Impacts of Particulate Emissions from International Shipping on Climate

Chien Wang

(Contributing group members: Q. Jin and B. Grandey)

Massachusetts Institute of Technology

(Now at Laboratoire d'Aerologie/CNRS/UPS, Toulouse, France)

wangc@mit.edu or wangc@aero.obs-mip.fr

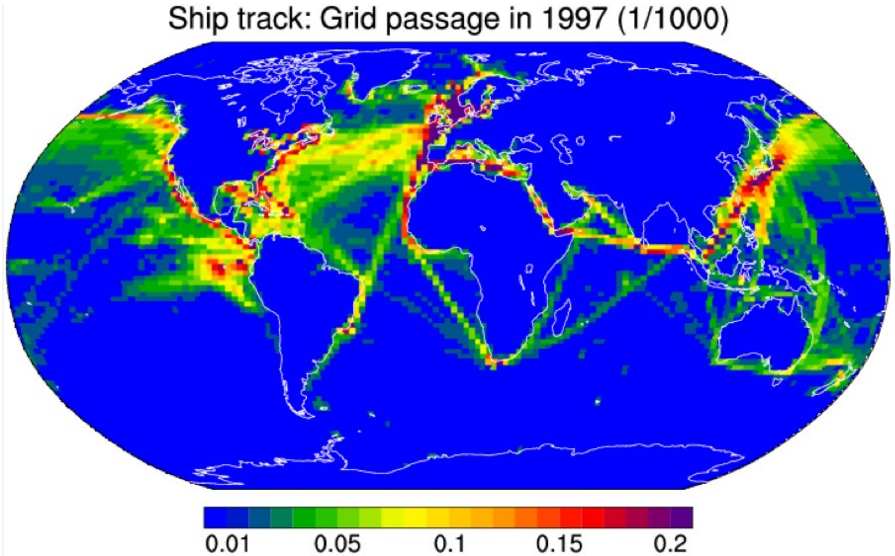
- *Climate impacts of ship-emitted aerosols*
- *Critical influence of natural aerosols on above impacts*

MIT

Concawe
Environmental Science for European Refining

Major Objectives of CONCAWE-MIT project:

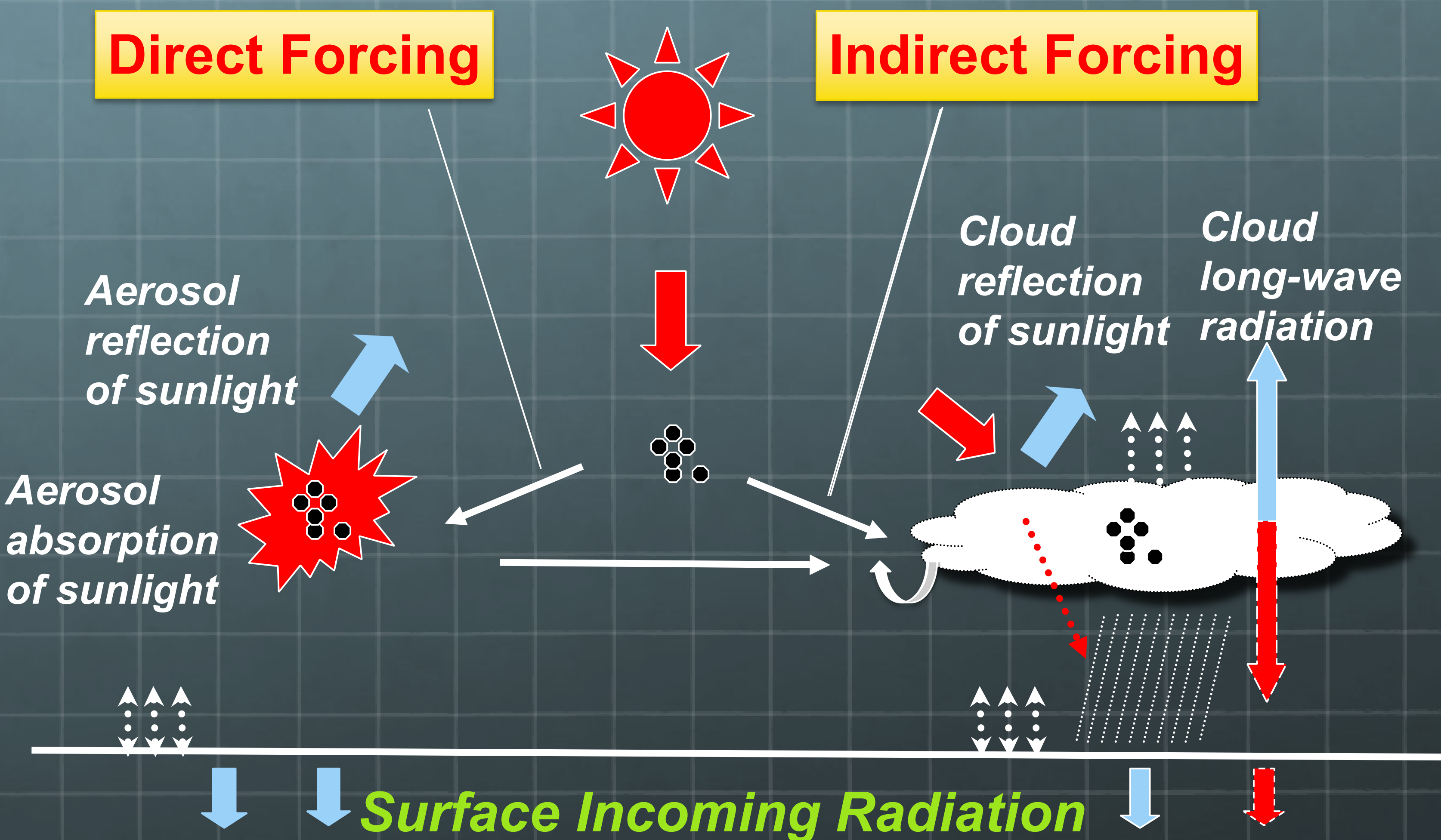
- Using the state-of-the-art Earth system model with process-based aerosol module to study detailed direct and indirect effects of ship-emitted aerosols on climate
- Quantifying climate forcing alongside responses to scenarios of using ship fuels with different sulfur content of:
  - (a) current average of 2.7%
  - (b) IMO 2020 target of 0.5%
  - (c) an extreme case of 3.5%
  - (d) a partially LNG approach



International Comprehensive Ocean-Atmosphere Data Set (ICOADS) of NOAA

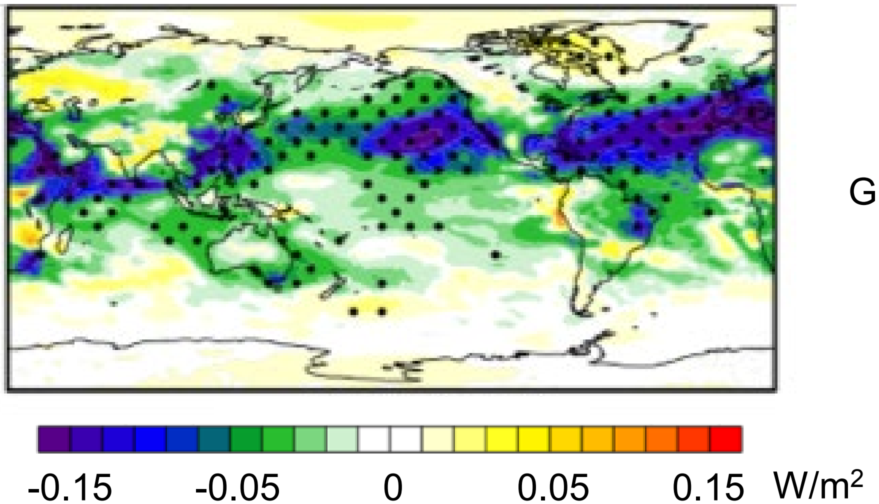
- International shipping accounts ~2% global anthropogenic emissions of long-lived GHGs, 5-10% of short-lived pollutants, and ≤2% of primary particles, ***all depending on fuels***
- Ship-emitted sulfate, nitrate and organic carbon (OC) are ”cooling” aerosols (scattering sunlight)
- Black carbon (BC) and brown OC can be “warming” aerosols (absorbing sunlight)
- Sulfate and nitrate are active cloud condensation nuclei (CCN), they can also convert BC and OC to be CCN
- Shipping tracks cover a vast of remote oceans besides coastal, where aerosol climate effect is a critical while poorly addressed issue

Aerosols, Clouds, and Their Interactions in Earth's Radiation and Water Cycle



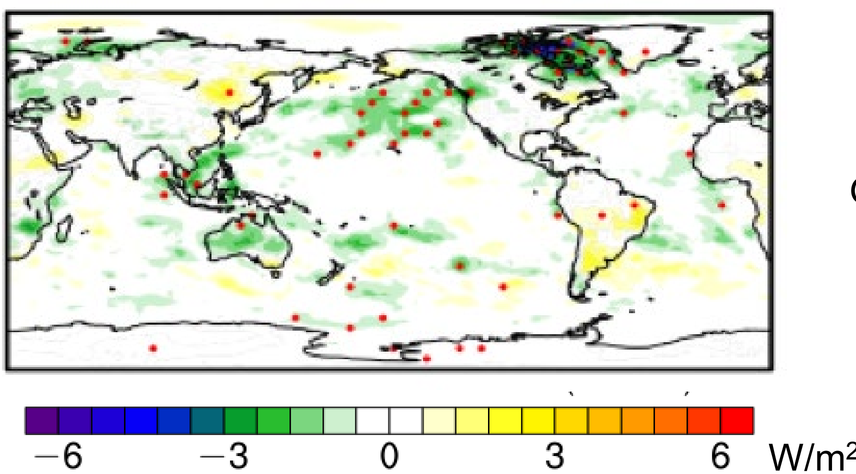
➢ Climate Effects of Ship-Emitted Aerosols

Aerosol Radiative Effects due to International Shipping
indirect > direct (note different color scale)



Direct Radiative Forcing

Global mean = - 0.024 (99% confidence) W/m^2

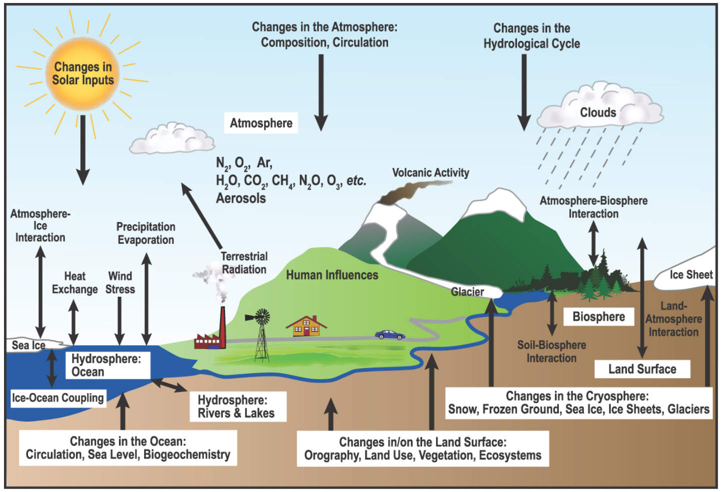


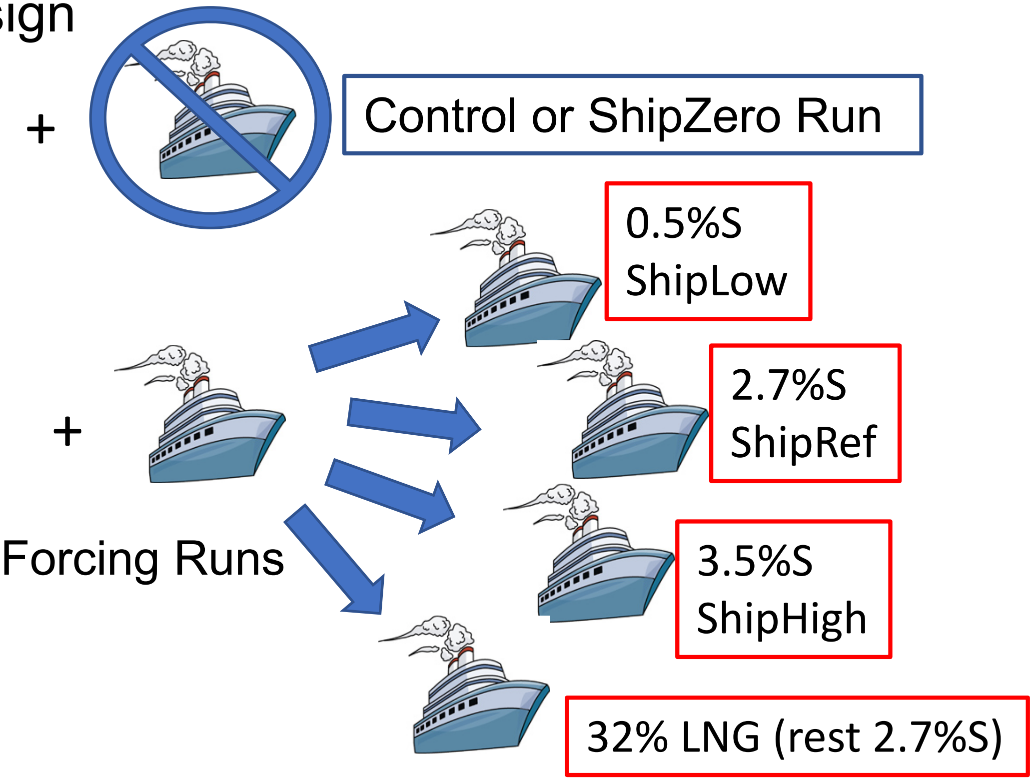
Indirect Aerosol Effects

Global mean = - 0.153 (99% confidence) W/m^2

(Jin *et al*., 2018, Atmos. Chem. Phys.)

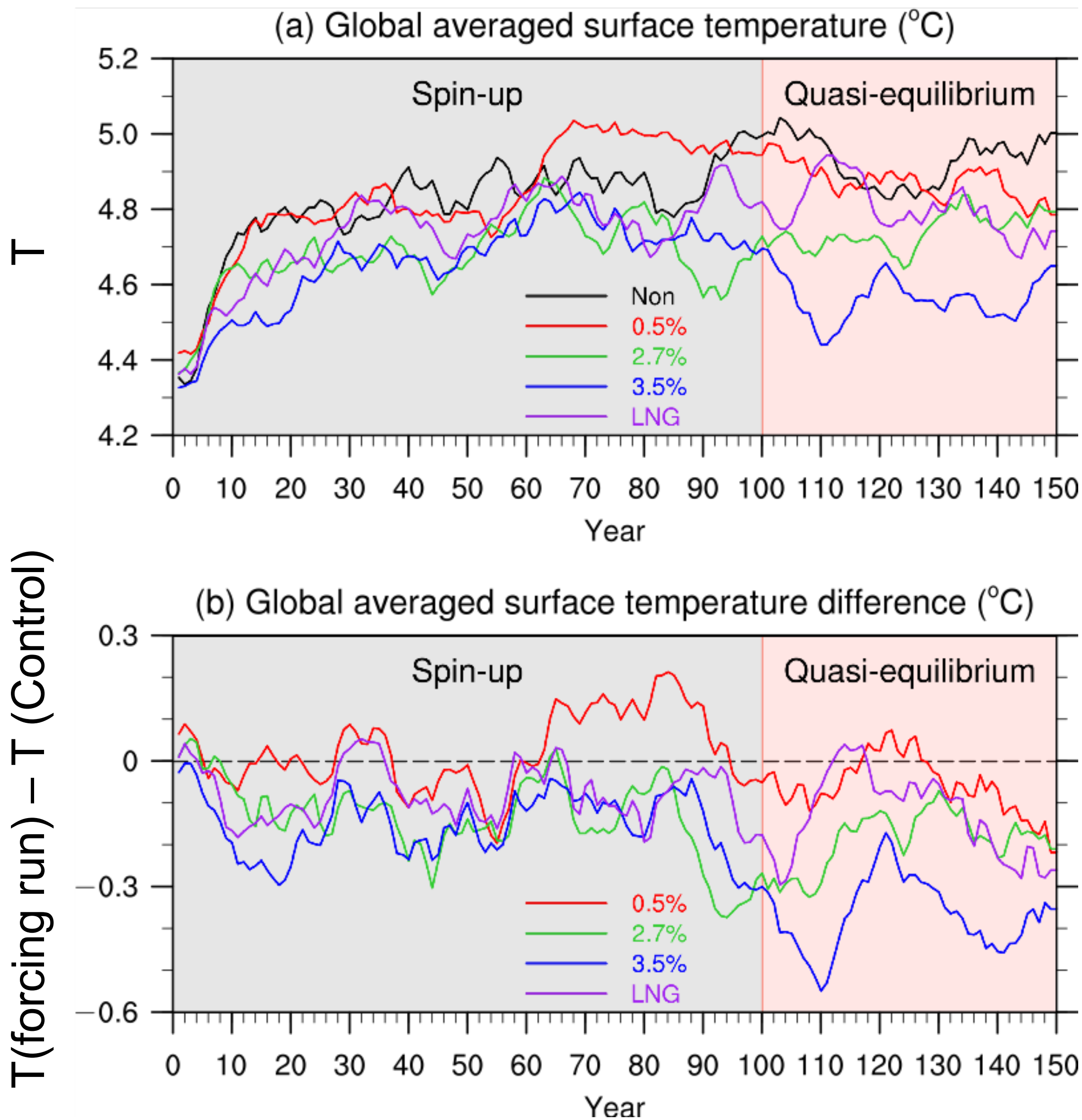
Climate Model Experimental Design





- ➢Simulation period: 150 years
- ➢Largely, modeled climate enters a quasi-equilibrium after 50 years
- ➢Analyses are emphasized on the last 50 yrs;
- ➢Induced climate change = forcing runs – ShipZero
- ➢Using dynamic ocean module
- ➢MARC aerosol module (MIT) in NCAR CESM

Temperature responses in various model runs



Notes.

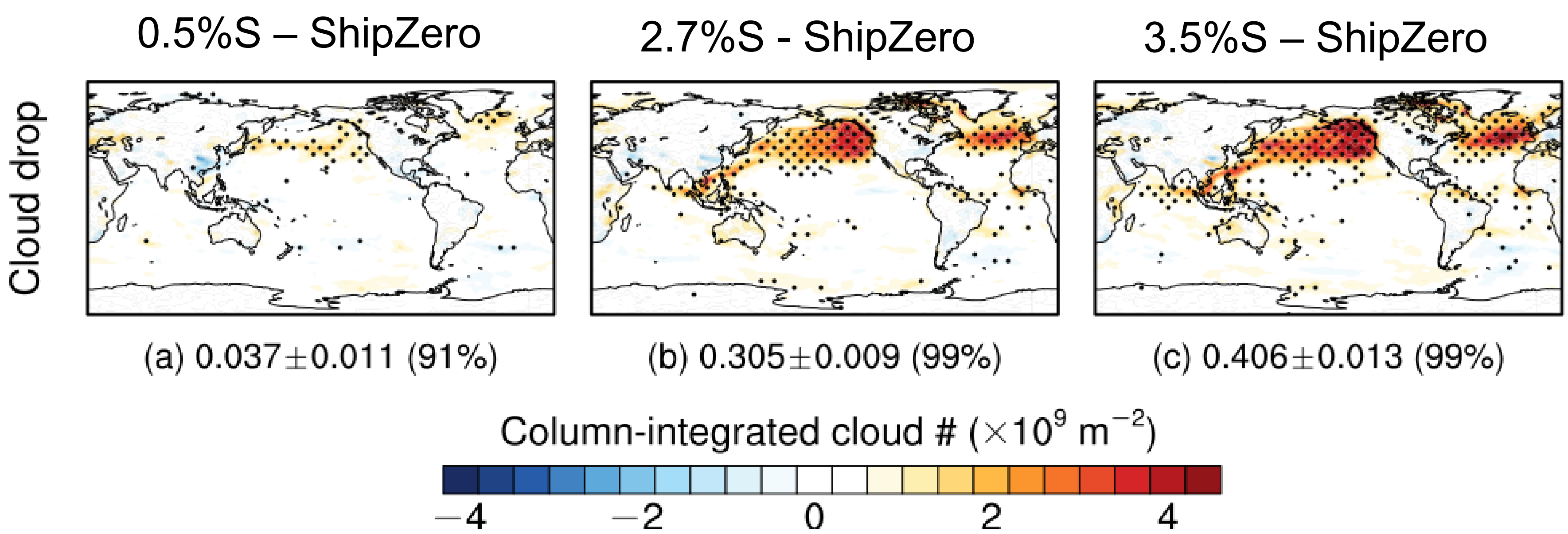
(a) Only results during the “quasi-equilibrium” stage or year 101-150 are used for analyses

(b) Quasi-equilibrium climate state is reached when heat exchange between atmosphere and ocean reaches an equilibrium

(c) Natural variations of the model always exist, and are not necessarily due to aerosol forcing

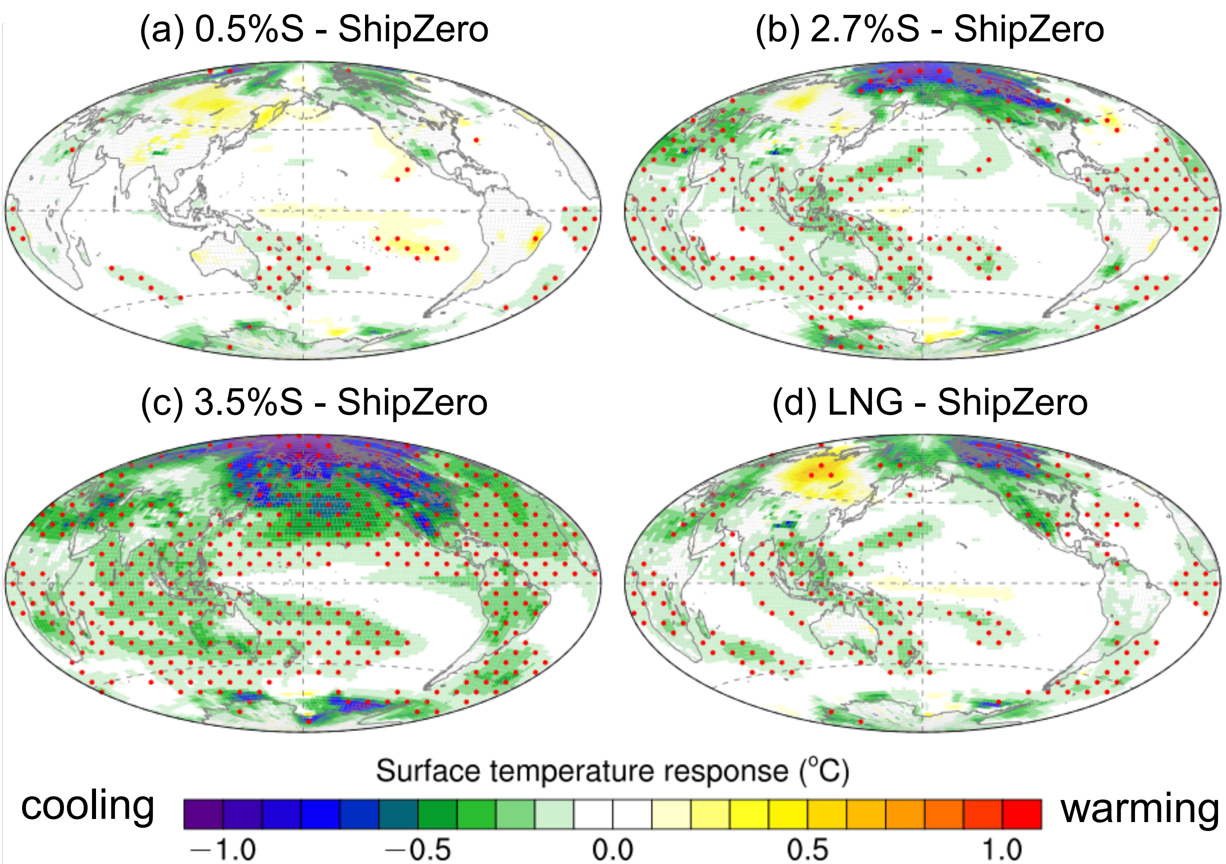
How does the aerosol indirect effect work?

Ship-emitted aerosols make clouds to have
more droplets and thus become more reflective to sunlight
= a cooling effect to the Earth



(Jin *et al*., 2018, Atmos. Chem. Phys.)

Mean temperature response over quasi-equilibrium stage: An overall "cooling" effect of ship-emitted aerosols

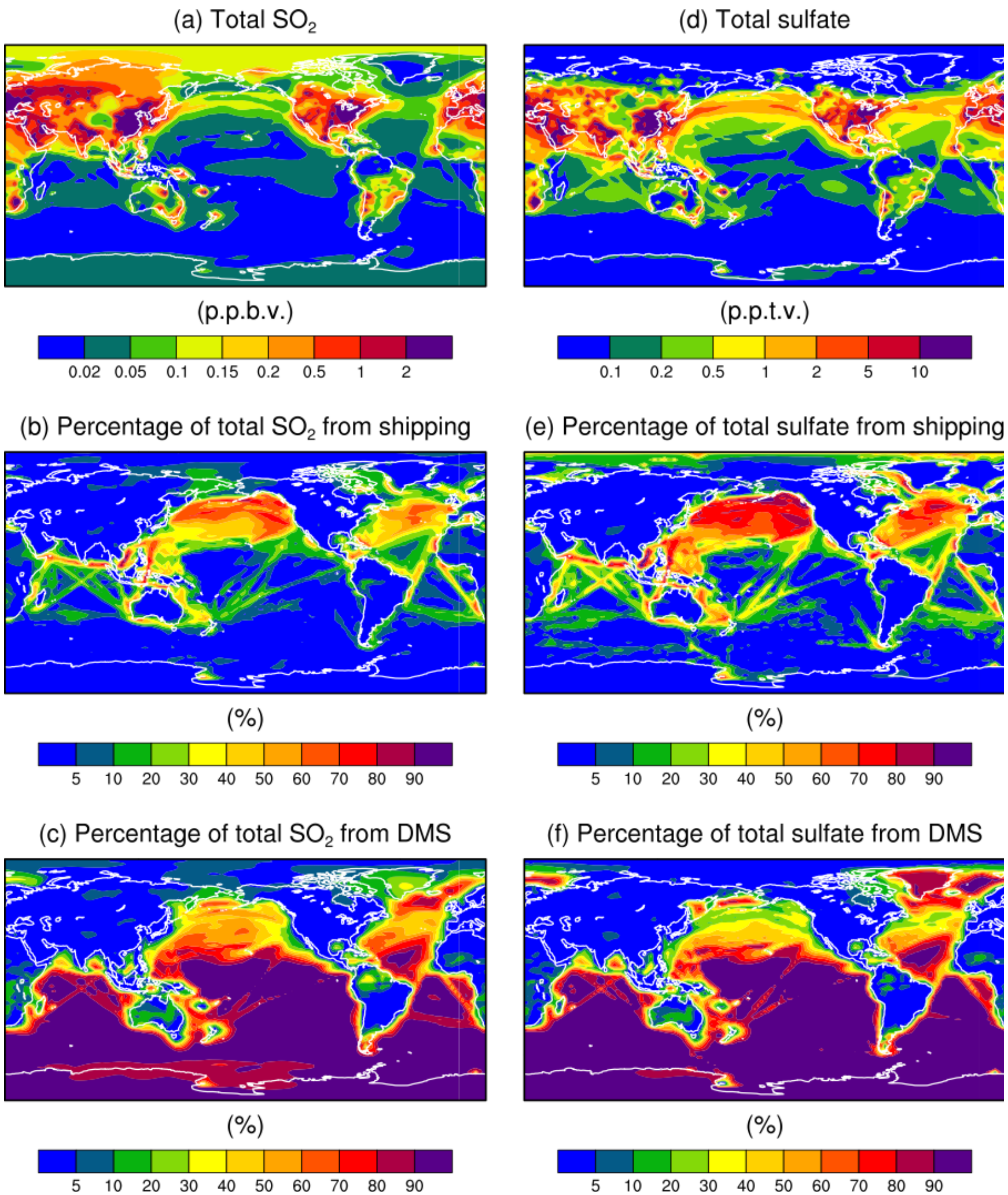


	(a)	(b)	(c)	(d)
NH	−0.07/0.04/0.19	−0.28/0.05/0.00	−0.57/0.05/0.00	−0.17/0.05/0.00
SH	−0.05/0.02/0.11	−0.10/0.03/0.00	−0.16/0.02/0.00	−0.09/0.03/0.00
Global	−0.06/0.03/0.08	−0.19/0.03/0.00	−0.36/0.03/0.00	−0.13/0.03/0.00

- Results are year 101-150 averages
- Global average, standard error, and *p*-value (statistical significance) are shown in the table
- Red dots marks points with statistical significance above 90% (t-test)

Adopting fuel with sulfur content ≤0.5% would largely eliminate aerosol climate effects from international shipping

➢ An interesting finding over mostly remote oceans



Estimating ship-emitted aerosol effect: would natural aerosols matter?

- Dimethyl sulfide $(CH_3)_2S$ or DMS is the major sulfur source over remote oceans
- DMS can be oxidized by OH and NO_3 (nighttime) to form SO_2 besides others
- Would their effects and those due to ship-emitted aerosols linearly add up?

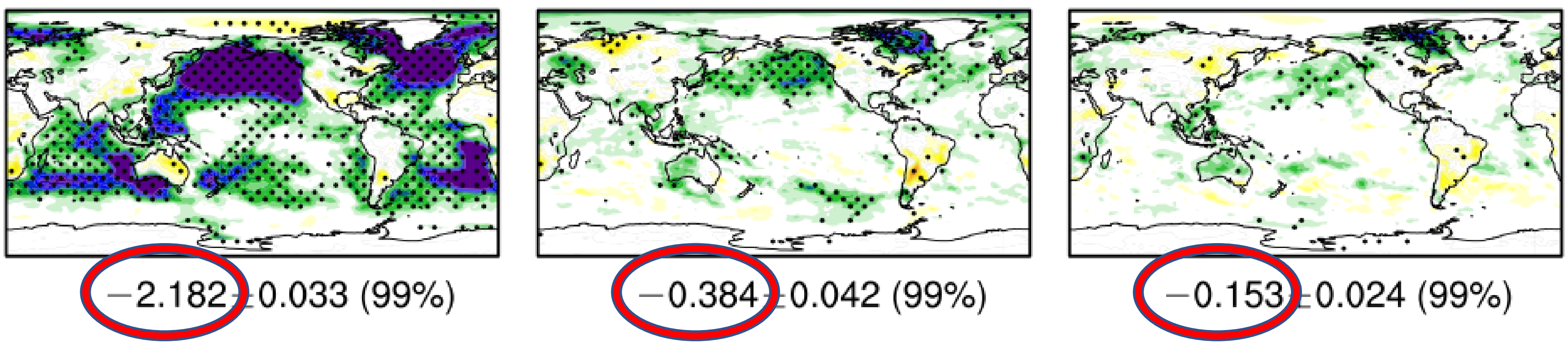
(Jin *et al*., 2018, Atmos. Chem. Phys.)

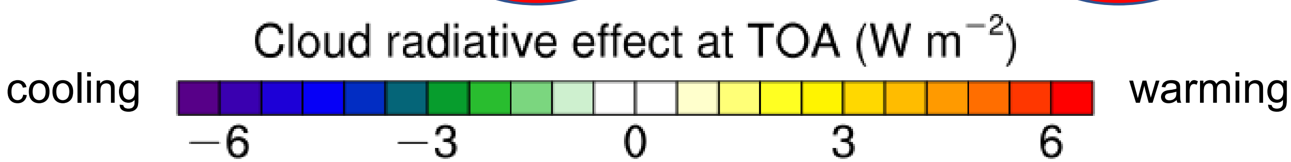
Representation of DMS emissions in the model DOES MATTER in estimating shipping-emitted aerosol indirect effects

Net Cloud Radiative Effect = 2.7%S – ShipZero

(global mean ± standard error (p-value))

DMS = zero | DMS = 50% ref | DMS = ref (18.2TgS/yr)





Note the difference in an order of magnitude

(Jin et al., 2018, ACP)

Summary

- International shipping using fuels with 3.5% and 2.7% sulfur-content could cause significant global mean cooling of −0.36 °C and −0.19 °C, respectively, more prominent in the Northern Hemisphere than Southern Hemisphere
- This cooling is mainly caused by ship-emitted aerosols in reducing surface radiation through the indirect effects
- Adopting fuels of 0.5%S or lower would largely eliminate the above-indicated climate effects
- Replacing 32% of 2.7%S fuel oils by liquefied natural gas could reduce the global cooling from −0.19 to −0.13 °C
- The effectiveness of ship-emitted aerosols in influencing climate can be affected by natural aerosols, e.g., from marine DMS emissions; assessment of climate effects of international shipping needs to be performed with adequate consideration of natural emissions in the framework