MIT Joint Program on the Science and Policy of Global Change

Impact of Sulfur and Carbonaceous Emissions from International Shipping on Aerosol Distributions and Direct Radiative Forcing

Chien Wang and Dongchul Kim

Report No. 159
April 2008

The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

Henry D. Jacoby and Ronald G. Prinn,
Program Co-Directors

For more information, please contact the Joint Program Office

Postal Address: Joint Program on the Science and Policy of Global Change
77 Massachusetts Avenue
MIT E40-428
Cambridge MA 02139-4307 (USA)

Location: One Amherst Street, Cambridge
Building E40, Room 428
Massachusetts Institute of Technology

Access: Phone: (617) 253-7492
Fax: (617) 253-9845
E-mail: globalchange@mit.edu
Web site: http://mit.edu/globalchange/

Printed on recycled paper

Impact of Sulfur and Carbonaceous Emissions from International Shipping on Aerosol Distributions and Direct Radiative Forcing

Chien Wang* and Dongchul Kim*

Abstract

We describe in this report an effort using the MIT/NCAR three-dimensional aerosol-climate model to study the impact of ship emissions on chemical composition and radiative forcing of aerosols. Our results indicate that international shipping can be a non-negligible factor in determining the radiative forcing of aerosols over specific regions with intensive ship activities. These places include the European, eastern Asian, and American coastal regions. The global mean aerosol radiative forcing caused by the ship emissions ranges from -12.5 to -23 mW/m^2, depending on whether the mixing between black carbon and sulfate is included in the model. However, over the aforementioned places, the radiative forcing resulting from ship emissions can be much more important in the total regional aerosol forcing.

Contents

1. INTRODUCTION

International shipping represents a large sector of heavy diesel consumption (~ 200 Mt of bunker fuel in 2000; L. Post, personal communication, 2007; Endersen *et al*., 2007). The ships thus emit a considerable amount of pollutants including particulate matter and aerosol precursors such as sulfur dioxide. Due to their short lifetime in the atmosphere (~1-2 weeks), aerosols distribute themselves inhomogeneously, with greatest concentrations over Northern Hemispheric lands. Emissions from ships traveling across the open ocean would hence have impacts on the aerosol composition and distribution in otherwise low aerosol regions.

The radiative forcing of aerosols associated with emissions of international shipping has been discussed in recent years (*e.g*., Capaldo *et al*., 1999; Eyring *et al*., 2007; Lauer *et al*., 2007). Various limitations are seen in these previous studies that often used overly simplified models without considering important factors such as aerosol mixing. A better understanding of the impact of ship emissions on radiative forcing and aerosol composition over remote parts of the ocean could improve our modeling capability of global change and also be helpful in making corresponding policies.

We describe in this report an effort using the MIT/NCAR three-dimensional aerosol-climate model to study the impact of ship emissions on chemical composition and radiative forcing of aerosols.

* MIT Joint Program on the Science and Policy of Global Change (E-mail: wangc@mit.edu).
* MIT Joint Program on the Science and Policy of Global Change (E-mail: dckim@mit.edu).

2. MODELS AND EMISSIONS

The model used in this study is an interactive aerosol-climate model developed recently at MIT based on the Community Climate System Model (CCSM) of the National Center for Atmospheric Researches (NCAR). The climate model framework includes an atmospheric model (Community Atmospheric Model version 3, CAM3), a land surface model (Common Land Model version 2, CLM2), and a mixed-layer ocean model (Collins *et al*., 2006). Specifically in this study we have adopted a climatological sea surface temperature dataset derived based on observations instead of the mixed-layer ocean model in the integration.

Coupled with the climate model framework interactively is a size- and chemistry-dependent aerosol model consists of 7 different types of aerosols, namely three types of sulfate (nucleation, Aitken, and accumulation modes), one type each of external black carbon and external organic carbon, and two mixed aerosol types respectively one with a black carbon core and sulfate shell and the other a mix of organic carbon with sulfate. Both mass and number concentrations of each aerosol type (mode) as well as the mass of carbonaceous species in the mixed modes are predicted by the model so that the chemical, physical, and radiative processes of various aerosols can be formulated depending on the aerosol size, chemical composition, and mixing state. The modeled results of aerosol distributions using our model have been previously compared with available observations and a reasonable agreement between them has been demonstrated (Kim *et al*., 2007).

The spatial resolution of the model is 2 and 2.5 degrees respectively in the latitudinal and longitudinal directions. The model has 26 vertical layers distributed in a hybrid coordinate, (*i.e*. a terrain-following sigma coordinate near the surface and a pressure-following one in the upper atmosphere).

The annual emission of sulfur dioxide is derived based on an annual bunker fuel consumption of 200 Mt with a 2.7% sulfur mass ratio, *i.e*., 5.4 TgS/yr (L. Post, CONCAWE, personal communication, 2007; Endersen *et al*., 2007). The annual black carbon ship emission of 0.204 Tg/yr is derived based on the above fuel consumption and an emission efficiency provided by Bond *et al*. (2004). The anthropogenic emissions of SO_2 from sources other than international shipping are 71.4 TgS/yr, augmented by a natural dimethyl sulfide (DMS) emission from the oceans of 19.3 TgS/yr. The total emissions of black carbon from sources other than international shipping are 14.4 Tg/yr. The annual primary emissions of organic carbon are 54.4 Tg/yr. The secondary production of organic carbon is calculated based on biogenic emissions of isoprene and monoterpenes of 629 TgC/yr. Overall, the amount of ship emitted sulfur dioxide and BC accounts respectively for about 6% and 1.4% of the global total sulfur and BC emissions. The annual ship emissions are then mapped into the model grids scaled using the ship travel frequency derived from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) of NOAA (http://icoads.noaa.gov; **Figure 1**). For the major objective of this study, the seasonal change in ship emissions are of secondary importance and thus not considered.

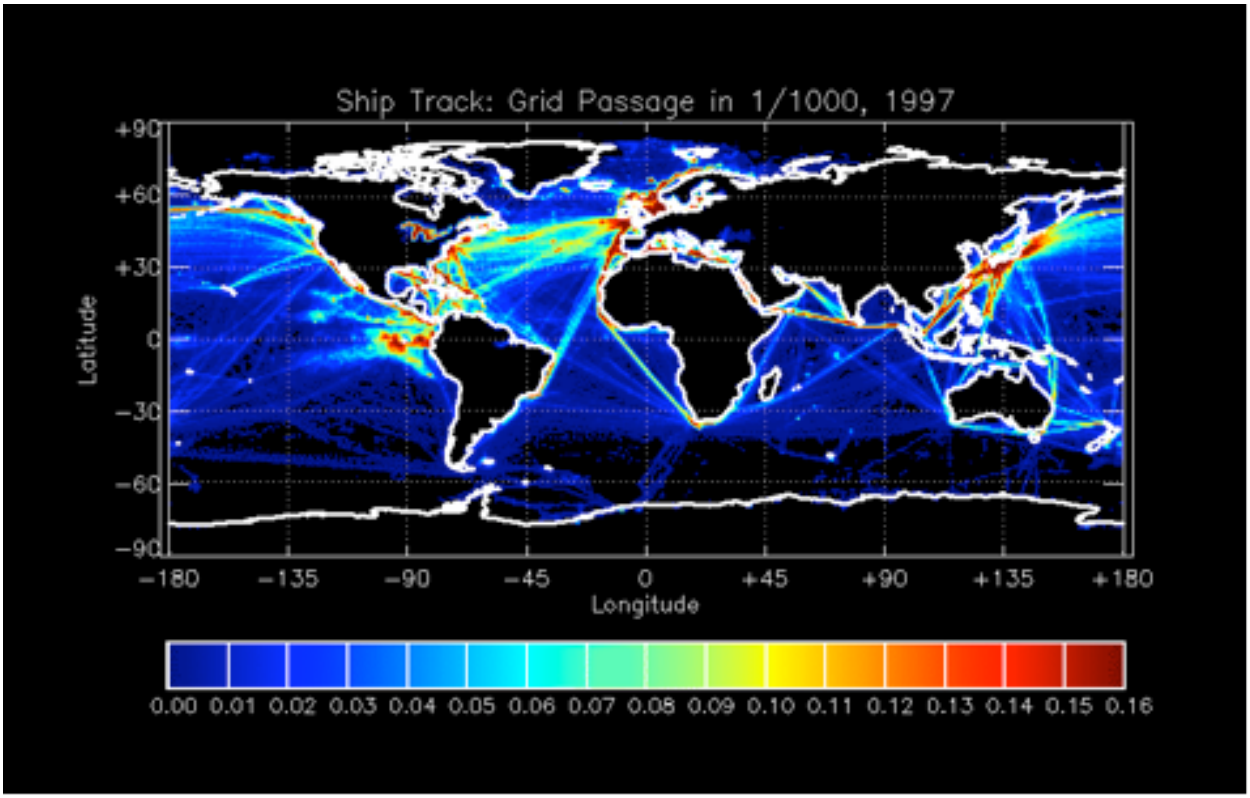

Figure 1. Ship passage frequency normalized by the total passages. Source: NOAA ICOADS, http://icoads.noaa.gov/ (acknowledgement, Tan Qian).

The primary objective of this study is to isolate the influences of ship emissions of sulfur and carbonaceous compound on the global aerosol distribution and direct radiative forcing. The much more complicated indirect forcing is not a priority for this study but important for defining the overall roles of shipping emissions. We have designed 2 sets of numerical experiments using respectively the model version that includes all types of aerosols (hereafter, ALL) and the version that only contains sulfate aerosols (hereafter, SUL). In the former set of experiment, both sulfur dioxide and BC emissions from ships are included while only sulfur emissions from ships are included in the latter set. The latter set is also specifically designed to be able to compare with other previous studies. Each set of experiments has a pair of model runs, (one includes and one excludes the ship emissions, respectively), and the difference between these two runs for the radiative forcing by aerosols hence reflects the effects of the ship-emitted aerosols. The integration time for each of these simulations is three years. The last two-year averages are used in the analyses unless indicated otherwise. To isolate the effect of ship emissions from that of the other sources, the emission rates are set to be time-invariant throughout the simulation.

3. RESULTS

When only sulfate aerosols and ship-emitted sulfur dioxide are considered in the model, the ship emissions cause an additional negative (cooling) forcing to the Earth-atmosphere system, represented by a negative forcing at the top of the atmosphere (TOA) as shown in **Figure 2**. The forcing is largest over the three major regions polluted by shipping activities: East and Southeast Asian coast, eastern Atlantic coast from Europe to North Africa, and North American coast from west Atlantic to east Pacific. Note that the distribution of added radiative forcing by ship emissions extends into North American and Eurasian continents. The globally averaged forcing caused by ship emissions is rather small (-12.5mW/m$^{2)}$ when compared with total sulfate forcing. Over certain regions, the forcing can reach as high as 5% of the total so that the regional effects should not be ignored (**Figure 3**). These results are consistent with other estimations (*e.g.*, -11 to 13 mW/m^2 in Lauer *et al*., 2007).

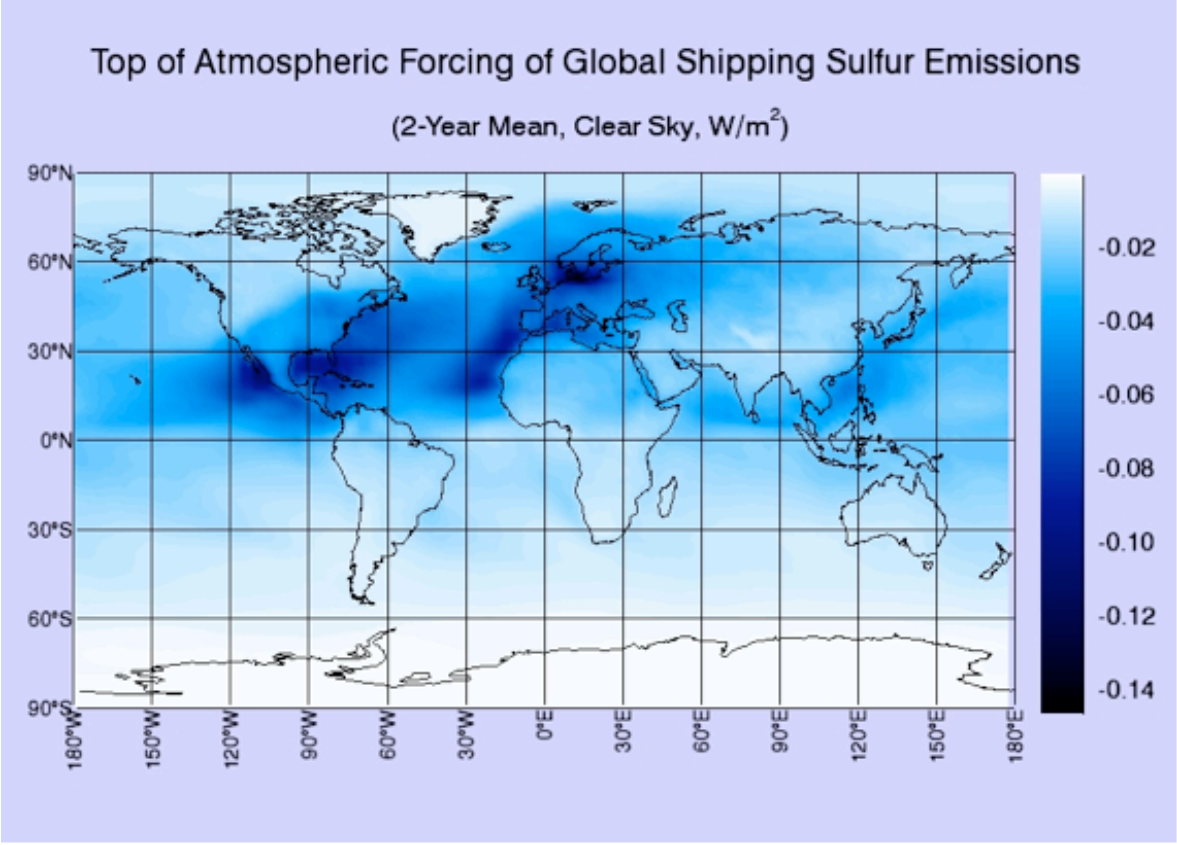

Figure 2. The clear-sky radiative forcing of sulfate aerosols at the top of the atmosphere resulting from global shipping emissions. The results are 2-year means of the SUL set of model runs in W/m^2.

This quantity of cooling caused by ship-emitted sulfate aerosols is usefully compared with the benefit of reduction of CO_2 emissions. Specifically, the radiative forcing of sulfate aerosols obtained in the SUL set of simulations is compared here with targeted reduction of CO_2 concentration in 2012 based on the Kyoto Protocol. The reduction of concentration is estimated

to be 2.45 ppmv, based on the difference between the business-as-usual (BAU) and Kyoto (KYO) scenarios produced by the MIT EPPA and full IGSM models (Reilly *et al*., 1999). The corresponding reduction in radiative forcing due to this CO_2 reduction is 33.2 mW/m^2 and is assumed to be uniformly distributed over the globe due to the obvious extremely long lifetime of CO_2 in the atmosphere. In comparison, the (all-sky) radiative forcing of sulfate aerosols produced from ship emissions in set SUL can be as high as or in some places (*e.g*., North America and eastern coastal regions of Atlantic) a factor of 2 larger than the weakening in radiative forcing due to the targeted CO_2 reduction (**Figure 4**).

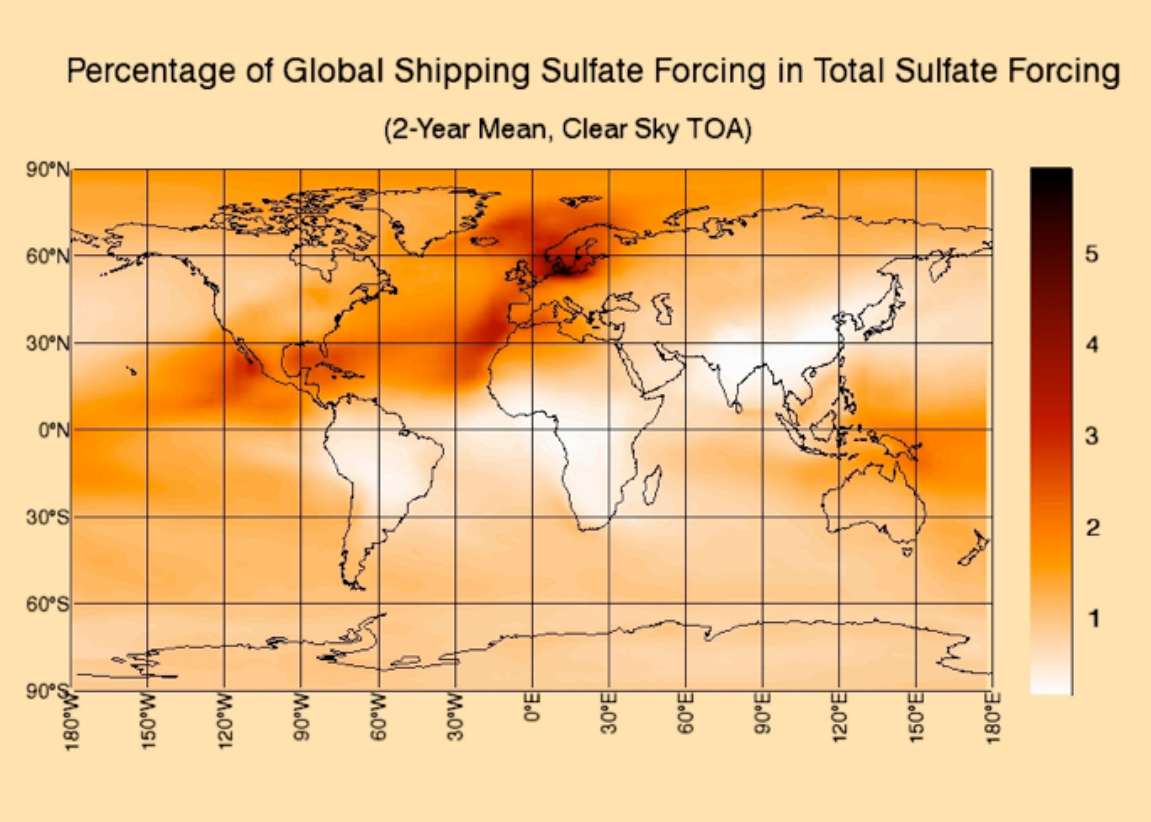

Figure 3. Fraction of radiative forcing of ship-emitted sulfate aerosol in the total sulfate aerosol forcing as percentages. Results are 2-year means of the SUL set of model runs.

To further assess the radiative effects of ship emissions, we include in the ALL set of model runs various carbonaceous and sulfate aerosols along with condensation of sulfuric acid gas on these aerosols and coagulation and mixing among them. Both sulfur and BC emissions are included. The total aerosol forcing resulted from ship emissions at the top of the atmosphere derived using this more complicated aerosol model (**Figure 5**) generally matches the pattern of the results derived using the sulfate only model in the SUL set of simulations (Figure 2). However, the forcing in East Asian coastal regions is relatively higher in comparison. In addition, atmospheric warming is found over several land areas mainly over East Asia and the east coast of North America (represented by the positive forcing values in Figure 5). The global

mean of all-sky forcing resulting from ship emissions derived using the complicated aerosol model is about -23 mW/m2, almost double that of the sulfate-only aerosol model result. This result suggests that the coating of sulfate on the surface of black carbon can change the sign of the aerosol forcing in some cases while enhancing the negative forcing in other cases as revealed also by our previous modeling study (Kim *et al.*, 2007). Further study of this enhancement is recommended.

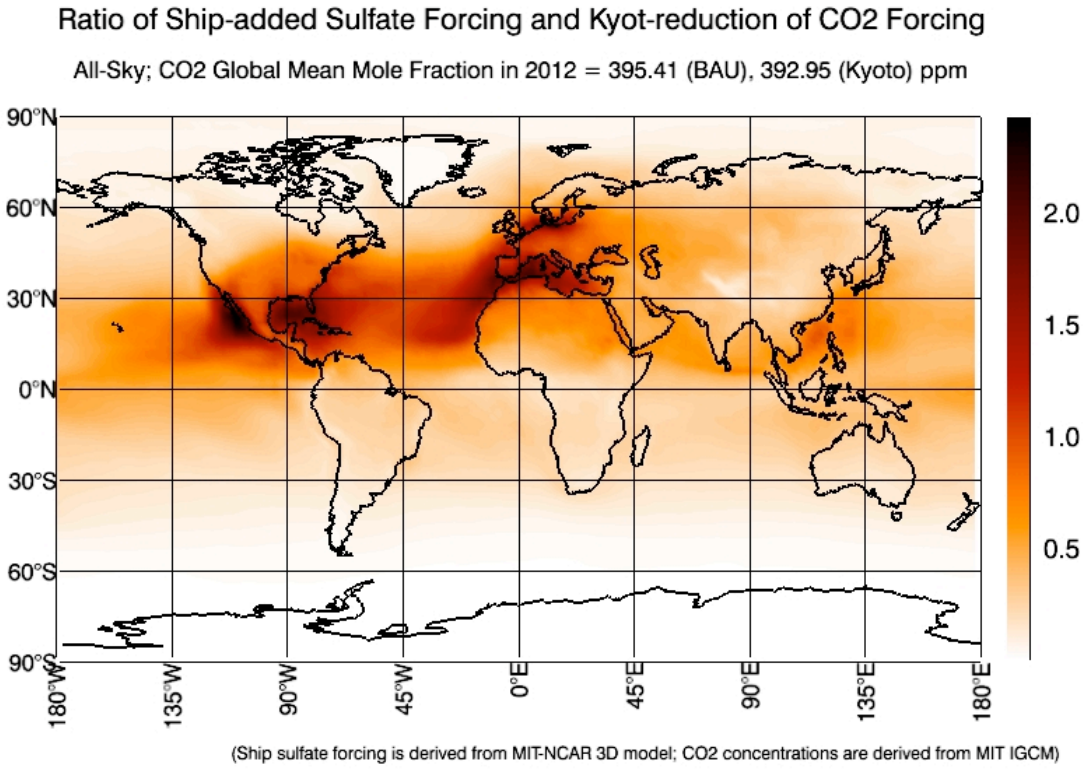

Figure 4. The ratio of ship-emitted sulfate aerosol radiative forcing and the estimated reduction in radiative forcing of CO_2 following the Kyoto Protocol. Note that both forcings are negative in sign. The model results are 2-year means from the SUL set of runs.

4. SUMMARY AND DISCUSSION

Our model results indicate that international shipping can be a non-negligible factor in determining the radiative forcing of aerosols over specific regions with intensive ship activities. These places include the European, eastern Asian, and American coastal regions. The global mean aerosol radiative forcing caused by the ship emissions ranges from -12.5 to -23 mW/m^2, depending on whether the mixing between black carbon and sulfate is included in the model. However, over the aforementioned places, the radiative forcing resulting from ship emissions can be much more important in the total regional aerosol forcing.

Over regions of intensive shipping activities, lowering the ship emissions would lead to a warming effect for the surface and atmosphere that could partially cancel the cooling resulting

from the reduction of CO_2 (without considering the benefit in air quality improvement from lowered ship emissions).

The results of this study are derived without considering the different emission efficiencies among various types of ships. Should the ship emissions be a function of speed, the emissions near the coastal regions would account for a much higher ratio of the global ship emissions and thus the distribution pattern of this emission would be different. Further investigation is necessary to define the radiative effects of ship-emitted aerosols under such an alternative assumption.

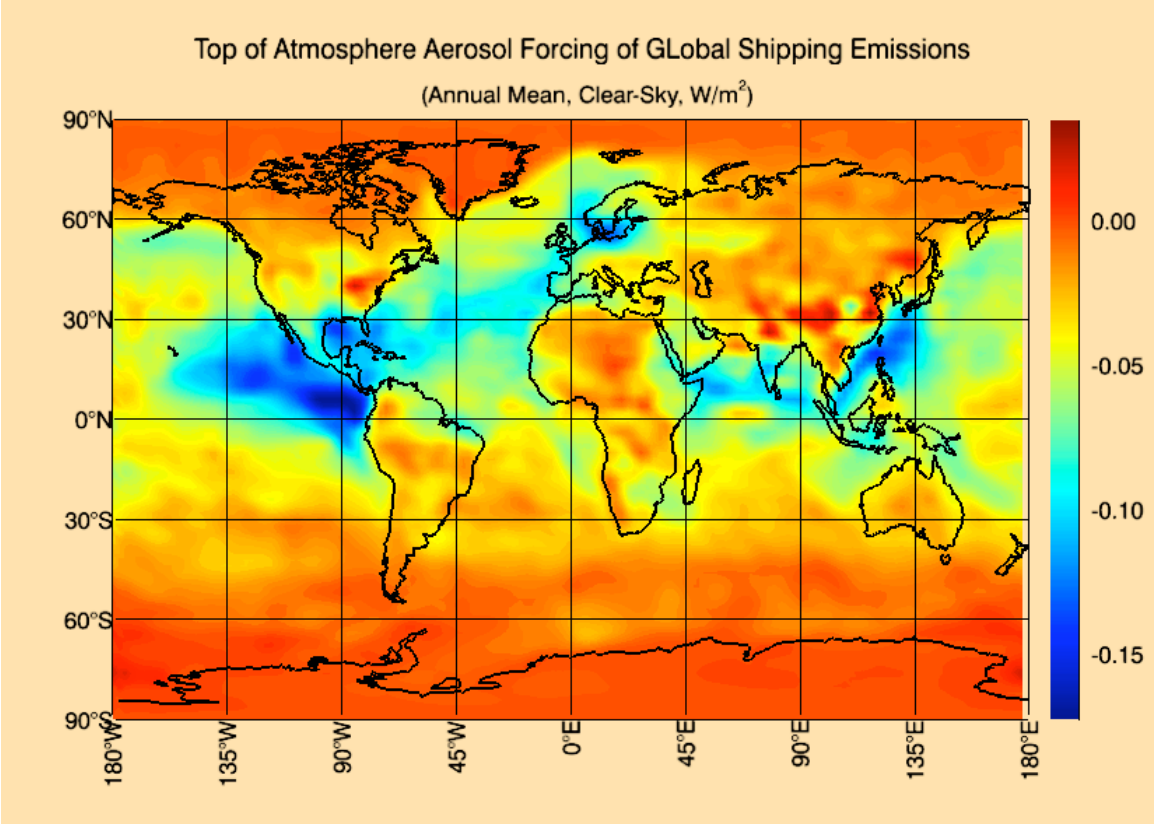

Figure 5. Total additional aerosol forcing resulted from including ship emissions of sulfur dioxide and black carbon. The results are from the ALL set of runs.

Acknowledgments

L. Post (CONCAWE), R. G. Prinn and T. Qian (MIT); NOAA/ESRL/PSD; MIT Joint Program for the Science and Policy of Global Change; NSF (Climate Dynamics and Atmospheric Chemistry); and NASA (IDS and Atmospheric Composition).

5. REFERENCES

Bond, T. C., D. G. Streets, K. F. Yarber, S. M. Nelson, J.-H. Woo, and Z. Klimont, 2004: A technology-based global inventory of black and organic carbon emissions from combustion, *J. Geophys. Res*., **109**, D14203, doi:10.1029/2003JD003697.

Capaldo, K., J. J. Corbett, P. Kasibhatla, P. Fischbeck, and S. N. Pandis, 1999: Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean, *Nature*, **400**, 743-746.

Collins, W., *et al*., 2006: The Community Climate System Model Version 3 (CCSM3), *J. Climate*, **19**, 2122-2143.

Eyring, V., *et al*., 2007: Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030, *Atmos. Chem. Phys*., **7**, 757-780.

Endresen, Ø., E. Sørgard, H. L. Behrens, P. O. Brett, and I. S. A. Isaksen, 2007: A historical reconstruction of ships' fuel consumption and emissions, *J. Geophys. Res*., **112**, D12301, doi:10.1029/2006JD007630.

Kim, D., C. Wang, A.M.L. Ekman, M. C. Barth, and P. Rasch, 2007: Distribution and direct radiative forcing of carbonaceous and sulfate aerosols in an interactive size-resolving aerosol-climate model, *J. Geophys. Res*., in review.

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

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, P. Stone, A. Sokolov, and C. Wang, 1999: Multi-gas assessment of the Kyoto Protocol, *Nature*, **401**, 549-555.

REPORT SERIES of the **MIT** *Joint Program on the Science and Policy of Global Change*

1. **Uncertainty in Climate Change Policy Analysis** *Jacoby & Prinn* December 1994
2. **Description and Validation of the MIT Version of the GISS 2D Model** *Sokolov & Stone* June 1995
3. **Responses of Primary Production and Carbon Storage to Changes in Climate and Atmospheric CO_2 Concentration** *Xiao et al.* October 1995
4. **Application of the Probabilistic Collocation Method for an Uncertainty Analysis** *Webster et al.* January 1996
5. **World Energy Consumption and CO_2 Emissions: 1950-2050** *Schmalensee et al.* April 1996
6. **The MIT Emission Prediction and Policy Analysis (EPPA) Model** *Yang et al.* May 1996 (*superseded by No. 125*)
7. **Integrated Global System Model for Climate Policy Analysis** *Prinn et al.* June 1996 (*superseded by No. 124*)
8. **Relative Roles of Changes in CO_2 and Climate to Equilibrium Responses of Net Primary Production and Carbon Storage** *Xiao et al.* June 1996
9. **CO_2 Emissions Limits:** ***Economic Adjustments and the Distribution of Burdens*** *Jacoby et al.* July 1997
10. **Modeling the Emissions of N_2O and CH_4 from the Terrestrial Biosphere to the Atmosphere** *Liu* Aug. 1996
11. **Global Warming Projections:** ***Sensitivity to Deep Ocean Mixing*** *Sokolov & Stone* September 1996
12. **Net Primary Production of Ecosystems in China and its Equilibrium Responses to Climate Changes** *Xiao et al.* November 1996
13. **Greenhouse Policy Architectures and Institutions** *Schmalensee* November 1996
14. **What Does Stabilizing Greenhouse Gas Concentrations Mean?** *Jacoby et al.* November 1996
15. **Economic Assessment of CO_2 Capture and Disposal** *Eckaus et al.* December 1996
16. **What Drives Deforestation in the Brazilian Amazon?** *Pfaff* December 1996
17. **A Flexible Climate Model For Use In Integrated Assessments** *Sokolov & Stone* March 1997
18. **Transient Climate Change and Potential Croplands of the World in the 21st Century** *Xiao et al.* May 1997
19. **Joint Implementation:** ***Lessons from Title IV's Voluntary Compliance Programs*** *Atkeson* June 1997
20. **Parameterization of Urban Subgrid Scale Processes in Global Atm. Chemistry Models** *Calbo* et al. July 1997
21. **Needed: A Realistic Strategy for Global Warming** *Jacoby, Prinn & Schmalensee* August 1997
22. **Same Science, Differing Policies;** ***The Saga of Global Climate Change*** *Skolnikoff* August 1997
23. **Uncertainty in the Oceanic Heat and Carbon Uptake and their Impact on Climate Projections** *Sokolov et al.* September 1997
24. **A Global Interactive Chemistry and Climate Model** *Wang, Prinn & Sokolov* September 1997
25. **Interactions Among Emissions, Atmospheric Chemistry & Climate Change** *Wang & Prinn* Sept. 1997
26. **Necessary Conditions for Stabilization Agreements** *Yang & Jacoby* October 1997
27. **Annex I Differentiation Proposals:** ***Implications for Welfare, Equity and Policy*** *Reiner & Jacoby* Oct. 1997
28. **Transient Climate Change and Net Ecosystem Production of the Terrestrial Biosphere** *Xiao et al.* November 1997
29. **Analysis of CO_2 Emissions from Fossil Fuel in Korea: 1961–1994** *Choi* November 1997
30. **Uncertainty in Future Carbon Emissions:** ***A Preliminary Exploration*** *Webster* November 1997
31. **Beyond Emissions Paths:** ***Rethinking the Climate Impacts of Emissions Protocols*** *Webster & Reiner* November 1997
32. **Kyoto's Unfinished Business** *Jacoby et al.* June 1998
33. **Economic Development and the Structure of the Demand for Commercial Energy** *Judson et al.* April 1998
34. **Combined Effects of Anthropogenic Emissions and Resultant Climatic Changes on Atmospheric OH** *Wang & Prinn* April 1998
35. **Impact of Emissions, Chemistry, and Climate on Atmospheric Carbon Monoxide** *Wang & Prinn* April 1998
36. **Integrated Global System Model for Climate Policy Assessment:** ***Feedbacks and Sensitivity Studies*** *Prinn et al.* June 1998
37. **Quantifying the Uncertainty in Climate Predictions** *Webster & Sokolov* July 1998
38. **Sequential Climate Decisions Under Uncertainty:** ***An Integrated Framework*** *Valverde et al.* September 1998
39. **Uncertainty in Atmospheric CO_2 (Ocean Carbon Cycle Model Analysis)** *Holian* Oct. 1998 (*superseded by No. 80*)
40. **Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves** *Ellerman & Decaux* Oct. 1998
41. **The Effects on Developing Countries of the Kyoto Protocol and CO_2 Emissions Trading** *Ellerman et al.* November 1998
42. **Obstacles to Global CO_2 Trading:** ***A Familiar Problem*** *Ellerman* November 1998
43. **The Uses and Misuses of Technology Development as a Component of Climate Policy** *Jacoby* November 1998
44. **Primary Aluminum Production:** ***Climate Policy, Emissions and Costs*** *Harnisch et al.* December 1998
45. **Multi-Gas Assessment of the Kyoto Protocol** *Reilly et al.* January 1999
46. **From Science to Policy:** ***The Science-Related Politics of Climate Change Policy in the U.S.*** *Skolnikoff* January 1999
47. **Constraining Uncertainties in Climate Models Using Climate Change Detection Techniques** *Forest et al.* April 1999
48. **Adjusting to Policy Expectations in Climate Change Modeling** *Shackley et al.* May 1999
49. **Toward a Useful Architecture for Climate Change Negotiations** *Jacoby et al.* May 1999
50. **A Study of the Effects of Natural Fertility, Weather and Productive Inputs in Chinese Agriculture** *Eckaus & Tso* July 1999
51. **Japanese Nuclear Power and the Kyoto Agreement** *Babiker, Reilly & Ellerman* August 1999
52. **Interactive Chemistry and Climate Models in Global Change Studies** *Wang & Prinn* September 1999
53. **Developing Country Effects of Kyoto-Type Emissions Restrictions** *Babiker & Jacoby* October 1999

Contact the Joint Program Office to request a copy. The Report Series is distributed at no charge.

Contact the Joint Program Office to request a copy. The Report Series is distributed at no charge.

Contact the Joint Program Office to request a copy. The Report Series is distributed at no charge.