world, this assumption is not expected to have a significant effect on the results.

Table 6. 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	On

**Boilers are assumed to be off for some ship classes while at berth. See Appendix E for more details.*

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

The ME power demand varies as the ship SOG changes:

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

Where:

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

There are some instances where the ME load factor (LF) is greater than one. In these cases, the SOG is assumed to be inaccurate. In these instances, SOG is replaced with the ship's average speed for that phase and the LF is recalculated. When there is no valid average speed for the phase for a particular ship, the average speed for the ship by phase, class, capacity, and tier is used. The LF is then recalculated with the replaced SOG.

2.3.3. Emission factors

This analysis uses ME EFs from the *Third IMO GHG Study 2014*, with a few exceptions (see Appendix F for a complete description of the EFs used in this study). For instance, the *Third IMO GHG Study 2014* assumed that all LNG MEs were Otto cycle. Today, there are several diesel-cycle LNG MEs, which have different EFs than Otto-cycle LNG MEs. The authors estimate that diesel-cycle LNG MEs are approximately 20% more efficient than Otto-cycle LNG MEs and to have higher NO_X emissions because of higher combustion temperatures; however, diesel-cycle LNG MEs are assumed to have much less CH_4 slip than Otto-cycle LNG MEs, as a result of the more complete LNG combustion with the diesel cycle. There is only one LNG diesel-cycle engine in this analysis and it is in the Geographic Arctic.

Additionally, the *Third IMO GHG Study 2014* did not estimate BC emissions. In this study, BC EFs for slow speed diesel (SSD), medium speed diesel (MSD), and high speed diesel (HSD) engines were adopted from the Netherlands Organization for Applied Scientific Research (TNO) POSEIDON marine emissions inventory and air dispersion model.[9] BC EFs for other engines needed to be estimated. Based on the PM and BC EFs for MSD and HSD engines in the TNO POSEIDON model, BC accounts for approximately 8.4% of PM emissions by mass. Thus, BC emissions from gas turbine (GT), steam turbine (ST), LNG-Otto cycle, and LNG-diesel cycle engines are estimated as about 8.4% of these engines' corresponding PM EFs. These types of engines represent only a small proportion (approximately 1%) of MEs on ships in the Arctic in 2015. Main engine EFs are found in Appendix F.

AE EFs used in this study are presented in Appendix G and BO EFs are presented in Appendix H. The *Third IMO GHG Study 2014* assumes identical emission factors for AEs and BOs. However, BOs are typically ST engines. As such, this study uses the same AE EFs as the *Third IMO GHG Study 2014*, but BO EFs are taken from ST EFs found in *Current methodologies in preparing mobile source port-related emission inventories* (U.S. Environmental Protection Agency [EPA], 2009). In cases where the

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

ME is an ST or GT, neither AEs nor BOs are assumed to be onboard the ships, as steam and gas turbine main engines also provide auxiliary power and heat; however, power demand for auxiliary equipment and heat, and associated emissions, are still estimated according to the AE and BO power demand for that ship. Regarding BC EFs, AE BC EFs are assumed to be the same as the BC emission factors for MSD engines. Boiler BC EFs are assumed to be the same as the derived BC emission factors for ST engines.

Emission factors tend to increase at low loads. Low load adjustment factors from the *Third IMO GHG Study 2014* were applied when estimated ME load fell below 20% for all pollutants except BC, which is not estimated in the IMO study. In this case, the low load adjustment factor for PM is taken as the low load factor for BC. Low load adjustment factors are presented in Appendix I.

2.4 ESTIMATING 2015 FUEL CONSUMPTION

Fuel consumption was estimated on a ship-by-ship basis based on the amount of CO_2 that ship emitted, according to the equation in Section 2.3 and its main fuel type. Different fuels emit different amounts of CO_2 when burned; this is referred to as the *CO_2 intensity* of the fuel and is reported in units of g CO_2/g fuel, as shown in Table 7.

Table 7. Carbon dioxide intensity by fuel type[a]

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

Source: IMO (2014).
[a]*Does not account for emissions of other GHGs, such as CH_4.*

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

$$FC_i = \frac{CO_{2_i}}{CI_f}$$

Where:

i = ship
f = main fuel type of ship i
FC_i = the fuel consumption of ship i in g fuel
CO_{2_i} = total CO_2 emissions for ship i in 2015 in g CO_2
CI_f = CO_2 intensity for fuel f in g CO_2/g fuel

2.5 ESTIMATING 2015 FUEL CARRIAGE

The amount (t) of fuel a ship carries is calculated using its main fuel type capacity (m^3) as found in the IHS ShipData database and the assumed density of the fuel (Table 8). 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 DNV (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 8. Assumed fuel density by fuel type

Fuel type	Density (t/m³)
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).*

2.6 PROJECTING EMISSIONS, FUEL CONSUMPTION, AND FUEL CARRIAGE FROM 2015 TO 2020 AND 2025

Over the past decade, several studies have estimated Arctic vessel activity and emissions increases, including Corbett et al. (2010) and Winther et al. (2014). Winther et al. (2014) estimated shipping activity, fuel consumption, and emissions for 2012, with projections to 2020, 2030, and 2050 based on traffic scaling factors associated with the BAU growth scenarios outlined in Corbett et al. (2010). Winther et al. (2014) accounts for future regulatory actions, such as the energy efficiency design index (EEDI) standards, restrictions on sulfur content in marine fuels, and the expansion of the Baltic/North Sea Sulfur Emission Control Area (SECA) to a full emission control area (ECA).

This study developed BAU growth multipliers without vessel diversions for 2020 and 2025 by ship class based on projected emissions and fuel consumption found in Winther et al. (2014). Winther et al. estimated SO_X, NO_X, and BC emissions and fuel consumption for the years 2012, 2020, 2030, and 2050. For this study, emissions and fuel consumption for 2015, 2020, and 2025 were interpolated between Winther et al.'s scenario using power regression.[10] By doing so, one can derive a series of growth multipliers, which are shown in Table 9.

This study uses the growth multipliers for fuel consumption, SO_X, NO_X, and BC as listed in Table 9. These growth multipliers are applied to 2015 baseline emissions and fuel consumption. Growth factors for pollutants not listed in Table 9 are assumed to be the same as the fuel consumption multiplier, because emissions of these pollutants are directly proportional to fuel consumption. Although fuel consumption for most ship classes is expected to increase, SO_X growth multipliers decrease relative to 2015 (i.e., they are less than 1) because of the implementation of the 0.5% global fuel sulfur cap in 2020. Growth multipliers for NO_X for some ship classes increase relative to 2015 (i.e., they are greater than 1) because of projected growth in activity and associated fuel consumption; however, any growth in NO_X emissions will not keep pace with increases in fuel consumption—meaning the NO_X growth factor is less than the fuel consumption growth factor—as a result of increasingly stringent NO_X regulations.

Regarding growth in residual fuel consumption, given the upcoming implementation of the 0.5% global fuel sulfur cap in 2020, this study assumes that 12% of residual fuel consumption in 2020 will be residual fuel with a greater than 0.5% sulfur content,

10 For example, according to Winther et al., oil tankers emitted 25 t BC, 46 t in 2020, and 53 t in 2050. Power regression analysis where y = BC and x = year yields a line of best fit as: *y = 0.0008x3 - 0.0586x2 + 1.7918x + 35*. Therefore, emissions of BC in 2015, 2020, and 2025 are estimated as 40, 46, and 50 t, respectively. This results in a 2020 BC growth multiplier for oil tankers of 1.15 relative to 2015 (46/40 = 1.15). The 2025 growth multiplier is 1.25 (50/40 = 1.25). Thus, BC emissions from oil tankers are expected to be 15% and 25% higher than 2015 BC emissions in 2020 and 2025, respectively.

which assumes some ships will continue to operate on high-sulfur HFO but install scrubbers to comply with the regulations, and that 88% of residual fuel consumption will be residual fuel that is less than 0.5% sulfur. This could be desulfurized residual fuel or a blended fuel that is partly high-sulfur HFO and partly lower-sulfur distillate fuel. This assumption is based on the IMO's *Assessment of Fuel Oil Availability—Final Report* undertaken by CE Delft (2016), as presented at MEPC 70 in October 2016.[11] This study assumes that the share of HFO and less than 0.5% sulfur fuel in 2025 will be the same as in 2020.

Table 9. Growth multipliers (BAU) with 2015 as the baseline year

Ship class	Winther et al. category	Fuel consumption		Fuel carriage		SO_X		NO_X		BC	
		2020	2025	2020	2025	2020	2025	2020	2025	2020	2025
Bulk carrier **Refrigerated bulk**	Bulk carrier	1.026	1.048	1.019	1.04	0.321	0.166	0.967	0.907	1.020	1.041
Chemical tanker **Other liquid tankers**	Chem/prod	1.156	1.265	1.002	1.001	0.362	0.233	1.071	1.042	1.155	1.264
Container	Container	1.116	1.255	1.005	1.008	0.314	0.185	1.020	1.009	1.114	1.257
Cruise	Passenger	1.003	1.005	1.001	1.003	0.349	0.195	0.967	0.875	1.007	1.010
Ro-ro	Ro-ro	0.998	0.997	1.001	1.003	0.267	0.093	0.951	0.823	0.996	0.995
Oil tanker	Oil tanker	1.150	1.243	1.002	1.001	0.315	0.168	1.069	1.007	1.154	1.258
General cargo	General cargo	0.978	0.966	1.001	1.002	0.275	0.101	0.909	0.800	0.977	0.965
Liquefied gas tanker	Gas carrier	1.153	1.256	1.002	1.001	0.388	0.264	1.086	1.080	1.167	1.291
Fishing vessel	Fishing	0.982	0.953	1.004	1.008	0.917	0.886	0.969	0.908	0.972	0.954
Ferry-pax only **Ferry-ro-pax**	Fast ferry	1.000	1.000	1.001	1.003	0.591	0.492	0.902	0.796	1.000	1.000
Service other **Service tug offshore**	Support vessel	1.068	1.109	1.001	1.001	0.610	0.531	1.035	0.732	1.071	1.114
Other **Vehicle** **Yacht**	Other	0.968	0.931	1.004	1.008	0.565	0.444	0.924	0.829	0.963	0.925

Given the economic advantage of using either the NWP or NSR over conventional routes, it is likely that some ship traffic will be diverted from conventional routes to Arctic routes. Taking the approach used by Corbett et al. (2010), as applied in Winther et al. (2014), diversion factors estimating the amount of traffic diverted from the Panama and Suez canals through the Arctic are assumed to be 1% in 2020, 3% in 2030, and 5% in 2050. Winther et al. (2014) estimated CO_2, BC, NO_X, and SO_X emissions in 2020, 2030, and 2050 based on these diversion assumptions. This study calculated *diversion multipliers* that grow 2020 and 2025 BAU fuel consumption and emissions, accounting for potential diversion of traffic from the Suez and Panama Canals through the Arctic. Winther et al. does not break down these future emissions by ship class. As such, this study applies diversion multipliers to the total estimated emissions of CO_2, BC, NO_X, and SO_X. Further assumptions include: (1) fuel consumption with diversion grows at the same rate as CO_2 emissions; (2) fuel carriage with diversion grows at the same rate as fuel consumption; (3) all future diversions are powered by residual fuel, with 12% assumed to be HFO and 88% assumed to be less than 0.5% sulfur residual;

11 Total residual fuel demand for regions with Arctic territory (Europe, North America, and Russia), as estimated in Faber et al. (2016), is 99 million tonnes (Mt), of which 87 Mt (~88%) is <0.5% S residual fuel and the rest (~12%) is >0.5% S residual fuel (e.g., HFO).

and (4) ships that would be diverted would be larger cargo vessels, the majority of which would operate on residual fuel. Based on these assumptions, diversion multiplier factors were calculated. The method for calculating 2020 and 2025 multipliers for each pollutant was as follows:

- 2020 diversion multiplier:
  - Divide 2020 emissions with diversion by 2020 emissions without diversion, as found in Winther et al. (2014)
  - Use this value as the 2020 diversion multiplier
- 2025 diversion multiplier
  - First, divide 2030 emissions with diversion by 2030 emissions without diversion, as found in Winther et al. (2014)
  - Then take the mean of the 2030 diversion multiplier and the 2020 diversion multiplier and use this as the 2025 diversion multiplier

The diversion multipliers used in this study are listed in Table 10. These diversion multipliers are applied to the total emissions, residual fuel consumption, and residual fuel carriage in the BAU 2020 and 2025 emissions scenarios as follows:

*2020 emissions with diversion = 2020 BAU emissions*2020 diversion multiplier*

*2025 emissions with diversion = 2025 BAU emissions*2025 diversion multiplier*

The same procedure is followed to estimate growth in residual fuel consumption and carriage in 2020 and 2025, assuming that all diverted ships would operate on and therefore carry residual fuel consisting of 12% HFO and 88% less than 0.5% sulfur.

Table 10. Diversion multipliers for residual fuel consumption and carriage by pollutant in 2020 and 2025

Fuel or pollutant	2020	2025
Residual fuel consumption (HFO or <0.5% S)	1.36	1.37
Residual fuel carriage (HFO or <0.5% S)	1.36	1.37
CO_2	1.36	1.37
BC	1.36	1.38
NO_x	1.37	1.44
SO_x	1.63	1.68

3. RESULTS

This section presents fuel consumption, fuel carriage, and emissions for ships operating in three Arctic areas—the Geographic Arctic, the IMO Arctic, and the U.S. Arctic—in 2015. Results are summarized by ship class and flag state. Total fuel consumption, fuel carriage, and emissions of CO_2, NO_X, SO_X, and BC are also projected from 2015 to 2020 and 2025, with and without diversion of ships from the Panama and Suez Canals through the Arctic.

3.1 FLEET CHARACTERISTICS

All three Arctic areas contain many fishing vessels and ships that transport cargo; however, there are some differences. As shown in Table 11, the Geographic Arctic has more general cargo vessels than the IMO Arctic and it has a larger proportion of ferries than the IMO Arctic and U.S. Arctic regions. The IMO Arctic is dominated by fishing vessels (36%), followed by general cargo vessels, service vessels, and bulk carriers. Tugs, fishing vessels, bulk carriers, and service vessels are plentiful in the U.S. Arctic, with all of the bulk carriers servicing Alaska's Red Dog zinc and lead mine.

Table 11. Number of ships by ship class in the Arctic,[a] 2015

Ship class	Geographic Arctic		IMO Arctic		U.S. Arctic	
	Number of ships	Percent of fleet	Number of ships	Percent of fleet	Number of ships	Percent of fleet
Fishing vessel	1903	18.8%	755	36.2%	42	23.3%
General cargo	2035	20.2%	243	11.6%	5	2.8%
Service vessel	618	6.1%	198	9.5%	21	11.7%
Bulk carrier	1287	12.7%	181	8.7%	28	15.6%
Tug boats	501	5.0%	138	6.6%	50	27.8%
Chemical tanker	874	8.7%	109	5.2%	5	2.8%
Oil tanker	691	6.8%	94	4.5%	7	3.9%
Refrigerated bulk	213	2.1%	90	4.3%	—	—
Offshore	520	5.1%	64	3.1%	7	3.9%
Cruise	154	1.5%	63	3.0%	6	3.3%
Container	292	2.9%	43	2.1%	2	1.1%
Ferry-ro-pax	387	3.8%	37	1.8%	—	—
Ferry-pax only	192	1.9%	21	1.0%	1	0.6%
Ro-ro	119	1.2%	20	1.0%	4	2.2%
Yacht	76	0.8%	13	0.6%	—	—
Vehicle	51	0.5%	11	0.5%	2	1.1%
Liquefied gas tanker	172	1.7%	4	0.2%	—	—
Other	4	0.0%	1	0.0%	—	—
Non propelled	7	0.1%	1	0.0%	—	—
Other liquid tankers	3	0.0%	—	—	—	—
Total	**10,099**	**100%**	**2,086**	**100%**	**180**	**100%**

[a]Sorted largest to smallest percent share for the IMO Arctic.

In addition to the raw number of ships operating in these areas, there are differences in the total number of operating hours, distance traveled, and fuel consumed in each region. Table 12, Table 13, and Table 14 present the total number of operating hours, distance traveled, and fuel consumed by ship class for each region. In the Geographic Arctic and the IMO Arctic, fishing vessels are by far the most active ship class in terms of both operating hours and distance traveled. Fishing vessels in the Geographic Arctic account for nearly one third of all operating hours and distance traveled, followed by general cargo vessels, with 14% of all operating hours and 19% of distance traveled. However, in terms of fuel consumption, roll-on/roll-off passenger ferries (ferry-ro-pax) represent the largest amount of fuel consumed, accounting for almost 17% of fuel consumed within the Geographic Arctic, with fishing vessels in the same area accounting for 12% of total fuel consumed.

In the IMO Arctic, fishing vessels account for more than half the total operating hours (53%) and distance traveled (54%) in 2015, with service vessels a distant second at about 12% operating hours and 11% distance traveled. In terms of fuel consumption, fishing vessels again lead, but with 26% of total fuel consumed, followed by general cargo ships at 17%. In the U.S. Arctic, operating hours and distance traveled are dominated by tugboats, which account for about 50% of all operating hours and 42% of distance traveled. However, tugboats account for only 13% of total fuel consumed in the U.S. Arctic, with service vessels—anchor handling tug supply vessels, buoy tenders, icebreakers, and research vessels—accounting for 33% of total fuel consumed.

Table 12. Totals operating hours by ship class in the Arctic,[a] 2015

	Geographic Arctic		IMO Arctic		U.S. Arctic	
Ship class	Total operating hours	Percent of all operating hours	Total operating hours	Percent of all operating hours	Total operating hours	Percent of all operating hours
Fishing vessel	7,188,800	32.3%	1,379,000	53.4%	8,400	6.5%
Service vessel	1,929,300	8.7%	303,500	11.8%	21,500	16.6%
General cargo	3,099,800	13.9%	249,600	9.7%	600	0.5%
Tug boats	1,749,100	7.9%	167,200	6.5%	63,300	49.0%
Refrigerated bulk	303,600	1.4%	78,700	3.1%	—	—
Oil tanker	642,900	2.9%	71,100	2.8%	6,200	4.8%
Chemical tanker	799,800	3.6%	71,000	2.8%	4,700	3.6%
Cruise	227,200	1.0%	65,700	2.5%	1,100	0.9%
Bulk carrier	618,900	2.8%	63,600	2.5%	5,400	4.2%
Ferry-pax only	1,068,100	4.8%	43,400	1.7%	0	0.0%
Offshore	1,569,100	7.1%	42,700	1.7%	13,200	10.2%
Container	339,800	1.5%	22,500	0.9%	0	0.0%
Ro-ro	270,600	1.2%	11,200	0.4%	4,500	3.5%
Yacht	48,100	0.2%	8,000	0.3%	300	0.0%
Other	9,700	0.0%	2,700	0.1%	—	—
Ferry-ro-pax	2,207,400	9.9%	2,500	0.1%	—	—
Liquefied gas tanker	134,300	0.6%	0	0.0%	—	—
Vehicle	27,000	0.1%	0	0.0%	—	—
Other liquid tankers	15,900	0.1%	—	—	—	—
Total[b]	**22,262,500**	**100%**	**2,582,400**	**100%**	**129,200**	**100%**

[a]Sorted largest to smallest percent share for the IMO Arctic. [b]May not sum because of rounding.

Table 13. Total distance traveled by ship class in the Arctic,[a] 2015

Ship class	Geographic Arctic		IMO Arctic		U.S. Arctic	
	Distance traveled (nm)	Percent of all distance traveled	Distance traveled (nm)	Percent of all distance traveled	Distance traveled (nm)	Percent of all distance traveled
Fishing vessel	19,518,000	28.2%	5,623,700	54.5%	37,700	9.6%
Service vessel	3,212,700	4.6%	1,117,000	10.8%	81,800	20.8%
General cargo	13,191,800	19.0%	1,043,400	10.1%	5,300	1.4%
Tug boats	1,965,400	2.8%	399,400	3.9%	163,600	41.6%
Cruise	1,356,800	2.0%	382,400	3.7%	8,600	2.2%
Oil tanker	2,333,900	3.4%	328,200	3.2%	7,300	1.9%
Chemical tanker	3,881,000	5.6%	316,400	3.1%	13,000	3.3%
Bulk carrier	2,909,300	4.2%	255,900	2.5%	18,400	4.7%
Refrigerated bulk	1,359,700	2.0%	251,100	2.4%	—	—
Ferry-pax only	3,502,200	5.1%	185,900	1.8%	0	0.0%
Container	2,348,900	3.4%	180,300	1.8%	300	0.1%
Offshore	2,576,600	3.7%	127,200	1.2%	35,900	9.1%
Ro-ro	1,558,500	2.3%	39,200	0.4%	19,500	5.0%
Ferry-ro-pax	8,729,900	12.6%	38,200	0.4%	—	—
Yacht	102,200	0.2%	29,100	0.3%	2,400	0.6%
Other	11,600	0.0%	4,500	0.0%	—	—
Vehicle	212,400	0.3%	400	0.0%	—	—
Liquefied gas tanker	553,600	0.8%	300	0.0%	—	—
Other liquid tankers	8,200	0.0%	—	—	—	—
Total[b]	**69,336,600**	**100%**	**10,322,500**	**100%**	**393,700**	**100%**

[a]Sorted largest to smallest percent share for the IMO Arctic. [b]May not sum because of rounding.

Table 14. Total fuel consumed by ship class in the Arctic,[a] 2015

Ship Class	Geographic Arctic		IMO Arctic		U.S. Arctic	
	Fuel consumed (t)	% fuel consumed	Fuel consumed (t)	% fuel consumed	Fuel consumed (t)	% all fuel consumed
Fishing vessel	543,400	12.4%	113,900	26.1%	600	2.8%
General cargo	464,900	10.6%	72,600	16.6%	100	0.6%
Service vessels	220,800	5.0%	56,900	13.0%	7,100	33.1%
Oil tanker	409,900	9.3%	45,000	10.3%	2,300	10.8%
Cruise	416,900	9.5%	34,800	8.0%	900	4.4%
Refrigerated bulk	128,900	2.9%	29,000	6.6%	—	—
Bulk carrier	257,900	5.9%	23,900	5.5%	2,100	9.8%
Chemical tanker	294,400	6.7%	19,100	4.4%	1,500	7.1%
Container	210,000	4.8%	12,700	2.9%	0	0.0%
Tug boats	61,100	1.4%	10,500	2.4%	2,700	12.9%
Offshore	237,300	5.4%	7,100	1.6%	2,800	12.9%
Ferry-pax only	79,800	1.8%	5,000	1.1%	—	—
Ro-ro	209,700	4.8%	3,400	0.8%	1,200	5.4%
Ferry-ro-pax	735,000	16.7%	1,500	0.3%	0	0.0%
Yacht	2,600	0.1%	700	0.2%	100	0.3%
Other	500	0.0%	100	0.0%	—	—
Vehicle	17,400	0.4%	0	0.0%	—	—
Liquefied gas tanker	92,500	2.1%	0	0.0%	—	—
Other liquid tankers	6,000	0.1%	—	0.0%	—	—
Total[b]	**4,389,000**	**100%**	**436,400**	**100%**	**21,400**	**100%**

[a]Sorted largest to smallest percent share for the IMO Arctic. [b]May not sum because of rounding.

3.2 HFO USE

Heavy fuel oil is the most consumed marine fuel in the Arctic, as shown in Table 15. In the Geographic Arctic, almost 60% of the fuel consumed is estimated to be HFO, followed by distillate (38%), and LNG (4%). Ro-pax ferries consume the most HFO in this area (427,000 t), followed by oil tankers (386,000 t) and cruise ships (361,000 t). In the IMO Arctic, HFO represents 57% of fuel consumed, followed by distillate (43%), but almost no LNG (0.1%) is consumed. General cargo vessels consume the most HFO in this area (66,000 t), followed by oil tankers (43,000 t), and cruise ships (25,000 t). Excluding large portions of the Geographic Arctic from the IMO definition of the Arctic results in a 90% decrease in so-called Arctic HFO fuel consumption.

In the U.S. Arctic, 53% of fuel consumed is HFO, followed by distillate (47%), with no LNG consumption. Service vessels consume the most HFO in this area (4,000 t, of which 3,800 t is ice breaker fuel), followed by oil tankers (2,300 t), and bulk carriers (2,100 t). See Appendix J, Appendix K, and Appendix L for a full break down of fuel use by ship class for all fuels.

Table 15. Heavy fuel oil use in the Arctic,[a] 2015

Ship Class	Geographic Arctic		IMO Arctic		US Arctic	
	Fuel consumed (t)	% of all fuel consumed	Fuel consumed (t)	% of all fuel consumed	Fuel consumed (t)	% of all fuel consumed
HFO	**2,568,000**	**59%**	**249,800**	**57%**	**11,300**	**53%**
General cargo	242,300	5.5%	66,000	15.1%	20	0.1%
Oil tanker	385,700	8.8%	43,100	9.9%	2,300	10.7%
Cruise	360,600	8.2%	24,500	5.6%	800	3.6%
Bulk carrier	248,100	5.7%	23,500	5.4%	2,100	9.8%
Fishing vessel	68,000	1.5%	23,400	5.4%	20	0.1%
Refrigerated bulk	81,600	1.9%	17,600	4.0%	—	—
Chemical tanker	269,400	6.1%	17,200	3.9%	1,500	7.1%
Service-other	40,100	0.9%	15,400	3.5%	4,000	18.5%
Container	207,300	4.7%	12,700	2.9%	10	0.0%
Ferry-ro-pax	426,900	9.7%	1,500	0.3%	—	—
Roro	161,200	3.7%	1,500	0.3%	—	—
Ferry-pax only	2,700	0.1%	1,400	0.3%	—	—
Service-tug	7,100	0.2%	1,200	0.3%	300	1.4%
Offshore	15,300	0.4%	700	0.2%	300	1.4%
Other	200	0.0%	100	0.0%	—	—
Vehicle	12,000	0.3%	30	0.0%	—	—
Liquefied gas tanker	39,400	0.9%	0	0.0%	—	—
Yacht	100	0.0%	—	—	—	—
Distillate	**1,655,200**	**38%**	**186,300**	**43%**	**10,100**	**47%**
LNG	**149,700**	**3%**	**400**	**0.1%**	**—**	**—**
Total[b]	**4,372,900**	**100%**	**436,400**	**100%**	**21,400**	**100%**

[a]Sorted largest to smallest percent share for the IMO Arctic. [b]May not sum because of rounding.

The distribution of HFO use above 58.95°N (Geographic Arctic) is shown in Figure 3. The blue outline represents the IMO Arctic boundary. As illustrated in the figure, the most intense HFO use falls outside the IMO Arctic, primarily near northern Europe.

Figure 3 overlays 2015 HFO use with the minimum sea ice extent in 1979 (light blue area) and in 2015 (black line). Note the 2015 HFO use associated with activity along the northern coast of Russia (part of the Northern Sea Route) and Canada (the Northwest Passage) that would have been ice-locked in 1979.

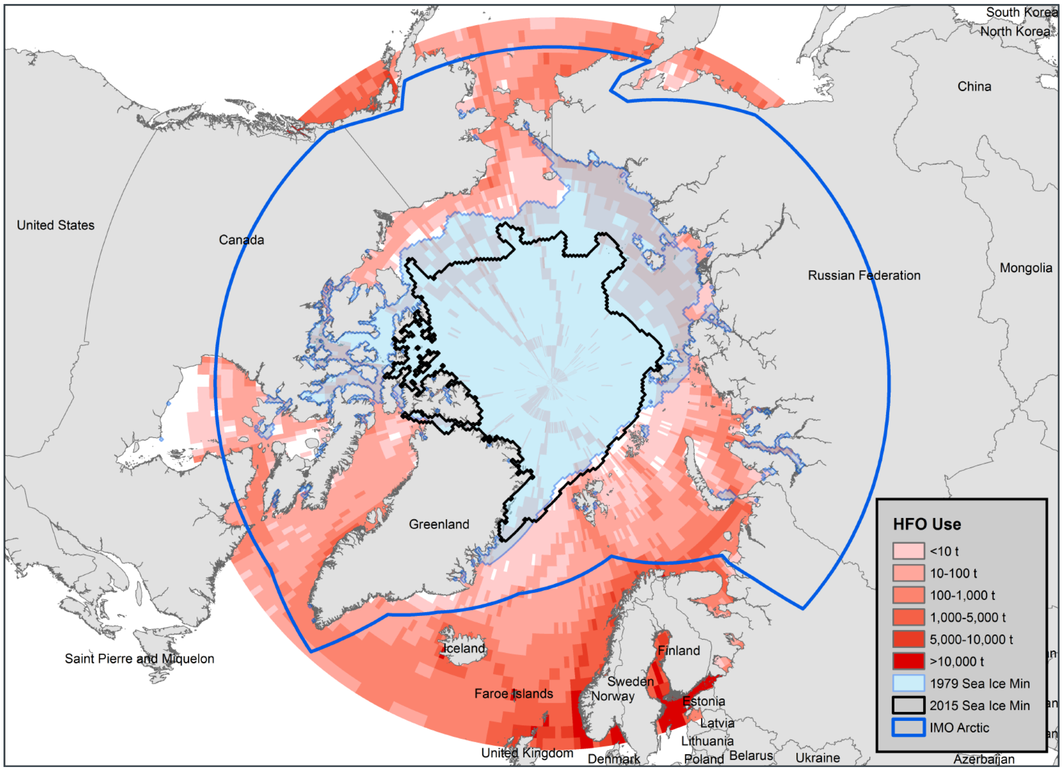

Figure 3. Heavy fuel oil use in the Arctic, 2015, with minimum sea extents displayed

3.3 HFO CARRIAGE AND TRANSPORT

In all regions, HFO dominated the total mass of bunker fuel onboard vessels in the Arctic in 2015 (Table 16). In the Geographic Arctic, 85% of the fuel onboard was HFO, followed by distillate (15%), with less than 1% of fuel carried as LNG or nuclear fuel. Bulk carriers carried the most HFO in this area (1,734,000 t), followed by oil tankers (1,120,000 t), and chemical tankers (494,000 t). In the IMO Arctic, HFO represents more than 76% of fuel onboard, followed by distillate (23%), with the remaining 1% of fuel carried as LNG or nuclear fuel. Bulk carriers carried the most HFO in this area (248,000 t), followed by container ships (113,000 t), and oil tankers (111,000 t). Likewise, in the U.S. Arctic nearly 75% of fuel carried was HFO, followed by distillate (25%), with no LNG or nuclear fuel carried. Bulk carriers carried the most HFO in this area (42,000 t), followed by oil tankers (7,700 t) and fishing vessels (5,200 t). See Appendix M for a full breakdown of fuel carried by ship class for all fuels.

The geospatial distribution of HFO carriage in the Arctic is assumed to be similar to the distribution of HFO use, as presented in Figure 3.

Table 16. Heavy fuel oil carriage and transport as bunker fuel in the Arctic,[a] 2015

Ship Class	Geographic Arctic				IMO Arctic				US Arctic			
	Fuel onboard (t)	% of total fuel onboard	Fuel transported (10^6 t-nm)	% of fuel transported	Fuel onboard (t)	% of total fuel onboard	Fuel transported (10^6 t-nm)	% of fuel transported	Fuel onboard (t)	% of total fuel onboard	Fuel transported (10^6 t-nm)	% of fuel transported
HFO	**4,935,500**	**85%**	**18,180**	**69%**	**827,300**	**76%**	**2,070**	**56%**	**71,300**	**75%**	**76**	**54%**
Bulk carrier	1,733,900	29.7%	3,390	12.8%	247,500	22.8%	280	7.5%	41,900	43.8%	28	19.6%
Container	415,700	7.1%	1,590	6.0%	112,800	10.4%	100	2.7%	2,000	2.1%	0	0.1%
Oil tanker	1,120,200	19.2%	1,950	7.4%	110,700	10.2%	100	2.6%	7,700	8.1%	11	8.0%
General cargo	411,100	7.0%	1,090	4.1%	77,200	7.1%	110	3.1%	700	0.7%	0	0.1%
Fishing vessel	107,900	1.8%	10	0.0%	67,600	6.2%	10	0.2%	5,200	5.5%	0	0.3%
Chemical tanker	493,800	8.5%	2,390	9.0%	51,800	4.8%	0	0.1%	3,700	3.9%	8	5.7%
Refrigerated bulk	130,700	2.2%	1,690	6.4%	49,700	4.6%	300	8.1%	0	0.0%	0	0.0%
Cruise	132,300	2.3%	230	0.9%	40,600	3.7%	550	14.8%	900	0.9%	2	1.1%
Service vessel	79,300	1.4%	800	3.0%	30,000	2.8%	0	0.0%	5,400	5.6%	18	12.7%
Vehicle	57,200	1.0%	1	0.0%	19,100	1.8%	0	0.0%	0	0.0%	0	0.0%
Tug	64,900	1.1%	80	0.3%	6,500	0.6%	0	0.1%	0	0.0%	0	0.0%
Ro-ro	17,100	0.3%	3,210	12.1%	5,800	0.5%	320	8.7%	3,300	3.5%	7	4.8%
Offshore	50,900	0.9%	440	1.7%	3,100	0.3%	120	3.2%	0	0.0%	0	0.0%
Ferry-ro-pax	25,800	0.4%	790	3.0%	2,200	0.2%	10	0.1%	300	0.3%	2	1.5%
Liquefied gas tankers	93,500	1.6%	360	1.3%	2,100	0.2%	160	4.4%	—	0.0%	—	—
Passenger ferry	900	0.0%	60	0.2%	500	0.0%	20	0.6%	—	0.0%	—	—
Other	200	0.0%	100	0.4%	200	0.0%	1	0.0%	—	—	—	—
Yacht	200	0.0%	1	0.0%	—	—	—	—	—	—	—	—
Distillate	**859,700**	**15%**	**7,650**	**29%**	**251,500**	**23%**	**1,490**	**41%**	**24,500**	**25%**	**65**	**46%**
LNG	**39,400**	**0.7%**	**530**	**2%**	**3,800**	**0.4%**	**3**	**0.1%**	**—**	**—**	**—**	**—**
Nuclear*	**4,800**	**0.1%**	**120**	**0.5%**	**2,800**	**0.3%**	**120**	**3%**	**—**	**—**	**—**	**—**
Total[b]	**5,839,400**	**100%**	**26,490**	**100%**	**1,085,400**	**100%**	**3,680**	**100%**	**95,700**	**100%**	**141**	**100%**

**Assumes nuclear fuel has a density of 1 t/m³ for ease of comparison with other fuel types. [a]Sorted largest to smallest percent share for the IMO Arctic. [b]May not sum because of rounding.*

Although only about half of the ships in the Geographic Arctic and IMO Arctic and one third of the ships in the U.S. Arctic operated on HFO in 2015, HFO represented the vast majority of fuel carried onboard vessels in each region, as shown in Figure 4. Note that LNG is not depicted in the figure because it represents less than 1% of the mass of fuel onboard ships in the Arctic. In the Geographic Arctic, 48% of ships operated on HFO, but 84% of the mass of fuel onboard those ships was HFO. Within the IMO Arctic, 42% of ships operated on HFO, but this accounted for 76% of the mass of fuel onboard those vessels. In the U.S. Arctic, 34% of vessels operated on HFO, accounting for 75% of the mass of fuel onboard those vessels.

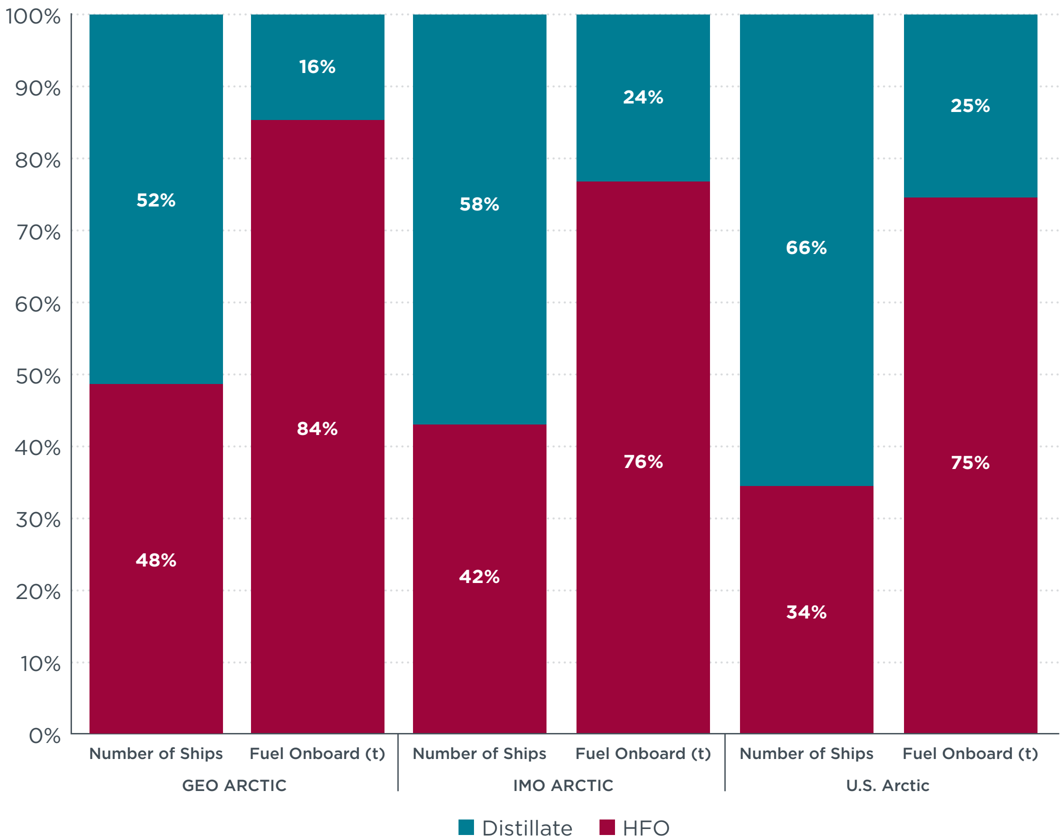

Figure 4. Number of ships and total fuel carriage type for the Geographic Arctic, IMO Arctic, and U.S. Arctic regions

3.4 BLACK CARBON EMISSIONS

Heavy fuel oil use accounts for roughly two thirds of BC emissions in the Arctic as shown in Table 17. Total BC emissions from shipping in 2015 were estimated to be about 1,453 t in the Geographic Arctic, about 193 t in the IMO Arctic, and less than 5% of that was in the U.S. Arctic (9 t). The relative share of BC emissions in the Arctic regions is presented in Figure 5. In the Geographic Arctic, the top three emitters of BC were Ferry-ro-pax vessels (209 t, 14%), fishing vessels (191 t, 13%), and general cargo vessels (167 t, 12%). In the IMO Arctic, the top three emitters of BC were fishing vessels (47 t, 25%), general cargo vessels (36 t, 19%), and service vessels (24 t, 12%). In the U.S. Arctic, the top three emitters of BC were service vessels (3.3 t, 37%), tugs (1.1 t, 13%), and oil tankers (1 t, 11%). See Appendix N for a full breakdown of BC emissions by ship class for all fuels.

Table 17. Black carbon emissions in the Arctic, 2015

Ship Class	Geographic Arctic		IMO Arctic		U.S. Arctic	
	BC (t)	% of total BC	BC (t)	% of total BC	BC (t)	% of total BC
HFO	**966**	**66%**	**131**	**68%**	**6**	**64%**
General cargo	104	7.2%	34	17.7%	0.1	0.1%
Oil tanker	135	9.3%	22	11.6%	1	11.2%
Fishing vessel	42	2.9%	16	8.0%	0.1	0.1%
Cruise	143	9.9%	13	6.9%	0.4	4.6%
Bulk carrier	97	6.7%	10	5.3%	1	10.0%
Service vessel	21	1.4%	9	4.8%	2	26.0%
Refrigerated bulk	34	2.3%	8	4.2%	—	—
Chemical tanker	95	6.5%	8	4.1%	1	7.2%
Container	75	5.2%	7	3.4%	0.1	0.1%
Ferry-ro-pax	142	9.8%	1	0.4%	—	—
Tug	3	0.2%	1	0.4%	0.2	2.6%
Passenger ferry	1	0.1%	1	0.4%	—	—
Ro-ro	53	3.7%	1	0.4%	—	—
Offshore	6	0.4%	0.4	0.2%	0.2	1.9%
Other	0	0.0%	0.1	0.0%	—	—
Vehicle	4	0.3%	—	0.0%	—	—
Liquefied gas tankers	11	0.8%	—	0.0%	—	—
Yacht	0	0.0%	—	—	—	—
Distillate	**485**	**33%**	**62**	**32%**	**3**	**36%**
LNG	**2**	**0%**	**<<1**	**0%**	**—**	**—**
Nuclear	**—**	**—**	**—**	**—**	**—**	**—**
Total	**1,453**	**100%**	**193**	**100%**	**9**	**100%**

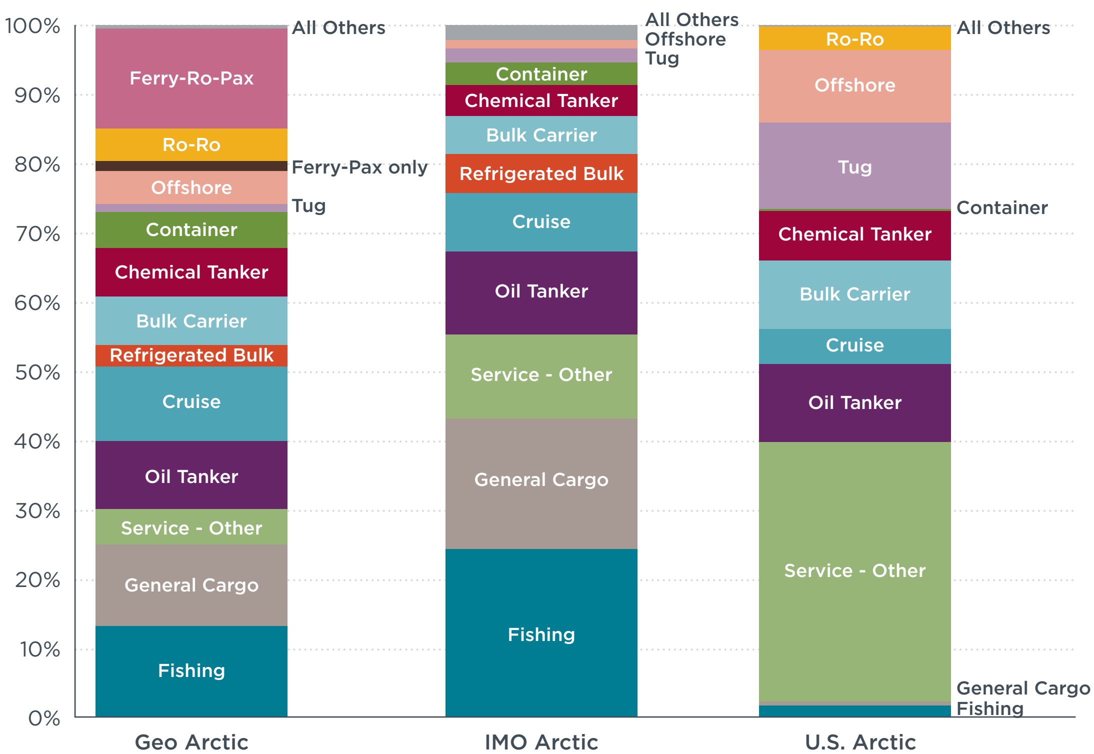

Figure 5. Share of total black carbon emissions by ship class in the U.S. Arctic, 2015

The geographic distribution of BC emissions in the Arctic is shown in Figure 6. Note that the figure shows where BC was emitted from ships and does not account for atmospheric transport of these emissions. The blue outline represents the IMO Arctic boundary. Although BC emissions are more intense near Arctic landmasses, especially near northern Europe, BC emissions extend all the way to the North Pole, primarily from icebreaker and research activities. Although there are substantial BC emissions within the IMO Arctic, especially above northwest Russia, the east coast of Russia, and the west coast of Greenland, one can see that much of the most intense BC emissions fall outside the IMO Arctic. Black carbon emissions are especially severe around Norway, Sweden, Finland, the Faroe Islands, the northern United Kingdom, Iceland, and northwest North America. In fact, the IMO Arctic contained only about 13% of BC within the Geographic Arctic in 2015.[12]

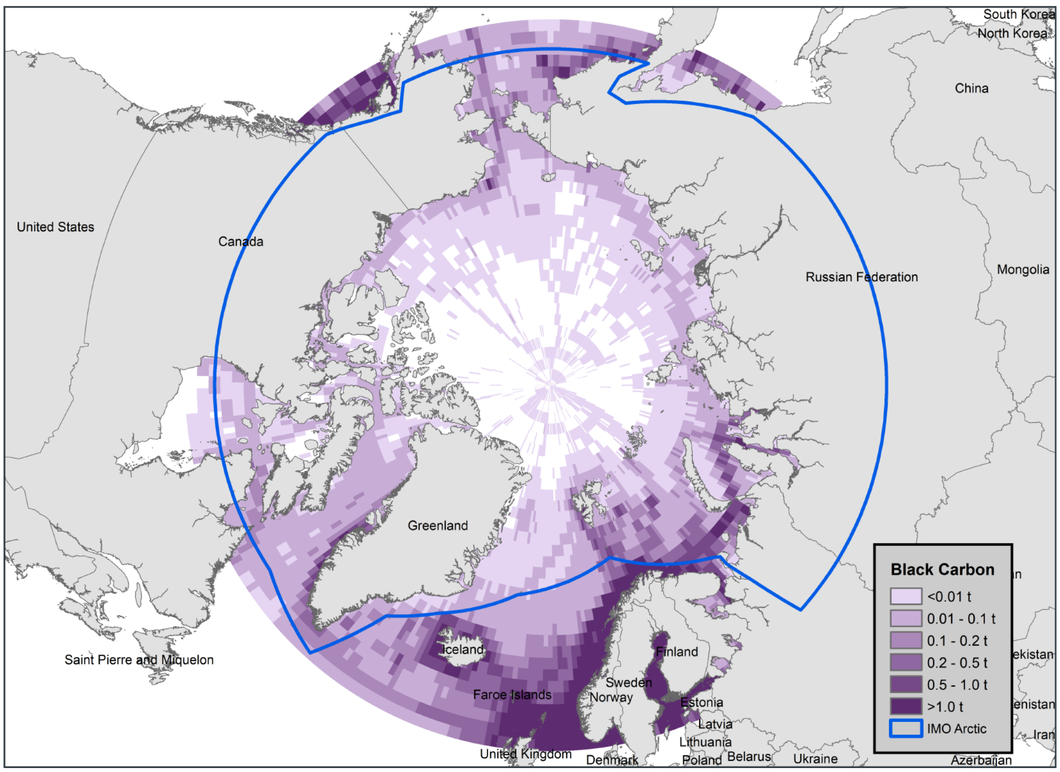

Figure 6. Black carbon emissions in the Arctic, 2015

Note: White cells above 58.95°N indicate zero emissions or no data.

3.5 FUEL USE, FUEL CARRIAGE, AND EMISSIONS BY FLAG STATE

3.5.1. Geographic Arctic

Five flag states dominate shipping activity in the Geographic Arctic: Norway, Russia, Finland, Panama, and the Marshall Islands (see Table 18). Norway leads in terms of overall fuel consumption including distillate, HFO, and LNG but excluding nuclear fuel, accounting for 18%; Russia follows Norway, accounting for 11% of overall fuel consumption. However, the vast majority of Norwegian vessels operate on distillate and LNG fuels, so Russia accounts for the largest share of HFO consumption (12%),

12 Per Table 17, BC emissions in the IMO Arctic were 193 t, compared to 1,453 t in the Geographic Arctic.

followed by Finland (9%). On the other hand, among the highest HFO-consuming flag states operating in the Arctic region, Malta has the highest percentage of its fleet operating on HFO (80%), followed by Bahamas (70%) and Finland (67%). This indicates that almost three-quarters of the fleet registered under Malta and Bahamas operate on HFO. Norway and Russia also account for the most BC emissions, representing 15% and 14%, respectively.

Onboard carriage of all fuels, including HFO, is dominated mostly by non-Arctic flag states; larger vessels with fewer operating hours but a larger fuel capacity tend to be flagged outside of Arctic countries. In this case, Panama and the Marshall Islands hold the largest share in terms of fuel carriage. No Arctic state cracks the top five for total fuel carriage. Additionally, 99% of Liberian registered ships operate on HFO, closely followed by Panama (98%), Marshall Islands (97%) and Malta (95%). This is because it is generally the large ocean going vessels that are registered under these flags. Together they represent 37% of total onboard carriage of all fuels, and 44% of total HFO carriage. Norway and Russia account for the most operating hours and distance traveled in this region, with Norway accounting for 32% of operating hours and 28% of distance traveled, and Russia accounting for 16% of operating hours and 14% of distance traveled.

Table 18. Fuel consumption, emissions, and activity in the Geographic Arctic by Top Five flag states

Fuel consumption (t)	**Norway**	**Russia**	**Finland**	**Bahamas**	**Malta**
	786,000	489,600	326,500	260,000	187,800
	18%	11%	7%	6%	4%
HFO consumption (t)	**Russia**	**Finland**	**Bahamas**	**Malta**	**Netherlands**
	309,300	219,400	187,600	151,500	124,900
	12%	9%	7%	6%	5%
Black carbon emissions (t)	**Norway**	**Russia**	**Finland**	**Bahamas**	**Netherlands**
	225	205	92	81	62
	15%	14%	6%	6%	4%
Onboard carriage (t)	**Panama**	**Marshall Islands**	**Liberia**	**Malta**	**Russia**
	612,700	604,000	572,300	420,500	390,000
	10%	10%	10%	7%	7%
Onboard carriage — HFO only (t)	**Panama**	**Marshall Islands**	**Liberia**	**Malta**	**Bahamas**
	603,000	587,400	567,700	402,800	308,800
	12%	12%	12%	8%	6%
Operating hours	**Norway**	**Russia**	**Iceland**	**Finland**	**Sweden**
	7,023,000	3,642,500	1,456,400	992,300	772,000
	32%	16%	7%	4%	3%
Distance traveled (nm)	**Norway**	**Russia**	**Iceland**	**Finland**	**Netherlands**
	19,692,600	9,800,300	3,261,000	2,972,000	2,767100
	28%	14%	5%	4%	4%

3.5.2. IMO Arctic

Russian flagged vessels dominated ship activity, fuel consumption, HFO consumption, HFO carriage, and BC emissions in the IMO Arctic, as shown in Table 19. Russian vessels accounted for about half of all fuel consumed, HFO consumed, BC emitted (Figure 7), operating hours, and distance traveled. Norway represents the second most prevalent flag state in terms of total fuel consumption (6%), operating hours (11%), and distance traveled (12%), whereas Canada is the second most dominant flag state for HFO consumption (6%) and BC emissions (6%). Onboard fuel carriage in the IMO Arctic is mainly from ships registered to prominent IMO flag states; however, Russian flagged vessels account for the most carriage of all fuels (24%) and HFO (20%) within the IMO Arctic. Panama follows in second place, representing 11% of non-nuclear fuel carriage and 15% of HFO carriage in the same region. Danish (DIS[13]) flagged vessels have the highest HFO fuel consumption as a proportion of total fuel consumption (85%), followed by Russia (67%) and Canada (59%). It must also be noted that for flag states like Panama and the Marshall Islands, more than 90% of the fuel carried onboard is HFO. In fact, for Liberia almost 100% of the fuel onboard is HFO. Therefore, although such flag states have fewer BC emissions in the Arctic, the potential for a serious HFO spill looms large for these flag states' fleets.

Table 19. Fuel consumption, emissions, and activity in the IMO Arctic by Top Five flag states

Fuel consumption (t)	**Russia**	**Norway**	**Canada**	**Denmark**	**Denmark (DIS)**
	210,000	27,700	24,600	19,100	16,300
	48%	6%	6%	4%	4%
HFO consumption (t)	**Russia**	**Canada**	**Denmark (DIS)**	**Bahamas**	**Panama**
	140,300	14,600	13,900	10,400	7,400
	56%	6%	6%	4%	3%
Black carbon emissions (t)	**Russia**	**Canada**	**Norway**	**Denmark (DIS)**	**Bahamas**
	98	11	10	8	7
	51%	6%	5%	4%	4%
Onboard carriage (t)	**Russia**	**Panama**	**Marshall Islands**	**Liberia**	**Bahamas**
	261,900	122,900	103,700	85,700	44,900
	24%	11%	10%	8%	4%
Onboard carriage — HFO only (t)	**Russia**	**Panama**	**Marshall Islands**	**Liberia**	**Singapore**
	168,400	121,000	96,900	85,200	42,600
	20%	15%	12%	10%	5%
Operating hours	**Russia**	**Norway**	**Denmark**	**United States**	**Canada**
	1,233,000	288,700	225,200	122,600	119,500
	48%	11%	9%	5%	5%
Distance traveled (nm)	**Russia**	**Norway**	**Denmark**	**Canada**	**United States**
	5,044,000	1,228,500	613,100	436,500	328,200
	49%	12%	6%	4%	3%

13 Danish International Ship Register

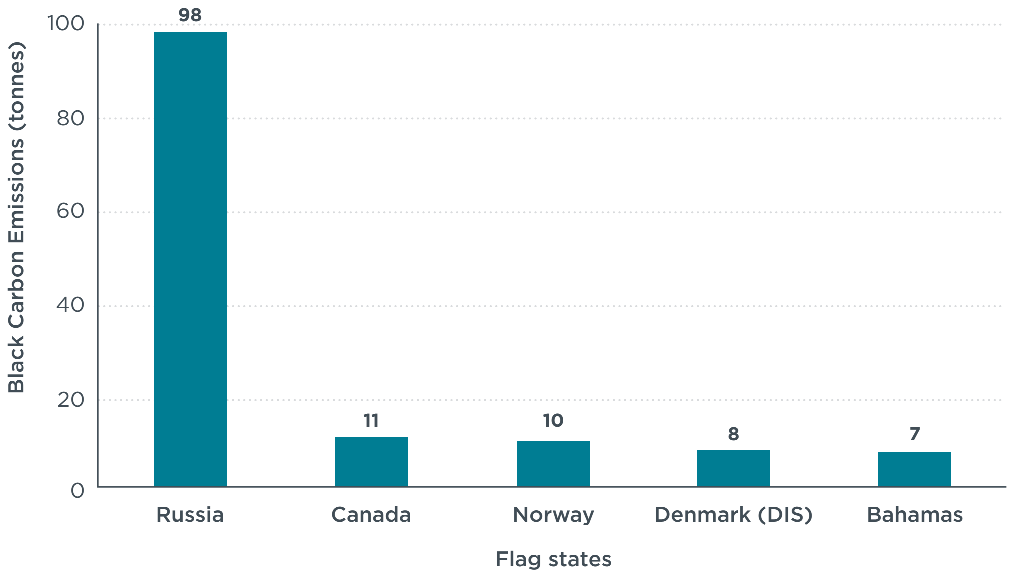

Figure 7. Black carbon emissions by top five emitting flag states in the IMO Arctic, 2015

3.5.3. U.S. Arctic

Not surprisingly, in the U.S. Arctic U.S.-flag vessels account for the most fuel consumption (46%), black carbon emissions (41%), onboard fuel carriage (21%), total operating hours (75%), and total distance traveled (76%); however, they rank a close second in HFO fuel consumption to Finland and only fifth in HFO fuel carriage, behind the Marshall Islands, Panama, Liberia and Singapore. Although 100% of the fuel consumption by Finnish flagged vessels in the U.S. Arctic is HFO, similar to Panama and closely followed by Marshall Islands (66%), only 17% of the fuel consumed by U.S.-flagged vessels in this region is HFO.

Table 20. Fuel consumption, emissions, and activity in the U.S. Arctic by Top Five flag states

Fuel consumption (t)	**United States**	**Finland**	**Marshall Islands**	**Panama**	**Singapore**
	9,800	2,400	1,500	100	900
	46%	11%	7%	5%	4%
HFO consumption (t)	**Finland**	**United States**	**Marshall Islands**	**Panama**	**France**
	2,400	1,700	1,000	1000	800
	21%	15%	9%	9%	7%
Black carbon emissions (t)	**United States**	**Finland**	**Marshall Islands**	**Panama**	**France**
	3.6	1.4	0.6	0.4	0.4
	41%	16%	6%	5%	5%
Onboard carriage (t)	**United States**	**Marshall Islands**	**Panama**	**Liberia**	**Russia**
	20,100	13,400	8,900	8,400	7,100
	21%	14%	9%	9%	7%
Onboard carriage — HFO only (t)	**Marshall Islands**	**Panama**	**Liberia**	**Singapore**	**United States**
	13,000	8,900	8,400	5,100	4,900
	18%	13%	12%	7%	7%
Operating hours	**United States**	**Singapore**	**Marshall Islands**	**Finland**	**Panama**
	96,900	5,100	5,100	4,200	2,600
	75%	4%	4%	3%	2%
Distance traveled (nm)	**United States**	**Singapore**	**Marshall Islands**	**Finland**	**Canada**
	301,000	12,400	10,300	10,300	8,000
	76%	3%	3%	3%	2%

3.6 PROJECTIONS OF FUEL USE, FUEL CARRIAGE, AND EMISSIONS IN 2020 AND 2025

Fuel use, fuel carriage, and emissions are projected from 2015 to 2020 and 2025 under two scenarios: (1) BAU, and (2) with diversion. The *with diversion* scenario assumes that a small portion of ships are diverted from the Panama and Suez Canals in favor of a trans-Arctic route, as described in the Methodology section.

3.6.1. Geographic Arctic

As shown in Table 21, the use of high-sulfur HFO in the Geographic Arctic is expected to decrease from approximately 2.6 million t in 2015 to 325,000 t in 2020, a decrease of 87%, and to 337,000 in 2025, also representing a decrease of 87% from 2015. However, the total consumption of residual oil, including less than 0.5% sulfur fuel, is expected to increase by 5% in 2020, and 5% in 2025. Moreover, trans-Arctic diversions of large cargo ships from the Suez and Panama canals could increase HFO use compared to the BAU scenario. With diversion, it is estimated that the total quantity of HFO used by vessels in the Geographic Arctic would be roughly 443,000 t in 2020—down just 83% from 2015—and 463,000 t in 2025, which is down 82% from 2015. However, under the diversion scenario, the net residual oil consumption in the region is projected to increase by 43% and 50% by 2020 and 2025, respectively, as a result of a large increase in the use of less than 0.5% sulfur residual fuel. The use of distillate and LNG is expected to increase modestly.

The carriage of high-sulfur HFO is expected to decrease from about 5 million t in 2015 to 597,000 t in 2020—which is down 88% from 2015—and 602,000 t in 2025, which is also down 88% from 2015. However, trans-Arctic diversions of large cargo ships from the Suez and Panama canals could lessen the reduction in HFO carriage as fuel. With diversion, it is estimated that the total quantity of HFO carried would be roughly 815,000 t in 2020—down just 83% from 2015—and 827,000 t in 2025, which is also down 83% from 2015. In total, the net carriage of residual oil under the BAU model is expected to rise by 0.8% and 1.7% in 2020 and 2025, respectively. However, with diversions there would be a significant increase of up to 37% in 2020 and 39% by 2025 in HFO fuel carriage. The carriage of distillate and LNG is projected to increase slightly.

The transport of HFO is projected to fall by 85% from 2015 to 2025, whereas the net transport of residual fuel is expected to increase by 23%. Similarly, transport of other fuels is projected to increase 8%–10% over the same period. Fuel transport for the with diversion scenario cannot be projected with certainty and is not estimated.

Black carbon emissions are expected to rise from 1,453 t in 2015 to 1,506 t in 2020—up 3.9% from 2015—and 1,549 t in 2025—up 6.5% from 2015—assuming no diversions. With diversion, BC emissions could equal 2,046 t in 2020, which is 41% higher than 2015, and 2,144 t in 2025, up 48% from 2015. A similar pattern is observed for CO_2 emissions. Emissions of SO_x are projected to decrease when the 0.5% global fuel sulfur cap takes effect in 2020. Emissions of NO_x are expected to decrease from 2015 to 2020 and 2025 under the BAU scenario, but increase from 2015 levels with diversion, because the increased ship traffic would more than offset the expected NO_x reductions expected from more of the fleet complying with stricter NO_x standards.

Table 21. Fuel use, fuel carriage, and emissions in the Geographic Arctic in 2015, 2020, and 2025 by scenario

		BAU			With diversions		
	2015	2020	2025	% change, 2015-2025	2020	2025	% change, 2015-2025
Fuel used (t)							
All residual	2,568,000	2,704,600	2,807,800	9.3%	3,690,400	3,857,300	50%
HFO (>0.5% S)	2,568,000	324,600	336,900	-86.9%	442,900	462,900	-82.0%
Residual (<0.5% S)	—	2,380,000	2,470,800	—	3,247,600	3,394,400	—
Distillate	1,655,200	1,680,700	1,688,600	2.0%	1,680,700	1,688,600	2.0%
LNG	149,700	157,500	162,700	8.7%	157,500	162,700	8.7%
Fuel carried (t)							
All residual	4,935,500	4,977,800	5,018,00	1.7%	6,792,200	6,893,900	39.7%
HFO (>0.5% S)	4,935,500	597,300	602,200	-87.8%	815,000	827,300	-83.2%
Residual (<0.5% S)	—	4,380,500	4,416,000	—	5,977,200	6,066,700	—
Distillate	859,700	861,600	863,400	0.4%	861,600	863,400	0.4%
LNG	39,400	39,500	39,500	0.1%	39,500	39,500	0.1%
Fuel transport (t-nm)							
All residual	18,181,500,000	20,333,800,000	22,313,080,000	22.7%			
HFO (>0.5%)	18,181,500,000	2,440,000,000	2,677,600,000	-85.3%			
Residual (<0.5%)	—	17,893,800,000	19,635,500,000	—			
Distillate	7,646,400,000	7,985,400,000	8,253,500,000	7.9%			
LNG	533,000,000	561,000,000	586,300,000	10.0%			
Emissions (t)							
CO_2	13,714,900	14,243,600	14,604,400	6.5%	19,435,400	20,063,600	46.3%
BC	1,453	1,506	1,549	6.6%	2,046	2,144	47.6%
NO_x	254,100	248,000	222,000	-12.7%	340,300	319,600	25.8%
SO_x	62,600	24,900	16,400	-73.7%	40,700	27,600	-55.8%

3.6.2. IMO Arctic

As shown in Table 22, the use of high-sulfur HFO in the IMO Arctic is expected to decrease from approximately 250,000 t in 2015 to 31,000 t in 2020 and 32,000 t in 2025, both representing an 87% reduction from 2015, with some lower reductions if trans-Arctic diversions of large cargo ships from the Suez and Panama canals occur. However, the total consumption of residual oil, including less than 0.5% sulfur fuel, is expected to increase by 4% in 2020 and by 7% in 2025. With diversion, it is estimated that the total quantity of HFO used by vessels in the IMO Arctic would be roughly 42,700 t in 2020, which is down 83% from 2015, and 44,300 t in 2025, an 82% reduction from 2015. These diversions would therefore result in an even higher percentage increase in total residual fuel consumption of nearly 50% by 2025. Furthermore, the use of distillate and LNG is expected to increase modestly.

The carriage of HFO will decrease from about 827,000 t in 2015 to 100,000 t in 2020—an 87% decrease from 2015—and 101,000 t in 2025, also down 87% from 2015. Similarly, the net carriage of residual oil under the BAU model is expected to rise by 0.9% and 1.7% in 2020 and 2025, respectively. Moreover, trans-Arctic diversions of large cargo ships from the Suez and Panama canals could lessen the reduction in HFO carriage as fuel. With diversion, it is estimated that the total quantity of HFO carried by vessels in the IMO Arctic would be roughly 137,000 t in 2020—83% less than in 2015—and 139,000 t in 2025, down 83% from 2015. However, following previous trends, the net residual fuel carriage onboard will increase by 37% and 40% in 2020 and 2025, respectively. The carriage of distillate and LNG is projected to increase slightly.

Although the transport of HFO is projected to fall by 86% from 2015 to 2025, the net residual oil transport is projected to increase by 17% by 2025. Furthermore, the transport of other fuels is expected to increase 8%-17% over the same period. Again, fuel transport for the with diversion scenario cannot be projected with certainty and is not estimated.

Black carbon emissions in the IMO Arctic are expected to rise from 193 t in 2015 to 199 t in 2020, up 3.1% from 2015, and 204 t in 2025, which is up 5.6% from 2015. This is because of the net increase in residual oil consumption, highlighting the fact that reducing sulfur content in the fuel will not necessarily reduce the black carbon emissions. With diversion, BC emissions could equal 271 t in 2020, up 40% from 2015, and 282 t in 2025, 46% above 2015 levels. A similar pattern is observed for CO_2 emissions. Emissions of NO_x and SO_x are projected to decrease as more ships comply with increasingly stringent NO_x standards and as the 0.5% global fuel sulfur cap takes effect in 2020. However, considering the diversion scenario, the NO_x emissions in the region could rise by as much as 25% by 2025 compared to 2015 levels.

Table 22. Fuel use, fuel carriage, and emissions for the IMO Arctic region in 2015, 2020, and 2025, by scenario

		BAU			With diversions		
	2015	2020	2025	% change, 2015-2025	2020	2025	% change, 2015-2025
Fuel used (t)							
All residual	249,800	260,800	268,700	7.6%	355,900	369,100	47.8%
HFO (>0.5%)	249,800	31,300	32,200	-87.1%	42,700	44,300	-82.3%
Residual (<0.5%)	—	229,600	236,400	—	313,200	324,800	—
Distillate	186,300	189,200	189,500	1.7%	189,200	189,500	1.7%
LNG	390	430	450	12.7%	430	450	12.7%
Fuel carried (t)							
All residual	827,300	834,400	841,300	1.7%	1,138,500	1,155,800	39.7%
HFO (>0.5%)	827,300	100,100	101,000	-87.8%	136,600	138,700	-83.2%
Residual (<0.5%)	—	734,300	740,400	—	1,001,900	1,017,100	—
Distillate	251,500	252,200	252,900	0.5%	252,200	252,900	0.5%
LNG	3,800	3,800	3,800	<0.1%	3,800	3,800	<0.1%
Fuel transport (t-nm)							
All residual	2,073,600,000	2,267,400,000	2,429,900,000	17.2%			
HFO (>0.5%)	2,073,600,000	272,000,000	291,600,000	-85.9%			
Residual (<0.5%)	—	1,995,400,000	2,138,300,000	—			
Distillate	1,490,900,000	1,560,600,000	1,613,100,000	8.2%			
LNG	2,736,500	3,010,300	3,212,900	17.4%			
Emissions (t)							
CO_2	1,376,000	1,420,100	1,445,500	5.0%	1,937,800	1,985,800	44.3%
BC	193	199	204	5.6%	271	282	46.1%
NO_x	27,800	27,400	24,300	-12.7%	37,500	34,900	25.8%
SO_x	12,800	5,200	3,400	-73.1%	8,400	5,800	-54.7%

3.6.3. U.S. Arctic

Heavy fuel oil use in the U.S. Arctic is expected to decrease from approximately 11,000 t in 2015 to 1,500 t in 2020 and 2025, a decrease of 87% from 2015, as shown in Table 23. However, with diversion of ships from the Panama and Suez canals, the total quantity of HFO used by vessels in the U.S. Arctic could be roughly 2,000 t in 2020, 82% less than in 2015, and 2,100 t in 2025, which is down 81% from 2015. Yet, similar to previous regions, the net residual oil consumption will increase by 8% and 14% in 2020 and 2025, respectively, under the BAU model, and by 48% and 56% in 2020 and 2025, respectively, with diversions. In fact, it must be noted that the 56% projected increase under the diversion scenario is highest for the U.S. Arctic region.

The carriage of HFO will decrease from about 71,000 t in 2015 to 8,700 t in 2020—down 87% from 2015—and 8,800 t in 2025—also down 87% from 2015. However, as with other regions, trans-Arctic diversions of large cargo ships from the Suez and Panama canals could lessen the reduction in HFO carriage as fuel. With diversion, it is estimated that the total quantity of HFO carried as fuel by vessels would be roughly 11,800 t in 2020—83% less than in 2015—and 12,000 t in 2025—also 83% less than in 2015. The carriage of distillate is projected to increase slightly.

Black carbon emissions in the U.S. Arctic are expected to rise from 9 t in 2015 to 10 t in 2020 and 2025, which is up 12% from 2015. However, diversion could mean very large increases in BC emissions, on the order of 13 t in 2020—46% greater than in 2015—and 14 t in 2025—55% above 2015 levels. Local emission increases within the U.S. Arctic, for example through the Bering Strait, could be much larger (Azzara & Rutherford, 2015). A similar pattern is observed for CO_2 emissions. Emissions of SO_x are projected to decrease as the 0.5% global fuel sulfur cap takes effect in 2020. Emissions of NO_x are expected to decrease from 2015 to 2025 under the BAU scenario, but increase from 2015 levels with diversion, as the increased ship traffic would more than offset the expected NO_x reductions expected from more of the fleet complying with stricter NO_x standards. Therefore, it is evident that in all the Arctic regions reducing fuel sulfur content will primarily reduce only the SO_x and sulfate PM emissions over the next decade. Other emissions, particularly CO_2 and BC, are expected grow.

Table 23. Fuel use, fuel carriage, and emissions for the U.S. Arctic in 2015, 2020, and 2025 by scenario

	BAU				With diversions		
	2015	2020	2025	% change, 2015-2025	2020	2025	% change, 2015-2025
Fuel used (t)							
All residual	11,300	12,200	12,800	13.9%	16,700	17,600	56.4%
HFO (>0.5%)	11,300	1,500	1,500	-86.3%	2,000	2,100	-81.2%
Residual (<0.5%)	—	10,800	11,300	—	14,700	15,500	—
Distillate	10,100	10,600	10,900	8.3%	10,600	10,900	8.3%
Fuel carried (t)							
All residual	71,300	72,100	73,000	2.5%	98,400	100,300	40.8%
HFO (>0.5%)	71,300	8,700	8,800	-87.7%	11,800	12,000	-83.1%
Residual (<0.5%)	—	63,500	64,300	—	86,600	88,300	—
Distillate	24,460	24,510	24,540	0.3%	24,510	24,540	0.3%
Fuel transport (t-nm)							
All residual	76,160,700	86,536,800	95,297,600	25.1%			
HFO (>0.5%)	76,160,700	10,384,400	11,435,700	-85.0%			
Residual (<0.5%)	—	76,152,300	83,861,900	—			
Distillate	65,182,200	71,714,100	76,492,500	17.4%			
Emissions (t)							
CO_2	67,500	72,100	75,000	11.2%	98,400	103,100	52.7%
BC	9	10	10	12.0%	13	14	54.9%
NO_x	1,300	1,330	1,060	-18.5%	1,830	1,530	17.3%
SO_x	580	260	190	-66.6%	430	330	-43.8%

4. COMPARISON TO OTHER STUDIES

Two prior studies, DNV (2013) and Winther et al. (2014), offer ship activity and BC inventories for the same geospatial regions as reported here.

Table 24 compares the DNV (2013) results to the results of this report. DNV (2013) estimates that ships operating within the IMO Arctic in 2012 emitted 52 t of BC, about 27% of the BC emissions estimated in this report for 2015. DNV estimated much less fuel consumption than estimated in this study; however, DNV did not apportion fuel consumption by fuel type (e.g., HFO versus distillate, LNG, etc.). Although there was likely some increase in HFO carriage and BC emissions from ships in the IMO Arctic from 2012 to 2015, the bulk of this difference likely resulted from having more complete ship position and ship characteristics data in the 2016 ICCT study than the 2013 DNV study and a difference in the BC EF used in each. Specifically, the difference in BC, fuel consumption, and carriage between this study and DNV is a result of DNV reporting less ship activity and a smaller fleet overall, and using a smaller emission factor for BC. Black carbon emission factors used in this report are drawn from the TNO POSEIDON model and range from about 0.30 to 0.56 g BC/kg fuel depending on engine type and fuel type. The DNV report uses a BC EF of 0.18 g BC/kg fuel across all engine types and fuel types. Accounting for these differences, our results are largely consistent with the DNV report.

Table 24. Findings compared to DNV (2013) results for the IMO Arctic region

Metric	DNV results (2012 activity)	This study (2015 activity)
BC (t)	52	193
Sailed distance (nm)	5,694,450	10,322,500
Number of ships	1,347	2,086
Operating hours	1,859,382	2,582,400
HFO fuel carried (t)	396,554	827,300
Distillate fuel carried (t)	132,464	251,500
Total fuel consumption (t)	290,624	436,400
BC EF (g BC/kg fuel)	0.18	0.30–0.56 (0.44 avg. in the IMO Arctic)

Table 25 compares the Winther et al. (2014) results to the results of this report. The Winther et al. 2014 study reported BC emissions and ship activity within the Arctic region bounded by 58.95°N and above, which we call the Geographic Arctic. The study estimates that 2012 ship activity within this region resulted in 1,584 t of black carbon, about 7% more emissions than reported in this report. This is expected, as Winther et al. also reported slightly greater ship activity in terms of sailed distance (5% greater), and fuel consumption (3% greater). It is possible that Winther et al. obtained a more complete dataset for regions around the lower latitudes because they acquired their data from the Danish Maritime Authority, which tracks AIS data using several land-based satellites at the lower latitudes. Additionally, this report estimates an average emission factor of about 0.34 g BC/kg fuel across all engine and oil-based fuel types for the 58.95°N and above region, which is about 3% lower than Winther et al. factor of 0.35 g BC/kg.

In all, the results of this study align well with Winther et al. (2014). However, one major difference should be highlighted: Winther et al. estimated that fishing vessels accounted for 45% of BC emissions in 2012 in the Geographic Arctic, much more than any other ship type, followed by passenger ships, which includes cruise ships and ferries. This study found that ro-pax ferries accounted for the most BC emissions in the Geographic Arctic in 2015 (209 t, 14%), followed by fishing vessels (191 t, 13.1%). The difference in distance sailed, energy use, fuel consumption, and BC emissions from fishing vessels in the Winther et al. study and this study are presented in Table 26. Winther et al. (2014) explain that "the results for fishing vessels are the least certain, caused by a less precise engine power-sailing speed relation." For all ship types except fishing vessels, Winther et al. estimated ME and AE power at the ship's design speed using a generic ship design model developed by the Technical University of Denmark called SHIP-DESMO. For fishing vessels, they rely on estimates of installed ME and AE power from the Danish Fishermen's Association and assume a constant load of 60% of total installed power (ME + AE power) at all times. The present study uses ship characteristic data from IHS Fairplay to estimate installed ME power and AIS data to estimate ship speed and the associated ME load for fishing vessels. Auxiliary engine power demand from fishing vessels is assumed to be 200 kW at all times. The results of this study suggest that Winther et al. may have overestimated energy use, fuel consumption, and BC emissions from fishing vessels.

Table 25. Findings compared to Winther et al. (2014) results for Geographic Arctic

Metric	Winther et al. results (2012 activity)	This study (2015 activity)
BC (t)	1,584	1,453
Distance sailed (10^6 km)	134	128
Number of ships	—[a]	10,099
Operating hours	—	22,262,500
HFO fuel carried (t)	—	4,935,500
Distillate carried (t)	—	859,700
Fuel consumption (10^3 t)	4,529	4,373
BC EF (g BC/kg fuel)	0.35	0.30–0.56 (0.34 avg. in the Geo. Arctic)

[a] *"—" indicates a field not reported by Winther et al. (2014).*

Table 26. Discrepancies in fishing vessel results between Winther et al. (2014) and this report

Metric	Winther et al. results (2012 activity)	This study (2015 activity)	Difference (this study to Winther et al.)
Distance sailed (10^6 km)	33.5	36.1	8%
Energy use (10^6 kWh)	9,989	2,550	-74%
Fuel consumption (10^3 t)	2,020	543	-73%
BC (t)	707	191	-73%

5. FUTURE WORK

The international marine industry is one of the least regulated transportation modes in terms of emissions. Consequently, quality data on emission factors across all engines and fuel types currently in use is generally lacking. Ship emissions vary based on several factors, including engine load, engine age, rated power, fuel type, and time since maintenance. Emission factors used to calculate emissions from ships, including the EFs used in this study, typically do not take these nuances into account, leading to some uncertainty in emissions estimates. Because of the lack of data and uncertainty surrounding marine EFs, continued work needs to be done to characterize emissions from ships under different conditions, speeds, and fuels.

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 designations of residual fuel, distillate fuel, LNG and so on. As a result, this report assumes that the quality of any fuel is consistent and that the emission factors for each fuel type are consistent. Given the importance of fuel quality on emissions, future work should measure emissions from various fuels and record key fuel quality characteristics, including sulfur content, aromatic content, asphaltene content, and so forth.

Although both the AIS and IHS datasets were predominantly complete, missing data were backfilled to complete the emissions inventory. 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 also were classified based on information within the IHS ShipData database to match ships to the correct 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 were sometimes incomplete. In cases where short periods of activity, which is to say less than 24 hours, were missing from the AIS dataset, 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 in a river. Because 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 take into account navigational obstacles such as bends in rivers or coastal geography. Linear interpolation likely results in an underestimation of emissions, because it can result in shorter estimated distances, lower speeds, and lower power demand. Future work should strive to more accurately interpolate ship position and speed, which will improve confidence in ship emissions inventories and will better reflect the geospatial distribution of ship emissions, which could be important, especially when analyzing the effects of regional policies, such as ECAs, in reducing ship emissions.

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 ships operating at slow speeds (0-3 knots) and far from port or shore are at anchor, in which case their main engine is assumed to be turned off. However, ships traveling through the Arctic 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 because of 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, especially for activity close to sea ice. Future work could include a sensitivity analysis to estimate the potential effects on ship emissions inventories by altering the phase assignment classification scheme.

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. No ports in the IMO Arctic have shoreside power capabilities, however, 8 ports within the Geographic Arctic offer shore-side power: the Swedish ports of Stockholm and Pitea; the Norwegian ports of Oslo and Bergen; the port of Tallinn in Estonia; and the Finnish ports of Oulu, Kemi, and Helsinki (Ericsson & Fazlagic, 2008). That said, several ports only offer shoreside power to smaller vessels such as ferries, and shoreside power may not be used even when it is available. Future work could explore the characteristics of existing shore power facilities in the Arctic, including the number of electrified berths, power supply, electricity source, potential air emissions, and so forth to estimate the emissions impacts of using shore power in the Arctic. Additional work could also explore the emissions impacts of expanding the use of shore power in the Arctic.

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

This study does not account for any atmospheric transport of BC emissions after they are emitted from ships. It is likely that ship BC emissions are transported some distance before they are deposited on the earth's surface. Future research could build on the BC emissions inventory presented here by modeling the transport of BC emissions within the Arctic. Additional analysis to model the transport of BC emissions from ships operating in lower latitudes could also be done to enhance the understanding of the effect BC emissions from these ships on the Arctic.

6. POLICY ALTERNATIVES

Left unregulated, HFO will continue to be used in the Arctic and BC will continue to be emitted. Despite the implementation of the 0.5% global fuel sulfur cap in 2020, HFO will be used by ships whose owners and operators choose to comply with the regulation through the use of scrubbers. Additionally, 0.5% sulfur compliant fuels may be blends of HFO and lower sulfur distillate fuels that are just as harmful to the environment as HFO. Residual oil spill risks persist with the use of 0.5% sulfur compliant fuel, and BC emissions from desulfurized or blended residuals may be as much or higher than those from HFO (University of California, Riverside, 2016). Several policy alternatives to reduce these potential damages from ships in the Arctic are considered below.

6.1 ALTERNATIVE 1 – ESTABLISH AN ARCTIC EMISSION CONTROL AREA

Establishing an Arctic Sulfur Emission Control Area (ECA) would be a positive step toward eliminating the use of HFO in the Arctic and could reduce BC emissions. To comply with an ECA, many ships would switch to distillate fuels, which emit less BC than residual fuels. However, such a regulation would not prohibit the use of HFO in the Arctic, as ships could comply with ECA fuel sulfur standards by using scrubbers, enabling a ship to continue to operate on (and carry) high sulfur HFO but to scrub out sulfur emissions from the exhaust stream. Scrubbers may yield modest BC reductions, but the focus is on reducing gas phase sulfur oxides and, to a lesser extent, sulfur particulates. An ECA would not prohibit the carriage of HFO and therefore would not reduce the ecological dangers associated with a HFO spills in the Arctic.

6.2 ALTERNATIVE 2 – PROHIBIT THE USE OF HFO IN THE ARCTIC (NO LIMITATION ON CARRIAGE)

Prohibiting the use of HFO in the Arctic, as has been done in the Antarctic since 2011, would reduce the air pollutant emissions because alternative fuels emit less air and climate pollutants, including BC in most cases. However, such a scenario allows ships to continue transporting HFO through the Arctic, and therefore the risk of an HFO fuel oil spill will persist.

6.3 ALTERNATIVE 3 – PROHIBIT THE USE AND CARRIAGE OF HFO IN THE ARCTIC

Prohibiting the use and carriage of HFO in the Arctic would greatly reduce the risk of HFO oil spills and would reduce air emissions, including BC. Black carbon emissions would be reduced with a shift to distillate or LNG, but could remain roughly the same, or even increase, if ships use blended fuels. Thus, one could also prohibit the use of fuels blended with HFO to promote a shift to distillates, LNG, or other alternative fuels that emit less BC.

6.4 ALTERNATIVE 4 – PROHIBIT THE USE OF ANY PETROLEUM-BASED FUEL OIL IN THE ARCTIC

Prohibiting the use of petroleum-based fuels in the Arctic would greatly reduce air emissions, including BC, and would reduce some of the risks associated with fuel oil spills. In practice, prohibiting the use of petroleum-based fuels would mean that ships would operate on LNG, biofuel, electricity (fuel cells), or other alternative propulsion technologies. This alternative provides the greatest protection to the Arctic environment from HFO and distillate spills but would mean that nearly all the vessels that currently operate in the IMO Arctic would need to be retrofitted for alternative fuel use or retired from use in the region.

6.5 ALTERNATIVE 5 – LIMIT BC EMISSIONS FROM SHIPS

Regulations could be promulgated that limit BC emissions from ships. Such regulations could apply to ships that operate specifically in the Arctic or to the entire global fleet. Black carbon emissions could be limited by setting BC emission limits from new marine engines, by requiring the use of low- or zero-BC fuels such as LNG and hydrogen, by requiring the retrofit of BC reduction devices such as diesel particulate filters for certain applications, or by restricting certain operational practices such as soot blowout from ship economizers. This alternative would reduce BC emissions in the Arctic and might also encourage a shift toward fuels that are less damaging when spilled than HFO.

6.6 SUMMARY

The policy alternatives presented above could be applied at the global, regional, national, or subnational scales. Regional policies that apply specifically to the Arctic could be effective because ships registered to Arctic states, particularly Russia, account for the majority of HFO use, carriage, and BC emissions in the Arctic. That said, global policies tend to deliver the greatest benefits to the marine environment; however, in some cases, it may be prudent to implement some policies at the national or regional level to protect sensitive areas and to serve as a model for international policy actions. For example, although the effects of HFO use and carriage in the Arctic are being discussed at the IMO, the Obama and Trudeau administrations announced plans to phase down the use of HFO in their respective Arctic regions without IMO action. 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.

Policies that apply globally are particularly attractive alternatives to protect the Arctic from increased traffic, given that diversion of ship from traditional trade routes in favor of trans-Arctic routes is likely to increase BC emissions as well as HFO use and carriage by ships registered in non-Arctic states. Furthermore, emissions of BC outside of the IMO Arctic can be, and are being, transported to the Arctic region. In fact, the IMO Arctic contained only about 13% of BC emitted in the Geographic Arctic in 2015, and BC emissions at lower latitudes can also be transported northward. As a result, global policies that reduce BC from marine engines will help ensure that the impact of BC from ships on the Arctic environment is meaningfully reduced.

7. CONCLUSIONS

This report estimated fuel use, fuel carriage, fuel transport, BC emissions, and other air pollutant emissions for ships in the Arctic in 2015, with projections to 2020 and 2025. Results suggest that despite global fuel quality regulations that will enter into force in 2020, the use, carriage, and transport of HFO will persist in the Arctic. Additionally, BC emissions are expected to rise. The report finds that Russian-flagged vessels are responsible for the majority of BC emissions and HFO used, carried, and transported in the region.

Heavy fuel oil was the most consumed marine fuel in the Arctic in 2015. Heavy fuel oil represented 57% of fuel consumed in the IMO Arctic, with general cargo vessels, oil tankers, and cruise ships consuming the most HFO. Furthermore, HFO dominated the total mass of bunker fuel onboard vessels in the Arctic in 2015. For example, whereas approximately 42% of ships in the IMO Arctic operated on HFO in 2015, these ships represent 76% of the mass of fuel onboard all ships operating in that area. Bulk carriers, container ships, oil tankers, general cargo vessels, and fishing vessels together accounted for 75% of the HFO carried in the IMO Arctic in 2015. The use and carriage of HFO is expected to persist in the Arctic, despite upcoming regulations to limit the sulfur content of marine fuels to 0.5% in 2020. The continued use and carriage of HFO threatens the Arctic environment, primarily because of the risk of oil spills, but also because of harmful air pollutant emissions, including BC.

The consumption of HFO and other marine fuels leads to BC emissions. Roughly two thirds of BC emissions in the Arctic in 2015 were the consequence of consuming HFO. In the IMO Arctic, the top three emitters of BC were fishing vessels, general cargo vessels, and service vessels. Black carbon emissions are expected to increase steadily from 2015 to 2020 and 2025, with potentially large increases in BC emissions if even a small percentage of ships are diverted from the Suez and Panama canals over the next decade.

Some flag states are responsible for a larger share of HFO use, consumption, and BC emissions than others. Russian-flagged ships currently dominate HFO use, carriage, and BC emissions in the Arctic. However, trans-Arctic shipping by vessels flying non-Arctic-state flags may increase if ships are diverted from the Panama and Suez canals to take advantage of shorter routes to and from Asia, Europe, and North America, leading to potentially large increases in BC emissions and HFO use and carriage in the Arctic.

Policies that limit BC emissions from ships or that prohibit the use and carriage of HFO in the Arctic could reduce the potential for damage to the climate and the sensitive Arctic ecosystem.

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9. APPENDIXES

APPENDIX A. SHIP TYPES REPRESENTED BY THE SHIP CLASSES USED

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	**Fishing vessel**	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	**Other**	Chemical tanker, inland waterways		Mechanical lift dock
Cruise	Passenger/cruise		Chemical/products tanker, inland waterways		Mooring buoy
Ferry-pax only	Passenger ship		Container ship (fully cellular), inland waterways		Museum, stationary
Ferry-ro-pax	Passenger/landing craft		Cruise ship, inland waterways		Pontoon (function unknown)
	Passenger/ro-ro ship (vehicles)		Dredging, inland waterways		Power station pontoon, non propelled
	Passenger/ro-ro ship (vehicles/rail)		Exhibition vessel		Products tank barge, non propelled
General cargo	Barge carrier		General cargo, inland waterways		Restaurant vessel, stationary
	Deck cargo ship		Incinerator		Sheerlegs pontoon
	General cargo ship		Lighthouse tender		Steam supply pontoon, non propelled
	General cargo ship (with ro-ro facility)		Mission ship		Trans shipment barge, non propelled
	General cargo ship, self-discharging		Oil tanker, inland waterways		Water tank barge, non propelled
	General cargo/passenger ship		Other activities, inland waterways		Work/maintenance pontoon, non propelled
	General cargo/tanker		Passenger ship, inland waterways	**Non-ship structure**	Air cushion vehicle passenger
	Heavy load carrier		Passenger/ro-ro ship (vehicles), inland waterways		Air cushion vehicle passenger/ro-ro (vehicles)
	Heavy load carrier, semi submersible		Pearl shells carrier		Car park
	Livestock carrier		Ro-Ro cargo ship, inland waterways		Floating dock
	Nuclear fuel carrier		Shopping complex		Wing in ground effect vessel
	Nuclear fuel carrier (with ro-ro facility)		Towing/pushing, inland waterways		

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

APPENDIX B. SHIP CAPACITY BIN BY SHIP CLASS

Ship class	Capacity bin	Capacity	Unit
Bulk carrier	1	<10,000	dwt
	2	10,000-35,000	
	3	35,000-60,000	
	4	60,000-100,000	
	5	100,000-200,000	
	6	>200,000	
Chemical tanker	1	<5,000	dwt
	2	5,000-10,000	
	3	10,000-20,000	
	4	>20,000	
Container	1	<1,000	teu
	2	1,000-2,000	
	3	2,000-3,000	
	4	3,000-5,000	
	5	5,000-8,000	
	6	8,000-12,000	
	7	12,000-14,500	
	8	>14,500	
General cargo	1	<5,000	dwt
	2	5,000-10,000	
	3	>10,000	
Liquefied gas tanker	1	<50,000	cubic meters
	2	50,000-200,000	
	3	>200,000	
Oil tanker	1	<5,000	dwt
	2	5,000-10,000	
	3	10,000-20,000	
	4	20,000-60,000	
	5	60,000-80,000	
	6	80,000-120,000	
	7	120,000-200,000	
	8	>200,000	

Ship class	Capacity bin	Capacity	Unit
Other liquid tankers	1	All	dwt
Ferry-pax only	1	<2,000	gt
	2	>2,000	
Cruise	1	<2,000	gt
	2	2,000-10,000	
	3	10,000-60,000	
	4	60,000-100,000	
	5	>100,000	
Ferry-ro-pax	1	<2,000	gt
	2	>2,000	
Refrigerated bulk	1	<2,000	dwt
Ro-ro	1	<5,000	gt
	2	>5,000	
Vehicle	1	All	gt
Yacht	1	All	gt
Service–tug	1	All	gt
Fishing vessel	1	All	gt
Offshore	1	All	gt
Service–other	1	All	gt
Other	1	All	gt

APPENDIX C. LINEAR REGRESSION USED TO DETERMINE THE MAIN FUEL CAPACITY

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

Ship class	DWT R^2	GT R^2	DWT Intercept	DWT Beta	GT Intercept	GT Beta	All Ships Intercept (corresponds with GT)	All Ships Beta (corresponds with GT)
Bulk carrier	0.89	0.90	706.78	0.02	538.67	0.05	247.11	0.06
Chemical tanker	0.80	0.81	223.38	0.03	194.81	0.05	247.11	0.06
Container	0.90	0.89	175.69	0.09	617.71	0.09	247.11	0.06
Cruise	0.82	0.79	199.73	0.28	408.32	0.03	247.11	0.06
Ferry-pax only	0.55	0.47	-39.32	0.70	-58.81	0.20	247.11	0.06
Ferry-ro-pax	0.55	0.57	61.77	0.13	67.03	0.03	247.11	0.06
General cargo	0.66	0.73	58.27	0.06	24.59	0.08	247.11	0.06
Liquefied gas tanker	0.78	0.76	172.27	0.06	393.92	0.05	247.11	0.06
Fishing vessel	0.59	0.66	92.56	0.24	68.33	0.17	247.11	0.06
Other	0.19	0.32	42.35	0.04	8.93	0.07	247.11	0.06
Oil tanker	0.96	0.96	261.02	0.03	156.05	0.05	247.11	0.06
Other liquid tankers	0.84	0.82	26.85	0.06	13.52	0.07	247.11	0.06
Refrigerated bulk	0.57	0.62	226.92	0.12	200.61	0.13	247.11	0.06
Ro-ro	0.72	0.69	233.09	0.09	241.41	0.05	247.11	0.06
Service-other	0.69	0.70	392.60	0.03	341.93	0.05	247.11	0.06
Service-tug	0.69	0.73	51.66	0.60	-9.62	0.50	247.11	0.06
Vehicle	0.77	0.72	292.51	0.14	111.07	0.05	247.11	0.06
Yacht	0.25	0.62	59.71	0.21	28.31	0.09	247.11	0.06

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
Bulk carrier	<10,000	190	310	280	190	dwt
Bulk carrier	10,000-35,000	190	310	280	190	
Bulk carrier	35,000-60,000	260	420	370	260	
Bulk carrier	60,000-100,000	420	680	600	420	
Bulk carrier	100,000-200,000	420	680	600	420	
Bulk carrier	>200,000	420	680	600	420	
Chemical tanker	<5,000	80	110	160	80	dwt
Chemical tanker	5,000-10,000	230	330	490	230	
Chemical tanker	10,000-20,000	230	330	490	230	
Chemical tanker	>20,000	550	780	1170	550	
Container	<1,000	300	550	340	300	teu
Container	1,000-2,000	820	1320	600	820	
Container	2,000-3,000	1230	1800	700	1230	
Container	3,000-5,000	1390	2470	940	1390	
Container	5,000-8,000	1420	2600	970	1420	
Container	8,000-12,000	1630	2780	1000	1630	
Container	12,000-14,500	1960	3330	1200	1960	
Container	>14,500	2160	3670	1320	2160	
General cargo	<5,000	60	90	120	60	dwt
General cargo	5,000-10,000	170	250	330	170	
General cargo	>10,000	490	730	970	490	
Liquefied gas tanker	<50,000	240	360	240	240	cubic meters
Liquefied gas tanker	50,000-200,000	1710	2565	1710	1710	
Liquefied gas tanker	>200,000	1710	2565	1710	1710	

Ship class	Ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	Capacity unit
Oil tanker	<5,000	250	375	250	250	dwt
Oil tanker	50,00-10,000	375	563	375	375	
Oil tanker	10,000-20,000	625	938	625	625	
Oil tanker	20,000-60,000	750	1125	750	750	
Oil tanker	60,000-80,000	750	1125	750	750	
Oil tanker	80,000-120,000	1000	1500	1000	1000	
Oil tanker	120,000-200,000	1250	1875	1250	1250	
Oil tanker	>200,000	1500	2250	1500	1500	
Other liquid tankers	—	500	750	500	500	dwt
Ferry-pax only	<2,000	186	186	186	186	gt
Ferry-pax only	>2,000	524	524	524	524	
Cruise	<2,000	450	580	450	450	gt
Cruise	2,000-10000	450	580	450	450	
Cruise	10,000-60,000	3500	5460	3500	3500	
Cruise	60,000-100,000	11480	14900	11480	11480	
Cruise	>100,000	11480	14900	11480	11480	
Ferry-ro-pax	<2,000	105	105	105	105	gt
Ferry-ro-pax	>2,000	710	710	710	710	
Refrigerated bulk	<2,000	1170	1150	1080	1080	dwt
Ro-ro	<5,000	600	1700	800	800	gt
Ro-ro	>5,000	950	2720	1200	1200	
Vehicle	—	500	1125	800	800	gt
Yacht	—	130	130	130	130	gt
Service-tug	—	50	50	50	50	gt
Fishing vessel	—	200	200	200	200	gt
Offshore	—	320	320	320	320	gt
Service-other	—	220	220	220	220	gt
Other	—	190	190	190	190	gt

APPENDIX E. BOILER 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
Bulk carrier	<10,000	0	50	50	50	dwt
Bulk carrier	10,000–35,000	0	50	50	50	
Bulk carrier	35,000–60,000	0	100	100	100	
Bulk carrier	60,000–100,000	0	200	200	200	
Bulk carrier	100,000–200,000	0	200	200	200	
Bulk carrier	>200,000	0	200	200	200	
Chemical tanker	<5,000	0	125	125	125	dwt
Chemical tanker	5,000–10,000	0	250	250	250	
Chemical tanker	10,000–20,000	0	250	250	250	
Chemical tanker	>20,000	0	250	250	250	
Container	<1,000	0	120	120	120	teu
Container	1,000–2,000	0	290	290	290	
Container	2,000–3,000	0	350	350	350	
Container	3,000–5,000	0	450	450	450	
Container	5,000–8,000	0	450	450	450	
Container	8,000–12,000	0	520	520	520	
Container	12,000–14,500	0	630	630	630	
Container	>14,500	0	700	700	700	
General cargo	<5,000	0	0	0	0	dwt
General cargo	5,000–10,000	0	75	75	75	
General cargo	>10,000	0	100	100	100	
Liquefied gas tanker	<50,000	100	200	1000	200	cubic meters
Liquefied gas tanker	50,000–200,000	150	300	1500	300	
Liquefied gas tanker	>200,000	300	600	3000	600	

Ship class	Ship capacity bin	Cruise demand	Maneuver demand	Berth demand	Anchor demand	Capacity unit
Oil tanker	<5,000	0	100	500	100	dwt
Oil tanker	5,000–10,000	0	150	750	150	
Oil tanker	10,000–20,000	0	250	1,250	250	
Oil tanker	20,000–60,000	150	300	1,500	300	
Oil tanker	60,000–80,000	150	300	1,500	300	
Oil tanker	80,000–120,000	200	400	2,000	400	
Oil tanker	120,000–200,000	250	500	2,500	500	
Oil tanker	>200,000	300	600	3,000	600	
Other liquid tankers	—	100	200	1,000	200	dwt
Ferry-pax only	<2,000	0	0	0	0	gt
Ferry-pax only	>2,000	0	0	0	0	
Cruise	<2,000	0	250	250	250	gt
Cruise	2,000–10,000	0	250	250	250	
Cruise	10,000–60,000	0	1,000	1,000	1,000	
Cruise	60,000–100,000	0	500	500	500	
Cruise	>100,000	0	500	500	500	
Ferry-ro-pax	<2,000	0	0	0	0	gt
Ferry-ro-pax	>2,000	0	0	0	0	
Refrigerated bulk	<2,000	0	270	270	270	dwt
Ro-ro	<5,000	0	200	200	200	gt
Ro-ro	>5,000	0	300	300	300	
Vehicle	—	0	268	268	268	gt
Yacht	—	0	0	0	0	gt
Service-tug	—	0	0	0	0	gt
Fishing vessel	—	0	0	0	0	gt
Offshore	—	0	0	0	0	gt
Service-other	—	0	0	0	0	gt
Other	—	0	0	0	0	gt

APPENDIX F. MAIN ENGINE EMISSION FACTORS (g/kWH) USED

Pollutant	Engine tier	Engine type	HFO (2.5% S)	Distillate (0.14% S)	ECA fuel (0.1% S)	LNG
CO_2	All	SSD	607	593	593	–
		MSD/HSD	670	658	658	–
		GT/ST	950	962	962	457
		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	–
		130–1,999 rpm	0.94*45*rpm^(–0.2)	0.94*45*rpm^(–0.2)	0.94*45*rpm^(–0.2)	–
		2,000+ rpm	9.80	9.21	9.21	–
	Tier II	0–130 rpm	14.40	13.54	13.54	–
		130–1,999 rpm	0.94*44*rpm^(–0.23)	0.94*44*rpm^(–0.23)	0.94*44*rpm^(–0.23)	–
		2,000+ rpm	7.70	7.24	7.24	–
	All	GT	6.10	5.92	5.92	–
		ST	2.10	2.00	2.00	1.3
		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	0.0027
		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	0.03
		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	1.30
		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	8.5
		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	0.02
		LNG-Otto	–	–	–	0.02
		LNG-diesel	–	–	–	0.01
NMVOC	All	SSD	0.60	0.60	0.60	–
		MSD/HSD	0.50	0.50	0.50	–
		GT/ST	0.10	0.10	0.10	0.50
		LNG-Otto	–	–	–	0.50
		LNG-diesel	–	–	–	0.40
BC	All	SSD	0.08	0.06	0.06	–
		MSD/HSD	0.12	0.06	0.06	–
		GT	0.01	0.00	0.00	0.003
		ST	0.08	0.06	0.06	0.003
		LNG-Otto	–	–	–	0.003
		LNG-diesel	–	–	–	0.002

APPENDIX G. AUXILIARY ENGINE EMISSION FACTORS (g/kWH) USED

Pollutant	Engine tier	Engine type	HFO (2.5% S)	Distillate (0.14% S)	ECA fuel (0.1% S)	LNG
CO_2	All	SSD/MSD/HSD	707	696	696	–
		LNG-Otto	–	–	–	457
		LNG-diesel	–	–	–	366
NO_x	Tier 0	All	14.70	13.82	13.82	–
	Tier I	0–130 rpm	13.00	12.22	12.22	–
		130–1,999 rpm	0.94*45*rpm^(–0.2)	0.94*45*rpm^(–0.2)	0.94*45*rpm^(–0.2)	–
		2,000+ rpm	13.00	12.22	12.22	–
		LNG-Otto	–	–	–	1.3
		LNG-diesel	–	–	–	–
	Tier II	0–130 rpm	11.20	10.53	10.53	–
		130–1,999 rpm	0.94*44*rpm^(–0.23)	0.94*44*rpm^(–0.23)	0.94*44*rpm^(–0.23)	–
		2,000+ 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	11.98
		LNG-Otto/LNG-diesel	–	–	–	0.00
PM	All	SSD/MSD/HSD	1.44	0.20	0.19	1.44
		LNG-Otto	–	–	–	0.03
		LNG-diesel	–	–	–	0.02
CO	All	SSD/MSD/HSD	0.54	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	0.01
		LNG-Otto	–	–	–	8.50
		LNG-diesel	–	–	–	0.94
N_2O	All	SSD/MSD/HSD	0.04	0.03	0.03	0.04
		LNG-Otto	–	–	–	0.02
		LNG-diesel	–	–	–	0.01
NMVOC	All	SSD/MSD/HSD	0.40	0.40	0.40	0.40
		LNG-Otto	–	–	–	0.50
		LNG-diesel	–	–	–	0.40
BC	All	SSD/MSD/HSD	0.12	0.06	0.06	0.12
		LNG-Otto	–	–	–	0.003
		LNG-diesel	–	–	–	0.002

APPENDIX H. BOILER EMISSION FACTORS (g/kWH) USED

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

APPENDIX I. LOW LOAD ADJUSTMENT FACTORS FOR MAIN PROPULSION ENGINES

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

APPENDIX J. EMISSIONS (t) FROM SHIP ACTIVITY BY FUEL TYPE AND SHIP CLASS IN THE GEOGRAPHIC ARCTIC

	Ships	CO_2	BC	CH_4	N_2O	NO_x	SO_x	PM	CO	NMVOC	Fuel consumption
Distillate fuel	**5,141**	**5,306,546**	**485**	**84**	**237**	**96,612**	**4,086**	**1,593**	**4,537**	**4,208**	**1,655,192**
Bulk carrier	32	31,337	3	0	1	578	23	9	25	22	9,774
Chemical tanker	67	54,356	4	1	2	753	40	13	36	31	16,954
Container	10	8,720	1	0	0	163	6	2	7	6	2,720
Cruise	44	180,524	10	2	8	2,454	135	32	95	81	56,308
Passenger ferry	183	239,151	21	3	10	4,088	187	70	196	167	74,595
Ferry-ro-pax	292	736,227	67	11	32	13,648	551	219	619	548	229,640
General cargo	1,203	702,801	63	10	31	12,927	513	205	575	519	219,214
Liquefied gas tanker	15	8,760	1	0	0	75	6	2	4	3	2,732
Fishing vessel	1,619	1,524,367	149	28	70	30,276	1,266	499	1,432	1,406	475,473
Other	3	1,133	0	0	0	21	1	0	1	1	353
Non propelled	5	0	0	0	0	0	0	0	0	0	0
Offshore	459	651,787	58	10	29	10,764	463	193	556	495	203,302
Oil tanker	67	77,687	6	1	3	839	61	16	42	33	24,232
Other liquid tankers	3	19,159	1	0	1	141	14	3	7	5	5,976
Refrigerated bulk	43	151,678	13	2	7	2,650	125	42	112	91	47,311
Ro-ro	30	147,311	13	2	6	2,458	104	40	112	95	45,949
Service vessel	524	573,520	55	11	26	10,935	440	184	538	531	178,890
Tug	462	172,590	17	3	8	3,322	136	55	161	157	53,833
Vehicle	6	17,194	2	0	1	374	11	5	14	14	5,363
Yacht	74	8,245	1	0	0	149	6	2	7	6	2,572
LNG	**93**	**411,611**	**2**	**8,297**	**16**	**1,145**	**2**	**28**	**1,228**	**488**	**149,677**
Bulk carrier	1	14	0	0	0	0	0	0	0	0	5
Chemical tanker	3	22,248	0	419	1	63	0	1	64	25	8,090
Passenger ferry	3	6,690	0	125	0	19	0	0	19	7	2,433
Ferry-ro-pax	24	215,694	1	4,190	9	586	1	14	629	246	78,434
General cargo	4	9,213	0	187	0	27	0	1	28	11	3,350
Liquefied gas tanker	28	94,114	1	1,961	4	260	1	6	288	115	34,223
Offshore	22	51,221	0	1,129	2	151	0	4	161	66	18,626
Ro-ro	2	7,008	0	136	0	20	0	0	20	8	2,548
Service vessel	4	4,896	0	140	0	15	0	0	18	8	1,780
Tug	2	513	0	9	0	4	0	0	2	1	187
Nuclear	**5**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**
Cruise	1	—	—	—	—	—	—	—	—	—	—
General cargo	1	—	—	—	—	—	—	—	—	—	—
Service vessel	3	—	—	—	—	—	—	—	—	—	—
Residual fuel	**4,860**	**7,996,792**	**965**	**122**	**378**	**156,352**	**58,471**	**8,327**	**6,426**	**6,111**	**2,568,013**
Bulk carrier	1,254	772,552	97	14	38	18,229	8,045	1,167	671	713	248,090
Chemical tanker	804	838,926	95	13	39	16,665	5,103	759	669	641	269,405
Container	282	645,421	75	11	30	13,585	3,987	589	537	526	207,264
Cruise	109	1,122,843	143	14	54	20,379	9,799	1,271	853	723	360,579
Passenger ferry	6	8,514	1	0	0	152	130	15	6	5	2,734
Ferry-ro-pax	71	1,329,457	142	21	60	26,050	4,264	793	1,129	1,053	426,929
General cargo	827	754,586	104	11	37	14,807	7,645	1,050	614	575	242,320
Liquefied gas tanker	129	122,755	11	1	6	1,600	464	63	71	67	39,420
Fishing vessel	284	211,636	42	5	12	4,812	3,096	473	215	236	67,963
Other	1	503	0	0	0	10	8	1	0	0	161
Non propelled	2	—	—	—	—	—	—	—	—	—	—
Offshore	39	47,748	6	1	2	900	379	54	40	36	15,333
Oil tanker	624	1,201,027	135	17	57	21,023	9,043	1,169	858	835	385,686
Refrigerated bulk	170	254,201	34	3	12	4,874	2,827	348	188	163	81,632
Ro-ro	87	501,980	53	7	23	9,359	1,988	318	401	358	161,201
Service vessel	87	125,020	21	3	7	2,661	1,451	218	123	130	40,148
Tug	37	22,034	3	0	1	459	135	22	20	20	7,076
Vehicle	45	37,404	4	1	2	784	105	19	31	30	12,012
Yacht	2	184	0	0	0	4	2	0	0	0	59
Total	**10,099**	**13,714,949**	**1,453**	**8,504**	**632**	**254,110**	**62,560**	**9,948**	**12,191**	**10,807**	**4,372,882**

APPENDIX K. EMISSIONS (t) AND FUEL CONSUMPTION (t) FROM SHIPS BY FUEL TYPE AND SHIP CLASS IN THE IMO ARCTIC, 2015

	Ships	CO_2	BC	CH_4	N_2O	NO_x	SO_x	PM	CO	NMVOC	Fuel consumption
Distillate fuel	**1184**	**597,137**	**62**	**13**	**28**	**11,964**	**514**	**206**	**599**	**642**	**186,256**
Bulk carrier	5	1,458	0	0	0	26	1	0	1	1	455
Chemical tanker	15	6,192	1	0	0	91	5	2	4	4	1,931
Cruise	22	32,825	3	0	1	556	28	9	24	20	10,239
Passenger ferry	18	11,503	1	0	1	219	10	3	9	8	3,588
Ferry-ro-pax	29	44	0	0	0	1	0	0	0	0	14
General cargo	85	21,224	2	0	1	393	18	6	17	16	6,620
Fishing vessel	596	290,335	32	7	14	6,238	250	107	318	358	90,560
Non propelled	1	0	0	0	0	0	0	0	0	0	0
Offshore	55	20,401	2	0	1	337	18	6	18	16	6,363
Oil tanker	25	6,086	0	0	0	87	5	1	4	3	1,898
Refrigerated bulk	23	36,642	3	0	2	619	31	10	25	20	11,429
Ro-ro	10	6,375	1	0	0	101	5	2	4	3	1,988
Service vessel	160	132,154	14	3	6	2,684	114	48	141	159	41,221
Tug	127	29,722	3	1	1	576	26	10	30	32	9,271
Yacht	13	2,177	0	0	0	37	2	1	2	2	679
LNG	**9**	**1,085**	**0**	**32**	**0**	**3**	**0**	**0**	**4**	**2**	**394**
Chemical tanker	1	65	0	1	0	0	0	0	0	0	24
Ferry-ro-pax	1	4	0	0	0	0	0	0	0	0	2
Liquefied gas tanker	2	69	0	3	0	0	0	0	0	0	25
Offshore	3	275	0	6	0	1	0	0	1	0	100
Service vessel	2	671	0	22	0	2	0	0	3	1	244
Nuclear	**4**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**	**—**
Cruise	1	—	—	—	—	—	—	—	—	—	—
Service vessel	3	—	—	—	—	—	—	—	—	—	—
Residual fuel	**889**	**777,805**	**131**	**13**	**41**	**15,817**	**12,257**	**1,620**	**651**	**637**	**249,777**
Bulk carrier	176	73,024	10	1	4	1,713	1,151	159	64	68	23,450
Chemical tanker	93	53,468	8	1	3	1,086	843	105	41	40	17,170
Container	43	39,699	7	1	2	856	626	82	33	31	12,749
Cruise	40	76,381	13	1	4	1,477	1,204	151	60	52	24,528
Passenger ferry	3	4,265	1	0	0	91	67	9	4	3	1,370
Ferry-ro-pax	7	4,628	1	0	0	85	73	10	4	4	1,486
General cargo	158	205,494	34	3	11	4,031	3,238	424	168	160	65,990
Liquefied gas tanker	2	12	0	0	0	0	0	0	0	0	4
Fishing vessel	159	72,808	15	2	4	1,724	1,147	179	78	89	23,381
Other	1	437	0	0	0	9	7	1	0	0	140
Offshore	6	2,043	0	0	0	40	32	4	2	1	656
Oil tanker	69	134,287	22	2	7	2,461	2,116	265	105	98	43,124
Refrigerated bulk	67	54,737	8	1	3	996	863	101	39	33	17,578
Ro-ro	10	4,526	1	0	0	87	71	9	3	3	1,453
Service vessel	33	48,085	9	1	3	1,075	758	111	47	51	15,441
Tug	11	3,821	1	0	0	83	60	9	4	4	1,227
Vehicle	11	91	0	0	0	2	1	0	0	0	29
Total	**2,086**	**1,376,027**	**193**	**58**	**69**	**27,784**	**12,771**	**1,826**	**1,254**	**1,281**	**436,427**

APPENDIX L. EMISSIONS (t) AND FUEL CONSUMPTION (t) FROM SHIP ACTIVITY WITHIN THE U.S. ARCTIC

	Ships	CO_2	BC	CH_4	N_2O	NO_x	SO_x	PM	CO	NMVOC	Fuel consumption
Distillate fuel	**118**	**32,389**	**3**	**1**	**1**	**596**	**28**	**11**	**31**	**31**	**10,103**
Cruise	3	535	0	0	0	10	0	0	0	0	167
Ferry-pax only	1	0	0	0	0	0	0	0	0	0	0
General cargo	3	351	0	0	0	7	0	0	0	0	109
Fishing vessel	36	1,847	0	0	0	37	2	1	2	1	576
Offshore	6	7,861	1	0	0	121	7	2	7	7	2,452
Oil tanker	1	4	0	0	0	0	0	0	0	0	1
Ro-ro	4	3,710	0	0	0	62	3	1	3	2	1,157
Service-other	16	10,007	1	0	0	191	9	3	10	10	3,121
Service-tug	46	7,863	1	0	0	164	7	3	9	10	2,452
Yacht	2	210	0	0	0	3	0	0	0	0	65
Residual fuel	**62**	**35,106**	**6**	**1**	**2**	**704**	**553**	**71**	**29**	**28**	**11,274**
Bulk carrier	28	6,493	1	0	0	147	102	14	5	6	2,085
Chemical tanker	5	4,727	1	0	0	96	75	9	3	3	1,518
Container	2	31	0	0	0	1	0	0	0	0	10
Cruise	3	2,402	0	0	0	41	38	5	2	1	771
General cargo	2	66	0	0	0	1	1	0	0	0	21
Fishing vessel	6	46	0	0	0	0	1	0	0	0	15
Offshore	1	933	0	0	0	17	15	2	1	1	299
Oil tanker	6	7,154	1	0	0	114	113	12	5	4	2,297
Service-other	5	12,337	2	0	1	267	194	27	11	11	3,962
Service-tug	4	918	0	0	0	20	14	3	1	2	295
Total	**180**	**67,495**	**9**	**1**	**3**	**1,300**	**581**	**82**	**60**	**59**	**21,376**

APPENDIX M. FUEL CARRIAGE BY SHIP CLASS

	Geographic Arctic				IMO Arctic				U.S. EEZ			
	Ships	% of total fleet	Fuel onboard (t)	% of total fuel onboard	Ships	% of total fleet	Fuel onboard (t)	% of total fuel onboard	Ships	% of total fleet	Fuel onboard (t)	% of total fuel onboard
Residual fuel	**4860**	**48%**	**4,935,454**	**85%**	**889**	**43%**	**827,347**	**76%**	**62**	**34%**	**71,284**	**74%**
Bulk carrier	1254	12%	1,733,928	30%	176	8%	247,540	23%	28	16%	41,939	44%
Chemical tanker	804	8%	493,774	8%	93	4%	51,756	5%	5	3%	3,728	4%
Container	282	3%	415,670	7%	43	2%	112,770	10%	2	1%	1,992	2%
Cruise	109	1%	132,258	2%	40	2%	40,566	4%	3	2%	907	1%
Ferry-pax only	6	0%	867	0%	3	0%	523	0%	—	—	—	—
Ferry-ro-pax	71	1%	50,876	1%	7	0%	3,134	0%	—	—	—	—
General cargo	827	8%	411,123	7%	158	8%	77,242	7%	2	1%	707	1%
Liquefied gas tanker	129	1%	93,544	2%	2	0%	2,133	0%	—	—	—	—
Fishing vessel	284	3%	107,875	2%	159	8%	67,558	6%	6	3%	5,223	5%
Other	1	0%	166	0%	1	0%	166	0%	—	—	—	—
Non propelled	2	0%	0	0%	—	—	—	—	—	—	—	—
Offshore	39	0%	25,813	0%	6	0%	2,238	0%	1	1%	327	0%
Oil tanker	624	6%	1,120,164	19%	69	3%	110,653	10%	6	3%	7,748	8%
Refrigerated bulk	170	2%	130,660	2%	67	3%	49,659	5%	—	—	—	—
Ro-ro	87	1%	64,920	1%	10	0%	6,489	1%	—	—	—	—
Service-other	87	1%	79,257	1%	33	2%	30,045	3%	5	3%	5,395	6%
Service-tug	37	0%	17,138	0%	11	1%	5,797	1%	4	2%	3,319	3%
Vehicle	45	0%	57,178	1%	11	1%	19,078	2%	—	—	—	—
Yacht	2	0%	244	0%	—	—	—	—	—	—	—	—
Distillate Fuel	**5141**	**51%**	**859,699**	**15%**	**1184**	**57%**	**251,514**	**23%**	**118**	**66%**	**24,460**	**26%**
Bulk carrier	32	0%	6,874	0%	5	0%	409	0%	—	—	—	—
Chemical tanker	67	1%	9,153	0%	15	1%	2,302	0%	—	—	—	—
Container	10	0%	3,375	0%	—	—	—	—	—	—	—	—
Cruise	44	0%	21,029	0%	22	1%	6,503	1%	3	2%	778	1%
Ferry-pax only	183	2%	20,279	0%	18	1%	1,713	0%	1	1%	11	0%
Ferry-ro-pax	292	3%	46,004	1%	29	1%	4,527	0%	—	—	—	—
General cargo	1203	12%	185,033	3%	85	4%	14,003	1%	3	2%	753	1%
Liquefied gas tanker	15	0%	2,609	0%	—	—	—	—	—	—	—	—
Fishing vessel	1619	16%	217,906	4%	596	29%	108,332	10%	36	20%	7,084	7%
Other	3	0%	540	0%	—	—	—	—	—	—	—	—
Non propelled	5	0%	75	0%	1	0%	15	0%	—	—	—	—
Offshore	459	5%	67,713	1%	55	3%	11,905	1%	6	3%	2,062	2%
Oil tanker	67	1%	7,110	0%	25	1%	2,709	0%	1	1%	256	0%
Other liquid tankers	3	0%	199	0%	—	—	—	—	—	—	—	—
Refrigerated bulk	43	0%	12,425	0%	23	1%	6,549	1%	—	—	—	—
Ro-ro	30	0%	8,666	0%	10	0%	1,303	0%	4	2%	562	1%
Service-other	524	5%	188,964	3%	160	8%	72,407	7%	16	9%	7,248	8%
Service-tug	462	5%	52,739	1%	127	6%	17,402	2%	46	26%	5,499	6%
Vehicle	6	0%	3,225	0%	—	—	—	—	—	—	—	—
Yacht	74	1%	5,779	0%	13	1%	1,436	0%	2	1%	209	0%
LNG	**93**	**1%**	**39,401**	**1%**	**9**	**0%**	**3,823**	**0%**				
Bulk carrier	1	0%	219	0%	—	—	—	—	—	—	—	—
Chemical tanker	3	0%	529	0%	1	0.%	92	0%	—	—	—	—
Ferry-pax only	3	0%	27	0%	—	—	—	—	—	—	—	—
Ferry-ro-pax	24	0%	3,677	0%	1	0.%	44	0%	—	—	—	—
General cargo	4	0%	181	0%	—	—	—	—	—	—	—	—
Liquefied gas tanker	28	0%	32,625	1%	2	0%	3,239	0%	—	—	—	—
Offshore	22	0%	1,047	0%	3	0%	119	0%	—	—	—	—
Ro-ro	2	0%	313	0%	—	—	—	—	—	—	—	—
Service-other	4	0%	562	0%	2	0.%	329	0%	—	—	—	—
Service-tug	2	0%	221	0%	—	—	—	—	—	—	—	—
Nuclear	**5**	**0.0%**	**4,833**	**0.1%**	**4**	**0.19%**	**2,766**	**0.25%**				
Cruise	1	0.0%	623	0.0%	1	0.05%	623	0.06%	—	—	—	—
General cargo	1	0.0%	2,067	0.0%	—	—	—	—	—	—	—	—
Service-other	3	0.0%	2,143	0.0%	3	0.14%	2,143	0.20%	—	—	—	—
Total	**10,099**	**100.0%**	**5,839,399**	**100.0%**	**2,086**	**100.0%**	**1,085,438**	**100.0%**	**180**	**100.0%**	**95,744**	**100.0%**

APPENDIX N. BLACK CARBON EMISSIONS BY FUEL AND SHIP CLASS

	Geographic Arctic				IMO Arctic				U.S. Arctic			
	Ships	% of total fleet	BC (t)	% of total BC emissions	Ships	% of total fleet	BC (t)	% of total BC emissions	Ships	% of total fleet	BC (t)	% of total BC emissions
Residual fuel	**4,860**	**48%**	**957**	**67%**	**889**	**43%**	**131**	**68%**	**62**	**34%**	**6**	**64%**
Bulk carrier	1254	12.4%	96.7	6.7%	176	8.4%	10.2	5.3%	28	15.6%	0.9	10.0%
Chemical tanker	804	8.0%	95.2	6.6%	93	4.5%	8.0	4.1%	5	2.8%	0.6	7.2%
Container	282	2.8%	75.2	5.2%	43	2.1%	6.5	3.4%	2	1.1%	0.0	0.1%
Cruise	109	1.1%	143.1	9.8%	40	1.9%	13.3	6.9%	3	1.7%	0.4	4.6%
Ferry-pax only	6	0.1%	1.4	0.1%	3	0.1%	0.8	0.4%	—	—	—	—
Ferry-ro-pax	71	0.7%	141.6	9.7%	7	0.3%	0.9	0.4%	—	—	—	—
General cargo	827	8.2%	103.6	7.1%	158	7.6%	34.2	17.7%	2	1.1%	0.0	0.1%
Liquefied gas tanker	129	1.3%	10.8	0.7%	2	0.1%	0.0	0.0%	—	—	—	—
Fishing vessel	284	2.8%	42.0	2.9%	159	7.6%	15.5	8.0%	6	3.3%	0.0	0.1%
Other	1	0.0%	0.1	0.0%	1	0.0%	0.1	0.0%	—	—	—	—
Non propelled	2	0.0%	0.0	0.0%	—	—	—	—	—	—	—	—
Offshore	39	0.4%	6.3	0.4%	6	0.3%	0.4	0.2%	1	0.6%	0.2	1.9%
Oil tanker	624	6.2%	135.2	9.3%	69	3.3%	22.4	11.6%	6	3.3%	1.0	11.2%
Refrigerated bulk	170	1.7%	34.1	2.3%	67	3.2%	8.2	4.2%	—	—	—	—
Ro-ro	87	0.9%	53.2	3.7%	10	0.5%	0.8	0.4%	—	—	—	—
Service-other	87	0.9%	20.6	1.4%	33	1.6%	9.3	4.8%	5	2.8%	2.3	26.0%
Service-tug	37	0.4%	2.9	0.2%	11	0.5%	0.8	0.4%	4	2.2%	0.2	2.6%
Vehicle	45	0.4%	3.8	0.3%	11	0.5%	0.0	0.0%	—	—	—	—
Yacht	2	0.0%	0.0	0.0%	—	—	—	—	—	—	—	—
Distillate fuel	**5,141**	**51%**	**484**	**33%**	**1,184**	**57%**	**62**	**32%**	**118**	**66%**	**3**	**36%**
Bulk carrier	32	0.3%	2.8	0.2%	5	0.2%	0.1	0.1%	—	—	—	—
Chemical tanker	67	0.7%	4.5	0.3%	15	0.7%	0.5	0.3%	—	—	—	—
Container	10	0.1%	0.8	0.1%	—	—	—	—	—	—	—	—
Cruise	44	0.4%	10.4	0.7%	22	1.1%	2.8	1.5%	3	1.7%	0.0	0.5%
Ferry-pax only	183	1.8%	21.3	1.5%	18	0.9%	1.0	0.5%	1	0.6%	0.0	0.0%
Ferry-ro-pax	292	2.9%	66.6	4.6%	29	1.4%	0.0	0.0%	—	—	—	—
General cargo	1203	11.9%	63.5	4.4%	85	4.1%	1.9	1.0%	3	1.7%	0.0	0.4%
Liquefied gas tanker	15	0.1%	0.6	0.0%	—	—	—	—	—	—	—	—
Fishing vessel	1619	16.0%	149.2	10.3%	596	28.6%	31.9	16.5%	36	20.0%	0.2	1.9%
Other	3	0.0%	0.1	0.0%	—	—	—	—	—	—	—	—
Non propelled	5	0.0%	0.0	0.0%	1	0.0%	0.0	0.0%	—	—	—	—
Offshore	459	4.5%	58.5	4.0%	55	2.6%	1.9	1.0%	6	3.3%	0.7	8.4%
Oil tanker	67	0.7%	5.9	0.4%	25	1.2%	0.5	0.3%	1	0.6%	0.0	0.0%
Other liquid tankers	3	0.0%	1.3	0.1%	—	—	—	—	—	—	—	—
Refrigerated bulk	43	0.4%	13.0	0.9%	23	1.1%	3.1	1.6%	—	—	—	—
Ro-ro	30	0.3%	12.7	0.9%	10	0.5%	0.5	0.3%	4	2.2%	0.3	3.6%
Service-other	524	5.2%	54.9	3.8%	160	7.7%	14.3	7.4%	16	8.9%	1.0	11.4%
Service-tug	462	4.6%	16.5	1.1%	127	6.1%	3.1	1.6%	46	25.6%	0.9	10.0%
Vehicle	6	0.1%	1.6	0.1%	—	—	—	—	—	—	—	—
Yacht	74	0.7%	0.7	0.1%	13	0.6%	0.2	0.1%	2	1.1%	0.0	0.2%
LNG	**93**	**1%**	**2**	**0.2%**	**9**	**0.5%**	**<0.1**	**0%**	**—**	**—**	**—**	**—**
Bulk carrier	1	0.0%	0.0	0.0%	—	—	—	—	—	—	—	—
Chemical tanker	3	0.0%	0.1	0.0%	1	0.1%	0.0	0.00%	—	—	—	—
Ferry-pax only	3	0.0%	0.0	0.0%	—	—	—	—	—	—	—	—
Ferry-ro-pax	24	0.2%	1.2	0.1%	1	0.1%	0.0	0.00%	—	—	—	—
General cargo	4	0.0%	0.1	0.0%	—	—	—	—	—	—	—	—
Liquefied gas tanker	28	0.3%	0.5	0.0%	2	0.1%	—	—	—	—	—	—
Offshore	22	0.2%	0.3	0.0%	3	0.1%	0.0	0.00%	—	—	—	—
Ro-ro	2	0.0%	0.0	0.0%	—	—	—	—	—	—	—	—
Service-other	4	0.0%	0.0	0.0%	2	0.1%	0.0	0.00%	—	—	—	—
Service-tug	2	0.0%	0.0	0.0%	—	—	—	—	—	—	—	—
Nuclear	**5**	**0.0%**	**—**	**0.00%**	**4**	**0.2%**	**—**	**0.00%**	**—**	**—**	**—**	**—**
Cruise	1	0.0%	—	0.00%	1	0.1%	—	0.00%	—	—	—	—
General cargo	1	0.0%	—	0.00%	—	—	—	—	—	—	—	—
Service-other	3	0.0%	—	0.00%	3	0.1%	—	0.00%	—	—	—	—
Total	**10,099**	**100%**	**1,453**	**100%**	**2,086**	**100%**	**191.45**	**100%**	**180**	**100%**	**9**	**100%**

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