Cloud contamination in satellite products enhances the aerosol indirect forcing estimate

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Effective Aerosol Indirect Radiative Forcing

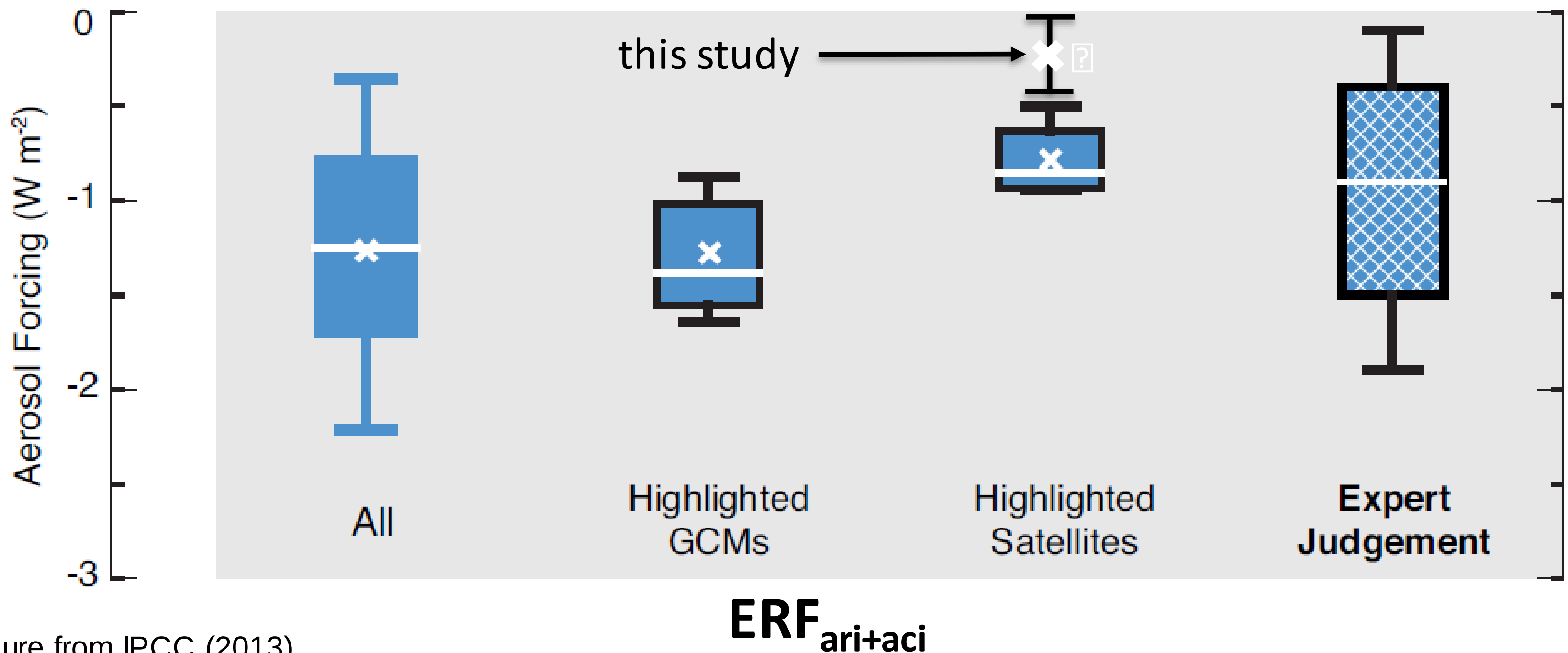
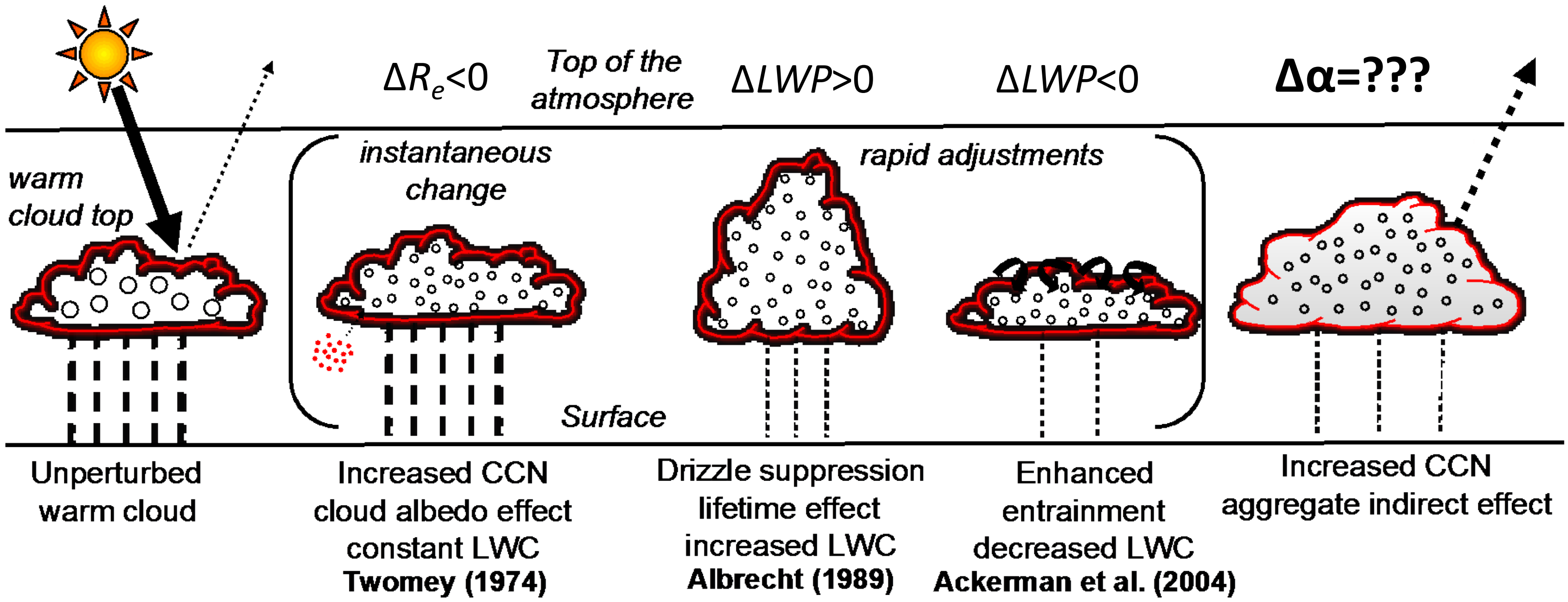


Figure from IPCC (2013)

- Radiative impact from anthropogenic CO_2 since 1750 is **2.63 ± 0.26** W m^{-2}
- **Aerosol indirect effects** cause large uncertainty in projections of climate change.
  - → Satellites: –**0.85 [-0.93 to -0.45]** W m^{-2}
  - → GCMs: –**1.38 [-1.68 to -0.81]** W m^{-2}

What are the sources of uncertainty?

Aerosol Indirect Effect in *Warm* Clouds



<u>Key processes that influence the aerosol indirect radiative forcing response (cause and effect)</u>

- **Meteorology** (humidity & stability)
- **Precipitation** (suppression & invigoration)
- **Ice phase** (glaciation and cloud dissipation)
- **Aerosol type** (absorption and particle size)
- **Cloud type** (shallow cumulus VS deep convection)

<u>Uncertainties in the satellite retrieval</u>

- Radiation scattered by 3D clouds, cloud shadows, aerosol humidification/swelling, cloud contamination.

CC4CL
(Community Code 4 CLimate)

- Algorithm used in the ESA CCI (Climate Change Initiative)

Aerosol-ORAC

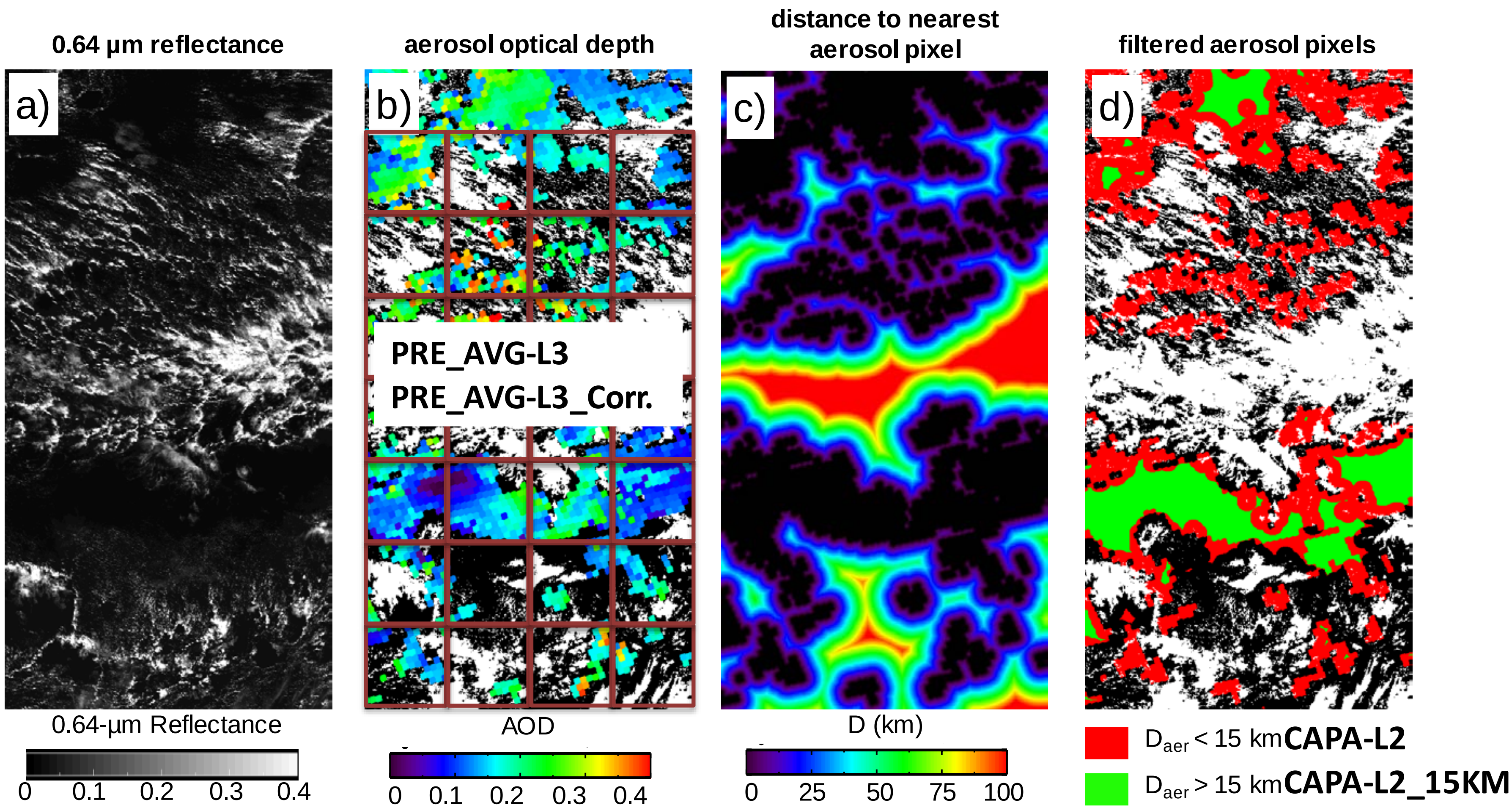
- Optimal estimation algorithm
- Similar forward model to cloud retrieval
- Dual view algorithm
- Visible channels only
- NN cloud mask
- 1km product
- Thomas et al. 2010

Cloud-CC4CL

- Optimal estimation algorithm
- Similar forward model to aerosol
- Single view algorithm
- Visible and IR
- NN cloud mask
- 1km retrievals
- Poulsen et al 2012

*TOA radiative fluxes computed using BUGSrad (Stephens et al. 2001, *JAS*)

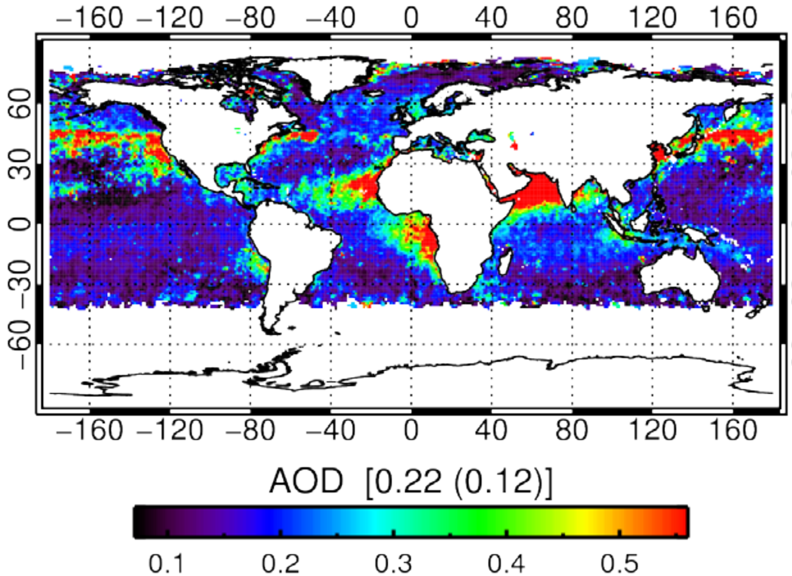
Cloud-Aerosol Pairing Algorithm (CAPA)



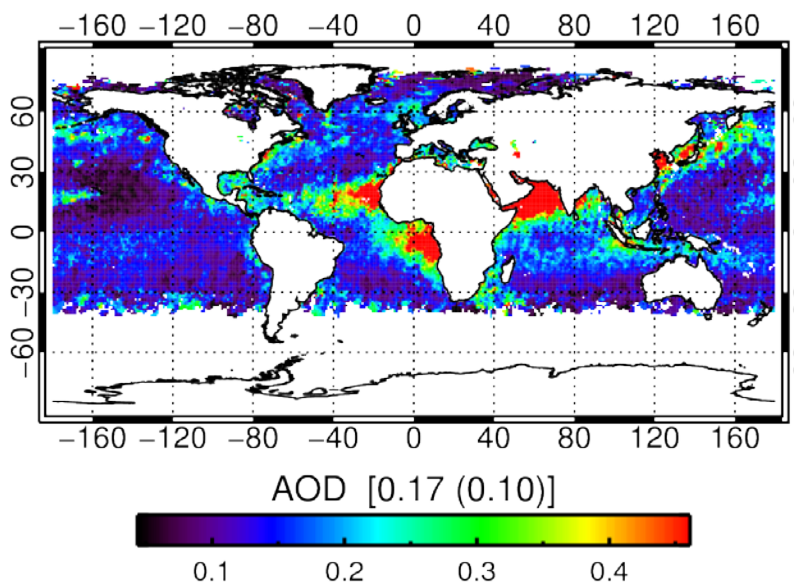
Aerosols near cloud are affected by: 1) cloud contamination, 2) radiation scattered by 3D clouds and 3) humidification/aerosol swelling.

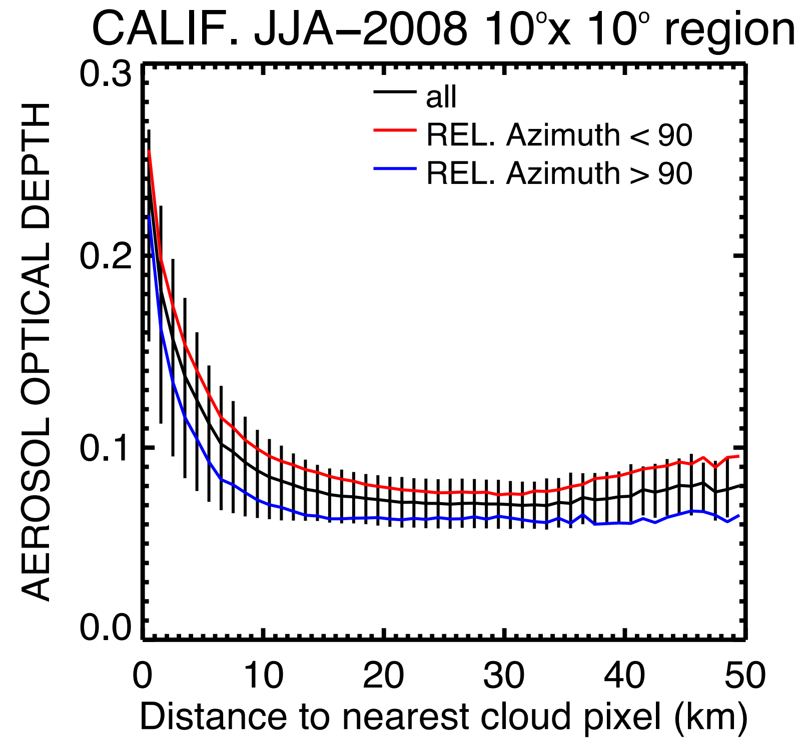
Near-Cloud Aerosol Optical Depth

MEAN AOD **(no cloud distance threshold)**



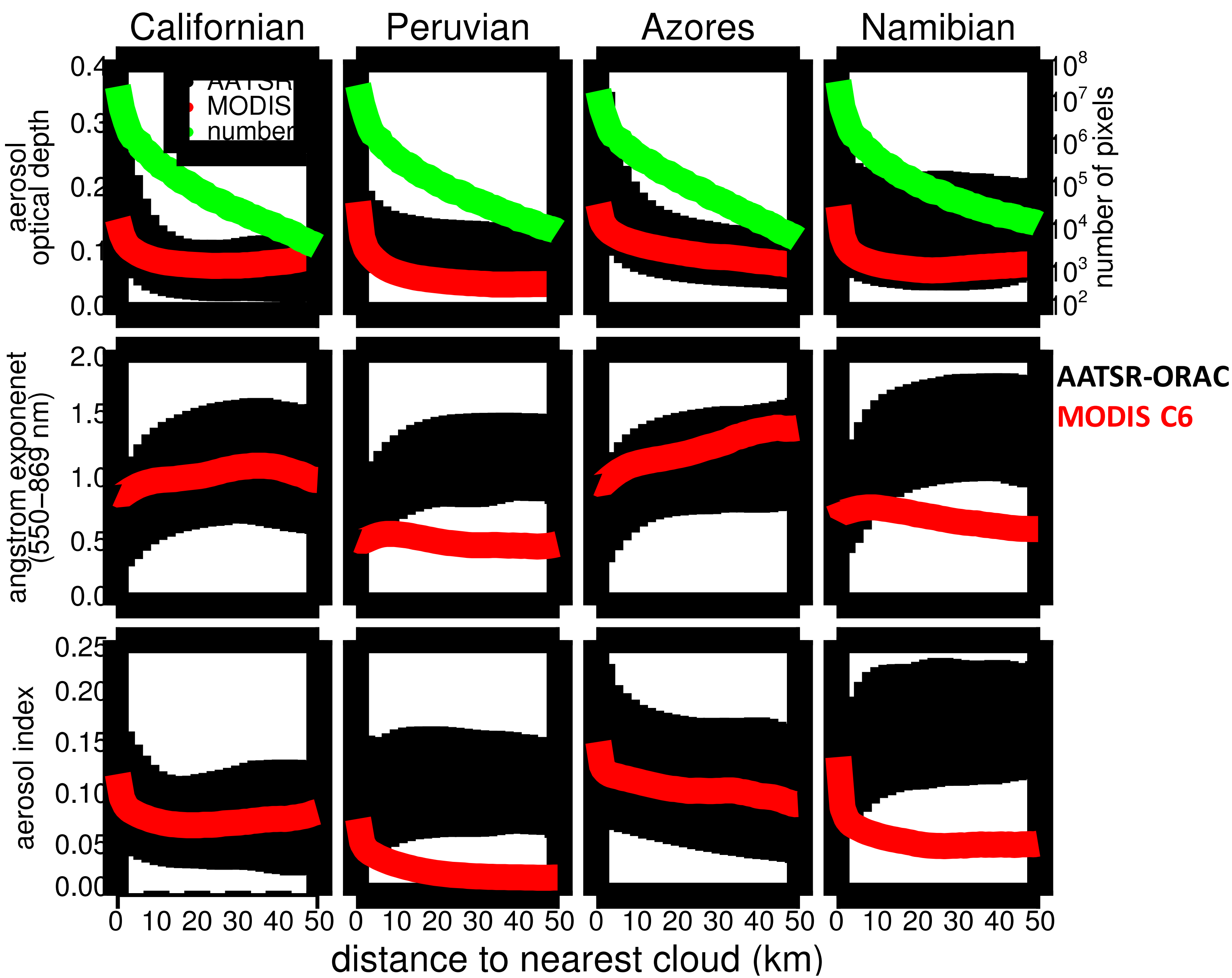
MEAN AOD **(distance from cloud > 15 km)**



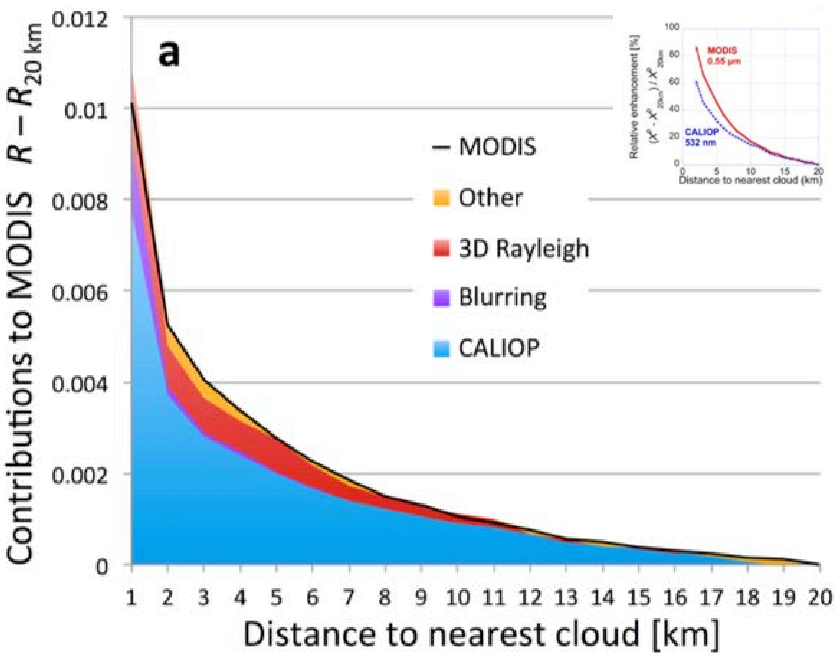


- AOD is artificially large near cloud edges.
- Use aerosol-cloud pairs in which the aerosol is located at least 15 km from cloud edge and located at least 150 km from the nearest cloud pixel.

Near-Cloud Aerosol Optical Depth



LIDAR Aerosol Observations in the Vicinity of Clouds



Várnai et al. (2013), ACP, Fig. 6

- 3D radiative transfer simulations by a Monte Carlo method tested in I3RC project.
- Aircraft observations of Redemann et al. (2009), JGR also show similar responses using airborne sunphotometer near clouds.

"Real Microphyiscs"

- Increased hydroscopic aerosol particles, new particle production, or other in-cloud processes.

"Artificial"

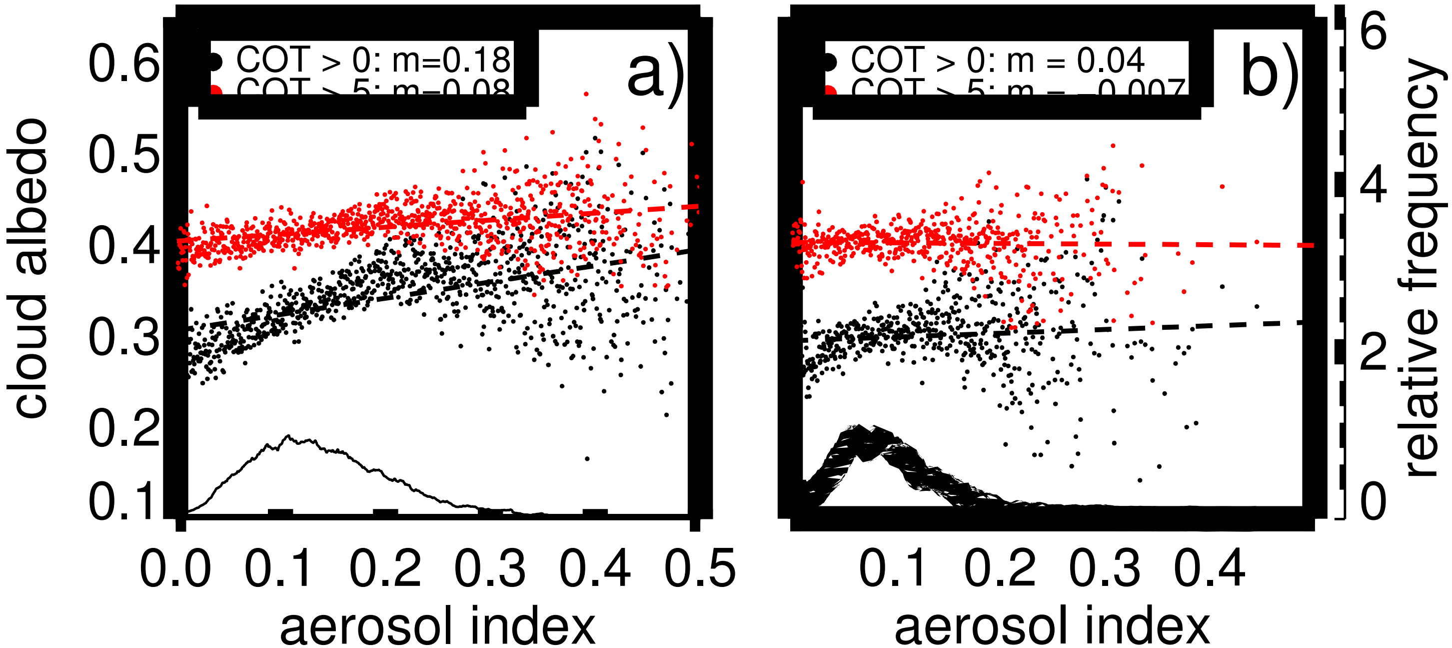
- 3D cloud effects
- Cloud contamination from sub-pixel clouds tends to increase "coarse" mode AOD.
- Extra illumination from clouds (or aerosol "bluing") is caused by shorter wavelengths being scattered much more from the sides of clouds through the column of the atmosphere by Rayleigh scattering.

Cloud Albedo Aerosol Sensitivity

- ***region***: California (20° −30°N, 140° −130°W)
- ***period***: 2002 – 2012
- ***cloud albedo***: AATSR-ORAC (BugsRad)
- ***aerosol index***: AATSR-ORAC (v4.02)

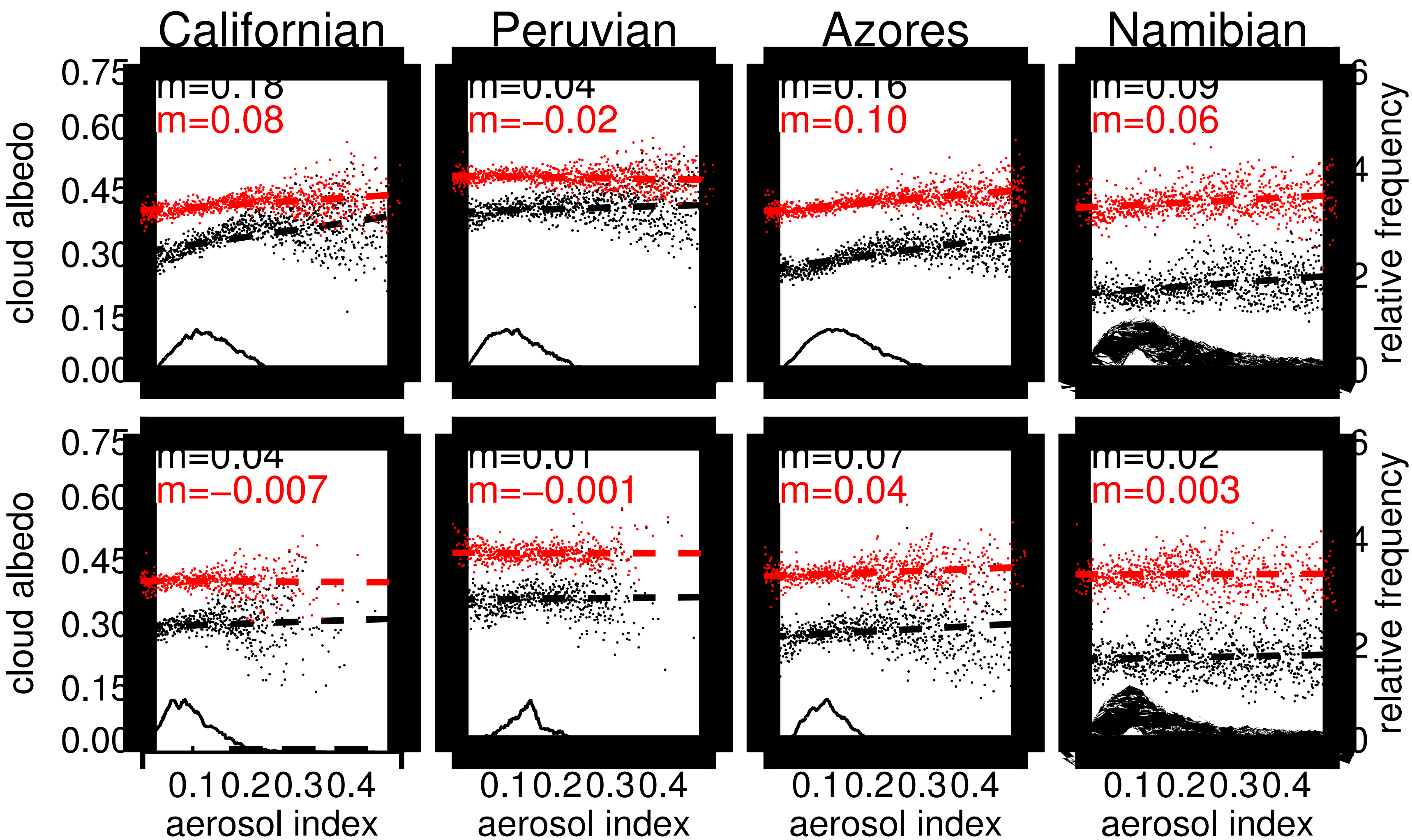
CAPA-L2 (nearest neighbor)

CAPA-L2_15km (aerosol at least 15 km from cloud)

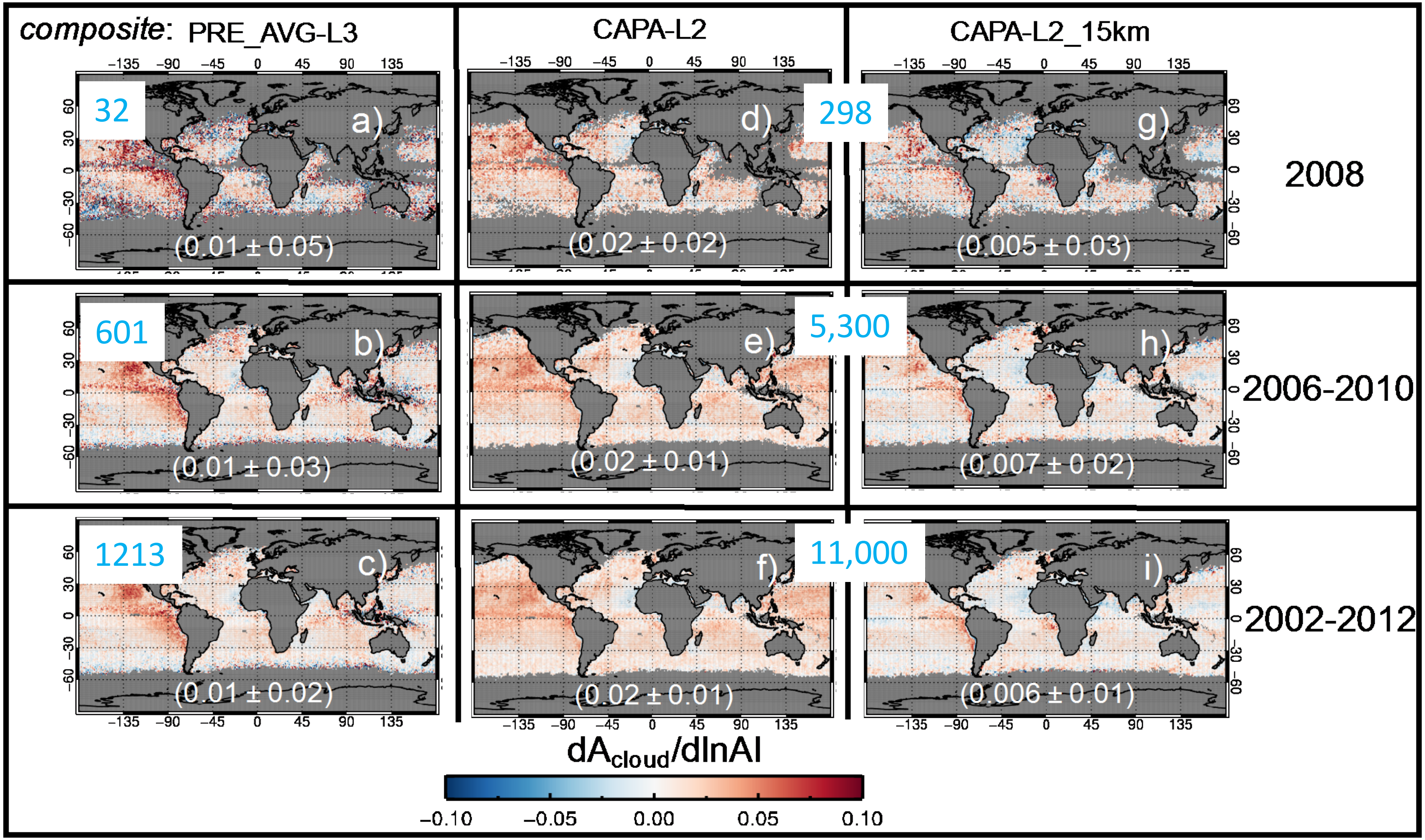


- Aerosol size distribution is shifted to smaller values using CAPA-L2_15km pairs.
- Slope of the linear least squares is smaller using CAPA-L2_15km pairs.
  - ➢ Near-cloud aerosol *AI* enhances the strength of the cloud albedo effect relationship.
  - ➢ Sensitivity is reduced using thicker clouds .

Cloud Albedo Aerosol Sensitivity

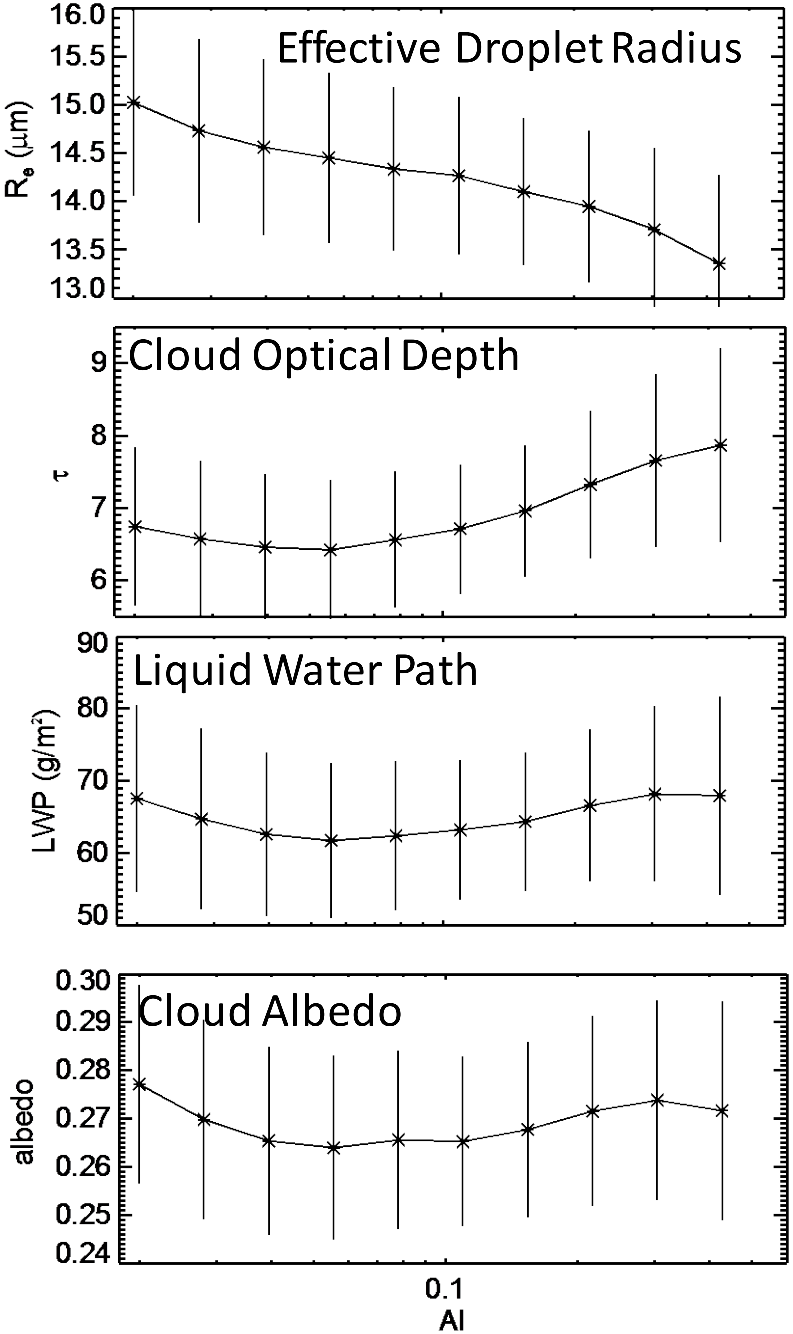


Cloud Albedo Aerosol Sensitivity



- CAPA composites have ~10 times more unique samples compared to *pre-averaged* data.
- Increasing the number of samples does not change the forcing estimate but does decrease σ.

Statistical relationships between aerosol and cloud properties



$$\frac{d\ln(R_e)}{d\ln \mathrm{AI}} = -0.1$$

$$\frac{d\ln(\tau)}{d\ln \mathrm{AI}} = 0.06$$

$$\frac{d\ln LWP}{d\ln \mathrm{AI}} \cong 0$$

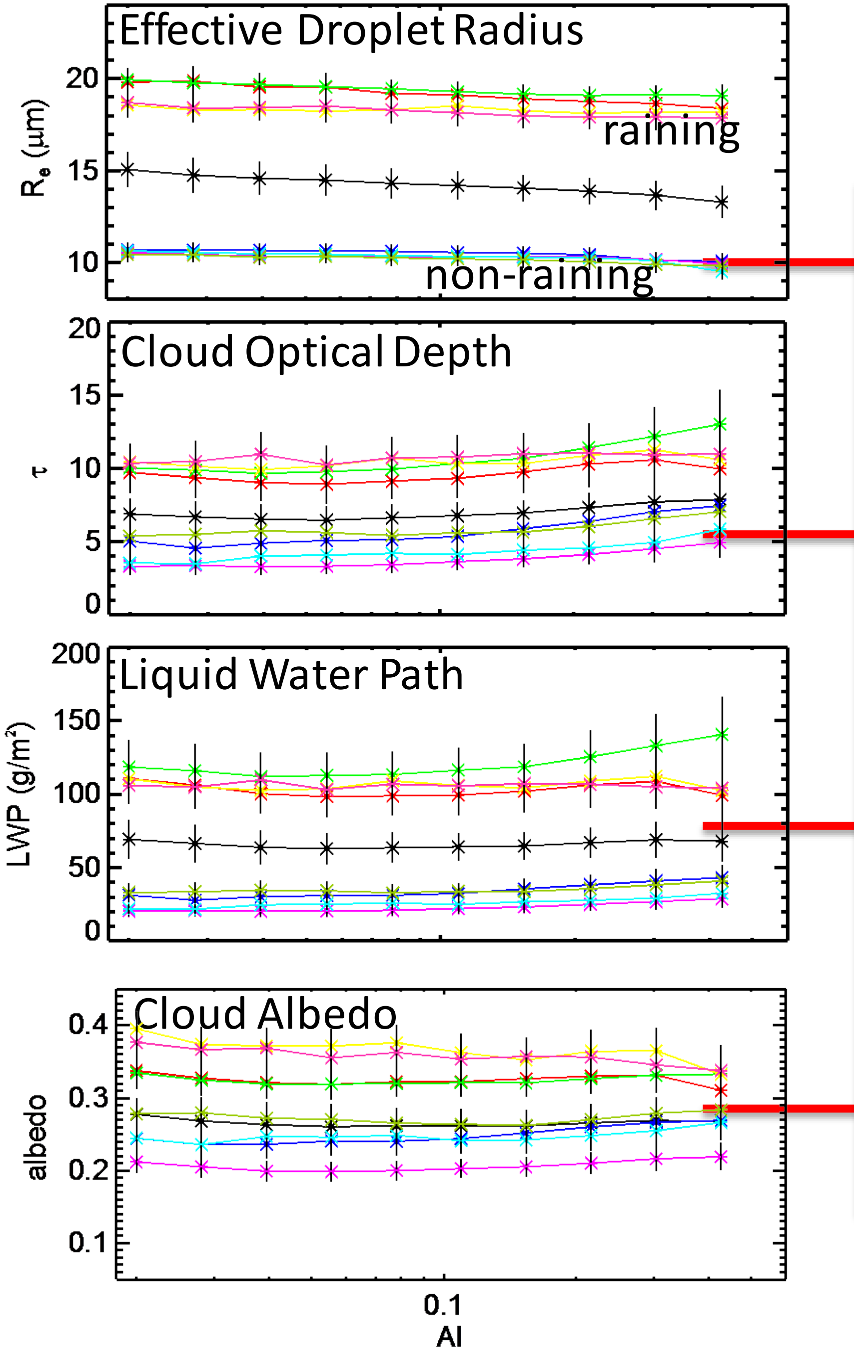
$$\frac{d\ln A}{d\ln \mathrm{AI}} = 0.02$$

AATSR on ENVISAT Data

- Aerosol index: product of aerosol optical depth and angstrom exponent is a proxy for cloud condensation nuclei.
- Aerosol-cloud pairs gridded into 1°×1° regions.
- Each region contains ~12,000 unique L2 cloud-aerosol data points.
- Aerosol (ATSR) properties are paired to 1-km cloud pixels through nearest neighbor method.

How do these observations vary with meteorology?

Statistical relationships between aerosol and cloud properties



ysical

ptical

hysic
me

lbedo

- all
- Moist/Stable Raining
- Moist/Stable Non-Raining
- Moist/Unstable Raining
- Moist/Unstable Non-raining
- Dry/Stable Raining
- Dry/Stable Non-Raining
- Dry/Unstable Raining
- Dry/Unstable Non-Raining

ECMWF ERA-INTERIM

DRY: FTH < 40%
Moist: FTH > 40%
Stable: LTS > 17 K
Unstable: LTS < 17 K
Raining: Re > 14 um
Non-raining: Re < 14 um

FTH: relative humidity at 700 hPa
LTS: potential temperature difference between surface and 700 hPa

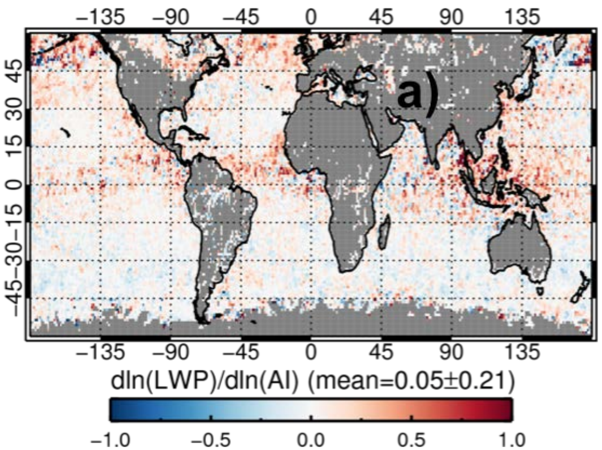
How do these observations compare with the ECHAM6 HAM model?

Satellite-Model Comparison

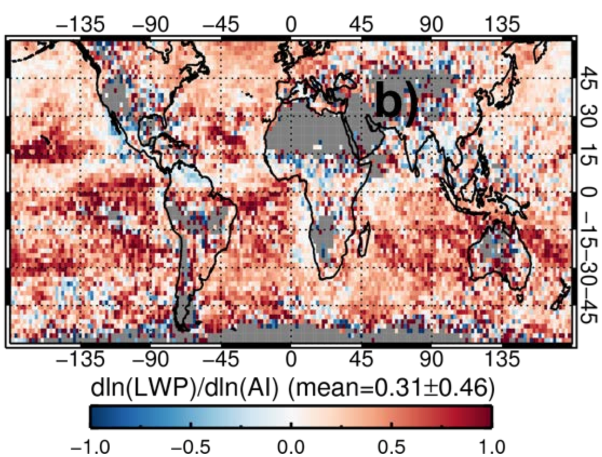
Cloud Water Path Sensitivity Satellite-Model Comparisons

2006 – 2010; 60S° – 60° N (Ocean only)

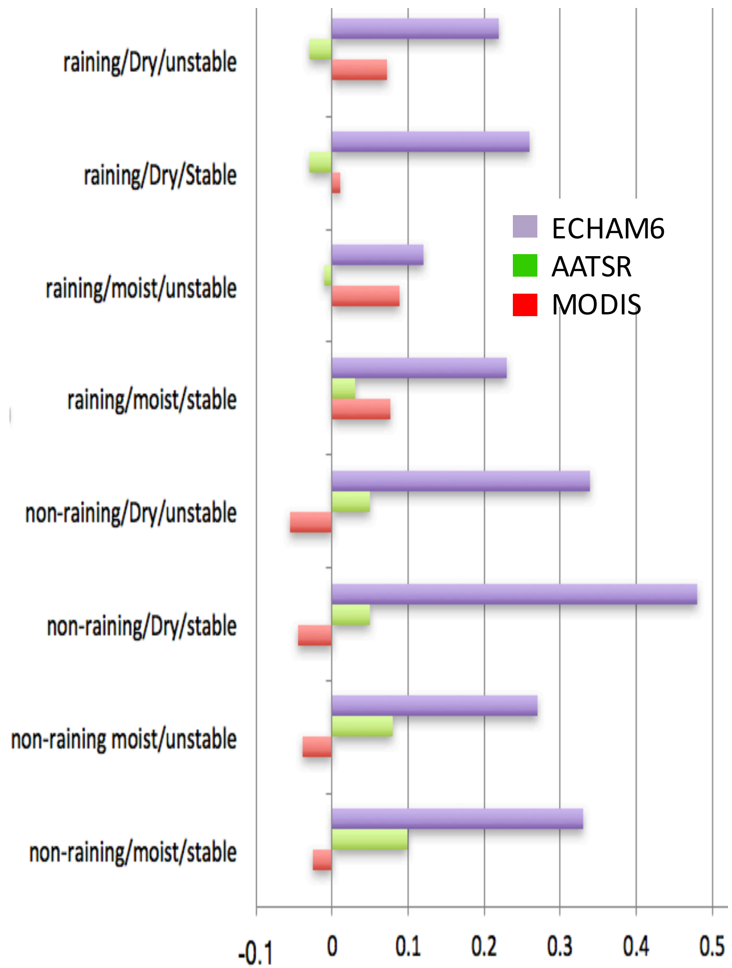
Satellite: AATSR



Model: ECHAM6 HAM 2



Global mean sensitivity ($\frac{d \ln LWP}{d \ln \mathrm{AI}}$) by cloud regime



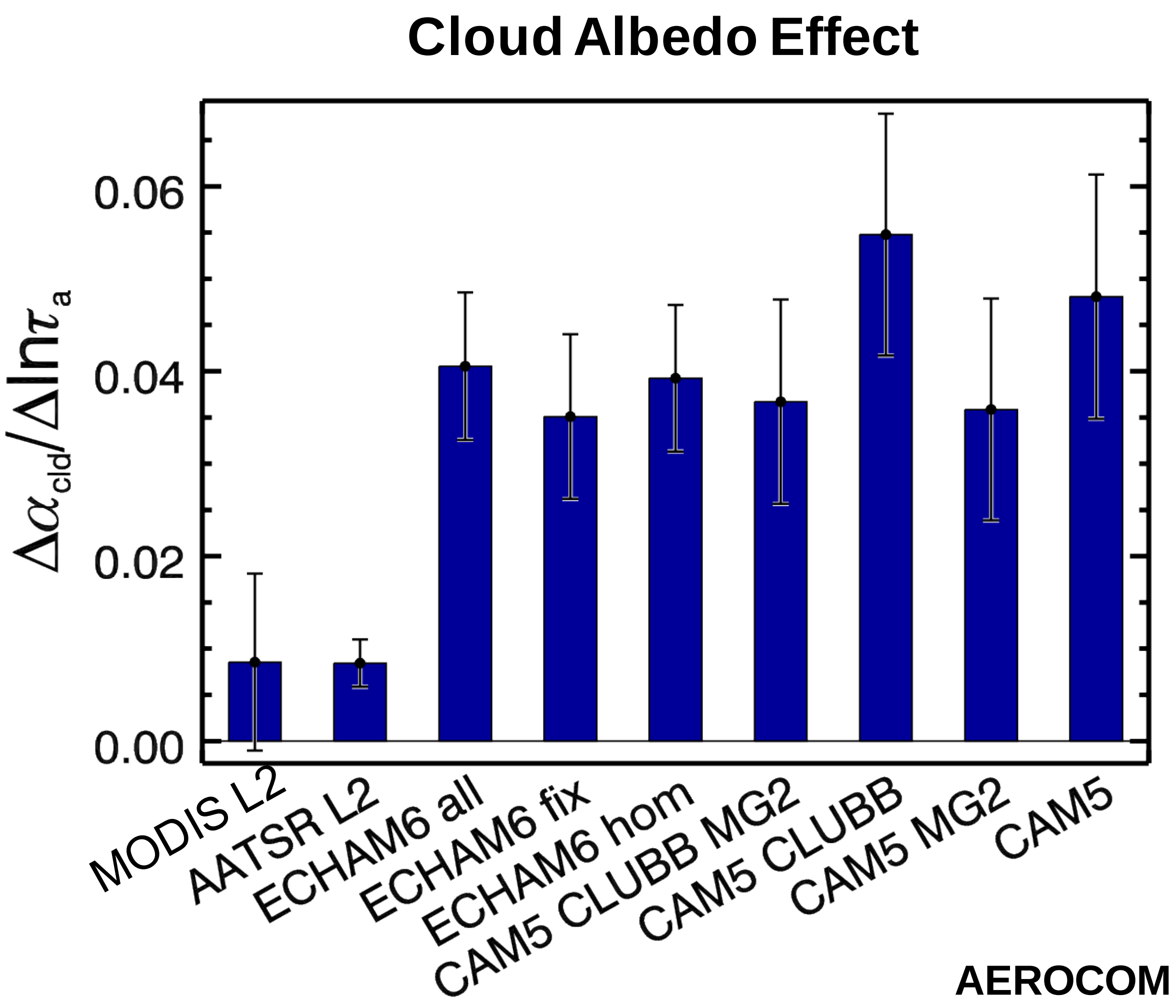
Main result

- LWP sensitivity to increasing aerosols is significantly larger in the ECHAM6 model compared to AATSR observations.
- Model derived aerosol indirect forcing is more than two times larger than satellite data (IPCC, 2013).
- Feedbacks that reduce the LWP sensitivity (e.g., entrainment) are poorly parameterized in model simulated clouds which may explain the significant difference between model and satellite observations.

Satellite-Model Comparison

Cloud Water Path Sensitivity Satellite-Model Comparisons

2006 – 2010; 60S° – 60° N (Ocean only)



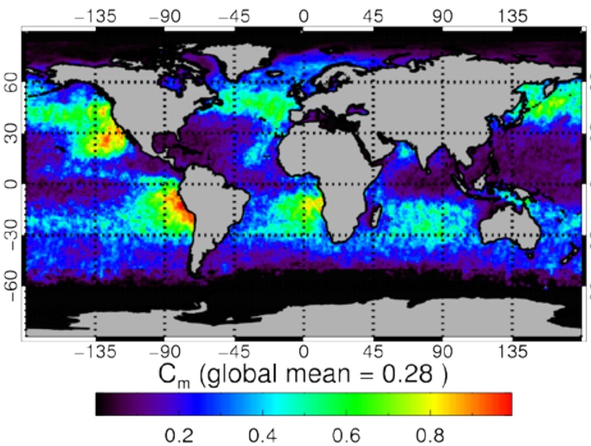
AEROCOM models

(https://wiki.met.no/aerocom/indirect)

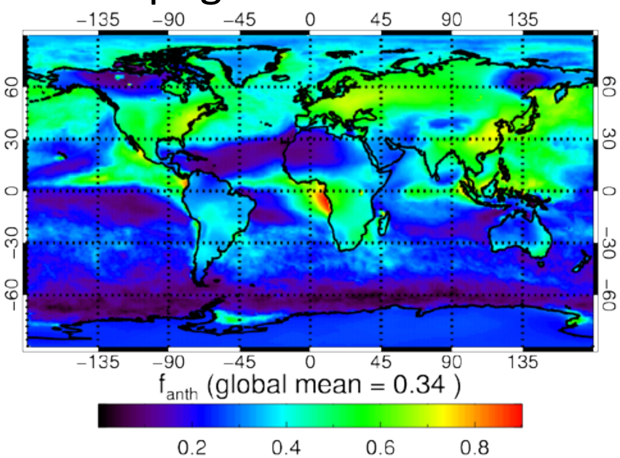
Data from Ghan et al. (2016), PNAS

Aerosol Indirect Radiative Forcing Estimate

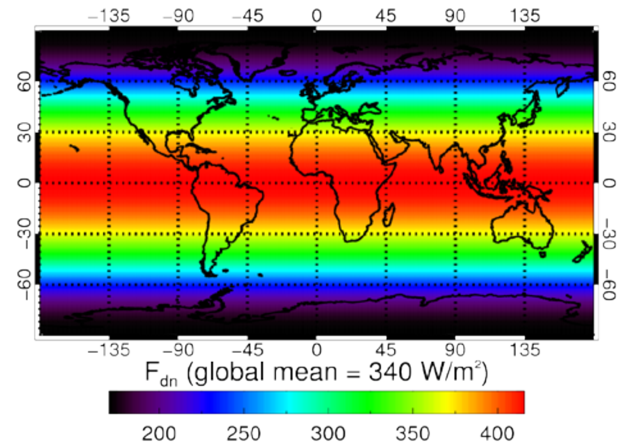
Low-level cloud fraction



Anthropogenic Aerosol Fraction



Annual Solar Insolation



Aerosol Indirect Forcing Calculation

$$F = F_{clr} - F_{allsky}$$ "cloud radiative effect"

$$F_{allsky} = (1 - c_f)\, F_{clr} + c_f F_{cld}$$

$$\boldsymbol{\Delta F = c_f \Delta a F^{\downarrow}_{SW} \frac{d\alpha}{d\ln AI}}$$

Δa: change in anthropogenic aerosol
AI*:* aerosol index
c**$_f$:** cloud fraction;
A$_{clr}$: clear sky albedo
A$_{cld}$: cloud albedo (CERES)
α: planetary albedo

Method: Chen et al. (2014)

Low-level cloud fraction (AATSR)

- Water cloud below 500 hPa (~5.5 km)

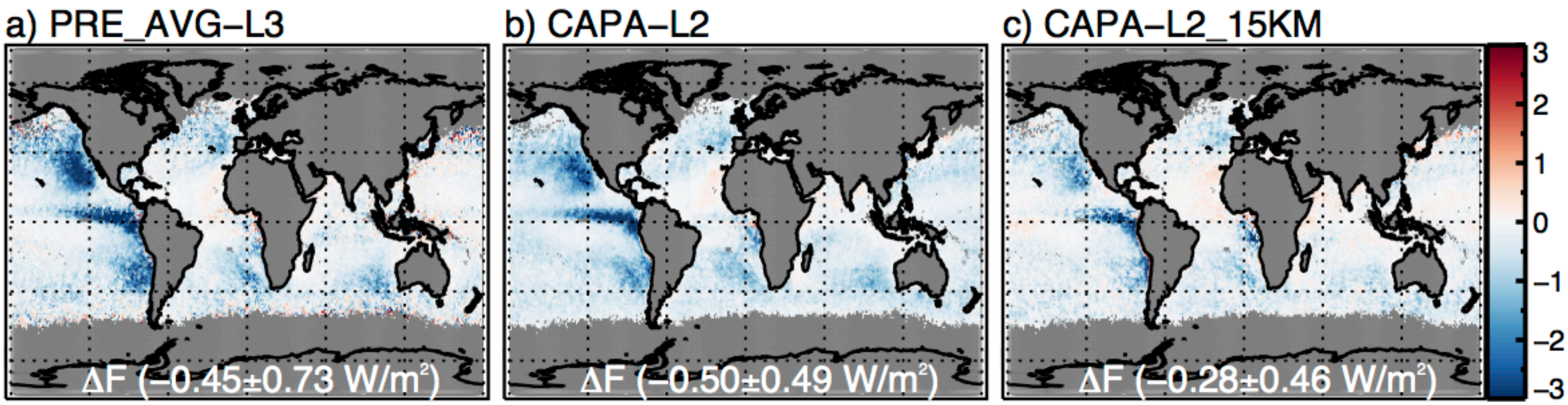
Anthropogenic aerosol fraction (MACC-II)

- Grid: 1.25° x 1.25° - 8 times daily
- AOD for: Black Carbon, Dust, Organic Carbon, Sea Salt, Sulphate
- MACC-II estimates the anthropogenic contribution to the aerosol optical depth (Bellouin et al., 2013).

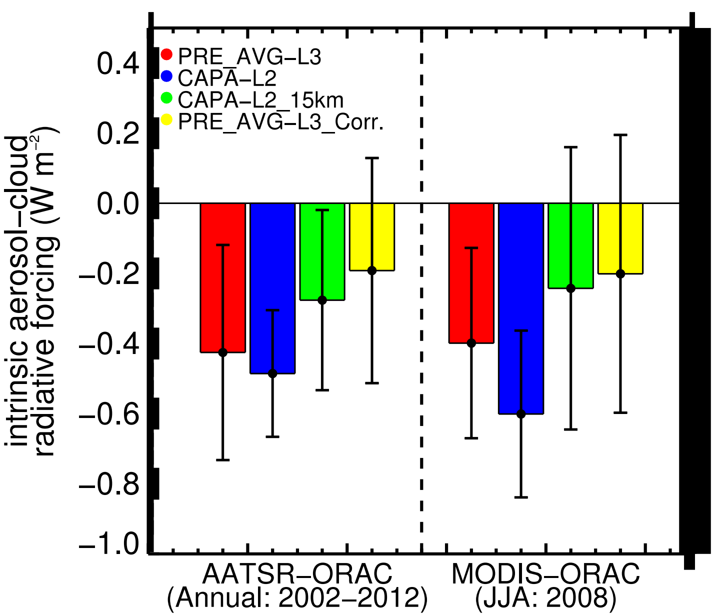
$$\frac{d\alpha}{d\ln AI} = \left(\frac{\partial A_{clr}}{\partial \ln AI} - \frac{\partial A_{cld}}{\partial \ln AI}\right) + \frac{A_{clr} - A_{cld}}{c_f}\frac{\partial c_f}{\partial \ln AI}$$

Intrinsic AIE ***Extrinsic AIE***

Intrinsic Aerosol Indirect Radiative Forcing Estimate

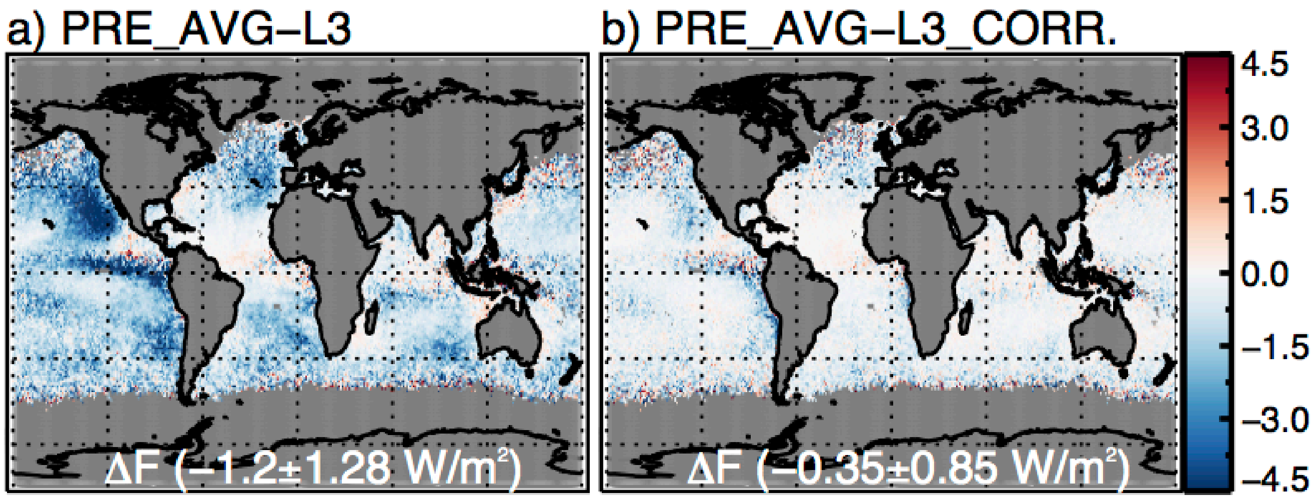


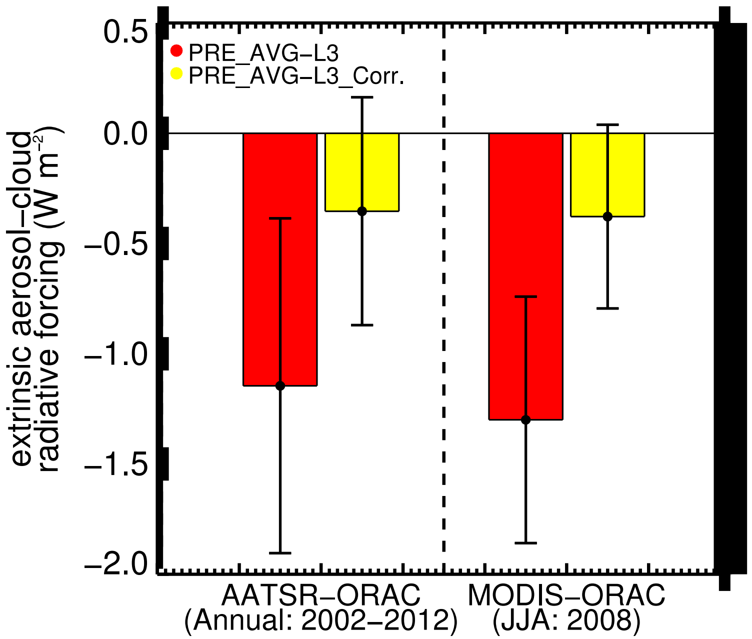
$$\Delta F = \left(\frac{\partial A_{clr}}{\partial \ln AI} - \frac{\partial A_{cld}}{\partial \ln AI}\right) c_f \Delta a F_{SW}^{\downarrow}$$



- MODIS C6 and AATSR-ORAC are in good agreement.
- Forcing estimate decreases using aerosols located farther away from clouds in CAPA.
- Removing near-cloud aerosols in PRE-AVERAGED L3 products gives similar results as the CAPA-L2_15km data for both MODIS and AATSR observations.

Extrinsic Aerosol Indirect Radiative Forcing Estimate



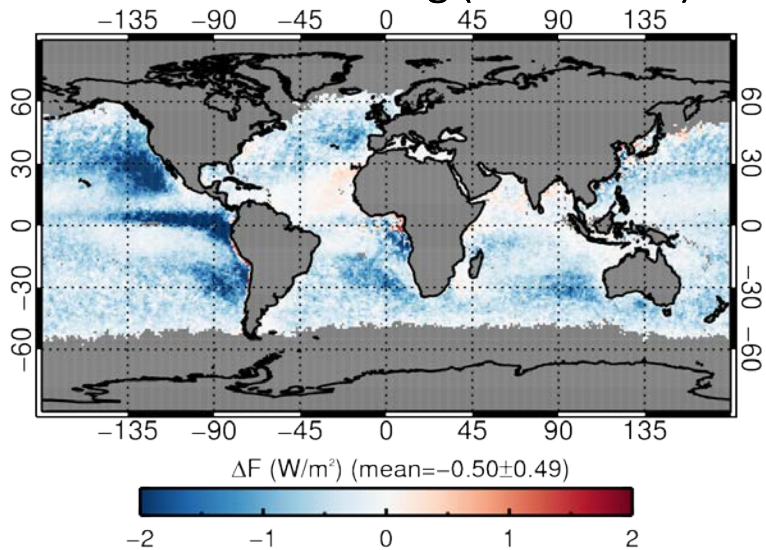


$$\Delta F = \left[(A_{clr} - A_{cld}) \frac{\partial c_f}{\partial \ln AI} \right] \Delta a F_{SW}^{\downarrow}$$

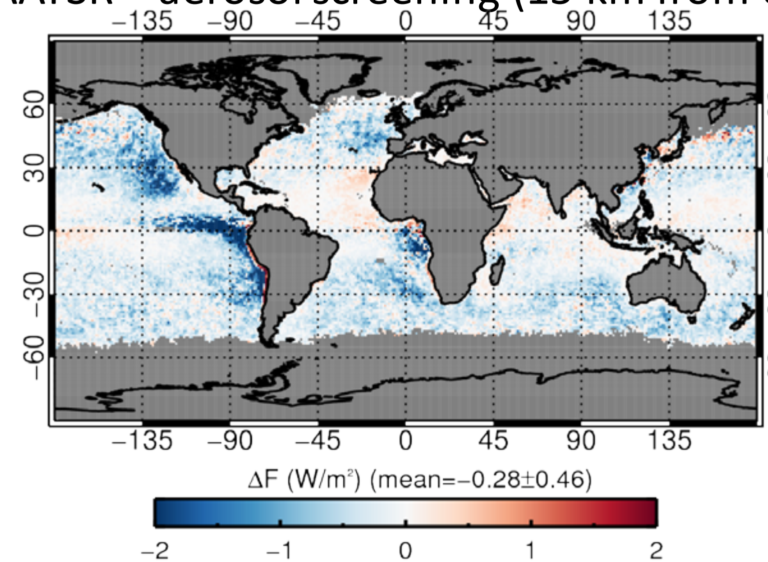
- CAPA is used to remove near-cloud aerosol from gridded L3 products.
- Extrinsic aerosol indirect effect is significantly smaller by removing aerosols in the vicinity of clouds.
- Similar decreases in the *AOD*–c_f relationship are observed by modulating by cloud droplet number concentration to reduce impact from meteorology (Gryspeerdt et al. 2016).

Aerosol Indirect Radiative Forcing Estimation

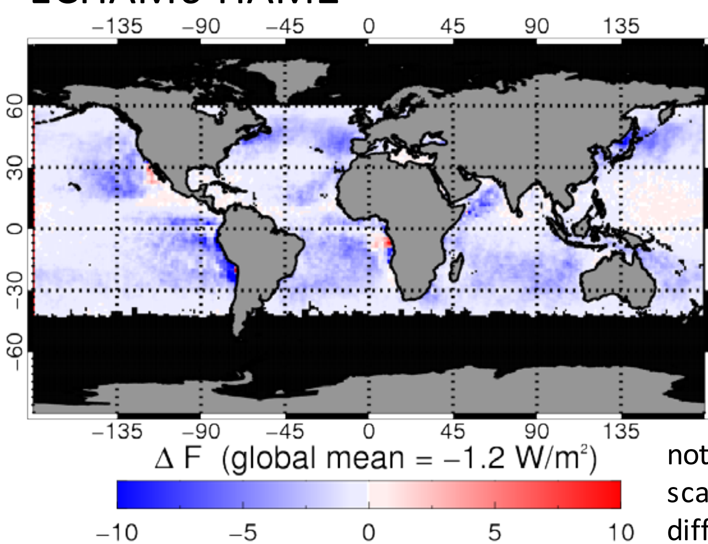
AATSR – no screening (2002-2012)



AATSR – aerosol screening (15 km from cloud)

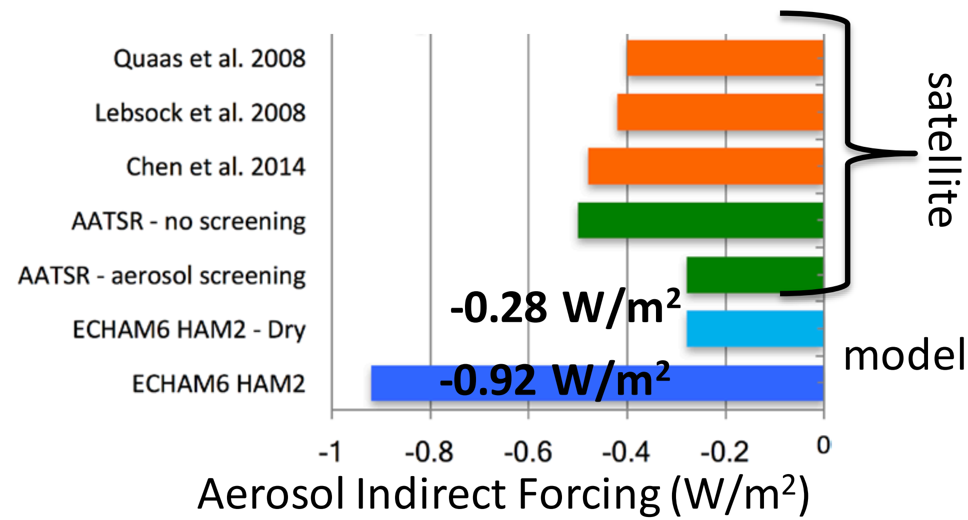


ECHAM6-HAM2



note scale difference

Aerosol Indirect Forcing Estimate



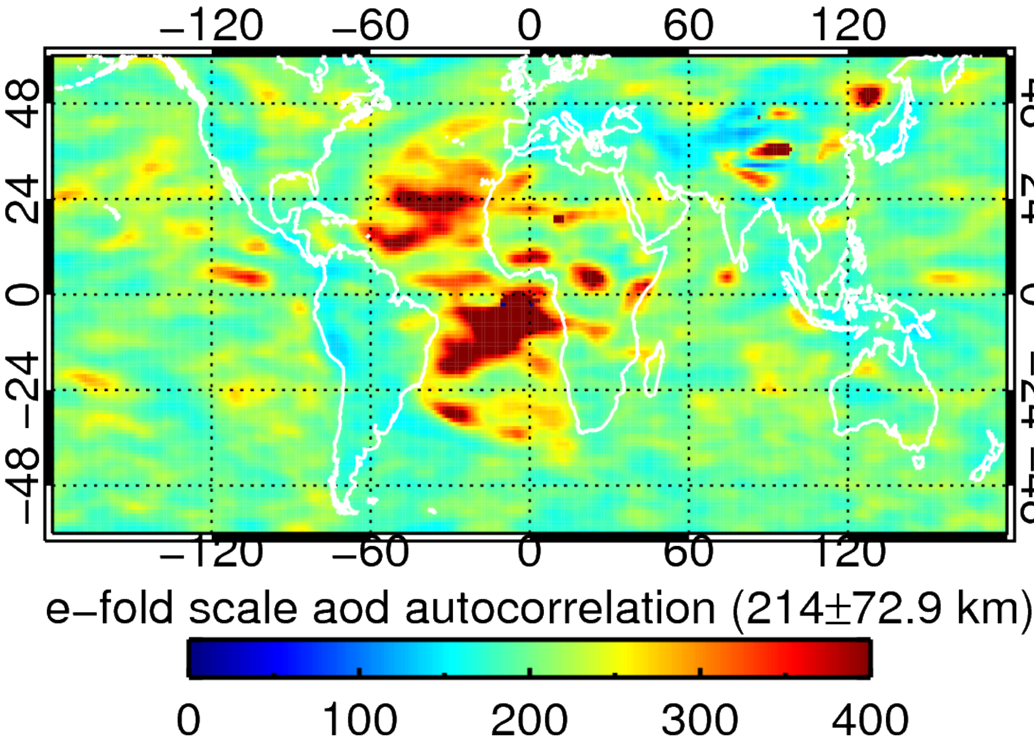
Summary

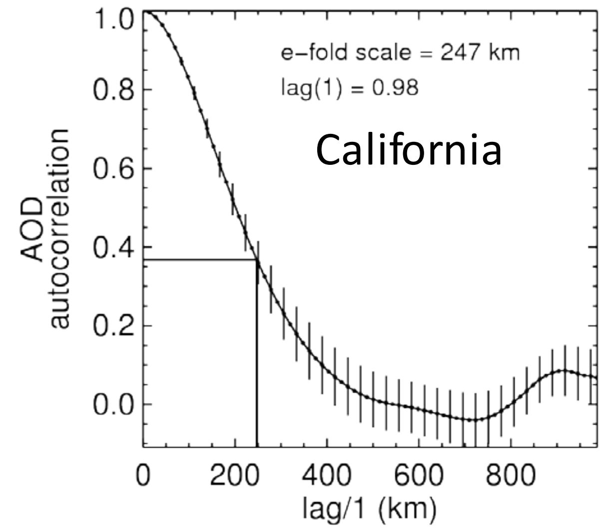
- Aerosol and cloud products retrieved using ORAC are combined together using the CAPA nearest-neighbor approach to limit cloud contamination and to study aerosol-cloud susceptibilities under various meteorological regimes.
- Previous satellite-based radiative forcing estimates represented in key climate reports may be exaggerated due to including retrieval artefacts in the aerosol located near clouds.
- Comparison with ECHAM6 HAM2 simulations reveal significantly larger susceptibilities in the model compared to the satellite derived values.
- Larger model susceptibilities lead to significantly larger aerosol indirect radiative forcing. Missing processes in the model may explain the lack of LWP changes.

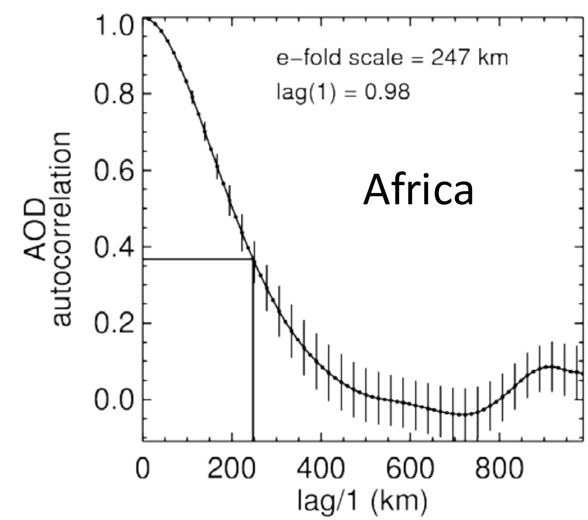
Unveiling aerosol-cloud interactions Part 1: Cloud contamination in satellite products enhances the aerosol indirect forcing estimate
Matthew W. Christensen, David Neubauer, Caroline Poulsen, Gareth Thomas, Greg McGarragh, Adam C. Povey, Simon Proud, and Roy G. Grainger

Unveiling aerosol-cloud interactions Part 2: Minimizing the effects of aerosol swelling and wet scavenging in ECHAM6-HAM2 for comparison to satellite data
David Neubauer, Matthew W. Christensen, Caroline Poulsen, and Ulrike Lohmann

Spatial Autocorrelation Length-Scale of Aerosol Optical Depth

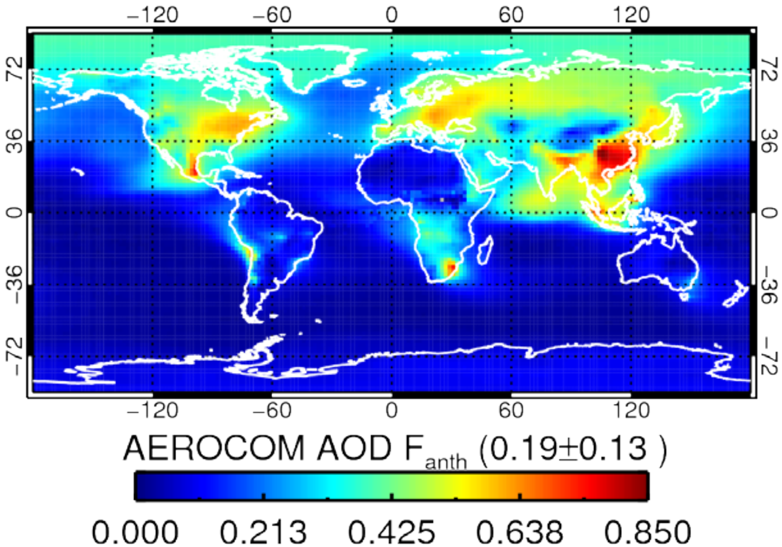


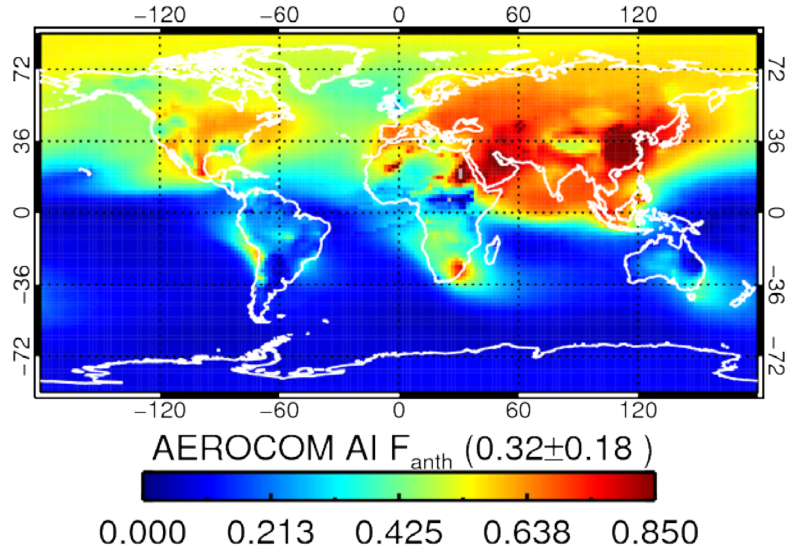




Aerosol optical depth e-folding scale is the length at which the auto-correlation falls to a value of 1/e using CAMS 0.125 degree spatial resolution data daily mean over 2015.

Anthropogenic Aerosol Fraction
AOD VS AI



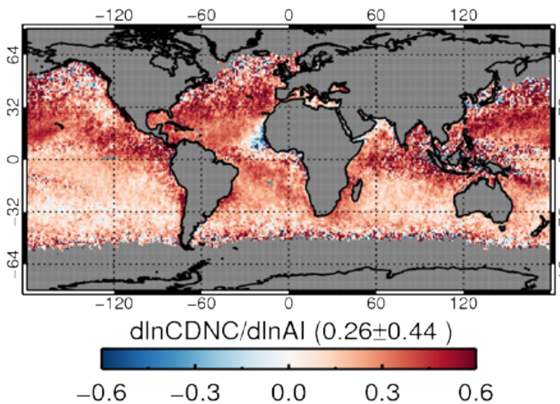


Mean difference between present day and pre-industrial emissions from three AeroCom models (ECHAM6-HAM2, HadGem3, and CAM5)

Data courtesy of David Neubauer

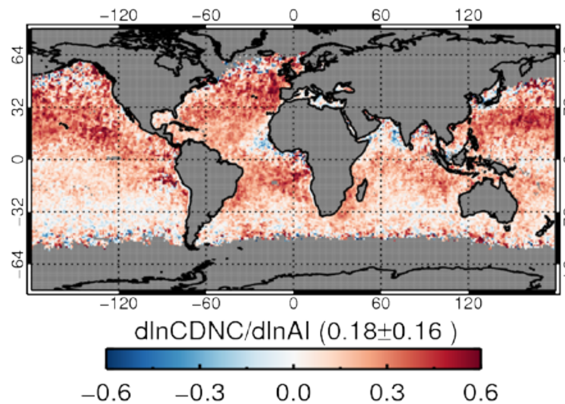
Aerosol Indirect Forcing Estimate: Quaas et al. (2008)

PRE_AVG



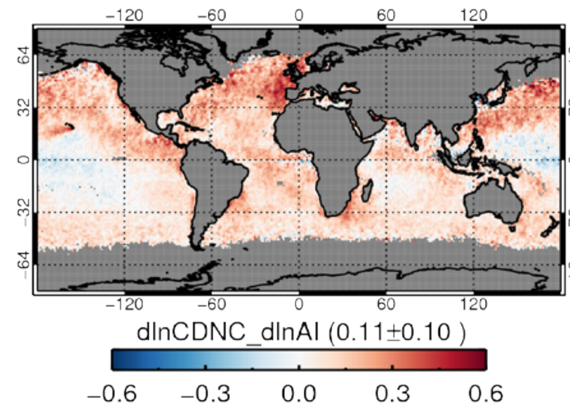
ΔAIE=-0.14 W/m^2

CAPA_L2



ΔAIE=-0.13 W/m^2

CAPA_L2-15km



ΔAIE=-0.09 W/m^2

$$\Delta AIE = c_f F_{SW}^{\downarrow} \Delta a A(f,t) \frac{1}{3} \frac{dCDNC}{d\ln AI}$$

$$\Delta F = c_f F_{SW}^{\downarrow} \Delta a \frac{d\alpha}{d\ln AI}$$

$$\frac{d\alpha}{d\ln AI} = \left(\frac{\partial A_{clr}}{\partial \ln AI} - \frac{\partial A_{cld}}{\partial \ln AI} \right) + \frac{A_{clr} - A_{cld}}{c_f} \frac{\partial c_f}{\partial \ln AI}$$

Intrinsic AIE ***Extrinsic AIE***

$$\frac{d\alpha}{d\ln\tau_a} = (1-f)a_2 + (\alpha - (a_1 + a_2 \ln\tau_a)) \frac{d\ln f}{d\ln\tau_a} + f_{liq} \cdot A(f,\tau_c) \cdot \left[\frac{d\ln f}{d\ln\tau_a} + \frac{5}{6}\frac{d\ln L}{d\ln\tau_a} + \frac{1}{3}\frac{d\ln N_d}{d\ln\tau_a} \right]$$

Δa: change in anthropogenic aerosol
AI: aerosol index
c_f: cloud fraction;
A_{clr}: clear sky albedo
A_{cld}: cloud albedo (CERES)
α: planetary albedo