Extensive Decline of Reflective Clouds over the North Atlantic and Northeast Pacific from Aerosol Reductions

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MARINE CLOUD BRIGHTENING RESEARCH PROGRAM

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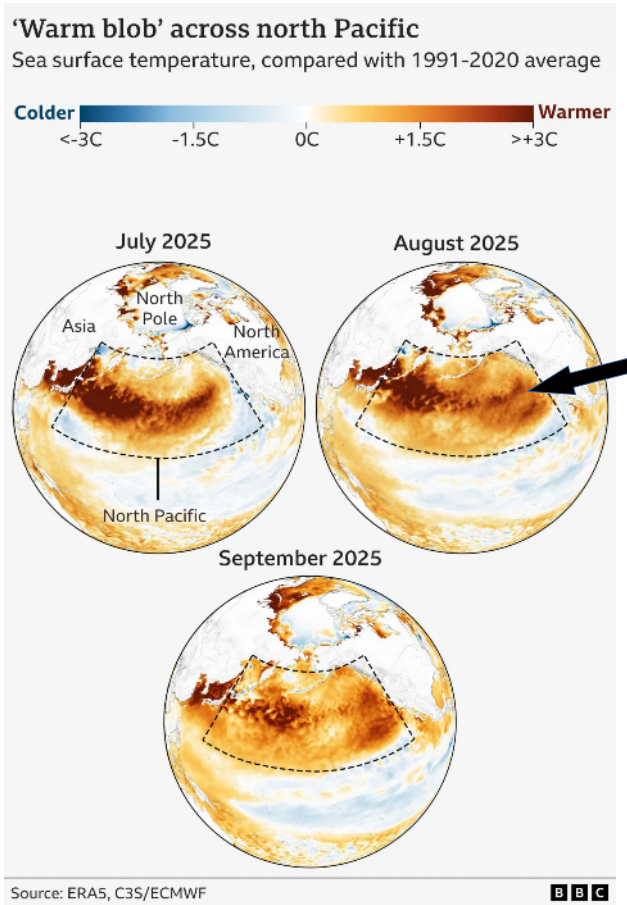
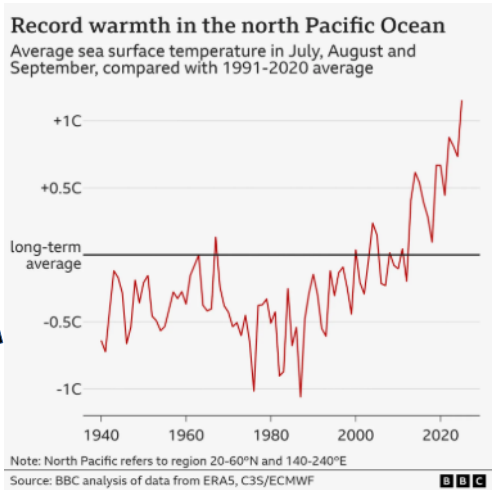
Has warming accelerated over the recent years?

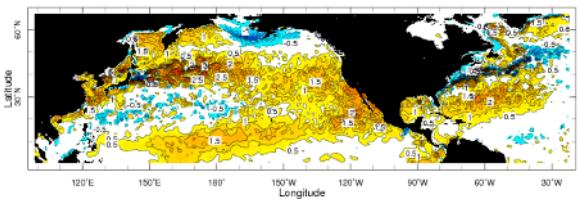
- Recent North Pacific warming not consistent with Pacific Decadal Oscillation (Xiao et al., 2023; Hu et al., 2024)
- Global warming has accelerated significantly (Foster and Rahmstorf, 2026)





https://www.bbc.com/news/articles/ce3xynwwx4yo

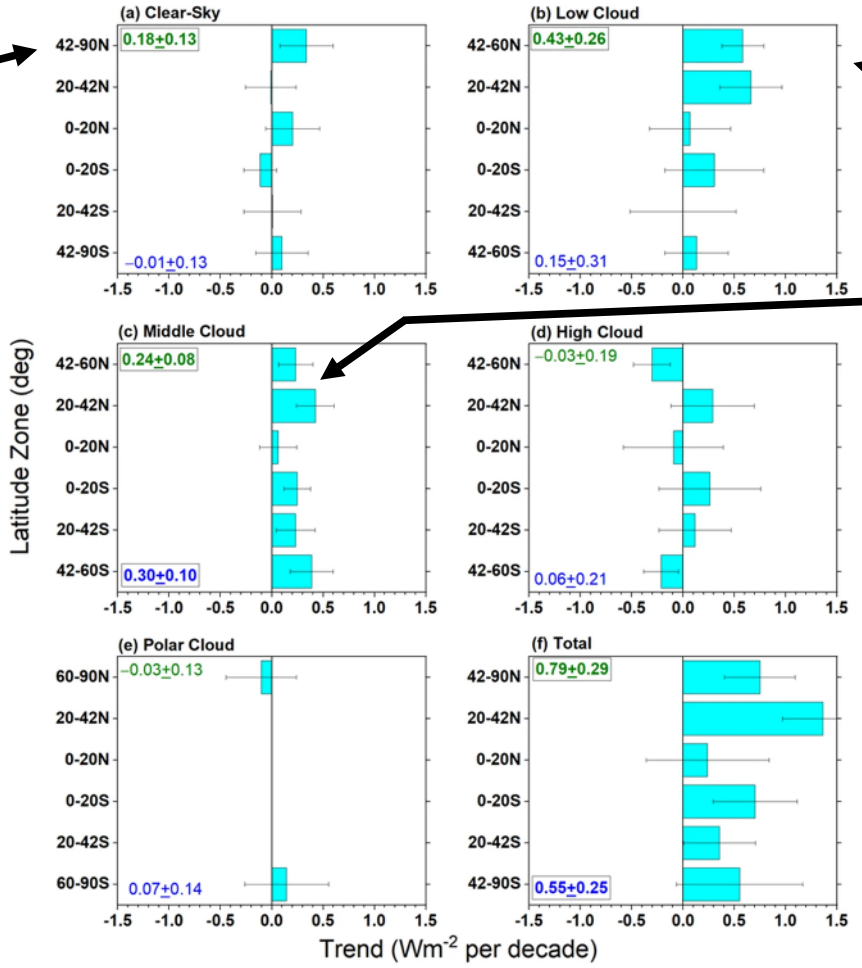
17-23 March 2026



Columbia University IRI Data Library (IRIDL)
(currently shutting down operations)

The Earth is becoming less reflective

Arctic: Declining snow and ice



Northern hemisphere: **Declining cloud reflectivity** (primarily low and middle clouds)

Trend in SW radiation at the top of the atmosphere (sign switched)

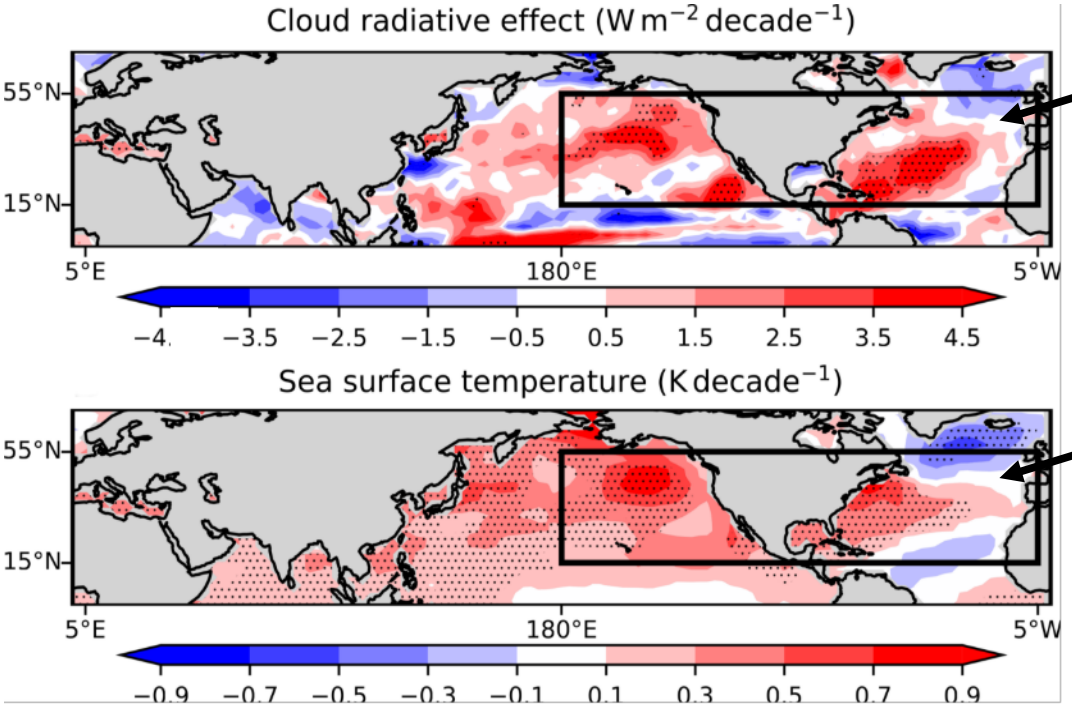
CERES EBAF Ed4.2

07/2002 – 12/2022

Source: Loeb et al. (2024), Surveys in Geophysics

Clouds are becoming less reflective over the North Atlantic and Northeast Pacific

Observed CRE and SST linear trends for 2003-2022 (20 years)



1.04 ± 0.45 Wm^{-2} decade^{-1}

Difference between shortwave all-sky and clear-sky reflected radiative flux at the top of the atmosphere

0.19 ± 0.08 K decade^{-1}

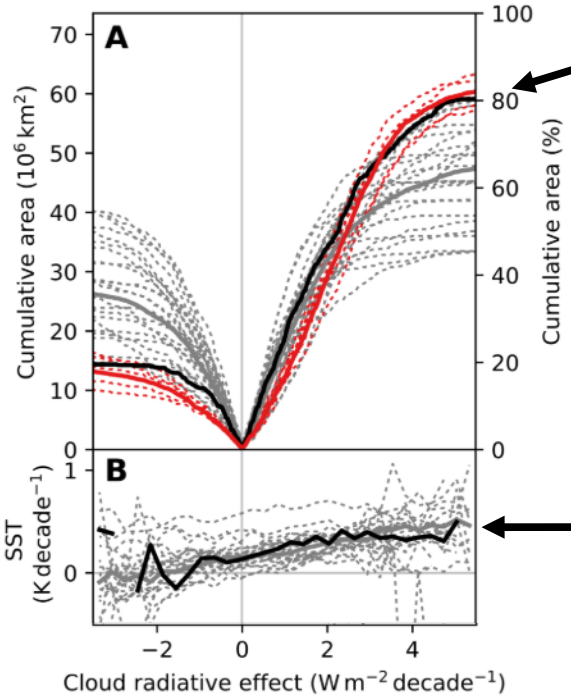
Source: von Salzen et al. (nature communications, 2025)

Data: CERES EBAF Ed4.2 (top), HadCRUT5 (bottom)

Stippling: 95% confidence

Clouds are becoming less reflective over the North Atlantic and Northeast Pacific

Spatial extents of CRE trends



The cloud radiative effect increased **in 80%** of these regions

The simulated cloud radiative effect increased **in 64%** of these regions (24 CMIP6 models) CanAM5.1-PAM matches the observed cloud trends well

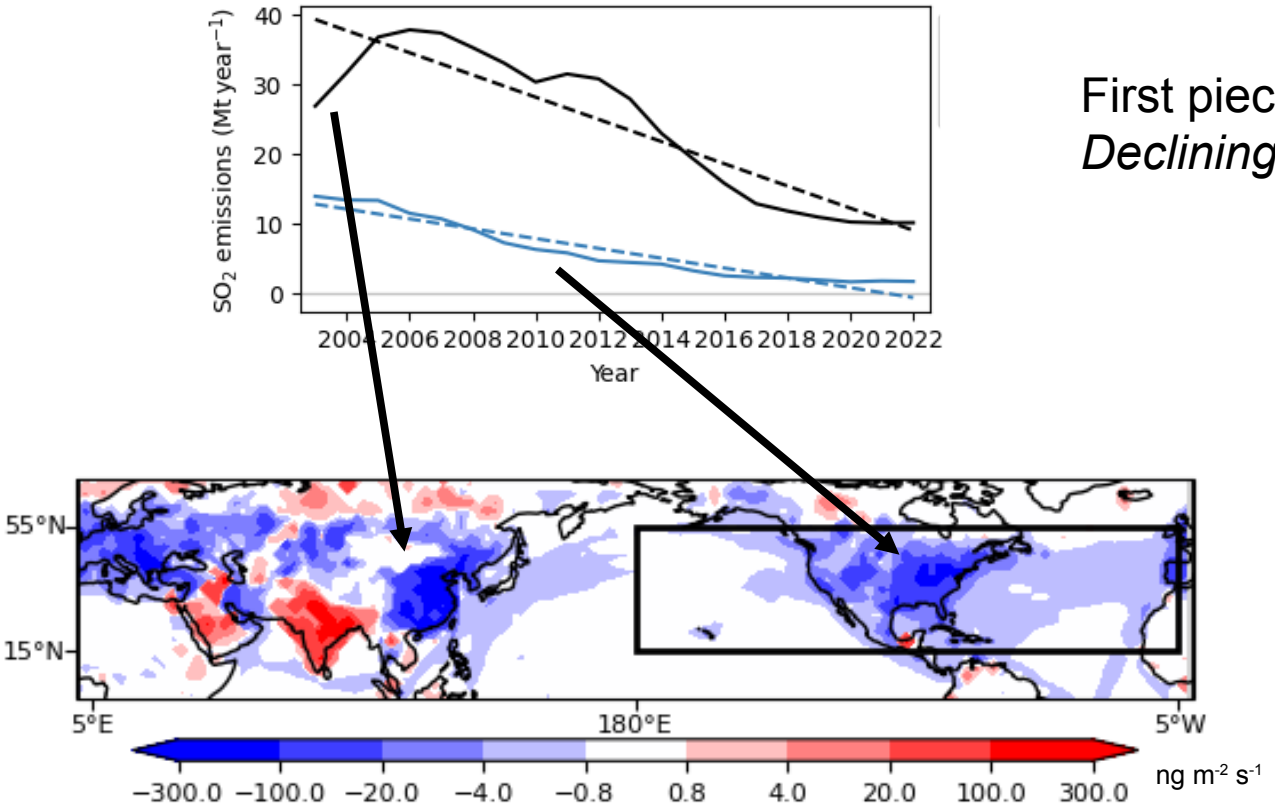
CMIP6 models correctly simulate that the **warming was stronger in regions with rapidly declining cloud reflectivity**

Data: CERES EBAF Ed4.2, HadCRUT5, MODIS collection 6.1

Dashed lines: Model ensemble members

Source: von Salzen et al. (nature communications, 2025)

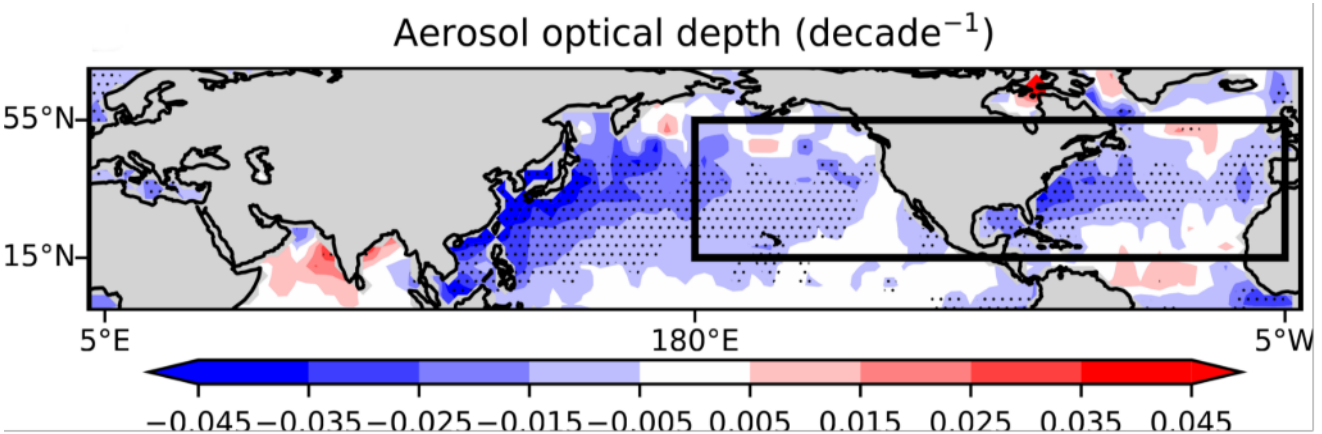
Why have marine clouds become less reflective?

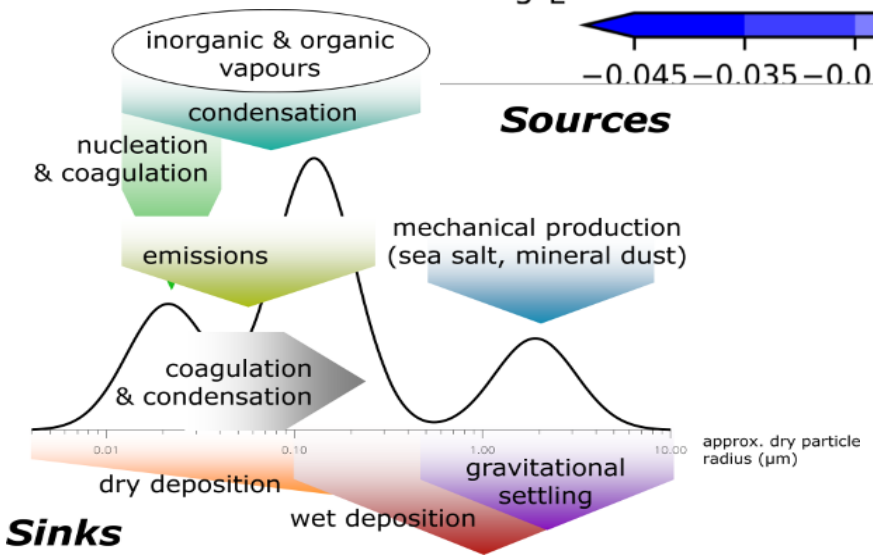


First piece of “the puzzle”:
Declining sulfur emissions

Data: CEDSv2021 (top), CMIP6 SSP2-4.5 (bottom)

Why have marine clouds become less reflective?

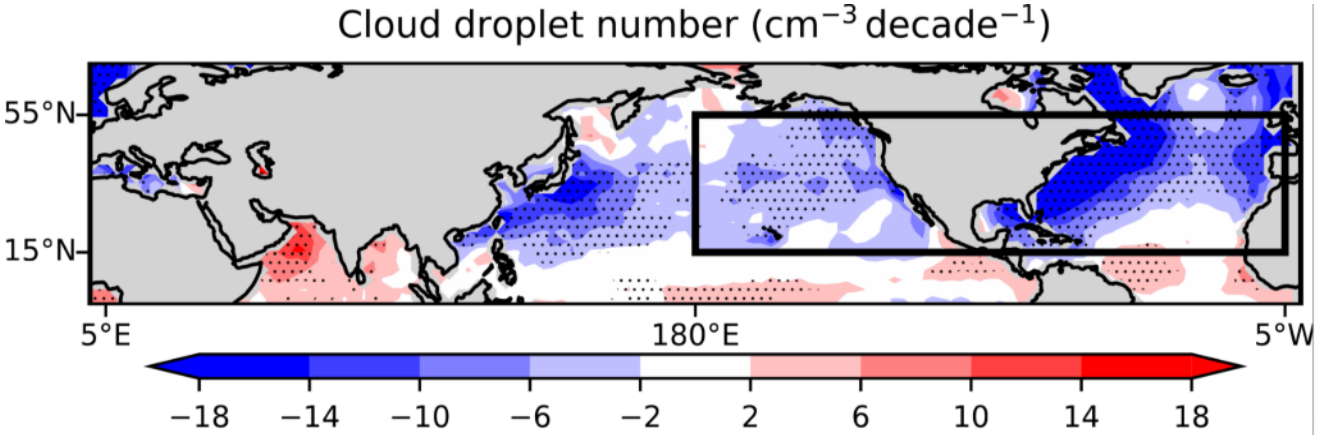




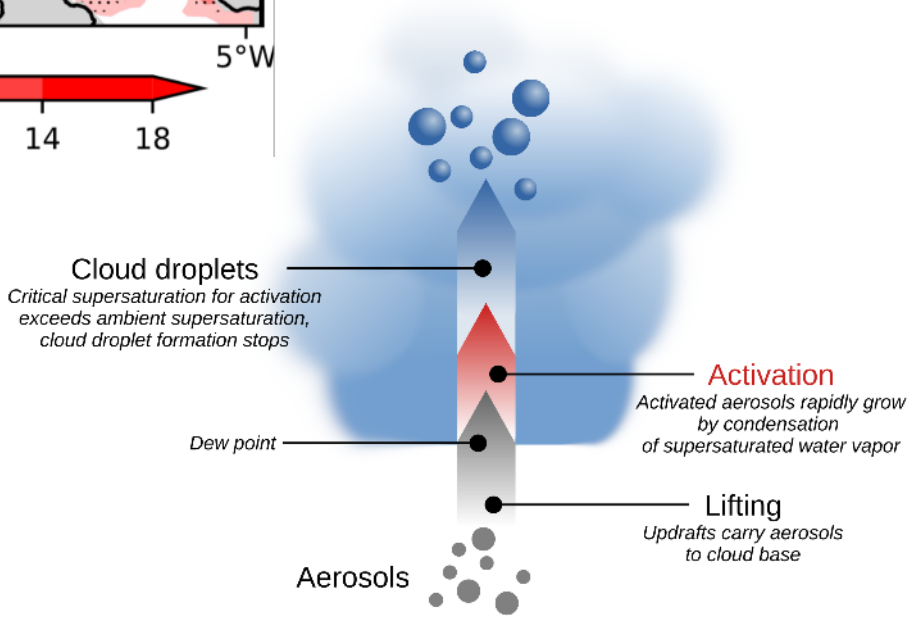
Second piece of “the puzzle”:
Declining aerosols

Data: MISR L3 Global Joint Aerosol V002

Why have marine clouds become less reflective?

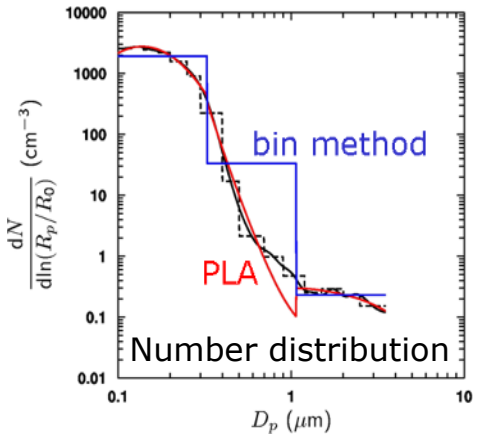


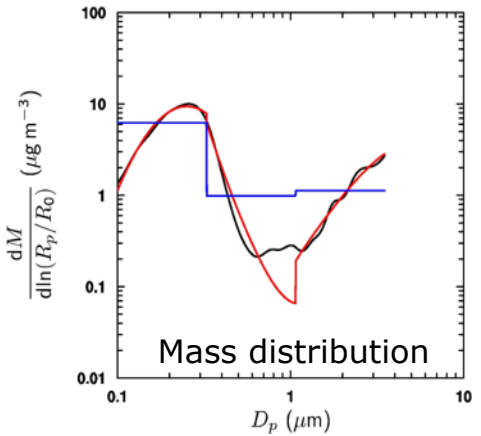
Third piece of “the puzzle”:
Loss of cloud droplets



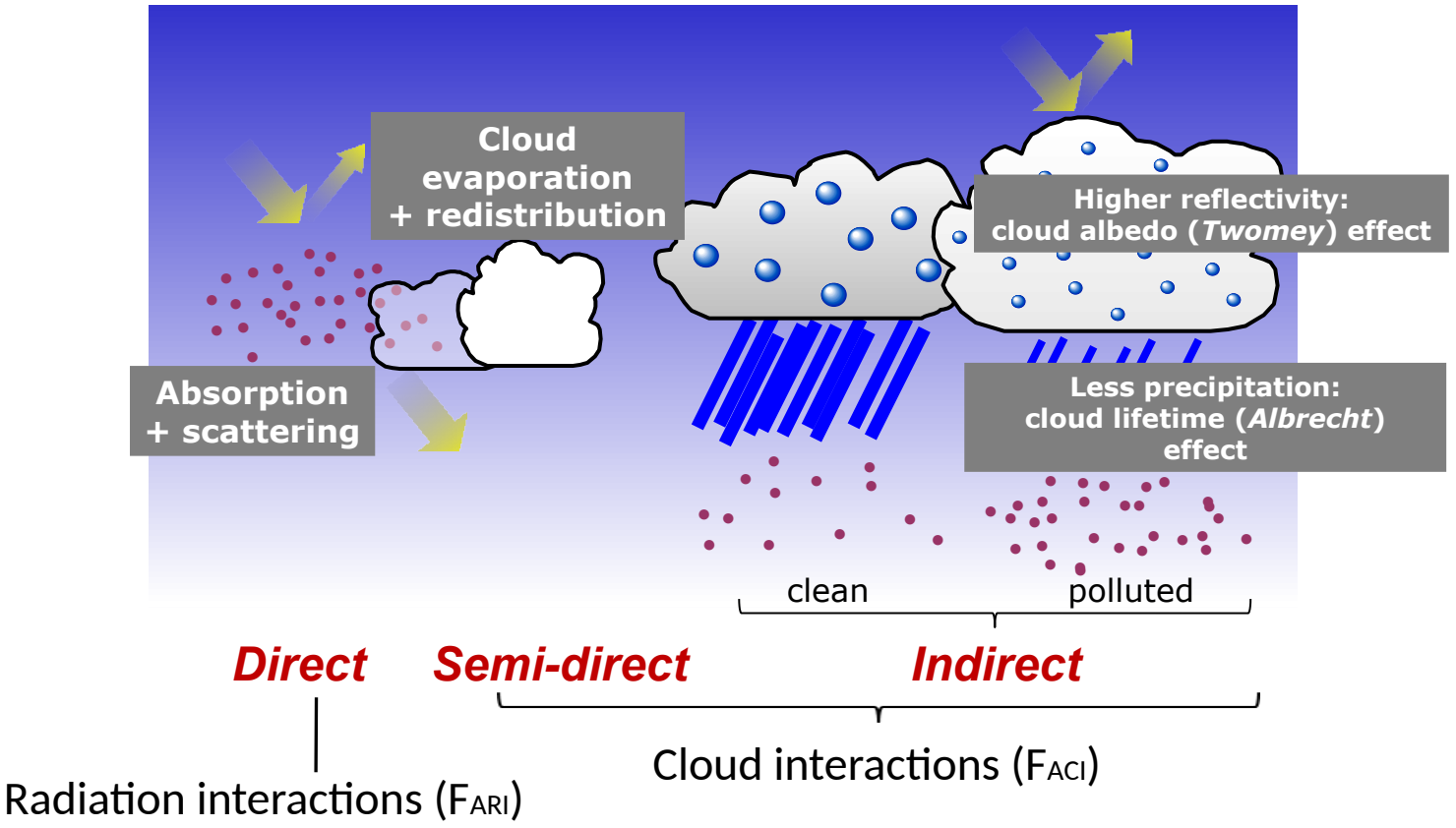
CanAM5.1-PAM

- Canada's Atmospheric global climate Model with specified SSTs and sea ice
- Piecewise-Lognormal Approximation (PLA) of aerosol size distributions (von Salzen, 2006)
- Internally mixed: Sulfate, black carbon, organic carbon
- Externally mixed: Sea salt, mineral dust
- Embedded cloud parcel model for simulation of aerosol activation (Wang et al., 2022)





How do aerosols affect the atmosphere and climate?



Reduced aerosols diminished cloud reflectivity

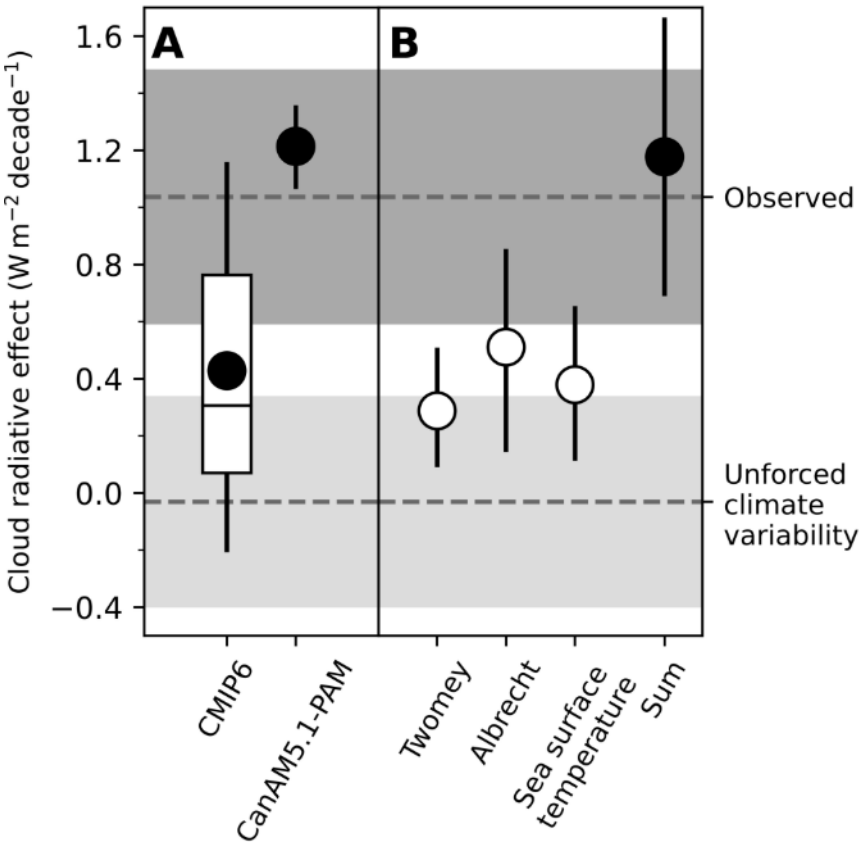
Causes of cloud reflectivity loss

0.80 Wm^{-2} $decade^{-1}$ or 69% (range 55 to 85%) from **declining aerosols**

Contributions:

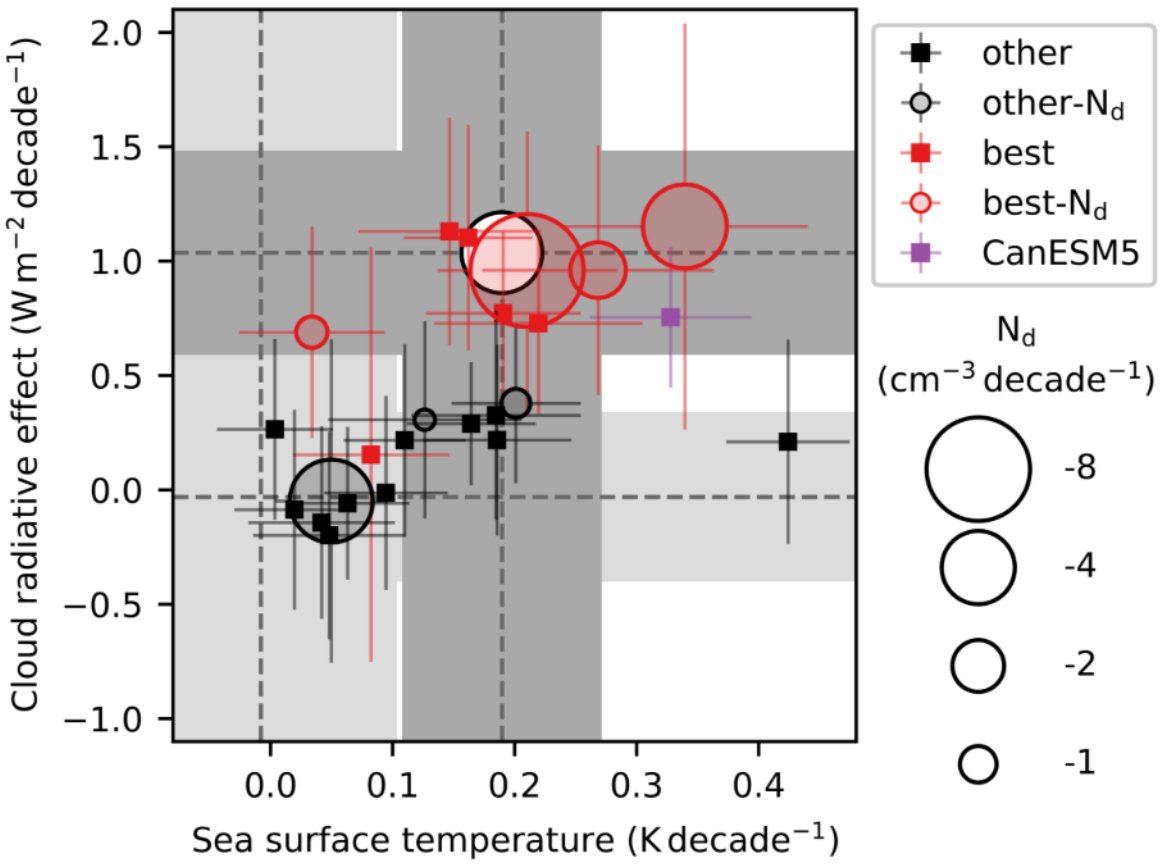
- Twomey effect: 0.29 Wm^{-2} $decade^{-1}$
- Albrecht effect: 0.51 Wm^{-2} $decade^{-1}$
- SST warming: 0.38 Wm^{-2} $decade^{-1}$

Compare: CO_2 radiative forcing change 0.31 Wm^{-2} $decade^{-1}$



Source: von Salzen et al. (nature communications, 2025)

Many CMIP6 models appear to underestimate trends



Source: von Salzen et al. (nature communications, 2025)

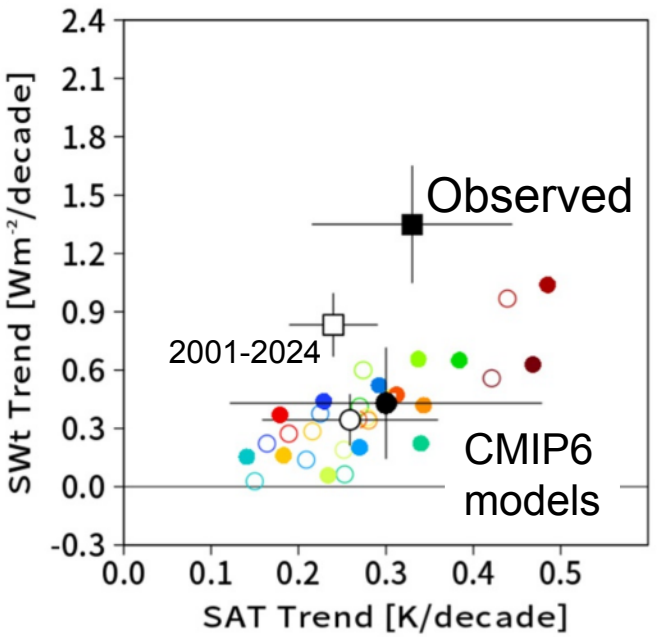
Global changes from 2010 to 2024 are too large to be explained by cloud feedbacks alone

- Total effective radiative forcing (mostly from clouds) **~ 1.00 Wm^{-2} $decade^{-1}$**
- Warming feedback **~ 0.35 Wm^{-2} $decade^{-1}$**
- SST trend: 0.33 K $decade^{-1}$

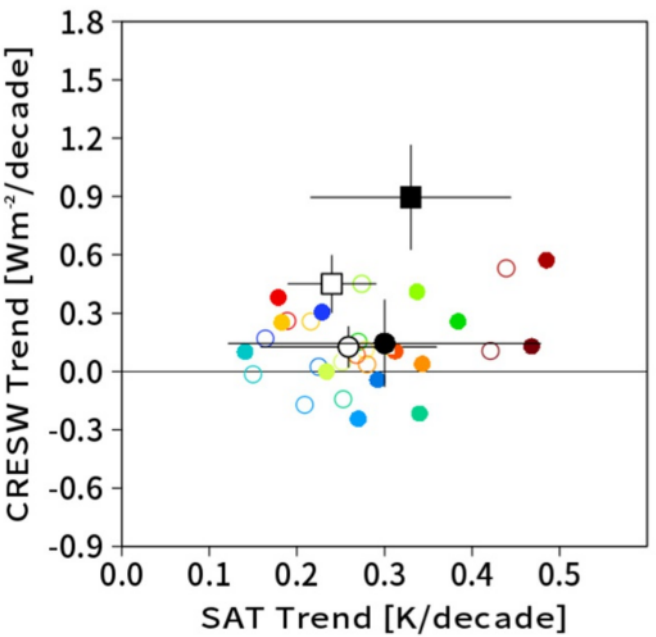
Based on a regression analysis, exploiting interannual CRE and SST variability

Source: Yukimoto et al. (GRL, 2026), with modifications

Global net shortwave

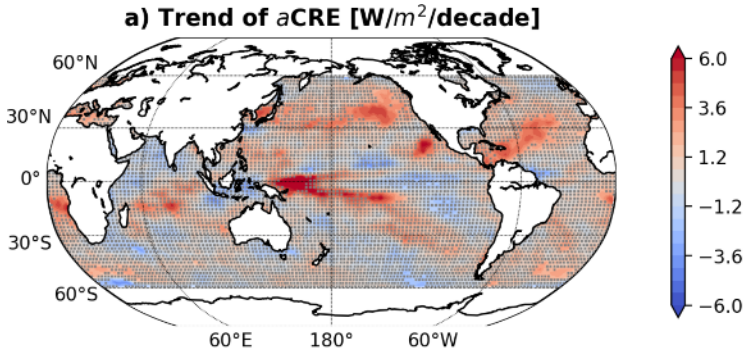


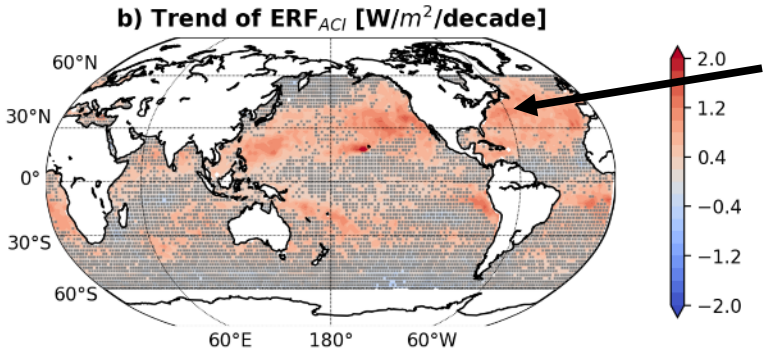
Global shortwave cloud radiative effect



Global satellite-based trends for 2003-2023

Yuan et al., nature communications (in press)

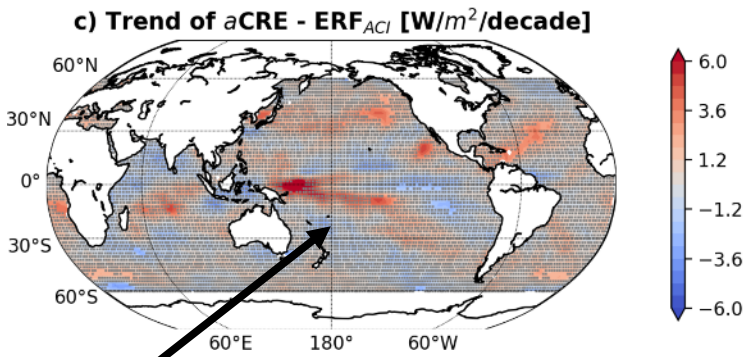


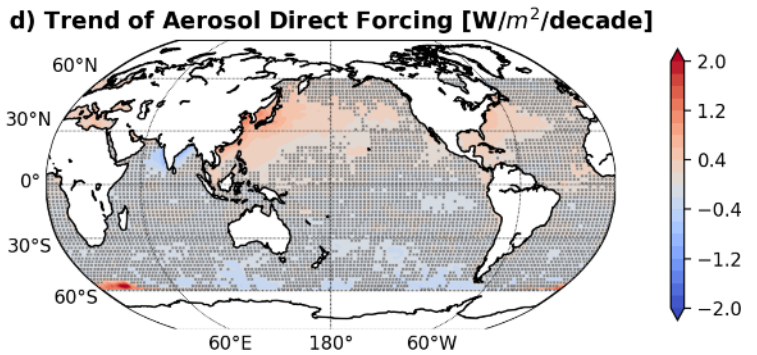


Effective radiative forcing from **aerosol-cloud interactions**:

0.33 Wm^{-2} decade^{-1}

43% of the cloud radiative effect trend (shortwave)





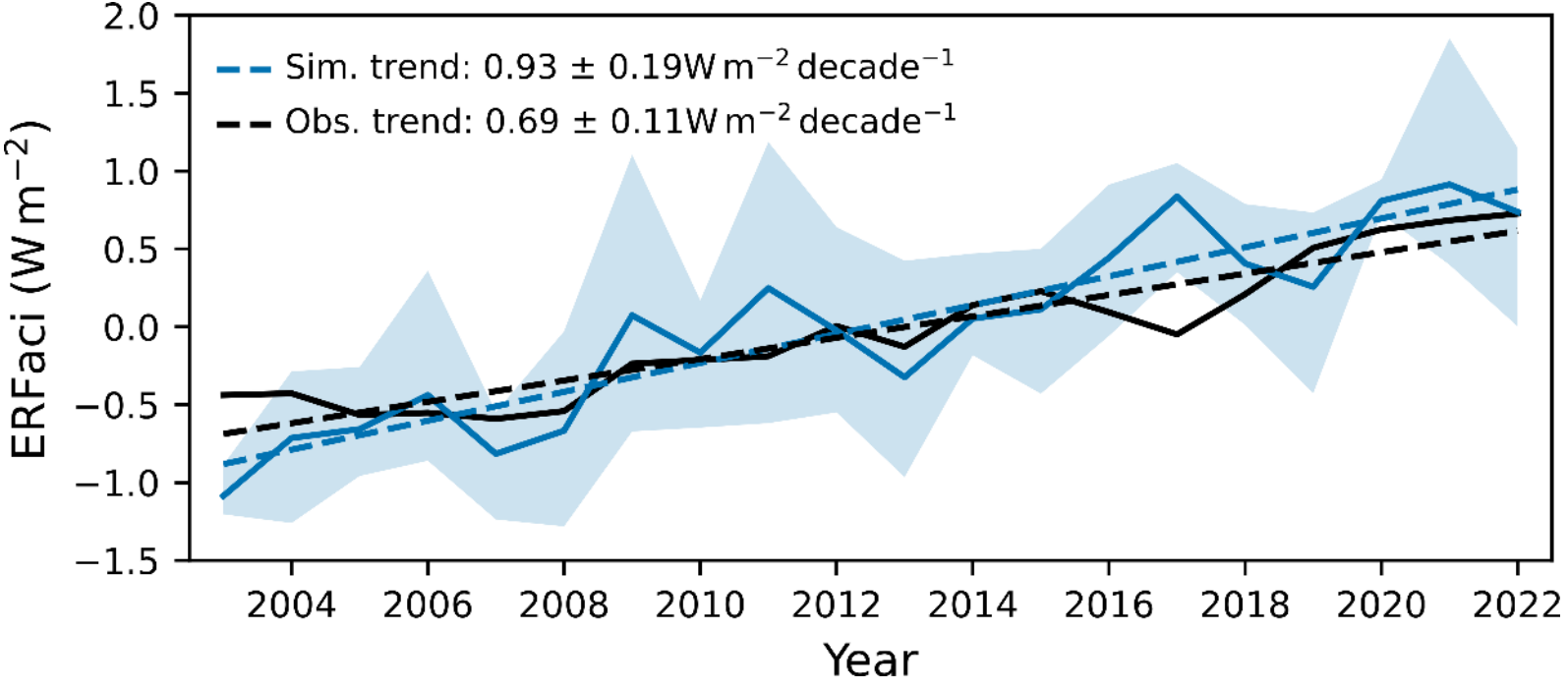
Cloud feedbacks to warming and GHGs

~ half of the cloud radiative effect trend

Northeast Pacific & North Atlantic trends

Simulated vs. observed **effective radiative forcing from aerosol-cloud interactions**

Data from CanAM5.1-PAM & Yuan et al.



Conclusions

- Simulated marine **cloud reflectivity reductions** over the NE Pacific and N Atlantic between 2003 and 2022 were **largely caused by declining aerosols**, likely to continue
- Consistency with recent studies, based on observations
- Few of the **CMIP6 model simulations reproduce** the large magnitude and spatial extent of **the observed cloud reflectivity los**s
- **New opportunities to robustly assess aerosol-cloud interactions** in CMIP7 models and impacts on projected warming