

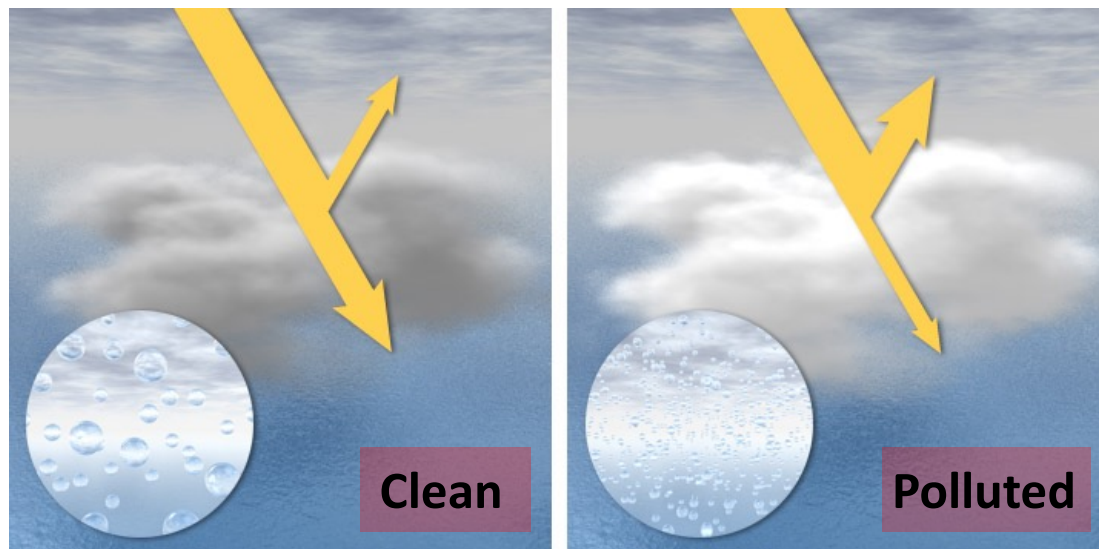
A Satellite Perspective on Aerosol-Cloud-Radiation Interactions

David Painemal

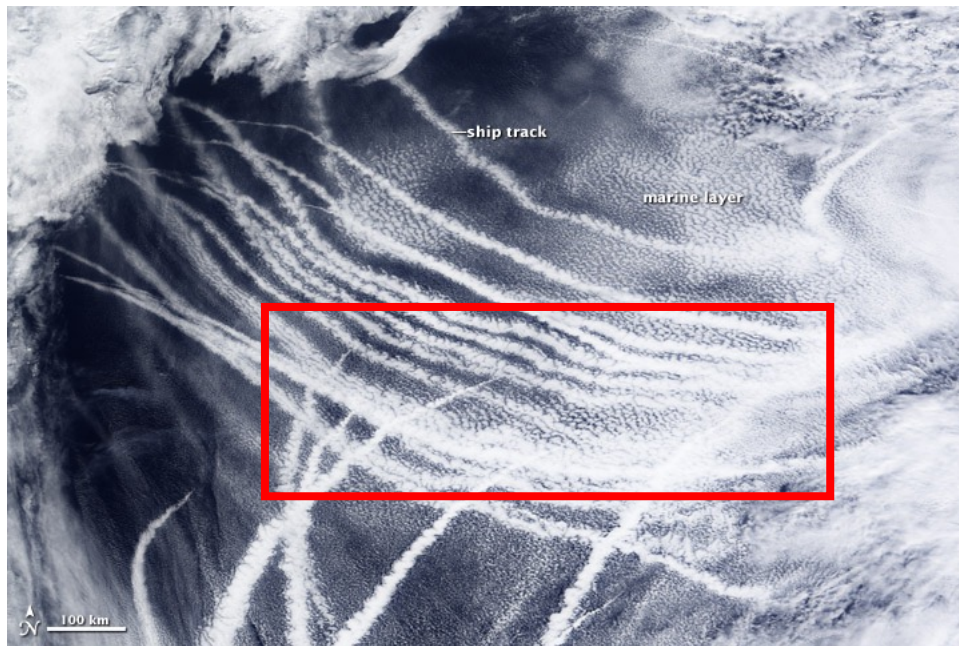
Science Systems and Applications Inc.
NASA Langley Research Center

Introduction

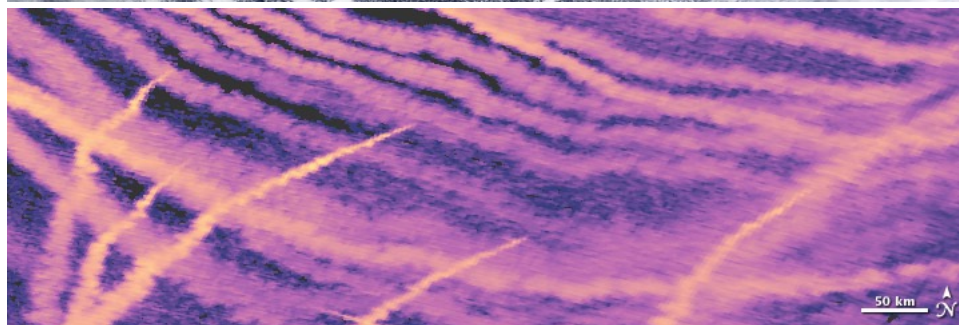
- Formation of cloud droplet embryos require atmospheric aerosol.
- Natural/anthropogenic increase of aerosol could, thus, modify the cloud “micro” structure.
- Link between effects of aerosol on cloud albedo first established by Twomey (1977).



Introduction



- Ship tracks are a compelling evidence of radiative impacts of aerosol on clouds modulated by human activity
- Interactions can be more complex: effects on precipitation, cloud physical thickness, convection, etc.



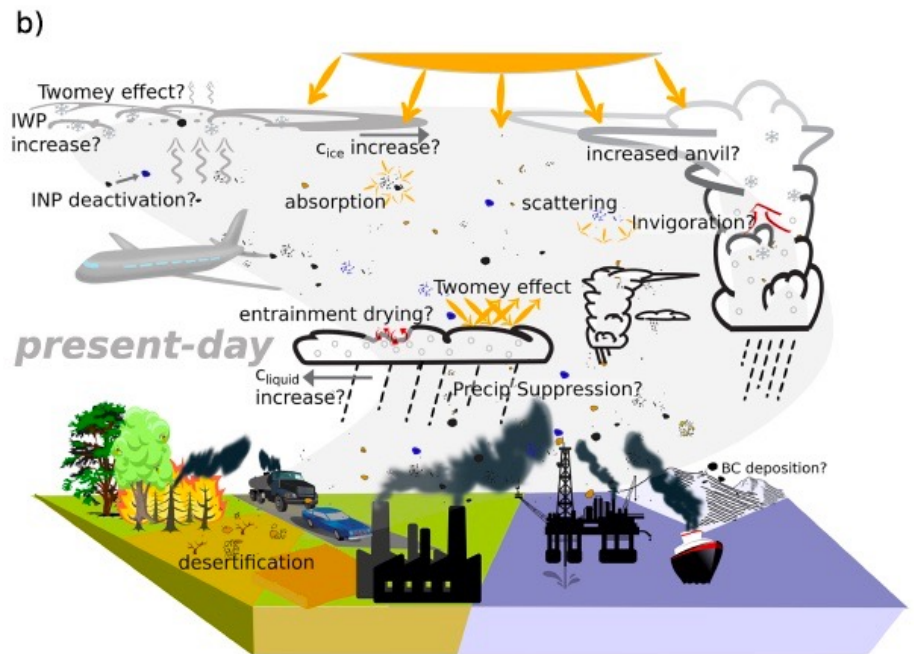
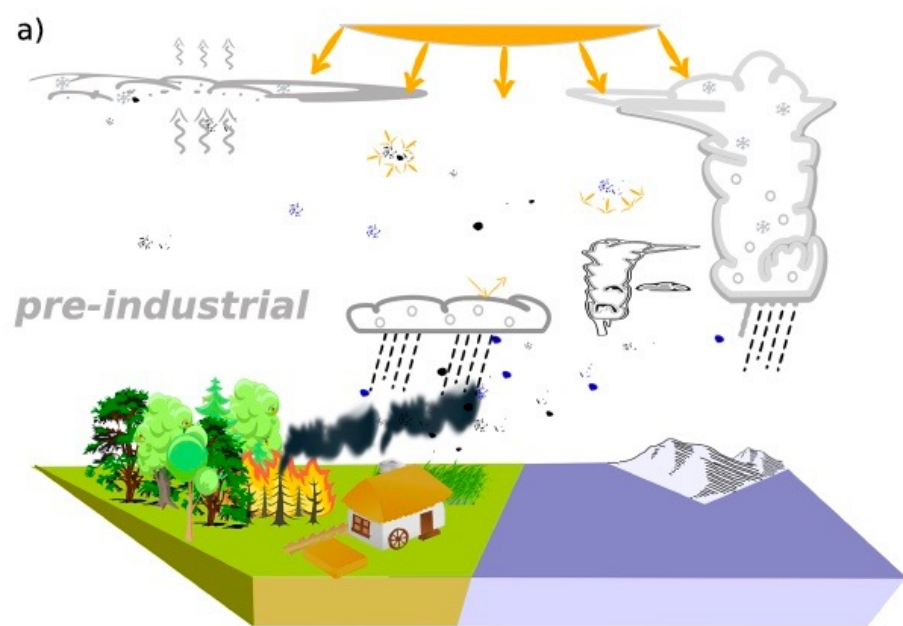
Cloud Droplet Radius (μm)

6 12 18 24 30

<https://earthobservatory.nasa.gov/features/Aerosols/page4.php>

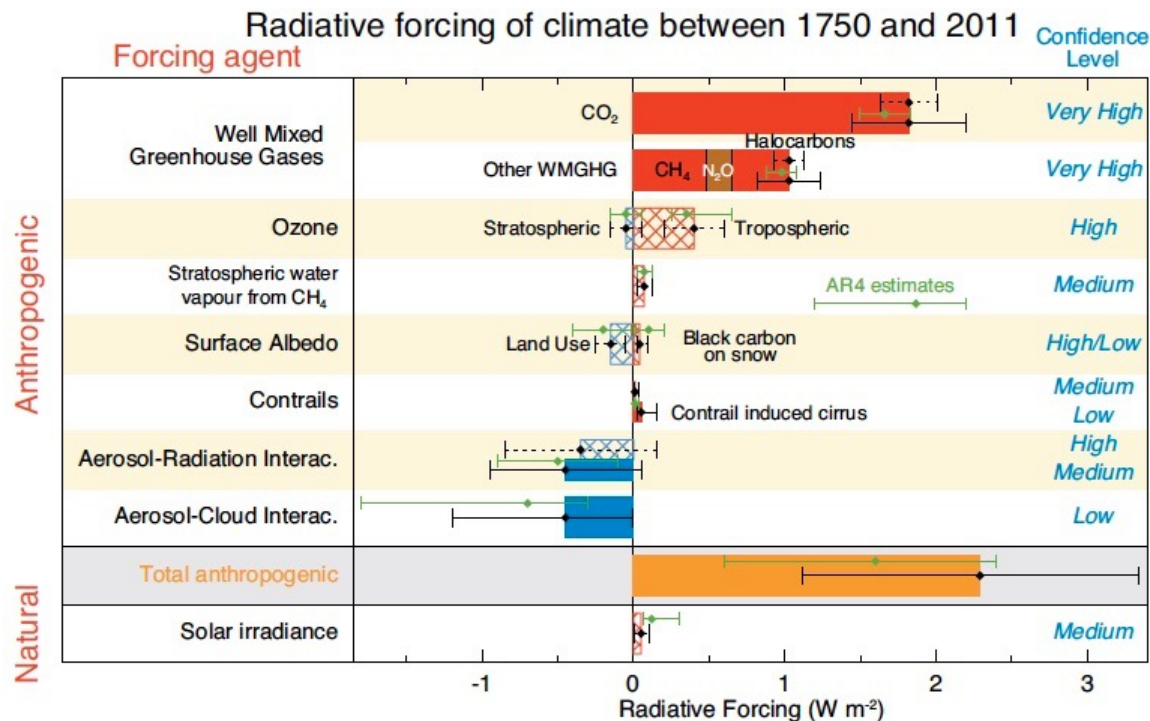
Introduction

- Pre-industrial to present-day changes in aerosols are dramatic



Introduction: The role of different forcing agents

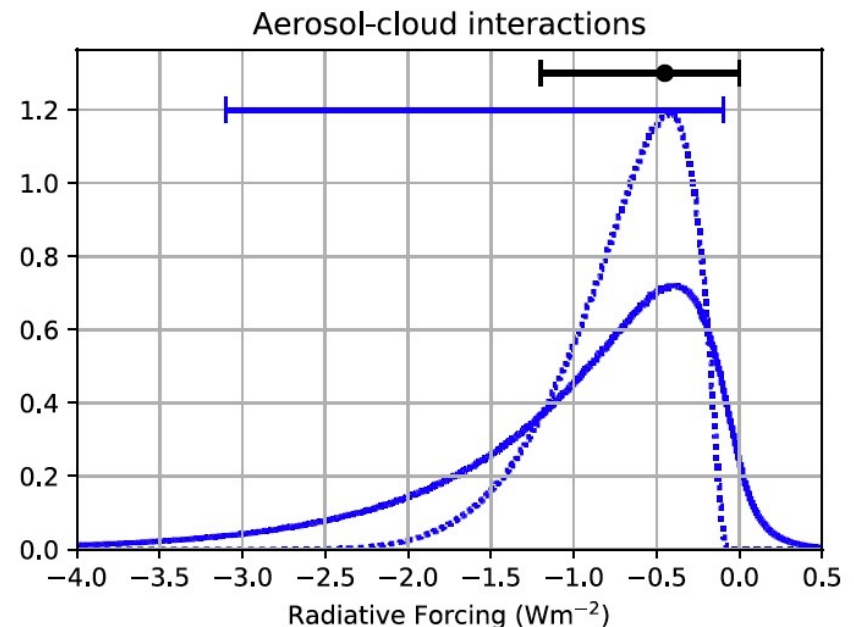
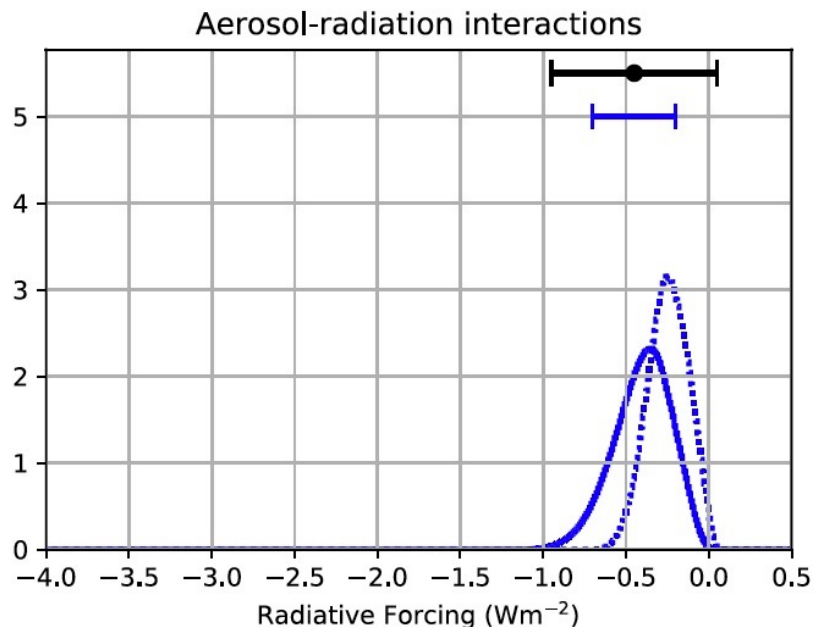
- Substantial changes in aerosol concentration since pre-industrial times
- The effect of aerosols (direct and indirect on clouds) is thought to be negative (cooling).
- However, the combined modeling and observational uncertainties give rise to a wide range plausible radiative forcing.



AR5

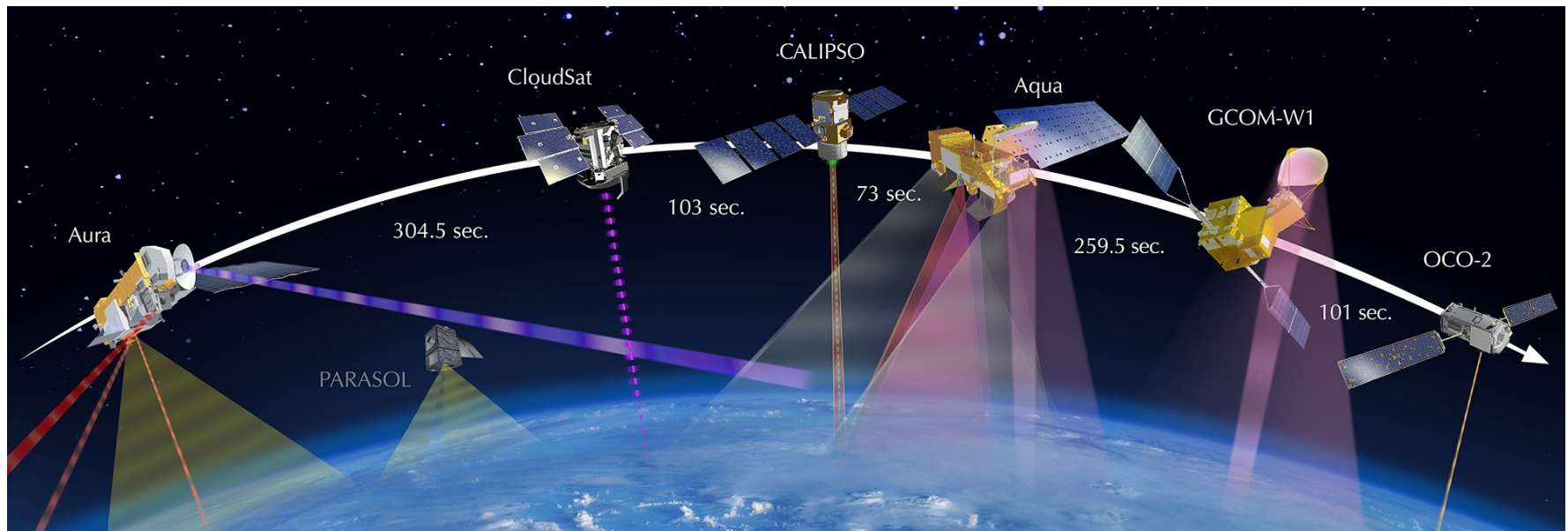
Introduction: aerosol-cloud radiative forcing

- Update by Bellouin et al. (2019):
- *“...working through traceable and arguable lines of evidence, as done in this review, produces uncertainty ranges that are similar to the expert judgment of IPCC AR5, albeit shifted toward more negative ERFs”*



Monitoring aerosol, clouds, and radiation with satellites

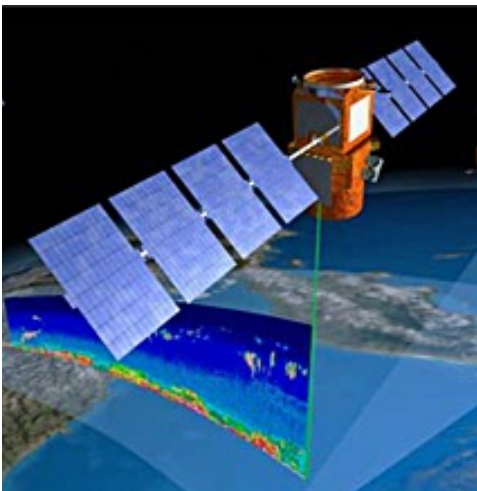
- NASA's afternoon constellation: **A-Train**
 - Constellation of satellites with the same orbit, temporally separated less than a few min.
 - Satellite passive and active sensors with multiple wavelengths
 - Aerosols, clouds, sea surface temp, wind, gases, etc. can be retrieved using remote sensing algorithms.



https://atrain.nasa.gov/images/A-Train_w-Time2017_web.jpg

NASA Langley Flagship Sensors

- **CERES**, aboard multiple satellites (Terra, Aqua, Suomi-NPP)
 - Well-calibrated sensor that measures top-of-the atmosphere visible and infrared radiation
 - Fundamental measurements for deriving the planet's energy budget and the energy imbalance.



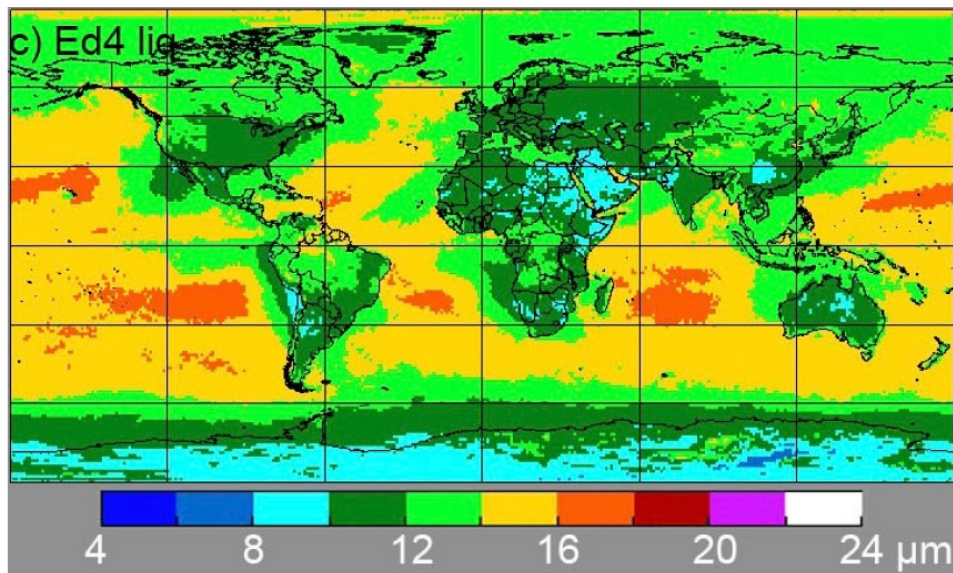
CALIOP on CALIPSO

- Elastic backscatter lidar at 532 nm and 1064 nm.
- CALIOP is able to resolve vertical structure of aerosols and clouds.
- Revolutionary 3D view of aerosols (Winker et al. 2013, BAMS).

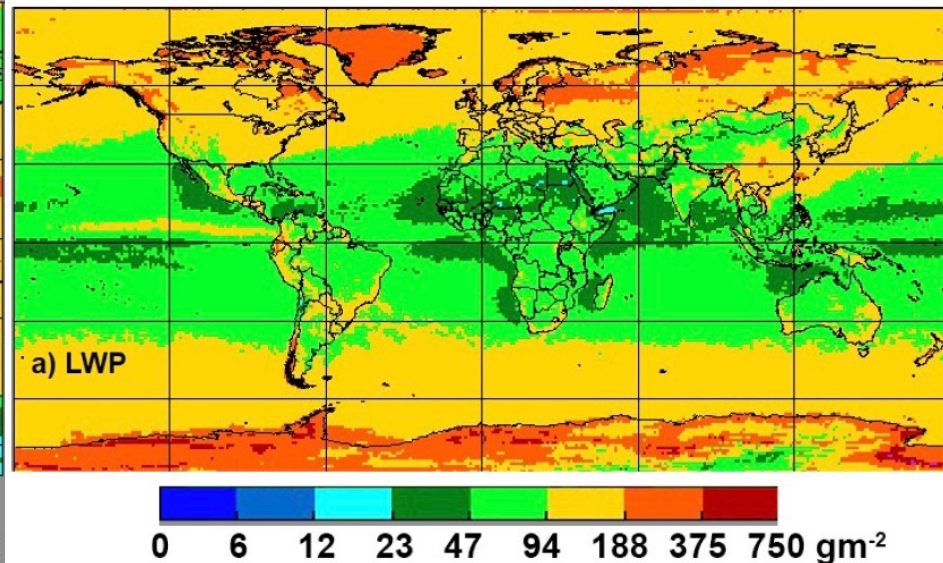
Satellite-derived cloud properties

- Well-established methods based on the use of a visible and a near-infrared wavelength for estimating, respectively cloud optical depth and droplet effective radius.
- Standard CERES algorithm based on Minnis et al. (2011, 2020) applied to MODIS sensor.

Cloud droplet effective radius



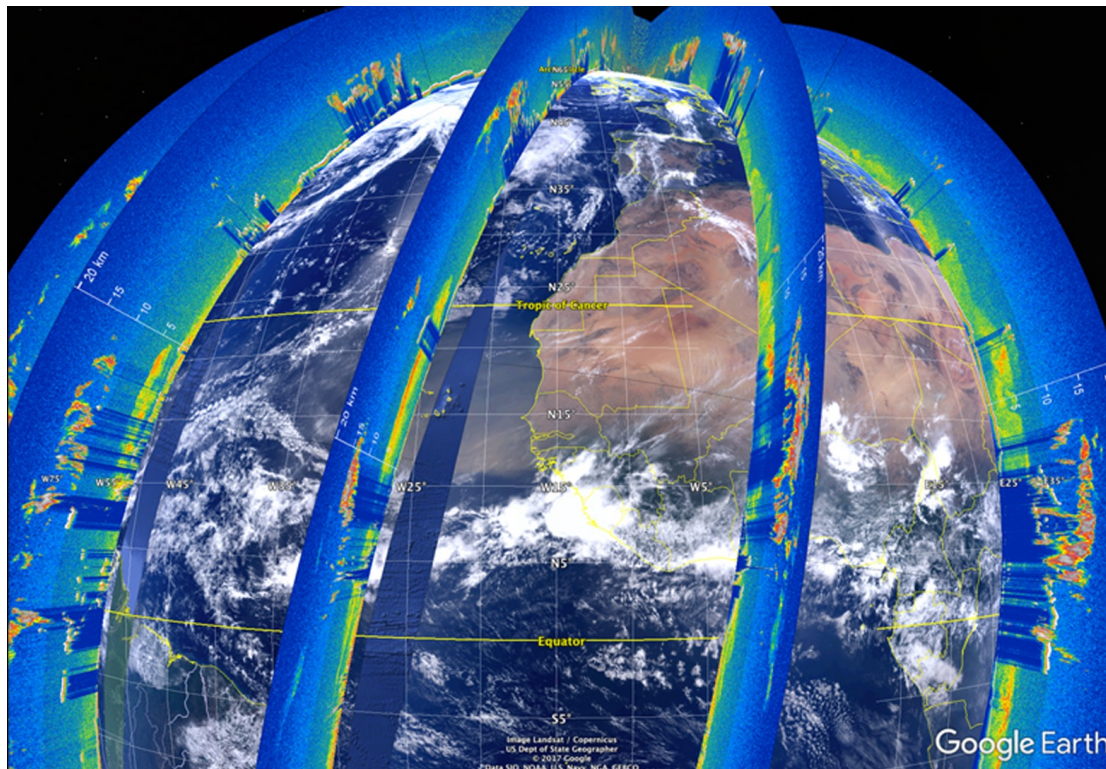
Liquid water path (vertically integrated water content)



Minnis et al. (2021, ITGRS)

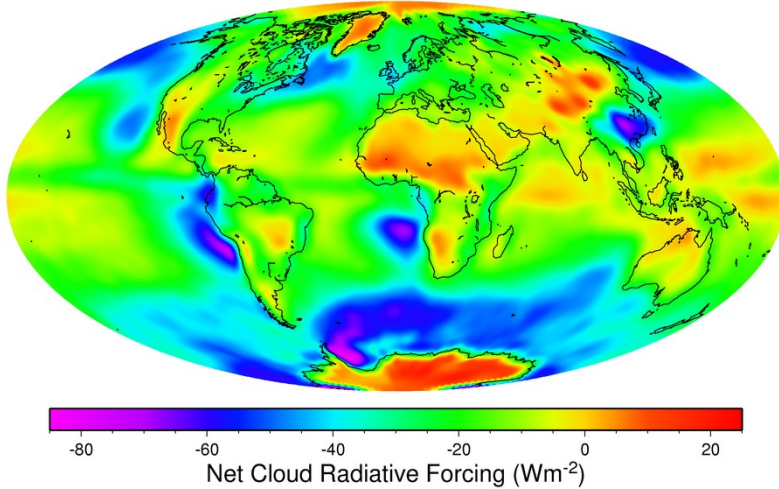
CALIOP aerosol properties

- Aerosol type (dust, smoke, polluted continental, clean continental, polluted dust dusty marine, marine).
- Aerosol extinction coefficient



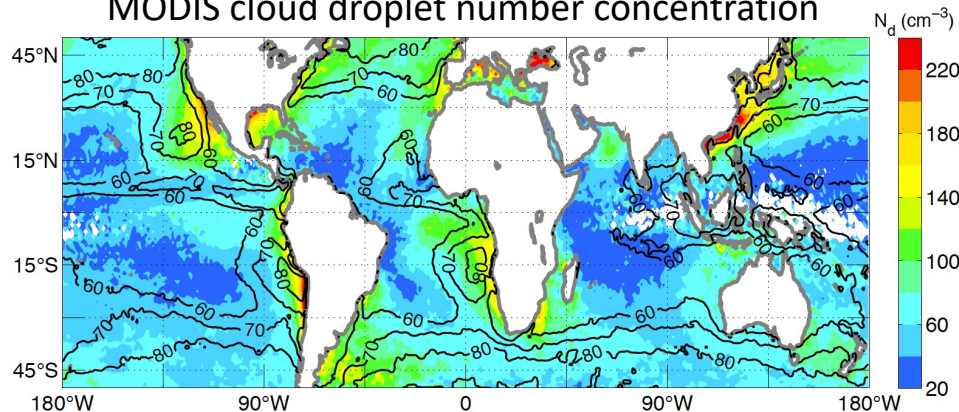
Radiative and cloud microphysical properties

CERES



- Cloud radiative cooling in regions dominated by low clouds

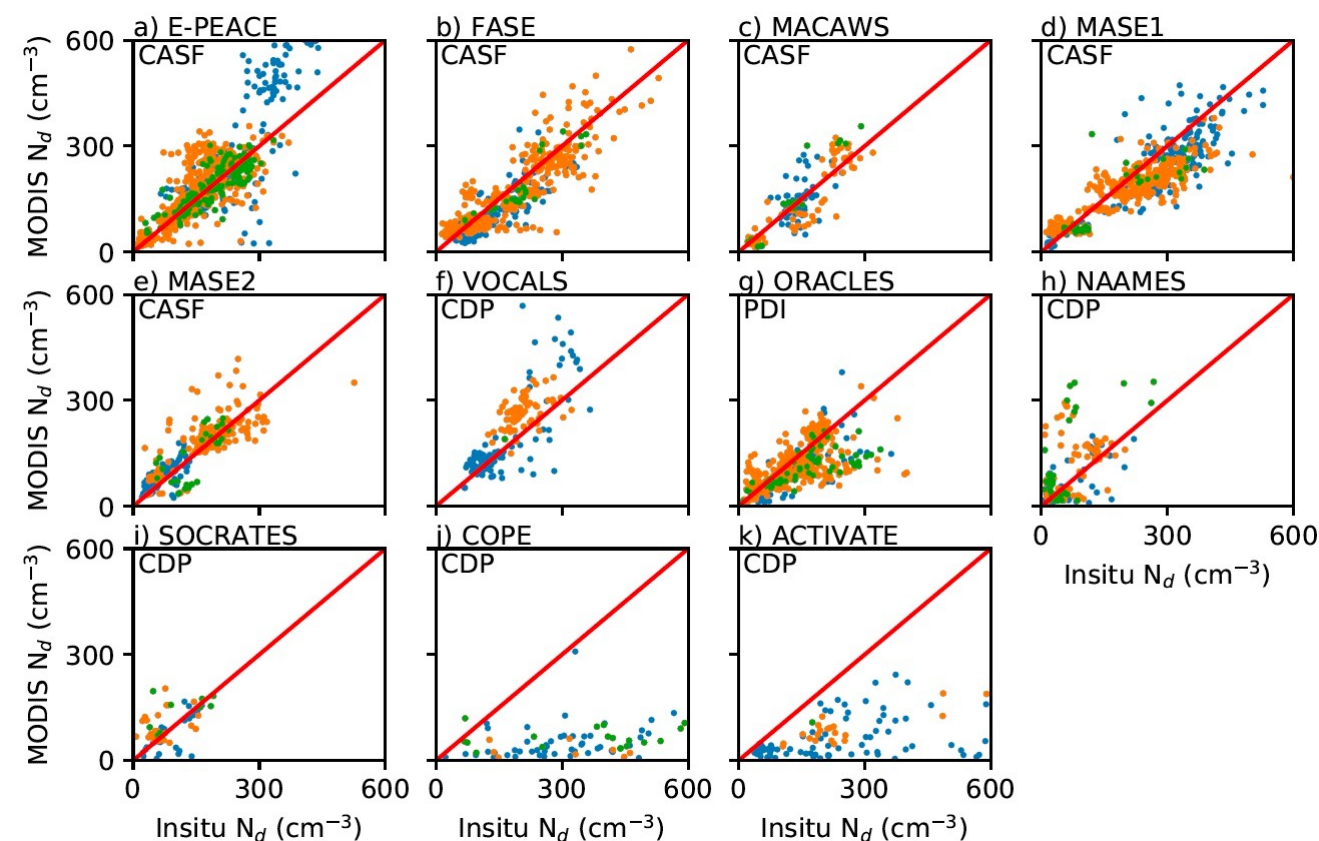
MODIS cloud droplet number concentration



- Higher concentration near the continents suggest microphysical interactions between low clouds and continental aerosols.
- Modelling evidence also indicates that low clouds are a central source of uncertainty in climate models (Bony and Dufresne 2005).

Satellite vs in situ cloud droplet number concentration (N_d)

- Satellite retrievals over ocean generally compare



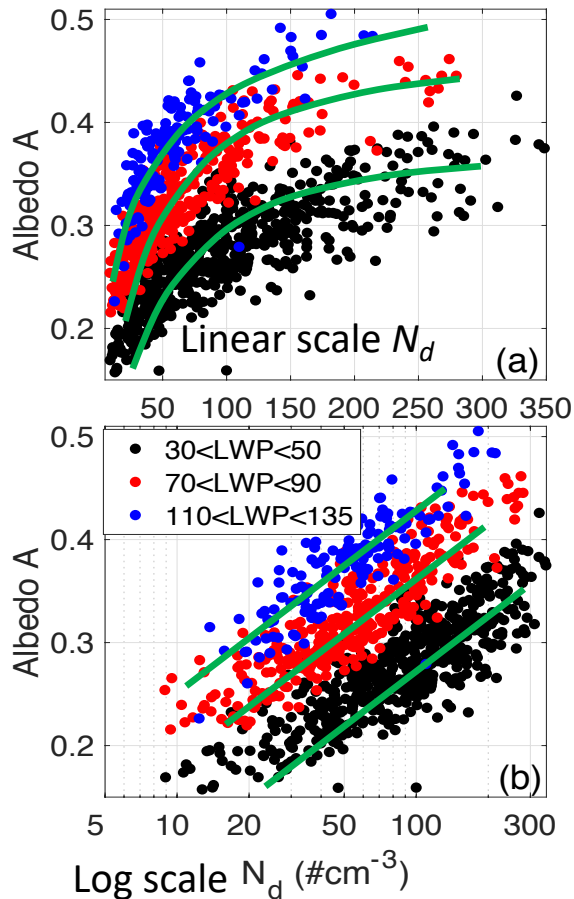
Observational quantification of aerosol-cloud-radiation interaction

- A simple formulation to link albedo in the aerosol-cloud interaction context:

$$\frac{\partial \text{cloud albedo}}{\partial \text{aerosol}} = \frac{\partial \text{cloud albedo}}{\partial \text{cloud } \mu\text{physics}} \cdot \frac{\partial \text{cloud } \mu\text{physics}}{\partial \text{aerosol}}$$

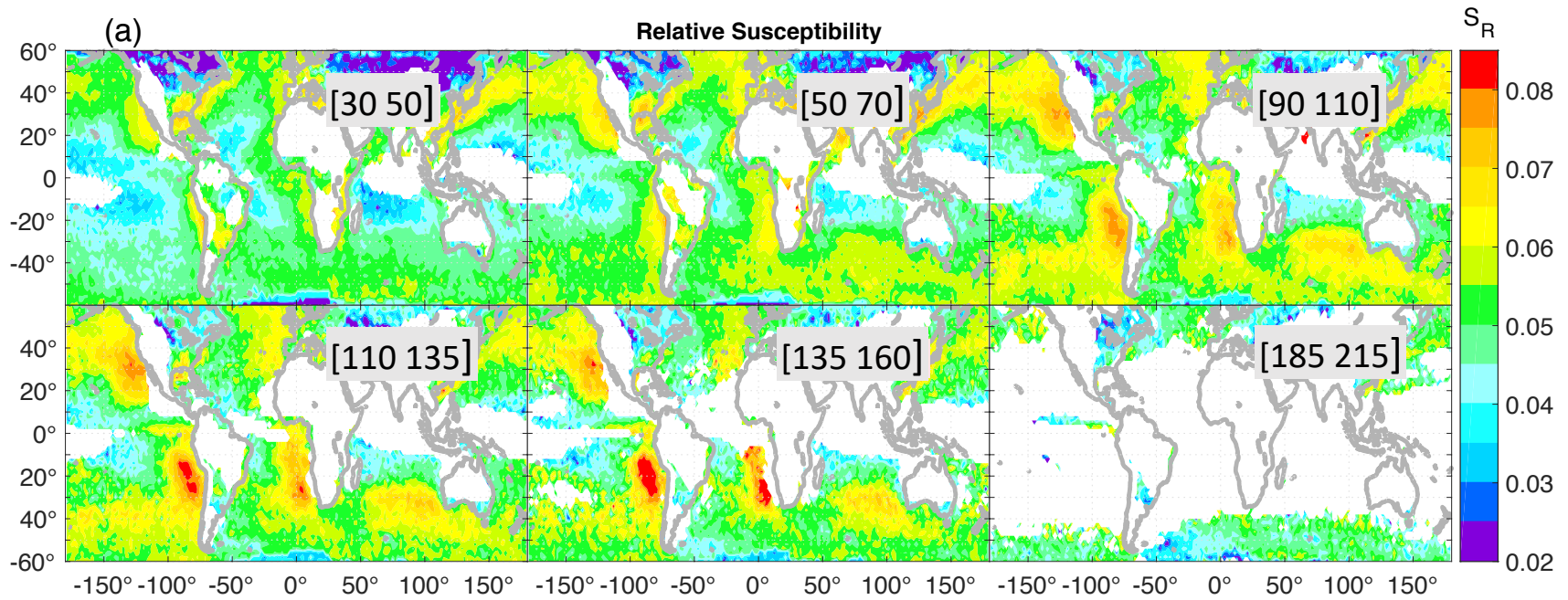
Cloud-radiation component: Albedo susceptibility

$$\frac{\partial \text{cloud albedo}}{\partial \text{aerosol}} = \boxed{\frac{\partial \text{cloud albedo}}{\partial \text{cloud } \mu\text{physics}}} \cdot \frac{\partial \text{cloud } \mu\text{physics}}{\partial \text{aerosol}}$$



- Observational quantification of albedo variations with N_d by combining CERES albedo and MODIS N_d .
- Linear $\ln(N_d)$ - Albedo relationship $\Rightarrow$ Relative susceptibility (S_r) = $\frac{\partial A}{\partial \ln(N_d)} = \text{constant}$
- S_r = Changes in A due to fractional changes in N_d
- N_d - A needs to be constrained by liquid water path (LWP).
- S_r is estimated for fixed LWP bins: 10-250 g/m².

$$S_r = \frac{\partial A}{\partial \ln(N_d)} \text{ dependence on water path (LWP)}$$



- S_r increases with LWP until reaching a nearly-constant value in some regions.

- Total relative susceptibility:

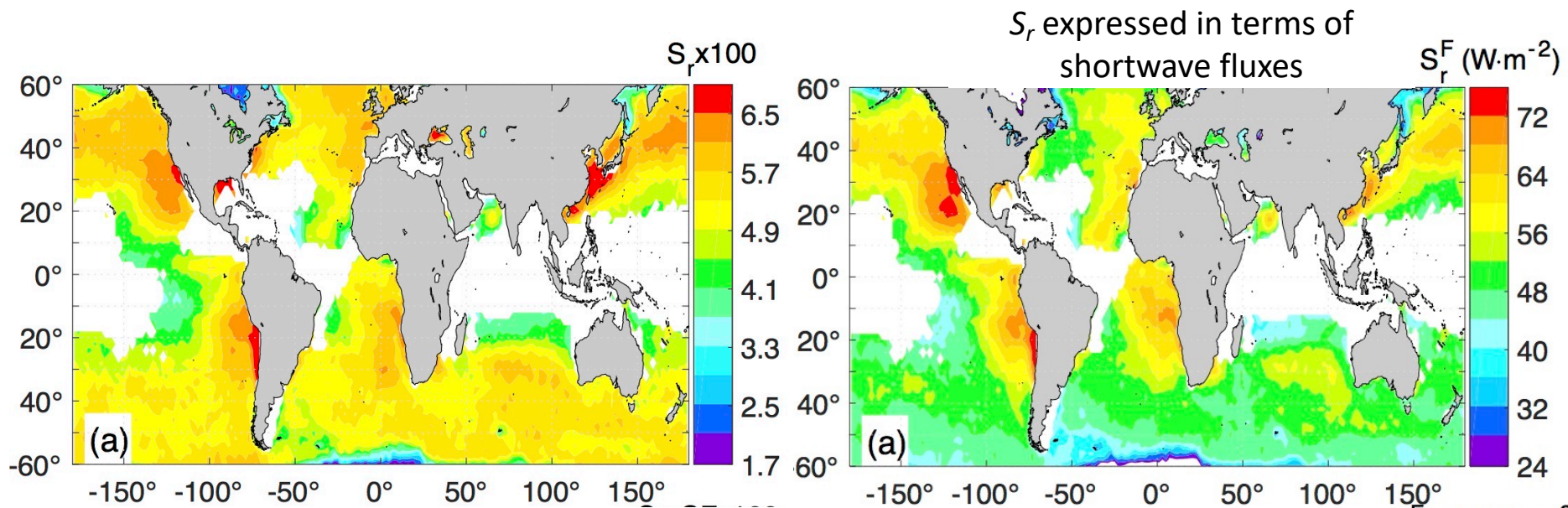
$$Total\ S_r = \sum_i S_r|_{LWP_i} \cdot w_{LWP_i}$$

The term w_{LWP_i} is circled in red, with an arrow pointing to a histogram of the probability density function (PDF) of w_{LWP_i} .

PDF (w_{LWP_i})

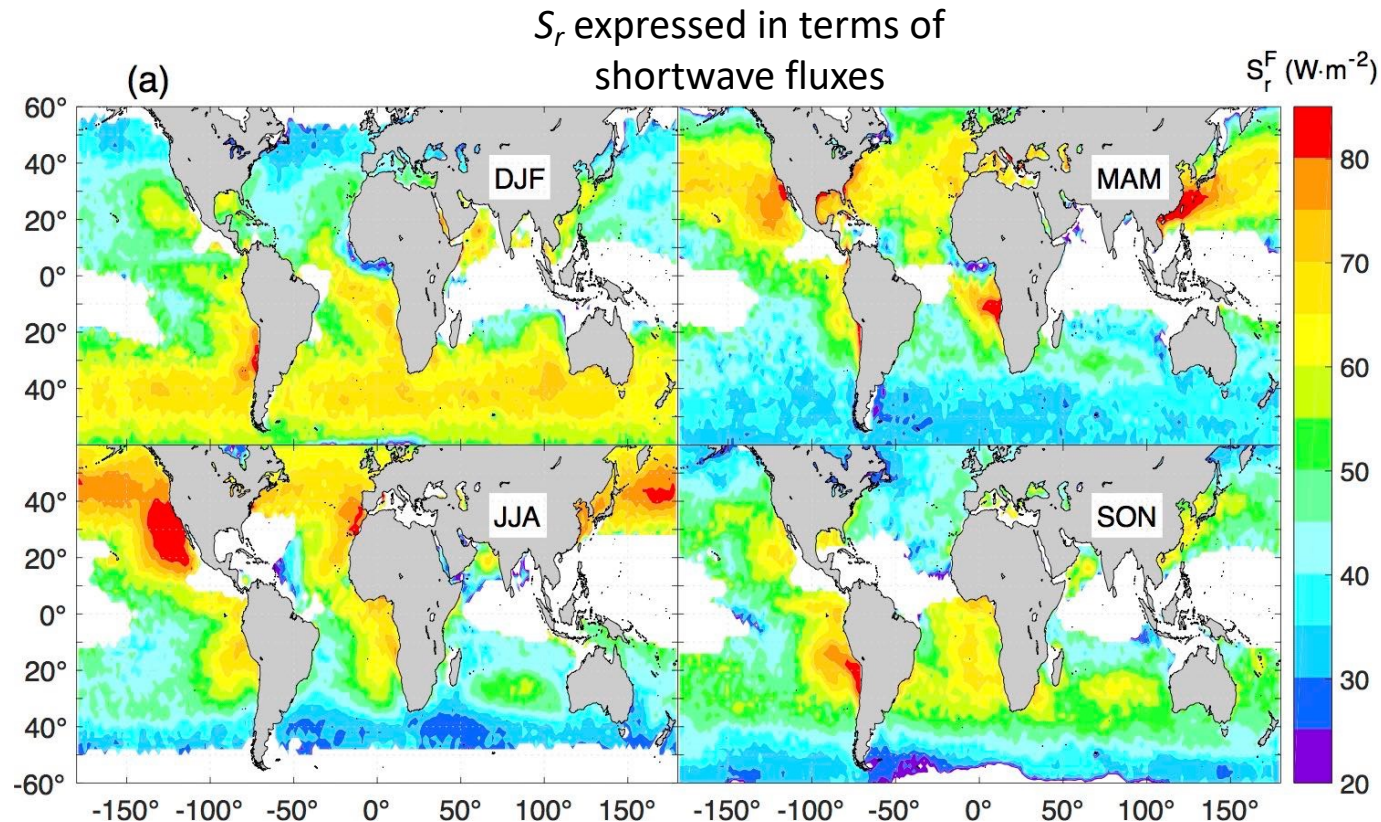
LWP_i

Global radiative susceptibility S_r



- Eastern Pacific clouds and clouds off the coast of China and Japan are the most susceptible to fractional changes in N_d .
- S_r expressed in shortwave fluxes, instead of A , provides usable information about energy changes associated with the Twomey effect.
 - Near coastal clouds are radiatively more sensitive to N_d .
 - E.g.: 1% N_d increase $\Rightarrow$ 0.5-0.7 W/m^2 increase in shortwave fluxes in marine stratocumulus regimes (Aqua afternoon overpass).

S_r Seasonal cycle



- In terms of shortwave fluxes, susceptibility presents a clear annual cycle. High latitudes modulated by changes in sun elevation.
 - high-latitude clouds are radiatively more important during their corresponding hemispheric summer

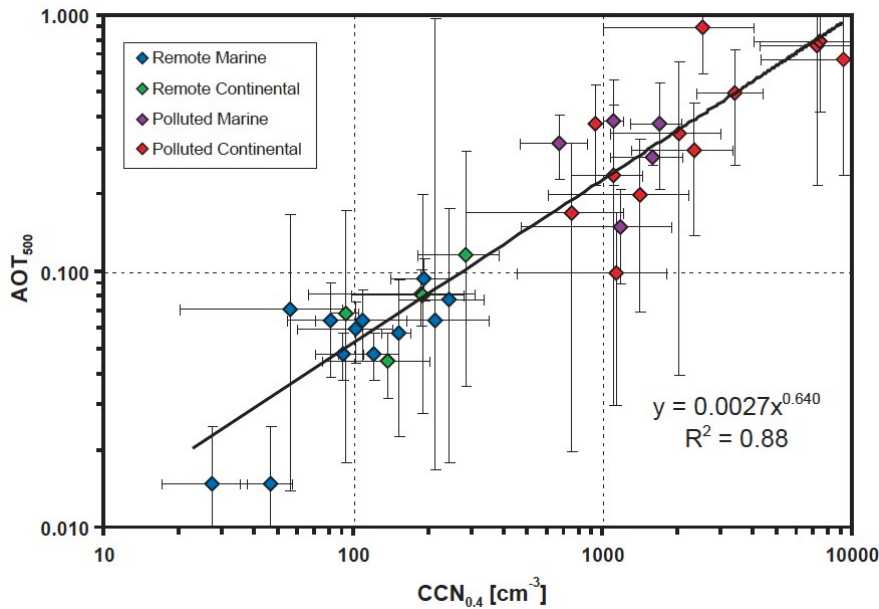
Aerosol-cloud component: Aerosol-cloud interactions (ACI)

$$\frac{\partial \text{cloud albedo}}{\partial \text{aerosol}} = \frac{\partial \text{cloud albedo}}{\partial \text{cloud } \mu\text{physics}} \cdot \frac{\partial \text{cloud } \mu\text{physics}}{\partial \text{aerosol}}$$

- Covariation between aerosol concentration (or cloud condensation nuclei) and cloud droplet number concentration have been observed in numerous field campaigns.

Aerosol-cloud component: Aerosol-cloud interactions (ACI)

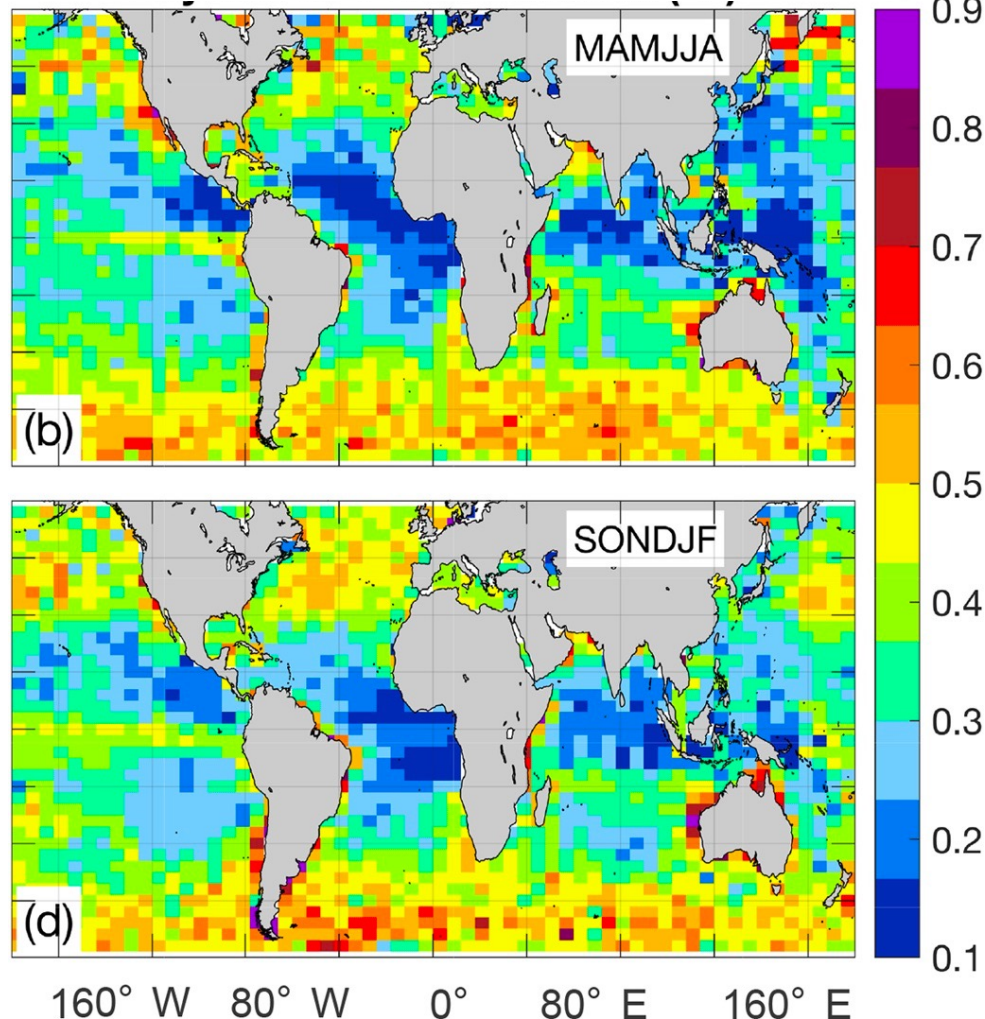
- ACI is arguably the most difficult component to quantify with satellite data, because:
 - Aerosol and cloud retrievals cannot be fully collocated in space.
 - Calculations rely on aerosol optical depth as aerosol concentration proxy. However, the AOD-CCN relationship can be highly variable and correlation modest



- While CCN and AOD are highly correlated, the relationship is poorly characterized in relatively clean marine environments.

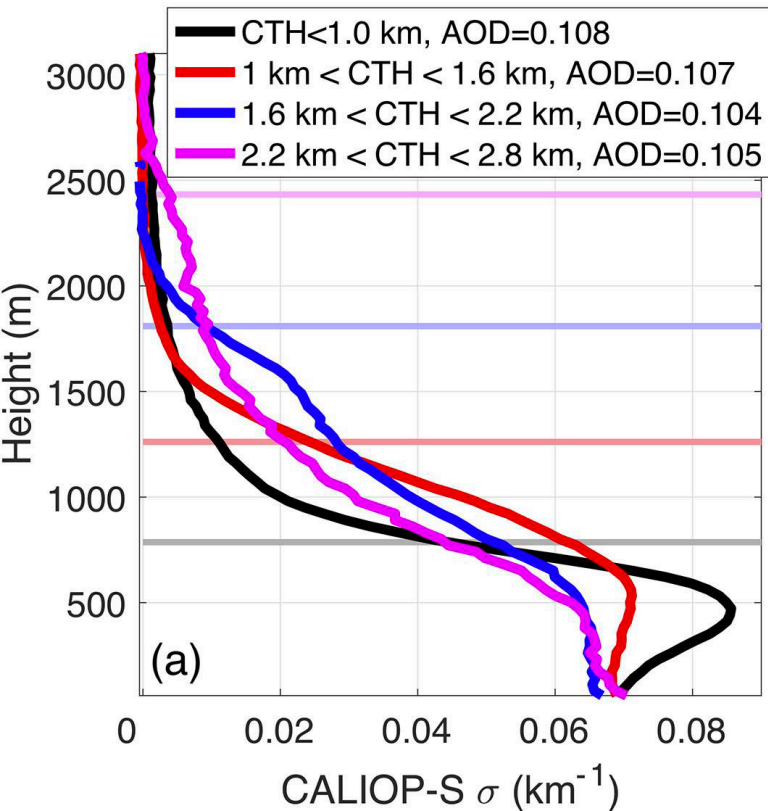
Aerosol-cloud component: the inadequacy of using AOD

AOD fraction contributed by the boundary layer according to CALIOP



- Boundary layer aerosols contribute less than half to the total AOD.
- Strong boundary layer contribution over the Southern Ocean possibly associated with sea salt production over a region with strong zonal winds.

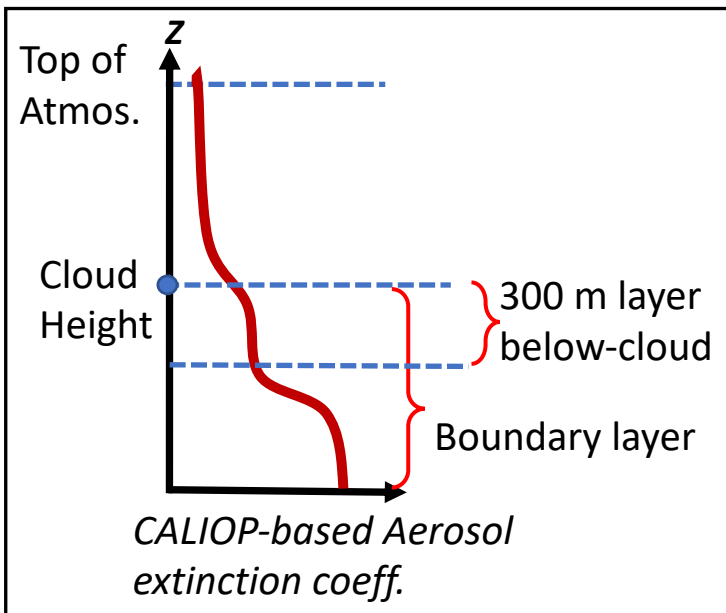
Aerosol-cloud component: Accounting for vertical variability.



- Dissimilar aerosol vertical profiles can yield almost identical AOD.
- Aerosol near the cloud layer are

Aerosol-cloud interactions: A novel approach with CALIOP

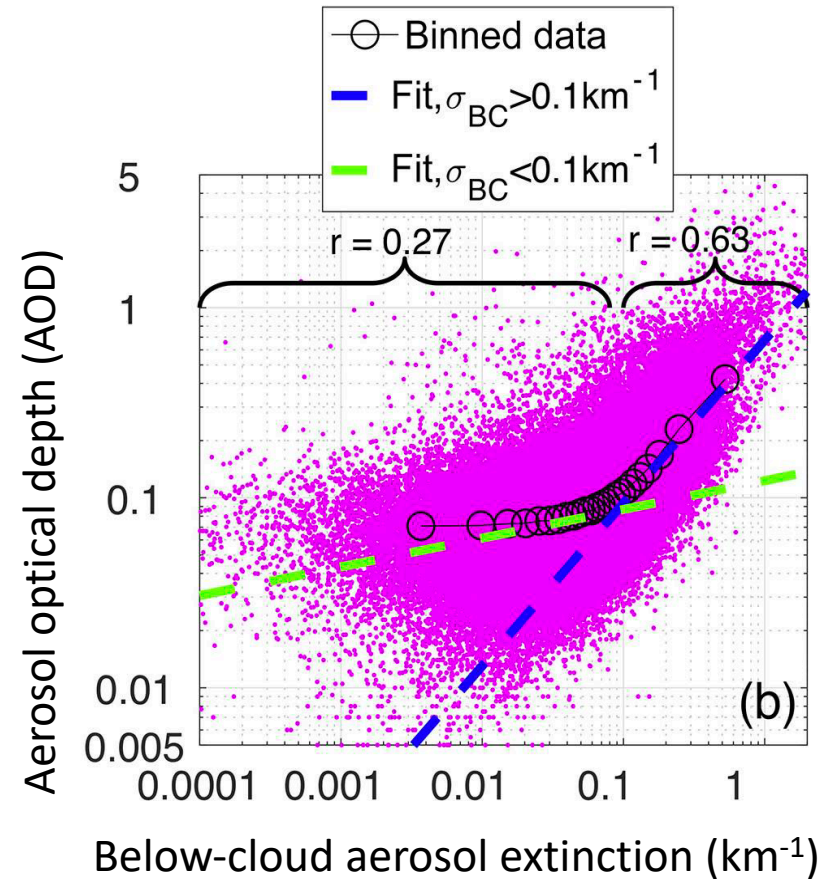
$$\frac{\partial \text{cloud albedo}}{\partial \text{aerosol}} = \frac{\partial \text{cloud albedo}}{\partial \text{cloud } \mu\text{physics}} \cdot \boxed{\frac{\partial \text{cloud } \mu\text{physics}}{\partial \text{aerosol}}}$$



- We utilize vertically-resolved **aerosol extinction instead of AOD**.
- Aerosol extinction is average for the layer between cloud top height and 300 m below.
- 5-km spatially averaged and collocated MODIS-CALIOP. Preliminary study uses 6 months of data.
- Limitation of satellite remote sensing: aerosol and cloud retrievals are only possible in clear-sky and cloudy pixels, respectively.
- $\Rightarrow$ neighboring MODIS and CALIOP pixels are matched along CALIPSO track.

Aerosol-cloud interactions: A novel approach with CALIOP

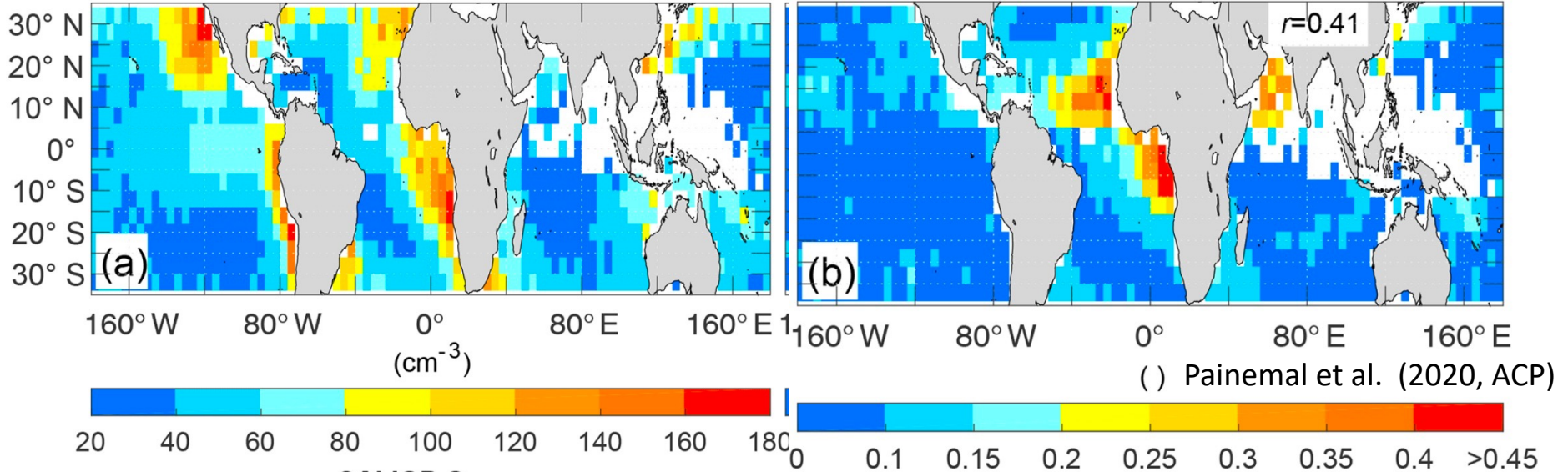
- W



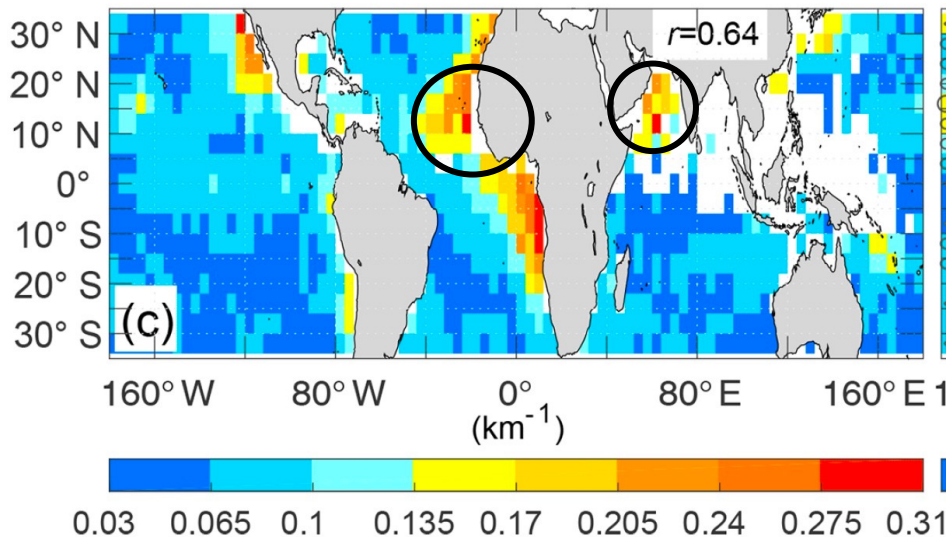
Aerosol-cloud spatial distribution

MODIS N_d

CALIOP-S AOD

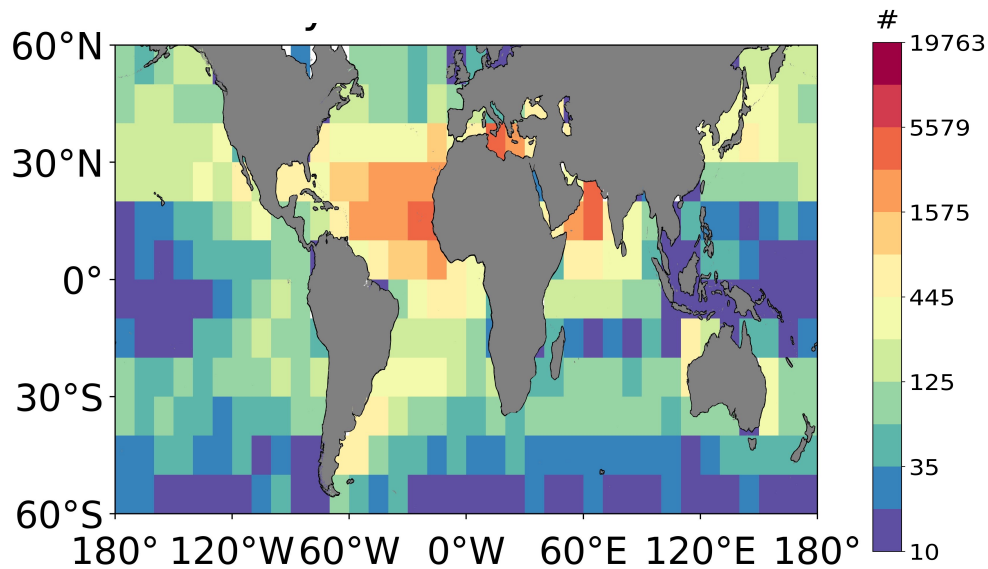


CALIOP-S σ_{BC}



• W

North Atlantic and Arabian Sea

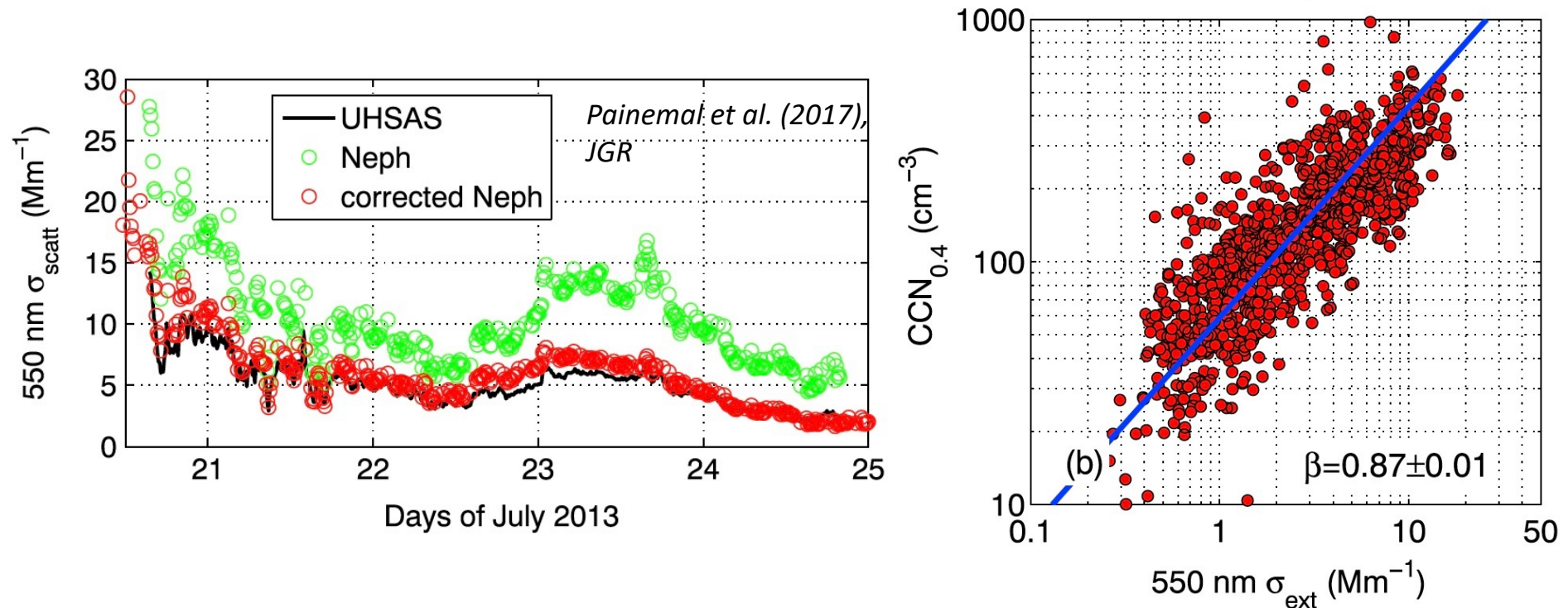


- Regions where N_d does not covary with aerosol extinction are dominated by dust

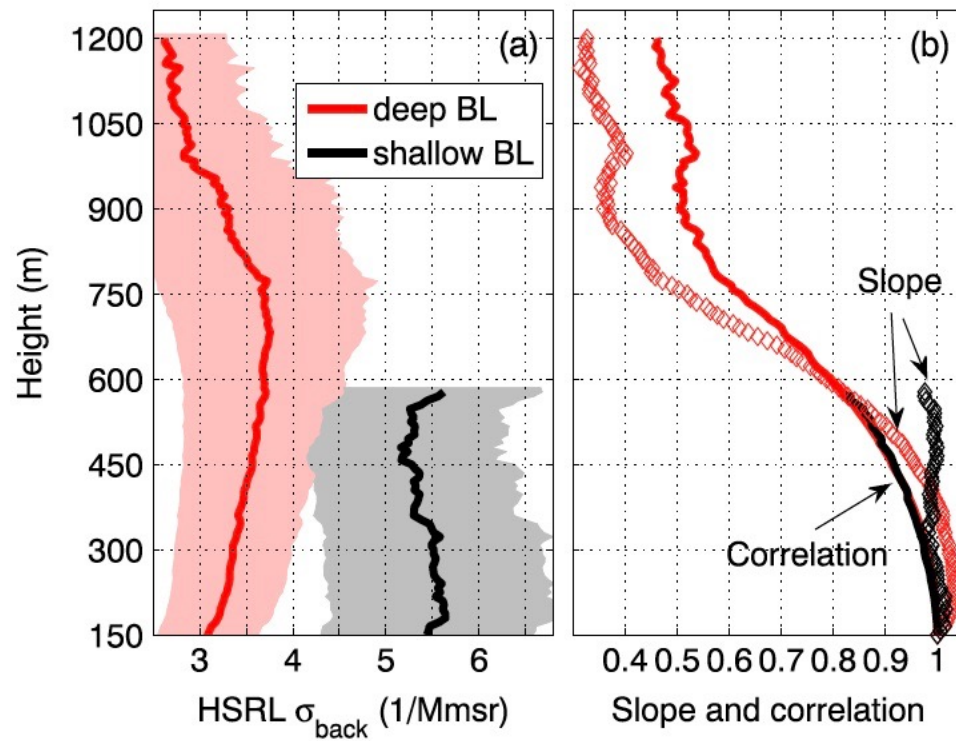
Li et al., 2021, AMT, submitted

Can we use aerosol extinction coefficient as a proxy of aerosol concentration

- Yes, but we need to account for other factors that modify the aerosol optical properties.



- Z



Summary

- Progress in the observational quantification of the aerosol indirect effect can be achieved by exploiting the strengths of different satellite remote sensing techniques.
- In light of the importance of the aerosol vertical distribution, satellite assessments need to be revisited/revisted.
- Challenges remain in:
 - characterizing small scattered cumulus clouds, as satellite product struggle to derive reliable cloud properties.
 - Describing aerosol type and rough chemical/optical properties
- precipitation
- In-situ observations are irreplaceable for a more in-depth characterization of aerosol-clouds and better characterization of satellite observations.

The future of satellite constellation

- Most of A-Train satellites are approaching the end of their operational life.
- Several CERES sensors aboard other satellites (e.g. Suomi-NPP) will guarantee the continuity of the climate data record.
- Satellite cloud retrievals will be also available through geostationary satellites and new sensors (e.g. VIIRS).

NASA's Atmosphere Observing System (AOS) vision

“The Aerosol, Cloud, Convection and Precipitation (ACCP) study is assessing designs for NASA's next suite of atmospheric observations. The goal is to optimize how we examine links among tiny particles known as "aerosols," clouds, atmospheric convection, and precipitation.”

NASA's Atmosphere Observing System

Selected architecture



Constellation of satellites: polar orbit and inclined (60°) orbit

1 Polar:

- Ka+W doppler radar
- Microwave radiometer
- HSRL lidar
- Polarimeter
- TIR spectrometer
- UV-VIS Spectrometer

2 Inclined satellites:

- W,Ku Doppler radar
- Microwave radiometer
- Backscatter lidar
- Polarimeter
- Camera

NASA Postdoctoral Program at Langley

Research opportunities in the Satellite Cloud Group:

- Studies that make use of radiative transfer simulations for interpreting viewing and solar geometry effects on cloud retrievals.
- Algorithm development and validation studies that combine satellite retrievals from numerous platforms as well as from aircraft data are also of interest.
- Studies that relate aerosol variability to cloud microphysical and radiative changes (aerosol indirect effect and contrail forcing) are solicited.
- Research that combines satellite retrievals with observations from recent field campaigns supported by the group (<https://satcorps.larc.nasa.gov>)
- Projects that propose novel use of machine learning techniques for algorithm development and data analysis of the climate data record are also encouraged.
- Developing new products and applications that utilize hyperspectral infrared remote sensing measurements from current and future operational satellite systems.
- *Contact: Bill Smith Jr. (william.l.smith@nasa.gov), David Painemal (david.Painemal@nasa.gov)*