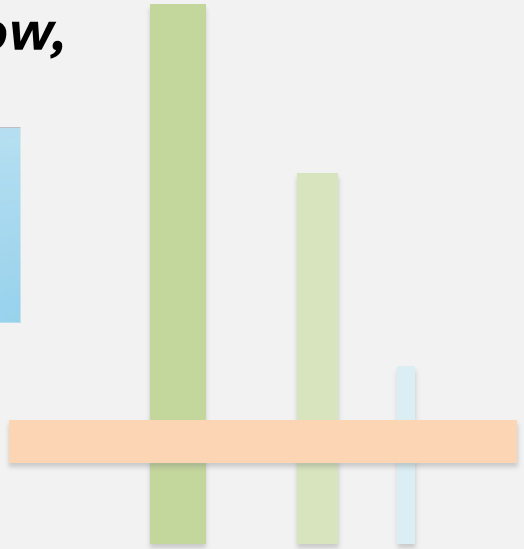
# New Insights on Aerosol Indirect Effects and Forcing from Ship Emissions and Their Impacts on Marine Low clouds

***- uncertain in the past, improving now, and still important in the future***

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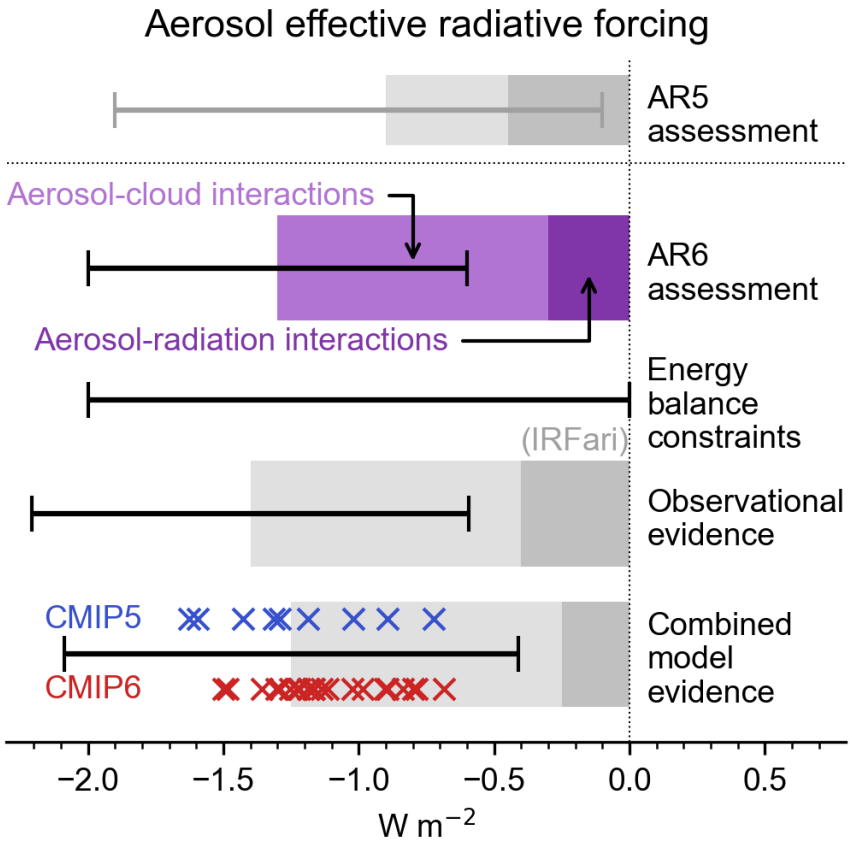


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Contributors:
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# Introduction: Aerosol Indirect Forcing




**IPCC AR6**

**The uncertainty range of AIF in AR6 is 1.4Wm$^{-2}$, about half of all greenhouse gas forcing so far, which has implications for a host of study areas.**

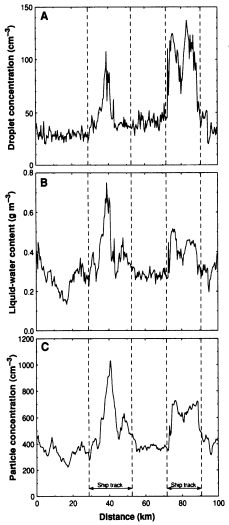
## Introduction: Sources of Uncertainty

$$\frac{\mathrm{d}R}{\mathrm{d}\ln N_\mathrm{d}} \approx \left.\frac{\partial R}{\partial \ln N_\mathrm{d}}\right|_{\mathcal{L},C} + \frac{\partial R}{\partial C}\frac{\mathrm{d}C}{\mathrm{d}\ln N_\mathrm{d}} + \frac{\partial R}{\partial \mathcal{L}}\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\ln N_\mathrm{d}} = S_N + S_{C,N} + S_{\mathcal{L},N}$$

**R: cloudy scene albedo**
**$N_d$: cloud droplet number concentration**
**L: liquid water path**
**C: cloud fraction**
**$S_x$: Partial derivatives of R to $N_d$ under different constraints**

- **$\frac{dC}{dlnN_d}$ and $\frac{dL}{dlnN_d}$ are nonlinear functions of background and environmental conditions.**
  e.g., Albrecht, 1989; Ackerman et al., 2004; Wang et al., 2011; Possner et al., 2018; Toll et al., 2019; Christensen et al., 2022
- **We aim to characterize these functions with actual observations.**

# Introduction: Ship-tracks




Radke et al, 1989

**Number of cloud droplets**

**LWP**

**Aerosol number**

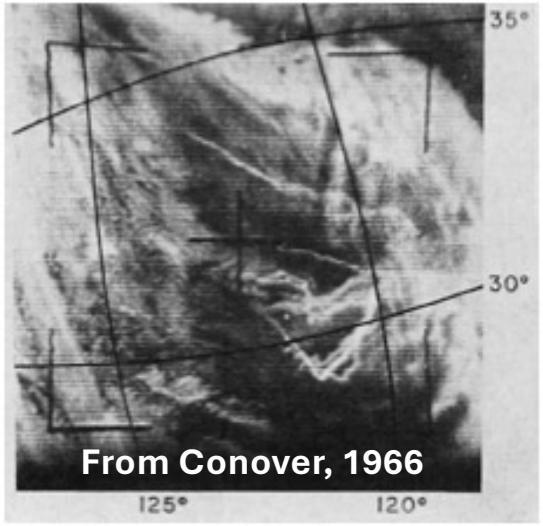
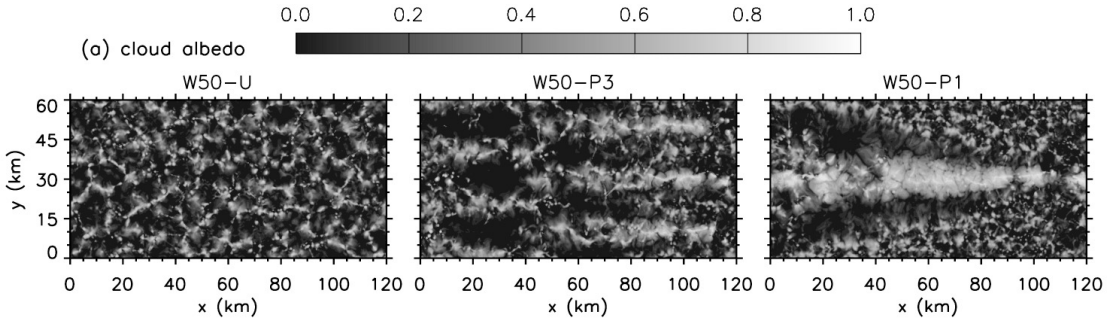


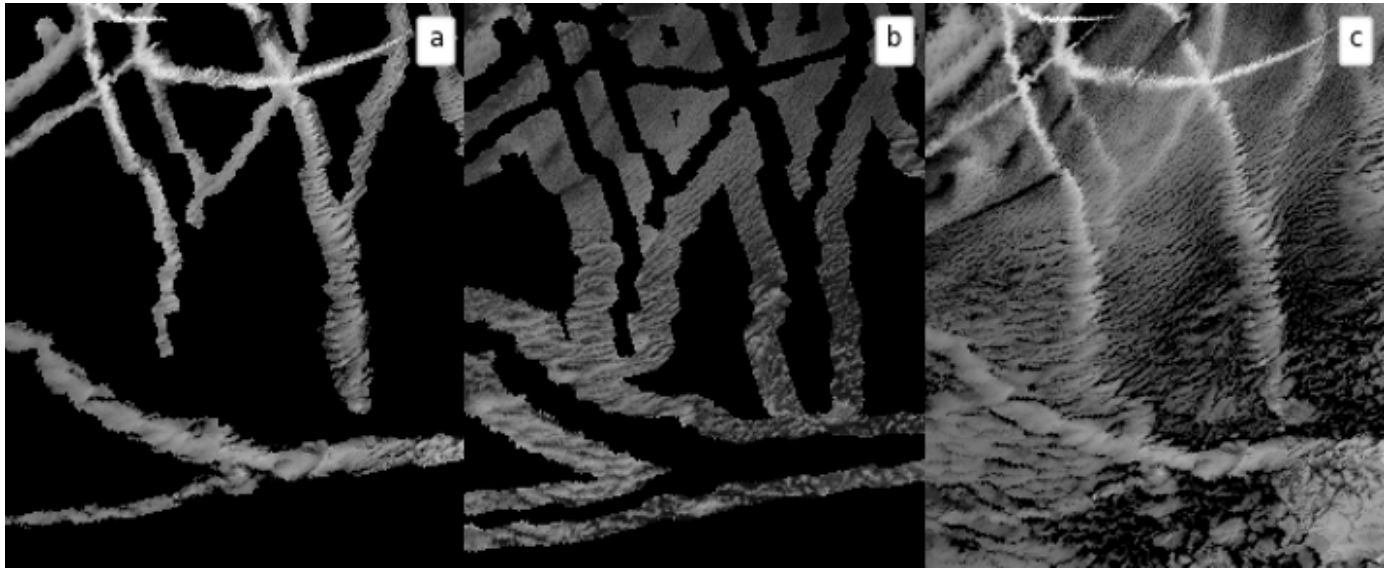

FIG. 2. Family of anomalous lines. California coast and islands south of Santa Barbara are shown on the right. Case 4.

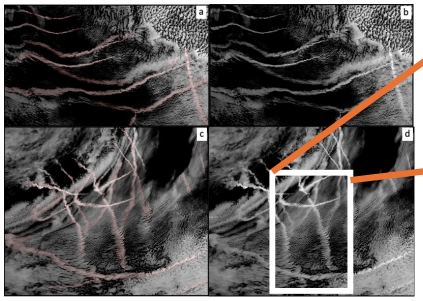
**Ship tracks are great experiments for aerosol-cloud interactions. (see Christensen, et al., 2022 for a review)**




Wang et al., 2011

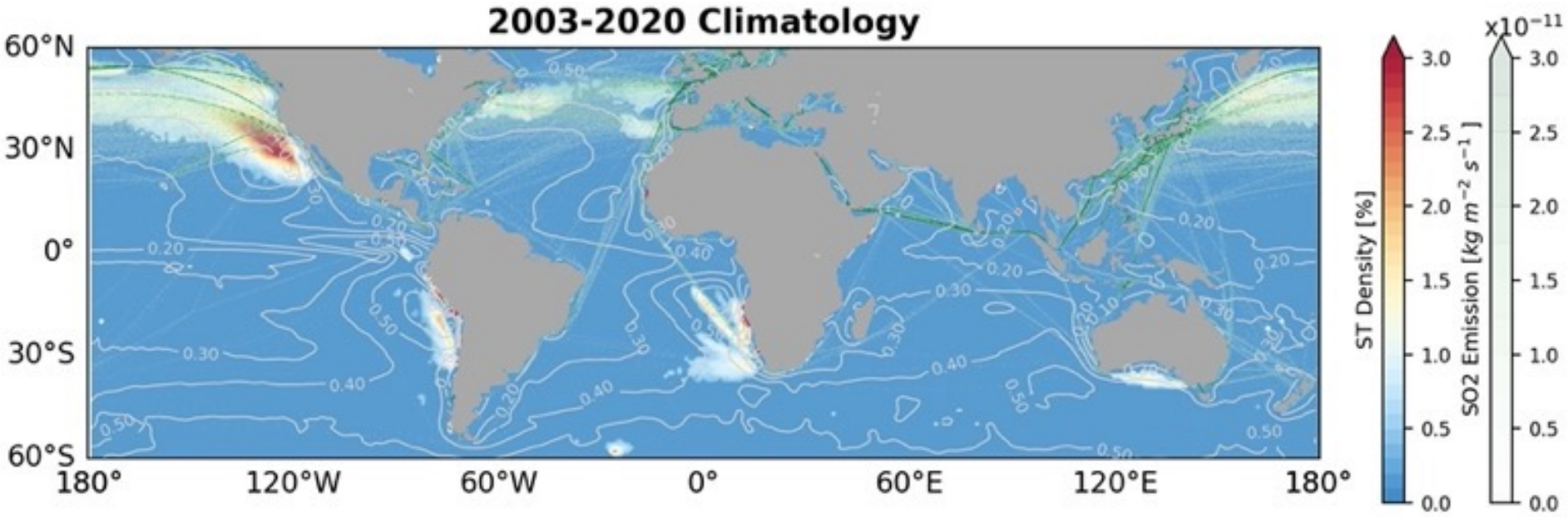
## Automatic analysis : Background VS ship-track



Yuan et al., 2019; Yuan et al., 2022; Yuan et al., 2023

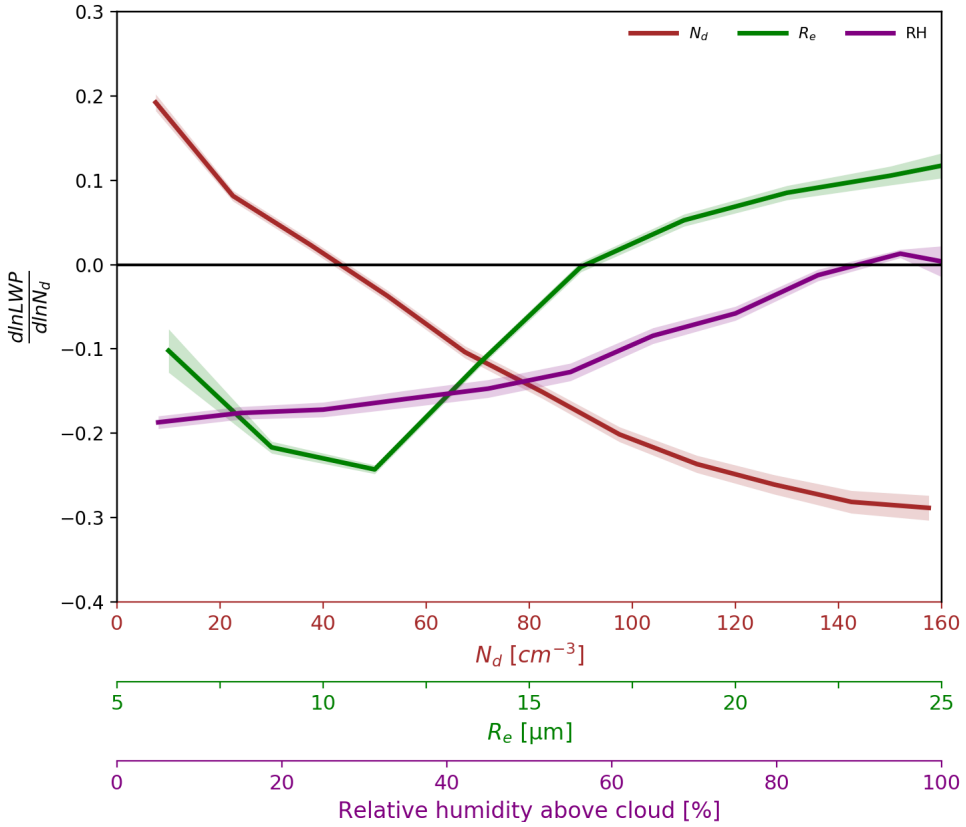
# Results: Sample ship-tracks under diverse conditions




**Sampling these experiments under a variety of conditions gives us representative cloud adjustments.**

**Yuan et al., 2022, Sci. Adv.**

# LWP adjustments: role of humidity and background clouds



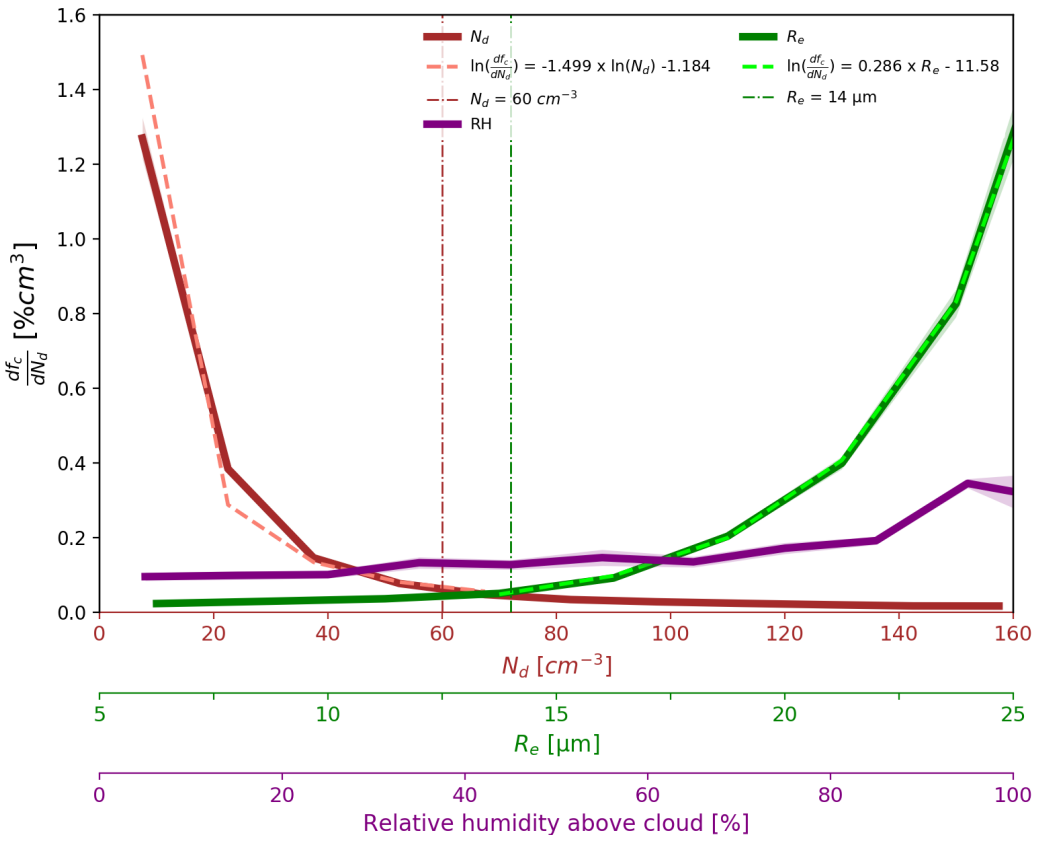

**dlnLWP/dlnN$_d$ systematically depends on background R$_{eff}$, N$_d$, and above cloud top RH. Similar to Toll et al. (2019) and refs. in Bellouin et al. (2020).**

Such behaviors are often explained by the competing effects of entrainment drying and aerosol-precipitation interactions.

There are regional differences.

**Yuan et al., 2023, Sci. Adv.**

# CF adjustment: role of background clouds




CF strongly increases inside ship-tracks once clouds are clean and likely precipitating and the sensitivity is an exponential function of background $R_e$. Minimum CF change under relatively polluted background clouds (e.g. $R_{eff} < 14$ μm or $N_d > 60$ $cm^{-3}$).

Background cloud and drizzle properties are important for this adjustment.

**Quantitative agreement with modeling studies, e.g., Wang et al., 2011; Possner et al., 2018**

**Yuan et al., 2023, Sci. Adv.**

# Observation-based estimate: method

$$\Delta SW_{TOA} = -SW_{downwelling} \times Cf \times A_c \times (1 - A_c) \times \left(\frac{1}{3} + \frac{5}{6}\frac{dlnLWP}{dln\ N_d}\right) \times \Delta lnN_d$$

**Only consider LWP and the Twomey effect**

$$S^* = \frac{dA}{dN_d} = \frac{d(A_{ac}\,Cf_{total} + A_s(1 - Cf_{total}))}{dN_d} \approx Cf \times S + \left(1 - Cf_{high}\right) \times \frac{dCf}{dN_d} \times (A_{ac} - A_s)$$

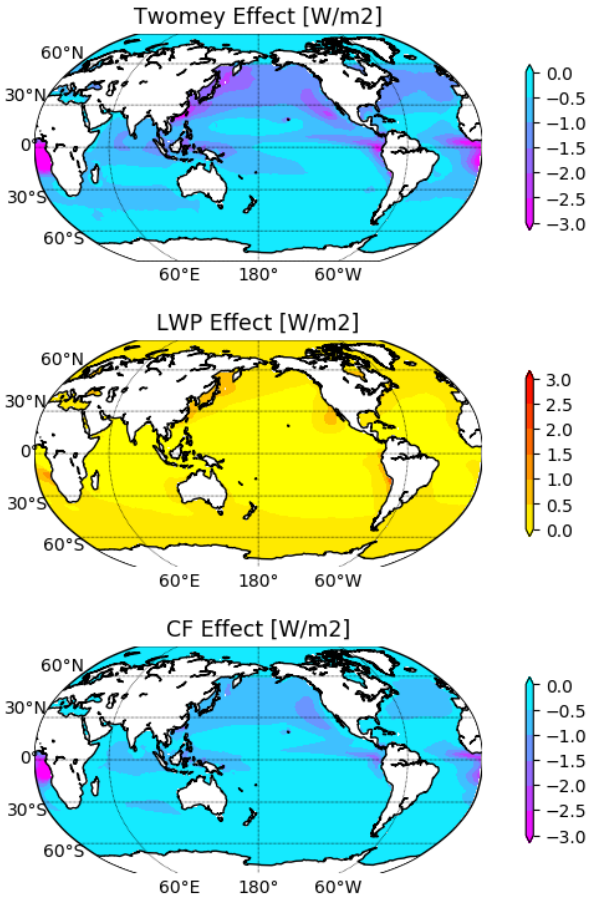
$$\Delta SW_{TOA} = -SW_{downwelling} \times S^* \times \Delta N_d$$

**Consider all three effects: LWP and CF adjustment as well as the Twomey**

$\Delta N_d$ is from Toll et al., 2019

**Yuan et al., 2023; Yuan et al., 2024**

# Aerosol indirect forcing: CF-adjustment makes a difference




CF adjustment amounts to at least 59% of the Twomey effect, could be larger.

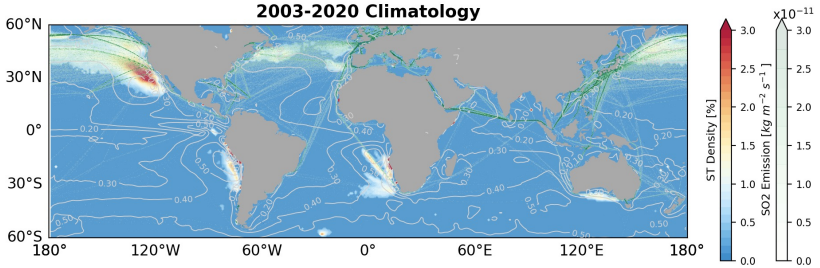
Effect of LWP adjustment is close to zero when averaged over global ocean.

The CF-effect may be a key driver for the uncertainty in total indirect forcing in low clouds.

**Our estimate of AIF: -1.1+/- 0.8Wm$^{-2}$**

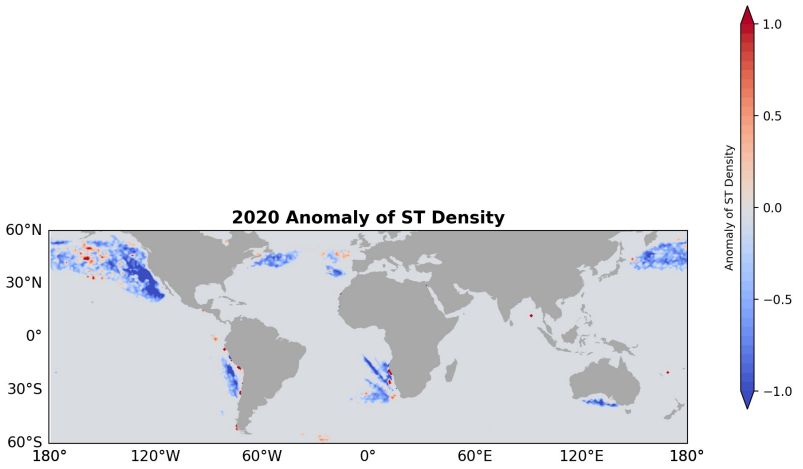
**Yuan et al., 2023, Sci. Adv.**

# IMO 2020 Fuel Regulations: impact on ship – tracks




Climatology

**Effectively, ship emissions have been doing an inadvertent geoengineering experiment for decades. Our estimate of its radiative forcing is uncertain, from <1mWm$^{-2}$ to 0.6Wm$^{-2}$.**

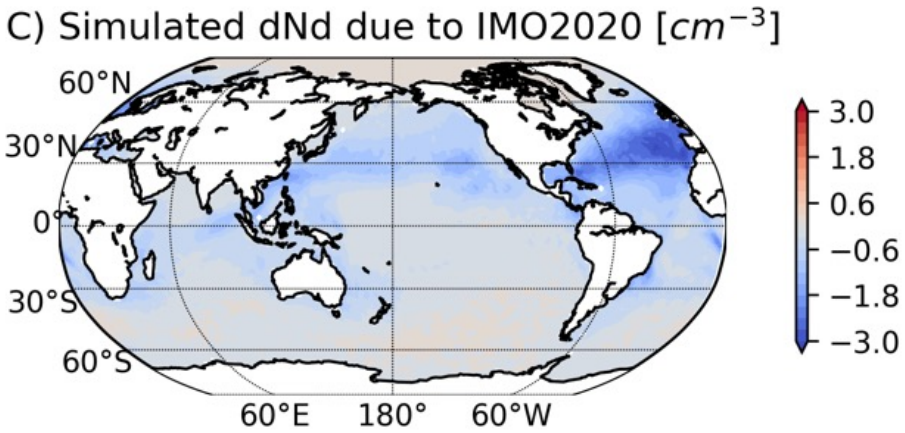



2020

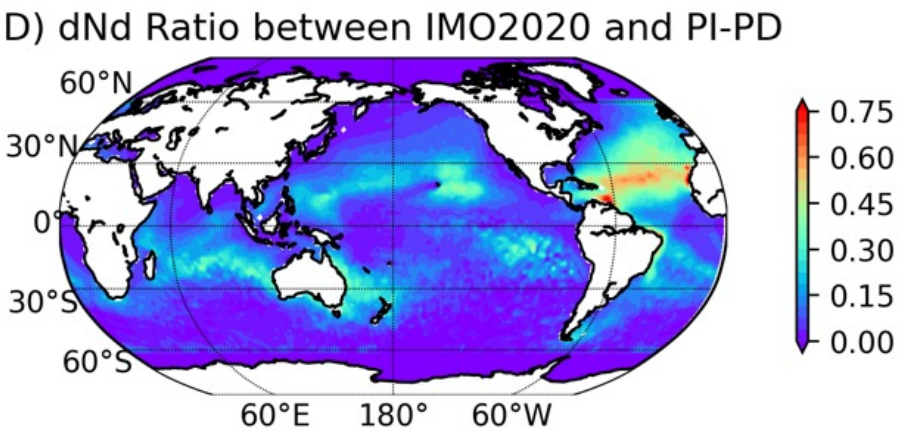
In 2020, International Maritime Organization reduce the emission of sulfur from the shipping industry by more than 80%

**Yuan et al., 2022, Sci. Adv.**

## IMO 2020 Fuel Regulation: $\Delta N_d$ *and* $\Delta AOD$



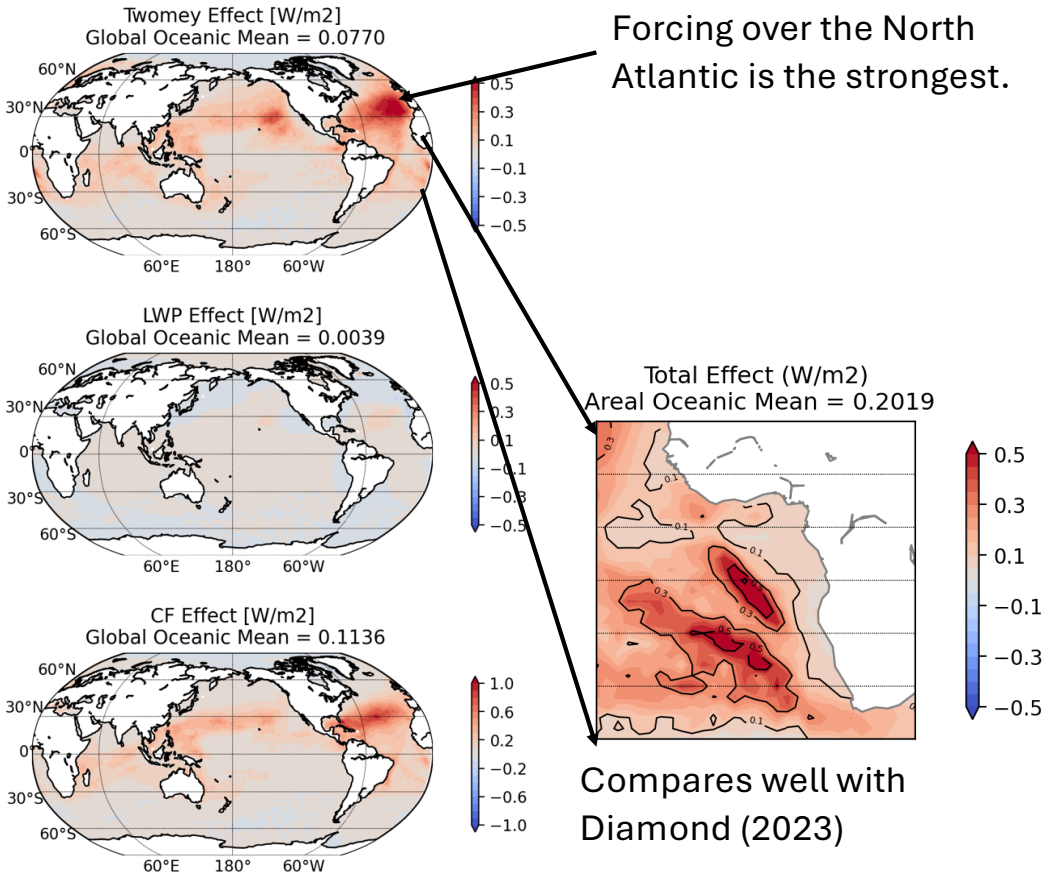

**Simulated $\Delta N_d$**




**IMO2020-induced $\Delta N_d$ relative to total PI-PD**

**Yuan et al., 2024, Comm. E&E**

# IMO 2020 Fuel Regulation: Forcing and impacts




Forcing over the North Atlantic is the strongest.




Compares well with Diamond (2023)

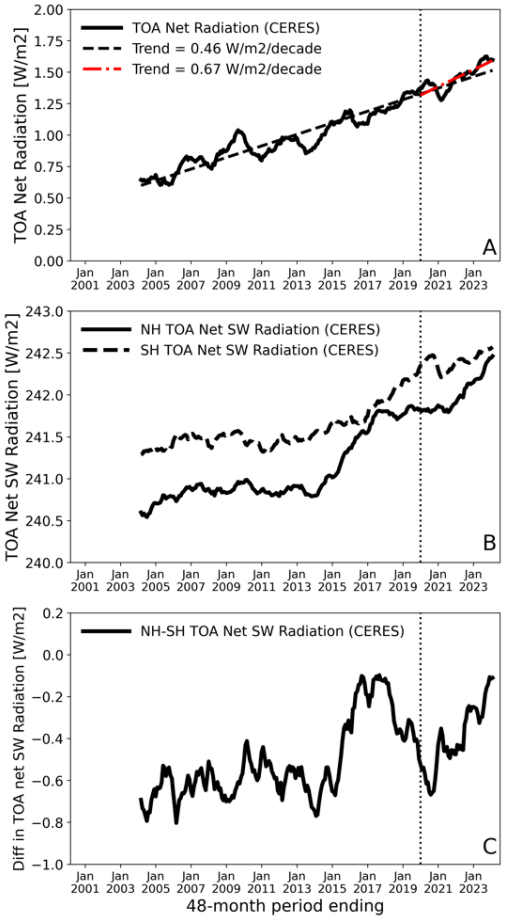
**Total forcing is around +0.2 +/-0.11 $Wm^{-2}$, which is a conservative estimate because we ignored a few factors that can make the forcing stronger.**

**IMO 2020 is effectively a termination shock for a long running inadvertent geoengineering experiment that is the global shipping emission.**

Agrees well with other studies: Gettelman et al., 2024; Jordan and Henry, 2024; Skeie et al., 2024; Quaglia and Visioni, 2024; Schmidt, 2024; Hansen et al., 2023; Goessling et al., 2024

**Yuan et al., 2024, Comm. E&E**

## IMO 2020 Fuel Regulation: Forcing and impacts




CERES measured TOA net radiation

NH and SH TOA net shortwave

NH-SH contrast in TOA net SW

**The rate of increase in CERES measured TOA net radiation has an uptick starting from 2020 and the magnitude is consistent with our forcing estimate as well as others (e.g., Gettelman et al., 2024; Visioni et al., 2024)**

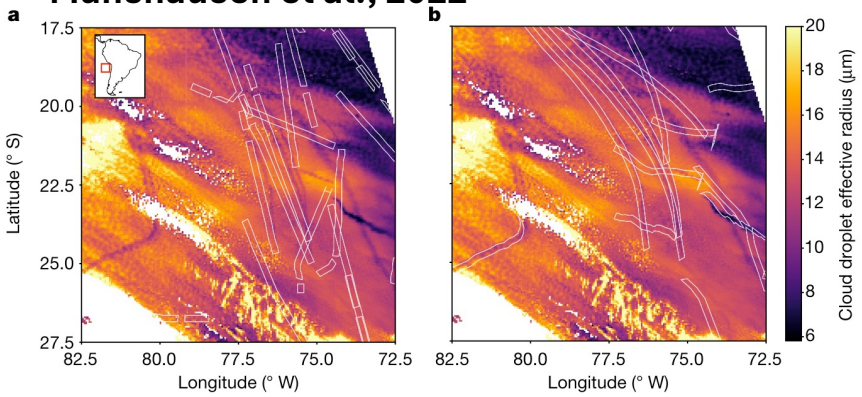
**The IMO2020 increases the absorbed SW radiation more in the NH than SH.**

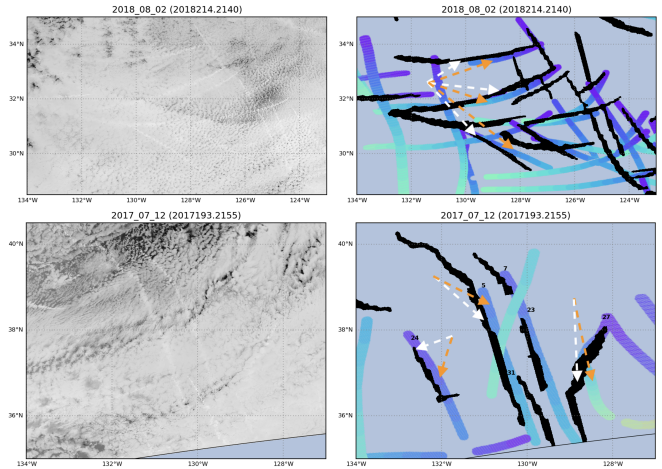
**The heterogeneity of forcing from marine cloud brightening warrants much further study due their consequences on regional climate and precipitation patterns (e.g., Jones et al., 2009; Hill and Ming, 2012; Ricke et al., 2023; Haywood et al., 2023).**

**Yuan et al., 2024, Comm. E&E**

# Virtual ship-tracks: issues to be solved

**Manshausen et al., 2022**




**Yuan et al., 2025, under review**

**Virtual ship-tracks expands the scale and coverage of ship-track analyses.**

- **Fixed width assumption introduces more than 10% error in cloud adjustments**
- **Positional errors introduce much larger errors in cloud adjustments.**

| | $\Delta N_d$ $(cm^{-3})$ | | $\Delta LWP$ $(g\,m^{-2})$ | | $\Delta R_{eff}$ $(\mu m)$ | |
|---|---|---|---|---|---|---|
| Track pair | Detected | virtual | Detected | virtual | Detected | virtual |
| 1 | +24.7 | +9.2 | +1.03 | -3.9 | -1.5 | +0.05 |
| 2 | +17.3 | +4.2 | +0.27 | +0.26 | -0.5 | -0.09 |
| 3 | +36.7 | +5.9 | +0.39 | -5.24 | -0.9 | -0.4 |

## Conclusions

**Aerosol indirect forcing: uncertain in the past, improving now, and still important in the future**

- Ship tracks are great experiments
- Total AIF is estimated to be -1.1$Wm^{-2}$ with CF adjustment critically important while total effect of LWP adjustment is small
- Global shipping produces meaningful forcing and IMO2020 contributed to recent warming.
- To-do: explore unknowns e.g., temporal variations, scale, $\Delta N_d$

# Looking for a talent

**Machine learning/deep learning engineer working at the intersection of climate science and ML/DL**

**Please contact tianle.yuan@nasa.gov**