Ship Plumes: Impacts on atmospheric chemistry, climate and nutrient supply to the oceans

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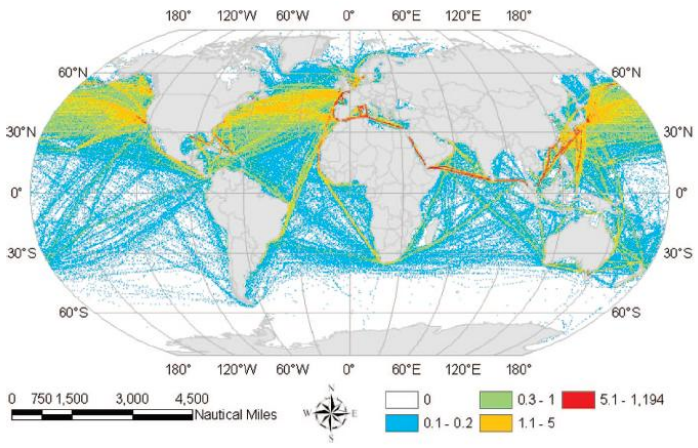
1. Background and significance

a) Significance

Emissions of gases and particles from ocean-going ships may have a major impact on both photochemistry of the marine boundary layer and the biogeochemistry of the surface ocean. Throughout large regions of the ocean, ship emissions of SO_2 and sulfate aerosols greatly exceed the natural DMS-borne sulfur emissions. Ship emissions must, therefore, be taken into account in estimates of global climate forcing by sulfate aerosols (Activity 1.3 of the SOLAS Science and Implementation Plan). Ship emissions are also a significant source of atmospheric nitrogen, and the deposition of this nitrogen into marine ecosystems might affect marine productivity (Activity 1.5). Finally, ship emissions of gaseous hydrocarbons and carbonaceous aerosol particles may impact both gas phase photochemistry and aerosol radiative properties over the oceans. The effects of ship emissions on atmospheric photochemistry include the production of ozone in regions that are usually sinks for ozone and the pollution-induced release of reactive chlorine from sea salt (Activity 1.2). The photochemical and radiative impacts of ship emissions may persist considerably longer than the lifetime of the ship plume itself.

Ship traffic has increased significantly in recent years and is projected to keep increasing. In the Arctic Ocean, which is a particularly sensitive region, new routes are becoming available for international shipping due to decreasing sea ice cover in summer. Open ocean ship emissions are currently largely unregulated and shipping often relies on very dirty fuels that cannot be used for land-based transport.



Current (2000-2002) global ship traffic as a fraction of global traffic per cell; from Wang et al. (2008); see this publication for details.

b) Background information stated in the SOLAS Science Plan and Implementation Strategy

The issue of ship plumes and their significance was not anticipated in the SOLAS Science Plan but several of the associated issues relate directly to a number of Activities in Focus 1 (see above).

2. Questions to be addressed

(1) How large are ship emissions and where are they located?

In the last decade, several groups have used different approaches ("top-down" and "bottom-up"; e.g. Corbett and Fischbeck, 1997, Corbett et al., 1999, Eyring et al., 2005a.b, Wang et al., 2008) to estimate current and future emissions from shipping. The estimates still show quite large differences, however.

(2) How can sub-grid-scale ship plumes be parameterized in numerical models?

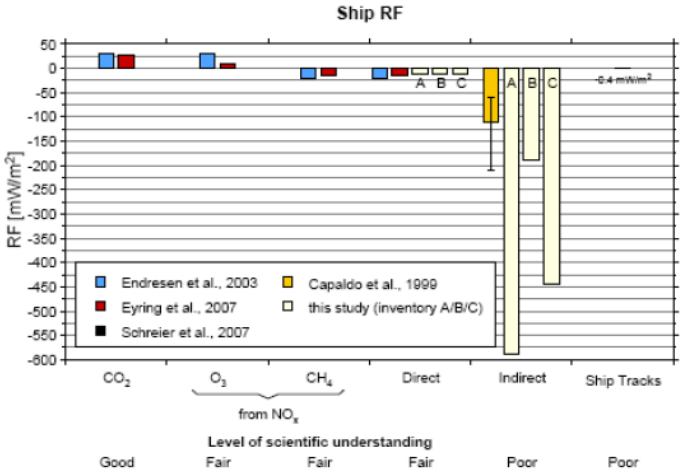
For most numerical models, ship plumes are sub-grid scale (i.e. smaller than the size of grid boxes, e.g. Eyring et al., 2007). Because many related processes, especially the photochemical ones, are non-linear, one cannot simply assume that emissions are homogeneously distributed within a grid box. This problem was recognized early on (e.g. Kashibatla et al., 2000, von Glasow et al., 2003) but remains to be solved and is critical for reliable model estimates of the effects of ship plumes. A first study in this regard was done by Franke et al. (2008).

(3) What are the regional and global quantitative impacts of ship emissions on atmospheric photochemistry?

A detailed assessment of the effects will require focused field campaigns, long term monitoring at coastal or island stations and satellite-based studies in collaboration with a hierarchy of numerical models.

(4) What are the regional and global impacts of ship emissions on climate forcing?

In many ocean regions, sulfur emissions from ships exceed those from biogenic sources (largely DMS) and have therefore to be considered in studies of the indirect aerosol effects. Black carbon emitted from ships may also have radiative impacts that have yet to be determined and quantified.



Radiative forcing due to ship emissions (Lauer et al, 2007).

(5) Does nitrogen deposition due to ship emissions impact ocean biogeochemistry?

In a recent paper it was estimated that anthropogenic emissions are responsible for about a third of the nitrogen input to the open ocean (Duce et al., 2008). Since this estimate did not include deposition due to emissions from ships, it most likely is an underestimate. The ship-related N inputs would not only follow the atmospheric transport pathways away from continents but would be focused along major shipping routes.

3. What needs to be done to address the questions?

Please describe field experiments, lab work, models, sampling strategy… (500 words)

Question 1: SOLAS should organize and sponsor a workshop that brings together the scientists that have made emissions inventories for ships. The workshop should identify shortcomings in the estimates and design further studies to reduce the uncertainties. The inventory studies should build on existing and new measurements of ship emissions both in ports and under typical cruise loads. Involvement of experts from the international shipping industry would be beneficial.

Question 2: Two alternative approaches to addressing this question are: a) use of theoretical approaches to derive a way to treat sub-grid scale emissions from first principles; or b) perhaps more realistically, use detailed, high-resolution local/regional 3D models to resolve plumes and plume effects explicitly. From these models, parameterizations can be derived and the effects of non-linearities assessed so that plume effects can be studied with coarser models on larger (e.g. global) scales. Importantly these parameterizations have to be validated with field observations. This work should be conducted by individual research groups.

Question 3: Several successful large-scale experiments to investigate the microphysical effects of ship emissions (indirect aerosol effects) have been conducted, either as dedicated campaigns (e.g. MAST campaign 1994, Durkee et al., 2000) or as part of other campaigns (e.g., ITCT2k2). A similar combination of aircraft, possibly involving airships, and ships, would yield detailed process understanding of chemical effects in ship plumes which have so far not been studied to the same extent as microphysical and radiative effects of ship plumes.

An appropriate experiment would include Lagrangian tracking of ship plume evolution by steaming against the course of a ship whose plume is to be studied. This will allow the plume from an individual ship to be sampled / studied along a gradient of increasing plume age in "quick motion". Use of an airship or a least tethered sonde from the research vessel would allow the dilution and physical and chemical effects of ship plumes to be probed in the vertical as well as a function of plume age in the horizontal dimension. In contrast, airplane measurements would require very high frequency sampling to achieve this.

Time series studies should be done from coastal and island stations that are regularly impacted by ship plumes, in conjunction with satellite studies (Beirle et al., 2004, Richter et al., 2005). Use of instruments (e.g., CO, NO_x) on ships of opportunity, and analysis of existing data sets with this question in mind, would provide an opportunity to provide inexpensive datasets with a large global and temporal coverage.

Combining these field campaigns and approaches with numerical model and satellite studies would allow assessment of the global impacts of ship emissions in a much more quantitative way than is currently possible.. Numerical models should be developed in the context of such campaigns in order to: 1) improve process understanding, 2) upscale campaign results to regional and global scales, and 3) provide a basis for investigating future and past scenarios.
Such a combination of experiments and modeling will require significant focusing of resources and research teams and would benefit from SOLAS coordination at the international level.

Question 4: Non-linearities in ship plumes are less critical for the assessment of the climate impact of ship emissions, so that good emissions inventories (see (1)) are probably sufficient to produce improved studies of the climate effect of ship plumes in conjunction with state-of-the-art aerosol models. Current estimates of indirect aerosol effects have large uncertainties but could be improved as part of this project by measurements of CCN/CN ratios and integrative cloud properties (effective radius, LWP, ..) within and outside of ship plumes and as the plume is processed downwind. This work can be done by individual research groups but larger field campaigns should be coordinated.

Question 5: A first estimate of the ship-derived input into the oceans could be based on ship emissions estimates used in conjunction with numerical models of

transport and deposition. Long time-series data, from sites like BATS or Station Papa, could be explored in this context as well. Data from previous and current cruises could be re-analyzed to investigate whether distinct features wrt nutrients can found within and outside of major shipping routes. Information on the chemical forms of nitrogen deposited and its bioavailability may need to be collected. Combining this information with models of the oceanic biogeochemical response would allow an estimate of the impact on the oceans. Initial estimates can be made by individual research groups but there may be a need for community involvement in order to investigate effects.

4. What is planned, possible and missing?

Several of the suggested activities can be performed by single research groups. However a focused field experiment would require the coordination of many groups working on research vessel(s) with potential support by airborne platforms (aircraft, air ships, UAVs).

There are several ongoing research projects which touch on elements of this issue, but there appears to be no concerted research program in this area. The "EU FP6 ATTICA, WP2: European Assessment of Transport Impacts on Climate Change and Ozone Depletion – Shipping" had a much more narrow focus.

At this stage an internationally coordinated program that acts as an umbrella for conducting the range of studies mentioned in this document would be very beneficial and lead to significant advances. SOLAS could lead such a program.

5. Needed co-ordination and planning tasks

This field got started with the publication of the first global emissions inventory by Corbett and Fishbeck (1997) and Corbett et al. (1999). There have been a number of field, model and satellite studies as well as updated emissions inventories. An internationally coordinated research program is still missing, so that workshops that aim at bringing the community together, potentially together with other IGBP programs like IGAC, should be the first step.

Workshops
A series of workshops would form the basis for research initiation and coordination. Initially, 3-4 workshops covering the following topics could be considered:

- Community involvement: bring together researchers working on this topic; link with ongoing smaller and larger projects that we are unaware of a this stage
- Address and update emissions inventory
- Field campaign planning (where, what platforms)
- Model intercomparison/development workshop

6. Prospect for answering the questions

An overall timeframe of 5 years is assumed.

Question 1: This question has been studied for more than 10 years and significant progress has been made. In an area like this a fair degree of uncertainties will remain but an improved global inventory is likely to be achieved within 5 years.

Question 2: So far only one study has been published tackling this question and it could provide a good, however case-dependent, answer. Again within 5 years one could expect important improvements in this regard.

Question 3: This question probably requires the largest community involvement and with the help of several small and one or two large field campaigns, accompanied by satellite and models studies again a 5-year timeframe sounds realistic to make important advances.

Question 5: This question is largely dependent on the outcome of question (1) but improved estimates should be available within a few years.

Question 6: An initial assessment of the input of ship-related nitrogen into the ocean should be straight forward. The impacts could be investigated with ocean biogeochemical models within a few years and existing data sets from long-term monitoring stations could also be investigated within this time frame.

Appendix: References

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