Black carbon from ship emissions: a review of its measurement and estimation methods, emissions factors, global emissions, and impacts

Issoufou Mamoudou [*], **Kpatinde Talagbe Aime** [*], **James Njuguna** [*]

[*] UN-Environment-Tongji Institute of Environment for Sustainable Development,
College of Environmental Science and Engineering, Tongji University, Shanghai 200092, P.R. China

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Abstract- Black carbon (BC), an outcome of incomplete combustion of fossil fuel and biomass burning, has a global and regional influence on radiative forcing and a large effect on the environment and human health. Several studies concerning black carbon emissions and its impacts on climate, environment and human health, have been carried out, but only a few have considered ship emissions. However, it was reported that black carbon from ship emissions affected the climate, environment, as well as human health, particularly in the Arctic region and coastal areas. Therefore, the aim of this paper is to do a review on BC emissions from the ship. In achieving the objective of this study, several papers including articles, reports, and scientific assessments on black carbon emissions from the ship were reviewed and synthesized.

As results, it was reported in the literature that shipping contributed about 2% of global anthropogenic BC emissions and 9% of total BC from diesel emissions, and the annual global BC from ship emissions was reported to 131 Gg. In the case of the remote regions, particularly the Arctic, the annual global BC from the ship was estimated to 1.2 Gg.

Black carbon pollutes the environment by contributing to the $PM_{2.5}$ composition, as well as the climate change by either warming or cooling effects. It also has a great effect on cardiopulmonary diseases and premature deaths.

Index Terms- Black carbon, Climate Change, Pollution, ship emissions.

I. INTRODUCTION

Black carbon is an aerosol mostly formed during the process of an incomplete combustion of biomass, biofuels, and fossil fuels. It is the highest ranked light-absorbing compound of particulate matter (PM) and has a warming effect by absorbing heat from the atmosphere and reducing the albedo when deposited on ice or snow (The Intergovernmental Panel on Climate Change, IPCC). Black carbon was defined as a distinct type of carbonaceous material, formed primarily in flames, then directly emitted to the atmosphere, and has a unique combination of physical properties (Bond et al. 2013). Hence, two properties related to light absorption and heat resistance were reported to be particularly useful for measurement purposes: (1) BC strongly absorbs visible light with a mass absorption coefficient (MAC) value above 5 $m^2\ g^{-1}$ at $\lambda = 550$ nanometers (nm) wavelength for freshly produced particles, (2) BC is refractory, with a volatilization temperature near 4000 K (Bond et al. 2013).

Relatively, these distinct properties give to black carbon its relevance in various research fields such as climate change, air chemistry, ambient air quality, biogeochemistry, and paleoclimatology (Bond et al. 2013).

The evidence is that many studies concerning black carbon emissions and its impact on climate, environment and human health had been undertaken, but only a few had taken ship emissions into consideration. Within those few, both Lack et al., 2008 and ICCT-2015 reported that ship contributed about 2% to the total anthropogenic BC emissions, and 9% of the total diesel BC emissions.

Black carbon from ship emissions was reported to have adverse impacts on climate, human health, ecosystems, and visibility, particularly in the Arctic region and coastal areas. Thus, it was reported in EPA 2012-Report to Congress of black carbon that BC influenced climate through multiple mechanisms. Within those mechanisms, EPA 2012 noted that: (1) BC absorbed radiations of all wavelengths, which contributed to warming of the atmosphere and dimming at the surface, (2) BC darkened the surface and decreased reflectivity, once deposited on snow and ice, and (3) BC altered the distribution of clouds and their properties. These latest are most likely greater in the Arctic region and other snow-ice covered regions because atmospheric BC layers absorb radiation both from incident sunlight and reflected rays from the surface (Corbett et al., 2010). Black carbon emissions from the international ship are significant, and contribute to global and regional climate change, particularly in the Arctic (IMO-2012).

In the case of human health, as a part of $PM_{2.5,}$ BC has been consistently linked to cases of pulmonary and respiratory diseases and implicated as a contributor to premature deaths from these illnesses (Corbett et al., 2007 and Liu et al., 2016). However, we can mention that black carbon effects on human health were not clearly detailed in the literature due to the lack of studies in that field.

From all these reasons cited above, black carbon from ship emissions is of concern in this review. Therefore, we focus on BC measurement and estimation methods, EF_{BCs} and its influential parameters, BC global emissions, and BC impacts on climate, environment and human health.

II. MEASUREMENT AND ESTIMATION METHODS.

There are multiple techniques and methods for black carbon measurement.

Shina et al., (2003) have measured black carbon concentration with an optical transmission technique. That method compared the attenuation of white light through a loaded filter relative to that of a blank filter. The relationship between optical attenuation (ATN) and the BC concentration (µg cm^{-2}) was given by ATN = σ BC, where ATN = 100 x ln (I_0/I), σ was the mass absorption cross-section for BC deposited on quartz filter (m^2 g^{-1}), and I_0 and I were the transmitted light intensities through the blank and loaded filters, respectively.

Lack et al., (2012) reported that BC emissions factors measured by photo-acoustic, filter-based absorption (PSAP and MAAP), and laser-induced incandescence were consistent on an absolute level. BC also showed good correlation with thermal-optical reflectance-measured for EC; however, the TOA method showed inconsistent results to both BC_{FSN} and BC_{Filter} (Lack et al., 2012).

Table 1 summarizes different BC measurement techniques with their prevalence of use.

Table 1: Description of BC measurement techniques

Method type	Method Description	Prevalence of Use
Light absorption/optical	***Filter-based:*** Light absorption by particles measured through a filter loaded with particles; BC quantified using factors that relate light absorption to a mass concentration.	High
	Photoacoustic: Light absorption by particles measured by heated particles transferring energy to the surrounding air and generating sound waves; BC is quantified using factors that relate light absorption to a mass concentration.	Low
	Incandescence: Incandescent (glowing) particles mass is measured; BC quantified by calibrating the incandescent signal to laboratory-generated soot.	Low
Isolation of specific carbon fraction	***Thermal-optical:*** measured as carbon fraction that resists removal through heating to high temperature and has a laser correction for carbon that chars during the analysis procedure; BC quantified as the amount of carbon mass evolved during heating.	High
	Thermal: BC measured as the carbon fraction that resists removal through heating to high temperatures; BC quantified as the amount of carbon mass evolved during heating.	Low

<u>Source:</u> EPA 2012- Report to Congress on Black Carbon, page 116.

In the case of BC estimation, it was shown in EEA. (2009) that calculation of black carbon emissions from all sources, except on-road transport, can be expressed by:

BC emissions = fuel (kg) × PM emission factor (g/kg) × (BC/ PM) ratio.

However, in IMO. (2012)-global emissions of marine black carbon-BLG\17\INF-2.doc; it was remarked that most of the studies used the single EF_{BC} approach to estimate BC emissions. Evidently, the single EF_{BC} approach did not consider some important parameters in BC estimation such as the physical and operational characteristics of ships. Therefore, they constructed a refined activity-based methodology to model global and regional BC emissions from the international ship, which included fuel consumption for each ship type, engine type, fuel type, and sensitivity of EF_{BC} to each of these parameters.

However, the same estimation approach was used by IMO. (2012) to estimate the total BC emission in the Arctic for the year 2004, but IMO. (2012) found twice the average value recorded by the other authors. The higher BC emissions value found by the IMO-2012 was likely due to the higher EF_{BC} (0.56) used in that estimation.

III. EMISSION FACTORS AND ITS INFLUENTIAL PARAMETERS

As previously shown, there are different types of measurement techniques used during black carbon measurement, and that comes with consequences on the related data. In addition, EF_{BC} from the ship (in g per Kg fuel) depends on the broader metric of light absorbing carbon (LAC), or light-absorbing elemental carbon (EC) considered. However, both LAC and EC were encountered in literature as black carbon emissions factors depending on the measurement methods. For example, the photoacoustic measurement can estimate optical properties of LAC, but it is still limited in characterizing the mass of LAC. While, EC mass is measured using thermo-optical methods, and that strips away OC in the measurement process.

The discrepancy of BC emissions factors viewed on the measurement angle was highlighted by (Petzold et al. 2010), where both elemental carbon (EC) and black carbon (BC) emissions factors were represented depending on the engine load. Wherein, for an engine loaded about 85-110%, EC and BC emissions factors were 0.179 ± 0.018 g kg^{-1} and 0.062 ± 0.007 respectively.

Table 2 outlines different EF_{BC} from a ship found in the literature.

Table 2: EF_{BC} from a ship found in the literature depending on some non-exhaustive influential parameters.

Year	Literature	Influential parameters (not exhaustive)	EF_{BC} (g Kg^{-1})
2003	Sinha et al.	Tanker and container, diesel engine, diesel oil, gross tonnage.	0.18 ± 0.02
2004	Bond et al.	Diesel engine, heavy fuel oil.	0.34
2008	Petzold et al.	Container, diesel engine, heavy fuel oil, 85% - 110% loaded.	0.174 ±0.04 *
2008	Lack et al.	Tanker, container, cargo and bulk ships, diesel, slow speed diesel (SSD).	0.41 ±0.27
		Tug and large fishing boats, diesel, medium speed diesel (MSD).	0.97±0.66
		Passenger vessels (e.g. ferries, pilot boats), diesel, high-speed diesel (HSD).	0.36 ± 0.23
2010	Corbett et al.	All ship type, diesel engine, diesel oil.	0.35
2010	Petzold et al.	Four-stroke, diesel engine, heavy fuel oil, 85% - 110% loaded.	0.179 ± 0.31 *
		Four-stroke, diesel engine, heavy fuel oil, 85% - 110% loaded.	0.06 ± 0.04
		Four-stroke, diesel engine, heavy fuel oil, 85% - 110% loaded.	0.367
2012	IMO	Tanker, container, cargo carriers, bulk carriers, tugboats, and passenger boat, diesel engine, MDO and HFO fuel oil.	0.56
2015	ICCT	Container vessel, diesel engine, DPFs and HFO fuel oil.	0.31 ±0.31

**means BC emission factor is considered in terms of element carbon (EC)*

As we remarked above, the discrepancy of black carbon emissions factors found in the literature was not only due to the higher uncertainty but also due to the different methods used in its measurement.

The results portrayed by Petzold et al., (2008*, 2010*) and Sinha et al., (2003) agreed. However, the figures were low when compared to the other authors, and that makes us conclude that there had been under-estimation since only EC had been used as a factor for BC estimation. (Petzold et al., 2013).

Petzold et al., (2013) reported that the correlation of EC mass estimated from the thermo-optical approach to BC mass estimated from photoacoustic measurements has been shown to be good for sources, where EC dominates total PM, such as diesel engines. As it was shown, most of the ships have a diesel engine, the EC mass estimated from the thermal-optical approach can be used to extrapolate the BC mass until the scientists find a new and unique BC measurement technique.

Black carbon emission is generally related to the combustion process as well as other factors that are called influential parameters (or factors). Thus, the fuel type, the engine type, age, load, the emission abatement technology, the maneuvering time, and the speed of the engine were shown to play a significant role in black carbon emissions (Lack et al. 2012). To link BC emission factors to the engine speed, Lack et al., (2008) came up with mass-based emission factors of light absorbing carbon (EF_{LAC}) of 0.41, 0.97, and 0.36 for slow (SSD), medium (MSD), and high-speed diesel (HSD) powered vessels respectively.

Furthermore, the role of ship and fuel type on BC emission factors was highlighted by IMO. (2012)-global emissions of marine black carbon-BLG\17\INF-2.doc. The table 3 summarizes BC emission factors based on ship and fuel type found out by IMO-2012.

Table 3: Emission factors estimated in IMO. (2012).

	Centrale 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		1.3
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

Source: IMO. (2012)-global emissions of marine black carbon-BLG\17\INF-2.doc.

The average value of emission factor based on ship and fuel types in this chart shows a higher black carbon emission factor for each ship type with HFO than with MDO. The second conclusion is that black carbon emission factor for each ship type using either HFO or MDO is higher in Port than in Sea. That is due to the fact that ship at offshore operates at a lower speed. To highlight the other influential parameters, it was reported by ICCT-2015 that available technologies and operational practices, such as fuel switching, scrubbers, and vessel speed reduction, could reduce shipping emissions by up to 70 percent.

IV. GLOBAL EMISSIONS .

The global emissions of black carbon using bottom-up inventory method were reported by Bond et al., (2013) to be 7500 Gg yr^{-1} in the year 2000. Out of that global BC emissions value, Bond et al., (2013) reported that marine ship contributed about 2% with a large fraction of remote regions such as the Arctic.

The likely annual global black carbon emissions from the ship were reported to be around 131 Gg (Lack et al., 2008, Bond et al., 2004 &2007, Eyring et al., 2009). Whereby, that average value represented about 2% of the global anthropogenic black carbon emissions and 9% of the global diesel black carbon emissions (Lack et al., 2008 and ICCT-2015).

In addition to this global value of black carbon emissions from the ship, some regional black carbon values such as the Arctic region and the Southern Atlantic Ocean have been recorded. Thus, for the year 2004, the annual global black carbon emissions from the ship in the Arctic region was reported to be around 1.2 Gg (AMAP-2011, AMSA-2009, and Corbett et al 2010). However, for the same year, the IMO. (2012)-global emissions of marine black carbon-BLG\17\INF-2.doc estimated average BC emissions of 2.3 Gg from international ship operating in the Arctic, based on an average EFBC of 0.56 g kg-1 fuel.

On the other hand, Shina et al., (2003) reported that the global black carbon emissions from ocean-going ships in the Southern Atlantic Ocean for the year 2000 ranged from 19-26 Gg yr^{-1}. The table 4 below gives the summary of black carbon emissions found in the literature.

Table 4: Annual black carbon from ship emissions found in the literature.

Year of study	Study area	Literature	Total emissions (Gg y^{-1})
2003	Southern Atlantic Ocean	Sinha et al.	19-26[a]
2004 & 2007	Global scale	Bond et al.	132
2005	Global scale	Eyring et al.	33
2008	Global scale	Lack et al.	133 (± 27)
2009	Global scale	Eyring et al.	130
2009	Arctic	AMSA	1.18[b]
2010	Arctic	Corbett et al.	1.23[b]
2011	Arctic	AMAP	1.2[b]
2012	Arctic	IMO	2.3[b]

[a] *total yearly BC from ocean-going ship emissions in the Southern Atlantic Ocean off the coast of Namibia in 2000.*

[b] *total yearly BC from shipping emissions in Arctic region for the year 2004.*

The yearly global black carbon emissions recorded by Lack et al., (2008), Bond et al., (2004 &2007), and Eyring et al., (2009) were in close agreement, and were higher than the value recorded by Eyring et al., (2005). The lower BC global emissions recorded by Eyring et al., (2005) was likely due to the Lower emission factor used to estimate that global BC emissions.

In the case of the yearly regional black carbon emissions outlined in the chart above, the Southern Atlantic Ocean BC emissions from the ship (Sinha et al., 2003) was higher than that recorded in the Arctic region. Probably, these lower BC values from ship emissions found in the Arctic region for the year 2004 were due to the difference in location between the emissions site and the recording site. However, it is important to note that between four studies undertaken for the year 2004 in the Arctic region, three (AMSA-2009, Corbett et al., 2010, and AMAP-2011) were in agreement, with around 1.2 Gg y^{-1} BC. That makes us conclude that the annual BC emissions from the ship in the Arctic for the year 2004 were very likely about 1.2 Gg. Elsewhere, IMO-2012 found twice the average value of the previous studies. That was probably linked to the uncertainty encountered in black carbon measurement, the discrepancy in BC emissions factors, the higher EF_{BC} used (0.56 g kg^{-1}), and the different technique used during BC measurement and estimation.

In the case of the seasonal BC emissions in the Arctic region, Corbett et al., (2010) reported that BC emissions of in-Arctic ship traffic for the year 2004 were 0.18, 0.19, 0.28, and 0.23 Gg y^{-1} for winter, spring, summer, and fall (Autumn) respectively. BC emissions in summer were the highest followed by the fall. That was due to the higher number of trips in summer (4807) followed by fall (3729), spring (3390) and winter (3072). In addition to the year 2004 BC emissions inventory in the Arctic region, Corbett et al., (2010) did some projections based on "Business As Usually (BAU)" and the high-growth scenarios for the years 2020, 2030, and 2050. Table 5 resumes those projection figures.

Table 5: Potentials emissions inventories of in-Arctic shipping and diverted the global ship to Arctic routes for 2020, 2030, and 2050.

Year	Inventories/diversions	In-Arctic BC emissions projections (gg y^{-1})	global shipping to arctic routes BC emissions projections (gg y-1)
2020	BAU[1]	1.2	0.70
2030	BAU	1.5	0.90
2050	BAU	2.7	2.4
2020	High-growth[2]	1.5	0.91
2030	High-growth	2	2.5
2050	High-growth	4.7	12

Source: Corbett et al., (2010)-Arctic shipping emissions inventories and future scenarios

[1] *BAU diversions in 2020, 2030, and 2050 are 1%, 1%, and 1.8% of global shipping in each of those future years, respectively. Global shipping growth outside of Arctic is ~2.1% per year.*

[2] *High-growth diversions in 2020, 2030, and 2050 are 1%, 2%, and 5% of global shipping in each of those future years, respectively. Global shipping growth outside of Arctic is ~3.3% per year.*

Corbett et al., (2010) reported that in 2004, Arctic transport vessels contributed less than 1% of ship BC emissions, and in 2050, ships in the Arctic may contribute less than 2.5% of global ship BC emissions. However, this is not without consequences on the Arctic region as shown previously. The Arctic region is sensitive to BC emissions in terms of radiative forcing, snow, and ice melting even though the emissions level is still low.

V. IMPACTS OF BLACK CARBON ON ENVIRONMENT, CLIMATE, AND HUMAN HEALTH

The obvious impact of black carbon on the environment is visibility (smog). However, it may contribute to some photochemical reactions with the co-emitted aerosols generating some secondary pollutants. Black carbon may also affect the environment via its significant proportion in $PM_{2.5}$ from ship emissions. Different proportions of black carbon such as 15%, 6.6%, 4%, and 2.7% in $PM_{2.5}$ were argued in the previous studies by Corbett et al., (2010), Liu et al., (2016), Sinha et al., (2003), and Petzold et al., (2008) respectively. $PM_{2.5}$, including BC, had been linked to a reduction in crop yields and damage to materials and buildings (Evens et al., 2015).

With respect to climate, IMO-2012 reported that BC emissions from the international ship were significant, and contributed to global and regional climate change particularly in the Arctic. Somewhere, it was reported that within Arctic BC sources, the ship was cited to have a large impact on low-altitude BC concentrations and deposition, therefore, it seemed likely to have a large forcing per unit emissions. Furthermore, the previous global BC emissions from the ship of about 1.2 Gg y^{-1} recorded in the Arctic shows that the Arctic is still being impacted. In the case of future perspective, Corbett et al., (2010), suggested that the first-order calculation of global warming potential, due to 2030 emissions in the high-growth scenario of short-lived forcing of ~ 4.5 Gg of black carbon from Arctic ship might increase global warming potential by some 17% to 78%.

In the case of black carbon from ship radiative forcing, the debate is not clear since some argued for the negative RF while other argued for the positive one. For example, Liu et al., (2016) concluded in their study that the radiative forcing of BC from ship emissions in East Asia was strongly negative off the coast of China, Japan, and Korea ($< -0.3W\ m^{-2}$). On the other hand, in EEA Technical report, (2013), it was reported that BC from ship emissions had a positive RF of about $+0.002\ W\ m^{-2}$. Thus, to control effectiveness, it urges to harmonize the ideas about the trade-off of radiative forcing of BC from ship emissions.

Smith et al., (2009), made evidence of black carbon impacts on human health, that is, BC had a distinct health effect despite being only a small fraction of PM. In the study conducted by Corbett et al., (2007) to examine cardiopulmonary and lung cancer mortalities due to ship emissions, it was reported that PM emissions from ships were responsible for approximately 60,000 deaths annually with most deaths occurring near coastlines in Europe, East Asia, and South Asia. Liu et al., (2016) did a study on health and climate impacts of ocean-going vessels in East Asia and reported that ship emissions led to more than 24,000 premature deaths annually.

VI. IMPLICATIONS

In measuring BC, the challenge is that air pollution inventories are focusing on mass emissions (EC), while BC is characterized by its optical properties (LAC) (Wang et al., 2016). Thus, a measurement that forms the basis of underlying emissions and speciation factors does not provide a complete accounting for these optical properties. It is important then for scientists to come up with a measuring method that combines the photoacoustic and the thermal-optical methods, which give the optical properties of LAC and EC mass respectively. Once EF_{BC} is measured in a good manner, it will likely solve most of the uncertainties encountered in BC global emissions estimation.

During our review, we concurred concerning the need for black carbon emissions reduction. To begin with, since possible future ship fuel quality regulations through the MARPOL Annex VI legislation on sulfur content do not necessarily reduce emissions of BC (Lack et al., 2009); we propose to undertake some limitations techniques through the best available technology (BAT) and the best environmental practices (BEP) approach during the ship conception and operation. This BAT/BEP approach should be applied not only for the engine conception but also for the ship emissions abatement technologies such as scrubbers and filters. Further, the Container vessels using HFO oil and the Tugboats using MDO oil were shown to have the highest EF_{BC} among the ship types, therefore, the International Maritime Organization (IMO) should regulate the operating time of these vessels, particularly in port, in order to reduce BC global emissions

VII. CONCLUSION

There was a large discrepancy concerning black carbon emissions factors as well as the global emissions. That non-uniformity was not only due to the various methods used in the measurement but also the higher level of uncertainty. Furthermore, the various definitions of black carbon played a role in its measurement methods resulting in different EF_{BC}. In addition, we mention that fuel factors and EF_{BC} are sources of uncertainty in BC inventory; and the latter is sensitive to ship operational conditions.

As a part of PM, and with a global average emission of 131 Gg y^{-1}, BC from the ship is affecting the climate, the environment, as well as human health, unfortunately.

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AUTHORS

First Author – Issoufou Mamoudou, Master’s Degree Candidate, * UN-Environment-Tongji Institute of Environment for Sustainable Development,
College of Environmental Science and Engineering, Tongji University, Shanghai 200092, P.R. China
Email: issoufoumamoudou@yahoo.com
Tel: +86 13052107556
Second Author – KPATINDE Talagbe Aime, Master’s Degree Candidate, * UN-Environment-Tongji Institute of Environment for Sustainable Development,
College of Environmental Science and Engineering, Tongji University, Shanghai 200092, P.R. China
Email: ktalagbeaime@gmail.com
Tel: +86 13120697573

Third Author – James Njuguna, Master’s Degree Candidate, * UN-Environment-Tongji Institute of Environment for Sustainable Development,
College of Environmental Science and Engineering, Tongji University, Shanghai 200092, P.R. China.
Email: njugunajksrk@gmail.com
Tel: +86 15026447304

Correspondence Author – Issoufou Mamoudou, Master’s Degree Candidate, * UN-Environment-Tongji Institute of Environment for Sustainable Development,
College of Environmental Science and Engineering, Tongji University, Shanghai 200092, P.R. China
Tel: +86 13052107556
Email: issoufoumamoudou@yahoo.com , 1693379@tongji.edu.cn