Reflections on using Satellite Data as Model Constraints

Matthew Christensen, University of Oxford

AeroSAT, Barcelona, 2019

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(for quantifying aerosol radiative forcing)

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Aerosol Radiative Forcing

$$\Delta F_{TOA} = -F^{\downarrow} C \alpha_c (1-\alpha_c) \frac{d\ln N_d}{d \ln AOD}\left(\frac{1}{3}+\frac{5}{6}\frac{\Delta \ln \mathcal{L}}{\Delta \ln N_d}+\frac{\Delta \ln C}{\Delta \ln N_d}\right)\Delta \ln AOD_{anth}$$

solar flux
Kopp & Lean (2011)

cloud albedo
Loeb et al. (2018)
Platnick et al. (2017)

cloud sensitivity
Gryspeerdt et al (2016); Andersen et al (2017)
Christensen et al. (2017); Possner et al. (2018)
Bellouin et al. (under review)

anthropogenic aerosol
Reanalysis: Bellouin et al. 2013
MODIS fine mode AOD: Kaufman et al. 2005

Uncertainty:	0.035%	7.5%	50 - 200%	40%

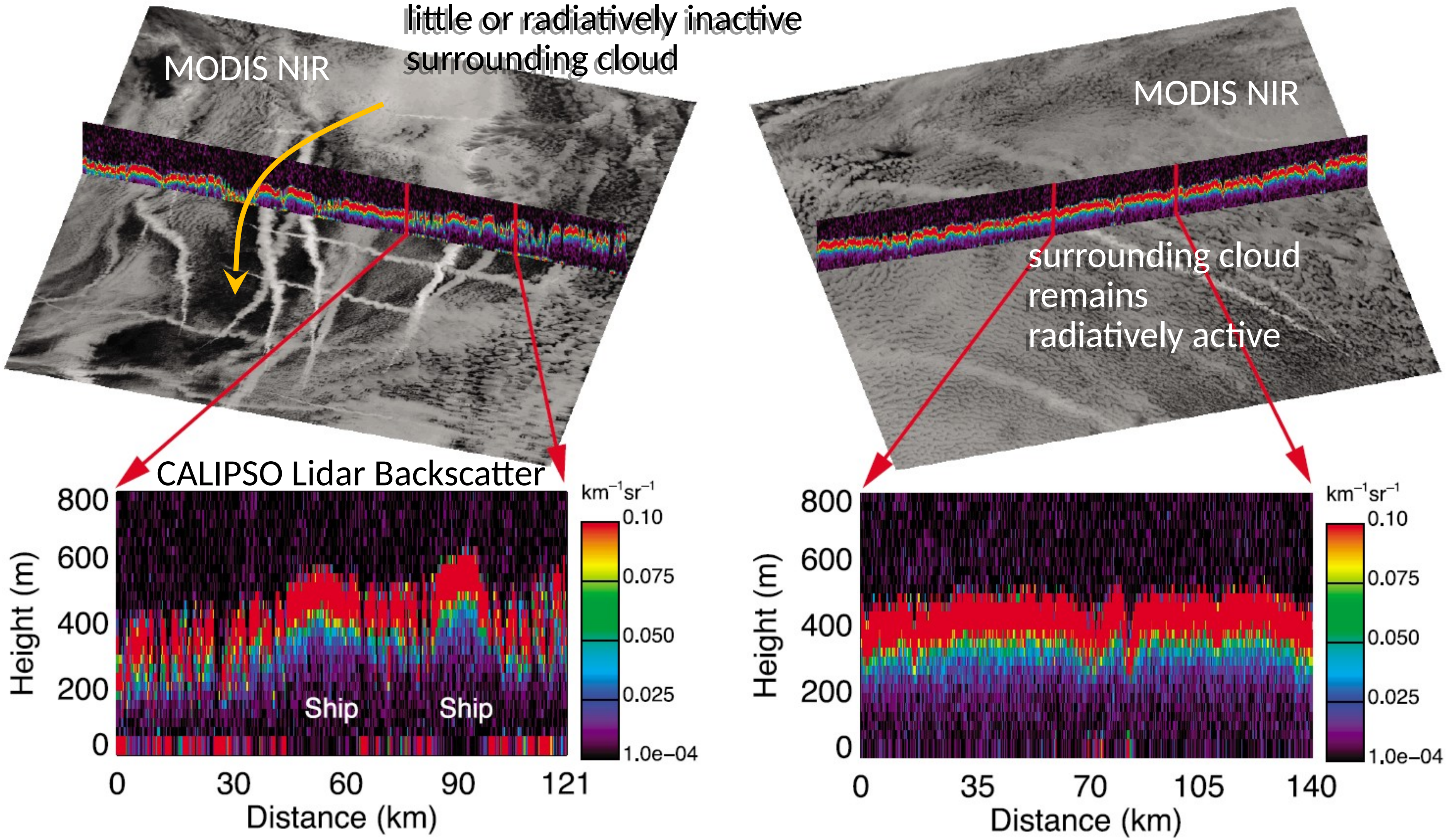
(5-95th %)

- Bulk of uncertainty stems from cloud sensitivities constructed from linear statistics of the regression between retrieved cloud and aerosol properties.
- Forcing is directly proportional to anthropogenic aerosol fraction so constraining this term is also essential.

ΔF_{TOA}: radiative effect
$F^{\downarrow}$: incoming solar flux
C: cloud fraction;
α_c: cloud albedo
$\mathcal{L}$: liquid water path
N_d: droplet concentration
AOD: aerosol optical depth
anth: anthropogenic aerosol

Why is the uncertainty on cloud sensitivity so large?

Evidence of Cloud Deepening



Open cells: 16% increase in cloud top height

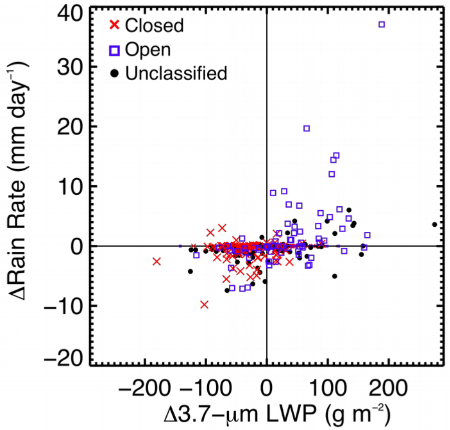
Closed cells:
no change in cloud top height

Christensen and Stephens (2011)

Cloud Sensitivity – ACI Adjustments

Ship & Volcano Tracks

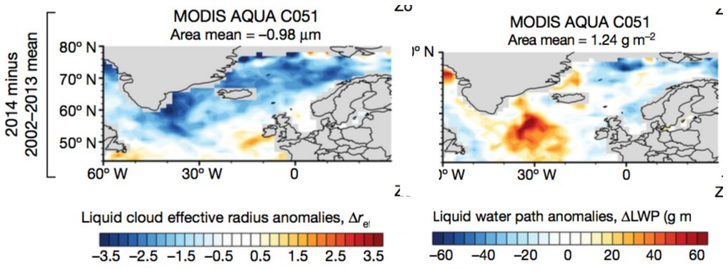
- LWP responses can be positive or negative



Christensen and Stephens (2012)
Toll et al. (2017)

Holuhraun volcanic eruption

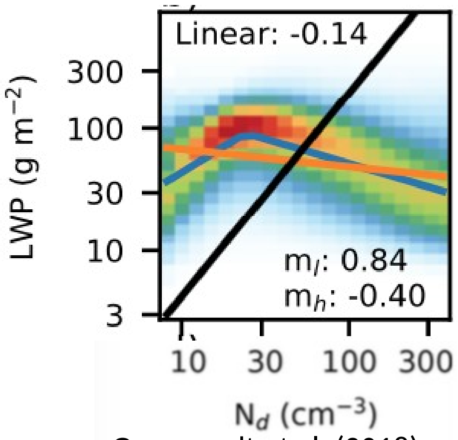
- No impact on LWP observed

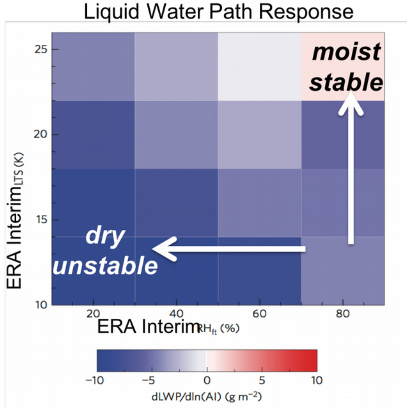


Malavelle et al. (2017)

Synoptic Scale LWP Response – meteorology

- LWP decreases on average



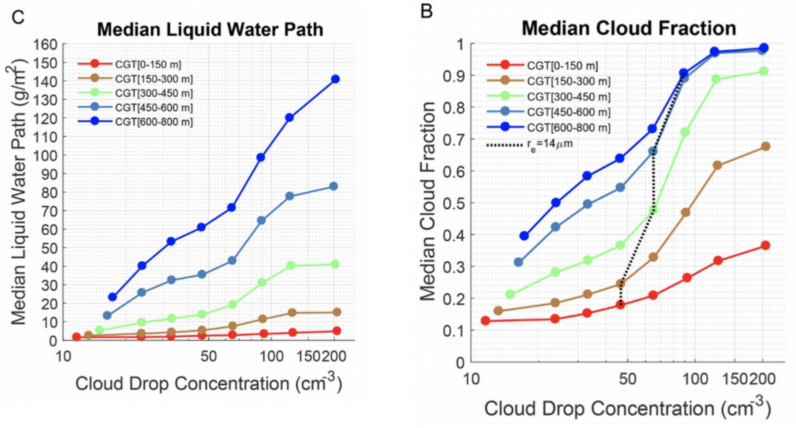


Gryspeerdt et al. (2018)

Chen et al (2014)

Synoptic Scale Cloud Fraction Response

- Significant increase in cloud fraction

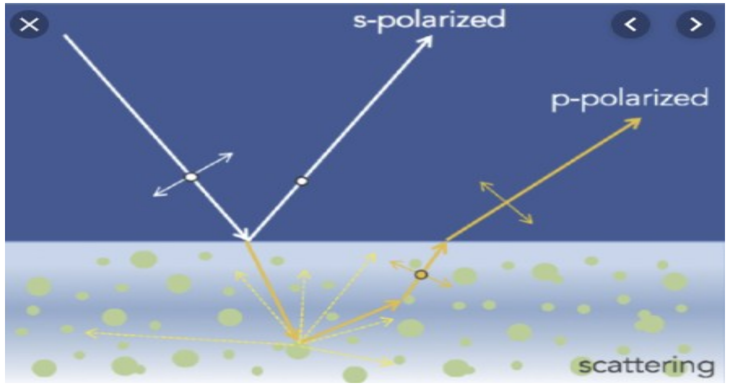


Rosenfeld et al. (2019)

Pathways to Reduce Uncertainty

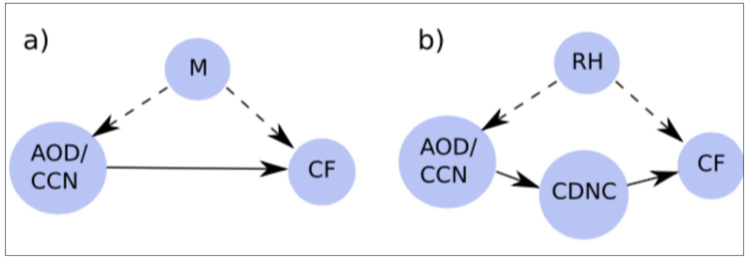
<u>Better aerosol & cloud retrievals</u>

- *Clear-sky pixels*
  - CCN retrievals from high-precision multiangle polarization measurements (Mishchenko et al. 1997, Hasekamp et al. 2019)
  - Remove 3D effects and cloud contamination near clouds (Christensen et al. 2017)
- Cloudy-sky pixels
  - Relate CDNC to CCN through adiabatic cores (Rosenfeld et al. 2019)



<u>Account for confounders/mediating variables</u>

- Mediate cloud responses by relative humidity (Gryspeerdt et al. 2016, JGR)
- Stratify cloud responses by precipitation and meteorology (Chen et al., 2014)

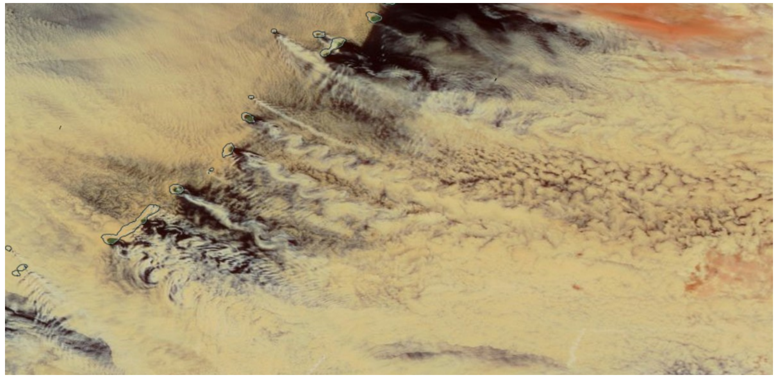


<u>Geostationary satellite observations</u>

- Lagrangian trajectories to connect cloud to aerosol history and precipitation changes.

<u>Natural Laboratories to improve process-scale understanding</u>

- Quantify perturbations from known aerosol sources occurring in similar meteorology
- Ship, volcano industrial and megacity tracks (Christensen et al., 2011; Toll et al. 2019)



Challenges

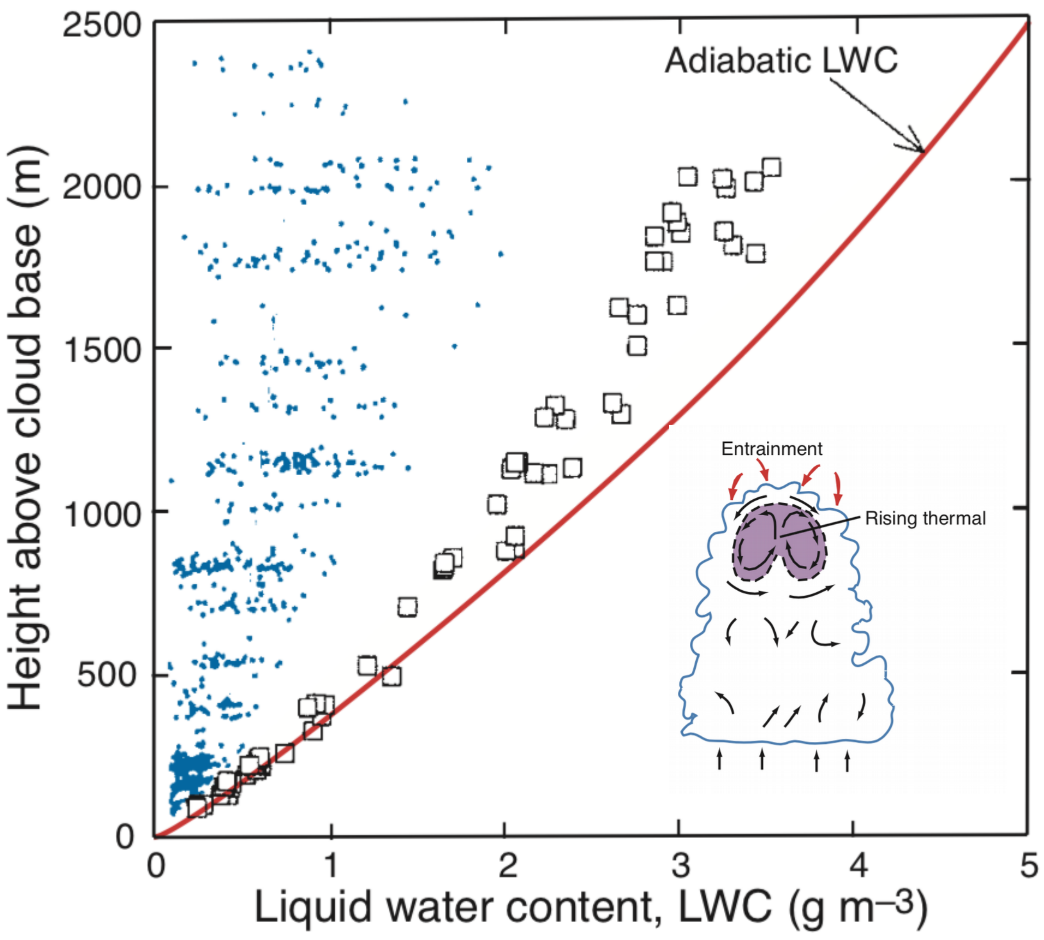
- Aerosol-cloud collocation
  - ➢Spatial size of domain is critical to ensure the cloud and aerosol are in the same location (Grandey and Stier, 2010)
  - ➢**CAPA** to link individual cloud pixels to nearest *trustworthy* aerosol retrieval
  - ➢Trajectory method linking aerosol to cloud (Breon et al. 2002).

- Aerosol composition and vertical profile
  - ➢Black carbon aerosol layers above cloud induce semi-direct effects (Wilcox,2010)
  - ➢MODIS standard retrieval products contain retrieval biases in cloud properties under smoke layers (Meyer et al.)
  - ➢CALIPSO is useful but may have difficulty retrieving semi-detached aerosol layers
  - ➢ORACLES show that aerosol mixing with cloud can have different effects (Diamond et al. 2018)

- AOD threshold retrieval considerations
  - ➢MODIS suitable range is 0.06 – 1 and clouds are most sensitive in clean conditions below 0.06
  - ➢MISR might be better
  - ➢CALIPSO has similar difficulty retrieving optically thin layers

- Quasi-buffered cloud states
  - ➢Feedbacks between entrainment and precipitation buffer cloud albedo effect (Stevens and Feingold, 2008).

Cloud Retrievals



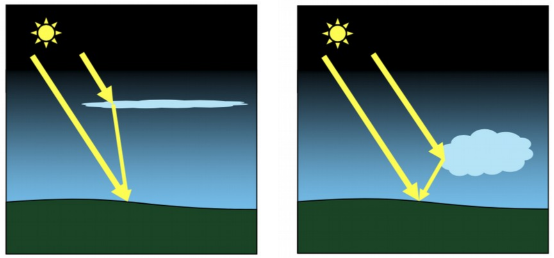
Source: Wallace and Hobbs, 2006

Adiabaticity – assumed adiabatic in most Sc clouds

$$N_{eff} = \sqrt{2}B^3\Gamma_{eff}^{1/2}\frac{LWP^{1/2}}{r_e(h)^3}$$

LES experiments LWP differs by 2x depending on the degree of sub-adiabaticity (Miller et al. 2016).

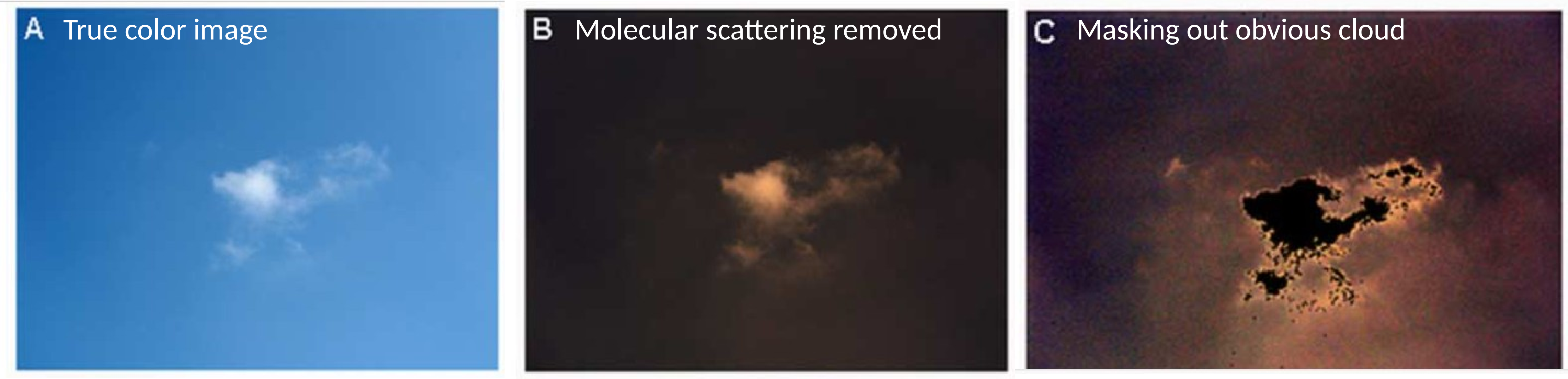
Plane parallel clouds – 1D radiative transfer



Broken cloudy areas need constraints!

<u>Uncertainty</u> in CDNC is between **50 – 80%** (Grosvenor et al. 2018).

Into the Twilight Zone

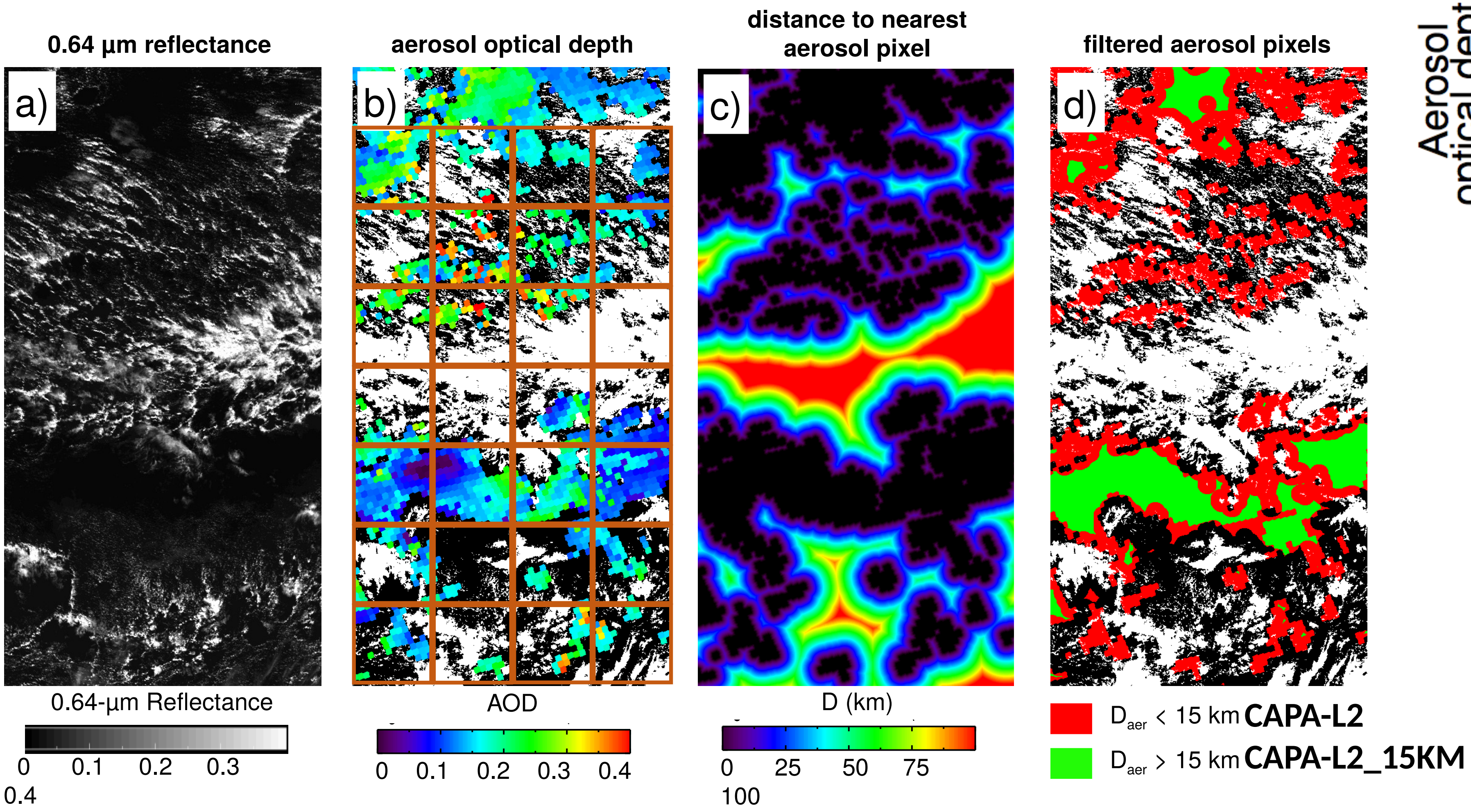


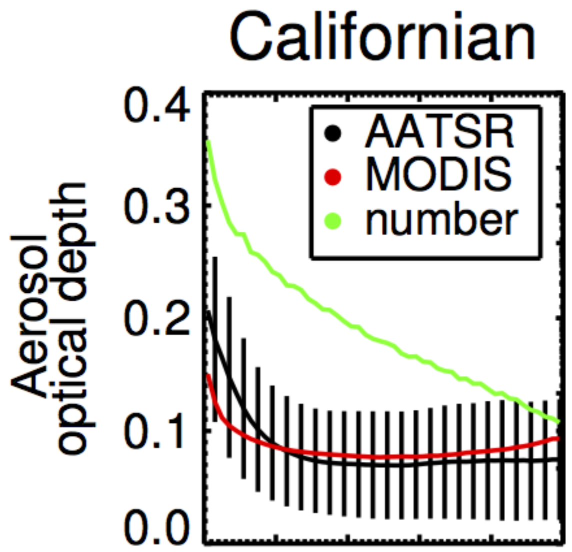
Koren et al. (2007), GRL

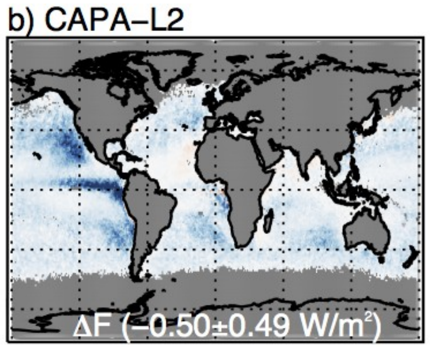
- Clouds are surrounded by the "***twilight zone***"
  - Belt of forming and evaporating cloud fragments and hydrated aerosols extending tens of km.

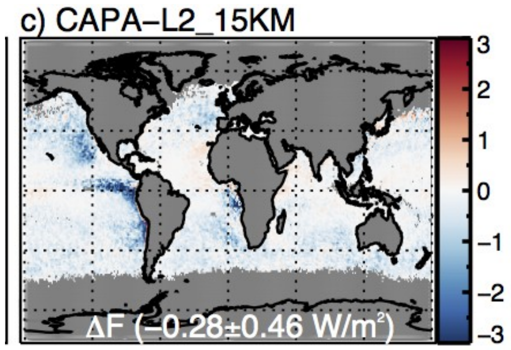
- To what extent does the twilight zone influence estimates of the aerosol indirect forcing?
  - In situ estimates from Ted Van Hoeve 2016
  - Satellite based estimates from Christensen et al. 2017, ACP

Aerosol Retrievals
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.

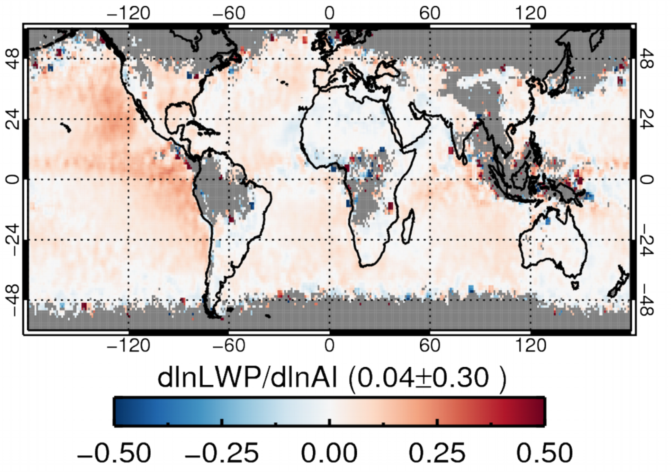
Christensen et al. (2017), ACP

Satellite-Model Comparison

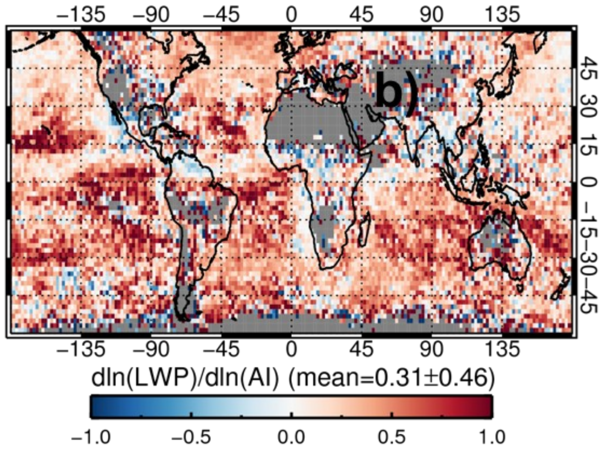
Cloud Water Path Sensitivity Satellite-Model Comparisons

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

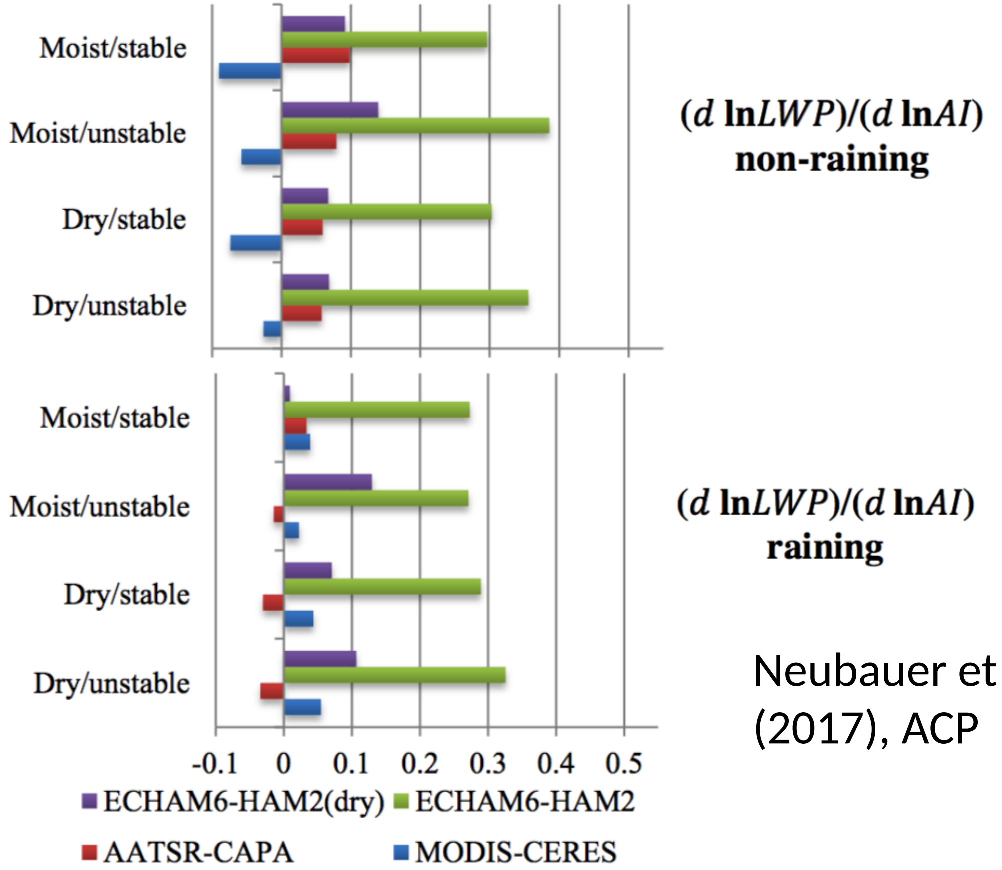
Satellite: AATSR



Model: ECHAM6 HAM 2



Liquid water path sensitivity



Neubauer et al. (2017), ACP

Satellites disagree on the sign but agree on magnitude

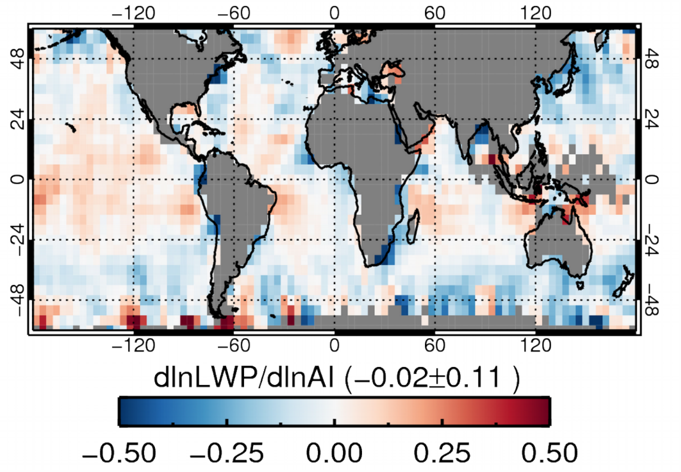
Improvement in model is observed if using dry aerosol.

Satellite-Model Comparison

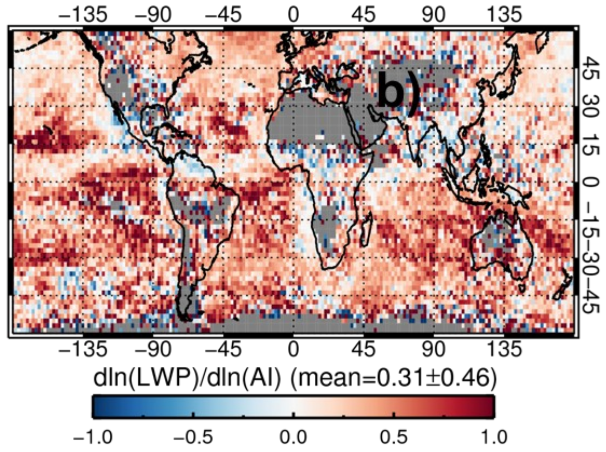
Cloud Water Path Sensitivity Satellite-Model Comparisons

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

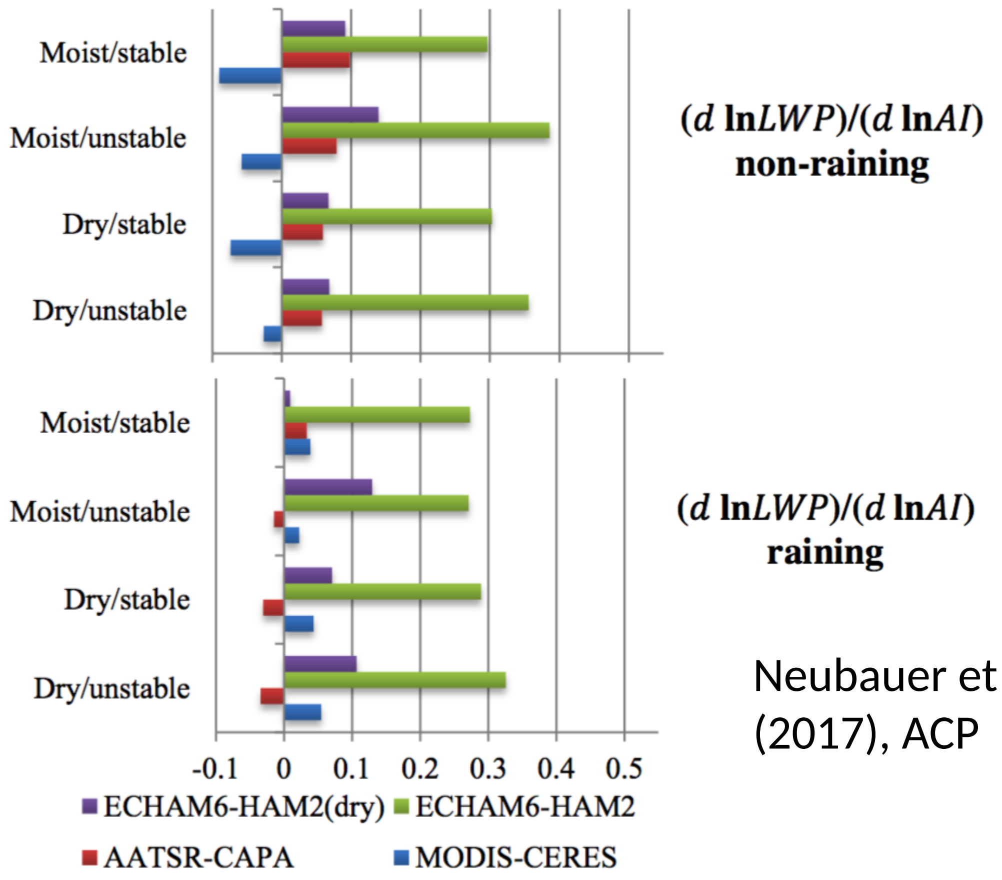
Satellite: MODIS



Model: ECHAM6 HAM 2



Liquid water path sensitivity

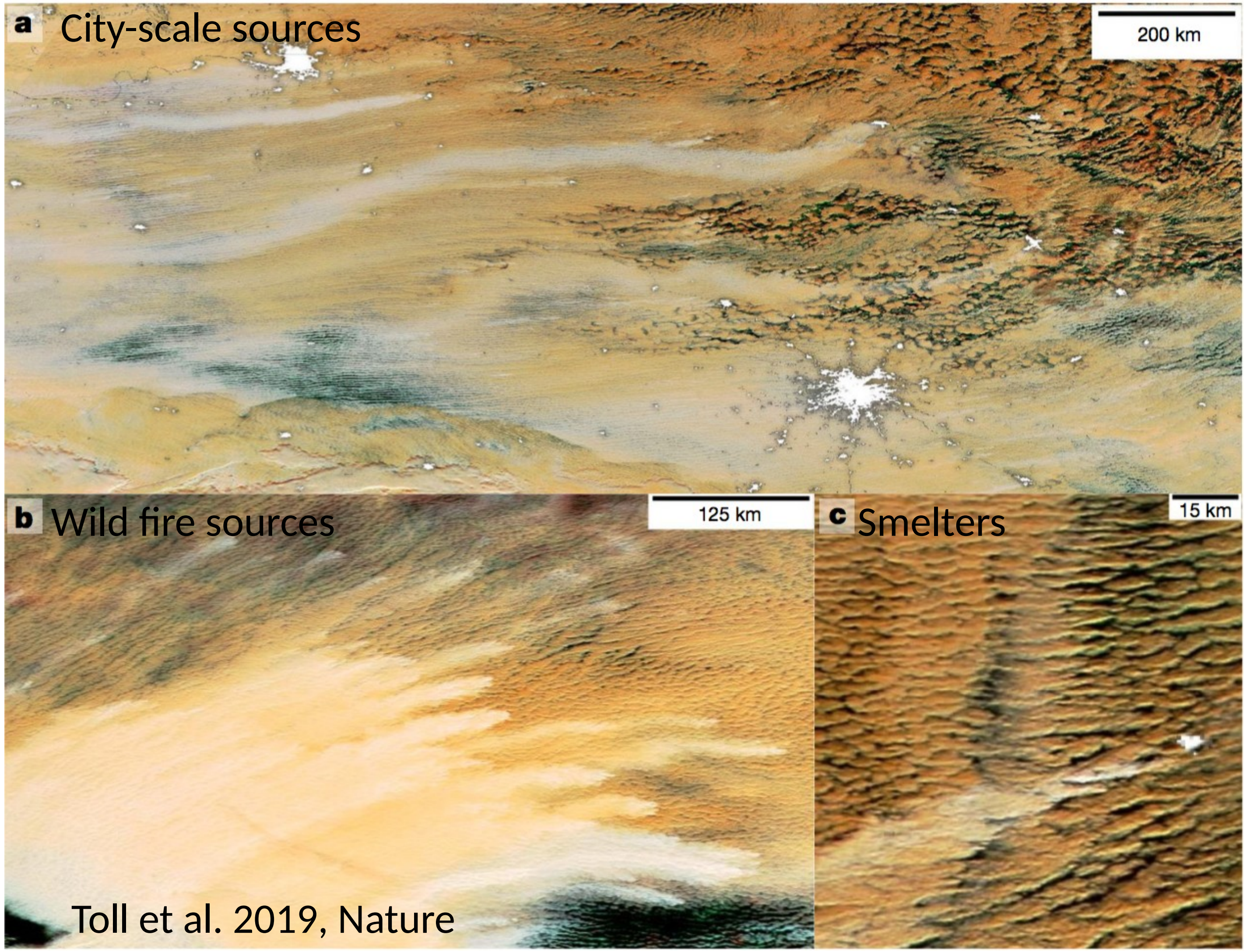


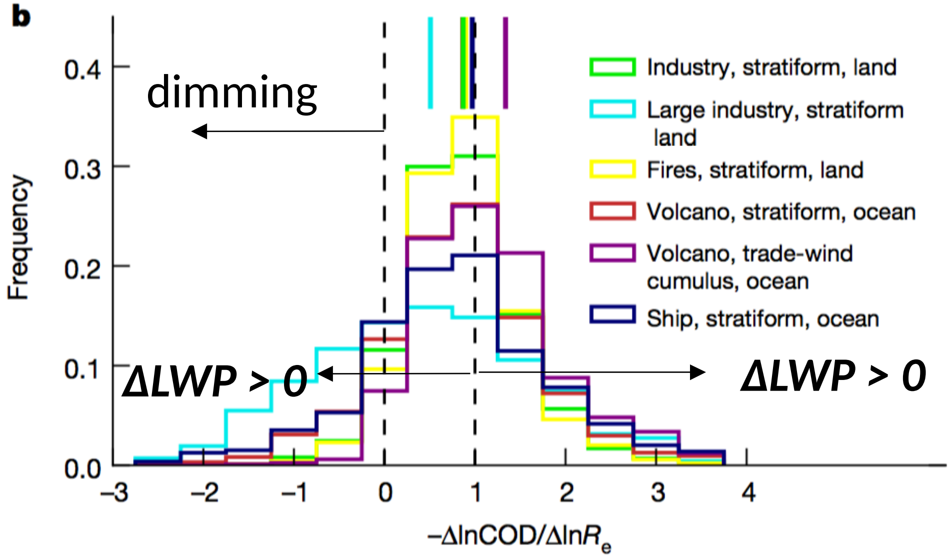
Neubauer et al. (2017), ACP

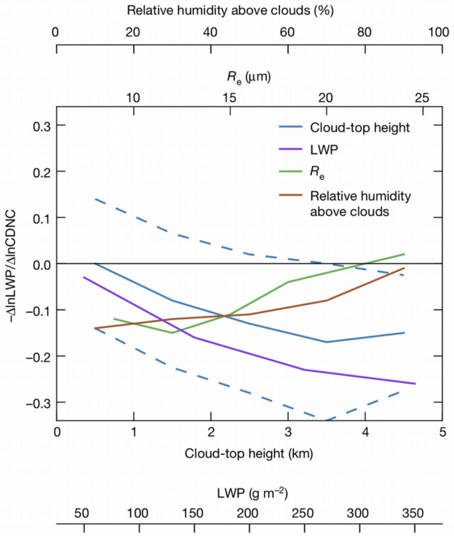
Satellites disagree on the sign but agree on magnitude

Improvement in model is observed if using dry aerosol.

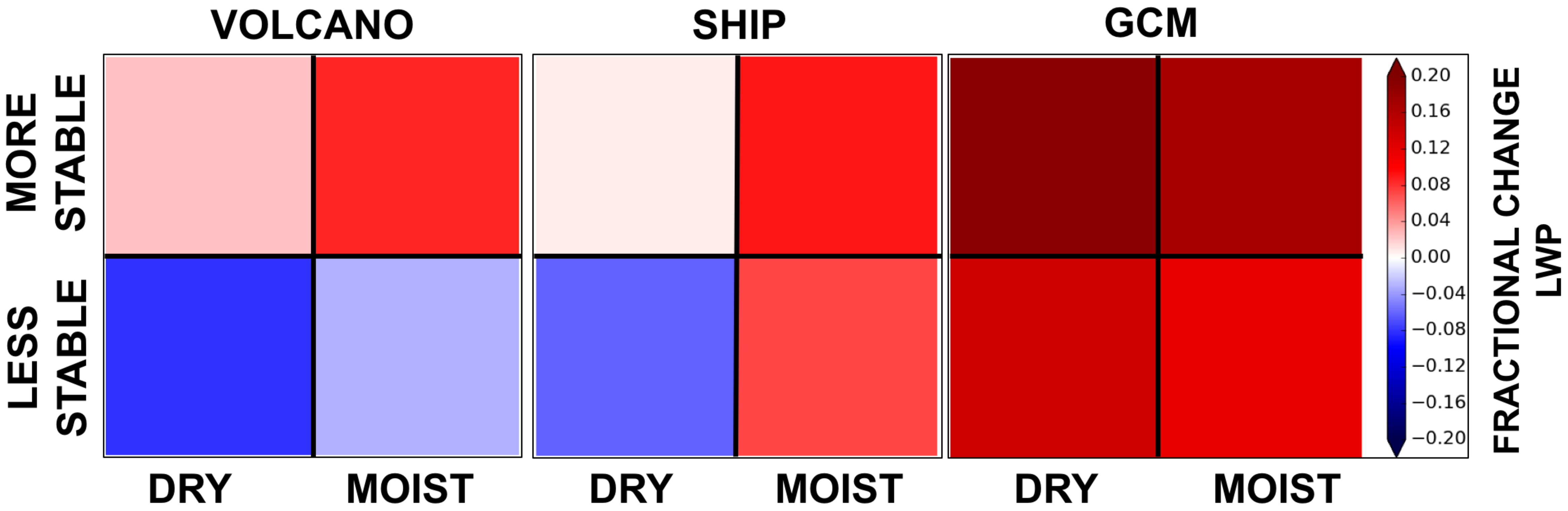
Natural and Anthropogenic Laboratories





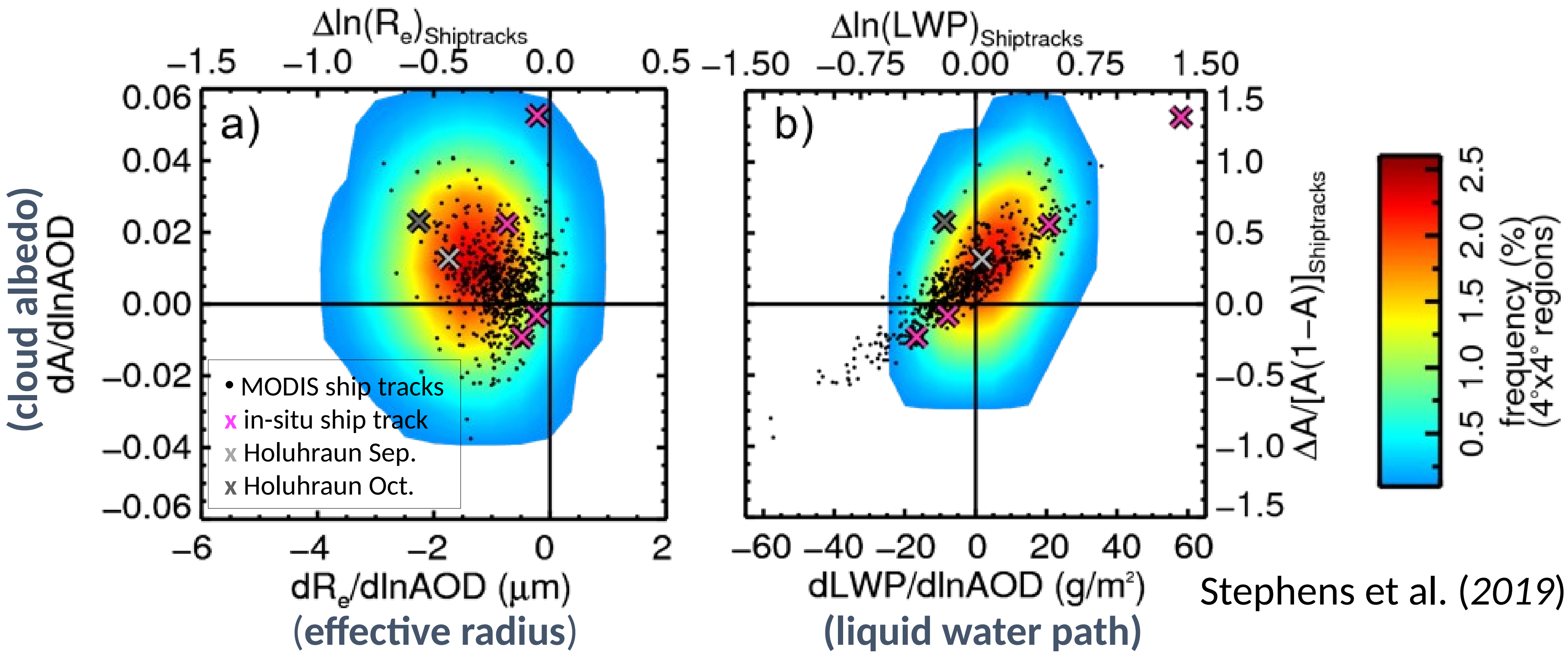


Ship and Volcano Track Responses



- HADGEM LWP response shows no dependence on meteorology.

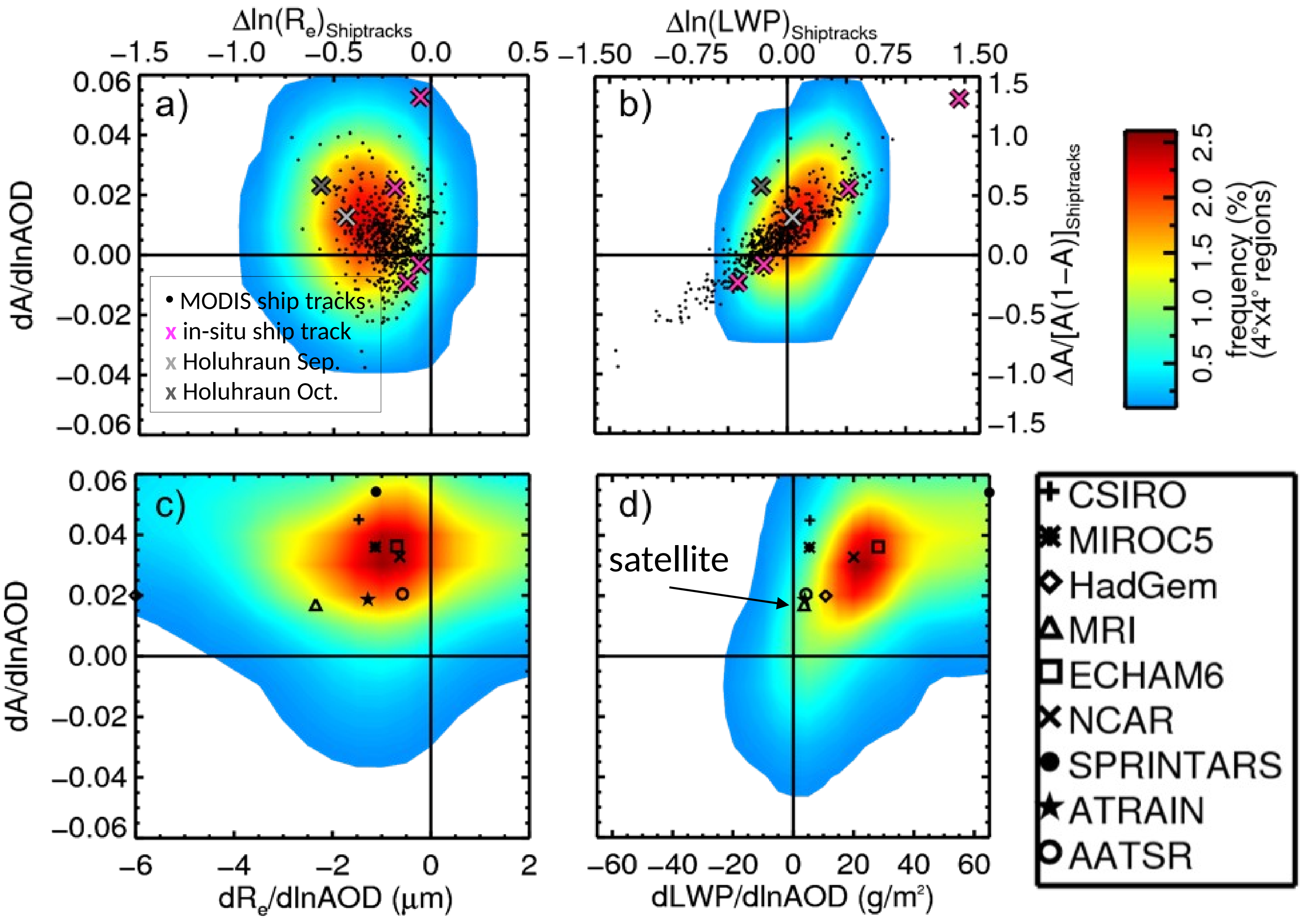
Cloud Albedo Comparison



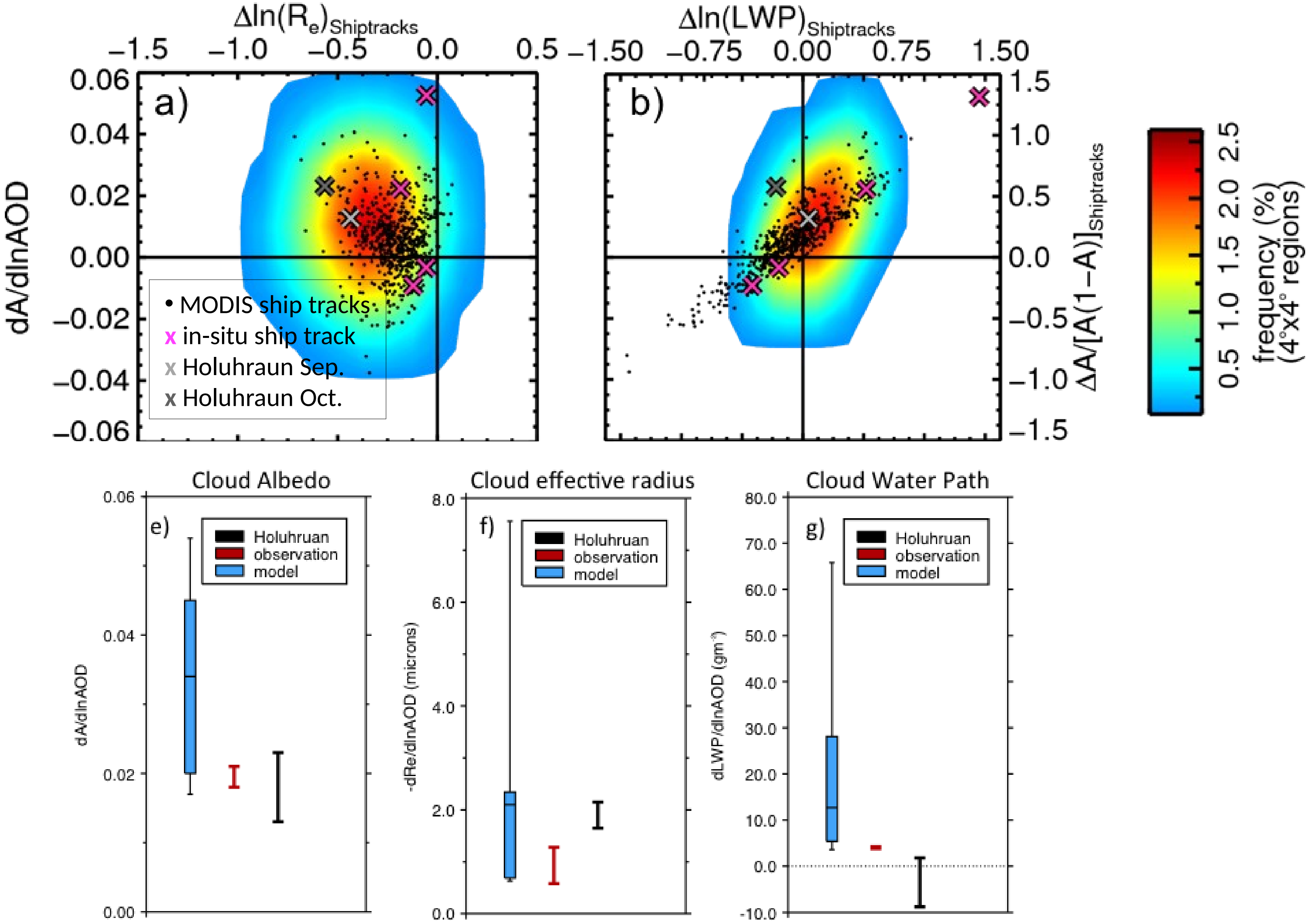
Stephens et al. (*2019*)

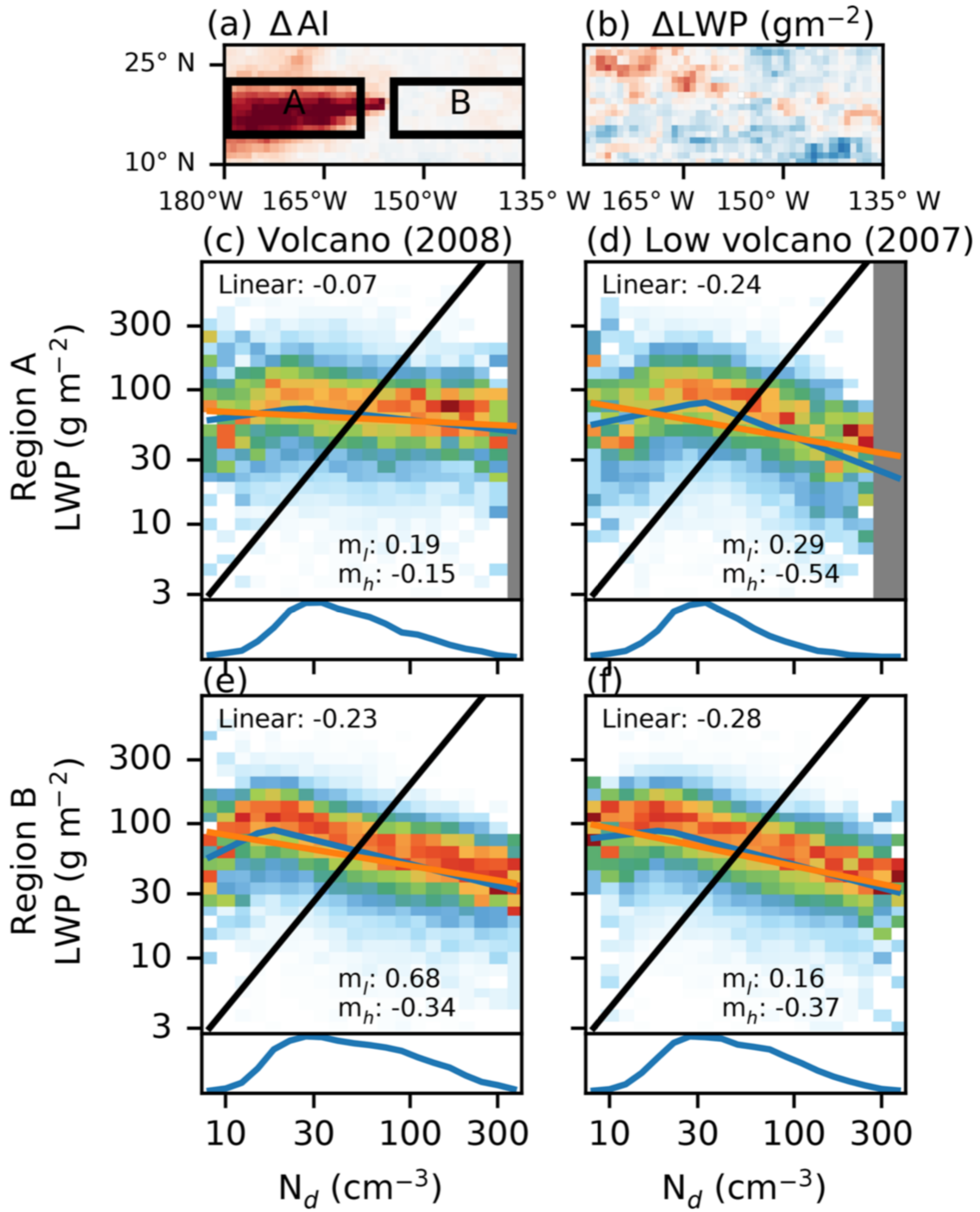
- Albedo calculation: regional-scale (colors) based on CERES – Ship tracks based on MODIS BUGSrad
- Holuhraun eruption data from Malavelle et al. (2017).
- Ship tracks and global-scale A-train observations indicate that cloud albedo is strongly influenced by *macrophysical* (LWP) changes associated with increased aerosol loading.

Cloud Albedo Comparisons

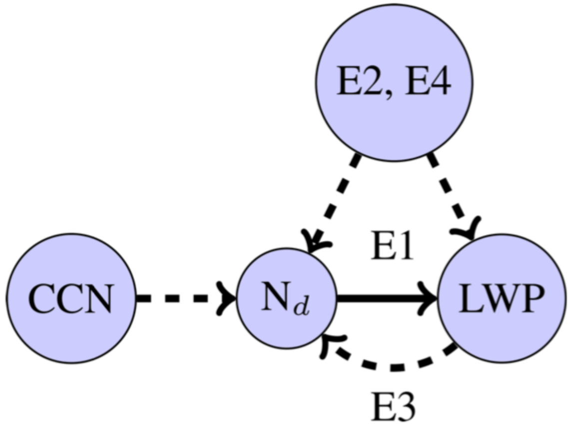


Cloud Albedo Comparisons





Feedback, Confounder or Satellite Retrieval Error?



- LWP vs CDNC relationship "flattens" when the emission rates increase.

Future Satellite Missions

- Plankton, Aerosols, Clouds, ocean Ecosystems (PACE) mission (2022)
  I. Ocean Color Instrument (hyperspectral radiometer 350 – 885 nm).
  II. Spectro-Polarimeter for Planetary Exploration-1 (hyperspectral; 100 km narrow swath)
  III. Hyper Angle Rainbow Polarimeter-2; prism beam splitting (440, 550, 670, and 870 nm; 1500 km broad swath; 2.5 km pixel from 10- 60 different angles)

- Multi-Viewing Multi-Channel Multi-Polarisation Imaging (3MI) (2022)
  - 12 spectral channels, 14 angles, 2200 km swath at 4 km resolution, polarization (−60°, 0°, and +60°)

- EarthCare (2012 – 2021???); ACCP
  I. ATLID – ESA 354.8 nm depolarization lidar
  II. CPR – -36 dBZ sensitivity, 500 m horizontal and 100 m vertical resolution doppler cloud profile radar
  III. MSI – 7 channels, 150 km swath, 500 m resolution
  IV. BBR – broadband radiometer; 10 km resolution

- Meteosat next generation geostationary satellites
  I. Four Imaging Satellites (MTG-I) (20 years of operational services expected)
  II. Two Sounding Satellites (MTG-S) (15.5 years of operational services expected)