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Agenda item 10

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CONSIDERATION OF THE IMPACT ON THE ARCTIC OF EMISSIONS OF BLACK CARBON FROM INTERNATIONAL SHIPPING

Revised estimates of Black Carbon emissions from global and arctic shipping

Submitted by the Institute of Marine Engineering, Science and Technology (IMarEST)

SUMMARY

Executive summary:	This document provides a critical review of marine Black Carbon (BC) inventories, identifies differences in published estimates, and revises the IMO BC inventory based on measured emission factors and refinements to emission factor estimates. IMarEST finds a wide range of estimates in BC emissions from international shipping due primarily to uncertainties in emission factors. Using higher-resolution emission factors drawn from real-world testing on ships and activity data taken from both the second IMO GHG study and the peer-reviewed literature, IMarEST estimates that shipping was responsible for about 184,000 tonnes of BC in 2007 and about 2,800 tonnes in the Arctic in 2004. These estimates are higher by 42% and 90%, respectively, than previously published IMO and peer-reviewed estimates.
Strategic direction:	7.3
High-level action:	7.3.2
Planned output:	7.3.2.1
Action to be taken:	Paragraph 5
Related documents:	MEPC 64/24; MEPC 62/4/10, MEPC 62/4/16, MEPC 62/4/18 and MEPC 59/INF.10

Background

1 MEPC 62 agreed a work plan to consider the impact on the Arctic of Black Carbon (BC) emissions from ships (MEPC 62/24, paragraphs 4.20.1 to 4.20.4) and instructed the Sub-Committee on Bulk Liquids and Gases (BLG) to:

.1 develop a definition for BC emissions from international shipping;

.2 consider measurement methods for BC and identify the most appropriate method for measuring BC emissions from international shipping;

.3 investigate appropriate control measures to reduce the impact of BC emissions from international shipping; and

.4 submit a final report to MEPC 65.

2 The International Council on Clean Transportation (ICCT), in cooperation with the Institute of Marine Engineering, Science and Technology (IMarEST), conducted a critical review of marine BC inventories. The ICCT demonstrates how fuel consumption and the emission factor of BC (EF_{BC}) are a major source of uncertainty across BC inventory estimates and how the inventory estimate is sensitive to operational conditions of ships. The ICCT concludes that the EF_{BC} is a significant source of differences between inventories due to poor sensitivity to ship engine type, fuel quality, and engine load.

3 The ICCT developed a framework for producing more refined estimates of EF_{BC} to improve upon existing inventories, and applied these more refined estimates to each study. The ICCT found that shipping was responsible for about 184,000 tonnes of BC in 2007. This estimate is 42 per cent higher than the current IMO estimate, but comparable to recent studies informed by measured EF_{BC}. The ICCT estimates that shipping contributed about 2,300 tonnes of BC in the Arctic in 2004, which is 90 per cent higher than prevailing estimates.

4 These findings suggest that international marine BC emissions may be widely underestimated, and that improvements to major BC inventories can be made to reflect state-of-the-art data on marine EF_{BC}. The full study is set out in the annex to this document.

5 The ICCT cautions that further improvements with more disaggregated input data from more vessels in more conditions would improve the accuracy of BC inventory estimates. Future activities could include a concerted effort to updated activity-based shipping inventories and a measurement campaign to address unresolved issues related to the EF_{BC}.

6 The ICCT, in collaboration with IMarEST, is organizing a measurement campaign to resolve the latter issue, which is open to collaboration with all interested parties. The ICCT is working with the California Air Resource Board, the University of California Riverside, and the Port of Los Angeles to develop a test protocol for BC emissions from shipping and to apply this in a test of BC emissions from scrubbers and other control strategies. These results may provide more information for future discussion.

Action requested of the Committee

5 The Committee is invited to note this document and take action as appropriate.

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ANNEX

GLOBAL EMISSIONS OF MARINE BLACK CARBON: CRITICAL REVIEW AND REVISED ASSESSMENT

ABSTRACT:

1 Black Carbon (BC) emissions from international shipping are significant and contribute to global and regional climate change, particularly in the Arctic. This document reviews global estimates of international marine BC emissions, identifies differences in inventory methods, and proposes an approach for improving existing estimates. A critical review of the literature reveals that highly resolved BC emission factors (EF_{BC}) by ship engine type, fuel quality, and engine load are rarely found in most global inventories. In addition, we find that EF_{BC} is a significant contributor to differences among inventories. In an effort to reduce these differences and improve existing inventories, we propose a weighting framework for estimating EF_{BC} that more accurately captures variation in ship emissions. Using fuel consumption estimates from the International Maritime Organization (IMO) 2009 Greenhouse Gas (GHG) report and a set of more highly resolved estimates of EF_{BC}, we estimate that shipping was responsible for about 184,000 tonnes of BC in 2007. This estimate is 42 per cent higher than what is used in the IMO 2009 GHG Report, but comparable to recent studies informed by measured EF_{BC}. We estimate that shipping contributed about 2,300 tonnes of BC in the Arctic in 2004, which is 90 per cent higher than prevailing estimates. Our findings suggest that coarse calculations of EF_{BC} and uncertainty in marine BC emission factors have contributed to conservative estimates of BC emissions from international shipping. Future inventories should reflect the variation in BC emissions from representative ship types, fuels, and engine loads.

INTRODUCTION

2 Anthropogenic emissions of greenhouse gases (GHGs) and aerosols have caused changes in global and regional temperatures with profound human and environmental impacts. Short-lived climate-affecting species, which are notable for their strong warming effects over short time periods, are increasingly recognized as an important contributor to this climate change. Black carbon (BC) is a pollutant that contributes a significant share of this warming, but has not been the target of international climate policy. BC and short-lived climate pollutants present a more complex set of temporal and spatial dynamics than long-lived GHGs, hence assessment of their climate impact has been delayed. But recent advances in atmospheric science have answered important questions about their role [1-4]. In addition, recent studies have provided important information about key sources and mitigation strategies for BC [5, 6].

3 Global emissions of BC in the year 2000 from all sources were approximately 7.66 Tg/yr and 5.02 Tg/yr from anthropogenic sources [7]. Transportation-related sources were 1.48 Tg/yr or 29 per cent of global anthropogenic BC emissions. Diesel emissions are a major source of BC and account for approximately 90 per cent of global transportation-related BC emissions [8]. BC is a combustion by-product consisting of fractal chain-like aggregates of primary spherules of refractory carbon that are strongly light-absorbing [1, 9, 10]. It causes warming by direct absorption of both short- and long-wave radiation in the atmosphere, and by changes to the albedo of ice and snow surfaces [11]. Changes to cloud lifetime and properties can cause cooling, although the magnitude of this cooling remains one of the least certain aspects of climate science. BC is co-emitted with organic carbon and other aerosols, which can cause cooling as well, although the effect and emissions ratio of co-emitted species varies by source [12]. Diesel

emissions contain among the lowest shares of co-emitted organic carbon [13]. By itself, BC is as much as 790 (± 530) times more potent than carbon dioxide from energy-related sources on a global basis over a 100-year time horizon and 2,800 (± 1,800) times more potent on a shorter 20-year time horizon [11].

4 BC is the third largest contributor (after carbon dioxide and ozone production over the oceans) to the increase in global temperature caused by international maritime emissions [14, 15]. Shipping also causes significant cooling via emissions of sulphate aerosols and reduction of methane caused by NOx emissions [14]. International shipping may cause particularly acute impacts in the Arctic due to the presence of significant ice and snow that are sensitive to the albedo effect caused by BC [5]. Ships in the Arctic frequently operate at variable speeds in response to ice conditions and safety concerns, generating additional emissions under less efficient loads [16]. Approximately 15,000 annual voyages of all ship types travel through the Arctic, depositing potentially large amounts of BC on snow and ice [17].

5 Emissions from shipping will continue to climb despite the recent global economic downturn [18]. The International Maritime Organization (IMO) estimates that GHG emissions from shipping will likely triple between now and 2050. IMO efforts to reduce GHG emissions are unlikely to place the industry on a low-carbon growth trajectory, even after taking into consideration the recently passed Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan [14, 39]. In addition, the decline of Arctic sea ice would make possible longer navigation seasons and new trade routes that facilitate increased shipping activity. More BC emissions along increasingly viable trans-Arctic shipping routes could, in turn, increase deposition on fragile ice and snow surfaces that would melt at an accelerated pace. The Arctic already experiences twice the global rate of temperature increase [19], so these BC emissions would exacerbate harm to an already fragile region.

6 Due to the potent short-term climate forcing of BC indicated by a high 20-year global warming potential, the marine sector's disproportionate contribution to emissions, and the available emissions control options, there has been increasing focus within the IMO on actions to better measure, inventory, and reduce these marine BC emissions. In response to concerns expressed by the Government of Norway, the Marine Environmental Protection Committee (MEPC) of the IMO adopted a work plan in the summer of 2011 to investigate the control of marine BC emissions [20]. The MEPC instructed its Bulk Liquid and Gases (BLG) Sub-Committee to respond to a series of questions in advance of MEPC's sixty-fifth meeting in 2013. In response, in January 2012, the BLG at its sixteenth meeting adopted terms of reference for this work that include the following actions: (1) develop a definition for BC emissions from international shipping; (2) consider measurement methods for BC and identify the most appropriate method for measuring BC emissions from international shipping; (3) investigate appropriate control measures to reduce the impact of BC emissions from international shipping; (4) submit a final report to MEPC 65.

7 Vessel-based inventories have been published for current and future international shipping emissions of BC at the global scale and for the Arctic region [14, 15, 21-24]. These estimates use similar methodologies – a single emission factor (EF), usually grams of BC per kilogram of fuel, applied to fuel consumption – with few exceptions. This document investigates the sources of EF and hypothesizes that a single-EF approach systematically miscounts BC emissions.

8 The next section provides a critical review of existing literature on BC inventories, EFs, and vessel fuel consumption in order to understand what contributes to differences among estimates. Section 3 introduces a methodology that addresses limitations of existing estimates, applies updated and refined data from the technical literature, and analyses the

impact on prevailing global BC inventory estimates. A sensitivity analysis is included to illustrate the range of effects of newly introduced variables. A concluding section outlines the technical and policy implications of this study, points to knowledge gaps, and puts forward additional research needs.

REVIEW OF BC EMISSIONS INVENTORY METHODS FOR INTERNATIONAL SHIPPING

General Methods

9 The methodology to estimate emissions is relatively consistent across pollutant types, and at its most fundamental level requires two inputs: a single EF for the pollutant in question, and total fuel consumption. Equation 1 illustrates the way in which these inputs are generally applied,

$$E_i = FC \times EF_i \qquad \text{Equation 1}$$

where E_i is the emission of pollutant i; FC is the total fuel consumption; EF_i is the EF of pollutant i.

10 This so-called fuel-based method provides a straightforward way to estimate shipping emission inventories and is generally assumed to be accurate when EFs vary little with Maximum Continuous Rating (MCR). However, EFs can fluctuate widely under certain operating conditions and for certain pollutants, causing this method to lose precision. In addition, the composition of particulate matter may differ significantly when high sulphur heavy fuel oil is replaced with lower sulphur marine diesel oil. The perspective of emissions given by fuel consumption and EF_{BC} is meant to be considered as a broad overview at a large scale, while more fine-grained inventory approaches may be more useful where greater precision is needed.

Literature Review

11 Few studies have published estimates of global BC emissions from international shipping. Eyring et al. (2005) calculated fuel consumption from the international fleet of ships in 2001 using information on fleet size, activity, and average fuel consumption for various ship types [22]. Annual fuel consumption for each ship type was multiplied by a single EF_{BC} to yield an estimate of global BC emissions – about 50,000 tonnes (kt) – from international shipping. Dalsøren et al. (2008) estimated shipping emissions and their environmental impact in 2004, including BC [23]. This study used a global ship activity dataset based on 15 profiles of ship activity, each representing a category of ship type and size. Emissions at sea and in port were distributed globally using about 2 million global ship observations from a combination of unpublished AMVER and COADS data. This produced an estimate of total fuel consumption of about 217 million metric tonnes (mmt) and BC emissions of 39 kt, more than 90 per cent of which was emitted at sea. Fuglestvedt et al. (2008) used the EDGAR database to generate an estimate of 182 mmt fuel consumption and 197 kt BC from international shipping in 2000 [25]. Using the same EDGAR database, Dentener et al. (2006) estimated 130 kt BC emissions from international shipping [26]. Lack et al. (2008) examined BC emissions factors and found these to vary widely for different fuel types, engine types and engine loads [24]. Lacking high-resolution data to distinguish fuel consumption by engine type and loads, the study calculated BC emissions using EF_{BC} specific to ship type, which served as a proxy for engine type. This produced an estimate of 254 mmt fuel consumed in 2001 and 133 kt BC emitted. Results from these studies are summarized in table 1.

12 A smaller number of studies have given estimates of BC emissions from international shipping specifically in the Arctic. Corbett et al. (2010) presented 5 km × 5 km gridded emissions of BC [21]. The study estimated in-Arctic fuel consumption of 3.5 mmt and BC emissions of 1.2 kt in 2004. The study also forecasted BC emissions through 2030, accounting for increases in ship activity driven by potential use of ice-free trans-Arctic routes and projecting the effect of future emission control measures. Peters et al. (2011) modeled Arctic shipping emissions for transpolar (or trans-Arctic) shipping and shipping related to in-Arctic petroleum extraction. For transpolar shipping the number of voyages was estimated using a cost-benefit comparison with traditional routes through the Suez Canal [27]. Activity from petroleum was not modeled explicitly, but assumed to be proportional to the production data given by a model for predicting future oil and gas production. This produced estimates of fuel consumption and BC emissions from international shipping in the Arctic of 3.3 mt and 1.15 kt, respectively, in 2004. The results of these studies are included in table 1.

Table 1 – Summary of Estimates of International Shipping Emissions of BC

Study	Modelled year	Reported Emissions (kt)	Derived or Reported Fuel consumption (mmt)	Derived or Reported EF_{BC} (kg per ton)
Global BC Inventories [a]				
Buhaug et al. (2009)	2007	120	333	0.39[b]
Dalsøren et al. (2008)	2004	39	216	0.18[c]
Dentener et al. (2006)	2000	130	182	0.69
Eyring et al. (2006)	2001	50	280	0.18[b]
Eyring et al. (2010)	2005	160	300	0.53
Lack et al. (2008)	2001	133	254	0.53[d]
Fuglestvedt et al. (2010)	2000	197	182	1.08
Arctic BC Inventories				
Corbett et al. (2010)	2004	1.25	3.5	0.35
Peters et al. (2011)	2004	1.15	3.3	0.35

[a] Lauer et al. (2009) produced a global BC inventory but details were not given in the published document and attempts to clarify with the author were unsuccessful [28].

[b] Buhaug et al. (2009) did not estimate BC emissions directly, but cited Eyring et al. (2010) and its estimate of BC emissions. The authors provided two sets of BC emission estimates. One is 130 kt in 2000 and the other is 120 kt in 2007, both of which were used to model radiative forcing in shipping.

[c] BC emissions factor from Sinha et al. (2003) [29]. Emissions of trace gases and particles are taken from two ships in the southern Atlantic Ocean.

[d] Weighted average.

13 Table 1 shows fuel consumption, EF_{BC}, and BC emission for studies that have estimated BC emissions from international shipping. Some did not provide either fuel consumption or EF_{BC}, in which case values were derived. In the derivation, we assume the fuel-based methodology in calculating BC emissions is used. For example, shipping fuel consumption data from Fuglestvedt et al. (2008) were based on shipping CO_2 emissions (derived from the EDGAR database), assuming a fixed EF of CO_2, while a EF_{BC} was then derived from the total shipping fuel consumption estimate and BC emissions [25]. The BC emissions in Fuglestvedt et al. (2008) were taken from Bond et al. (2004) [30]. Shipping fuel consumption data in Dentener et al. (2006) were assumed to be equivalent to the fuel consumption estimate derived from Fuglestvedt et al. (2008), because the same data year

and model were used [26]. Buhaug et al. (2009) cited BC in 2000 and 2007, but did not give an EF_{BC}. The EF_{BC} in Buhaug et al. (2009) was derived from 2007 shipping fuel consumption [14]. The EF_{BC} in Eyring et al. (2010), Corbett et al. (2010), and Peters et al. (2011) comes from Lack et al. (2008) [15, 21, 27]. Lack et al. (2008) provided EF_{BC} for multiple ship types and was the only study to do so. A weighted average EF_{BC} from Lack et al. (2008) was estimated using predictions of fuel consumption for each ship type evaluated.

Sensitivity of BC Inventories to Key Variables

14 To compare BC emissions estimates, we employ the consensus fuel consumption estimate from the IMO Expert Group (Buhaug et al., 2009) as a baseline and extrapolate likely estimates of BC emissions using EF_{BC} from each study in table 1 [14]. Fuel consumption in the IMO study was calculated using an activity-based bottom-up approach, where annual ship activity for each ship category is estimated and used to calculate total annual fuel consumption. This approach proves to be more accurate than simply using fuel sales data or average fleet activity. Upper- and lower-bound estimates of fuel consumption given in the IMO study are used to quantify uncertainty. Results are given in figure 1.

15 Upper- and lower-bound inventory estimates reflect a range of possible BC emissions using fuel consumption and EF_{BC} taken from the IMO study. No other global BC inventory estimates fall in this range, and their variability is greater than a factor of four. Extrapolation of estimates of in-Arctic BC emissions at the global scale does produce global estimates that fall within the IMO emissions range. The IMO-based estimate appears to represent a reasonable mid-point estimate when compared to these other studies, but the wide range in all estimates does suggest significant uncertainty and differences in approach.

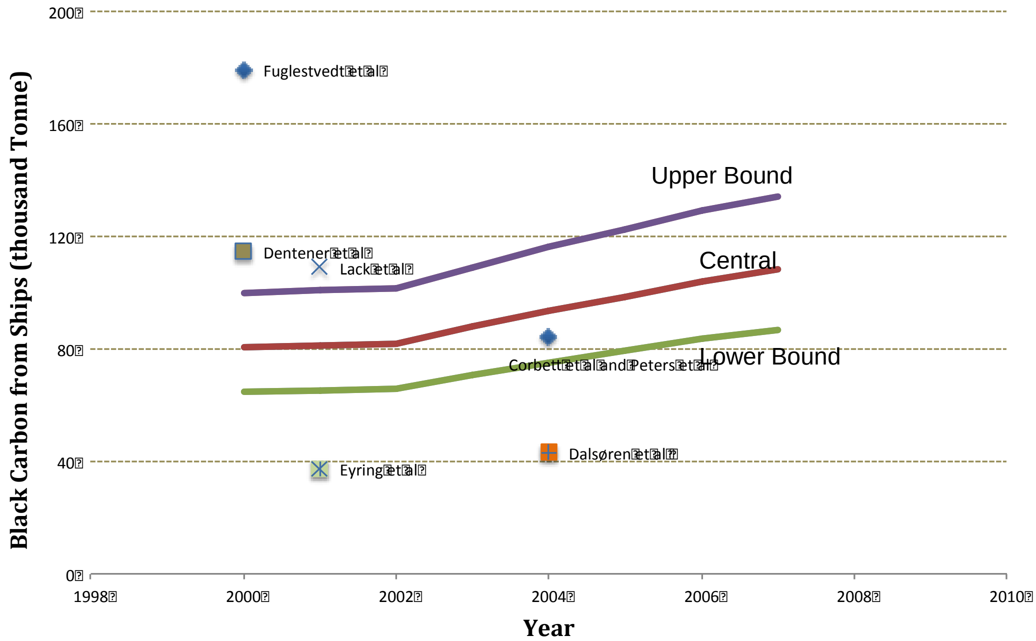

Figure 1 – IMO global BC emission projections compared to the literature

16 These large differences in BC emission inventories may be attributable to fuel consumption or EF_{BC} estimates. To evaluate this further, a weighted average EF_{BC} derived from Lack et al. (2008) is applied to fuel consumption estimates in each study and compared to original emission estimates [24]. This source of emission factors is chosen because it represents the only set of measured BC emission values for a range of ship types. EF_{BC} for each ship type is then weighted by fuel consumption for a range of diesel engines, assuming

ship type/engine/fuel mix is similar to Lack et al. (2008) [24]. Results are presented in figure 2.

17 Adjustments for the new weighted average EF_{BC} for the various studies' emission estimates range between 27 per cent and 190 per cent of original emission estimates. After adjustment, smaller variability across the studies is seen, suggesting that the EF_{BC} contributed a substantial amount to the differences between BC emission inventories. This illustrates how more consistent, refined, and specific EF_{BC} by ship engine type may reduce the variability in global BC estimates.

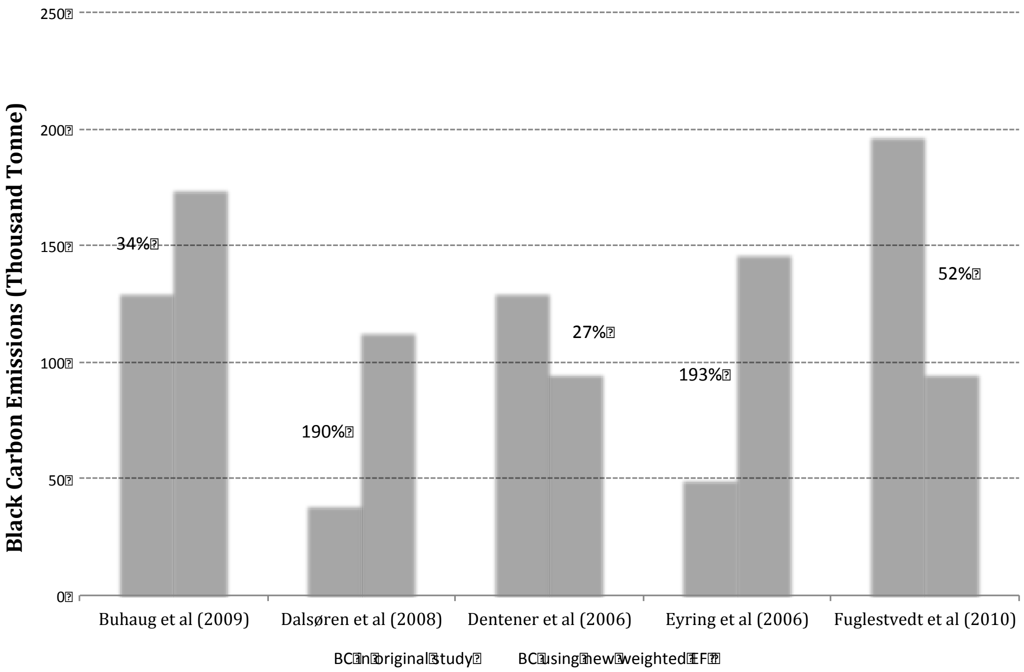

Figure 2 – Sensitivity of BC inventories to EF_{BC} inputs

BC Emission Factors

18 The physical and operational characteristics of ships are key variables when estimating EF_{BC}. Marine diesel engines are tuned to achieve maximum energy output and minimum fuel consumption during regular operation, but certain operations occur outside these bounds. This includes super-slow steaming and/or idling at berth, which can rely only on auxiliary engines. These operational variables become particularly important in the Arctic where floating and/or solid ice cause ships to slow down or speed up at irregular intervals. A sharp increase in EF_{BC} from various ship engine types has been frequently noted in the literature for engine loads below 25 per cent [31-33]. Lack et al. (2012) reviewed and summarized the literature on engine load effects, concluding that absolute BC emissions may increase as much as 50-100 per cent due to low engine loads [16].

19 Fuel quality can also have a significant effect on the EF_{BC} from various ship types. Most studies agree that marine fuel with lower sulphur content results in a lower EF_{BC} [33-35], although one study suggested the opposite effect [32]. Lack et al. (2012) concluded from a review of the literature that the EF_{BC} most likely declines to levels between 30 per cent-80 per cent from baseline for ships that switch from residual fuels to distillate fuels [16].

20 A third variable that informs differences in EF_{BC} is the marine diesel engine itself. Ocean-going vessels usually run large slow-speed diesel (SSD) engines. Smaller vessels, including tugboats, fishing ships, and ferries, operate medium-speed diesel engines (MSD). Some passenger boats use high-speed diesel (HSD) engines. Some literature illustrates EF_{BC} for SSD, MSD, and HSD engines [24, 33, 35-38]. These estimates vary considerably.

21 This review of EF_{BC} provides some insight into the existing literature on international marine BC emissions. First, application of a single EF_{BC} to fuel consumption for the whole shipping fleet may not reflect the dynamic nature of emissions under different operational scenarios for ships. The single EF_{BC} approach applied in most published studies to date does not capture the wide range of uncertainties in this estimate, suggesting a weakness in existing inventories.

22 Building on this review of EF_{BC}, in the next section we match different EF_{BC} with a matrix of engine load, fuel type, and engine combinations to re-calculate BC emissions from shipping at the global scale. This re-estimate is done using relatively high-resolution data provided by the IMO [14]. A re-estimate for BC emissions in the Arctic is also provided.

METHODOLOGY, ANALYSIS, AND FINDINGS

Methodology Overview

23 We construct a refined activity-based methodology to model global and regional BC emissions from international shipping. Refinements not available in previously published inventories include fuel consumption for each ship type, engine, and fuel type, and EF_{BC} sensitive to each of these parameters. A generic approach is presented in equation 2,

$$\sum_{t=h}^{n} E_h = FC_{i,j,k} \times EF_{i,j,k} \qquad \text{Equation 2}$$

where E_h is the annual mass of BC emissions for ship *h*; $FC_{i,j,k}$ is the fuel consumption of ship *h* with ship type *i*, engine load *j*, and fuel quality *k*; $EF_{i,j,k}$ is the EF_{BC} of ship *h* with ship type *i*, engine load *j*, and fuel quality *k*.

24 Table 2 shows estimated EF_{BC} using this approach. As discussed in section 2.4, emission factors are determined by engine load, fuel type and engine type. Due to data limitations, average engine load is used for each ship type. We assume ships will operate at low load when at berth. The central estimate of at-sea EF_{BC} is mainly derived from Lack et al. (2009) [24]. We then adjust EF_{BC} using estimates from Lack et al. (2012) for ships using Marine Diesel Oil (MDO) [16]. The EF_{BC} of low-sulphur fuel is much lower than the EF_{BC} of high-sulphur residual oil. Lack et al. (2012) reported a 30 per cent-80 per cent reduction from using low-sulphur fuel; we assume an adjustment factor of 0.5-0.7 by using MDO [16]. We also calculate the in-port EF_{BC} based on low-load adjustment estimated from [16, 33]. The effect of low load varies widely. Lack et al. (2012) estimated a 50 per cent-100 per cent increase in terms of EF_{BC} for a 25% engine load [16]. Petzold et al. (2010) showed almost 300 per cent increase in 25 per cent engine load and 500 per cent increase in 10 per cent load [33]. Since ships will shut down main engines at berth and keep a 10 per cent-20 per cent low engine load, we apply an adjustment factor of 1.5-5. The higher-bound and lower-bound at-sea EF_{BC} are from Lack et al. (2009) where estimates of at-sea EF_{BC} with 95 per cent confidence intervals are provided [34]. Tugboats are assumed to use MDO [34].

Table 2 – Emission Factors Assumed in This Study

	Central Estimate				High Estimate (95% CI)				Low Estimate (95% CI)			
	At sea		In port		At sea		In port		At sea		In port	
	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO	HFO	MDO
Tanker	0.38	0.228	0.95	0.57	0.44	0.31	2.18	1.53	0.32	0.16	0.49	0.24
Container	0.8	0.48	2	1.2	0.96	0.67	4.82	3.37	0.64	0.32	0.95	0.48
Cargo carriers	0.4	0.24	1	0.6	0.56	0.39	2.82	1.97	0.24	0.12	0.35	0.18
Bulk carriers	0.38	0.228	0.95	0.57	0.53	0.37	2.64	1.85	0.23	0.12	0.35	0.17
Tugboats		0.97		2.425		1.08		5.38		0.86		1.30
Passenger Boat	0.36	0.216	0.9	0.54	0.46	0.32	2.31	1.62	0.26	0.13	0.39	0.19

Fuel Consumption Data

25 For global BC inventory assessment, we use ship activity data given in the IMO GHG Report [14], where average engine loads and aggregated fuel-quality data for each ship type are provided. We assume ships that use MDO emit lower levels of BC than ships that burn HFO. We divide ship fuel consumption into fuel consumed at sea and in port based on Dalsøren et al. (2009) [23]. We assume ships in port will run auxiliary engines at low loads, when higher EF_{BC} should be applied. These relatively high-resolution data enable us to estimate fuel consumption under high/low engine load for major ship types and for different fuel qualities.

26 It is worth noting that even with IMO's data, this aggregated information is not likely to yield the most precise BC inventory. Uncertainty comes from at least two sources. First, the IMO Report only publishes average engine loads, which are higher than 60 per cent for all types of ships. However, it is well known that engine loads are much lower during manoeuvring. Because we cannot distinguish maneuvering from cruising based on these aggregated data and because EF_{BC} is much higher in low load than in high load, the true BC inventory will be higher than is estimated here. Additionally, while we can approximate MDO and HFO used by each ship type from data provided in various sections of the Report, the true amount of MDO and HFO that ships consumed in 2007 is less certain. Uncertainty in fuel consumption is less problematic than engine load, because uncertainty in the MDO/HFO ratio and the resulting errors in the inventory estimate may be cancelled out.

27 The absence of high-resolution activity data for the Arctic makes production of an in-Arctic BC inventory challenging. We rely on ship activity data published by Corbett et al. (2010), which only distinguishes fuel consumption by ship type. Despite low-resolution activity data, we are able to show that more refined EF can produce significant changes to the in-Arctic BC emissions estimates [21].

Results

28 Table 3 – provides estimates of a revised global BC inventory from international shipping. Emissions were between 143 kt and 231 kt in 2007. A majority of BC was generated from at-sea HFO, an important point for future BC projections. Our central estimate suggests that nearly 184 kt was emitted in 2007, a value 42 per cent higher than the 130 kt estimate given in Buhaug et al. (2009) for the IMO [14].

Table 3 – BC Emission from Shipping in 2007 (in kt)

	Central Estimate	High Estimate	Low Estimate
At Sea HFO	151	185	117
At Sea MDO	29	35	23
In port HFO	3	7	2
In Port MDO	1	3	1
Total Emissions	184	231	143

29 We compare these results to the results in previous studies by applying an average EF_{BC} – 0.56 kg per ton fuel – to the fuel consumption reported in those studies. Figure 3 gives these results. With the exception of Lack et al. (2008) and Eyring et al. (2010), a revised EF_{BC} markedly increased the BC inventory estimates of previous studies. This demonstrates how a more updated EF_{BC} reflecting the latest science could dramatically change existing estimates of BC emissions from international shipping [24].

30 A revised EF_{BC} produces results that largely resemble Lack et al. (2008) [24] since source data are primarily derived from this study. The 9 per cent difference we see is a result of adjustment factors. The MDO adjustment produces an estimate of lower emissions while our in-port adjustment produces higher emissions. The result is very close to Eyring et al. (2010) [15] due to an identical EF_{BC} value.

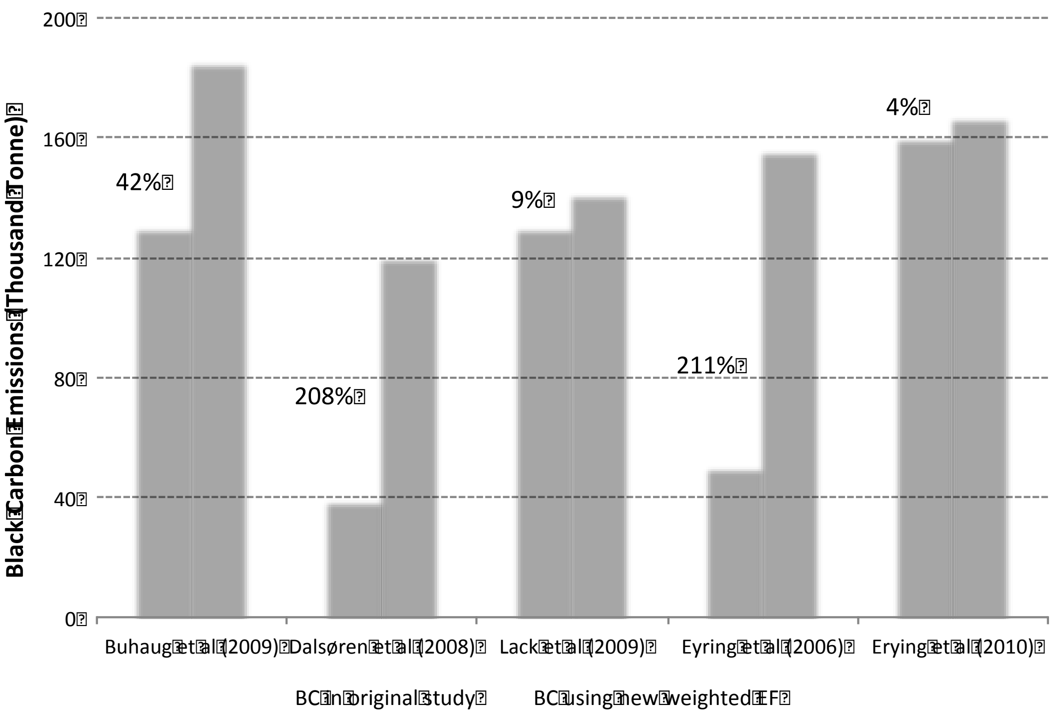

Figure 3 – Revision of global BC emission inventory estimates using refined EF_{BC}

31 We then backcast this BC inventory estimate to 1990 by calculating the weighted average EF_{BC} and applying this to the fuel consumption estimate in Buhaug et al. (2009) [14]. Figure 4 delineates the historical change in the last two decades. Real BC emissions were likely higher a decade ago than shown in figure 4, as the marine fuel in use a decade ago contains higher sulphur than in 2007, meaning that the EF_{BC} was larger than in 2007.

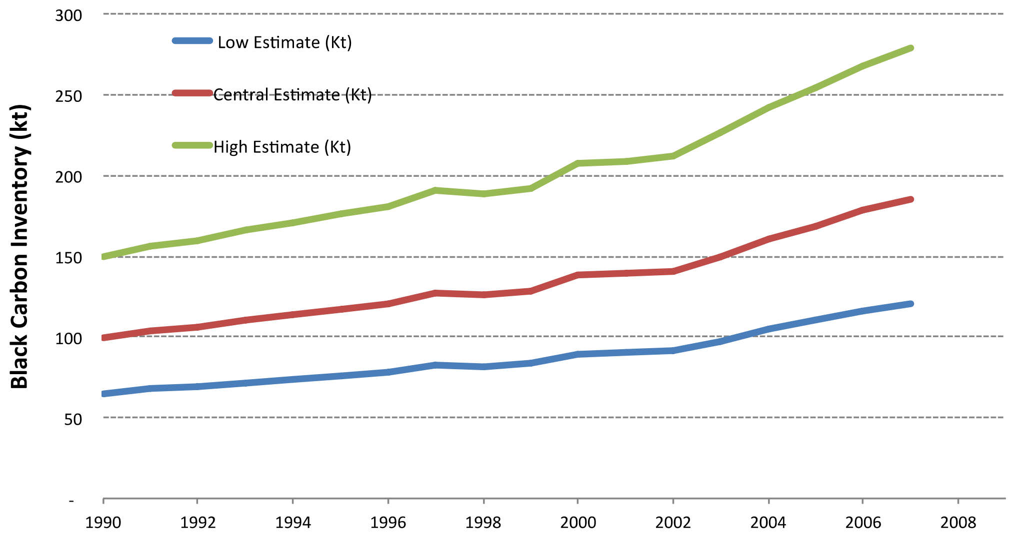

Figure 4 – BC emissions from ships between 1990 and 2007

32 Our central estimate of BC emissions in the Arctic from international shipping is 2300 kt in 2004, 90 per cent above what Corbett et al. (2010) and Peters et al. (2011) estimated [21, 27] (table 4). The weighted average EF_{BC} is 0.66 kg per tonne of fuel, reflecting different ship types relative to the global fleet.

33 It should be noted that the estimate in table 4 remains a coarse estimate for marine BC, given the uncertain nature of ship operations and uncertainty in EF_{BC}. Nonetheless, the methodology and EF_{BC} used here provide a refined assessment of marine BC emissions in the Arctic.

Table 4 – Estimates of marine BC emissions in the Arctic from this study and from the literature (in tonnes)

Year of study	This Study			Literature	
	Low	Central	High	Peters et al. 2011	Corbett et al. 2010
2004	1800	2300	2900	1150	1225

34 Fuel quality will play an increasingly important role in reducing BC emissions from shipping in the future. As more stringent fuel-quality mandates come into effect, first in Emission Control Areas, then worldwide, low-sulphur distillate is expected to gradually replace high-sulphur heavy fuel oil. This will produce changes over time in EF_{BC} that future projections of global BC emissions will need to account for. Second, as slow steaming becomes standard industry practice and as ships increasingly operate at low engine loads, emissions could rise substantially. Slow steaming is a fuel-saving measure for ship operators, but the relationship between engine load and BC emissions suggests that operations could play a more significant role in producing BC emissions in the future.

35 It may be the case that even this revised BC inventory is still an underestimate due to a number of inadequately characterized factors and lingering data limitations. For example, ships in the Arctic have to change speed for safety reasons more frequently than elsewhere. The resulting transient engine loads can routinely result in higher EF_{BC} (e.g. see Lack et al., 2012) than those utilized here.

CONCLUSIONS

36 This document reviews existing literature on BC inventories from shipping, identifies key differences among published estimates, explores areas of improvement, and provides refined emissions estimates. We demonstrate how BC fuel consumption and EF_{BC} are a large source of uncertainty across BC inventory estimates and how the inventory estimate is sensitive to operational conditions of ships. We also develop a framework for utilizing an entire set of EF_{BC} to improve upon existing estimates. Using updated global BC emissions factors, we calculate shipping BC emissions of 184 kt in 2007, which is over 40 per cent higher than the most widely cited estimate. We also estimate that shipping BC emissions in the Arctic were about 2,300 tonnes in 2004, 90 per cent higher than estimates in the literature.

37 We emphasize that further improvements with more disaggregated input data from more vessels in more conditions would improve the accuracy of BC inventory estimates. To overcome problems with using aggregated engine load data, the best approach may be to integrate updated technology- and operation-specific EF_{BC} with a bottom-up methodology that sums activities of each ship at each route. Data from activity models are capable of producing this. In the absence of more detailed data, the methodology in this document may provide a basis from which more elaborate inventory studies can be drawn. The findings may generate a more precise first-order estimate of the global marine BC inventory from which future studies can refine the framework and utilize further updated data.

38 Despite these limitations, these findings have significant implications for future marine BC inventory assessments. This study shows that recent scientific findings on EF_{BC} have greatly improved the accuracy and resolution of marine BC emissions. Incorporating such findings with higher-resolution data will further improve inventory assessments. Spatially resolved models may generate more accurate climate- and health-impact estimates of marine BC emissions and help better prioritize future mitigation actions. Marine BC inventories could be further improved by a uniform BC definition and measurement method applied consistently in the development of emission factors.

39 The findings presented in this document could inform policy making with regard to marine BC emissions. This study indicates that shipping-based BC emissions may be a more significant issue than previously understood. In IMO's climate modelling, a total of 130 kt of BC was assumed in 2007; a much higher volume of marine BC emissions, together with its especially potent near-term global warming effect, would only suggest higher climate impacts associated with shipping. In particular, the risk imposed by marine BC on in-Arctic climate may be more severe. High-sulphur fuel and low engine load may have contributed to a much higher level of BC emissions, compounding the albedo effect and worsening regional climate change.

40 The result also shows the potential magnitude of benefits from switching to low-sulphur fuel. In response to local health concerns, a number of ports have created incentives for ships to voluntarily switch to low-sulphur fuel. On a much larger scale, the IMO requires ships operating in Emission Control Areas (ECAs) to use 0.1 per cent sulphur fuel beginning in 2015. It also mandates that international shipping outside of ECAs use 0.5 per cent sulphur fuel from 2020, down from the current average of 2.7 per cent sulphur fuel, subject to a review in 2018. Along with the direct SO_x-related health benefits from these voluntary and binding marine fuel requirements, the related reduction of BC could indirectly lead to additional improvements in air quality and climate.

41 The quality of the BC inventory and related decision-making will be further strengthened by more research on the EF_{BC}. Unified measuring techniques and protocols will yield more robust results, fill in data gaps, and facilitate improved accuracy in BC inventories. More field observations and experiments on the relationship between the EF_{BC} that relate to changes in fuel type, engine load, and engine type would reduce uncertainties in modelling and could unify differences in inventories. These efforts would lay the foundation for more reliable marine BC inventory estimates and provide informative policy guidance on future emission reduction strategies.

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