The Impact of Black Carbon Emissions from Projected Arctic Shipping on Regional Ice Transport

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Abstract

The direct and indirect effects of global emissions of black carbon (BC) on the evolution of Arctic climate has been well documented. The significance of within-Arctic emissions of BC is less certain. In light of this, an ensemble of scenarios are developed that simulate the hypothetical diversion of 75% of current and projected shipping traffic from the Suez Canal to the Northern Sea Route (NSR). This experiment shows that BC from ships results in a small change in climate forcing that does not influence the Arctic-wide trajectory of change. However, the shift in forcing from the Suez route to the NSR not only influences regional evolution of sea ice cover, but also results in regional feedbacks that in some locations amplify (e.g. Greenland Sea) and in other locations damp (e.g. Labrador Sea) the sea ice retreat under anthropogenic climate change. The primary mechanism underlying these regional effects is a shift in circulation rather than direct thermodynamic forcing. The most significant impacts are distal from the emissions sources, which is likely to have policy implications as the expansion of industrial and transportation activities into the Arctic is considered.

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Key Points:

- Impact of black carbon emissions within-Arctic was quantified by re-routing 75% of shipping traffic from Suez Canal to Northern Sea Route

- Feedbacks were small Arctic-wide but amplified/dampened feedbacks were observed regionally primarily driven by a shift in circulation

- Largest feedback responses are distant from emission sources which has implications for good governance of expanding Arctic industries

20 **Abstract**

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22 Arctic climate has been well documented. The significance of within-Arctic emissions of BC is
23 less certain. In light of this, an ensemble of scenarios are developed that simulate the
24 hypothetical diversion of 75% of current and projected shipping traffic from the Suez Canal to
25 the Northern Sea Route (NSR). This experiment shows that BC from ships results in a small
26 change in climate forcing that does not influence the Arctic-wide trajectory of change. However,
27 the shift in forcing from the Suez route to the NSR not only influences regional evolution of sea
28 ice cover, but also results in regional feedbacks that in some locations amplify (e.g. Greenland
29 Sea) and in other locations damp (e.g. Labrador Sea) the sea ice retreat under anthropogenic
30 climate change. The primary mechanism underlying these regional effects is a shift in circulation
31 rather than direct thermodynamic forcing. The most significant impacts are distal from the
32 emissions sources, which is likely to have policy implications as the expansion of industrial and
33 transportation activities into the Arctic is considered.

34 **1 Introduction**

35   Investors and communities alike are planning for the possible regime shift in Arctic
36 shipping driven by receding ice, lower fuel prices, and industry consolidation [*Duarte et al.*,
37 2012; *Goldstein et al.*, 2018]. This shift has the potential, as yet unrealized, to make the
38 transpolar shipping route at least seasonally competitive with the Suez Canal [*Buixadé Farré et
39 al.*, 2014; *Meng et al.*, 2017; *Ng et al.*, 2018; *Theocharis et al.*, 2018]. Although the economic
40 viability of transit shipping along such Arctic routes remains under considerable debate
41 [*Hildebrand and Brigham*, 2018; *Lasserre*, 2014], ship traffic continues to increase due to
42 Russian cabotage[1] [*Gunnarson*, 2013], fish stock migrations, and increased tourism [*Miller et al.*,
43 2020; *Stewart et al.*, 2007].

44   Black carbon (hereinafter referred to as BC) deposition on Arctic sea ice has been posited
45 as one explanatory factor in observed rapid Arctic sea ice retreat [*Ramanathan and Carmichael*,
46 2008]. BC aerosols from sources including diesel engines, industrial processes and biomass
47 burning absorb strongly across visible and ultraviolet wavelengths. As a result, it can influence
48 Arctic temperatures and the extent of ice and snow cover by (i) directly absorbing solar
49 radiation; (ii) acting as nuclei to form cloud drops and ice crystals, indirectly influencing cloud
50 albedo via modifying the microphysical properties and lifetime of clouds [*Haywood and
51 Boucher*, 2000; *Ramanathan and Carmichael*, 2008]; and (iii) reducing ice and snow albedo
52 after deposition [*Flanner et al.*, 2009; *Ryan et al.*, 2018; *Warren*, 1982]. Previous studies suggest
53 a measured decrease in Arctic albedo of 1.5 – 3.0% caused by snow and ice darkening from BC
54 from all combustion sources, onshore and offshore [*Bond et al.*, 2013; *Hansen and Nazarenko*,
55 2004].

56   BC interactions and feedbacks are poorly constrained. For example, freshly emitted BC
57 particles are generally hydrophobic and cannot serve as cloud condensation nuclei (CCN).
58 Through microphysical aging processes, these carbonaceous particles gradually become
59 hydrophilic on timescales that are highly variable [*Fierce et al.*, 2015]. These particles have a
60 shorter average atmospheric residence time due to a high wet scavenging efficiency [*von

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[1] Cabotage in this paper, following *Gunnarsson* [2013], is defined as domestic port-to-port transport by both domestic and foreign carriers.

61   *Schneidemesser et al.*, 2015]. The uncertainty in atmospheric residence time of BC is particularly
62   evident in estimates of the distance from ship stacks to deposition. Given the complex web of
63   uncertain processes, ranging from changes in albedo upon deposition, changes in snow
64   metamorphism, phase partitioning in clouds, and cloud distribution properties, *Bond et al.* [2013]
65   suggest that BC has an overall positive radiative forcing, accounting for direct and indirect
66   effects, of +1.1 Wm^{-2} with 90% uncertainty bounds of +0.17 to +2.1 Wm^{-2}. The direct radiative
67   effect, globally averaged for the industrial era, is estimated at +0.71 Wm^{-2} with 90% uncertainty
68   bounds of +0.08 to +1.27 Wm^{-2}.

69   Maritime transport utilizing heavy fuel oil (HFO) contributes to BC emissions in the
70   Arctic via incomplete combustion [*Corbett et al.*, 2010; *Wu et al.*, 2018]. Unlike BC transported
71   to the Arctic from sub-Arctic terrestrial sources, BC emitted in the Arctic is more likely to
72   remain at low altitudes, due to the typically strong surface inversion, particularly in the winter
73   months. It has been posited that this has the potential to cause Arctic surface temperature to be
74   nearly five times more sensitive to BC emitted within the Arctic than to emissions from lower
75   latitudes, even though these emissions are much smaller in magnitude [*Sand et al.*, 2013a; *Sand*
76   *et al.*, 2016]. It is unclear, however, how the frequency of surface inversions will change in the
77   coming century [*Medeiros et al.*, 2011].

78   As a result of this potential sensitivity, studies have considered whether ship emissions of
79   BC and other particulates will amplify or damp sea ice extent and snow cover feedbacks.
80   Amplification of snow- and ice-albedo feedbacks can occur by deposition lowering the high
81   albedo of ice and snow [*Browse et al.*, 2013; *Corbett et al.*, 2010; *Ødemark et al.*, 2012; *Sand et*
82   *al.*, 2016]. Damping of these feedbacks can occur through indirect effects on clouds; for
83   example, *Stephenson et al.* [2018] find an increase in the formation of clouds with high liquid
84   water content could cause cooling relative to the shipping-free Arctic. All of these studies come
85   with the caveat that BC emissions from Arctic shipping are small compared to those from the
86   terrestrial sub-Arctic. These emissions may be reduced further in the context of a switch from
87   HFO to low-sulfur diesel fuel or LNG and the reduced need for icebreakers, but this significance
88   may increase as BC emissions from industry are reduced. Adding complexity to this issue, the
89   use of low-sulphur fuels has been linked with a possible 85 percent increase in BC emissions
90   [*DNV,* 2020]. We are seeking to understand the additional forcing of Arctic shipping-related BC,
91   and in particular whether it constitutes a feedback of significance in the evolving system.

92   **2 Data and methods**

93   2.1 Climate Model Configuration

94   To quantify climate feedbacks of BC, we use the newly released Community Earth
95   System Model version 2 (CESM2) at approximately 1° horizontal resolution with 32 vertical
96   layers. CESM2 is a fully coupled earth system model that provides state-of-the-art simulations of
97   climate. It contains seven prognostic model components (CAM6/WACCM6, CLM5, CISM2,
98   POP2, CICE5, MOSART, and WW3) to comprehensively represent interactions among
99   atmosphere, land, land-ice, ocean, and sea ice [*Danabasoglu et al.*, 2020].

100   CAM6 improves upon its previous version by including a unified turbulence scheme
101   [*Golaz et al.*, 2002], adopting an updated Morrison-Gettelman cloud microphysics scheme
102   (MG2) [*Gettelman and Morrison*, 2015], and applying a new scheme to calculate subgrid
103   orographic drag [*Beljaars et al.*, 2004]. Notably, CAM6 treats aerosols using a four-mode

104 version of Modal Aerosol Model (MAM4) [*Liu et al.*, 2016]. That is, apart from Aitken,
105 accumulation, and coarse modes preserved in the three-mode version (MAM3) [*Liu et al.*, 2012],
106 an additional primary carbon mode is included in MAM4 to reside freshly emitted particulate
107 organic matter (POM) and BC particles. This strategy allows for the conversion of particles from
108 hydrophobic to hydrophilic. Compared to simulations with MAM3 that combine the primary
109 carbon mode with the accumulation mode, which as a consequence, enhances wet removal of
110 BC, the treatment of separating the primary carbon mode from the accumulation mode in MAM4
111 increases near-surface BC concentrations in the polar regions by a factor of 2 to 10 [*Liu et al.*,
112 2016].

113 In addition, the CESM large ensemble (CESM1-LENS, *Kay et al. 2015*) is used as a kind
114 of proxy testbed [*Deser et al.*, 2020] to provide a more nuanced assessment of uncertainties
115 arising from internal variability. The Large Ensemble Project provides 40 ensemble members
116 performed with 1° resolution of fully-coupled CESM1 under RCP 8.5 from 2006-2100. As is
117 standard practice, the slightly varying initial condition leads to an ensemble spread solely due to
118 the model's internal climate variability [*Kay et al.*, 2015]. While this is not the model
119 implementation used here, it can provide guidance as to the spread that might be expected in
120 model responses in the present application. It should be noted that at the time of submission, all
121 of the required variables from the CESM2 implementation of this large ensemble were not
122 available.

123 2.2 Shipping emissions scenarios

124 Two sets of climate simulations with the CESM2 from 2015 to 2065 are performed. In
125 the control experiment, projected monthly BC emissions from simulated trans-Arctic voyages are
126 injected into the atmosphere along with BC emissions from *Peters et al.* [2011] and other
127 emissions inventories from IPCC AR5 [*Lamarque et al.*, 2010] based on the Shared
128 Socioeconomic Pathways (SSPs) 5 under the Representative Concentration Pathway (RCP) 8.5
129 scenario (*O'Neill et al.*, 2016, hereinafter referred to as SSP5-8.5). BC emitted from Arctic
130 shipping is injected in the primary carbon mode of CAM6.

131 Small errors in the existing CMIP6 SSP5-8.5 scenario forcing (Figure 1(a)) were
132 corrected to create a new control experiment rather than using the standard CMIP6 scenario. The
133 main issues with the original SSP5-8.5 data are as follows. First, BC emissions in the standard
134 scenario assume that the NSR is navigable all year round regardless of ice cover, when in reality,
135 Arctic voyages are heavily concentrated in the peak months of July through October. We
136 therefore limited shipping emissions to those months in which the NSR was technically
137 accessible following the method of *Stephenson* et al. [2018], in order to reflect the seasonal cycle
138 of Arctic shipping traffic. Second, there are interpolation artifacts in the standard scenario that
139 are evident year round near the North Pole, which we have termed the "Santa Claus effect";
140 these were removed. Third, the HFO ban was implemented from 2020 in the standard scenario,
141 but it is not yet in force. In October 2020, the IMO will vote on whether to approve a
142 recommendation to ban the use and carriage of HFO in the Arctic by July 1, 2029 for Arctic
143 country-flagged vessels operating in domestic waters, and by July 1, 2024 for all other voyages
144 [*Humpert*, 2020]. Given that Russian vessels operating along the NSR are exempted from the
145 shorter timeframe, approval by all Arctic states appears likely. Nevertheless, in the SSP5-8.5
146 forcing, the BC emissions are assumed to rise until 2020 and then begin to drop after this point,
147 likely due to other treaties and not related to the HFO ban [*O'Neill et al.*, 2014]. To address this

148 complexity, the BC emissions in the new control simulation are modified as shown in Figure
149 1(b).

150   With the recent fall in oil prices, reasons to utilize the NSR for transit shipping have been
151 less compelling in the near term. International transit shipping utilizing the entire NSR
152 comprised less than 1% of all voyages from 2016-2018 [*B. Gunnarson, personal communication*,
153 2020]. These transits were primarily associated with demonstration voyages and the
154 repositioning of vessels. In contrast, cabotage along the Russian Arctic coast comprised 88% of
155 the total voyages on average over the same period, with monthly peaks of at least 250 voyages
156 from July to October, and up to 400 voyages in September in some years. Thus, emissions
157 associated with NSR transit shipping are a small fraction of the total BC load associated with
158 Arctic shipping at present. Furthermore, the BC load in the Arctic is comprised primarily of sub-
159 Arctic terrestrial sources [*Law and Stohl*, 2007; *Shindell et al.*, 2008]. In this uncertain context,
160 to unambiguously characterize the climatic response to a postulated highly active route, a large
161 perturbation was designed. The experiment is thus designated "big kick". Specifically, this
162 approach lays the groundwork for understanding better what useful information might be gleaned
163 from climate simulations of the impacts of NSR shipping in general, and where greater precision
164 is likely to be most effective. In that spirit, an ensemble of integrations is conducted that re-
165 routes 75% of BC emissions from current and projected Suez Canal traffic [*Gidden et al.*, 2019]
166 to the Arctic, at equal 0.5-degree intervals along a route from the Bering Strait to Rotterdam
167 (Figure 1(c)). Each of the ensemble members was performed with the "big kick" emissions, and
168 a small perturbation to the surface air temperature to create internal variability. While four
169 ensemble members is small, this should be sufficient to detect a signal in atmospheric circulation
170 and sea ice responses, as described in *Deser et al.* [2012].

171   2.3 Quantifying feedback gain

172   An important target for this analysis is to reach an understanding of the potential for BC
173 load to amplify or damp greenhouse gas feedback effects, as opposed to simply quantifying the
174 additional forcing (both positive and negative) that BC imposes on the system. BC has potential
175 for impacts that both amplify (through albedo reduction, *Hansen and Nazarenko*, 2004) and
176 damp (through increases in cloud liquid water content, *Stephenson et al.*, 2018) the response to
177 climate change. This is addressed through a feedback gain calculation following *Dufresne and*
178 *Bony* [2008] based on the simple planetary energy balance response to a change in radiative
179 forcing ΔR, viz.,

$$\Delta T = \frac{\Delta F_{TOA}^{rad} - \Delta R}{\lambda} \tag{1}$$

181   The total feedback effect can be divided into:

$$\lambda = \lambda_0 + \lambda_w + \lambda_{LR} + \lambda_c + \lambda_\alpha \tag{2}$$

183 where λ_0, λ_w, λ_{LR}, λ_c, and λ_α are feedback parameters of Planck, water vapor, lapse rate, cloud,
184 and albedo, respectively. To this set, we add a hypothesized BC feedback parameter. Using this
185 we can compare the basic equilibrium response to the observed temperature response, for
186 example, by defining a feedback gain variable:

$$\Delta T = \frac{1}{1-g} \Delta T_E \tag{3}$$

188 in which $g = \sum_{x \neq 0} g_x$, and $g_x = -\frac{\lambda_x}{\lambda_0}$. Thus, we can calculate the feedback gain due to the

189 change in BC forcing between the control and "big kick" experiments by

$$\Delta T_{65-15,"big\ kick"} = \frac{1}{1-g_{BC}} \Delta T_{65-15,control} \qquad (4)$$

191 A similar procedure can be followed for ice volume and area. We acknowledge that our
192 experiments are not in equilibrium, but nevertheless this is a useful measure that allows the
193 integration of multiple interacting effects into a single metric. This serves to direct attention to
194 more detailed analysis.

195 For analysis of the whole Arctic Ocean and its sub-regions, we define the Arctic
196 following *Parkinson and Cavalieri* [2008] (thumbnail image shown in Figure 3(a)) with
197 constituent sub-regions demarcating the Labrador Sea, the Greenland Sea, the Barents and Kara
198 Seas, the Siberian Sea, the Beaufort Sea, the Central Arctic, the Arctic Ocean (including the
199 Siberian Sea, the Beaufort Sea, and the Central Arctic, not shown), the Bering Sea, Seas of
200 Okhotsk, the Canadian Archipelago, and Hudson Bay, abbreviated as Lab, GIN, Bar, Sib, Beau,
201 CArc, ArcOc, Bering, Okhotsk, CAArch, and Hudson, respectively.

3 Whole Arctic Response

203 The total response to BC over the whole Arctic - ice volume, concentration, and
204 distribution, surface temperature, broadband albedo, cloud fraction, longwave and shortwave
205 heating rates - is modest, in line with previous studies [*Flanner*, 2013; *Holland et al.*, 2012; *Sand*
206 *et al.*, 2013b]. These are not shown, since the significant differences (even at the 90%
207 significance level) are very small. An indication of these differences is summarized in Table 1, in
208 the form of linear trends for the last thirty years of the integrations (2035-2065) for the control
209 experiment and the "big kick" ensemble mean. Based on these trends, it could be argued that the
210 ice volume across the whole Arctic diminishes slightly more rapidly and the temperature
211 increases slightly more in the ensemble mean compared to the control, as the presence of
212 additional BC load in the atmosphere does result in the expected physical responses. But as is
213 readily apparent, in the context of high interannual variability in this system, these results in
214 aggregate are not statistically significant. More detail can be seen for example in Figure 2, which
215 shows the time series of ice volume differences from each season, averaged across the ensemble
216 members, expressed as a Z-score. This behavior is quite representative of individual ensemble
217 member results in every season, and of other measures such as surface temperature and
218 longwave heating rate. As is readily apparent, on an Arctic-wide basis, the rate of ice loss does
219 not accelerate in the "big kick" experiment ensemble relative to the control. Thus, it is apparent
220 that there is no net amplification (nor a damping) of the response that is sufficient to set up an
221 additional feedback in the whole Arctic system.

222 This conclusion is reflected most efficiently in the calculation of the feedback gain
223 parameter. In order to set bounds for significance in the feedback gain parameter, the CESM1-
224 LENS ensemble members were compared pairwise (Figure 3(a)). The gain calculation is shown
225 for the entire Arctic at the left of the figure, as well as being disaggregated into each the Arctic
226 Seas. The median feedback for the whole Arctic is 0.00 with standard deviation of 0.21 for
227 surface temperature, 0.21 for ice concentration and 0.20 for ice volume. The shading corresponds
228 to the probability that the feedback gain magnitude would have been evident through internal
229 system variability alone. This figure shows the potential for large feedback gain values evident

230   particularly in the Barents and Bering Seas generated by internal variability in the ensemble.
231   Bringing the focus to the range more typical of the experiments being assessed here (Figure 3(b))
232   shows that - for the whole Arctic - the feedback gain in the "big kick" experiment cannot be
233   considered to be significant for surface temperature, aggregate ice concentration or ice volume
234   per unit area. As a result, it can be concluded that this experiment confirms previous research
235   indicating that Arctic shipping, while having the potential to perhaps slightly influence the
236   trajectory of Arctic sea ice retreat, does not induce additional Arctic-wide feedbacks.

4 Regional response

238   The same cannot be said, however, when disaggregating the response. Figure 3 also
239   shows the feedback gain parameter for 11 distinct regions of the Arctic. The median feedback
240   gain for the CESM1-LENS is zero for each of these regions. It is apparent that feedbacks are
241   generated in the "big kick" ensemble in some of these regions at levels that amply exceed one
242   standard deviation in the CESM1-LENS. While this cannot be a strict test of statistical
243   significance, because of the different model configurations, it can serve as a guide to model
244   responses that are likely to be outside of expectation from random chance.

245   The larger feedback gain values are negative in Baffin Bay and the Labrador and Siberian
246   Seas, strongly positive in the Bering Sea, and somewhat positive in the GIN Seas and to a lesser
247   extent the Barents/Kara Seas. The differing signs of the feedback gain in different regions
248   suggest why the Arctic-wide feedback is effectively zero. That said, even though the median is
249   zero, the variance in internally generated feedback gain in the CESM1-LENS is substantially
250   greater than one in the Bering and Barents/Kara Seas, and as a result these two regions will be
251   largely excluded from the following discussion.

252   It is particularly meaningful from a policy standpoint that the regions showing the largest
253   "significant" feedback responses are distant from the regions where the additional BC load of the
254   "big kick" experiment is largest (Figure 1). Furthermore, this suggests that the ice changes are
255   influenced, if not driven, by perturbations in ice and atmosphere dynamical effects rather than
256   albedo forcing by proximal deposition, or local cloud radiative forcing. This is borne out by, for
257   example, a comparison of the longwave and shortwave heating rates in the GIN Seas (see
258   supplementary Figure S1).

259   The sea level pressure (SLP) changes provide a useful indicator of atmospheric
260   dynamical responses to the imposed BC load. The changes are modest but systematic, and may
261   be summarized as a small but consistent tendency toward less negative indices for both the
262   Northern Annular Mode and the Arctic dipole patterns (which can be diagnosed, for example,
263   from the loadings onto EOF1 and 2 in the 1000hPa height fields, but are also apparent in the SLP
264   patterns). This effect is in the context of an enhancement in the propensity toward a negative
265   index Northern Annular Mode associated with greenhouse gas emissions that is typical of most
266   climate change scenarios [*Gillett and Fyfe*; 2013]. These small shifts in the circulation that act as
267   a perturbation on greenhouse gas forcing result in a reduction in the transpolar drift stream, a
268   weakening of ice evacuation from the Siberian coast toward the Beaufort Sea, and a weakening
269   of the ice exported out through the Bering Strait. All of these effects are consistent with the
270   negative feedback gain parameter in the Siberian Sea and with findings such as those of *Wang et*
271   *al.* [2009]. This is also consistent with the small but positive feedback gain in the aggregate ice
272   area in the Beaufort Sea.

273   In the spring (MAM), there is also an eastward shift of the Siberian high associated with
274 the Arctic Dipole (AD) in the ensemble mean "big kick" experiment (Figure 4). While the
275 loading onto the AD mode varies across ensemble members, all members show an increasing
276 propensity toward a positive mode in the last two decades of the simulations. This shift towards a
277 slightly positive phase of AD has been demonstrated to lead to favorable conditions for enhanced
278 ice export toward the Atlantic [*Watanabe et al.*, 2006].

279   In the summer (JJA), the SLP difference between the ensemble mean and the control
280 reveals positive values centered on the western Arctic (that is, Iceland-Greenland-Canadian
281 Archipelago-Beaufort Sea) and negative values centered on the eastern Arctic (Barents and Kara
282 Seas-Laptev Sea-Siberian Sea). This feature is also evident in the results of *Overland et al.*
283 [2012]. This persistent AD signature facilitates southerly wind flow from the Bering Strait,
284 bringing warm North Pacific waters into the Arctic Ocean, but also accelerating ice export
285 through Fram Strait [*Wang et al.*, 2009].

286   The signal in the North Atlantic is stronger, whereby the deepening of the polar low
287 storm track in the GIN Seas is apparent, in all seasons, but particularly winter (DJF) and spring
288 (MAM) (Figure 4). The impact on the ice regime in MAM is shown in Figure 5 for total,
289 dynamic, ridging and thermodynamic ice differences from "big kick" ensemble member 1 for
290 enhanced clarity (with the total MAM ice volume change for the other ensemble members shown
291 in supplementary Figure S2). The overall impact in ice volume shows a redistribution from the
292 eastern Barents and Kara Seas to the marginal ice zone in the GIN Seas. This is as a result
293 particularly of the influence of dynamical processes as shown in the difference in ice volume due
294 to ice transport and ridging (Figures 5(b) and (c)), although this is also reflected somewhat in the
295 distribution of ice growth and melt (Figure 5(d)). An enhancement of the polar low storm track
296 in all seasons apart from summer (JJA) leads to an increase in the incursion of sub-Arctic air into
297 the region, with concomitant warming in the GIN and Barents Seas. Consistent with this logic
298 are ice velocities that are generally more cyclonic in this region in the "big kick" ensemble
299 members and increased ice drift speed in the region of enhanced export. As a result, significant
300 changes in the ice regime are manifest all along the eastern Greenland coast even though this is
301 distal from the perturbation in shipping activity.

302   The negative feedback gain parameters in the Baffin Bay and Labrador Sea region are
303 also driven primarily by ice transport effects. This region, typical of Arctic projections, maintains
304 a relatively heavy seasonal ice cover throughout much of the simulation across seasons, with
305 spring (MAM) ice concentrations relatively flat at around 60% throughout the entire integration,
306 even as the region is close to ice free in fall (SON). Ice thickness decreases in every season, and
307 most rapidly in winter (DJF) and spring (MAM). Consistent signals across all ensemble members
308 yielding statistically significant differences are also evident in warming temperatures and
309 increased ice export from Baffin Bay out through the Labrador Sea. These changes in ice regime
310 are then reflected in an increase in ice associated with thermodynamic growth. The conclusion
311 based on these observations is that the modest additional warming evident in the "big kick"
312 experiment is insufficient to offset the increased growth in ice as the shift in ice drift evacuates
313 ice toward the south. A negative feedback then results in the western Greenland coastal zone.

314   This kind of integrative impact on ice cover associated with subtle shifts in circulation
315 has been documented by *Kwok* [2000]; *Maslanik et al.* [2000]; and *Rigor et al.* [2002]. These
316 dynamical mechanisms may also have profound implications for weather extremes in the mid-
317 latitude [*Cohen et al.*, 2014; *Coumou et al.*, 2018].

5 Discussion

The future significance of international transit shipping in the Northern Sea Route will depend on numerous factors, including the interests and aspirations of Arctic nations, a sustainable cargo base, the length of the navigation season, and the availability of navigational support infrastructure. In this context, the effects of shipping on the climate system of the Arctic are small, but in our view, not insignificant.

The mitigation of black carbon emissions was expected to present "a potentially valuable opportunity with a very short delay between action and effect" [*Grieshop et al.*, 2009, p. 533]. This is particularly true for the Arctic due to the short time from emission to deposition (days to weeks [*Bond et al.*, 2013; *Hansen and Nazarenko*, 2004]). Our findings suggest this opportunity is more limited than might have been hoped. It is evident from these experiments and analyses that even a large perturbation in the usage of the Northern Sea Route, with its concomitant increase in black carbon emissions, is unlikely to be a significant factor in accelerating Arctic sea ice loss. Indeed, these simulations did not include the impacts of sulfate aerosols that attend enhancing shipping emissions, which can often yield a cooling effect [*Stephenson et al.*, 2018]. What is significant, however, is that these emissions do have the potential to affect regional feedback processes, that the mechanism underlying these effects is largely dynamical changes in the system, and that the most significant impacts are distal from the emissions themselves. Importantly, it appears that an important response is via the North Atlantic storm track, which has significance for operations in this busy region of the Arctic. As a result, policy-makers may have an interest in knowing more precisely what level of black carbon load, regardless of source, induces the observed regional changes.

Furthermore, the future of emissions contributions from Arctic ships - be they engaged in fishing, cabotage or transit - depends on the speed of technological developments and adoptions toward zero-emission fuels. The International Maritime Organization aims to halve emissions from shipping by 2050, while Arctic nations may adopt more ambitious targets in their sovereign seas. For example, the Norwegian Shipowners' Association has stated a goal of halving emissions by 2030, and to purchase only ships with zero-emissions technology from 2030. While these are relatively minor goals in the global black carbon budget, such aspirations form an important part of an overarching maritime shipping strategy.

Acknowledgments

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Table 1. Arctic wide average linear trend, per decade, 2035-2065, showing results from the control simulation, the ensemble mean and the standard deviation of the ensemble.

Figure 1. Global maps of BC anthropogenic emissions in February 2050 for (a) the standard SSP5-8.5 scenario forcing, (b) our modified forcing for the control simulation and (c) the emissions associated with the "big kick" ensemble.

Figure 2. Time series of ice volume difference between the "big kick" ensemble mean and the control simulation over the Arctic, expressed as a Z-score.

Figure 3. Response of BC in the Arctic and each subregion as defined by Parkinson and Cavalieri [2008] showing (a) the feedback gain parameter of the CESM1-LENS ensemble members selected pairwise (and a thumbnail map of the regions), and (b) a comparison between the CESM1-LENS ensemble members and the experiments. Shading of the CESM1-LENS results indicates the frequency of feedback gain value inferred from the probability density function, with darker colors implying higher frequency. The boxplot displays the median (white line) and interquartile range across four ensemble members of the "big kick" experiment.

Figure 4. Difference of sea level pressure between "big kick" ensemble mean and control for each season, defined by the months indicated, for the period 2035-2065.

Figure 5. Relative change in spring ice volume between "big kick" ensemble member 1 and control 2035-2065 by (a) total (b) dynamic (c) ridged and (d) thermodynamic processes. The relative change is computed using $(\text{Value}_{\text{"big kick"}} - \text{Value}_{\text{control}}) / \text{Value}_{\text{control}}$.
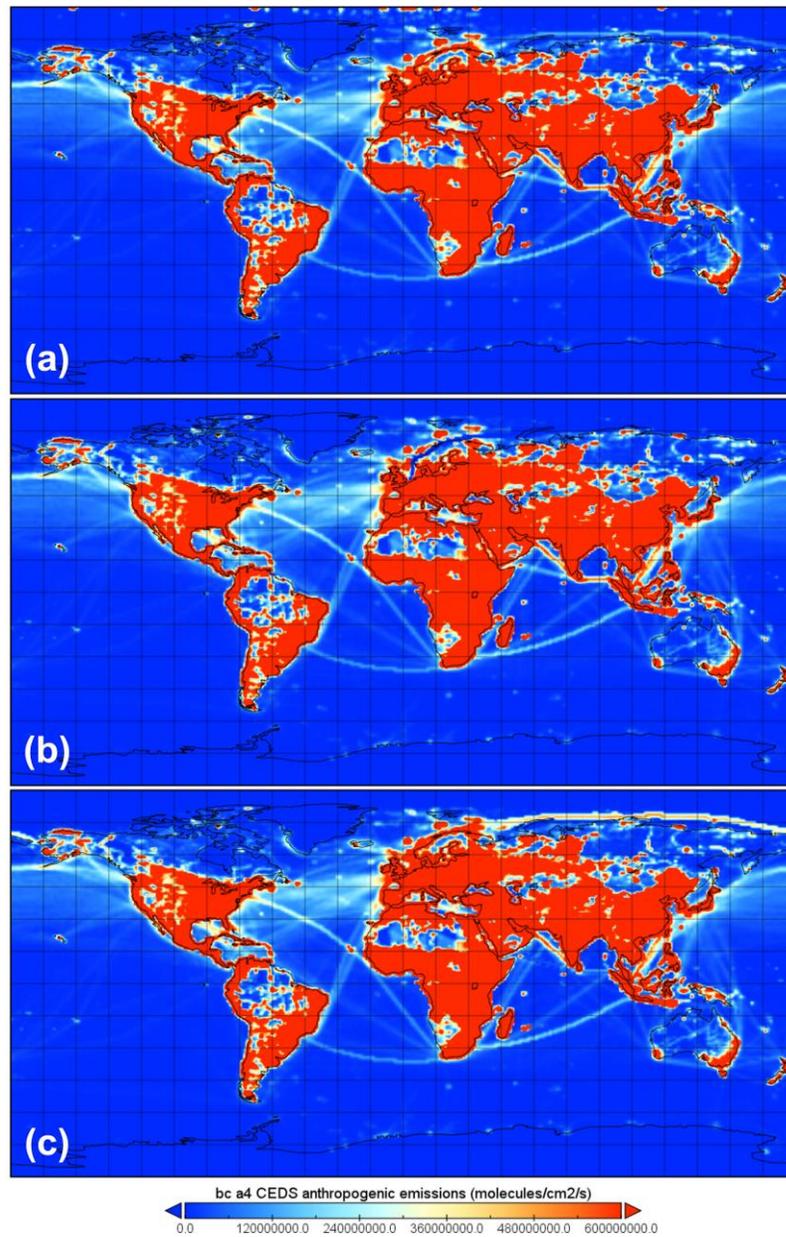
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		Season			
		DJF	MAM	JJA	SON
Ice volume	Control	-0.008	-0.008	-0.008	-0.004
	"Big Kick"	-0.010 (0.003)	-0.009 (0.002)	-0.008 (0.002)	-0.005 (0.001)
Ice area	Control	-0.297	-0.106	-0.373	-0.515
	"Big Kick"	-0.358 (0.140)	-0.075 (0.070)	-0.383 (0.110)	-0.559 (0.119)
Albedo	Control	-0.001	0	0	-0.001
	"Big Kick"	-0.001 (0)	0 (0.0005)	0 (0)	0 (0.0005)
Surface temperature	Control	0.125	0.052	0.041	0.085
	"Big Kick"	0.156 (0.049)	0.058 (0.020)	0.043 (0.009)	0.088 (0.020)

563

564   Table 1.

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bc a4 CEDS anthropogenic emissions (molecules/cm2/s)

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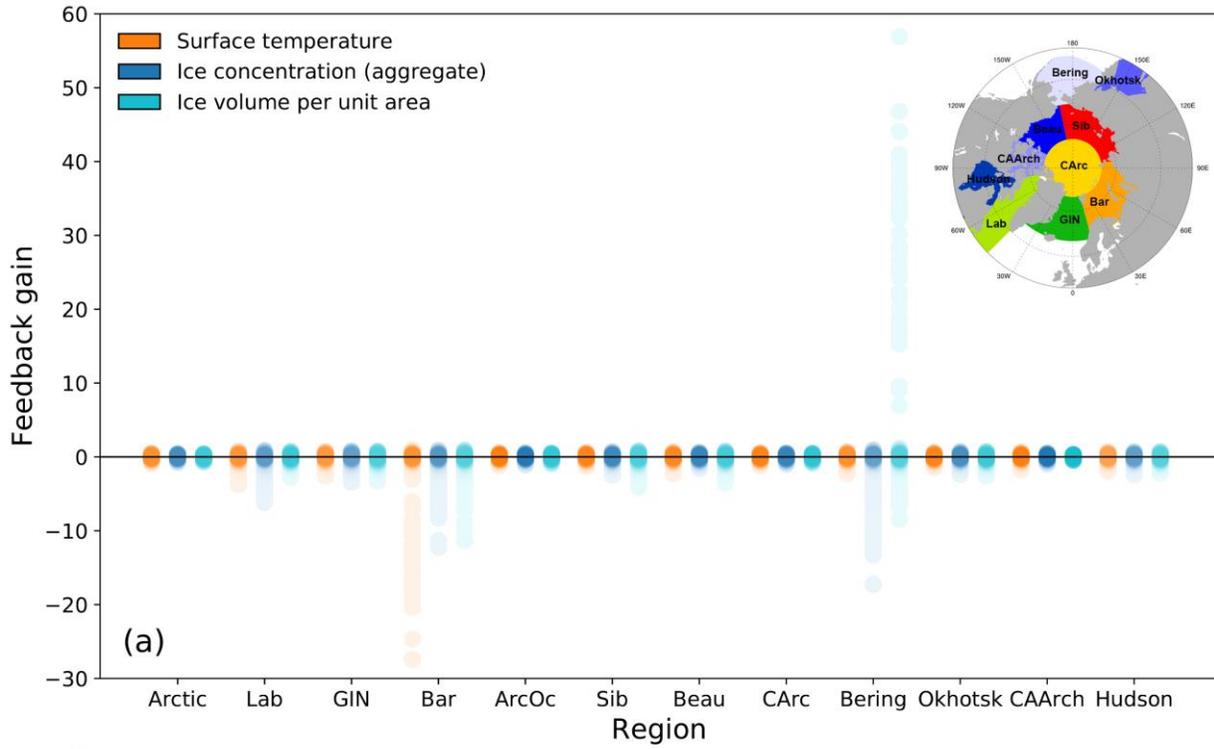568   Figure 1.

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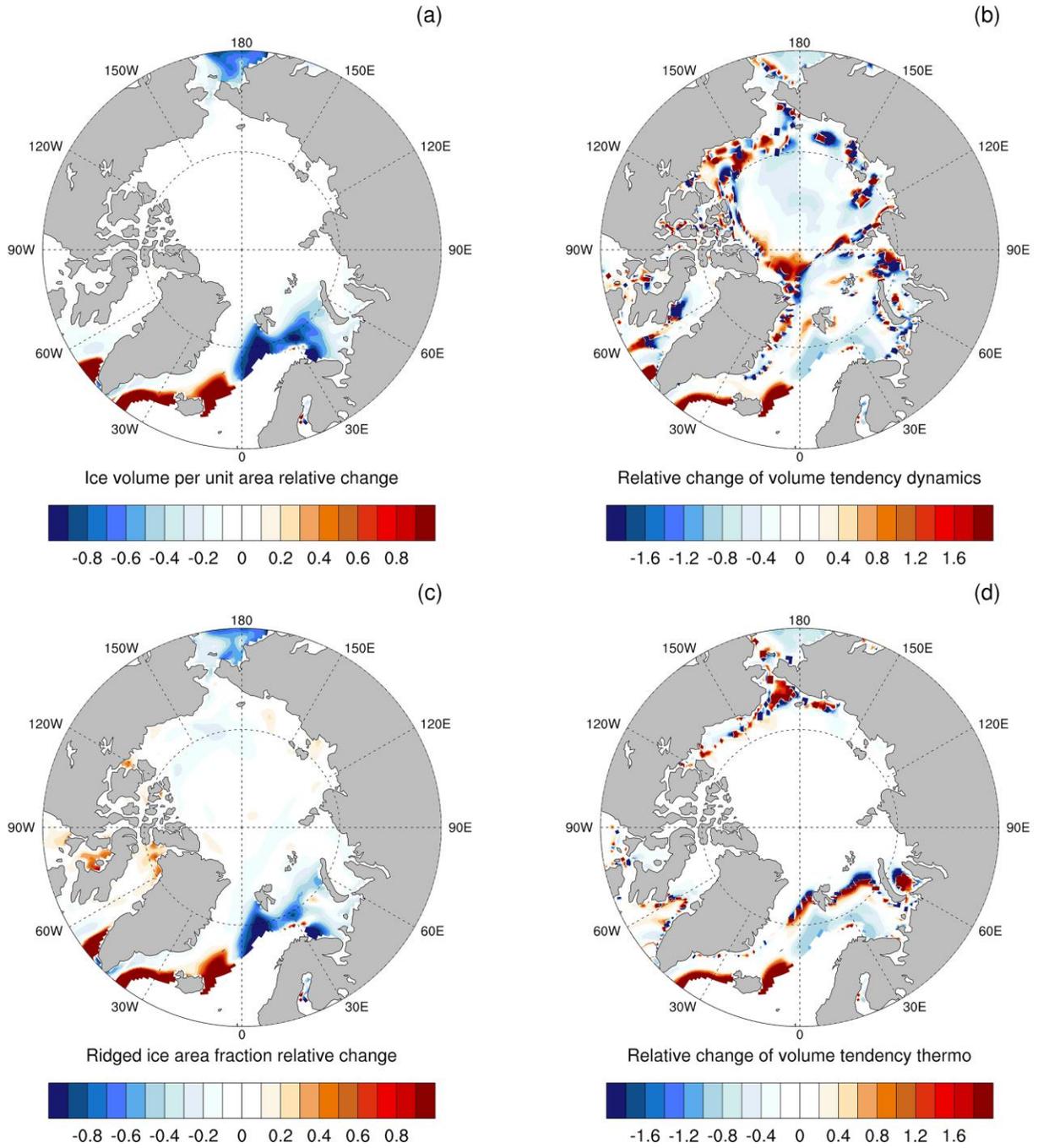
572   Figure 2.

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577   Figure 3.

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Figure 4.

(a)

Ice volume per unit area relative change

-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8

(b)

Relative change of volume tendency dynamics

-1.6 -1.2 -0.8 -0.4 0 0.4 0.8 1.2 1.6

(c)

Ridged ice area fraction relative change

-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8

(d)

Relative change of volume tendency thermo

-1.6 -1.2 -0.8 -0.4 0 0.4 0.8 1.2 1.6

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585   Figure 5.

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