

Reducing CO₂ from shipping

M. S. Eide et al.

Reducing CO₂ from shipping – do non-CO₂ effects matter?

M. S. Eide¹, S. B. Dalsøren², Ø. Endresen¹, B. Samset², G. Myhre²,
J. Fuglestad², and T. Berntsen^{2,3}

¹Det Norske Veritas, Research Department, Norway

²Center for International Climate and Environmental Research Oslo (CICERO), Norway

³University of Oslo, Department of Geosciences, Norway

Received: 22 May 2012 – Accepted: 8 October 2012 – Published: 18 October 2012

Correspondence to: M. S. Eide (magnus.strandmyr.eide@dnv.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Shipping is a growing sector in the global economy and its contributions to global CO₂ emissions are expected to increase. CO₂ 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 CO₂ 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 CO₂ emissions are reduced by 25–32 % relative to baseline by a ship type specific cost-effectiveness criterion, and 9 other emission compounds are changed as a technical implication of reducing CO₂. 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, show an initial strong positive forcing from non-CO₂ compounds. This warming effect is due to reduced cooling by aerosols and methane. After approximately 25 yr, the non-CO₂ forcing is balanced by the CO₂ 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 SO₄ forcing from tankers is 30 % higher than for container and bulk. The net long term effects on RF are similar due to similar CO₂ 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.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



We find a net temperature increase lasting until approximately 2080. We conclude that changes in non-CO₂ emission does matter significantly if reductions of CO₂ emissions are made on the year 2010 cargo shipping fleet. In sum, we find that emission changes motivated by CO₂ reductions in shipping will be beneficial from a long-term climate perspective, and there are also 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 Koehler, 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 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 15–50 % (Dalsøren et al., 2009). Sulfate deposition increases the acidity of soils, rivers and lakes. This harms ecosystem growth. Nitrate deposition increases the available nitrogen of soils (eutrophication) harming ecosystems through asymmetric growth in nitrogen poor regions.

Climate is impacted directly by the release of long lived greenhouse gases such as CO₂ and indirectly by the perturbation of greenhouse gases such as CH₄ and O₃ 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

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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. CO₂ is a well-mixed greenhouse gas, its atmospheric lifetime (> 100 yr) while SO₂ and NO_x are reactive species with much shorter lifetimes (days). Also secondary components such as SO₄ and O₃, have lifetimes of days to weeks in the troposphere. Emissions of NO_x, and the O₃ they form, lead to enhanced levels of the hydroxyl radical (OH). This increases the removal rates of CH₄, 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; Fuglestad et al., 2008; Berntsen and Fuglestad, 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, particulate matter (PM) and NO_x (IMO, 2009, 2010).

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Currently, the IMO is working to develop regulations on CO₂ (IMO, 2011) with the aim to reduce the climate impact from shipping, and significant efforts are directed towards finding technical, operational ways of mitigating CO₂ emissions.

To this end, several studies have documented the measures available for CO₂ 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 CO₂ 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) uses a model which captures the world fleet up to 2030, and the analysis includes 25 separate CO₂ reduction measures. They find that at a marginal cost of USD 0 per ton reduced emission in 2010 can 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 for the tanker fleet was 27 %, for the container fleet 25 % and for bulk fleet 32 %. Furthermore, Eide et al. (2009) proposed to use a cost-effectiveness criterion of USD 50 per ton CO₂ reduced as a guiding principle for what should be done to propose a policy criterion for mandating CO₂ 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 CO₂. 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. 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 CO₂. Some effects of upcoming regulations have been studied. Lauer et al. (2009) assessed the impact on radiative forcing from the introduction of low sulfur mandate, and Winebrake

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



et al. (2009) assessed the health impacts of same. Löhdal 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. Regarding CO₂, there is a lack in understanding how CO₂ 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.

In this study, we attempt to apply a holistic framework to assess several impacts simultaneously. The effects on non-CO₂ gases and particles resulting as a consequence of implementing measures to reduce CO₂ will be assessed. In this way a practical regulatory option available to policymaker is evaluated; the regulation of CO₂ 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 CO₂ 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, CH₄, N₂O, CO, BC, OC. For the reduction inventory, we assess overall climate impact, as well as environmental and health effects, and discusses 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

Reducing CO₂ from shipping

M. S. Eide et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

in climate impact from a number of short lived compounds found in several studies, i.a. 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, 2006; Naik et al., 2005; Lauer et al., 2007; Shindell and Faluvegi, 2009). 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, an reduction inventory for 2010 is developed, by estimating reductions of CO₂, SO_x, NO_x, and other relevant gases and particles resulting from assumed CO₂ 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, global averaged radiative forcings were used in a Simple Climate Model (SCM) to calculate the global temperature impacts resulting from the difference in emissions.

2 Emissions inventories

This section describes the baseline emission inventory for the 2010 world cargo fleet, as well as the constructed reduction inventory, covering CO₂ and 9 other compounds. Also, the geographical distribution of emissions (baseline and reduction inventory) is described.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 is collected from different sources and maritime data bases.

In this study, the CO₂ emissions for 2010 have been taken from Eide et al. (2011). The fleet fuel consumption is found by applying an emission CO₂ factor of 3.179 gCO₂ (gFuel)⁻¹ (Dalsøren et al., 2009). To produce estimates for non-CO₂ 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 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 CO₂ 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 CO₂. They also calculate corresponding potentials for each of the major ship types. It is 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 time of writing above USD 700 per ton HFO, re-applying the model by Eide et al. shows that 26 % reduction can be achieved at a marginal cost of USD 0 per ton CO₂. Even a more moderate fuel price

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of USD 500 per ton HFO produces a 26 % reduction at a marginal cost of USD 20 per ton CO₂. 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 CO₂ emissions.

The consequences on non-CO₂ emissions from the assumed reduction in CO₂ 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 CO₂ 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 incentivize him 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 which 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 as the engine to perform 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) allows 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.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



To understand how the CO₂ 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 constant. At reduced engine load, the performance of the engine changes.

According to Lloyds' (1995), SO_x and CO₂ 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 CO₂ emissions by 10 %. For the load change considered herein (from 80 % to ~ 50 %) this increase is considered to be significantly smaller. Hence no penalty is given to fuel consumption, CO₂ 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 Koehler (2003) (at least for the slow speed engines). However, as Corbett and Koehler (2003) indicates (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 CH₄ 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 to increased emissions of hydrocarbons at lower loads, although not as strong as ENTEC. Assuming non-linearity in the performance, and the likelihood of improvement through tuning, we assume a 40 % increase in the specific emissions of NMVOC and CH₄, 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 which display a 40 % increase. Lack et al. (2012) report observations which demonstrate that BC emission factors increases 3 to 6 times at very low engine loads (< 25 % compared to 85–100 % load). Assuming non-linearity 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 N₂O and CO we assume no penalty, arguing that these emissions will follow the emissions of CO₂, 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 CO₂ reductions (and hence engine load reductions) available at the given cost level. It is noted that NO_x, SO_x, N₂O and CO emissions change proportionally to changes in CO₂ emissions, and that emission of particles (PM, BC, OC) change less. For hydrocarbons (CH₄ and NMVOC) the change has opposite sign from CO₂, 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 British Columbia Ferry Corporation, from Environment Canada, and from the US Coast Guard.

Reducing CO₂ from shipping

M. S. Eide et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

2.3 Gridded inventory

Geographical distributions of ship emissions from world fleet traffic have been produced by several studies (Corbett and Kohler, 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 $1^\circ \times 1^\circ$ 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 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 world wide, but lower relative emissions in the Baltic Sea SECA and the North Sea SECA.

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

This section describes the models which 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 3.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.1 Atmospheric concentrations

We used the OsloCTM2 model to calculate atmospheric concentration changes due to emission mitigations. The OsloCTM2 model (Berntsen et al., 1997; Sundet, 1997) is a 3 dimensional off-line 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 chemical 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 ($2.8^\circ \times 2.8^\circ$) 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

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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), nor do we 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 current study. For O₃ 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.

Global averaged forcings for the short lived species were then used in the CICERO Simple Climate Model (SCM) (Fuglestad 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 CH₄, N₂O and CO₂. For CH₄ the CTM calculated lifetime change was used as input to the SCM. For N₂O and CO₂ 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 CO₂ the SCM has a separate scheme for the development from emission changes to CO₂ concentration using an ocean mixed-layer pulse response function (Joos et al., 1996; Siegenthaler et al., 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 CO₂ 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 CO₂ 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 is likely to be beneficial in polluted coastal regions, though quantification of effects on health impacts and crop yields are 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 CO₂ based mitigation could significantly reduce PM_{2.5} related mortality. It would also be efficient in symphony with IMO regulations on future fuel sulfur content (IMO, 2010).

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 %.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 Bay 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.

4.2 Climate impacts

In this section we present the results of the reduction inventory, in terms of response to a one-year pulse emission impacts on radiative forcing and global mean temperature

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



for the cargo fleet (Sect. 4.2.1) and for the tree major ship types (Sect. 4.2.2). From the one-year 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 CO₂ 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 O₃ perturbations induced by chemical cycling of NO_x emissions. Figure 6a shows annual averaged RF for the short lived species. NO_x also influence the lifetime of CH₄, which in turn affects O₃ and stratospheric water vapor. Since the e-folding time of a perturbation of methane is more than a decade, the forcing and its followers (O₃ and water vapor forcings) last for a few decades. N₂O and CO₂ are long-lived and the forcings exist for centuries. Figure 6a, b clearly shows a dominant initial contribution from the short-lived components such as SO₄ (direct and indirect) and O₃ (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

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 one-year 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) is 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, 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 $\sim 10\%$ higher than for the other two ship types. This is primarily due to the substantially higher direct SO_4 RF, which is $\sim 30\%$ 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

Reducing CO_2 from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 show 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 CO₂ is similar for all ship types and evens out the differences in a longer perspective. Again, we see that approximately 60 years 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 do not affect existing ships (only new ships), and are 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 CO₂ 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 CO₂ mitigation. It is noted that the change in sulfur emissions will likely 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.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 re-applied the emission reduction effects of the CO₂ 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 one year 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 one year of emissions, the effects of sulfur emissions are not dominant. Rather, it is the effects of NO_x and CO₂ which 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 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 CO₂ emissions and non-CO₂ 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-CO₂ emissions diminishes with time. Replicating the analysis for a scenario in which no low sulfur mandate is enforced, 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 CO₂ 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 representative (Corbett and Koehler, 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, which vary by size, age, fuel type, and market situation. For the

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



estimates used in the current study, uncertainty is particularly related to the actual operational profiles of the segments, considering the market turmoil which 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 CO₂ emissions used herein are derived from Eide et al. (2011), and we use the same uncertainty estimate as they do for fuel consumption and CO₂; ±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 somewhat higher, arguably as high as ±30%, while the other compounds have higher level of uncertainty, ranging up to ±40%. However, 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 which 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 Koehler, 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.

Regarding the uncertainty related to the non-CO₂ emission reductions attributable to the CO₂ 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, N₂O,

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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 are indication that NO_x emissions are reduced at low loads, and hence the reduction could be greater than for CO₂). 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 CH₄, O₃ and H₂O. Assuming, as a sensitivity test, a 20 % increase in forcing from CH₄, O₃ and H₂O (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 CO₂ 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., 2010), 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 is 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 global averaged BC and nitrate RF to be rather small (Eyring et al., 2010; Ødemark et al., 2012).

Uncertainty related to SCM calculations have 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 CO₂ 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

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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 SO₄ 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 CO₂ 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 yr 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-CO₂ emission does matter significantly if reductions of CO₂ 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 CO₂ and non-CO₂ 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 CO₂ 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

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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-CO₂ components complicate the picture it is clearly necessary, and should be taken into account in policymaking.

Acknowledgements. This study is partly funded by the Norwegian Research Council; projects EMISOL (192930/I40) and Low Carbon Shipping (200850/I40). We thank Marianne T. Lund (CICERO) and George Dimopoulos (DNV) for valuable comments.

References

- Berntsen, T. and Fuglestvedt, J.: Global temperature responses to current emissions from the transport sectors, *P. Natl. Acad. Sci. USA*, 105, 19154–19159, 2008.
- Berntsen, T. and Isaksen, I. S. A.: A global three-dimensional chemical transport model for the troposphere, 1. Model description and CO and ozone results, *J. Geophys. Res.*, 102, 21239–21280, 1997.
- Berntsen, T., Fuglestvedt, J. S., Joshi, M., Shine, K. P., Stuber, N., Ponater, M., Sausen, R., Li, L., and Hauglustaine, D. A.: Climate response to regional emissions of ozone precursors: sensitivities and warming potentials, *Tellus*, 57B, 283–304, 2005.
- Berntsen, T., Fuglestvedt, J. S., Myhre, G., Stordal, F., and Berglen, T. F.: Abatement of greenhouse gases: does location matter?, *Earth Environ. Sci.*, 74, 377–411, doi:10.1007/s10584-006-0433-4, 2006.
- Buhaus, Ø., Corbett, J. J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Markowska, A. Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J. J., Wu, W.-Q., and Yoshida, K.: Second IMO GHG study 2009, MEPC 59/INF.10, International Maritime Organization (IMO), London, UK, 2009.
- Capaldo, K., Corbett, J. J., Kasibhatla, P., Fischbeck, P. S., and Pandis, S. N.: Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean, *Nature*, 400, 743–746, 1999.
- Cariou, P.: Is slow steaming a sustainable mean for reducing liner shipping CO₂ emissions?, *Euromed Management Mare Forum* 14, Marseilles, September 2010.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Cohen, A. J., Anderson, H. R., Ostro, B., Pandey, K. D., Krzyzanowski, M., Künzli, N., Gutschmidt, K., Pope, A., Romieu, I., Samet, J. M., and Smith, K.: The global burden of disease due to outdoor air pollution, *J. Toxicol. Environ. Health A*, 68, 1301–1307, 2005.
- Corbett, J. J. and Fischbeck, P. S.: Emissions from ships, *Science*, 278, 823–824, 1997.
- 5 Corbett, J. J. and Köhler, H. W.: Updated emissions from ocean shipping, *J. Geophys. Res.*, 108, 4650, doi:10.1029/2003JD003751, 2003.
- Corbett, J. J. and Köhler, H. W.: Considering alternative input parameters in an activity-based ship fuel consumption and emissions model: reply to comment by Øyvind Endresen et al. on “Updated emissions from Ocean shipping”, *J. Geophys. Res.*, 109, D23303, doi:10.1029/2004JD005030, 2004.
- 10 Corbett, J. J., Fischbeck, P. S., and Pandis, S. N.: Global nitrogen and sulphur inventories for oceangoing ships, *J. Geophys. Res.*, 104, 3457–3470, 1999.
- Corbett, J., Winebrake, J., Green, E., Kasibhatla, P., Eyring, V., and Lauer, A.: Mortality from ship emissions: a global assessment, *Environ. Sci. Technol.*, 41, 8512–8518, 2007.
- 15 Corbett, J. J., Lack, D. A., Winebrake, J. J., Harder, S., Silberman, J. A., and Gold, M.: Arctic shipping emissions inventories and future scenarios, *Atmos. Chem. Phys.*, 10, 9689–9704, doi:10.5194/acp-10-9689-2010, 2010.
- Dalsoren, S., Endresen, Ø., Isaksen, I., Gravir, G., and Sorgard, E.: Environmental impacts of the expected increase in sea transportation, with a particular focus on oil and gas scenarios for Norway and northwest Russia, *J. Geophys. Res.-Atmos.*, 112, D02310, doi:10.1029/2005JD006927, 2007.
- 20 Dalsøren, S. B., Eide, M. S., Endresen, Ø., Mjelde, A., Gravir, G., and Isaksen, I. S. A.: Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports, *Atmos. Chem. Phys.*, 9, 2171–2194, doi:10.5194/acp-9-2171-2009, 2009.
- 25 Dalsøren, S. B., Eide, M. S., Endresen, Ø., Mjelde, A., Gravir, G., and Isaksen, I. S. A.: Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports, *Atmos. Chem. Phys.*, 9, 2171–2194, doi:10.5194/acp-9-2171-2009, 2009.
- 30 Dentener, F., Drevet, J., Lamarque, J. F., Bey, I., Eickhout, B., Fiore, A. M., Hauglustaine, D., Horowitz, L. W., Krol, M., Kulshrestha, U. C., Lawrence, M., Galy-Lacaux, C., Rast, S., Shindell, D., Stevenson, D., Van Noije, T., Atherton, C., Bell, N., Bergman, D., Butler, T., Cofala, J., Collins, B., Doherty, R., Ellingsen, K., Galloway, J., Gauss, M., Montanaro, V., Müller, J.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- F., Pitari, G., Rodriguez, J., Sanderson, M., Solmon, F., Strahan, S., Schultz, M., Sudo, K., Szopa, S., and Wild, O.: Nitrogen and sulfur deposition on regional and global scales: a multi-model evaluation, *Global Biogeochem. Cy.*, 20, GB4003, doi:10.1029/2005GB002672, 2006.
- Derwent, R., Collins, W. J., Johnson, C., and Stevenson, D. S.: Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects, *Clim. Change*, 25, 463–487, 2001.
- Eide, M. S., Endresen, Ø., Skjong, R., Longva, T., and Alvik, S.: Cost-effectiveness assessment of CO₂ reducing measures in shipping, *Mar. Pol. Manag.*, 36, 367–384, 2009.
- Eide, M., Longva, T., Hoffmann, P., Endresen, Ø., and Dalsøren, S.: Future cost scenarios for reduction of ship CO₂ emissions, *Mar. Pol. Manag.*, 38, 11–37, 2011.
- Endresen, Ø., Sørgård, E., Sundet, J., Dalsøren, S., Isaksen, I., Berglen, T., and Gravir, G.: Emission from international sea transportation and environmental impact, *J. Geophys. Res.*, 108, 4560, doi:10.1029/2002JD002898, 2003.
- Endresen, Ø., Sørgård, E., Bakke, J., and Isaksen, I. S. A.: Substantiation of a lower estimate for the bunker inventory: comment on “Updated emissions from ocean shipping” by J. J. Corbett and H. W. Köhler, *J. Geophys. Res.*, 109, D23302. doi:10.1029/2004JD004853, 2004.
- Endresen, Ø., Bakke, J., Sørgård, E., Berglen, T. F., and Holmvang, P.: Improved modelling of ship SO₂ emissions – a fuel based approach, *Atmos. Environ.*, 39, 3621–3628, 2005.
- Endresen, Ø., Sørgård, E., Behrens, H. L., Brett, P. O., and Isaksen, I. S. A.: A historical reconstruction of ships fuel consumption and emissions, *J. Geophys. Res.*, 112, D12301, doi:10.1029/2006JD007630, 2007.
- Endresen, Ø., Dalsøren, S., Eide, M., Isaksen, I. S., and Sørgård, E.: The environmental impacts of increased international maritime shipping, past trends and future perspectives, *OECD/ITF Global Forum on Transport and Environment in a Globalising World*, Guadalajara, Mexico, 2008.
- ENTEC: CONCAWE, Ship emissions inventory – Mediterranean sea, Final report, Entec UK limited, April 2007.
- Eyring, V., Köhler, H. W., van Aardenne, J., and Lauer, A.: Emissions from international shipping: 1. The last 50 years, *J. Geophys. Res.*, 110, D17306, doi:10.1029/2004JD005620, 2005.
- Eyring, V., Isaksen, I., Berntsen, T., Collins, W., Corbett, J., Endresen, Ø., Grainger, R., Moldanova, J., Schlager, H., and Stevenson, D.: Transport impacts on atmosphere and climate: Shipping, *Atmos. Environ.*, 44, 4735–4771, 2010.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Fuglestad, J., Isaksen, I. S. A., Mao, H., Liang, X.-Z., and Wang, W.-C.: Climatic forcing of nitrogen oxides through changes in tropospheric ozone and methane; global 3-D model studies, *Atmos. Environ.*, 33, 961–977, 1999.

Fuglestad, J., Berntsen, T., Myhre, G., Rypdal, K., and Skeie, R.: Climate forcing from the transport sectors, *P. Natl. Acad. Sci. USA*, 105, 454–458, 2008.

Heywood, J. B.: *Internal Combustion Engines Fundamentals*, Mc-Graw Hill, 1988.

Hoffmann, P., Eide, M. S., and Endresen, Ø.: Effect of proposed CO₂ emission reduction scenarios on capital expenditure, *Mar. Pol. Manag.*, 39, 443–460, 2012.

International Maritime Organization (IMO): Regulations for the prevention of air pollution from ships and NO_x technical code, ANNEX VI of MARPOL 73/78, International Maritime Organization, London, UK, 1998.

International Maritime Organization (IMO): MEPC.176(58) Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (Revised MARPOL Annex VI), International Maritime Organization, London, UK, 2009.

International Maritime Organization (IMO): Air pollution from ships cut, with entry into force of MARPOL amendments, International Maritime Organisation, available at: <http://www.imo.org/MediaCentre/PressBriefings/Pages/MARPOL-Annex-VI-EIF.aspx>, 2010.

International Maritime Organization (IMO): Mandatory energy efficiency measures for international shipping adopted at IMO environment meeting, International Maritime Organisation, available at: <http://www.imo.org/MediaCentre/PressBriefings/Pages/42-mepc-ghg.aspx>, 2011.

IPCC: *Climate Change 2007: AR4, Synthesis Report*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2007.

Joos, F., Bruno, M., Fink, R., Siegenthaler, U., Stocker, T. F., and LeQuere, C.: An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake, *Tellus B*, 48, 397–417, 1996.

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

Lack, D. A., Cappa, C. D., Langridge, J., Bahreini, R., Buffaloe, G., Brock, C., Cerully, K., Coffman, D., Hayden, K., Holloway, J., Lerner, B., Massoli, P., Li, S.-M., McLaren, R., Middlebrook, A. M., Moore, R., Nenes, A., Nuaaman, I., Onasch, T. B., Peischl, J., Perring, A.,

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Quinn, P. K., Ryerson, T., Schwartz, J. P., Spackman, R., Wofsy, S. C., Worsnop, D., Xiang, B., and Williams, E.: Impact of fuel quality regulation and seed reductions on shipping emissions: implications for climate and air quality, *Environ. Sci. Technol.*, 45, 9052–9060, 2011.

5 Lauer, A., Eyring, V., Hendricks, J., Jöckel, P., and Lohmann, U.: Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget, *Atmos. Chem. Phys.*, 7, 5061–5079, doi:10.5194/acp-7-5061-2007, 2007.

Lauer, A., Eyring, V., Corbett, J., Wang, C., and Winebrake, J.: Assessment of near-future policy instruments for oceangoing shipping: impact on atmospheric aerosol burdens and the Earth's radiation budget, *Environ. Sci. Technol.*, 43, 5592–5598, 2009.

10 Lee, D. S., Lim, L. L., Eyring, V., Sausen, R., Endresen, Ø., and Behrens, H. L.: Radiative forcing and temperature response from shipping, in: *Proceedings of the International Conference on Transport, Atmosphere and Climate (TAC)*, Oxford, UK, 208–213, 2007.

Lloyd's Register of Shipping (LR): Marine Exhaust Emissions Research Programme, Lloyd's Register Engineering Services, UK, London, 1995.

15 Lloyd's Register FairPlay (LRFP): World Merchant Fleet Database (all civil ocean-going cargo and passenger ships above or equal to 100 GT), LRFP, Redhill, UK, 2009.

Lloyds List: Slow-steaming VLCCs at 11 knots on ballast legs can save \$16 000 a day, *Lloyd's List* Friday September 9, Lloyd's List, 119 Farringdon Road, London, 2011.

20 Löndahl, J., Swietlicki, E., Lindgren, E., and Loft, S.: Aerosol exposure versus aerosol cooling of climate: what is the optimal emission reduction strategy for human health?, *Atmos. Chem. Phys.*, 10, 9441–9449, doi:10.5194/acp-10-9441-2010, 2010.

Lund, M. T., Eyring, V., Fuglestedt, J., Hendricks, J., Lauer, A., Lee, D. S., and Righi, M.: Global mean temperature change from shipping towards 2050: improved representation of the indirect aerosol effect in simple climate models, *Environ. Sci. Technol.*, 46, 8868–8877, 25 2012.

Mangset, L. E., Acciaro, M., and Eide, M. S.: A Global Seaborne Trade Pattern Forecasting Method for Shipping Emissions Modeling, IAME, Santiago De Chile, 25–28 October 2011.

Merker, G. P., Schwarz, C., Stiesch, G., and Otto, F.: *Simulating Combustion*, Springer-Verlag, Berlin, 2006.

30 Miola, A., Ciuffo, B., Giovine, E., and Marra, M.: Regulating air emissions from ships: the state of the art on methodologies, technologies and policy options, European Commission, Joint

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Research Centre, Institute for Environment and Sustainability, Luxembourg, doi:10.2788/4171, 2010.

Myhre, G., Berglen, T. F., Johnsrud, M., Hoyle, C. R., Berntsen, T. K., Christopher, S. A., Fahey, D. W., Isaksen, I. S. A., Jones, T. A., Kahn, R. A., Loeb, N., Quinn, P., Remer, L., Schwarz, J. P., and Yttri, K. E.: Modelled radiative forcing of the direct aerosol effect with multi-observation evaluation, *Atmos. Chem. Phys.*, 9, 1365–1392, doi:10.5194/acp-9-1365-2009, 2009.

Myhre, G., Shine, K. P., Raedel, G., Gauss, M., Isaksen, I. S. A., Tang, Q., Prather, M. J., Williams, J. E., van Velthoven, P., Dessens, O., Koffi, B., Szopa, S., Hoor, P., Grewe, V., Borken-Kleefeld, J., Berntsen, T. K., and Fuglestedt, J. S.: Radiative forcing due to changes in ozone and methane caused by the transport sector, *Atmos. Environ.*, 45, 387–394, doi:10.1016/j.atmosenv.2010.10.001, 2011.

Naik, V., Mauzerall, D., Horowitz, L., Schwarzkopf, M. D., Ramaswamy, V., and Oppenheimer, M.: Net radiative forcing due to changes in regional emissions of tropospheric ozone precursors, *J. Geophys. Res.*, 110, D24306, doi:10.1029/2005JD005908, 2005.

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

Olivie, D. and Stuber, N.: Emulating AOGCM results using simple climate models, *Clim. Dynam.*, 35, 1257–1287, doi:10.1007/s00382-009-0725-2, 2010.

Olivie, D. J. L., Cariolle, D., Teyssèdre, H., Salas, D., Voldoire, A., Clark, H., Saint-Martin, D., Michou, M., Karcher, F., Balkanski, Y., Gauss, M., Dessens, O., Koffi, B., and Sausen, R.: Modeling the climate impact of road transport, maritime shipping and aviation over the period 1860–2100 with an AOGCM, *Atmos. Chem. Phys.*, 12, 1449–1480, doi:10.5194/acp-12-1449-2012, 2012.

Paxian, A., Eyring, V., Beer, W., Sauen, R., and Wright, C.: Present-day and future global bottom-up ship emission inventories including polar routes, *Environ. Sci. Technol.*, 44, 1333–1339, 2010.

Penner, J. E., Xu, L., and Wang, M.: Satellite methods underestimate indirect climate forcing by aerosols, *P. Natl. Acad. Sci. USA*, 108, 13404–13408, 2011.

Petzold, A., Hasselbach, J., Lauer, P., Baumann, R., Franke, K., Gurk, C., Schlager, H., and Weingartner, E.: Experimental studies on particle emissions from cruising ship, their

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



characteristic properties, transformation and atmospheric lifetime in the marine boundary layer, *Atmos. Chem. Phys.*, 8, 2387–2403, doi:10.5194/acp-8-2387-2008, 2008.

PWC: A game changer for shipping industry? An analysis of the future impact of carbon regulations on environment and industry, PricewaterhouseCoopers, Oslo, Norway, June 2011.

5 Quaas, J. and Boucher, O.: Constraining the first aerosol indirect radiative forcing in the LMDZ GCMs using POLDER and MODIS satellite data, *Geophys. Res. Lett.*, 32, L17814, doi:10.1029/2005GL023850, 2005.

10 Quaas, J., Boucher, O., and Lohmann, U.: Constraining the total aerosol indirect effect in the LMDZ and ECHAM4 GCMs using MODIS satellite data, *Atmos. Chem. Phys.*, 6, 947–955, doi:10.5194/acp-6-947-2006, 2006.

Sausen, R., Isaksen, I. S. A., Grewe, V., Hauglustaine, D. A., Lee, D. S., Myhre, G., Köhler, M. O., Pitari, G., Schumann, U., Stordal, F., and Zerefos, C.: Aviation radiative forcing in 2000: an update on IPCC (1999), *Meteorol. Z.*, 14, 555–561, 2005.

15 Schlesinger, M. E., Jiang, X., and Charlson, R. J.: Implication of anthropogenic atmospheric sulphate for the sensitivity of the climate system, in: *Climate Change and Energy Policy: Proceedings of the International Conference on Global Climate Change: Its Mitigation Through Improved Production and Use of Energy*, edited by: Rosen, L. and Glasser, R., American Institute of Physics, New York, 75–108, 1992.

20 Shindell, D. and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century, *Nat. Geosci.*, 2, 294–300, 2009.

Siegenthaler, U. and Joos, F.: Use of a simple-model for studying oceanic tracer distributions and the global carbon-cycle, *Tellus B*, 44, 186–207, 1992.

25 Skeie, R., Fuglestvedt, J., Berntsen, T., Lund, M., Myhre, G., Rypdal, K.: Global temperature change from the transport sectors: historical development and future scenarios, *Atmos. Environ.*, 43, 6260–6270, 2009.

30 Skjølsvik, K. O., Andersen, A. B., Corbett, J. J., and Skjelvik, J. M.: Study of Greenhouse Gas Emissions from Ships, MEPC 45/8 Report to International Maritime Organization on the Outcome of the IMO Study on Greenhouse Gas Emissions from Ships, MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas, Trondheim, Norway, 2000.

Stamnes, K., Tsay, S., Wiscombe, W., and Jayaweera, K.: Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media, *Appl. Opt.*, 27, 2502–2509, 1988.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Streets, D. G., Carmichael, G. R., and Arndt, R. L.: Sulphur dioxide emissions and sulfur deposition from international shipping in Asian waters, *Atmos. Environ.*, 31, 1573–1582, 1997.
- Streets, D. G., Guttikunda, S. K., and Carmichael, G. R.: The growing contribution of sulfur emissions from ships in Asian waters, 1988–1995, *Atmos. Environ.*, 34, 4425–4439, 2000.
- 5 Sundet, J. K.: Model studies with a 3-D global CTM using ECMWF data, Thesis (Dr. scient.), University of Oslo, Norway, 1997.
- UNCTAD: Review of maritime transport, United Nations Conventions on Trade and Development, United Nations Publication, Geneva, Switzerland, 2010.
- UNEP: Bridging the emission gap, United Nations Environmental Programme (UNEP), United Nations Environment Programme, Nairobi, Kenya, 2011.
- 10 United States Environmental Protection Agency (US EPA): Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data, EPA420-R-00-002, US Environmental Protection Agency, Washington, DC, February 2000.
- Eyring, V., Stevenson, D. S., Lauer, A., Dentener, F. J., Butler, T., Collins, W. J., Ellingsen, K., Gauss, M., Hauglustaine, D. A., Isaksen, I. S. A., Lawrence, M. G., Richter, A., Rodriguez, J. M., Sanderson, M., Strahan, S. E., Sudo, K., Szopa, S., van Noije, T. P. C., and Wild, O.: Multi-model simulations of the impact of international shipping on Atmospheric Chemistry and Climate in 2000 and 2030, *Atmos. Chem. Phys.*, 7, 757–780, doi:10.5194/acp-7-757-2007, 2007.
- 20 Wang, C., Corbett, J. J., and Firestone, J.: Improving spatial representation of global ship emissions inventories, *Environ. Sci. Technol.*, 42, 193–199, doi:10.1021/es0700799, 2007.
- Wang, H., Faber, J., Nelissen, D., Russell, B. and St. Amand, D.: Reduction of GHG Emissions from ships – Marginal abatement costs and cost effectiveness of energy efficiency measure, Document MEPC 61/INF.18, International Maritime Organization (IMO), London UK, 2010.
- 25 Wild, O., Prather, M., and Akimoto, H.: Indirect long-term global radiative cooling from NO_x emissions, *Geophys. Res. Lett.*, 28, 1719–1722, 2001.
- Winebrake, J., Corbett, J., Green, E., Lauer, A., and Eyring, V.: Mitigating the health impacts of pollution from oceangoing shipping: an assessment of low-sulfur fuel mandates, *Environ. Sci. Technol.*, 43, 4776–4782, 2009.

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Overview of main global climate effects from shipping emissions¹.

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 ₂ O (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.

Reducing CO₂ from shipping

M. S. Eide et al.

Table 2. Ship type specific emission baselines and the reduction potential at marginal cost USD 50 per ton CO₂ applied to the baseline to generate the reduction inventory.

Fleet segment	NO _x	SO _x *	CO ₂	PM*	NMVOC	CH ₄	N ₂ O	CO	BC	OC*
Emission baseline 2010 (kilo ton)										
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 USD 50 per ton CO ₂ (% 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 world wide, but 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.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[I◀](#)
[▶I](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)


Reducing CO₂ from shipping

M. S. Eide et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)**Table 3.** 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 (<i>T</i>)
CO ₂	SCM	SCM	
N ₂ O	SCM	SCM	
CH ₄	Lifetime change from CTM	SCM	
O ₃	CTM	RF model ¹	SCM
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).

Reducing CO₂ from shipping

M. S. Eide et al.

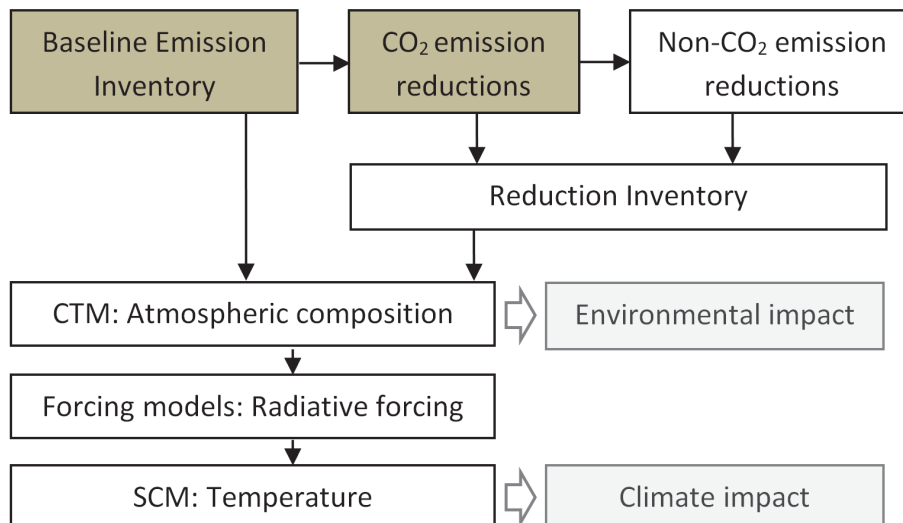


Fig. 1. Outline of main modeling steps. The dark shaded boxes indicate components from previous studies. Light shaded boxes indicate outputs, while non-shaded boxes indicate modeling steps new to this work.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

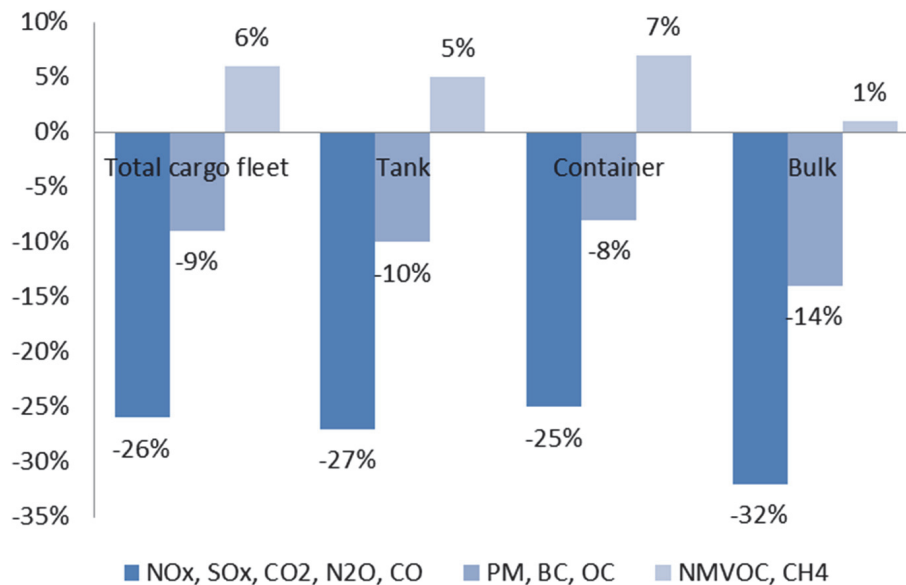


Fig. 2. Resulting emission changes in % of baseline, per ship type and emission component.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

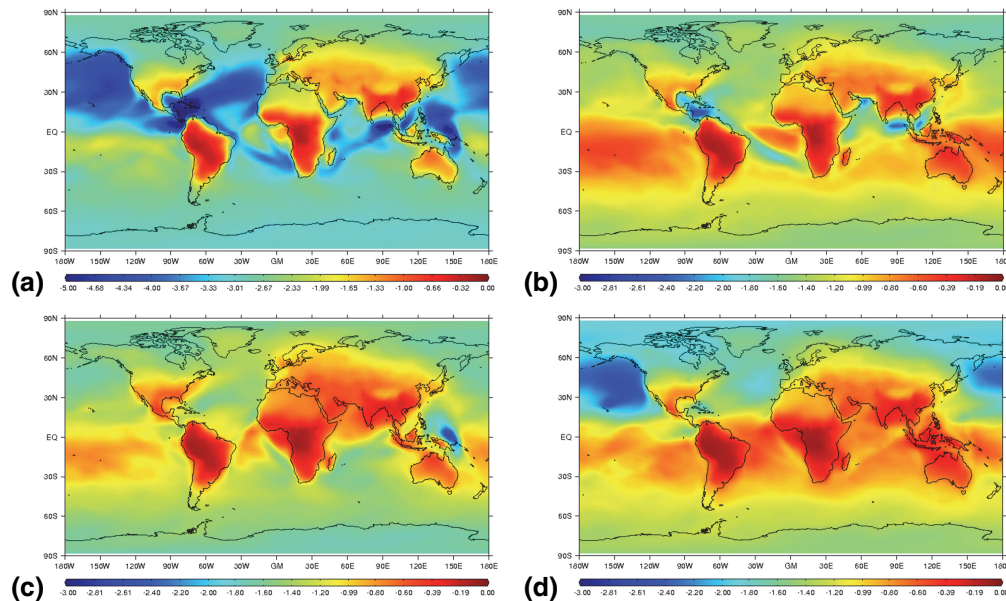


Fig. 3. Yearly mean relative changes (%) in surface ozone due to CO₂ mitigation on (a) the year 2010 cargo fleet (scale from -5% to 0%), (b) tank fleet, (c) bulk fleet, (d) container fleet (scale from -3% to 0%).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Reducing CO₂ from shipping

M. S. Eide et al.

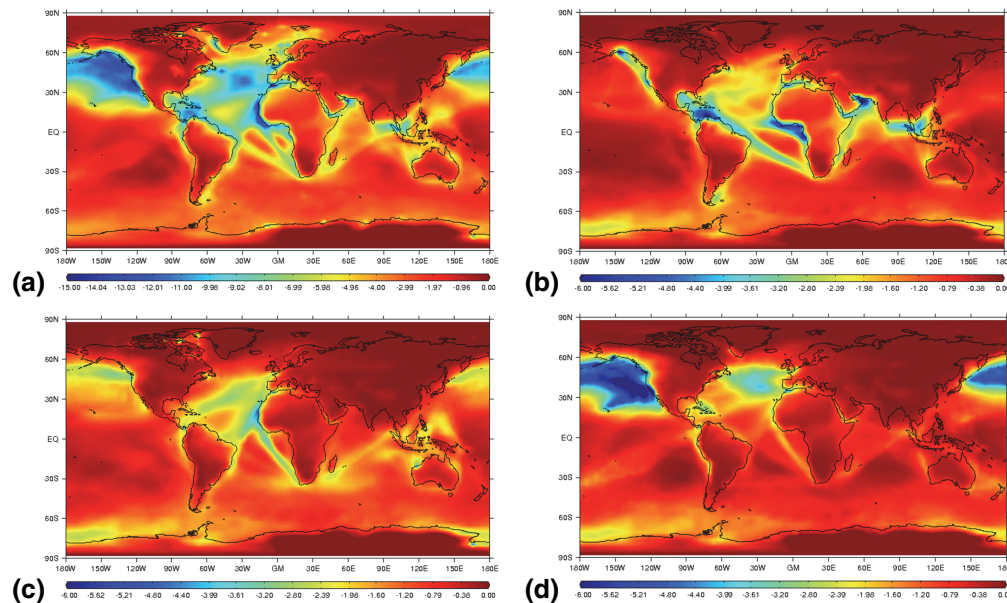


Fig. 4. Yearly mean relative changes (in % of total burden) in surface sulfate due to CO₂ mitigation on **(a)** the year 2010 cargo fleet (scale from –15% to 0%), **(b)** tank fleet, **(c)** bulk fleet, **(d)** container fleet (scale from –5% to 0%).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Reducing CO₂ from shipping

M. S. Eide et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

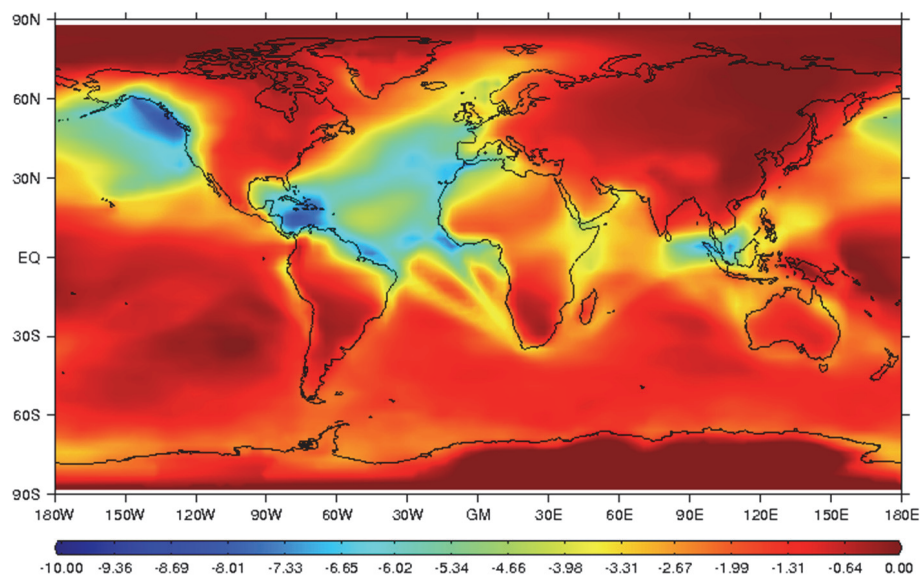


Fig. 5. Yearly mean relative changes (%) in wet deposition of sulfate due to CO₂ mitigation on the year 2010 cargo fleet.



Reducing CO₂ from shipping

M. S. Eide et al.

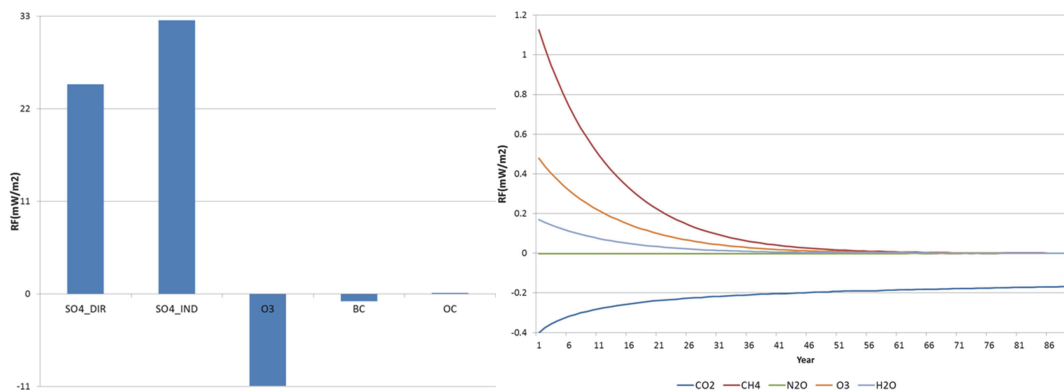


Fig. 6. (a) RF of short-lived components in year of release into the atmosphere (year 1), due to reductions in CO₂ and concurrent emissions. (b) RF per component in years 2–90. Note that CH₄ perturbations are caused indirectly by NO_x emissions, not by primary emissions of shipping CH₄. Note also that the O₃ perturbations in (a) are induced by chemical cycling of NO_x emissions, while O₃ perturbations as well as H₂O perturbations in (b) are due to perturbations in CH₄. See Table 1.

Reducing CO₂ from shipping

M. S. Eide et al.

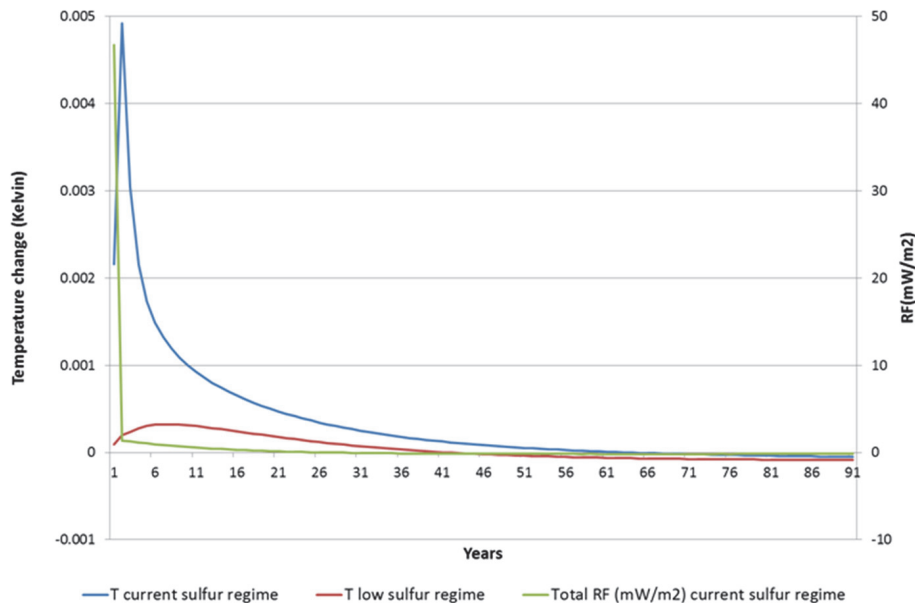


Fig. 7. Change in global average temperature response, in a given year after emissions under the current sulfur regime and under an assumed low sulfur regime with 80 % reduction in sulfur emissions from baseline, and net RF from all compounds, current sulfur regime.

Reducing CO₂ from shipping

M. S. Eide et al.

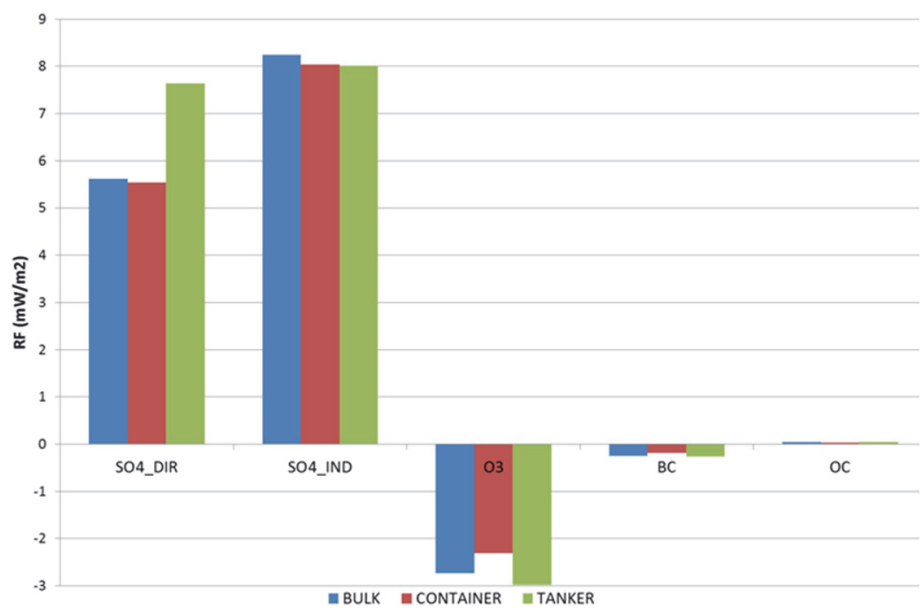


Fig. 8. RF for short lived components for the major ship types in year 1.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

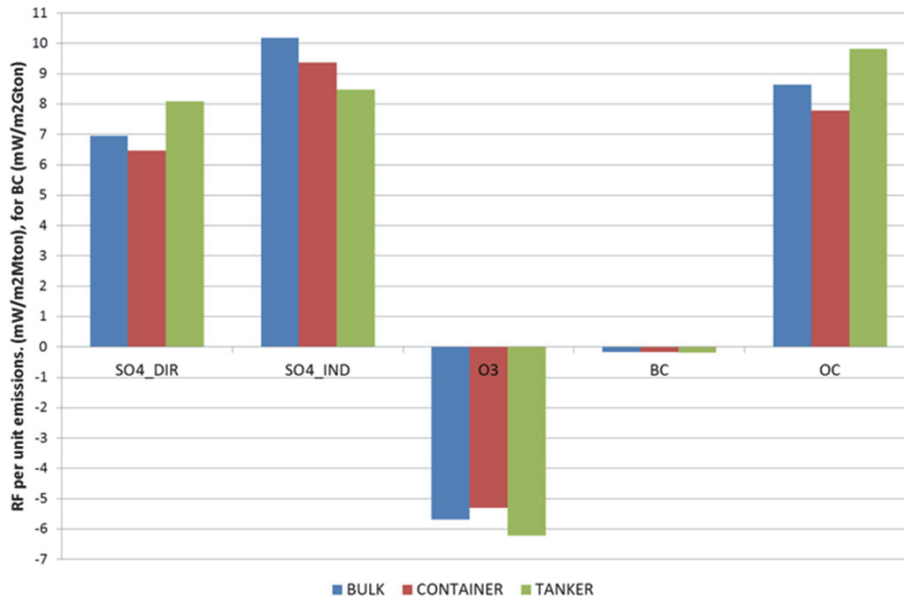


Fig. 9. Normalized RF for short lived components for the major ship types in year 1. RF per unit emission. Note that the unit for BC is per Gton, while the other components are normalized per Mton.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

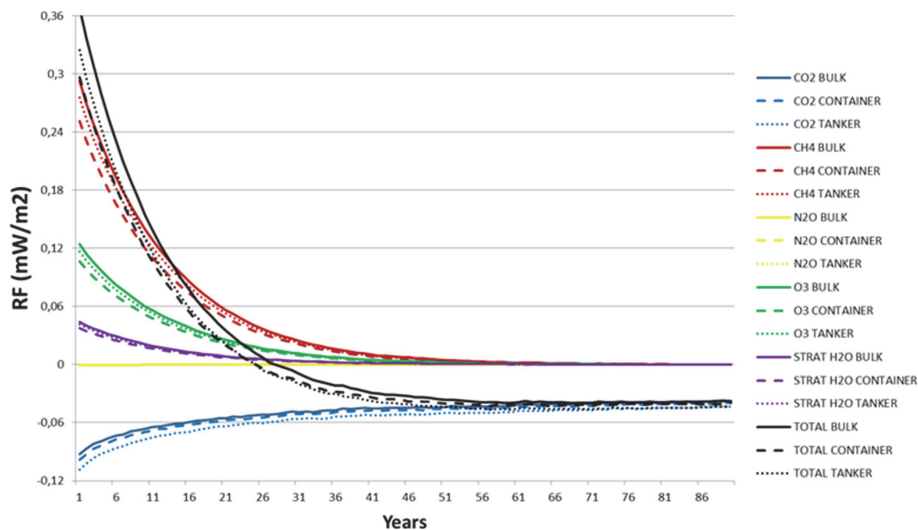


Fig. 10. RF for each component, per ship type, years 2–90. Total RF is for all components, including short-lived.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Reducing CO₂ from shipping

M. S. Eide et al.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	

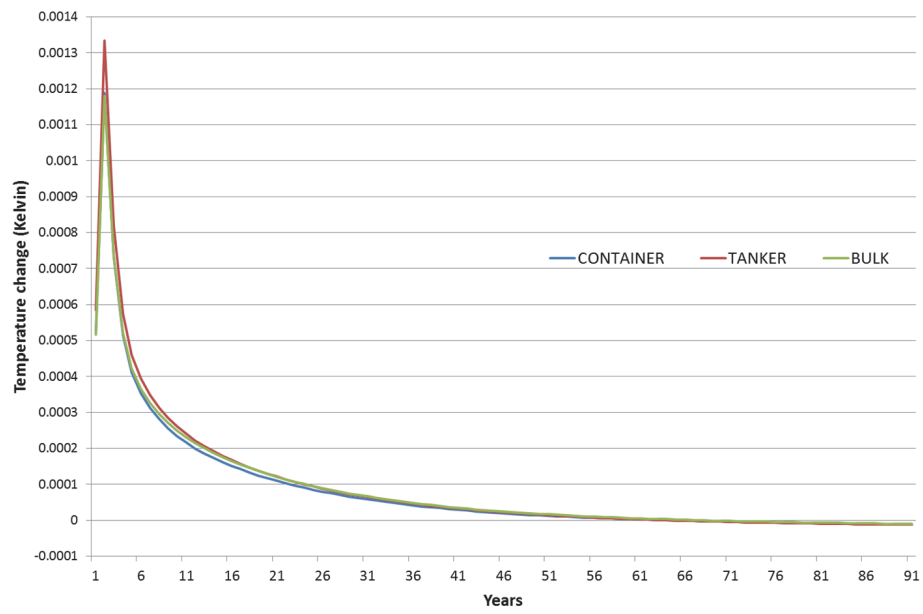


Fig. 11. Change in global average temperature response, years 2–90, per ship type.



Reducing CO₂ from shipping

M. S. Eide et al.

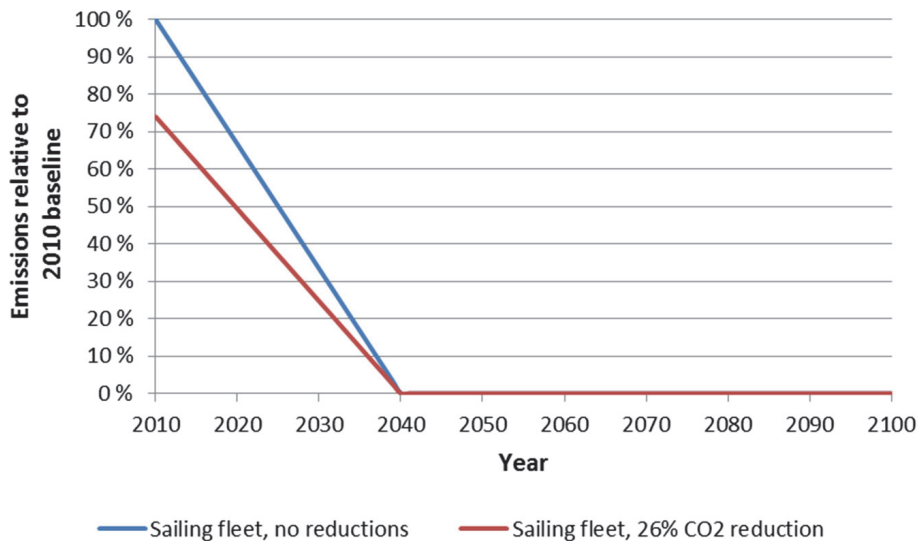


Fig. 12. Scenario for fleet emission development; the reduction inventory is sustained on the fleet as it steadily diminishes over time due to scrapping and disappears in 2040.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[I◀](#)[▶I](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Reducing CO₂ from shipping

M. S. Eide et al.

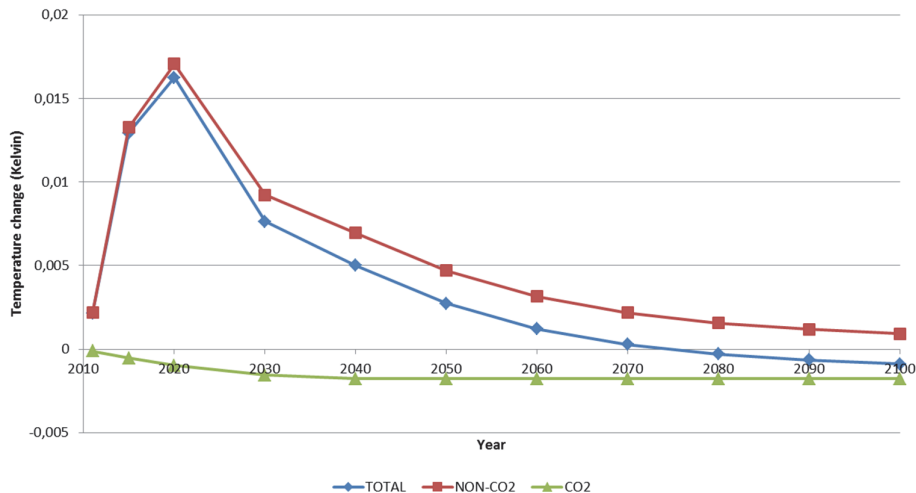


Fig. 13. Temperature response in varying evaluation years from an emission scenario where the reduction inventory is sustained on the fleet as it steadily diminishes over time due to scrapping and disappears in 2040. Response from CO₂ and non-CO₂ components shown separately, as well as combined (total).

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

◀
▶

◀
▶

Back
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

