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

Haifeng Wang
The International Council on Clean Transportation
1225 I Street NW Suite 900
Washington DC, 20005
Tel: +1 202 534 1606
Fax: +1 202 534 1601
haifeng@theicct.org

Ray Minjares*
The International Council on Clean Transportation
One Post Street, Suite 2700
San Francisco, CA 94104
Tel: +1 415 202 5748
Fax: +1 415 399 9172
ray@theicct.org

*Corresponding Author

Submission Date: August 1, 2012
Word Count: 5968 words plus 6 tables & figures. 7468 total words.

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

ABSTRACT:

Black carbon (BC) emissions from international shipping are significant and contribute to global and regional climate change, particularly in the Arctic. This paper reviews global estimates of international marine BC emissions, identifies differences in inventory methods, and proposes an approach for improving upon existing estimates. A critical review of the literature reveals that more refined, specific marine vessel BC emission factors (EF_{BC}) are not generally accounted for in most global inventories. We find that EF_{BC} are the single most important source of differences in inventories due to poor sensitivity to ship engine type, fuel quality, and engine load, and we propose a weighting framework that better encapsulates such effects. Using fuel consumption estimates from the International Maritime Organization (IMO) 2009 GHG report and updated EF_{BC}, we estimate that shipping was responsible for about 184 thousand tonnes of BC in 2007. This estimate is 42 percent higher than the current IMO estimate, 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% higher than prevailing estimates. Our findings suggest that the international marine BC contribution is widely underestimated, and that improvements to major BC inventories can be made to reflect state-of-the-art data on marine EF_{BC}.

INTRODUCTION

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 pollutants, which are notable for their strong warming effects over short time periods, are increasingly recognized as an important contributor to this climate change. One of them is black carbon (BC), 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 greenhouse gases, so 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].

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 percent of global anthropogenic BC emissions. Diesel emissions are a major source of BC and account for approximately 90 percent 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 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 in terms of warming effect (measured as integrated radiative forcing) than carbon dioxide from energy-related sources on a global basis over a 100-year time horizon and 2800 (± 1800) times more potent on a shorter 20-year time horizon [11].

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. 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].

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 [14]. 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.

Due to the potent short-term atmospheric climate forcing of BC, the marine sector's disproportionate contribution to emissions, and the available emissions control options, there has been increasing focus on actions to better measure, inventory, and reduce these marine BC emissions within the IMO. 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 65th meeting in 2013. In response, in January 2012, the BLG at its 16th meeting adopted terms of reference for this work that includes 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) identify and collate possible control measures to reduce the impact of BC emissions from international shipping; (4) and submit a report to the 17th meeting of the BLG in 2013.

Vessel-based inventories have been published for present day 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 paper investigates the sources of EF and hypothesizes that a single-EF approach systematically miscounts BC emissions.

The next section provides a critical review of existing literature on BC inventories, emission factors, and vessel fuel consumption 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 analyzes the impact on the 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

2.1. General methods

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 these inputs are 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.

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 the Maximum Continuous Rating (MCR). However, it is worth pointing out that EFs can fluctuate widely under certain ship operation circumstances and for certain aerosols, causing this method to lose precision. In addition, the composition of particulate matter may differ significantly when the sulfur level changes from high sulfur heavy fuel oil to low sulfur marine diesel oil. The perspective of emissions given by fuel consumption and EF_{BC} is meant as a broad overview at large scales, while more fine grained inventory approaches may be more useful where precision is needed.

Literature Review

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 thousand 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 tonnes (mmt) and BC emissions of 39 kt, more than 90 percent 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 vary widely for different fuel types, engine types and engine loads [24]. Using data from Eyring et al (2010), Buhaug et al (2009) quantified climate impact of BC emissions. 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.

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 Arctic fuel consumption and BC emissions of 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	Modeled year	Reported Emissions (kt)	Derived or Reported Fuel consumption (mmt)	Derived or Reported EF_{BC} (kg per ton)
Global BC Inventory [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
BC in the Arctic				
Corbett *et al* (2010)	2004	1.25	3.5	0.35
Peters *et al* (2011)	2004	1.15	3.3	0.35

[a] Another study related to global BC inventory is Lauer *et al* (2009) [28]. It is not included because BC inventories were not given. Attempts for clarification by the author were unsuccessful

[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 Shina *et al* (2003) [29]. Emissions of trace gases and particles are taken from two ships in the southern Atlantic Ocean

[d] Weighted average

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) was 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) was assumed to be equivalent to the fuel consumption estimate derived from Fuglestvedt *et al* (2008), because they examined the same year data using the same model [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) came 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} of Lack *et al* (2008) was estimated using predictions of fuel consumption for each ship type evaluated.

Sensitivity of BC inventories to key variables

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 [14]. 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 [14]. Results are given in FIGURE 1.

Areas among the three lines reflect a range of possible BC emissions using fuel consumption estimates and implied EF_{BC} in the IMO study. No other global BC inventory estimates fall in this range, and the wide change of estimates 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.

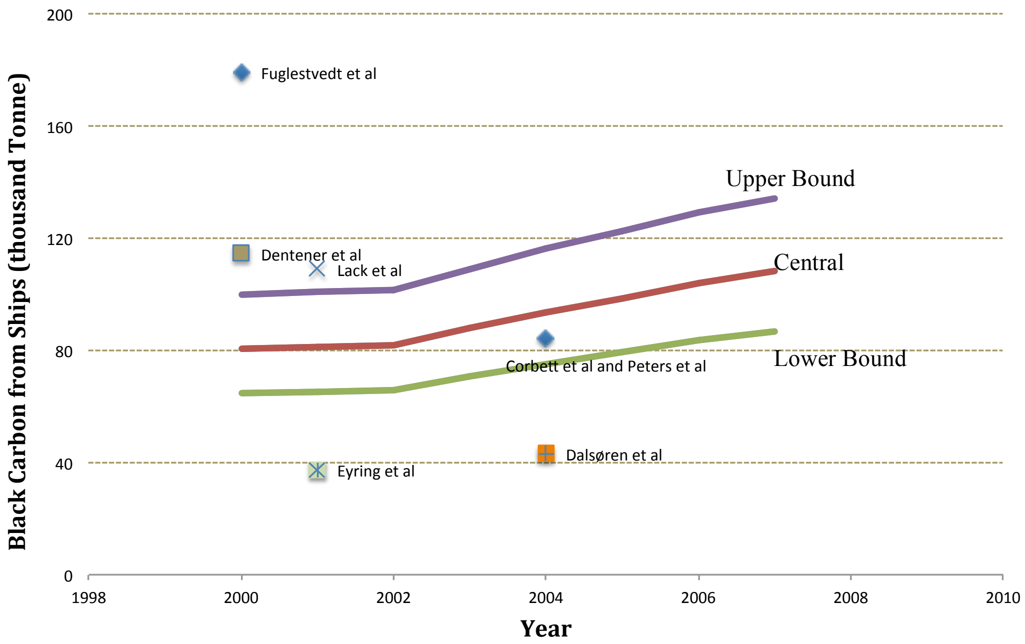

FIGURE 1 IMO global BC emission projections compared to the literature.

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]. The EF_{BC} are weighted by fuel consumptions of different diesel engines. In doing so, we assume the ship type/engine/fuel mix in other studies are similar to Lack *et al* (2008) [24]. Given the slow changes of fleet composition and long lifetime of ships, the assumption appears valid. Results are presented in FIGURE 2. Adjustments for the new weighted average EF_{BC} for the various studies' emission estimates range between 27 percent and 190 percent of original emission estimates. After the adjustments, the resulting smaller change across the studies suggests that the EF_{BC} contributed a substantial amount to the differences in BC emission estimates. Therefore the use of more consistent, refined, and specific EF_{BC} based on ship engine type reduce the change in global BC estimates in the literature.

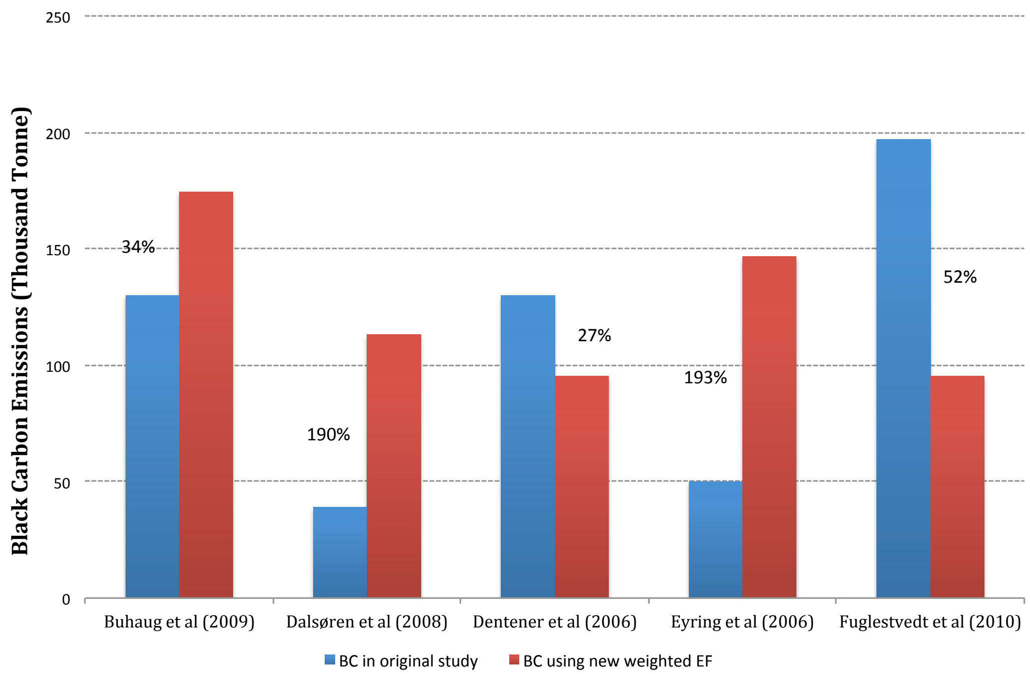

FIGURE 2 Sensitivity of BC inventories to EF_{BC} inputs.

BC emission factors

The physical and operational characteristics of ships are key variables when estimating EF_{BC}. One of these variables is engine load. 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 or idles at berth, which can rely only on auxiliary engines. These operational variables become particularly important in the Arctic where floating 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% [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% due to low engine loads [16].

Fuel quality can also have a significant effect on the EF_{BC} from various ship types. Most studies agree that marine fuel with lower sulfur 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%-80% from baseline for ships that switch from residual fuels to distillate fuels [16].

A third variable that informs differences in EF_{BC} is the marine diesel engine itself. Oceangoing 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.

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.

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 combination 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

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.

TABLE 2 shows estimated EF_{BC} using this approach. 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 sulfur fuel is much lower than the EF_{BC} of high sulfur residual oil. Lack *et al* (2012) reported a 30%-80% reduction from using low sulfur 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%-100% increase in terms of EF_{BC} for a 25% engine load [16]. Petzold *et al* (2010) showed almost 300% increase in 25% engine load and 500% increase in 10% load [33]. As ships will shut down main engines at berth and keep a 10%-20% 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% 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

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. This relatively high-resolution data enables us to estimate fuel consumption under high/low engine load for major ship types and for different fuel qualities.

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% for all types of ships. However, it is well known that engine loads are much lower during maneuvering. Because we cannot distinguish maneuvering from cruising based on this aggregated data and because EF_{BC} is much higher in low load than in high load, the true BC inventory will be higher than what 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 inventory estimate may be cancelled out.

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 produce significant changes to the in-Arctic BC emissions estimates [21].

Results

TABLE 3 provides estimates of a revised global BC inventory from international shipping. This suggests that 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 percent higher than the 130 kt estimate 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

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), revised EF_{BC} markedly increased the BC inventory estimates of previous studies by a large margin. This demonstrates how a more updated EF_{BC} reflecting the latest science could dramatically change existing estimate of BC emissions from international shipping [24].

A revised EF_{BC} produces results that largely resemble Lack *et al* (2008) [24] since source data is primarily derived from this study. The 9% 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], as our EF_{BC} is identical to theirs.

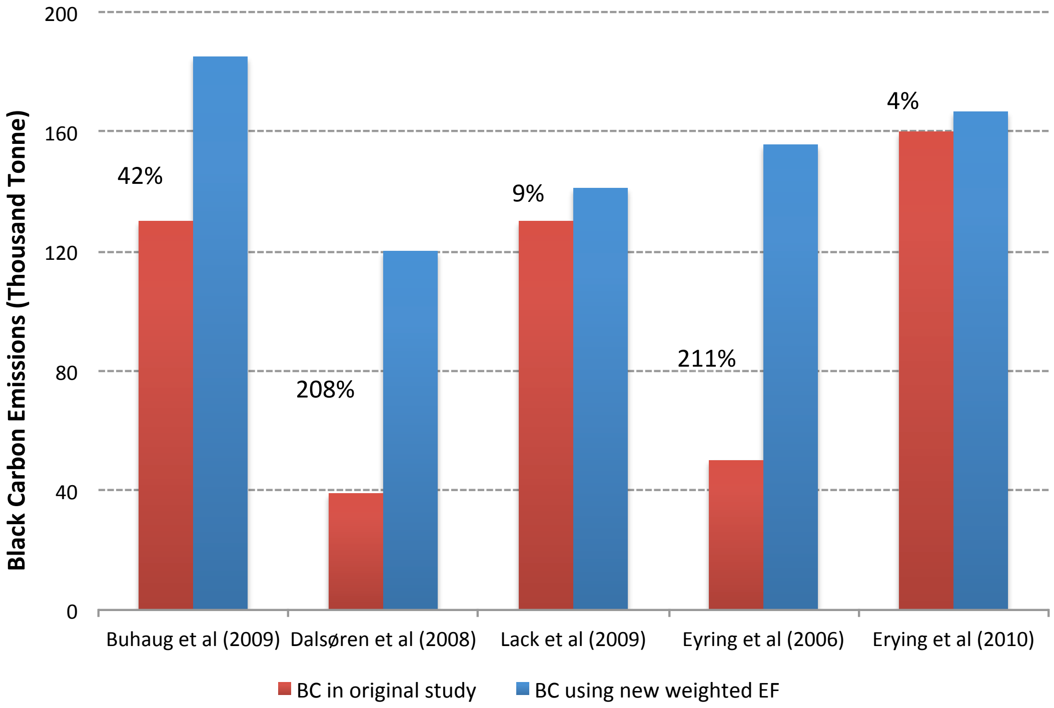

FIGURE 3 Sensitivity of global BC emission inventory estimates to refined EF_{BC}.

Our central estimates of BC emissions in the Arctic from international shipping is 2300 kt in 2004, 90% above what Corbett *et al* (2010) and Peters *et al* (2011) estimated [21, 27]. The weighted average EF_{BC} is 0.66 kg per tonne of fuel, reflecting the different ship types compared with the composition of the global fleet.

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 sulfur distillate is expected to gradually replace high sulfur 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.

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

This paper 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 a third 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% higher than estimates in the literature.

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 paper 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.

Despite these limitations, these findings have significant implications on 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.

The findings presented in this paper 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 modeling, 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 sulfur 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.

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

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 BC inventory accuracy. 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 modeling and could unify differences in inventories. These efforts would lay the foundation for more reliable marine BC inventory estimates and policy guidance on future emission reduction strategies.

ACKNOWLEDGEMENTS

Thanks to Daniel Lack (National Oceanic and Atmospheric Administration) and Nicholas Lutsey (The International Council on Clean Transportation) for useful comments

REFERENCE:

1. Bond, T. and R. Bergstorm, *Light absorption by carbonaceous particles: an investigative review.* Aerosol Science and Technology, 2006. 40(1): p. 27-67.
2. Flanner, M., et al., *Present-day climate forcing and response from black carbon in snow.* Journal of Geophysical Research, 2007. 112.
3. Jacobson, M., *Strong radiative heating due to the mixing state of black carbon.* Nature, 2001. 409: p. 695-697.
4. Ramanathan, V. and G. Carmichael, *Global and regional climate changes due to black carbon.* Nature Geoscience, 2008. 1: p. 221 - 227.
5. Quinn, P., et al., *The Impact of Transported Pollution on Arctic Climate.* American Geophysical Union, Fall Meeting 2011, 2011.
6. Shindell, D., et al., *Climate, health, agricultural and economic impacts of tighter vehicle emissions standards.* Nature Climate Change, 2011. 1: p. 59-66.
7. Lamarque, J., et al., *Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application.* Atmospheric Chemistry and Physics, 2010(10): p. 7017–7039.
8. Bond, T., et al., *Historical Emissions of black and organic carbon aerosol from energy-related combustion.* Global Biogeochem. Cycles, 2007. 21.
9. Sorensen, M., *Light Scattering by Fractal Aggregates: A Review.* Aerosol Science and Technology, 2001(35): p. 648–687.
10. Andreae, M. and A. Gelencser, *Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols.* Atmospheric Chemistry and Physics, 2006(6): p. 3131–3148.
11. Bond, T., C. Zarzycki, and M. Flanner, *Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse.* Atmospheric Chemistry and Physics, 2011(11): p. 1505-1525.
12. Unger, N., et al., *Attribution of climate forcing to economic sectors.* PNAS, 2010. 107: p. 3382-3387.
13. Koch, D., et al., *Global impacts of aerosols from particular source regions and sectors.* Journal of Geophysical Research, 2007. 112.
14. Buhaug, Ø., et al., *Second IMO GHG Study 2009 Update of the 2000 GHG Study: Final Report covering Phase 1 and Pase 2*, 2009, IMO: Longdon.
15. Eyring, V., et al., *Transport impacts on atomosphere and climate: Shipping.* Atmospheric Environment, 2010. 44(37): p. 4735-4771.
16. Lack, D. and J.J. Corbett, *Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing.* Atmospheric Chemistry and Physics, 2012(12): p. 3985-4000.
17. Brigham, L., ed. *Arctic Marine Shipping Assessment 2009 Report*. ed. B. Ellis and L. Brigham2009, Arctic Council: Tromsø, Norway.
18. DNV and Lloyd's Register, *Assessment of IMO Mandated Energy Efficiency Measures for International Shipping*, 2011, IMO: London.
19. The Arctic Council, *An assessment of emissions and mitigation options for Black Carbon for the Artctic Council*, 2011.
20. IMO, *Work plan for the reduction of Black Carbon emissions from international shipping Submitted by Norway*, in *MEPC 62/4/10*2011, IMO: London.

21. Corbett, J.J., et al., *Arctic shipping emissions inventories and future scenarios.* Atmospheric Chemistry and Physics, 2010. 10: p. 9689-9704.

22. Eyring, V., et al., *Emissions from international shipping: 1. The last 50 years.* JOURNAL OF GEOPHYSICAL RESEARCH, 2005. 110.

23. Dalsøren, S.B., et al., *Update on emissions and environmental impacts from the international fleet of ships. The contribution from major ship types and ports.* Atmospheric Chemistry and Physics Discussions, 2009. 8(5): p. 18323-18384.

24. Lack, D., et al., *Light absorbing carbon emissions from commerical shipping.* Geophysical Research Letters, 2008. 38.

25. Fuglestvedt, J., et al., *Climate forcing from the transport sectors.* PNAS, 2008. 105(2): p. 454-458.

26. Dentener, E., et al., *Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data-sets for AeroCom.* Atmospheric Chemistry and Physics, 2006(6): p. 4321-4344.

27. Peters, G.P., et al., *Future emissions from shipping and petroleum activities in the Arctic.* Atmospheric Chemistry and Physics, 2011(11): p. 5305-5320.

28. Lauer, A., et al., *Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget.* Atmospheric Chemistry and Physics, 2007(7): p. 5061–5079.

29. Shiha, P., et al., *Emission of trace gases and partices from two ships in the southern Atlantic Ocean.* Atmospheric Environment, 2003. 7(15): p. 2139-2148.

30. Bond, T., et al., *A technology-based global inventory of black and organic carbon emissions from combustion.* Journal of Geophysical Research, 2004. 109.

31. Kasper, A., et al., *Particulate emissions from a low-speed marine diesel engine.* Aerosol Science and Technology, 2007. 41(1): p. 24-32.

32. Ristimaki, J., G. Hellen, and M. Lappi, *Chemical and physical characterization of exhaust particulate matter from a marine medium speed diesel engine*, in *International council on combustion engines*2011: Bergen.

33. Petzold, A., et al., *Phyical properties, chemical compostion, and cloud forming potential of particulate emissions from a marine diesel engine at various load conditions.* Environment Science & Technology, 2010(44): p. 3800-3805.

34. Lack, D., et al., *Particulate emissions from commerical shipping: chemical, physical, and optical properties.* Journal of Geophysical Research, 2009. 114.

35. Agrawal, H., et al., *Emission from main propulsion engine on container ship at sea.* Journal of Geophysical Research, 2010. 115.

36. Lack, D., et al., *Impact of fuel quality regulation and speed reduction on shipping emissions: Implications for climate and air quality.* Environment Science & Technology, 2011.

37. Petzold, A., et al., *Experimental studies on particule emissions from cruising ship, their characteristic properties, transformation and atmospheric lifetime in the marine boundary layer.* Atmospheric Chemistry and Physics, 2008. 8: p. 2387-2403.

38. Agrawal, H., et al., *In-use gaseous and particulate matter emissions from a modern ocean going container vessel.* Atmospheric Environment, 2008. 42: p. 5504-5510.