Climate impacts of particulate pollutants emitted from international shipping

A Concawe study aims to provide a better understanding of the uncertainties relating to the climate impacts of international shipping emissions.

International shipping represents a large sector for heavy fuel oil consumption. Ocean-going ships are estimated to contribute up to 2–3% of long-lived greenhouse gas emissions annually.[1] In addition, these ships simultaneously emit a considerable amount of other pollutants including particulate matter (PM) and precursors such as sulphur dioxide (SO_2). These small airborne particles converted from ships' exhausts could directly reflect ('direct aerosol effect'), or cause clouds to reflect ('indirect aerosol effect'), more sunshine back to space, cooling down the planet and partly counteracting global warming from greenhouse gases.[2] Furthermore, ocean-going ships travel across open oceans that are difficult for aerosols from land-based emission sources to reach due to their short lifetimes (1–2 weeks). As a result, aerosols emitted from ships might have a climate impact that is more than proportional to their mass contribution. International shipping emissions (ISEs) contribute only about 5% (5.6 Tg S yr^{-1}) to total anthropogenic sulphur emissions.[3] However, their total climate forcing via cloud radiative effects (CREs) due to ships' exhausts perturbing marine stratiform clouds could be more than 10% in total anthropogenic aerosol forcing, according to a recent study conducted by Dr Chien Wang's group (sponsored by Concawe) at MIT.[4]

In the study, the researchers have applied a state-of-the-science Earth system model, the Community Earth System Model (CESM), developed by the National Center for Atmospheric Research (NCAR) and the U.S. Department of Energy (DOE). To address the detailed aerosol-climate interaction, the group has also utilised an advanced aerosol module developed in-house—the two-Moment, Multi-Modal, Mixing-state resolving Aerosol model for Research of Climate, or MARC.[5,6,7] MARC uses seven lognormal modes to represent the size distributions of sulphate and carbonaceous aerosol population: three modes for sulphate with different sizes, one of each for pure black carbon (BC) and pure organic carbon (OC), one of each for mixtures of BC-sulphate (core-shell structured; MBS) and OC-sulphate (internal mixture; MOS). MARC predicts total particle mass and number concentrations within each of the seven modes based on the assumption of the lognormal distribution of particle size. In addition, carbonaceous mass concentrations inside MBS and MOS are also predicted. Therefore, the mass ratios of the mixed aerosols evolve over time, changing the optical and chemical properties of the mixed aerosols. Mineral dust and sea salt are each represented by four bins with fixed sizes in MARC. Their emissions are calculated by the land and atmospheric component model of CESM, respectively. MARC connects to the cloud physics module of CESM through a new aerosol activation scheme developed by the group. Compared with similar previous studies, the CESM-MARC model has more physical-based and detailed representations of aerosol-cloud interactions, as well as direct aerosol effects. For the purpose of comparison, the group has also deployed CESM with the default aerosol module, MAM[8] in the study.

CESM-MARC or CESM-MAM were run at a horizontal resolution of 1.875°×2.5° and 30 vertical layers, and in two configurations:

1. Runs with ocean data, in which CESM-MARC or CESM-MAM were run with prescribed sea surface temperature, sea ice, and greenhouse gas concentrations, at their year 2000 levels; and
2. Fully-coupled runs, i.e. with fully-coupled atmosphere, ocean, sea ice and land components.

The former configuration is used to derive radiative effects of aerosols, while the latter is used to calculate long-term climate responses.

Physical processes involved

Among various aerosols emitted from ocean-going ships, the sulphate or sulphate-containing aerosols are efficient cloud condensation nuclei; they have a substantial influence on the formation of marine clouds and their micro- and macro-physical properties. On one hand, marine stratiform clouds have a strong cooling effect on the climate system. They cover about 30% of the global ocean surface, and can reflect more solar radiation back to space than the dark ocean surface under cloud free conditions.[9] On the other hand, low-altitude marine stratiform clouds form and develop near the ocean surface (at only a few degrees cooler than ocean surface) and thus have limited impacts on the long-wave radiation balance.[10] Therefore, the annual-mean net cloud radiative effect (CRE) at the top of the atmosphere (TOA), a measure of the cloud radiative effect in reference to clear sky conditions, is negative (i.e. cooling) and can be up to −20 W m^{-2} on the global scale.[2] Consequently, even a few percent change in marine stratiform clouds, either by aerosols or other factors, can either enhance or offset substantially the anthropogenic global warming due to greenhouse gases. It is therefore expected that the most effective impact of ship-emitted aerosols is to alter the properties of these low-altitude marine clouds that are otherwise often at a considerable distance from other anthropogenic emissions.

In addition to ship-emitted sulphur compounds, another significant component in the atmospheric sulphur cycle over oceans is the oceanic phytoplankton-derived dimethyl sulphide (DMS). DMS can be oxidized by hydroxyl radical (OH) or nitrate radical (NO_3) to produce SO_2 and eventually be converted to sulphate aerosols. Total global emissions of DMS are estimated to be about 18.2 Tg S yr^{-1} based on model simulations, and about one third of these are oxidized to sulphate aerosols (6.1 Tg S yr^{-1}), which is comparable to sulphates emitted from shipping.[11] Aerosols from this natural pathway play the same role in controlling cloud formation as those from shipping emissions.

Defining the radiative effects of ship-emitted aerosols

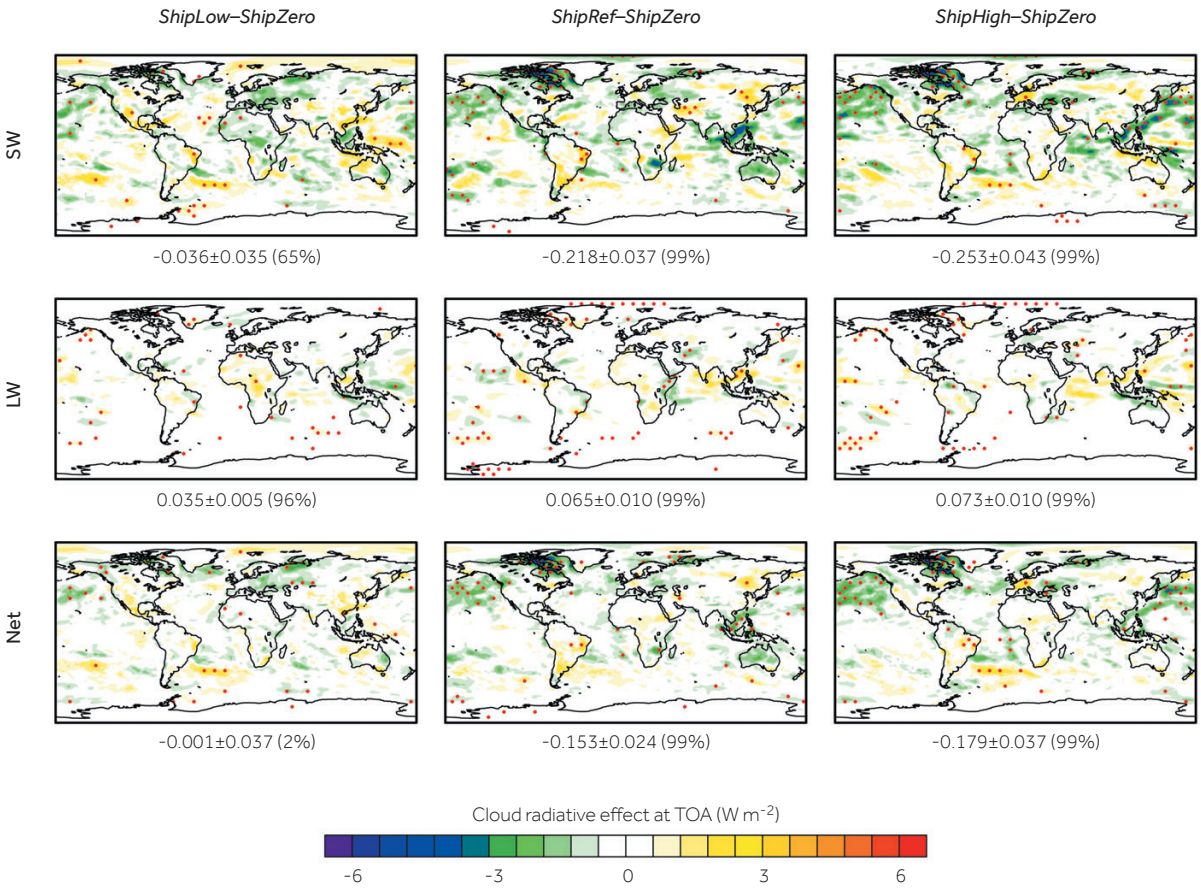
To facilitate an assessment of both direct (DRE or direct radiative effects) and indirect radiative effects (measured by perturbation or CRE by aerosols) of ship-emitted aerosols, the group has designed a comprehensive set of experiments. All simulations use the aerosol emissions in 2000, except for shipping and DMS emissions.

For shipping emissions, three scenarios were designed based on the assumption of sulphur content in the fuel oils used by ocean-going ships. Currently, the average sulphur content is 2.7%, which is equivalent to about 5.6 Tg S $year^{-1}$; this is referred to as *ShipRef*. On the other hand, as of 2013, the high-sulphur fuel oil that has 3.5% sulphur content (and which is still permitted outside the Emission Control Areas) is referred to as *ShipHigh*. However, the IMO has planned to lower the sulphur content to 0.5% outside the Emission Control Areas after 2020, and the corresponding scenario is referred to as *ShipLow*. In the *ShipLow* and *ShipHigh* scenarios, the total global sulphur shipping emissions are 1.0 and 7.2 Tg S $year^{-1}$, respectively. The differences between these three scenarios and a zero shipping-emission scenario, or *ShipZero,* represent how various regulations on ship fuel influence the shipping emission-induced CRE.

To consider the uncertainty of DMS emissions and thus different levels of natural aerosols particularly over remote oceans overlapping ship tracks, different annual emissions of DMS are designed as well, with a base scenario of 18.2 Tg S $year^{-1}$ (*DMSRef*), and a low scenario with half of base emissions (*DMSLow*) as well as a scenario excluding DMS emissions (*DMSZero*).

Twelve simulations paring different emission scenarios of DMS and ship emissions have been conducted. Each simulation runs for 32 years driven by 12-month cyclonic climatological sea surface temperature, with the first 2 years as spin-up and discarded. The global mean direct radiative effect of ship-emitted aerosol is −23.5 mW m^{-2} and is derived by comparing *ShipRef_DMSRef* and *ShipZero_DMSRef,* with the strongest negative (cooling) DRE in the areas with intense shipping tracks, from mid-latitude Pacific Ocean and Atlantic Ocean, to South China Sea, North Indian Ocean and the Red Sea. The accumulation-mode sulphate contributes 89% to total global DRE, followed by the OC-sulphate mixture (MOS). The contributions of other aerosol species are very limited (note that BC and MBS provide net positive forcing). The magnitude of DRE is within the range from −50 to −10 mW m^{-2} of previous studies.[12,13]

Figure 1: Spatial patterns of simulated cloud radiative effects (CRE; units: W m^{-2}) of international shipping emissions at various shipping emission levels (*DMSRef*)



The CREs created by ship-emitted aerosols, however, are about an order of magnitude higher than the DREs and show different spatial patterns under various shipping emission regulations (Figure 1). The CRE is calculated as the differences of radiation flux at TOA and at all-sky conditions, between the simulation without shipping emissions and three simulations with various shipping emissions levels (i.e. low, reference, high) and keeping DMS emissions unchanged at the reference level. Predicted differences in short-wave (SW), long-wave (LW) and net (SW+LW) are shown in Figure 1, averaged over the 30-year simulation period. The numbers below each panel on Figure 1 are the global means, standard deviation across the 30-year period, and the confidence level. The red dots represent grid points that are statistically significant above the 90% confidence level based on the two-tailed Student's t-test.[4] At reference shipping emissions, significant cooling CRE in shortwave radiation (SW; calculated by *ShipRef_DMSRef - ShipZero_DMSZero*, the same for other quantities) is simulated in areas of mid-latitude Pacific Ocean and the Baffin Bay between Canada and Greenland, with a global average of -0.218 W m^{-2}. The long-wave (LW) CRE shows a global average of +0.065 W m^{-2}. Consequently, the global net CRE (SW+LW) is -0.153 W m^{-2} with a similar spatial pattern to that of SW. At the high shipping emissions (*ShipHigh_DMSRef*), the net CRE changes as expected to -0.179 W m^{-2}, and more areas show significant changes than in *ShipRef_DMSRef*. However, at the low reference level of shipping emissions (*ShipLow_DMSRef*), fewer areas demonstrate significant changes compared to *ShipRef_DMSRef* and *ShipHigh_DMSRef,* and the global averages of the CRE are not significant at a 90% confidence level at SW and net. These results indicate that more stringent shipping emission regulations proposed by the IMO to be applied after 2020 could effectively reduce or even largely eliminate the net CRE induced by shipping emissions.

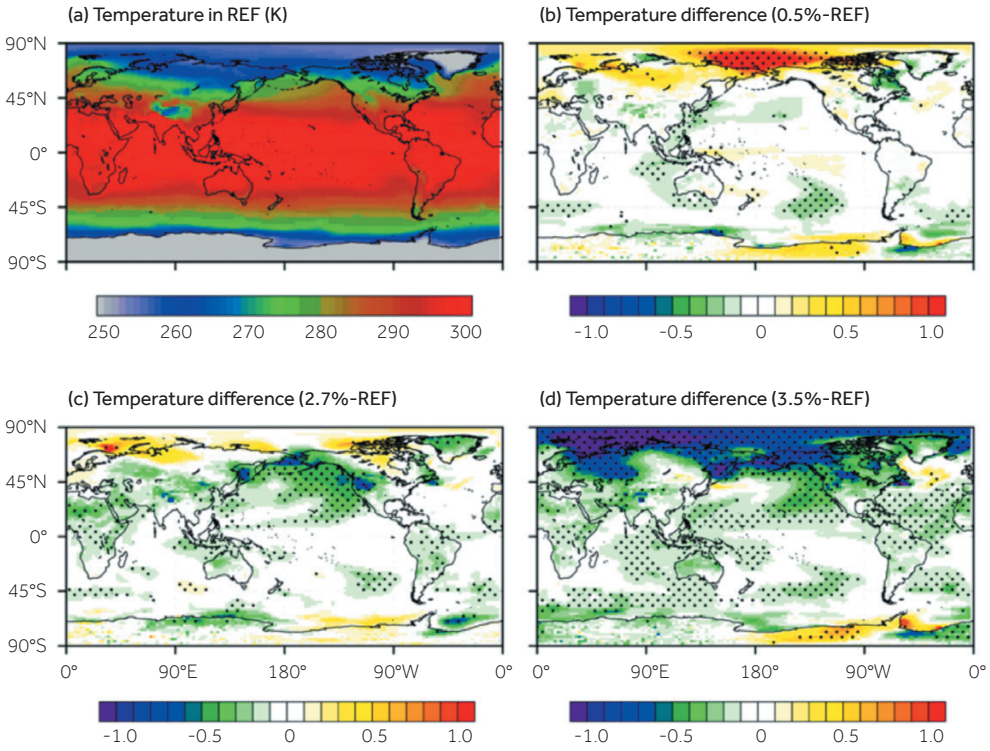
Interestingly, researchers find that the shipping emission-induced CRE exhibits very different patterns and global averages at different emission levels of DMS. With DMS emissions ranging from the reference level to low and zero levels, the shipping-induced cooling CRE at SW increases from -0.218 to -0.457 and -2.435 W m^{-2} on the global scale, respectively. This is because the natural aerosol from DMS causes shipping emission-induced changes in cloud droplet number and water content, and thus radiative effects. Similarly, the shipping emissions could also influence the DMS emission-induced CRE and cloud properties. Generally, stronger cooling CRE (-8.492 vs -6.463 W m^{-2}) induced by DMS emissions are seen when shipping emissions are ignored, particularly in areas of intense shipping tracks, such as the North Indian Ocean, mid-latitude areas of the Pacific Ocean and the Atlantic. This finding reveals a critical interplay between anthropogenic and natural aerosols particularly over remote oceans.

Ongoing estimation of the net climate responses of ship-emitted aerosols

The group is currently analysing results from a set of long-term fully coupled model simulations. The preliminary result in the equilibrium simulation set indicates that using 2.7% and 3.5% sulphur content in fuel would cause a global average cooling of 0.2° or more (Figure 2). Besides scenarios with different levels of sulphur content in ships' fuel, black carbon aerosols emitted from international shipping will also be quantified. This type of simulation applies a constant forcing to an often 100–150 year long integration where oceans are allowed a long adjustment time to absorb extra heat. Another set of simulations are

conducted to estimate the relative climate impacts on temperature in comparison with CO_2 with the 'global temperature potential' metric.

Figure 2: (a) Surface temperature in reference run; (b)–(d) Surface temperature change relative to reference run in simulation with ship fuel sulphur content at 0.5%, 2.7%, and 3.5%, respectively. All results are last 40-year means from a 150-year long integration.[4]



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