The Impacts of Arctic Shipping Operations on Black Carbon Emissions

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Dr Daniel Lack is a atmospheric physicist and chemist with 16 years of experience in the academic and consulting areas of climate science. During a ten-year career at the US National Oceanic and Atmospheric Administration (NOAA) laboratories in Colorado Dr Lack established expertise in the measurement and impacts of black carbon from biomass burning and transport sources. Dr Lack's speciality in the measurement of the particle emissions from commercial ships has lead to established collaborations with local, regional, national and global legislators on ship emission policy. He is now an independent consultant specialising in the measurement and climate impact assessment of transport emissions.

Cover Picture: Ships at Spitsbergen, Svalbard. Photo by Hannes Grobe via Wikipedia

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Introduction

As ship navigation in the Arctic becomes more accessible due to ice melt, direct emissions of atmospheric pollution will increase. It is expected that trans-Arctic travel, which will replace longer routes such as the Asia to Europe route via the Suez Canal, total emissions of CO_2 will decrease due to less fuel consumption across the shorter routes. However direct emissions of Black Carbon (BC) in the Arctic will increase and exert a climate forcing locally.

Ship operations in the Arctic will vary significantly due to rapid shifts in weather, the loss of ice, relatively shallow route depths contributing to rougher seas, and the dangers of sea ice slowing vessel speeds (Humbart and Raspotnik 2012). This variability is in contrast to open ocean operation of large vessels that can operate at optimum speeds for the majority of a trans-oceanic voyage. The variability of ship operating conditions lead to variations in fuel consumption and atmospheric emissions. This report assesses the variability in the emissions of BC from ships operating in the Arctic. The emissions from ships operating heavy fuel oil (HFO) at varying speeds is also investigated.

An iceberg at the Ilulissat Fjord, Greenland. Photo credit: Dmitry Yumashev

Ship propulsion in open waters

Due to vessel resistance in water, fuel consumption and emissions increase exponentially (3rd power) with increased speed.
Slow steaming operations can decrease fuel consumption considerably.

For BC emissions to decline with this decreased fuel consumption, engines must be de-rated or re-tuned to the lower engine load.

Ship speed is determined by many factors including hull friction, water viscosity, speed, displacement, hull form, bow wave formation, eddy resistance, air resistance, wave conditions, wind etc. (MAN 2004). In an ideal environment, where just the vessel and water are at play, speed is proportional to engine load (power) to the third power (MAN 2004). This cubic function is the main determinant of the fuel consumption at various vessel speeds and contributes to the fuel savings associated with “slow steaming”, where vessels are run at loads well below maximum. For example, the Maersk line operated their fleet at an average load of 60% prior to 2007 and, following the implementation of a slow steaming policy, an average load of 35% as of 2010 (Lack and Corbett 2012). According to the fuel consumption curve this reduces fuel consumption, and most emissions by 25%.

Ship engines are tuned to the expected engine load for maximum efficiency (American-Bureau-of-Shipping 2001). Under these conditions engines consume the least amount of fuel for each unit of work, and likewise produce the least amount of BC emissions. When engines operate outside of the tuned engine load without retuning, fuel efficiency often decreases and emissions (including BC) increase due to less than ideal combustion. These conditions may be transient load reductions for speed limitations, navigation or maneuvering, or longer-term speed reductions for fuel efficiency or scheduling purposes. Engines can be re-tuned for different loads (Wettstein and Brown 2008); while some advanced engines with electronic controlled fuel systems may be able to modify combustion settings, per cylinder, essentially tuning during operational changes to better approximate best performance conditions.

Ship propulsion in Arctic waters

Ships operating in the Arctic Ocean will encounter conditions that lead to less efficient propulsion and include the presence of sea ice (for many decades to come), wave height, visibility, route depth and weather.

The Arctic Ocean will provide sailing conditions that may regularly lead to less efficient propulsion and excursions from ideal engine load. The most obvious of these conditions is sea ice within the shipping route that, for some parts of the year, may be sparse yet pose a danger to shipping, or yet may need to be cleared by dedicated ice-breakers. Depending on the class of ship, speed reductions will be necessary for safety. McCallum (1996) showed that ships in the Arctic are speed limited by ice conditions and ship construction and formulated an index of safe Arctic travel speeds within varying ice conditions. The ice decision numeral (IDN) is a number that scales from 0–20 where an IDN of 0 indicates very thick ice where no travel is possible, while an IDN of 20 indicates very limited ice where open water travel is possible (Timco et al. 2005). Ship construction also dictates the conditions of travel of a ship, with seven "polar classifications" of ship operation dictating their construction and other aspects of safety. The IMO has produced guidelines for polar operations (IMO 2010) and recently a guidance system for assessing risk of ships during polar operations (POLARIS) (IMO 2016). This system incorporates experience within Canadian (which includes the IDN system) and Russian waters, polar shipping classifications, icebreaker escort and changing ice conditions. Risk Index Values (RIV) for different polar ship classes, and ice conditions guide ship operators in voyage planning including whether normal operations are possible, and if not whether reduced safe speeds can be adopted, or whether travel is possible at all (IMO 2016).

Other factors that may dictate ship operation in the Arctic are the variability in sailing conditions determined by the relatively shallow ocean along the likely sailing routes, and loss of ice leading to an expected increase in wave heights (Khon et al. 2014). High winds, visibility, other adverse weather conditions and voyage planning requirements will also affect engine load and transit speeds.

Emissions with engine load

Most experimental evidence suggests that ships using HFO produce 2, 3 and 5 times more BC (per kg fuel used) at 50%, 25% and 10% engine loads compared to 100% engine load.

Some studies suggest that higher quality fuels, compared to HFO, produce less BC at low engine loads.

Engines that use HFO are tuned for optimum combustion at the loads most likely to be encountered. This tuning optimises cylinder pressures and timing so the HFO can burn as efficiently as possible. The complexity of the hydrocarbons in the HFO mean a slower burning time results (American-Bureau-of-Shipping 2001) and so engine tuning is essential to an efficient operation (Wettstein and Brown 2008). When these engines are operated outside of the tuned conditions inefficiencies result and fuel consumption increases as does BC emissions.

Lack et al. (2008), Lack and Corbett (2012) and Buffaloe et al. (2014) reported on 100s of BC emissions factors from slow speed diesel engine ships and reviewed the literature for BC emission experiments. These reviews showed significant variability, highlighting the difficulty in separating the many variables that contribute to combustion emissions from ship engines. However, when the results for measurement of emissions from HFO are collated a trend of increasing BC emissions with decreasing load is apparent (see Figure 1). This relationship is extracted from over 40 studies and over 200 hundred individual measurements. More recent studies continue to show the increase in BC emissions with decreasing load (Acevedo and Mantilla 2011, Robinson et al. 2015, Streibel et al. 2016).

Utilising the BC emissions trend observed in Figure 1 Lack and Corbett (2012) was able to show that the Maersk slow steaming operations (discussed above), could have led to a 20% drop in BC emissions if all of the vessels were de-rated/re-tuned. If no vessels were de-rated/re-tuned BC emissions could have increased by 7% despite significant fuel savings.

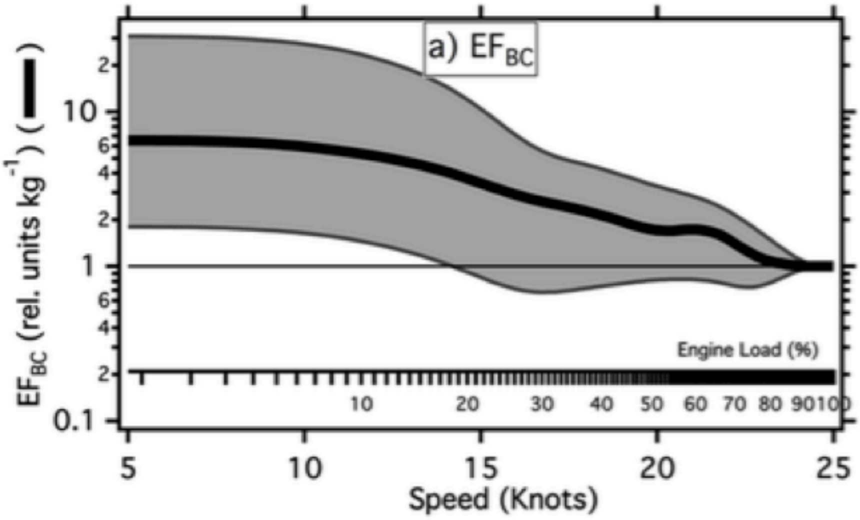

Figure 1: Emissions of Black Carbon as a function of engine load (and speed) for Slow Speed Diesel Engines. Reproduced from Lack and Corbett (2012)

There are some studies, particularly those involving distillate and medium speed diesel engines, that show a relatively flat response of BC emissions (or an increase) with engine load. In a recent study Streibel et al. (2016) showed an increase in BC with reduced loads for HFO, while showing the opposite trend for distillate fuel. This study was not on a SSD engine. This may suggest that operations at low loads on distillate will have an improved BC emissions profile compared to HFO.

Arctic operations and relative emissions of BC

Ships operating in the Arctic will experience highly variable engine loads, due to variable ice conditions, until at least 2050. Without consideration for engine de-rating or re-tuning BC emissions may be up to 3 times larger than baseline.

Studies making assessments of current and future Arctic shipping include sea ice extent, wave height, visibility, and other environmental factors to adjust fuel consumption to the changes in load that will be experienced (e.g. Eide et al. 2010, Peters et al. 2011, Smith and Stephenson 2013, Fuglestvedt et al. 2014, Melia et al. 2016). These studies suggest that it is unlikely that any Arctic transit of non-ice classed ships will operate at high speed and engine loads until 2050. Whether these vessels will be tuned for the variable conditions is uncertain, however these conditions will reduce the potential time savings and increase build and operational costs. The Maersk example (Lack and Corbett 2012) shows that BC emissions could increase at low load operation despite significant reductions in fuel consumption.

Lack and Corbett (2012) were able to estimate that Arctic ships would operate for most of the year at loads between 10 and 40% leading to BC emissions 30 to 100% larger than expected for full load operations. These loads and emissions are based primary on ice conditions encountered.

Eide et al. (2010) predicted the range of speeds across the Arctic in 2030 for an Arctic-class cargo vessel and estimated that loads of around 75 would be possible for almost all of an Arctic transit through the NSR, resulting in 25 – 30% higher BC emissions, if optimal tuning is not carried out. Polar and NWP transits for the same vessel would span loads from approximately 10–100% with the lower load range required for approximately 20–50% of the distance of the transit resulting in two to three times as much BC emitted. This estimate was for a PC4 ice-class vessel that is designed for summer ice conditions that can operate in normal routes the rest of the year. Eide et al. (2010) indicate that these vessels have a 30% higher building cost and 50% higher operational cost.

Smith and Stephenson (2013) modeled Arctic sea ice conditions out to 2050 and found that for the month of minimum sea ice extent (September) only the NSR would be capable of trans-Arctic ice-free shipping using non-ice-strengthened vessels. The study found that the NSR and trans-polar routes would still require ice-classed vessels resulting in variable load conditions.

For vessels that are not rated for the conditions of the Arctic there is the possibility of being escorted by ice breaking vessels. Russia has already provided escorts to commercial vessels along the NSR and is planning to continue this activity (Micallef 2016). This of course will increase the total fuel consumption for a transit (except where the nuclear powered ice breakers are used) as well as expose inappropriately non-ice-class vessels to adverse conditions.

It is apparent from the available data that ships currently operating in the Arctic, and operations well into the future will have highly variable engine load profiles and require specialised ice-class vessels due to ice and weather conditions and safety. With this variability it may not be viable to have a vessel de-rated/re-tuned to optimise engine load, fuel consumption and emissions during a voyage. If engine load profiles are indeed so variable, predicting the additional emissions of BC emissions is difficult for Arctic operations, particularly if engine de-rating technology is introduced in time. It is apparent however that BC emissions in the Arctic will be dependent on the speed and engine load, fuel type and whether the engines can be optimally tuned or de-rated for the variable loads encountered. As the Maersk example shows, no consideration for engine operational characteristics can increase BC emissions by almost 30% under ideal sailing conditions. In a highly variable Arctic, where absolute engine loads may fluctuate widely and more often than in the open ocean, BC emissions will increase beyond this 30% value.

Photo: Brooks Range in Northern Alaska showing black carbon aerosol

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