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Arctic shipping emissions inventories and future scenarios

J. J. Corbett[1], D. A. Lack[2,3], J. J. Winebrake[4], S. Harder[5], J. A. Silberman[6], and M. Gold[7]

[1]College of Earth, Ocean, and Atmosphere, University of Delaware, Newark, 19716 DE, USA
[2]NOAA Earth System Research Laboratory, Boulder, 80305, CO, USA
[3]Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, 80309, CO, USA
[4]Rochester Institute of Technology, Rochester, 14623, NY, USA
[5]Transport Canada, Vancouver, V6Z 2J8, British Columbia, Canada
[6]GIS Consulting, Unionville, 19375, PA, USA
[7]Canadian Coast Guard, Ottawa, K1A 0E6, Ontario, Canada

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Correspondence to: J. J. Corbett (jcorbett@udel.edu)

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Abstract

The Arctic is a sensitive region in terms of climate change and a rich natural resource for global economic activity. Arctic shipping is an important contributor to the region's anthropogenic air emissions, including black carbon – a short-lived climate forcing pollutant especially effective in accelerating the melting of ice and snow. These emissions are projected to increase as declining sea ice coverage due to climate change allows for increased shipping activity in the Arctic. To understand the impacts of these increased emissions, scientists and modelers require high-resolution, geospatial emissions inventories that can be used for regional assessment modeling. This paper presents 5 km×5 km Arctic emissions inventories of important greenhouse gases, black carbon and other pollutants under existing and future (2050) scenarios that account for growth of shipping in the region, potential diversion traffic through emerging routes, and possible emissions control measures. Short-lived forcing of ∼4.5 gigagrams of black carbon from Arctic shipping may increase climate forcing; a first-order calculation of global warming potential due to 2030 emissions in the high-growth scenario suggests that short-lived forcing of ∼4.5 gigagrams of black carbon from Arctic shipping may increase climate forcing due to Arctic ships by at least 17% compared to warming from these vessels' CO_2 emissions (∼42 000 gigagrams). The paper also presents maximum feasible reduction scenarios for black carbon in particular. These emissions reduction scenarios will enable scientists and policymakers to evaluate the efficacy and benefits of technological controls for black carbon, and other pollutants from ships.

1 Introduction

Dramatic decline of Arctic sea ice has been observed over the past few decades, culminating in a record minimum sea ice extent of 4.28 million km^2 in 2007 (∼10 million in 1970) (NSIDC, 2007). This decline in Arctic sea ice has re-ignited interest in efforts to establish new trade passages, raising the possibility of economically viable trans-

Arctic shipping as well as increasing access to regional resources and spurring growth in localized shipping supporting natural resource extraction and tourism (ACIA, 2004; Jakobson, 2010; Westcott, 2007). Although increased Arctic shipping may provide commercial and social development opportunities, the associated increased environmental burdens are also of concern.

Studies assessing the potential impacts of international shipping on climate and air pollution demonstrate that ships contribute significantly to global climate change and health impacts through emission of greenhouse gases (GHGs) and other pollutants (e.g., carbon dioxide [CO_2], methane [CH_4], nitrogen oxides [NO_x], sulfur oxides [SO_x], carbon monoxide [CO], and various species of particulate matter [PM] including organic carbon [OC] and black carbon [BC]) (Capaldo et al., 1999; Corbett et al., 2007; Fuglestvedt et al., 2009a, 2008; Lauer et al., 2009; Winebrake et al., 2009b). Although at present in-Arctic ship emissions make up a relatively small proportion of global shipping emissions, there are region-specific effects from substances such as BC and ozone (O_3) which are becoming increasingly important to quantify and understand.

Most significant for the Arctic is the additional source of short-lived climate forcing agents (such as, BC, CH_4, and O_3) from ships in proximal transport distance (within a few hundred kilometers); Arctic impacts from regional shipping may compare with long-range transport of larger emissions sources from lower latitude biomass and fossil fuel combustion. In the recent Tromso Declaration of the Arctic Council, Ministers highlighted this issue by specifically calling out the important role that shorter-lived forcers play in Arctic climate change and recognizing that reducing these shorter-lived pollutants can reduce near-term climate change impacts such as snow, sea ice, and sheet ice melting (Arctic Council, 2009a).

Current estimates (for the year 2007) report that international shipping emits about 1000 Tg CO_2/y, with projected increases attributed to growth in international trade (Buhaug et al., 2009). Black carbon, a component of PM produced by marine vessels through the incomplete oxidation of carbon in diesel cycles, has a positive climate-

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forcing effect since it absorbs sunlight (Flanner et al., 2007; Reddy and Boucher, 2006). This effect is likely greater in the Arctic region and other snow- and ice-covered regions, because atmospheric BC layers absorb radiation both from incident sunlight and sunlight reflected from the surface. Also, when deposited to the snow or ice surface, BC can reduce surface reflectivity (i.e., albedo), accelerating the melting process (Flanner et al., 2009, 2007; Hansen and Nazarenko, 2004; Hansen et al., 2005).

International shipping emits between 71 000 and 160 000 metric tons (mt) of BC annually, representing about 15% of total PM emitted by ships and about ~2% of global BC from all sources (Corbett et al., 2007; Lack et al., 2008, 2009). Uncertainties are currently driven by confidence bounds on emissions rates for BC. The total near-term warming impact of BC emissions from global sources has been estimated to range between 18% and 55% of global CO_2 forcing. This percentage is greater than forcing from CH_4, CFCs, N_2O or tropospheric O_3 (Ramanathan and Carmichael, 2008). The total climate forcing impacts attributable to BC from ships have not been estimated independent of other PM impacts (IPCC, 2007; Ramanathan and Carmichael, 2008).

To better understand the potential impact of Arctic ship emissions on the climate, scientists and modelers require high-resolution geospatial emissions inventories suitable for regional-scale evaluation. This paper presents such inventories for emissions of BC, OC, PM, NO_x, SO_x, CO and CO_2. We produce future inventory scenarios for in-Arctic shipping that includes growth, emissions changes through current legislation, and potential access of navigable routes for diversion traffic to provide insights into current and future impacts. Lastly, we provide maximum feasible reduction (MFR) scenarios aimed at reducing short-lived forcing impacts of BC.

2 Estimating geospatially resolved emissions from in-arctic shipping

Empirical data of shipping activity reported by Arctic Council member states is used to produce a present-day (2004) Arctic emissions inventory (Arctic Council et al., 2009b). This inventory methodology employs the most recent estimates of PM emission factors and an activity-based approach that is the state-of-practice for ship inventories, tailored for Arctic shipping as described in the Arctic Marine Shipping Assessment 2009 (AMSA) report (Arctic Council et al., 2009). Emissions are calculated for each vessel-trip for which data were available for the base year 2004. Future seasonal emissions are projected under high-growth and business as usual (BAU) assumptions and adopted future regulations. Emissions from trans-Arctic navigation routes are also projected with emissions assuming 1%, 2%, and 5% diversion of global shipping for 2020, 2030, and 2050, respectively.

2.1 Route identification

AMSA nations provided input on seasonal- and route-specific activity, from which the following vessel-specific routes were constructed and evaluated. The data included: (1) vessel characteristics (ship identification number, vessel size, vessel type, main engine power, design speed); (2) trip data (duration, distance, origin port, destination port); and (3) geospatial information (latitude and longitude values for ship movements, where available). We use data provided by Arctic nations nations and used in the AMSA analysis. The AMSA data included a range of assumptions and limitations, but represents the best data available to date. Listed in Table 1 are ship types from the AMSA, with route counts for each type of ship. These vessel trips were mapped to the season in which they occurred, also shown in Table 1.

2.2 Vessel characterization

Different vessel types have variable emissions and thus an assessment of vessel characterization was performed for activity in Arctic waters (Arctic Council et al., 2009). Recent work by Norwegian researchers at Det Norske Veritas (DNV) suggests that the AMSA assumptions for most ship types were valid, except that general cargo ships for Arctic operations have less installed power than globally typical. Based on comparisons with (DNV) data for these vessel types (Mjelde and Hustad, 2009), general cargo ship characteristics were modified downward for this inventory to conform better to empirical data for Arctic activity of these vessels. Fishing vessel data were based on the number of days operating underway associated with large marine ecosystems (LME) or fishing areas, instead of number of trips; therefore, their activity-based emissions are computed slightly differently. Given the focus on transport vessels in this work, fishing vessel emissions are not provided geospatially in this study, but can be provided in future work. It is important to note that for the AMSA study fishing vessels constituted a significant portion of all vessel traffic in the Arctic regions, making up more than half of all vessels reported (Arctic Council et al., 2009).

2.3 Emissions Factor (EF) determination

Combustion PM is a general term representing a composite of primary particles formed during combustion processes and/or secondary particles formed via exhaust gas chemistry (Eyring et al., 2009; Lack et al., 2008, 2009; Robinson et al., 2007). Particulate matter species generally associated with combustion of heavy-fuels in marine diesel engines include BC, OC, sulfur aerosols, ash, and trace metals, among others. Particulate matter speciation is primarily a function of fuel quality and consumed cylinder lubricants, while their size and number depends mostly upon combustion conditions. For future scenarios, legislation to reduce sulfur content in marine fuels and control NO_x emissions rates will, in turn, affect fuel-quality and lubricant emissions of organic carbon (International Maritime Organization, 2008).

The BC fraction of PM observed in marine engine exhaust has been investigated in both stack exhaust and atmospheric plume studies (Lack et al., 2008, 2009; Moldanová et al., 2009; Petzold et al., 2008), and has been variously reported to range from less than 5% to more than 40% on a mass basis (Bond et al., 2004; Lack et al., 2009; Lyyranen et al., 1999; Moldanová et al., 2009). The Second International Maritime Organization (IMO) GHG Study 2009 reported that BC contributed about 5.1% to total PM mass, partly due to inclusion of water mass associated with sulphate (Buhaug et al., 2009). Lack et al. (2009) and Bond et al. (2004) report central values of approximately

15% and 8%, respectively, on a dry particle basis. Importantly, a large number of fine particles from high-temperature, high-pressure combustion is typical of marine diesel engine combustion, and the BC mass variability is statistically independent of correlated changes in fuel-sulfur content and OC emissions (Lack et al., 2009).

The emission factors (EFs) used here for BC, OC, and sulfur emissions (SO_x as SO_2) are from the IMO Study (Buhaug et al., 2009), with additional speciation of PM to provide emissions factors for BC and OC based on literature (Lack et al., 2008; Lack et al., 2009). Future EFs generally follow the IMO Study (Buhaug et al., 2009) reporting changes in SO_x and NO_x due to IMO legislation to be implemented by 2020, with two exceptions. We adjusted future EFs to reflect Annex VI emissions controls of SO_x from the current world average (about 2.7%) to 0.5% (International Maritime Organization, 2008). Recent field measurement campaigns observed that BC EFs are statistically unchanged by lower-sulfur fuels whereas OC and SO_x EFs are correlated (Lack et al., 2008, 2009). Therefore, we apply an emission rate for BC of 0.35 g/kg fuel and a rate for OC that varies proportionally with a sulfur content range of 2.7% to 0.5%. We recognize that reported standard deviations on the many observations in Lack et al. (2008, 2009) are large, and capture reported point estimates from other studies of individual engines. Table 2 presents these emissions factors in units of grams pollutant per kilogram fuel, consistent with the Second IMO GHG study (Buhaug et al., 2009) and published studies; these can be also reported in grams per kilowatt-hour (g/kWh) using typical specific fuel oil consumption rates as a conversion factor.

2.4 Emissions estimation

The activity-based model follows the general formula shown in Eq. (1):

$$E_{ijk} = \mathrm{EF}_{ij} \times \mathrm{LF}_{ij} \times \frac{\mathrm{KW}_j}{n_j} \times T_{jk} \quad (1)$$

where, E_{ijk} are emissions of type i from vessel j on route k in grams (g); EF_{ij} is the emissions factor for emissions of type i on vessel j in g/kwh; LF_{ij} is the average engine load factor for vessel i on route j and takes into account periods of maneuvering, slow cruise, and full cruise operations; KW_j is the rated main engine power in kilowatts for vessel j; η_j is the engine efficiency; and T_{jk} is the duration of the trip for vessel j on route k in hours (h). Table 3 presents an updated emissions summary (in mt/y) by vessel type to compare with prior estimates for the AMSA study; the key differences are the emissions for general cargo ships. Auxiliary engines for in-Arctic ships are not explicitly estimated, but the installed auxiliary engine power is typically a small fraction of main engine power. Comparison of in-Arctic emissions by ship-type for the Norwegian data with a DNV report showed that all transport vessel inventories reported here are within 10% to 20% of the DNV estimates for vessels in this study. Assuming similarity among Arctic shipping reported by other nations, this agreement is considered to be strong for transport ship emissions described by these data.

2.5 Geospatial emissions profiles

Arctic shipping routes, vessel characterization and EFs were combined to produce the geospatial emissions inventory. Data fields include longitude and latitude degrees for each grid cell at 5 km resolution, and emissions data in grams per cell for BC, OC, PM, and CO, and in kg per cell for CO_2, SO_x (as SO_2), and NO_x (as NO_2). Both annual and seasonal data are provided. Seasonal representation of these data is shown in plates (b) through (e) in Fig. 1, alongside a polar projection of prior global inventory coverage of Arctic regions (Fig. 1a), and a depiction of potential routes for diversion traffic if ice-free navigation becomes attractive in the future for shorter-voyage diversion of global shipping (Fig. 1f and discussed below).

The 5 km×5 km resolution is coarser than the original AMSA data used to generate the inventory but provides greater resolution than the maps produced by AMSA (1:30 000 000 scale, where 1 cm=∼300 km). As part of the GIS data processing, the Universal Polar Stereographic (UPS) projection coordinate system that covers regions above 84 degrees North with a central point at the North Pole was maintained; therefore potential additional distortion due to projection-conversion was minimized. Comparisons of emissions totals were accumulated to provide quality assurance on the processing results. Seasonal data provided gridded representations of Arctic shipping emissions that sum to the annual inventory totals (see Table 5) and indicated a post-processing cumulative error attributed to the conversion of data of $\sim \pm 1.3\%$.

2.6 In-arctic future year scenarios

In-Arctic shipping traffic is predicted to increase with increases in a variety of activities, including resource extraction, tourism and cargo transportation. Most forecasts of emissions in the shipping industry are allocated spatially by assuming homogeneous distribution among vessel types (Wang et al., 2008). However, the asymmetric growth in activity among ship types is well understood in terms of economics and trade, with vessel activity involved in moving containerized goods and energy products growing faster than other ship types. To date, only a few regional studies are considering spatial differences among different vessel types (Corbett et al., 2007; Dalsoren et al., 2007). The seasonal inventories of in-Arctic shipping by vessel type were grown independently using growth rates from the scenario model employed in the Second IMO GHG Study 2009 (Buhaug et al., 2009). We defined lower-growth rates to represent a business-as-usual (BAU) scenario and higher growth rates to represent a high-growth scenario for in-Arctic shipping (see Table 5). This produced future shipping patterns where changes in routes are dominated by growth in one or a few vessel types.

2.7 Maximum feasible reductions

Future Arctic emissions may be targeted for reductions via a number of pathways including the expected global fuel quality regulations to be introduced through the MARPOL Annex VI legislation. Technologies may be employed, individually or in combinations, to achieve further controls; these include seawater scrubbing, slide valves, water-in-fuel emulsions, diesel particulate filters, and emissions scrubbing technologies. The MARPOL Annex VI legislation will mostly address SO_2 and particulate sulfate emissions, with some associated OM reductions (Lack et al., 2009). BC emissions may benefit from MARPOL Annex VI legislation because some technically feasible BC controls require lower sulfur marine fuels and related changes in lubricating oil properties.

For this work, we assume the fleet wide maximum feasible reduction (MFR) for BC is 70%, representing a combination technology performance (Winebrake et al., 2009a), and/or reasonable advances in single-technology performance. Not all technologies work equally well on BC particles as their efficacy rates for PM overall. For example, reported control efficiencies and principles of seawater scrubbing suggest that BC is controlled less effectively by current scrubbing technologies. Published studies of seawater scrubber performance report control efficiencies for PM in the range of 25–80%, suggesting that volatile and semi-volatile particles are effectively absorbed (Kircher, 2008; Winebrake et al., 2009a). While many studies do not report species-specific PM reductions, very small particles like BC are reported to be less controlled than larger ones. Moreover, hot-gaseous sulfur adsorption at the seawater droplet surface is enhanced by chemical reactions with seawater alkaline species (Caiazzo et al., 2009). One seawater scrubbing trial on an auxiliary engine using HFO measured 98% reductions in PM_2, 74% reductions in $PM_{1.5}$, 59% reductions in PM_1, and 45% reductions in $PM_{0.05}$ (Entec UK Limited et al., 2005). A December 2009 unpublished study undertaken by Sustainable Maritime Solutions Inc. and Ricardo Inc. (UK) indicate 55–70% reductions in BC mass using sea-water scrubbing technology (D. Gregory, Personnel Communication, 2010). In other words, achieving 70% MFR goals for BC may require further scrubber demonstration. Notwithstanding the potential for a single technology to achieve 70% control, combinations of technologies such as fuel-emulsions, in-engine modifications, and further sulfur removal in the fuels or exhaust can achieve MFR BC reductions along with reductions in other PM.

3 Results

3.1 In-arctic shipping

The Arctic environment is sensitive to change and impacts resulting from the changing climate are already emerging. The emissions inventory derived from (2004) reported shipping activity can help to assess the role shipping may play in present and future impacts. Seasonal emissions of Arctic shipping for 2004 (Table 6) are dominated by Summer and Fall activity, with Winter and Spring being comparable and ~30% lower than the other seasons. However, the total vessel trips within Fall, Winter and Spring vary little, indicating a shift in the vessel mix across seasons.

This vessel mix becomes evident by assessing the 2004 Arctic shipping composite regional growth rates for all ship-types operating in Arctic waters produced by the emissions model. Table 6 shows these composite growth rates for BC, OC, PM, SO_x, NO_x, CO and CO_2 emissions. These growth rates differ from other forecasts for Arctic shipping but are more consistent than contradicting. For example, Dalsøren et al. (2007) estimate some 3.8 Tg CO_2 in 2000, forecasting growth in 2015 to as much as 4.9 Tg CO_2 – a growth rate of ~1.8% per year. Given that Dalsøren et al. (2007) mainly focuses on Norwegian coastal shipping dominated by oil transport (see their Tables 1 and 4), and that the scenario model produced a high-scenario growth rate for tankers of less than 2% per year, this close agreement in growth rates demonstrates consistency among the scenario model and others' work at national scales. Given that this work considers more vessel types and higher growth rates, these differences are expected.

Shipping patterns vary geospatially over time as illustrated in Fig. 2. This is a function of the asymmetric growth patterns produced by different vessel-specific growth rates, and results in a shift in the contribution to total emissions among ship types as shown in Table 7. Worth noting is that fishing vessels (not represented geospatially here) contribute proportionally less to future emissions under the assumed constancy in fish stocks and corresponding fishing-vessel activity. Given the conservatively high estimate for fishing vessel emissions by the AMSA study (reported above to be a factor of three greater than comparison with a Norwegian fishing inventory; Mjelde and Hustad, 2009), transport ships in the Arctic will remain the dominant contributor to in-Arctic marine vessel emissions.

Growth rates in energy use (as reflected by proportional increases in CO_2, BC, and CO) are similar to IMO Study growth rates (Buhaug et al., 2009). Emissions are reported in Tables 8 and 9 for the BAU and high-growth scenarios, respectively. The in-Arctic BAU scenario is closest to the Base-case B1, B2, and A2 scenarios in the IMO Study (Buhaug et al., 2009). The in-Arctic high-growth scenario falls between the A1 base-case and high-growth scenarios, reflecting activity that may conform loosely either to the so-called Arctic Saga or Arctic Race scenarios found in the AMSA study (Arctic Council et al., 2009; Buhaug et al., 2009). Arctic Saga and Arctic Race are described respectively as "a healthy rate of Arctic development that includes concern for the preservation of Arctic ecosystems and cultures and shared economic and political interests," and a "lack of an integrated set of maritime rules and regulations, and insufficient infrastructure to support such a high level of marine activity". Therefore, the scenarios developed here should be valuable for impact assessment by scientists that produce results relevant for policy decision-making regarding the sensitive Arctic region.

3.2 Potential diversion in ice-free seasons

Dramatic decline in Arctic sea ice extent over the past few years has raised the possibility of regular Arctic traffic diverted from current shipping routes (diversion traffic) producing both economic enthusiasm and environmental concern. Distance savings of ~25% and ~50% (and coincident time and fuel savings) are estimated for the Northwest Passage (NWP) and Northeast Passage (NEP), respectively. Commercial NWP transits between Japan, and Eastern Canada are estimated to be financially viable, although how much is debated (Somanathan et al., 2009). Commercial NEP transits between Shanghai and Hamburg are currently viable, yet double the cost of the traditional route (Verny and Grigentin, 2009).

Representing the potential emissions from these diversion routes even with the uncertainty in future diversion route viability is an important input to allow for prospective scientific assessment, to evaluate impact mitigation options and costs, and to inform good policy decisions. Therefore we construct four potential diversion routes, depicted in Fig. 1g, including the NEP, NWP and two polar routes. These routes are selected based on current Arctic shipping lanes (see Fig. 1b–f) and predictions of likely polar routes from other studies (Arctic Council et al., 2009). Existing routes along Canada are not really NWP routes but depict local service; therefore, we defined the potential NWP route to represent a shorter transit path enabled by receding ice extent, at least seasonally.

We produce Arctic diversion inventories for potential opening of routes diverting current global ship traffic by assuming a global annual growth in non-Arctic shipping of 3.3% per year (a value between the various IMO base case and high-growth scenarios, representing selective diversion of the faster-growing segments of global trade), and then assuming an increase in Arctic diversion in emissions proportional to the percent of global trade diversion through Arctic routes. The percent of global shipping diverting into the Arctic was determined from current literature regarding the feasibility of Arctic shipping and global shipping volumes through the Suez and Panama Canals (∼4% and ∼8% of global trade volume, respectively; Egyptian Maritime Data Bank, 2010; GlobalSecurity.org, 2010). Acknowledging uncertainty as to when diversion traffic may emerge, we chose to scale the percent diversion beginning in 2020 at 1% of global shipping, increasing to 2% in 2030, and increasing to 5% in 2050.

Table 10 presents pollutant inventories for these future year projections. Incidentally, the sum of 2050 in-Arctic and 5% global diversion route emissions for the high-growth scenario result in a NO_x estimate that compares very well with previous work (Granier et al., 2006); our estimated sum (0.75 Tg NO_x in-Arctic plus 1.9 Tg NO_x from diversions) results in 2.65 Tg NO_x or ∼0.7 Tg N – within the range of 0.65 to 1.3 Tg N estimated by Granier et al. (2006). Under the BAU scenarios, and if trans-Arctic shipping does not emerge, expected impacts to regional ozone would be similar to work by Paxian et al. (2010). The scenarios reported here produce 2050 emissions ∼2–4 times greater than Paxian et al. (2010) estimates (depending on which of their scenarios we compare), partly attributable to their focus on diversion traffic and our inclusion of in-Arctic traffic reported by the Arctic nations. A shipping traffic diversion rate of ∼1.8% and BAU in-Arctic rates would produce similar inventory totals estimated by Paxian et al. (2010). Differences may also be attributed to different inputs for emissions rates for some pollutants.

Diverted emissions are expected to be distributed during ice-free or navigable seasons spanning longer periods as Arctic ice melts and the diversion potential increases, as illustrated in Tables 11 and 12. The inventories provided can be allocated by modelers and policy analysts to explore additional diversion scenarios, based on updated predictions of route navigability and economic incentive to assign ships to one or more of these routes.

4 Discussion

The future scenarios for shipping emissions (both in-Arctic and global) provide asymmetric trends among pollutants due to a combination of current legislation implementation for some pollutants, efficiencies in new technologies, and expected growth in shipping activity driven by economic opportunities. The net effect of these drivers on in-Arctic shipping (not including potential diversion routes) is embedded in the inventory scenarios reported here as illustrated by the annual trends in Fig. 3. For both high-growth and BAU scenarios, the IMO legislation to reduce fuel-sulfur emissions will reduce SO_x emissions substantially between now and 2020 (International Maritime Organization, 2008). Coincident with that will be reductions in OC, due primarily to fuel and lubricating oil changes driven by lower-sulfur fuels. Black carbon emissions are expected to increase without control requirements, along with CO_2; NO_x controls under IMO legislation will help level emissions growth in the 2020–2030 decade but reduced emissions rates per kWh will be outstripped by growth in shipping activity. If

MFR controls for fine particles such as BC are implemented, the technologies are expected to capture all PM with similar efficacy; this leads to expected reductions in OC with MFR policies.

Black carbon emissions from shipping in the Arctic can be evaluated in terms of in-Arctic ship activity, with and without potential diversion of global shipping to navigable Arctic routes for diversion traffic, and with regard to global (non-Arctic) shipping inventories. Table 13 presents these results for high-growth scenarios with and without control action to achieve maximum feasible reductions; Table 14 presents these results for the BAU scenario. Based on evaluation of emissions alone, in-Arctic shipping contributes modestly to total BC from shipping; in 2004, Arctic transport vessels contributed less than 1% of ship BC emissions, and in 2050 ships may contribute less than 2.5% of global ship BC emissions.

Effects of the inclusion of navigable routes for diversion traffic in the Arctic are illustrated for BC in Fig. 4. In ~2030, diversion traffic (if ice-free) at only 2% of global shipping (about half of the Panama Canal volume currently and much less than the Suez Canal volume) the diversion traffic could rival emissions from future in-Arctic traffic. By 2050, diversion traffic could dominate shipping sources of Arctic emissions. MFR scenarios can substantially reduce shipping pollution in the Arctic, but growth and diversion may still produce higher emissions of BC and other pollutants in later decades (Fig. 4b).

Regulatory action would be merited if the mitigating benefits are substantial, given that low-sulfur marine fuels will enable technological feasibility to control ship BC and other PM species. While modeling studies need to be conducted to demonstrate and quantify the potential benefits, our MFR scenario shows that with controls Arctic BC from shipping can be reduced in the near-term and held nearly constant through 2050. The MFR scenario affords greater opportunity to compare and explore the merits of policy action on short-lived forcing pollutants from ships.

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4.1 Framing potential impacts

Given that shorter routes will be associated with avoided CO_2 emissions compared to longer routes, assessing the short-lived climate forcing components of these scenarios is important. A first-order comparator can assess the relative potential of non-CO_2 species to contribute to global warming potential (GWP) and to global temperature change potential (GTP). Simplified expressions of these terms have been derived by Fuglestvedt et al. (2009b) for transportation sources of short-lived pollutants. These metrics have informed climate policy implementation decisions by assessing, in a common metric, the net climate impact of technological, policy or operational changes of a mode of transport. Global warming potential is based on the time-integrated radiative forcing due to a pulse emission of a unit mass of gas, and can be calculated for various time intervals. Global temperature change potential provides a metric for the response of the global-mean surface temperature, representing potential temperature change at a given time due to a pulse emission (Shine et al., 2005). While not specifically calibrated to the Arctic conditions and highly uncertain, default relationships are available using radiative forcings and lifetimes from the literature to derive GWPs and GTPs for the main transport-related emissions. Using these default parameters on a 20-year horizon, we estimate first-order comparisons of non-CO_2 emissions from in-Arctic shipping activity in 2030 (Table 15).

The GWP contribution in 2030 of uncontrolled BC from Arctic shipping is at least 17% of CO_2 GWP from ships under the high-growth scenario; GTP contribution is about 5% of CO_2 from ships. These are perhaps lower-bound estimates, given the exclusion in this estimate of fishing vessels and dissimilar impact potential for near-ice emissions. As reported in Table 15, the MFR scenarios reduce BC and OC forcing by a factor of three, illustrating the relative benefit of controlling short-lived forcing pollutants. Moreover, these results may be mitigated if diversion routes through the Arctic do not capture ~2% of global traffic in 2030 as our scenario suggests, either due to non-navigable routes or vessel traffic restrictions; some 55% of GWP and GTP esti-

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mated for 2030 are due to diversion scenario shipping. Notably, sulphate produces negative forcing equivalent to about 25% and 7% of GWP and GTP, respectively, in 2030. Using the 2030 time period for this example reveals the potential for projected growth in shipping to offset the environmental benefits of current legislation reducing marine fuel sulfur content by 2020 (International Maritime Organization, 2008).

Modeling potential impacts using these inventories will clarify both the assessment of impacts and mitigation potential attributable to Arctic shipping. Arctic-specific metrics will improve the first-order assessment for shipping, as has been done for other sources (Quinn et al., 2008). In order to inform technological and policy decisions, important comparisons that are needed include (a) the relative contribution to the climate impact of short-lived pollutants in the Arctic by in-Arctic shipping, non-Arctic shipping, and other anthropogenic sources; (b) mitigation provided by MFR scenarios for Arctic shipping relative to other strategies to control short-lived forcing pollutants from other sources; (c) cost-benefit and cost-efficacy of action to control shipping emissions impacting Arctic conditions, and (d) ranking in-Arctic controls and non-Arctic controls alongside non-shipping costs and benefits. Beyond this, the data sources can be modified to produce new vessel-specific Arctic shipping scenarios as Arctic climate policy strategies and targets are clarified. Inventory data are posted at (http://coast.cms.udel.edu/ArcticShipping/).

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Table 1. 2004 Ship Traffic by Type and Season Reported by the Arctic Marine Shipping Assessment (Arctic Council et al., 2009).

Ship Type	Annual Trips	Season	Seasonal Trips
Bulk Trips	1052	Winter (Dec–Feb)	3072
Container Trips	2096		
General Cargo Trips	1403	Spring (Mar–May)	3390
Government Vessel Trips	273		
OSV Trips	58	Summer (Jun–Aug)	4807
Passenger Vessel Trips	6972		
Tanker Trips	2827	Fall (Sep–Nov)	3729
Tug and Barge Trips	317		
Total Trips in 2004	14 998		14 998

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Table 2. Gas and PM Emission Factors Applied to Current and Future Arctic Shipping (g/kg fuel).

	Ship Type	2004 EFs	2020 EFs	2030 EFs	2050 EFs
CO	All	7.4	7.4	7.4	7.4
NO_x	Transport	78	67	56	56
	Fishing vessels[b]	56	56	56	56
PM	Transport	5.3	1.4	1.4	1.4
	Fishing vessels[b]	1.1	1.1	1.1	1.1
SO_x	Transport	54	10	10	10
	Fishing vessels[b]	10	10	10	10
CO_b	Transport	3206	3206	3206	3206
	Fishing vessels[b]	3114	3114	3114	3114
BC	All	0.35	0.35	0.35	0.35
OC	All	1.07	0.39	0.39	0.39

[a] Based on IMO Study (Buhaug et al., 2009) and Lack et al. (2008, 2009); future EFs reflect current legislation implementation schedules. [b] Fishing emissions rates provided for comparison; estimates included totals even though spatial processing of fishing emissions is not included here.

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Table 3. In-Arctic Shipping Emissions Estimates by Vessel Type 2004 (mt/y)[a].

Vessel Category	CO_2 (000 mt/y)	BC (mt/y)	OC (mt/y)	SO_x (mt/y)	NO_x (mt/y)	PM (mt/y)	CO (mt/y)
Container Ship[b]	2400	260	790	40 000	58 000	3900	5500
General Cargo Ship	2000	220	670	34 000	49 000	3300	4600
Bulk Ships	1200	130	410	21 000	30 000	2000	2800
Passenger Vessels	1100	120	380	19 000	27 000	1900	2600
Tanker	900	100	300	15 000	22 000	1500	2100
Government Vessels	380	40	130	6000	9000	630	880
Tug and Barge	40	4	12	600	863	59	82
Offshore Service Vessel	10	1	4	183	263	18	25
Transit Total	8100	880	2690	136 000	195 000	13 300	18 600
Fishing[c]	3200	350	1080	10 000	58 000	1100	7500
In-Arctic Total (t/y)	11 300	1230	3770	146 000	253 000	14 500	26 100

[a] Values are rounded to nearest 10 mt/y, except for CO_2 (rounded to 10 000 mt/y) and for values that would round to zero (rounded to integer); data sets reported in grams and not rounded. [b] Containership activity includes a portion of a transpacific route within the AMSA domain. [c] Fishing vessel estimates reported in this table for comparison, but not provided within the Transport Vessel inventory reported here. Estimates for fishing vessels should be considered very uncertain.

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Table 4. Input Growth Rates by Vessel Type from Scenario Model used in IMO Study (Buhaug et al., 2009).

	2004 To 2020		2004 To 2030		2004 To 2050	
Vessel Category	BAU Growth	Hi-Growth	BAU Growth	Hi-Growth	BAU Growth	Hi-Growth
Container Ship	2.98%	4.77%	3.42%	5.05%	3.82%	5.38%
General Cargo Ship	0.29%	1.13%	0.42%	1.16%	0.54%	1.22%
Bulk Ships	1.43%	2.27%	1.59%	2.34%	1.72%	2.40%
Passenger Vessels	0.68%	1.53%	0.84%	1.58%	0.99%	1.66%
Tanker	4.46%	5.31%	3.41%	4.16%	2.71%	3.38%
Government Vessels	−0.08%	0.77%	0.10%	0.85%	0.23%	0.90%
Tug and Barge	−0.08%	0.77%	0.10%	0.85%	0.23%	0.90%
Offshore Service Vessel	2.19%	3.04%	1.76%	2.50%	1.47%	2.14%

Note: Growth rates use the same scenario model as the IMO GHG study (Buhaug et al., 2009).

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Table 5. Seasonal Emissions of in-Arctic Ship Traffic for 2004.

Seasonal Summary	CO_2 (000 mt/y)	BC (mt/y)	OC (mt/y)	SO_x (mt/y)	NO_x (mt/y)	PM (mt/y)	CO (mt/y)
Winter	1640	179	550	28 000	39 700	2700	3800
Spring	1790	195	600	30 000	43 300	3000	4100
Summer	2550	278	850	43 000	61 700	4200	5900
Fall	2110	230	700	35 000	51 100	3500	4900
Annual Total (mt/y)	8100	880	2700	136 000	195 800	13 400	18 700

Note: Estimates rounded before summing.

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Table 6. Regional growth rates resulting from vessel-specific growth rates.

	CO_2, BC, CO (Δ/y)	OC (Δ/y)	SOx (Δ/y)	NOx (Δ/y)	PM (Δ/y)
BAU 2004–2020	1.96%	−4.25%	−8.24%	1.03%	−6.37%
Hi-Growth 2004–2020	3.18%	−3.18%	−7.14%	2.24%	−5.25%
BAU 2004–2030	2.12%	−1.76%	−4.30%	0.86%	−3.10%
Hi-Growth 2004–2030	3.29%	−0.63%	−3.20%	2.02%	−1.98%
BAU 2004–2050	2.44%	0.22%	−4.30%	0.86%	−3.10%
Hi-Growth 2004–2050	3.69%	1.45%	−3.20%	2.02%	−1.98%

Note: Growth rates calculated using compound annual growth rate (CAGR) equation.

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Table 7. In-Arctic Shipping Activity by Vessel Type Across Future Scenarios.

Vessel Category	2004 Pct of Total	2020 BAU Pct of Total	2030 BAU Pct of Total	2050 BAU Pct of Total	2020 Hi-G Pct of Total	2030 Hi-G Pct of Total	2050 Hi-G Pct of Total
Container Ship	21%	27%	34%	50%	31%	40%	61%
General Cargo Ship	18%	15%	13%	9%	15%	12%	8%
Bulk Ships	11%	11%	11%	10%	11%	10%	8%
Passenger Vessels	10%	9%	8%	6%	9%	8%	5%
Tanker	8%	13%	13%	11%	13%	12%	9%
Government Vessels	3%	3%	2%	2%	3%	2%	1%
Tug and Barge	0%	0%	0%	0%	0%	0%	0%
Offshore Service Vessel	0%	0%	0%	0%	0%	0%	0%
Transit Total	71%	77%	81%	88%	80%	85%	93%
Fishing[a]	29%	23%	19%	12%	20%	15%	7%

[a] Decline in fishing vessels and increase in transport vessels is attributed to growth scenarios by vessel type (see IMO study for discussion; Buhaug et al., 2009) and negligible change in fish stocks assumed for this work.

Table 8. Summary of in-Arctic Pollutant Inventories for 2004 and BAU Projections.

BAU Scenarios	2004	2020	2030	2050
CO_2 (mt/y)	8 100 000	11 000 000	14 000 000	24 000 000
NO_x as NO_2 (mt/y)	196 000	231 000	244 000	429 000
SO_x as SO_2 (mt/y)	136 000	34 000	43 000	76 000
PM (mt/y)[a]	13 000	4700	5900	10 000
CO (mt/y)	19 000	25 000	32 000	56 000
BC (mt/y)	880	1200	1500	2700
OC (mt/y)	2700	1300	1700	3000
MFR BC (mt/y)	880	360	460	800
MFR OC (mt/y)	2700	400	510	890

[a] PM reductions result from current legislation to reduce SO_x emissions from ships through marine fuel standards and associated decreases in OC due to lower-sufur fuels (Buhaug et al., 2009; Lack et al., 2008, 2009). MFR scenarios aimed at BC would reduce total PM as well, by controlling BC directly and indirectly by reducing OC emissions.

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Table 9. Summary of in-Arctic Pollutant Inventories for 2004 and Hi-growth projections.

High Growth Scenarios	2004	2020	2030	2050
CO_2 (mt/y)	8 100 000	13 000 000	19 000 000	43 000 000
NO_x as NO_2 (mt/y)	196 000	279 000	329 000	752 000
SO_x as SO_2 (mt/y)	136 000	46 000	58 000	133 000
PM (mt/y)[a]	13 000	5600	7900	18 000
CO (mt/y)	19 000	31 000	43 000	99 000
BC (mt/y)	880	1500	2000	4700
OC (mt/y)	2700	2800	2300	5200
MFR BC (mt/y)	880	480	610	1400
MFR OC (mt/y)	2700	840	690	1570

[a] PM reductions result from current legislation to reduce SO_x emissions from ships through marine fuel standards and associated decreases in OC due to lower-sufur fuels (Buhaug et al., 2009; Lack et al., 2008, 2009). MFR scenarios aimed at BC would reduce total PM as well, by controlling BC directly and indirectly by reducing OC emissions.

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Table 10. Summary of Potential Pollutant Inventories from Diverted Global Shipping to Arctic Routes.

Diversions Summary	CO_2 (mt/y)	NO_x (mt/y)	SO_x (mt/y)	PM (mt/y)	CO (mt/y)	BC (mt/y)	OC (mt/y)
2020 Hi-Growth[a]	8 400 000	180 000	26 000	3500	19 000	910	1000
2030 Hi-Growth[a]	23 100 000	410 000	72 000	10 000	53 000	2500	2800
2050 Hi-Growth[a]	110 400 000	1 900 000	344 000	47 000	255 000	12 000	13 500
2020 BAU[b]	6 400 000	130 000	20 000	2700	15 000	700	800
2030 BAU[b]	7 900 000	140 000	25 000	3400	18 000	900	1000
2050 BAU[b]	21 700 000	380 000	68 000	9200	50 000	2400	2700

[a] Hi-growth diversions in 2020, 2030, and 2050 are 1%, 2%, and 5% of global shipping in each of those future years, respectively. Global shipping growth outside of Arctic is ~3.3% per year. [b] BAU diversions in 2020, 2030, and 2050 are 1%, 1%, and 1.8% of global shipping in each of those future years, respectively. Global shipping growth outside of Arctic is ~2.1% per year.

Table 11. Flexibility in Diversion Route Allocation Scenarios.

Route allocation ratios	Equally	Non-polar	Polar-only	Singly
Northeast Passage (NEP in Red)	25%	50%	0%	100%
Northwest Passage (NWP in Light Blue)	25%	50%	0%	100%
Western Polar Route (WPR in Dark Blue)	25%	0%	50%	100%
Eastern Polar Route (EPR in Orange)	25%	0%	50%	100%

Note: Allocations above provided in data for this work; other allocations possible. Colors correspond to Fig. 1g.

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Table 12. Example of Future through-Arctic Shipping Traffic Diversions.

Year	Global Shipping Diverted	Diversion Months	NEP	NWP	EPR	WPR
2010–2020	1%	Aug, Sep, Oct	100%	0%	0%	0%
2020–2030	2%	Aug, Sep, Oct	50%	50%	0%	0%
2031–2040	3.5%	Jul, Aug, Sep, Oct	40%	40%	10%	10%
2041–2050	5%	Jul, Aug, Sep, Oct, Nov	25%	25%	25%	25%

Table 13. High-Growth Scenarios for Black Carbon, With and Without Emissions Control.

Units: Gg/yr	2001[a]	2004[b]	2020	2030	2050
BC non-Arctic	130 (100%)[c]	140 (99.39%)	270 (99.14%)	380 (98.80%)	710 (97.70%)
No Controls, High-Growth Scenario					
BC in-Arctic		0.9 (0.61%)	1.5 (0.53%)	2.0 (0.54%)	4.7 (0.64%)
BC diversion traffic		0 (0.00%)	0.9 (0.33%)	2.5 (0.66%)	12.0 (1.66%)
BC Arctic no control		0.9 (0.61%)	2.4 (0.86%)	4.6 (1.20%)	17.0 (2.30%)
BC Global with Arctic	130	140	280	380	730
Maximum Feasible Regulatory (MFR) Controls, High-Growth Scenario					
BC MFR in-Arctic		0.9 (0.61%)	0.4 (0.18%)	0.6 (0.16%)	1.4 (0.20%)
BC MFR for diversion		0.0 (0.00%)	0.3 (0.10%)	0.8 (0.20%)	3.6 (0.50%)
BC Arctic MFR		0.9 (0.61%)	0.8 (0.28%)	1.4 (0.36%)	5.0 (0.70%)
BC Global with Arctic MFR	130	140	270	377	720

Note: Values rounded for presentation to two significant figures. [a] Previous estimate per Lack et al. (2008, 2009) [b] Updated estimate given in-Arctic data (this work) [c] Percentages represent percent of global BC, presuming that in-Arctic emissions reported here are additive to previous global inventories and allowing for diversion according to scenarios reported here.

Table 14. BAU-Growth Scenarios for Black Carbon, With and Without Emissions Control.

Units: Gg/yr	2001[a]	2004[b]	2020	2030	2050
BC non-Arctic	130 (100%)[c]	140 (99.39%)	210 (99.10%)	260 (99.09%)	393 (98.73%)
No Controls, High-Growth Scenario					
BC in-Arctic		0.9 (0.61%)	1.2 (0.57%)	1.5 (0.58%)	2.7 (0.67%)
BC diversion		0.0 (0.00%)	0.7 (0.33%)	0.9 (0.33%)	2.4 (0.60%)
BC Arctic no control		0.9 (0.63%)	1.9 (0.90%)	2.4 (0.91%)	5.0 (1.27%)
BC Global with Arctic	130	140	212	262	398
Maximum Feasible Regulatory (MFR) Controls, High-Growth Scenario					
BC MFR in-Arctic		0.9 (0.63%)	0.4 (0.17%)	0.5 (0.18%)	0.8 (0.20%)
BC MFR for diversion		0 (0.00%)	0.20 (0.10%)	0.3 (0.10%)	0.7 (0.18%)
BC Arctic MFR		0.9 (0.63%)	0.8 (0.27%)	1.4 (0.28%)	5.0 (0.38%)
BC Global with Arctic MFR	130	140	212	261	394

Note: Values rounded for presentation to two significant figures. [a] Previous estimate per Lack et al. (2008, 2009) [b] Updated estimate given in-Arctic data (this work) [c] Percentages represent percent of global BC, presuming that in-Arctic emissions reported here are additive to previous global inventories and allowing for diversion according to scenarios reported here.

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Table 15. Estimated 20-year GWP and GTP for 2030 Projections of Arctic Shipping and Potential Diversions (Fuglestvedt et al., 2009b).

Pollutant	Diversion (Gg/y)	In-Arctic (Gg/y)	GWP Ratio to CO_2	Gg CO_2 eq GWP	GTP Ratio to CO_2	Gg CO_2 eq GTP
Carbon Dioxide	23 100	18 700	1	41 800	1	41 800
Black Carbon (BC)	2.5	2.0	1600	7235	470	2125
MFR BC	0.8	0.6		2171		638
Organic Carbon (OC)	2.8	2.3	−240	(1229)	−71	(364)
MFR OC	0.8	0.7		(369)		(109)
Carbon Monoxide	53.0	43.0	7	674	4.6	443
Sulfate[a]	28.0	45.0	−140	(10 268)	−41	(3007)

[a] Assumes that SO_x emitted by ships converts to sulfate with 26% conversion ratio, per Khoder (2002); modeled results would be required to verify or update this.

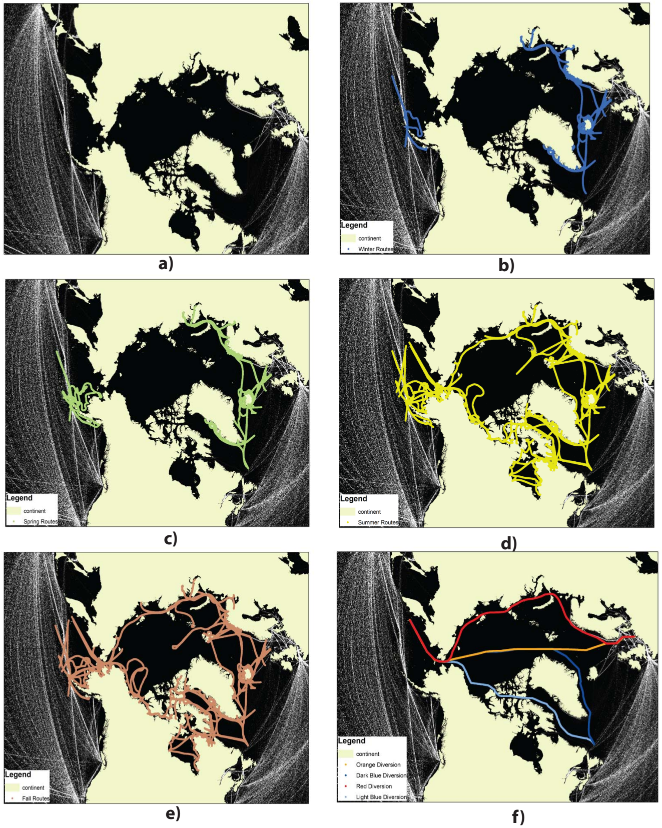

Fig. 1. Summary of Seasonal Traffic Patterns for In-Arctic Shipping: **(a)** Global data prior to this work; **(b)** Winter shipping 2004; **(c)** Spring shipping 2004; **(d)** Summer shipping 2004; **(e)** Fall shipping 2004; and **(f)** Potential global shipping diversion routes given navigable routes for diversion traffic open in Arctic.

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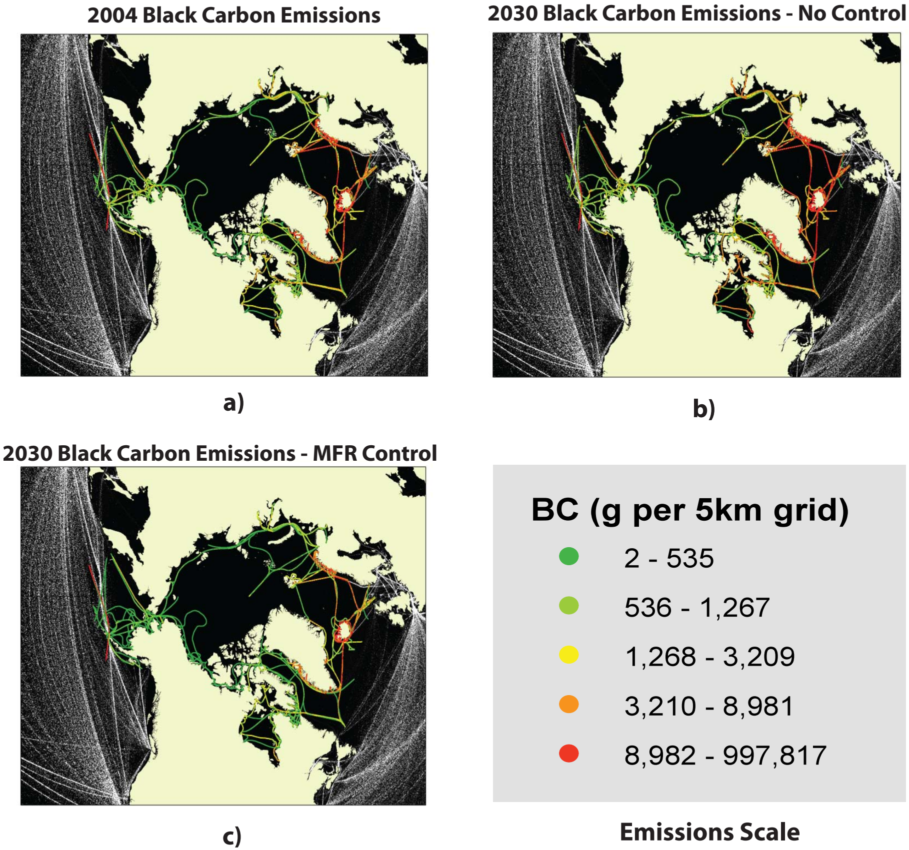

Fig. 2. Illustration of **(a)** 2004 Black Carbon Emissions; **(b)** 2030 projections for Black Carbon; **(c)** 2030 Black Carbon with MFR Controls.

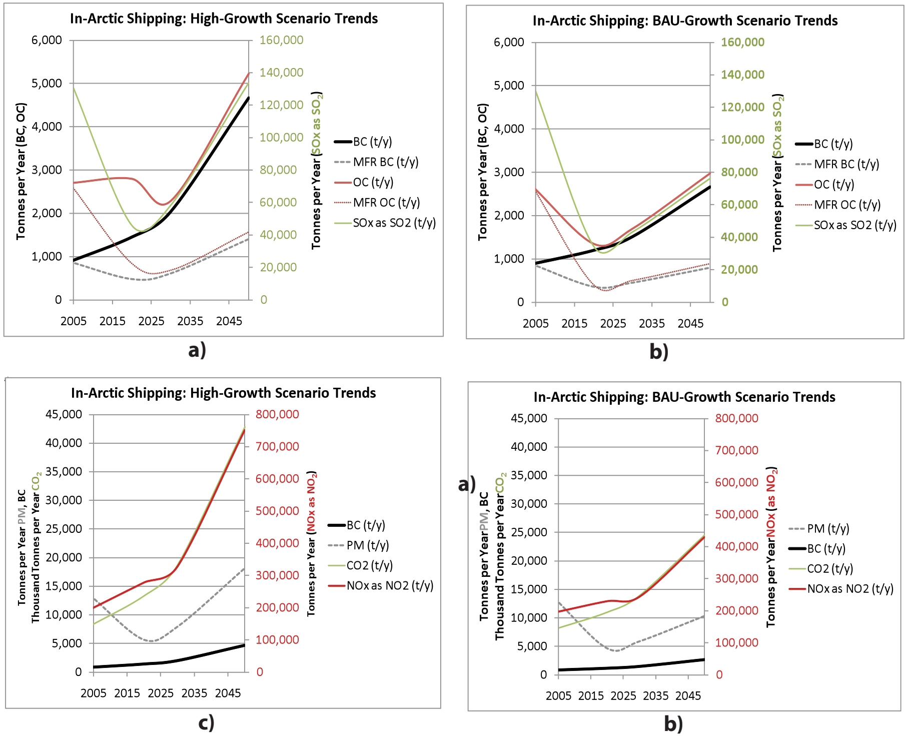

Fig. 3. Comparison of in-Arctic Trends for Black Carbon, Organic Carbon, and SO_x Emissions under **(a)** High Growth and **(b)** BAU Scenarios. Also Shown are the Comparison of Black Carbon, Particulate Matter, CO2 and NO_x Under **(c)** High Growth and **(d)** BAU Scenarios.

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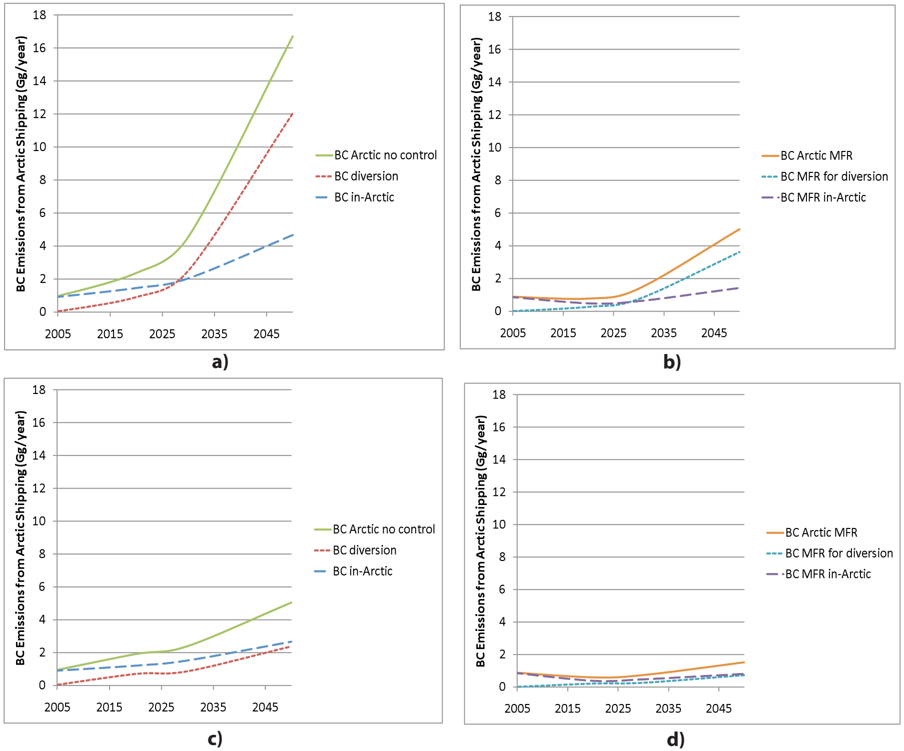

Fig. 4. Comparison of in-Arctic and Potential Diversion Trends for Black Carbon Through 2050 with the Following Scenarios: **(a)** High Growth – No Control, **(b)** and High Growth – MFR Control, **(c)** BAU – No Control and **(d)** BAU – MFR Control.

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