

***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

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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.

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

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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/m², 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.

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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.

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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 SO₂ 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.

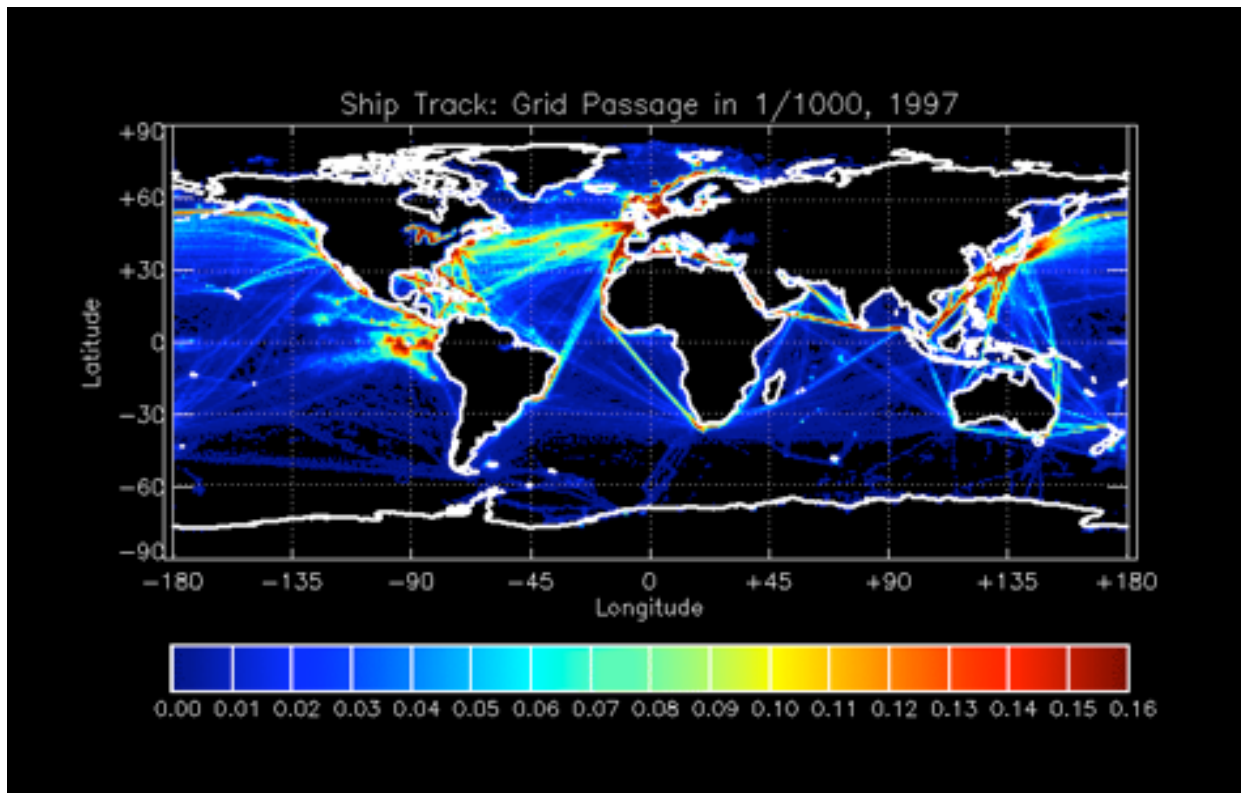


Figure 1. Ship passage frequency normalized by the total passages. Source: NOAA ICOADS, <http://icoads.noaa.gov/> (acknowledgement, Tan Qian).

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).

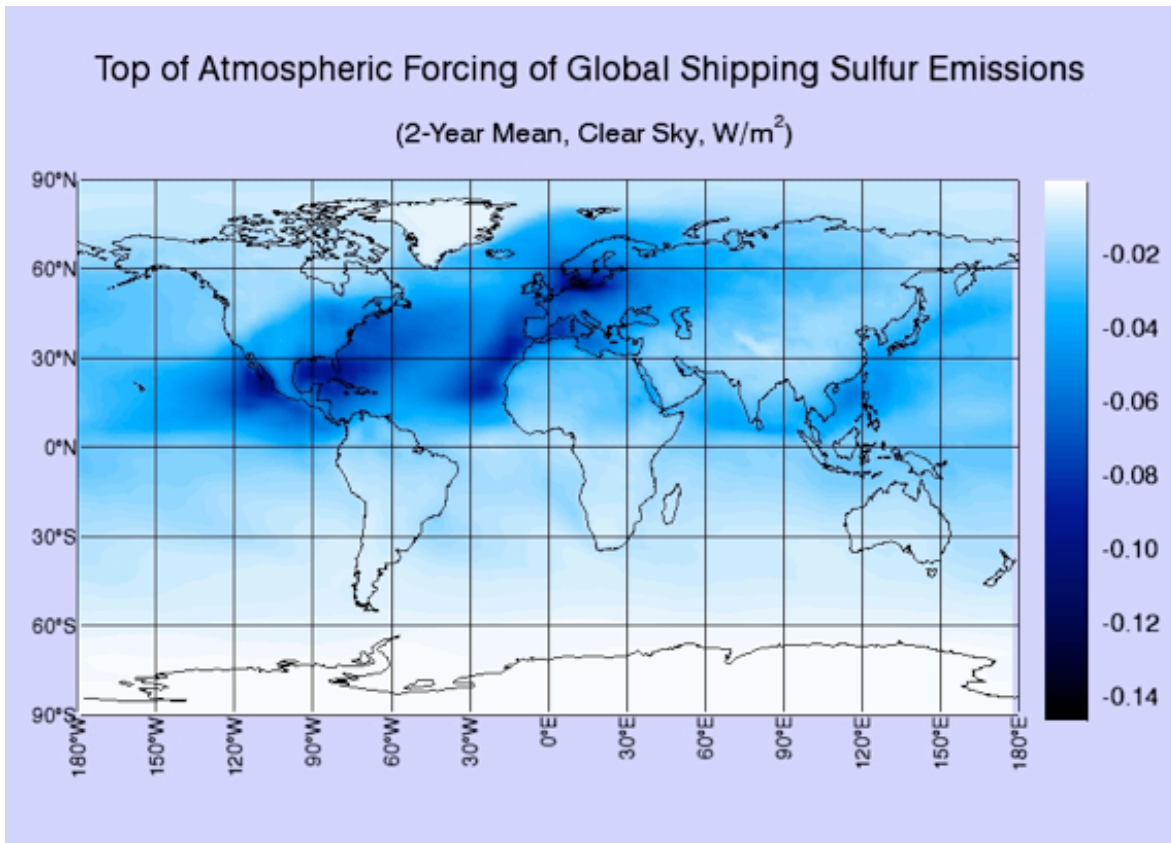


Figure 2. The clear-sky radiative forcing of sulfate aerosols at the top of the atmosphere resulting from global shipping emissions. The results are 2-year means of the SUL set of model runs in W/m^2 .

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 CO₂ reduction is 33.2 mW/m² and is assumed to be uniformly distributed over the globe due to the obvious extremely long lifetime of CO₂ 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 CO₂ reduction (**Figure 4**).

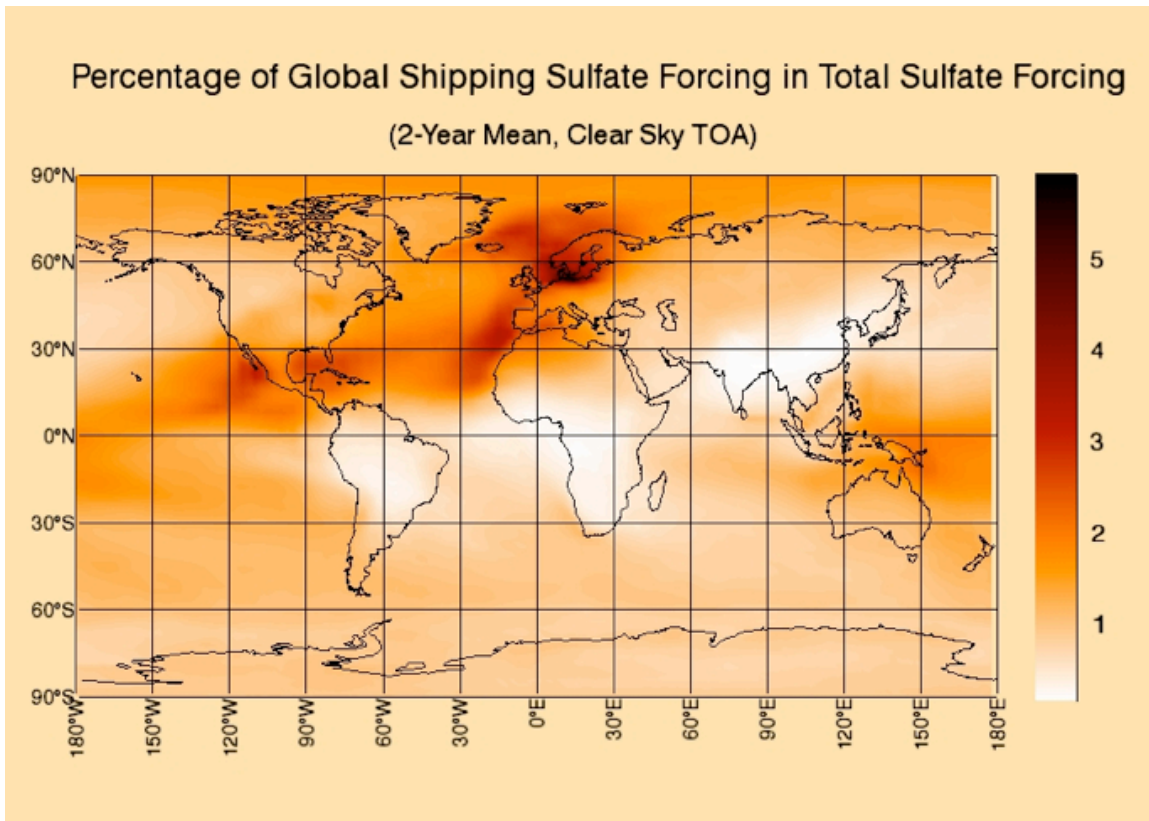


Figure 3. Fraction of radiative forcing of ship-emitted sulfate aerosol in the total sulfate aerosol forcing as percentages. Results are 2-year means of the SUL set of model runs.

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/m^2 , 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.

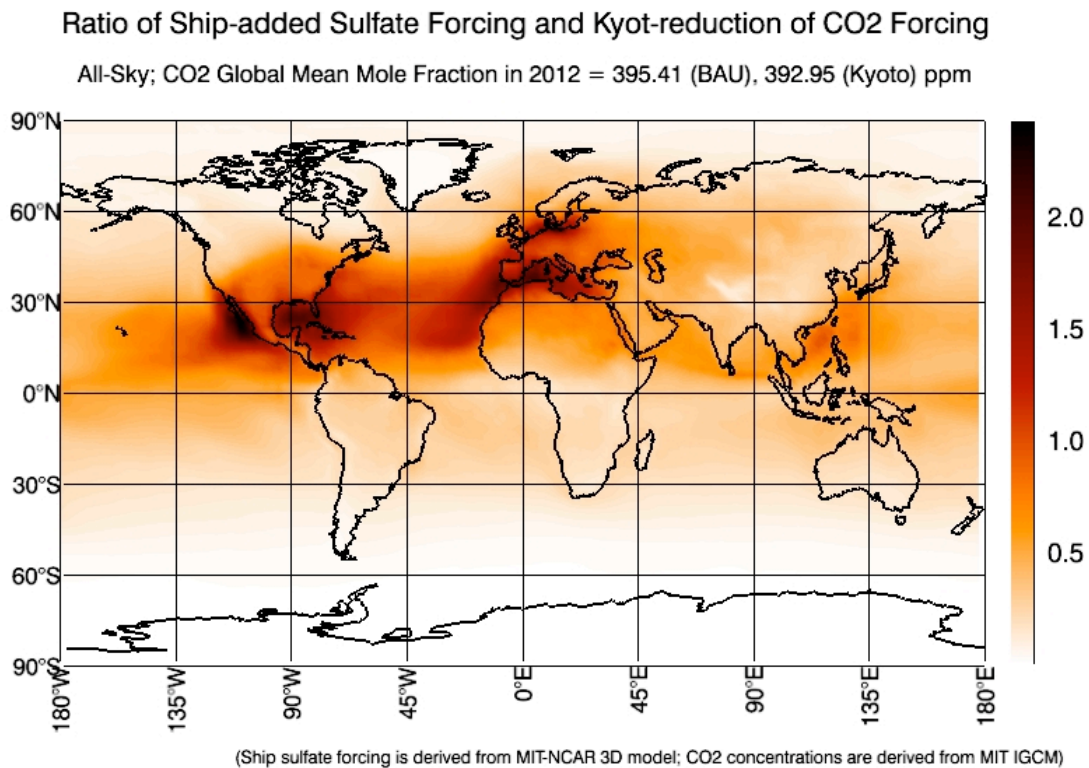


Figure 4. The ratio of ship-emitted sulfate aerosol radiative forcing and the estimated reduction in radiative forcing of CO₂ following the Kyoto Protocol. Note that both forcings are negative in sign. The model results are 2-year means from the SUL set of runs.

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 CO₂ (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.

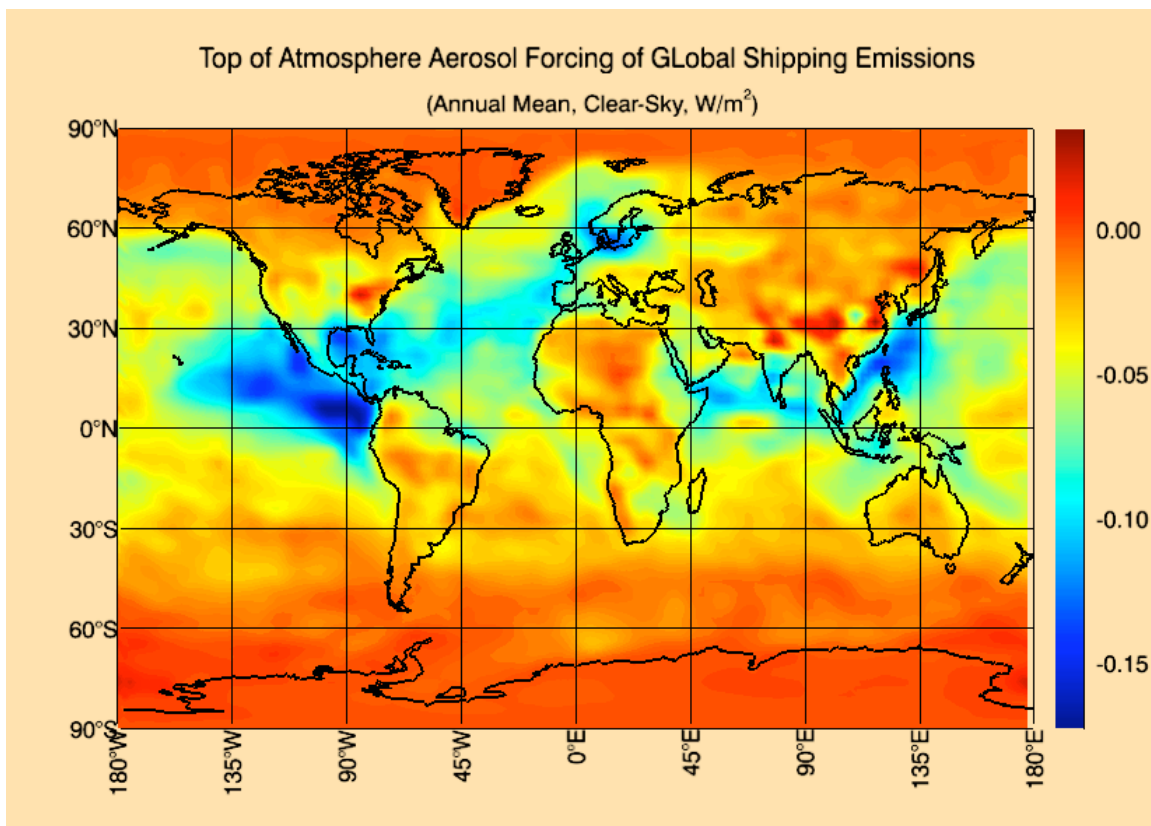


Figure 5. Total additional aerosol forcing resulted from including ship emissions of sulfur dioxide and black carbon. The results are from the ALL set of runs.

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