Marine Black Carbon Emissions:
Testing Protocols and Reporting; Instrumentation; and Emission Factors

Technical Workshop Background Document

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Netherlands Organization for Applied Scientific Research (TNO)

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1.0 INTRODUCTION

The International Council on Clean Transportation (ICCT)[1], in coordination with the Dutch Ministry of Infrastructure and Environment and the Netherlands Organization for Applied Scientific Research (TNO), is hosting a technical workshop on marine black carbon (BC) emissions. This workshop is the second of three designed to shape a two-year project on marine BC emissions funded by the Climate and Clean Air Coalition (CCAC), an international cooperative partnership of over 40 member nations and more than 50 intergovernmental and non-governmental organizations to promote strategies to reduce emissions of short-lived climate pollutants, including BC. Under that project, the ICCT, working with the United Nations Environment Program (UNEP), will develop a refined global marine BC inventory and control technology performance database for use by CCAC member states.

The first workshop, held in Ottawa, Canada, in September 2014, focused on building consensus on a definition of BC that would be suitable for research purposes. The third workshop, to be held in fall 2016, will focus on ways to control marine BC emissions.

The goal of this second workshop is to work toward consensus on a standardized BC measurement and reporting approach that can be applied in marine BC emissions testing campaigns. To achieve this goal, the workshop will convene international experts on BC measurement and reporting protocols, instrumentation, and inventory development.

Workshop participants will identify areas of consensus as well as open questions and future research needs related to these three topics. Specifically, participants will work toward consensus on appropriate BC measurement and reporting protocols, instruments that should be used to measure BC, and types of emission factors needed to improve inventories (e.g. by engine/fuel type, engine load points, etc.). Workshop outcomes will help guide the measurement and reporting approach for an upcoming marine BC testing campaign that will be carried out by a consortium of researchers led by the University of California-Riverside (UCR) and funded by the ICCT and the U.S. Department of Transportation's Maritime Administration (MARAD). Workshop outcomes may also inform CCAC member state submissions to the International Maritime Organization (IMO) on BC measurement.

2.0 BACKGROUND

A key outcome of the first workshop on marine BC emissions held in Ottawa, Canada, in September 2014 was a general agreement on the definition of BC as defined by Bond et al. (2013): BC is a "distinct type of carbonaceous material, formed primarily in flames, is

[1] The International Council on Clean Transportation is an independent nonprofit organization founded to provide first-rate, unbiased research and technical and scientific analysis to environmental regulators. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change.

directly emitted to the atmosphere, and has a unique combination of physical properties." Two properties in particular were considered to be useful for measurement purposes:

- BC strongly absorbs visible light with a mass absorption coefficient (MAC) value above 5 $m^2 g^{-1}$ at a wavelength $\lambda = 550$ nanometers (nm) for freshly produced particles
- BC is refractory, with a volatilization temperature near 4000 K

This definition was formally accepted by IMO at MEPC 68 in May 2015.

Black carbon is the second largest contributor to human induced climate warming to-date, after carbon dioxide (CO_2), according to Bond et al.'s (2013) landmark four-year study on BC. Marine vessels are a large source of diesel particulate matter (PM) and BC emissions. International shipping was estimated to account for 7-9% of diesel BC emissions in 2000 (Bond et al, 2013; Eyring et al., 2010), growing to 8-13% by 2010.[2] From a climate perspective, marine BC emissions are particularly concerning in the Arctic, where BC deposition to snow and ice reduces albedo, promoting warming and melting. One widely cited 2010 study (Corbett, Lack, & Winebrake, 2010) estimated that, barring additional controls, global BC emissions from marine vessels will nearly triple from 2004 to 2050 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 (Johnson et al., 2015), increasing the relative importance of shipping emissions. In addition to its climate impacts, exposure to PM and BC emissions has been linked to negative human health impacts including cardiopulmonary disease, respiratory illness, and lung cancer.

Climate and health impacts can be mitigated by reducing BC emissions. A number of technologies and operational practices can reduce PM and BC emissions from marine vessels. These include fuel switching, slow-steaming combined with engine de-rating, exhaust gas scrubbers, exhaust gas recirculation, slide valves, water in fuel emulsion, liquefied natural gas (LNG), and diesel particulate filters (DPFs), which can reduce marine BC emissions up to 80-90% for select applications.. However there are challenges in implementing some of these control strategies. For example, many exhaust emissions control technologies require low-sulfur fuel to function properly. While ships operating in Emission Control Areas (ECAs) burn low-sulfur distillate fuels (<0.1% S by mass) such as marine diesel oil (MDO) and marine gas oil (MGO), they burn less expensive high-sulfur fuels such as heavy fuel oil (HFO, ~2.7% S by mass) on the open ocean. The high S content of HFO inhibits the use DPFs and other advanced pollution control technologies on marine vessels. Scrubbers are one technology that could be used to reduce PM and BC emissions, but there are potentially serious environmental impacts associated with disposing of polluted scrubber washwater, as well as substantial installation, operation, and maintenance costs. Additionally, the effectiveness of scrubbers to reduce BC emissions is not yet well-understood.

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[2] Azzara, A., Minjares, R., and Rutherford, D. Needs and opportunities to reduce black carbon emissions from maritime shipping. Available at: http://www.theicct.org/sites/default/files/publications/ICCT_black-carbon-maritime-shipping_20150324.pdf

A remaining barrier to reducing marine BC emissions is a lack of confidence concerning the global inventory of marine BC. Uncertainty can make it difficult to prioritize the need for measures to control marine BC emissions compared to other pollutants amidst policy constraints, notably cost. The estimates of marine BC contribution to the global BC budget rely on a number of simplifying assumptions. One important set of assumptions when estimating the global marine BC inventory are BC emission factors. Assumptions for how much BC is emitted by various vessel types (emission factors) are based on a limited number of scientific studies, most of which calculate BC as a fraction of PM emissions. These emission factors can vary based on the following factors, among others:

- Testing protocol
- Instrumentation
- Vessel type
- Engine type (2-stroke vs. 4-stroke, certification Tier level)
- Engine speed
- Engine load
- Fuel type
- Exhaust gas aftertreatment system

A better understanding of how these factors influence marine BC emission factors is needed to develop a refined marine BC emissions inventory and to evaluate the effectiveness of BC emissions reduction technologies and strategies.

3.0 BREAKOUT GROUP MATERIALS

This section provides background material that may be useful as part of the three concurrent breakout groups on Day 1 of the workshop. The breakout groups focus on:

- Testing protocols and reporting
- Instrumentation
- Emission Factors

3.1 Testing Protocols and Reporting

At this workshop, we would like to work toward consensus on standardized BC testing and reporting protocols. Participants of the first workshop on marine BC in Ottawa in 2014 recognized the need for developing a standardized BC testing and reporting approach. Specifically, participants recommended a standard pretreatment protocol for BC sampling. Pretreating BC samples through heating and dilution can allow for more precise measurements by removing volatile organics and preventing gases from condensing on BC particles.

3.1.1 Testing Protocol

Some groups have already recommended factors that should be considered when developing a standardized BC measurement protocol. For instance, the European Association of Internal Combustion Engine Manufacturers (EUROMOT) submitted the following factors for IMO to consider in document MEPC 68/12/9:

- Probe installation location
- Instrument calibration
- Probe characteristics
- Sample line characteristics
- Measurement instrument cell characteristics
- Sampling time
- Sampling operating condition
- Engine operating condition
- Distinction between engine sizes/speeds deemed to be necessary
- Fuel type, fuel sulfur content, fuel oil consumption, lube oil specifications, and cylinder lube oil feed rate
- Operating conditions including engine speed and load
- How BC will be reported

The breakout group is asked to identify the key factors to include in a standardized BC testing protocol. The factors above provide a reasonable starting point for discussion.

3.1.2 Reporting Protocol

Reporting BC measurements can be guided by Petzold et al. (2013). Petzold and colleagues lay out a recommended terminology and related measurement techniques and instruments as the basis for reporting BC emissions measurements, as summarized in Table 1, excerpted from Petzold et al. (2013). Note that Petzold and colleagues recommend using BC only as a *qualitative* descriptor. When reporting measurement results, they recommend using more specific terminology, as described in the "Recommendation" column of .

Table 1. Recommended terminology and related measurement techniques and instruments, excerpted from Petzold et al. (2013).

Property	Technique	Instrument	Recommendation
Light absorption	Light absorption measurement	various in-situ and filter-based methods Photoacoustic Spec. Aethalometer MAAP PSAP COSMOS	report as σ_{ap}: If reported as EBC, specify MAC value used for the conversion from light absorption into mass concentration
Refractory	Measurement of thermal radiation Soot Particle Aerosol Mass Spectrometry	SP2 LII SP-AMS	report as rBC; specify means of calibration, conversion factor from thermal radiation to carbon mass, and the size-cut of rBC particles
Chemical composition, carbon content	Evolved carbon methods, thermal evolution of carbon with optical correction for pyrolysis	various temperature protocols	report as EC; specify temperature protocol used for the sample analysis
	Aerosol Time-of-Flight Mass Spectrometry	ATOFMS	report as EC
	Soot Particle Aerosol Mass Spectrometry	SP-AMS	report as rBC, because technique detects carbon that is evaporating under incandescent conditions
Graphite-like microstructure	Raman spectroscopy		report as EC; specify means of calibration
Particle morphology	Electron microscopy	TEM	N/A

More detailed recommendations for reporting "BC" emissions measurements from Petzold et al. (2013) are as follows:

- **Equivalent black carbon (EBC)**
    - Use when data are derived from optical absorption methods
    - Identify the MAC value used
    - Specify the approach for separating potential contributions of brown carbon (BrC) or mineral dust to the aerosol light absorption coefficient
- **Elemental carbon (EC)**
    - Use when data are derived from methods specific to the carbon content of carbonaceous material (e.g., evolved carbon and aerosol mass spectrometry methods)
    - Specify the temperature protocol used for sample analysis when using evolved carbon methods (e.g., IMPROVE and NIOSH)
    - Also use when data are derived from Raman spectroscopy and be sure to specify the means of calibration
- **Refractory black carbon (rBC)**
    - Use when data are derived from incandescence methods (e.g., LII, SP2, and SP-AMS)
    - Specify means of calibration, conversion factor from thermal radiation to carbon mass, and the size-cut of rBC particles
    - Replace terms such as *refractory BC, equivalent refractory BC, erBC*, and similar terms containing EC or refractory carbon, *RC*, with rBC
- **Soot**
    - Use for *qualitative* descriptions of carbonaceous particles formed from incomplete combustion
- **BC-containing particles**
    - Use when particles contain a BC fraction
    - Do not refer to BC-containing particles as *BC particles* or *soot particles*

The breakout group is asked to identify an appropriate BC reporting protocol. It should comport with the testing protocol identified by the group.

3.2 Instrumentation

At this workshop, we would like to work toward consensus on instruments to be included and evaluated in the upcoming marine BC emissions testing campaign led by UCR.

Black carbon can be measured by a wide variety of instruments; however, some instruments may be more appropriate than others for developing refined marine BC emission factors. Two properties of BC were identified as particularly important at the first workshop on marine BC emissions:

- BC strongly absorbs visible light with a mass absorption coefficient (MAC) value above 5 m^2 g^{-1} at a wavelength $\lambda = 550$ nanometers (nm) for freshly produced particles
- BC is refractory, with a volatilization temperature near 4000 K

Thus, instruments that measure the *light absorption* properties of BC and the *refractory* properties of BC should be considered.

Existing instruments that measure the light absorption properties of BC (reported as EBC with a MAC value specified) include:

- Aethalometer
- COntinuous Soot MOnitoring System (COSMOS)
- Filter Smoke Number (FSN)[3]
- Micro Soot Sensor (MSS)
- Multi-Angle Absorption Photometer (MAAP)
- Particle Soot Absorption Photometer (PSAP)

Existing instruments that measure the refractory properties of BC (reported as rBC) include:

- Laser Induced Incandescence (LII)
- Single-particle Soot Photometer (SP2)
- Soot Particle Aerosol Mass Spectrometer (SP-AMS)

This is not an exhaustive list of existing instruments that could be used to measure marine BC.

The breakout group is asked to (1) identify instruments that may be included and evaluated in the upcoming marine BC emissions testing campaign led by UCR; (2) identify research needs to enable cross comparison of results obtained by different instruments; and (3) discuss performance criteria for instruments suitable for aligned future research on marine BC emissions. Note that the instrument(s) will need to comport with the testing and reporting protocols that the group eventually agrees on.

3.3 Emission Factors

At this workshop, we would like to work toward consensus on the types of marine BC emission factors that are most needed to develop a refined marine BC emissions inventory and to evaluate the effectiveness of BC emissions reduction technologies and strategies.

[3] FSN is a common, filter-based technique for measuring BC. Although FSN measurements follow standard protocols for ISO 8178, they have not been subject to the same artifact corrections used for the other filter-based light absorption methods, as explained by Lack et al. (2014), available at http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3877426/.

There are large discrepancies in marine BC emission factors used in existing global and Arctic marine BC emissions inventories. These discrepancies were noted by Wang and Minjares (2013), as shown in the far right hand column of Table 2.

Table 2. Black carbon emission factors used in various studies

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

[a] Did not estimate BC emissions directly, but cited Eyring et al's (2010) estimate of BC emissions, which estimated BC emissions to be 130 and 120 thousand tonnes in 2000 and 2007, respectively.
[b] BC emissions factor from Shina et al. (2003) [29].
[c] Weighted average.

In addition to BC emission factors, others have measured and reported EC emission factors. For example, Agrawal et al. (2008) reported a range of EC emission factors of 0.016-0.029 g/kWh depending on main engine load for a large, in-use PanaMax container vessel. Similarly, Agrawal et al. (2010) observed a substantially lower range of EC emission factors of 0.0058 to 0.0085 g/kWh, depending on engine load, with a weighted EC emission factor of 0.007 g/kWh, for a post-PanaMax container vessel. In both studies they measured EC using a Thermal/Optical Carbon Aerosol Analyzer according to the NIOSH 5040 (1996) reference method.

The BC emissions factor has a substantial impact on total estimates of marine BC emissions. Emission factors can vary based on a number of factors, including:

- Testing protocol
- Instrumentation
- Vessel type
- Engine type (2-stroke vs. 4-stroke, certification Tier level)
- Engine speed
- Engine load

- Fuel type
- Exhaust gas aftertreatment system

Uncertainty about total marine BC emissions has potentially serious policy implications. A refined, accurate, and geospatially allocated global marine BC emissions inventory can inform policy decisions related to controlling marine BC emissions, but will require developing updated marine BC emission factors. Some of these updated emission factors will be developed as part of the UCR-led emissions testing campaign.

The breakout group is asked to identify the marine BC emission factors that are most needed to create a more accurate global marine BC emissions inventory. These emission factors may include, but are not limited to:

- vessel-type-specific BC EFs
- fuel-type-specific BC EFs
- Engine speed/load-specific BC EFs
- Exhaust gas aftertreatment-specific BC EFs

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