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Reducing CO_2 from shipping – do non-CO_2 effects matter?

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Abstract. Shipping is a growing sector in the global economy, and it contributions to global CO_2 emissions are expected to increase. CO_2 emissions from the world shipping fleet will likely be regulated in the near future, and studies have shown that significant emission reductions can be achieved at low cost. Regulations are being discussed for both existing ships as well as for future additions to the fleet. In this study a plausible CO_2 emission reduction inventory is constructed for the cargo fleet existing in 2010, as well as for container ships, bulk ships and tankers separately. In the reduction inventories, CO_2 emissions are reduced by 25–32 % relative to baseline by applying 15 technical and operational emission reduction measures in accordance with a ship-type-specific cost-effectiveness criterion, and 9 other emission compounds are changed as a technical implication of reducing CO_2. The overall climate and environmental effects of the changes to all 10 emission components in the reduction inventory are assessed using a chemical transport model, radiative forcing (RF) models and a simple climate model. We find substantial environmental and health benefits with up to 5 % reduction in surface ozone levels, 15 % reductions in surface sulfate and 10 % reductions in wet deposition of sulfate in certain regions exposed to heavy ship traffic. The major ship types show distinctly different contributions in specific locations. For instance, the container fleet contributes 50 % of the sulfate decline on the west coast of North America. The global radiative forcing from a 1 yr emission equal to the difference between baseline and reduction inventory shows an initial strong positive forcing from non-CO_2 compounds. This warming effect is due to reduced cooling by aerosols and methane. After approximately 25 yr, the non-CO_2 forcing is balanced by the CO_2 forcing. For the global mean temperature change, we find a shift from warming to cooling after approximately 60 yr. The major ship types show significant differences in the short-term radiative forcing. For instance, the direct SO_4 forcing from tankers is 30 % higher than for container and bulk. The net long-term effects on RF are similar due to similar CO_2 forcing. We assess an emission scenario where the reduction inventory is sustained on the fleet as it steadily diminishes over time due to scrapping and disappears in 2040. We find a net temperature increase lasting until approximately 2080. We conclude that changes in non-CO_2 emission does matter significantly if reductions of CO_2 emissions are made on the year 2010 cargo shipping fleet. In sum, we find that emission changes motivated by CO_2 reductions in shipping will be beneficial from a long-term climate perspective, and that there are positive environmental and health effects identified as concentrations of key short-lived pollutants are reduced.

1 Introduction

Shipping emissions have an impact on climate, human health and the environment (Eyring et al., 2010; Endresen et al., 2008; Buhaug et al., 2009), and to assess these impacts several studies have previously produced global ship emission inventories (Corbett and Köhler, 2003, 2004; Endresen et al., 2003, 2004, 2007; Eyring et al., 2005; Dalsøren et al., 2009; Buhaug et al., 2009). Shipping impacts on human health through formation of surface ozone and particulate matter (PM). Corbett et al. (2007) indicate that shipping-related PM emissions are responsible for 20 000–104 000 premature cardiopulmonary and lung cancer deaths annually, or 3–8 % of global $PM_{2.5}$-related mortalities (Cohen et al., 2005). Also, shipping contributes significantly to surface ozone, e.g., in

Table 1. Overview of main global climate effects from shipping emissions.[1]

Emission component	Response component	Effect	Time horizon for RF effects[2]
CO_2	CO_2	Warming	Century scale
NO_x	Increased Tropospheric O_3	Warming	Weeks–months
	Reduced CH_4	Cooling	Decadal scale
	Reduced O_3 (via CH_4 change)	Cooling	Decadal scale
	Reduced stratospheric H_2O (via CH_4 change)	Cooling	Decadal scale
SO_x	SO_4 particles	Cooling	Days–weeks
	Clouds	Cooling	Days–weeks

[1] Based on the reviews by Eyring et al. (2010) and Buhaug et al. (2009), [2] Temperature will be impacted longer due to the inertia of the climate system.

western North America (contribution 15–25 %) and Western Europe (5–15 %) (Dalsøren et al., 2009). Ships also contribute 11 % to nitrate wet deposition and 4.5 % to sulfur wet deposition globally. In certain coastal regions the contributions may be in the range of 15–50 % (Dalsøren et al., 2009). Sulfate deposition increases the acidity of soils, rivers and lakes. This harms ecosystems. Nitrate deposition increases the available nitrogen in soils (eutrophication), harming ecosystems through asymmetric plant competition in nitrogen poor regions.

Climate is impacted directly by the release of long-lived greenhouse gases such as CO_2 and indirectly by the perturbation of greenhouse gases such as CH_4 and O_3 due to chemical interactions with NO_x emitted from ships, as well as through direct and indirect aerosol effects, mainly due to shipping SO_x emissions. Aerosols have a direct effect on climate by influencing the radiative balance through scattering and/or absorbing solar radiation. Also, aerosols can act as condensation nuclei, modifying cloud properties and precipitation rates, thus indirectly impacting climate.

The different climate effects are typically assessed with respect to their impact on radiative forcing (RF). Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth atmosphere system (IPCC, 2007). However, the temporal dimension of different RF factors can be quite different, making assessment of combined effects challenging. CO_2 is a well-mixed greenhouse gas with a long atmospheric lifetime ($>$ 100 yr), while SO_2 and NO_x are reactive species with much shorter lifetimes (days). Also, secondary components such as SO_4 and O_3, have lifetimes of days to weeks in the troposphere. Emissions of NO_x, and the O_3 they form, lead to enhanced levels of the hydroxyl radical (OH). This increases the removal rates of CH_4, which have a lifetime of decades. The temperature response to any forcing occurs over much longer timescales because of the thermal inertia of the climate system, which is largely controlled by timescales of heat exchange between the surface ocean and the atmosphere. An overview of the main global climate effects from shipping emissions components are provided in Table 1.

Several studies have made estimates on the ship emissions impact on climate for one or more components (Capaldo et al., 1999; Endresen et al., 2003, 2008; Eyring et al., 2007, 2010; Lee et al., 2007; Lauer et al., 2007; Dalsøren et al., 2007; Fuglestvedt et al., 2008; Berntsen and Fuglestvedt, 2008; Skeie et al., 2009; Olivie et al., 2012). The uncertainties reported are large, in particular for indirect effects. However, it is notable that for shipping, in contrast to, for instance aircraft (Sausen et al., 2005), the overall effect of emissions is a relatively strong cooling of the atmosphere.

Emissions from ships in international trade are regulated by the International Maritime Organization (IMO) under Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78 (IMO, 1998). To counteract the adverse effects of shipping emissions on health and environment, the IMO has agreed on regulations on emissions of SO_x and NO_x (IMO, 2010) (IMO, 2009). Currently, the IMO is working to develop regulations on CO_2 (IMO, 2011) with the aim to reduce the climate impact from shipping, and significant efforts are directed towards finding technical, operational ways of mitigating CO_2 emissions.

To this end, several studies have documented the measures available for CO_2 reductions in shipping, ranging from operational changes, such as reduced speed, to alternative fuels, to technical measures (Skjølsvik et al., 2000; Buhaug et al. 2009; Eide et al., 2009, 2011; UNEP, 2011). Lately, studies have documented the potential for CO_2 emissions reduction in shipping and the associated cost levels in an effort to aid in decision making (Buhaug et al., 2009; Eide et al., 2009, 2011; Wang et al., 2010; Hoffmann et al., 2012). Eide et al. (2011) use a model that captures the world fleet up to 2030, and the analysis includes 25 separate CO_2 reduction measures. They find that, at a marginal cost of USD 0 per ton, reduced emission in 2010 could be reduced by 19 %. Accepting an abatement cost of USD 50 per ton increases this potential to 26 %. For the future fleet the potential grows as new technologies may be introduced. The analyzed fleet is divided into 59 segments, which allows for detailed assessment of the major ship types. At USD 50 per ton the potential in 2010 for the tanker fleet was 27 %, for the container fleet 25 % and for bulk fleet 32 %. Furthermore, Eide et al. (2009)

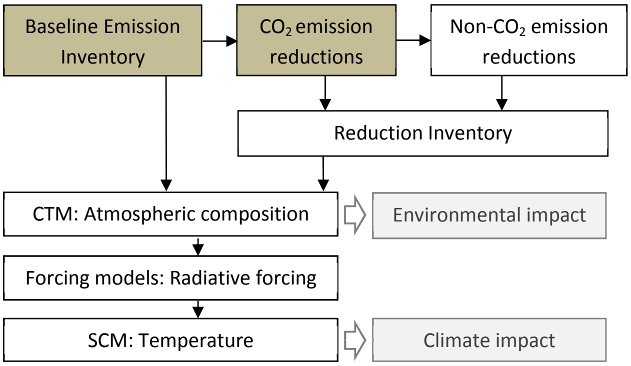


Fig. 1. Outline of main modeling steps. The dark shaded boxes indicate components from previous studies. Light shaded boxes indicate outputs, while non-shaded boxes indicate modeling steps new to this work.

proposed to use a cost-effectiveness criterion of USD 50 per ton CO_2 reduced as a guiding principle for what should be done to propose a policy criterion for mandating CO_2 reduction measures in the IMO. Such a criterion aligns shipping ambitions with the target of 2 °C temperature increase, and cost-effective reduction potentials across all sectors.

Regulatory ambitions have guided studies first towards NO_x and SO_x reductions, and later towards CO_2. However, a holistic view on regulation and the effects of such is missing. For instance, the agreed regulations on shipping emissions of SO_x and NO_x will, as an unintended side effect, affect climate in the following ways: firstly, because the indirect cooling effects of NO_x and SO_x will diminish and, secondly, because some of the measures needed to comply with the new rules may increase fuel consumption and emissions of CO_2. Some effects of upcoming regulations have been studied. Lauer et al. (2009) assessed the impact on radiative forcing from the introduction of a low-sulfur mandate, and Winebrake et al. (2009) assessed the health impacts of the same. Löndahl et al. (2010) make a first attempt to estimate climate change effects and health effects from aerosol emissions, which include both exposure to particles and consequences for climate change initiated by particles, thus providing a means for prioritizing policy and technology options with different impacts. They analyze the effect of zero emissions from shipping, compared to baseline.

However, few studies have assessed impacts of practical policy options on a global level, covering more than one component at a time, although Lack and Corbett (2012) investigates impact on BC emission as a consequence of SO_x mitigation and CO_2 mitigation. Regarding CO_2, there is a lack of understanding as to how CO_2 regulation might affect other emission components, and how these in turn may affect climate, health and the environment. The effects of these concurrent emission changes are potentially important as it is well established that the emissions of other gases and particles impact climate in a significant way (Eyring et al., 2010).

In this study we attempt to apply a holistic framework to assess several impacts simultaneously. The effects on non-CO_2 gases and particles resulting as a consequence of implementing measures to reduce CO_2 will be assessed. In this way a practical regulatory option available to policymaker is evaluated: the regulation of CO_2 on the existing fleet (as opposed to new ships built in the future). Building on previous studies (Eide et al., 2011; Dalsøren et al., 2009), we establish a baseline emission inventory for the 2010 cargo fleet. Then, building on Eide et al. (2009, 2011), a plausible reduction inventory is generated, simulating the introduction of regulation to reduce CO_2 from the 2010 fleet of cargo ships and the concurrent change in the mixture of emissions, including 9 other emission compounds: NO_x, SO_x, PM, NMVOC, CH_4, N_2O, CO, BC, OC. For the reduction inventory, we assess overall climate impact, as well as environmental and health effects, and discuss the trade-offs between these effects.

In addition to analyzing the reduction inventory for the full cargo fleet, we also assess the differences in impacts between the three major ship types: container, bulk and tank fleet. This is potentially of importance as it is well established that the major ship types have distinctly separate traffic distributions (see, e.g., Dalsøren et al., 2009). This distinction must be seen in connection with the significant geographic variations in climate impact from a number of short-lived compounds found in several studies, i.e., due to variations in solar intensity, cloud cover and background concentrations (Fuglestvedt et al., 1999; Derwent et al., 2001; Wild et al., 2001; Berntsen et al., 2005; Naik et al., 2005; Lauer et al., 2007; Shindell and Faluvegi, 2009; Berntsen et al., 2006). For instance, Dalsøren et al. (2009) showed ship-type-dependent variations in the OH and methane lifetime resulting from shipping NO_x emissions.

The overall structure of this study is illustrated in Fig. 1, including the main modeling steps and inventories used. First, an emission inventory baseline for the fleet, including spatial distribution, is established for 2010, based on previous studies. Note that this study covers only emissions from the combustion of fuel onboard, and not emissions of cargo vapor or refrigerants. Second, a reduction inventory for 2010 is developed by estimating reductions of CO_2, SO_x, NO_x and other relevant gases and particles resulting from assumed CO_2 reduction policies. Then the OsloCTM2 model is used to calculate the resulting differences in atmospheric concentrations. The output from the chemistry transport model (CTM) is further used as input for calculations with a radiative forcing model. Lastly, globally averaged radiative forcings were used in a simple climate model (SCM) to calculate the global temperature impacts resulting from the difference in emissions.

Table 2. Ship type specific emission baselines and the reduction potential at marginal cost \$50 t^{-1} CO_2 applied to the baseline to generate the reduction inventory.

Emission baseline 2010 (kilo ton)										
Fleet segment	NO_x	SO_x*	CO_2	PM*	NMVOC	CH_4	N_2O	CO	BC	OC*
Total cargo fleet	22 455	13 434	999 000	2367	755	15.2	24.5	2325	56.6	189.3
Tank	5844	3496	260 000	616	196	4.0	6.4	605	14.7	49.3
Container	5732	3429	255 000	604	193	3.9	6.3	593	14.4	48.3
Bulk	4226	2528	188 000	445	142	2.9	4.6	437	10.7	35.6
Emission reduction at \$50 t^{-1} (% of baseline)										
Total cargo fleet	26	26	26	9	−6	−6	26	26	9	9
Tank	27	27	27	10	−5	−5	27	27	10	10
Container	25	25	25	8	−7	−7	25	25	8	8
Bulk	32	32	32	14	−1	−1	32	32	14	14

* Note that the SO_x, PM and OC emissions are not distributed uniformly word wide, but have lower relative emissions in the Baltic Sea SECA and the North Sea SECA. Based on Petzold et al. (2008) it is assumed that 40 % of the PM mass is emitted as sulfate.

2 Emissions inventories

This section describes the baseline emission inventory for the 2010 world cargo fleet, as well as the constructed reduction inventory, covering CO_2 and 9 other compounds. Also, the geographical distribution of emissions (baseline and reduction inventory) is described.

2.1 Baseline inventory

To estimate the baseline emissions volumes for the world cargo fleet, an activity-based approach is used. The emissions are calculated via fuel consumption, which in turn is estimated based on installed engine power for a ship, number of hours at sea, bunker fuel consumed per power unit (kW) and an assumed average engine load. Input data for these models are collected from different sources and maritime databases.

In this study the CO_2 emissions for 2010 have been taken from Eide et al. (2011). The fleet fuel consumption is found by applying an emission CO_2 factor of 3.179 gCO_2 $gFuel^{-1}$ (Dalsøren et al., 2009). To produce estimates for non-CO_2 emissions for the year 2010 fleet we apply the emission factors used in the activity-based model used by Dalsøren et al. (2009) to the fuel estimate, and adjust for the effect of emission control areas (ECAs). The main source for emission factors used by Dalsøren et al. (2009) is Cooper (2002). The emission factor for PM is taken from Whall et al. (2002). For the composition of PM, the black carbon (BC) emission is taken from Sinha et al. (2003), while organic carbon (OC) emission is from Petzold et al. (2004). For the PM mass emitted as primary sulfate, Petzold et al. (2008) is referenced. It is noted that for shipping primary sulfate (emitted from the chimney) is often a relatively small part of the total sulfate generated by shipping. It is noted that while Dalsøren et al. (2009) is among the most recent global inventories available, there is significant uncertainty in the emission factors applied. The sparse data from the referenced sources are mainly from data recorded for marine diesel engines running on heavy fuel oils. The present study is concerned with the cargo fleet that is dominated by heavy fuel oil, omitting many of the segments using lighter oil. Thus, the data from the references are thought to be appropriate for this study.

The resulting cargo fleet emission baseline are presented in Table 2. The cargo fleet included in this study represents 88 % of total world fleet emissions (Eide et al., 2011). Table 2 also presents baseline emissions calculated for the three major ship types: container, bulk and tank.

2.2 Reduction inventory

With the emission baseline established, a reduction inventory is constructed, intended to reflect a plausible change in the CO_2 emissions from the sailing fleet. Eide et al. (2011) have presented reduction potentials for the cargo fleet and the associated cost levels both for the 2010 fleet and future fleets (2020 and 2030), and have shown that 26 % reductions can be achieved in the fleet at USD 50 per ton CO_2. They also calculate corresponding potentials for each of the major ship types. The technical and operational measures included by Eide et al. (2011) in their modeling of the reduction potential for the fleet are listed in Table 3. Only measures labeled applicable to existing ships are included in the modeling of the 2010 potentials. Note that not all listed measures are applied, depending on their cost-effectiveness level for the various ship segments. It is also noted that the fuel price used by Eide et al. (2011) is significantly lower than present levels, implying that a 26 % reduction is a conservative estimate. The study by Eide et al. (2011) uses a fuel price of USD 350 per ton HFO. With prices at the time of writing above USD 700 per ton HFO, reapplying the model by Eide et al. (2011) shows that 26 % reduction can be achieved at a marginal cost of USD 0 per ton CO_2. Even a more moderate

Table 3. CO_2 reduction measures and their applicability, as modeled by Eide et al. (2011).

Measure		Application
Alternative Energy Source	Wind Generator	New ships only
	Kite	New and existing ships
	Fixed Sails or Wings	New and existing ships
	Solar Panels	New and existing ships
Technical Measures (Main Engine)	Electronic Engine Control	New ships only
	Waste Heat Recovery	New ships only
	Speed Reduction (Fleet Increase)	Existing ships only
	Hull Condition	New and existing ships
	Air Cavity Lubrication	New ships only
	Contra-Rotating Propeller	New ships only
	Propulsion Efficiency Devices	New and existing ships
Technical Measures (Auxiliary Engine)	Cold Ironing	New and existing ships
	Fuel Cells	New ships only
	Frequency Converters	New ships only
	Reduced Aux. Power Usage	Existing ships only
	Exhaust Gas Boilers	New ships only
	Efficient Lighting System	New ships only
Operational Improvements	Trim/Draft Optimization	New and existing ships
	Weather Routing	New and existing ships
	Voyage Execution	New and existing ships
	Steam Plant Improvements	New and existing ships
	Engine Monitoring	Existing ships only
	Speed Reduction (Port efficiency)	New and existing ships
	Propeller Condition	New and existing ships

fuel price of USD 500 per ton HFO produces a 26 % reduction at a marginal cost of USD 20 per ton CO_2. Also, evidence is emerging that ship owners and charterers are voluntarily reducing emissions, suggesting that some of this potential is, at least in part, already being realized (e.g., speed reductions) as a result of high fuel prices and weak shipping markets (Cariou, 2010; Lloyds List, 2011; UNCTAD, 2010; PWC, 2011), although some of these reductions will likely be reversed when market conditions improve. Thus, it is considered that a realistic and plausible reduction inventory for use in this study is to assume 26 % reduction in CO_2 emissions.

The consequences on non-CO_2 emissions from the assumed reduction in CO_2 are considered in the following section. In order to analyze this, it is noted that the premise for the calculations by Eide et al. (2011) is that the CO_2 measures introduced will allow the cargo ships to perform the same amount of transport work, but with reduced engine load and thus reduced energy consumption. For instance, a measure such as reducing the drag on the ship hull will allow the master to maintain the original vessel speed at reduced engine load, rather than providing the incentive to maintain engine load and thereby increase speed. At reduced engine load, the performance of the engine changes, as does the emission factors for gases and particles that depend on the combustion process and engine load. In the following analysis, it is vital to note that only the 2010 fleet is examined with no addition of new built ships. Also, when existing ships/engines reduce the load, they do not apply any engine de-rating – retrofitting technology so that the engine performs better at low loads.

Limited studies have been performed documenting the dependence of emission factors on engine load. However, data reported by Lloyds' (1995) and ENTEC (2007) allow for reasonable assumptions about the changes for fleet averages with emphasis on slow-speed engines, which dominate the considered fleet. It is noted that the fleet under consideration consist of a wide range of different engines, in terms of production year, make, sizes, types and maintenance levels, and that the different engines may have substantially different characteristics. This expected variability is also evident in the reported data.

To understand how the CO_2 emission reduction impacts on other emissions, one must understand the mechanism used to reduce the emissions. The emission reducing measures applied to the 2010 fleet by Eide et al. (2011) fall into one of the following two categories: (i) deliberate speed reduction or (ii) reducing engine load. The latter is achieved either by replacing (in part) diesel power production or by reducing energy losses. For both (i) and (ii) the main engine load is reduced, assuming under category (ii) that vessel speed is kept

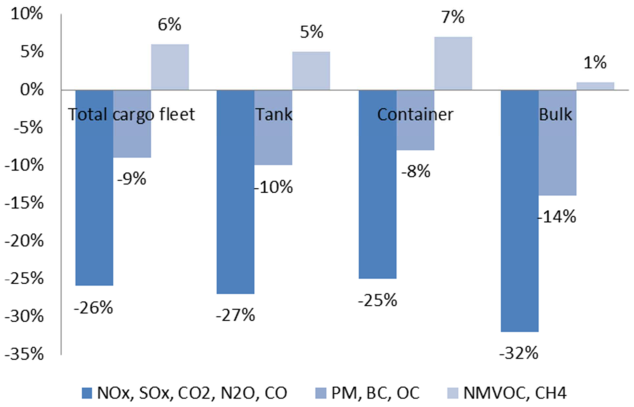


Fig. 2. Resulting emission changes in % of baseline, per ship type and emission component.

constant. At reduced engine load, the performance of the engine changes.

According to Lloyds' (1995), SO_x and CO_2 emissions are independent of engine power. ENTEC (2007) shows that large reduction in engine load (from 80 to 20 %) increases fuel consumption and thus also SO_x and CO_2 emissions by 10 %. For the load change considered herein (from 80 to $\sim$50 %) this increase is considered to be significantly smaller. Hence, no penalty is given to fuel consumption, CO_2 or SO_x.

For NO_x, ENTEC (2007) indicates significant improvement in performance at low loads. This seems to be in contrast to Corbett and Köhler (2003) (at least for the slow-speed engines). However, as Corbett and Köhler (2003) indicate (for medium-speed engines), there is not much variation of the emission profile for the most interesting load points between 50 % and 100 %. The data reported by Lloyds' (1995) shows no clearly defined trends in NO_x emissions as function of engine load. Hence, no change is given to NO_x. This conclusion is supported by engine combustion theory (Merker et al., 2006; Heywood, 1988), which indicates that the problem area for NO_x appears in low loads, i.e., around 30 % of maximum continuous rating (MCR).

For CH_4 and NMVOC the performance drops dramatically: at low loads the emissions are three times the emissions at high load (ENTEC, 2007). Lloyds' (1995) also report a tendency toward increased emissions of hydrocarbons at lower loads, although not as strong as ENTEC. Assuming nonlinearity in the performance, and the likelihood of improvement through tuning, we assume a 40 % increase in the specific emissions of NMVOC and CH_4, given a 20 % reduction in engine load, and 50 % increase given a 35 % reduction in engine load.

For PM, BC and OC the performance also drops dramatically according to ENTEC (2007). At low loads the emissions are three times the emissions at high load, although not as much for the dominant engine/fuel combination in the fleet; slow-speed engines on residual oils display a 40 % increase. Lack and Corbett (2012) report observations that demonstrate BC emission factors increasing 3 to 6 times at very low engine loads ($<$ 25 % compared to 85–100 % load). Assuming nonlinearity in the performance, and the likelihood of improvement through tuning, we assume a 20 % increase in the specific emissions of PM, BC and OC given a 20 % reduction in engine load, and 30 % increase given a 35 % reduction in engine load.

For N_2O and CO we assume no penalty, arguing that these emissions will follow the emissions of CO_2, NO_x and SO_x. Data from Lloyds' (1995) confirm this assumption for CO. It is noted that for the results for both NO_x and CO would be quite different at engine loads below those considered herein, i.e., below 50 % of MCR.

The resulting changes in emissions are presented in Table 2 and illustrated in Fig. 2. By applying the changes to the baseline inventory, the reduction inventory is established. The variation seen between the ship types is a consequence of the difference in CO_2 reductions (and hence engine load reductions) available at the given cost level. It is noted that NO_x, SO_x, N_2O and CO emissions change proportionally to changes in CO_2 emissions, and that emission of particles (PM, BC, OC) change less. For hydrocarbons (CH_4 and NMVOC) the change has opposite sign from CO_2, as the combustion becomes less effective at low loads. Based on the available information, it is believed that the assumptions made are reasonably robust, considering fleet averages. The above values have also been found to be in reasonable agreement with the findings of US EPA (2000). This report covers the data from Lloyds (1995), but includes additional measurements from the British Columbia Ferry Corporation, Environment Canada and the US Coast Guard.

2.3 Gridded inventory

Geographical distributions of ship emissions from world fleet traffic have been produced by several studies (Corbett and Köhler, 2003; Endresen et al., 2003; Dalsøren et al., 2007, 2009; Wang et al., 2007). In this study the calculated atmospheric emissions reduction inventory have been distributed geographically, based on a method reported by Endresen et al. (2003), using the gridded-traffic observation data reported by Dalsøren et al. (2009) (their Fig. 4). The vessel traffic densities (relative number of observations per 1° × 1° grid cell) for the total cargo fleet are based on a combined COADS/AMVER dataset. The AMVER data for year 2001/2002 include a total of 993 000 marine reports. The COADS traffic densities for 2000 include 997 000 marine reports. In addition to a distribution for the total cargo fleet, separate distributions are made for tankers, dry bulk and container ships. These distributions are based on the AMVER data alone. Dalsøren et al. (2009) also produced a distribution specifically for emissions in port. This is not used in the present study as the emission reductions are considered valid

Table 4. Model setup applied to the produced reduction inventory to assess effects on climate and health the environment.

Climate forcers	Atmospheric concentrations	Radiative forcing (RF)	Temperature (T)
CO_2	SCM	SCM	SCM
N_2O	SCM	SCM	
CH_4	Lifetime change from CTM	SCM	
O_3	CTM	RF model[1]	
Aerosols direct effect (primarily SO_4)	CTM	RF model[1]	
Clouds (albedo/Twomey effect)	Based on aerosol concentration in CTM	RF model[2]	

[1] model and method described in Myhre et al. (2009), [2] Parameterization of cloud droplet number concentration versus aerosol optical depth as described by Quaas et al. (2006) and Quaas and Boucher (2005).

only for at-sea emission. Note that to account for the Baltic Sea SECA and the North Sea SECA established before 2010, the SO_x, PM and OC emissions are not distributed uniformly word wide, but have lower relative emissions in the Baltic Sea SECA and the North Sea SECA. The adjustment in ECA for SO_x emissions builds on the assessment by Buhaug et al. (2009), who find that the existing ECAs have contributed to a 3.4 % reduction in global SO_x emissions, which corresponds to a 42 % reduction in SECA emissions (Buhaug et al., 2009, their table 4–8). Moreover, we have applied a reduction factor for PM and its components scaled to 1/4 of the SO_x reduction factor, based on the findings of ENTEC (2005, 2007). The exception is BC emissions, which are reported by Corbett et al. (2010b) to be not well correlated with fuel sulfur content.

3 Methods and models for calculation of climate, health and environmental impacts

This section describes the models that are applied to the produced reduction inventory to assess effects on climate, health and the environment. An overview of the applied models and methods are provided in Table 4.

3.1 Atmospheric concentrations

We used the OsloCTM2 model to calculate atmospheric concentration changes due to emission mitigations. The OsloCTM2 model (Berntsen and Isaksen, 1997; Sundet, 1997) is a 3 dimensional offline global aerosol-chemistry transport model with several options for resolution, model domain (troposphere, stratosphere, both), meteorological data, type of chemistry and number of chemical components. Transport of species by advection, convection, and diffusion is included in the model. The model has been compared to observation in regions affected by shipping in previous studies (Endresen et al., 2003; Dalsøren et al., 2007, 2010). The atmospheric distribution of chemically active components of hydrogen, oxygen, nitrogen, carbon, sulfur, primary organic aerosols, black carbon and sea salt aerosols was quantified. The setup used is similar to that used by Dalsøren et al. (2009, 2010). The model simulations were done with T42 resolution (2.8° × 2.8°) with 60 vertical layers using meteorological data for year 2000. We performed a basis simulation with the baseline emissions from Table 2. In four perturbation runs the emissions from the cargo fleet and three major ship types were changed from the baseline in accordance with Table 2 to assess the reduction inventory. We use the concentration changes found in the CTM to discuss changes in pollution levels in Sect. 4.1. The change in chemical composition is also used as input to calculations of radiative forcing (RF), as described in the following section.

3.2 Radiative forcing and temperature change

To calculate the aerosol RF, we simulate the difference in top-of-atmosphere shortwave fluxes induced by adding all estimated emissions to a standard background aerosol distribution. The fluxes are calculated using a state of the art radiative transfer model (Myhre et al., 2009) based on the DISORT codebase (Stamnes et al., 1988), using four radiation bands and eight streams. Temporal and spatial resolutions are the same as for OsloCTM2. Individual component forcings are found by removing single emission components and running separate RF calculations for each aerosol species. Black carbon is considered as a combination of externally and internally mixed (Myhre et al., 2009). Calculation of the first indirect aerosol effect (cloud albedo effect) is performed through a parameterization of cloud droplet number concentration versus aerosol optical depth, following a method outlined in Quaas et al. (2006) and Quaas and Boucher (2005). The indirect aerosol effect is only estimated for water clouds (no mixed-phase clouds or ice clouds); we do not attempt to include other indirect aerosol effects. Recent discussions in, e.g., Penner et al. (2011), indicate that this method may underestimate the total atmospheric perturbation caused by anthropogenic aerosol emissions over the industrial era. In this study we perform a small perturbation around the current aerosol abundance, and thus the concern raised by Penner et al. (2011) should not be of very high relevance in the

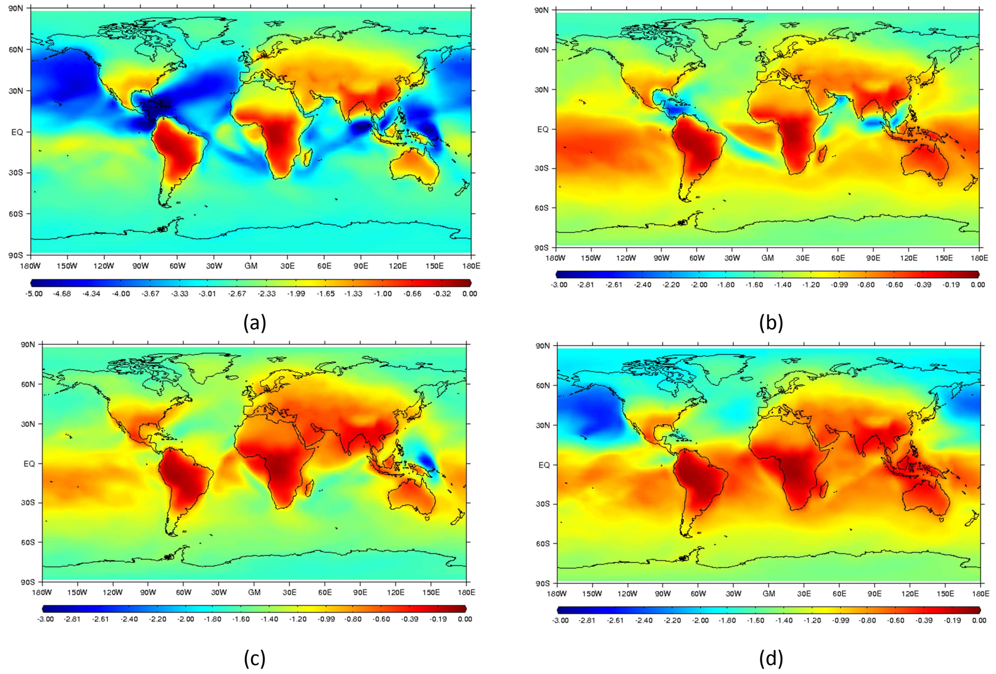


Fig. 3. Yearly mean relative changes (%) in surface ozone due to CO_2 mitigation on **(a)** the year 2010 cargo fleet (scale from −5 to 0 %), **(b)** tank fleet, **(c)** bulk fleet and **(d)** container fleet (scale from −3 to 0 %).

current study. For O_3 changes the DISORT code is used for shortwave calculations and a broadband scheme is used for thermal infrared radiation (Myhre et al., 2011) to simulate the RF at the tropopause altitude including stratospheric temperature adjustment.

Globally averaged forcings for the short-lived species were then used in the CICERO simple climate model (SCM) (Fuglestvedt and Berntsen, 1999; Olivie and Stuber, 2010). Further, global mean temperature change is modeled in the SCM by use of an energy-balance climate/up-welling diffusion model first developed by Schlesinger et al. (1992). The CTM does not calculate the full evolution of the long-lived greenhouse gases CH_4, N_2O and CO_2. For CH_4 the CTM calculated lifetime change was used as input to the SCM. For N_2O and CO_2 the SCM was used for the whole path from emissions to temperature change. The SCM calculates radiative forcing from emissions or concentrations of source gases by applying standard parameterizations published in the literature. For CO_2 the SCM has a separate scheme for the development from emission changes to CO_2 concentration using an ocean mixed-layer pulse response function (Joos et al., 1996; Siegenthaler and Joos, 1992).

4 Climate and environmental impacts

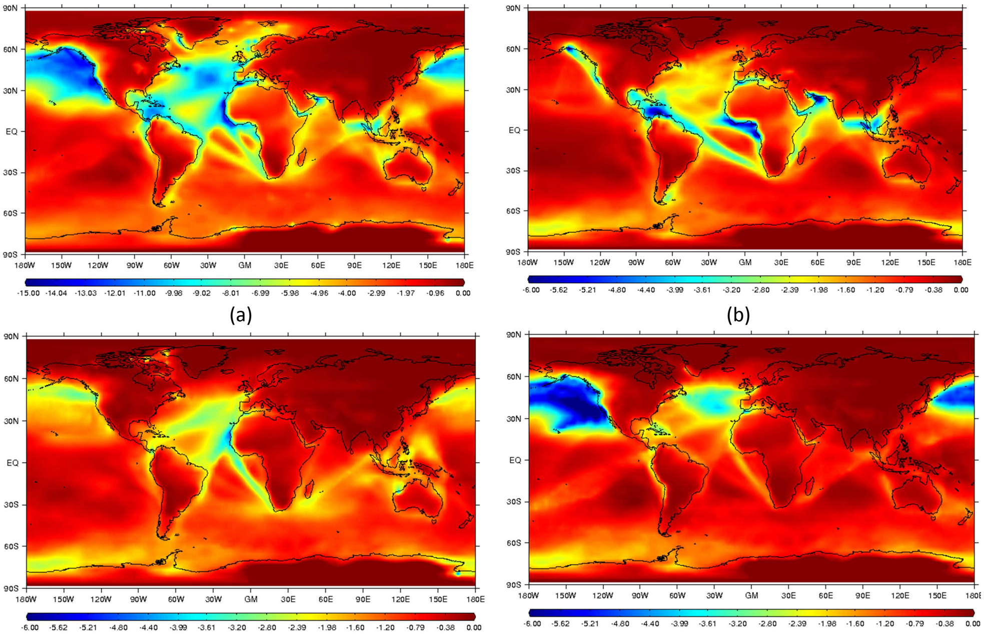
4.1 Environmental impacts

In this section, we present the modeled impacts of the difference between the baseline and reduction inventory.

4.1.1 Cargo fleet

The changes for surface ozone due to emission changes following CO_2 mitigation of the 2010 cargo fleet is shown in Fig. 3a. Reductions of surface ozone up to 5 % (or 2 ppbv) are found. The perturbations are of similar magnitude but opposite sign to those found in Dalsøren et al. (2010) investigating impacts from the 33 % increase in 2000–2007 cargo fleet emissions. For ozone, efforts to reduce CO_2 could therefore compensate for the recent large increase. Ozone changes of a few percent were shown in Dalsøren et al. (2010) to be of importance for understanding of recent trends on the US west coast. Changes of this magnitude are likely to be beneficial in polluted coastal regions, though quantification of effects on health impacts and crop yields is uncertain and goes beyond the scope of this study.

Sulfate is the major component contributing to $PM_{2.5}$ from shipping. Corbett et al. (2007) estimate that shipping-related emissions are responsible for 20 000–104 000 premature cardiopulmonary and lung cancer deaths annually due to $PM_{2.5}$ particles. In this study we find surface sulfate concentration decreases of 5–15 % (Fig. 4a) in some of the coastal areas with many casualties (e.g., western North America, Mexican Gulf, eastern South America, Western Europe, Gulf of Guinea and the Malacca Strait). The applied CO_2-based mitigation could significantly reduce $PM_{2.5}$ related mortality. It would also be efficient in concert with IMO regulations on future fuel sulfur content (IMO, 2010).



(a) (b)

(c) (d)

Fig. 4. Yearly mean relative changes (in % of total burden) in surface sulfate due to CO_2 mitigation on **(a)** the year 2010 cargo fleet (scale from −15 to 0 %), **(b)** tank fleet, **(c)** bulk fleet and **(d)** container fleet (scale from −5 to 0 %).

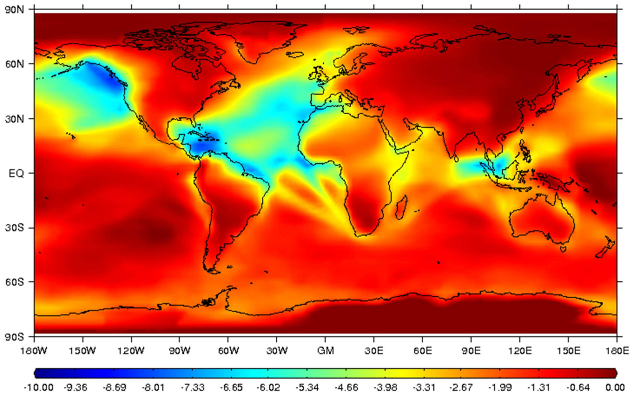


Fig. 5. Yearly mean relative changes (%) in wet deposition of sulfate due to CO_2 mitigation on the year 2010 cargo fleet.

We also find a decrease in wet deposition of sulfate (Fig. 5), with similar patterns as observed for surface sulfate concentrations. The global average decrease is 2.3 %. Decreases are 3–10 % over coastal northwestern America, 3–7 % on the coasts of Western Europe and Scandinavia and 5–7 % over parts of Malaysia and Indonesia. For the two first regions there are still areas exceeding critical loads for acidification, while Southeast Asia may become a region with strong growth in the extent of critical acidification levels in the future (Dentener et al., 2006).

4.1.2 Main ship types

Figure 4 also shows the relative changes in sulfate at the surface for the three major ship types in the cargo fleet. The mitigations for the container fleet give largest reductions of sulfate over the oceans at mid-northern latitudes. Relative to the whole cargo fleet, the container fleet makes up about 50 % of the sulfate decline on the west coast of North America. The share for the tanker fleet is also up to 50 % in the Mexican Gulf, eastern South America, Gulf of Guinea, Persian Gulf and the Malacca Strait. These are some of the coastal regions where expected exposure and health impacts (Corbett et al., 2007) of the $PM_{2.5}$ particles are large. The signal from the bulk ships is more dispersed than for the container and tanker fleet. This is related to larger geographical spread of trade routes and discussed in detail by Dalsøren et al. (2009). Over Western Europe there is no specific ship type in the cargo fleet standing out as a dominant contributor to the sulfate reductions. Also, for surface ozone the contribution from container traffic is large in the North Pacific (Fig. 3b). Reductions of 2–2.5 % are found in this region. Bulk traffic is the ship type giving largest decreases at mid and high latitudes in the Southern Hemisphere (Fig. 3c). Tankers dominate the surface ozone effects in the tropics (Fig. 3b). Also, for other components we find that the regional responses are quite different.

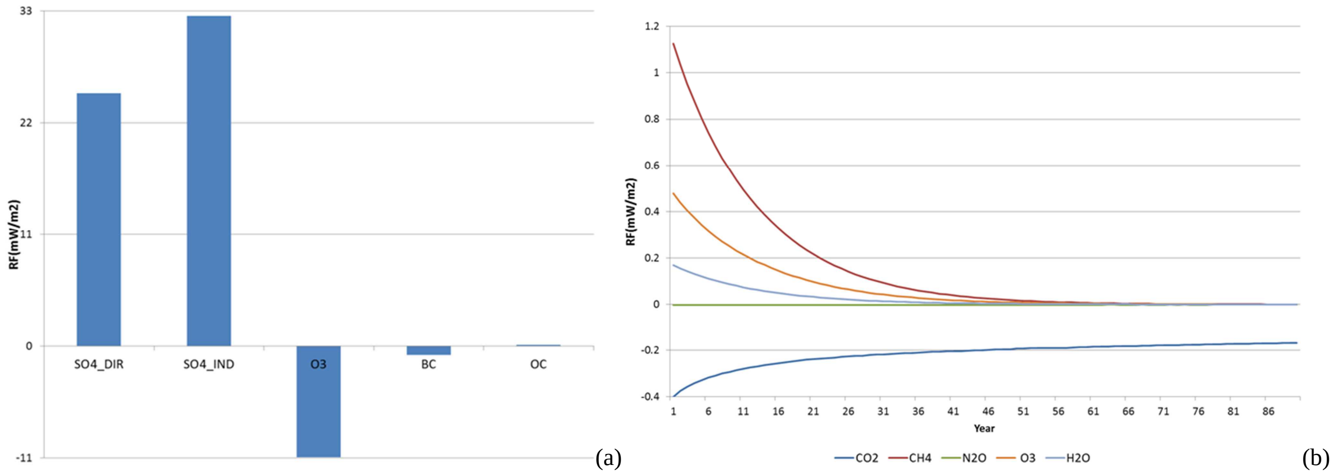


Fig. 6. (a) RF of short-lived components in year of release into the atmosphere (year 1) due to reductions in CO_2 and concurrent emissions. **(b)** RF per component in years 2–90. Note that CH_4 perturbations are caused indirectly by NO_x emissions, not by primary emissions of shipping CH_4. Note also that the O_3 perturbations in **(a)** are induced by chemical cycling of NO_x emissions, while O_3 perturbations as well as H_2O perturbations in **(b)** are due to perturbations in CH_4. See Table 1.

4.2 Climate impacts

In this section we present the results of the reduction inventory, in terms of response to 1 yr pulse emission impacts on radiative forcing and global mean temperature for the cargo fleet (Sect. 4.2.1) and for the tree major ship types (Sect. 4.2.2). From the 1 yr pulse responses, the impact over time of different scenarios can be constructed assuming linearity in the response. We then assess modifications to the reduction inventory under the assumption of a low-sulfur fuel regime consistent with the upcoming requirements on the cargo fleet (Sect. 4.2.3). Finally, we assess the temperature impact from a sustained emission scenario building on the reduction inventory (Sect. 4.2.4).

4.2.1 Impacts from the cargo fleet

In the following we look at the changes in emissions introduced in the reduction inventory, and analyze what the difference in radiative forcing and global mean temperature is compared to leaving emissions from the fleet unchanged. The RF resulting from changes in the major pollutants due to CO_2 mitigation of the 2010 cargo fleet is shown in Fig. 6. When an emission pulse ceases, there is a large span in how long the resulting RF for different components prevail in the atmosphere. The short-lived aerosol components from emissions of SO_x, BC and OC stay in the atmosphere up to a few weeks. The same is the case for the O_3 perturbations induced by chemical cycling of NO_x emissions. Figure 6a shows annually averaged RF for the short-lived species. NO_x also influence the lifetime of CH_4, which in turn affects O_3 and stratospheric water vapor. Since the e-folding time of a perturbation of methane is more than a decade, the forcing and its followers (O_3 and water vapor forcings) last for a few decades. N_2O and CO_2 are long-lived and the forcings exist for centuries. Figure 6 (a and b) clearly shows a dominant initial contribution from the short-lived components such as SO_4 (direct and indirect) and O_3 (due to NO_x, CO and VOCs) the first year, then the impacts fade away when emissions cease. Figure 6b shows that at intermediate time scales (up to 20 yr), the forcings due to methane changes become more important. These effects, with distinctly different timescales for the different components, are expected, as indicated also in Table 1. After approximately 25 yr, the difference in net forcing has turned from positive to negative, as the forcing is dominated by the long-lived perturbation in CO_2 (Fig. 6b).

Figure 7 shows the change in global average temperature in a given year after a 1 yr perturbation to the atmosphere imposed by the reduction scenario, providing a measure of the combined forcing effects, integrated over time. Due to the inertia of the climate system the temperature change lags the RF signal. Until 5 yr after the emissions, we see a sharp increase in temperature due to the strong positive forcing from the short-lived components. It is noted, however, that the absolute values of this increase (0.005 °C) are small in a global context, when all emission sources are considered. The effect stems primarily from the direct and indirect effects of reduced SO_2 emissions, as well as perturbations to methane. After 5 yr we see a steady moderation of this warming effect, until the impact on global temperature shifts sign around year 60 after emission release to the atmosphere. Thus, it is clear that if the prime objective of climate change mitigation is long term, then the desired effect is accomplished. However, on a short to medium time horizon, there are undesired climate effects from introducing measures to limit shipping CO_2 emissions. These results are consistent with those in the review by Eyring et al. (2010), who find that after approximately 50 yr, the net effect of current shipping emissions is nearly neutral through cancellation of warming by CO_2 and cooling by sulfate and NO_x.

4.2.2 Pulse emission from the three major ship types

Considering the RF per component for each of the major ship types, it is clear that considering the ship types independently yields noticeable difference (Fig. 8). The first-year net RF from the emission reductions in the tanker fleet is ∼ 10 % higher than for the other two ship types. This is primarily due to the substantially higher direct SO_4 RF, which is ∼ 30 % higher than for the other two. Normalizing the ship-type-specific RF from each component by the emission volume of each gas/particle, we can compare the effects due to the different geographical trading patterns for the ship types. Interestingly, we see that while the tanker fleet has the strongest direct SO_4 forcing per unit emissions, it also has the weakest indirect effect (Fig. 9). Part of the explanation for this can be found in Fig. 4, showing that the perturbations in surface sulfate from tankers are most pronounced in low-latitude areas, typically associated with few clouds and strong solar radiation. Bulk and container vessels are more frequently impacting areas with low-altitude oceanic stratocumulus clouds, contributing more effectively to the indirect effects.

The RF impact 2–90 yr after emissions from the ship types (Fig. 10) also shows variation, although less pronounced than for year 1. The net effect of the differences becomes apparent when considering the impact on global average temperature from the major ship types (Fig. 11): although a difference in short-term temperature impact is visible, the long-term impact from CO_2 is similar for all ship types and evens out the differences in a longer perspective. Again, we see that approximately 60 yr is needed before the intended temperature decreases are achieved for each of the major ship types.

4.2.3 Impact of upcoming MARPOL low-sulfur regime

We see from Fig. 6 that a main contributor to the warming effects is from the reductions in sulfur emissions. Thus, the effect of the upcoming MARPOL regulation on SO_x emissions from shipping becomes interesting. We also observe the importance of components related to emissions of NO_x. However, the upcoming MARPOL regulation on NO_x does not affect existing ships (only new ships), and is as such not of relevance in this study. A simplified approach is employed in an attempt to assess the effect of the upcoming low-sulfur regime on the issue of CO_2 reduction. We do not attempt to assess the impact of the reduction in sulfur per se (such as Winebrake et al., 2009), but only the implications for CO_2 mitigation. It is noted that the change in sulfur emissions will likely have influence on emissions of OC and BC (e.g., Lack et al., 2011; Lack and Corbett, 2012). While this may substantially impact on BC and OC emissions, their relative importance to sulfur is minor (see Fig. 6a) and is disregarded in the following.

To mimic a low-sulfur regime on the 2010 fleet, we reduced the direct and indirect sulfur forcing with 80 %. We then assume a traditional linear relation between emissions and forcing (Lund et al., 2012). This reflects the upcoming requirement to reduce fuel sulfur content to 0.5 % in 2020, from the present average of 2.6 % (IMO, 2010). We do not account for the effect of emission control areas (ECAs). We then reapplied the emission reduction effects of the CO_2 measures (Fig. 2) to the 2010 baseline inventory and assess the impacts the emission differences under this low-sulfur regime. The change in temperature due to 1 yr of emission reductions is shown in Fig. 7. We see that in the low-sulfur case, the warming impact from the reduction on the current fleet in the first few years is less abrupt and reaches levels one order of magnitude below that of the high-sulfur case. However, the warming still persists for decades, obtaining a cooling effect after 40 yr. Lack et al. (2011) finds similar results for the regional emission reductions off the coast of California. 40 yr persistence in warming, as compared to 60 yr in the case of current sulfur levels, also illustrates that for 1 yr of emissions, the effects of sulfur emissions are not dominant. Rather, it is the effects of NO_x and CO_2 that are dominating, although SO_x clearly has an influence.

4.2.4 Scenario for sustained cargo fleet emissions

In the above only temperature responses from a single year of emissions are considered. In the following we apply the method of Berntsen and Fuglestvedt (2008) to assess the impact of emissions scenarios by convolution of emissions as a function of time. We construct a scenario where the above described emission reductions are sustained on the ships in the cargo fleet over time, but where the fleet is steadily declining as the ships age and are scrapped until no ships remain in 2040. This corresponds to an observed average age for scrapped vessels of around 30 yr for cargo ships (LRFP, 2009). The scenario emissions from this fleet, relative to 2010 emissions, are shown in Fig. 12.

We assume a low-sulfur regime from 2020, i.e., the temperature impact as a function time follows the "current sulfur" trajectory shown in Fig. 7 up until year 2020, and then the "low-sulfur" trajectory thereafter. No considerations are made for new ships entering the fleet, and no changes are made to account for new NO_x rules, as these apply to new ships and will thus not impact on the fleet under consideration (see IMO, 2010). The results are shown in Fig. 13, displaying both the total temperature impact as well as the respective contributions from reduced CO_2 emissions and non-CO_2 emissions. We see that compared to doing nothing, the effect of emission reduction on the currently sailing cargo fleet is an increase in global mean temperature in 2050. On a longer time horizon, temperature reduction is achieved by 2080. The results also show how the importance of non-CO_2

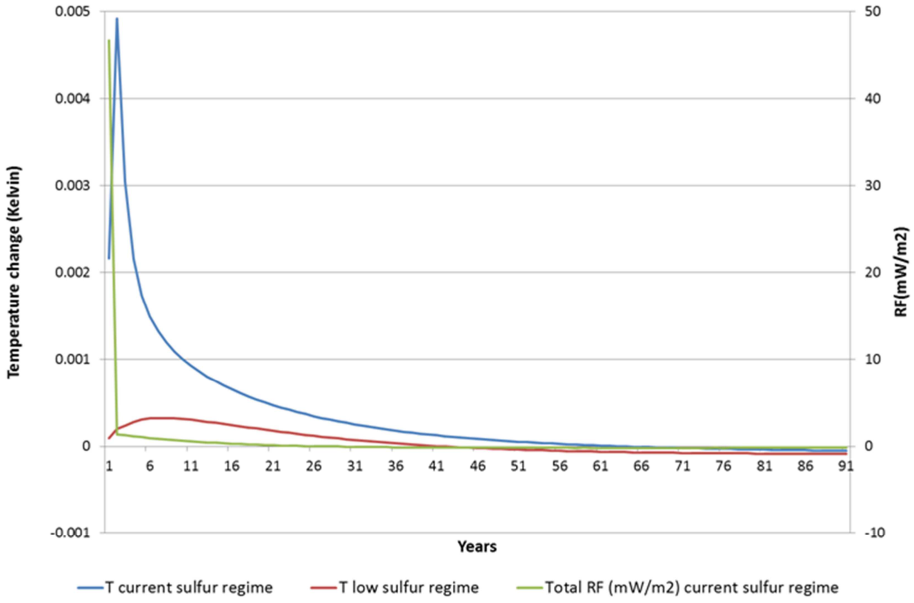


Fig. 7. Change in global average temperature response, in a given year after emissions under the current sulfur regime and under an assumed low-sulfur regime with 80 % reduction in sulfur emissions from baseline, and net RF from all compounds, as well as current sulfur regime.

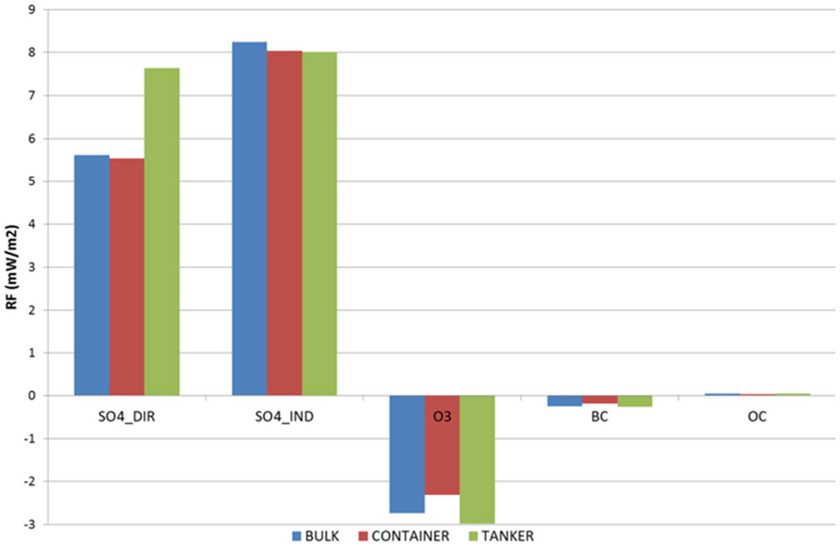


Fig. 8. RF for short-lived components for the major ship types in year 1.

emissions diminishes with time. Replicating the analysis for a scenario in which no low-sulfur mandate is enforced, the baseline sulfur emissions are larger and the volume of sulfur removed as a result of CO_2 abatement is larger. Consequently, we find that the warming in 2050 is twice that in the low-sulfur case, and that cooling is delayed until 2090.

5 Discussion and uncertainty

This study analyzes the resulting change in the mixture of emissions arising from an effort to reduce CO_2 from the 2010 fleet of cargo ships. Although there are significant uncertainties for the associated data and models used, they do not affect our overall conclusion.

Regarding the baseline emissions, there have been significant differences among the reported inventories for fuel consumption and emission inventories for a number of years. A scientific debate regarding past and current levels of emissions has ensued. Key points in the debate included whether bunker sale statistics are representative when estimating fuel based emissions, and whether input data on engine operational profiles for different ship types and size categories are

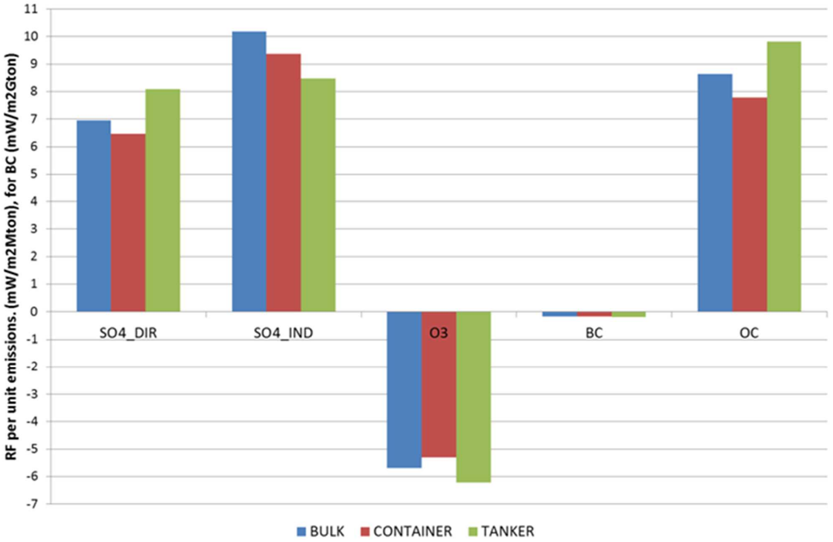


Fig. 9. Normalized RF for short-lived components for the major ship types in year 1. RF per unit emission. Note that the unit for BC is per Gton, while the other components are normalized per Mton.

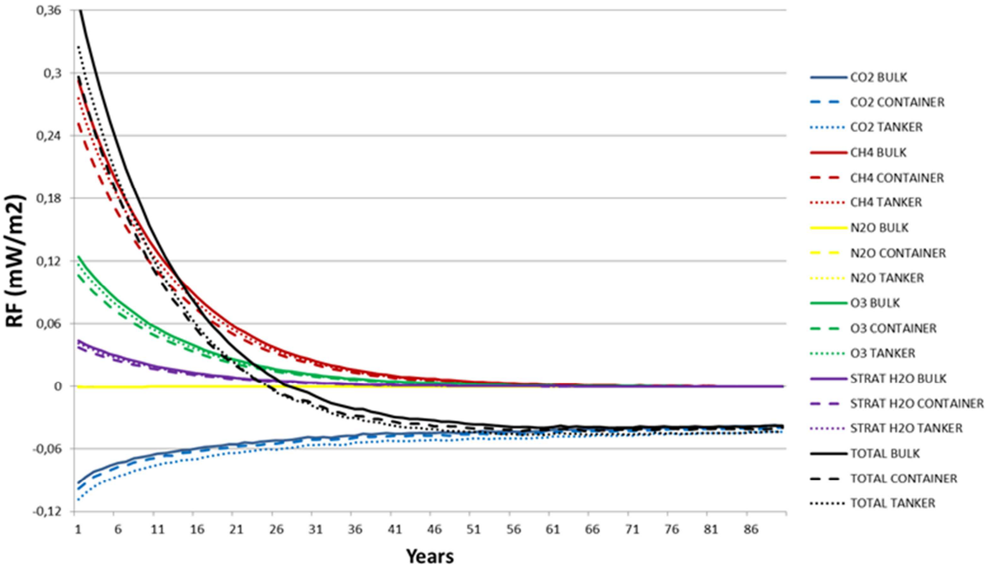


Fig. 10. RF for each component, per ship type, years 2–90. Total RF is for all components, including short-lived.

representative (Corbett and Köhler, 2003, 2004; Endresen et al., 2003, 2004; Eyring et al., 2005), The second IMO GHG study (Buhaug et al., 2009) managed to resolve some of the dispute by arriving at a “consensus estimate”. However, activity-based modeling on the global scale remains a challenge (Miola et al., 2010) as the input parameters in the selected ship type classes vary by size, age, fuel type, and market situation. For the estimates used in the current study, uncertainty is particularly related to the actual operational profiles of the segments, considering the market turmoil that has followed the 2008 global financial crisis. Accurately representing the operational profiles of the large cargo ships is particularly important as they are the dominant contributors to the global inventory. As the emission baseline for the CO_2 emissions used herein is derived from Eide et al. (2011), we use the same uncertainty estimate as they do for fuel consumption and CO_2 – ±20 %. This is also the range used by Buhaug et al. (2009). Building on the uncertainty discussion by Dalsøren et al. (2009), we assess that the uncertainty in the NO_x and SO_x emission estimates to be somewhat higher, arguably as high as ±30 %, while the other compounds have higher level of uncertainty, ranging up to ±40 %. It is recognized that more recent literature on emission factors is now available, as reviewed, e.g., by Lack and Corbett (2012),

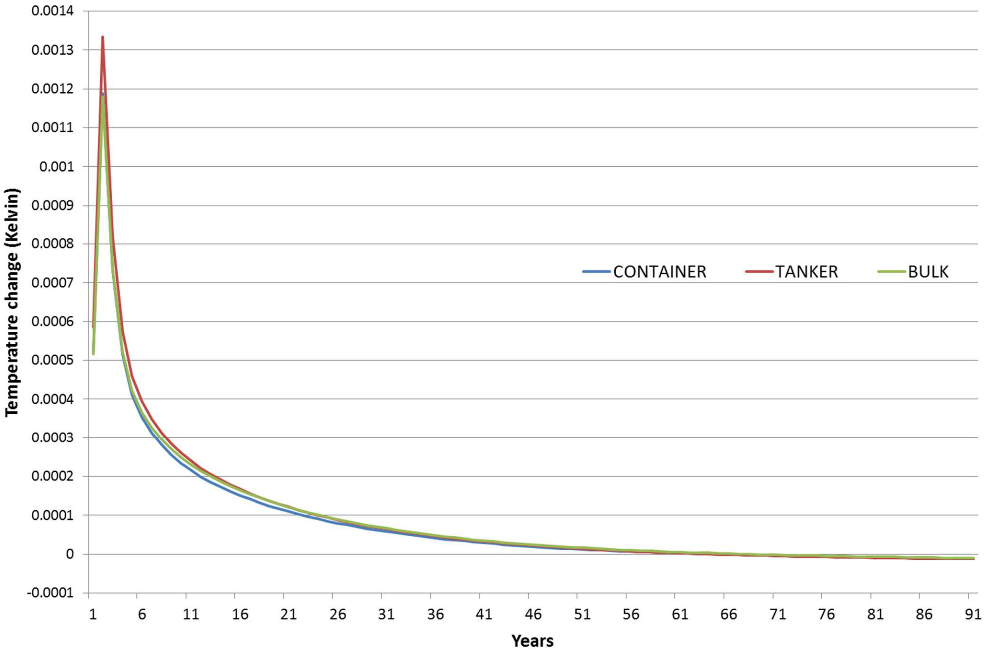


Fig. 11. Change in global average temperature response, years 2–90, per ship type.

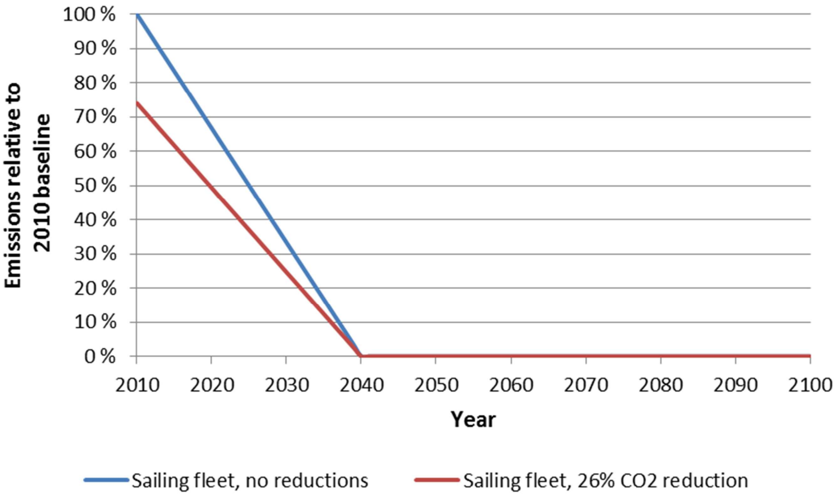


Fig. 12. Scenario for fleet emission development: the reduction inventory is sustained on the fleet as it steadily diminishes over time due to scrapping and disappears in 2040.

who assess the impact of engine load, fuel quality and exhaust after treatment systems for engines used by navigation. While it is recognized that there are substantial uncertainties in these emission factors and that updated inventories are due, this is beyond the scope of this work. It should be pointed out that the accuracy of the baseline emission levels are not of primary concern in this study as it is the effect of relative changes that are of importance.

Another contested point is whether the geographical distribution of emissions used in the studies capture the actual world fleet traffic (Corbett and Köhler, 2003; Endresen et al., 2003; Dalsøren et al., 2007). A number of studies have offered a global spatial representation of ship traffic based either on historical or current geographic emission inventory studies or both (Corbett and Fishbeck, 1997; Corbett et al., 1999; Streets et al., 1997, 2000; Endresen et al., 2003; Eyring et al., 2005; Wang et al., 2007; Dalsøren et al., 2009). The isolated effect of uncertainty in the geographical distribution is hard to quantify. However, as our results for the different ship types reveal, the conclusions regarding temperature impacts in the long run seem robust.

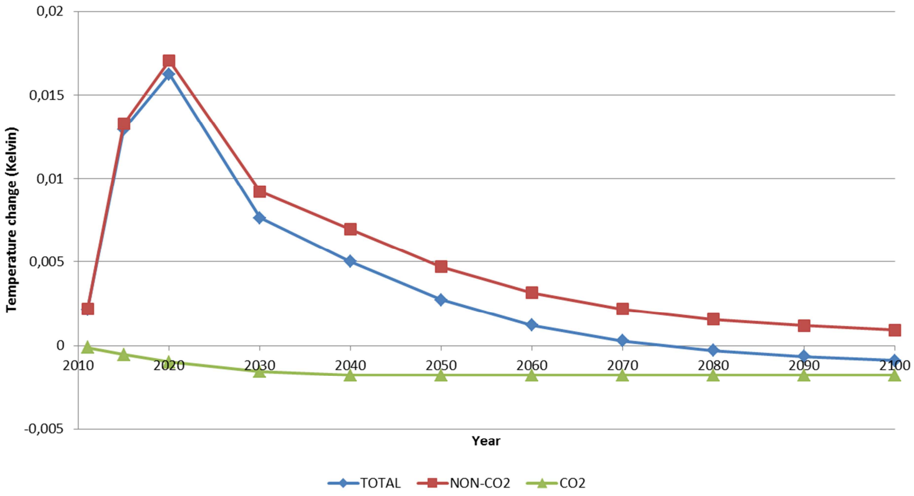


Fig. 13. Temperature response in varying evaluation years from an emission scenario where the reduction inventory is sustained on the fleet as it steadily diminishes over time due to scrapping and disappears in 2040. Response from CO_2 and non-CO_2 components shown separately, as well as combined (total).

Regarding the uncertainty related to the non-CO_2 emission reductions attributable to the CO_2 reductions, limited studies have been performed documenting the dependence of emission factors on engine load, as discussed in Sect. 3. It is recognized that there will be substantial variation between different engines, in terms of production year, make, sizes, types and maintenance levels, and that the different engines may have substantially different characteristics. However, on a fleet average the assumptions on SO_x are likely robust as emissions are proportional to fuel sulfur content. Also, N_2O, CO and NO_x have limited uncertainty, probably within 30 % uncertainty. However, it is noted that for the NO_x emission factors, the evidence is less conclusive than for the other compounds (there is indication that NO_x emissions are reduced at low loads, and hence the reduction could be greater than for CO_2). As NO_x emission changes are found to be important for the conclusions regarding temperature change, we perform a sensitivity test to investigate the possible impact of the uncertainty in this factor. Assuming NO_x emissions to be reduced at low engine loads, the NO_x reductions would be larger than in this study, and so would the corresponding increase in CH_4, O_3 and H_2O. Assuming, as a sensitivity test, a 20 % increase in forcing from CH_4, O_3 and H_2O (relative to the values in Fig. 6b), the shift in net RF from positive to negative is delayed by only 3 yr. Hence, this would not significantly alter the findings presented herein. For VOC, PM, BC and OC the uncertainties are more substantial. Our best judgment is in the order of 50 %. However, as our results indicate, these emissions have limited impact on our conclusions.

This study considers only the current fleet. However, the future impact of shipping will be gradually dominated by the new additions to the fleet. Thus, the options for emission reductions on new ships are of high relevance, including alternative fuels, such as LNG and biofuel. In combination with upcoming regulation of NO_x and SO_x, this means that the future options to reduce CO_2 may have a different impact on the atmospheric composition than the results of the present study show. In addition, shifts in the geographical trading patterns of the world fleet (e.g., Eyring et al., 2005; Paxian et al., 2010; Mangset et al., 2011; Corbett et al., 2010a), could mean changes in the impacts of emissions.

The OsloCTM2 model has been described and compared to observations in previous ship impact studies (Endresen et al., 2003; Dalsøren et al., 2007). In these studies the calculated impacts of ship emissions were also compared to other model studies, and likely causes for similarities and differences were discussed. Overall, the model was able to reasonably reproduce available observations in areas affected by ship emissions. A thorough discussion of the uncertainty related to the OsloCTM2 model and the RF model is beyond the scope of this work, and the reader is referred to the discussion, e.g., by Ødemark et al. (2012), who uses a model setup similar to the one used in this study.

It is noted that the temperature effects due to the second indirect aerosol effect (cloud lifetime), as well as changes in nitrate aerosols and BC deposition on snow, are not calculated in this study. Ship track measurements indicate that precipitation is affected by exhaust from individual ships (Eyring et al., 2010), but the impact on cloud lifetimes on a global scale is uncertain. Former studies on climate impacts from shipping have found the globally averaged BC and nitrate RF to be rather small (Eyring et al., 2010; Ødemark et al., 2012).

Uncertainty related to SCM calculations has been discussed, e.g., by Skeie et al. (2009). They find that, at least on a medium- to long-term perspective, uncertainty in RF estimates are more important than uncertainty in climate sensitivity. Uncertainties in RF calculations are also discussed by Eyring et al. (2010). They find that the main uncertainty relates to the aerosol indirect effect on clouds.

6 Conclusions

We have established a plausible reduction inventory for the 2010 world cargo shipping fleet, reflecting a 26 % reduction in CO_2 and the concurrent emission changes for 9 other components. This inventory is a realistic, achievable alternative to the baseline, and should be of relevance to policymakers and geoscientists. Inventories are also established separately for the three main ship types: container, bulk and tank.

We apply a holistic framework to assess several impacts of the assumed emission reductions simultaneously. We find that the reduction inventory results in up to 5 % reduction in surface ozone levels in certain regions exposed to heavy ship traffic. Similarly, we find up to 15 % reductions in surface sulfate and up to 10 % reductions in wet deposition of sulfate. These reductions are substantial in terms of environmental and health benefits. We find that the major ship types have distinctly different contributions to the emission reductions in specific locations.

Considering the radiative forcing change from a 1 yr pulse emission of the reduction inventory, we find that the negative and positive forcing components are balanced after approximately 25 yr. Considering the global mean temperature change from this emission pulse, we find a shift from warming to cooling after approximately 60 yr due to the difference in the decay times of the forcing agents and the inertia of the climate system.

For the major ship types, we find significant differences in the short-term radiative forcing; for instance, the direct SO_4 forcing from the tanker segment is 30 % higher than for container and bulk. However, the long-term pulse effects on RF are similar due to similar CO_2 forcing.

For the cargo fleet, we find that assuming a low-sulfur regime corresponding to upcoming MARPOL regulation will change the point at which the temperature change from a pulse shifts from warming to cooling from 60 to 40 yr.

We also assess an emission scenario where the reduction inventory is sustained on the fleet as it steadily diminishes over time until it disappears in 2040 due to scrapping. In this scenario we find that the net temperature impact is a warming effect until approximately 2080.

Thus, non-CO_2 emission does matter significantly if reductions of CO_2 emissions are made on the current cargo shipping fleet. In the short to medium term, the net global temperature effect due to atmospheric changes in CO_2 and non-CO_2 components is a warming. We find that the upcoming low-sulfur regime would mediate this, but not remove the short-term warming. There are also positive environmental and health effects identified as concentrations of key pollutants are reduced. Thus, emission changes motivated by CO_2 reductions within shipping will be beneficial from a long-term climate perspective, as well as from a near-term environmental and health point of view.

This study is an attempt to jointly assess several effects of a plausible emission reduction inventory. Although this study is limited to the fleet sailing in 2010 with no consideration for the new additions to the fleet, the results demonstrate the importance of considering a mix of emissions jointly in order to accurately assess whether the intended effects of policy are achieved. Though considering concurrent emission changes of non-CO_2 components complicate the picture, it is clearly necessary and should be taken into account in policymaking.

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