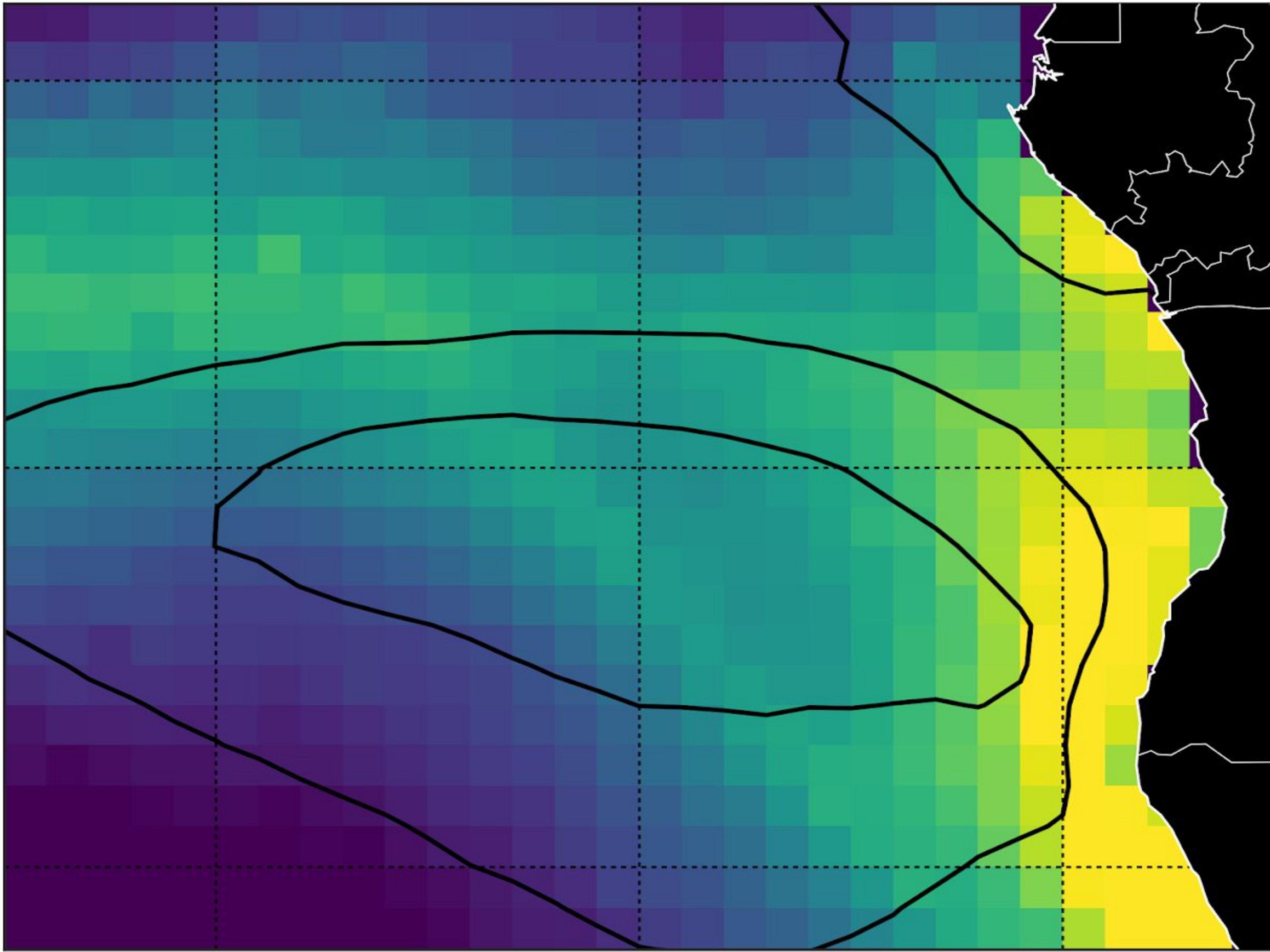
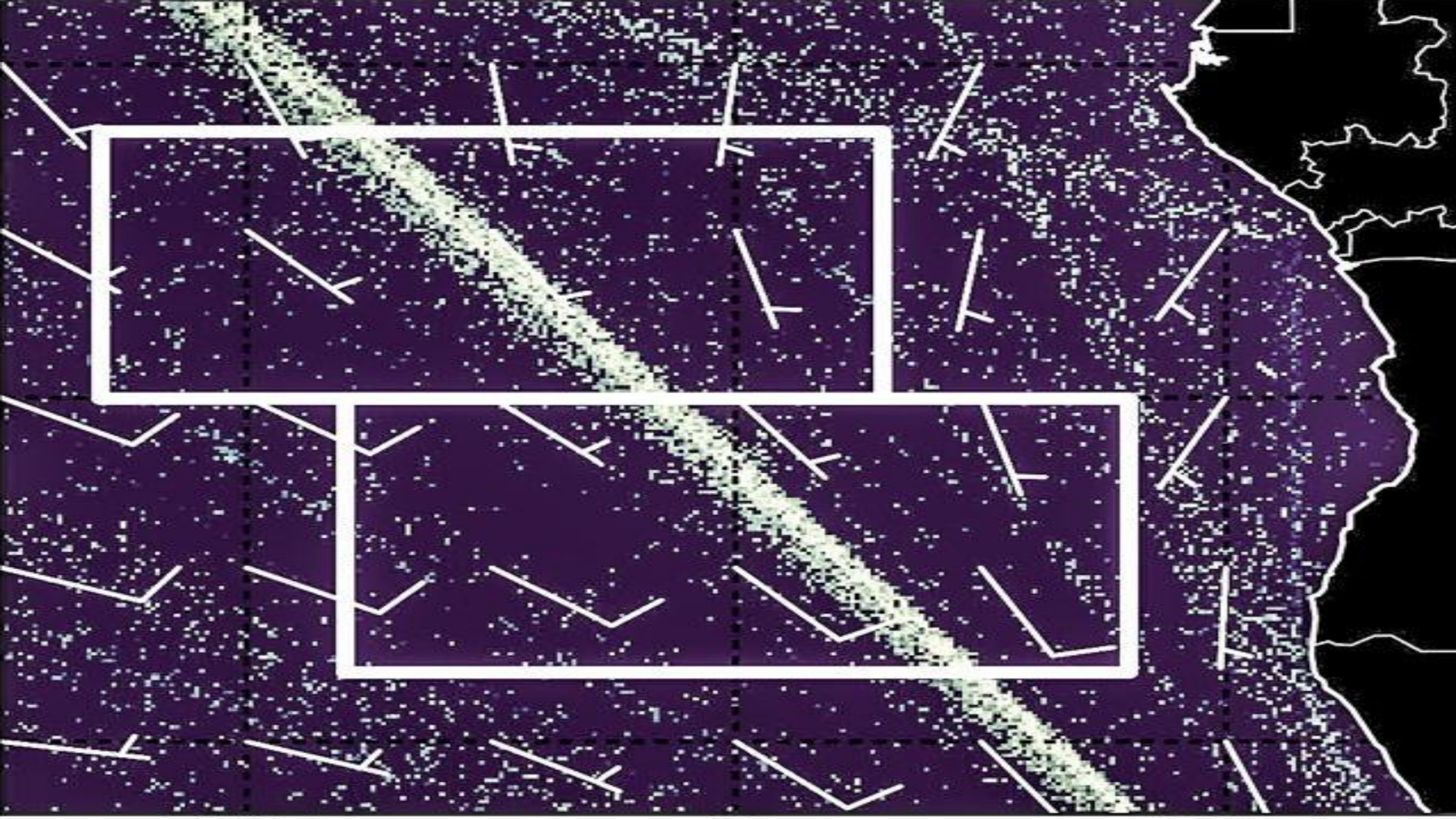




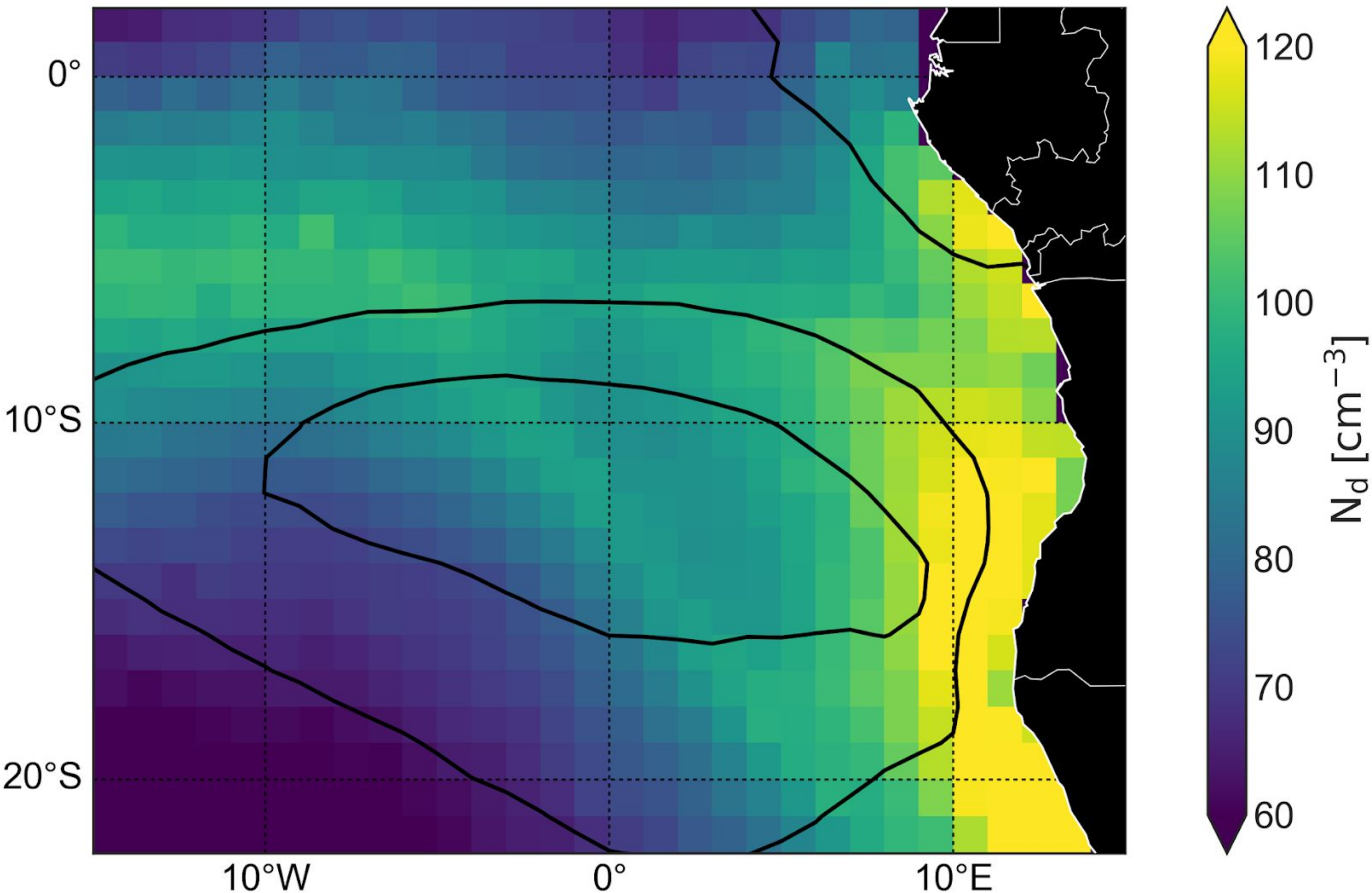
Substantial cloud brightening from shipping in subtropical low clouds

Michael Diamond[1], Hannah Director[2]
Anna Possner[3], Robert Wood[1]

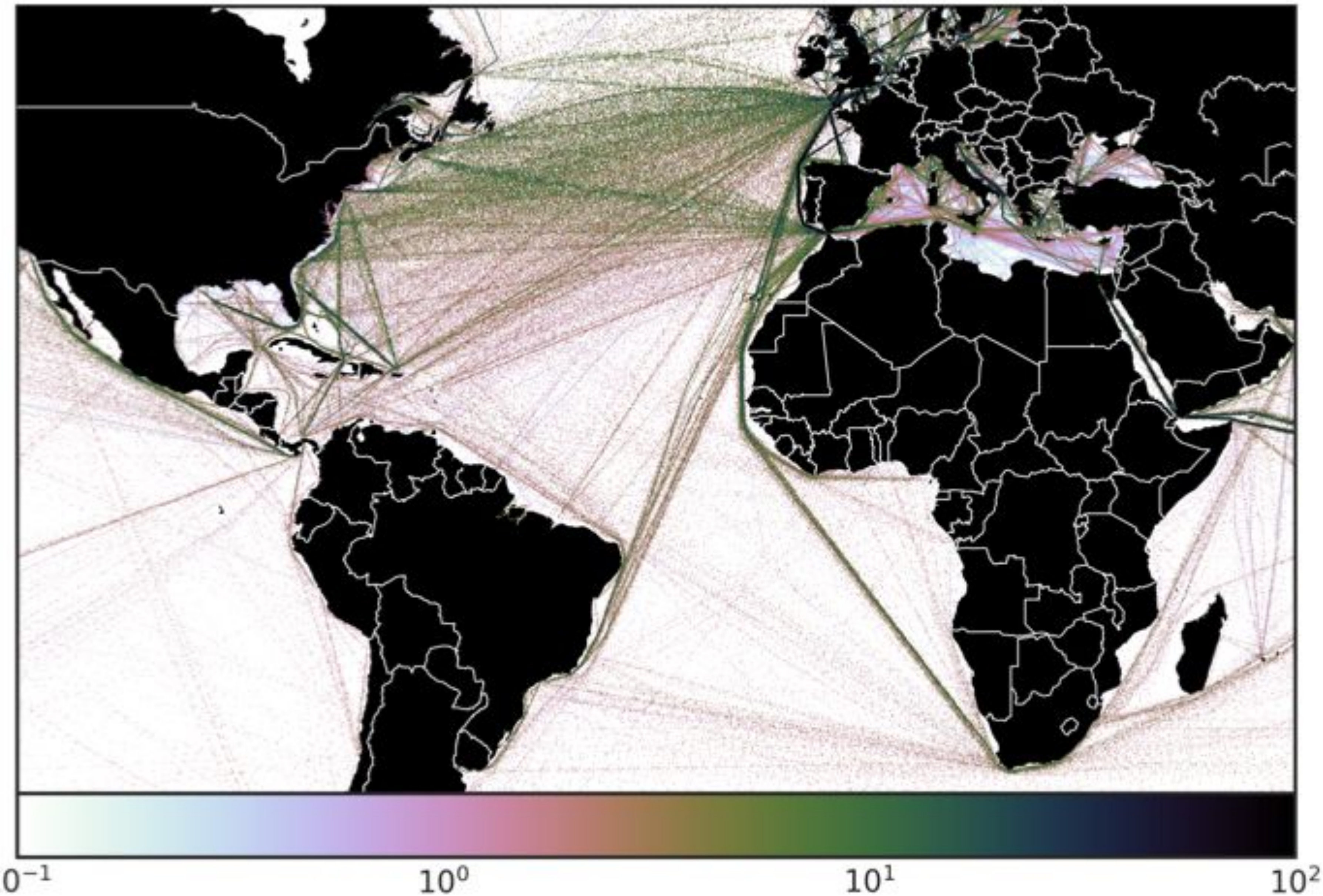
1. Department of Atmospheric Sciences, University of Washington
2. Department of Statistics, University of Washington
3. Institute for Atmosphere and Environment, Goethe University in Frankfurt

CFMIP-2019 Meeting, Mykonos, Greece. October 4th, 2019

Pattern of cloud droplet concentration (MODIS)



Austral Spring (September-October-November) climatology from 2003-2015

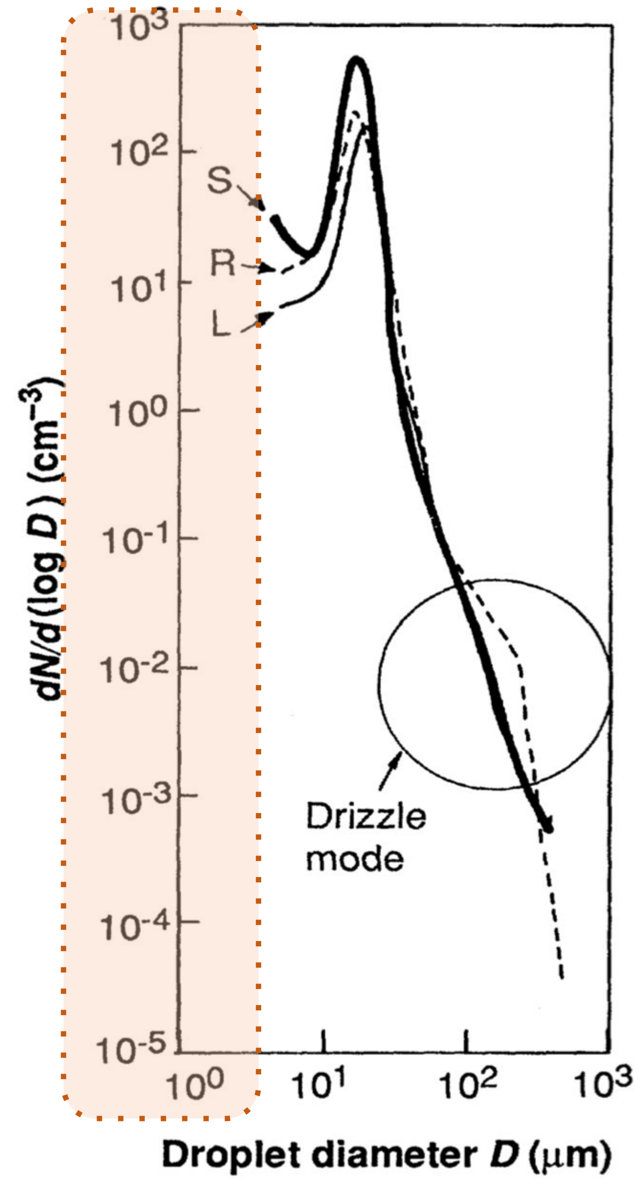


SO_2 emissions from international shipping [ng/m^2/s]

Why do we care about shipping emissions?

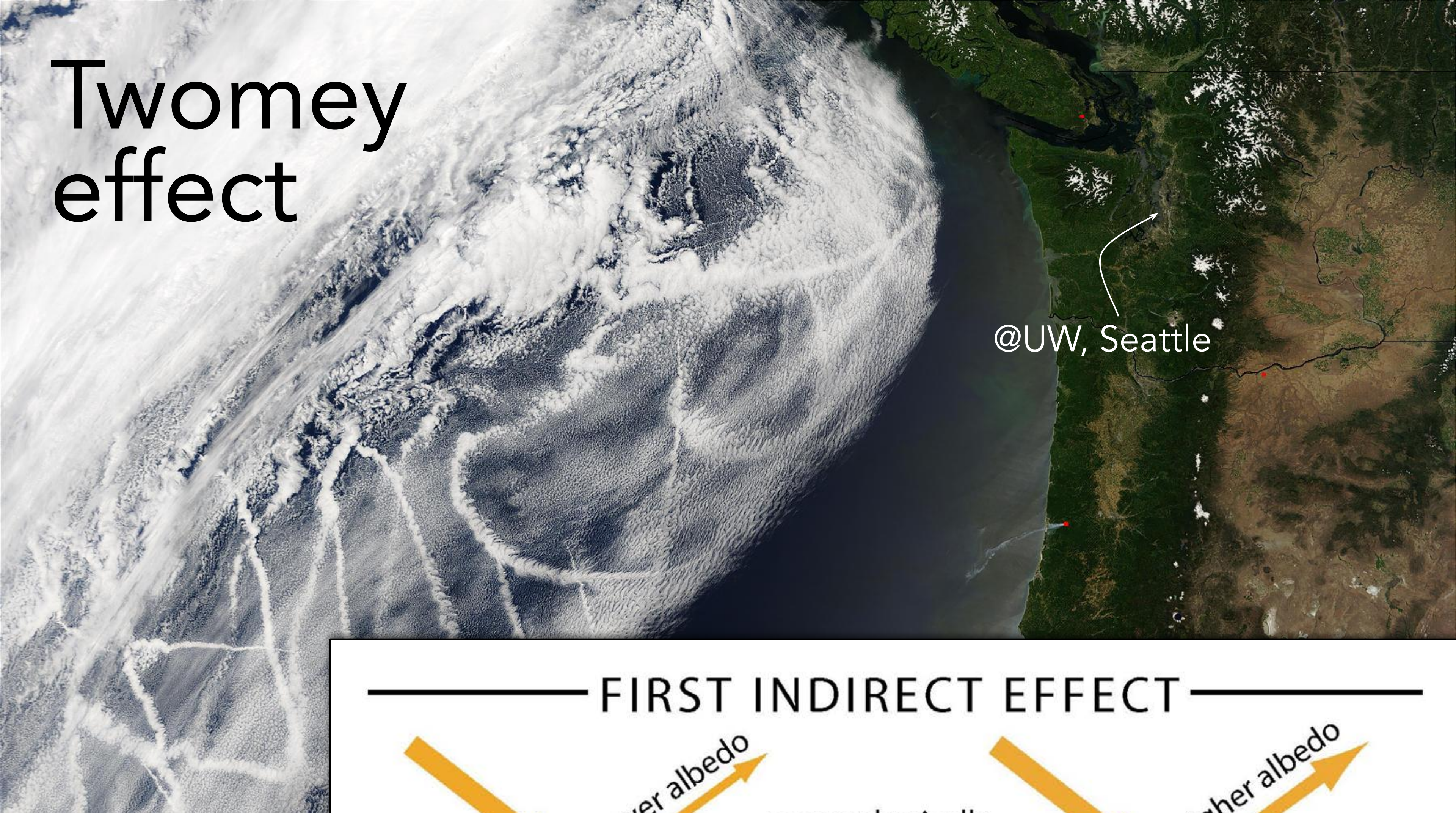
What sets N_d in low clouds?

- 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

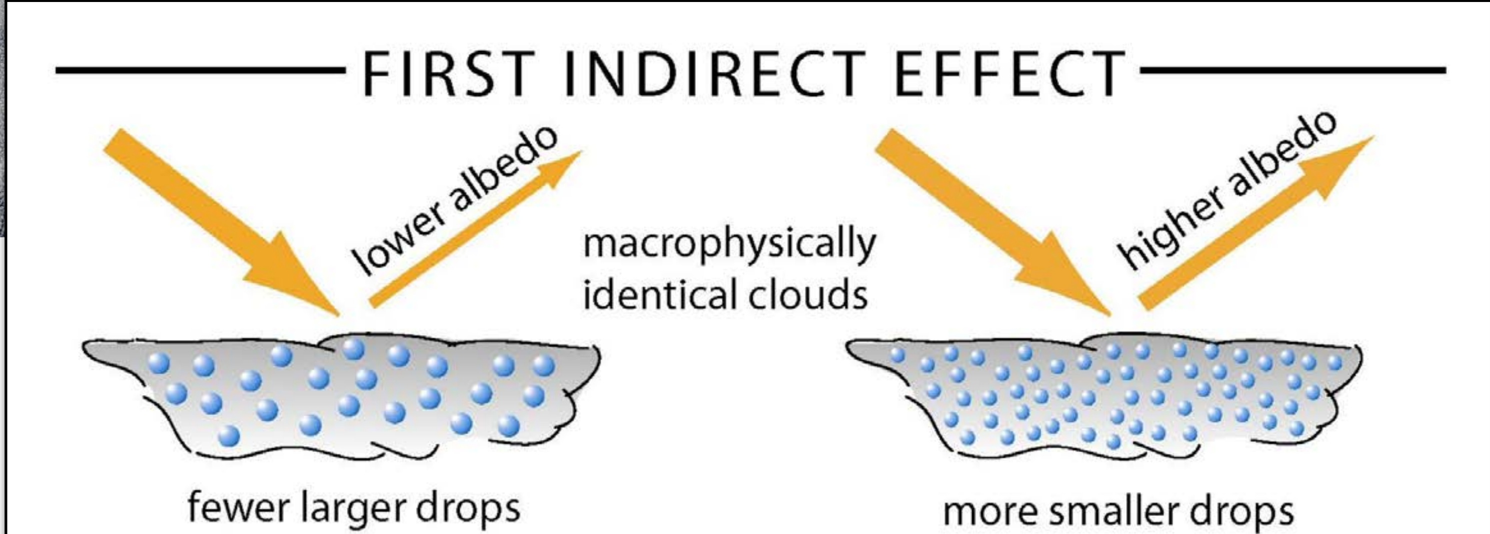


Carslaw et al. (2013), Nature

Twomey effect

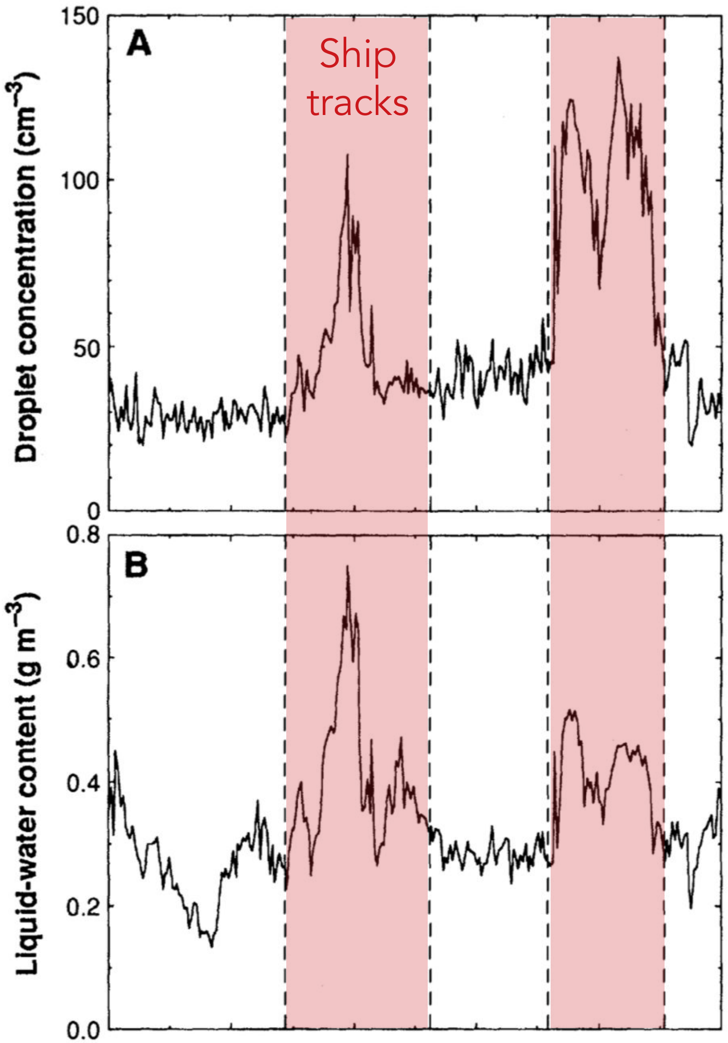


NASA/MODIS



Wood (2012)

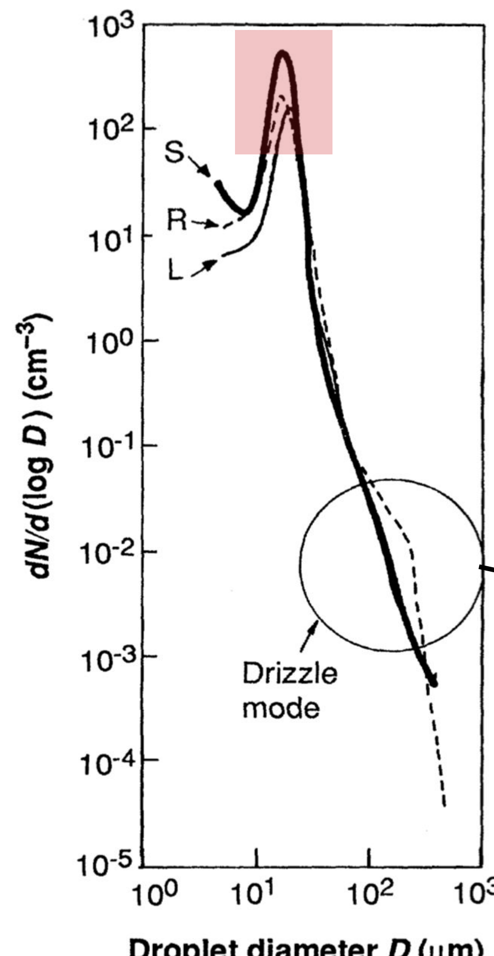
Radke et al. (1989)



Aerosols, Cloud Microphysics, and Fractional Cloudiness

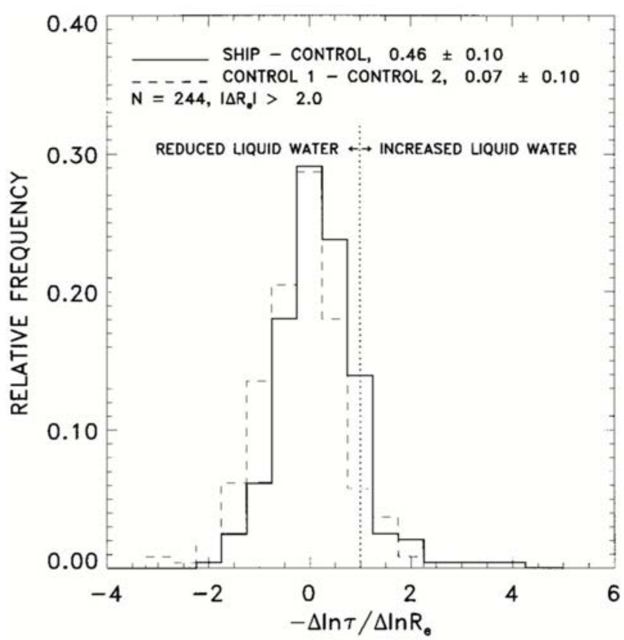
BRUCE A. ALBRECHT

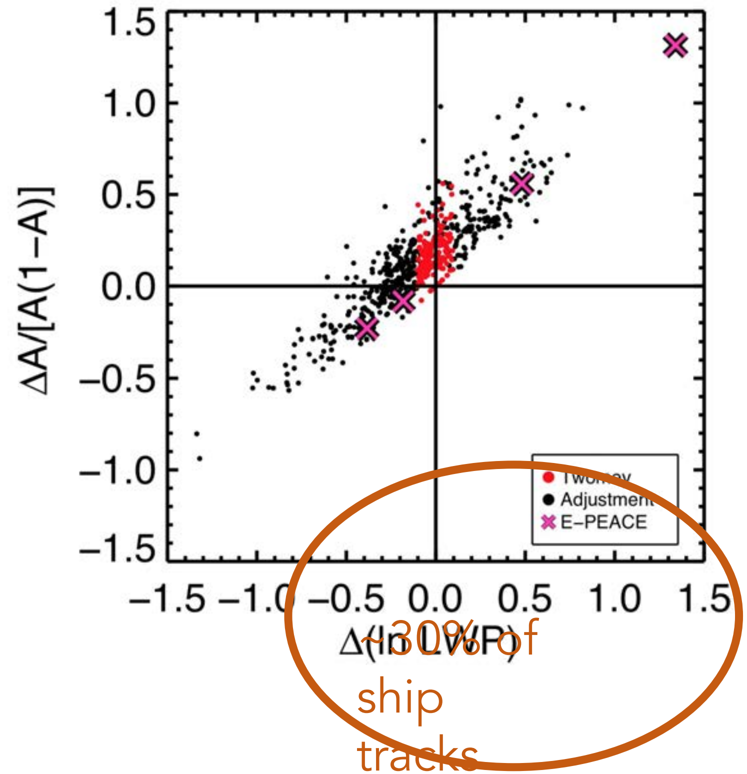
Increases in aerosol concentrations over the oceans may increase the amount of low-level cloudiness through a reduction in drizzle—a process that regulates the liquid-water content and the energetics of shallow marine clouds. The resulting increase in the global albedo would be in addition to the increase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



Inspiration for…

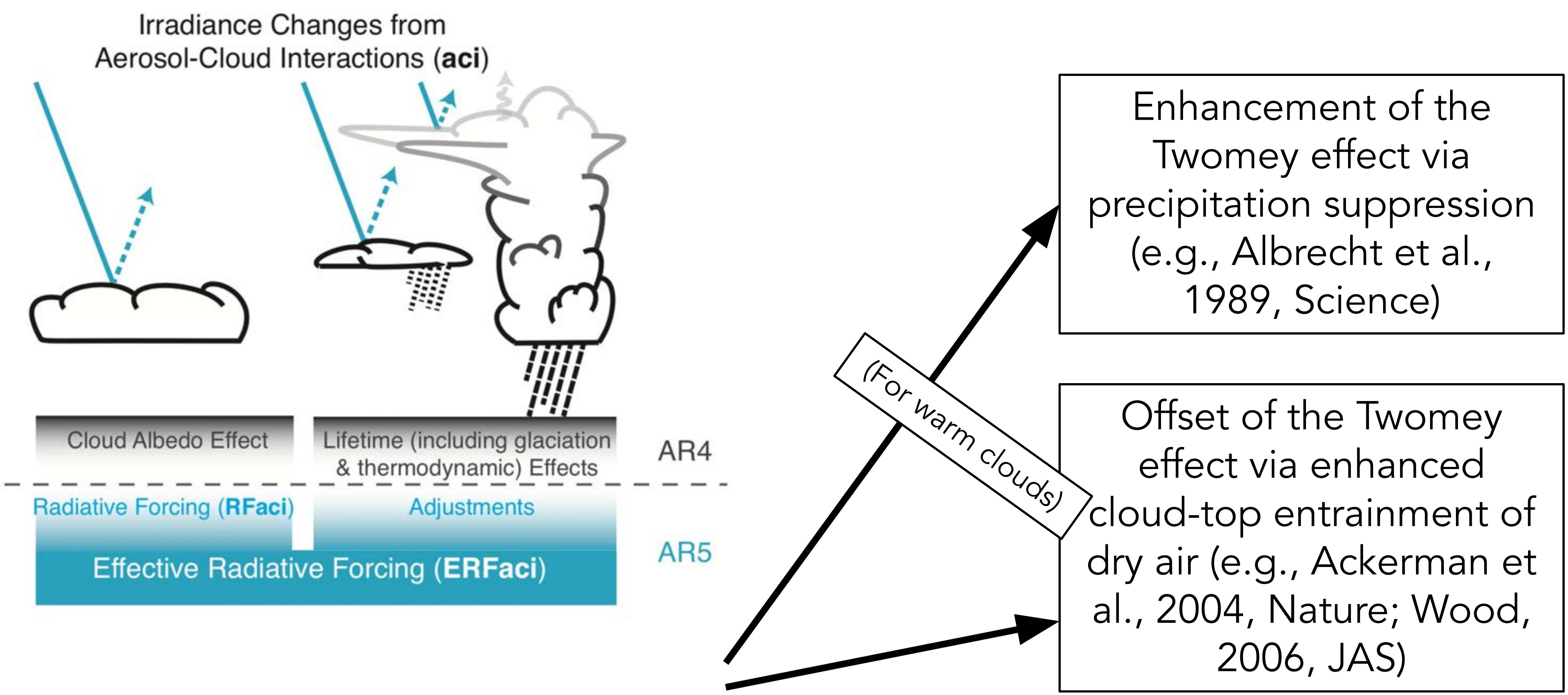
Some cloud darkening in ship tracks





Coakley & Walsh (2002), JAS

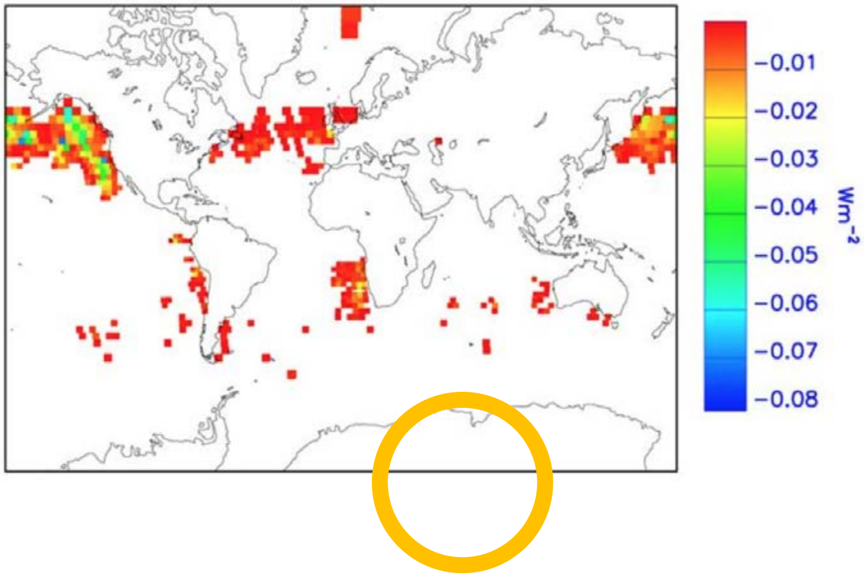
Chen et al. (2012), ACP



Boucher et al. (2013), IPCC AR5

Do ship tracks matter globally?

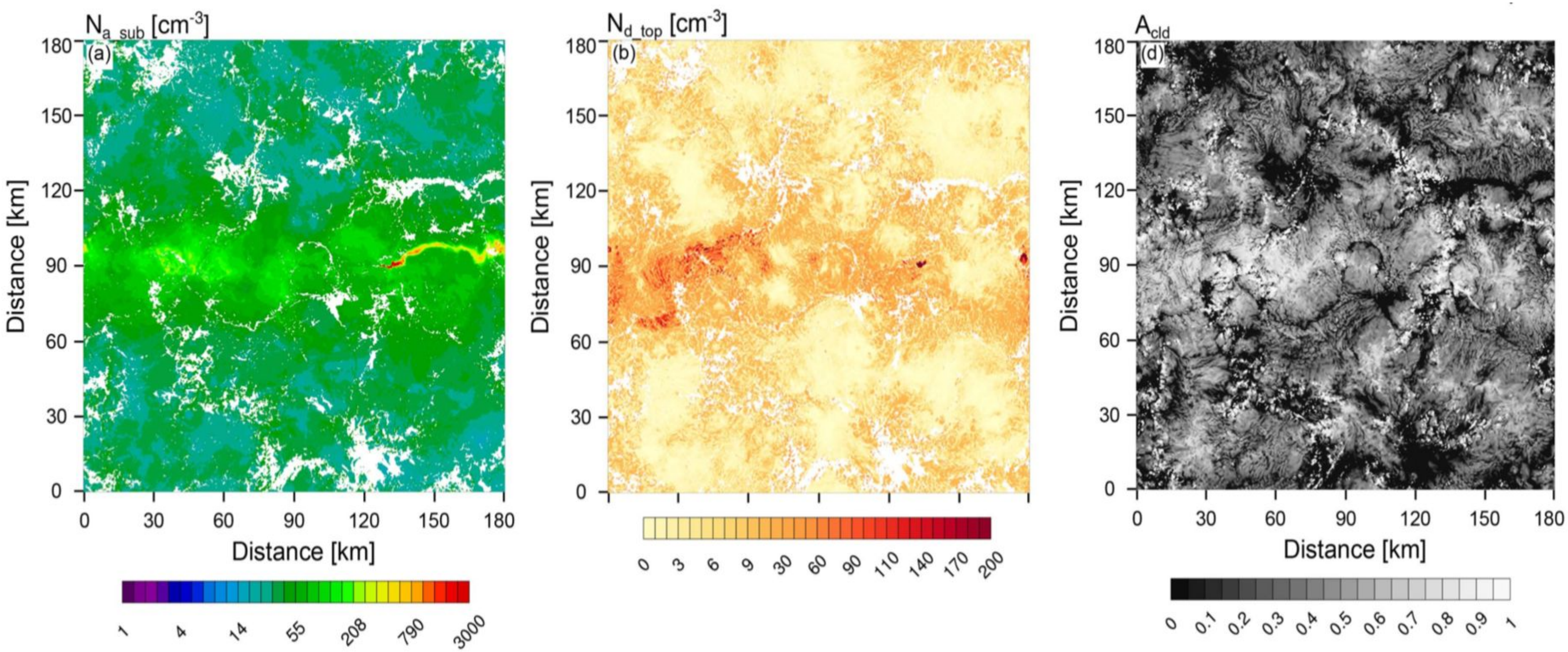
- Global ERF_{ACI} estimate of -0.0005 W/m^2 from one year's worth of ship track data from AATSR
- But model spread of ERF_{ACI} ranges from approximately -0.06 to -0.6 W/m^2...



Our region of focus

Schrier et al. (2007), GRL; Capaldo et al. (1999), Nature; Lauer et al. (2007), ACP

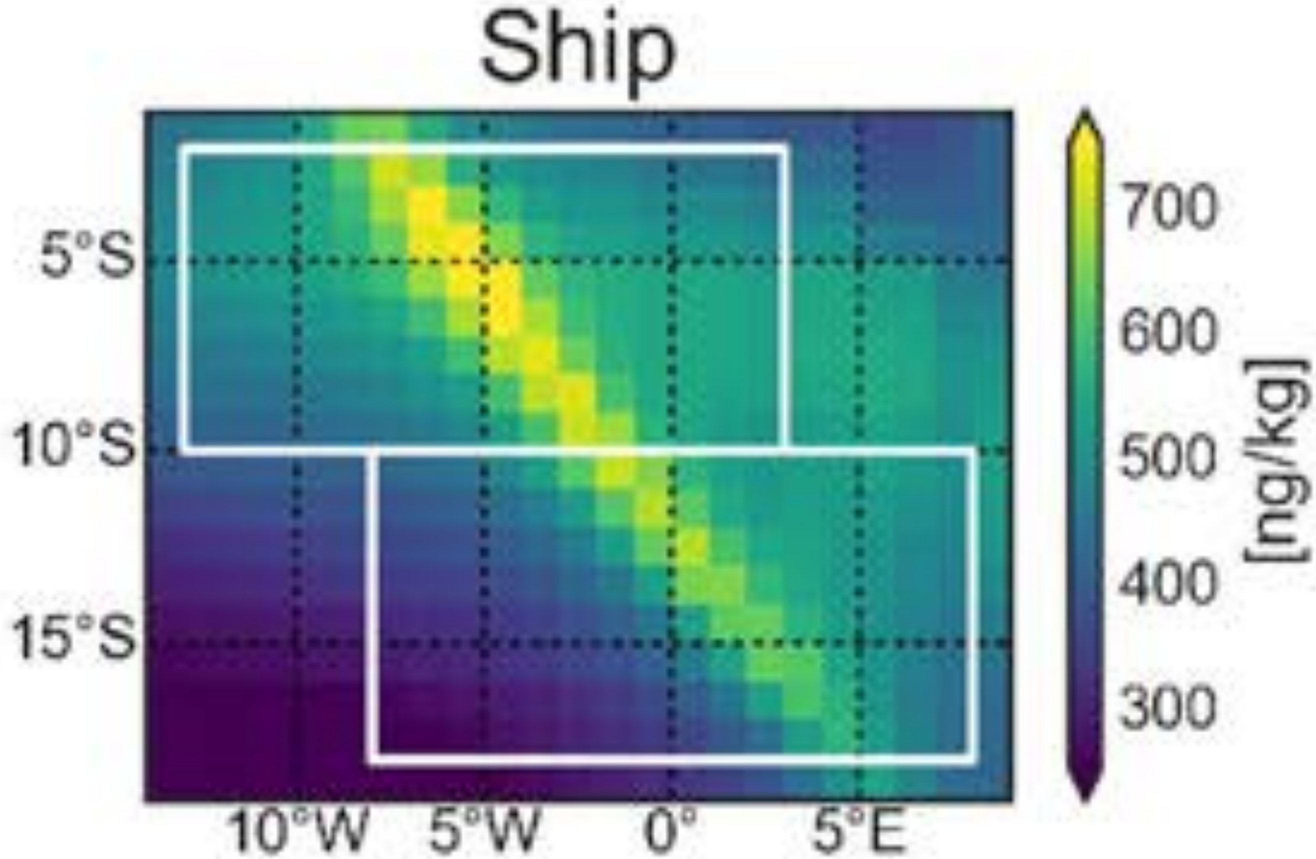
Ship tracks may not be readily visible given natural cloud variability



Possner et al. (2018), ACP

Methods: Universal kriging

Example: MERRA-2 surface [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

$$Y(\boldsymbol{s}) = \mu(\boldsymbol{s}, \boldsymbol{\beta}) + e(\boldsymbol{s})$$

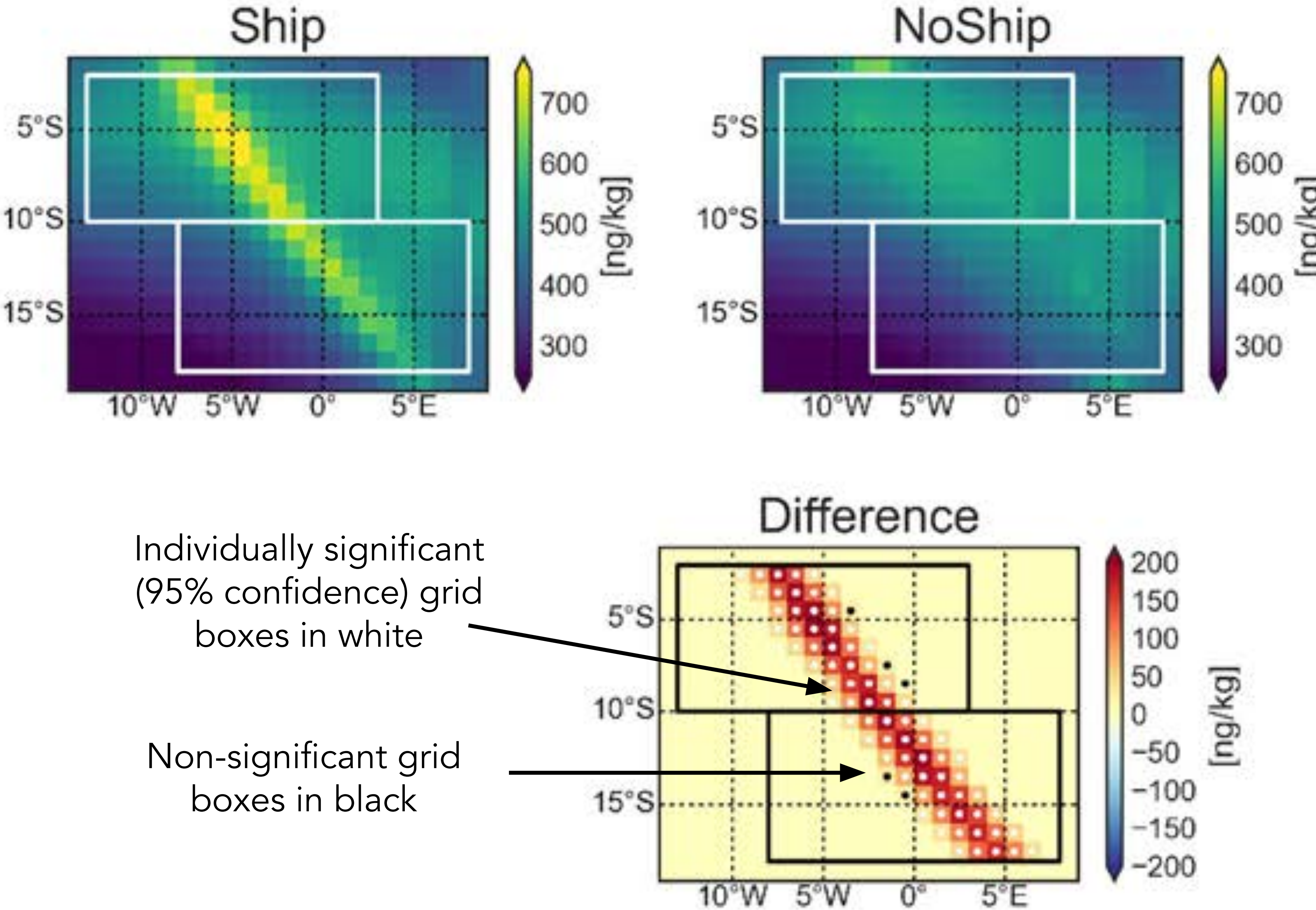
Variable of interest

Spatial location

Mean function

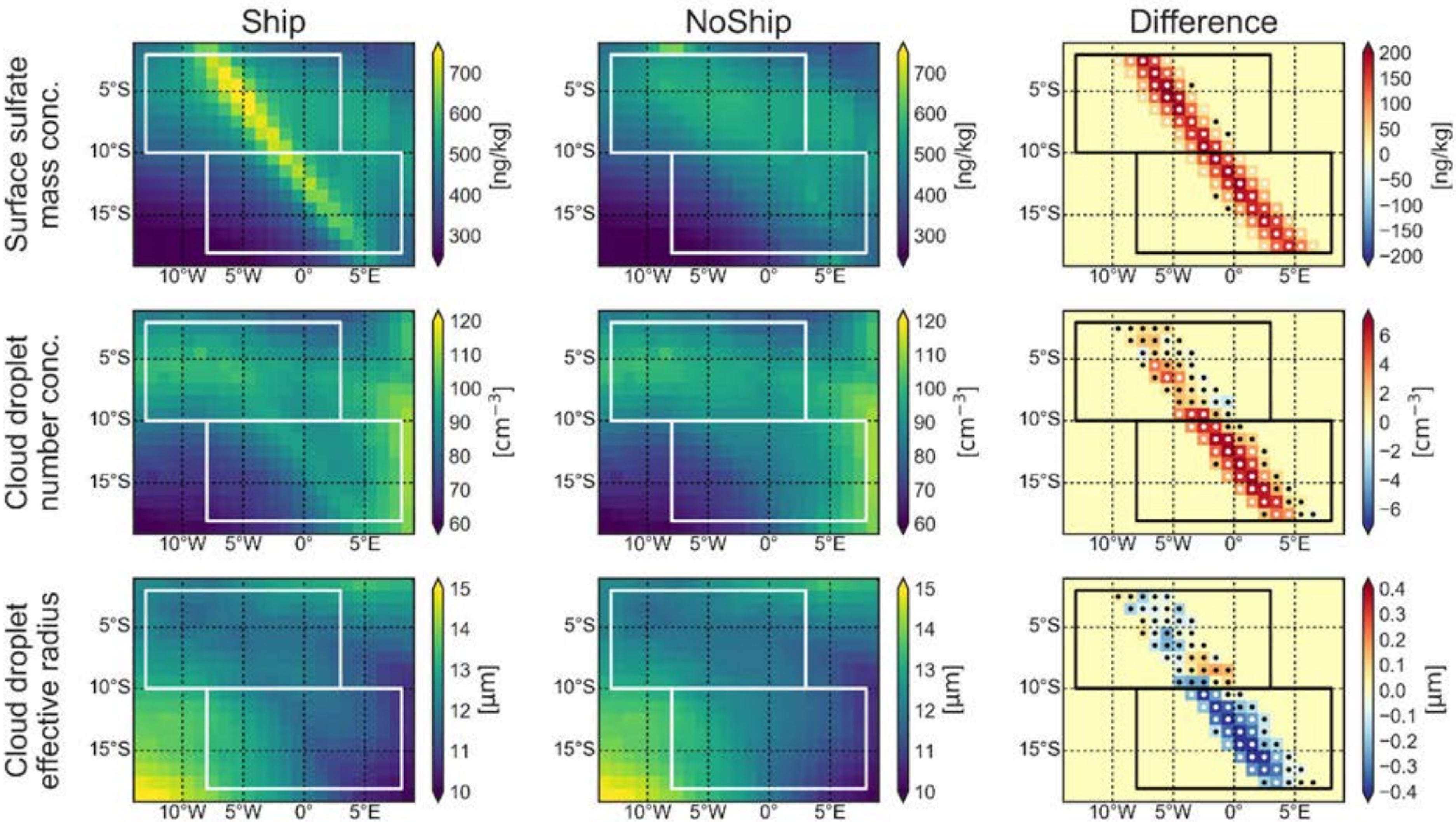
Regression coefficients
(lat, lon, lat^2, lon^2, lat*lon, LTS, LTS+advection)

Stationary error term
(function of distance only)

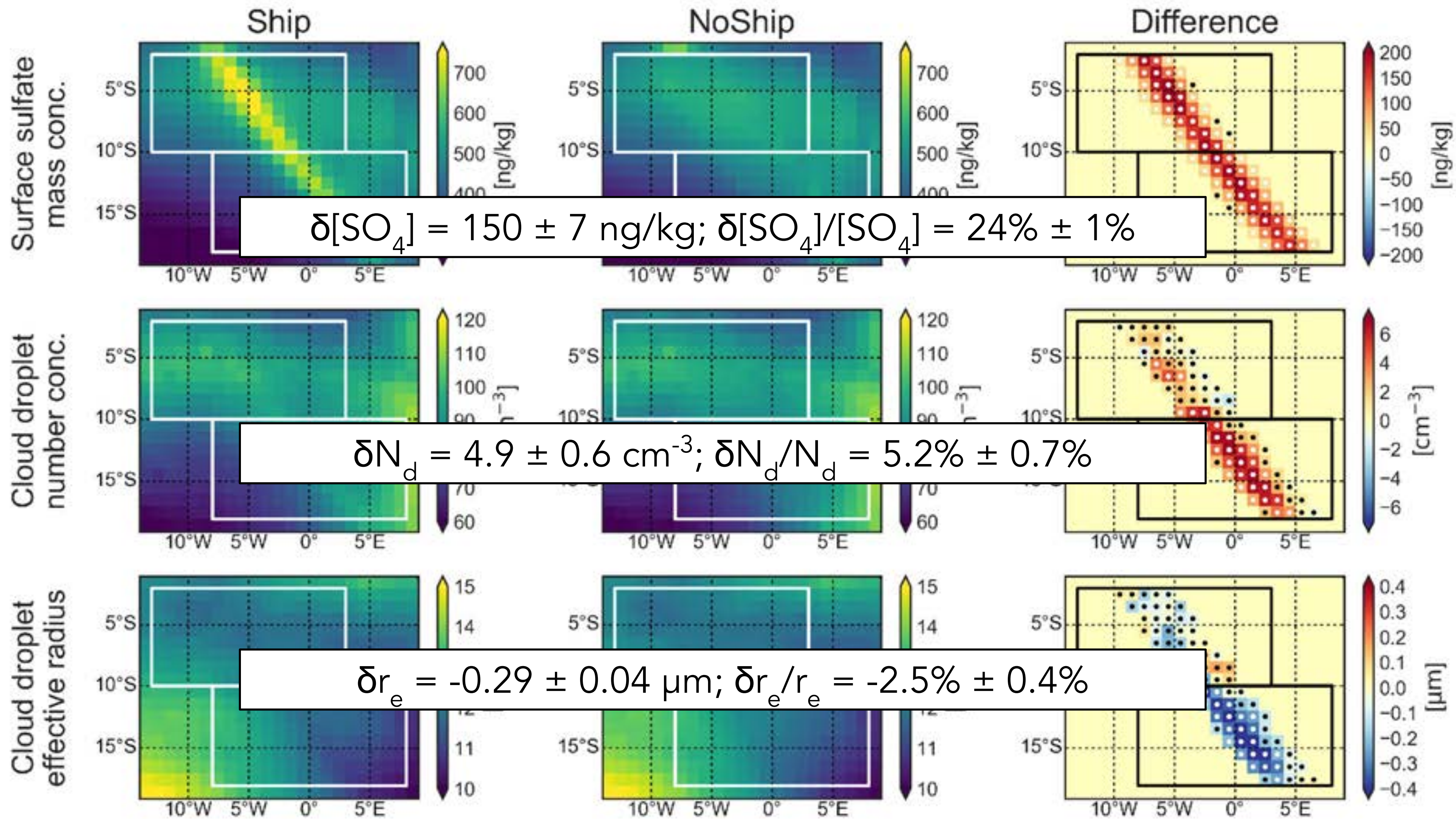


Ship
NoShip
Difference
5°S
10°S
15°S
10°W
5°W
0°
5°E
700
600
500
400
300
[ng/kg]
200
150
100
50
0
−50
−100
−150
−200
Individually significant (95% confidence) grid boxes in white
Non-significant grid boxes in black

Results: Microphysics



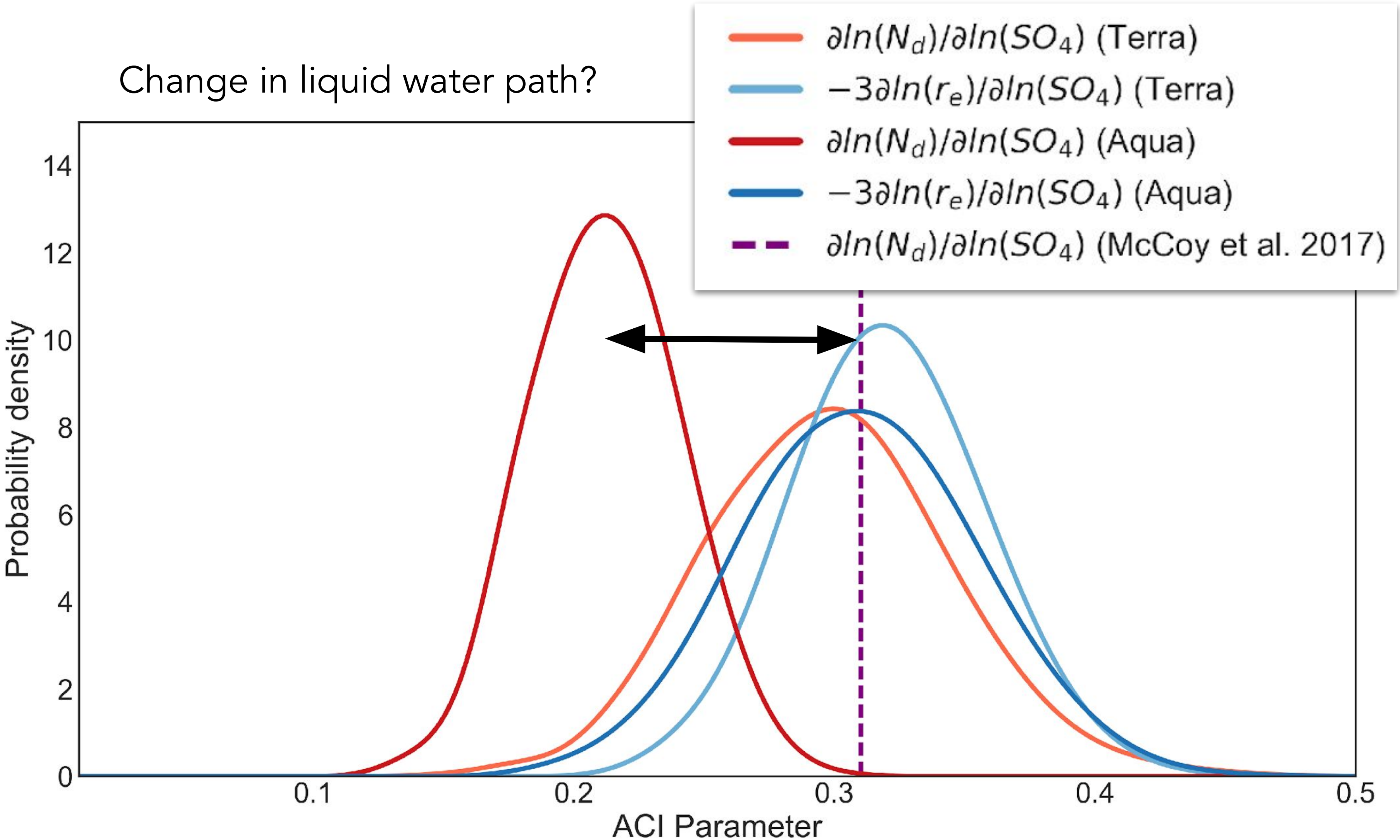
N_d & r_e from MODIS/Aqua

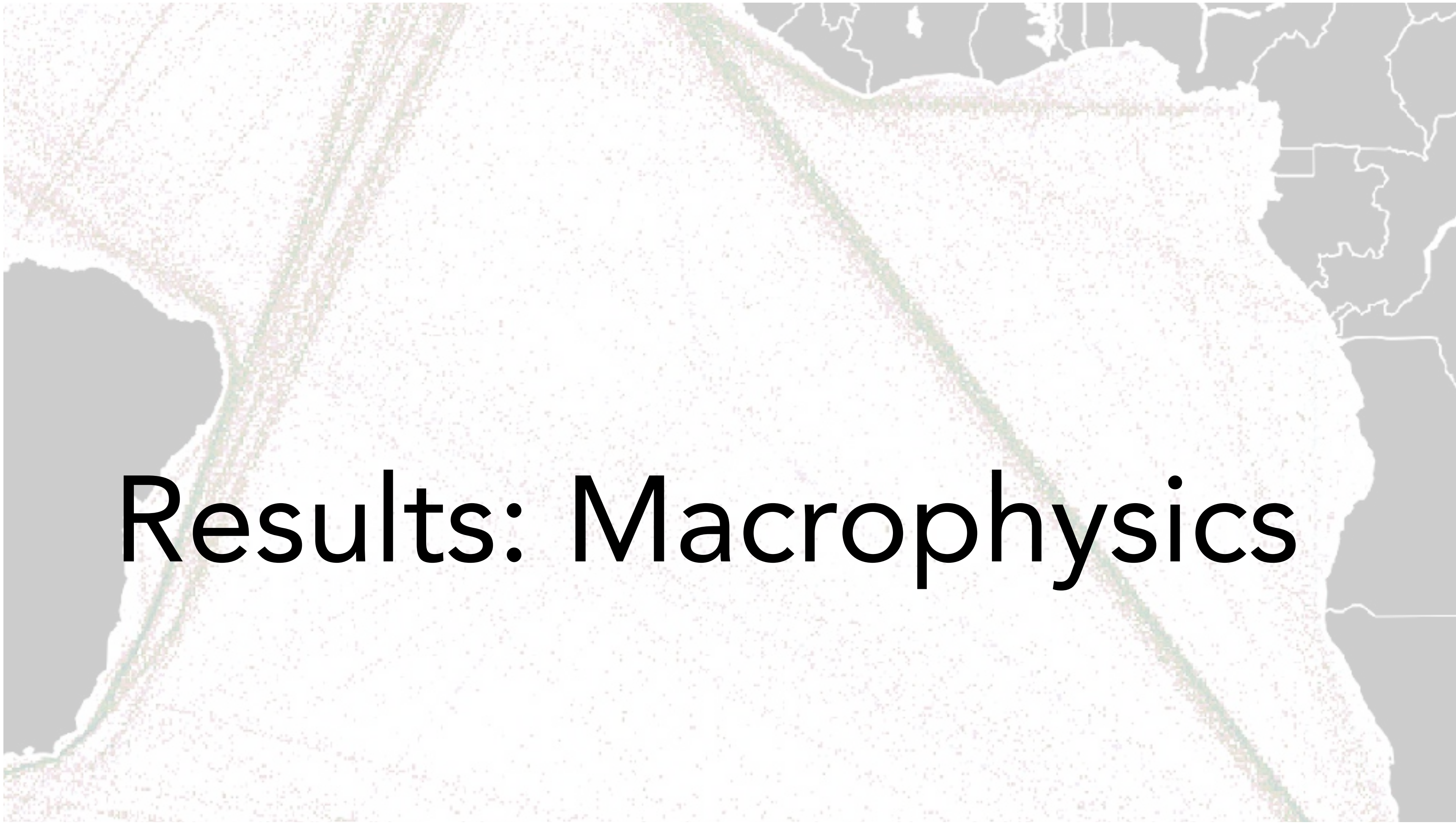


****Values for southern/stratocumulus-dominated region only****

Microphysical sensitivity to aerosol consistent with studies across the oceans

Change in liquid water path?





Results: Macrophysics

Cloud fraction changes

Time (local)	Mean value	Effect size	p_{field}
01:30 (Aqua)	95.98%	-0.04% ± 0.26%	1.0
10:30 (Terra)	88.09%	0.06% ± 0.34%	1.0
13:30 (Aqua)	91.30%	0.16% ± 0.42%	1.0
22:30 (Terra)	86.44%	-0.28% ± 0.36%	0.762

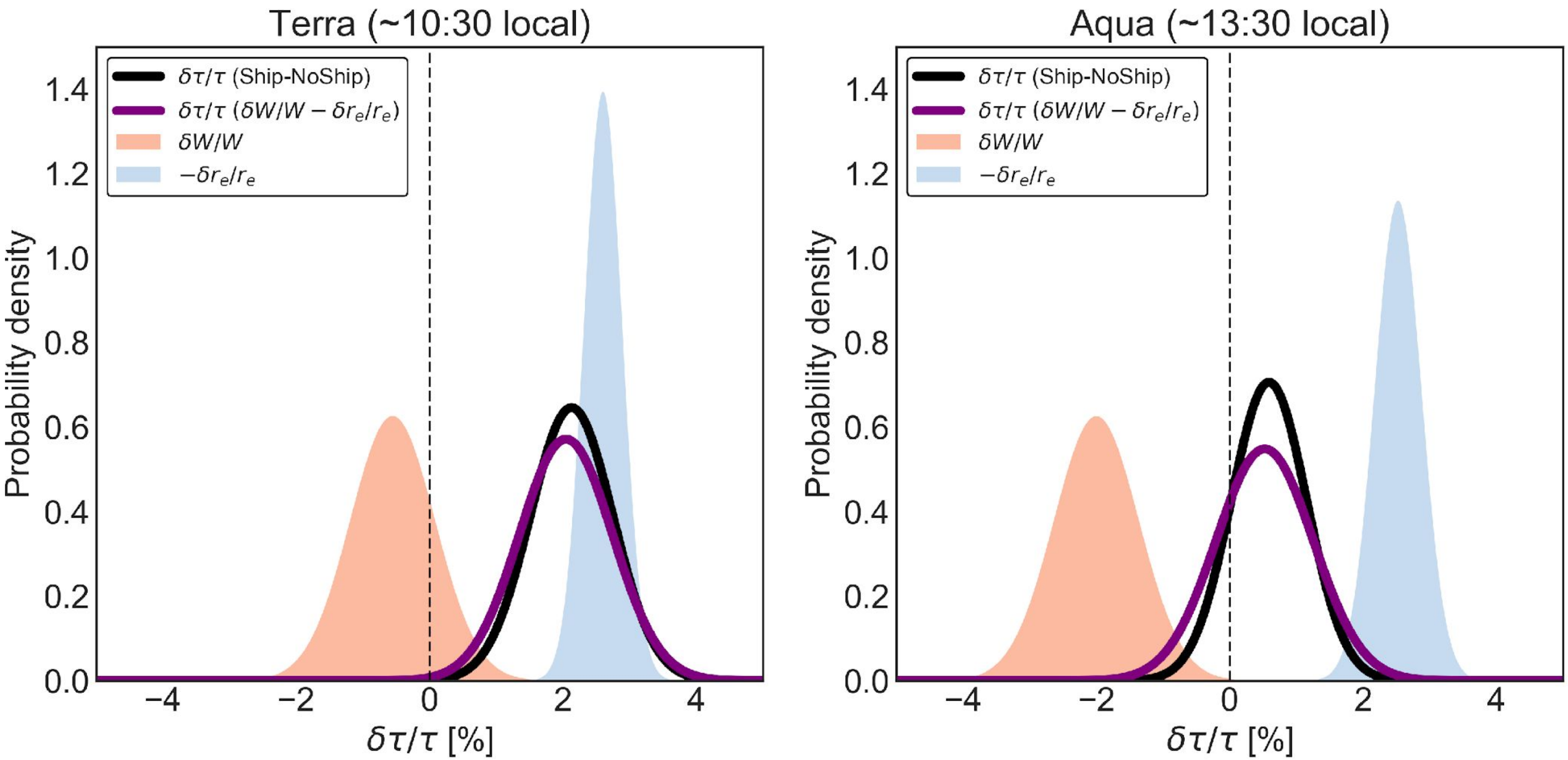
Cloud optical thickness

- Cloud optical thickness (τ) 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

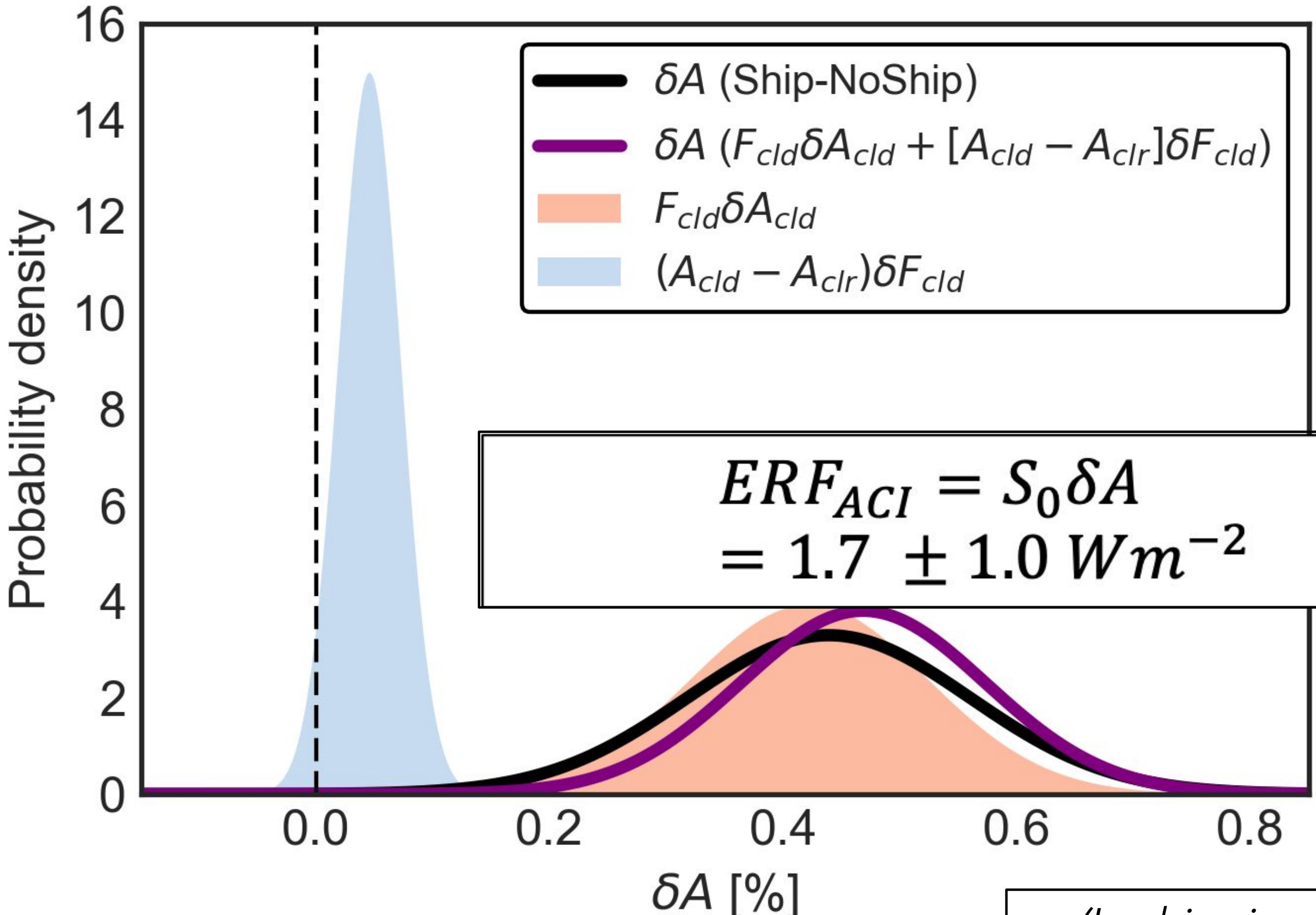
- All-sky albedo (A), clear-sky albedo (A_{clr}), and cloud fraction (F_{cld}) from CERES (Energy Balanced and Filled product) used to estimate cloud albedo (A_{cld}):

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

- 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:

$$\delta A \approx F_{cld}\delta A_{cld} + (A_{cld} - A_{clr})\delta F_{cld}$$

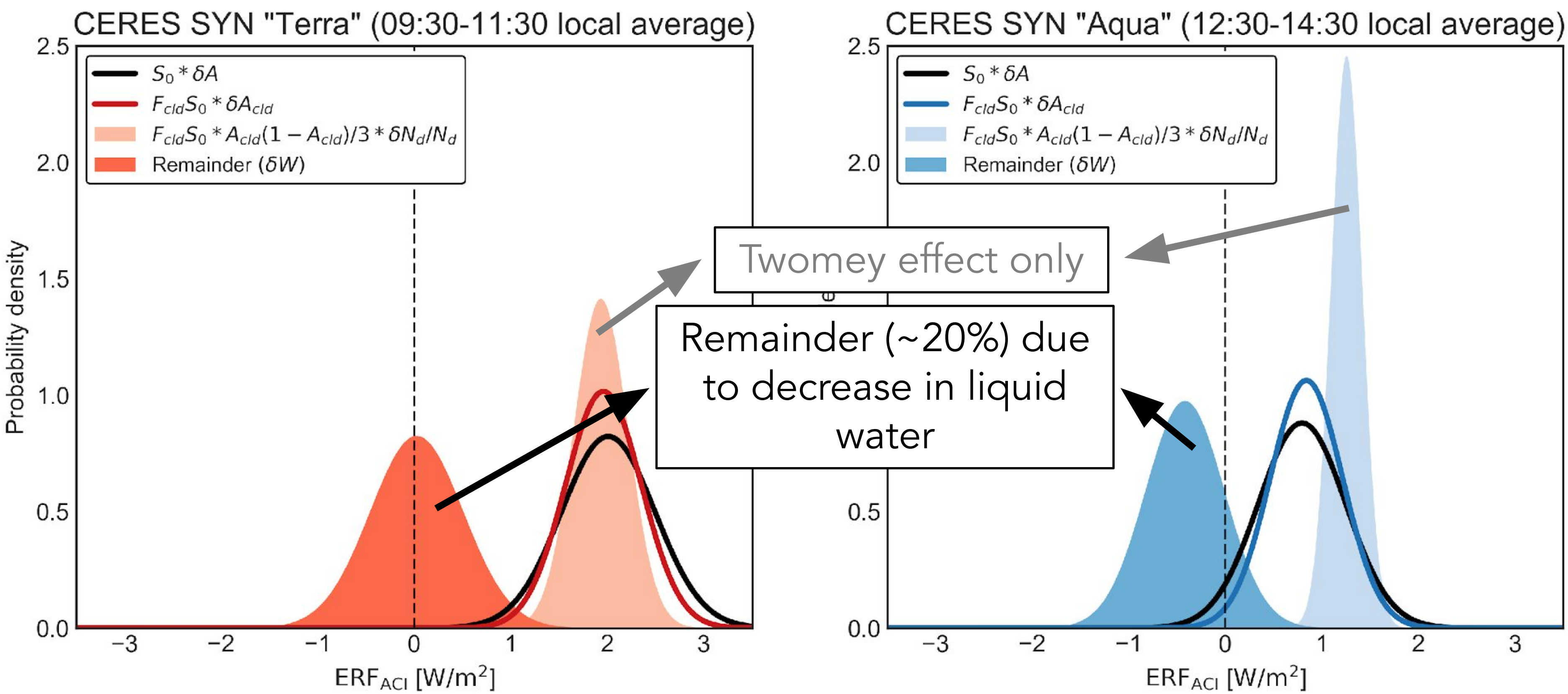
Cloud fraction increases are negligible



$$ERF_{ACI} = S_0 \delta A$$
$$= 1.7 \pm 1.0\, Wm^{-2}$$

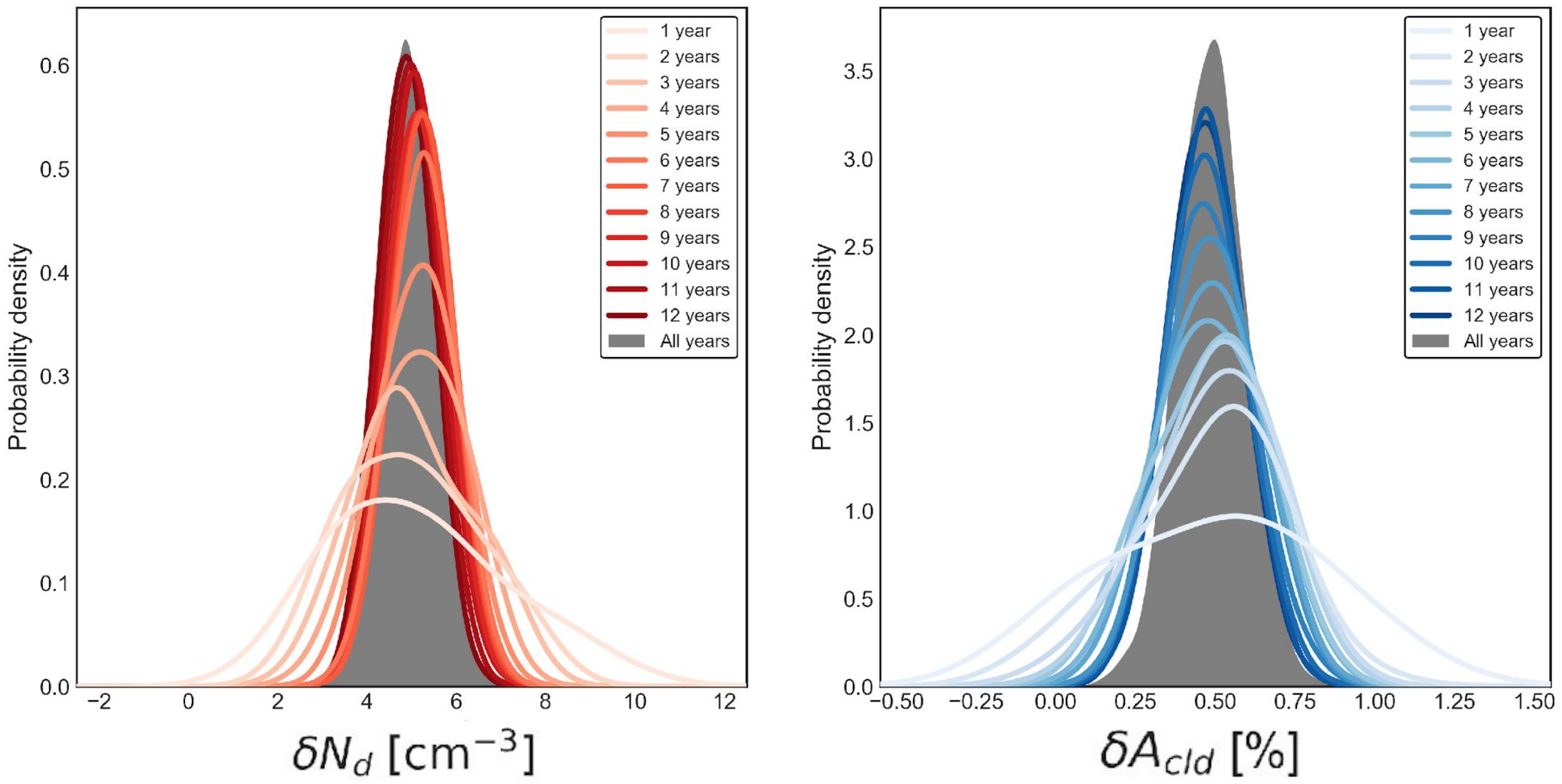
(In shipping lane only)

LWP adjustment is negative but quite weak



Detectability

It takes ~5-6 years for signal to become clear



Climatic Change (2013) 121:459–472
DOI 10.1007/s10584-013-0932-z

Defining success and limits of field experiments to test geoengineering by marine cloud brightening

Robert Wood · Thomas P. Ackerman

AGU PUBLICATIONS

Earth's Future

COMMENTARY
10.1002/2017EF000601

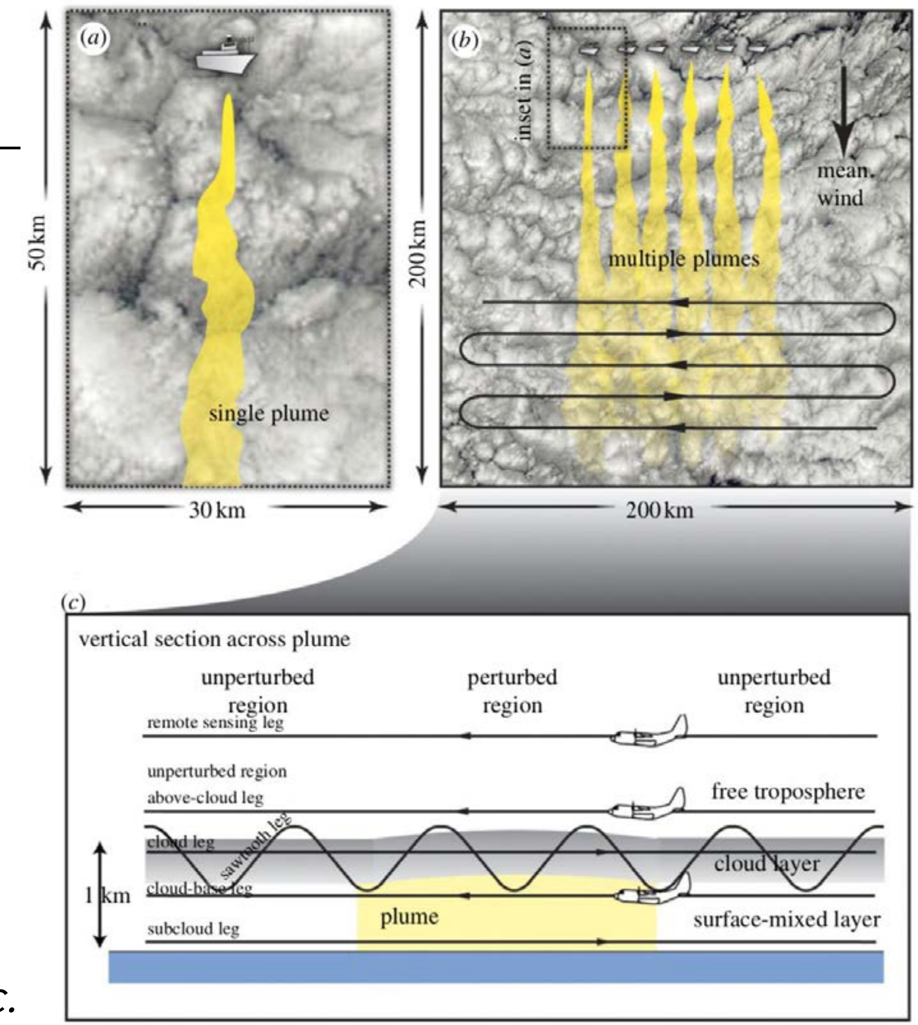
Could geoengineering research help answer one of the biggest questions in climate science?

Robert Wood[1], Thomas Ackerman[1], Philip Rasch[2], and Kelly Wanser[3]

nature climate change
LETTERS
https://doi.org/10.1038/s41558-019-0398-8

Halving warming with idealized solar geoengineering moderates key climate hazards

Peter Irvine[1*], Kerry Emanuel[2], Jie He[3,4,5], Larry W. Horowitz[4], Gabriel Vecchi[6] and David Keith[1]



Latham et al. (2012), Phil. Trans. R. Soc.

Implications for 2020 IMO regulations

RESOLUTION MEPC.280(70)
(Adopted on 28 October 2016)
EFFECTIVE DATE OF IMPLEMENTATION OF THE FUEL OIL STANDARD IN
REGULATION 14.1.3 OF MARPOL ANNEX VI

ANNEX 6

RESOLUTION MEPC.280(70)
(Adopted on 28 October 2016)

EFFECTIVE DATE OF IMPLEMENTATION OF THE FUEL OIL STANDARD IN REGULATION 14.1.3 OF MARPOL ANNEX VI

THE MARINE ENVIRONMENT PROTECTION COMMITTEE,

RECALLING Article 38(a) of the Convention on the International Maritime Organization concerning the functions of the Marine Environment Protection Committee conferred upon it by international conventions for the prevention and control of marine pollution from ships,

RECALLING ALSO that the revised MARPOL Annex VI entered into force on 1 July 2010,

RECALLING FURTHER that regulation 14.1.3 of MARPOL Annex VI stipulates that the sulphur content of any fuel oil used on board ships shall not exceed 0.50% m/m on or after 1 January 2020,

RECALLING that regulations 14.8 to 14.10 of MARPOL Annex VI require that a review shall be completed by 2018 to determine the availability of fuel oil to comply with the fuel oil standard

😊 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

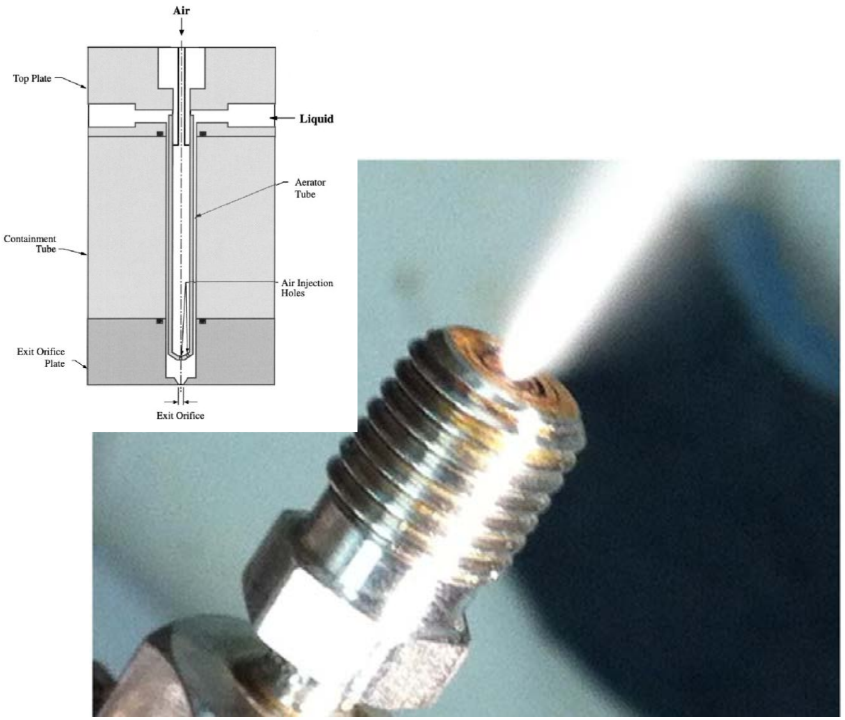
😓 Work to do in detection/attribution of forcing change. Will we have the global observing system in place to detect these changes?

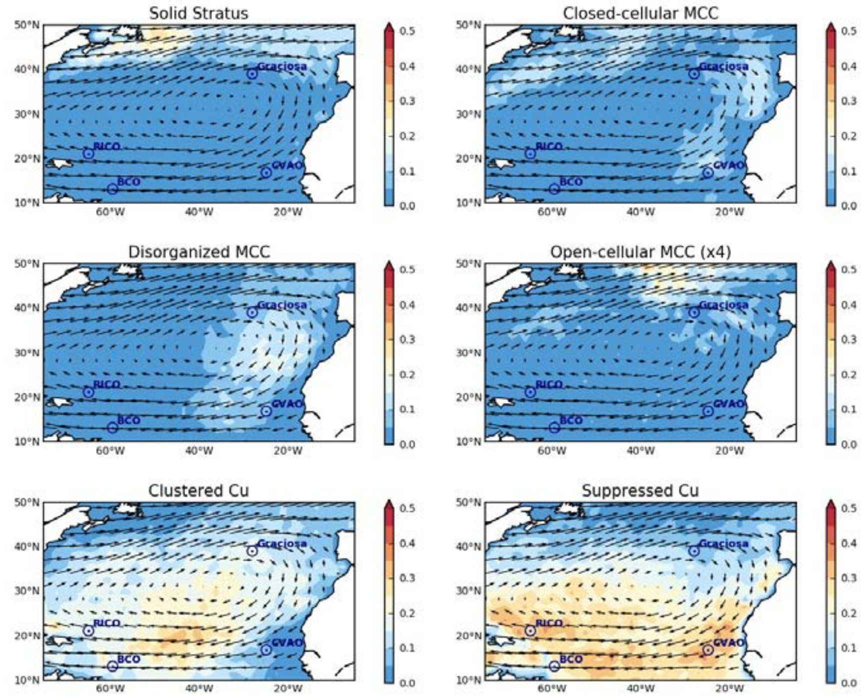
Stay tuned for estimates of global shipping radiative forcing and ERFaci

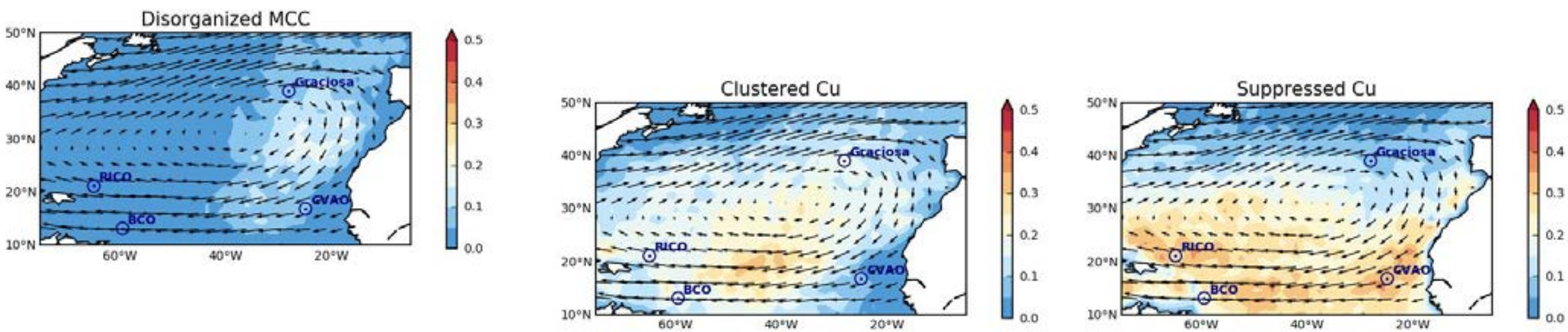
Summary and conclusions

- 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 ERF_{ACI} due to shipping from some models may be unrealistic

A new Instrument for Cloud Physics

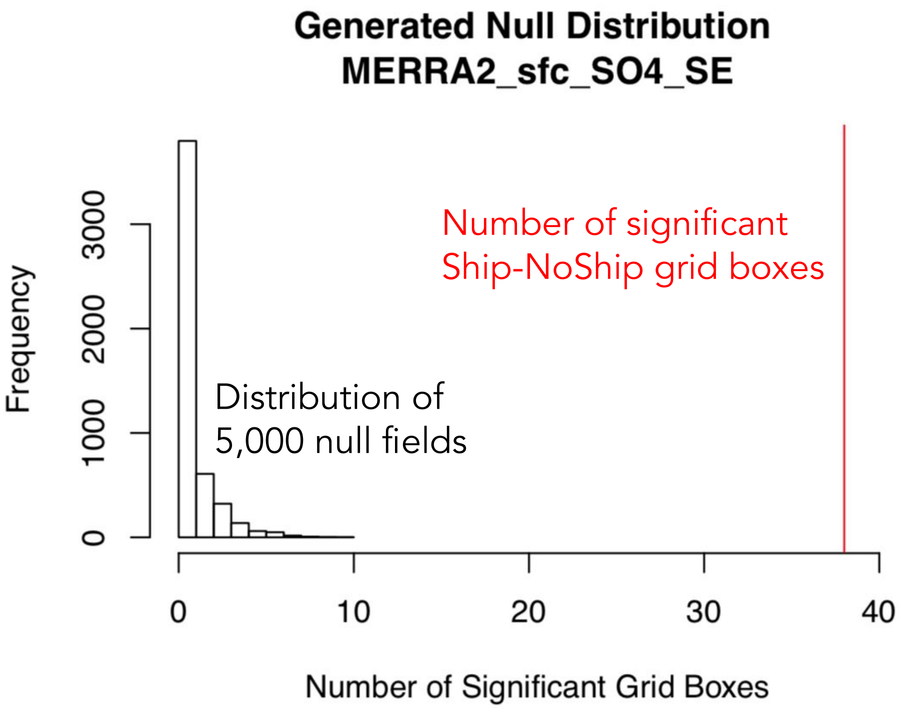



Solid Stratus
Closed-cellular MCC
Disorganized MCC
Open-cellular MCC (x4)
Clustered Cu
Suppressed Cu
50°N
40°N
30°N
20°N
10°N
60°W
40°W
20°W
Graciosa
RICO
GVAO
BCO
0.5
0.4
0.3
0.2
0.1
0.0


Disorganized MCC
Clustered Cu
Suppressed Cu
50°N
40°N
30°N
20°N
10°N
60°W
40°W
20°W
Graciosa
RICO
GVAO
BCO
0.5
0.4
0.3
0.2
0.1
0.0

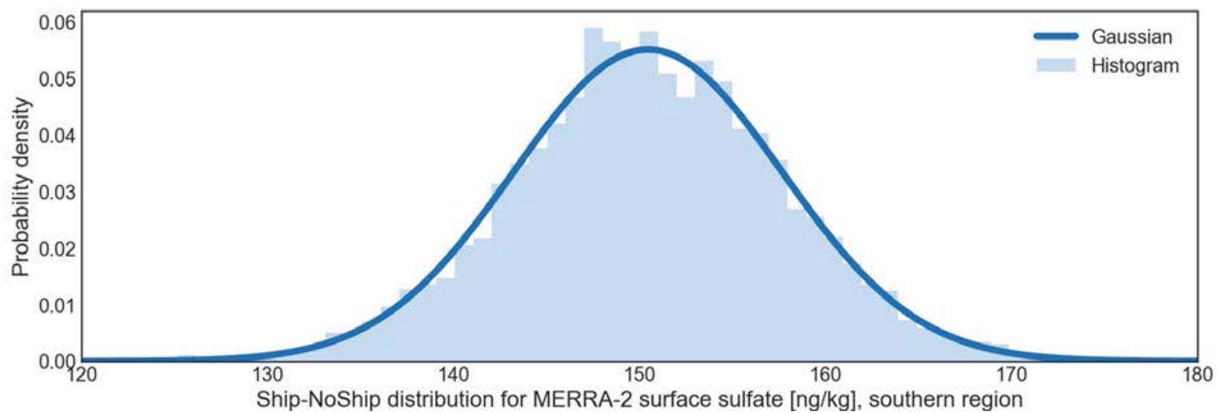
Field significance

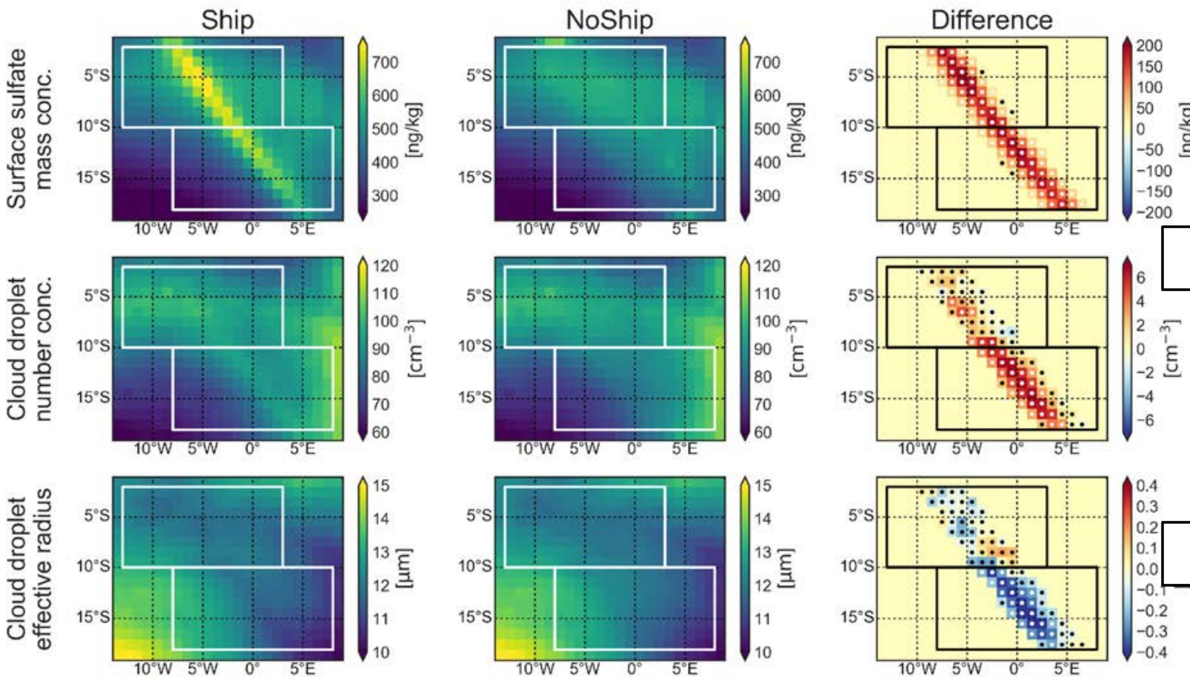
- 5,000 kriged fields are simulated to test for significance and estimate effect size
- Variables are field significant if the number of significant Ship-NoShip grid boxes is extreme compared to the number expected by chance



Effect size

- For each of the 5,000 kriged fields, effect size is measured as the Ship-NoShip difference for grid boxes with $\delta[SO_4]/[SO_4] > 20\%$
  - Avoid flanks of the aerosol-perturbed area





$p_{field} = 0$

$p_{field} = 0$

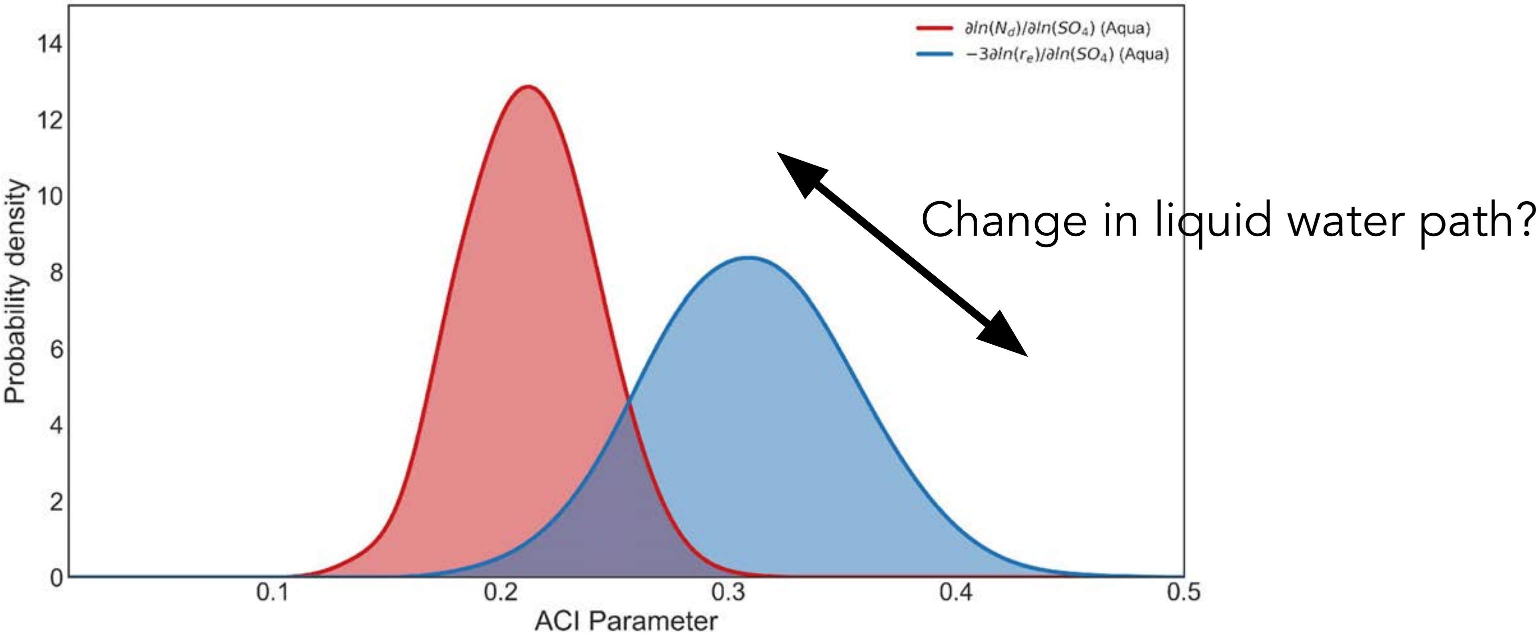
$p_{field} = 0.03$

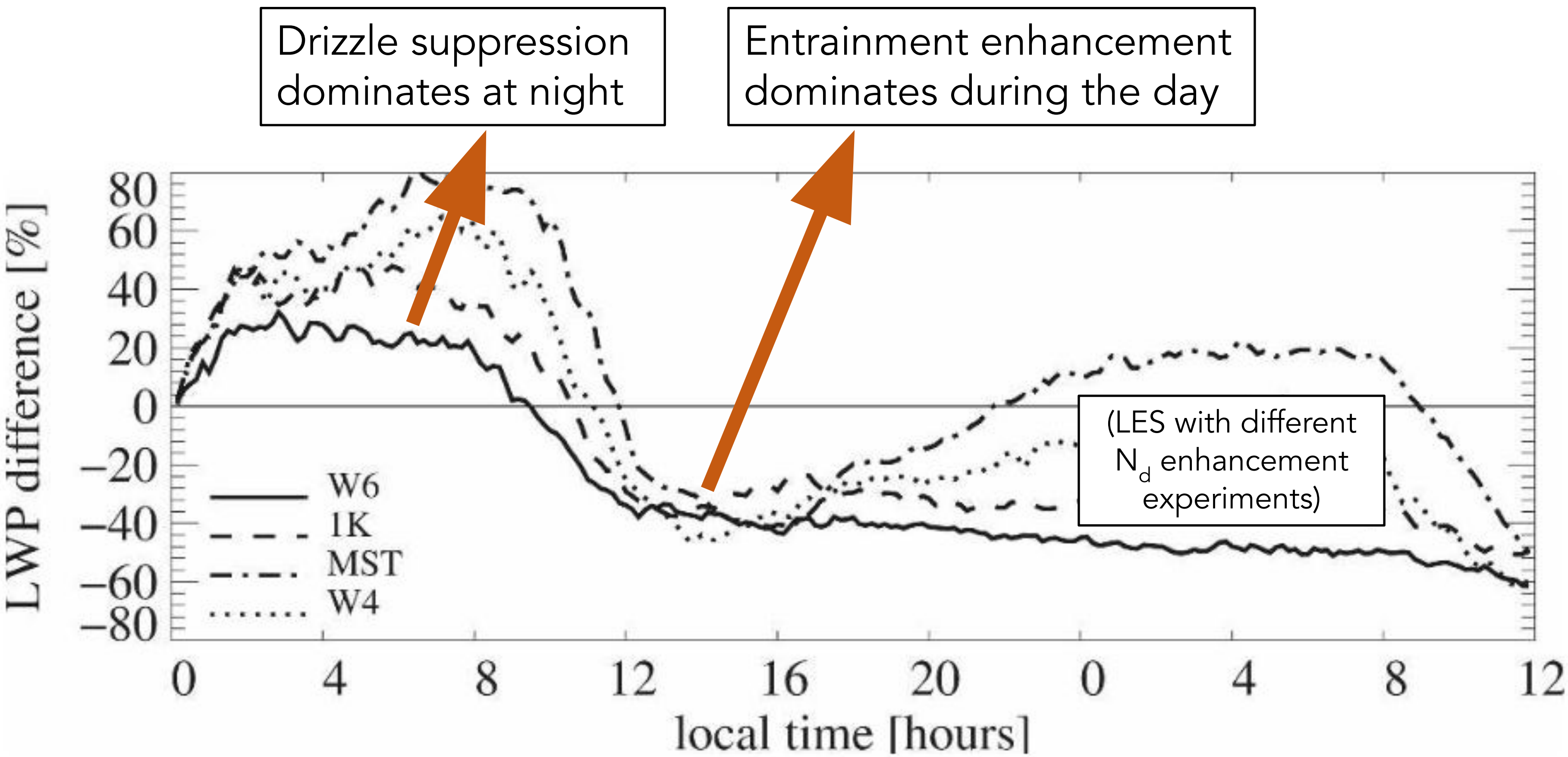
$p_{field} = 0$

$p_{field} = 1$

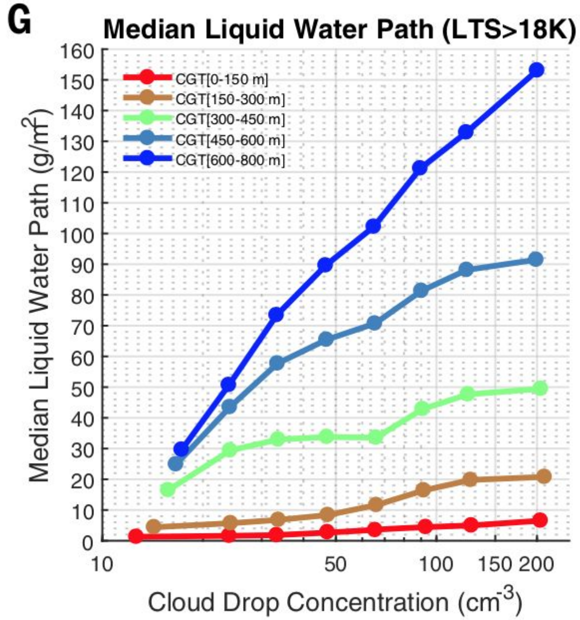
$p_{field} = 0$

N_d & r_e from MODIS/Aqua


$\partial ln(N_d)/\partial ln(SO_4)$ (Aqua)
$-3\partial ln(r_e)/\partial ln(SO_4)$ (Aqua)
Probability density
ACI Parameter
0
2
4
6
8
10
12
14
0.1
0.2
0.3
0.4
0.5
Change in liquid water path?



Sandu et al. (2008), JAS



Rosenfeld et al. (2019), Science

Table 1. The susceptibility of Cf, LWP, and CRE to N_d, based on the slopes of the lines of figs. S1 and S2. The numbers are based on the means and standard deviations of the slopes of the lines for the different CGTs in each panel.

LTS	All	LTS > 18 K	18 K ≥ LTS ≥ 14 K	LTS < 14 K
$\partial \ln(Cf)/\partial \ln(N_d)$	0.38 ± 0.06	0.32 ± 0.07	0.34 ± 0.06	0.23 ± 0.06
$\lambda = \partial \ln(LWP)/\partial \ln(N_d)$	0.58 ± 0.10	0.47 ± 0.08	0.50 ± 0.08	0.40 ± 0.14
$\partial \ln(CRE)/\partial \ln(N_d)$	0.76 ± 0.08	0.68 ± 0.08	0.69 ± 0.07	0.56 ± 0.04

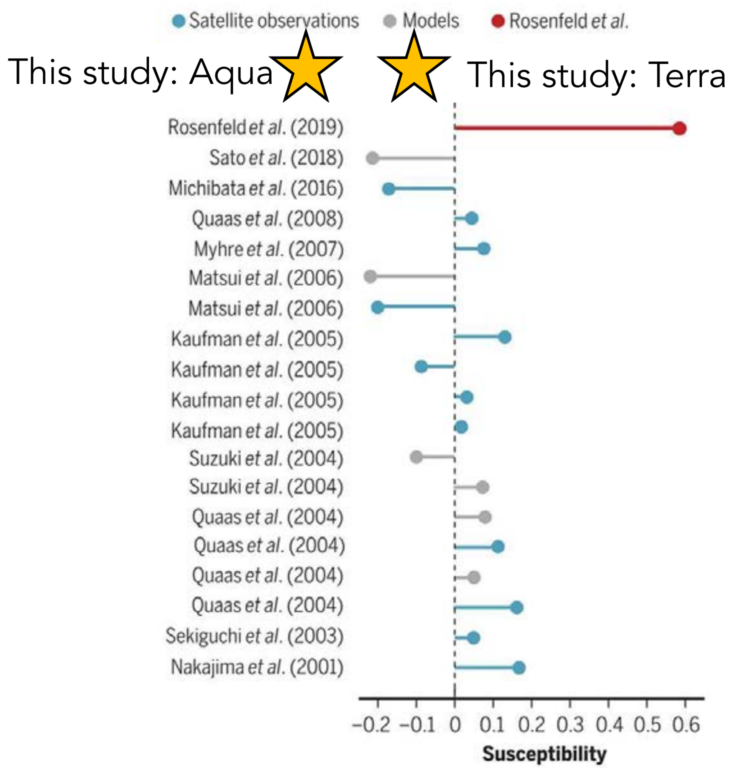
For our $\delta N_d/N_d$ of ~5% (for Aqua), Rosenfeld et al.'s values would predict a LWP increase of ~2.5%…

We instead see a 2% decrease in LWP!

- Consistent with previous work on ship tracks (even though we're not focusing on tracks alone)

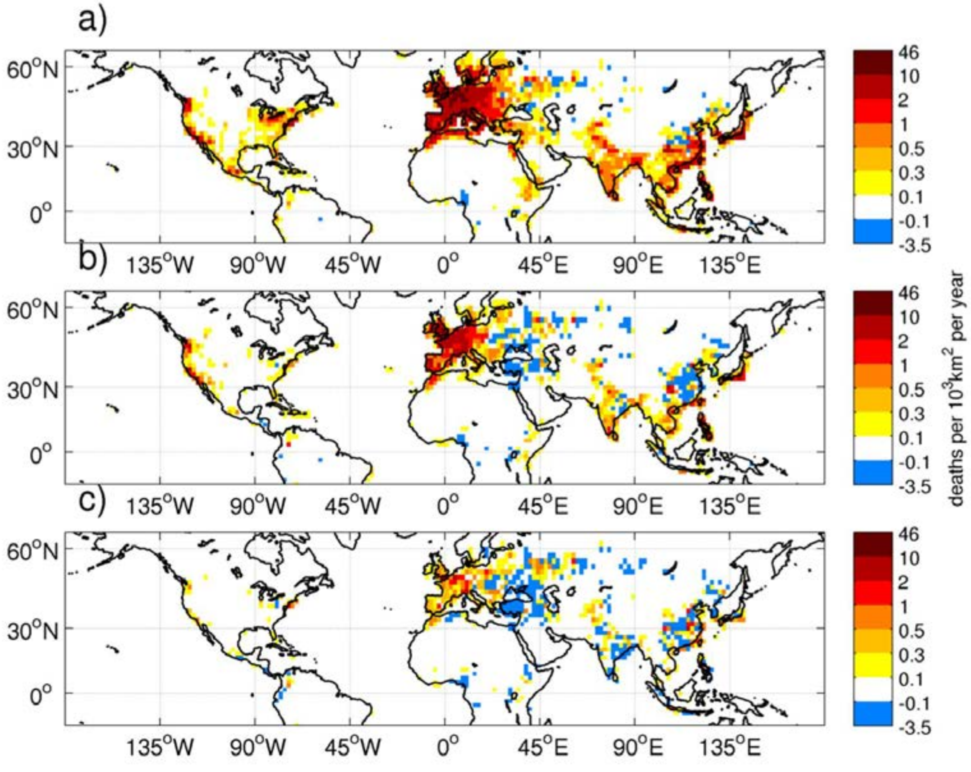
Two decades of cloud susceptibility estimates $\equiv \dfrac{\partial \ln(LWP)}{\partial \ln(N_d)}$

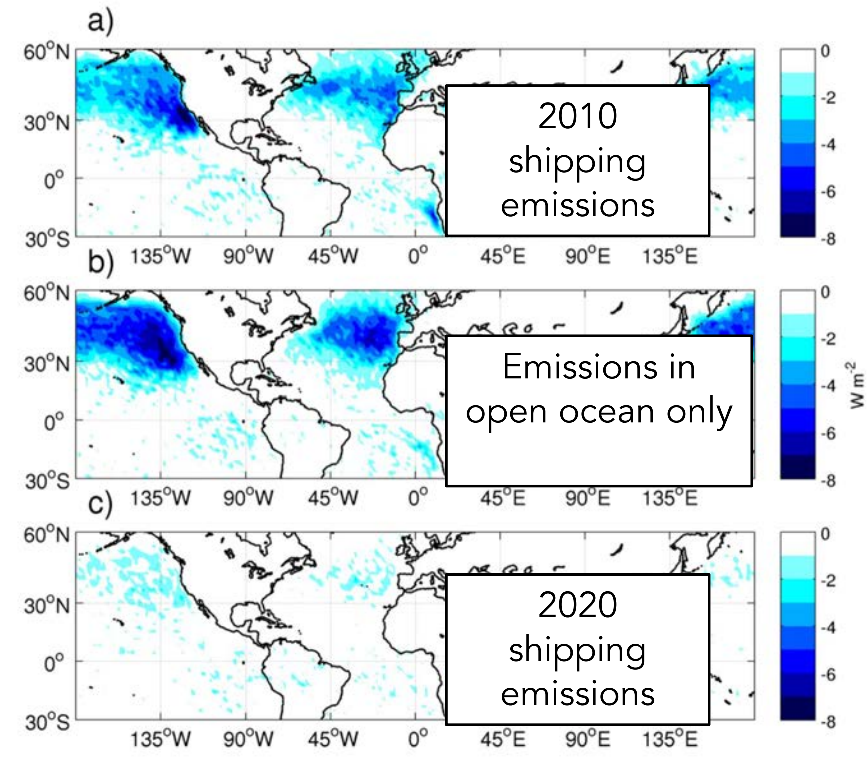
Numerous model and observational studies have estimated the effect of increased aerosols on cloudiness, a quantity termed cloud susceptibility. Rosenfeld *et al.* obtain a higher estimate by separating meteorological from aerosol effects on clouds. See supplementary materials for a full list of references.



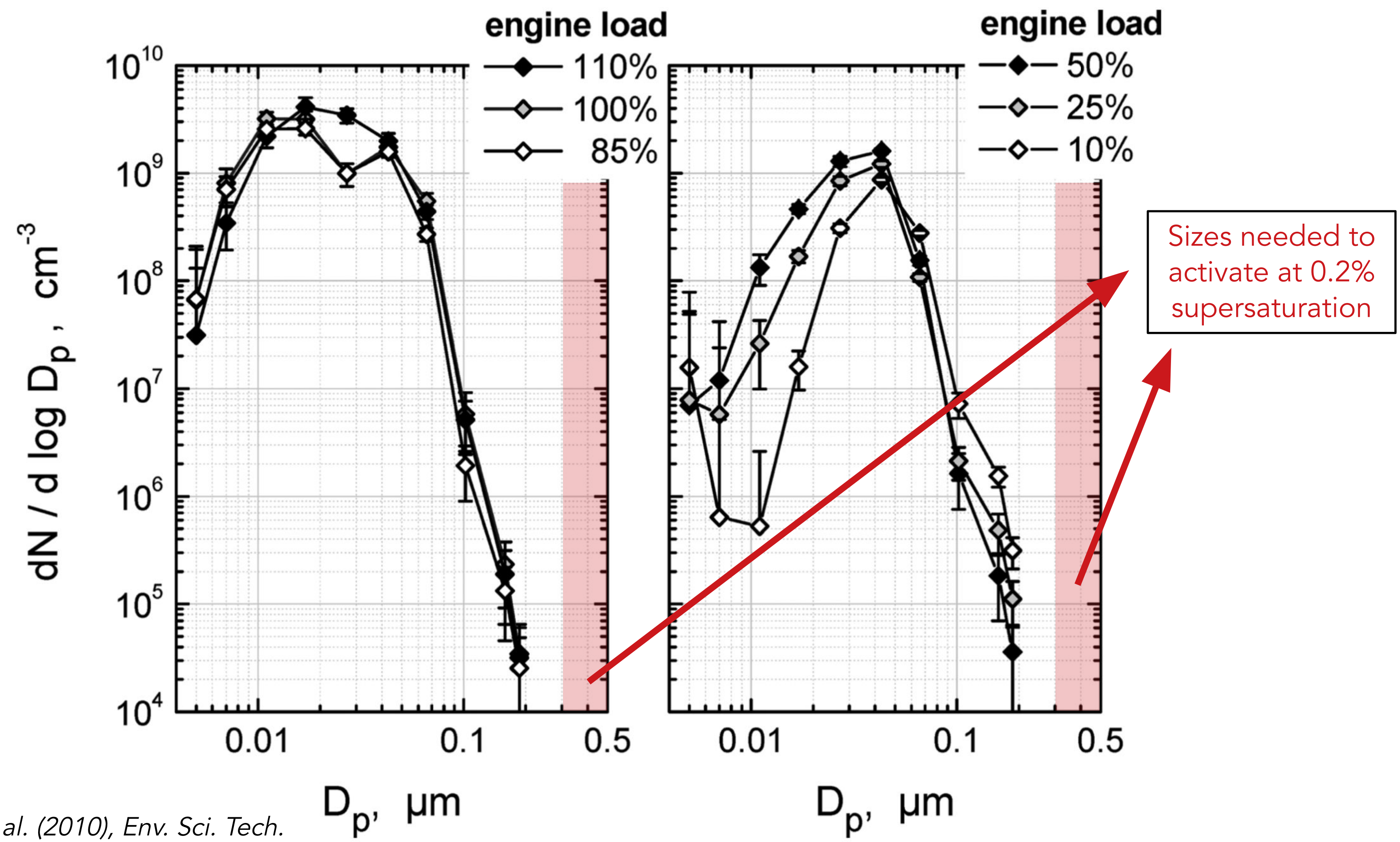
Sato & Suzuki (2019), Science

Proposals to use global shipping fleet for geoengineering





Partanen et al. (2013), ACP



Petzold et al. (2010), Env. Sci. Tech.

Stay tuned for global shipping radiative forcing and ERF_{aci}

- Radiative forcing efficiency (per percentage increase in $[SO_4]$) in southeast Atlantic during SON can be estimated as:

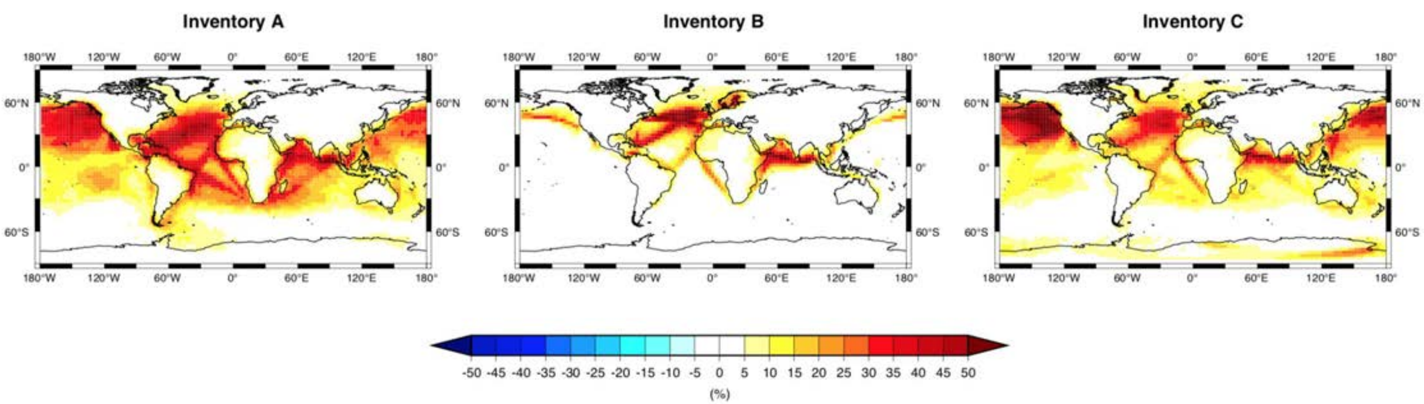
$$\frac{\mathrm{ERF_{ACI}}}{\delta[SO_4]/[SO_4]} = \frac{-1.7 \pm 1.0\, Wm^{-2}}{24.4\% \pm 1.2\%} = -0.07\ \pm 0.04\, Wm^{-2}\%^{-1}$$

  - 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 ± 0.04 $W/m^2/\%$

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

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

- Multiplying by 0.25 (for ocean low cloud coverage) and 5% (for shipping sulfate burden), we get -0.09 ± 0.05 W/m^2

Global forcing estimate (rough)

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- Multiplying by 0.25 (for ocean low cloud coverage) and 5% (for shipping sulfate burden), we get -0.09 ± 0.05 W/m^2

- Model estimates are high: -0.6 W/m^2 forcing from Lauer et al. (2007), -0.45 W/m^2 from Peters et al. (2013) likely too large
  - Very close agreement with -0.11 “base estimate” from Capaldo et al. (1999), Nature

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  - Very close agreement with -0.11 "base estimate" from Capaldo et al. (1999), Nature

- Ship-track-only estimates far too low: For southeast Atlantic shipping lane, Schrier et al. (2007) method is two orders of magnitude too small