Substantial cloud brightening from shipping in subtropical low clouds

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Pattern of cloud droplet concentration (MODIS)

Austral Spring (September-October-November) climatology from 2003-2015
SO$_2$ emissions from international shipping [ng/m$^2$/s]
Why do we care about shipping emissions?
What sets $N_d$ in low clouds?

- The cloud droplet number concentration ($N_d$) is set by the number of aerosol particles that activate
  - Cloud condensation nuclei (CCN): Need hydroscopic aerosol particles for water to condense on
  - Supersaturation: Sets the minimum size CCN that activates
  - Updraft velocity: Sets the peak supersaturation

*Carslaw et al. (2013), Nature*
Twomey effect

FIRST INDIRECT EFFECT

lower albedo
macrophysically identical clouds
higher albedo

fewer larger drops
more smaller drops

NASA/MODIS

Wood (2012)
Aerosols, Cloud Microphysics, and Fractional Cloudiness

Bruce A. Albrecht

Increases in aerosol concentrations over the oceans may increase the amount of low-level cloudiness through a reduction in drizzle—a process that regulates the liquid-water content and the energetics of shallow marine clouds. The resulting increase in the global albedo would be in addition to the increase due to enhancement in reflectivity associated with a decrease in droplet size and would contribute to a cooling of the earth’s surface.
Some cloud darkening in ship tracks

Coakley & Walsh (2002), JAS

Chen et al. (2012), ACP
Irradiance Changes from Aerosol-Cloud Interactions \( \text{(aci)} \)

Enhancement of the Twomey effect via precipitation suppression (e.g., Albrecht et al., 1989, Science)

Offset of the Twomey effect via enhanced cloud-top entrainment of dry air (e.g., Ackerman et al., 2004, Nature; Wood, 2006, JAS)

*Boucher et al. (2013), IPCC AR5*
Do ship tracks matter globally?

• Global \( ERF_{ACI} \) estimate of -0.0005 W/m\(^2\) from one year’s worth of ship track data from AATSR.

• But model spread of \( ERF_{ACI} \) ranges from approximately -0.06 to -0.6 W/m\(^2\). . .

Schrier et al. (2007), GRL; Capaldo et al. (1999), Nature; Lauer et al. (2007), ACP.
Ship tracks may not be readily visible given natural cloud variability

Possner et al. (2018), ACP
Methods: Universal kriging
Example: MERRA-2 surface $[\text{SO}_4]$
Universal kriging

- Geostatistical method that provides the best linear unbiased predictor for a spatial model composed of some underlying mean spatial trend and a stationary “error” pattern.

\[ Y(s) = \mu(s, \beta) + e(s) \]

- Variable of interest
- Spatial location
- Mean function
- Regression coefficients (lat, lon, \( \text{lat}^2 \), \( \text{lon}^2 \), \( \text{lat} \times \text{lon} \), LTS, LTS+advection)
- Stationary error term (function of distance only)
Individually significant (95% confidence) grid boxes in white

Non-significant grid boxes in black
Results: Microphysics
$N_d$ & $r_e$ from MODIS/Aqua
\[ \delta[\text{SO}_4] = 150 \pm 7 \text{ ng/kg}; \delta[\text{SO}_4]/[\text{SO}_4] = 24\% \pm 1\% \]

\[ \delta N_d = 4.9 \pm 0.6 \text{ cm}^{-3}; \delta N_d/N_d = 5.2\% \pm 0.7\% \]

\[ \delta r_e = -0.29 \pm 0.04 \mu \text{m}; \delta r_e/r_e = -2.5\% \pm 0.4\% \]

***Values for southern/stratocumulus-dominated region only***
Microphysical sensitivity to aerosol consistent with studies across the oceans

Change in liquid water path?

- $\partial \ln(N_d)/\partial \ln(SO_4)$ (Terra)
- $-3\partial \ln(r_e)/\partial \ln(SO_4)$ (Terra)
- $\partial \ln(N_d)/\partial \ln(SO_4)$ (Aqua)
- $-3\partial \ln(r_e)/\partial \ln(SO_4)$ (Aqua)
- $\partial \ln(N_d)/\partial \ln(SO_4)$ (McCoy et al. 2017)
Results: Macrophysics
Cloud fraction changes

<table>
<thead>
<tr>
<th>Time (local)</th>
<th>Mean value</th>
<th>Effect size</th>
<th>$p_{field}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>01:30 (Aqua)</td>
<td>95.98%</td>
<td>-0.04% ± 0.26%</td>
<td>1.0</td>
</tr>
<tr>
<td>10:30 (Terra)</td>
<td>88.09%</td>
<td>0.06% ± 0.34%</td>
<td>1.0</td>
</tr>
<tr>
<td>13:30 (Aqua)</td>
<td>91.30%</td>
<td>0.16% ± 0.42%</td>
<td>1.0</td>
</tr>
<tr>
<td>22:30 (Terra)</td>
<td>86.44%</td>
<td>-0.28% ± 0.36%</td>
<td>0.762</td>
</tr>
</tbody>
</table>
Cloud optical thickness

- Cloud optical thickness ($\tau$) is proportional to liquid water path ($W$) and the inverse of effective radius ($r_e$): $\tau \propto W \, r_e^{-1}$

- Thus, the relative change in cloud optical thickness can be decomposed as:

\[
\frac{\delta \tau}{\tau} = \frac{\delta W}{W} - \frac{\delta r_e}{r_e}
\]
Twomey in the morning
Negative adjustments in the afternoon

Consistent with LES studies across the diurnal cycle, e.g., Sandu et al. (2008), JAS
Results: Radiative forcing
Albedo decomposition

• All-sky albedo ($A$), clear-sky albedo ($A_{clr}$), and cloud fraction ($F_{cld}$) from CERES (Energy Balanced and Filled product) used to estimate cloud albedo ($A_{cld}$):

$$A = F_{cld}A_{cld} + (1 - F_{cld})A_{clr}$$

• Assuming the clear-sky albedo change is negligible, all-sky albedo change can be decomposed into components related to changes in cloud brightness and changes in cloud fraction:

$$\delta A \approx F_{cld}\delta A_{cld} + (A_{cld} - A_{clr})\delta F_{cld}$$
Cloud fraction increases are negligible

\[
\text{ERF}_{ACI} = S_0 \delta A = 1.7 \pm 1.0 \text{ Wm}^{-2}
\]

(In shipping lane only)
LWP adjustment is negative but quite weak.

CERES SYN "Terra" (09:30-11:30 local average)

- $S_0 \cdot \delta A$
- $F_{cd}S_0 \cdot \delta A_{cd}$
- $F_{cd}S_0 \cdot A_{cd}(1 - A_{cd})/3 \cdot \delta N_d/N_d$
- Remainder ($\delta W$)

CERES SYN "Aqua" (12:30-14:30 local average)

- $S_0 \cdot \delta A$
- $F_{cd}S_0 \cdot \delta A_{cd}$
- $F_{cd}S_0 \cdot A_{cd}(1 - A_{cd})/3 \cdot \delta N_d/N_d$
- Remainder ($\delta W$)

Twomey effect only

Remainder (~20%) due to decrease in liquid water
Detectability
It takes $\sim 5-6$ years for signal to become clear.
Defining success and limits of field experiments to test geoengineering by marine cloud brightening

Robert Wood • Thomas P. Ackerman

Halving warming with idealized solar geoengineering moderates key climate hazards

Peter Irvine1, Kerry Emanuel2, Jie He3,4,5, Larry W. Horowitz3, Gabriel Vecchi6, and David Keith1

Latham et al. (2012), Phil. Trans. R. Soc.
Implications for 2020 IMO regulations
On 1st Jan 2020, fuels will be limited to 0.5% sulphur (by mass); 4.5% prior
Possibly large loss of negative forcing; implications for global warming
Work to do in detection/attribution of forcing change. Will we have the global observing system in place to detect these changes?
Stay tuned for estimates of global shipping radiative forcing and ERFaci
Summary and conclusions

- First unambiguous detection of climate-relevant cloud radiative effects due to international shipping emissions
- Emissions from a shipping corridor in the southeast Atlantic are associated with an ~5% increase in \( N_d \) and -2.5% decrease in \( r_e \) during austral spring
  - Liquid water path decreases by ~-2% in the afternoon
- All-sky albedo increase dominated by Twomey with negative LWP adjustment of ~20%, not by changes in fractional cloudiness
- Could be an ideal test for model aerosol-cloud interactions!
  - Preliminary analysis (not shown) suggests higher end of \( \text{ERF}_{\text{ACL}} \) due to shipping from some models may be unrealistic
A new Instrument for Cloud Physics
Field significance

• 5,000 kriged fields are simulated to test for significance and estimate effect size

• Variables are field significant if the number of significant Ship-NoShip grid boxes is extreme compared to the number expected by chance
Effect size

- For each of the 5,000 kriged fields, effect size is measured as the Ship-NoShip difference for grid boxes with $\delta[\text{SO}_4]/[\text{SO}_4] > 20$
  - Avoid flanks of the aerosol-perturbed area
$N_d$ & $r_e$ from MODIS/Aqua
Change in liquid water path?
Drizzle suppression dominates at night

Entrainment enhancement dominates during the day

(LES with different $N_d$ enhancement experiments)

Sandu et al. (2008), JAS
For our $\delta N_d / N_d$ of ~5% (for Aqua), Rosenfeld et al.'s values would predict a LWP increase of ~2.5%...

We instead see a 2% decrease in LWP!
- Consistent with previous work on ship tracks (even though we’re not focusing on tracks alone)

Rosenfeld et al. (2019), Science
Two decades of cloud susceptibility estimates
Numerous model and observational studies have estimated the effect of increased aerosols on cloudiness, a quantity termed cloud susceptibility. Rosenfeld et al. obtain a higher estimate by separating meteorological from aerosol effects on clouds. See supplementary materials for a full list of references.

\[ \frac{\partial \ln(LWP)}{\partial \ln(N_d)} \]

This study: Aqua

This study: Terra

Satellite observations
Models
Rosenfeld et al.

Rosenfeld et al. (2019)
Sato et al. (2018)
Michibata et al. (2016)
Quaas et al. (2008)
Myhre et al. (2007)
Matsui et al. (2006)
Matsui et al. (2006)
Kaufman et al. (2005)
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Suzuki et al. (2004)
Suzuki et al. (2004)
Quaas et al. (2004)
Quaas et al. (2004)
Quaas et al. (2004)
Quaas et al. (2004)
Sekiguchi et al. (2003)
Nakajima et al. (2001)

Sato & Suzuki (2019), Science
Proposals to use global shipping fleet for geoengineering

Partanen et al. (2013), ACP
Sizes needed to activate at 0.2% supersaturation

Petzold et al. (2010), Env. Sci. Tech.
Stay tuned for global shipping radiative forcing and $\text{ERF}_{\text{ACi}}$

- Radiative forcing efficiency (per percentage increase in $[\text{SO}_4]_2^-$) in southeast Atlantic during SON can be estimated as:

$$\frac{\text{ERF}_{\text{ACi}}}{\delta [\text{SO}_4]_2^-/[\text{SO}_4]} = \frac{-1.7 \pm 1.0 \text{ Wm}^{-2}}{24.4\% \pm 1.2\%} = -0.07 \pm 0.04 \text{ Wm}^{-2}\%^{-1}$$

- This is nearly certainly an overestimate because low cloud fractional coverage is much larger than for most other areas.

- Accounting for cloud cover, we can divide by 0.93 to get an adjusted efficiency of $-0.08 \pm 0.04 \text{ W/m}^2/\%$
Global forcing estimate (rough)

- From Lauer et al. (2007), ACP, take higher estimate of 3.6% global sulfate burden from shipping, assume 5% for ocean-only

Increase in surface sulfate due to shipping
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• Multiplying by 0.25 (for ocean low cloud coverage) and 5% (for shipping sulfate burden), we get $-0.09 \pm 0.05 \text{ W/m}^2$
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  - Very close agreement with $-0.11$ “base estimate” from Capaldo et al. (1999), Nature
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• Ship-track-only estimates far too low: For southeast Atlantic shipping lane, Schrier et al. (2007) method is two orders of magnitude too small