Brief summary of the impact of ship emissions on atmospheric composition, climate, and human health

Document submitted to the Health and Environment sub-group
of the International Maritime Organization on 6 November 2007

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1. Emissions

Emission of exhaust gases and particles into the marine boundary layer from seagoing ships contribute significantly to the total emissions from the transportation sector (*Corbett and Fischbeck*, 1997; *Eyring et al.*, 2005a, see Figure 1). Key compounds emitted from international shipping are carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), black carbon (BC) and particulate organic matter (POM). Emissions of NO_x and other ozone precursors from shipping lead to tropospheric ozone (O_3) formation and perturb hydroxyl radical (OH) concentrations, and hence the lifetime of methane[1] (CH_4). The dominant aerosol component resulting from ship emissions is sulphate (SO_4), which is formed by the oxidation of SO_2.

Recent studies reveal converging estimates of current ship emissions and suggest that ocean-going ships consumed around 280 million metric tons (Mt)[2] per year of fuel and emitted around 800 Tg CO_2, contributing around 2.7% to all anthropogenic CO_2 emissions in 2000 (*Eyring et al.*, 2005a; *Corbett and Köhler*, 2003). Given uncertainties in all emission inventories, these figures should be considered our best estimates for the base year 2000 within a bounded range of 600 to 900 Tg of CO_2 (*Corbett and Köhler*, 2003). We conclude that CO_2 emissions from shipping are of the same order as CO_2 estimates for aviation (see Figure 1). NO_x emissions from shipping are relatively high because most marine engines operate at high temperatures and pressures without effective reduction technologies. SO_2 emissions are high because of the high average sulphur content (2.4%-2.7%) of marine fuels used by most ocean-going ships. Importantly, future scenarios demonstrate that significant reductions in specific emissions are needed to offset increased emissions due to the predicted growth in seaborne trade (*Eyring et al.*, 2005b).

However, global emission totals from different transport modes describe only part of the picture from perspectives of both global impacts and 'traffic efficiency'. From the 'impacts' point of view with regard to CO_2, the history of emissions is critical, as is demonstrated below, since CO_2 has a long lifetime in the atmosphere. Related passenger and freight volumes transported also need to be taken into account. For instance, marine shipping currently transports more than 90% of the global freight volume in terms of tonne km. In this regard, the ability of shipping to move cargo globally while mitigating growth in emissions

[1] Methane is a greenhouse gas, principally emitted by other sectors (agriculture, mining etc.)
[2] 1 million metric tons = 1 Mt = 1 Tg = 10^{12} g

may be improved, and waterborne commerce may be less energy-intensive per unit of cargo than other transport modes.

In addition, while the geospatial distribution of CO_2 emissions is not as important, the same cannot be said for other pollutants. Ship emissions occur along heavily transited trade routes connecting the network of world ports. Multiple studies and independent representations of shipping routes show that some 70% or more of emissions by international ships occurs within 400 km of land (*Corbett et al.*, 1999; *Endresen et al.*, 2003; *Eyring et al.*, 2005a). Modelling and measurements of shipping emissions and their fate over the last two decades confirm that they may be transported hundreds of kilometres inland (*Benkovitz et al.*, 1994; *Eyring et al.*, 2007; *Corbett et al.*, 2007). The long range transport of ship emissions motivated the Task Force on Hemispheric Transport of Air Pollution (TF HTAP) working under the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) to include ship emissions among sources relevant for the intercontinental transport of air pollution. Importantly, while the geographical distributions of ship emissions varies with the choice of ICOADS[3] or AMVER[4] (*Wang et al.*, 2007a), the net exposure in coastal regions, where the potential impact on human health is highest, is similar (*Corbett et al.*, 2007).

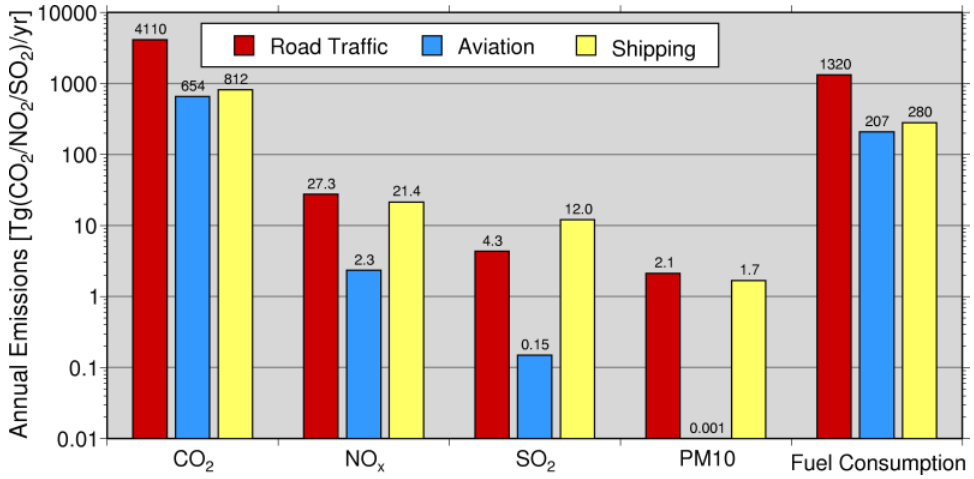

Figure 1. Transport-related annual emissions of CO_2, NO_x, SO_2 and PM_{10} and the fuel consumption in Tg (1 Tg = 1 × 10^{12} g = Mt) estimated for the year 2000. Modified from Figure 3 of *Eyring et al.* (2005a).

2. Impacts

2.1 Evidence of Shipping Impacts

Evidence for the importance of large-scale NO_x enhancements due to international shipping comes from satellite observations from SCIAMACHY[5] aboard the European research satellite ENVISAT that show enhanced tropospheric NO_2 concentrations along the major international shipping routes in the Red Sea and over the Indian Ocean (*Richter et al.*, 2004; see Figure 2). Model simulations show future increases in NO_x and ozone burden which scale almost linearly with increases in NO_x emission totals, i.e. a doubling of NO_x emissions will result in approximately a doubling of global tropospheric ozone attributable to shipping. In addition, increasing emissions from shipping would significantly counteract the benefits derived from

[3] International Comprehensive Ocean-Atmosphere Data Set
[4] Automated Mutual-assistance Vessel Rescue system
[5] The SCanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY

reducing SO_2 emissions from all other anthropogenic sources over the continents, for example in Europe (*Eyring et al.*, 2007).

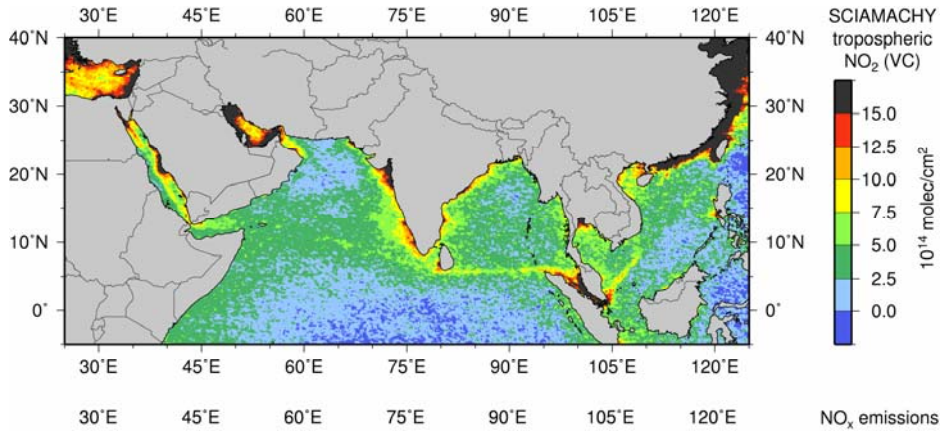

Figure 2: NO_x signature of shipping in the Indian Ocean. Tropospheric NO_2 columns derived from SCIAMACHY data from August 2002 to April 2004 (from *Richter et al.*, 2004).

2.2 Local to regional-scale effects: human health and acidification

At a local and regional-scale, ocean-going ships impact human health through the formation and transport of ground-level ozone, sulphur emissions and particulate matter (*Corbett et al.*, 2007). In harbour cities, ship emissions are in many cases a dominant source of urban pollution. Furthermore, emissions of NO_x, CO, VOCs, particles and sulphur (and their derivative species) from ships may be transported in the atmosphere over several hundreds of kilometres, and thus can contribute to air quality problems on land, even if they are emitted at sea (*Eyring et al.*, 2007). This pathway is especially relevant for deposition of sulphur and nitrogen compounds, which cause acidification / eutrophication of natural ecosystems and freshwater bodies and threaten biodiversity through excessive nitrogen input. Therefore, control of NO_x, SO_2 and particle emissions will have beneficial impacts on air quality, acidification and eutrophication.

In recent work, *Corbett et al.* (2007) demonstrated that PM emissions from ocean-going ships could cause approximately 60,000 premature mortalities annually from cardiopulmonary disease and lung cancer. This value is expected to increase by 40% by 2012. In addition, this mortality estimate does not account for additional health impacts such as respiratory illnesses like bronchitis, asthma, and pneumonia. These health impacts are particularly concentrated in areas of Southeast Asia and Europe.

From this new research, policymakers can now begin to assess the costs and benefits associated with alternative policy mechanisms to control ship emissions. Other research recently published explores the cost-effectiveness of such mechanisms for a 'Sulfur Emissions Control Area' (SECA) along the U.S. West Coast (*Wang and Corbett*, 2007; *Wang et al.*, 2007b). The aforementioned research indicates that regional approaches to controlling emissions from ships can be as cost-effective as land-side controls, particularly if flexible market-based policy instruments (such as regional emissions credits trading regimes) are employed. Integrating these regional control policies into a multi-pollutant and international regulatory regime will be a key challenge facing policymakers in the coming years.

2.3 Effects on global climate

In addition, shipping has impacts on climate principally through its emissions of CO_2, NO_x, SO_2 and particles which may affect cloudiness (*Lauer et al.*, 2007; *Lee et al.*, 2007). The

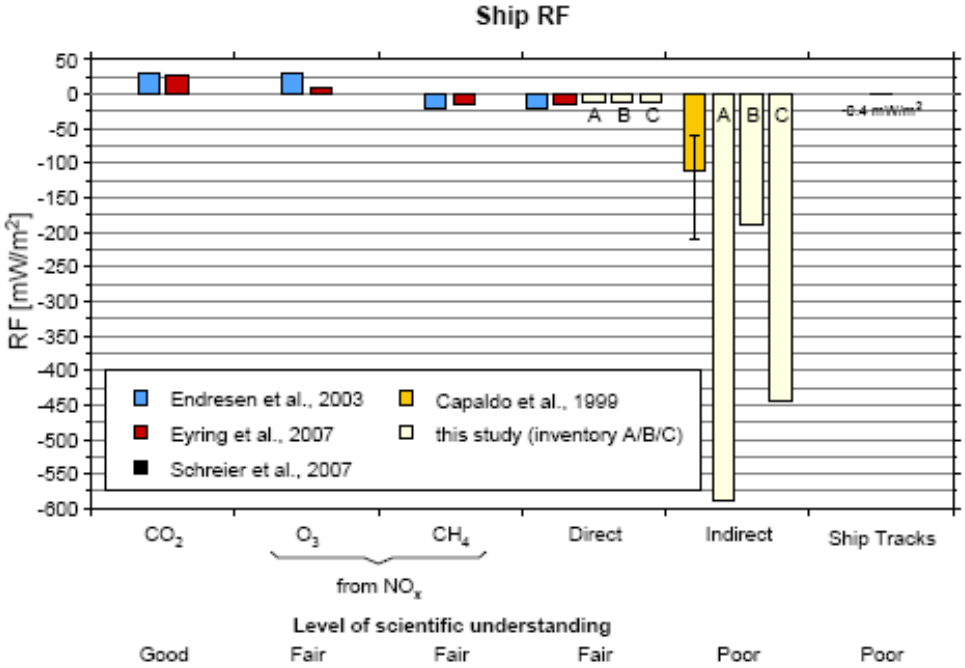

Figure 3. Annual mean radiative forcing (RF) due to emissions from international shipping in mW/m^2. Values for CO_2, O_3, CH_4, and sulfate (direct aerosol effect) are taken from different modeling studies. The indirect aerosol effect displayed with the orange bar includes the first indirect effect of sulfate aerosols only. The error bar depicts the range spanned by additional sensitivity studies. The estimated direct and indirect aerosol effect calculated for various emission inventories (yellow bars A, B, and C) also includes changes due to black carbon, particulate organic matter, ammonium, nitrate, and H_2O from shipping in addition to sulfate and refers to the changes in all-sky shortwave radiation fluxes and net cloud forcing at the top of the atmosphere (from *Lauer et al.* (2007).

Intergovernmental Panel on Climate Change (IPCC) also recently assessed some aspects of shipping emissions on climate (*Forster et al.*, 2007) and potential future mitigation options (*Kahn-Ribiero et al.*, 2007). A common metric to quantify climate impacts from different sources is 'Radiative Forcing[6]' (RF) in units of W/m^2, since there is an approximately linear relationship between global mean radiative forcing and change in global mean surface temperature. A positive RF implies warming whereas negative RF implies cooling to present-day climate. For some of the compounds (CO_2, O_3 and BC) the RF due to shipping is positive whilst for others the forcing is negative (direct effect of sulphate particles, reduced methane from NO_x emissions). The particles can also have an indirect effect on climate through their ability to act as cloud condensation nuclei (CCN) or by changing the optical properties of the clouds that makes them more reflective (a cooling effect). *Lauer et al.* (2007) showed a high impact of gaseous and particulate emissions from ocean-going ships on maritime clouds. The additional aerosol particles brighten the clouds above the oceans, which then are able to reflect more sunlight back into space. Although the uncertainties associated with this study are still high (see results for inventories A, B, and C in Figure 3), the model results clearly indicate that the cooling due to altered clouds far outweighs the warming effects from greenhouse gases such as carbon dioxide (CO_2) or ozone from shipping, overall causing a negative radiative forcing today. The indirect aerosol effect of ships on climate is found to be far larger than previously estimated contributing up to 39% to the total indirect effect of anthropogenic aerosols. This contribution is high because ship emissions are released in

[6] Radiative forcing refers to the change in the earth-atmosphere energy balance since the pre-industrial period. If the atmosphere is subject to a positive radiative forcing from, for example, the addition of a greenhouse gas such as CO_2, the atmosphere attempts to re-establish a radiative equilibrium, resulting in a warming of the atmosphere.

regions with frequent low marine clouds in an otherwise clean environment and the potential impact of particulate matter on the radiation budget is larger over the dark ocean surface than over polluted regions over land.

However, an overall global mean negative RF does not imply that it is benign or good for climate, cancelling its warming effects from CO_2. This is because the RF metric is a global mean and CO_2 is a long-lived species for which a global mean response is appropriate. Sulphate negative forcing, however, is regional and exhibits a highly heterogeneous pattern of forcing that cannot necessarily be said to cancel with a homogeneous positive forcing in terms of climate impacts (e.g. changes in surface temperature, precipitation patterns and circulation).

3. Conclusions

We conclude that efforts to reduce CO_2 and other pollutants from ships should be strongly considered in light of the recent research that has identified: (1) the long-range fate and transport of these pollutants; (2) the impact of these pollutants on human health and climate; and (3) the cost-effectiveness of reducing such pollutants in the context of alternative reduction options.

With respect to local pollutants such as particulate matter and sulphur emissions, mounting evidence shows that the benefits of emissions reductions of these pollutants outweigh the costs of control for many regions of the globe. Policy action to reduce ship emissions is no longer in question, although the choice among a diverse set of policy strategies to achieve needed reduction targets may not be simple. Policymakers need to consider issues such as technological feasibility, economic efficiency, and total fuel cycle tradeoffs (*Winebrake et al.*, 2007; *Corbett and Winebrake*, 2007). However, these considerations will help determine the appropriate and necessary policy response paths given the evidence that action is needed. While more research is needed to better understand regional environmental and economic impacts of such reductions, we believe that these can be pursued along with climate-scale strategies for CO_2 and greenhouse gases. The integration of science-based and policy-focused research continues to provide important insight and context to the policy dialogue that IMO needs to engage with.

As new research has indicated, reductions in sulphur emissions could result in regional reductions in its resultant negative radiative forcing. The climatic trade-off between positive and negative radiative forcing is still a topic of scientific research, but from what is currently known, a simple cancellation of global means is potentially inappropriate and a more comprehensive assessment metric is required. We emphasize, however, that CO_2 remains in the atmosphere for a long-time and will continue to have a warming effect long after its emission. In contrast, sulphate has a residence time in the atmosphere of approximately 10 days, and the climate response from sulphate is of the order decades whilst that of CO_2 is of the order of centuries. While the control of NO_x, SO_2 and particle emissions from ships will have beneficial impacts on air quality, acidification and eutrophication, CO_2 reductions from all sources, including ships and other freight modes, are urgently required to reduce global warming.

The European Assessment of Transport Impacts on Climate Change and Ozone Depletion will provide an up-to-date assessment of the impact of shipping on atmospheric composition and climate (ATTICA, see http://www.pa.op.dlr.de/attica/). This assessment and other ongoing research efforts will continue to inform policymakers and will help to further implementation of needed emission reduction and mitigation strategies.

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