Multi-model Simulations of the Impact of International Shipping on Atmospheric Chemistry and Climate in 2000 and 2030

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ABSTRACT: The global impact of shipping on atmospheric chemistry and radiative forcing, as well as the associated uncertainties, have been quantified using an ensemble of ten state-of-the-art atmospheric chemistry models and a pre-defined set of emission data. The analysis is performed for present-day conditions (year 2000) and for two future ship emission scenarios. In one scenario emissions stabilize at 2000 levels; in the other emissions increase with a constant annual growth rate of 2.2% up to 2030 (termed the 'Constant Growth Scenario'). The first key question addressed by this study is how NO_x and SO_2 emissions from international shipping might influence atmospheric chemistry in the next three decades if these emissions increase unabated. The models show future increases in NO_2 and ozone burden which scale almost linearly with increases in NO_x emission totals. For the same ship emission totals but higher emissions from other sources a slightly smaller response is found. The most pronounced changes in annual mean tropospheric NO_2 and sulphate columns are simulated over the Baltic and North Seas; other significant changes occur over the North Atlantic, the Gulf of Mexico and along the main shipping lane from Europe to Asia, across the Red and Arabian Seas. The second key issue was to examine the range of results given by the individual models compared to the ensemble mean. Uncertainties in the different model ap-

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proaches in the simulated ozone contributions from ships are found to be significantly smaller than estimated uncertainties stemming from the ship emission inventory, mainly the ship emission totals, the neglect of ship plume dispersion, and the distribution of the emissions over the globe.

1 INTRODUCTION

Emissions from international shipping contribute significantly to the total budget of anthropogenic emissions from the transportation sector (Eyring et al., 2005) and have been recognized as a growing problem by both policymakers and scientists (Corbett, 2003). Here we use an ensemble of ten state-of-the-art global atmospheric chemistry models to assess the impact of NO_x emissions from international shipping on ozone for present-day conditions (year 2000). A subset of four models has been applied to investigate the changes in sulphate distributions due to SO_2 emissions from international shipping. This multi-model approach accounts for intermodel differences and therefore makes the results more robust compared to previous studies based on single models (e.g., Lawrence and Crutzen, 1999; Endresen et al., 2003). In addition, this study for the first time quantifies the potential impact of ship emissions in the future (year 2030) for two different future ship emission scenarios. The participating models have also been evaluated and used in accompanying studies (e.g. Stevenson et al., 2006; Dentener et al., 2006; Shindell et al., 2006, van Noije et al., 2006) as part of the European Union project ACCENT ('Atmospheric Composition Change: the European NeTwork of excellence'; http://www.accent-network.org). Full details of this study are given in Eyring et al. (2006) and only a brief summary is presented here.

2 MODELS AND MODEL SIMULATIONS

Ten global atmospheric chemistry models have participated in this study. Seven of these models are Chemistry-Transport Models (CTMs) driven by meteorological assimilation fields and three models are atmospheric General Circulation Models (GCMs). Two of the GCMs are driven with the dynamical fields calculated by the GCM in climatological mode, but the fully coupled mode (interaction between changes in radiatively active gases and radiation) has been switched off in the simulations of this study. The other GCM runs in nudged mode, where winds and temperature fields are assimilated towards meteorological analyses. Therefore, changes in the chemical fields do not influence the radiation and hence the meteorology in any of the model simulations used here; so for a given model, each scenario is driven by identical meteorology. The main characteristics of the ten models can be found in Table 1 of Eyring et al. (2006) and the models are described in detail in the cited literature.

Two of the five simulations that have been defined as part of the wider PHOTOCOMP-ACCENT-IPCC study have been used in this work: a year 2000 base case (S1) and a year 2030 emissions case (S4) following the IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emission Scenarios) A2 scenario (Nakicenovic et al., 2000). Full details on the emissions used in the S1 and S4 simulations are summarised in Stevenson et al. (2006). To retain consistency with all other emissions, ship emissions in the year 2000 (S1) are based on the EDGAR3.2 dataset (Olivier et al., 2001) at a spatial resolution of 1° latitude x 1° longitude. The global distribution of ship emissions in EDGAR3.2 is based on the world's main shipping routes and traffic intensities. EDGAR3.2 includes data for 1995, which have been scaled to 2000 values assuming a growth rate of 1.5%/yr, resulting in annual NO_x and SO_2 emissions of 3.10 Tg(N) and 3.88 Tg(S), respectively, similar to the emission totals published by Corbett et al. (1999). As noted in Stevenson et al. (2006) in the S4 simulation emissions from ships were included at year 2000 levels by mistake. All other anthropogenic sources (except biomass burning emissions, which remain fixed at year 2000 levels) vary according to A2 broadly representing a 'pessimistic' future situation. The simulation S4 is used in this study to assess the impact of ship emissions under different background levels. An additional model simulation for 2030 (S4s) has been designed to assess the impact of shipping if emission growth remains unabated. Ship emissions in S4s are based on a 'Constant Growth Scenario' in which emission factors are unchanged and emissions increase with an annual growth rate of 2.2% between 2000 and 2030. Vessel traffic distributions are assumed to stay the same for all model simulations presented here. Full details on the model simulations and model analyses are given in Eyring et al. (2006).

3 RESULTS

For present-day conditions the most pronounced changes in annual mean tropospheric NO_2 and SO_4 columns are found over the Baltic and the North Sea, and also though smaller over the Atlantic, Gulf of Mexico, and along the main shipping lane from Europe to Asia. Maximum near-surface ozone changes due to NO_x ship emissions are simulated over the North Atlantic in July (~12 ppbv) in agreement with previously reported results (Lawrence and Crutzen, 1999; Endresen et al., 2003). However, in contrast to Endresen et al. (2003), a decrease in ozone in winter is found over large areas in Europe (~3 ppbv) due to titration (see Figure 1). Overall NO_x emissions most effectively produce ozone over the remote ocean, where background NO_x levels are small.

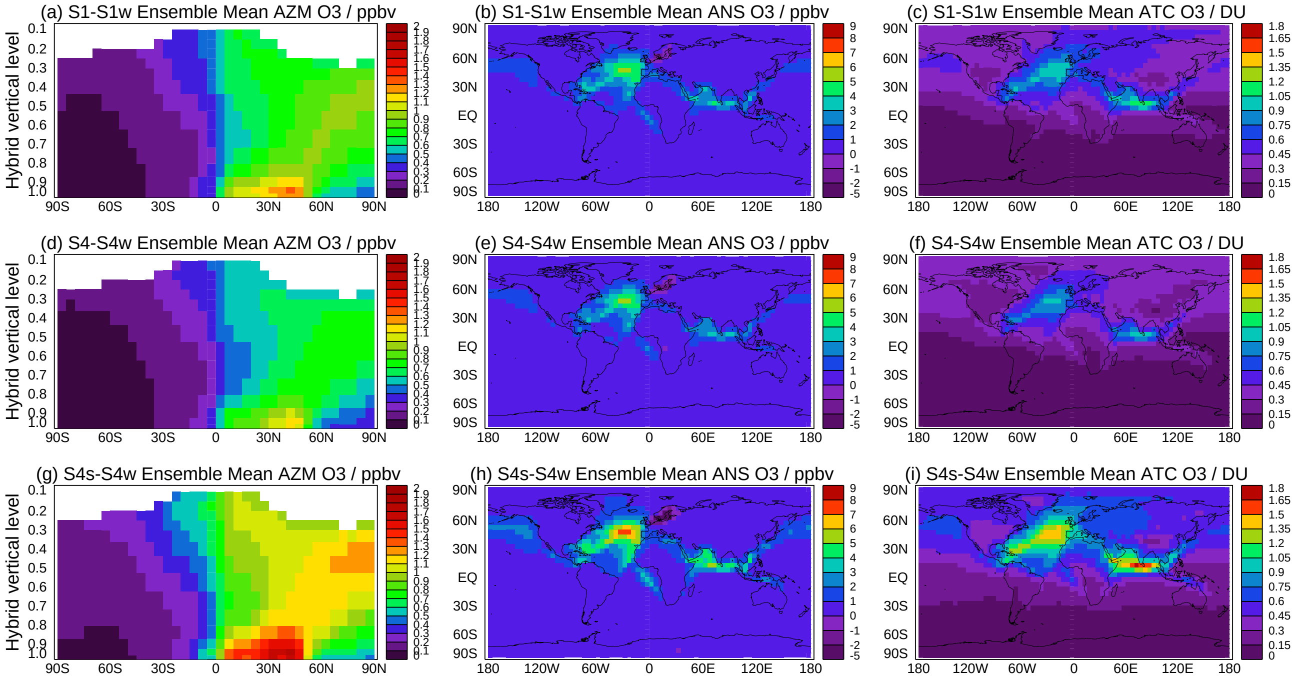

Figure 1: Modelled ensemble mean ozone change between (a-c) case S1 (year 2000) and S1w (year 2000 without ship emissions), (d-f) case S4 (year 2030) and S4w (year 2030 without ship emissions), and (g-i) case S4s (year 2030) and S4w. Figure 1a, 1d, and 1g are zonal mean changes (ppbv), Figures 1b, 1e, and 1h are near-surface ozone changes (ppbv) and Figure 1c, 1f, and 1i are tropospheric ozone column changes (DU). From Eyring et al. (2006).

The two 2030 scenarios both specify emissions following the IPCC SRES A2 scenario (Nakicenovic et al., 2000). The first future scenario assumes that ship emissions remain constant at 2000 levels and under this scenario a slightly smaller response in ozone and sulphate changes due to shipping is found compared to the present-day contribution from shipping. This indicates that higher background levels tend to slightly reduce the perturbation from ships. The second emission scenario addresses the question of how NO_x and SO_2 emissions from international shipping might influence atmospheric chemistry in the next three decades if these emissions grow unabated and one assumes a constant annual growth rate of 2.2% between 2000 and 2030 ('Constant Growth Scenario'). The models show future increases in NO_x and ozone burden which scale almost linearly with increases in NO_x emission totals under the same background conditions (see Figure 2).

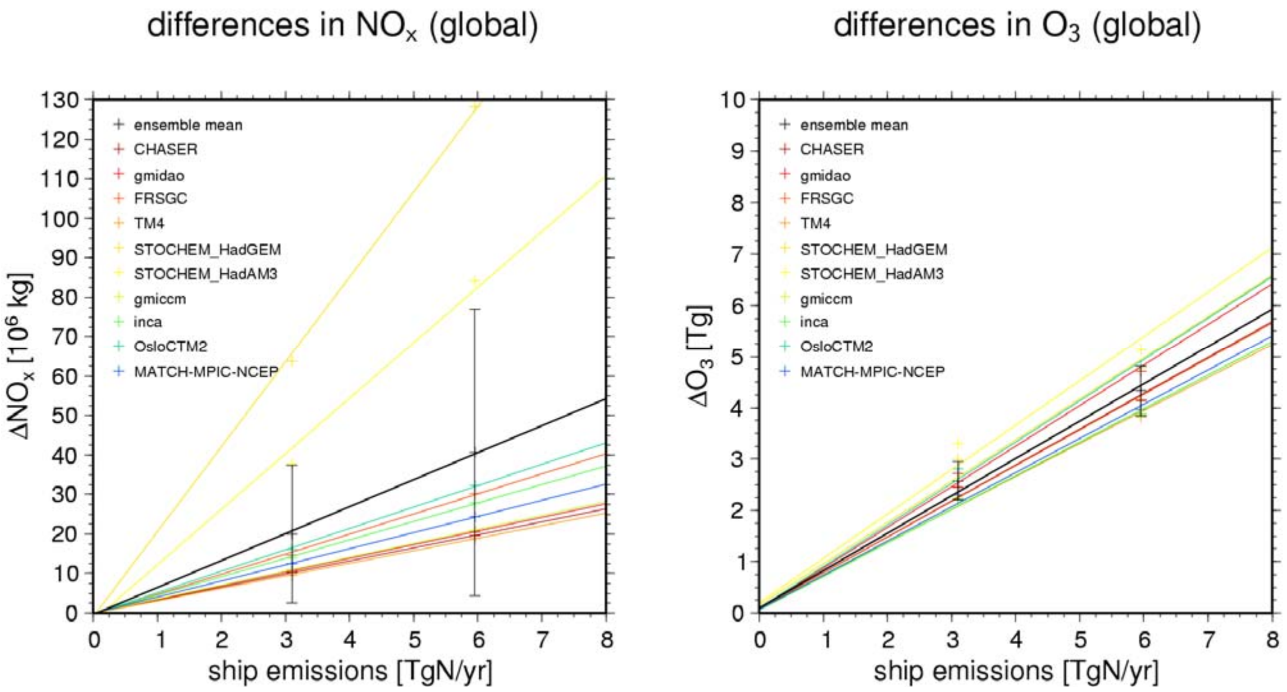

Figure 2. Global total change in annual mean tropospheric NOx burden (left) and ozone burden (right) due to ship emissions (S4-S4w and S4s-S4w) in each individual model (coloured lines) and the ensemble mean (black line). Inter-model standard deviations are shown as bars. From Eyring et al. (2006).

Therefore, there is evidence that the ship NO_x effect is only weakly subject to saturation in its current magnitude range, and that saturation cannot be expected to help mitigate the effects of near-future increases. In other words a doubling of NO_x emissions from ships in the future might lead to a doubling in atmospheric ozone burdens due to ship emissions. In addition, increasing emissions from shipping would significantly counteract the benefits derived from reducing SO_2 emissions from all other anthropogenic sources under the A2 scenario over the continents for example in Europe. Under the 'Constant Growth Scenario' shipping globally contributes with 3% to increases in ozone burden until 2030 and with 4.5% to increases in sulphate. The results discussed above are calculated under the assumption that all other emissions follow the A2 scenario broadly representing a 'pessimistic' future situation. However, if future ground based emissions follow a more stringent scenario, the relative importance of ship emissions becomes larger.

Tropospheric ozone forcings due to ships of 9.8 mW/m^2 in 2000 and 13.6 mW/m^2 in 2030 are simulated by the ensemble mean, with standard deviations of 10-15%. Compared to aviation (~ 20 mW/m^2; Sausen et al., 2005) tropospheric ozone forcings from shipping are of the same order in 2000, despite the much higher NO_x emissions from ships (Eyring et al., 2005). This can be understood because peak changes in ozone due to shipping occur close to the surface, whereas changes in ozone due to aviation peak in the upper troposphere. A rough estimate of RF from shipping CO_2 suggests 26 mW/m^2 in 2000 compared to 23 mW/m^2 from aviation CO_2. The direct aerosol effect resulting from SO_2 ship emissions is approximately -14 mW/m^2 in 2000 and decreases to a more negative value of -26 mW/m^2 in 2030 under the 'Constant Growth Scenario'.

We have also investigated the range of results given by the individual models compared to other uncertainties. Uncertainties in the simulated ozone contributions from ships for the different model approaches revealed by the intermodel standard deviations are found to be significantly smaller than estimated uncertainties stemming from the ship emission inventory, mainly the ship emission totals, the neglect of ship plume dispersion, and the distribution of the emissions over the globe. This reflects that the simulated net change from ship emissions under otherwise relatively clean conditions in global models is rather similar and shows that the atmospheric models used here are suitable tools to study these effects.

4 SUMMARY

Maximum contributions from shipping to annual mean near-surface ozone quantified from an ensemble of ten state-of-the-art atmospheric chemistry models and a pre-defined set of emission data are found over the Atlantic (5-6 ppbv in 2000 reaching up to 8 ppbv in the 2030 Constant Growth Scenario). Large increases in tropospheric ozone column are found over the Atlantic and even stronger over the Indian Ocean (1 DU in 2000 and up to 1.8 DU in 2030). Tropospheric ozone forcings due to shipping are 9.8 ± 2.0 mW/m^2 in 2000 and 13.6 ± 2.3 mW/m^2 in 2030. Whilst increasing ozone, ship NO_x simultaneously enhances OH, reducing the CH_4 lifetime by 0.13 yr in 2000, and by up to 0.17 yr in 2030, introducing a negative radiative forcing. Over Europe, the increase in ship emissions under the 'Constant Growth Scenario' will enhance the positive trend in NO_2 over land up to 2030. In addition, efforts to lower European sulphate levels through reductions in SO_2 emissions from anthropogenic sources on land will be partly counteracted by the rise in ship emissions. Globally, shipping contributes with 3% to increases in ozone burden until 2030 and with 4.5% to increases in sulphate. The results discussed above are calculated under the assumption that all other emissions follow the IPCC SRES A2 scenario. However, if future ground based emissions follow a more stringent scenario, the relative importance of ship emissions becomes larger. The range of results given by the individual models compared to other uncertainties has also been investigated. Uncertainties in the simulated ozone contributions from ships for the different model approaches revealed by the intermodel standard deviations are found to be significantly smaller than estimated uncertainties stemming from the ship emission inventory, mainly the ship emission totals, the neglect of ship plume dispersion, and the distribution of the emissions over the globe. This reflects that the simulated net change from ship emissions under otherwise relatively clean conditions in global models is rather similar and shows that the atmospheric models used here are suitable tools to study these effects. Full details of this study can be found in Eyring et al. (2006).

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