Radiative forcing and temperature response from shipping

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ABSTRACT: A simplified global climate response model was used to calculate radiative forcings and temperature responses from the emissions of shipping. Radiative forcings were calculated for 2000, which were: 0.043 W m^{-2} (CO_2); 0.021 W m^{-2} (O_3); -0.011 W m^{-2} (CH_4). If these forcings are combined with literature values for SO_4, black carbon and the indirect aerosol effect, a total forcing of -0.08 W m^{-2} was calculated. Comparing the 2000 CO_2 shipping radiative forcing and temperature responses with those for aviation showed them to be approximately 1.8× and 2.7× greater.

1 INTRODUCTION

Ocean-going shipping provides an important means of international transportation of goods, along with other purposes such as fishing, leisure transport etc. Shipping has been operational on an international scale since approximately the industrial revolution, initially as sail ships, then steam ships powered by coal. Since *circa* 1910, diesel engines were introduced. By 1961, there were still over 10,000 steam engine powered ships and ~3,500 steam turbine powered ships in operation.

The combustion of coal and diesel results in a variety of emissions including carbon dioxide (CO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), methane (CH_4), other non-methane volatile organic compounds (VOCs) and particles. In addition to sulphate particles (SO_4) resulting from SO_2 emissions, ships also release black carbon (BC) and particulate organic matter (POM).

These emissions contribute to perturbation of the global carbon, sulphur and nitrogen budgets. They result in both direct warming effects from CO_2 and CH_4, potential indirect warming effects from the emission of ozone (O_3) precursors (NO_x, CH_4, CO and VOCs) and indirect cooling effects from shipping emissions of NO_x, which increases OH resulting in a reduction in CH_4 lifetime (Endresen et al., 2003; Eyring et al., 2007). The increases in SO_4 and BC concentrations also have direct but opposing effects resulting from enhanced scattering and reflection of solar radiation/downwelling of long-wave radiation and an indirect effect from the formation of 'ship tracks' (e.g. Schreier et al., 2006) and large-scale low marine clouds (Capaldo et al., 1999).

In this work, the global mean radiative forcing (RF) and temperature response from shipping emissions was calculated for most of the forcing agents. A climate response model was adapted to deal with shipping radiative effects in a parameterized way from a similar model developed for evaluating global mean aviation effects (Lim et al., 2007), which in turn was developed from the simpler model of Sausen and Schumann (2000). Such climate response modelling was originally developed by Hasselmann et al. (1993), which has been adapted for a variety of applications.

Since much research has been dedicated to understanding the response of the climate system to aircraft emissions, some simple comparisons are made between the two transportation sectors and projected emissions scenarios in the future.

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2 METHODOLOGY

In this section, the emissions estimations are summarized and details of the climate response model provided that are particular to the quantification of shipping RF and temperature responses.

2.1 *Emissions*

Present day shipping emissions are taken from Eyring et al. (2005a; hereafter EY2005a) for CO_2, NO_x, VOCs, CH_4 and CO. Historical emissions from shipping were taken from two different sources for comparison. EY2005a calculated emissions from 1950 to 2001. However, engine-driven shipping has a much longer history that dates back to *circa* 1870. For earlier shipping emissions, shipping emissions data are taken from Endresen et al. (2007). Two estimations of shipping CO_2 radiative forcing can be made to 2000; one using the data of Endresen et al. (2007; hereafter EN2007) and another using these data from 1870 to 1950 combined with EY2005a from 1950 to 2000.

For future emissions, Eyring et al. (2005b) provided estimations according to four demand scenarios (DS1-DS4) and four technology scenarios (TS1-TS4) to 2050. However, in order to better represent the climate response, transient runs to 2100 are needed. Therefore, the central demand/technology scenario (DS1-TS4) of Eyring et al. (2005b) has been extrapolated out to 2100.

For the comparison with aviation, a full historical and projected scenario of emissions from 1940 through to 2050, extrapolated out until 2100 has been taken from Sausen and Schumann (2000).

2.2 *Climate response model*

The LinClim climate response model (Lim et al., 2007) has been adapted to calculate RFs and temperature responses from shipping emissions. The contribution of shipping emissions of CO_2 to concentrations was calculated according to the method of Hasselmann et al. (1997) and these were subtracted from historical 'background' CO_2 concentrations up until 1995, thereafter using concentrations from the IS92a scenario to 2100. The CO_2 RF was then calculated from the CO_2 concentrations according to the method of IPCC (2001). The temperature response was calculated via a convolution integral method (Hasselmann et al., 1993) using an updated fit to the parent GCM, ECHAM4/OPYC3 (Lim et al., 2007).

For CH_4, a global mean mass balance equation was used, which accounts for changes in CH_4 lifetime from tropospheric, stratospheric and soil sinks (Wigley et al., 2002). The tropospheric lifetime, τ_{OH}, was determined from Equation [1] (IPCC, 2001).

$$\delta \ln(\tau_{OH})_t = -0.32\delta \ln(C)_{t-1} + 0.0042\delta(e-NO_X)_t - 0.000105\delta(e-CO)_t - 0.000315\delta(e-VOC)_t \quad [1]$$

where $(\tau_{OH})_t$ is the tropospheric sink at time t (yr), $(e\text{-}NO_x)_t$ are the anthropogenic NO_x emissions at time t (Tg(N)/yr), $(e\text{-}CO)_t$ are the anthropogenic CO emissions at time t (Tg/yr), and $(e\text{-}VOC)_t$ are the anthropogenic VOC emissions at time t (Tg/yr)

It was assumed that all changes in lifetime, concentration and emissions are relative to the year 2001. It was also assumed that the natural emissions of CH_4, NO_x, CO and VOC remain constant. The mass balance equation predicts background CH_4 and the same equation was used to calculate the shipping component, using the difference between background and shipping emissions of NO_x, CO, CH_4 and VOCs in Equation [1].

The RF arising from the CH_4 perturbation was calculated from the method presented by IPCC (2001) which accounts for N_2O overlap.

$$RF_{CH_4} = \alpha\left(\sqrt{C_{(t)}} - \sqrt{C_0}\right) - \left(f(C_t, N_0) - f(C_0, N_0)\right) \quad [2]$$

where α is 0.036, C_t is the CH_4 concentration at time t (ppbv), C_0 is the pre-industrial CH_4 concentration (700 ppbv), N_0 is the pre-industrial N_2O concentration (280 ppbv) and $f(C,N)$ is the correction for overlap with N_2O:

$$f(C,N) = 0.47\ln\left(1 + 2.01\times10^{-5}(C\cdot N)^{0.75} + 5.31\times10^{-15}C(C\cdot N)^{1.52}\right) \quad [3]$$

The CH_4 RF from shipping emissions was calculated from Equation [4]

$$RF_{CH_4}(shipping) = RF_{CH_4}(C_{Background}) - RF_{CH_4}(C_{Background-shipping}) \quad [4]$$

A simple relationship between a change in O_3 column (Dobson Units – DU) and O_3 RF was presented by IPCC (2001). The pre-industrial global mean O_3 column was taken as 25 DU and historical O_3 forcings were also taken from IPCC (2001) to 2000, for which the RF was estimated to be 0.38 W m^{-2}. The mean forcing per DU is 0.042 W m^{-2}/DU. For future changes in column O_3 the relationship presented by IPCC (2001) between O_3 DU and NO_x, CH_4, CO and VOC emissions was used:

$$\delta(\mathrm{O}_3)_t = +5.0\delta\ln(CH_4)_{t-1} + 0.125\delta(e-NO_X)_t + 0.0011\delta(e-CO)_t + 0.0033\delta(e-VOC)_t \quad [5]$$

where $(O_3)_t$ is the tropospheric O_3 at time t (DU), CH_4 (ppbv), $(e\text{-}NO_x)_t$ are the anthropogenic NO_x emissions at time t (Tg(N)/yr); $(e\text{-}CO)_t$ are the anthropogenic CO emissions at time t (Tg/yr), and $(e\text{-}VOC)_t$ are the anthropogenic VOC emissions at time t (Tg/yr).

It was also assumed that the natural emissions of CH_4, NO_x, CO and VOC remain constant. Therefore, the emissions scenario describes all changes in emissions.

It was assumed that equation [5] predicts background tropospheric O_3 (in DU) relative to the year 2001 and the same equation was used to calculate the shipping component, using shipping emissions of NO_x, CO, CH_4 and VOCs. Therefore, the O_3 concentrations arising from shipping are assumed to be the difference between the background and shipping O_3 concentrations as in Equation [5]. The RF from the O_3 perturbation was calculated using Equation [6].

$$(RF_{\mathrm{O}_3})_t = 0.042 \times \delta(\mathrm{O}_3) + (RF_{\mathrm{O}_3})_{2000} \quad [6]$$

3 RESULTS

Two time-evolved CO_2 RF responses from shipping have been calculated from the emission datasets (i.e. EN2007, and EN2007+EY2005a) to 2000. The emissions are shown in Figure 1a and the subsequent CO_2 RF in Figure 1b. The time-evolution of emissions is evidently quite different over the period 1940 to 2000, with the estimates of EY2005a being based on interpolation of individual years (1950, 1960, 1970, 1980, 1995 and 2001), such that the reductions and subsequent increases between 1980 and 1990 as shown by EN2007 are not featured. By contrast, the emissions estimates of EN2007 between 1940 and 1975 are greater than those of EY2005a. These two features in the data have a cancelling effect in the CO_2 RF (Figure 2) by 2000 such that they reach approximately the same value of ~0.0425 W m^{-2}.

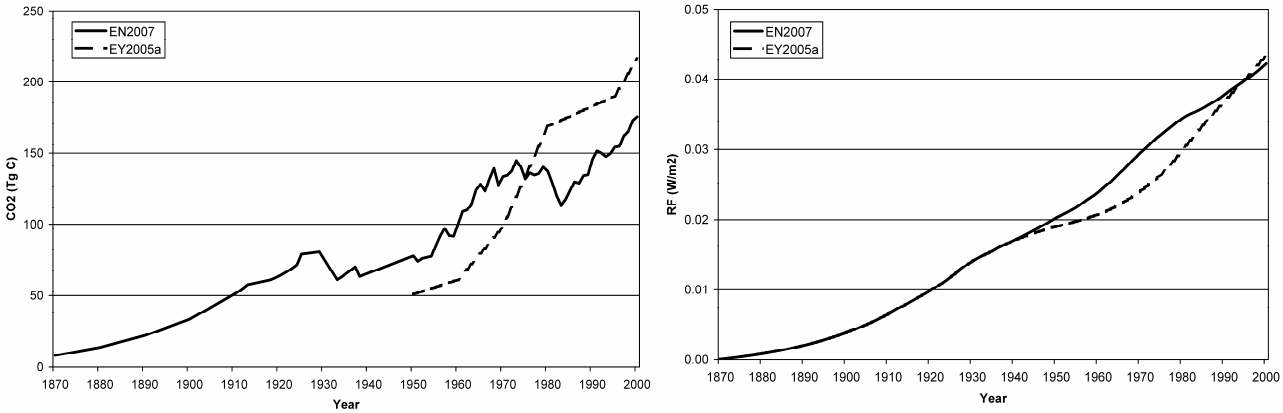

Figure 1. Panel a. Emissions of CO_2 from shipping between 1870 and 2000 according to EY2005a and EN2007, including back-extrapolation from 1925 to 1870. Panel b. Radiative forcing of CO_2 from shipping according to estimates of EY2005a and EN2007, including back-extrapolation from 1925 to 1870.

4 DISCUSSION

4.1 *An estimation of the total radiative forcing impact from shipping in 2000*

The model can be used to estimate RFs from shipping for CO_2, O_3 and CH_4, and SO_4. Currently, it does not have BC and the indirect aerosol effect implemented. If shipping RFs for 2000 calculated here are combined with independent estimates of these RFs not calculated in the model, an overall RF chart for 2000 can be given in a similar fashion (Figure 2) to those presented for aviation (IPCC, 1999; Sausen et al., 2005).

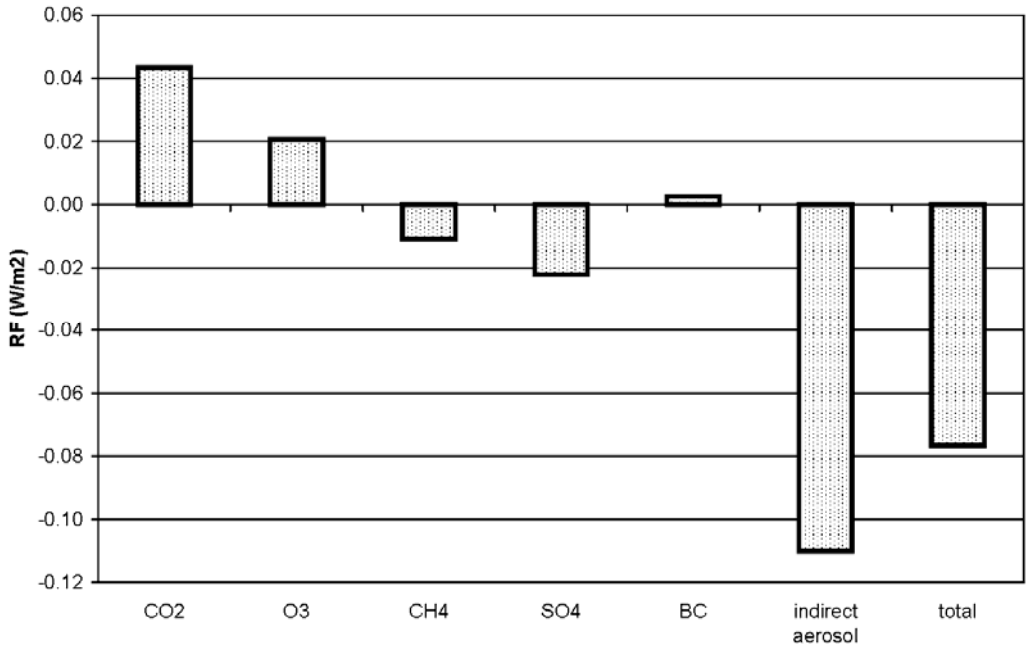

Figure 2. Radiative forcing from shipping effects in 2000: CO_2, O_3, CH_4 responses as calculated with the linear response model; BC and the indirect effect from Berntsen (2004) and Capaldo et al. (1999).

The O_3 RF was calculated to be 0.021 W m^{-2}. This is approximately twice the value of 0.0098 ± 0.002 W m^{-2} calculated by Eyring et al. (2007) using a suite of chemical transport models (CTMs). However, the emissions used by Eyring et al. (2007) were approximately one half those (in 2000) used in this study (3.10 TgN instead of 6.51 Tg N yr^{-1}), such that the response scales linearly.

Since the negative RFs from the direct effect of SO_4 and the indirect effect dominate, the total RF is negative, implying an overall cooling on a global mean basis. However, it is questionable as to whether such a global mean additivity is meaningful where strong positive and negative forcings are involved, some of which are spatially heterogeneous – this is basically a question over the usefulness of the RF metric which is a subject of debate for issues such as this. An overall negative RF from shipping that comprises both positive and negative forcings could mistakenly be interpreted as either being benign, or even *in extremis* counteracting other positive RFs. The fallacy of this interpretation is that if the sulphur in the fuel were removed, then the negative SO_4 RF would disappear in a matter of weeks, and a similar response is possible for the overall indirect aerosol effect due to shipping. In such a case where S was reduced, and the RF from this effect reduced, one would still be left with a long-term positive RF and warming from historical CO_2 emissions.

4.2 *A comparison of shipping and aviation CO_2 radiative forcing and temperature response*

It is of interest to compare aviation with shipping effects on climate since the international emissions from both of these sectors are not covered by the Kyoto Protocol because of the complication of allocating emissions. Here, only the CO_2 RF and temperature responses for shipping and aviation are compared. A more comprehensive comparison of RF effects is not yet possible because of limited emissions data availability.

In the comparison made here, the responses from the 'beginning' of shipping and aviation, i.e. 1870 and 1940 were calculated for a range of scenarios through to 2050, and thereafter to 2100 for

a single scenario. In 2000, the CO_2 RF from shipping was approximately 1.8 times that of aviation's CO_2 RF. However, the assumed growth of aviation and shipping CO_2 emissions means that the difference between the RFs diminishes and starts to converge by 2100.

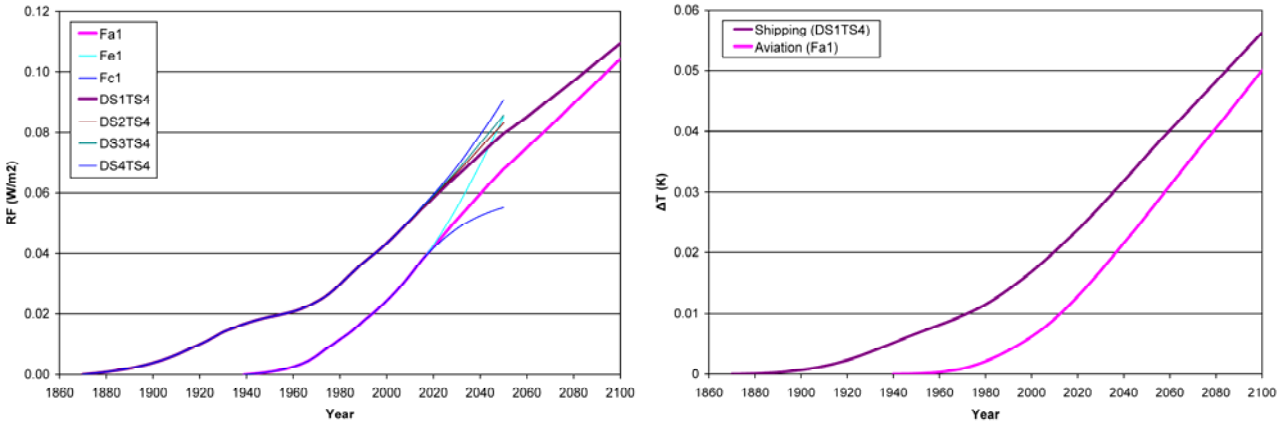

Figure 3. Panel a. Time evolution of CO_2 radiative forcing from shipping and aviation from 1870 and 1940, respectively, to 2050 under assumptions of central emission scenarios, thereafter linearly extrapolated to 2100. Panel b. Time evolution of CO_2 temperature response from shipping and aviation from 1870 and 1940, respectively, to 2050 under assumptions of central emission scenarios, thereafter linearly extrapolated to 2100.

If Figure 3b is examined for the temperature response effect on climate from these sectoral CO_2 emissions, the shipping temperature effects is a factor of ~2.7 times that of aviation in 2000 and ~1.1 times that of aviation in 2100.

4.3 *Future work and limitations of the modelling approach*

The purpose of the model is to calculate *time-evolved* RFs for the calculation of temperature response(s). For some forcing agents such as CO_2, O_3 and CH_4, the RFs can be calculated explicitly, albeit in a parameterized manner. For other agents such as the direct effect from SO_4 and BC or the indirect aerosol effect, individual yearly values may be used with some parameter (such as fuel) to scale these RFs over time in order to calculate temperature responses. As independent estimates of some of these forcing effects become available, they will be implemented in the model. Whilst the RF response to shorter-lived climate forcing agents such as O_3, SO_4 etc. is relatively fast, it should be remembered that the *temperature* response to these forcings is longer because of the thermal inertia of the climate system arising from the slow exchange times of heat between the ocean and the atmosphere. In the future, a complete history of emissions of NO_x, CO, VOCs and CH_4 are needed to calculate the temperature response from shipping-induced changes in O_3 and CH_4 RFs.

The nature of the model has limitations that should be born in mind when interpreting the output: it is a *global mean* model, such that it is a robust method to calculate temperature response for homogeneous forcings (assuming that it is appropriately tuned to some GCM). For other forcings such as O_3, BC, SO_4 or the indirect aerosol effect, the spatial forcing is highly heterogeneous and it is not necessarily the case that a global mean response is entirely appropriate for interpreting the overall temperature response to, e.g., shipping emissions in an additive manner. However, to a first order, such global mean models can produce useful initial data for a first-order interpretation of the impacts of a transport sector such as shipping.

5 CONCLUSIONS

- This study addresses time-evolved RFs and temperature responses from some of the effects of shipping, particularly CO_2, O_3 and CH_4.
- A robust estimate of shipping CO_2 RF has been made for 2000 with the usage of a full history of shipping's emissions of 0.043 W m^{-2}. A shipping O_3 RF of 0.021 W m^{-2} in 2000 has been calculated using a simple method, which is in agreement with independent calculations using complex

3D chemical transport models, allowing for a linear scaling of emissions. Shipping NO_x emissions result in a negative CH_4 RF of -0.01 W m^{-2} in 2000, as calculated with a simplified methodology.
- Combining these RFs with others not calculated with the model result in an overall global mean RF due to shipping in 2000 of approximately -0.08 W m^{-2}.
- Shipping CO_2 RF was approximately 1.8 times that of aviation in 2000 and the resultant temperature response of (CO_2 only) for shipping was found to be 2.7 times that of aviation in 2000.

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