LWP Control on Cloud Albedo and the Aerosol Indirect Effect

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many thanks to:
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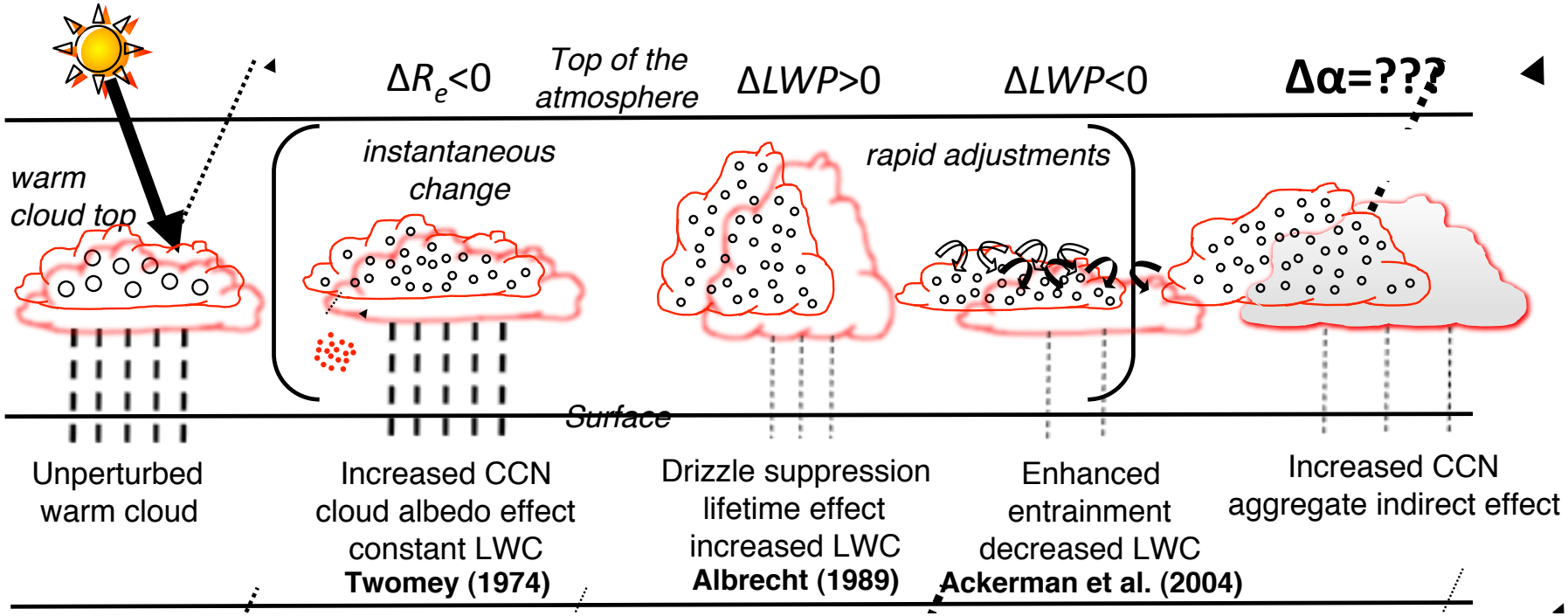
Kenta Suzuki
Brian Zambri
David Neubauer
John Seinfeld
Graeme Stephens

RAL Space

Colorado State University

JPL
Jet Propulsion Laboratory
California Institute of Technology

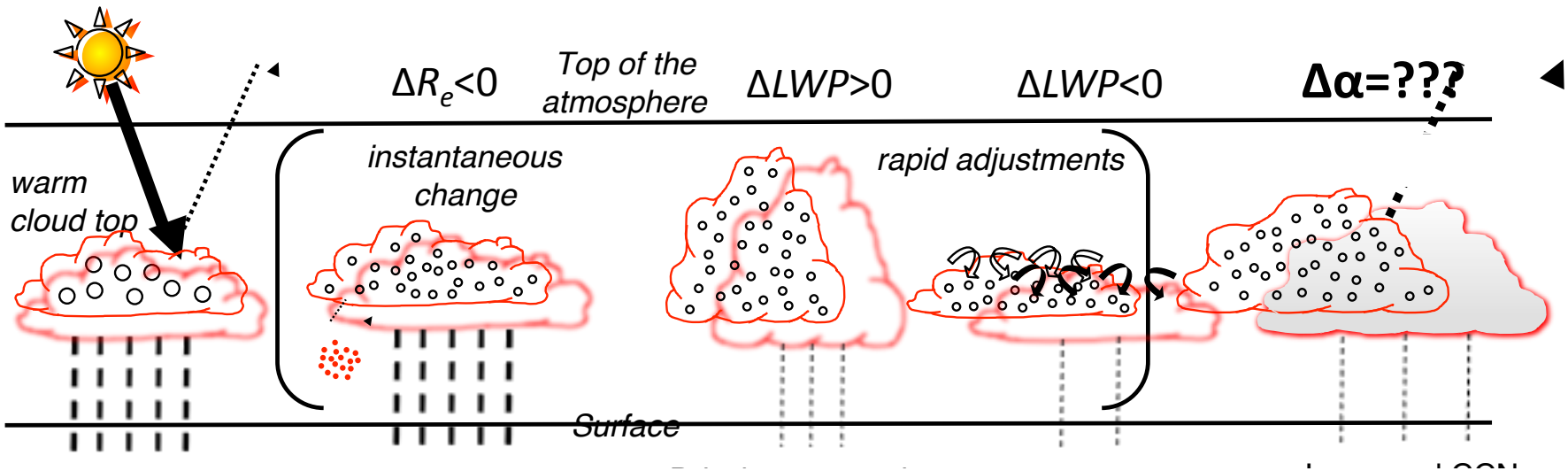
Aerosol Indirect Effect: ***Warm*** Cloud

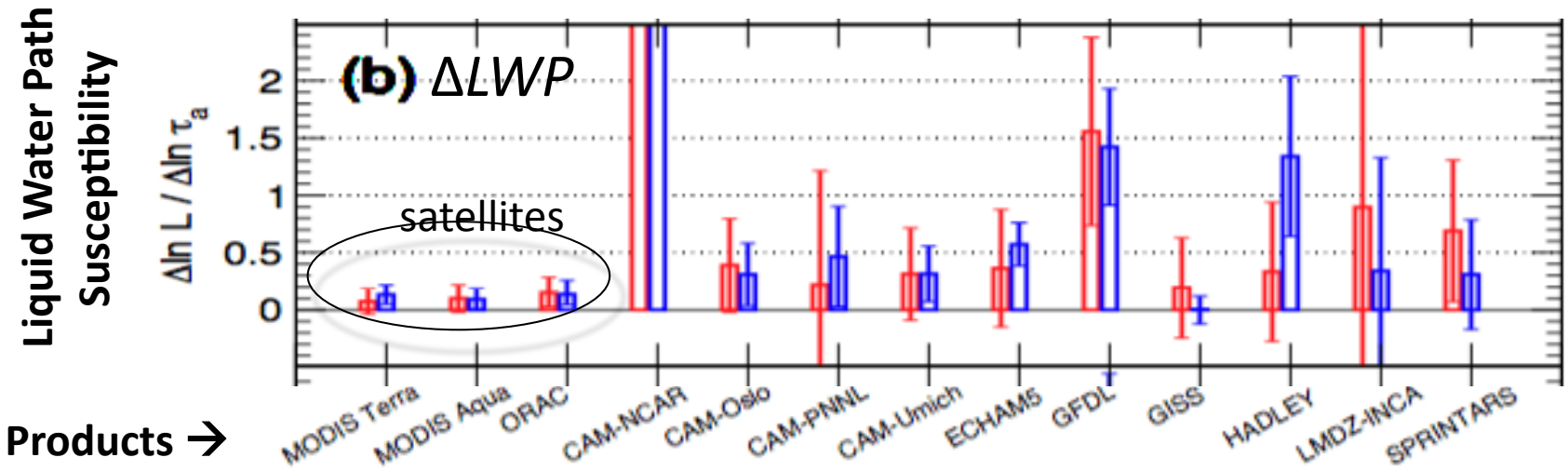


$$\underbrace{\frac{\Delta\tau}{\tau}}_{\text{Cloud Optical Depth}} = -\underbrace{\frac{\Delta R_e}{R_e}}_{\text{Effective Droplet Radius (Instantaneous)}} + \underbrace{\frac{\Delta LWP}{LWP}}_{\text{Liquid Water Path (Adjusted)}} \propto \underbrace{\frac{\Delta\alpha}{\alpha}}_{\text{Cloud Albedo}}$$

τ: cloud optical thickness
LWP: liquid water path
R_e: effective radius
α: cloud albedo

Aerosol Indirect Effect: *Warm* Cloud



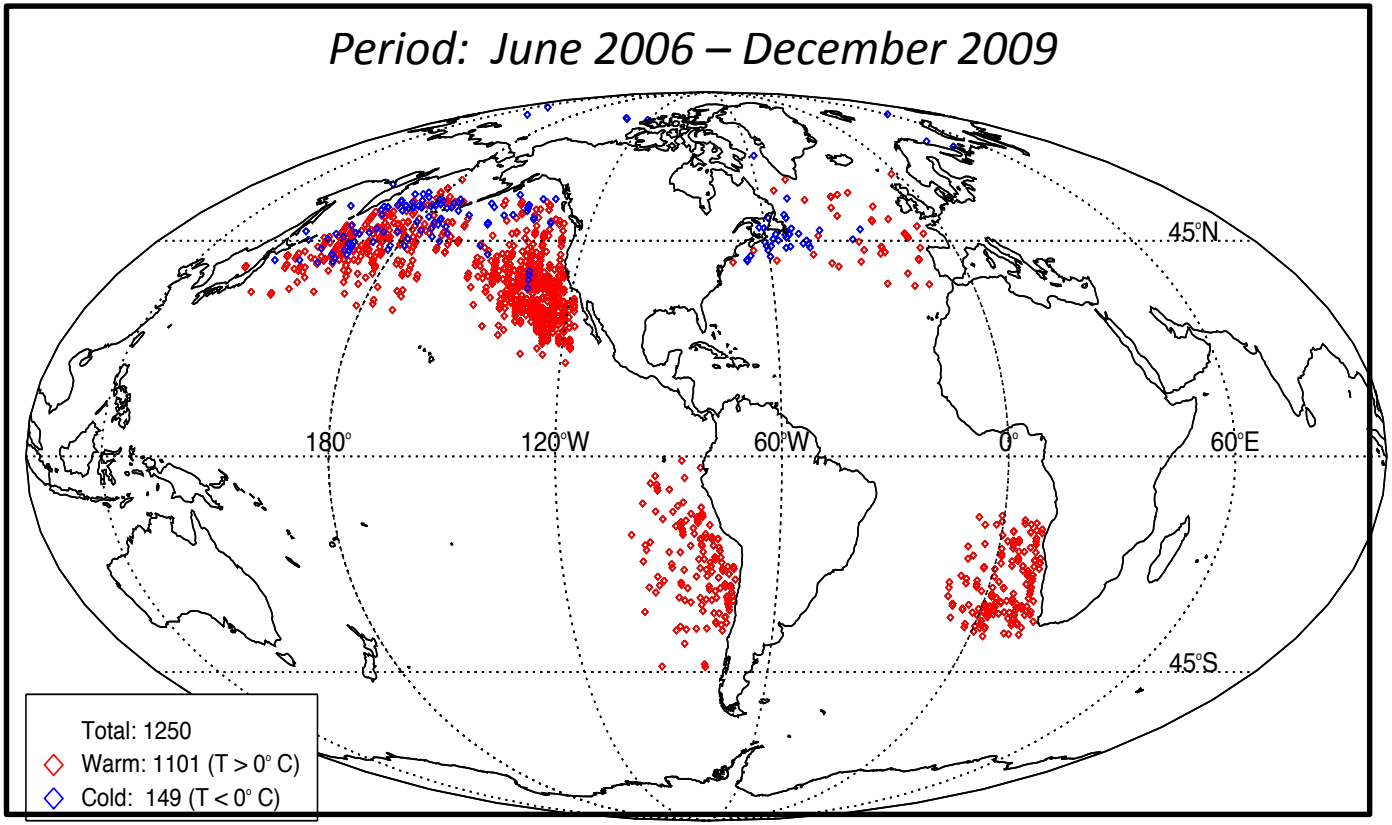


Quass et al. (2009)

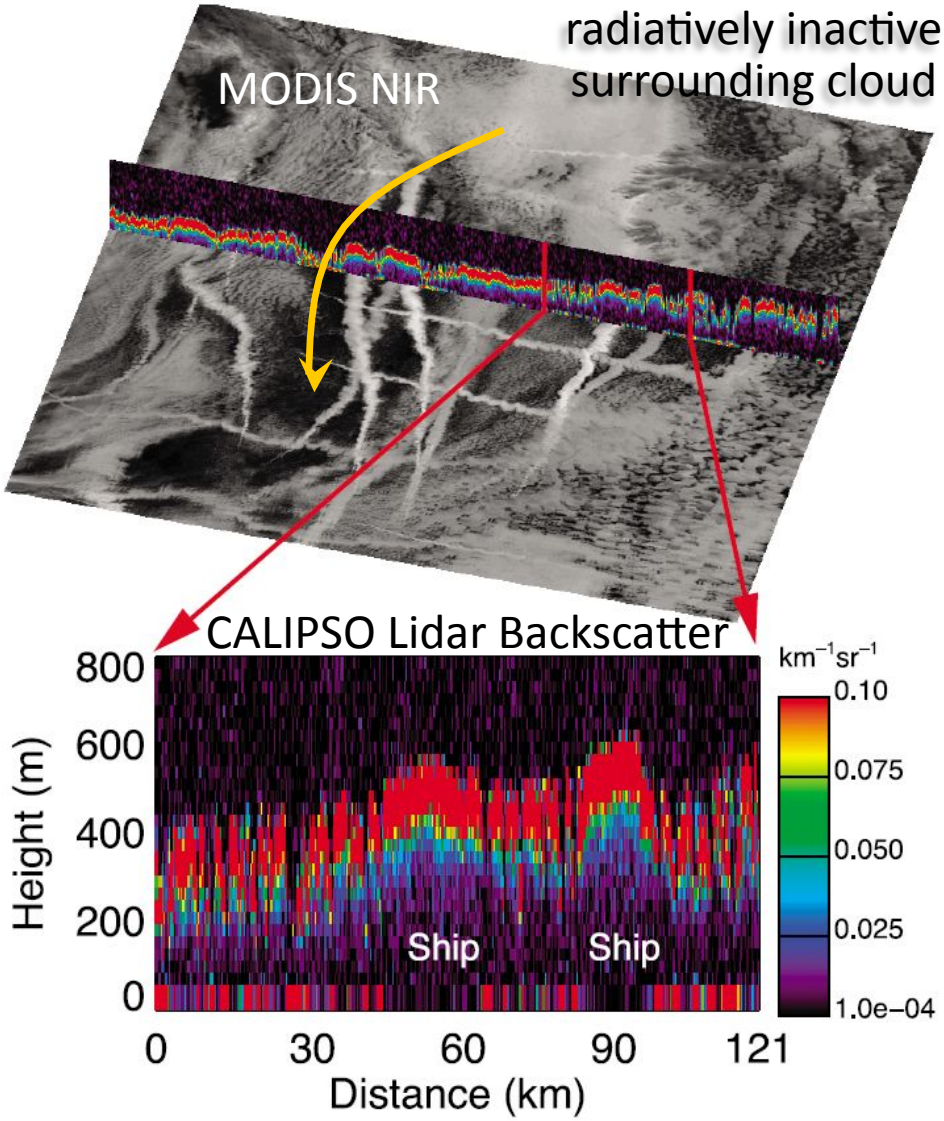
- ***Cloud properties & aerosol-cloud feedbacks are poorly parameterized in GCMs.***
- ***The recipe for progress lies in improving our understanding of physical processes and in better representing these processes in models.***

A-Train Ship Track Database

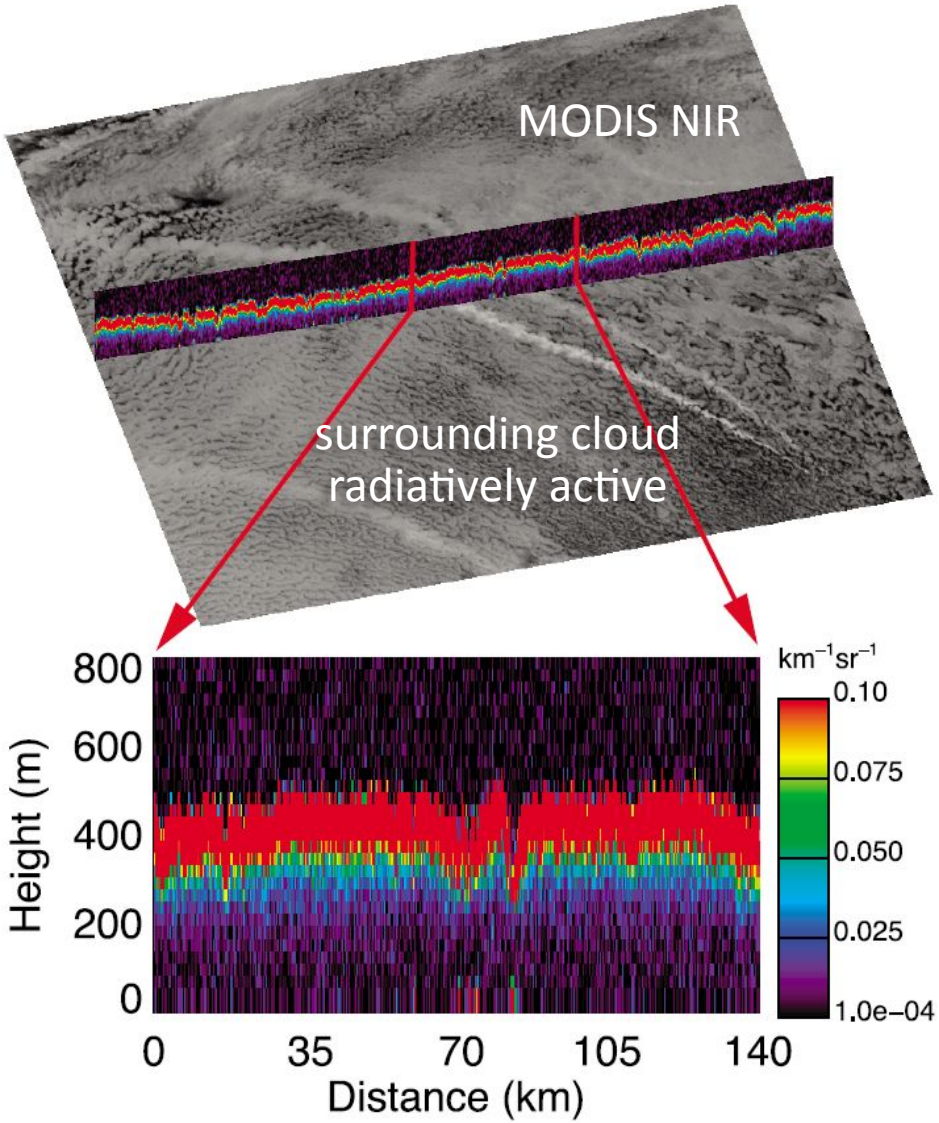
CALIPSO – lidar cloud top height
CloudSat – radar reflectivity, precipitation occurrence/intensity
MODIS – particle size, optical depth, liquid water path, cloud albedo



Evidence of Cloud Deepening



Open cells: 16% increase in cloud top height

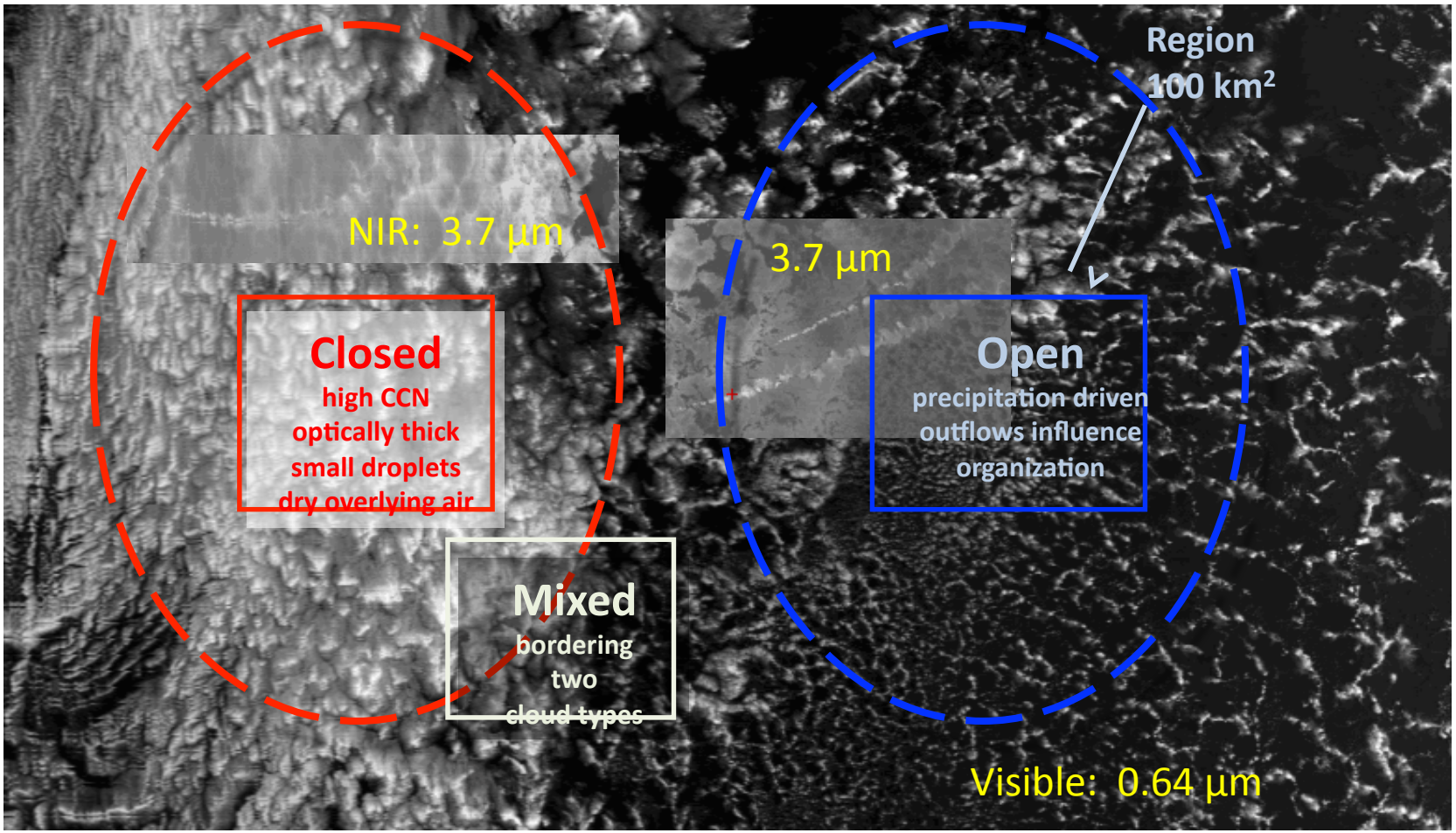


Closed cells:
no change in cloud top height

Christensen and Stephens (2011)

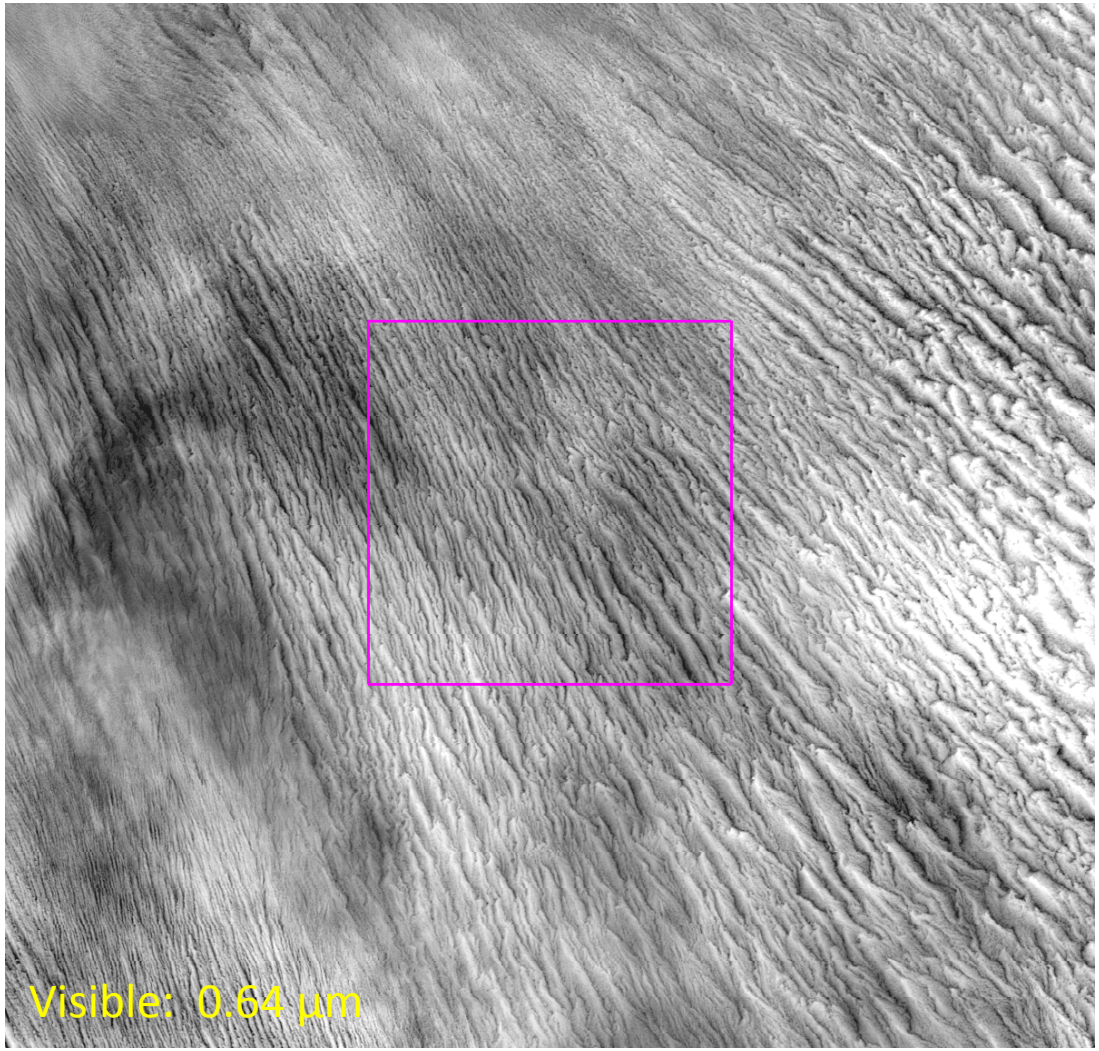
Cloud Type Classification

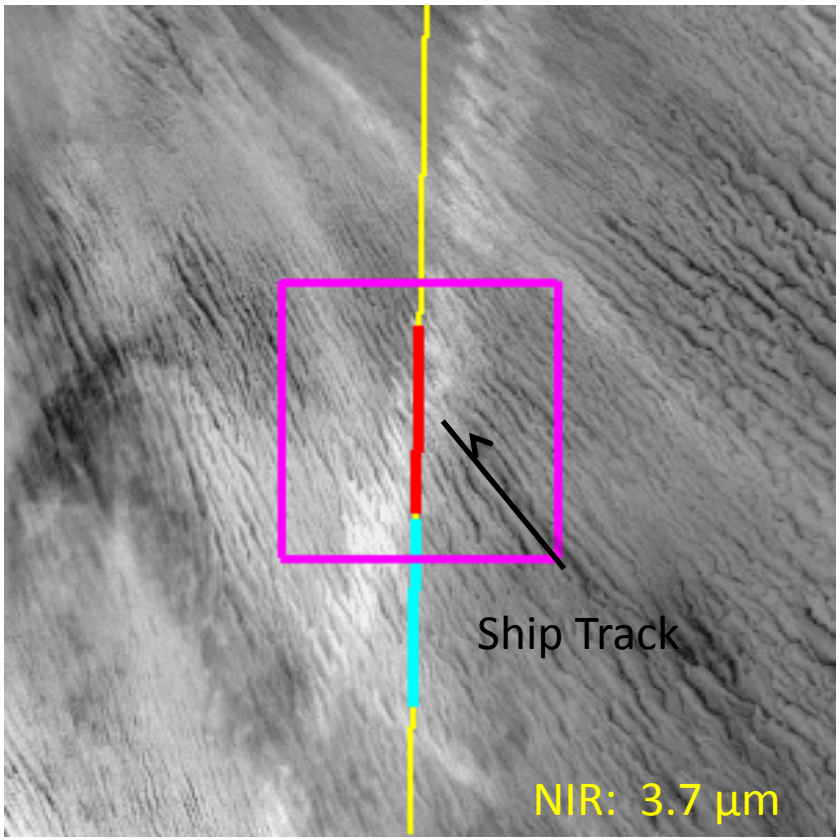
- Stratocumulus cloud type classification: ***visual inspection* (subjective approach)**.
- **Dominant** types: closed, open, mixed/unclassifiable, no MCC
- **Subtype**: none, rolled, wavy, POC, streets



Cloud Type Identification

Rolled Stratocumulus

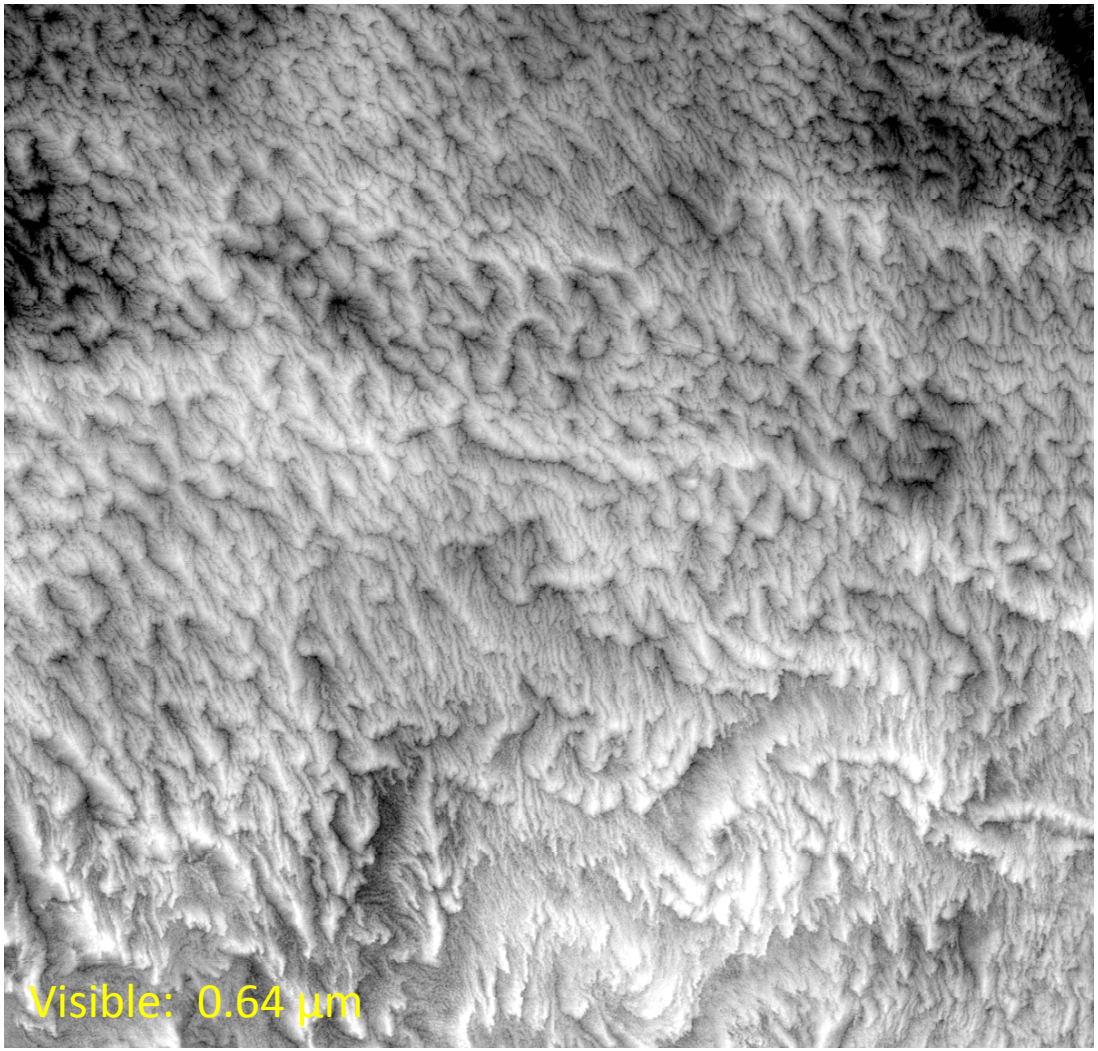


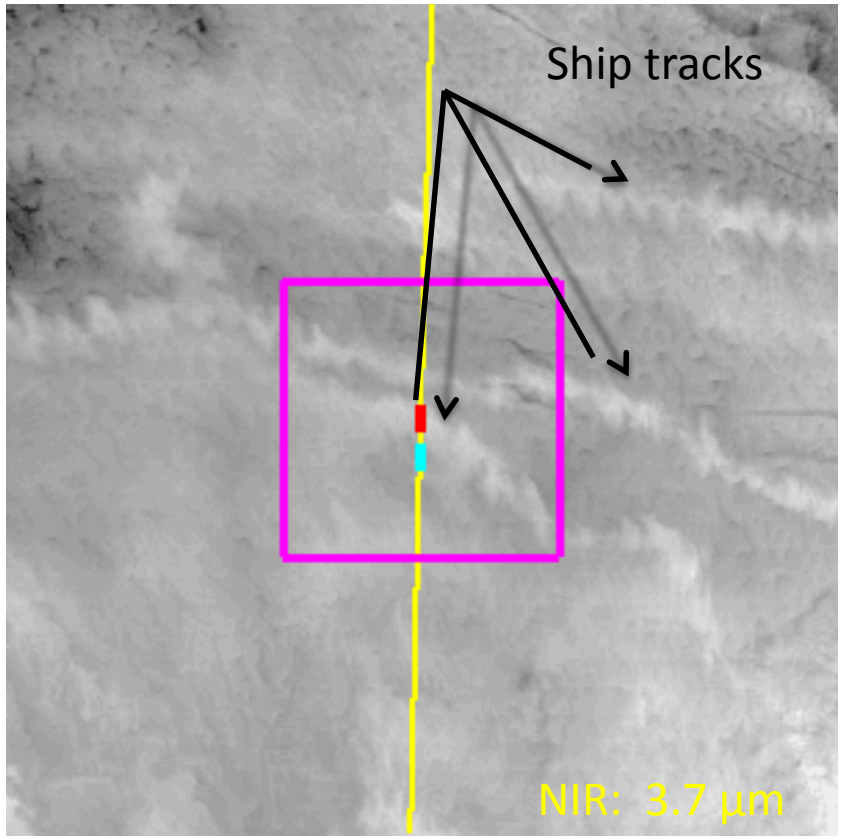


Year: 2006 Julian day: 204 time: 2145 UTC

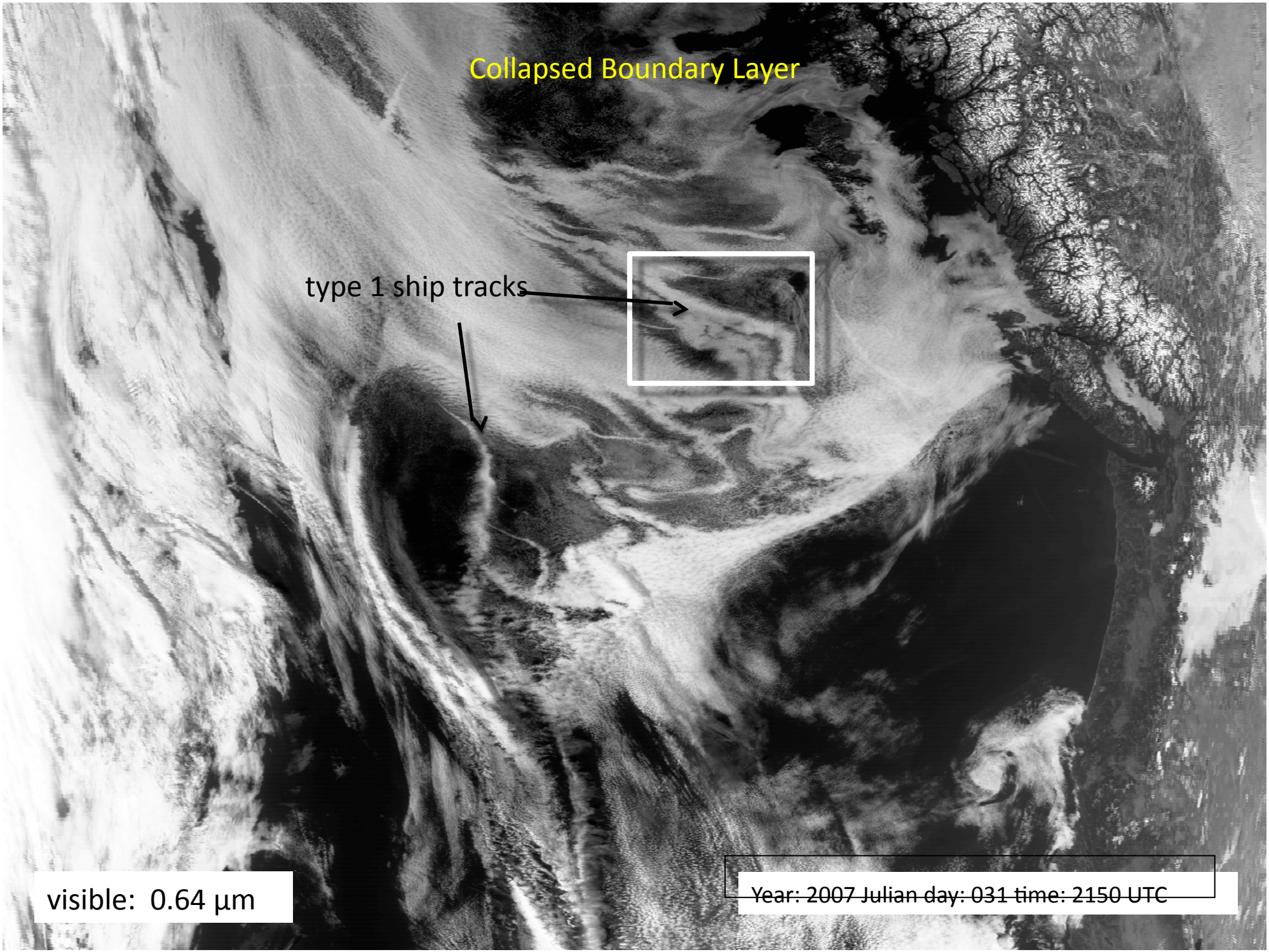
Cloud Type Identification

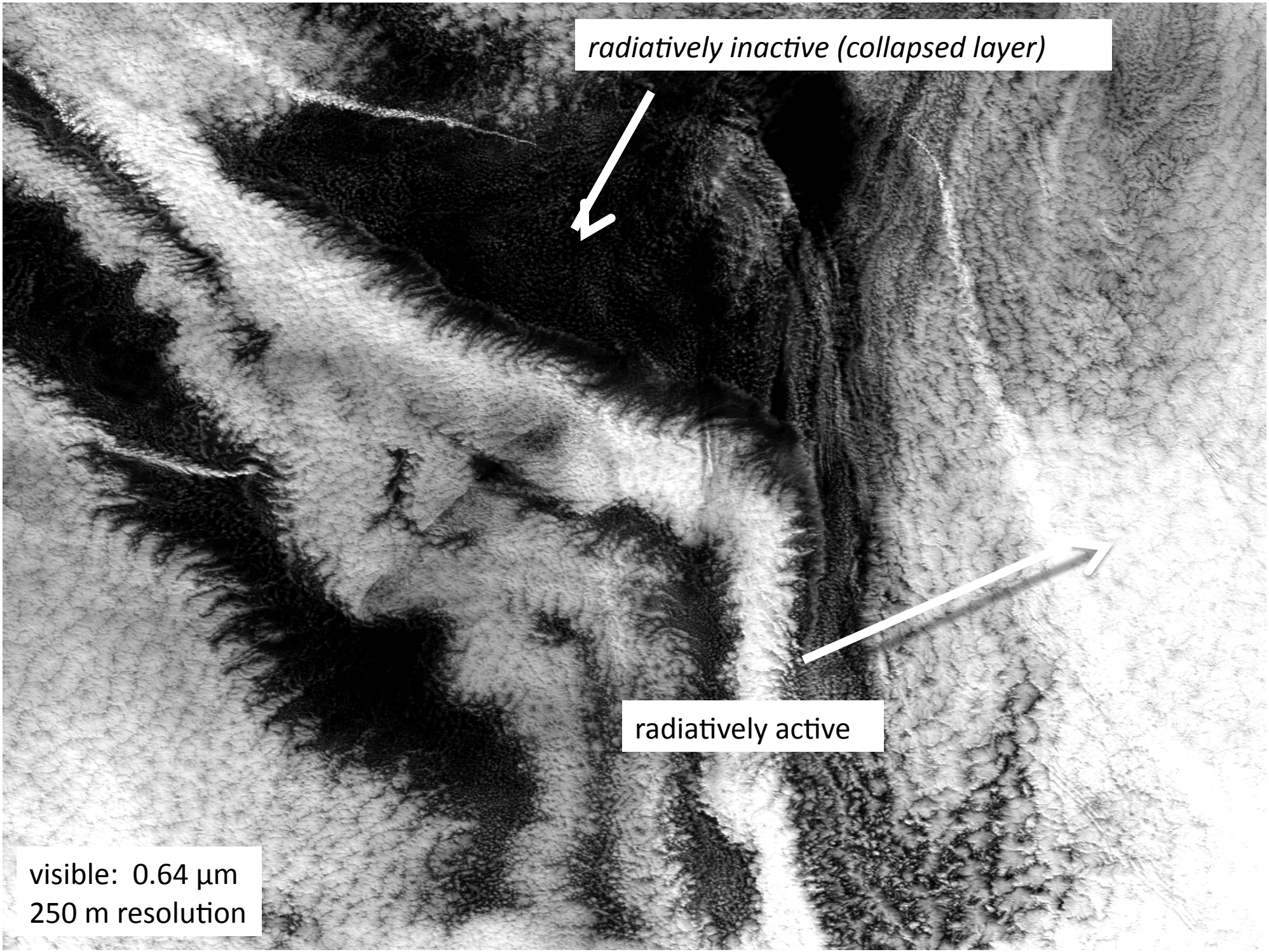
Wavy Stratocumulus





Year: 2006 Julian day: 175 time: 0055 UTC


Collapsed Boundary Layer
type 1 ship tracks
visible: 0.64 µm
Year: 2007 Julian day: 031 time: 2150 UTC


radiatively inactive (collapsed layer)
radiatively active
visible: 0.64 µm
250 m resolution

AGU PUBLICATIONS

Geophysical Research Letters

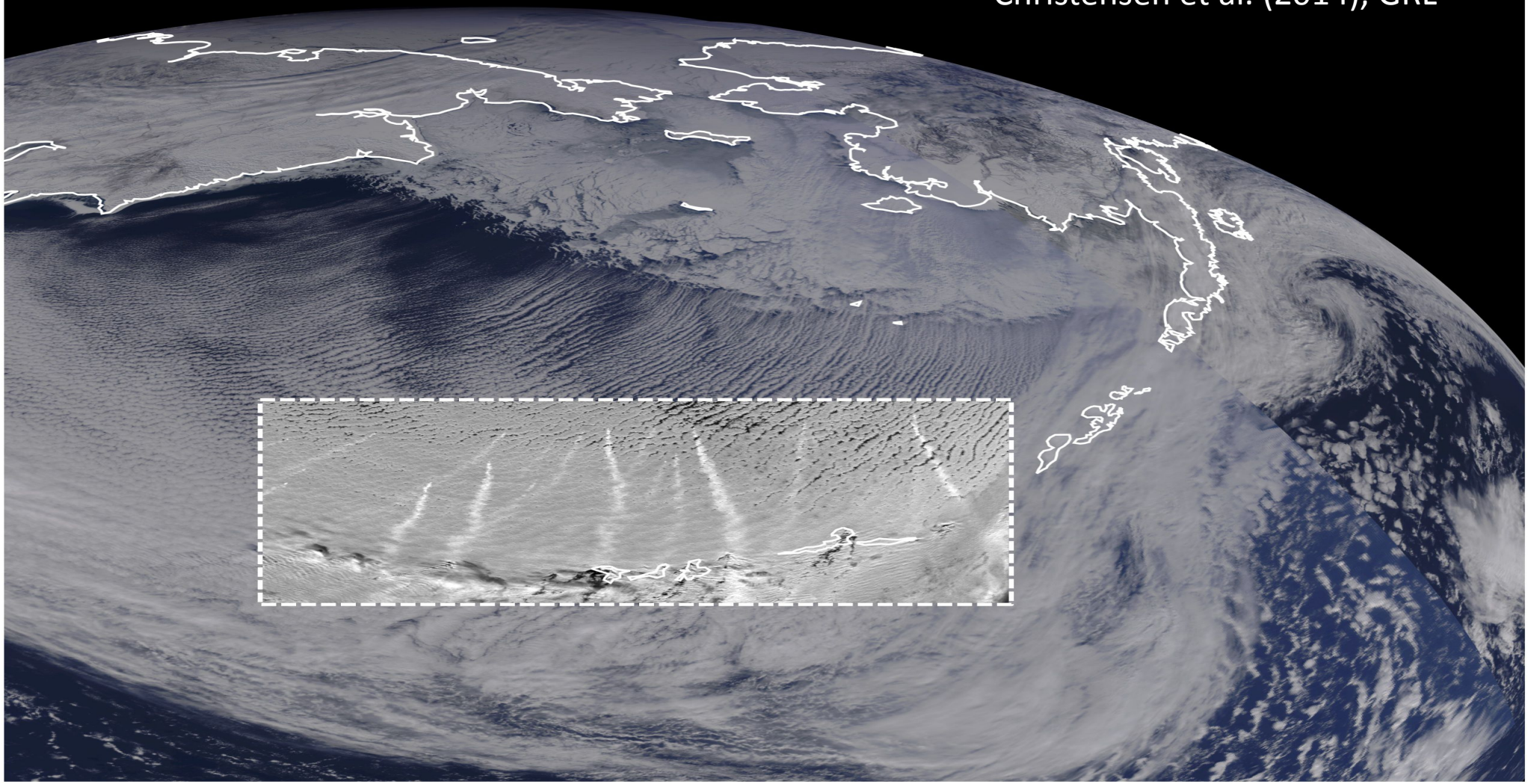
RESEARCH LETTER
10.1002/2014GL061320

Ship track observations of a reduced shortwave aerosol indirect effect in mixed-phase clouds

M. W. Christensen[1,2], K. Suzuki[2], B. Zambri[3], and G. L. Stephens[2]

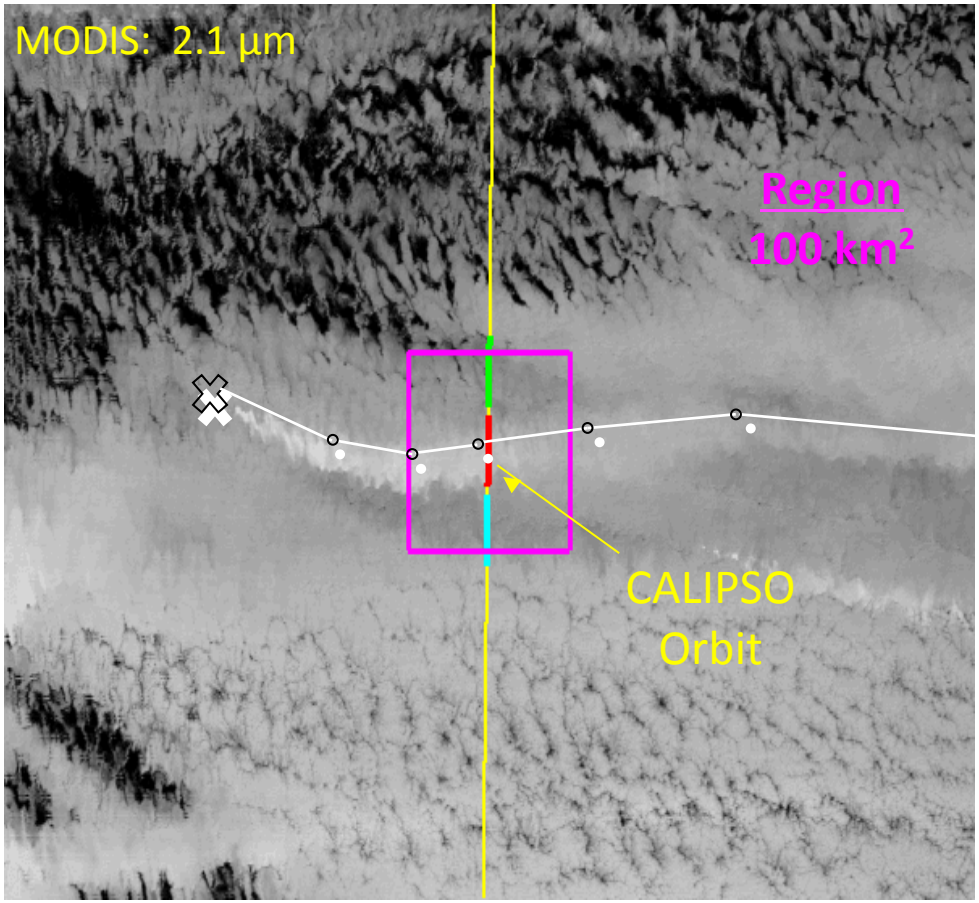
Key Points:
- Ship tracks discovered in ice clouds

Christensen et al. (2014), GRL



Ship Track Identification

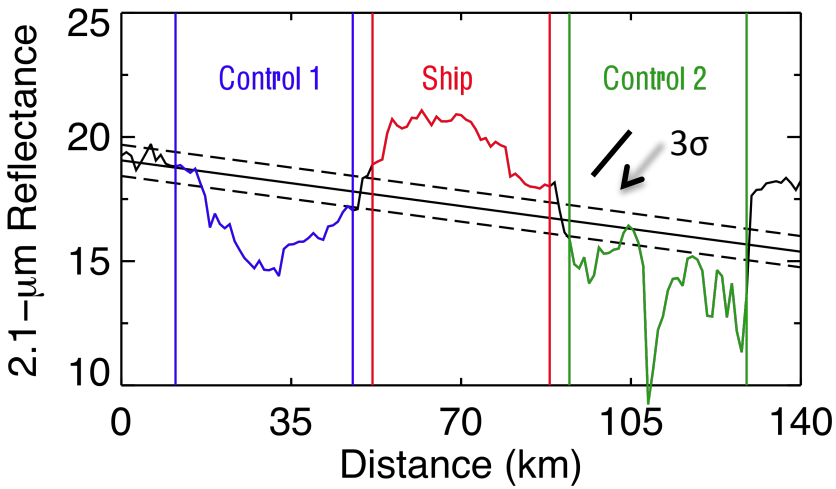
1. Locate ship track



February 3rd, 2008 at 2145 UTC

2. Automated Pixel Identification

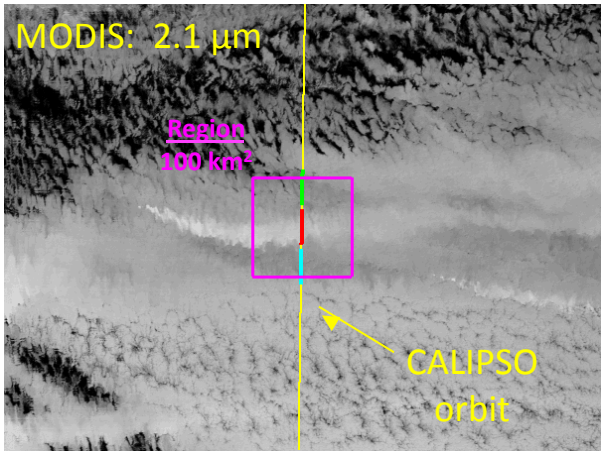
(based on Segrin et al. 2007)



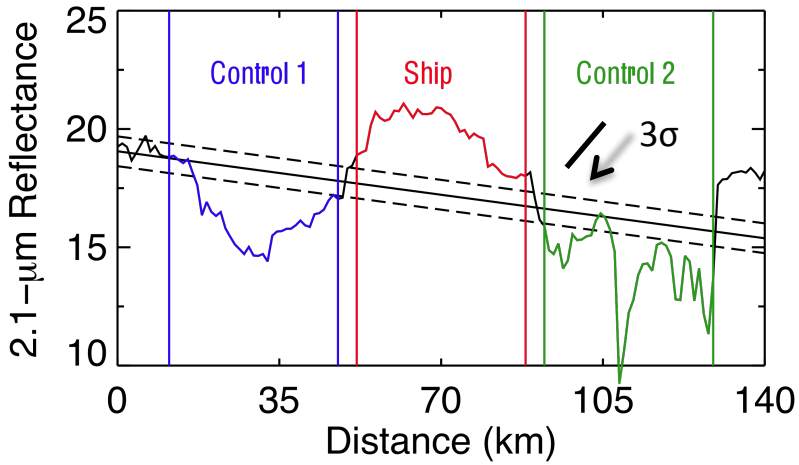
3. Cloud type classification

Ship Track Identification

1. Locate ship track



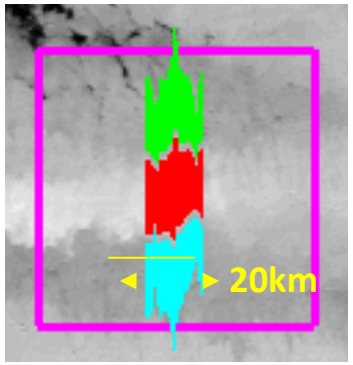
3. Automated pixel identification



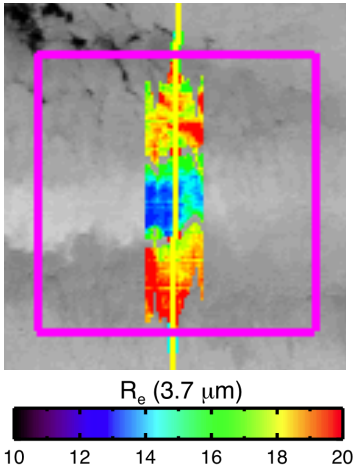
2. Cloud type classification

4. Construct along track segment

pixel identification

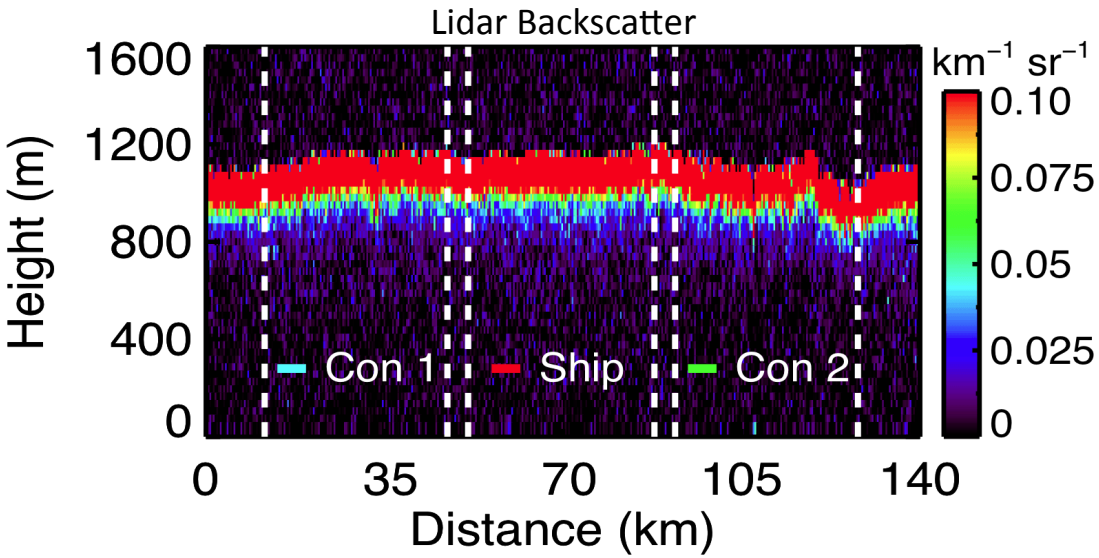


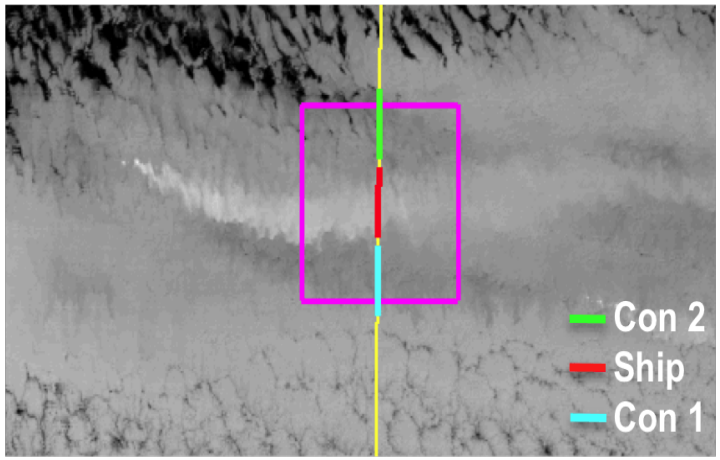
droplet radius



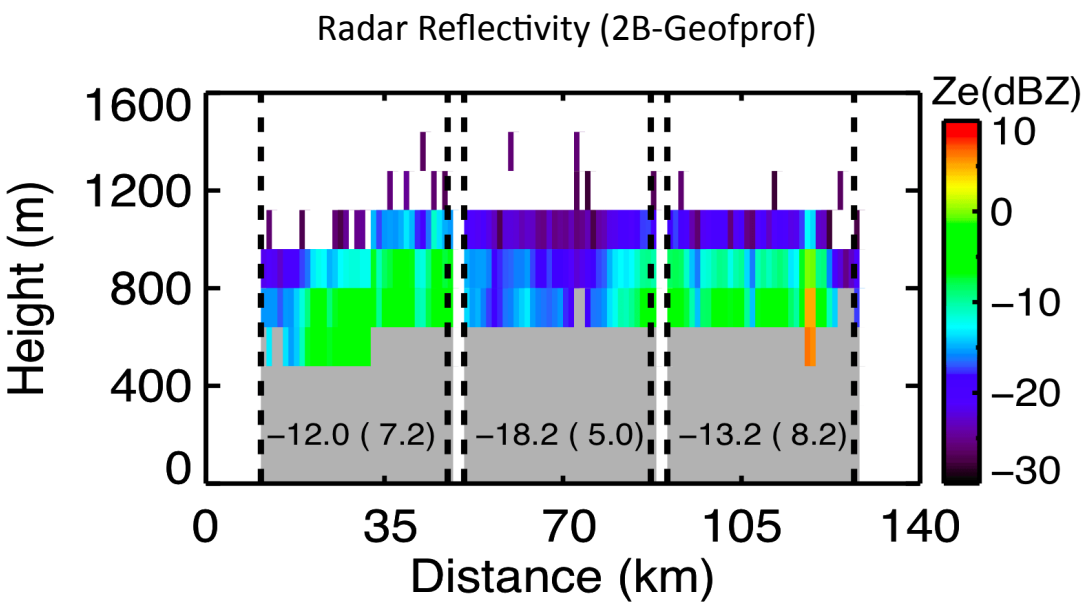
Ship pixels have ***smaller*** cloud droplets than the nearby unpolluted control pixels.

5. Collocate CALIOP to MODIS





6. Collocate CloudSat to MODIS



*Drizzle rates are lighter in polluted pixels compared to nearby unpolluted clouds.

<u>Rain rate (2C-Column-Precip)</u>

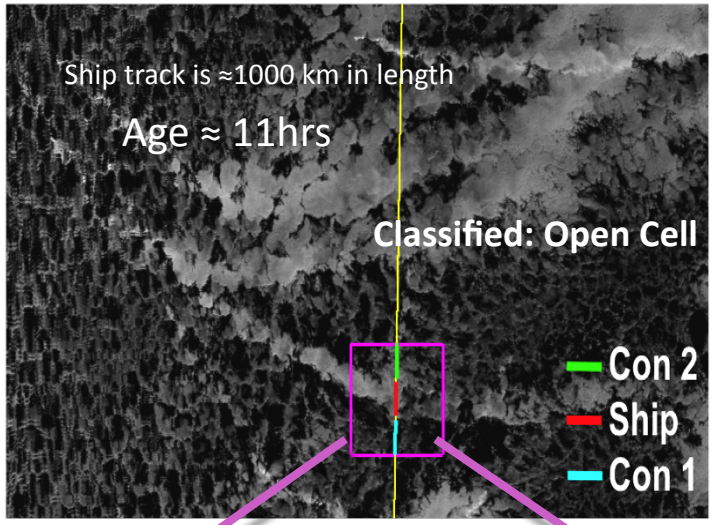
Con1 = 0.19 mm/day

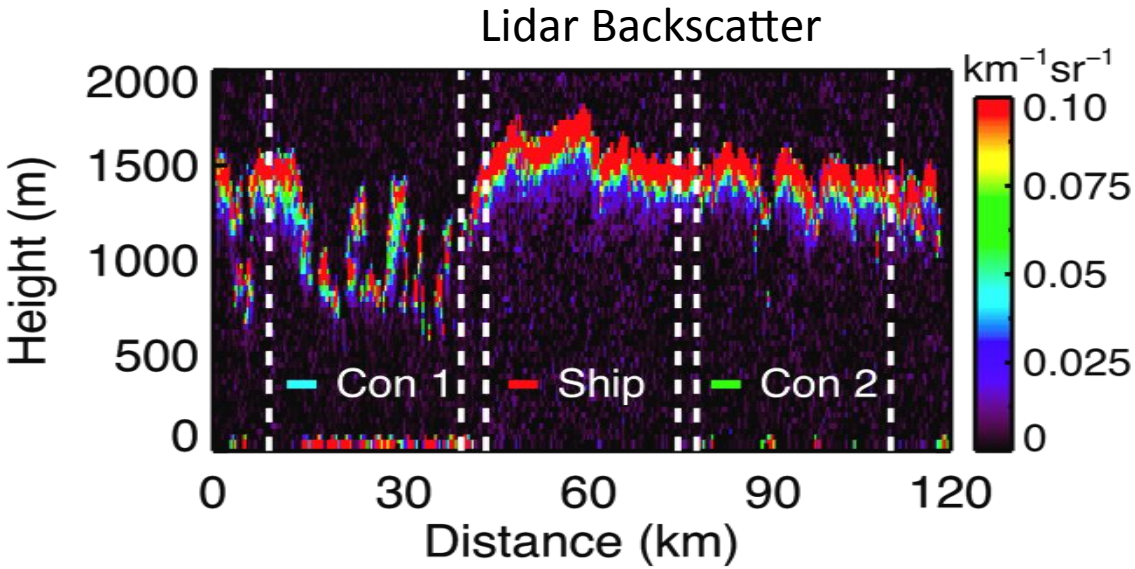
Ship = 0.08 mm/day

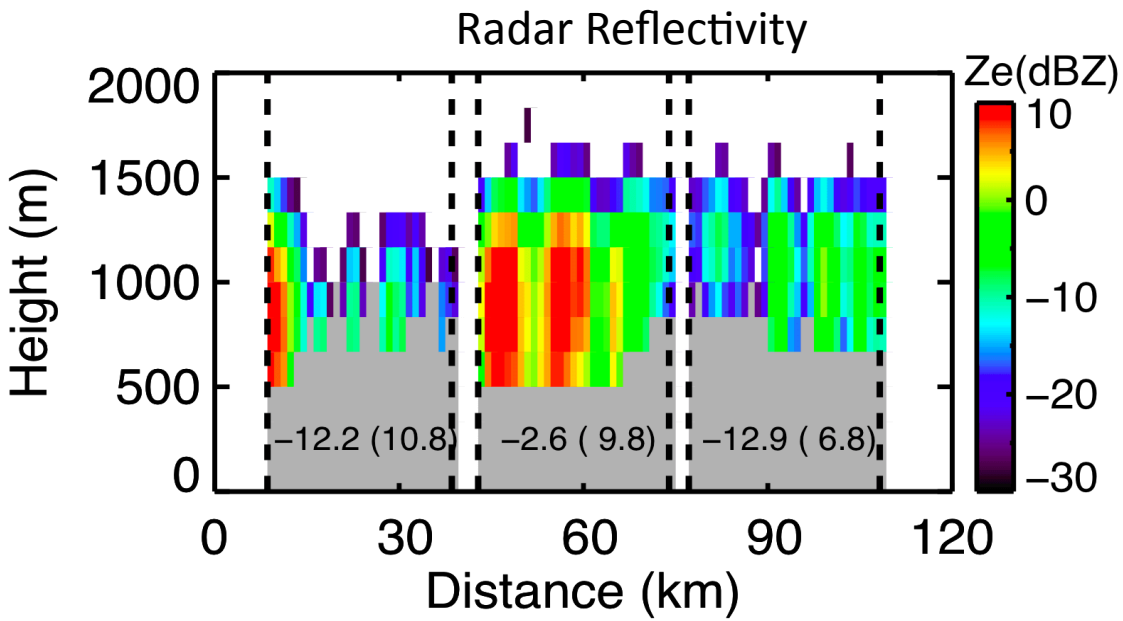
Con2 = 0.19 mm/day

Case Study: Enhanced Precipitation in Ship Track

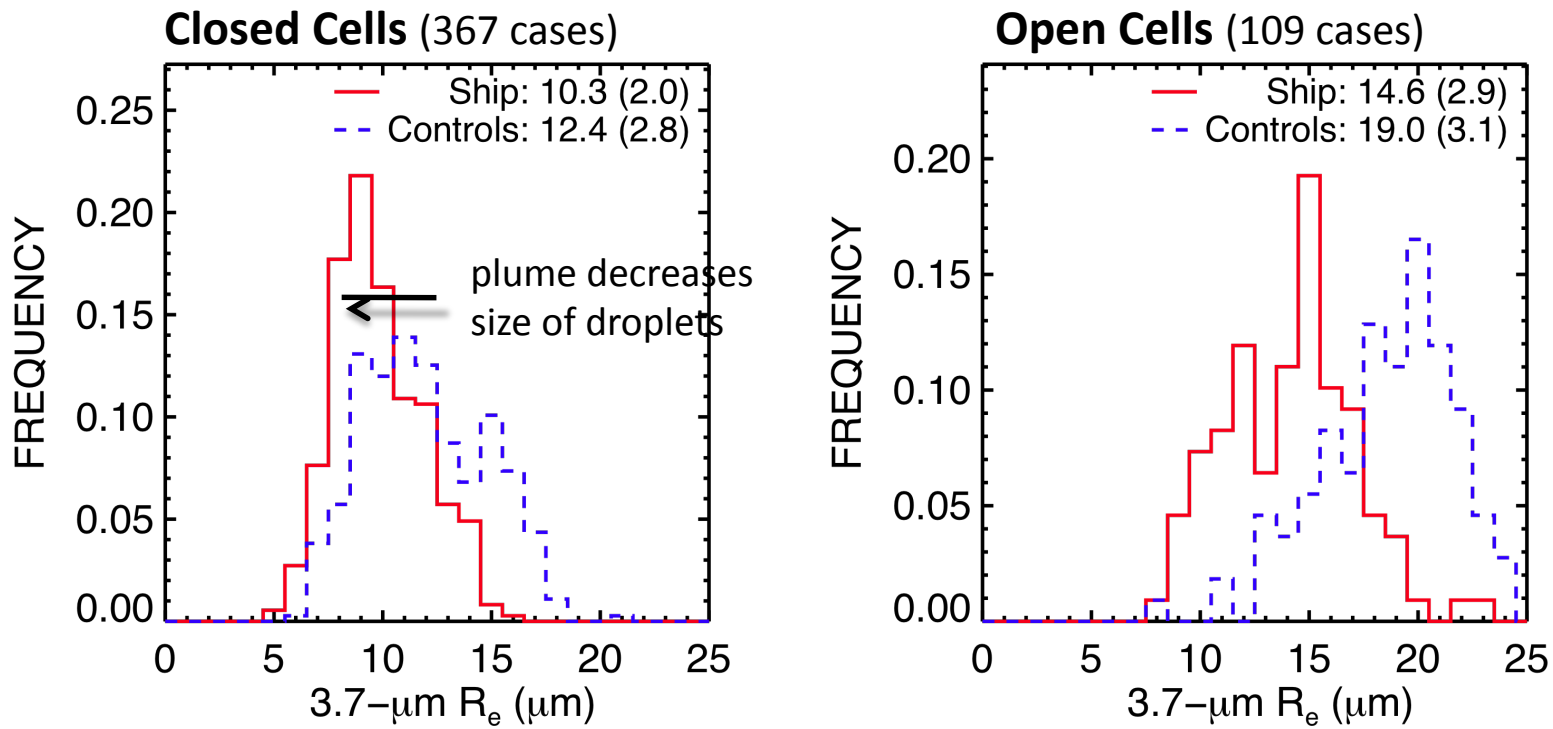
January 11th, 2007 at 2210 UTC







Droplet Effective Radius



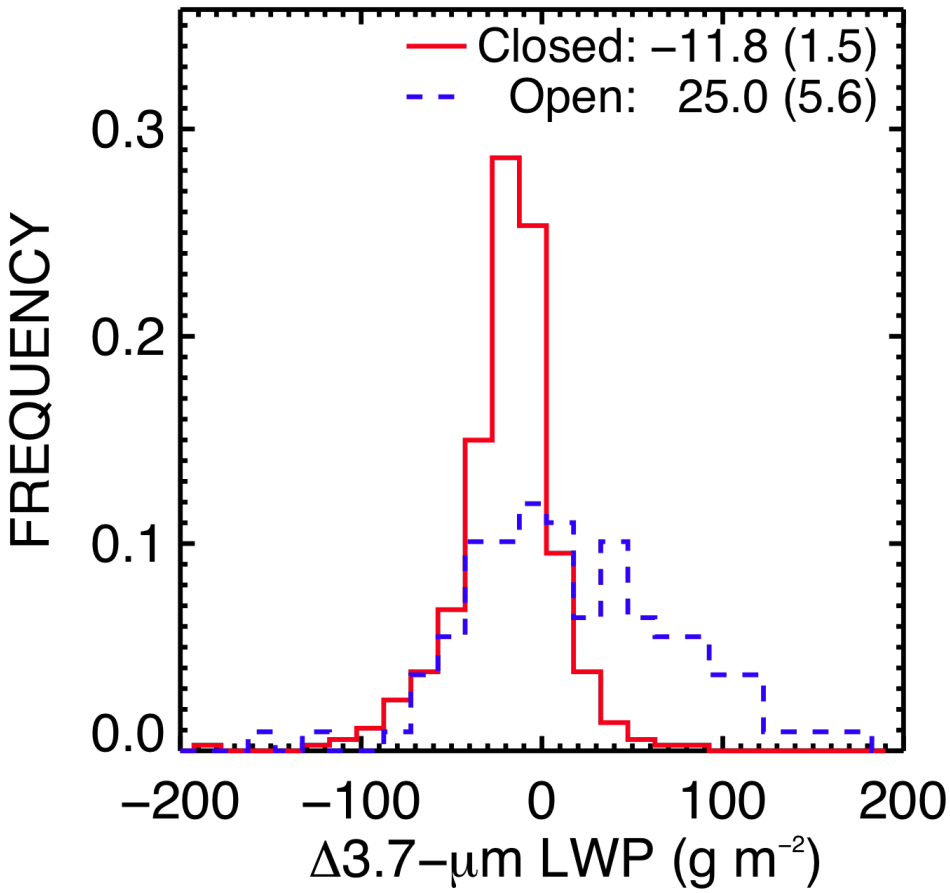
- Larger effective radii are found in open cell clouds (deficient in cloud nuclei).
- Increased aerosol burden from the ship decrease the size of cloud droplets.

- Fractional change in effective radius:

  Closed cells: -18% **Open cells: -22%**

Liquid Water Path Differences

Ship - Controls



$$\underbrace{\frac{\Delta\tau}{\tau}}_{\text{Cloud Optical Depth}} = -\underbrace{\frac{\Delta R_e}{R_e}}_{\text{Effective Droplet Radius (Instantaneous)}} + \underbrace{\frac{\Delta LWP}{LWP}}_{\text{Liquid Water Path (Adjusted)}} \propto \underbrace{\frac{\Delta\alpha}{\alpha}}_{\text{Cloud Albedo}}$$

	Instantaneous	Adjusted	Total
Closed	+0.18	−0.06	0.12
Open	+0.22	+0.39	0.61

Implications: cloud albedo effect is masked by decreases in liquid water.

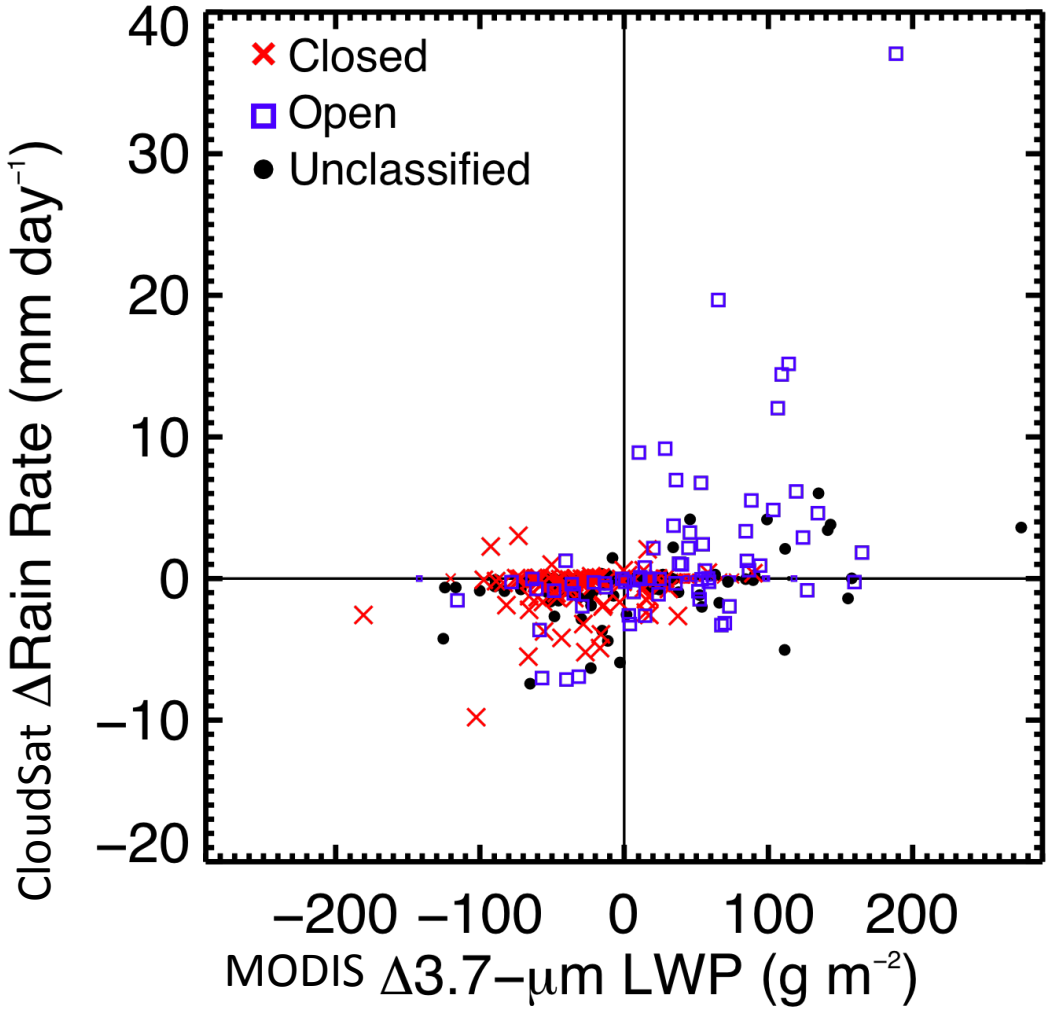
→Closed Cell Regime: −12 W m^{-2}

→Open Cell Regime: −59 W m^{-2}

Does aerosol suppress precipitation and cause liquid water path to increase?

Does decreased drizzle allow Liquid Water Path (LWP) to increase?

(as suggested by Albrecht, [1989], and many others…)



Answer: rarely, in less then 10% of ship track cases.

→ suggests importance of entrainment and other boundary layer mixing processes in regulating the aerosol-liquid water path response.

How often is rainfall suppressed?

Answer: **72% of the time**

Closed Cells: **85%** **& Open *Cells:*** **50%**

<u>Liquid water path differences:</u>

Closed Cells: ΔLWP = −11.8 (1.5) g m^{-2}

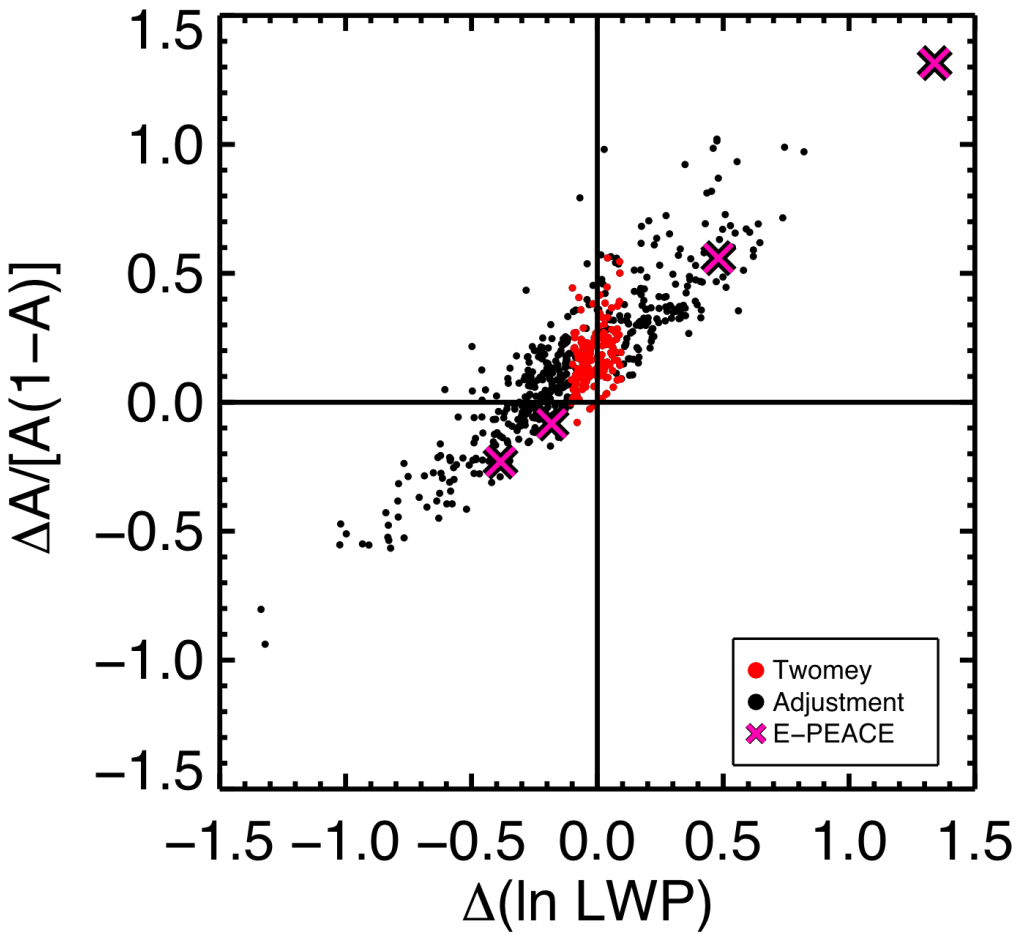
Open *Cells:* ΔLWP = +25.0 (5.6) g m^{-2}

To what extent is cloud albedo affected by these processes?

Christensen and Stephens (2012)

Cloud Albedo

liquid water path response



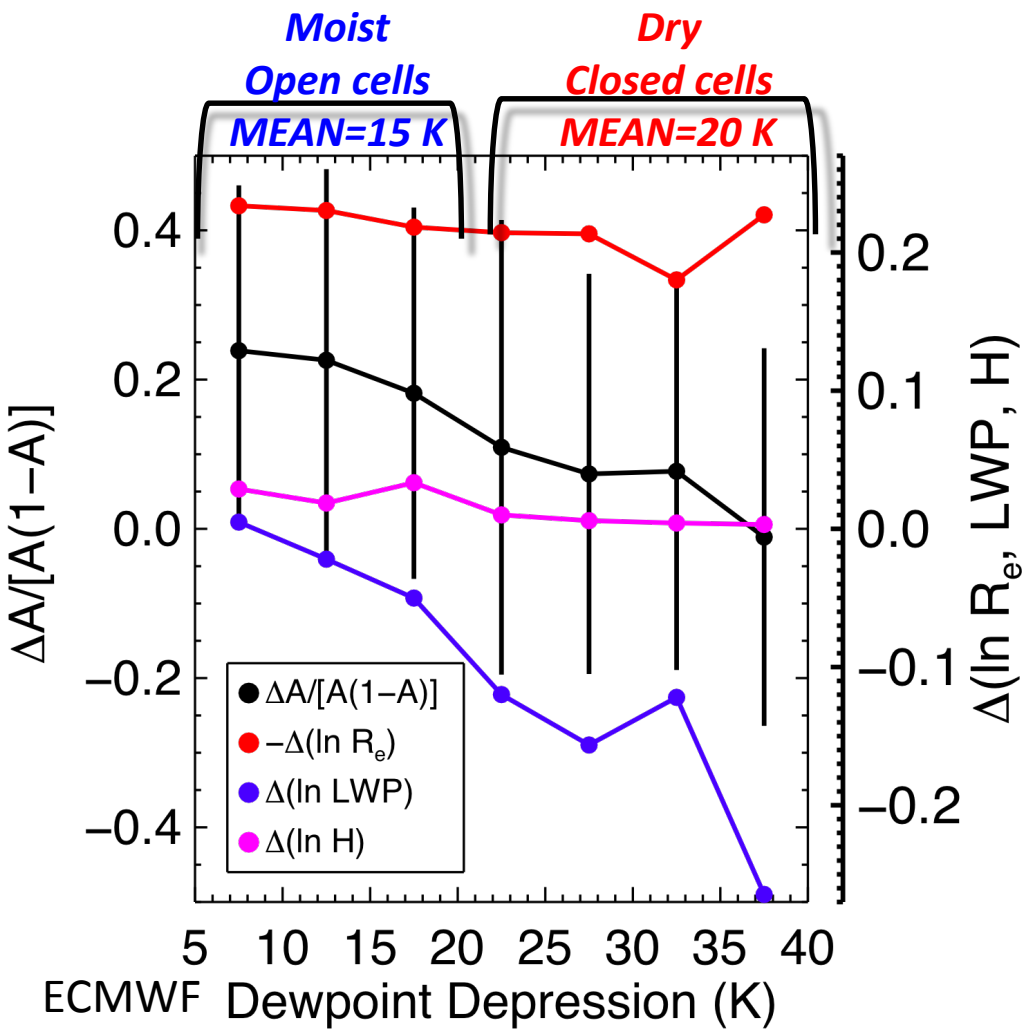
- Changes in liquid water path primarily determine the sign and strength of the cloud albedo response.
- Twomey regime accounts for ~30% of cases:
  - Criteria: i.e., macrophysically similar clouds (ΔLWP & ΔH < 5%)
- E-PEACE field campaign results are in good agreement with A-train observations.

A: Cloud albedo (derived from BUGSRAD radiation code)
LWP: Liquid water path

source: Chen et al. (2012)

Cloud Albedo

free-troposphere humidity response



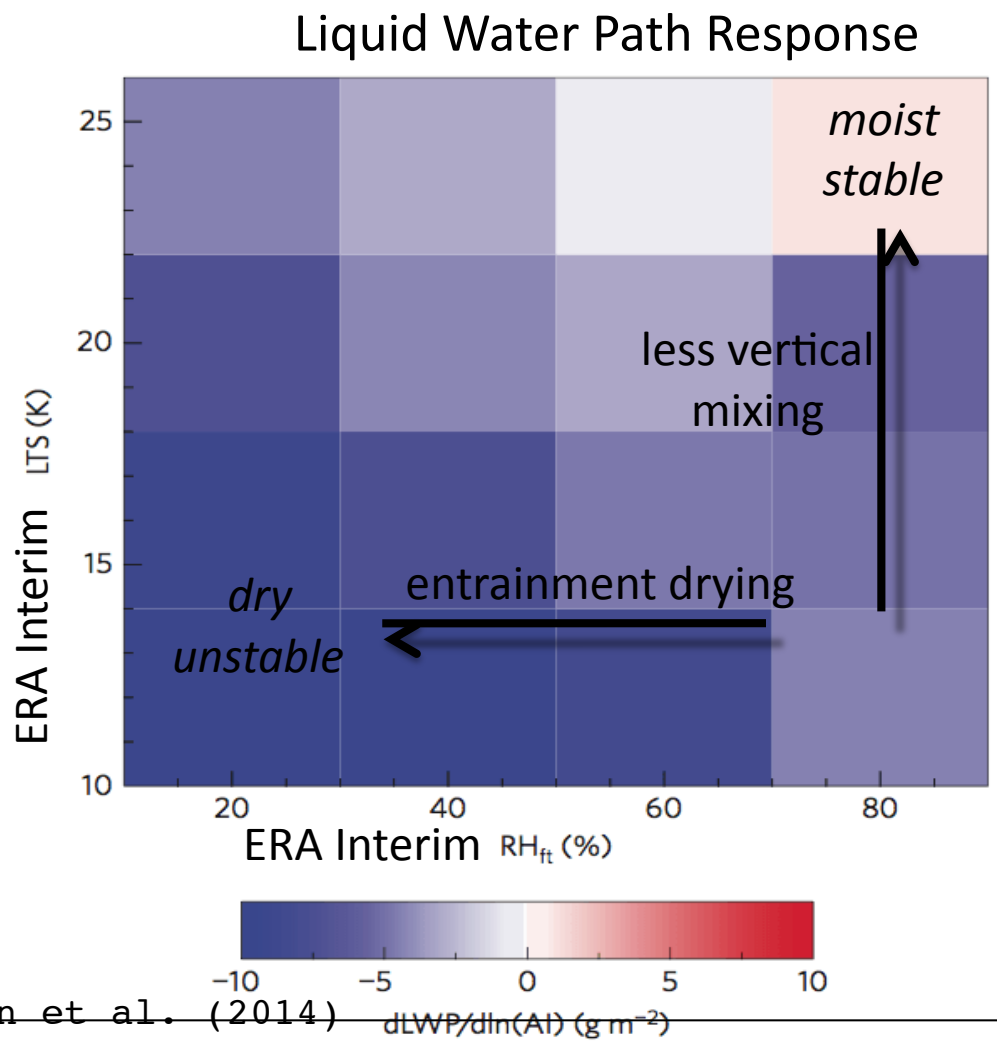
Chen et al. (2012)

Free-troposphere humidity is critical

- Cloud top entrainment/drying effect becomes more pronounced as the relative humidity in the free troposphere decreases.
  - Cloud albedo effect is reduced as the free troposphere humidity decreases.
  - Moisture averaged between 850 and 700 hPa using ECMWF-AUX.

Do we see evidence for this effect on regional/global scales?

Global A-Train Observations



Chen et al. (2014)

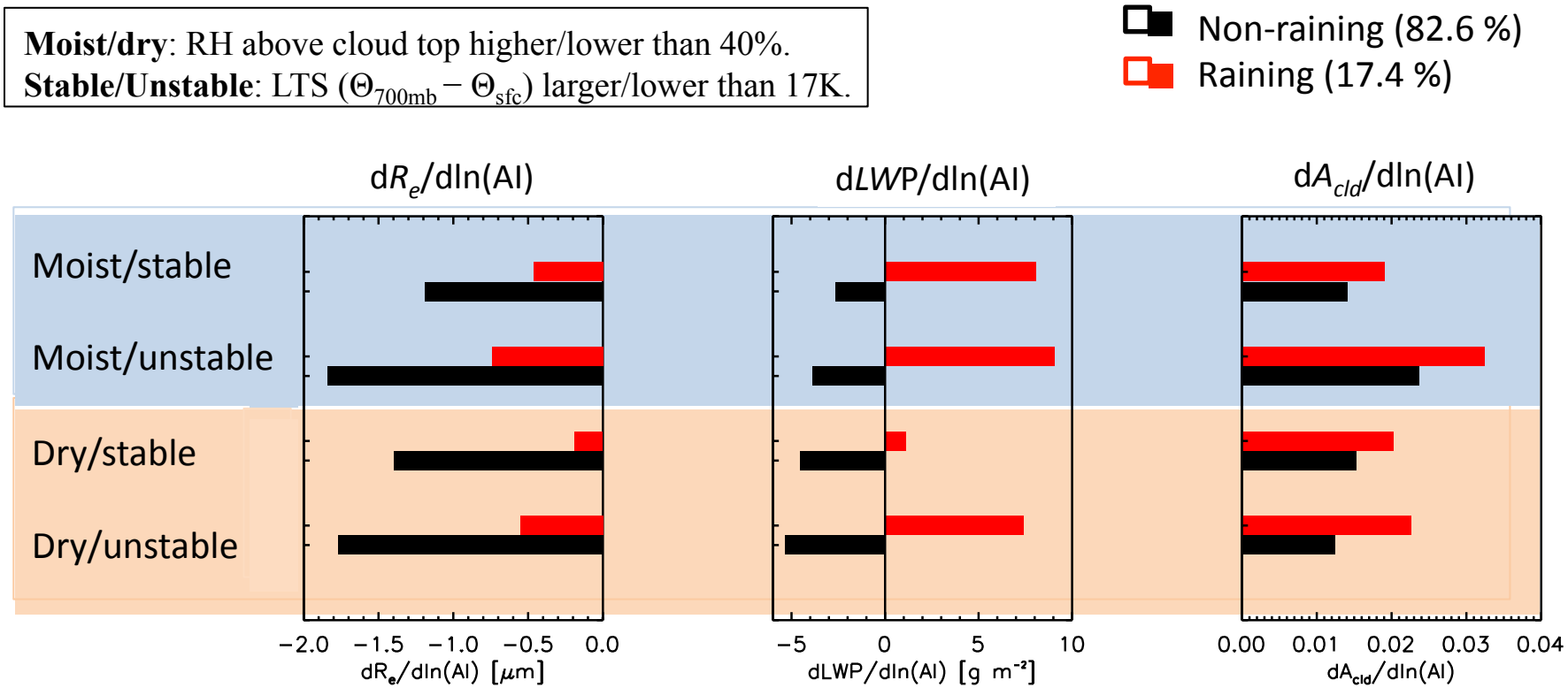
LTS: Lower Troposphere Stability ($LTS = \Theta_{700mb} - \Theta_{surface}$)
RH_{ft}: Free-troposphere Humidity (relative humidity above cloud top)
LWP: Liquid Water Path (MODIS)
AI: Aerosol Index (MODIS)

- Under moist and stable condition, LWP enhances with AI.
- Entrainment/drying effect is largest in dry and unstable conditions.
  - Consistent with ship track assessment and the LES simulations performed by Ackerman et al. (2004) & Chen et al. (2011).
- Co-variability of LTS and RH_{ft} *buffer* the liquid water path response to increasing aerosol concentration.

How does precipitation influence the strength of the aerosol indirect effect?

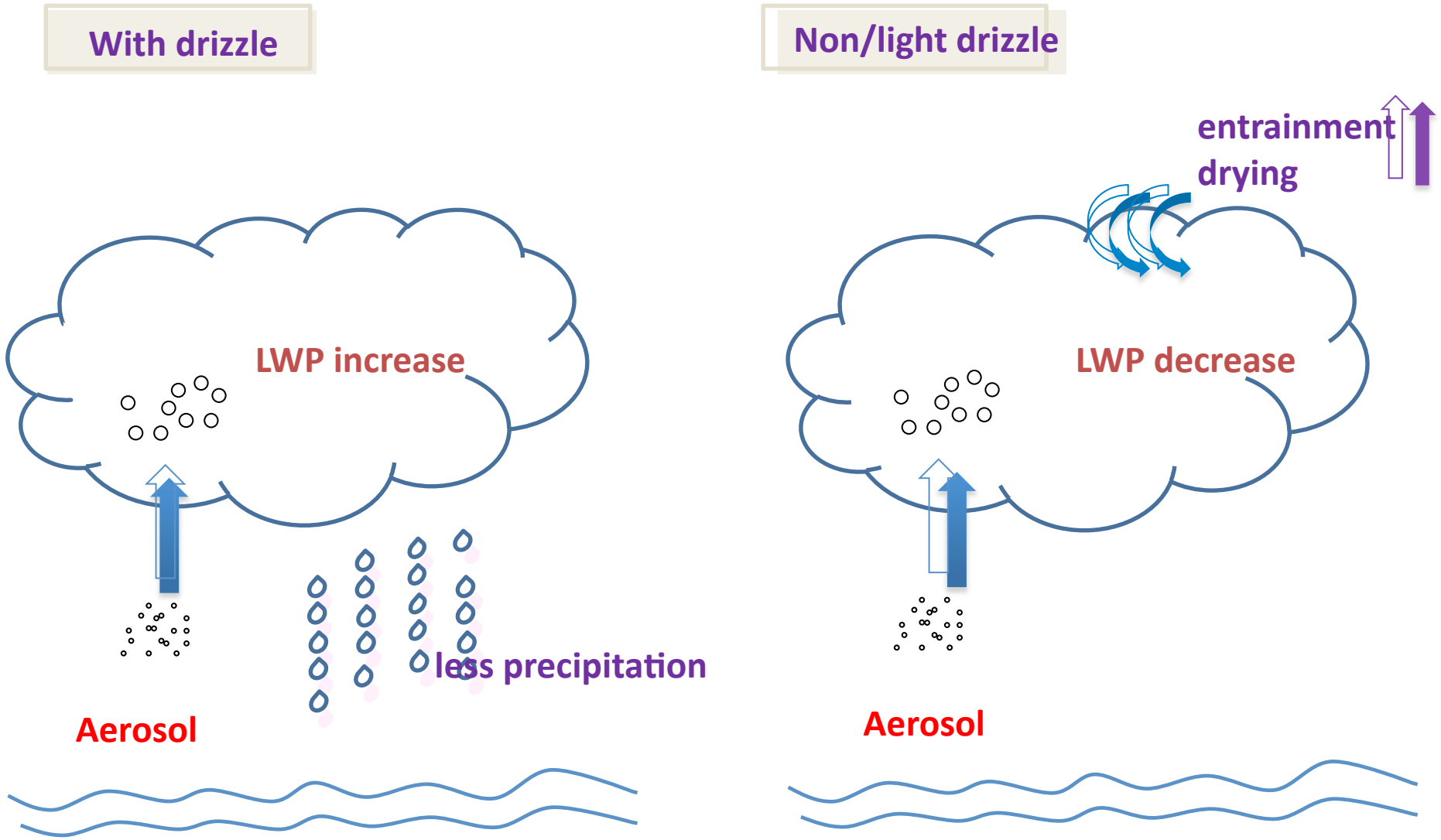
Cloud response under different environments

Moist/dry: RH above cloud top higher/lower than 40%.
Stable/Unstable: LTS ($\Theta_{700mb} - \Theta_{sfc}$) larger/lower than 17K.



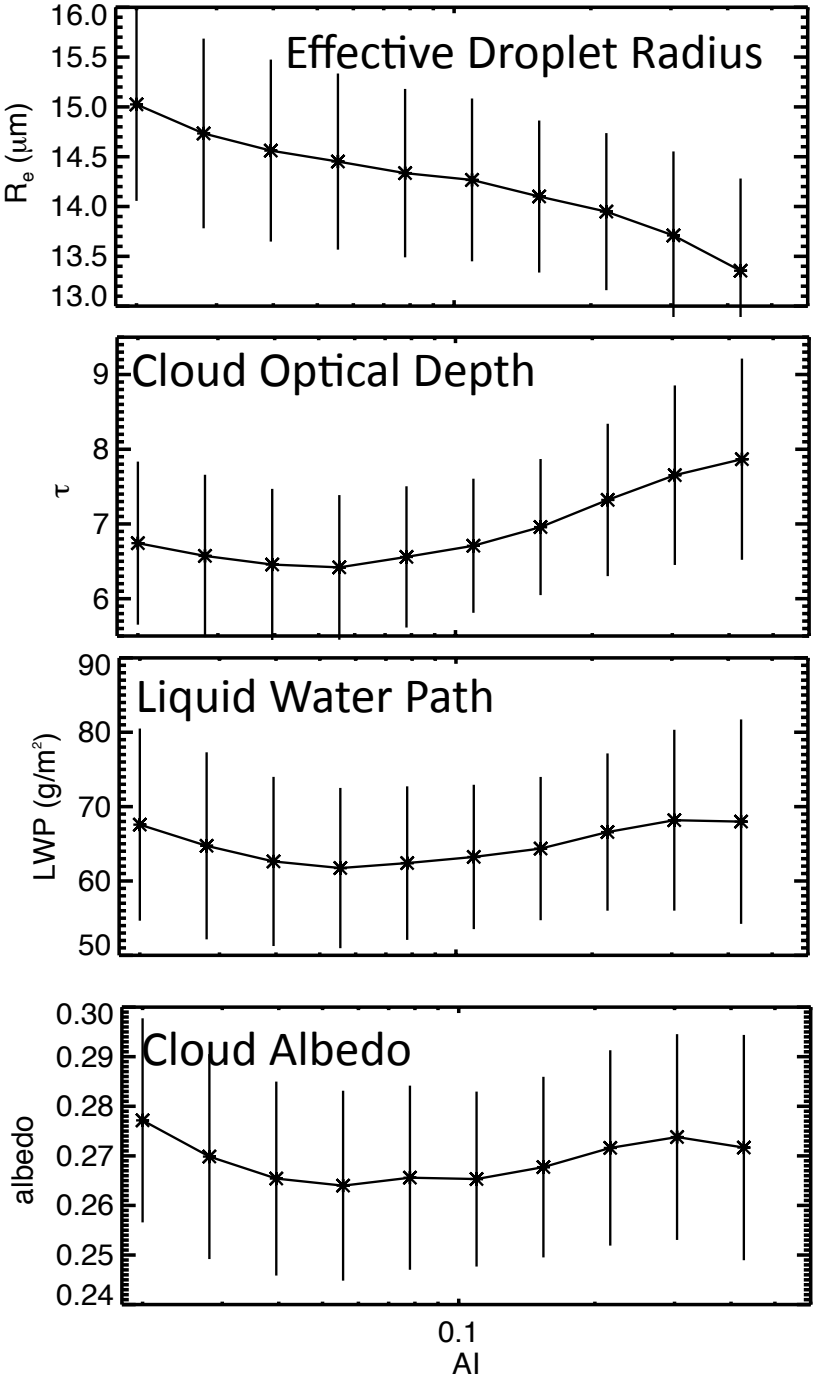
- **Non-raining** clouds: LWP *decreases* with AI.
  Raining clouds: LWP *increases* with AI; cloud albedo increases more.
- Under **moist free troposphere**: LWP increases more for raining clouds, and decreases less for non-raining clouds.
- Under **moist/unstable** environment, cloud albedo increases most.

Drizzling vs. Non-drizzling marine warm clouds



Source: Jean Chen

Statistical relationships between aerosol and cloud properties



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

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

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

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

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 ~40,000 data L2 cloud-aerosol data points.
- Aerosol (ATSR) properties are paired to 1-km cloud pixels through nearest neighbor method.

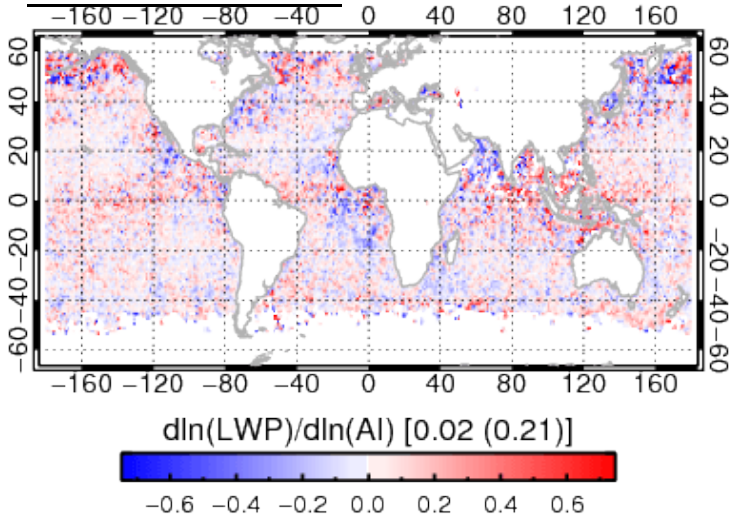
How do these observations vary with meteorology?

Aerosol-Cloud Interactions

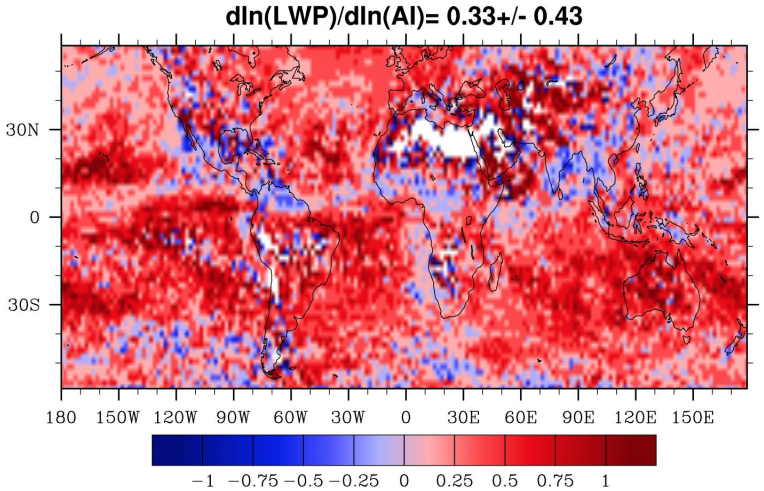
Cloud Water Path Sensitivity Satellite-Model Comparisons

JJA 2008; 60S° – 60° N (Ocean only)

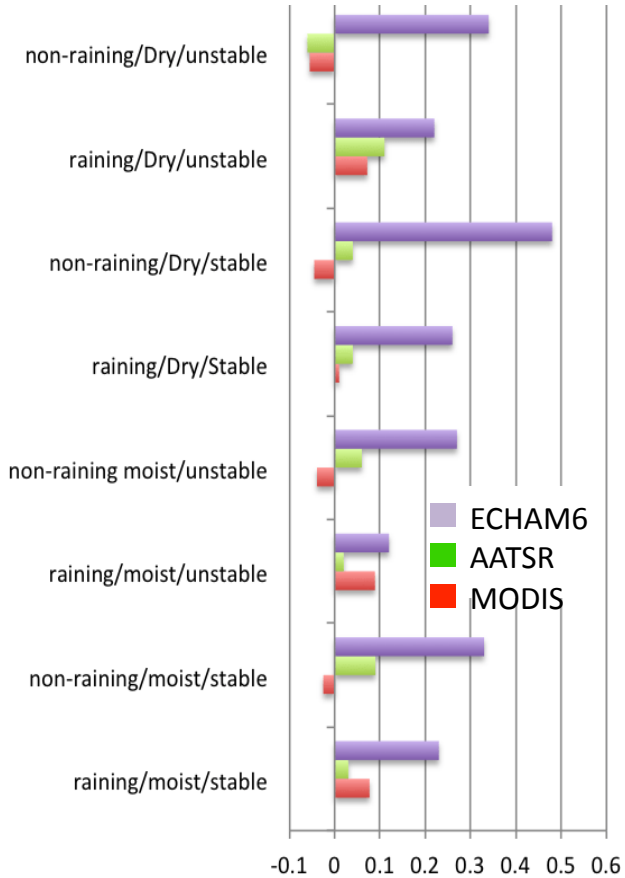
Satellite: AATSR



Model: ECHAM6 HAM 2



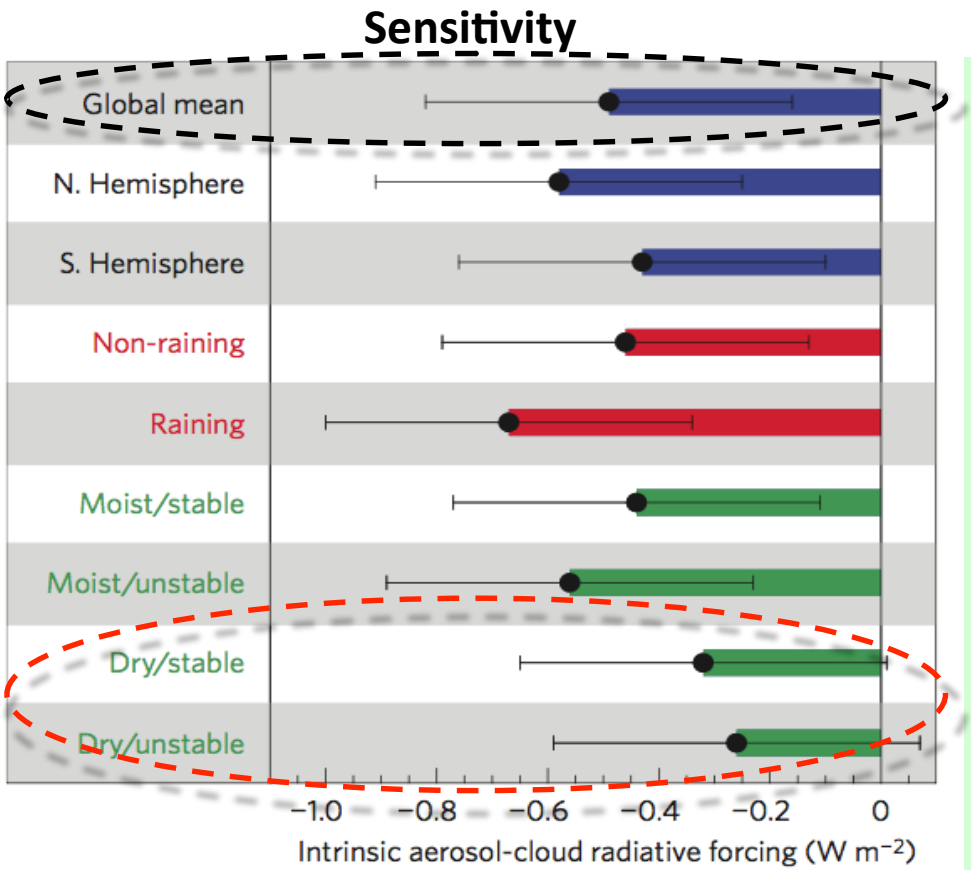
Global mean sensitivity ($\frac{d \ln LWP}{d \ln \mathrm{AI}}$) by cloud regime



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.

Global Aerosol Indirect Forcing



Indirect Forcing Estimates:

- Intrinsic = **−0.49±0.33 W/m²**
- Extrinsic = **−0.46±0.31 W/m²**

−0.95 W/m²

Summary

- Environmental condition and cloud type exert strong controls on the aerosol indirect effect sensitivity at both local (e.g., ship tracks) and global scales.
- *For observational studies:* it's imperative to isolate aerosol indirect effects by environmental conditions and, improve cloud albedo, aerosol, precipitation rate, and infrared sounding retrievals.
- *For modeling studies:* feedbacks involving entrainment, drizzle, and surface coupling should be incorporated into GCM's to improve estimates of the aerosol indirect forcing.

$$\frac{dC_{sw}}{d\ln(AI)} = \left[\overline{c_m}\left(\frac{dA_{clr}}{d\ln(AI)} - \frac{dA_{cld}}{d\ln(AI)}\right) + \overline{(A_{clr} - A_{cld})}\frac{dc_f}{d\ln(AI)}\right]\overline{F}^{\downarrow}$$

intrinsic effect
aerosol changes on cloud properties

extrinsic effect
impact of aerosol on cloud fraction

Chen et al. (2014), Nat. Geosci.

C_{sw}: Shortwave Cloud Forcing (CERES)
A_{clr}: clear-sky albedo (CERES)
A_{cld}: cloudy sky albedo (CERES)
c_f: cloud cover fraction over CERES footprint
c_m: annual mean marine warm cloud coverage
AI: Aerosol index (MODIS)