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Key Points:

- Fishing vessels are a significant, overlooked source of SLCF emission
- Global fishing vessel black carbon emissions are an order of magnitude larger than prior estimates
- Emerging policies may further enhance the net climate warming from fishing vessels

Supporting Information:

- Text S1 and Tables S1–S7

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Emissions and climate forcing from global and Arctic fishing vessels

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Abstract Fishing vessels were recently found to be the largest source of black carbon ship emissions in the Arctic, suggesting that the fishing sector should be a focus for future studies. Here we developed a global and Arctic emissions inventory for fishing vessel emissions of short-lived and long-lived climate forcers based on data from a wide range of vessel sizes, fuel sulfur contents, engine types, and operational characteristics. We found that previous work generally underestimated emissions of short-lived climate forcers due to a failure to account for small fishing vessels as well as variability in emission factors. In particular, global black carbon emissions were underestimated by an order of magnitude. Furthermore, our order of magnitude estimate of the net climate effect from these fishing vessel emissions suggests that short-lived climate forcing may be particularly important in regions where fuel has a low sulfur content. These results have implications for proposed maritime policies and provide a foundation for future climate simulations to forecast climate change impacts in the Arctic.

1. Introduction

Atmospheric emissions from ships are a potentially critical source of regional climate forcing [*Aliabadi et al.*, 2015; *Corbett et al.*, 2010a]. While land-based emissions are generally larger than ship emissions, emissions from ships have a unique spatial distribution because they are injected into the atmosphere along ship routes and at low vessel smokestack heights. This spatial distribution of ship emissions is particularly important for short-lived climate forcers (SLCFs) that have climate forcing properties that are spatially explicit [*Winther et al.*, 2014; *Coello et al.*, 2015].

SLCFs such as black carbon (BC), organic carbon (OC), sulfur dioxide (SO_2), and nitrogen oxides ($NOx = NO_2 + NO$) have short atmospheric lifetimes and can cause both climate warming and cooling [*Myhre et al.*, 2013]. BC has an atmospheric lifetime ranging from days to approximately 2 weeks. The BC climate effect results in warming and is recognized as the second most important emission after CO_2 in terms of anthropogenic climate forcing [*Bond et al.*, 2013]. OC, NOx, and SO_2 are often coemitted with BC and generally have an overall cooling effect [*Shindell et al.*, 2009; *Faloona*, 2009; *Eyring et al.*, 2010]. NO_x emissions from ships produce ozone (O_3) and hydroxyl radicals (OH), which reduces the lifetime of methane (CH_4). The net climate effect of ship NOx depends on the balance of warming (due to O_3) and cooling (due to CH_4) [*Holmes et al.*, 2014; *Eyring et al.*, 2010; *Myhre et al.*, 2011]. As a consequence of the short atmospheric lifetimes of SLCFs, their climate impacts occur on relatively short time scales (less than 30 years), and their spatial distribution is heterogeneous [*Collins et al.*, 2013; *Baker et al.*, 2015]. Therefore, the resulting climate forcing from SLCFs is also inhomogeneous. The heterogeneous distribution of emissions makes diagnosing the regional and global climate impacts complex for SLCFs [*Baker et al.*, 2015; *Shindell et al.*, 2009]. When SLCFs are considered together with CO_2, management choices to mitigate climate change can be significantly different from considering CO_2 alone [*Unger et al.*, 2010; *Peters et al.*, 2011].

Fishing vessels were recently discovered to be the largest source of ship SLCF emissions in the Arctic, suggesting that fishing studies are an important focus area for improved estimation [*Winther et al.*, 2014]. The Arctic region may be of particular interest for understanding fishing emissions because the vessel emissions occur in more northerly places in comparison to land-based emissions. Ships operating in the Arctic may emit up to 50% more BC than in other regions due to highly variable engine loads depending on ice conditions and ice breaking requirements [*Lack and Corbett*, 2012]. A net warming from SLCFs may also be enhanced in the Arctic. For instance, there may be less cooling from SO_2 emissions in the Arctic because the indirect aerosol effect is reported to be weaker than the direct sulfate forcing due to less efficient cloud formation. Due to inactive photochemistry during the winter, the changes in OH concentrations due to NOx emissions from ships are small [*Ødemark et al.*, 2012]. The effect of OH on CH_4 lifetime is further limited by continuous low temperatures in the Arctic [*Ødemark et al.*, 2012]. Furthermore, the Arctic climate is particularly sensitive to BC both in the atmosphere and from deposition on snow and ice [*Quinn et al.*, 2008; *Bond et al.*, 2013; *Flanner*, 2013]. However, emission estimates for Arctic fishing vessels have relied on coarse assumptions regarding BC emission factors which is an important area for future work [*Winther et al.*, 2014].

In addition to Arctic fishing emissions, there is also a reason to suspect that global SLCF emissions from fishing vessels have been underestimated in previous inventories. Previous work has investigated the impact that fishing gears have on fuel consumption and emissions [*Tyedmers*, 2001; *Ziegler and Hansson*, 2003]. While many inventories of maritime emissions include only large vessels, estimates of emissions that include small vessels suggest that fishing vessel CO_2 emissions are 2 to 7 times larger than reported in previous inventories [*Tyedmers et al.*, 2005]. However, emissions estimates that include small vessels have only focused on long-lived climate forcers (LLCFs), namely, CO_2, methane (CH_4), and nitrous oxide (N_2O), whereas SLCFs have been overlooked.

While the global contribution of SLCF emissions from all maritime vessels has been studied extensively [*Corbett and Koehler*, 2003; *Endresen et al.*, 2007; *Lack et al.*, 2008; *Eyring et al.*, 2010; *Dalsøren et al.*, 2009; *Fuglestvedt et al.*, 2010], our study seeks to address three critical knowledge gaps that are specific to fishing vessels. First, global maritime SLCF emission studies focus on vessels larger than 100 gross tonnage (GT) which excludes an estimated 1.3 million fishing vessels [*Endresen et al.*, 2007]. Second, previous work has used constant BC emission factors based on a limited data set from a single study of only two ships [*Sinha et al.*, 2003] overlooking an expanded literature of measurements that includes a wide range of engine speeds, engine types, fuel qualities associated with regional fuel sulfur control laws, and the ship-to-ship variability of a diverse fleet [*Lack et al.*, 2008]. For example, most fishing vessels operate medium speed diesel (MSD) engines with distillate fuels within nonroad equipment fuel quality standards [*Lack et al.*, 2009] and are reported to emit twice as much BC as slow speed diesel (SSD) engines (used to operate transport ships) [*Lack et al.*, 2008; *Wang and Minjares*, 2013]. Third, we are not aware of any previous work that has estimated the climate forcing associated with fishery SLCF emissions. Thus, the net climate forcing from fisheries remains largely unknown.

In addition to regional and global inventories, an improved understanding of fishing vessel emissions is also of importance for advancing food sustainability. Demand for sustainably certified seafood is growing rapidly, as major global retailers have promised to source fish and crustaceans from sustainable sources [*Sampson et al.*, 2015]. Fishing vessel emissions have recently emerged as one important sustainability criterion for seafood [*Parker et al.*, 2015; *Smith et al.*, 2010; *Thrane et al.*, 2009]. These emission concerns have led to ecolabel initiatives such as Seafood Watch that are working to inform consumers about greenhouse gas (GHG) impacts of the seafood industry [*Parker et al.*, 2015; *Pelletier and Tyedmers*, 2008].

Given the importance of fishing vessel emissions and the critical knowledge gaps related to fishing vessel size and emission factors, we seek to develop a revised global and Arctic emissions inventory. We hypothesize that previous global inventories of commercial shipping may be understated due to the lack of inclusion of smaller fishing vessels (<100 GT) and previously assumed emission factors that did not account for the more extensive measurements across a range of engine speeds, engine types, fuel quality and regional fuel sulfur control laws, and the ship-to-ship variability of a diverse fleet. We provide a global and Arctic estimate for the emissions and climate forcing of combined LLCF and SLCF emissions from fisheries using recently published plume-sampling and test-rig data from an ensemble of ships [*Lack et al.*, 2008; *Petzold et al.*, 2010; *Petzold et al.*, 2011; *Buffaloe et al.*, 2014; *Cappa et al.*, 2014]. Our analysis considers the impact of newly enacted regulations on emissions of fuel sulfur, engine type, and operational characteristics of the fishing fleet. Further, we provide a first estimate of the contribution of SLCFs to the climate forcing of global seafood per unit protein and compare this impact to other nonseafood protein sources.

2. Methods

2.1. Fuel Consumption

We calculated the global fisheries fuel consumption using a catch-based approach. This approach is based on the global median fuel use intensity (FUI = 0.639 L of fuel used per kilogram of live weight fish landings) from the Fisheries Energy Use Database and global catch statistics [*Parker and Tyedmers*, 2014]. The global average annual landed catch (2000–2010) is 80 Tg [*Food and Agriculture Organization* (*FAO)*, 2015]. The average annual landed catch for countries that have emission control areas (ECAs) including North America and the European Union (2000–2010) is 14 Tg [*FAO*, 2015]. The majority of global fish landings, approximately 88%, occur within exclusive economic zones (EEZs) [*Sumaila et al.*, 2015]. Thus, we estimate approximately 68 Tg of landings occur outside of ECAs and 12 Tg of landings occur inside the EEZs of ECAs. The weighted average of the fuel density is 0.86 kg l^{-1}. We calculated the global fisheries fuel consumption using the following formula:

$$\mathrm{FC} = \mathrm{FUI}{\cdot}\rho{\cdot}\mathrm{GC} \tag{1}$$

where FC is the fuel consumption (Tg fuel), FUI is the fuel use intensity (l fuel/kg live-weight fish landings), ρ is the fuel density (kg fuel/l fuel), and GC is the global average annual landed catch (Tg live-weight fish landings).

For the Arctic we did not use this catch-based approach because fuel use intensity and catch data were not readily available. Instead, we used a recently published estimate of 2.0 Tg fuel yr^{-1} based on ship track data [*Winther et al.*, 2014].

2.2. Global Commercial Fishing Vessel Characterization

Our emissions estimates are based on the following vessel characteristics. The average engine power of commercial fishing vessels is 701 kW for the main engine and 55 kW for the auxiliary engine [*ICF International*, 2009]. The average size of decked fishing vessels is 20 GT (around 10–15 m). Only a small fraction of vessels, 1% of the global fishing fleet, are larger than 100 GT (or longer than 24 m) (FAO, 2005, Fisheries and Aquaculture topics, Fishing vessels: http://www.fao.org/fishery/topic/1616/en). Globally, 88% of the installed main engines of commercial fishing vessels operate MSD, and 12% operate high speed diesel (HSD) engines [*Trozzi*, 2010]. Marine distillate oil (MDO, also called marine gas oil or MGO) is the most commonly used fuel for fishing boats and other MSD engines [*ICF Consulting*, 1999]. However, a small fraction of fishing boats use heavy fuel oil (HFO) [*Trozzi*, 2010].

2.3. Fuel Specifications

The fuel specifications for our model are based on current policies related to emission controls. MARPOL 73/78 (short for marine pollution) is the principal international instrument covering prevention of pollution of the marine environment by ships. According to MARPOL Annex VI, Regulation 14, ships 400 GT or greater operating in designated ECAs are required to use onboard fuel oil with a sulfur content of no more than 0.1% (all sulfur contents are by weight) effective January 2015. The ECAs include the Baltic Sea area, North Sea area, North American area (covering designated coastal areas off of the United States and Canada), and United States Caribbean Sea area (including Puerto Rico and the United States Virgin Islands). Outside the ECAs the maximum fuel sulfur content is 3.5%, but reduction to 0.5% in 2020 is under consideration. For ships less than 400 GT, state flag regulations apply. The average fishing vessel is likely to be in a weight class less than 400 GT and thus exempt from international sulfur and particulate matter control laws. Globally, the maximum allowable fuel sulfur for state flag regulations is as low as 0.001% and as high as 1%. Based on the regulations described above, we use the following approach. Inside ECAs we used a fuel sulfur content of 0.051% (±0.050%). Outside ECAs we used a weighted average of fuel sulfur contents for MGO, MDO, and HFO. The global commercial fishing fleet operates over 96% of installed engines with MGO or MDO, and the remaining 4% operate on HFO [*Trozzi*, 2010]. The average fuel sulfur contents of MGO, MDO, and HFO are 0.38% (±0.21%), 0.65% (±0.37%), and 2.7% (±0.7%), respectively [*Notteboom et al.*, 2010; *Lack et al.*, 2011]. The resulting fuel sulfur content outside ECAs was 0.59% (±0.31%). MGO and HFO are reported to have fuel densities of 0.86 and 0.98 kg l^{-1}, respectively [*Energy and Environmental Analysis, Inc.,* 2000]. We used a lower heating value of 42.8 and 39.5 MJ kg^{-1} for marine distillates (MGO and MDO) and HFO, respectively [*Argonne National Laboratory*, 2014].

2.4. Emission Factors

We calculated the BC emission factor using three approaches. First, we used an average of all available emission factor data for MSD and HSD engine types [*Lack et al.*, 2008; *Petzold et al.*, 2010, 2011; *Buffaloe et al.*, 2014; *Cappa et al.*, 2014]. Second, we calculated an emission factor based on a weighted average of engine and fuel types (equation (S1) in the supporting information). Third, we calculated the emission factor by binning the data and calculating a weighted average of the bins based on the frequency of fuel types, vessel types, and engine loads used in the fishing sector (equations (2)–(4)). We used published emission factors from plume intercept and test-rig sampling studies summarized in Table 1 [*Lack et al.*, 2008; *Petzold et al.*, 2010, 2011; *Buffaloe et al.*, 2014]. The emissions of BC are influenced by the fuel sulfur content, engine type, maintenance, and other operational characteristics such as engine load or engine speed [*ICF International*, 2009; *Lack et al.*, 2011; *Cappa et al.*, 2014]. We sorted the BC emission data into bins (marine diesel engine type, fuel type, fuel sulfur content, and engine load percentage) and when possible used statistical software to generate probability distributions for each bin using Kolmogorov-Smirnov, Anderson-Darling, and chi-square statistics [*Mathwave Data Analysis and Simulation*, 2015]. We sampled the distribution from each bin 10,000 times with a Monte Carlo simulation to calculate the average and standard deviations of BC emissions for each bin (Table S7). To estimate the BC emissions as a function of engine load, we assume a load profile from a trawl and gillnet gear study [*Ziegler and Hansson*, 2003].

We binned the available data and weighted the data as a function of fuel sulfur content as follows:

$$EF_l^{BC} = \sum_{m=1}^{2} f_m^C \cdot EF_{l,m}^{BC} \tag{2}$$

where EF_l^{BC} is the average emission factor (g BC/kg fuel) for fuel sulfur content l, f_m^C is the global fraction of catch using gear m (trawl or gillnet) and $EF_{l,m}^{BC}$ (g BC/kg fuel) is the average BC emission factor for gear m and fuel sulfur content l. Fuel sulfur (F_s, units wt %) is binned into two categories for low (0.05% ± 0.05%) and high (0.59% ± 0.31%) content. The inputs for equation (2) are given in Tables S2 and S3.

The BC emission factor as a function of fuel sulfur and fishing gear, $EF_{l,m}^{BC}$, was calculated as follows:

$$EF_{l,m}^{BC} = \sum_{j=1}^{2} \sum_{k=1}^{2} f_{j,k,l}^{Char} \cdot EF_{j,k,l,m}^{BC} \tag{3}$$

where $f_{j,k,l}^{Char}$ is the fraction of the global fishing fleet with the vessel characteristics engine type j (MSD or HSD) and fuel type k (MDO or HFO). The inputs for equation (3) are given in Tables S4 and S5.

The BC emission factor as a function of engine type, fuel type, fuel sulfur level, and fishing gear was calculated using the following formula:

$$EF_{j,k,l,m}^{BC} = \sum_{i=1}^{5} f_{i,m}^{t} \cdot EF_{i,j,k,l}^{BC} \tag{4}$$

where $f_{i,m}^t$ is the fraction of time the ship is run at load i, and $EF_{i,j,k,l}^{BC}$ is the BC emission factor as a function of load i, engine type j, fuel type k, and fuel sulfur level l. The engine loads included five bins (0–20%, 20–40%, 40–60%, 60–80%, and 80–100%). The inputs for equation (4) are given in Tables S6 and S7.

The emission factor for OC (EF_{OC}, g OC/kg fuel) was calculated as a function of BC and the ratio of particulate organic matter (POM) and BC:

$$EF^{OC} = EF^{BC} \times f^{POM/BC} \times f^{OC/POM} \tag{5}$$

where $f^{POM/BC}$ is the fraction of POM emissions to BC emissions as 1.4 and $f^{OC/POM}$ is the ratio of OC to POM as 0.83 [*Petzold et al.*, 2011; *Fuglestvedt et al.*, 2010].

SO_2 emissions are directly related to fuel sulfur [*Lack and Corbett*, 2012; *Faloona*, 2009]. The SO_2 emission factors, EF^{SO2} (gSO_2/kg fuel), were calculated as a function of the fuel sulfur content:

$$EF^{SO_2} = f^S \cdot 2 \cdot f^{SO_2} \tag{6}$$

where f^S is the fuel sulfur fraction (g S/kg fuel), 2 is the ratio of molecular weights of SO_2 to S, and f^{SO2} is the fraction of fuel sulfur emitted as SO_2 (97.8%) [*ICF International*, 2009]. The emission factors of LLCFs and NOx were taken from a technical report on mobile source port-related emission inventories [*ICF International*, 2009].

2.5. Global Warming Potential

While climate models are often used to quantify the climate forcing for an industrial sector, here we use a range of global warming potentials (GWPs) to provide a first approximation of climate forcing from the fishing industry.

Table 1. Black Carbon Emission Factors From the Literature as a Function of Engine Type, Fuel Type, Estimated Engine Speed, and Fuel Sulfur Content[a]

Engine Type[b]	Fuel Type[c]	Engine Speed (% of Maximum)	N[d]	Fuel Sulfur (wt %)	Black Carbon ($g\ kg^{-1}$ Fuel)	Reference
MSD	MGO/MDO	>0–20%	10	≤0.1	1.06 (±1.11)	*Buffaloe et al.* [2014]
MSD	MGO/MDO	>0–20%	2	0.4 ± 0.6	1.5	*Lack et al.* [2008]
HSD	MGO/MDO	>0–20%	3	≤0.1	0.30 (±0.19)	*Buffaloe et al.* [2014]
HSD	MGO/MDO	>0–20%	1	0.4 ± 0.6	0.28	*Lack et al.* [2008]
MSD	HFO	>0–20%	2	2.2	0.48	*Petzold et al.* [2010, 2011]
MSD	MGO/MDO	>20–40%	3	≤0.1	2.05 (±2.53)	*Buffaloe et al.* [2014] and *Cappa et al.* [2014]
MSD	MGO/MDO	>20–40%	6	0.4 ± 0.6	0.90 (±0.67)	*Lack et al.* [2008]
HSD	MGO/MDO	>20–40%	3	≤0.1	0.55 (±0.34)	*Buffaloe et al.* [2014]
HSD	MGO/MDO	>20–40%	1	0.4 ± 0.6	0.19	*Lack et al.* [2008]
MSD	HFO	>20–40%	2	2.2	0.16	*Petzold et al.* [2010, 2011]
MSD	MGO/MDO	>40–60%	9	≤0.1	0.53 (±0.60)	*Buffaloe et al.* [2014], *Cappa et al.* [2014], and *Petzold et al.* [2011]
MSD	MGO/MDO	>40–60%	31	0.4 ± 0.6	0.92 (±0.65)	*Lack et al.* [2008]
HSD	MGO/MDO	>40–60%	8	≤0.1	0.39 (±0.18)	*Lack et al.* [2008]
HSD	MGO/MDO	>40–60%	2	0.4 ± 0.6	0.53	*Buffaloe et al.* [2014]
MSD	HFO	>40–60%	1	2.2	0.07	*Petzold et al.* [2010, 2011]
MSD	MGO/MDO	>60–80%	3	≤0.1	0.87 (±0.65)	*Buffaloe et al.* [2014] and *Petzold et al.* [2011]
MSD	MGO/MDO	>60–80%	9	0.4 ± 0.6	1.20 (±0.75)	*Lack et al.* [2008]
HSD	MGO/MDO	>60–80%	5	≤0.1	0.53 (±0.42)	*Buffaloe et al.* [2014]
HSD	MGO/MDO	>60–80%	2	0.4 ± 0.6	0.58	*Lack et al.* [2008]
MSD	HFO	>60–80%	1	2.2	0.05	*Petzold et al.* [2010, 2011]
MSD	MGO/MDO	>80–100%	13	≤0.1	0.68 (±0.54)	*Buffaloe et al.* [2014], *Cappa et al.* [2014], and *Petzold et al.* [2011]
MSD	MGO/MDO	>80–100%	1	0.4 ± 0.6	0.06	*Lack et al.* [2008]
HSD	MGO/MDO	>80–100%	9	≤0.1	0.33 (±0.21)	*Buffaloe et al.* [2014]
HSD	MGO/MDO	>80–100%	2	0.4 ± 0.6	0.22	*Lack et al.* [2008]
MSD	HFO	>80–100%	4	2.2	0.05 (±0.02)	*Petzold et al.* [2010, 2011]

[a]The uncertainty represents the standard deviations. Number weighted volume equivalent diameter particle size distribution for refractory black carbon (campaign average) 92 nm. Particle size distribution information not provided. Total aerosol particle size distribution 15, 40–60, and 25 nm for modal parameters 1, 2, and 3, respectively. Particle number size distribution 5 and 6, 27 and 25, and 120 and 55 nm for modal parameters 1, 2, and 3, respectively, measured at engine loads 10 and 100%, respectively. Number weighted volume equivalent diameter particle size distribution for refractory black carbon <60 and 100 nm for modal parameters 1 and 2, respectively.
[b]MSD: medium speed diesel, HSD: high speed diesel.
[c]MGO: marine gas oil, MDO: marine distillates oil, HFO: heavy fuel oil.
[d]Number of observations.

The GWPs for SLCFs have a large spread in model estimates and significant differences between observations and model results. The level of scientific confidence is low for GWPs that include aerosol-cloud interactions and land surface albedo effects for BC [*Myhre et al.*, 2013]. Due to the large uncertainty, we separately report climate forcing for total effects (direct and indirect) and only direct effects [*Bond et al.*, 2013, 2011; *Shindell et al.*, 2009]. SLCFs with equivalent 100 year GWPs have different impacts on climate, temperature, rainfall, and the timing of these impacts. Because questions have been raised about the appropriateness of using the 100 year GWP metric to compare SLCFs and LLCFs, we include the 20 year GWPs to evaluate the short-term climate impacts [*Fuglestvedt et al.*, 2010; *Boucher and Reddy*, 2008] (Table 2). As a special case, we also consider the GWPs of SLCFs for the Arctic [*Ødemark et al.*, 2012]. Owing to the fact that the density of shipping traffic and the climate impacts of NOx emissions peak in the summer, we use a seasonal (summer) shipping sector GWP for the Northern Hemisphere for our Arctic calculations [*Aamaas et al.*, 2015; *Ødemark et al.*, 2012].

3. Results

3.1. Fuel Use

Our catch-based estimate of global fishing fuel use is 44 $Tg\ yr^{-1}$ which is similar in magnitude to previous catch-based estimates [*Tyedmers et al.*, 2005]. Alternative approaches to estimating global fishing fuel use are considerably smaller. Bottom-up estimates (based on ship activity and engine power capacity data)

Table 2. Direct and Indirect Global Warming Potential (GWP)[a] (g CO_2-e g Pollutant^{-1})

GWP	CO_2[b]	CH_4[b]	N_2O[b]	NOx[c,d]	SO_2[e]	OC[f]	BC[g]
				Global 20 Year Time Horizon			
Direct	1	84	264	−14 (−21, −8)	−78 (±70)	−160 (−320, −160)	2,100 (420, 3,700)
Indirect		2	4		−190 (±171)		1,100 (−150, 2,500)
Total (including indirect)	1	86	268	−14 (−21, −8)	−268 (±241)	−160 (−320, −160)	3,200 (270, 6,200)
				Global 100 Year Time Horizon			
Direct	1	28	265	−10 (−6, −4)	−19 (±20)	−46 (−92, −18)	590 (140, 1,100)
Indirect		6	33		−57 (±49)		310 (−40, 600)
Total (including indirect)	1	34	298	−10 (−6, −4)	−76 (±69)	−46 (−92, −18)	900 (100, 1,700)
				Arctic 20 Year Time Horizon			
Direct	1	84	264	24	−71	−151	2,037
Indirect		2	4		−205		764
Total (including indirect)	1	86	268	24	−276	−151	2,801
				Arctic 100 Year Time Horizon			
Direct	1	28	265	−0.7	−19 (±20)	−43	579
Indirect		6	33		−57 (±49)		217
Total (including indirect)	1	34	298	−0.7	−76 (±69)	−43	796

[a]Uncertainties ranges or standard deviations are given where available.
[b][*Myhre et al.*, 2013].
[c]Nitrogen oxides (NOx) calculated as NO_2.
[d]Global values [*Fuglestvedt et al.*, 2010]; Arctic values [*Aamaas et al.*, 2015].
[e]Global values [*Shindell et al.*, 2009]; Arctic values [*Ødemark et al.*, 2012].
[f]Global values [*Bond et al.*, 2011]; Arctic values [*Ødemark et al.*, 2012].
[g]Global values [*Bond et al.*, 2013]; Arctic values [*Ødemark et al.*, 2012].

and top-down estimates based on fuel consumption are approximately 16 and 6 Tg yr^{-1}, respectively [*Smith et al.*, 2014]. Bottom-up estimates are thought to underestimate fishing fuel use because the engine data do not include ships smaller than 100 GT which excludes an estimated 1.3 million fishing vessels [*Endresen et al.*, 2007]. The top-down consumption approach may be accurate for estimating global marine fuel use, but the top-down approach suffers from large uncertainties with respect to allocating fuel use to fishing ships as opposed to other types of ships [*Smith et al.*, 2014]. Our catch-based approach suggests that fishing is responsible for 15% of global marine fuel use. The larger fraction for fishing vessels in our estimates as opposed to other studies is important for understanding fishing vessels emissions but may also impact the estimates of global climate forcing for all ships to the extent that emission factors and the spatial and temporal distribution of emissions are unique for fishing as opposed to other shipping sectors.

3.2. Emission Factors

The literature review of BC emission factors and the calculated fuel combustion emission factors for fishing vessels are presented in Tables 1 and 3, respectively. Our first BC emission factor, averaging all data for MSD and HSD engines, is 0.79 ± 0.06 g/kg (mean ± standard error; $n = 146$ measurements). Our second set of BC emission factors, weighted by engine and fuel types (equation (S1)), is 0.92 and 0.86, for low ($F_s = 0.051\%$) and high ($F_s = 0.59\%$) fuel sulfur levels, respectively. Our third set of BC emission factors, the binned approach (equation (2)–(4)), is somewhat larger than our first BC emission factor results (0.88 and 0.84 for ECAs and non-ECAs, respectively) because we weighted the emission factors by engine types and fishing engine loads. Our BC emission factor estimates are two or more times larger than previously assumed emission factors of 0.18 and 0.35 g/kg for global and Arctic inventories, respectively (Table 3). The previously assumed global estimate originates from a small data set ($n = 11$) that included two transport ships (SSDs) but not ships that are representative of the fishing sector [*Sinha et al.*, 2003]. The previously assumed Arctic estimate originates from a larger data set but includes a large number of transport ships (SSD engines) that are not representative of the fishing industry [*Corbett et al.*, 2010b]. However, fishing ships which are primarily MSD vessels operating with high fuel sulfur content have twice the emissions factors as SSD engines which are used in transport ships [*Lack et al.*, 2008; *Lack et al.*, 2009]. Thus, our BC estimates are higher because we account for a broader range of data and an ensemble of engine types and engine loads that are specific to fishing.

Table 3. Emissions Factors for Combustion of Marine Fuels Used in Commercial Fishing Vessels for This and Other Studies[a]

F_S (wt %)	EF_{CO2}	EF_{CH4}	EF_{N2O}	EF_{NOx}[b]	EF_{SO2}	EF_{OC}	EF_{BC}	Reference
				Global, Emission Control Area (ECA)				
0.05 (±0.05)	3,183	0.02	0.15	52 (±13)	1 (±1)	1.5 (±1.1)	0.88 (±0.66)	This study
				Global, Non-ECA				
0.6 (±0.3)	3,183	0.02	0.15	52 (±13)	12 (±6)	2.1 (±0.7)	0.84 (±0.42)	This study
2.3	2,927			52	40			*Eyring et al.* [2005]
	3,160							*Tyedmers et al.* [2005]
0.5	3,170				10			*Endresen et al.* [2007]
0.5	3,179	0.05	0.08	65	10	0.61	0.18	*Dalsøren et al.* [2009]
0.2	3,114	0.06	0.16	51	2.6			*Smith et al.* [2014][c]
0.5	3,114	0.06	0.16	51	9.8			*Smith et al.* [2014][d]
				Arctic, Non-ECA				
0.6 (±0.3)	3,183	0.02	0.15	52 (±13)	12 (±6)	2.1 (±0.7)	0.88 (±0.66)	This study
2.6	3,167			76	52.7		0.36	*The Arctic Council* [2009]
0.5	3,114				10	1.1	0.35	*Corbett et al.* [2010a]
							0.35	*Browse et al.* [2013]
0.5	3,183	0.02	0.20	58	9.9	0.39	0.35	*Winther et al.* [2014]
							0.35	*Mjelde et al.* [2014]

[a]All emission factor (EF) units are grams of pollutant per kilogram of fuel. Average and standard deviations are reported for this study.
[b]Nitrogen oxides (NOx) calculated as NO_2.
[c]Emission factors used for marine gas oil (MGO) or marine distillates oil (MDO).
[d]Emission factors used for heavy fuel oil (HFO).

The uncertainty in the BC emissions reflects the different emissions observed between the study types (test rig versus plume sampling), between different plume sampling studies, and between different ships in the same plume-sampling study. In general, the BC emissions from the test-rig study were smaller than the emissions from plume-sampling studies. The difference between test rigs and plume sampling could be a result of different vessel and engine ages. The test rig was reported to be substantially newer at the time of the study than some of the vessels in the plume-sampling studies [*Cappa et al.*, 2014]. When comparing the BC emissions of MSD engines, the emissions were lower in the $\leq$0.1% fuel sulfur category (ECAs) except at engine loads between 0–20% and 80–100%. When we compiled the BC emissions data using weightings for the typical engine loads used in fishing operations, we found similar emission factors for both low and high fuel sulfur contents. These results are consistent with a recent test-rig study that used high sulfur HFO, and low sulfur distillate fuels on the same engine and found BC emissions were unaffected by fuel type [*Mueller et al.*, 2015]

The emission factors and uncertainty for SO_2 were directly related to the fuel sulfur content. The sulfur in fuels used by fishing vessels is regionally dependent due to sulfur control laws in ECAs and non-ECAs. In ECAs the SO_2 emissions are lower than in non-ECAs by an order of magnitude.

3.3. Global and Arctic Emissions

It was our hypothesis that previous global inventories of commercial ships may be understated due to the lack of inclusion of smaller fishing vessels ($<$100 GT) and the use of a single emission factor that does not account for the full range of data for engine speed, engine type, fuel quality, and the ship-to-ship variability of a diverse fleet. The global and Arctic fuel consumption and emissions are summarized in Table 4 for our results and previous studies [*Tyedmers et al.*, 2005; *Eyring et al.*, 2005; *Endresen et al.*, 2007; *Dalsøren et al.*, 2009; *Smith et al.*, 2014; *The Arctic Council*, 2009; *Corbett et al.*, 2010a; *Browse et al.*, 2013; *Winther et al.*, 2014; *Mjelde et al.*, 2014]. We found that the global fishing fleet emits 139 Tg CO_2 yr^{-1}. Our global fuel consumption and CO_2 emissions estimates are more than twice all previously reported estimates except for one study which also accounted for smaller fishing vessels [*Tyedmers et al.*, 2005]. That study has similar fuel use results to our work because there have been only modest changes in the FUI and global catch statistics over the last decade. Our global estimates of SLCFs are generally several times previous estimates for SO_2 and an order of magnitude greater than previous estimates for BC and OC because of our larger fuel use and emission factor estimates.

A recent emission inventory for the Arctic found that fishing vessels were the dominant source of maritime BC emissions in this region [*Winther et al.*, 2014]. We used the fuel consumption data from this Arctic

Table 4. Annual Fuel Consumption and Emissions From Fishing Vessels

Year	Fuel Use (Tg)	CO_2 (Gg)	CH_4 (Gg)	N_2O (Gg)	NOx[a] (Gg)	SO_2 (Gg)	OC (Gg)	BC (Gg)	Source
					Global				
2001	23.6	69,000			1,219	950			*Eyring et al.* [2005][b]
2001	42.0	134,000							*Tyedmers et al.* [2005][c]
2000	20.0	63,400				200			*Endresen et al.* [2007][b]
2004	13.2	42,010	0.6	1.0	859	132	7.9	2.4	*Dalsøren et al.* [2009][b]
2011	6.0	19,000	2.9	0.9	520	55			*Smith et al.* [2014][d]
2012	16.0	11,000	0.7	2.4	834	261			*Smith et al.* [2014][b]
2012	43.8	139,420	0.9	6.6	2,278 (±570)	433 (±229)	63 (±34)	37 (±20)	This study[c]
					Arctic				
2004	1.0	3,230			78	54		0.36	*The Arctic Council* [2009][b]
2004		3,200			58	10	1.1	0.35	*Corbett et al.* [2010a][b]
2004								0.31	*Browse et al.* [2013][b]
2012	2.0	6,383	0.2	0.4	117	20	0.8	0.71	*Winther et al.* [2014][b]
2012								0.40	*Mjelde et al.* [2014][b]
2012	2.0	6,430	0.04	0.3	105 (±26)	23 (±12)	2.9 (±1.4)	1.7 (±0.9)	This study[b]

[a]Nitrogen oxides (NOx) calculated as NO_2.
[b]Fuel and emissions estimate using a bottom-up engine activity approach.
[c]Fuel estimate from the sum of the products of catches (by species) and the corresponding species-specific fuel use intensity estimates.
[d]Fuel and emissions estimate using a top-down approach from international sales of bunker fuel summed up by country.

inventory and our updated emission factors to estimate that the Arctic fishing fleet emits 105 (±26), 23 (±12), 2.9 (±1.4), and 1.7 (±0.9) Gg yr^{-1} of NOx, SO_2, OC, and BC, respectively. Our Arctic BC emissions estimate is 2 to 5 times the central estimates of previous work due to our larger emission factor.

3.4. Global Fuel-Specific Climate Forcing

We estimated the global fuel-specific climate impacts of the SLCF and LLCF emissions from fisheries for a 20 year and 100 year time horizon including the direct (aerosol-radiation interaction) and total (aerosol-cloud interactions and land surface albedo for BC) effects using our emission estimates and a range of published GWP values (Figure 1). The LLCF forcing was not sensitive to the time horizon, fuel sulfur content,

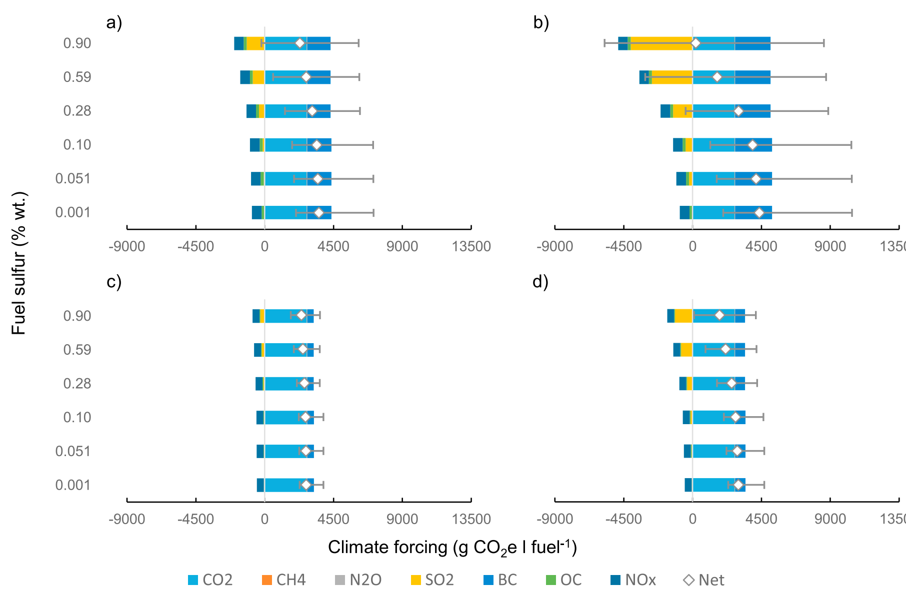

Figure 1. Climate forcing from fishery vessel emissions for (a and c) direct effects, (b and d) total effects, (Figures 1a and 1b) 20 year time horizon, and (Figures 1c and 1d) 100 year time horizon. The direct effect includes only aerosol-radiation for short-lived climate forcers (SLCFs), whereas the total effects include aerosol-cloud interaction for SO_2, and land surface albedo for black carbon (BC). The binned BC emission factors were used in the calculations presented here. The error bars represent standard deviations due to uncertainty in emissions factors and global warming potential.

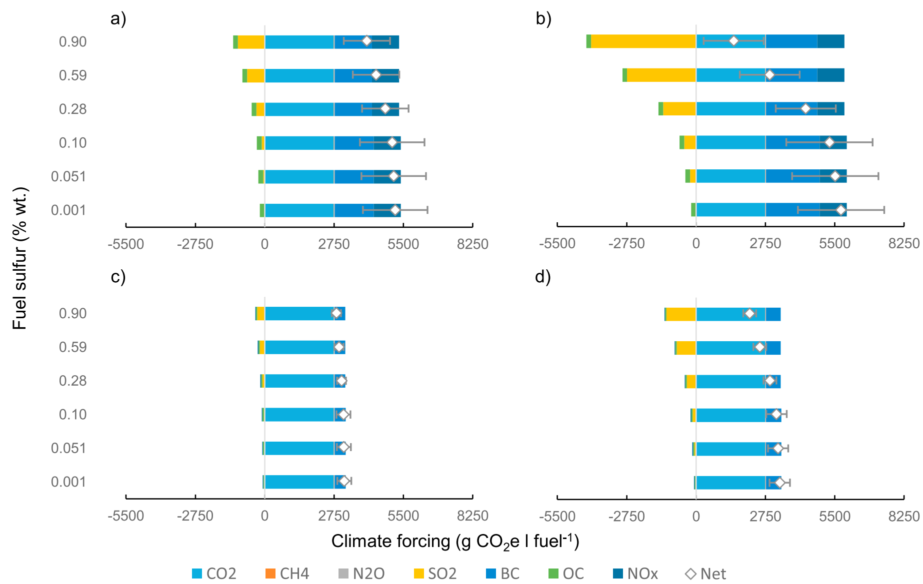

Figure 2. Climate forcing of fishery vessel emissions in the Arctic for (a and c) direct effects, (b and d) total effects, (Figures 2a and 2b) 20 year time horizon, and (Figures 2c and 2d) 100 year time horizon. The direct effect includes only aerosol-radiation for short-lived climate forcers (SLCFs), whereas the total effects include aerosol-cloud SO_2, and land surface albedo for black carbon (BC). The binned BC emission factors were used in the calculations presented here. The error bars represent standard deviations due to uncertainty in emissions factors and global warming potential.

consideration of direct or indirect effects, or GWP uncertainty. The LLCF emissions resulted in a warming of 2800 g CO_2e/L fuel and were dominated by CO_2.

For the global SLCF forcing, we begin by considering the baseline forcing using mean emission factors and GWPs. For the ECAs, F_s (wt %) 0.051, the mean climate forcing of SLCFs was dominated by the BC warming effect for all time horizons and for both direct and total climate effects. For the 20 year time horizon ECAs, the net warming was 25% and 49% greater than considering LLCFs alone for the direct and total effects, respectively. For the 100 year time horizon ECAs, the net warming resulted in relatively small differences from considering LLCFs alone. For non-ECAs, F_s (wt %) 0.590, the BC warming effect was outweighed by the SO_2, NOx, and OC cooling effects, resulting in reductions of 3–42% compared with LLCFs alone. The difference between ECA and non-ECA results is due to the fact that the emission factors increased with fuel sulfur content for SO_2 but not for BC, OC, or NOx.

Due to uncertainties in emission factors and GWPs, the net climate forcing (combined LLCF and SLCF forcing) ranged from a net cooling effect of 5719 g CO_2e/L fuel (Figure 1b, F_s (wt %) 0.9) to a net warming effect of 10,408 g CO_2e/L fuel (Figure 1b, F_s (wt % 0.001) across all fuel sulfur contents, all time horizons (20 and 100 year) and all climate impacts (direct and total). The cooling end of this range is associated with a high fuel sulfur content (0.9%), a short time horizon (20 year), the largest emission factors and GWP values for cooling SLCFs (NOx, SO_2, and OC), and the smallest emission factor and GWP value for BC. The warming end of this range is associated with a low fuel sulfur content (0.001%) and emission factors and GWP values that weight the BC emissions over the SO_2 emissions.

3.5. Arctic Fuel-Specific Climate Forcing

The fuel-specific climate impacts of the fishery emissions in the Arctic region are summarized in Figure 2. Although the Arctic is currently a non-ECA (high fuel sulfur content), here we include the results for the case of a designated ECA for this region. We begin by considering the baseline forcing using mean emission factors and GWPs. For the 20 year time horizons, the SO_2 and OC cooling effects were outweighed by the BC and NOx warming effects for both ECA and non-ECAs. For ECAs, the net warming was 85% and 100% greater than considering LLCFs alone for the direct and total effects, respectively. For the non-ECAs, the net warming was 60% and 6% greater than considering LLCFs alone for the direct and total effects, respectively. For 100 year time horizons, the trends observed for the Arctic region are similar to global fuel-specific climate forcing. For the ECAs (total and direct effects) and the direct effects non-ECA, the warming of BC outweighs the cooling effects of SO_2, NOx, and OC. For the non-ECA total effects, the warming BC is outweighed by the cooling

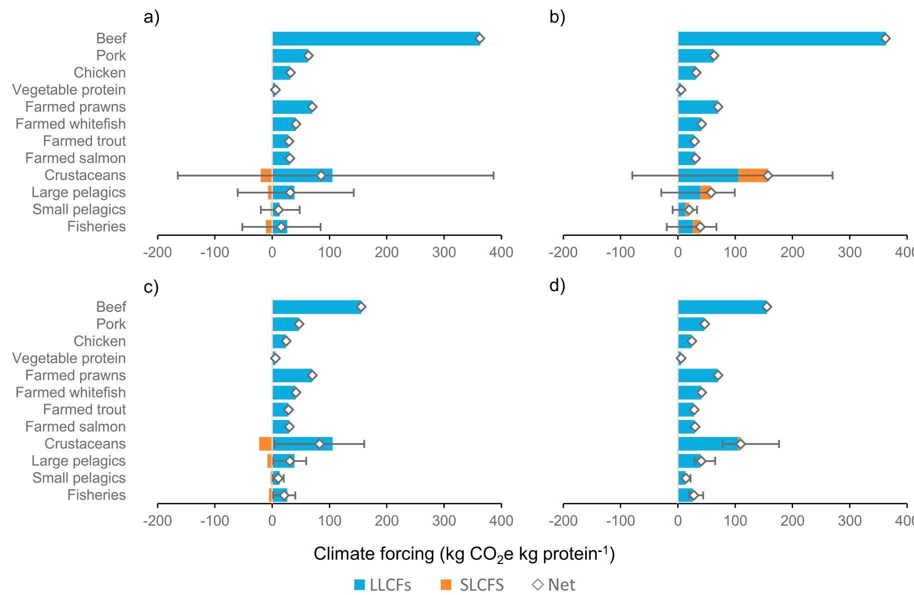

Figure 3. Climate forcing from global fisheries and other food sources for long-lived climate forcers (LLCFs), blue bars, and short-lived climate forcers (SLCFs), orange bars. Fishery protein is based on total climate effects (direct and indirect), (a and b) 20 year time horizon and (c and d) 100 year time horizon scenarios for nonemission control areas ((Figures 3a and 3c) non-ECAs) and (Figures 3b and 3d) ECAs. The binned BC emission factors were used in the calculations presented here. Error bars represent standard deviations for SLCF emissions factors and GWPs.

effects of the SLCFs. The mean ECA scenarios result in increases in warming of 12 and 16% greater than considering LLCFs alone for the direct and total climate effects, respectively. For the mean non-ECAs, the cooling of SO_2, NOx, and OC outweigh the warming effect of BC for the total effects. The mean non-ECA scenarios result in a net warming increase of 60% and a net cooling decrease of 10% compared with LLCFs alone for the direct and total climate effects, respectively.

The error bars in Figure 2 represent the low and high SLCF values associated with the range of emission factor and GWP values. The net climate forcing (combined LLCFs and SLCFs forcing) results in a net warming for all climate effects (direct and total) and time horizons (20 year and 100 year) of 331 g CO_2e/L (Figure 2b, F_s (wt % 0.9)) to 7488 g CO_2e/L(Figure 2b, F_s (wt % 001)).

3.6. Total Climate Forcing

We estimate the mean climate forcing (total effects) of 101 and 116 Tg CO_2e global emissions for the combustion of marine fuels used in fisheries for 20 year and 100 year time horizons, respectively. Of these totals, the SLCF forcing resulted in a warming from BC that was largely offset by cooling from SO_2, NOx, and OC. While the net SLCF contribution resulted in negligible effects at a global scale, the climate forcing in ECAs resulted in significant warming effects on a 20 year time horizon. In ECAs, we estimate approximately 33 and 23 Tg CO_2e yr^{-1} for the total effect 20 year and 100 year time horizons, respectively. Of this total, 11 and 0.9 Tg CO_2e yr^{-1} can be attributed to SLCFs for the 20 year and 100 year time horizons, respectively.

In the Arctic, we estimated the regional emissions for the combustion of fuels used by fisheries results in approximately 6.9 and 5.9 Tg CO_2e yr^{-1} with approximately 0.41 and −0.65 Tg CO_2e yr^{-1} forcing from SLCFs for the 20 year and 100 year time horizons, respectively. We used a reported fuel consumption of fisheries (2020 Mg) [*Winther et al.*, 2014] and a fuel density of 0.86 kg/L in our calculations. Policy discussions suggest that the Arctic may be designated an ECA in the future, lowering the sulfur fuel content of the region. In this case the regional forcing would be 13 and 7.6 Tg CO_2e yr^{-1} for the 20 year and 100 year horizons, respectively.

3.7. Food-Specific Climate Forcing

While SLCF emissions are needed for understanding global and regional climate change, they can also be useful for understanding climate impacts of food decisions when they are reported on a basis of food mass. Here we provide a first estimate of the food-specific climate forcing (kg CO_2e/kg protein) that includes both LLCFs and

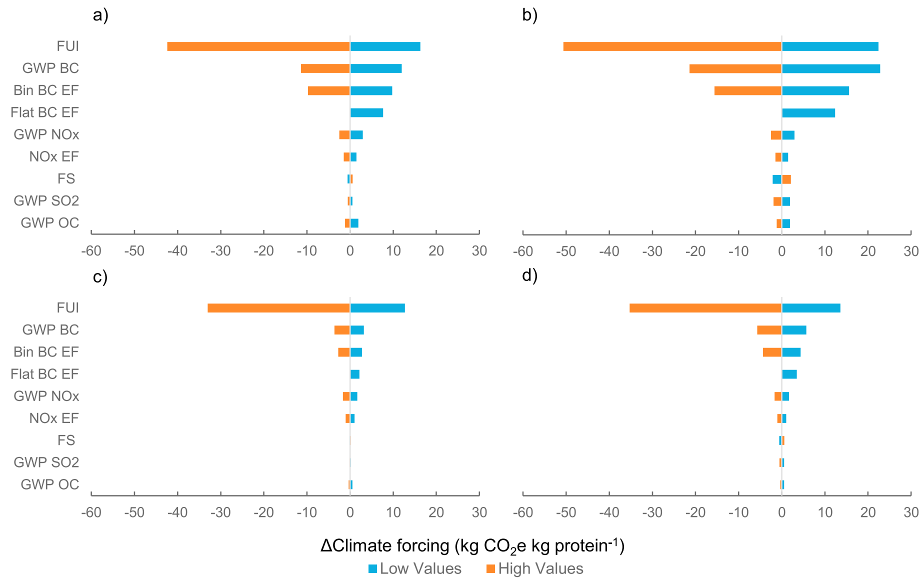

Figure 4. Tornado plots of uncertainty in global fishery climate forcing estimates for (a and c) direct effects, (b and d) total effects, (Figures 4a and 4b) 20 year horizons, and (Figures 4c and 4d) 100 year horizons. Sensitivity is simulated for model inputs including global warming potential (GWP), emission factors (EF), fuel use intensity (FUI), and fuel sulfur content (Fs). The centerline represents the baseline case. The binned BC emission factors were used in the calculations presented here.

SLCFs. We compare the emissions of fisheries to other foods prior to processing and transport. We used the median published values of fuel use of 0.32, 0.95, and 2.58 L fuel/kg catch for fisheries targeting small pelagics, large pelagics, and crustaceans, respectively [*Parker and Tyedmers*, 2014]. Our comparison to land-based protein includes only the median published values for life cycle emissions from land-based LLCFs (feed production, enteric fermentation, manure management, on-farm fuel use, etc.) [*Parker and Tyedmers*, 2014]. Land-based foods do not include SLCF emissions because their SLCF forcing is small in comparison to LLCF forcing [*Unger et al.*, 2010]. The live weights reported in *Parker and Tyedmers* [2014] were normalized by the relative yield factors in the meat chain (carcass weight of live weight and retail meat weight of carcass weight) and protein fractions [*Nijdam et al.*, 2012]. The median land-based protein LLCFs were allocated to farm activities based on technical reports and literature values [*Steinfield et al.*, 2006; *Blonk et al.*, 2008; *Nijdam et al.*, 2012; *Pelletier et al.*, 2009; *Pelletier and Tyedmers*, 2007; *d'Orbcastel et al.*, 2009; *Vergé et al.*, 2013; *Pelletier and Tyedmers*, 2010; *Cao et al.*, 2011]. The results summarized in Figure 3 show climate forcing (total effects, 20 year and 100 year time horizon scenarios) that varies widely among all protein sources. Beef protein has the largest climate forcing while vegetable protein has the smallest. There are also differences related to the choice of time horizon. Comparing the impacts from the 20 year (Figures 3a and 3b) to the 100 year time horizons (Figure 3c and 3d), it is evident that there is a negligible change in climate forcing for vegetable protein and aquaculture but substantial differences for beef, pork, chicken, and wild-caught seafood. In the case of land-based protein this increase in climate forcing for the 20 year time horizon can be attributed to the increase in the GWP of CH_4.

The mean climate impacts from wild-caught seafood (total effects, 20 year and 100 year time horizon scenarios) also vary widely within this category. One explanation for this variability is the different types of seafood considered here. Crustaceans have the greatest climate forcing, while small pelagics have the least. A second explanation for the variability in climate impacts for wild-caught seafood is the choice of time horizon. When considering the impacts for a 20 year time horizon, the climate forcing is 143% and 74% of the climate forcing for a 100 year time horizon for seafood caught in ECAs and non-ECAs, respectively. Lastly, the regional sulfur control laws have a role in the variability in climate forcing of wild-caught seafood. For seafood caught in ECAs (Figures 3b and 3d) there is significant warming from SLCFs for a 20 year time horizon (149% of total climate forcing over LLCFs alone), whereas for a 100 year time horizon the warming from BC is largely offset by the cooling from NOx. For seafood caught in non-ECAs (Figures 3a and 3c), there is significant cooling from SLCFs (58% and 78% of total climate forcing over LLCFs alone for 20 year and 100 year time horizons, respectively).

Comparison of wild-caught seafood to other animal-based protein sources can help to put climate impacts in perspective. For a 20 year time horizon, the median fisheries climate impact (26 kg CO_2e/kg protein) is lower than chicken, farmed salmon, and farmed trout (32, 30, and 29 kg CO_2e/kg protein, respectively) when only LLCFs are considered. When the net cooling from SLCFs is included for catches caught in non-ECAs, the median fisheries climate impact is smaller, 15 kg CO_2e/kg protein (Figure 3a), than all forms of animal protein considered here. However, when the net warming from SLCFs is included for catches caught in ECAs, the median fisheries impact is significantly larger, 39 kg CO_2e/kg protein (Figure 3b), and elevated to a similar climate impact as farmed whitefish (41 kg CO_2e/kg protein). The climate impact of large pelagics, 39 kg CO_2e/kg protein, is similar to farmed whitefish when only LLCFs are considered. When the net cooling from SLCFs is included for catches in non-ECAs, 31 kg CO_2e/kg protein (Figure 3a), the large pelagics climate impact is smaller than farmed whitefish and similar to chicken. For catches in ECAs, on the other hand, the net warming from SLCF significantly increases the climate impact of large pelagics, 56 kg CO_2e/kg protein (Figure 3b), to having a similar impact as pork, 63 CO_2e/kg protein. In the scenarios with the largest SLCF net warming, crustacean fisheries are elevated to having similar climate forcing as beef.

3.8. Parameter Sensitivity

A sensitivity analysis was undertaken to identify which components of the climate forcing assessment made the largest contributions to uncertainty. The results of our sensitivity analysis are presented as tornado plots in Figure 4. The sensitivity simulations were based on a baseline fuel sulfur of 0.051% with low and high values of 0.001% and 0.1%, respectively. The baseline FUI was the global median value of 0.639 L fuel/kg catch with low and high values of 0.32 and 1.47 L fuel/kg catch, respectively. The baseline emissions of SLCFs were the average values for ECAs with low and high values given by the standard deviations (Table 3). We also consider a flat emission factor for BC, 0.35 g BC/kg fuel, as an alternative to the binned approach we used to estimate the BC emission factors given in Table 3. The baseline GWPs for SO_2, NOx, OC, and BC were the average values for each climate effect (direct and total) and time horizon (20 year and 100 year horizons) with high and low values given by the standard deviations (Table 2). For all scenarios, the FUI was the dominant source of uncertainty. Secondary sources of uncertainty were from the BC emission factors and the BC GWP.

4. Discussion

Understanding fishing vessel emissions is timely as the International Maritime Organization is considering whether to uphold its decision to reduce international fuel sulfur limits from 3.5% to 0.5% in 2020. Our discussion of Arctic emissions is also relevant considering the Arctic Council has proposed to develop a standardized way to measure BC and investigate potential control options. Although fuel sulfur laws were designed to reduce air pollution, they may have an unintended consequence of increasing net climate forcing for fishing and other maritime industries [*Fuglestvedt et al.*, 2009]. With respect to the climate impacts of BC, the results of our analysis suggest that sulfur control regulation may not be the best mitigation approach.

We also hypothesized that previously published climate impact assessments of food had not included SLCFs and may have understated climate forcing. For some emission factors and GWP estimates, the added net warming from SLCFs caused crustacean fisheries to have a similar climate forcing as beef, while pelagic fishery impacts were elevated to have a similar forcing as pork. It would appear that seafood harvested in regions with fuel sulfur control laws has a larger climate forcing than in regions that are not regulated. This work is important because consumers reward fisheries that use sustainable harvesting processes with the help of consumer advisory groups.

4.1. Model Uncertainties

It has been pointed out that using catch statistics (as we have in our global estimate) for emissions inventories could be understated by a factor of two or three, due to poor reporting [*Greer*, 2014]. In addition to uncertainties related to global catch statistics, the climate forcing is particularly sensitive to FUI. As shown in Figure 4, at the low end of the FUI sensitivity range (0.32 L fuel/kg fish) the global median fishery climate forcing is 51% of the mean climate forcing, whereas at the high end of the FUI sensitivity range (1.5 L fuel/kg fish) the climate forcing is 230% of the mean climate forcing. The fuel consumption per kilogram of caught fish is reported to vary considerably as a function of fishing gear and vessel size, even when considering the same target species [*Thrane et al.*, 2009; *Tyedmers*, 2001; *Parker and Tyedmers*, 2014]. The global vessel characterization and the global FUI that we used in this study may not be representative of fishing communities at the regional scale. Vessel sizes can range from 2 m boats used in subsistence fisheries to industrial fishing ships that exceed 130 m in length (FAO, Fisheries and

Aquaculture topics. Fishing vessels: http://www.fao.org/fishery/topic/1616/en). The energy consumption increases as a function of vessel size because engine power increases with the size of the ship and larger fisheries substitute human power with mechanized fishing gears that require greater engine power [*Thrane et al.*, 2009]. Larger vessels are also reported to exploit more distant fish resources than small vessels, which would then require a longer sailing distance to and from the catch area and thus greater fuel consumption [*Thrane et al.*, 2009].

The climate forcing of fisheries is also sensitive to the GWP of SLCFs, particularly BC. The substantial uncertainties in our estimate are, in part, due to the heterogeneous distributions and radiative forcing patterns that are dependent on the aerosol emission location [*Collins et al.*, 2013]. The regional variability for BC is reported to be 30% to 40% for the direct effect, with the largest forcing typically found at low latitudes [*Bond et al.*, 2013]. For the snow albedo effect the regional variation is much larger with higher values for high-latitude regions where the emitted BC is more likely to be deposited on snow surfaces. The snow albedo effect of BC ranges from practically zero for emissions in the tropics to values that reach 30% to 60% of the direct effect in the higher-latitude regions [*Bond et al.*, 2013]. For all aerosols, model estimates of indirect effects have a much larger relative spread for indirect effects compared with direct effects. For example, the uncertainty estimate for the cloud albedo effect is double that of the aerosol direct effect [*Bond et al.*, 2013]. While we used GWP estimates for a first approximation of the climate forcing from fisheries, future work using spatially explicit emissions inventories and climate models may be useful in reducing the uncertainty of these estimates.

Another substantial source of uncertainty in our model is the BC emission factor. Previous fishing emission estimates have used a flat BC emission factor of 0.35 g BC/kg fuel for Arctic inventories and 0.18 g/kg for global inventories that both originate from a small subset of the published ship emission data and are not specific to the engine types of fishing vessels. Our binned BC emission factors used in this analysis (Table 3) are two or more times the previously applied BC emission factors. The climate forcing for global median fisheries using the flat 0.35 g/kg emission factor is 69% of the mean value of our binned approach (Figure 4). Due to bias in sampling of data points and methods used to sort the data into bins, we considered an alternative to the binned approach that does not depend on load or fishing gears (equation (S1)), resulting in 0.92 and 0.86 g BC/kg fuel for low and high sulfur fuel, respectively. We also tested the hypothesis that the alternate BC emission factors for engines using MDO were less than or equal to the flat emission factor and that the flat BC emission factor was greater than or equal to the emission factor for the MSD engine using HFO. We reject these hypotheses with high confidence (p values: 1×10^{-11}, $n = 51$; 5×10^{-6}, $n = 45$; 1×10^{-4}, $n = 12$; 0.06, $n = 30$) except the case of emissions for HSD using high sulfur MDO, 0.36 g BC/kg fuel, ($p = 0.45$, $n = 8$). Due to the similarity in values of the binned (described in equations (2)–(4) and presented in Table 3) to the alternative BC emission factors, it is likely that fishing vessels are better represented by our higher emission estimates than the lower emission factors used in previous studies [*Sinha et al.*, 2003; *Corbett et al.*, 2010a].

There are possible limitations to using plume sampling and test-rig data. Because only a small number of engines have been tested, there is a limited amount of in-use emissions data for MSD engines and an even smaller set of data specific to fishing boats [*Lack et al.*, 2008; *Buffaloe et al.*, 2014; *Cappa et al.*, 2014]. In one plume-sampling study, the emissions for fishing vessels were reported although the data for this category consist of only one ship sampled multiple times, and the ship was a research fishing vessel [*Buffaloe et al.*, 2014]. It should also be pointed out that although there is a large amount of ship-to-ship variability from the plume sampling ensemble studies, this data may not reflect the contribution of poorly functioning vessels with very high emissions. The fraction of such vessels and their emission factors are not well known which may result in an underestimation of inventories. Vessels in this category are likely to be more widespread in developing countries, but there is little data on the fraction of vessels with such high emissions [*Bond et al.*, 2013].

5. Conclusions

The emission estimates presented here advance the understanding of the fishing vessel contribution to global and regional emissions inventories. Emission uncertainties are on the order of 50% and could be reduced through plume intercept studies of fishing vessels that include measurement of emission factors under actual operating conditions (including the influence of engine load, ship size, engine type, and fuel quality) and atmospheric dilution conditions. Furthermore, mapping the spatial distribution and temporal variability of these emissions and simulating their impacts with climate models could reduce the uncertainties in the regional climate response. Despite these uncertainties, our inventories show significantly larger SLCF emissions than previous inventories. In particular, global BC had been underestimated by an order of magnitude. Emerging policies concerning global fuel sulfur reductions may result in net warming from fishing vessel emissions globally and in the Arctic. Considering the large contribution of emissions from fishing vessels compared to other ships in the Arctic, the climate sensitivity to BC in the Arctic, and the small number of studies dedicated to fishing vessels, fishing emissions studies may be an important focus area for further work.

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References

Aamaas, B., T. K. Berntsen, J. S. Fuglestvedt, K. P. Shine, and N. Bellouin (2015), Multimodel emission metrics for regional emissions of short lived climate forcers, *Atmos. Chem. Phys. Discuss.*, *15*(18), 26,089–26,130, doi:10.5194/acpd-15-26089-2015.

Aliabadi, A. A., R. M. Staebler, and S. Sharma (2015), Air quality monitoring in communities of the Canadian Arctic during the high shipping season with a focus on local and marine pollution, *Atmos. Chem. Phys.*, *15*(5), 2651–2673, doi:10.5194/acp-15-2651-2015.

Argonne National Laboratory (2014), The Greenhouse gases, Regulated Emissions, Energy use in Transportation (GREET) model.

Baker, L. H., W. J. Collins, D. J. L. Olivié, R. Cherian, Ø. Hodnebrog, G. Myhre, J. Quaas, and B. H. Samset (2015), Climate responses to anthropogenic emissions of short-lived climate pollutants, *Atmos. Chem. Phys. Discuss.*, *15*(3), 3823–3862, doi:10.5194/acpd-15-3823-2015.

Blonk, H., A. Kool, B. Luske, and S. de Waart (2008), *Environmental Effects of Protein-Rich Food Products in the Netherlands: Consequences of Animal Protein Substitutes*, Blonk Milieuadvies and the Dutch Vegetarian Association, Netherlands.

Bond, T. C., C. Zarzycki, M. G. Flanner, and D. M. Koch (2011), Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse, *Atmos. Chem. Phys.*, *11*(4), 1505–1525, doi:10.5194/acp-11-1505-2011.

Bond, T. C., et al. (2013), Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res. Atmos.*, *118*, 5380–5552, doi:10.1002/jgrd.50171.

Boucher, O., and M. S. Reddy (2008), Climate trade-off between black carbon and carbon dioxide emissions, *Energy Policy*, *36*(1), 193–200, doi:10.1016/j.enpol.2007.08.039.

Browse, J., K. S. Carslaw, A. Schmidt, and J. J. Corbett (2013), Impact of future Arctic shipping on high-latitude black carbon deposition, *Geophys. Res. Lett.*, *40*, 4459–4463, doi:10.1002/grl.50876.

Buffaloe, G. M., et al. (2014), Black carbon emissions from in-use ships: A California regional assessment, *Atmos. Chem. Phys.*, *14*(4), 1881–1896, doi:10.5194/acp-14-1881-2014.

Cao, L., J. S. Diana, G. A. Keoleian, and Q. Lai (2011), Life cycle assessment of Chinese shrimp farming systems targeted for export and domestic sales, *Environ. Sci. Technol.*, *45*(15), 6531–6538, doi:10.1021/es104058z.

Cappa, C. D., et al. (2014), A case study into the measurement of ship emissions from plume intercepts of the NOAA ship Miller Freeman, *Atmos. Chem. Phys.*, *14*(3), 1337–1352, doi:10.5194/acp-14-1337-2014.

Coello, J., I. Williams, D. A. Hudson, and S. Kemp (2015), An AIS-based approach to calculate atmospheric emissions from the UK fishing fleet, *Atmos. Environ.*, *114*, 1–7, doi:10.1016/j.atmosenv.2015.05.011.

Collins, W. J., M. M. Fry, H. Yu, J. S. Fuglestvedt, D. T. Shindell, and J. J. West (2013), Global and regional temperature-change potentials for near-term climate forcers, *Atmos. Chem. Phys.*, *13*(5), 2471–2485, doi:10.5194/acp-13-2471-2013.

Corbett, J. J., and H. W. Koehler (2003), Updated emissions from ocean shipping, *J. Geophys. Res.*, *108*(D20), 4650, doi:10.1029/2003JD003751.

Corbett, J. J., D. A. Lack, J. J. Winebrake, S. Harder, J. A. Silberman, and M. Gold (2010a), Arctic shipping emissions inventories and future scenarios, *Atmos. Chem. Phys.*, *10*(19), 9689–9704, doi:10.5194/acp-10-9689-2010.

Corbett, J. J., J. J. Winebrake, and E. H. Green (2010b), An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping, *Carbon Manag.*, *1*(2), 207–225, doi:10.4155/CMT.10.27.

d'Orbcastel, E. R., J. Blancheton, and J. Aubin (2009), Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using Life Cycle Assessment, *Aquacult. Eng.*, *40*(3), 113–119, doi:10.1016/j.aquaeng.2008.12.002.

Dalsøren, S. B., M. S. Eide, O. Endresen, A. Mjelde, G. Gravir, and I. S. A. Isaksen (2009), Update on emissions and environmental impacts from the international fleet of ships: The contribution from major ship types and ports, *Atmos. Chem. Phys.*, *9*(6), 2171–2194.

Endresen, O., E. Sorgard, H. L. Behrens, P. O. Brett, and I. S. A. Isaksen (2007), A historical reconstruction of ships' fuel consumption and emissions, *J. Geophys. Res.*, *112*, D12301, doi:10.1029/2006JD007630.

Energy and Environmental Analysis, Inc. (2000), Analysis of commercial marine vessels emissions and fuel consumption data, Rep. EPA420-R-00-002, U.S. Environ. Protection Agency, Washington, D. C.

Eyring, V., H. W. Kohler, J. van Aardenne, and A. Lauer (2005), Emissions from international shipping: 1. The last 50 years, *J. Geophys. Res.*, *110*, D17305, doi:10.1029/2004JD005619.

Eyring, V., I. S. A. Isaksen, T. Berntsen, W. J. Collins, J. J. Corbett, O. Endresen, R. G. Grainger, J. Moldanova, H. Schlager, and D. S. Stevenson (2010), Transport impacts on atmosphere and climate: Shipping, *Atmos. Environ.*, *44*(37), 4735–4771, doi:10.1016/j.atmosenv.2009.04.059.

Faloona, I. (2009), Sulfur processing in the marine atmospheric boundary layer: A review and critical assessment of modeling uncertainties, *Atmos. Environ.*, *43*(18), 2841–2854, doi:10.1016/j.atmosenv.2009.02.043.

FAO (2015), *Fisheries and Aquaculture Software. FishStatJ—Software for Fishery Statistical Time Series*, FAO Fisheries and Aquaculture Department, Rome [online]. Updated 23 June 2015. [Cited 24 2015]. [Available at http://www.fao.org/fishery/statistics/software/fishstatj/en.]

Flanner, M. G. (2013), Arctic climate sensitivity to local black carbon, *J. Geophys. Res. Atmos.*, *118*, 1840–1851, doi:10.1002/jgrd.50176.

Fuglestvedt, J. S., K. P. Shine, T. Berntsen, J. Cook, D. S. Lee, A. Stenke, R. B. Skeie, G. J. M. Velders, and I. A. Waitz (2010), Transport impacts on atmosphere and climate: Metrics, *Atmos. Environ.*, *44*(37), 4648–4677, doi:10.1016/j.atmosenv.2009.04.044.

Fuglestvedt, J., T. Berntsen, V. Eyring, I. Isaksen, D. S. Lee, and R. Sausen (2009), Shipping emissions: From cooling to warming of climate—and reducing impacts on health, *Environ. Sci. Technol.*, *43*(24), 9057–9062, doi:10.1021/es901944r.

Greer, K. (2014), Considering the "effort factor" in fisheries: a methodology for reconstructing global fishing effort and CO_2 emissions, 1950–2010, MS Thesis, The Univ. of British Columbia, Vancouver.

Holmes, C. D., M. J. Prather, and G. C. M. Vinken (2014), The climate impact of ship NOx emissions: An improved estimate accounting for plume chemistry, *Atmos. Chem. Phys.*, *14*(13), 6801–6812, doi:10.5194/acp-14-6801-2014.

ICF Consulting (1999), In-use marine diesel fuel, Rep. EPA 420-R-99-027, U.S. Environ. Protection Agency, Washington, D. C.

ICF International (2009), *Current Methodologies in Preparing Mobile Source Port-Related Emissions Inventories: Final Report Prepared for the US EPA*, U.S. Environ. Protection Agency, Washington, D. C.

Lack, D. A., and J. J. Corbett (2012), Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing, *Atmos. Chem. Phys.*, *12*(9), 3985–4000, doi:10.5194/acp-12-3985-2012.

Lack, D. A., et al. (2009), Particulate emissions from commercial shipping: Chemical, physical, and optical properties, *J. Geophys. Res.*, *114*, D00F04, doi:10.1029/2008JD011300.

Lack, D. A., et al. (2011), Impact of fuel quality regulation and speed reductions on shipping emissions: Implications for climate and air quality, *Environ. Sci. Technol.*, *45*(20), 9052–9060, doi:10.1021/es2013424.

Lack, D., B. Lerner, C. Granier, T. Baynard, E. Lovejoy, P. Massoli, A. R. Ravishankara and E. Williams (2008), Light absorbing carbon emissions from commercial shipping, *Geophys. Res. Lett.*, *35*, L13815, doi:10.1029/2008GL033906.

Mathwave Data Analysis and Simulation (2015), Mathwave data analysis and simulation, EasyFit Distribution Fitting Software for Excel, Version 5.6.

Mjelde, A., K. Martinsen, M. Eide, and Ø. Endresen (2014), Environmental accounting for Arctic shipping—A framework building on ship tracking data from satellites, *Mar. Pollut. Bull.*, *87*(1–2), 22–28, doi:10.1016/j.marpolbul.2014.07.013.

Mueller, L., et al. (2015), Characteristics and temporal evolution of particulate emissions from a ship diesel engine, *Appl. Energy*, *155*, 204–217, doi:10.1016/j.apenergy.2015.05.115.

Myhre, G., et al. (2011), Radiative forcing due to changes in ozone and methane caused by the transport sector, *Atmos. Environ.*, *45*(2), 387–394, doi:10.1016/j.atmosenv.2010.10.001.

Myhre, G., et al. (2013), Anthropogenic and natural radiative forcing in climate change 2013: The physical science basis, in *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., Cambridge Univ. Press, Cambridge and New York.

Nijdam, D., T. Rood, and H. Westhoek (2012), The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes, *Food Policy*, *37*(6), 760–770, doi:10.1016/j.foodpol.2012.08.002.

Notteboom, T., E. Delhaye, and K. Vanherele (2010), *Analysis of the Consequences of Low Sulphur Fuel Requirements*, European Community Shipowners Association, Leuven.

Ødemark, K., S. B. Dalsøren, B. H. Samset, T. K. Berntsen, J. S. Fuglestvedt, and G. Myhre (2012), Short-lived climate forcers from current shipping and petroleum activities in the Arctic, *Atmos. Chem. Phys.*, *12*(4), 1979–1993, doi:10.5194/acp-12-1979-2012.

Parker, R. W. R., and P. H. Tyedmers (2014), Fuel consumption of global fishing fleets: current understanding and knowledge gaps, *Fish Fish.*, doi:10.1111/faf.12087.

Parker, R. W. R., K. Hartmann, B. S. Green, C. Gardner, and R. A. Watson (2015), Environmental and economic dimensions of fuel use in Australian fisheries, *J. Cleaner Prod.*, *87*, 78–86, doi:10.1016/j.jclepro.2014.09.081.

Pelletier, N., and P. Tyedmers (2007), Feeding farmed salmon: Is organic better?, *Aquaculture*, *272*(1–4), 399–416, doi:10.1016/j.aquaculture.2007.06.024.

Pelletier, N., and P. Tyedmers (2008), Life cycle considerations for improving sustainability assessments in seafood awareness campaigns, *Environ. Manag.*, *42*(5), 918–931, doi:10.1007/s00267-008-9148-9.

Pelletier, N., and P. Tyedmers (2010), Life cycle assessment of frozen tilapia Fillets from Indonesian lake-based and pond-based intensive aquaculture systems, *J. Ind. Ecol.*, *14*(3), 467–481, doi:10.1111/j.1530-9290.2010.00244.x.

Pelletier, N., P. Tyedmers, U. Sonesson, A. Scholz, F. Ziegler, A. Flysjo, S. Kruse, B. Cancino, and H. Silverman (2009), Not all salmon are created equal: Life cycle assessment (LCA) of global salmon farming systems, *Environ. Sci. Technol.*, *43*(23), 8730–8736, doi:10.1021/es9010114.

Peters, G. P., B. Aamaas, M. T. Lund, C. Solli, and J. S. Fuglestvedt (2011), Alternative "global warming" metrics in life cycle assessment: A case study with existing transportation data, *Environ. Sci. Technol.*, *45*(20), 8633–8641, doi:10.1021/es200627s.

Petzold, A., E. Weingartner, I. Hasselbach, P. Lauer, C. Kurok, and F. Fleischer (2010), Physical properties, chemical composition, and cloud forming potential of particulate emissions from a marine diesel engine at various load conditions, *Environ. Sci. Technol.*, *44*(10), 3800–3805, doi:10.1021/es903681z.

Petzold, A., P. Lauer, U. Fritsche, J. Hasselbach, M. Lichtenstern, H. Schlager, and F. Fleischer (2011), Operation of marine diesel engines on biogenic fuels: Modification of emissions and resulting climate effects, *Environ. Sci. Technol.*, *45*(24), 10,394–10,400, doi:10.1021/es2021439.

Quinn, P. K., et al. (2008), Short-lived pollutants in the Arctic: Their climate impact and possible mitigation strategies, *Atmos. Chem. Phys.*, *8*(6), 1723–1735, doi:10.5194/acp-8-1723-2008.

Sampson, G. S., et al. (2015), Secure sustainable seafood from developing countries, *Science*, *348*(6234), 504–506, doi:10.1126/science.aaa4639.

Shindell, D. T., G. Faluvegi, D. M. Koch, G. A. Schmidt, N. Unger, and S. E. Bauer (2009), Improved attribution of climate forcing to emissions, *Science*, *326*(5953), 716–718, doi:10.1126/science.1174760.

Sinha, P., P. V. Hobbs, R. J. Yokelson, T. J. Christian, T. W. Kirchstetter, and R. Bruintjes (2003), Emissions of trace gases and particles from two ships in the southern Atlantic Ocean, *Atmos. Environ.*, *37*(15), 2139–2148, doi:10.1016/S1352-2310(03)00080-3.

Smith, M. D., et al. (2010), Sustainability and global seafood, *Science*, *327*(5967), 784–786, doi:10.1126/science.1185345.

Smith, T. W. P., et al. (2014), Third International Maritime Organization (IMO) GHG Study 2014, Rep. MEPC 67/INF.3, International Maritime Organization, London.

Steinfield, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan (2006), *Livestock's Long Shadow: Environmental Issues and Options*, Food and Agricultural Organization of the United Nations, Rome.

Sumaila, U. R., et al. (2015), Winners and losers in a world where the high seas is closed to fishing, *Sci. Rep.*, *5*, 8481, doi:10.1038/srep08481.

The Arctic Council (2009), Arctic marine shipping assessment 2009 report, The Arctic Council.

Thrane, M., F. Ziegler, and U. Sonesson (2009), Eco-labelling of wild-caught seafood products, *J. Cleaner Prod.*, *17*(3), 416–423, doi:10.1016/j.jclepro.2008.08.007.

Trozzi, C. (2010), *Emission Estimate Methodology for Maritime Navigation*, Techne Consulting, Rome.

Tyedmers, P. (2001), Fisheries impacts on North AtlanticeEcosystems: Catch, effort and national/regional data sets. Part 1. Basin scale analysis: Energy consumed by North Atlantic fisheries, in *Fisheries' Impacts on North Atlantic Ecosystems: Catch, Effort, and National/Regional Datasets*, edited by D. Zeller, R. Watson, and D. Pauly, Fisheries Centre, Univ. of British Columbia, Vancouver.

Tyedmers, P. H., R. Watson, and D. Pauly (2005), Fueling global fishing fleets, *Ambio*, *34*(8), 635–638, doi:10.1639/0044-7447(2005)034[0635:FGFF]2.0.CO;2.

Unger, N., T. C. Bond, J. S. Wang, D. M. Koch, S. Menon, D. T. Shindell, and S. Bauer (2010), Attribution of climate forcing to economic sectors, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(8), 3382–3387, doi:10.1073/pnas.0906548107.

Vergé, X. P. C., D. Maxime, J. A. Dyer, R. L. Desjardins, Y. Arcand, and A. Vanderzaag (2013), Carbon footprint of Canadian dairy products: Calculations and issues, *J. Dairy Sci.*, *96*(9), 6091–6104, doi:10.3168/jds.2013-6563.

Wang, H., and R. Minjares (2013), *Global Emissions of Marine Black Carbon: Critical Review and Revised Assessment*, Transportation Research Board of the National Academies, Washington, D. C.

Winther, M., J. H. Christensen, M. S. Plejdrup, E. S. Ravn, O. F. Eriksson, and H. O. Kristensen (2014), Emission inventories for ships in the arctic based on satellite sampled AIS data, *Atmos. Environ.*, *91*, 1–14, doi:10.1016/j.atmosenv.2014.03.006.

Ziegler, F., and P. A. Hansson (2003), Emissions from fuel combustion in Swedish cod fishery, *J. Cleaner Prod.*, *11*(3), 303–314, doi:10.1016/S0959-6526(02)00050-1.