Strong Aerosol Indirect Forcing from Increasing Low-cloud Coverage

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Acknowledgement:

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Introduction: Ship-tracks

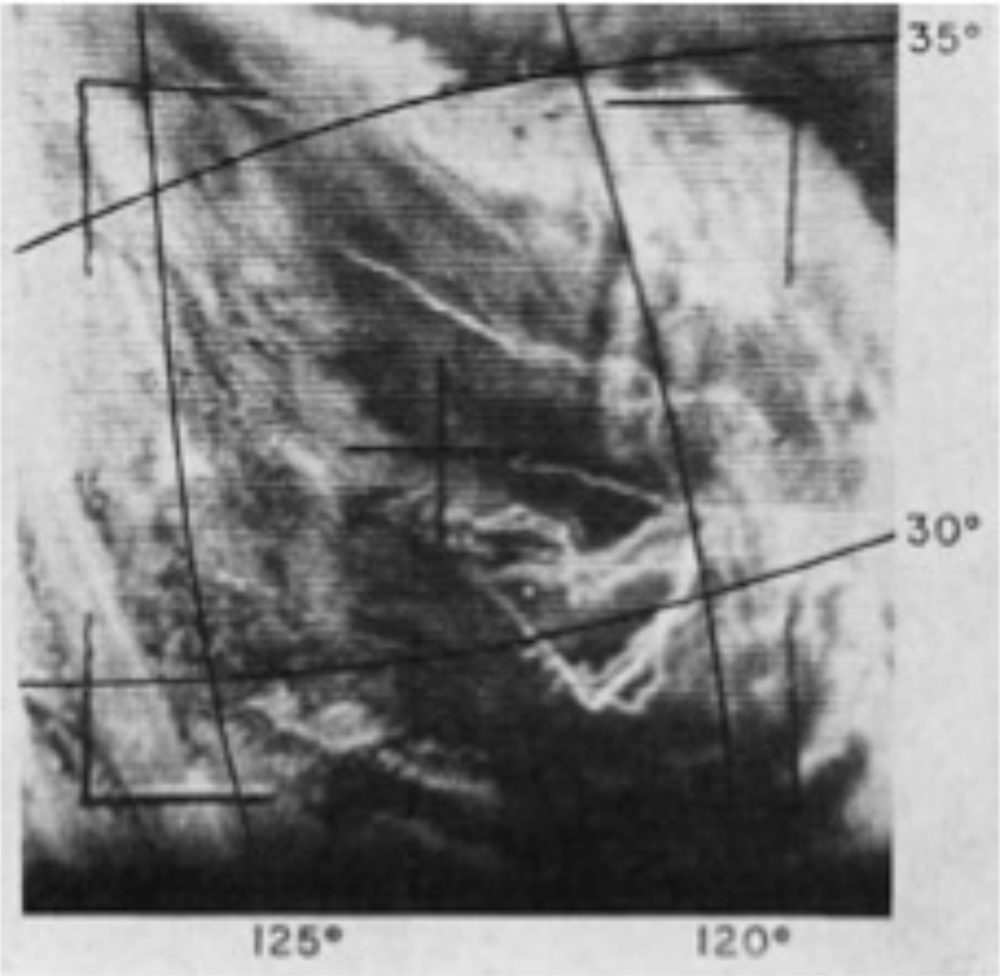


Fig. 2. Family of anomalous lines. California coast and islands south of Santa Barbara are shown on the right. Case 4.

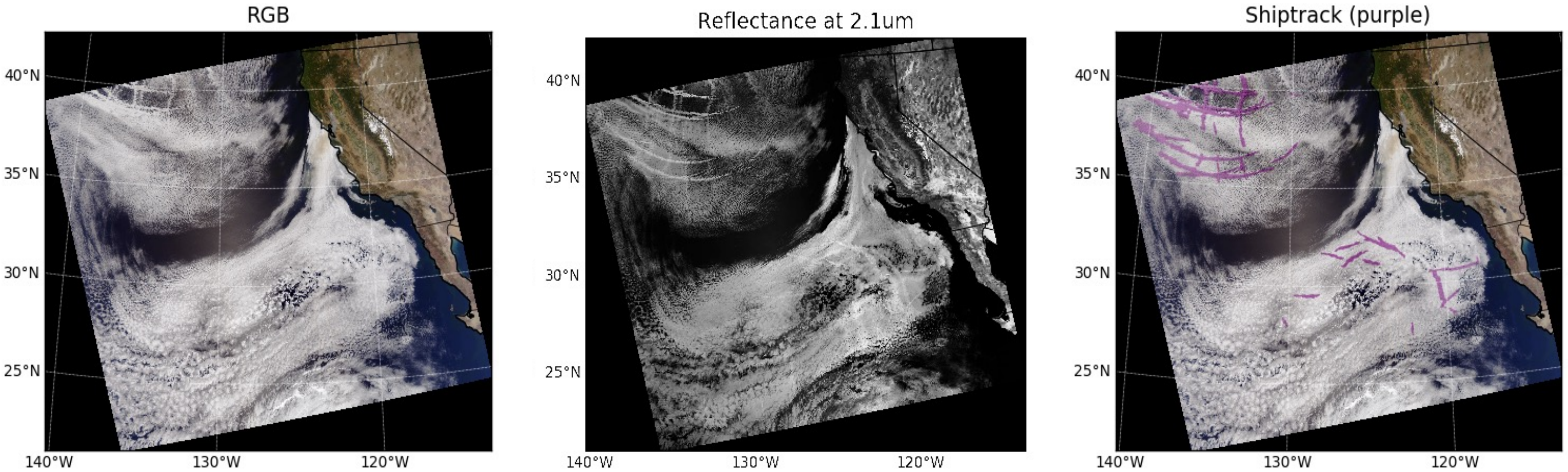
Conover (1966)

Anomalous cloud lines

Christensen et al., 2022

Excellent 'opportunistic experiments' for aerosol indirect effects

Detection : ML method

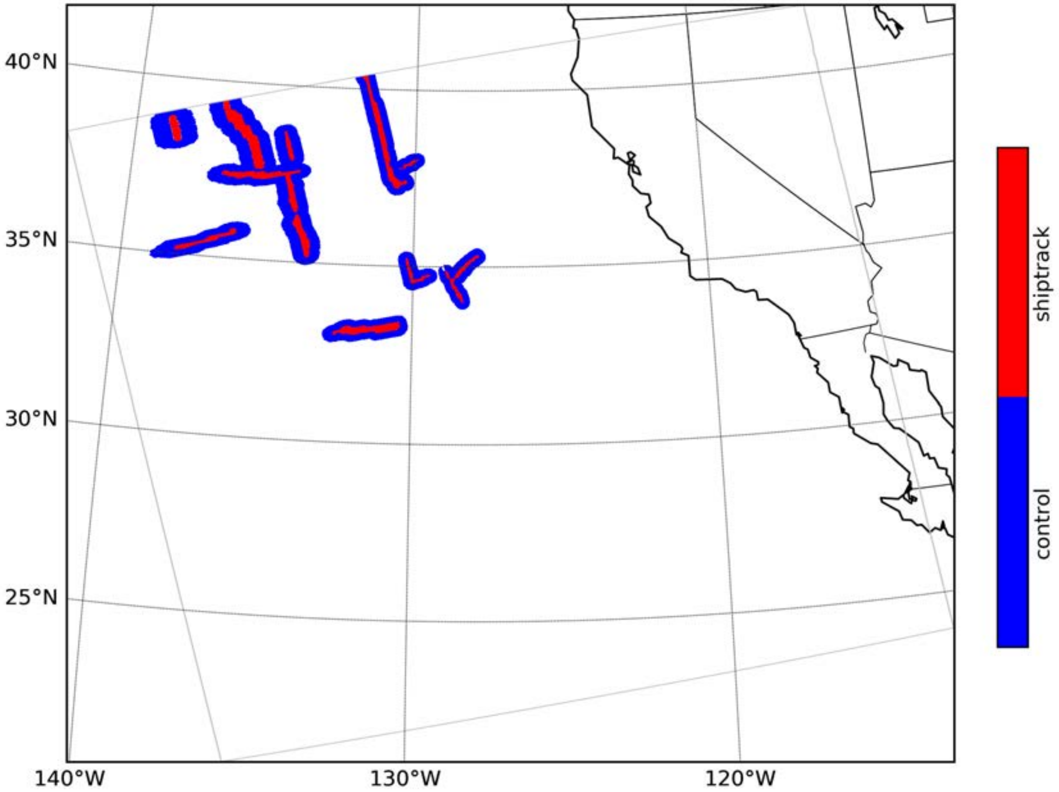


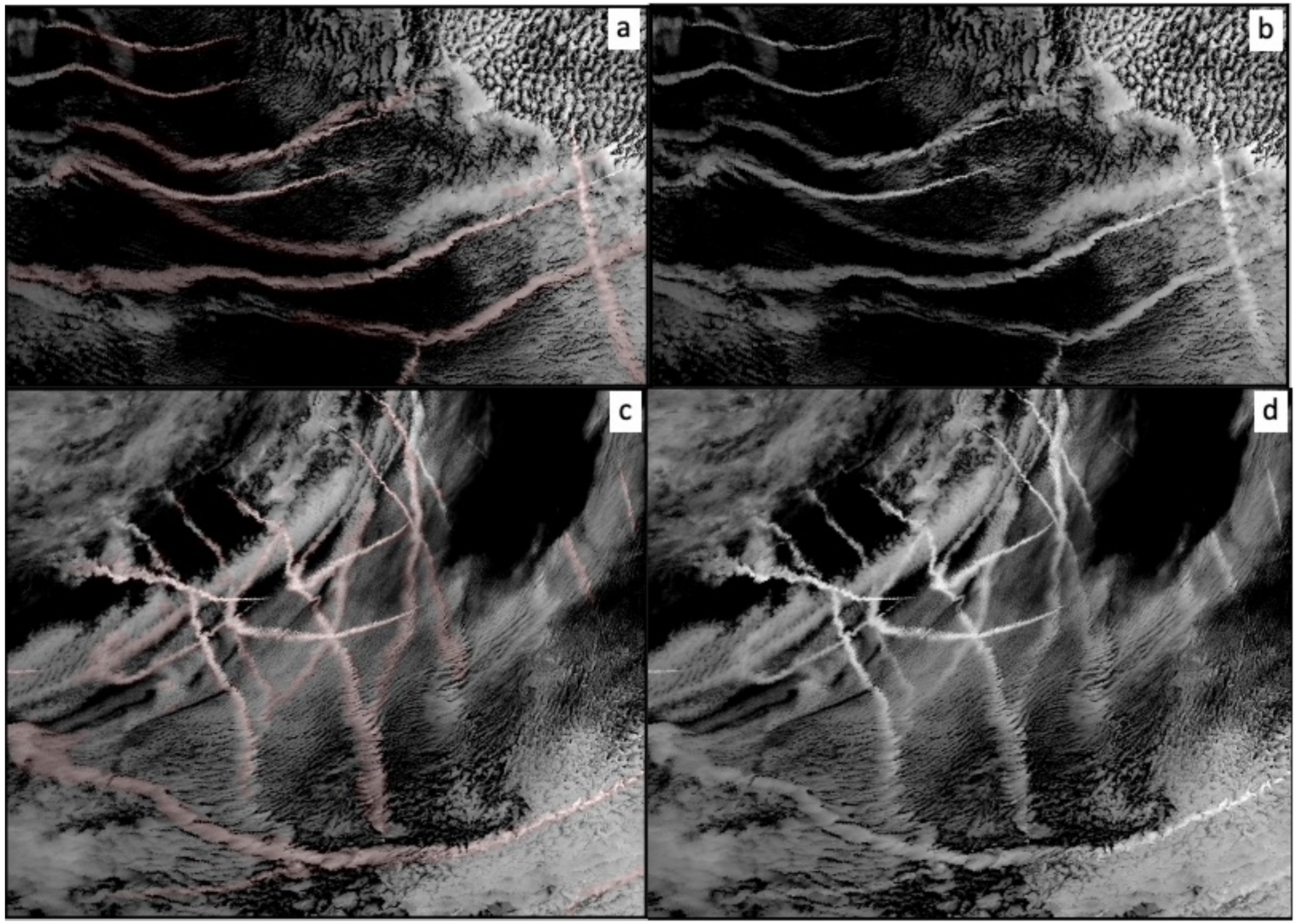
Yuan et al (2019 & 2022)

Automatic detection of ship-tracks at both day and night time

Analysis method: Aerosol-cloud interactions

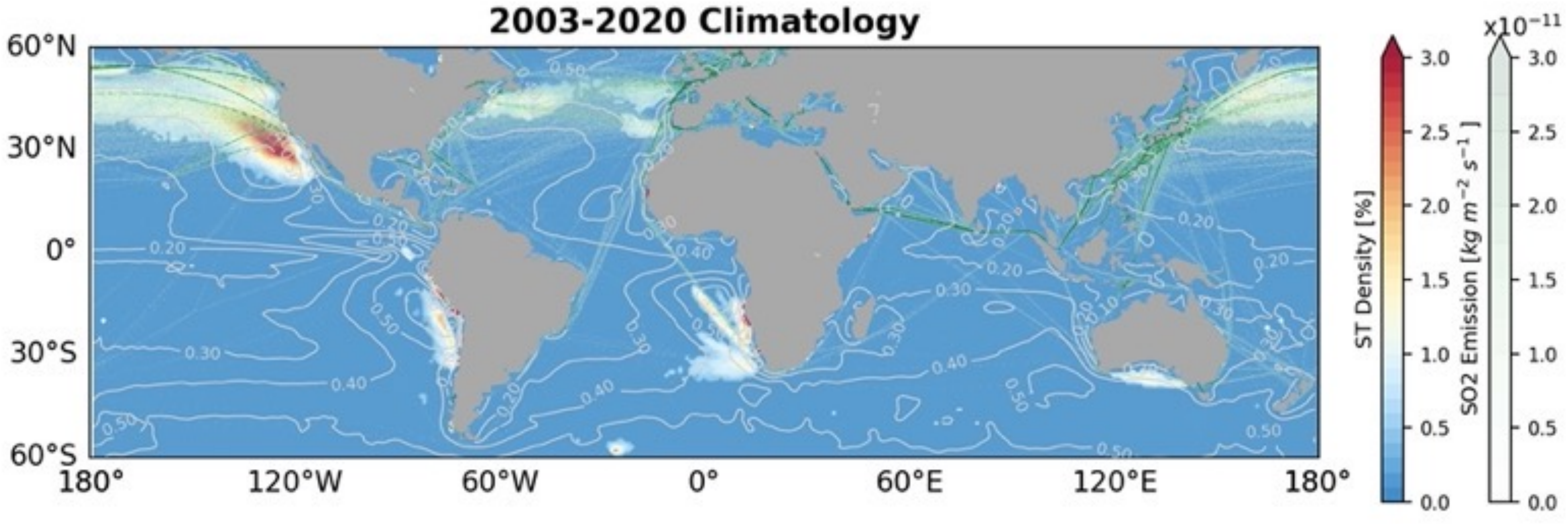
Study ACI





Detection and analysis

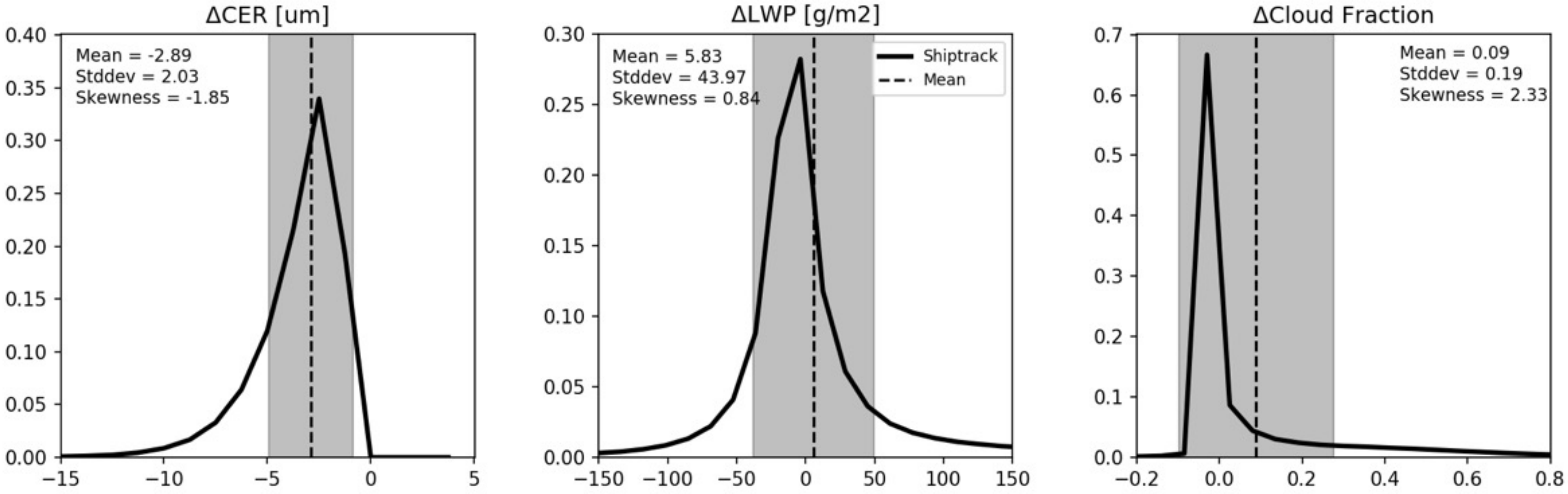
Ship-track distribution



Yuan et al. (2022)

First global climatology map of ship-tracks

Results: PDFs of bulk changes



Yuan et al. (2022b)

PDFs of changes in cloud properties; high variance

Observation-based AIF estimation: **method**

Measurement-based

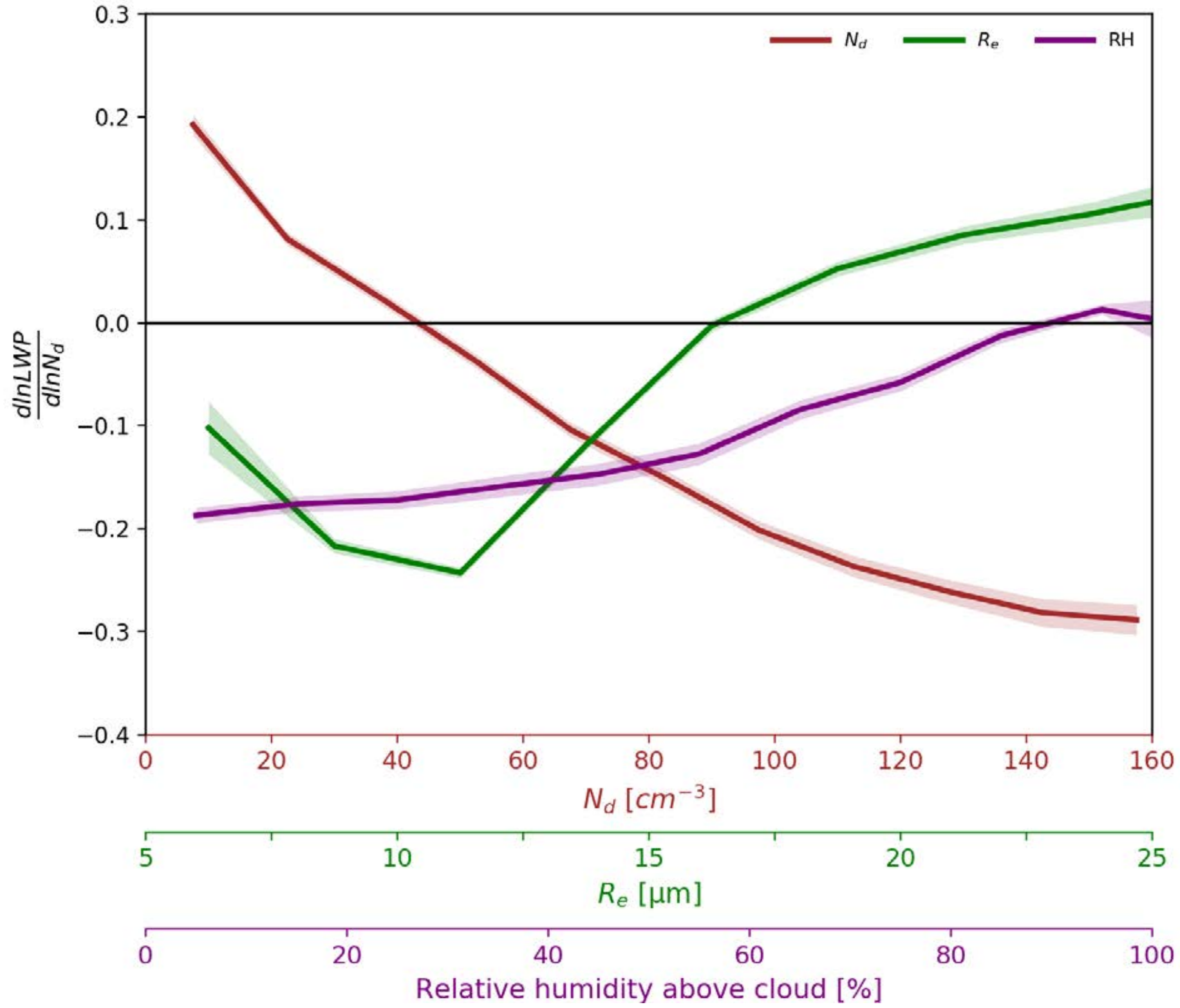
$$S = \frac{dA_c}{dN_d} = \frac{A_c(1-A_c)}{3N_d} \times \left(1 + \frac{5}{2}\frac{d\ln LWP}{d\ln N_d}\right)$$

Cloud albedo susceptibility

$$S^* = \frac{dA}{dN_d} = \frac{d(A_{ac}f_{ac} + A_s(1 - f_{ac}))}{dN_d} \approx f_c \times S + \frac{df_c}{dN_d} \times (A_c - A_s)$$

Scene albedo susceptibility

A Few Curious Connections: Aerosol- ML - clouds

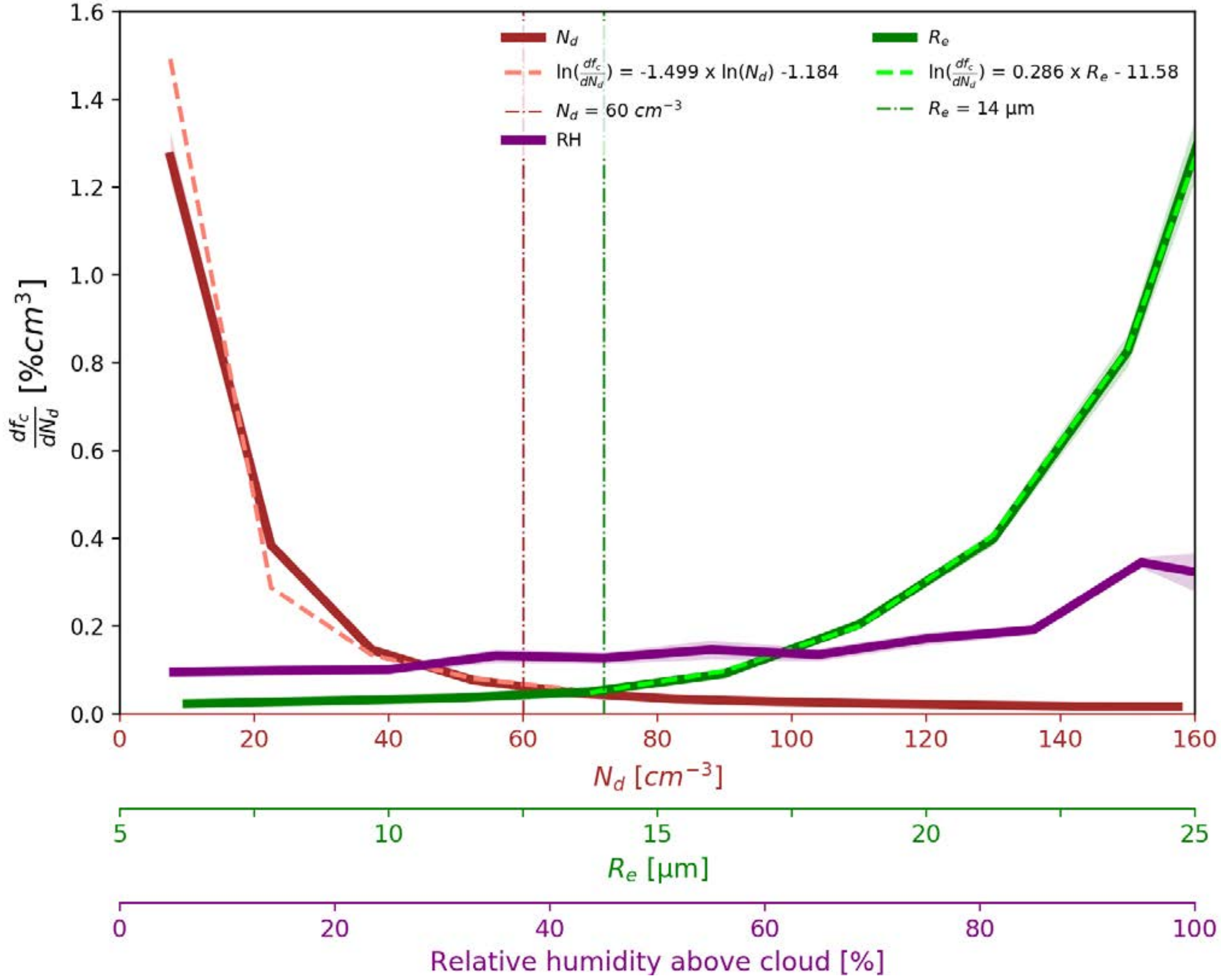


dlnLWP/dlnN$_d$ systematically depends on background R$_{eff}$, N$_d$, and above cloud top RH. Similar to Toll et al. (2019) and refs. in Bellouin et al. (2020).

Drier air above clouds, more polluted and non-precipitating low clouds tend to reduce LWP in response to ship-emitted aerosols.

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

A Few Curious Connections: Aerosol- ML - clouds

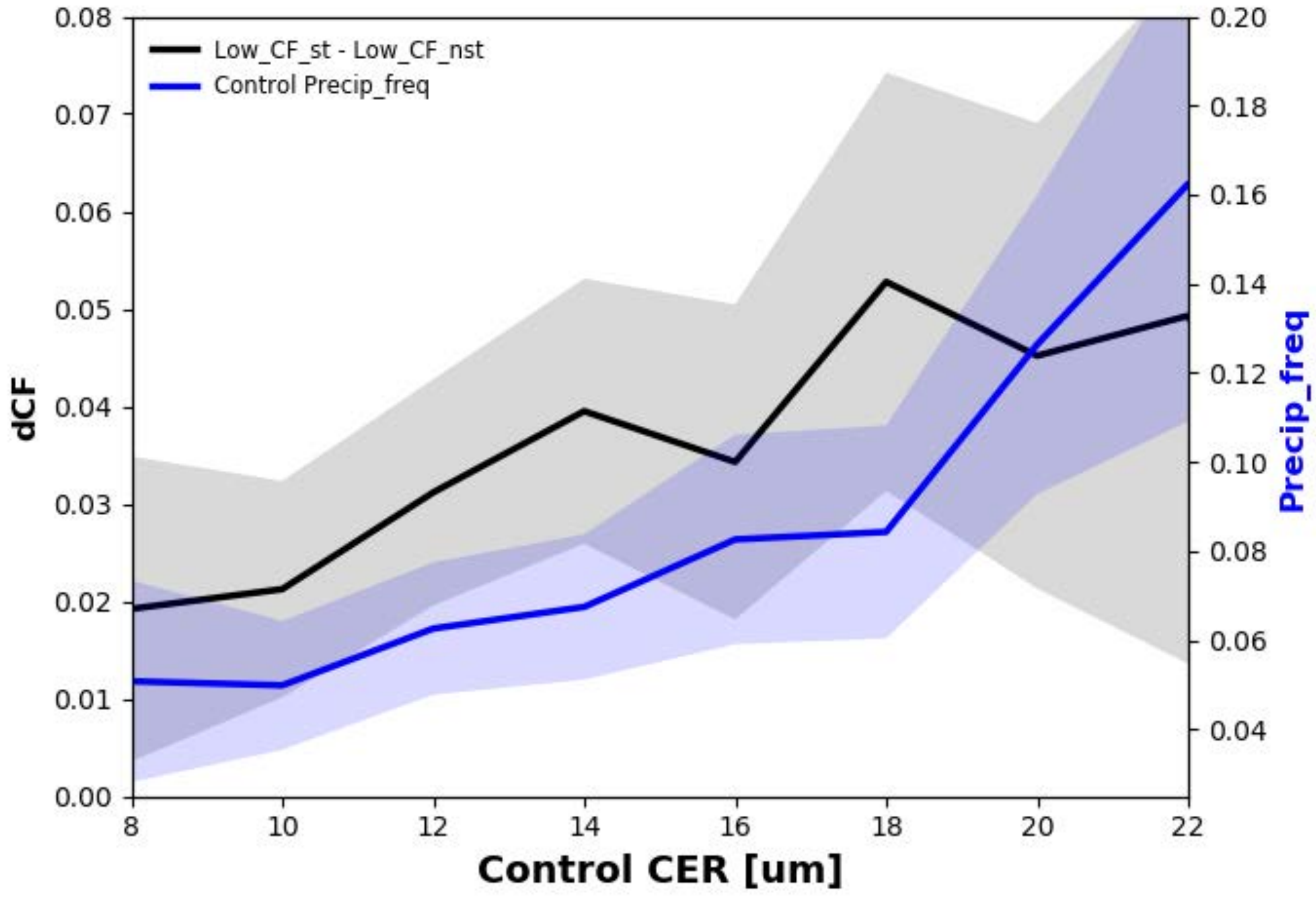


CF strongly increases inside ship-tracks once clouds are clean and likely precipitating and the sensitivity is an exponential function of background R_e. Minimum CF change under relatively polluted background clouds (e.g. $R_{eff} <$ 14 µm or $N_d > 60$ cm^{-3}).

The sensitivity is quantitatively similar to what is reported in Possner et al. (2018).

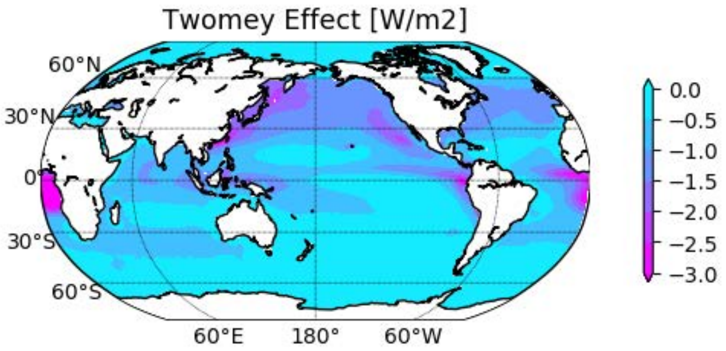
Rosenfeld et al. (2006); Christensen and Stephens (2011); Goren and Rosenfeld (2012); Wang et al., (2011); Christensen et al. (2020); Possner et al. (2018); Gryspeerdt et al. (2016); Rosenfeld et al. (2019) etc.

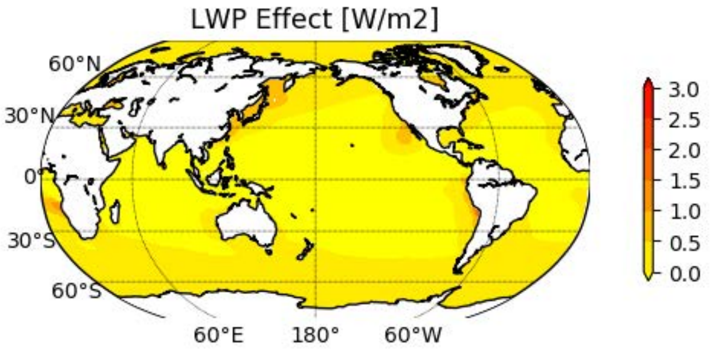
CF changes and precipitation

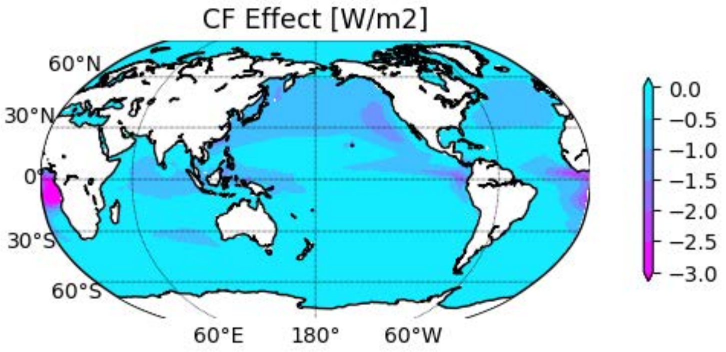


CF change is proportional to the background cloud droplet size and precipitation frequency.

Forcing from three effects: CF effect is strong


Twomey Effect [W/m2]


LWP Effect [W/m2]


CF Effect [W/m2]

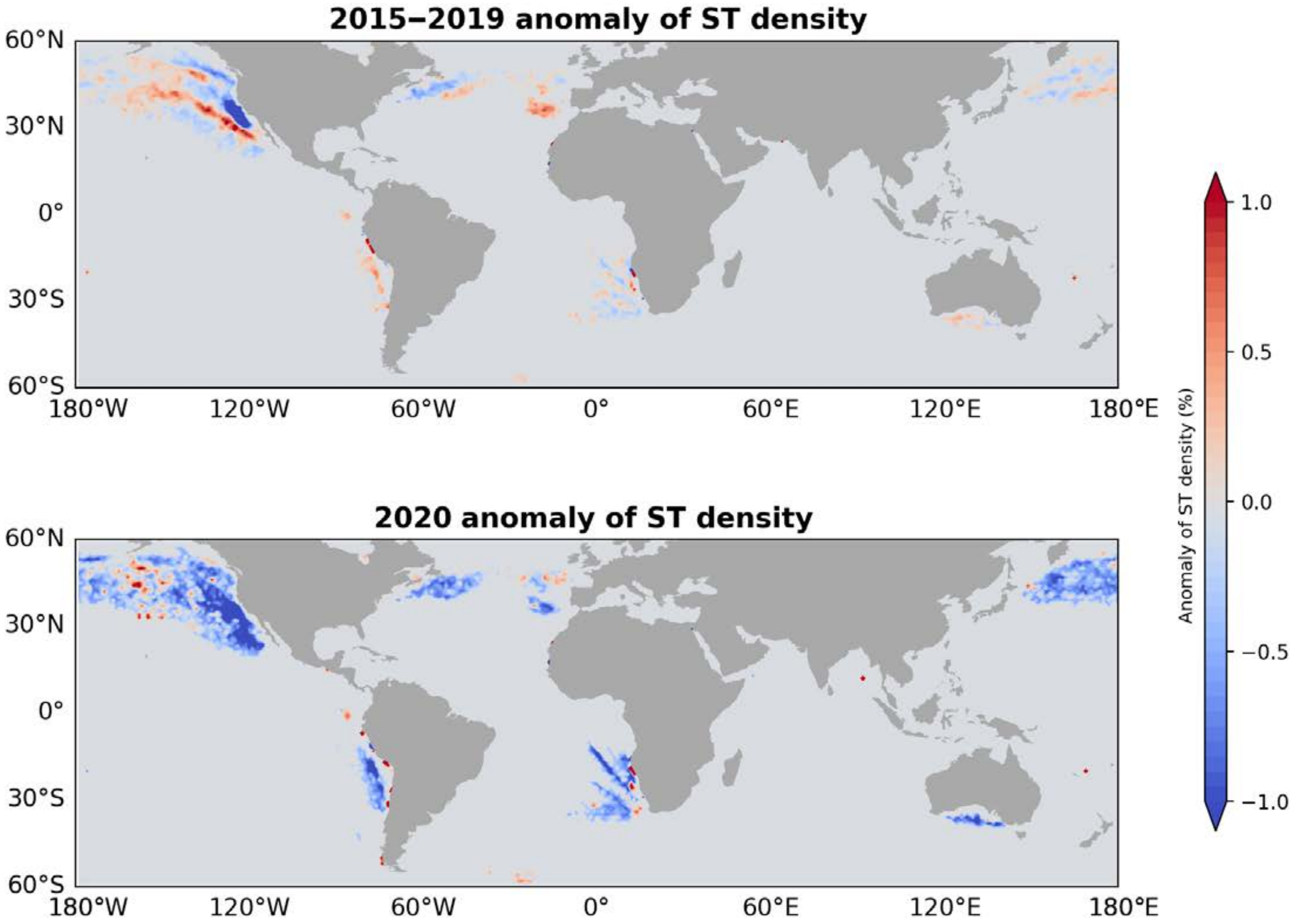
- CF adjustment amounts to at least 59% of the Twomey effect, could be larger.
- LWP adjustment is close to zero when averaged over global ocean.
- The CF-effect may be a key driver for the uncertainty in total indirect forcing in low clouds.

Sensitivity: A large variation for CF effect

Table: Forcing Using Different Explanatory Variables (W/m²)

Explanatory variable(s)	Cf Effect/Twomey
N_d only	59%
N_d and Cf	202%
N_d and RH	59%
N_d and SST	130%
N_d and EIS	68%
N_d, CF, and RH	193%
N_d, EIS, and RH	73%

Changes: Impact from shipping fuel regulation



Yuan et al. (2022)

Forcing?

Emission control areas

Global regulation

Conclusions

- CF effect is strong and LWP effect is overall weak
- Forcing from CF adjustment could be as large as the Twomey effect
- 59% to 202% of the forcing from the Twomey effect is possible
- Precipitation-mediated processes are likely important
- Reducing the uncertainty of AIF due to CF effect is critical.