OCTOBER 2017

GREENHOUSE GAS EMISSIONS FROM GLOBAL SHIPPING, 2013–2015

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ACKNOWLEDGMENTS

The authors thank Tristan Smith, Jasper Faber, Renske Schuitmaker, Jan Holskotte, Jen Fela, and Joe Schultz for their review and support. The authors would like to acknowledge exactEarth for providing satellite Automatic Identification System data and processing support, and Global Fishing Watch and IHS Fairplay for contributing vessel characteristics data. This study was funded through the generous support of the ClimateWorks Foundation.

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EXECUTIVE SUMMARY

Reducing greenhouse gas (GHG) emissions is the key to avoiding the most catastrophic impacts of climate change. Countries have committed to reducing their GHG emissions under the Paris Agreement, which aims to limit global warming to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C. Despite international shipping being excluded from the Paris Agreement, the International Maritime Organization (IMO) is developing its own strategy to reduce GHGs from ships. IMO member states will need to understand recent trends in ship activity and emissions to develop an effective strategy.

We know that ships accounted for approximately 1 billion tonnes of GHG emissions over the period 2007 to 2012 (Smith et al., 2015). However, we do not know how much GHG ships emitted in recent years. Other information, including which ship classes emit the most GHG and under the jurisdiction of which flag states, should also be updated. Finally, policymakers would benefit from the most recent understanding of the drivers of shipping emissions (e.g., transport demand, ship capacity, and speed), in order to make informed decisions. By considering this information, IMO is more likely to reduce GHG emissions from international shipping in a targeted and cost-effective way.

In this report, we describe trends in global ship activity and emissions for the years 2013 to 2015. Specifically, we estimate fuel consumption, carbon dioxide (CO_2), other GHGs, operational efficiency, energy use, installed power, cargo carrying capacity, operating hours, distance traveled, and operating speed. We found that emissions generally increased over this period, with efficiency improvements more than offset by increases in activity. Key findings are highlighted below.

FUEL CONSUMPTION IS INCREASING

Total shipping fuel consumption increased from 291 million tonnes to 298 million tonnes (+2.4%) from 2013 to 2015, compared to a 7% increase in transport supply (dwt-nm). Like the Third IMO GHG Study (Smith et al., 2015), our bottom-up (activity-based) fuel consumption estimates are systematically higher than the International Energy Agency's (IEA's) top-down fuel consumption estimates (Figure ES-1). However, the gap between our bottom-up estimates and IEA's top-down findings is smaller than IMO's. This is likely a result of improving AIS data coverage over time, which reduces the uncertainty in bottom-up estimates. Overall, bottom-up emissions remain below the 2008 peak estimated in the Third IMO GHG Study, although there are minor differences in methodologies across the bottom-up ICCT and IMO studies.

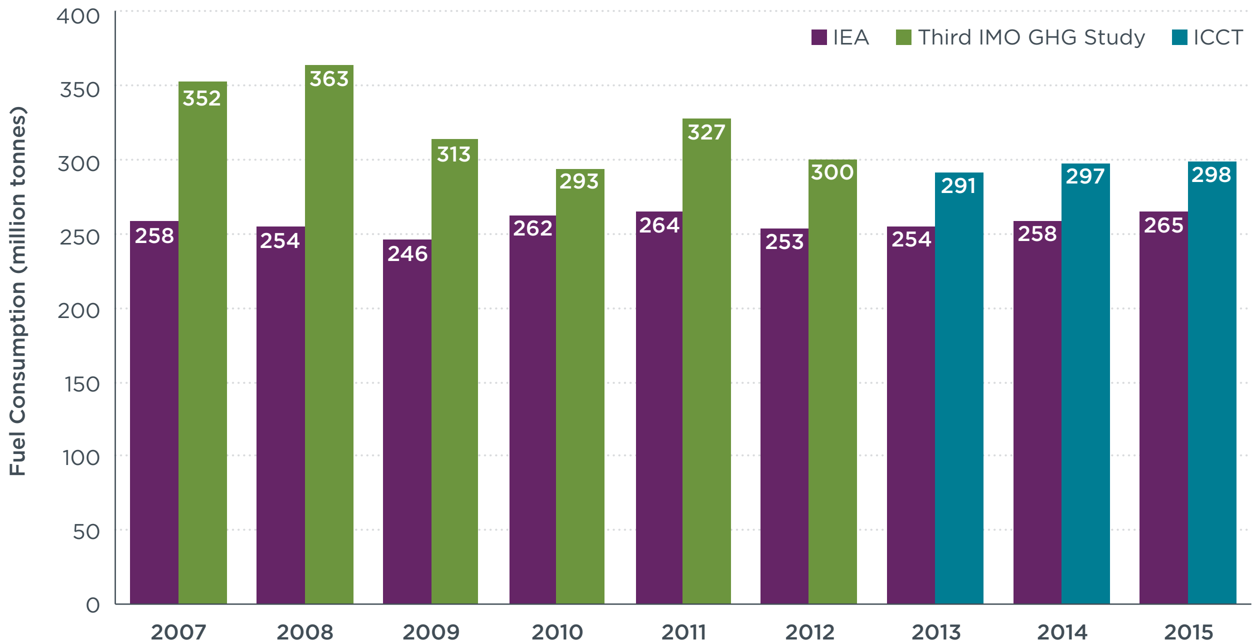

Figure ES-1. Total shipping fuel consumption estimates from IEA, IMO, and ICCT, 2007–2015

CO_2 AND OTHER CLIMATE POLLUTANT EMISSIONS ARE INCREASING

Total shipping CO_2 emissions increased from 910 million tonnes to 932 million tonnes (+2.4%) from 2013 to 2015 (Table ES-1). International shipping emissions increased by 1.4%; domestic shipping emissions increased by 6.8%; and fishing emissions increased by 17%. In 2015, total shipping emissions were responsible for 2.6% of global CO_2 emissions from fossil fuel use and industrial processes. International shipping contributed the most, representing about 87% of total CO_2 emissions from ships each year. If treated as a country, international shipping would have been the sixth largest emitter of energy-related CO_2 in 2015, just above Germany (Olivier, Janssens-Maenhout, Muntean, & Peters, 2016).

Table ES-1. Shipping CO_2 emissions compared to global CO_2 emissions

	Third IMO GHG Study (million tonnes)						ICCT (million tonnes)		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Global CO_2 Emissions*	**31,959**	**32,133**	**31,822**	**33,661**	**34,726**	**34,968**	**35,672**	**36,084**	**36,062**
International Shipping	881	916	858	773	853	805	801	813	812
Domestic Shipping	133	139	75	83	110	87	73	78	78
Fishing	86	80	44	58	58	51	36	39	42
Total Shipping % of global	**1,100** 3.5%	**1,135** 3.5%	**977** 3.1%	**914** 2.7%	**1,021** 2.9%	**942** 2.6%	**910** 2.5%	**930** 2.6%	**932** 2.6%

**Global CO_2 estimates include CO_2 from fossil fuel use and industrial processes (EDGAR, 2017).*

Ship CO_2-eq emissions also increased from 2013–2015, increasing by 2.5% over that period. On a 100-year timescale, ship CO_2-eq emissions increased from 1,000 million tonnes to 1,025 million tonnes. Similarly, on a 20-year timescale, CO_2-eq emissions increased from 1,189 million tonnes to 1,222 million tonnes.

THREE SHIP CLASSES AND SIX FLAG STATES ACCOUNT FOR MOST CO_2 EMISSIONS

Three ship classes accounted for 55% of the total shipping CO_2 emissions: container ships (23%), bulk carriers (19%), and oil tankers (13%), as shown in Figure ES-2. These three ship classes also accounted for 84% of total shipping transport supply (deadweight tonne nautical miles, or dwt-nm). Similarly, out of the 223 flag states, most CO_2 emissions can be attributed to ships flying six flags: Panama (15%), China (11%), Liberia (9%), Marshall Islands (7%), Singapore (6%), and Malta (5%). These flags also have large numbers of ships registered to them and account for 66% of the global shipping fleet's deadweight tonnage. Although all ships and flags have a role to play in combating climate change, reducing emissions will require addressing these major ship classes and flags in a way that minimizes both impacts on vulnerable states and potential competitive distortions.

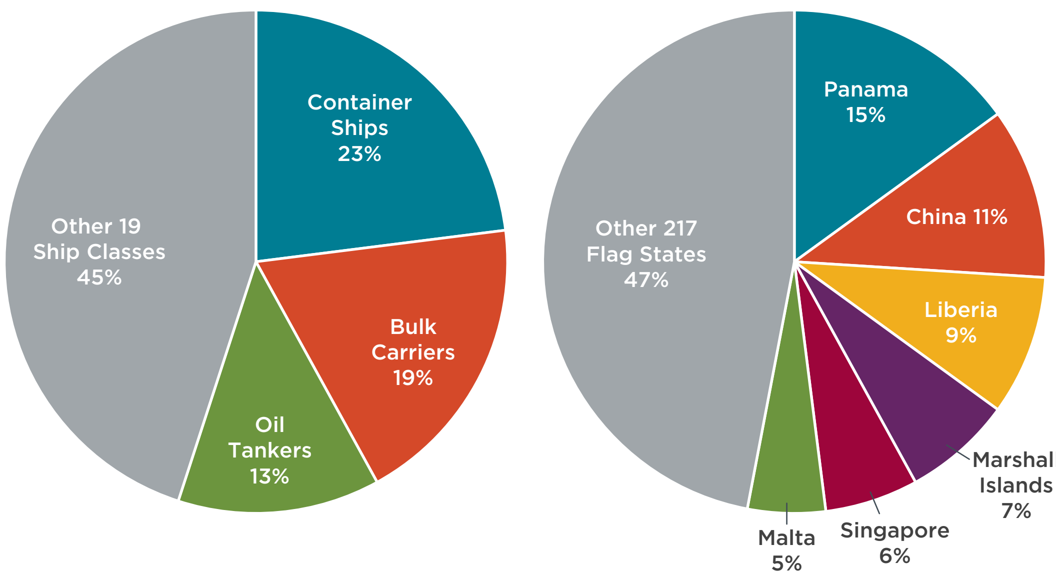

Figure ES-2. Share of CO_2 emissions by ship class (left) and flag state (right), 2013–2015

BLACK CARBON IS A MAJOR CONTRIBUTOR TO SHIPPING'S CLIMATE IMPACTS

After CO_2, black carbon (BC) contributes the most to the climate impact of shipping, representing 7% of total shipping CO_2-eq emissions on a 100-year timescale and 21% of CO_2-eq emissions on a 20-year time scale (Figure ES-3). Because BC is a short-lived climate pollutant, reducing BC emissions from ships would immediately reduce shipping's climate impacts. Until now, BC has been largely ignored as a climate pollutant from ships. In this study, we report the "missing inventory" of BC emissions that ought to be considered when evaluating the climate impacts of shipping.

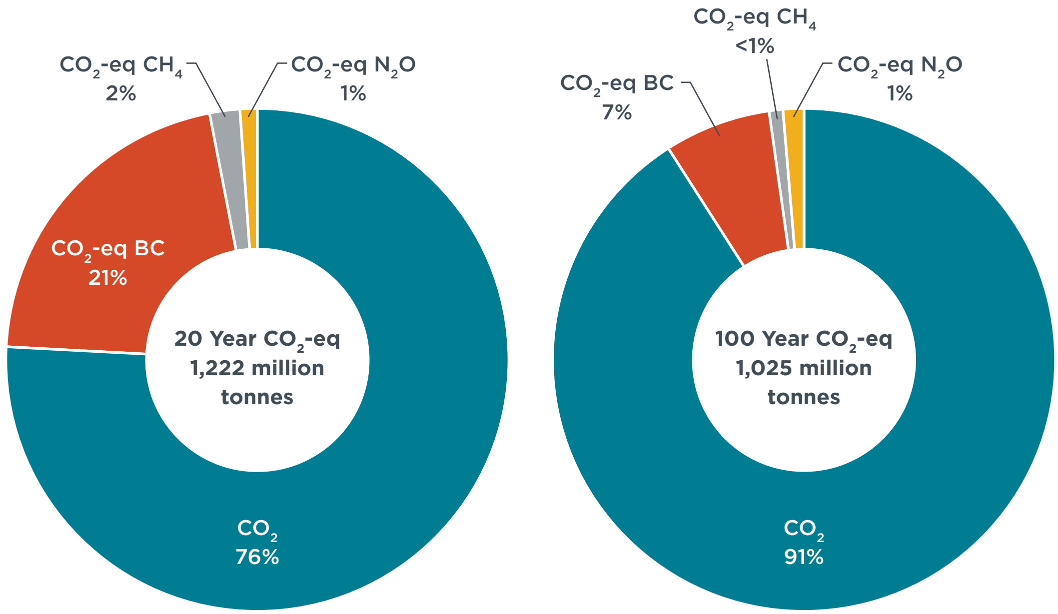

Figure ES-3. Total shipping CO_2-eq emissions, 20-year and 100-year GWP, 2015

INCREASES IN EFFICIENCY HAVE NOT REDUCED ABSOLUTE CO_2 EMISSIONS FROM SHIPS

Although the CO_2 intensity of many major ship classes decreased (i.e., they became more efficient) from 2013 to 2015, total CO_2 emissions from ships increased. Even in some cases where a ship class became much more efficient, their CO_2 emissions increased. For example, although the CO_2 intensity of general cargo ships (measured as emissions per unit of transport supply) decreased by 5%, CO_2 emissions increased by 9% (Figure ES-4). Thus, increases in distance traveled due to a greater demand for shipping more than offset gains in operational efficiency during the period studied. As an example, the CO_2 intensities of bulk carriers and container ships decreased (improved) by 6% and 9%, respectively, from 2013 to 2015, but their total CO_2 emissions dropped less than 1%. That is because the overall transport supply (dwt-nm) for shipping increased by about 6% for container ships and 9% for oil tankers. Only refrigerated bulk carriers managed to reduce their CO_2 emissions by a greater percentage than they reduced their CO_2 intensity, owing to a 5% drop in overall supply for these ships from 2013 to 2015. The disconnect between CO_2 intensity and total emissions suggests that business as usual improvements in energy efficiency are unlikely to yield substantial reductions in CO_2 emissions from ships.

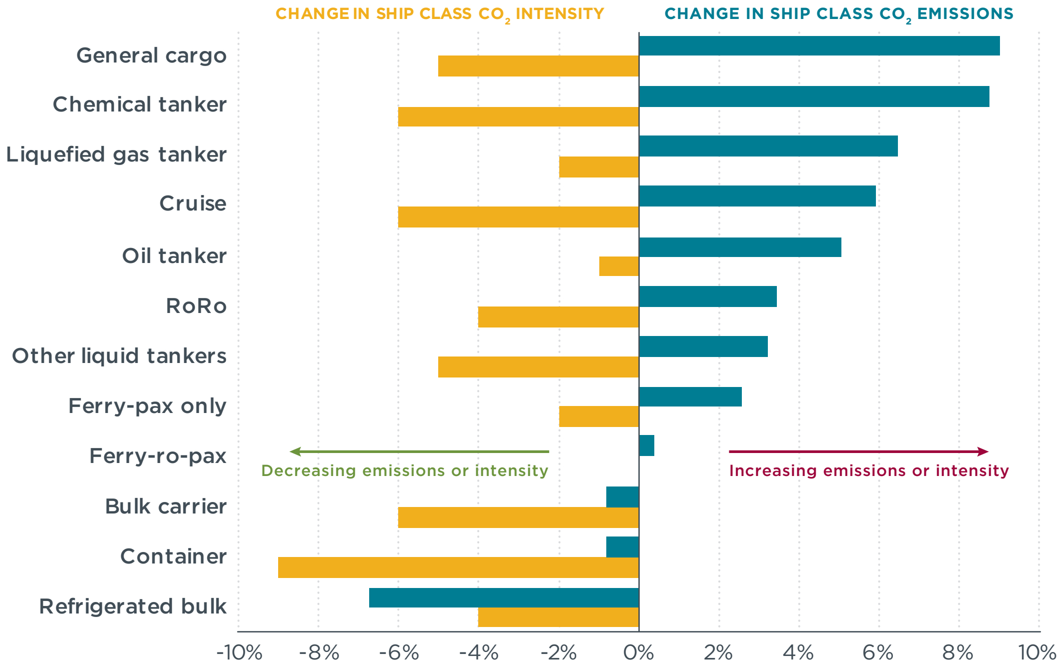

Figure ES-4. Change in CO_2 emissions and CO_2 intensity for key ship classes

THE BIGGEST SHIPS ARE SPEEDING UP AND POLLUTING MORE

Whereas average ship cruising speeds remained largely unchanged between 2013 and 2015, the largest oil tankers (>200,000 dwt) and the largest container ships (>14,500 TEU) sped up. In fact, the largest oil tankers increased their cruising speed over ground (SOG) by nearly 4%, and the largest container ships increased their cruising SOG by more than 11% (Figure ES-5). As these ships speed up, they cover greater distances in a shorter amount of time. They also consume more fuel and emit more CO_2. In fact, while the carbon intensity of oil tankers and container ships *as a class* decreased (became more efficient), the carbon intensity of the largest oil tankers and container ships increased (became less efficient) from 2013 to 2015, with >200,000 dwt oil tankers emitting 1% more CO_2/dwt-nm in 2015 and >14,500 TEU container ships emitting 18% more CO_2/dwt-nm in 2015. From an emissions perspective, this is worrisome because if more ships follow suit and speed up, the CO_2 efficiency of the maritime transport sector will degrade. We already see a statistically significant increase in ship speeds for the next largest oil tankers: +2.3% for 120,000–199,999 dwt and +1.4% for 80,000–119,999 dwt (see the supplemental information[1] for more details).

1 Supplemental information as well as a detailed methodology for this report is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

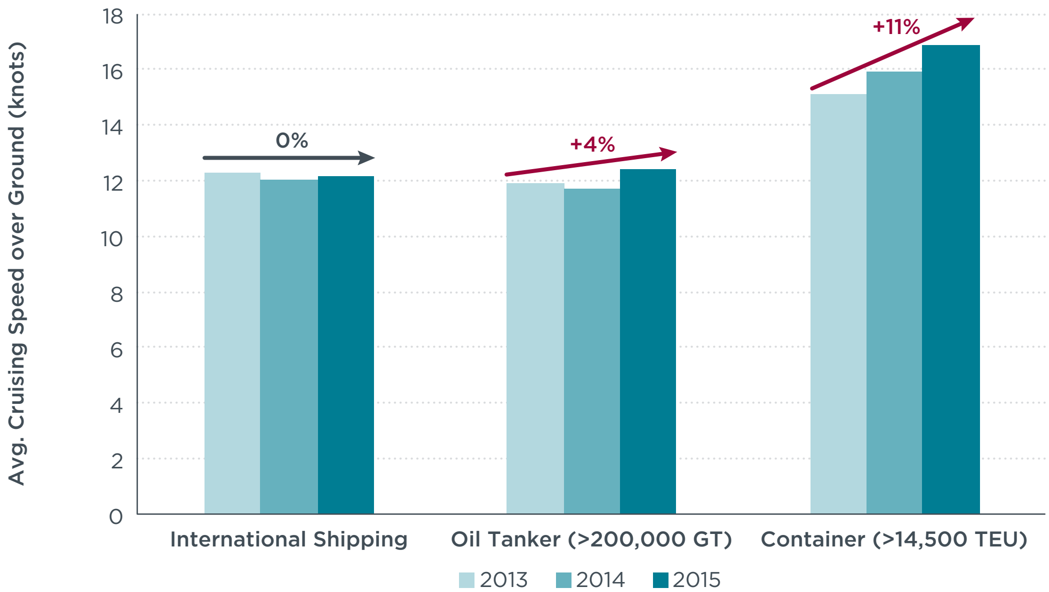

Figure ES-5. Changes in speed over ground for the largest oil tankers and container ships vs the international shipping average, 2013–2015

To summarize:

- **Shipping GHG emissions are increasing despite improvements in operational efficiency for many ship classes**. Increasing emissions are being driven by rising demand for shipping and the associated consumption of fossil fuels.
- **Emissions are concentrated in a handful of ship classes and flag states**. Just three ship classes (container ships, bulk carriers, and oil tankers) account for 55% of CO_2 emissions. Similarly, six flag states (Panama, China, Liberia, Marshall Islands, Singapore, and Malta) account for 52% of CO_2 emissions.
- **Black carbon is a major contributor to shipping's climate impacts**. On a 20-year timescale, BC accounts for 21% of CO_2-eq emissions from ships.
- **The biggest ships are speeding up and emitting more GHGs.** Unlike most ships, the largest container and oil tankers sped up between 2013 and 2015 and became less efficient, emitting more CO_2/dwt-nm in 2015 than they did in 2013. As more ships follow their lead, shipping efficiency will drop and ship emissions will continue to rise.
- **Absolute reductions in ship emissions will require concerted action to improve the energy efficiency of shipping and to develop and deploy alternative fuel and propulsion concepts.** The only way to reduce emissions from ships without constraining demand is to substantially reduce the amount of CO_2 and CO_2-eq emitted per unit of transport supply.

1 INTRODUCTION

Reducing greenhouse gas (GHG) emissions is the key to avoiding the most catastrophic impacts of climate change. Countries have committed to reducing their GHG emissions under the Paris Agreement, which aims to limit global warming to well below 2°C above pre-industrial levels and to pursue efforts to limit the increase to 1.5°C. Despite international shipping being excluded from the Paris Agreement, the International Maritime Organization (IMO) is developing its own strategy to reduce GHGs[2] from ships. IMO member states will need to understand recent trends in ship activity and emissions to develop an effective strategy.

We know that ships accounted for approximately 1 billion tonnes of GHG emissions over the period 2007 to 2012 (Smith et al., 2015). However, we do not know how much GHG ships emitted in recent years. Other information, including which ship classes emit the most GHG and under the jurisdiction of which flag states, should also be updated. Finally, policymakers would benefit from the most recent understanding of the drivers of shipping emissions (e.g., transport demand, ship capacity, and speed), in order to make informed decisions. By considering this information, IMO is more likely to reduce GHG emissions from international shipping in a targeted and cost-effective way.

In this report, we describe trends in global ship activity and emissions for the years 2013 to 2015. Specifically, we estimate fuel consumption, CO_2, other climate pollutants, operational efficiency, energy use, installed power, cargo carrying capacity, operating hours, distance traveled, and operating speed. We found that emissions generally increased over this period, with increases in efficiency more than offset by increases in activity.

The webpage for this report contains a detailed methodology and supplemental information.[3]

2 For the purposes of this study, GHG emissions from global shipping is assumed to include carbon dioxide, methane, nitrous oxide, and black carbon (BC). Although BC is not strictly a gas, for the purposes of simplicity we include it as in our definition of GHG in this report.

3 A detailed methodology for this report, as well as supplemental information, is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

2 BACKGROUND

2.1 GHG EMISSIONS FROM SHIPS

Ships are responsible for roughly 3% of global CO_2 and GHG emissions (CO_2-eq), emitting approximately 1 billion tonnes of CO_2 and GHGs per year, on average from 2007 to 2012 (Smith et al., 2015). Ship emissions are expected to increase in both absolute terms and in shipping's share of global CO_2 and GHG emissions. Smith et al. (2015) estimate that ship CO_2 emissions will increase 50%–250% from 2012 to 2050, and CE Delft (2017) projects that emissions will increase 20%–120% over the same period for global temperature rise scenarios less than 2°C. The actual increase will depend on future social and economic conditions. Under all scenarios, however, shipping emissions are expected to increase. As other sectors reduce their GHG emissions, shipping will account for an increasingly large share of global climate pollution. Without further action, the international shipping sector could account for 17% of global CO_2 emissions in 2050 (Cames, Graichen, Siemons, & Cook, 2015).

2.2 EXISTING REGULATIONS THAT REDUCE GHGS FROM SHIPS

The IMO is responsible for regulating the global shipping sector. To date, there is only one IMO regulation mandating improvements in ship energy efficiency: the Energy Efficiency Design Index (EEDI).[4] The EEDI mandates that new ship designs become more energy efficient over time. The EEDI entered into force in 2013 and applies to many of the largest ships engaged in international shipping. Essentially, the EEDI requires new ships to emit less CO_2 per unit of "transport work," typically described as g CO_2/dwt-nm. Ships built between 2015 and 2019 are required to be 10% more efficient than a baseline of ships built between 1999 and 2009. Subsequently, ships built between 2020 and 2024 must be 20% more efficient, and those built in 2025 or later must be 30% more efficient than the baseline.

Evidence suggests that these EEDI targets can be further strengthened for key ship types because the EEDI baseline was artificially weak (Faber & 't Hoen, 2015). IMO member states have proposed tightening the existing EEDI standards. Others have advocated for moving up the implementation date of Phase 3 (30%) EEDI standards from 2025 to 2022 and then creating a new, more stringent "Phase 4" EEDI standard for 2025. The IMO has not agreed to change the EEDI yet. In any case, because the EEDI only applies only to new ships, it cannot meaningfully reduce GHGs from the shipping sector in the short term. Even in the long-term, the EEDI, as currently designed, is expected to reduce shipping's cumulative CO_2 emissions by only 3% over the period 2010 to 2050 (Smith et al., 2016). Unfortunately, the EEDI alone is not enough to reverse the trend of increasing CO_2 and GHG emissions from ships (IEA, 2017; Smith et al., 2015, 2016).

2.3 IMO STRATEGY TO REDUCE GHG EMISSIONS FROM SHIPS

IMO member states and organizations are developing a roadmap to determine the amount of GHG emissions that need to be reduced from the shipping sector, by when, and by what means. The IMO will deliver an initial comprehensive strategy to reduce GHG emissions from shipping in 2018, with a final strategy in 2023. Opinions differ

4 Two other IMO regulations, the Ship Energy Efficiency Management Plan (SEEMP) and Fuel Consumption Data Collection System (DCS), impose planning rather than substantive requirements for operational efficiency and the collection and reporting of marine fuel consumption by in-service vessels, respectively.

on the level of ambition and implementation mode (aspirational vs. binding targets) to be included in the strategy. In their submission to the 71st meeting of IMO's Marine Environmental Protection Committee (MEPC), the Marshall Islands and Solomon Islands (2017) called for a high level of ambition to be incorporated into IMO's GHG strategy, including an overall "fair share" global target for shipping. In contrast, other countries oppose IMO adopting a sectoral emissions target for international shipping. A third approach, championed by Japan (2017), calls for aspirational short- and long-term goals for international shipping. Specifically, Japan calls for a reduction in CO_2 emissions per unit transport work[5] of 40% by 2030, and a reduction of net CO_2 emissions from international shipping by 50%, both from 2008 levels.

IMO member states are still debating what the strategy will look like, but we do know that the strategy will include short-, mid-, and long-term measures to reduce GHGs. Given that existing ship energy-efficiency policies that apply only to new ships (the EEDI) will take a long time to work their way through the in-service fleet, it will be particularly important to reduce emissions from the existing fleet. In the short term, limiting ship speeds can immediately reduce GHG emissions. Main engine power demand is proportional to the cube of the speed; as the ship's speed decreases, its main engine power demand falls even more rapidly, reducing fuel consumption and emissions. Various studies (Faber, Nelissen, Hon, Wang, & Tsimplis, 2013; Maddox Consulting, 2012; Yuan, Ng, & Sou, 2016) found that slowing down is a cost-effective way to reduce GHG emissions.

In the mid- and long-term, new marine propulsion technologies and low-carbon and zero-carbon fuels will be needed to decarbonize the sector. At the moment, existing regulations provide little incentive to invest in research and development of new technologies and fuels. DNV-GL's recent study Low Carbon Shipping Towards 2050 (Chryssakis et al., 2017), highlights that although scrubbers might be a financially attractive option for complying with the upcoming 0.5% global fuel sulfur cap in 2020, such a strategy will not allow significant reductions in GHG emissions because ship owners will be "locked in" to using carbon-intensive bunker fuels over the life of the ship. Furthermore, the study also recommends biofuel as one of the least carbon-intensive fuels, and proposes developing future market-based measures (MBMs) to counter their price differentials to fossil fuels. Similar thoughts are echoed by Bouman, Lindstad, Rialland, & Strømman (2017), who regard biofuels as the key to decarbonizing the marine transportation system.

The Institute of Marine Engineering, Science and Technology (IMarEST) and the Royal Institution of Naval Architects (RINA) (2017) estimate that the operational efficiency, as measured by the Energy Efficiency Operational Index (EEOI), of ships in 2015 can be reduced (improved) by 7.5% to 19.4% from 2010 levels using available technologies, but that advanced wind technologies and low-carbon fuels would be needed to achieve large (54% to 90%) reductions. Thus, there needs to be some driver to encourage a shift toward low-carbon technologies and fuels. Some sort of MBM could be used to accelerate decarbonization and research and development of alternative technologies and fuels.

5 Japan has proposed the use of the Annual Efficiency Ratio (AER), which uses deadweight tonnage (dwt) as a proxy for cargo carriage, as a means to monitor operational efficiency performance. The AER is expressed in grams of CO_2 emitted per deadweight tonne-nautical mile, similar to the operational efficiency metric used in this report. Assuming no change in the utilization (loading) of ships over time, dwt-nm can be considered as a proxy for transport work; in this study, we refer to dwt-nm as a measure of transport supply to distinguish it from direct measurements of transport work or demand, as typically expressed in units of cargo mass moved times a distance.

3 METHODOLOGY

This report presents trends in ship CO_2 and CO_2-eq intensity (g/dwt-nm and g/GT-nm) along with operating speed (kts) for the years 2013, 2014, and 2015. Using exactEarth satellite AIS data along with ship characteristics data from two databases—IHS ShipData and Global Fishing Watch (GFW)—we also estimated gross emissions of CO_2, methane (CH_4), nitrous oxide (N_2O), and black carbon (BC), among other pollutants. Fuel consumption by fuel type (residual, distillate, and LNG) is also calculated. A brief overview of the methodology is found in this section. A detailed explanation of the methodology is available as a separate document, available for download at the ICCT website.[6]

3.1 DATASET PREPARATION

We used three main datasets in this study: (1) terrestrial and satellite Automatic Identification System (AIS) data from exactEarth, (2) ship characteristics data from the IHS ShipData database, and (3) ship characteristics data from GFW. AIS data reported the hourly location, speed, and draught for individual ships. The IHS and GFW data provided ship-specific characteristics that can be used to estimate a ship's energy demand and emissions. Each dataset includes a field for the ship's unique identification number (IMO number) or the unique identification number of its AIS transponder (MMSI number). We used these identification numbers to match the AIS ship activity data to a unique ship in the IHS and GFW databases.

We estimated emissions for three types of data: Type 1, Type 2, and Type 3, as summarized in Table 1.

Type 1: Starting with the AIS data and the IHS database, we were able to identify the ships that accounted for 55% of the hourly AIS signals, which equates to 756 million data points. From those signals, we removed records that had invalid latitudes or longitudes or unreasonably high speeds over ground. Of the 756 million data points, 0.12% had an invalid latitude, 0.54% had an invalid longitude, and 0.18% had an invalid SOG. We then interpolated missing AIS signals. Few ships have unbroken coverage in their activity for all 3 years, either because the ship turned off its AIS transponder or because its signals were not successfully picked up. To account for activity occurring during these missing hours and to geospatially allocate all emissions for each ship, we linearly interpolated the ship's position and speed over ground assuming great circle distance travel between valid AIS points. An hourly speed adjustment factor for each ship was then introduced to correct for underestimated speeds due to circuitous routing. Linearly interpolated positions represent 54% of total records in the inventory. For ferries, tugs, and fishing vessels, the SOG was not linearly interpolated, but taken as a random sample of all valid SOGs for each individual ship.[7] Overall, the AIS data

6 A detailed methodology for this report, as well as supplemental information, is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

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

matched to the IHS data, plus the interpolated data, are the most detailed and we have the greatest confidence in the emissions and activity estimated with this "Type 1" data.

Type 2: For the remaining, unidentified AIS signals, we were able to identify the type and size (GT) of the ships emitting 70% of those signals. Using that information, we described each ship as either international, domestic, or fishing (see Table 2 for the assigned categories). For the other 30% of unidentified AIS signals, we assumed that the proportion of signals that were international, domestic, or fishing was the same. This gave us a data set of hourly activity for international, domestic, and fishing ships, which we call Type 2 data. To estimate emissions from these ships, we developed hourly emissions rates for similarly sized international, domestic, and fishing ships from the Type 1 data and applied those to the Type 2 data. This gave us an estimate of emissions and fuel consumption for ships that we observed in the AIS data but could not identify using the IHS database.

Type 3: Finally, we estimated emissions from small ships (<300 GT) that were listed as "in-service" in the IHS database but that we did not observe in the AIS data. We call this Type 3 data. We focused on <300 GT ships because ships 300 GT and larger are required to have an AIS transponder, meaning that we should have seen them in the AIS dataset and, if not, we assumed they were not in service. Ships <300 GT are not required to have an AIS transponder and could be operating without appearing in the AIS data. We assumed these vessels emitted the same average emissions per hour as ships of their ship type (which is a more specific categorization than "ship class") and capacity bin (size) in the Type 1 data. In cases where there was no valid average annual emission rate for a specific ship type and capacity bin, the average annual emission rate for the ship class and capacity bin was used instead.

From these Type 1, 2, and 3 data, we estimated ship activity, emissions, and fuel consumption for ships in 2013, 2014, and 2015. The metrics we can measure using each type of data are summarized in Table 3.

Table 1. Data used in this inventory

Data Type	Description
Type 1	AIS data matched to a vessel in the IHS ship characteristics database
Type 2	AIS data matched to Global Fishing Watch ship characteristics database
Type 3	Vessels < 300 GT in the IHS database that are not matched to signals in the AIS database

Table 2. How ships are assigned to international, domestic, and fishing categories

Category	Ship classes	Gross tonnages
International	Passenger ferries, roll on-passenger ferries	≥2,000 GT
International	Bulk carrier, chemical tanker, container, cruise, general cargo, liquefied gas tanker, oil tanker, other liquid tankers, refrigerated bulk, Ro-Ro, vehicle	All
Domestic	Passenger ferries, roll on-passenger ferries	<2,000 GT
Domestic	Miscellaneous-other, offshore, service-other, service-tug, yacht	All
Fishing	Miscellaneous-fishing	All

Table 3. Metrics each data type contains

Metric	Type 1	Type 2	Type 3
Number of ships	✓	✓	✓
Gross tonnage (GT)	✓	✓	✓
Deadweight tonnage (dwt)	✓		✓
Distance traveled (nm)	✓		
Operating hours (h)	✓	✓	
Transport supply (dwt-nm or GT-nm)	✓		
Main engine power (kW)	✓		✓
Carbon dioxide (CO_2, tonnes)	✓	✓	✓
Black carbon (BC, tonnes)	✓	✓	✓
Methane (CH_4, tonnes)	✓	✓	✓
Nitrous oxide (N_2O, tonnes)	✓	✓	✓
Nitrogen oxides (NO_x, tonnes)	✓	✓	✓
Sulfur oxides (SO_x, tonnes)	✓	✓	✓
Carbon monoxide (CO, tonnes)	✓	✓	✓
Non-methane volatile organic compounds (NMVOC, tonnes)	✓	✓	✓
Distillate fuel consumption (tonnes)	✓		✓
Residual fuel consumption (tonnes)	✓		✓
LNG fuel consumption (tonnes)	✓		✓
Total fuel consumption (tonnes)	✓	✓	✓
Average cruising SOG (kts)	✓		
Average cruising main engine load factor (%)	✓		
Speed over ground-to-design-speed ratio	✓		
CO_2 intensity (g CO_2/dwt-nm or g CO_2/GT-nm)	✓		
20-year CO_2-eq intensity (g CO_2-eq/dwt-nm or g CO_2-eq/GT-nm)	✓		
100-year CO_2-eq intensity (g CO_2-eq/dwt-nm or g CO_2-eq/GT-nm)	✓		

3.2 ESTIMATING EMISSIONS

3.2.1 Emission factors

This analysis uses all other air emission factors from the Third IMO GHG Study 2014 (Smith et al., 2015), with a few exceptions. One key difference is that we estimate BC emissions, whereas the Third IMO GHG Study 2014 did not. We developed a range of main engine BC emission factors (EFs) for slow-, medium-, and high-speed diesel engines as a function of engine stroke type, fuel type, and engine load, as described in the detailed methodology.[8] Black carbon EFs for other engine types (gas and steam turbines, LNG-Otto cycle, and LNG-Diesel cycle) are taken from Comer, Olmer, Mao, Roy, & Rutherford (in press).

8 A detailed methodology for this report, as well as supplemental information, is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

Emissions factors tend to increase at low loads. Low-load adjustment factors from the Third IMO GHG Study 2014 were applied when estimated main engine load fell below 20% for all pollutants except BC, which is not estimated in the IMO study. In this case, BC EFs are determined from equations that already account for changes in BC EFs as a function of engine load, as described in Comer et al. (in press) and in the detailed methodology.[9]

3.2.2 Estimating emissions of all pollutants except black carbon

Emissions from ships come from main engines (MEs), auxiliary engines (AEs), and boilers (BOs). In the following equations, ME power demand is a function of installed ME power and ME load factor; AE and BO power demand depends on the ship class and capacity bin and the phase in which the ship is operating (cruise, maneuver, anchor, or berth). AE and BO power demand assumptions are the same as those in Smith et al. (2015), as described in the detailed methodology.[10] Emissions for all air pollutants except BC are estimated according to the following equation:

$$E_{i,j} = \sum_{t=0}^{t=n} ((P_{ME_i} * LF_{i,t} * EF_{ME_{j,k,l,m}} + DA_{E_{p,i,t}} * EF_{AE_{j,k,l,m}} + D_{BO_{p,i,t}} * EF_{BO_{j,m}}) * 1 \text{ hour})$$

where:

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

Load factor (LF) is a function of the SOG at time *t* modified by a speed adjustment factor that corrects for underestimating SOG for interpolated AIS signals, a hull fouling factor that accounts for increasing hydrodynamic resistance due to hull fouling as the ship ages and as biofouling builds up between drydock, a weather factor that accounts for increased main engine power demand when the ship encounters bad weather, and a draught adjustment factor that reduces the load factor when the ship is light loaded. A description of how we developed each adjustment factor can be found in the detailed methodology.[11]

9 A detailed methodology for this report, as well as supplemental information, is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

10 Ibid.

11 Ibid.

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

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

where:

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

There are some instances where the ship's speed over ground is larger than its maximum designed speed. In these instances, SOG is replaced with the ship's average SOG for that phase and the load factor is recalculated. In case of an invalid average SOG phase value of a ship, the average SOG for similar ship type, capacity bin, and phase is used. The load factor is then recalculated with the replaced SOG.

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

3.2.3 Estimating emissions of black carbon

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

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

where:

i	=	ship
t	=	time (operating hour, h)
k	=	engine type
m	=	fuel type
n	=	main engine load factor
p	=	phase (cruise, maneuvering, anchor, berth)
BC_i	=	black carbon emissions (g) for ship *i*
$FC_{i,t_{ME}}$	=	main engine fuel consumption (kg) for ship *i* at time *t*, equivalent to the quotient of main engine CO_2 emissions and the CO_2 intensity for the ship's main fuel type *m,* as found in Table 4
$EF_{ME_{k,m,n}}$	=	main engine black carbon emission factor (g/kg fuel), which is a function of engine type *k*, fuel type *m*, and main engine load factor *n*
$D_{AE_{p,i,t}}$	=	auxiliary engine power demand (kW) in phase *p* for ship *i* at time *t*
$EF_{AE_{k,m}}$	=	auxiliary engine black carbon emission factor (g/kWh) for engine type *k* and main fuel type *m*
$D_{BO_{p,i,t}}$	=	boiler power demand (kW) in phase *p* for ship *i* at time *t*
EF_{BO_m}	=	boiler black carbon emission factor (g/kWh) for main fuel type *m*

Emissions of all pollutants were calculated on a ship-by-ship basis and aggregated to the ship class level, as reported in the Results section.

3.3 ESTIMATING FUEL CONSUMPTION

Fuel consumption was estimated on a ship-by-ship basis based on the amount of CO_2 that the ship emitted and its main fuel type. Marine fuels emit varying amounts of CO_2 when burned; this is called the "CO_2 intensity of the fuel" and is reported in units of g CO_2/g fuel (Table 4).

Table 4. CO_2 intensity by fuel type

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

Fuel consumption is calculated as follows:

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

where:

i = ship
y = year
f = fuel type
$FC_{i,y,f}$ = fuel consumption (g) for ship i in year y of fuel type f
$CO_{2i,y,f}$ = total CO_2 emissions (g) for ship i in year y for fuel type f
CI_f = CO_2 intensity for fuel type f in g CO_2/g fuel, as found in Table 4

3.4 ESTIMATING CO_2 AND CO_2-eq INTENSITIES

Multiple metrics have been proposed to measure the CO_2 intensity of marine freight transport. Emissions per unit of cargo moved, in the form of grams CO_2 per tonne-nautical mile or TEU-nautical mile, directly measures the emissions intensity of per unit transport work. Transparent data on cargo carriage is poor, however, leading researchers to rely upon various proxies of transport work. AIS-derived instantaneous draught, which is a function of cargo and fuel carriage plus ballast, can be used to estimate cargo carriage if one makes simplifying assumptions about fuel carriage, ballasting approaches, sea conditions, etc. In this study, we are concerned predominately with absolute emissions rather than trends in cargo carriage over time, so we have adopted a somewhat simplified approach of estimating emissions per unit transport supply.

Depending on the ship class, *transport supply* is defined as either deadweight tonne-nautical mile travelled (dwt-nm) or gross tonne-nautical mile travelled (GT-nm). In general, we apply the dwt-nm definition to most ship classes. However, for some ship classes, such as cruise ships, ro-pax ferries, RoRos, and pax ferries, dwt is an inappropriate metric. This is because these ship classes carry passengers or motor vehicles, which occupy larger volumes, resulting in lower deadweights. This leads to lower transport supply and disproportionately higher emission intensities in terms of deadweight. Instead, transport supply for such ship classes are calculated in terms of GT, which takes into account the molded volume of all the enclosed spaces of the ship and thus provides a better metric for comparing transport work for these ship classes.

The CO_2 intensity (gCO_2/dwt-nm or gCO_2/GT-nm) and CO_2-eq intensity (gCO_2-eq/dwt-nm or gCO_2-eq/GT-nm) were estimated as follows:

$$CO_2\,Intensity_i = \frac{\sum CO_{2\,t,i}}{Capacity_i * \sum nm_{t,i}}$$

where:

i	=	ship
t	=	time (operating hour, h)
$CO_{2\,t,i}$	=	CO_2 emitted at time t, in grams for ship i
$Capacity_i$	=	capacity (dwt or GT) of ship i
$nm_{t,i}$	=	nautical miles travelled by ship i at time t

The CO_2-eq intensity is the sum of the CO_2-equivalent emissions of CO_2, CH_4, N_2O, and BC:

$$CO_2\text{-}eq\,Intensity_{i,q} = \frac{\sum CO_{2\,t,i} + \sum(CH_{4\,t,i} * GWP_{CH4\,q}) + \sum(N_2O_{t,i} * GWP_{N_2O\,q}) + \sum(BC_{t,i} * GWP_{BC\,q})}{Capacity_i * \sum nm_{t,i}}$$

where:

i	=	ship
q	=	time scale (20 or 100 years)
t	=	time (operating hour, h)
$CO_2\text{-}eq\,Intensity_{i,q}$	=	the GHG intensity of ship i over time scale q
$CO_{2\,t,i}$	=	CO_2 emissions at time t for ship i
$CH_{4\,t,i}$	=	CH_4 emissions at time t for ship i
$GWP_{CH4\,q}$	=	global warming potential of CH_4 over time scale q
$N_2O_{t,i}$	=	N_2O emissions at time t for ship i
GWP_{N_2Oq}	=	global warming potential of N_2O over time scale q
$BC_{t,i}$	=	BC emissions at time t for ship i
$GWP_{BC\,q}$	=	global warming potential of BC over time scale q
$Capacity_i$	=	capacity (dwt or GT) of ship i
$nm_{t,i}$	=	nautical miles travelled by ship i at time t

The 20-year and 100-year GWP used in this study are outlined in Table 5.

Table 5. 20-year and 100-year GPW for each of the climate pollutants included in this report

Climate Pollutant	20-year GWP	100-year GWP
CO_2	1	1
CH_4	72	25
N_2O	289	298
BC	3,200	900

Sources: CH_4 and N_2O GWP from *IPCC (2007)*; BC GWP from Bond et al. (2013).

4 RESULTS

This section presents the results of our analysis. Unless otherwise described, all tables and figures include results from Types 1, 2, and 3 data.

4.1 FUEL CONSUMPTION

Total fuel consumption (international + domestic + fishing) increased from 291 to 298 million tonnes (+2.4%) from 2013–2015. Fuel consumption was dominated by residual fuels, which accounted for 72% of total shipping fuel consumption in 2015 (Figure 1). Distillate fuel accounted for approximately one quarter of fuel consumption, with LNG representing approximately 2% of fuel consumption. Similar proportions of residual, distillate, and LNG fuel consumption were observed for 2013 and 2014.

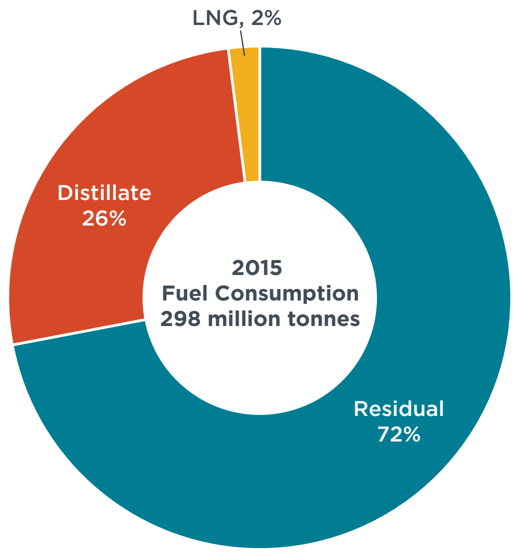

Figure 1. Fuel consumption by the global shipping fleet by fuel type, 2015

Other researchers have estimated total shipping fuel consumption in the past, including IEA (2017) in their annual World Energy Statistics reports and Smith et al. (2015) in the Third IMO GHG Study 2014. Figure 2 compares total shipping fuel consumption estimates from the IEA, the Third IMO GHG Study 2014 (Smith et al., 2015), and the ICCT (this study). As shown in Figure 2, estimates differ between IEA's "top-down" estimate of fuel consumption based on fuel sales data and the Third GHG Study 2014 (Smith et al, 2015) and ICCT's fuel "bottom-up" activity-based approach. Overall, bottom-up emissions remain below the 2008 peak estimated in the Third IMO GHG Study 2014 (Smith et al., 2015). Although fuel consumption is still below the 2008 peak, fuel consumption trends may continue to increase as the global economy recovers from the global financial crisis.

Figure 2 shows that IEA top-down estimates are consistently lower than bottom-up estimates of shipping fuel consumption. In general, the gap between IEA's top-down data and bottom-up estimates from IMO and ICCT is closing. For global (international, domestic, and fishing) shipping, the Third IMO GHG Study 2014 reported 12%–43% higher fuel consumption, and we report 12%–15% higher fuel consumption than IEA for 2013 to 2015. The gap for international shipping, partly imputable to a different methodological approach, is closing somewhat slower, from an average of 32% (20%–44%) in the Third IMO GHG Study down to 28% (24%–31%) in this work. It is likely that improving AIS data coverage over time has reduced the uncertainty in bottom-up estimates, in particular for domestic and fishing vessels, as seen by the smaller annual variability in emissions from these ships (see Table 6 below). Separately, IEA is working to improve the fuel sales data collected from its members for top-down analysis to avoid potential underreporting.

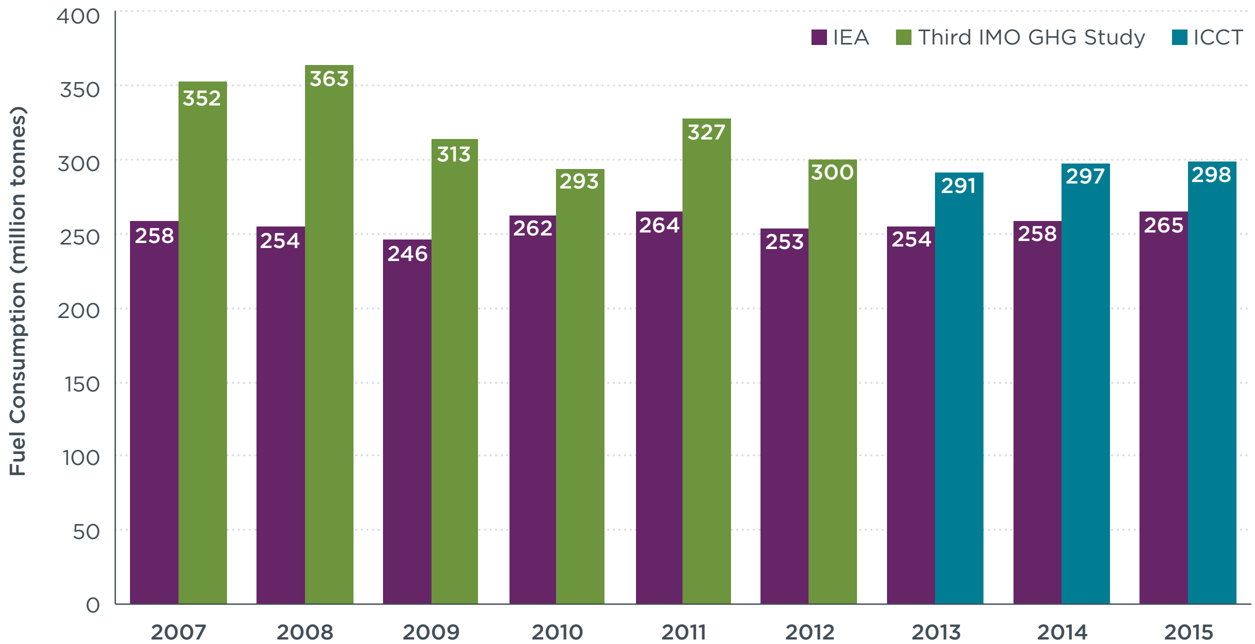

Figure 2. Fuel consumption estimates from IEA, IMO, and ICCT, 2007–2015
Sources: IEA (2017) and Smith et al. (2015)

In addition, although both this report and the IEA show that international shipping accounts for the vast majority of fuel consumption, the IEA reports greater fuel consumption by domestic ships compared with our estimates (Figure 3). This may be linked to IEA's differing definition for international versus domestic ships. The IEA defines international shipping as shipping occurring between ports in two different countries. Domestic shipping, on the other hand, is defined as shipping between two ports in the same country. This study, on the other hand, defines international and domestic shipping by ship class and capacity bin, the same as Smith et al. (2015), as described in the Methodology section above. In general, we assume that large ships engage in international shipping and smaller ships engage in domestic shipping. Of course, some large ships engage in domestic shipping; thus, we may be underestimating domestic fuel consumption compared to IEA. Nevertheless, the bottom-up and top-down estimates of fuel consumption are converging over time, suggesting increased certainty in these estimates as data quality improves.

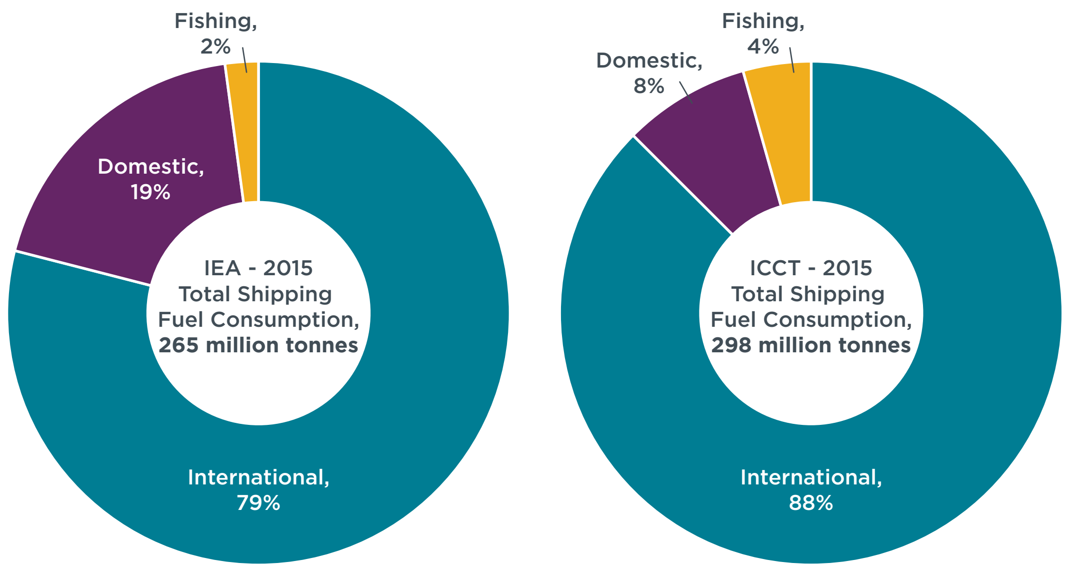

Figure 3. Fuel consumption by international, domestic, and fishing activity, 2015

Sources: IEA (2017) and this analysis

4.2 CO_2 EMISSIONS

4.2.1 Fleetwide

Ships emitted 932 million tonnes of CO_2 in 2015. Figure 4 shows the distribution of CO_2 emissions from total shipping (international + domestic + fishing) for 2015. Major shipping routes are clearly visible.

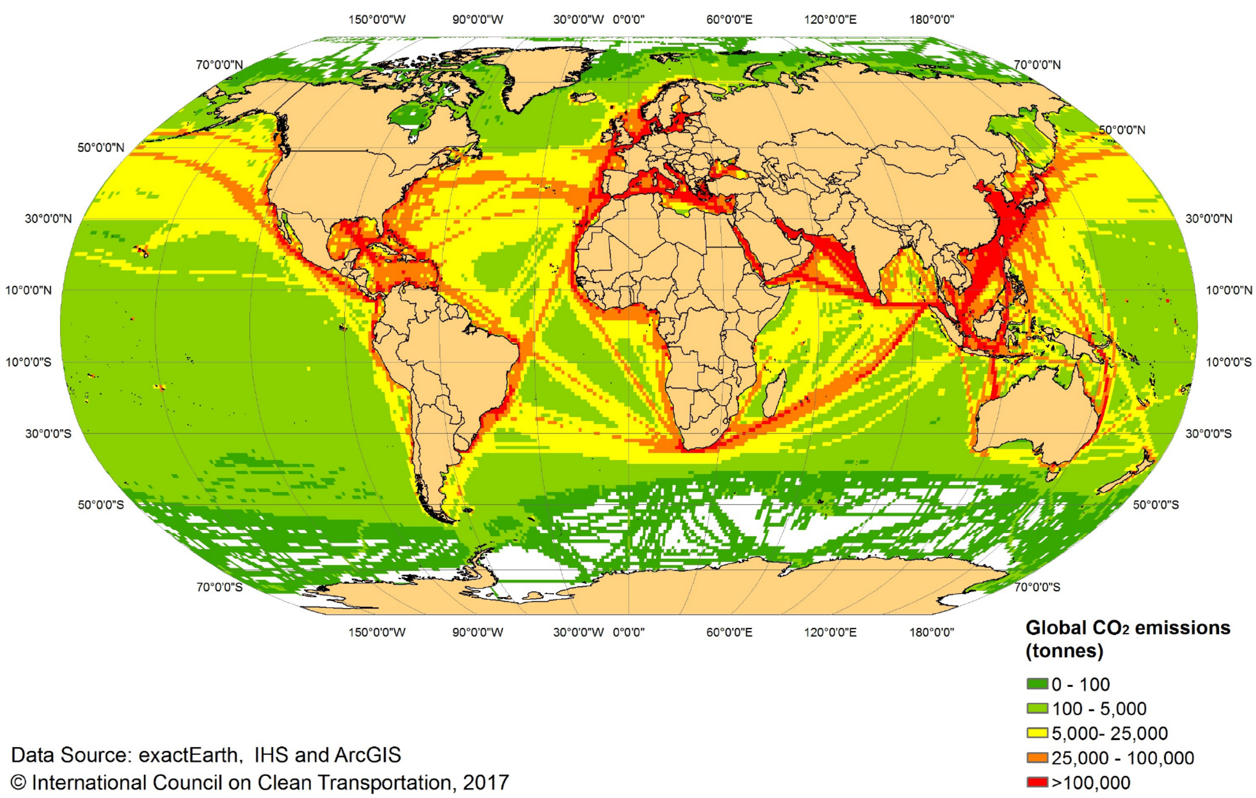

Figure 4. Global distribution of shipping CO_2 emissions, 1°x 1°, 2015

Total shipping CO_2 emissions increased from 910 million tonnes to 932 million tonnes (+2.4%) from 2013 to 2015 (Table 6). In 2015, global shipping accounted for approximately 2.6% of global CO_2 emissions, with the majority (87%) of shipping CO_2 emissions attributable to international shipping activity. Domestic shipping accounted for ~9% of total shipping CO_2 emissions and fishing accounted for ~4% in 2015. Although still below the 2008 peak, international shipping emissions may be rebounding from the 2010 minimum as the global economy recovers from the 2008 recession.

Table 6. Shipping CO_2 emissions compared to global CO_2 emissions, 2007–2015

Source	3rd IMO GHG Study (million tonnes)						ICCT (million tonnes)		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Global CO_2 emissions*	**31,959**	**32,133**	**31,822**	**33,661**	**34,726**	**34,968**	**35,672**	**36,084**	**36,062**
International shipping	881	916	858	773	853	805	801	813	812
Domestic shipping	133	139	75	83	110	87	73	78	78
Fishing	86	80	44	58	58	51	36	39	42
Total shipping	**1,100**	**1,135**	**977**	**914**	**1,021**	**942**	**910**	**930**	**932**
% of global	3.5%	3.5%	3.1%	2.7%	2.9%	2.6%	2.5%	2.6%	2.6%

** Global CO_2 estimates include CO_2 from fossil fuel use and industrial processes (EDGAR, 2017).*

4.2.2 By ship class

Within the global fleet, a few key ship classes account for the majority of CO_2 emissions. Container ships accounted for the largest share (23%) of CO_2 emissions from 2013–2015, as shown in Figure 5. Container ships, bulk carriers, and oil tankers together accounted for over half (55%) of the nearly 1 billion tonnes of CO_2 emitted in 2013, 2014, and 2015. These three ship classes also accounted for 84% of total shipping transport supply (dwt-nm), which contributes to their overall CO_2 emissions compared to other ship classes. A full table of CO_2 emissions and transport supply by ship class can be found in the supplemental information.[12]

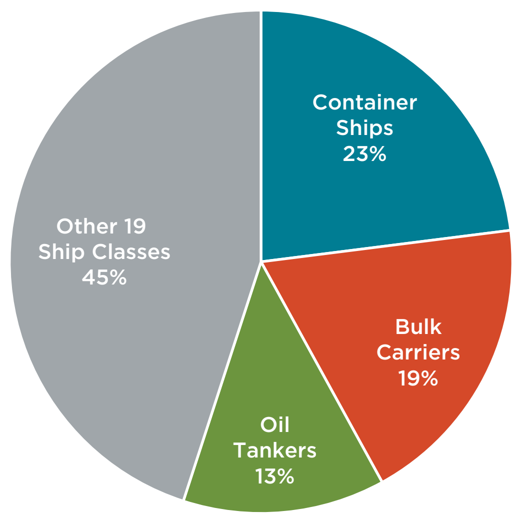

Figure 5. Average percent share of CO_2 emissions by ship class, 2013–2015

4.2.3 By operating phase

Cruising accounts for most CO_2 emissions across all ship classes, while maneuvering accounts for the least (Figure 6). Tankers have significantly higher emissions in their berthing phase due to higher AE load demand during discharging operations. Therefore, certain emission-reduction alternatives like shore power could reduce emissions from tankers. Emissions in anchor phase also depends on the ship class. General cargo,

12 Supplemental information for this report is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

tankers, and bulk carriers, which wait relatively long times at anchor before berthing, have higher emissions in that phase.

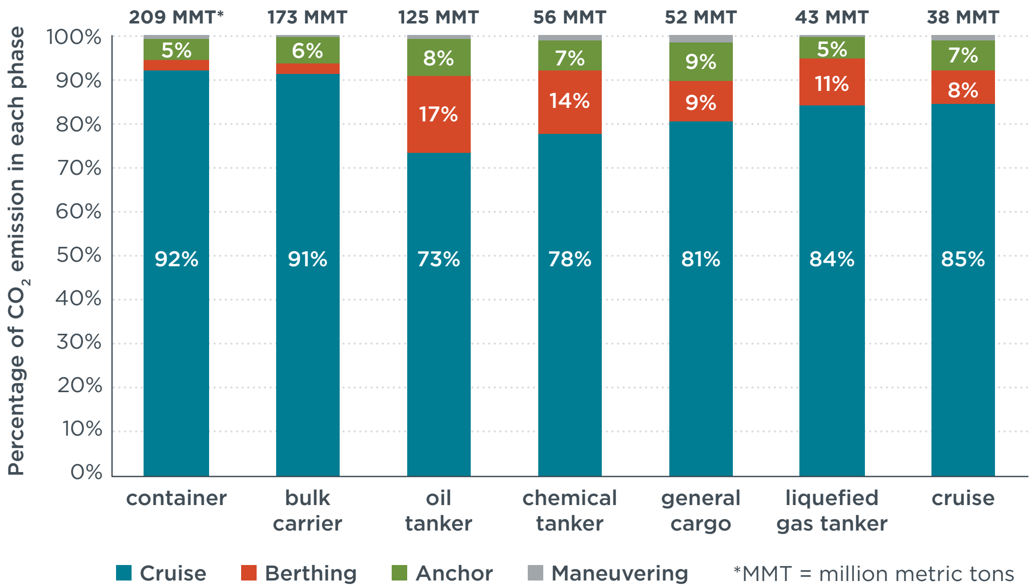

Figure 6: CO_2 emissions by phase for top-emitting ship classes, 2015

4.2.4 By flag

As with ship classes, several flag states dominate the shipping fleet and its overall activity. As shown in Figure 7, out of the 223 flag states, most CO_2 emissions can be attributed to ships flying seven flags: Panama (15%), China (11%), Liberia (9%), Marshall Islands (7%), Singapore (6%), and Malta (5%). These flags also have large numbers of ships registered to them and account for 66% of the global shipping fleet's dwt. Larger ships and the sheer number of vessels registered to these flags contributes to their overall CO_2 emissions relative to other flag states.

A full table of annual CO_2 emissions by flag state can be found in the supplemental information.[13]

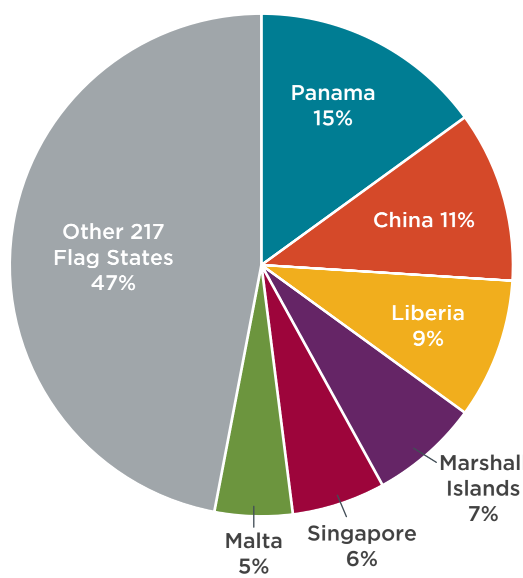

Figure 7. Average share of CO_2 emissions by flag state, 2013–2015

13 Supplemental information for this report is available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

4.3 NON-CO_2 CLIMATE POLLUTANTS

CO_2 is not the only climate pollutant ships emit. So-called "non-CO_2 climate pollutants" like BC, CH_4, and N_2O also contribute to climate change. These emissions remained relatively unchanged from 2013–2015 (Table 7). Although N_2O emissions decreased following the 2008 economic recession, CH_4 emissions have continued to increase. Note the increase in CH_4 emissions in recent years compared with 2007–2012; this is largely attributable to greater use of LNG. Domestic ships have an especially high percentage growth in CH_4 emissions for 2013–2015, driven by increased use of LNG ferries as an air pollution abatement strategy and increases in LNG tanker activity.

Table 7. Non-CO_2 climate pollutants, 2013–2015

Pollutant	2013	2014	2015
BC Total (kilotonnes, kt)	**75**	**78**	**78**
International	64	66	66
Domestic	7	8	8
Fishing	4	4	4
CH_4 Total (kt)	**362**	**367**	**363**
International	358	362	358
Domestic	4	4	5
Fishing	1	1	1
N_2O Total (kt)	**45**	**46**	**46**
International	40	41	41
Domestic	3	4	4
Fishing	2	2	2

We can evaluate the climate impacts of shipping emissions by converting climate pollutant emissions to their CO_2 equivalences (CO_2-eq). Table 8 sums up the 20-year and 100-year CO_2-eq emissions from CO_2, BC, CH_4, and N_2O, based on the GWP presented in Table 5. As shown in Table 8, CO_2-eq emissions increased from 1,189 to 1,222 (+2.8%) on a 20-year timescale and 1,000 to 1,025 (+2.5%) on a 100-year timescale from 2013 to 2015.

Table 8. CO_2-eq emissions, 2007–2015

	Third IMO GHG Study						ICCT		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total 20-year CO_2-eq (MMT)	**1,119**	**1,155**	**995**	**932**	**1,042**	**963**	**932 (1,189)***	**952 (1,219)**	**954 (1,222)**
International	898	934	875	790	872	823	821 (1,044)	834 (1,063)	833 (1,061)
Domestic	135	141	76	84	111	88	74 (97)	79 (104)	79 (105)
Fishing	87	81	45	59	59	52	36 (48)	39 (52)	42 (56)
Total 100-year CO_2-eq (MMT)	**1,127**	**1,164**	**1,003**	**943**	**1,055**	**976**	**949 (1,000)**	**969 (1,023)**	**971 (1,025)**
International	905	942	883	800	885	836	838 (880)	850 (894)	849 (893)
Domestic	135	141	76	84	111	88	74 (80)	79 (86)	79 (86)
Fishing	87	81	45	59	59	52	36 (37)	39 (43)	42 (46)

* Values in parentheses represent $CO_{2\text{-eq}}$ for CO_2+BC+CH_4+N_2O. The Third IMO GHG Study 2014 did not estimate $CO_{2\text{-eq}}$ for BC, but did estimate $CO_{2\text{-eq}}$ for the other climate pollutants; thus, the values outside the parentheses can be compared to the Third IMO GHG Study, understanding that there are some methodological differences between our study and the Third IMO GHG Study, as explained in the detailed methodology, available at http://theicct.org/GHG-emissions-global-shipping-2013-2015

* MMT = million metric tons

Some climate pollutants, including BC, are "short-lived"; they have a warming impact over relatively short time span. Others have a longer lasting impact. As such, we evaluate the global warming potential on 20-year and 100-year timescales. Notice the large impact of BC emissions in Figure 8. Over a 20-year timescale, BC accounts for 21% of the climate warming impact from ships. Even over a 100-year timescale, BC accounts for 7%. Because BC only stays in the atmosphere for a few days or weeks, reducing BC emissions from ships would have an immediate impact on shipping's overall global warming effects.

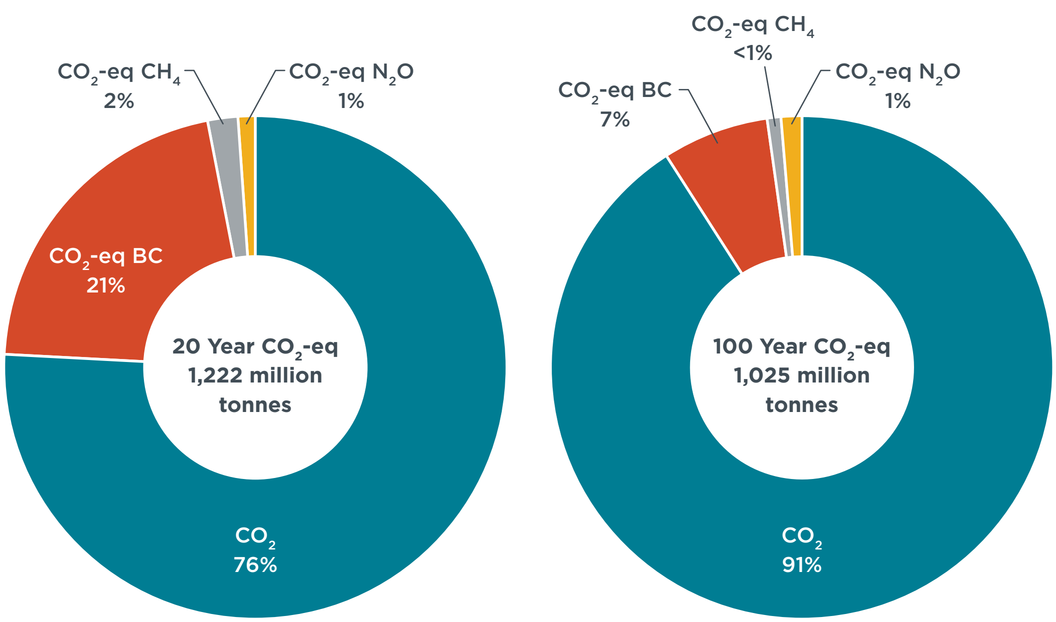

Figure 8. Average share of CO_2-eq emissions by pollutant type, 2013–2015

4.4 TRANSPORT SUPPLY

Total transport supply (dwt-nm) increased 7% from 2013 to 2015—slightly higher than the UNCTAD (2017) estimated 6% increase in total world seaborne trade (goods loaded and unloaded) over the same period. Bulk carriers have the highest transport supply (42 trillion dwt-nm in 2015), more than 60% higher the next highest ship class (oil tankers: 26 trillion dwt-nm in 2015) and the third highest (container ships: 21 trillion dwt-nm in 2015). Together, bulk carriers, oil tankers, and container ships account for 86% of global transport supply (102 trillion dwt-nm in 2015). Out of the major ship classes, general cargo and chemical tankers show the largest increase in transport supply (+15%) from 2013–2015 and container ships also show a growth of 9% in transport supply during this period. Full details can be found in the supplemental information. Increasing transport supply for most ship classes indicates an overall upward trend in shipping activity and suggests that markets are recovering from the 2008 downturn. Moreover, with the average deadweight of the fleet increasing as larger and larger ships enter the fleet, transport supply will likely continue to increase.

4.5 CO_2 AND CO_2-eq INTENSITIES

In general, as ships become larger, their CO_2 and CO_2-eq intensities (g/dwt-nm or g/GT-nm) decrease because their dwt or GT increases, meaning that the ship seems to become more efficient. In reality, the actual CO_2 and CO_2-eq intensities per unit cargo will depend on the amount of cargo the ship is carrying (i.e., tonnes), not its capacity (i.e., its dwt or GT). Furthermore, if ships speed up, they will emit more CO_2 and CO_2-eq per mile, increasing their intensities. Here, we discuss the CO_2 and CO_2-eq intensities by ship class.[14]

Although the CO_2 intensity of many major ship classes decreased (i.e., the ship class became more efficient) from 2013 to 2015, total CO_2 emissions from ships increased. Even in some cases where a ship class became much more efficient, the amount of CO_2 emitted from the ships increased. For example, although the CO_2 intensity of general cargo ships decreased by 5%, CO_2 emissions increased by 9% (Figure 9). In cases where CO_2 emissions increased or did not decrease as much as CO_2 intensity decreased, either the total transport supply for the ship class was higher in 2015 than 2013 or the ships in that class spent more time at anchor or berth in 2015 than in 2013, increasing their total CO_2 emissions without increasing their transport supply. In the case of bulk carriers and container ships, increases in transport supply and operating hours between 2013 and 2015 resulted in modest (<1%) decreases in total CO_2 emissions, despite 6% and 9% decreases (improvements) in CO_2 intensities, respectively. Only refrigerated bulk carriers managed to reduce their CO_2 emissions by a greater percentage than they reduced their CO_2 intensity, owing to an overall drop in transport supply for these ships from 2013 to 2015.

14 We expect to relate these trends in CO_2 intensity to changes in cruise speed, ship capacity, technical efficiency, etc., in future work, but that analysis exceeds the scope of this study.

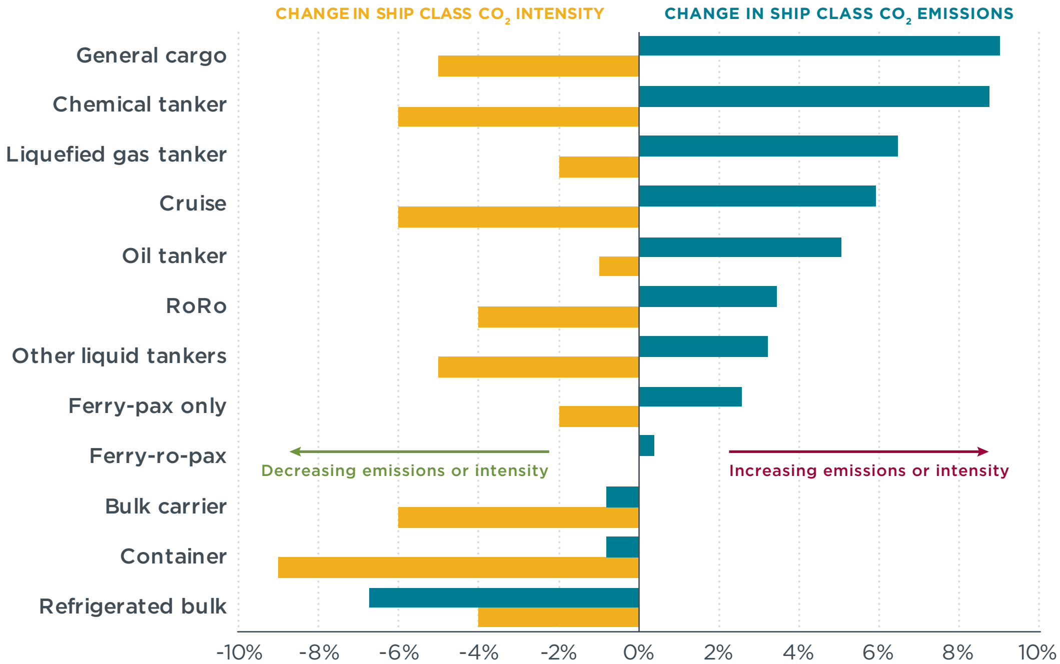

Figure 9. Change in CO_2 emissions and CO_2 intensity for key ship classes

Overall, the CO_2 intensity of cargo carrying ships for which deadweight tonnage is an appropriate capacity unit decreased (improved) by 3.5% from 2013 to 2015, compared to a 6% increase in transport demand (UNCTAD) and a 7% increase in transport supply (dwt-nm in this study). The net increase in emissions seen (+2.4%) is a result of these countervailing forces. In the future, we expect CO_2 emissions to continue to increase even as the fuel efficiency of international shipping increases, as the global economy improves, and as demand for shipping intensifies.

4.6 AIR POLLUTANTS

Table 9 summarizes air pollutant emissions from 2007 to 2015. Nitrogen oxides (NO_x) increased the most between 2013 and 2015, by 3.5%, while sulfur oxides (SO_x) increased the least from 2013–2015, by about 1%. In the future, NO_x emissions from new ships that operate in ECAs will be much lower than existing ships, but given the given the slow rate of turnover in the global fleet, total NO_x emissions will likely continue to rise. On the other hand, total SO_x and particulate matter (PM) emissions will decrease dramatically beginning in 2020 as ships begin to comply with the 0.5% global fuel sulfur cap.

Table 9. Air pollutant emissions, 2007–2015

Pollutant and Source	Third IMO GHG Study						ICCT		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
NO_x (kilotonnes, kt)	**22,801**	**23,639**	**20,756**	**18,756**	**20,310**	**19,002**	**18,426**	**18,398**	**19,062**
International	19,943	20,759	19,104	16,708	18,047	16,997	16,941	16,818	17,058
Domestic	1,564	1,639	930	1,114	1,323	1,171	1,030	1,093	1,238
Fishing	1,294	1,242	722	935	940	834	455	487	766
SO_x (kt)	**11,581**	**11,892**	**11,646**	**10,550**	**11,632**	**10,240**	**10,355**	**10,361**	**10,457**
International	10,771	11,041	11,164	9,895	10,851	9,712	128.3	136.7	122.5
Domestic	278	331	202	251	358	268	90.9	94.1	95.4
Fishing	533	521	280	405	423	261	10574.3	10592.1	10674.6
PM (kt)	**1,622**	**1,679**	**1,574**	**1,432**	**1,563**	**1,402**	**1,475**	**1,504**	**1,492**
International	1,493	1,545	1,500	1,332	1,446	1,317	1,426	1,452	1,441
Domestic	51	58	33	41	56	44	30	32	31
Fishing	78	76	41	59	61	41	18	19	20
CO (kt)	**998**	**1,039**	**921**	**893**	**975**	**936**	**797**	**809**	**814**
International	823	864	816	763	834	806	704.0	708.9	710.6
Domestic	99	103	60	72	82	76	62.6	66.8	67.7
Fishing	76	72	46	59	58	53	30.8	33.3	35.8
NMVOC (kt)	**827**	**858**	**739**	**683**	**741**	**696**	**781**	**786**	**795**
International	696	727	672	593	643	609	697	697	701
Domestic	76	78	38	51	59	53	57	60	62
Fishing	55	52	28	39	39	35	27	29	32

4.7 DRIVERS OF EMISSIONS

A number of factors drive shipping emissions, including fleet size, operating hours, dwt, ME power, SOG, nm, and dwt-nm. Figure 10 shows trends in drivers of emissions for the international shipping fleet, plus the top seven CO_2-emitting ships classes, normalized to 2013 (black dotted line). In general, there is an increasing trend for most drivers between 2013 and 2015 across all the ship classes. Key findings for the years 2013–2015 include:

» The international fleet is growing.
  - The world fleet of ships used for international trade increased 1.5% from 2013 to 2015, with increases in fleet size for chemical tankers, cruise ships, fishing vessels, general cargo ships, and liquefied gas tankers. The number of bulk carriers, container vessels, and oil tankers declined slightly.

» The largest ships are increasingly active.
  - Transport supply (dwt-nm) increased 7% across the international fleet from 2013–2015, with chemical tankers and general cargo ships seeing the largest

increases (+15%) and cruise ships (+11%) and container ships (+9%) realizing significant growth.

- Operating hours increased substantially for general cargo ships (+12%), cruise ships (+8%), and chemical tankers (+7%), but not for bulk carriers or container ships.

» Main engines are getting more powerful.

- Main engine power for many ship classes increased between 2013 and 2015, with the largest gains in chemical tankers (+10%), cruise ships (+7%), general cargo ships (+6%), and container ships (+6%). Main engine power for bulk carriers and oil tankers was unchanged.

» Most ship speeds are unchanged, but the biggest ships are speeding up.

- The average cruise speed of the international fleet was largely unchanged from 2013 to 2015 (Figure 10), including for container and oil tanker fleets. However, the largest container ships and oil tankers are speeding up. We observe a 11.4% increase in SOG for the largest container ships and a smaller, but still significant, 3.8% increase in SOG for the largest oil tankers (Figure 11). More details can be found in the following section.

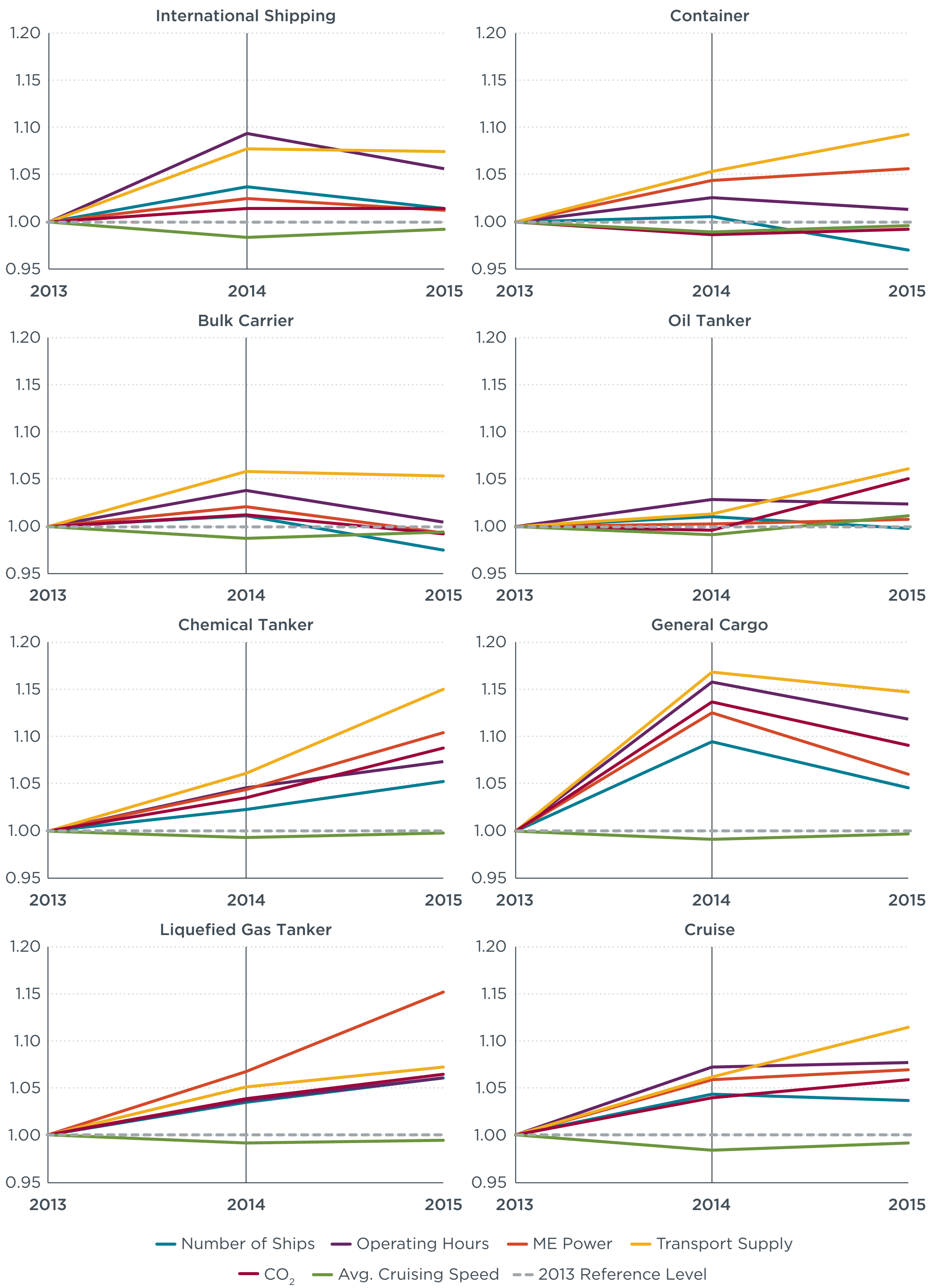

Figure 10. Drivers of emissions for major ship classes, 2013–2015

4.8 SPEED TRENDS FOR LARGE CONTAINER SHIPS AND OIL TANKERS

While most ship speeds remained unchanged between 2013 and 2015, the largest oil tankers (>200,000 dwt) and the largest container ships (>14,500 TEU) sped up (Figure 11). In general, speed across the entire fleet has been steady, with average cruising speed between 11.4 and 11.6 kts, an average SOG/max speed ratio of 0.75–0.76, and an average cruising engine load factor of 0.51–0.52, depending on the year. Most container ships have slightly reduced their SOG and cruising engine load factors, except for >14,500 TEU container ships, which increased their SOG by 11.4% and their load factors by 77%. These large container ships are also the fastest growing segment, growing from 24 ships in 2013 to 68 ships in 2015.

Large capacity oil tankers also saw a significant increase in cruising SOG. The largest oil tankers (>200,000 dwt) increased cruising SOGs by 4% from 2013 to 2015. This correlates to the collapse in oil prices starting at the end of 2014 and continuing through 2015; as the price of oil dropped, demand for oil increased, driving increased activity among the largest oil tankers.

As these ships speed up, they cover greater distances in a shorter amount of time. They also consume more fuel and emit more CO_2. In fact, as shown earlier (Figure 9), while the carbon intensity of oil tankers and container ships *as a class* decreased (became more efficient), the carbon intensity of the largest oil tankers and container ships increased (became less efficient) from 2013 to 2015, with >200,000 dwt oil tankers emitting 1% more CO_2/dwt-nm in 2015 and >14,500 TEU container ships emitting 18% more CO_2/dwt-nm in 2015. From an emissions perspective, this is worrisome because if more ships follow suit and speed up, the CO_2 efficiency of the maritime transport sector will degrade. We already see a statistically significant increase in ship speeds for the next largest oil tankers: +2.3% for 120,000–199,999 dwt and +1.4% for 80,000–119,999 dwt (see the supplemental materials for more information).

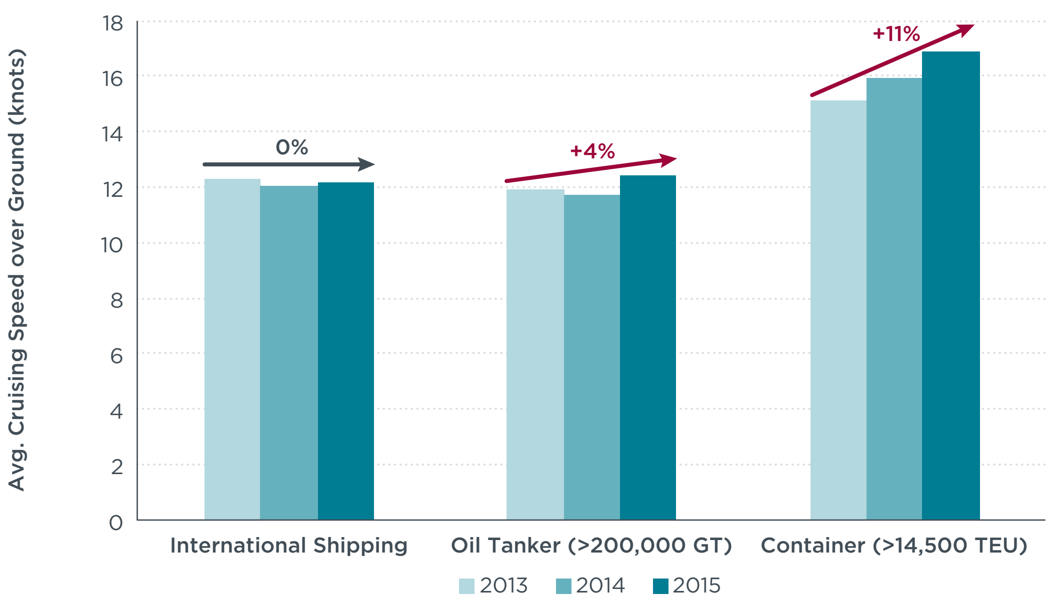

Figure 11. Changes in speed over ground for the largest container ships and oil tankers, 2013-2015.

Figure 12 shows trends in the SOG-to-design-speed ratio for the largest container ships (>14,500 TEU) and oil tankers (>200,000 dwt) compared to the global fleet between 2013–2015, normalized to 2013 levels. Earlier, we noted that the largest container ships significantly increased their SOG during this period. Interestingly, there is even higher increase in the SOG-to-design-speed ratio, indicating that the average design speed has reduced during the period. Thus, these ships have been operating closer to their design speed. The trend is similar for the container fleet as a whole too, but to a lesser extent.

The increased use of the largest container ships is associated with their economics of trade. Because the capacities of these ships have grown enormously over the last few years (up to ~19,000 TEUs in 2015), they are able to carry a lot more cargo. This provides them with the leeway to operate at higher (i.e., not the most economical) speeds, because the net value of the cargo carried is much higher. The largest oil tankers also show a substantial increase in SOG during this period, but the increase in their SOG to design speed ratio remains similar, indicating that unlike the largest containerships, their design speeds have remained constant.

A table showing speed trends by ship class and capacity bin can be found in the supplemental information.

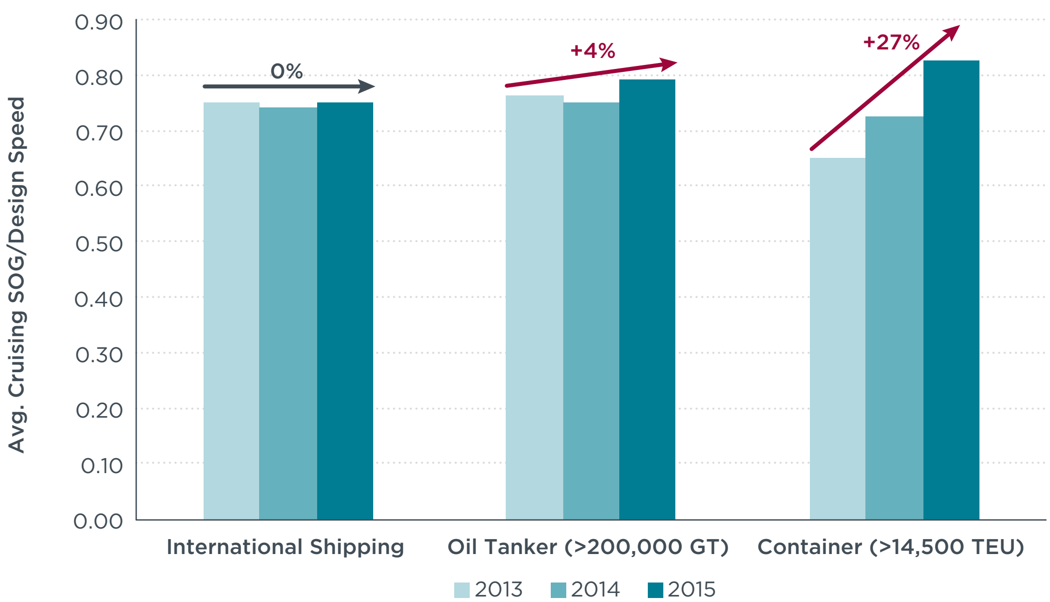

Figure 12. Changes in speed over ground to design-speed ratios for largest container ships and oil tankers, 2013–2015

5 CONCLUSIONS

In this report, we assessed recent trends in emissions and activity for the global shipping fleet, including international, domestic, and fishing vessels. This report summarizes the state of GHG emissions from ships in a time when the IMO is working to develop its initial GHG strategy. We found that despite increases in operational efficiency for many ship classes, CO_2 emissions, CO_2-eq emissions, and fuel consumption increased more than 2.4% from 2013 to 2015. Specifically, we found that:

» **GHG emissions and fuel consumption are increasing despite improvements in efficiency for many ship classes**. Although the CO_2 intensity of many major ship classes decreased (i.e., they became more efficient) from 2013 to 2015, total CO_2 and CO_2-eq emissions from ships increased. Increasing emissions are being driven by rising demand for shipping and the associated consumption of fossil fuels.

» **Emissions are concentrated in a handful of ship classes and flag states**. Just three ship classes (container ships, bulk carriers, and oil tankers) account for 55% of CO_2 emissions. Similarly, six flag states (Panama, China, Liberia, Marshall Islands, Singapore, and Malta) account for 52% of CO_2 emissions. Although all ships and flags have a role to play in combating climate change, reducing emissions will require addressing these major ship classes and flags in a way that minimizes both impacts on vulnerable states and potential competitive distortions.

» **Black carbon is a major contributor to shipping's climate impacts**. On a 20-year timescale, BC accounts for 21% of CO_2-eq emissions from ships. Because BC is a short-lived climate pollutant, reducing BC emissions from ships would immediately reduce shipping's climate impacts.

» **The biggest ships are speeding up and polluting more.** Unlike most ships, the largest container and oil tankers sped up between 2013 and 2015 and became less efficient, emitting more CO_2/dwt-nm in 2015 than they did in 2013. In fact, the largest oil tankers (>200,000 dwt) increased their cruising SOG nearly 4% and the largest container ships (>14,500 TEU) increased their cruising speed over ground (SOG) more than 11%. As more ships follow their lead, shipping efficiency will decrease and ship emissions will continue to increase.

Our results suggest that absolute reductions in ship emissions will require concerted action to improve the energy efficiency of shipping and to develop and deploy alternative fuel and propulsion concepts. This is consistent with the work of Smith et al. (2016), who indicated that shipping will need to move beyond energy efficiency interventions alone to achieve absolute emission reductions. Ultimately, the only way to reduce emissions from ships without constraining demand is to substantially reduce the volume of GHGs emitted per unit of transport supply.

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