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Review

Reducing black carbon emissions from Arctic shipping: Solutions and policy implications

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ABSTRACT

As the most efficient atmospheric particulate matter to absorb visible light among shipping air pollutants, black carbon (BC) can significantly affect the Arctic climate because of its strong effect on reducing snow albedo. Thus, mitigation efforts to curb BC emissions from Arctic shipping have elicited considerable research interest. In this study, we revisit potential technical and operational solutions to reduce BC emission from shipping. Possible barriers to the main solutions that are applicable to Arctic shipping are discussed. We argue that Arctic shipping, which operates in a sensitive region with complicated navigational conditions, can affect the practical performance of BC abatement solutions. On the basis of a comprehensive analysis, this study mainly recommends that 1) combinations of technical and operational solutions are encouraged, but empirical studies are needed to test the effectiveness of those abatement technologies in the Arctic; 2) given the potential costs and average robust BC reduction performance, the switch from heavy fuel oil to distillate fuels should be prioritized for adoption by shipowners; 3) low impact and fuel efficient fishing needs to be introduced for fishing vessels, which are the largest fleet in the Arctic, to improve fishing practices and gears; and 4) regional actions and global cooperation are imperative for the governance of Arctic shipping.

Contents

1. Introduction

In the 21st century, the rate of warming is expected to increase rapidly, leading to the loss of sea ice, the recession of ice shelves, and even the melting of the entire Arctic ice sheet (Zhang et al.,

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2015). Dwindling sea ice is making the Arctic Ocean more easily available to increased shipping activities. For example, in 2014, Arctic shipping accounted for over 9% of global shipping traffic flows (Eguíluz et al., 2016). Shipping through the Arctic Ocean could obviously reduce the sailing distance from Asia to Europe compared to the traditional route via the Suez Canal; therefore, it has potential economic competitiveness (Liu and Kronbak, 2010). An estimated 4.7% of the world's future shipping trade could be rerouted through the trans-Arctic routes by 2030 (Bekkers et al., 2016). However, ocean shipping heavily depends on fossil fuels (Wan et al., 2018a), more specifically, on heavy fuel oil (HFO), the combustion of which is highly polluting and thereby results in high emissions of sulphur oxides (SO_x), heavy metals, volatile organic compounds, and black carbon (BC) particles (Transport and Environment, 2018a). At present, HFO is the most used marine fuel in the Arctic (International Council on Clean Transportation (ICCT), 2017a). Among the air pollutants emitted from Arctic shipping, BC accounts for a relatively small proportion of emission amounts (Peters et al., 2011); however, BC has been proven to be a carbonaceous material with unique physical properties (Bond et al., 2013), which can significantly influence snow and ice albedo and further accelerate Arctic sea ice melt (Arctic Council, 2009).

The impacts of BC emissions in the Arctic have been well documented (McConnell et al., 2007; Arctic Monitoring and Assessment Programme (AMAP), 2011; Sand et al., 2013). As one of the most critical local sources of BC emissions in the Arctic area, Arctic shipping has elicited increasing interest not only from the academic domain but also from the international shipping regulator (i.e., the International Maritime Organization, IMO). The subcommittee on Pollution Prevention and Response (PPR) of the IMO's Marine Environment Protection Committee (MEPC) was given the task in 2011 to determine the definition, measurement, and control measures of marine BC emissions. Recently, at MEPC's 73rd session in October 2018, the IMO agreed that a ban should be developed by PPR on HFO for consumption and carriage by ships as marine fuel in Arctic waters based on an appropriate impact assessment (MEPC, 2018). Such a potential ban will undoubtedly facilitate the reduction of BC emissions from Arctic shipping. Lack (2017) showed that a switch from HFO to distillate fuels can contribute to an average BC reduction of 33%. However, reviewing the possible solutions to the abatement of BC emissions from Arctic shipping is indispensable due to the uncertainty of the time of the official promulgation and implementation of an Arctic HFO ban and the necessity of controlling BC emissions by comprehensive means. More specifically, it will probably take a long time before an Arctic HFO ban is effective. In the domain of international maritime governance, because of the requirements for the minimum number of signatory states and the minimum proportion of the world's shipping tonnage, international conventions usually require a decades-long crawl to global consensus and final implementation (Wan et al., 2016a). For example, the IMO adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments in 2004, and the treaty came into force in September 2017. The switch from HFO to distillate fuels generally means higher operational costs for shipowners, and therefore, the official promulgation and implementation time of an Arctic HFO ban will, to a great extent, affect shipowners' economic behavior. Compared with the fuel switch, they would take low-cost abatement measures to control BC emissions from Arctic shipping. Consequently, in addition to the switch from HFO to distillate fuels, other abatement solutions and their BC reduction performance should be reviewed, which can help policy and decision makers to more reasonably and effectively address related issues of controlling shipping BC emissions in the Arctic.

The present study focuses on technical and operational abatement solutions to shipping BC emissions and the potential barriers to the principal solutions that are applicable to Arctic shipping, based on the existing relevant studies. The major contributions of this study are three-fold. First, we identify a unique characteristic of Arctic shipping activities, which is closely related to BC emissions in the Arctic. Second, we present potential BC mitigation from the various technical and operational solutions and articulate demonstrated application barriers to several BC reduction solutions for Arctic shipping based on previous studies; some conflicting scientific perspectives are also presented. Third, several policy implications are elaborated for reaching the goal of reducing shipping BC emissions in the Arctic, which captures the originality of our research.

The current paper is organized as follows. The estimated BC emissions from Arctic shipping and recent developments in Arctic shipping are presented in Section 2. Section 3 discusses an array of technical and operational abatement solutions and their potential limitations in the Arctic. Three policy implications are consequently developed in Section 4. The final section concludes the paper.

2. BC emissions from Arctic shipping

With the development of ships' data collection, a bottom-up vessel activity-based estimation approach has been developed and widely adopted to estimate ship emissions to the Arctic atmosphere. The Arctic Marine Shipping Assessment (AMSA) report conducted by the Arctic Council (2009) developed the world's first shipping activity-based estimate of air emissions from ships in the Arctic using empirical shipping data reported by its member states. The report showed that approximately 1,180 metric tons of BC were emitted from ships in the Arctic region in 2004, representing a relatively small part of the estimated 71–160 kilotons released from the entire global fleet annually. A recent study by ICCT (2017b) estimated that global shipping BC emissions ranged from 53 to 80 kilotons in 2015, with a best trimmed estimate of approximately 67 kilotons, and further reported that approximately 1% of global shipping BC emissions were released from ships at 60°N latitude and above, and 11% of shipping BC emissions were emitted within the Arctic front (40°N latitude and above). Due to different definitions of the Arctic region, shipping data resources, BC emission factors, and business scenarios, the estimated BC emissions vary in the main existing studies (Table 1). Nevertheless, a widespread consensus claims that even a small amount of BC can still disproportionately affect Arctic ice melt and warming and that shipping BC emissions can continuously rise due to increased Arctic shipping activities.

With respect to Arctic shipping, four basic modes of Arctic marine transport are identified by the Arctic Council (2009): destination transport (i.e., the Arctic is taken as the final destination of a voyage), intra-Arctic transport (i.e., voyages that are limited to the generally geographical Arctic region), trans-Arctic transport (i.e., voyages that are conducted across the Arctic Ocean), and cabotage (i.e., voyages, between ports of an Arctic State, which are undertaken in domestic coastal waters). Among these modes, trans-Arctic transport has gained the greatest interest from the international shipping industry because shipping shortcuts through the Arctic ron reduce the sailing distances between the world's main trading regions (i.e., East Asia and Western Europe) with the potential for energy cost savings and a reduction in transportation time. Specifically, there are three Arctic shipping shortcuts: the Northern Sea Route (NSR), the Northwest Passage (NWP), and the potential Transpolar Sea Route (TSR) in the future (Wan et al., 2018b). Compared with the NSR, the NWP faces additional navigational obstacles, such as thick ice conditions and adverse weather conditions (Haas and Howell, 2015). The less harsh

Table 1
Estimated BC emissions from Arctic shipping in main existing studies.

Estimated BC emissions (metric tons/year)	Geographical scope adopted	Shipping activity data resource	Emission factor (g/kg fuel)	Reference
1,180 (Year 2004)	The Arctic is defined according to the internal policies among Arctic Council member states, including sub-Arctic areas	AMSA database	Not mentioned	Arctic Council (2009)
880 (Year 2004) Year / *Business-as-usual (BAU) scenario* / *High-growth scenario* 2020 / 1,200 / 1,500 2030 / 1,500 / 2,000 2050 / 2,700 / 4,700	The same Arctic area covered in Arctic Council (2009)	AMSA shipping database (Note: Fishing vessels are not considered in this research)	0.35	Corbett et al. (2010a)
1,151 (Year 2004) 2,160 (Year 2030) 2,960 (Year 2050)	Extended version of the AMAP's Arctic definition	A combination of the Comprehensive Ocean Atmosphere Data Set and the Automated Mutual Assistance Vessel Rescue System data	0.35	Peters et al. (2011)
52.3 (Year 2012)	IMO Arctic (as defined in the Polar Code)	Automatic Identification System (AIS) data and DNV ship database	0.18	Det Norske Veritas (2013)
1,585 (Year 2012) 1,615 (Year 2020) 1,656 (Year 2030) 1,845 (Year 2050)	The Arctic area north of 58.95°N	AIS data provided by Danish Maritime Authority	0.35	Winther et al. (2014)
IMO Arctic: 105 (Year 2012) Approximate AMAP Arctic: 1,165 (Year 2012) Geographic Arctic: 1,330 (Year 2012)	IMO Arctic (as defined in the Polar Code); Approximate AMAP Arctic (about 10% discrepancy with actual AMAP area); Geographic Arctic (area at or above 58.95°N)	AIS data from the Norwan satellite AISsat-1 and DNV GL vessels database and IHS Fairplay World Rster of Ships	0.35	Mjelde et al. (2014)
Year / Geographic Arctic / IMO Arctic / U.S. Arctic 2015 / 1,453 / 193 / 9 2020 (BAU) / 1,506 / 199 / 10 2020 (With diversions[a]) / 2,046 / 271 / 13 2025 (BAU) / 1,549 / 204 / 10 2025 (With diversions) / 2,144 / 282 / 14	The Geographic Arctic (area at or above 58.95°N); IMO Arctic (as defined in the Polar Code); U.S. Arctic (the U.S. exclusive economic zone within the IMO Arctic)	AIS data from exactEarth and IHS ship rstry database	0.3–0.56 (depending on engine type and fuel type)	ICCT (2017a)
7,370 (Year 2015)[b]	The Arctic front (area at or above 40°N)	AIS data from exactEarth and IHS ship rstry database	0.2–0.3 (0.25 average)	ICCT (2017b)

[a] Note: The "with diversion" scenario supposes that a small proportion of international seagoing vessels choose to use are a trans-Arctic route, instead of the Panama and Suez Canals (ICCT, 2017a).

[b] Note: According to ICCT (2017b), BC emissions from the whole global fleet were estimated to be between 53 kilotons and 80 kilotons in 2015, specifically estimated around 67 kilotons. Moreover, 11% of BC emissions (approximately 7,370 tons) were originated from vessels within the Arctic front (40°N latitude and above).

NSR has attracted business opportunities and geopolitical interest (Ren, 2016). For a shipping company, a number of economic, external policy, and internal company barriers (e.g., the absence of layover sites, Russia's territorial claim, and the limited financial capacities of companies) exist in conducting commercial voyages via the NSR (Lee and Kim, 2015). Nevertheless, a number of commercial ships have already utilized the NSR during summer. Bekkers et al. (2016) predicted that the share of world shipping trade that is rerouted through the NSR will be 4.7% by 2030. Although Wan et al. (2018b) indicated that shipping emissions can decrease by nearly 27% per loop by adopting the NSR compared with the traditional southern sea route (i.e., the Suez Canal route), BC was not included in their emission analysis.

Thus, given the considerable impact of BC climate forcing and the expected increase of Arctic shipping traffic, potential technical and operational solutions to BC emission reductions from Arctic shipping need to be revisited.

3. Technical and operational solutions

3.1. Technical solutions

Technical solutions aim at improving the energy efficiency of ships by using technical means. Generally, reduced fuel consumption can result in a corresponding reduction in ship emissions (Litehauz et al., 2012). The IMO energy efficiency design index (EEDI), which was officially adopted in July 2011, is applicable to newly built ships as a goal-based technical standard. According to Resolution MEPC.203 (62), the EEDI requires new ships to adhere to step-wise energy efficiency improvements to achieve 10%, 20% and 30% reductions in CO_2 per tonne-mile from 2015, 2020, and 2025, respectively. Litehauz et al. (2012) and Lack (2017) argued that equivalent BC reductions are expected in line with fuel efficiency gains achieved by the EEDI. Notably, the EEDI only applies to newly built ships of 400 gross tonnage and above (Marine Environment Protection Committee, 2018). In an intensive review study, Wan et al. (2018a) indicated that the EEDI cannot guarantee an improvement in energy efficiency in all practical cases because of various operational conditions. For instance, larger vessels could consume much more fuel per ton of goods carried if they are only half loaded as opposed to loaded to their full capacity (Wan et al., 2016b).

One of the unique characteristics of Arctic shipping is that fishing operations constitute a considerable portion of all shipping activities in the Arctic, given that some of the world's most productive fisheries are located in the Arctic area (Arctic Council, 2009). The ICCT (2017a) indicated that the IMO Arctic is dominated by fishing vessels, which comprised 36.2% of the Arctic fleet in 2015, followed by general cargo vessels (11.6%), service vessels (9.5%), and bulk carriers (8.7%). Moreover, the amount of fishing activity is underestimated to a certain extent because of incomplete data submission by fishing vessels, especially small fishing vessels (Arctic Council, 2009). Although the fishing fleet predominantly uses distillate fuel, it continues to be the largest contributor to BC emissions in the Arctic, accounting for 29.7% of the total BC emissions (Mjelde et al., 2014). With regard to the application of the EEDI, fishing vessels are not yet part of the EEDI regulations (IMO, 2016); thus, fishing vessels are not required to improve their fuel efficiency mandatorily when they are newly built or undergo a major conversion. Compared with other vessel types, a fishing vessel's fuel consumption is related to not only sailing operations but also the technical use of its fishing gears. Active fishing gears, such as bottom trawls, generally require more fuel (approximately 0.5–1.5 L/kg of fuel per catch) than passive fishing gears, such as pots, traps, long-lines, and gillnets (approximately 0.1–0.4 L/kg) (Suuronen et al., 2012). Suuronen et al. (2012) pointed out that as an active pelagic gear, the purse seine can achieve a high fuel efficiency (approximately 0.1 L/kg); however, increased fuel may be consumed in searching for fish schools when using this gear.

Many technical solutions for BC reduction from ships, such as the application of alternative fuels, including biodiesel, liquefied natural gas (LNG), and methanol, the use of water-in-fuel emulsion (WiFE) and colloidal catalyst technologies to improve the fuel atomization process, and the installation of diesel particular filters (DPFs), electrostatic precipitators, and exhaust gas scrubbers (EGS) for exhaust treating, has emerged or been discussed in recent years. Table 2 lists detailed information on the technical and operational solutions for BC reduction, which is derived from the intensive review study of Litehauz et al. (2012) and its update on measures by Lack (2017). The wide range of potential BC mitigation (i.e., the difference between the lower and upper bound of abatement potential) in each solution indicates poor agreement in the existing literature on BC reduction potentials. The reasons behind such a great degree of divergence are mainly as follows. (1) Some studies are limited to a certain series of research conditions, such as a certain type of vessel, a specific type of marine engine, and the quality of marine fuel, which means the research conclusions are not applicable to the entire shipping industry. (2) Some abatement measures have several subtypes with different reduction performances. For example, wet scrubbers, venturi scrubbers, bubble towers and wet electrostatic scrubbers have been used. Among them, wet electrostatic scrubbers show better fine particle removal than traditional wet scrubbers (Di Natale and Carotenuto, 2015). (3) Some studies are based on different research assumptions for relevant factors, such as the BC emission factor (Table 1), the capacity rate of engine loads, and the heating value of fuels.

Although most abatement measures in Table 2 are identified as CM/CF and IM/IN, meaning their commercial availability from the technological maturity and uptake time perspectives, it is worth noting that many technical solutions come with a significantly high price tag that may offer no economic motivation to the shipping industry to invest (Fig. 1). The average BC reduction cost is considerably more expensive than the average CO_2 reduction cost, which only ranges between 50 and 200 US $ per ton (Eide et al., 2011). Powering a vessel by LNG seems to be a theoretically applicable technology with sound cost-effectiveness to mitigate BC emissions. However, in practice, the high methane emissions (Verbeek et al., 2011), the fluctuating LNG price and supply cost (Chen et al., 2018), and the sacrifice of on board cargo storage space (Wan et al., 2018a) are challenges for LNG-powered vessels. In the Arctic, the lack of an LNG bunkering infrastructure network and the relatively limited practical operational range of present LNG-powered vessels are also barriers to applicability (Litehauz et al., 2012). Slow steaming also shows a high cost-effectiveness by generating savings of approximately 2.62 million US $ per reduced BC ton; however, its total BC reduction performance is at a lower level (more discussion on slow steaming is provided in Section 3.2).

Theoretically, all the mentioned abatement solutions are applicable not only to non-Arctic shipping but also to Arctic shipping. However, in comparison with shipping in ordinary waters, Arctic shipping operates in a sensitive region with more complicated navigational conditions, thereby possibly affecting the practical performance of the BC abatement solutions. To the best of our knowledge, few studies exist on BC control technologies, especially for Arctic shipping. Corbett et al. (2010b) conducted a cost-effectiveness assessment analysis of technologies for mitigating regional short-lived climate forcers, including BC, emitted by ships with suggestions for Arctic shipping; however, all assessed technologies or strates are implicitly assumed to be operationally applicable in the Arctic without additional scientific

Table 2
Potential BC mitigation from a series of technical and operational solutions.

Abatement Measure	BC Mitigation (%) LOW/ MID/HIGH	Technology Maturity	Uptake Time	Remarks/Limitations
Technical solutions (Vessel design)				
EEDI (excludes engine and fuel options)	10/20/30[a]	CM	2015/ 2020/2025	Required due to regulation for newly built ships of 400 tonnes and above
Technical solutions (Fuel treatment)				
Colloidal Catalyst	nr	OS	IM	–
WiFE	50/nr/90	CF	IM	Depends on H_2O; NO_X emissions can also be reduced
Technical solutions (Alternative fuels)				
Biodiesel (100%)	50/nr/75	DE	IM	Fuel availability
Biodiesel (20% Blend)	10/nr/30	DE	IM	Fuel availability
LNG	85/nr/99	CF	IN	Engine/fuel storage retrofit, supply of LNG in ports, and fugitive emissions
Methanol Dimethyl Ether	nr/97/100	DE	MT	Fuel storage retrofit and catalysis units required onboard
Nuclear	nr/nr/95	NA	LT/UI	Design, security, and waste issues; CO_2 and BC emissions from the processes of fuel production/disposal
Technical solutions (Exhaust treatment)				
Electrostatic Precipitators	15/nr/90	OS	IN	Size, commercial availability for ships
DPF on Low Sulphur Fuel	≥99	CF	IM	Commercial availability for ships
DPF on High Sulphur Fuel	80/85/90	CF	IN	Limited availability for ships
Diesel Oxidation Catalysts	nr/0/nr	CF	IN	Often combined with DPF
Selective Catalytic Reductions	0/nr/35	CM	IM	–
Exhaust Gas Recirculation	nr/0/nr	CF	IN	May increase BC soot build up reported
Scrubbers on High Sulphur Fuel	20/45/70	CM	IM	Unit cost; fuel regulation motivation
Scrubbers on Low Sulphur Fuel	20/37.5/55	CM	IM	Unit cost; fuel regulation motivation
Operational solutions (Vessel retrofit)				
Ballast Water and Trim	1/4/5	CM	IM	–
Propeller Optimization	3/nr/20	CM	IM	–
Construction Weight	nr/5/nr	CF	IN	New-build required
Air Lubrication	3.5/10/15	CF	IM	Retro-fit or new-build required
Aerodynamics	3/nr/4	DE	IN	Retro-fit or new-build required
Hull Coating	2/5/9	CM	IM	Material and dry dock costs
Hull Cleaning	3/5/10	CM	IM	Labor and dry dock costs
Wind-Flettner Rotors	3.6/nr/12.4	DE	MT	Design; commercialization
Wind-Sail/Kites	2/nr/26	CF	IM	Capital costs
Solar	5/nr/17	DE	IN	Retro-fit or new-build required
Operational solutions (Operational monitoring)				
Weather Routing	2/nr/10	CM	IM	–
Auto-Pilot Upgrades	0.5/nr/4	CM	IM	–
Operational solutions (Engine options)				
Slide Valves	10/25/50	CM	IM	Motivated by IMO NO_X regulations; hardware cost
Real Time Tuning with De-Rating	1/6.5/12	CM	IM	New engine and/or retro-fit required
Operational solutions (Slow steaming)				
Slow Steaming without De-Rating	0/nr/-30[b]	CM	IM	Fuel savings and increased travel time
Slow Steaming with De-Rating/Re-Tuning/ Slide Valves	0/nr/30	CM	IM/IN	New engine and/or retro-fit required
Operational solutions (Cleaner traditional fuels)				
Shift from HFO to Distillate Fuel with a 6% −8% Energy Content	6/nr/8	CM	IM	Fuel cost
Shift from HFO to Distillate Fuel	−12/33/78[c]	CM	IM	Fuel cost

Note: (1) LOW/MID/HIGH represent the lower, middle, and upper bound of BC reduction potential identified from the existing literature. (2) The abbreviations in the column of "Technology Maturity" are as follows. CM: Commercially Available-Multiple units that are operational in the shipping domain; CF: Commercially Available-Few units that are operational in the shipping domain; DE: Demonstration-Feasibility is demonstrated in the shipping domain but is not commercially unavailable yet; OS: Other Sectors-Technology is commercially available in the other domains and possibly applicable in the shipping industry; NA: Not Available-Technology may be unavailable in the long term. (3) The abbreviations in the column of "Uptake Time" are as follows. IM: Immediate-Less than 12 months and commercially available; IN: Intermediate-1−5 years and commercially available while major retro-fit or new-build required; MT: Medium Term-5−10 years and commercially unavailable, and during design and/or experimental stages and will require further development and research towards commercialization; LT: Long Term- More than 10 years, major design, safety, and commercialization efforts are necessarily needed; UI: Unlikely Implementation- Technology is unlikely to be implemented. (4) nr: not reported.
Source: Litehauz et al. (2012) and Lack (2017).
[a] Note: Here, 10%, 20%, and 30% BC reductions are achieved from 2015, 2020 and 2025, respectively, based on the IMO EEDI regulations.
[b] Note: According to Lack (2017), slow steaming without engine de-rating cannot reduce BC emissions, but can increase BC emission factors by up to 30% instead.
[c] Note: In the study of Lack (2017), "-12" and "78" representing the lower and upper bound of abatement potential, which are calculated by average reduction (33%) + and - standard deviation (45%) of the 57 collected data points, respectively.

demonstrations. Litehauz et al. (2012) briefly pointed out barriers to the applications of some BC abatement technologies. For instance, they argued that the use of SWS in the Arctic may require additional heating. Notably, nearly all potential BC abatement technologies have certain practical barriers to their application, especially when operated in the Arctic, a unique region with possible extreme weather and a vulnerable ecosystem. For example, as an open loop-type scrubber using sea water to clean or scrub the exhaust, SWS is only effective if the source water is alkaline. When lower alkalinity water is used to scrub the exhaust, more water and energy are needed to make the scrubbing process effective (American Bureau of Shipping, 2013). Recently, AMAP (2018) reported that the Arctic Ocean is experiencing widespread and relatively rapid ocean acidification with the reduction in the pH of the ocean, which to a certain extent may affect the effectiveness of the SWS scrubbing process in the Arctic. Furthermore, the

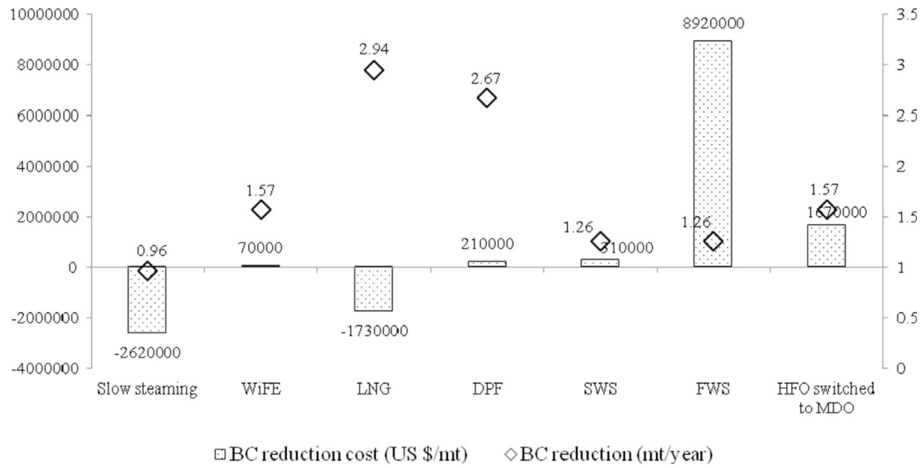

Fig. 1. Estimated BC reduction cost of six abatement technologies.
Note: (1) SWS: Sea water scrubbers; FWS: Fresh water scrubbers. (2) The estimations are made for a ship with an engine power of 10,000 kW, total operating hours of 6240 annually, an average engine load faction of 0.72, the use of marine diesel oil at the price of 1011.8 US $ per ton, HFO at the price of 659.8 US $ per ton, and a discount rate of 7%. (3) The above listed technologies (SWS and FWS are considered the same technology) are identified as the top six abatement measures based on their all air emission abatement potential and BC-only reduction potential.
Source: Data are extracted from Litehauz et al. (2012).

washwater generated during the scrubbing process usually contains particulate matter, ash, and heavy metals, and the discharge of such water should be strictly restricted in the Arctic.

3.2. Operational solutions

Operational solutions to shipping air emission reductions are generally implemented under the Ship Energy Efficiency Management Plan (SEEMP) (Wan et al., 2018a). The SEEMP is a management tool for improving the energy efficiency of a ship by planning, implementation, monitoring, and review of energy efficiency measures (IMO, 2016). Particularly, it includes slow steaming, optimized ballast water and trim, weather routing, hull coating, hull cleaning, auto-pilot upgrades, and engine maintenance. Generally, these measures require relatively low operating costs compared with technical measures.

With regard to the practical effectiveness of the SEEMP, Di Natale and Carotenuto (2015) indicated that a potential 40% particulate matter reduction is expected to arise from fuel burn savings from the implementation of the SEEMP; however, they clarified that the reduction is significantly dependent on the actual ship navigational route and the holistic logistic chain effects. Johnson et al. (2013) argued that large gaps exist between what the SEEMP actually requires from shipping enterprises and what is included in the international standard for the energy management system (i.e., ISO 50001) and the International Safety Management code in terms of energy management review and operational control. They further pointed out that these gaps are harmful to the successful implementation of the SEEMP. Unlike the EEDI, which should be verified by an authorized organization based on the EEDI technical file, the verification of the SEEMP is only limited to its existence on board, excluding the SEEMP's content (IMO, 2016).

Among the operational solutions to BC reduction, slow steaming has attracted much attention from academics and the maritime industry because of its direct link with the reduction of fuel consumption. Fuel consumption is generally approximated by a cubic function of vessel speed (Fagerholt et al., 2010). If additional transit time is required due to a slower speed, then a quadratic relationship will occur between speed and fuel consumption; thus, a 10% reduction in speed results in a 19% decrease in fuel consumption (Faber et al., 2012). Reduced fuel consumption results in a corresponding reduction in CO_2 and some other emissions (Litehauz et al., 2012). However, Lack and Corbett (2012) claimed that without engine de-rating or automatic tuning, absolute BC emissions can increase despite the reduced fuel consumption at lower speeds. In view of Arctic shipping, Faber et al. (2012) argued that regulated slow steaming in the Arctic waters could operationally prevent an increase in BC emissions, and they advocated for the design of an Arctic regulated slow steaming regime. Nevertheless, Lack and Corbett (2012) articulated that vessels sailing in the Arctic are likely to be operating at greatly variable engine loads (25%–100%) because of ice conditions, which can introduce difficulties to engine de-rating. In this case, abatement measures other than slow steaming should be considered to reduce BC emissions in the Arctic. Furthermore, both Lack et al. (2008) and Buffaloe et al. (2014) showed the complicated relationship between BC emissions and engine loads. The engine type, operational and maintenance conditions will swamp the BC emissions/engine load relationship. For fishing vessels, the largest fleet in the Arctic, there is a less precise engine power-sailing speed relation. Particularly, low sailing speeds of fishing vessels do not automatically imply correspondingly low engine loads, additional engine power is required either due to the essential characteristics of the fishing work or the practical need for the necessary handling of the fish catch at sea, such as processing and packing (Winther et al., 2014). Moreover, Mueller et al. (2015) indicated that the air-fuel mixture ratio is strongly linked to the major particulate matter emissions from ships.

In recent years, against the background of tighter rules introduced by IMO regulations for global marine fuel quality, a shift from HFO to distillate fuels that targets BC emission mitigation has elicited extensive interest. Based on an intensive review study, Litehauz et al. (2012) reported that an average BC reduction of 45% can result from a shift from HFO to distillate fuels. However, the International Council on Combustion Engines (CIMAC) (2012) argued that switching to distillate fuels will typically not lead to reduced BC emissions from large engines. Buffaloe et al. (2014) claimed that the CIMAC conclusions may be erroneous, and they clarified the potential reduction in BC emissions by an emission comparison between ships using HFO and ships using low sulphur distillate. Lack (2017) conducted a further review study and found that a significant variability in the BC response to a switch from HFO to a low sulphur fuel exists because of the presence of many variables (e.g., engine load, fuel injection, and aspiration) and fuel quality parameters (e.g., heavy metal, molecular oxygen and ash content) that can affect BC reduction in practice. In terms of the statistical robustness, Lack (2017) finally concluded a 33% reduction in BC emissions by shifting from HFO to distillate fuels. It is worth mentioning that some technically feasible BC controls prefer low sulphur fuels (Corbett et al., 2010a). For instance, the DPF technology is more efficient with low sulphur fuels (more than a 99% reduction in BC) than with high sulphur fuels (80%–90% reductions) (Lack, 2017). Fuel cost is a major concern with the switch from HFO to distillate fuels for the shipping industry. With regard to Arctic shipping, the recent cost analysis conducted by Transport and Environment (2018a) shows that the likely cost impact of an Arctic HFO ban will be small for shipowners.

Other operational solutions have gradually received attention recently. For instance, Coraddu et al. (2018) suggested that 0.5%–2.3% fuel savings can be achieved by optimizing the trim of the ship, depending on the actual extent of the range for the various types and angles of trim. However, this process has to be performed by an on-board monitoring system and requires advanced data analytics techniques. Meanwhile, improper trimming can endanger navigational safety (Wan et al., 2018a). Another example is the assistance of an optimal weather routing system during navigation, which can also theoretically reduce fuel consumption and proportionally cut shipping air emissions; however, the actual fuel consumption during operation may not decrease because of wave resistance and the additional route length (Di Natale and Carotenuto, 2015). Except for necessary equipment such as navigational aids, operational solutions usually require a skilled crew to respond correctly and quickly to a rapidly changing and often complex operational environment (Wan et al., 2018a). In the Arctic, safe navigation is largely dependent on the experience and skills of the crew due to the lack of adequate hydrographic data and accurate navigational charts (Arctic Council, 2009), harsh weather conditions, intermittent fog and free-floating ice (Buixadé Farré et al., 2014). However, at present, skilled and experienced labor is severely lacking for Arctic shipping (Sakhuja, 2014).

4. Policy implications for Arctic shipping

4.1. Combination of technical and operational solutions

Although the EEDI does not result in guaranteed energy efficiency improvements in real-world operations, ensuring the full implementation of the IMO's EEDI regulations remains important, and this process can continuously facilitate vessel design improvements and provide BC reductions at a certain anticipated level. Meanwhile, it is imperative to demonstrate the potential feasibility of the EEDI's application to fishing vessels, the largest fleet in the Arctic.

Both technical and operational abatement solutions to shipping BC emissions have pros and cons. From the perspective of BC emission reductions, a combination of technical and operational solutions shows more mitigation capabilities than either technical or operational solutions alone. Lack (2017) reported that the combination of DPF technology and the switch from HFO to distillate fuels could result in the best abatement performance, with BC reductions of ≥99%. Corbett et al. (2010b) also showed that the combined control strategy (i.e., slide valves and WiFE) has significant cost-effectiveness in terms of the average cost per ton of reducing BC. However, the early adoption of these combined solutions can still be very expensive for shipowners and without guaranteed investment returns, especially in the short term. Direct financial incentives, such as subsidies for mitigation equipment investment and preferential taxation treatment and market-based methods including emission credit systems and emission quota allocation, can be considered by governments to encourage shipowners (Zhu et al., 2017). With regard to Arctic shipping, the Arctic states can consider the development of relevant incentive regimes for vessels sailing in Arctic waters. In view of the relatively poor agreement in the literature on the BC reduction potential of technical solutions and the unique environment of the Arctic, more studies are needed to test and confirm the robustness of BC emission reductions of abatement technologies in the Arctic.

At the current stage, from the view of the potential costs and average robust BC reduction performance (i.e., 33% reduction), a switch from HFO to distillate fuels should be encouraged to be adopted by shipowners. Cleaner fuels not only can result in BC emission reductions in most cases but also in significant reductions in other pollutants such as sulphur oxides. Regarding the proposed ban on HFO use and carriage for use as fuel by vessels in Arctic waters, the ban mainly aims at preventing the increasing risk of an HFO spill because Arctic shipping is projected to continue to rise. Undoubtedly, the HFO ban can help to mitigate shipping emissions in the Arcticregion. To a certain extent, it can also facilitate the formation of a level playing field with rules that are clear and that treat all ships fairly for the growing Arctic shipping industry.

Beyond the short-term cost-effectiveness perspective, exploring potentially new technology pathways for BC emission reductions is imperative for the future of the shipping industry. According to Transport and Environment (2018b), battery-electric and hydrogen technologies and their combinations, as zero carbon technologies, are recommended to decarbonise shipping. In addition to reducing CO_2 emissions, these technologies will also lead to substantial BC emission reductions. However, a considerable level of additional investment will be required, so a cost-effectiveness analysis should be conducted by considering the overall potential social benefits from a long-term perspective.

4.2. Introduction of low impact and fuel efficient (LIFE) fishing

Fishing is an important marine use in the Arctic, marked by significant fishing vessel activities (Arctic Council, 2009). Corbett et al. (2010) argued that fishing vessels will contribute proportionally less to future Arctic emissions under the assumption that the Arctic fish stocks are at a certain level with negligible changes. However, the fishing fleet remains the largest of the Arctic fleet at present (ICCT, 2017a). Given the nature of the fishing work, most of the fish capture methods are strongly dependent on the use and consumption of fossil fuels. Fishing practices and gears vary greatly in their influences on marine ecosystems and their fuel efficiency (Suuronen et al., 2012); therefore, advanced fishing management, technological improvements, and behavioural changes can reduce fishing vessel emissions (Parker and Tyedmers, 2015). To achieve more economical and sustainable fisheries, it is important to facilitate the adoption and development of LIFE fishing, which refers to improving fishing practices and gears to ensure that fish capture occurs by minimizing fuel use and environmental impacts (Suuronen et al., 2012).

Specifically, according to Suuronen et al. (2012), LIFE fishing requires changes from high energy-consuming fishing methods to methods with lower energy consumption (for instance, bottom seining generally performs better than bottom trawling in fuel efficiency) and/or improvements only in operational techniques and gear designs without major changes in behavior, especially when uncertainties and high economic risks may exist in adopting completely new fishing methods. Moreover, LIFE fishing includes scientific studies on cost-effective gear designs and fishing operations, the analysis and popularization of best practice operations, and the development of appropriate fishery management policies. The excessive use of any gear type, even low energy-consuming gears, may result in severe emissions because of overexploitation and corresponding considerable fishing vessel activities. Among the numerous measures of LIFE fishing, the potentially most effective way to enhance the energy performance of fisheries is to rebuild stocks and manage capacity validly (Parker and Tyedmers, 2015).

Although fishing vessels primarily use distillate fuel, the adoption of other technical and operational solutions remains highly necessary to further mitigate BC emissions. For example, DPF and EGS are also potentially applicable to small ships, such as fishing vessels. However, a problem may exist because investment in these types of abatement equipment can be a heavy financial burden for small fishing vessels, especially when a vessel is owned by an individual or a family. In this case, financial incentives, such as government subsidies, will be imperative.

4.3. Regional actions and global cooperation

With regard to the governance of Arctic shipping, a fundamental framework is provided by the United Nations Convention on the Law of the Sea (UNCLOS). Meanwhile, the Polar Code, adopted by the IMO and in force from January 1, 2017, is a major step to ensure the robustness of ship operations in Arctic waters (Arctic Council, 2017). Although the IMO, as a specialized agency of the United Nations, is taking responsibility for the safety, security and environmental protection issues related to the international maritime industry including Arctic shipping, the Arctic Council, as a regional high-level intergovernmental forum among the Arctic states, also plays a vital role in common Arctic issues. Moreover, the Arctic states' roles cannot be neglected, especially in supporting the relevant work of the IMO and the Arctic Council and synergizing Arctic marine shipping regulatory regimes within their jurisdictions. The Arctic states should prioritize protecting the Arctic environment rather than massively exploring and exploiting the Arctic.

The achieved positive outcomes and progress in the enhancement of maritime safety and the marine environment protection in the Arctic in recent years (e.g., the Arctic Oil Spill Preparedness and Response Agreement and the Arctic Search and Rescue Agreement) have clearly shown the importance of constructive regional actions. As patchwork approaches, regional actions can sometimes even be superior to long-pending global policies (Wan et al., 2018a). Many Arctic issues generally have local and regional characteristics; therefore, regional actions should be more heavily emphasized. Specifically, The programme for the Protection of the Arctic Marine Environment (PAME) established by the Arctic Council should continue providing a forum for collaboration on various activities directed towards the protection and sustainable use of the Arctic marine environment, such as constructing a harmonized shipping dataset based on data collected from the Arctic states and designing marine protected areas network. PAME should also work continuously to strengthen its collaboration with other international organizations, such as the IMO and the International Whaling Commission. To ensure that discussion on an Arctic HFO ban will be continued in the IMO, the Arctic states need to collaborate with each other and actively ask for a new agenda item for future discussions. Moreover, specific projects on mitigating the risks associated with the use and carriage of HFO by vessels in the Arctic should be financially supported.

Although global cooperation to address shipping emissions in Arctic waters is difficult, it is urgently needed, especially as trans-Arctic transport is becoming increasingly popular. Additional vessels from non-Arctic countries are predicted to participate in Arctic shipping, and thus, additional stakeholders will be involved in Arctic issues. In this respect, improving multilateral cooperation, reaching a universal or majority consensus, and converging global efforts to develop more mitigation solutions to shipping emissions are crucial. Moreover, regional actions should remain consistent with globally cooperative actions or global policies because environmental protection in Arctic waters ultimately requires concerted global actions.

5. Conclusions

Arctic shipping traffic is increasing with the reduction in summer ice coverage in the Arctic region. Together with rising vessel activities, more air pollutants will be emitted into the Arctic atmosphere if no mitigation efforts are taken. As the most efficient atmospheric particulate species at absorbing visible light (AMAP, 2011), BC is one of the vessel-source air pollutants from the shipping industry and is exerting a significant impact on the Arctic climate by its strong snow albedo effect. Although some air pollutants emitted by ships have been gradually regulated by the IMO and some regional and/or national authorities, no specific BC abatement policies have yet been implemented at the global or regional level, even in the Arctic region. Fortunately, BC mitigation can largely benefit from abatement solutions for other concomitant pollutants. Different technical and operational abatement technologies have different BC reduction potentials. From the perspective of the comprehensive capability of reducing shipping air emissions, some abatement measures, such as the use of LNG as an alternative fuel, DPF, SWS, and the switch from HFO to distillate fuels seem to be potentially good options. However, their mitigation performance, the feasibility of application, and the cost-effectiveness for Arctic shipping must be deeply analyzed and reviewed to provide more evidence and an economic justification. The demand for further studies does not necessarily indicate no action is warranted to mitigate BC emissions at present. For instance, the switch from HFO to distillate fuels could be adopted as a favorable BC abatement option. From the perspective of BC reduction performance, a combination of technical and operational solutions would be more effective.

Fishing vessels dominate the Arctic fleet at present and they are the largest contributors to shipping BC emissions in the Arctic. Different from other vessel types, a fishing vessel has the important and special function of capturing fish as opposed to the conventional function of transport. Various fishing gears and operational methods have different energy efficiency performances. Towards a cleaner Arctic, LIFE fishing with a low impact on the environment should be introduced and advocated. Meanwhile, the potential feasibility of the EEDI's application to fishing vessels needs to be analyzed.

Regional actions and global cooperation are imperative for the governance of Arctic shipping. Facilitators at different levels, such as the IMO, the Arctic Council, and the Arctic states, should cooperate with one another to seek the possible harmonization and uniformity of Arctic shipping governance. Cooperation that links scientists, policymakers, shipowners, shipyards, and marine equipment suppliers is also needed to protect the Arctic environment.

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