Needs and opportunities to reduce black carbon emissions from maritime shipping

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Executive summary

Black carbon is the second largest contributor to human-induced climate warming, after carbon dioxide. International shipping is a major source of diesel black carbon emissions and not yet subject to international regulation. This paper investigates the contribution of black carbon from shipping to the global diesel black carbon inventory, by cross comparing results from a number of studies. While shipping contributed approximately 7 to 9 percent of global diesel black carbon in 2000, that contribution rose to between 8 and 13 percent in 2010 and is expected to maintain that share under current and planned International Maritime Organization policies. Available technologies and operational practices, such as fuel switching, scrubbers, and vessel speed reduction, can reduce shipping emissions by up to 70 percent.

1. Background

Ports and marine vessels are major sources of diesel particulate matter (PM) and black carbon (BC). There are growing concerns from global communities about the impacts that air pollution from shipping has on the environment, particularly in the Arctic region. BC is especially concerning from a climate change perspective. The Intergovernmental Panel on Climate Change (IPCC) defines black carbon as an aerosol that is "mostly formed by the incomplete combustion of fossil fuels, biofuels, and biomass, but also occurs naturally... It is the most strongly light–absorbing component of particulate matter (PM) and has a warming effect by absorbing heat into the atmosphere and reducing the albedo when deposited on ice or snow".[1] Black carbon is the second largest contributor to human-induced climate warming, after carbon dioxide, according to a landmark four-year study on black carbon released in 2013.[2]

BC has many sources—diesel engines, coal-fired power plants, cook stoves, biomass burning, forest fires, etc. This leads some to conclude that source-specific control measures are not effective, as any individual BC source constitutes only a fraction of overall BC emissions. For example, some members of the International Maritime Organization (IMO) have argued that since shipping contributed only 2 percent to global BC emissions in 2000, the IMO should cease development of potential control measures.[3] This argument underestimates the importance of marine BC emissions in three ways.

First, not all BC emissions are created equal. Scientists believe some BC sources have a disproportionate warming effect. Bond et al. systematically evaluates BC sources by sector—including wildfires, industry, and agricultural burning—and determines that, "mitigation of diesel-engine sources offers the most confidence in

1 Allwood J.M., V. Bosetti, N.K. Dubash, L. Gómez-Echeverri, and C. von Stechow, 2014: Glossary. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA Retrieved from: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-i.pdf

2 Bond T. C., Doherty S. J., Fahey D. W., Forster, P. M., et al.(2013) Bounding the role of black carbon in the climate system: a scientific assessment. J Geophys Res 118(11):5380–5552. doi:10. 1002/jgrd.50171

3 PPR 1/8/1 Some consideration based on recent publications Submitted by Liberia, the Oil Companies International Marine Forum (OCIMF) and the International Petroleum Industry Environmental Conservation Association (IPIECA) to the International Maritime Organization first session of the Pollution Prevention and Response subcommittee 29 November 2013.

reducing near-term climate forcing"[4] because diesel particles contain a significantly higher proportion of BC than other sources, which cause warming, and less of the organic carbon that causes atmospheric cooling.

Second, as international freight demand increases, BC emissions from the marine sector are expected to increase as well. One widely cited 2010 study estimated that, barring additional controls, global BC emissions from marine vessels will nearly triple from 2004 to 2050[5] due to increased shipping demand, with a growing share emitted in the Arctic region due to vessel diversion. At the same time, emissions from land-based sources are expected to fall due to stricter controls.[6] In the past decade, emission standards for heavy-duty trucks and buses in Japan (2005), Europe (2005), and the US (2007) began requiring diesel aftertreatment technologies such as particulate filters. Similar requirements are being taken up by emerging economies such as Mexico, Brazil, and China. When paired with ultralow (10–15 ppm) sulfur fuel, particulate filters can reduce diesel particulate and BC emissions by up to 99 percent.[7]

Third, the climate impact of BC depends on where it is emitted. The ability of BC to absorb and radiate light as heat alters regional heat budgets so that emissions near regions with high albedo, such as the Arctic, have a greater warming effect. As discussed below, a significant fraction of both BC emissions and deposition occur in or near the Arctic. This proportion may grow in the future as global warming increases access to Arctic shipping routes.[8] A recent study, linked to a ten-year vessel projection for the U.S. Arctic commissioned by the US Department of Transportation, concludes that air-pollution emissions from vessels in the U.S. High Arctic may increase as much as 600 percent by 2025 under current fuel use.[9]

If diesel BC matters the most, what fraction of the global diesel BC inventory comes from ships today, in what parts of the world, and what can be expected in the future?

2. Contribution of shipping to current and future diesel BC inventories

Using central model results, Bond et al. estimates that shipping contributed 7 percent of total BC emissions from diesel engines in 2000. The authors also reference a more "refined" estimate by Eyring et al. (2010) suggesting that shipping was responsible for 9 percent of diesel BC in 2000.[10] To update these values for 2010, and also to project future emissions, this study compares three of the climate scenarios used by the IPCC.

The IPCC recently released a tool modeling changes in BC from surface transportation and international shipping, among other sources, through 2100. The available results are based on the outcome of emission scenarios developed among climate scientists, to inform the work of the IPCC's 5th Assessment Report.[11] Scenarios are based on technology application assumptions designed to meet global warming limits by 2100. For example, the RCP 4.5 is a scenario that stabilizes radiative forcing at 4.5 Watts per meter squared in the year 2100 without ever exceeding that value[12]. The implementation assumptions used to produce the scenarios range from timely implementation and enforcement of standards for low-sulfur fuel use on marine engines to more steady-state assumptions, much like the current regulatory framework with little to no restrictions on emissions.

Shipping's contribution to diesel BC inventories through 2030 was bounded using Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5. These incorporate assumptions for emissions, pollutant concentrations, and land cover changes to the year 2100 representing low, medium, and high climate forcing futures. These RCPs are intended to serve as inputs for climate and atmospheric chemistry modeling (Table 1).

4 Bond T. C., Doherty S. J., Fahey D. W., Forster, P. M., et al. (2013) Page 5388 paragraph 40.

5 Corbett, J., Lack, D., & Winebrake, J. (2010). Arctic shipping emissions inventories and future scenarios. Atmospheric Chemistry and Physics, (10), 9689–9704. Retrieved from http://www.atmos-chem-phys.org/10/9689/2010/acp-10-9689-2010.pdf

6 Jonson, J. E., Jalkanen, J. P., and Johansson, L. et al. (2015). Model calcualtions of the effects of present and future emissions of air pollutants from shipping in the Baltic Sea and the North Sea, Atmos. Chem. Phys., 15, 783-798.

7 Application of DPFs to the marine sector is currently constrained due to the high sulfur content of fuels, which range from 27,000 ppm globally to 1000 ppm in designated Emission Control Areas (ECAs). See Section 5 for further details.

8 Azzara, A. J., Wang. H, Rutherford, D., Hurley, B, and Stephenson, S. 2015. A 10-Year Projection of Maritime Activity in the U.S. Arctic. A Report to the President. U.S. Committee on the Marine Transportation System, Integrated Action Team on the Arctic, Washington, D.C., 73 p..

9 Azzara, A. J. and Rutherford, D. (2015). Air pollution from marine vessels in the U.S. High Arctic in 2025. The ICCT, Washington, DC. Working Paper 2015-1.

10 Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., Moldanova, J., Schlager, H., and Stevenson, D. S. (2010) Assessment of Transport Impacts on Climate and Ozone: Shipping, Atmos. Environ., 44(37), 4735– 4771, doi:10.1016/j.atmosenv.2009.04.059.

11 IPCC 5th Assessment Report on Climate change, 2014. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved from: http://www.ipcc.ch/report/ar5/wg3/

12 Thompson, A., Et al: RCP4.5: A pathway for stabilization of radiative forcing by 2100. Joint Global Change Research Institute, Pacific Northwest National laboratory and the University of Maryland. Retrieved from: asr.science.energy.gov/publications/programs-docs/RCP4.5-Pathway.pdf

Table 1. Description of RCP scenarios used to model black carbon from shipping

RCP Model	Description of assumptions*
RCP 2.6	Represents scenarios in the literature leading to very low GHG concentrations. This scenario shows GHG levels peaking mid-century before declining, indicating a substantial reduction in GHG and other air pollutants over time. This results from an idealized implementation approach for countries and economic sectors with increasing implementation of reduction measures over time.
RCP 4.5	Represents a low to medium climate forcing scenario where total radiative forcing stabilizes before 2100 due to delayed implementation of GHG emissions reduction technologies and strategies.
RCP 8.5	Represents a scenario where climate forcing does not stabilize by 2100 and instead GHG emissions, and by extension other air pollutants, continue to increase. This results from fragmented action or delayed participation representing non-ideal international implementation scenarios and creates a high climate forcing scenario.

* Adapted from descriptions available on the RCP Database Version 2.0.5 [13,14]

Several other future marine emissions pathways studies were also investigated. Corbett et al. projected BC contributions by both Arctic shipping and global shipping out to 2030 and 2050. Their approach incorporates 2001 BC emission estimates from two additional papers[15,16] and a novel calculation for 2004 based on the Arctic Council's Arctic Marine Shipping Assessment.[17] Based on these estimates, shipping contributed 9 percent of diesel BC emissions to the total global BC inventory in 2000 and 2005.

Corbett et al. developed two future growth scenarios, one for business as usual (BAU) and one for high growth. The comparisons presented in this section use global BC emissions estimates for the BAU and high growth scenarios paired with RCP 4.5 and 8.5 diesel engine contributions, respectively. Because Corbett et al. used slightly different start dates than the IPCC, their estimates for 2001 emissions were paired with the IPCC 2000 estimates and the 2004 estimates were paired with IPCC 2005.

Future contribution predictions from the IPCC models and the Corbett et al. high and BAU scenarios vary due to differing assumptions about technological development, implementation rate, and consistency across countries and economic sectors. Estimates of diesel BC emissions from international shipping in 2030 range from only 5 percent (RCP 2.6) to as high as 35 percent (Corbett high growth), with more intermediate values of 11 to 19 percent for RCP's 4.5, 8.5, and Corbett's BAU scenario (Table 2 and Figure 1). The RCP 2.6 value may be artificially low because it assumes more aggressive implementation of emission reductions for marine vessels than for other modes, despite the fact that technology-forcing emission standards developed for on-road sources are already being implemented in a number of regions and spreading to others. At the same time, the Corbett scenarios have not been updated to reflect fuel-quality standards adopted by the IMO, notably the 0.5 percent global fuel-sulfur standard that will take effect in either 2020 or 2025.

These results highlight that marine black carbon emissions were 8 to 13 percent of all diesel emissions in 2010. Considerable uncertainty exists in the projections, but in general the results suggest that the marine sector will maintain and perhaps increase its share of diesel BC emissions by 2030 (Figure 1).

Table 2. Estimated marine black carbon contribution, 2000 to 2030

Source	Black carbon emissions from shipping by year (% of diesel total)				
	2000	**2005**	**2010**	**2020**	**2030**
IPCC RCP 2.6	9%	11%	8%	4%	5%
IPCC RCP 4.5	9%	9%	9%	10%	11%
IPCC RCP 8.5	9%	10%	13%	17%	19%
Corbett et al. 2010 (BAU)	9%	9%		13%	16%
Corbett et al. 2010 (High)	9%	10%		26%	35%
Bond et al. 2013	7%				
Eyring et al. (2010)	9%				

13 RCP Database http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=about#descript

14 Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, 2014: Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Retrieved from http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter6.pdf

15 Lack, D., Lemer, B., Granier, C., Baynard, T., Lovejoy, E., Massoli, P., Ravishankara, A. R., and Williams, E.: (2008) Light absorbing carbon emissions from commercial shipping, Geophys. Res. Lett., 35, L13815, doi:10.1029/2008GL03390.

16 Lack, D. A., Corbett, J. J., Onasch, T., Lerner, B., Massoli, P., Quinn, P. K., Bates, T. S., Covert, D. S., Coffman, D., Sierau, B., et al.: (2009) Particulate emissions from commercial shipping: Chemical, physical, and optical properties, J. Geophys. Res., 114, D00F04, doi:10.1029/2008JD011300.

17 Brigham, L., ed. Arctic Marine Shipping Assessment 2009 Report. ed. B. Ellis and L. Brigham 2009, Arctic Council: Tromsø, Norway.

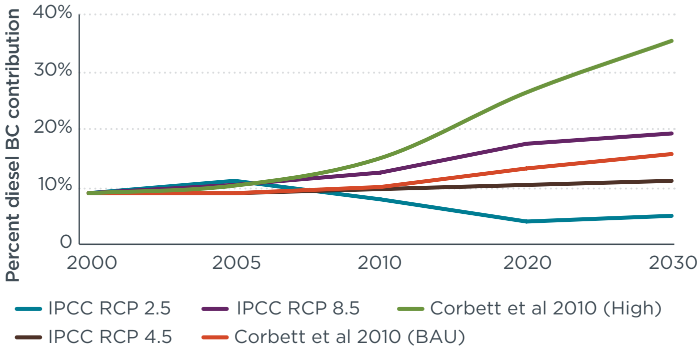

Figure 1. Potential change in BC emissions from shipping under different scenarios.

Separately, an effort was made to test the reasonableness of the high-level scenarios outlined in Table 2 through a bottom-up approach combining marine emissions projections from the IMO Second Greenhouse Gas Study with those for surface transportation to 2030 using the ICCT's Roadmap model.[18] This comparison took a conservative approach and assumes that all adopted emission control policies, including the use of 0.5% global fuel sulfur and 0.1% sulfur in assigned ECA areas, are implemented on time and with universal compliance.[19] This analysis suggests that shipping will contribute about 15 percent of BC emissions from diesel engines used for passenger and freight transportation (rail, buses, passenger vehicles, and on-road trucks, and ships) in both 2020 and 2030. An equivalent bottom-up assessment of other diesel sources, such as construction and agricultural equipment, cannot be conducted with the same confidence, so this figure cannot be directly compared to the top-down approaches highlighted above. Nonetheless, the results indicate that the marine sector will likely maintain its current contribution to diesel BC inventories through 2030.

Based on the results of the projections, implementing existing regulations and best practices can stabilize the contribution of BC from shipping. Timely implementation and enforcement of low-sulfur fuel regulations, in combination with application of best-available technologies, as discussed below, can reduce this contribution over time.

18 International Council on Clean Transportation (2014). Global Transportation Roadmap Model.

19 The IMO is currently conducting a review of the availability of 0.5% sulfur fuel to determine whether the standard should be implemented as scheduled in 2020 or delayed to 2025. Furthermore, there are questions regarding how the requirement will be enforced and the degree to which ship operators might choose to evade it.

3. Geographic distribution and implications

The climate impact of BC emissions can vary based on where they occur. It is a mistake to assume that global emissions are equally distributed globally. Recent studies[20] indicate that 80 percent of shipping emissions occur in the Northern Hemisphere, and that emissions above 40°N can significantly impact climate forcing and ice/snow melt within the Arctic.[21, 22] Figure 2 shows the approximate location of 40°N relative to international container shipping traffic. Much of the traffic for the Pacific Ocean's Great Circle Route and the Atlantic Ocean's U.S. to Europe routes occurs above this line.

In certain regions, the contribution of shipping to local air pollution is even more concerning. Quinn et al. (2011) examined BC emissions sources for Arctic states and nations. For Alaska, marine vessels were the largest source at 61 percent of anthropogenic BC emissions in 2005 (estimated from EPA US PM2.5 inventory). Greenland's fisheries were the largest source of BC in 2010 (60 percent) and its domestic vessels accounted for 8 percent. In the Faroe Islands, shipping accounted for 61 percent of total BC emissions. In Svalbard, Norway, a combination of cruise traffic and coal transportation accounts for 90 percent of BC emissions. With the growth in international shipping and the expansion of non-traditional shipping routes, it has been estimated that 11 percent of all emissions from shipping will occur within the Arctic by 2050.[23]

These unevenly distributed emissions can lead to substantial impacts on the greater Arctic region as well. Browse et al. (2013)[24] found that despite the comparatively low current emissions from shipping within the Arctic, 32 percent of high-latitude ship-sourced BC deposition (2.0 kilotons) originates from less than 1 percent of global

20 Eyring V., Isaksen, I., Berntsen, T., et al. (2010) Transport impacts on atmosphere and climate: Shipping, Atmospheric Environment, vol 44, issue 37, 4735-4771.

21 Quinn. P. K., Stohl, A., Arneth, A. et al. (2011). The impact of black carbon on Arctic Climate (2011) Report for Arctic Council, AMAP Technical Report No. 4.Retrieved from: http://www.amap.no/documents/doc/the-impact-of-black-carbon-on-arctic-climate/746

22 AMAP / Bluestein et al., 2008. Sources and Mitigation Opportunities to Reduce Emissions of Short-term Arctic Climate Forcers. AMAP Technical Report No. 2 (2008), Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

23 Eyring, V., Isaksen, I. S. A., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., Moldanova, J., Schlager, H., and Stevenson, D. S. (2010) Assessment of Transport Impacts on Climate and Ozone: Shipping, Atmos. Environ., 44(37), 4735– 4771, doi:10.1016/j.atmosenv.2009.04.059.

24 Browse et al. (2013). Impact of future Arctic shipping on high-latitude black carbon deposition, Geophysical Research Letters, V 40, pp 1-5

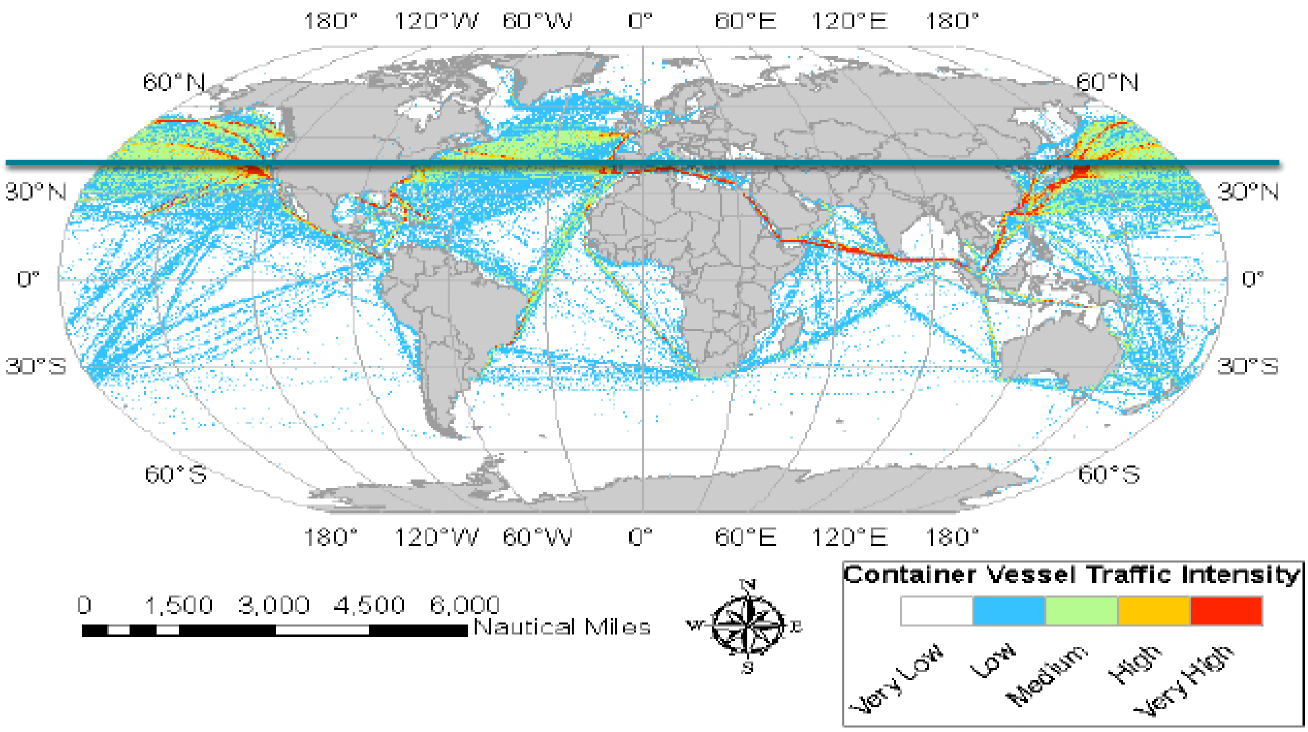

Figure 2. Container Vessel Traffic Intensity in 2009. Blue line represents the approximate location of 40°N, above which emissions from shipping significantly affect the Arctic.

shipping emissions. Dalsoren et al. (2013)[25] found that outside the Arctic, future shipping is expected to lead to a 10 to 20 percent increase in ambient BC concentrations in the vicinity of major shipping routes for the high-traffic scenario. The largest absolute changes are anticipated in the North Sea and other regions with highest vessel traffic where BC levels may increase more than 50 percent near vessel diversion routes.

Browse et al. also identified these areas as high BC deposition locations; that analysis estimated 6–8 percent of deposited BC originates from local ship traffic. BC deposition from shipping emissions over the west coast of Greenland and the Bering Sea may rise to 10–15 percent by 2050 in the high-growth (HiG) scenario. Dispersion calculations from Winther et al. (2014) indicate that local contributions of BC emissions around Iceland (in 2012) can reach up to 20 percent.[26]

The proximity of these emissions to the Arctic is of particular concern for international bodies, like the IMO, working to address the impact of international shipping emissions on the Arctic. This is a particularly important consideration from a climate perspective, since shipping emissions are one of few direct BC sources for the Arctic region and the effect of BC on albedo is directly linked to accelerated Arctic warming.[27] Emissions from ships operating beyond the Arctic have also been shown to impact the Arctic region, and are being considered for possible IMO regulation.

4. Control strategies for marine black carbon

A number of technologies and operational practices can reduce PM and BC emissions from international shipping. Near-term approaches to control marine BC, like slow steaming, fuel switching, and scrubbers, can reduce BC emissions by up to 70 percent. In the longer term, technologies like diesel particulate filters (DPFs) may become viable if low (50 ppm) and ultralow (10 to 15 ppm) sulfur fuels are adopted in the marine sector.

Switching from heavy fuel oil (HFO) to distillate fuel is a straightforward alternative that reduces BC and aligns with current and upcoming IMO emissions regulations on maximum allowable sulfur content for fuel oil. Switching to low-sulfur fuel can reduce marine BC emissions 30 to

25 Dalsøren, S.B., Samset, B.H., Myhre, G., Corbett, J.J., Minjares, R., Lack, D., and Fuglestvedt, J.S., (2013). Environmental impacts of shipping in 2030 with a particular focus on the Arctic region. Atmospheric Chemistry and Physics 13, 1941e1955. http://dx.doi.org/10.5194/acp-13-1941-2013.

26 Winther, M., Christensen, J. H., Plejdrup, M. S., Ravn, E. S., Eriksson, O. F., and Kristensen, H. O. (2014) Emission inventories for ships in the Arctic based on satellite sampled AIS data. Atmospheric Environment V91, pp1-14

27 Bond T. C., Doherty S. J., Fahey D. W., Forster, P. M., et al. (2013) Bounding the role of black carbon in the climate system: a scientific assessment. J Geophys Res 118(11):5380–5552. doi:10. 1002/jgrd.50171

80 percent. Improved fuel quality can also enable the use of particulate filters for more dramatic PM and BC reductions, as described below.

Slow steaming and de-rating became popular in the shipping industry at the end of 2007, mainly with containership owners and operators, due to increased fuel costs. De-rating is a process by which the maximum power of a ship engine is capped, keeping speeds low to provide better fuel efficiency. Combining slow steaming and de-rating is estimated to reduce marine BC emissions by approximately 15 percent.[28]

Exhaust gas scrubber trials have been conducted on marine vessels since 2006. Exhaust scrubbers expose exhaust gases to a water spray or other physical contact (such as a bubbler, etc.) to "scrub" out SOx emissions. The scrubbing system can be open-loop (seawater scrubbers), or closed-loop (freshwater scrubbers). Scrubbers are estimated to reduce marine BC emissions by 25 to 70 percent.

Additional approaches to reduce marine BC emissions include: exhaust gas recirculation (up to 20 percent reduction), slide valves (25 to 50 percent reduction) water-in-fuel emulsion (45 to 50 percent reduction), and LNG (around 90 percent reduction). Longer term, DPFs may become viable as marine fuel quality progresses to meet current standards for road fuels. DPFs with low-sulfur fuel are estimated to reduce marine BC emissions by 80 to 90 percent. There has been limited success with DPF and high-sulfur fuels however the arrangement of DPFs in series may reduce the need for filter regeneration making the pairing more viable.[29] Reductions of 80 percent have been reported when paired with HFO (1 percent max sulfur content).[30]

Table 3. Expected emissions reductions from marine technologies

Emission Reduction Technology	Expected Emissions Reductions (%)	
	LOW	HIGH
Fuel switching (LSF)	30	80
Slow steaming/de-rating	0	15
Exhaust gas scrubbers	20	70
Exhaust gas recirculation	0	20
Slide valves	25	50
Water in fuel emulsion	45	50
LNG	50	90
Diesel Particulate filters	80	90

5. Conclusions

As a major global BC source, diesel engines offer a promising mitigation opportunity. There are a number of currently available best practices and technologies which, when combined, can prevent up to 90 percent of diesel PM and BC emissions from marine engines. As the relative and absolute contributions of BC from shipping increase over the next decade, regulatory measures to reduce BC emissions from shipping will have a greater impact. This is particularly important for reducing the impact of shipping emissions on the Arctic. Scientists estimate that controlling 70 percent of BC emissions from ships operating in the Arctic would reduce Arctic warming from all marine short-lived forcers 30 percent by 2030.[31]

The IMO continues to explore options to control BC emissions from international shipping. At the most recent meeting of the subcommittee on Pollution Prevention and Response (PPR-2), the IMO preliminarily agreed to define black carbon by the Bond et al. 2013 definition, which is based on the unique physical properties of BC. Next steps for the IMO include testing BC measurement methods and identifying mitigation technologies to reduce the shipping BC emissions that impact the Arctic region. Understanding the importance of shipping emissions within an accurate global context facilitates informed discussion and future research leading to meaningful BC mitigation policy both globally and in the Arctic.

28 Litehauz, Lack, D. A., Thuesen, J., and Elliot, R (2012) Investigation of appropriate control measures (abatement technologies) to reduce black carbon emissions from international shipping

29 McWha, T. (2012) Analysis of emissions in the marine sector: NOx and black carbon emissions. Prepared for National Research Council of Canada.

30 Litehauz, Lack, D. A., Thuesen, J., and Elliot, R (2012) Investigation of appropriate control measures (abatement technologies) to reduce black carbon emissions from international shipping

31 Dalsoren et al. (2013). Environmental impacts of shipping in 2030 with a particular focus on the Arctic region. J. Atmos. chem. Phys., Vol 13, 1941-1955.