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Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing

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Abstract

The International Maritime Organization (IMO) has moved to address the health and climate impact of the emissions from the combustion of low-quality residual fuels within the commercial shipping industry. Fuel sulfur content (F_S) limits and an efficiency design index for future ships are examples of such IMO actions. The impacts of black carbon (BC) emissions from shipping are now under review by the IMO, with a particular focus on the potential impacts of future Arctic shipping.

Recognizing that associating impacts with BC emissions requires both ambient and onboard observations, we provide recommendations for the measurement of BC. We also evaluate current insights regarding the effect of ship speed (engine load), fuel quality and exhaust gas scrubbing on BC emissions from ships. Observations demonstrate that BC emission factors (EF_{BC}) increases 3 to 6 times at very low engine loads (<25 % compared to EF_{BC} at 85–100 % load); absolute BC emissions (per nautical mile of travel) also increase up to 100 % depending on engine load, even with reduced load fuel savings. If fleets were required to operate at lower maximum engine loads, presumably associated with reduced speeds, then engines could be re-tuned, which would reduce BC emissions.

Ships operating in the Arctic are likely running at highly variable engine loads (25–100 %) depending on ice conditions and ice breaking requirements. The ships operating at low load may be emitting up to 50 % more BC than they would at their rated load. Such variable load conditions make it difficult to assess the likely emissions rate of BC.

Current fuel sulfur regulations have the effect of reducing EF_{BC} by an average of 30 % and potentially up to 80 % regardless of engine load; a removal rate similar to that of scrubbers.

Uncertainties among current observations demonstrate there is a need for more information on (a) the impact of fuel quality on EF_{BC} using robust measurement methods and (b) the efficacy of scrubbers for the removal of particulate matter by size and composition.

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1 Introduction

The commercial shipping industry, through the United Nations International Maritime Organization (IMO), is subject to regulation on the quality of fuel that can be consumed within specially designated emission control areas (ECAs), in particularly sensitive regions like the Antarctic, and globally (IMO, 2008, 2009). These fuel quality requirements are motivated both by safety concerns about engine operation and vessel navigation (ISO, 1987), and to achieve human health and environmental protections from engine exhaust products. The IMO has also specified an efficiency design index that will reduce ship fuel consumption for energy savings and greenhouse gas emission reductions (IMO, 2011b) for an industry that emits 3.3 % of global CO_2 emissions (Buhaug et al., 2009). Current IMO environmental regulations are directed at limiting the emissions of sulfur dioxide (SO_2), which forms acid rain (harmful to ecosystems) and air quality-degrading primary and secondary particles.

Shipping emissions of concern for health include secondary ozone (formed from NO_x emissions), secondary particulate sulfate (formed from gaseous sulfur dioxide emissions) and directly emitted particulate sulfate, organic matter and black carbon (BC). Evidence is emerging that BC has a distinct health effect compared to other particulates despite being only a small fraction of PM mass emitted by many sources (Smith et al., 2009). Corbett et al. (2007) and Winebrake et al. (2009) identified the magnitude of current health impacts from shipping and those reductions in health impacts that would be brought about by the IMO regulations.

Shipping emissions also alter the radiative balance of the atmosphere via warming by CO_2, ozone and BC emissions, and cooling by particulate sulfate formation and subsequent formation and alteration of clouds (Eyring et al., 2010; Lauer et al., 2009). Cooling can also result from ship NO_x emissions reducing methane lifetime (Myhre et al., 2011). The cooling effect of particulate sulfate and the warming of CO_2 dominate the radiative impacts of shipping, however BC can have significant localized warming both in the atmosphere and on snow and ice surfaces (Flanner et al., 2007; Hansen and Nazarenko, 2004; Ramanathan and Carmichael, 2008). Of particular concern for climate is the likelihood that retreating sea ice in the Arctic will allow for a significant increase in shipping activity and related emissions (IMO, 2010a).

There are a number of alternatives for reducing emissions from shipping, some of which have already been assessed for their efficacy and cost effectiveness (e.g. speed reductions, fuel quality, engine slide valves, water-in-fuel emulsions, fuel emulsions, particulate filters, exhaust scrubbers) (Corbett et al., 2009, 2010b). There are three pathways that hold particular promise for emissions reductions; the effect of ship speed reductions (or “slow steaming”); fuel quality improvements; and exhaust scrubbers. These potential emissions mitigation options have not been rigorously assessed for their impact on BC emissions.

The recent downturn in the global economy led to a globally averaged reduction in ship speed of 15 % (PWC, 2011), influenced by the reduced demand for voyages and financial savings through reductions in fuel consumption. Maintaining some form of ship speed reductions as industry practice or regulation has been discussed within industry and regulatory circles as an emissions reduction strategy. In addition, some coastal regions have mandatory or voluntary ship speed reduction programs, mostly motivated by minimizing ship whale strikes and improving air quality (CARB, 2009b; NOAA, 2008; Port-of-San-Diego, 2009). For ships operating in optimal cruising conditions (open and calm waters), decreases in ship speed lead to decreases in absolute fuel consumption (as a cubic function) due to the reduced fluid resistance on the ship hull (Harvald, 1977), and so there can be significant CO_2 and other emissions reductions for a small reduction in speed. However, as engines are usually tuned for maximum speed (c.f. load), operation at lower loads creates a less efficient combustion process that could lead to increases in emissions such as CO and BC.

Regulations on the quality of fuel used by ships are already in force in specific regions (IMO, 2008, 2009), where fuel sulfur content (F_S), one aspect of fuel quality, is reduced so that emission of SO_2 and primary and secondary particulate sulfate are also reduced. Significant improvements to air quality are expected from such regulation (IMO,

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2009; Winebrake et al., 2009). However sparse data exist on how BC emissions from ship engines are affected by F_S or other aspects of fuel quality. Fuel quality is a general term describing the relative level of impurities, as well as the combustion ability of the hydrocarbons within the fuel. Residual fuels, the fraction of crude oil remaining after the refining process, can contain high levels of sulfur, heavy metals (e.g. vanadium, nickel), ash (non-combustible inorganic material) and high molecular weight aromatic hydrocarbons. Each of these impurities (except perhaps for heavy metals) is known to create slower and delayed combustion, potentially leading to BC formation (American-Bureau-of-Shipping, 2001). It is therefore somewhat expected that better combustion and lower emissions per unit of fuel consumed result from combustion of more refined fuels, as compared to residual fuels. There is some evidence that heavy metals create localized hot-spots within the flame and catalyze combustion of BC (Maricq, 2007; Ristimaki et al., 2010).

An alternative to complying with low F_S regulations is to employ exhaust gas scrubbers while still burning high sulfur (and the least expensive) fuel. Scrubbers can reduce gas and particle phase emissions from the exhaust stream before release to the atmosphere. Commercial organizations are developing scrubbers that are reported to provide SO_2 emissions reductions equivalent to the use of low F_S fuel required by regulation. Very little data exists on the efficacy of these scrubbers for BC emissions.

Here we review the science available on BC emissions from marine diesel engines. Section 2 of this paper considers several functional definitions for BC emissions variously provided in scientific literature. Section 2 also considers how these definitions emerge from (and/or align with) measurement methods to quantify BC emissions from international shipping (Sects. 2.1–2.6). The paper then investigates and compares three potential control measures to reduce BC emission[s] from international shipping, including (i) speed reduction (Sect. 3); (ii) improved fuel quality (Sect. 4); and exhaust treatment using scrubber technology (Sect. 5). The topics of this review were raised in the 62nd session of the IMO Marine Environment Protection Committee (MEPC) and investigation was then tasked to the Bulk Liquids and Gases (BLG) subcommittee of

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the MEPC (IMO, 2011a). We limit this review to the data available for marine diesel engines, and data available in peer-reviewed literature, industry reports and presentations that are in the public domain, or industry data where permission has been granted to publish the data.

2 Definition and measurement of black carbon

We can define black carbon as a set of species of strongly light absorbing carbon particles emitted by combustion of organic compounds. Various terms used to describe this species are defined by the measurement techniques used. Andreae and Gelencser (2006) provide a comprehensive review of this topic. Briefly, elemental carbon (EC) is "the fraction of carbon that is oxidized in combustion analysis above a certain temperature threshold, and only in the presence of an oxygen-containing atmosphere" (Andreae and Gelencser, 2006). The technique to make this measurement is referred to as thermal-optical-analysis (TOA). Black carbon (BC) is the common term used for the mass of strongly light absorbing carbon derived from the absorption of a specific wavelength of light by the particles and where a wavelength specific mass-to-absorption coefficient (MAC) is used to convert from absorption to mass. The MAC for particles containing mostly fractal carbon freshly emitted from efficient combustion of fossil fuels is reasonably well defined ($7.5\,m^2\,g^{-1}$) for 550 nm radiation (Bond and Bergstrom, 2006; Cross et al., 2010). Refractory BC (rBC) is the terminology applied to the mass of material that incandesces (emits visible light) when heated with a laser (Schwarz et al., 2006).

There are multiple techniques and methods for measuring EC, BC and rBC. Each technique has potential advantages and drawbacks. TOA analysis (measuring EC_{TOA}) exhibit substantial potential biases and requires data corrections due to interference of organic particulates and selection of thermal profiles (Boparai et al., 2008). Filter based light absorption requires significant calibration and corrections and may also suffer from organic particulate and particle size biases (Arnott et al., 2005; Bond et al., 1999; Kondo et al., 2009; Lack et al., 2008a; Nakayama et al., 2010). A common technique for measuring the opacity created by engine exhaust smoke, the filter smoke number (FSN), is a filter-based absorption method that requires substantial empirical corrections to derive BC mass (Northrop et al., 2011). Uncertainties on mass derived from FSN measurements are therefore dependent on the fit to empirical data. Photo-acoustic absorption spectroscopy (PAS) is a more accurate, precise and sensitive measure of absorption compared to the filter-based techniques (Arnott et al., 2006; Lack et al., 2006, 2008b). Laser induced incandescence (LII) is probably the most fundamental measurement of the strongly light absorbing carbon material, although this technique requires very careful calibration and operation (Cross et al., 2010; Moteki and Kondo, 2010). Various techniques for measurement of EC or BC have been used for diesel engine emissions (Burtscher, 2005), and almost all techniques mentioned vary for ship engine exhaust measurement despite the fact that they can show excellent agreement with each other under controlled laboratory conditions with controlled samples (Cross et al., 2010; Kondo et al., 2011; Sheridan et al., 2005). Moosmuller et al. (2009) provides additional details in their comprehensive review of the measurement techniques for particle light absorption. A single measurement technique for the target species would be the ideal to ensure consistent measurement and analysis. However, the varying degrees of expense, ease of use, and data accuracy of the instrumentation explain why different organizations may favor a specific technique for measuring ship, or engine emissions. Using consistent measurement methods (e.g. calibrations, corrections, temperature profiles, dilution etc.) is also essential. For example, one of the most important parameters in measuring combustion engine exhaust emissions is sample dilution. Burtscher (2005) highlight the inaccuracies in measurement of emissions from diesel engines when different exhaust dilution ratios are used. Ristimaki et al. (2010) found that accuracy of particulate mass measurement improved as dilution increased; dilution factors beyond the ISO-8178-1 standard were required for reproducible measurement. In this review we focus only on measurements made on the emissions of marine diesel engines. Sections 2.1–2.5 compare EC, BC and

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rBC measurements for emissions from marine diesel engines. We use the following terminology: photo-acoustic derived BC is BC_{PAS}, filter-based absorption-derived BC is BC_{Filter}, LII BC is rBC, filter smoke number derived BC is BC_{FSN} and thermal optical analysis EC is EC_{TOA}.

2.1 PAS BC – filter BC

Lack et al. (2008b) measured light absorption and converted this to BC mass emission factors (BC_{PAS}) from almost 100 ships. In a follow-up study Lack et al. (2009) compared these emission factors where both PAS and a filter-based absorption instrument (particle soot absorption photometer, PSAP) measured the same plume. Cappa et al. (2012) also measured $EF_{BC\text{-}PAS}$ and $EF_{BC\text{-}Filter}$ (using the PSAP) for a ship running a medium speed diesel (MSD) engine. The conversion from absorption to mass used a literature MAC value that can be applied to absorption measurements at the wavelength of 532 nm (7.75 $m^2\,g^{-1}$). Figure 1a shows the comparison of these data and reveals excellent agreement between two independent techniques for measuring BC emissions, from two independent studies. These data are for emissions from marine diesel engines under real world operating conditions where thermal equilibration and large dilution with the atmosphere has occurred, eliminating dilution issues discussed in Sect. 2.

2.2 Filter BC – TOA EC

Petzold et al. (2011) measured both EC_{TOA} and BC_{Filter} for emissions using a variety of fuels used in a marine diesel engine. Those results (Fig. 1b) show a strong deviation from the expected correlation of 1. Measured EC_{TOA} is over twice that of measured BC_{Filter} (using a multi angle absorption photometer, MAAP), with some significant scatter. Measurements were performed using the ISO-8178 standard. The reason for the discrepancy is unknown.

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2.3 PAS BC– LII rBC

Cappa et al. (2012) were able to measure BC_{PAS} and rBC emission factors for a ship running a MSD engine off the coast of California in 2010. A comparison of data from four plume intercepts using LII and two independent PAS measurements (Fig. 1c) show a slope of 1.14 and R^2 of 0.94 for the 8 measurements. This excellent correlation close to a slope of 1 indicates that the mass absorption coefficient used is generally valid for this dataset, which is an important consideration for the translation of light absorption and mass measurements (IMO, 2011c).

2.4 TOA EC – FSN BC

Ristimaki et al. (2010) measured EC_{TOA} and FSN for three types of fuels (two low quality and one high quality) at various load conditions. This study compared emissions between high and low fuel quality used in the same engine at varying loads. The FSN is a unitless number derived from filter based light absorption. The measurement technique has known biases (Northrop et al., 2011) that can, in principle, be corrected (Christian et al., 1993) and then translated BC concentrations. We apply the Christian et al. (1993) correction to all the FSN data in this review to produce a BC_{FSN} mass emission factor. The FSN requires a factor of 10 or more correction to derive BC mass concentrations ($g\,m^{-3}$). Despite these corrections being somewhat uncertain, Fig. 1d generally shows good agreement between the FSN and TOA methods, although the scatter in the data appears to increase at low EF values. The ISO-8179 standard was altered in this study to reduce dilution biases.

2.5 LII rBC – TOA EC

There are no published studies where the same BC emissions from marine diesel engines have been measured using LII (rBC) and TOA (EC_{TOA}).

2.6 Measurement Methods Summary

This assessment of limited available data sets show that BC_{PAS}, BC_{Filter} and rBC are consistent measurement techniques for BC emissions from ships. There is a poor correlation for EC_{TOA} and BC_{Filter} for the one study where both were used for the measurement of BC from a marine engine. EC_{TOA} and BC_{FSN} show good agreement. Under controlled laboratory conditions there is consistency between BC_{Filter}, EC_{TOA} and rBC, however there appears to be some inconsistency between EC_{TOA} and BC_{Filter} in field measurements of ship exhaust. In addition, the TOA method does not have the requisite time resolution to do plume analysis. We therefore conclude that BC_{PAS}, BC_{Filter} and rBC can be used for absolute emissions measurements, both in engine test bed studies and atmospheric sampling. Although BC_{FSN} and EC_{TOA} showed good agreement, obtaining BC mass from FSN requires substantial empirical corrections that expand the measurement uncertainties. Measurements of emissions after significant dilution beyond that recommended by the ISO 8178 standard for measuring engine exhaust emissions show the best comparison among instruments. Dilution is a significant factor in the measurement of diesel exhaust emissions, in particular the measured mass of particulate organic matter (POM) (Burtscher, 2005; Ristimaki et al., 2010). POM can impact the artifacts within the TOA method (Boparai et al., 2008). The use of the TOA method will be further discussed in section 4. From this point forward, all data are presented in relative terms normalized to 85–100 % load or as a ratio between "before" and "after" measurements (e.g. low to high fuel quality). We rely upon the equivalency between BC, rBC and EC under this method of presentation. In general discussion we will refer to EC, BC and rBC as simply BC.

3 Effect of engine load

We investigate how the load of a marine diesel engine affects BC emissions using original and metadata from published studies. Under ideal conditions, main engine load

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is correlated with vessel speed. How would mandatory or incentive-based ship speed limits affect BC emissions? What insights for potential future ship speed regulation can be found within the data currently available?

3.1 Literature review

Marine diesel engines can be tuned for maximum energy output at minimum fuel consumption during operation at the most common engine load conditions expected (American-Bureau-of-Shipping, 2001). Maximum efficiency results from the highest ratio between the maximum pressure at the top of the piston stroke (P_{MAX}) to the average pressure across the cylinder cycle (P_{Avg}); in the case of marine diesel engines the brake mean effective pressure (P_{BMEP}) is an often used version of P_{Avg} that considers engine torque (Wettstein and Brown, 2008). Under such tuning conditions these engines consume the least amount of fuel for each unit of work, and likewise produce the least amount of BC particles. When engines operate outside of the tuned engine load without retuning, fuel efficiency often decreases and emissions (including BC) increase due to variations in conditions away from stoichiometric combustion. Engines can be re-tuned for different loads in a process where the P_{Max}/P_{BMEP} is maximized (Wettstein and Brown, 2008); some advanced engines with electronically controlled fuel meters may be able to modify combustion settings, per cylinder, essentially tuning during operational changes to better approximate best-performance conditions. De-rating would likely be carried out if the engine were to operate at that new load on a somewhat permanent basis. Fuel efficiency can be improved by a few percent when de-rating is performed for loads lower than the maximum design load (Wettstein and Brown, 2008) (note: this study showed data for de-rating down to approximately 70 % of original engine power rating).

For MSD and slow speed diesel (SSD) engines most data within literature appear to be collected from engines tuned for their maximum rated load for continuous service. There is an inverse relationship between engine load and BC emissions (Kasper et al., 2007; MAN-Diesel-SE, 2007; Petzold et al., 2010, 2011; Ristimaki et al., 2010).

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A reanalysis of the BC data from Lack et al. (2008b) (using the cubic function between engine load and speed to calculate engine loads) also show this inverse relationship for 101 vessels. In contrast, some studies that show a direct relationship between engine load and BC emissions (Cappa et al., 2012; Jayaram et al., 2011). Figure 2 (and Table 1) show all data of BC emissions and engine load available (we note that some data may exist that is not accessible to us), all of which are normalized to a BC emission factor (EF_{BC}) of 1 kg^{-1} at 85–100 % engine load – typical of in-service maximum engine loads at unrestricted cruise speeds. (Note: normalization to typical unrestricted cruise speeds allows all data to be compared.) The average and 10th and 90th percentiles[1] for all data (SSD and MSD marine engines) are also shown and forms the basis of further analysis (red lines Fig. 3).

To better illustrate the BC emissions changes in an environmental context under varying engine conditions we calculate the absolute emissions of BC for a nautical mile of travel. Fuel consumption (F_{Cons}; kilograms of fuel per nautical mile of travel) is calculated (Eq. 1) based on the specific fuel consumption relationship to load (Eq. 2) presented by the US EPA (2000) and is estimated for an engine with a rated power (P_{MW}) of 70 MW and a rated speed of 25 knots (example taken from Lack et al., 2011). F_{Cons} is shown as the black dashed line in Fig. 3.

$$F_{Cons}(\mathrm{kg\,h^{-1}}) = F_{Cons\text{-}kWh} \times 1000 P_{MW} \times f_{Load} \quad (1)$$

$$F_{Cons\text{-}kWh}(\mathrm{kg\,(kW\,h)^{-1}}) = 0.0142 \times \left(\frac{1}{f_{Load}}\right) + 0.195 \quad (2)$$

Using the average EF_{BC} with fractional engine load (f_{Load}) and the F_{Cons}, the net per-nautical-mile BC mass emissions is presented in Fig. 3 which shows that, on average absolute emissions of BC per mile do not change significantly at loads between 50 to 100 %. Above ~ 50 % main engine load the reduced fuel consumption offsets potential

[1] For calculation of average and 10th–90th percentile, data were binned using central engine load values (10, 25, 50, 65, 75, 85 and 100 %), interpolated to 99 points from 1–100 % load and then smoothed using a 11-point running smooth function.

increases in the EF_{BC}. Below 25 % load absolute BC emissions may increase by 50–100 %. The exact behavior results from a balancing between the increase in EF_{BC} and decrease in F_{Cons} with decreasing ship speed. This assessment is critically dependent on the EF_{BC} used and thus highlights the uncertainty associated with relationship between BC emissions and ship speed, and the need for more measurements. Importantly, these estimates do not adjust for potential de-rating conditions; in other words, the EF_{BC} from these studies and the calculated average are from measurements on engines that were tuned for operation at maximum loads.

3.2 Example of effect of engine load

In 2007 the AP Moller-Maersk[2] shipping company implemented a systematic management system for reducing ship speed in an effort to reduce fuel consumption, vessel idle time and emissions. Based on changes in main engine load across the fleet average main engine load has decreased from 60 % to 35 % of maximum engine rating realizing measurable reductions in fuel consumption and CO_2 emissions (de Kat, 2011a) (Fig. 4). To assess potential BC changes we define two scenarios. The first scenario is where no engines were re-tuned across the time period. Using the average BC mass change from Sect. 3.1, Fig. 3b, BC emissions could have increased by up to 7 % for the load changes reported. This is shown in Fig. 4 as the high range of the shaded area. The alternative scenario is where all engines are re-tuned to the lower load. Under this scenario BC emissions are linearly correlated to fuel consumption and could have decreased by over 20 % (low range of the shaded are in Fig. 4). This example highlights the importance of ensuring engines are tuned for the dominant load characteristics to minimize BC emissions. In actuality, the "vessels comprising that figure (Fig. 4) present a mix of de-rated (re-tuned) and non-de-rated engines" (de Kat, 2011b). It is therefore

[2]Data were obtained from certain commercial organizations mentioned in this review. This does not represent an endorsement or disapproval by that or any other organizations of the analyses presented using these data.

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difficult to assess the actual change in BC emissions without direct measurements. However, if the operators retuned even some of the engines, then Fig. 4 suggests that BC emissions likely declined as a result of the Maersk speed reduction program.

3.3 Regional effect of engine load – Arctic fleet

The Arctic environment is particularly sensitive to BC both in the atmosphere and when deposited on snow and ice (Quinn et al., 2008). As sea ice extent declines the possibility of more Arctic shipping traffic increases as resource exploration/extraction and full Arctic ship transits become possible. Ships, therefore, may represent an increasing local source of Arctic pollution (Corbett et al., 2010a). In addition to emissions from local ship traffic, BC emissions from ships as far South as 40° N may impact the Arctic climate (IMO, 2010a). To understand how shipping activities in the Arctic may contribute to BC emissions and how this may change with ice conditions we must have some sense for the current and potential future operating conditions (i.e. engine load at different ice conditions) of ships in that region.

Based on review of literature there are three possible engine load conditions under which a ship may operate in Arctic waters; (i) where up to 100 % of engine load may be required to break ice and maintain a minimum forward motion (IMO, 2012c): (ii) where ship hull resistance is dictated by water only and speed α engine load^3 (MAN, 2004), although the vessel may be required to slow in response to various conditions (no ice breaking or moving) and (iii) an intermediate condition between (i) and (ii) where ships may invest energy into breaking or moving ice but faster than minimum speeds are possible. For this intermediate condition we apply a speed α load relationship. We investigate these three conditions further below.

The study by McCallum (1996) showed that ships in the Arctic are speed limited according to ice conditions and ship construction. Safe Arctic travel speeds through varying ice conditions are determined by the ice decision numeral (IDN), a number that scales from 0–20 (i.e. IDN of 0 = very thick ice/no travel possible, IDN of 20 = very limited ice/open water travel) (Timco et al., 2005). McCallum (1996) produced an IDN

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framework for the Canadian Arctic using historical speed data from class A (smaller support ships) and class B ships (larger, cargo carrying) (Fig. 5a). The Arctic marine shipping assessment (AMSA, 2009) identified the maximum rated speeds for ships currently operating in the Arctic (Table 2).

In Fig. 5b we show estimated engine loads under the three different scenarios mentioned above. Ice breaking and minimal forward motion (scenario i) would occur with IDNs around 0 ± 5. Under these conditions ships may operate engines at very high engine loads (85–100 %) despite travelling at a minimal speed (IMO, 2012a,b,c) (see Fig. 5b, black shaded region). If this high load is maintained then BC emissions are optimized low. However if ice conditions vary then these high loads may be part of a duty cycle between ice breaking activity and lower load operation, resulting in increases in BC emissions (based on Fig. 3b).

By combining the safe speed/IDN data (Fig. 5a), the rated speed data (Table 2) we can offer some insights into the operating load of non-ice breaking ships operating in the Arctic with varying sea ice conditions. Here we convert the safe speed/IDN data (Fig. 5a) and the rated speed data (Table 2) (using the speed – load relationships discussed in scenarios ii and iii above) to engine load. For scenario (ii) ship speed and engine load follow a cubic function as would be expected for ideal cruising conditions. For scenario (iii) we assign a linear relationship between engine load and speed, suggesting that at low speeds Arctic vessels are investing engine energy into breaking and moving ice as well as forward movement. This serves to construct a bounding range of expected relationships between speed and load, pending additional empirical data for Arctic ship operations.

Figure 5b shows that, based on historical average speeds, ships operating in the Arctic are running at loads between 10 % (speed α load^3, light grey) and 40 % (speed α load, dark grey) for IDN up to approximately 16. Although a specific IDN is difficult to represent visually (depending on ship class, ice type and ice surface coverage), waters with thinner and fragmented ice with more than 70 % open water would have an IDN of ~ 11 for class B ship and an IDN of ~ 17 for class A ships (Timco and Johnson, 2003).

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For conditions of IDN <= 16 the average BC emissions are 30–100 % larger (using data from Fig. 3b) than they would be under maximum load assuming the engines are not re-tuned for the lower engine loads.

We point out that this analysis is based on the limited historical data and that as ice conditions change, future Arctic ships may not have the same speed, engine or design configurations as the current Arctic fleet. For example, Somanathan et al. (2009) predicted, for an Arctic-class cargo vessel, an average operating load of 75 % using the IDN system for 1999–2003 North West Passage ice conditions. Eide et al. (2010) predicted the range of speeds across the Arctic in 2030 for an Arctic-class cargo vessel and estimated that high speeds (approx. 75–100 % load) would be possible for almost all of an Arctic transit through the Northern Sea Route. Polar and North West Passage transits for the same vessel would span loads from approximately 10–100 % with the lower load range required for approximately 20–50 % of the distance of the transit.

It is apparent from the available data that ships currently operating in the Arctic will have highly variable engine load profiles, due to ice conditions and ship activity. If engine load profiles are indeed so variable, predicting how de-rating or speed limits may affect BC emissions is difficult for Arctic operations. It is apparent that for ships operating in the Arctic that aren't involved in ice-breaking activities, engine loads are $\leq$ 40 % and as such BC emissions are larger than they otherwise would be for a re-tuned engine or an engine operating at higher loads.

4 Fuel quality

The effect of fuel quality or speed on BC is more complex than fuel-emissions relationships for other shipping emissions. In this section we investigate the effect of fuel quality on BC emission factors. Given that all regulations on fuel quality are currently motivated by reductions in SO_2 and particulate sulfate, is there a co-benefit reduction in BC, or an unintended increase?

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4.1 Literature review

The relationship between sulfur emissions and fuel quality is explicitly understood. SO_2 emissions are directly related to F_S (e.g. Williams et al., 2009) and primary particulate sulfate is linked to F_S and engine load (Lack et al., 2009; Petzold et al., 2010). However the impacts of fuel quality on some emissions is unknown or there have been relatively few studies performed. Recently, it has been observed that better quality fuels (i.e. processed distillates versus residual blends) reduce particulate sulfate and organic particles from unburned lubricating oil and fuel (Lack et al., 2009, 2011). These organic particles contain large molecular weight aromatic hydrocarbons and may cause significant health effects (Marin-Morales et al., 2009). Lack et al. (2011) also suggest that BC emissions decline as fuel quality improves.

A review of literature reporting on the effect of fuel quality on EF_{BC} is shown in Table 3 and Fig. 6. These studies provide converging evidence that improved fuel quality is linked to reductions in EF_{BC} for marine diesel engines. This is consistent with the well-understood relationship between fuel quality and EF_{BC} for on-road diesel engines (Maricq, 2007). Figure 6a shows the ratio between EF_{BC} for distillate fuels ($EF_{BC\text{-}Distillate}$) and the EF_{BC} for residual fuels ($EF_{BC\text{-}Residual}$) as the same engines switched fuels. A ratio < 1 indicates a decrease in EF_{BC}, while a ratio > 1 indicates an increase in EF_{BC} as fuel quality improves. At 100 % engine load the EF_{BC} decreases by an average of 30 % between residual and distillate fuels. EF_{BC} reduction is at most 80 % for the data presented.

There are some irregularities within the data presented that highlight the importance of careful measurement protocols. Figure 6 includes a study by an engine manufacturer (Ristimaki et al., 2010) where $EF_{EC\text{-}TOA}$ was measured and shows a dramatic $EF_{EC\text{-}TOA}$ increase as fuel quality improved, opposite to the majority of the trends observed in Fig. 6a. Ristimaki et al. (2010) cite heavy metal oxidation of BC as the reason for reduced BC emissions from residual fuel. In what is a problematic inconsistency, that study also reported filter smoke number (FSN) trends opposite to their

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EC_{TOA} trends. We find that all derived $EF_{BC\text{-}FSN}$ of Ristimaki et al. (2010) actually decrease for distillate fuel, in contrast to their measured $EF_{EC\text{-}TOA}$ (Fig. 6b). Given the acceptable correlation in absolute $EF_{BC\text{-}FSN}$ and $EF_{EC\text{-}TOA}$ from Fig. 1c, it is difficult to assess which of the trends is in error. When we remove the Ristimaki et al. (2010) data from the statistical analysis the average EF_{BC} decreases 45 % (at 100 % load). The 10th and 90th percentile ranges do not change significantly, except for the 90th percentile range at high loads (Fig. 6b). The study of Petzold et al. (2011) measured both $EF_{BC\text{-}Filter}$ and $EF_{EC\text{-}TOA}$. $EF_{BC\text{-}Filter}$ data show a consistent 80 % decrease when shifting from residual to distillate and bio fuels. However the $EF_{EC\text{-}TOA}$ data show 20–60 % decreases for MGO, palm oil and animal fat bio-diesel whereas the soya bean and sunflower oil biodiesel show increases in $EF_{EC\text{-}TOA}$ of 20–50 % for intermediate loads. These data suggest some inconsistency between BC_{Filter} and EC_{TOA} measurements. We suggest that EC_{TOA} measurements are not as reliable measurement tool as the others reviewed here. This is possibly due to organic particle biases discussed in Sect. 2.

Specific components of the residual fuel that may be linked to BC formation are not clearly understood, and BC formation is affected by marine engine combustion conditions that may be associated with residual fuel operation. The lower concentrations of fuel sulfur, ash or high molecular weight aromatic hydrocarbons in refined fossil and biogenic fuels are responsible for an increase in combustion efficiency (American-Bureau-of-Shipping, 2001). The oxidative ability of heavy metals in decreasing BC production for residual fuel may be an opposing factor, however the balance of information available suggests that distillate fuels result in a decrease in BC emissions.

We also note that the effect of speed on EF_{BC} emissions was removed from the Lack et al. (2011) data (see Fig. A1 and text for details). The EF_{BC} before and after this correction is included in Fig. 6.

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4.2 Evidence from field measurements

A link between fuel quality (using F_S as a proxy) and EF_{BC} is evident within the data of Lack et al. (2008b) and Buffaloe et al. (2012). In the waters off California, F_S is regulated to $< 0.5\,\%$ for marine distillate oil (MDO) and $< 1.5\,\%$ for marine gas oil (MGO) (CARB, 2009a). Buffaloe et al. (2012) measured EF_{BC} for 41 ships in compliance with the Californian F_S regulations ($F_S = 0.4 \pm 0.3\,\%$, average load $= 10 \pm 5\,\%$). These EF_{BC} data are 57 % lower than the EF_{BC} measured by Lack et al. (2008b) in the Gulf of Mexico and Houston where no F_S regulations exist (40 ships, $F_S = 1.6 \pm 0.7\,\%$, load $= 44 \pm 28\,\%$) (Fig. 7). If we consider the trend of increased EF_{BC} with engine load from Sect. 3, we might expect, ignoring any competing factors, that BC emissions from California would be higher than for Texas. That EF_{BC} are lower for California is suggestive of a link between EF_{BC} and fuel quality. We suspect that the variability in vessel and engine type and operating conditions in the field study of Lack et al. (2009) swamped the ability to observe a link between EF_{BC} and F_S.

5 Efficacy of scrubbers for BC removal

Exhaust scrubbing technology can be applied to marine diesel engines to reduce emissions, particularly gas phase emissions of SO_x, NO_x. With a scrubber onboard, a ship can continue to consume high F_S (i.e. lower cost) fuel and yet comply with F_S regulations (e.g. Hamworthy, 2011). Scrubbers can use wet or dry physical scrubbing or chemical adsorption to remove combustion products. Removal of particles is possible however the removal rates by species are uncertain. What is the scrubbing efficacy of BC particles? How do BC removal rates compare to the effect of shifting from residual to distillate fuels?

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5.1 Literature review

Current studies show scrubbers to be efficient at reducing the mass of PM emissions from anywhere from 25 to 98 % (Kircher, 2008; Marine-Exhaust-Solutions, 2006; Ritchie et al., 2005; Andersson and de Vries, 2009). These estimates are based on different particle mass diameter cut offs (<= 1, 2.5 or 10 µm (PM_1, $PM_{2.5}$, PM_{10})). Despite the potential to remove a large amount of total particle mass, there is uncertainty as to their effectiveness for smaller BC particles for three reasons; (i) BC may comprise up to 4 % of PM mass from shipping (including hydrated sulfate) (Lack et al., 2009); (ii) BC within from ship exhaust is usually associated with particles having mass median diameters of ≤ 0.2 µm (Lack et al., 2009, 2011; Petzold et al., 2011); and (iii) The wet scrubbing efficiency for BC is uncertain because BC particles in engine exhaust can be hydrophobic or hydrophilic, depending on the mixing state and water uptake ability of co-emitted species.

In a review of sea water scrubbing efficacy Corbett et al. (2010b) concluded that $PM_{2.5}$ removal was likely 75 ± 15 % and inferred from this review (mostly from the measurements from Ritchie et al., 2005) that BC removal was likely 40 (+10, −15) %. The study of Ritchie et al. (2005) showed that the PM reductions for the scrubber used were 98 % for PM_2, 74 % for $PM_{1.5}$, 59 % for PM_1 and 45 % for $PM_{0.05}$. Given the common mass median diameter range for BC (0.2 µm), a likely BC scrubbing efficiency of around 45–50 % is inferred from these results. Andersson and de Vries (2009)[3] showed EC_{TOA} reductions of 55 % for low sulfur diesel and 70 % for 1.5 % F_S diesel, indicating a potential increase in scrubbing efficiency when the higher F_S fuel is used. This can be explained by the formation of hygroscopic particulate sulfates that are internally mixed with the BC. It must be noted that Andersson and de Vries (2009) used a light duty diesel engine and fuel doped with an organic sulfur compound to produce the high sulfur fuel. Based on current studies, scrubbers can remove BC from the exhaust of marine diesel engines between 25–70 %, dependent on F_S and scrubber

[3] Report and data used with permission from Sustainable Maritime Solutions.

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design (shown in Fig. 8 as dark shaded bar in comparison to the effects of fuel quality changes on EF_{BC}). There is no data showing scrubber BC removal rates as a function of engine load and so we assume constant removal for illustrative purposes. This removal rate is within the ranges presented for fuel switching from residual to distillate fuels, and BC control may be more consistently effective across transient engine loads.

6 Implications for regulation

Evaluation of literature data on the emissions of BC from marine diesel engines (Sects. 3, 4, and 5) allows us to assess the effects of current or potential regulation on ships. For example, ship speed reductions can reduce fuel consumption and some emissions significantly. Many shipping companies are using ship speed reductions to reduce fuel consumption and costs. Will a ship speed regulation provide any benefit by locking in the voluntary speed reductions already taking place? Fuel sulfur limits are regulated in certain regions of the word to reduce the negative air quality impacts of ship emissions. Stricter global regulations will come into force within a few years. Will these regulations effectively reduce BC emissions, without other measures like re-tuning engines? The concern of the sensitivity of the Arctic environment to a potential increase in shipping has triggered discussions on possible regulatory action for that region. What might the best regulatory actions be for reducing, or minimizing the emission of BC in the Arctic?

6.1 Ship engine load and black carbon

Regulations of ship speed for reductions in fuel consumption may be accompanied by increases in BC unless automatic tuning or engine de-rating are employed. When ships reduce load from 100 to 25 % without retuning the engine, an increase in EF_{BC} of a factor of 3 occurs. At loads < 25 % EF_{BC} increase significantly (up to 6.5 times). This EF_{BC} increase is a result of when engines are operated at a loading condition

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outside of the tuned load. When the EF_{BC} increases are combined with the reduced fuel consumption associated with lower loads, absolute emissions of BC increase by 15–40 % down to 25 % load. Below 25 % load, absolute emissions of BC increase by 100–150 %.

Technology is emerging on newer ships where electronically controlled engines can be optimally tuned in real time for the current load (between 30 and 100 % load, Brown, 2009). In addition, engines can be re-tuned for operation at specific loads (Wettstein and Brown, 2008). Under these optimal tuning conditions fuel efficiency is maximized and it is likely that EF_{BC} would remain approximately constant across a wide load range. Assuming an optimum EF_{BC} across all loads (i.e. EF_{BC} of unity: using the convention of EF_{BC} at 100 % load = 1) absolute BC reductions equivalent of the fuel savings are achievable.

De-rating or investment in automatic tuning to achieve these BC reductions are likely to be motivated by regulations on ship speed, where a ship operator has certainty that an engine will be operated within a specific range of reduced load. If ship speed regulations were a permanent part of the regulatory environment, new ship designs could innovate to use smaller engines with maximum-load ratings appropriate for the required speed.

6.2 Fuel quality and black carbon

The balance of evidence suggests that shifting from high sulfur, high ash residual fuels to low sulfur, low ash distillate fuels will decrease BC emissions. Up to 80 % reductions in EF_{BC} have been observed for such fuel quality shifts within several studies. From the data presented, an average EF_{BC} reduction of 30 % at 100 % engine load is observed. It is therefore likely that F_S regulations, such as those implemented in the Baltic and North Seas (IMO, 2005, 2007) and California (CARB, 2009a), and those to be introduced for North America (IMO, 2009) and globally (IMO, 2010b), will reduce BC emissions. In addition, the call by the European Parliament for the IMO to ban HFO in the Arctic (to eliminate effects of spilled fuel) is strengthened as this will likely reduce

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and/or minimize BC emissions in the Arctic (EU, 2011). Current regulation on fuel quality addresses F_S only. From the reviewed literature, it was not possible to determine whether F_S, or another component of fuel quality, such as ash, aromatic hydrocarbon or heavy metal content, was responsible for the changes in EF_{BC}. There is limited evidence that heavy metals catalyze the combustion of BC and so it has been suggested that lower metal-content fuels may increase EF_{BC}.

6.3 Scrubbers and black carbon

Scrubbers that reduce emissions of SO_2 to levels equivalent to consuming regulatory-compliant low sulfur fuel offer an alternative to using distillate fuels. In addition to reductions in SO_2 emissions, it is apparent, from the very limited data available, that BC removal by scrubbers is between 40–70 %, dependent on F_S. While more work is needed to characterize scrubber BC control efficacy across varying loads, scrubbing residual high F_S fuel appears to provide similar BC reduction rates to switching from residual to distillate fuels.

6.4 Regional regulatory combination: arctic shipping

Given the sensitive eco-systems of the Arctic, careful consideration is being given to minimizing the impact of Arctic shipping. Emissions of BC from ships have been identified as one of a number of priority BC mitigation opportunities for the Arctic (Arctic-Council, 2010; Rosenthal and Watson, 2011). Distillate fuels already required in the Antarctic could become required in the Arctic for reasons unrelated to BC and climate forcing (e.g. elimination of residual oil spills). It is apparent, however that the use of distillate fuel may also reduce BC emissions, therefore providing a co-benefit for the Arctic. If Arctic shipping routes evolve into commonly used alternatives to the traditional Panama and Suez canal routes for transits from Europe to Asia and North America to Asia (e.g. Somanathan et al., 2009), activity of ships consuming residual fuels is likely to increase in the Arctic. The use of distillate fuels by these ships in the Arctic (similar

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to the Antarctic) would reduce BC emissions that would result from using residual fuel. Policies requiring scrubbing of residual or distillate fuel exhaust would provide alternate or additional options for BC reductions.

Arctic ship speed limits might serve to reduce the probability of whale strikes, reduce navigation hazards, and will reduce some emissions (e.g. CO_2). Ship speed-engine load relationships may be atypical under ice-safe operations compared to ice-free voyages and so it is difficult to assess the characteristics of current or future engine loads. Under ice breaking conditions engine load is likely near a maximum while ships moving slowly through loose ice flows are likely running at low engine loads and may be emitting up to twice as much BC per nautical mile of travel that is estimated using current methodologies (Corbett et al., 2010a) (assuming engines are tuned for maximum load ratings). For the next few decades it is likely that the transit paths of ships in the Arctic would encounter a variety of ice conditions (and require a range of engine load). De-rating may not be a viable option for the variability in lower loads possible. BC emission reduction strategies may require an automatic tuning technology or assessment of each ships load distribution history to ensure the engine can be optimally tuned. If there is so much variability in the engine load distribution as to make a specific tuning below maximum-load rating unviable, exhaust scrubbing or consumption of higher quality fuel would be effective options for controlling BC under speed-restriction policies.

7 Summary

Emissions of BC are of concern from both an air quality and climate (particularly Arctic climate) perspective. The International Maritime Organization (IMO) has begun to investigate the impacts of BC emitted from shipping activity and tasked an IMO subcommittee with providing more details on the definition of BC, measurement methods and possible strategies for BC mitigation. This review addressed the definition, measurement methods and effects of speed, fuel quality and exhaust gas scrubbing on BC emissions from ships.

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We find that BC emission factors measured by photo-acoustic, filter-based absorption (PSAP and MAAP) and laser-induced incandescence are consistent with one another on an absolute level. Corrected filter smoke number (FSN) BC also show good correlation with thermal optical reflectance-measured EC, however the TOA method shows inconsistent results to both BC_{FSN} and BC_{Filter} for two studies.

BC emission factors increase as engine load decreases and absolute emissions of BC increase up to 100 % at low loads when the average EF_{BC} is combined with the reduced fuel consumption that results from reduced ship speeds.

Ships currently operating in the Arctic are likely operating at highly variable engine loads (25–100 %) due to ice conditions. If this load engine variability makes it difficult for engine de-rating the most effective measures for reducing BC from Arctic shipping would be through the use of exhaust scrubbing or a switch to higher quality fuel.

Based on available literature, improvements to fuel quality (from residual to distillate fuels) can reduce BC emissions by an average of 30 % and potentially up to 80 %. More research is required to determine how each component of fuel quality affects BC emissions. Although data are very limited, exhaust scrubbing systems likely remove BC with an efficiency of 25–70 %, dependent on fuel sulfur content. More research is needed by scrubbing manufacturers to understand the removal of particulate matter by size and composition.

Appendix A

The study of Lack et al. (2011) measured EF_{BC} changes as a large container ship switched from low to high quality fuel and slowed. Using the average EF_{BC} with engine load relationship ($EF_{BC\text{-}Load}$) derived from literature data in Sect. 3, the effect of speed on EF_{BC} emissions was removed from this data. To do this we divide the Lack et al. (2011) data at 70, 45, 30 and 10 % load by the normalized average $EF_{BC\text{-}Load}$ value for that load. The results of which are presented as the red data in Appendix Fig. 1. We then divide the average of the corrected EF_{BC} at lower sulfur by the average EF_{BC} at high sulfur to determine the EF_{BC} reduction due to the change in F_S.

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Table 1. Studies on the effect of engine load on BC emissions found in literature.

Study (#)	Engine type	Fuel type	Measurement	Reference
1–6	MSD	HFO, LFO	EC-TOA, BC-FSN	Ristimaki et al. (2010)
7–12, 22–27	MSD	HFO, MGO, Biodiesels	BC-Filter, EC-TOA	Petzold et al. (2011)
13	MSD	HFO	EC-TOA	Petzold et al. (2004)
14	MSD	HFO	EC-TOA, BC-Filter	Petzold et al. (2010)
15	MSD	MDO	BC-PAS	Cappa et al. (2012)
16	SSD	HFO, MDO	EC-TOA	Kasper et al. (2007)
17	SSD	HFO	EC-TOA	Agrawal et al. (2010)
18	SSD	HFO	EC-TOA	Agrawal et al. (2008)
19–21	MSD	Biodiesel	EC-TOA	Jayaram et al. (2011)
22	SSD, MSD	HFO, MDO, MGO	BC-PAS	Lack et al. (2008b)
23, 24	MSD	HFO, MGO	EC-TOA	MAN-Diesel-SE (2007)
31–38	MSD	HFO	BC-FSN	Sarvi et al. (2008a,b)
39, 40	MSD	MDO	BC-FSN	Sarvi et al. (2008a)

Table 2. Average design speed of ships operating in the Arctic (AMSA, 2009).

Reporting category	Average at-sea design speed [knots] (# of ships)
Bulk carrier	14 (99)
Container	15 (321)
General cargo	14 (248)
Government/icebreakers	17 (67)
Passenger	16 (147)
Special purpose	11 (14)
Tanker	13 (174)
Tug and barge	10 (11)
Unknown	14 (396)
	Average speed: 14 (total ships: 1477)

* Note: fishing vessels are not included here due to the difference in operation compared to merchant ships.

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Table 3. Studies on the effect of fuel quality found in literature.

Study (#)	Low quality fuel			High quality fuel			Measurement type	Reference
	Type	F_S (%)	Ash (%)	Type	F_S (%)	Ash (%)		
1	HFO	2.2	0.03	MGO	< 0.01	< 0.01	EC-TOA	MAN-Diesel-SE (2010)
2	HFO	0.9	0.02	LFO	< 0.05	< 0.01	EC-TOA	Ristimaki et al. (2010)
3	HFO	0.9	0.02	LFO	< 0.05	< 0.01	BC-FSN	Ristimaki et al. (2010)
4	HFO	2.4	0.07	LFO	< 0.05	< 0.01	EC-TOA	Ristimaki et al. (2010)
5	HFO	2.4	0.07	LFO	< 0.05	< 0.01	BC-FSN	Ristimaki et al. (2010)
6	HFO	2.2	0.02	MDO	0.1	0.001	BC-Filter	Petzold et al. (2011)
7	HFO	2.2	0.02	Biodiesel – Palm Oil	< 0.01	0.002	BC-Filter	Petzold et al. (2011)
8	HFO	2.2	0.02	Biodiesel – Animal Fat	< 0.01	0.002	BC-Filter	Petzold et al. (2011)
9	HFO	2.2	0.02	Biodiesel – Soya Bean	< 0.1	< 0.001	BC-Filter	Petzold et al. (2011)
10	HFO	2.2	0.02	Biodiesel – Sunflower Oil	< 0.01	< 0.001	BC-Filter	Petzold et al. (2011)
11	HFO	2.2	0.02	MDO	0.1	0.001	EC-TOA	Petzold et al. (2011)
12	HFO	2.2	0.02	Biodiesel – Palm Oil	< 0.01	0.002	EC-TOA	Petzold et al. (2011)
13	HFO	2.2	0.02	Biodiesel – Animal Fat	< 0.01	0.002	EC-TOA	Petzold et al. (2011)
14	HFO	2.2	0.02	Biodiesel – Soya Bean	< 0.1	< 0.001	EC-TOA	Petzold et al. (2011)
15	HFO	2.2	0.02	Biodiesel – Sunflower Oil	< 0.1	< 0.001	EC-TOA	Petzold et al. (2011)
16,17[a]	HFO	3.15	0.07	MDO	0.07	< 0.01	rBC	Lack et al. (2011)
18,19	HFO	0.83	0.04	MGO	0.1	< 0.01	BC-FSN	Sarvi et al. (2008a)

[a] Includes effects of engine load changes.

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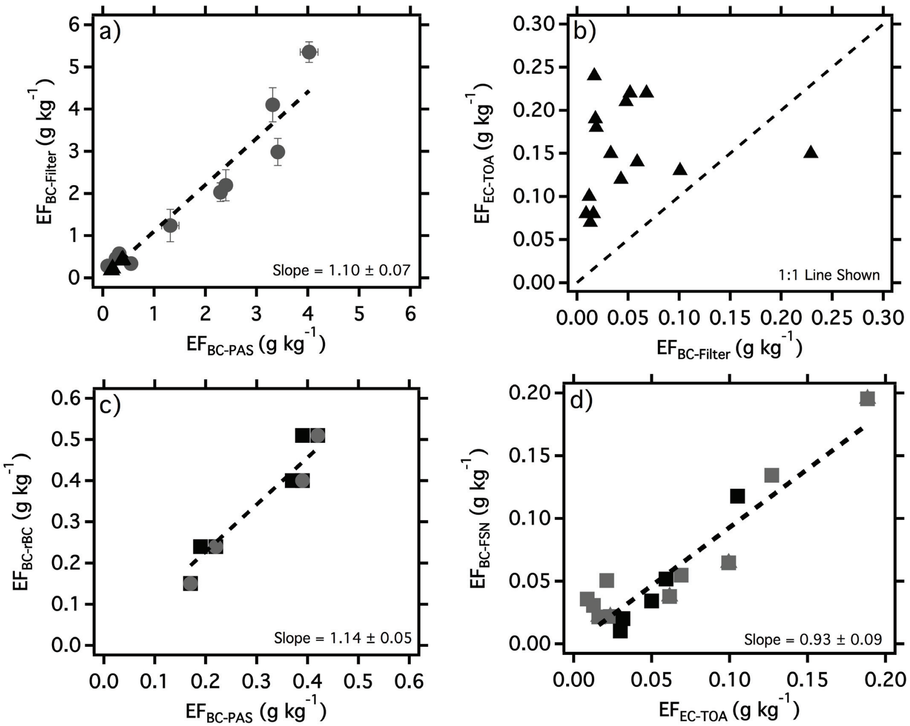

Fig. 1. Comparison of emission factors from marine diesel engines. **(a)** $EF_{BC\text{-}PAS}$ and $EF_{BC\text{-}Filter}$ from Lack et al. (2009) (circles) and Cappa et al. (2012) (triangles), **(b)** $EF_{BC\text{-}Filter}$ and $EF_{EC\text{-}TOA}$ from Petzold et al. (2011), **(c)** $EF_{BC\text{-}rBC}$ and $EF_{BC\text{-}PAS}$ from Cappa et al. (2012) and **(d)** $EF_{EC\text{-}TOA}$ and $EF_{BC\text{-}FSN}$ from Ristimaki et al. (2010). Linear regression fit shown by dashed line in **(a)**, **(c)** and **(d)**. 1 : 1 line shown by dashed line in **(b)**.

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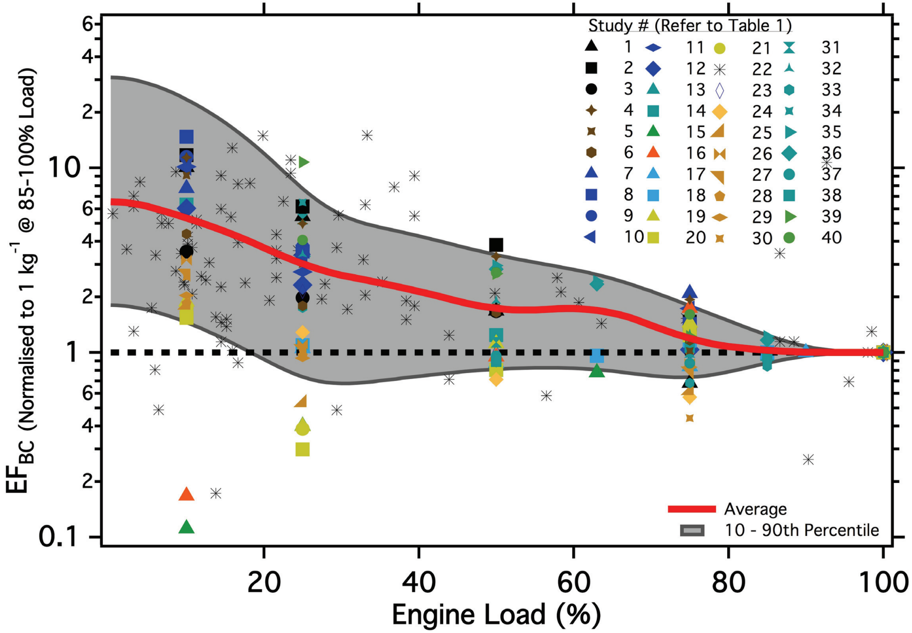

Fig. 2. The relationship between EFBC and ship engine load. Average = red, 10th and 90th percentile = grey.

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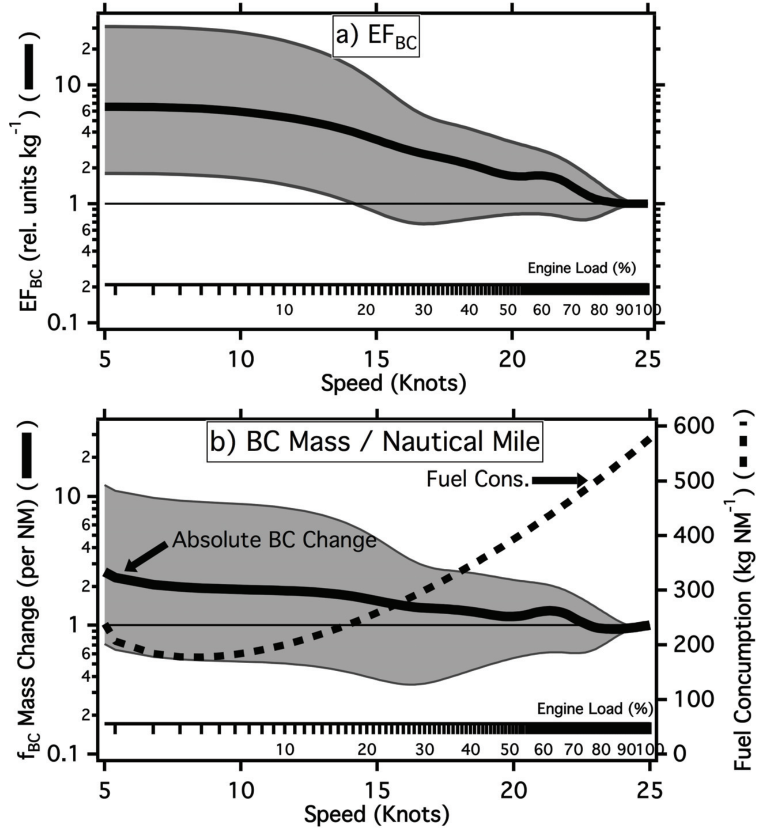

Fig. 3. **(a)** Average EF_{BC} change with ship speed and engine load (with 10th and 90th percentiles) and **(b)** the potential absolute changes in BC emissions with ship speed and engine load (with 10th and 90th percentiles). EF_{BC} data from a) combined with fuel consumption data from b) (circle points) to produce data in figure **(b)**. All but F_{Cons} are normalized to 1 at 100 % load.

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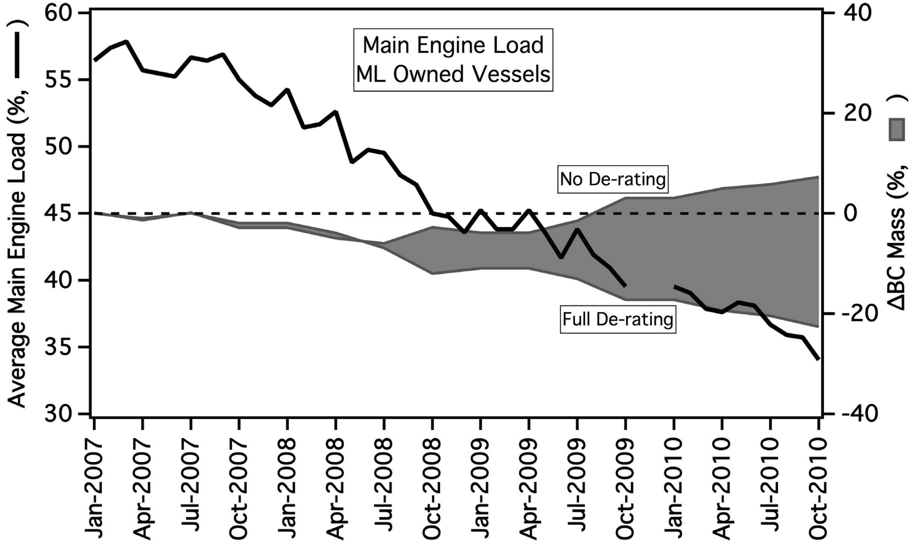

Fig. 4. Average main engine load change for the Maersk fleet (black line). Reproduced with permission from AP Moller-Maersk (de Kat, 2011a). The potential range of BC mass changes due to the Maersk speed reduction program is also shown as the shaded region.

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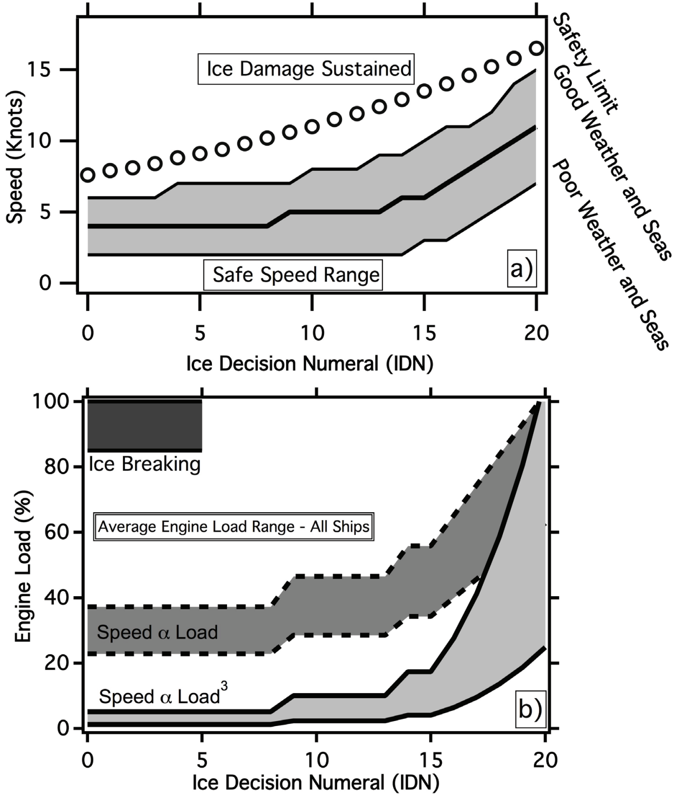

Fig. 5. (a) Ice Decision Numeral relationship to safe ship speeds in the Arctic. Reproduced from the data from Table 6 of McCallum (1996). Shaded area is standard deviation of data from multiple ships and different ship classes. **(b)** The estimated engine load characteristics of all ship types currently operating in the Arctic, as a function of IDN. Average speed/IDN and high speed/IDN relationship presented.

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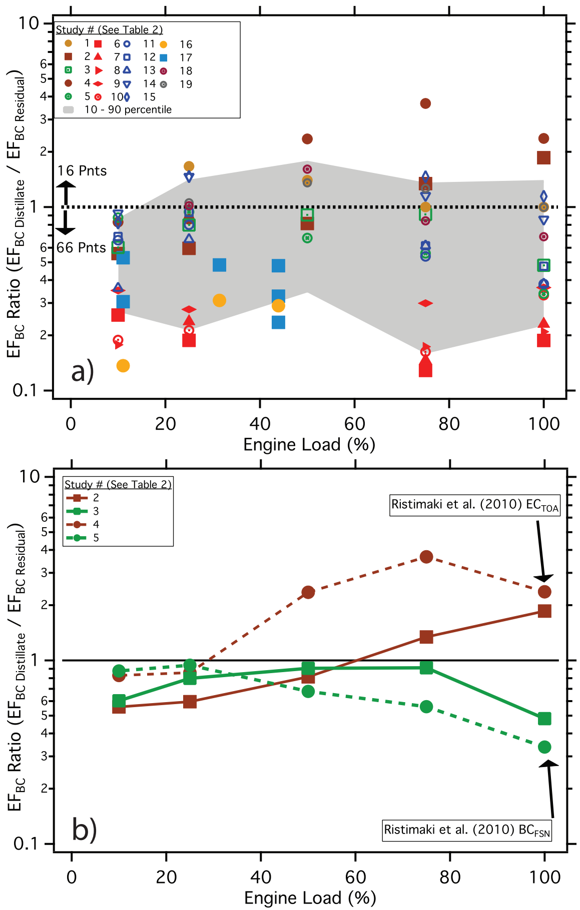

Fig. 6. (a) The change in EFBC as fuel quality improves (as a ratio between $EF_{BC\text{-}Distillate}$ and $EF_{BC\text{-}Residual}$). 10th–90th percentile range of data shown as shaded region. **(b)** Illustration of measurement inconsistency.

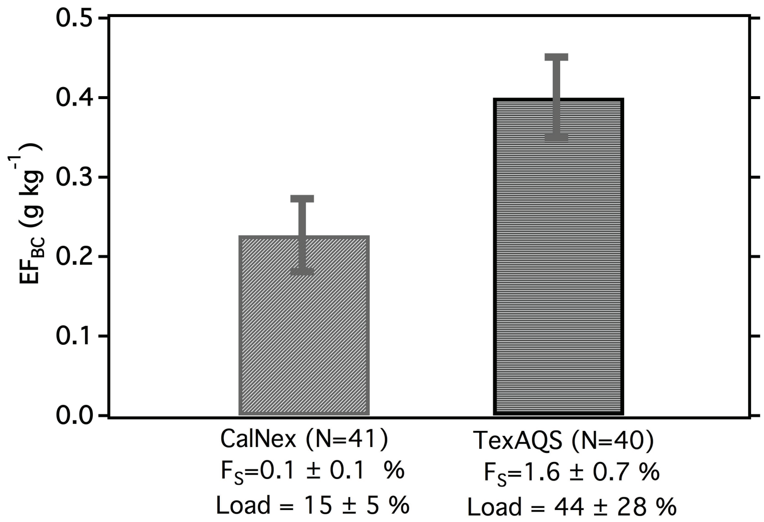

Fig. 7. EF_{BC} (for SSD ships) in the California and the Gulf of Mexico/Houston coastal areas (Buffaloe et al., 2012).

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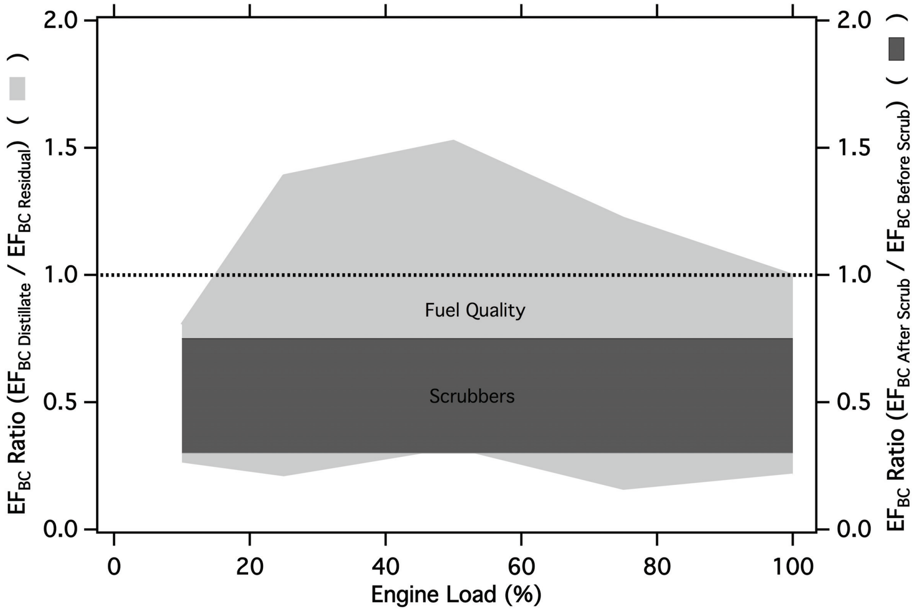

Fig. 8. Comparison of the range of EFBC changes due to fuel quality improvement (grey) and exhaust scrubbing (black).

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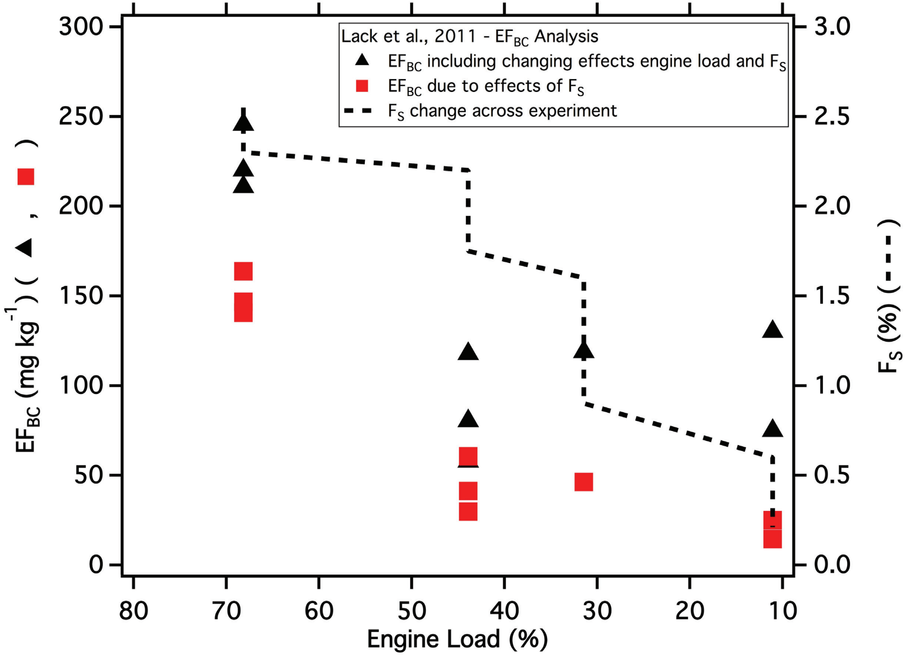

Figure A1. EF_{BC} changes with engine load (and F_S) from the study of Lack et al. (2011). Red data has the effects of engine load removed, using the average EF_{BC} engine load relationship from Sect. 3 (grey line).

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