Marine Black Carbon Emissions:

Identifying Research Gaps

A technical workshop sponsored by
the International Council on Clean Transportation
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CLIMATE AND CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

Executive Summary

This workshop was the first of three designed to inform and guide a new two-year project on marine black carbon funded by the Climate and Clean Air Coalition (CCAC). The project will develop a refined global marine black carbon (BC) inventory and technology performance database for mitigation strategies. The goal for this kickoff workshop was to refine the project work plan based upon a solid understanding of the current state of knowledge on BC measurement and testing, emissions inventories, and control strategies for marine vessels.

The workshop was held in Ottawa, Canada at the Environment Canada River Road Air Quality Laboratory. It included 35 in-person participants and multiple remote attendees, representing 21 organizations and 10 countries. The two-day agenda included seven sessions with 24 expert presentations on materials covering definition, measurement, and mitigation of black carbon, the state of the knowledge, gaps, and next steps for a research agenda.

Key workshop outcomes included a consensus definition of marine black carbon for research purposes, next steps for aligning diagnostic approaches (appropriate measurement and sampling protocols), and four main recommendations for priority research. This report is divided into four sections: Overview, Workshop Format, Session Outcomes, and Conclusions. The Session Outcomes include a discussion on definition and measurement, black carbon inventories, mitigation technology and testing, and next steps.

Regarding black carbon definition, participants agreed to use the Bond et al (2013) definition of black carbon for climate research purposes. Measurement methods linked to the light absorbing and refractory properties of black carbon were considered to be most consistent with this definition, although the value of parallel testing with other methods was also recognized. Support was also expressed for establishing minimum performance requirements for appropriate instrumentation methods. Given the high sulfur content of current marine fuels, the establishment of standardized pre-treatment protocols to remove volatile fractions was recommended to facilitate the comparisons of results

Fuel switching, scrubbers, filters (where available), and slow steaming were identified as priority control strategies for investigation. An additional outcome identified was the need to refine BC marine inventories through coordinated research on baseline emission factors using some combination of on-board, test bench, and plume studies of marine vessels.

Near term research steps include 1) a comprehensive review of existing emission factors, 2) a vessel activity and fleet composition review to identify key sources (i.e. ship/engine types, operational conditions, etc.) not yet characterized, 3) a focused discussion and research plan to evaluate diagnostics (i.e. measurement instrument protocols and sample pre-treatment), and 4) an analysis of the relative merits of on-board measures, test bench analyses, and plume studies research for inventory development and evaluation of control strategies. All parties agreed to continuing work facilitating the sharing of information and to developing an inclusive research approach.

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I. Overview

This workshop was the kickoff event for the marine component of a new two-year project on marine and ports black carbon emissions funded by the Climate and Clean Air Coalition (CCAC) and implemented by the International Council on Clean Transportation (ICCT). The CCAC is an international cooperative partnership to reduce emissions of short-lived climate pollutants, including black carbon (BC).[1] The ICCT is a research-based, environmental non-profit with offices in the US, Europe, and China. ICCT works to support environmental policymakers worldwide with the best technical information to develop policies to reduce transport emissions.[2] ICCT staff are active in a variety of policy venues, including IMO, and have contributed papers related to marine black carbon emissions to that forum since 2011 through the IMarEST delegation.

Ports and marine vessels are a large source of diesel particulate matter and black carbon. Black carbon is the second largest contributor to human induced climate warming to-date, after carbon dioxide, according to a landmark four year-study on black carbon released in 2013 (Bond et al, 2013). Representing the consensus on BC climate science, this study found that "mitigation of diesel-engine sources offers the most confidence in reducing near-term climate forcing" because particles from diesel engines with no aftertreatment devices contain a significantly higher proportion of BC than other sources, and less of the sulfate which causes atmospheric cooling. On the other hand, diesel particles emitted from ships could potentially contain a large amount of sulfate apart from the BC owing to the high sulfur contents of marine fuels. This creates certain challenges when adopting BC measuring techniques that are currently used for BC detection in vehicular emissions directly to ship emission applications.

International shipping contributes approximately 2% of global black carbon emissions, and 9% of overall diesel BC emissions, with one-third of those emissions occurring north of 40 degrees latitude. Under a high growth scenario, future Arctic BC emissions from international shipping are expected to grow five-fold through 2050[3], while emissions from land-based sources are expected to fall as controls are enacted, increasing the relative importance of shipping. Controls to reduce black carbon emissions from vessels operating in the Arctic by 70 percent in 2030 would reduce Arctic warming from all marine short-lived forcers by 30%.[4]

The maritime sector faces unique challenges in controlling black carbon emissions. Although stricter requirements apply in certain regions, marine vessels typically operate on low quality "bunker" fuels that currently average 27,000 ppm sulfur, inhibiting the adoption of advanced pollution control equipment used to control diesel emissions in other sectors. Lacking additional controls, it is estimated that global BC emissions from marine vessels may more than quintuple from 2004 to 2050, to a total of more than 744,000 tons BC, due to increased shipping demand, with a growing share emitted within the Arctic due to vessel diversion. Despite progress in some areas, best practices for PM/BC control from marine sources are slow to develop. Key barriers to progress include: poor data on baseline emissions and resulting health and climate impacts at local, regional and global scales; lack of a comprehensive assessment of control technologies and measures, especially for ocean going vessels; and poor capacity for policy implementation,

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[1] For further information on the CCAC please see http://www.unep.org/ccac
[2] For further information on the ICCT please see http://www.theicct.org
[3] Corbett, J., Lack, D., & Winebrake, J. (2010). Arctic shipping emissions inventories and future scenarios. Atmospheric Chemistry and Physics, (10), 9689–9704. Retrieved from http://atmos-chem-phys.net/10/9689/2010/acp-10-9689-2010
[4] 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.

particularly at emerging ports which is compounded by overlapping, fragmented and sometimes conflicting jurisdiction hindering coordinated policy making.

The overall objective of this project is to address two areas – ports and marine vessels– where there is significant need and opportunity for improved climate and health benefits through major black carbon reductions. The ports component of this project is being led by UNEP on a parallel track and is not discussed further here. The objective of the marine component is to directly address barriers to progress through a series of activities that will develop, compile, and share information, provide real-world testing of emissions controls on in-use marine vessels, and train stakeholders. The end result will be a major contribution to policy-relevant knowledge supporting emission controls across multiple venues. The CCAC, with a mix of committed state and expert non-state partners, offers an ideal venue to coordinate the project.

More research in particular is needed to characterize the marine BC inventory and mitigation potential in order to enable local, domestic, and international control measures. IMO's Correspondence Group on black carbon recommended a discussion for a BC measurement campaign to assess test methods on a selection of ships or new ship engines.[5] A core element of the maritime activity is real world ship testing to characterize baseline emissions and to identify best available control technologies (BACT) for marine BC. This testing should build upon existing research by groups such as Environment Canada, the California Air Resources Board (CARB), Japan, and other CCAC member countries and stakeholders to avoid duplication of effort and to leverage maximum resource and expertise. The testing will aim to fill identified research gaps to compile the best available information on marine emissions, performance, and economics of emission control technologies to inform policy discussions across multiple venues. The project will provide information and knowledge for CCAC Member Countries to support action at the IMO related to marine Black Carbon.

The goal of this workshop – the first of three under the CCAC project – was to address and set-up a series of research tasks, including the creation of a technology performance database for BC emissions control in the marine sector and a global black carbon inventory for international shipping. Proper measurement of BC is key to both of these. The format is as a structured dialogue among experts from a range of countries who have worked on BC measurement, inventories, control strategies, and policy. The workshop will

1. Review the state of the knowledge on marine black carbon including measurement, inventories, technology demonstration and testing;
2. Identify knowledge gaps to develop an improved marine BC inventory and a technology database of mitigation options; and
3. Develop a blueprint for addressing those gaps.

II. Workshop format

The workshop was divided into seven sessions with the intent of providing expert overviews and subject matter presentations covering the range of BC topics. Each session was assigned a facilitator to lead the discussion following the expert presentations. The topics and goals for each session are presented in Table 1 below.

[5] IMO Subcommittee on Pollution Prevention and Response. PPR 1/8 1 November 2013

Table 1. Workshop sessions and goals

Session	Session goal
1) Background and institutional overview	*Provide a general overview of the BC policy landscape and related international forums.*
2) Black carbon definition and measurement approaches	*Determine a working definition of black carbon, along with acceptable measurement methods, for aligned research.*
3) Marine black carbon inventories	*Identify specific elements that require investigation or refinement to produce a more accurate global BC inventory for the marine sector.*
4) Control strategies	*Prioritize control strategies for emissions testing within this project.*
5) Emissions Field Test Examples	*Survey existing research to identify emissions testing gaps*
6) Future Research	*Identify areas of focus for CCAC emissions testing*
7) Next steps	*Outline CCAC Marine Initiative work plan and next steps*

The complete agenda, along with a full participant list, is included in Appendix A. The following sections walk through the main agenda topics and summarize major discussion points and outcomes.

III. Session outcomes

A. Definition and Measurement

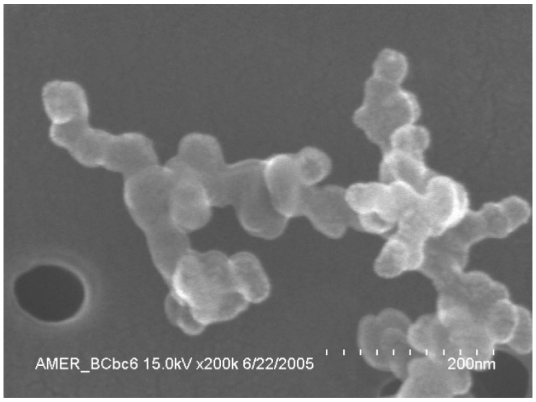
A major goal for the workshop was to determine a definition for black carbon for scientific research purposes supporting this project, informed by presentations from established experts in the field as well as larger group discussion. Session presentations framing the discussion provided background information on technical definition and measurement for research, black carbon morphology, origin, and climate impact, among other topics.

Light absorbing aerosols include not only black carbon but brown carbon and mineral dust as well. Definition and measurement is complicated by the fact that BC is not a single molecule and can include a range of double carbon bonds impacting light absorption. Black carbon has the lowest albedo of these three constituents, meaning that it scatters or reflects the least amount of incident optical light, retaining the most energy and heat. This absorption has the highest impact for areas where the natural surface is white or light colored (i.e. clouds, sand, snow and ice), which is why emissions of BC have a proportionally larger impact on Arctic environments.

To implement effective BC reduction, three overarching goals were proposed 1) A “first principle” definition; 2) Simple, robust and inexpensive implementation based on the definition; and 3) implementation for definition and measurement that is applicable to emissions, ambient, and deposited BC.[6]

[6] Lack, D., H. Moosmüller, G. R. McMeeking, R. K. Chakrabarty, and D. Baumgardner (2014). Characterizing Elemental, Equivalent Black, and Refractory Black Carbon Aerosol Particles: A Review of Techniques, Their Limitations and Uncertainties. *Anal. Bioanal. Chem.*, **406**, 99-122.

Views were exchanged on an appropriate general, operational, and finally measurement specific definitions. As a general definition, BC is a "distinct type of carbonaceous material that is formed primarily in flames, is directly emitted to the atmosphere, and has a unique combination of physical properties".[7]



These physical properties can be used to measure subtly different things. Each of these properties requires different measurement techniques and are associated with a different sub-definition of the relative component of black carbon that is being measured. Physical properties that can be leveraged for measurement purposes include.

1. It strongly absorbs visible light, with a MAC value above 5 $m^2 g^{-1}$ at a wavelength λ = 550 nm for freshly produced particles
   ➔ Methods for measuring this property use **Light Absorption**
2. It is refractory, with a volatilization temperature near 4000 K
   ➔ Methods for measuring this property use **Laser-induced incandescence and Thermal-Optical Analysis**
3. It is insoluble in water, in organic solvents including methanol and acetone, and in the other components of the atmospheric aerosol
   ➔ Methods for measuring this property use **Gravimetric**
4. It consists of aggregates of small carbon spherules of < 10 nm to approximately 50 nm in diameter
   ➔ Methods for measuring this property use **Imaging**
5. It contains a high fraction of graphite-like sp2-bonded carbon atoms
   ➔ Methods for measuring this property use **Spectroscopy**

The results of these techniques provide black carbon measures based on different characteristic definitions. Light absorption methods (i.e. photoacoustic spectroscopy, Multi-Angle Absorption Photometry) measure equivalent black carbon (eBC), which is derived from the absorption measure and the application of a mass absorption coefficient. Incandescence methods (i.e. laser induced incandescence) measure refractory black carbon (rBC) and are based on data derived from the thermal stability of the carbon component. Thermal-optical methods (i.e. filter based methods) measure elemental carbon (EC) and rely on combined thermal and gas analytics based on a heated filter sample. Other methods that develop proxies for these physical definitions, for example the use of filter smoke number (FSN) to estimate eBC through changes in light reflectance, are also under consideration by IMO.

The extent to which these different components and techniques provide equivalent measures was considered. While there have been comparisons published exploring agreement between instruments, it is difficult to establish repeatable and reliable measures. For some comparisons there can be differences of as little as 10% however, there are also variations in orders of magnitude. Some of this variability depends on the sample approach, which can cause variation based on losses (diffusion, impaction), as well as agglomeration and evaporation/condensation. These sources of variability directed the conversation towards the need to understand proper calibration of the instruments, and to develop a better understanding of uncertainties including a

[7] 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

need to verify that instruments are being calibrated in a standardized way. These issues were discussed at length during the session and developed into recommendations for additional work.

There was general agreement on the definition of black carbon as defined by Bond et al. (2013), particularly as it defines the physical properties of black carbon. Two properties in particular were considered to be useful for measurement purposes:

(1) Black carbon strongly absorbs visible light, with a MAC value above 5 $m^2 g^{-1}$ at a wavelength λ = 550 nm for freshly produced particles;
(2) Black carbon is refractory, with a volatilization temperature near 4000 K;

Measurement based upon these properties would require the use of light absorption or thermal optical analysis, likely photoacoustic spectroscopy (PAS) or laser induced incandescence (LII) to measure equivalent black carbon (eBC) or refractory black carbon (rBC), respectively. The measurement of elemental carbon (EC) was also recommended using filter based techniques, however it was noted that all methods should use a common set of measurement calibrations and sample pretreatment protocols to facilitate comparison among results.

The applicability of filter smoke number (FSN) for BC measurement was discussed. Although different perspectives were expressed, in general FSN was not favored as a principal research method. The sensitivity of FSN at low BC concentration ranges was questioned, and some participants felt that work to calibrate FSN against black carbon mass concentration remained outstanding. This could have an implication in the future once effective mitigation has been put in place on ships. A commercial instrumentation manufacturer described the development of advanced FSN instruments with improved capabilities, including lower detection limits. The group agreed that the inclusion of FSN in research testing could benefit future development and provide a true assessment of the applicability of the technique for ship BC measurements moving forward.

The discussion regarding appropriate measurement technologies generally agreed that as a first step for measurement of black carbon, PAS and LII were appropriate methods for on-board measurements. Photoacoustic methods have a high dynamic range ($\sim 10^6$) when compared to filter-based methods, which makes their use more practical if large concentration changes are encountered. For LII, there is currently more than one commercial instrument available, with one requiring dilution while the other can be used for raw exhaust measurements. Thermal/optical analysis for elemental carbon was another technique used by many researchers. This method also requires certain degree of dilution and more than one thermal protocol is currently used in the community.

It was also suggested that a general discussion on technology performance is needed. Rather than selecting a specific instrument, parameters for performance of an instrument should be established and linked to the relevant characteristics of BC presented above. Any instrument meeting the desired qualifications and able to use the agreed sampling protocol should be accepted as a suitable tool for research. If multiple instruments can meet the developed requirements, relationships among different measurement responses from various instruments could be established. Whatever the optimal method, it should yield comparable results with current marine instrument measurements as well as other modes and should be applicable for ambient measures or, at the very least, yield results that can be compared with other instruments used for ambient and deposition measures.

Further discussion focused on the accuracy or precision needed for different instruments and approaches. Participants noted that accuracy is less important than precision (repeatability) for measurements as long as the inherent errors in the measurement are understood and accounted for. All measurements, including on-board and ambient type techniques, will have uncertainty and variability. While some variability can be avoided, some could be caused by the sensitivity of the exhaust conditions. Key issues identified by participants were: a) the reliability and repeatability of the measure; b) understanding the representativeness of the measure to the actual concentration; c) considering the entire measurement procedure not just the instrument; and d) a need for a calibration method that can be used to insure that measurements using the same instruments can be compared.

The use of a standard pretreatment protocol for sampling was recommended to improve measurement precision. This pre-treatment (i.e., heating and dilution) would allow a more precise measurement of BC by removing volatile organic fractions and preventing the condensation of gaseous species onto particles. This methodology would prevent gas phase reactions of sulfur dioxide with water forming sulfuric acid which then condenses on BC particles, conserving the black carbon component. By standardizing exhaust conditioning methodology, biases can be accounted for in the total measure allowing for the development of an understood, standardized correction factor. This pre-treatment can help address potential interference from sulfates and organics during filter-based methods measuring BC concentrations using optical properties.

Although the volatile components are responsible for some climate impacts of emissions, they are less well understood than the BC component, which makes up a large fraction of the particle mass. Additionally, the BC portion is the conservative tracer allowing longer timescale studies of emissions in the atmosphere and eventual deposition. The development of measurement protocols that narrowly target BC are needed to track changes in emissions over time, a key characteristic of a useful emissions inventory.

B. Black Carbon Inventory

Session 3 of the workshop investigated specific elements that require investigation or refinement to improve global marine BC inventories. It was noted that there have been several global inventories in the last decade, with the best estimate at about ~130 kt of emissions per year, but with significant variability on the order of plus or minus 60%. Shipping emissions within the Arctic have been estimated at ~1-2 kt annually, although the definition of "Arctic" varies and that variation influences the estimated in-Arctic contribution.

Key components of an emission inventory include emission factors (EF), activity data, and a methodology for determining spatial distribution. Outstanding uncertainties for each of these components were considered. For emission factors, these included: whether enough distinct emission factors have been measured (with sufficient repeatability) and which specific emission factors are needed (e.g. specific EFs by sulfur fuel content, operating speed, vessel age etc.) For ship activity data, differences in coverage between the various approaches exist, with some higher resolution regional inventories available but facing challenges with integration into global inventories. Finally, the value of greater temporal resolution was recognized given that BC has an atmospheric lifetime of only several weeks and climate models of increasing power and resolution are now available.
Ultimately, the following possible means of improving future inventories were considered:

1) The use of fuel, vessel type, load, and speed specific emission factors;
2) Consideration of the penetration of PM control measures to the market and their impact on BC emissions;
3) Use of a common set of activity and spatial pattern data across all marine pollutants;
4) Including vessel age distribution to refine the assessment of future mitigation potentials; and

5) Moving toward a comprehensive marine inventory including both international and national-coastal activity, recreational boats, fishing, port activities, and inland shipping.

Availability and use of automatic identification system (AIS) data for vessel activity has greatly increased the potential quality of global marine inventories. Advancements in technology and associated data quality are driving rapid improvements in resolving uncertainties about vessel activity. This improved understanding highlights the need for refined emissions factors that take into consideration variability in operational parameters such speed, load, and fuel which could effect BC emissions. Currently there is one widely used emissions factor for black carbon originating from and Bond et al (2004) landmark study of 0.34 g BC/kg fuel.[8] Many studies since have used the same or similar emission factor across all vessel types and activities. Based on more recent measures of black carbon emissions, considerable variability in emissions has been recorded for different vessel type, speeds and load conditions, adding uncertainty to previous inventories based on a single emissions factor.

The point was made that often inventories suffer from the need to have the exact correct number. However a continuation on that point echoed the sentiments from the discussion of BC instrumentation; that the more important aspect is whether the uncertainties in the numbers are known and reasonable and that the resulting inventories are comparable regionally as well as temporally. The most important element is being able to use inventories to assess changes over time and make sure that the calculations use representative and comparable emissions factors.

To address this need, it was recommended that a comprehensive review of published emission factors from marine engines be made to better understand the current body of knowledge and to identify gaps and sources of uncertainty. Five characteristics were identified as likely having the largest impact on BC emissions: vessel type, fuel type, speed, load, and age of the vessel. These uncertainties are particularly pronounced when comparing emission factors of vessels under open ocean transit versus near-shore activities such as port approach and maneuvering.

A concurrent exploration of vessel activity cycles was also suggested. This analysis would explore the common activity patterns of vessels based on type and fuel quality. A better understanding of where emissions occur and the activity level of different fleets could then be used to further refine emission inventories. This analysis would rely on AIS data and be particularly valuable for comparing areas where inventories have been calculated in relation to where vessel activity is heaviest.

C. Mitigation Technology and Testing

Over the course of two sessions, participants discussed current mitigation technology availability and the state of field-testing and commercial application. One of the major issues identified was the paucity of data on effectiveness of mitigation technology. The range of technologies discussed covered fuel efficiency, slow steaming, fuel treatment, fuel quality, alternative fuels and exhaust treatment. Various approaches are estimated to reduce marine BC emissions by 30% (fuel efficiency, slow steaming) up to 99% (filters and scrubbers). Few focused studies have been undertaken to determine how well these various approaches work, complicating the development of [policy?] recommendations As was the case for emission factors, detailed measurements of emissions using accurate technologies is a significant challenge.

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[8] Bond, T. C., Streets, D.G., Yarber, K. F., Nelson, S. M., Woo, J. and Klimont, Z. (2004) A technology-based global inventory of black and organic carbon emissions from combustion, J Geophys Res., 109, D14203, doi:10.1029/2003JD003697

To address this data gap a small but critical concentrated effort has produced preliminary technology comparisons that were presented, with a focus on measurement instrumentation and scrubber effectiveness over different load conditions. On board measurements to date have been complicated by large variations in vessel load and speed, making exhaust sampling and calibration of instruments more difficult. Access to vessel time and the need to alter sampling practices based on time constraints also impacted the ability to test multiple instruments repeatability. These variables could be addressed through coordinated efforts by several research groups to align both instrument and mitigation technology testing. Emphasis was placed on the need for uniform calibration and sampling protocol to ensure comparable measurements.

A number of control strategies were discussed for possible inclusion in the project. It was highlighted that the most effective control strategies may not yet be commercially viable and widely available, and may be applicable to only certain vessel and engine types. Fuel switching, scrubbers, and water in fuel emulsion were viewed as the most applicable, commercially viable technologies to control BC emissions. Slow steaming was also recognized as an important operational practice that may influence emissions. Diesel particulate filters (DPFs), which are recognized as BACT for diesel engines in other sectors, have to date been mostly been applied to marine auxiliary engines, with wider application to harbor craft expected given expanding access to low sulfur fuel in some ports.

While fuel switching from high to low sulfur fuel or to LNG have been shown to reduce particulate emissions, their effect on BC emissions is less well resolved. A scrubber is equally capable of reducing PM (and by extension BC) emissions however; field tests have shown wide variability in efficacy based on load and speed and the type of scrubber used. DPF application is limited by commercial availability and the requirement of low sulfur fuel. Water in fuel emulsion has shown reductions in PM as well and is a commercially available technology. A key point of discussion focused on the need to understand and accurately characterize the BC component of PM in emissions. As sulfur components in the PM emissions decrease (from fuel changes, scrubbers etc.) the relative fraction of BC will change. Emission factors deriving BC from total PM need to reflect this fact, as do inventories using proxies of rather than direct BC measurements.

The two approaches with the widest opportunities for on-board testing are likely fuel switching and scrubber application, changes in speed (slow steaming) may also provide opportunities for comparative BC emissions measures. A gap analysis for available testing data and conditions is needed to facilitate systematic future research. The impact of sampling approach on the emission measurements highlights the need to standardize protocols and reporting requirements to maximize utility and applicability of on-board measures.

Because on board measures are difficult, a test bench approach could facilitate multiple tests under control conditions to address known testing gaps. Limitations for this approach include the ability to test slow-speed 2-stroke engines similar to those available for on-board testing and the difficulty in resolving differences in emission factors between control conditions and at-sea operation. Bench testing would, however, facilitate comparisons between measurement instruments, fuels types, engine load, and sample pre-treatment approaches, all key to developing better sampling protocols and understanding variability in the measurements. Plume sampling was another option to better understand BC emissions concentrations in the atmosphere. Plume studies provide the ability to sample many vessel emissions in a short period of time, and could be related to vessel stack emissions but additional information such as engine load, or/and fuel usage as well as other meteorological conditions would be required.

Further discussion on these options are needed before a research plan can be finalized. One suggestion was for the formation of an ad-hoc expert group to explore options from a technical standpoint and to set testing priorities. This will be further addressed as an outcome of the workshop.

D Next Steps

The following next steps were identified by the participants:

[1] Gather and synthesize existing BC emission factor data and research

The workshop highlighted that the research that has been conducted on marine BC emission factors remains poorly integrated, particularly the research that remains unpublished. Several workshop participants have been independently pursuing research but a systematic review of past testing was needed. Better consolidation of information would facilitate a gap analysis to inform future research.

[2] Analyze vessel activity data (AIS) and fleet characteristics to check coverage of existing marine inventory work

Emission testing to date has occurred on a largely ad hoc basis subject to vessel availability. Once the existing emissions test data has been compiled and organized it will be necessary to compare it to ship activity data to identify major holes in terms of ship/engine types, operating conditions (i.e. engine load), fuel types etc. that likely contribute substantially to global BC inventories but have not yet been tested. Output from this review could inform choices for vessel testing such as vessel and engine type as well as operating conditions and locations.

[3] Exploration of diagnostics for BC measurement, including defining performance specification for measurement instruments and standardizing measurement protocols

Instruments for measuring black carbon are increasing in capability and diversity. A review of current instrument capabilities in comparison to desired capabilities is needed. A matrix of desired instrument characteristics, including elements like dynamic range and calibration, should be developed to aid future instrument development as well as refining currently available technologies. As a first step, existing instrument capabilities should be cross compared in a test-bench setting to evaluate inter-comparison of measurement results and to help determine appropriate sample pretreatment protocols to standardize measurement procedures across instruments. The output from this analysis could directly support future on-board testing.

[4] Discussion of relative research approaches: on-board vessel vs. engine test bench vs. plume studies

As a final step for recommended research, participants highlighted a variety of opportunities that could be used to test instrument capability, mitigation technologies, and emission factors. Engine test bench approaches are useful to provide a controlled environment to explore instrument capabilities over a variety of engine loads, fuel types and possibly mitigation technologies. They would also facilitate the exploration of sample pre-treatment approaches. On-board approaches are well-suited for understanding actual vessel emissions under typical operating conditions in the real world. These tests should be planned based on input from emission factor reviews, inventory gaps and desired instrumentation comparisons. Plume studies were also suggested as a means to gather data from a large number of ships within a short period of time. The feasibility of this approach to provide direct comparisons to lab work is limited.

[5] Development of a request for proposals (RFP) to support the identified next steps

One of the workshop goals was to develop a workplan that would facilitate the release of an RFP to support the CCAC work. Suggestions for a workplan that would include testing as well as collaborative efforts were made in an effort to ensure that the future work facilitates wide collaboration rather than being exclusive to a smaller group of researchers. As an RFP is developed offers for collaboration will be taken into consideration so that organizations with interests in BC measurement, mitigation, and inventories have an opportunity to contribute. Lastly, although the focus of this workshop was not on application of research directly to international policy forums, participants reaffirmed the importance of tracking progress on IMO's black carbon workplan to maximize the policy relevance of the research work funded by CCAC.

IV. Conclusions

In closing, a few overarching conclusions were highlighted, including suggestions on short-term research needs to address knowledge gaps.

There was general agreement that the definition of black carbon provided by Bond et al. (2013) – a "distinct type of carbonaceous material that is formed primarily in flames, is directly emitted to the atmosphere, and has a unique combination of physical properties" – was appropriate for marine black carbon. Two physical properties in particular were felt to be useful for measurement purposes:

1) Strongly absorbs visible light, with a MAC value above 5 $m^2 g^{-1}$ at a wavelength $\lambda = 550$ nm for freshly produced particles;
2) Refractory, with a volatilization temperature near 4000 K;

These properties would require the use of light absorption or thermal optical analysis including PAS and LII to characterize eBC or rBC, respectively. The measurement of EC was recommended using filter-based techniques given their use in previous work and general familiarity to researchers. It was noted that FSN was not favored as a preferred method; nonetheless, the inclusion of FSN in research testing was recommended as a means to assess the applicability of the technique and to address concerns about calibration vs. eBC mass. Further, it was noted that all methods should use a common set of measurement calibrations and sample pretreatment protocols to facilitate comparison among results.

A general discussion on technology performance is also needed. Rather than selecting a specific instrument, parameters for minimum performance should be established and linked to the characteristics of BC to be measured. Whatever measurement method applied, it should yield comparable results with current marine instruments measurements as well as other modes and should ideally be applicable for ambient measures or, at the very least, yield results that can be compared with different instruments used for measuring ambient concentrations and deposition rates.

Developing a standard sample pretreatment protocol for emissions testing was discussed extensively given the recognized shortcomings of ISO 8178. Sample heating and dilution to remove volatile fractions and prevent the condensation of gaseous species onto particles was recognized as a needed protocol for a more precise measurement of BC. Although the volatile components are associated with climate implications of emissions, they are less well understood than the BC component, which makes up a large fraction of the particle mass. Additionally, the BC portion was recognized as a conservative tracer allowing longer timescale studies of emissions in the atmosphere and eventual deposition.

Participants highlighted key components of an emission inventory to include emission factors (EF), activity data, and a methodology for determining spatial distribution. Outstanding uncertainties for each of these components were discussed. The development of measurement protocols that narrowly target BC are needed to track changes in emissions over time, a key characteristic of a useful emissions inventory. To address this need, it was recommended that the project include a comprehensive review of existing data on emission factors from marine engines to determine the current body of knowledge to identify gaps and sources of uncertainty.

With respect to needed vessel engine testing, fuel switching and scrubbers were viewed as the two approaches with the widest opportunities for on-board testing. Additionally, changes in speed may also provide opportunities for comparative BC emissions measures. A gap analysis to better understand available testing data and the conditions and uncertainties inherent in the measurements was recommended. Because on board measures are difficult and expensive (~50k/test), complementary test bench approaches that would facilitate a number of tests under controlled conditions should also be considered.

Workshop participants supported the formation of an ad-hoc expert group to explore technical options and to set testing priorities. As ICCT progresses toward an RFP these suggestions as well as offers for collaboration will be taken into consideration to provide an opportunity for the groups interested in BC instrumentation, mitigation, and inventories have an opportunity to contribute. Those partners most interested in specific elements of the workplan will be approached for participation in focused discussions and as participants for upcoming workshops to facilitate additional expert exchange.

Lastly, it was generally agreed that outcomes from the research and the workshop should be shared widely among CCAC partner countries and other countries engaged in larger policy discussions in the IMO and Arctic Council to facilitate informed policy discussions and decisions. This would also ensure that future research remains policy relevant and applicable outside the research community.

Appendix A: Agenda and participants list

Day 1

8:30 – 8:45 am	**Welcome and Introduction –** Steve McCauley, Environment Canada
8:45 – 9:00 am	**Workshop Overview and Goals –** Dan Rutherford, International Council on Clean Transportation (ICCT)
9:00 – 10:30am	**Session 1 – Background and institutional overview** *Overall policy landscape* – Michael Geller, US EPA *IMO activities related to marine black carbon* – Jeffrey Smith, Transport Canada *Arctic Council work on SLCP – France* Jacovella & Rebecca Plumadore, Environment Canada *Introduction to CCAC marine diesel initiative* – Alyson Azzara, ICCT
10:30 – 10:45 am	**Coffee Break**
10:45 – 12:30 pm	**Session 2 – Black carbon definition and measurement approaches** **Objective: Develop a common research framework to address measurement of black carbon for research approach** *Background/overview/facilitation* – Hans Moosmüller, Desert Research Institute *Existing definitions of black carbon* – Dan Lack, Independent Consultant (formerly NOAA) *Measurement techniques and considerations* - Greg Smallwood, NRC Canada *Commercial Instrumentation options* – Monica Tutuianu, AVL *Practicability of sample preparation (dilution process) for on-board measurements* – Kazuyuki Maeda, National Fisheries University
12:35-12:55 pm	**Guided tour of the River Road testing facility**
12:30 – 1:30 pm	**Lunch**
1:30 – 3:15 pm	**Session 3 – Existing research for marine black carbon inventories** **Objective: Identify specific elements that require investigation or refinement to produce a more accurate global BC inventory** *Background/overview/facilitation* – Zig Klimont, IIASA *BC inventory map around Arctic sea, based on satellite AIS and updated Emission factors*– Shinichi Hanayama, OPRF *Emission inventory for ships based on aggregated AIS data* - Morten Winther, Aarhus University *Current global inventory capabilities and uncertainties using AIS* - Kjetil Martinsen, DNV
3:15 – 3:30 pm	**Coffee Break**
3:30 – 5:00 p.m.	**Session 4 – Control strategies** **Objective: Identify control strategies recommended for inclusion in emissions testing within this project** *Background/overview/facilitation* – Dan Lack, Independent Consultant (formerly NOAA) *Industry use of control strategies* - Tom Kirk, American Bureau of Shipping (ABS) *Diesel particulate filter experience on marine engines* - Joe Kubsh, Manufacturers of Emission Controls Association (MECA)
7:30 p.m.	**Dinner at the Empire Grill**

Day 2

9:00 – 9:15	**Recap from Day 1** – Outstanding issues, questions, or loose ends
9:15 – 10:30	**Session 5 – Emissions Testing** **Objective: Identify specific emissions testing gaps that could be addressed through this initiative.** *Background/overview/facilitation* – Greg Rideout, Environment Canada *Environment Canada testing work* – Tak Chan, Environment Canada *Emissions testing project for ARB/ICCT* – Kent Johnson, University of California, Riverside *Measurements of emissions of particulate matter: particle number, particle mass and its constituents*– Jana Moldanová, Swedish Environmental Research Institute
10:30 – 10:45 am	**Coffee Break**
10:45 – 12:30 pm	**Session 6 – Future Research** **Objective: Identify areas of focus for CCAC emissions testing** *Background/overview/facilitation* – Kevin Thomson, NRC Canada *Planned Air Resources Board future work* – Ryan Huft, Air Resources Board, California *On-board opportunities for testing* – Canada Steamship Lines (CSL)
12:30 – 1:30 pm	**Lunch**
1:30 – 4:00 pm	**Session 7- Outcome: Preliminary blueprint for future testing, including relative roles/responsibilities and areas of CCAC focus** **Objective: Outline CCAC Marine Initiative work plan and next steps.** *Background/overview/facilitation* – Dan Rutherford, ICCT
4:00 p.m.	**Adjourn**

List of Participants

Alyson Azzara, International Council on Clean Transportation (ICCT)
Amir Aliabadi, Environment Canada
Brett Taylor, Environment Canada
Pascal Bellavance, Environment Canada
Carrie Taylor, Environment Canada
Carrie Taylor, Environment Canada
Daniel Lack, Formerly, Independent Consultant (formerly NOAA)
Daniel Rutherford, International Council on Clean Transportation (ICCT)
Emily West, Environment Canada
France Jacovella, Environment Canada
Greg Rideout, Environment Canada
Greg Smallwood, National Research Council, Canada
Hans Moosmuller, Desert Research Institute
Jana Moldanova, Swedish Environmental Research Institute
Jeffrey Smith, Transport Canada
Joseph Kubsh, Manufacturers of Emission Controls Association (MECA)
Katherine Palmer, Lloyds Register
Kazuyuki Maeda, National Fisheries University, Japan
Kent Johnson, University of California, Riverside
Kevin Thompson, National Research Council, Canada
Kjetel Martinsen, Det Norske Veritas (DNV)
Lynn Lyons, Environment Canada
Mark McCurdy, Environment Canada
Michael Geller, U.S. Environmental Protection Agency (EPA)
Monica Tutuianu, AVL
Morten Winther, Aarhaus University
Paul Izbedski, Environment Canada
Paul Mudroch, Transport Canada
Paul Topping, Transport Canada
Rebecca Plumadore. Environment Canada
Ryan Huft, Air Resources Board
Scott Mckibbon, Environment Canada
Shinichi Hanayama, Ocean Policy Research Foundation (OPRF)
Sonja Henneman Environment Canada
Steve McCauley, Environment Canada
Tak Chan, Environment Canada
Thomas Kirk, American Bureau of Shipping (ABS)
Trisha Bergmann, U.S. National Oceanic and Atmospheric Administration (NOAA)
Zbigniew (Zig) Klimont - International Institute for Applied Systems Analysis (IIASA)