Inferences of Aerosol Indirect Effects from Satellite *(and Some Aircraft)* Observations

J.A. Coakley, Jr., M.W. Christensen, M.S. Segrin, C.R. Hayes, A.M. Schuetz, M.A. Matheson, C.H. Twohy, and W.R. Tahnk
College of Oceanic and Atmospheric Sciences
Oregon State University

A. Marshak and G. Wen
NASA Goddard Space Flight Center

N.G. Loeb
NASA Langley Research Center

A.S. Ackerman
NASA Goddard Institute for space Studies

GOAL: **Survey space-borne observations used to infer the aerosol indirect effect and aerosol indirect forcing.**

Four Types of Studies…

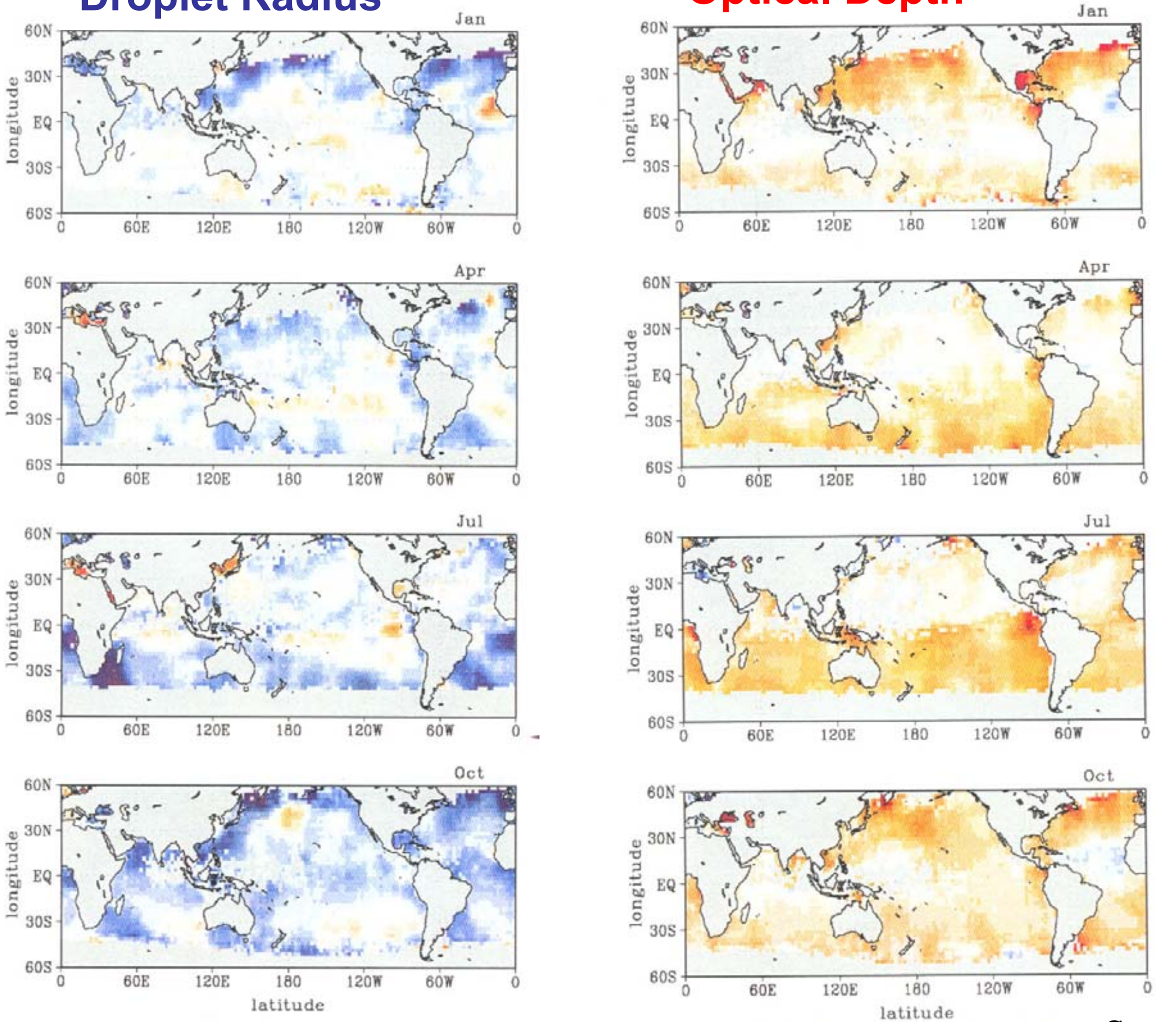
- **Aerosol-Cloud Studies**
  - **Aerosol and cloud properties analyzed together (*as closely in time and space as is feasible*):** Kaufman and Nakajima (1993), Kaufman and Fraser (1997), Nakajima et al. (2001), Sekiguchi et al. (2003), Quass et al. (2004), Kaufman et al. (2005), etc.
  - **Clouds analyzed but aerosol properties derived from climatology:** Boers et al. (2006)
  - **Clouds analyzed but aerosol properties derived from back trajectories or chemical transport models:** Bréon et al. (2002), Harshvardhan et al. (2002)
- **Cloud Response Studies—ship tracks:** Platnick et al. (2000), Coakley and Walsh (2002), Segrin et al. (2007)

Prejudices

- **In addition to aerosol effects on cloud optical depths and droplet radii, need to account for changes in cloud cover, cloud altitudes, and cloud liquid/ice water amounts.**
- **Changes in clouds must account for changes in thermodynamic forcing accompanying changes in aerosol forcing (i.e., *must solve the cloud-feedback problem*).**
- **Observations of clouds always include the response of the clouds to changes in cloud-environmental interactions that arise from the changes in the microphysical properties of the clouds (i.e., the *“first indirect effect”* is *never observed*; the *“second effect”* is *always* observed).**

Cloud Droplet Radius and Optical Depth and Aerosol Column Number

Droplet Radius | **Optical Depth**

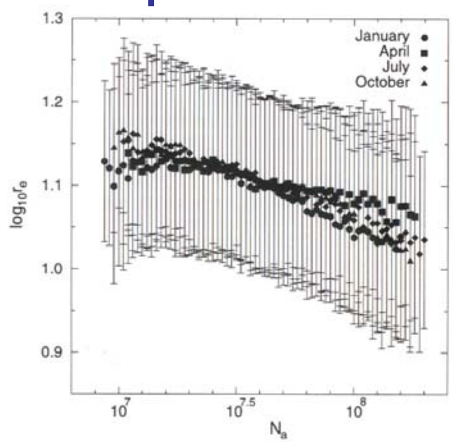


- **4-km AVHRR data for 1990.**
- **Correlations shown for month of daily average values composited for 17.5° × 17.5° latitude-longitude regions.**
- ***Blues* indicate negative and *Reds* positive correlations.**

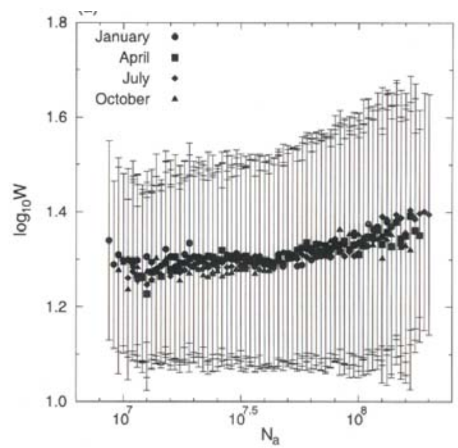
Source: Sekiguchi et al. (2003)

Aerosol Number, Cloud Droplet Radius, Optical Depth, Liquid Water, and Fractional Coverage

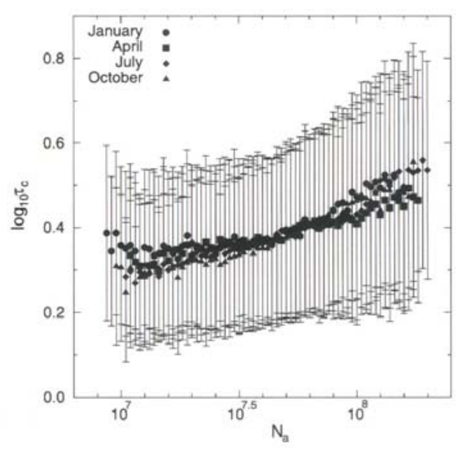
Droplet Radius



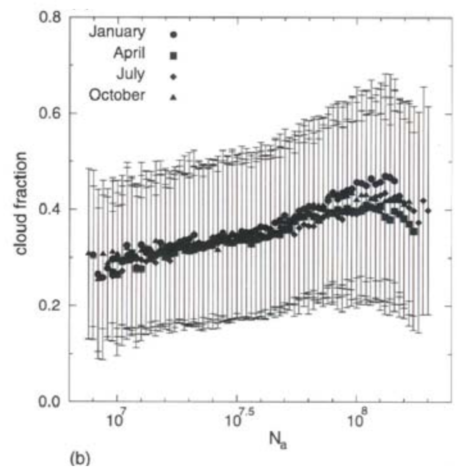
Liquid Water



Optical Depth



Cloud Cover

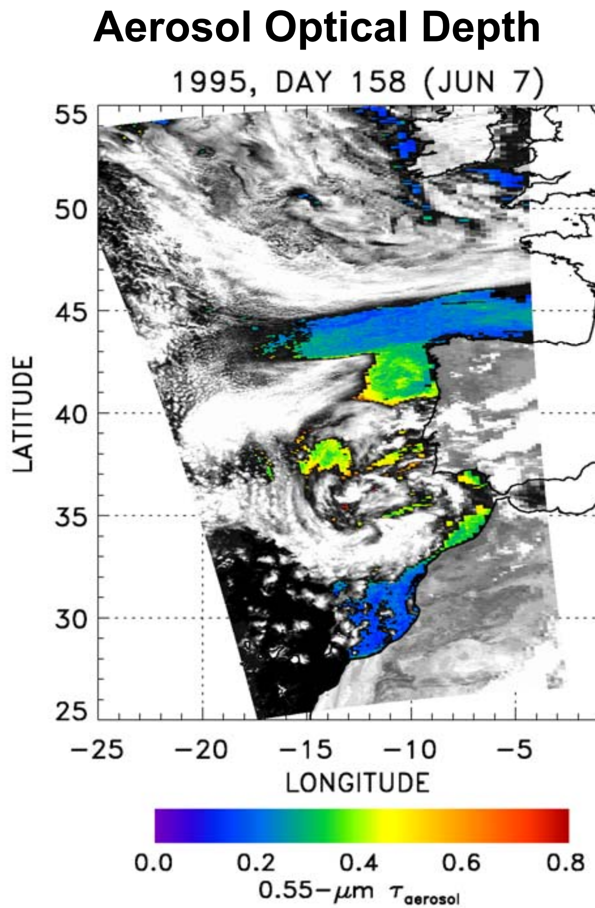


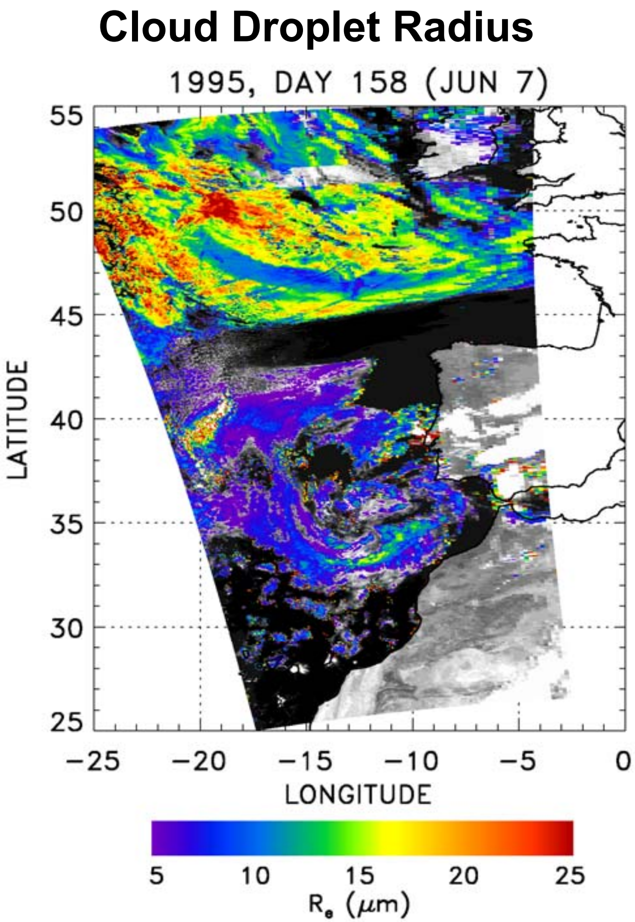
- **Daily averages for $2.5° \times 2.5°$ latitude-longitude regions composited for the indicated month and for the entire Earth.**
- **Droplet radius *decreases* while optical depth, column liquid water, and fractional coverage *increase* with *increasing* aerosol column number.**
- **Assuming a 30% increase in aerosol optical depth since the industrial revolution, the direct forcing is –0.4, the indirect forcing, assuming fixed cloud liquid water is –0.6 and the total is between –1.0 and –1.8 Wm^{-2}.**

Source: Sekiguchi et al. (2003)

Aerosol Optical Depth and Cloud Droplet Effective Radius

7 June 1995





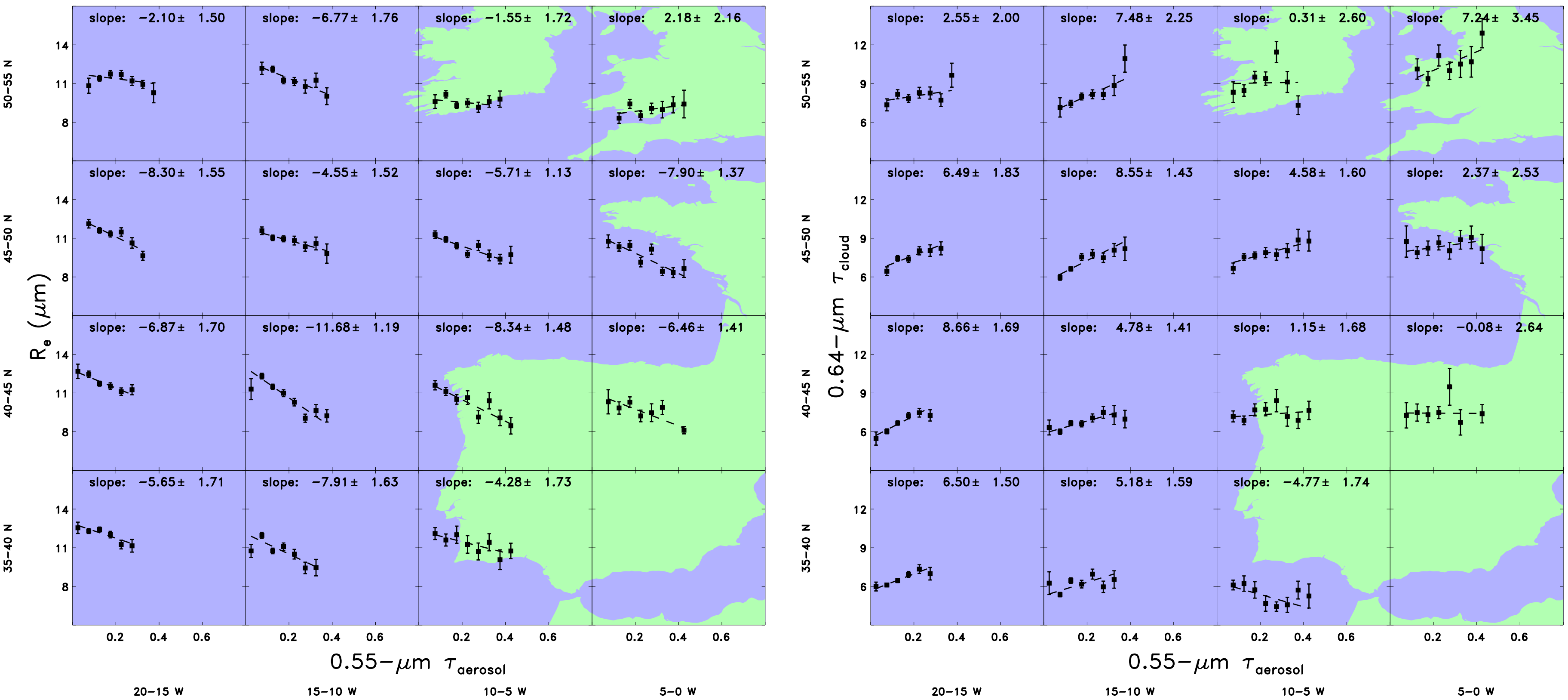
Source: Matheson et al. (2005)

Cloud Droplet Radius, Optical Depth and Aerosol Optical Depth

NOAA-14 AVHRR Summers 1995 – 1999

Droplet Radius

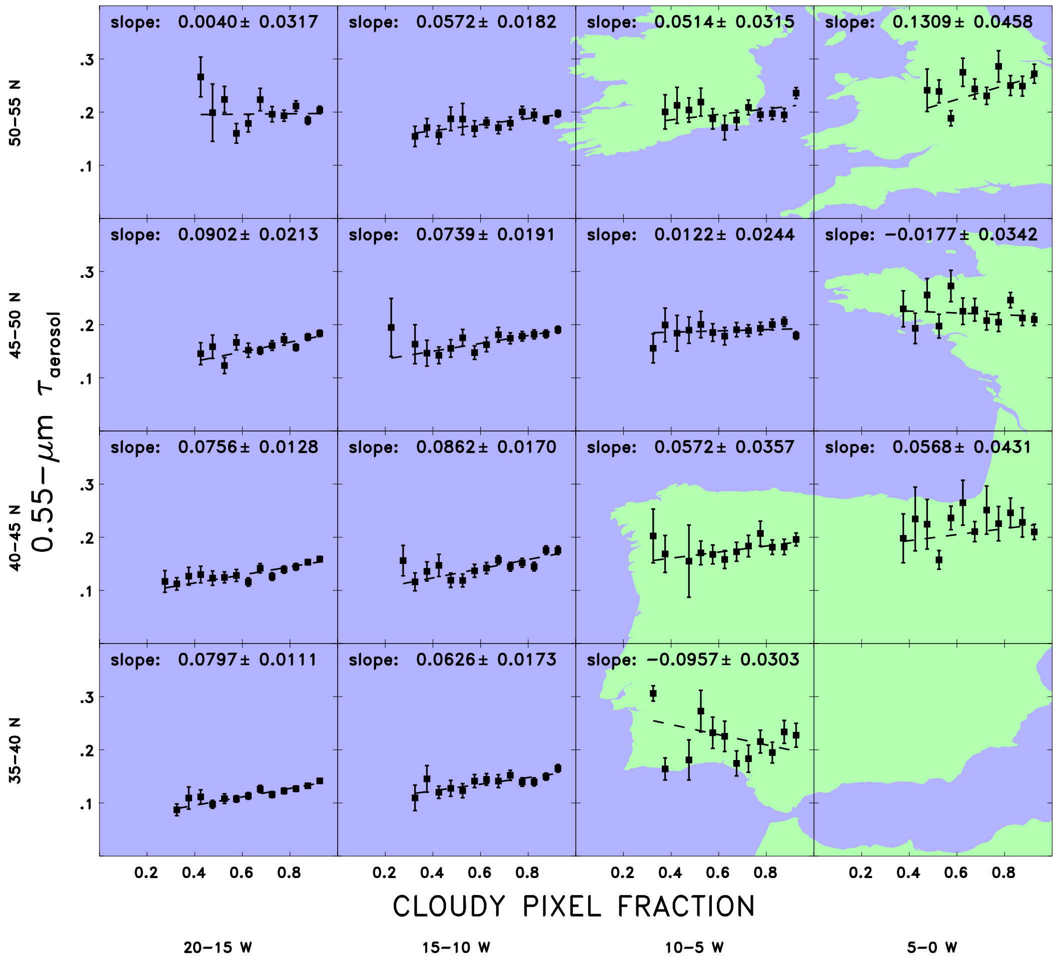
Cloud Optical Depth



Source: Matheson et al. (2006)

Aerosol Optical Depth and Cloud Cover

NOAA-14 AVHRR, Summers, 1995-1999



4-km AVHRR observations analyzed for aerosol optical depth and properties of marine stratocumulus found together in 1° × 1° latitude longitude regions.

Observations composited within 5° × 5° latitude longitude regions.

Aerosol and cloud properties within each 5° region were similar for the different years.

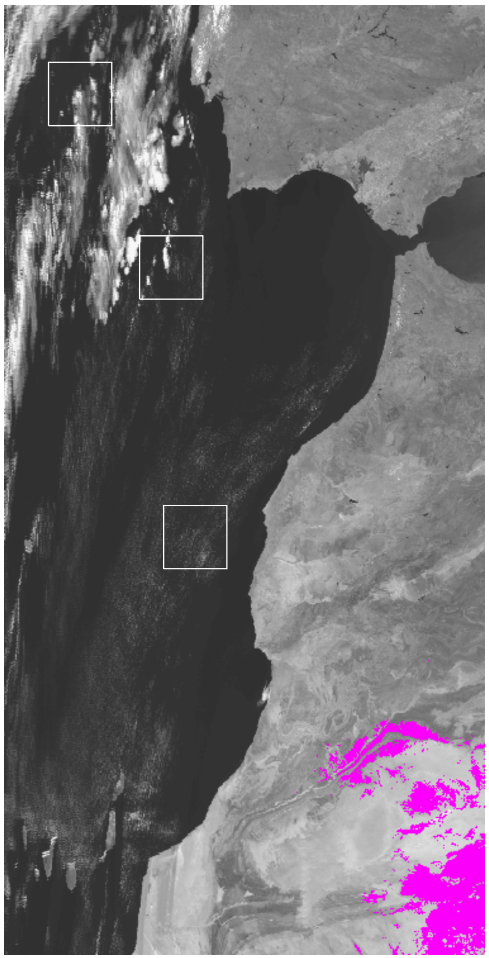
Aerosol optical depth increases as the fraction of cloudy pixels increases.

Source: Matheson et al. (2006)

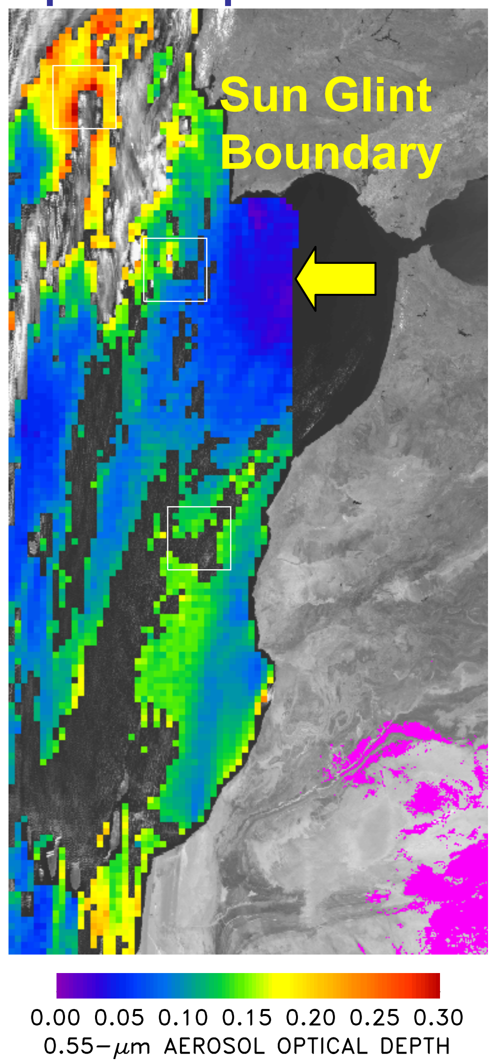
Aerosols and Clouds

1-km *Terra* MODIS Data

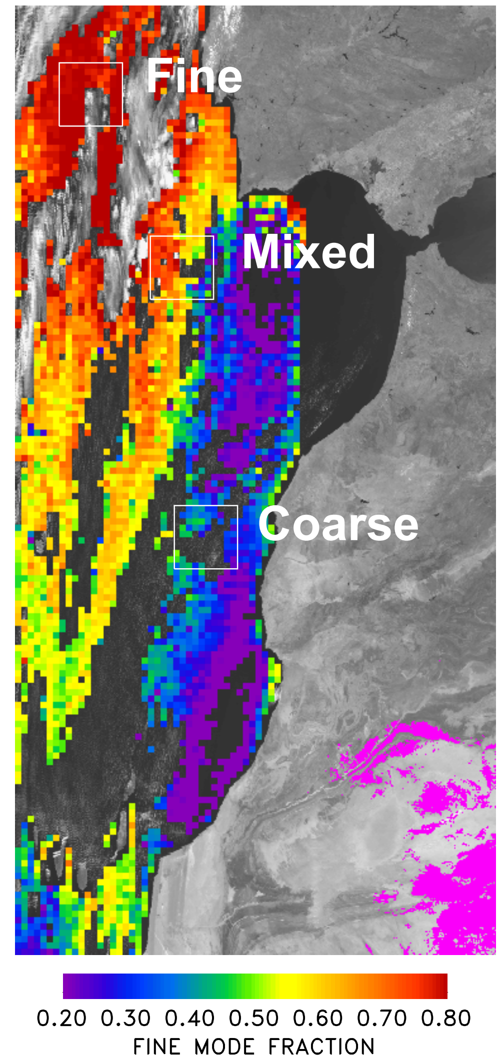
0.86-µm

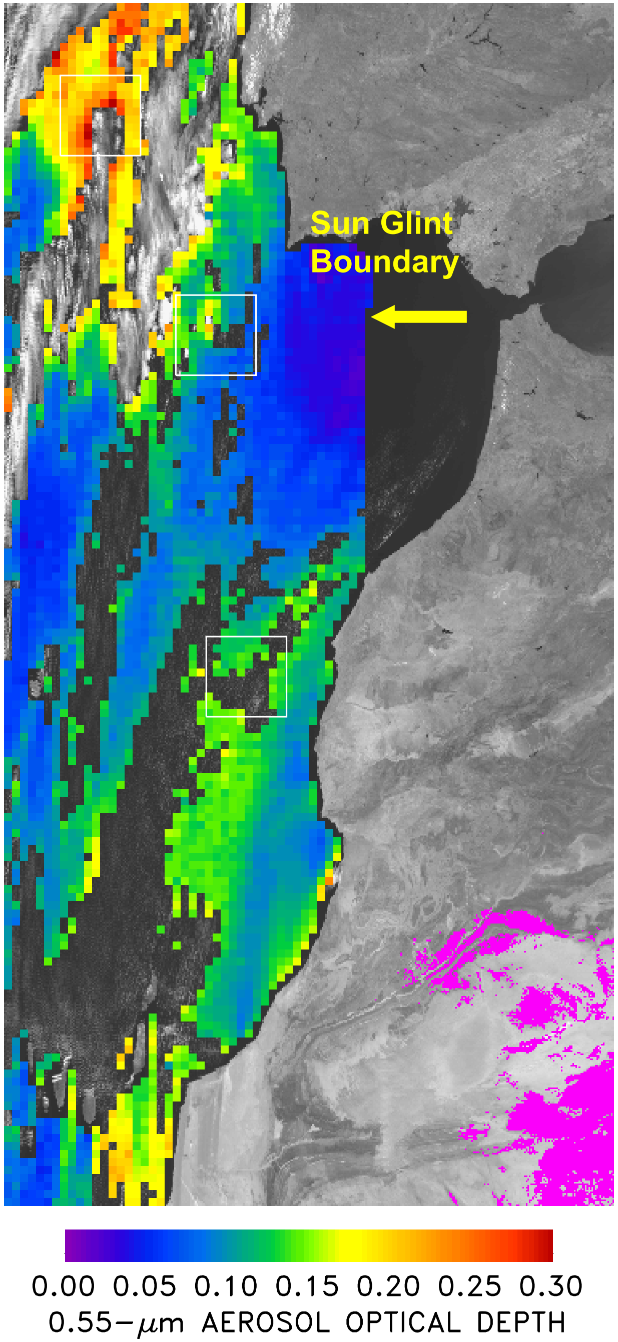


0.55-µm Aerosol Optical Depth



Fine Particle Fraction





MODIS Aerosol Optical Depth and Cloud Cover

- **Aerosols grow in humid environments near clouds.**
- **Aerosols grow through in-cloud processing.**
- **Aerosols remain when droplets evaporate**
- **New particle production in the vicinity of clouds.**
- **Illumination of cloud-free columns enhanced through scattering of sunlight by nearby clouds.**
- **Cloud contamination of the cloud-free pixels used to obtain aerosol properties.**
- **Aerosols are precursors to cloud formation.**

Strategy for Characterizing Aerosol-Cloud Interactions for Both the Aerosol Direct and Indirect Forcing of Climate

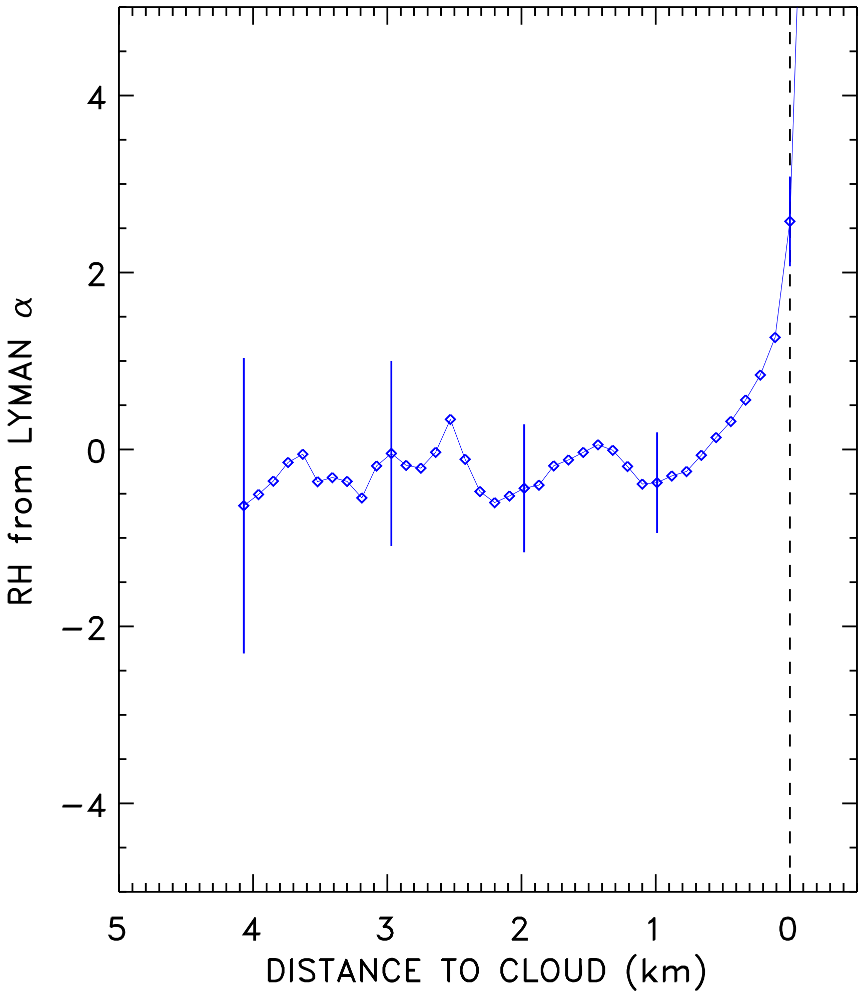
- *Given that:* **properties of clouds are well-characterized in heavily cloudy regions.**
- *Given that:* **properties of aerosols are well-characterized in large cloud-free regions.**

Seek to characterize cloud and aerosol properties where possible and seek to model the behavior of aerosols in the "vicinity" of clouds.

Aircraft Observations from **INDOEX**

Goal: **Characterize the change in aerosols in the vicinity of clouds.**

Relative Humidity Changes near Clouds



Departures from means of cloud entering and leaving flight legs composited from nine INDOEX flights.

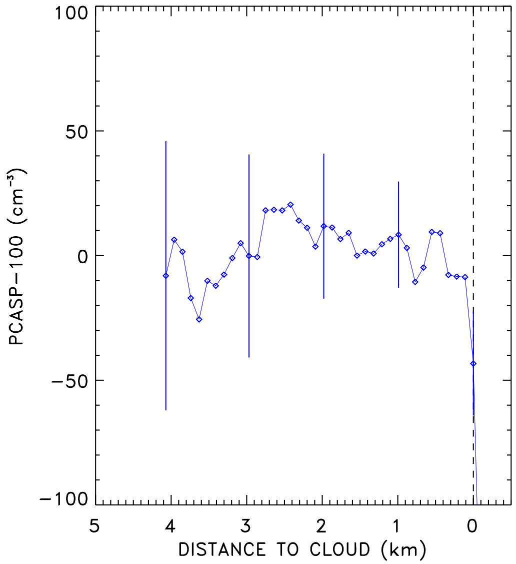
Clouds identified by LWC > 0.03 g m^{-3} and FSSP-100 > 10 cm^{-3} for more than 3 sec.

3% rise in RH (from 89-90%) within 1 km of clouds.

Rise corresponds to about a 4% increase in average particle radius but a 25% increase in extinction cross section for the "INDOEX aerosol."

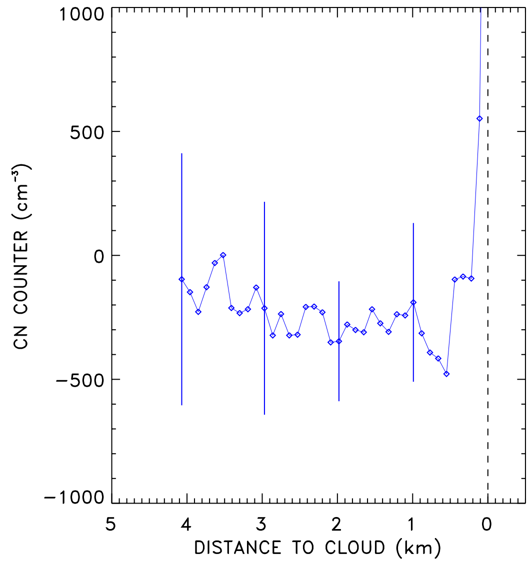
Particle Concentration Changes near Clouds

PCASP



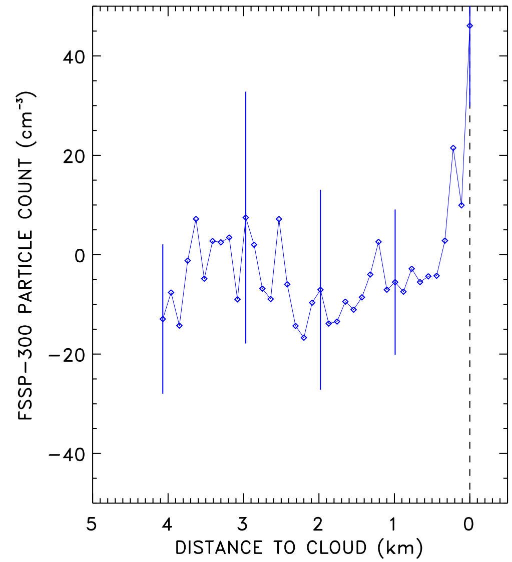
Change from 900 cm^{-3}

CN



Change from 2500 cm^{-3}

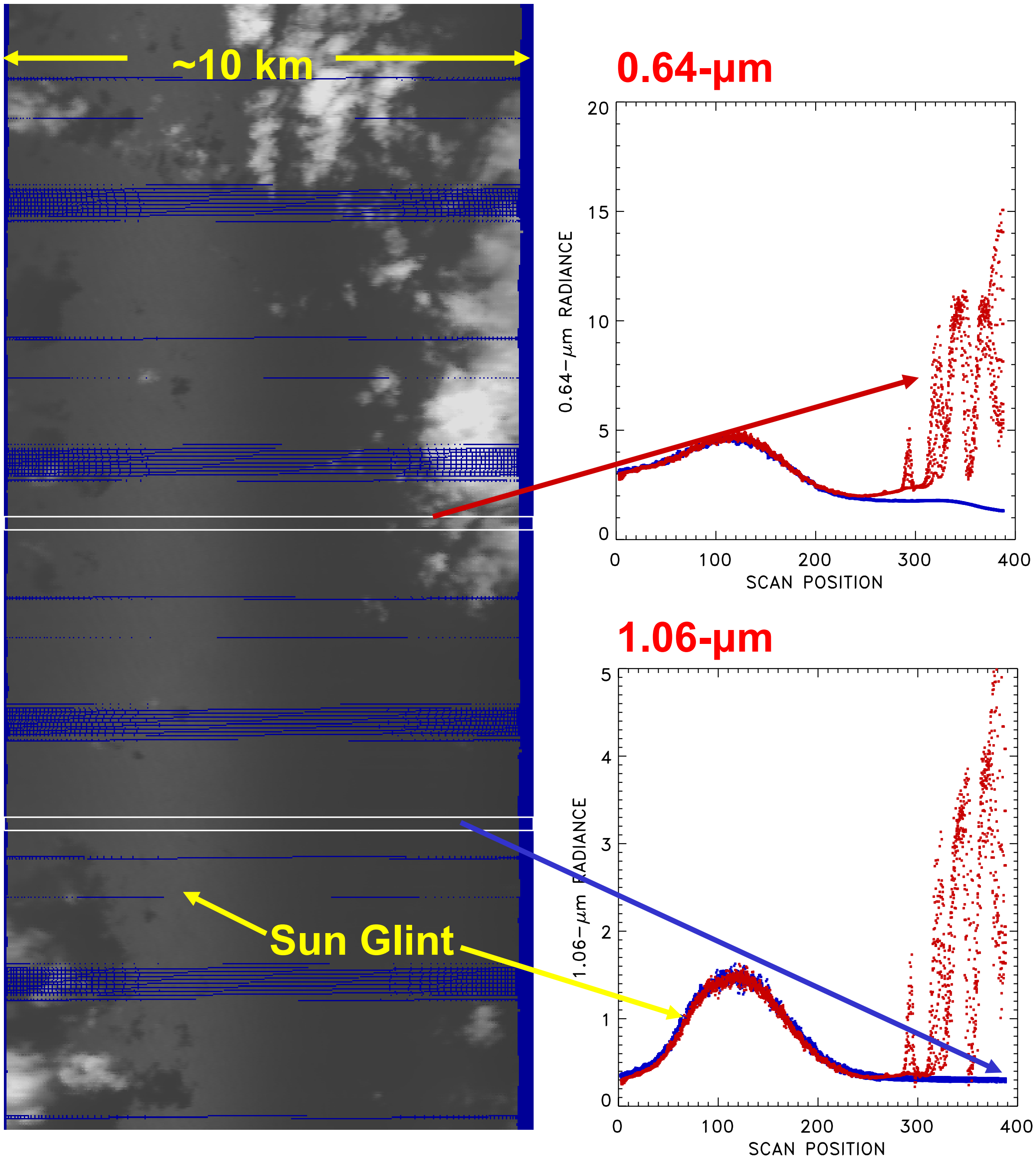
FSSP-300



Change from 30-40 cm^{-3}

Aside from a possible increase in FSSP-300 particle counts 200 m from clouds, there is no indication that particle concentrations increase as the clouds are approached.

MCR Imagery from INDOEX

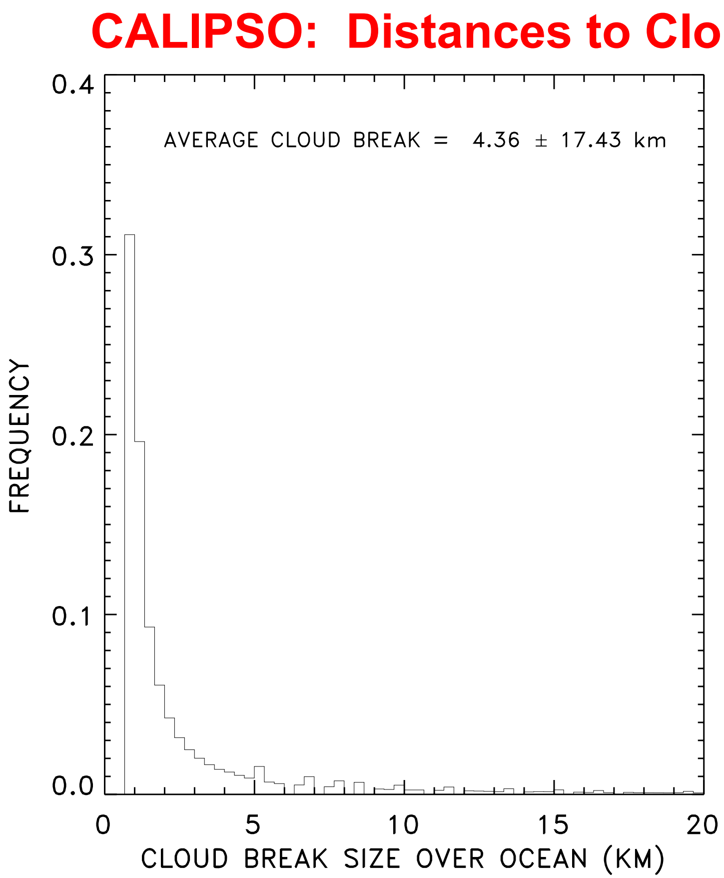


0.64-μm radiance enhanced ~10% within 1-km of cloud, roughly consistent with particle growth.

1.06-μm radiance shows little enhancement near cloud, indicating that the growth is in a small particle mode.

Enhanced illumination of the cloud-free column has not been accounted for in these observations.

Effect of Relative Humidity Increase near Clouds



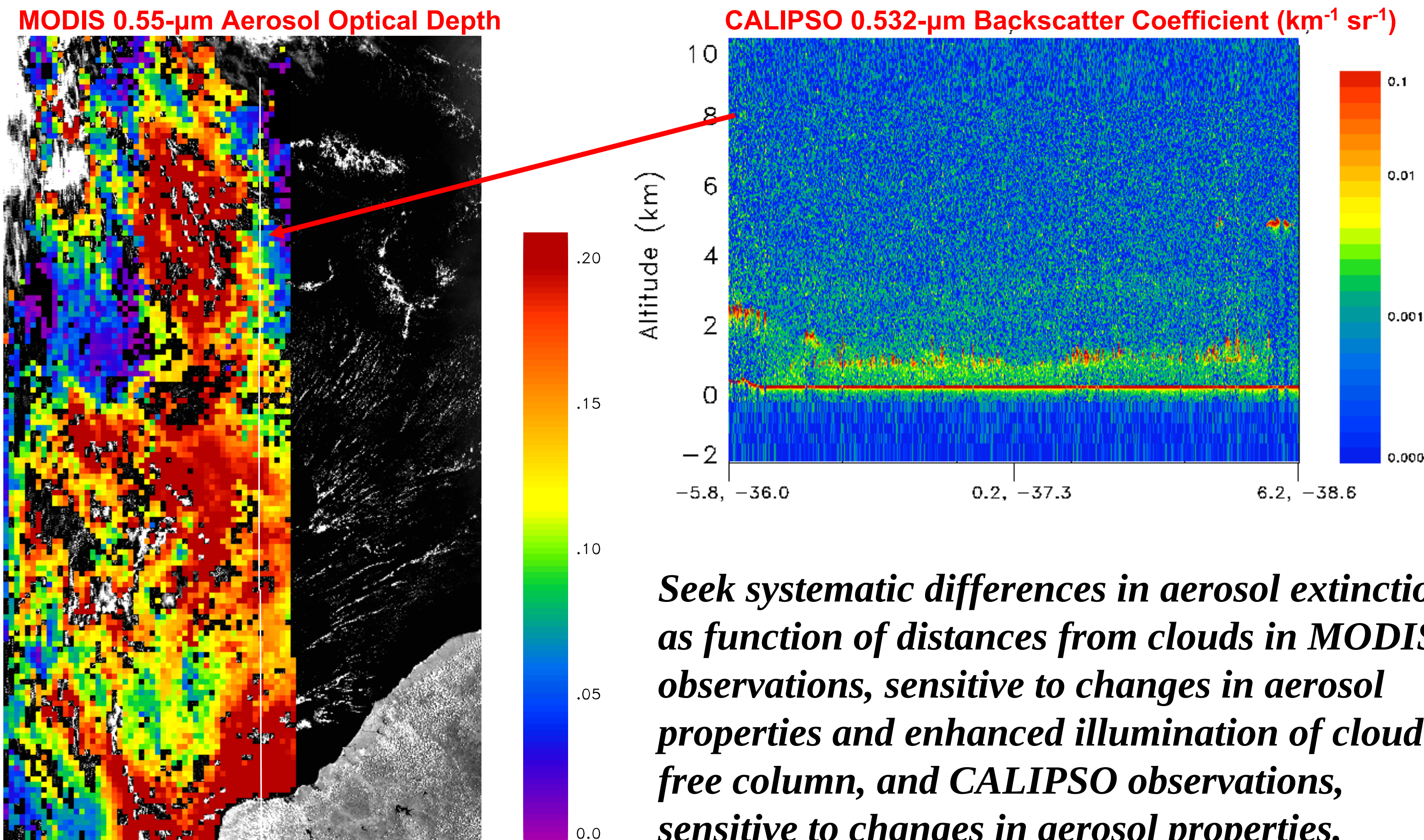
~40% of CALIPSO lidar observations fall in cloud-free regions within 1 km of clouds.

Assuming that the depth of enhanced RH ~25% of the boundary layer, enhancement of aerosol optical depths in vicinity of clouds due to particle swelling, ~0.4 $\times$ 0.25/2 $\times$ 0.25 $\leq$ 0.02

Particle swelling in the vicinity of clouds is not likely to be a significant factor.

MODIS and CALIPSO Observations

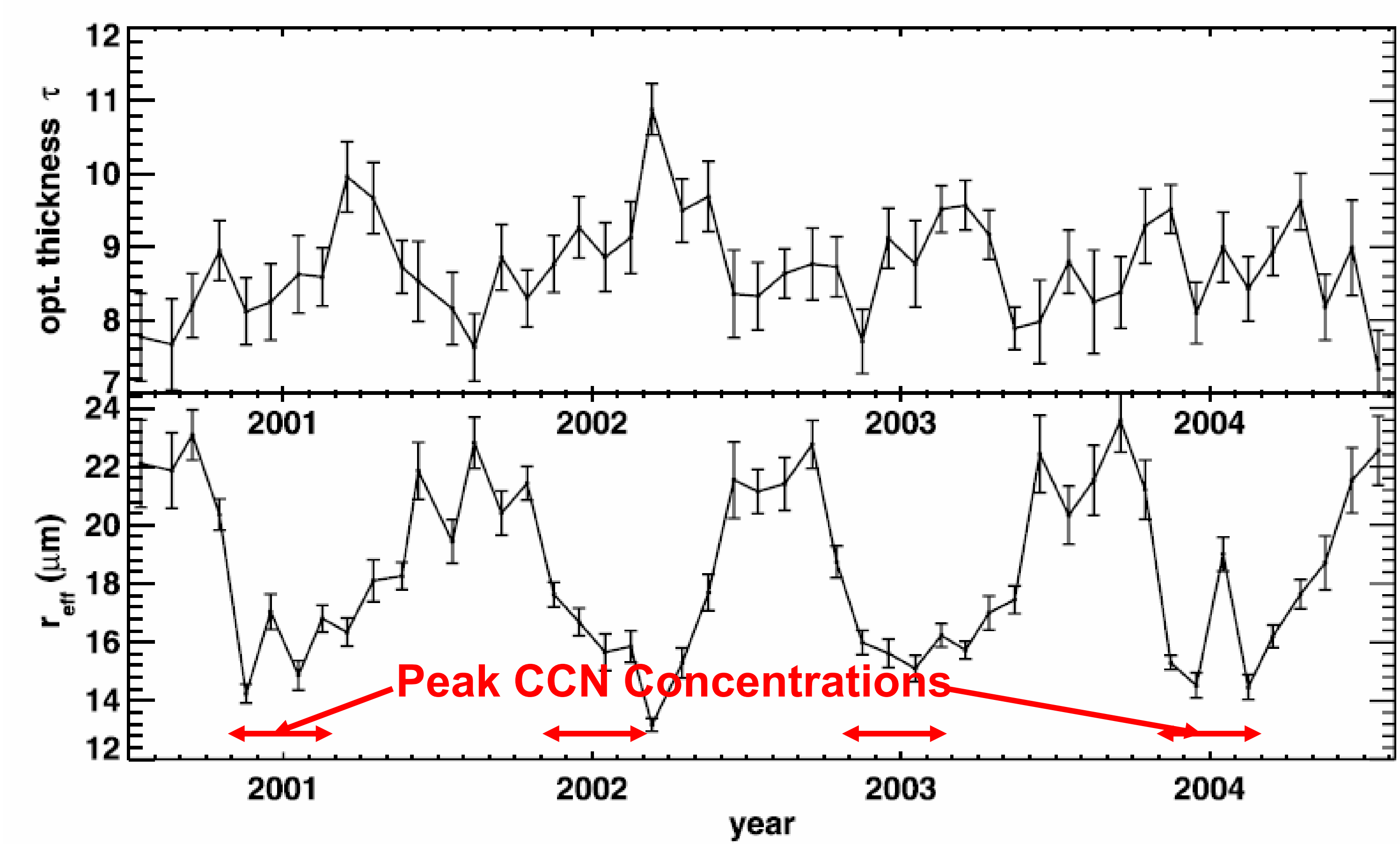
22 September 2006 1610 Z



Seek systematic differences in aerosol extinction as function of distances from clouds in MODIS observations, sensitive to changes in aerosol properties and enhanced illumination of cloud-free column, and CALIPSO observations, sensitive to changes in aerosol properties.

Sensitivity of Inferences to Cloud Properties

Cloud Properties and Surface-Based CCN Concentrations

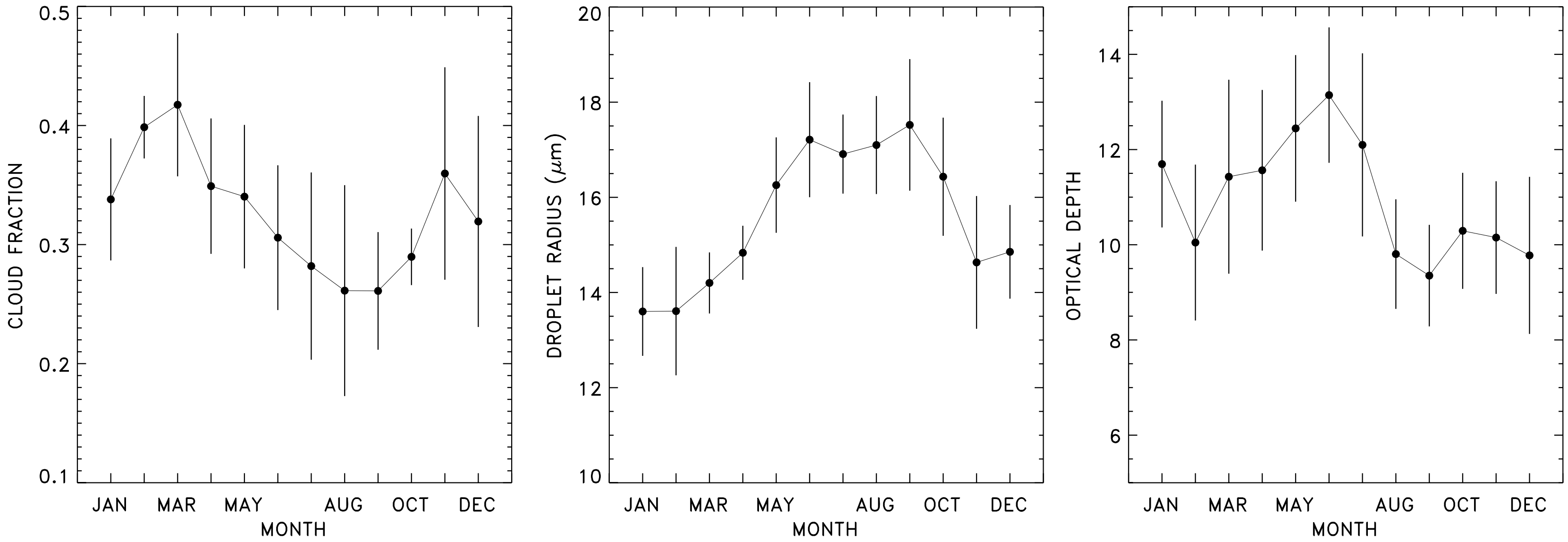


CCN concentrations at Cape Grim peak and droplet radii in marine stratocumulus reach minima during Austral Summers.

Source: Boers et al. (2006)

Annual Variations in Low-Level Marine Stratocumulus

West of Cape Grim



Composite for 7 years of MODIS Terra Level 3, monthly mean data.

Retrieval Method

Retrieval scheme follows Arking and Childs (1985) and is described in Coakley et al. (2005).

- **For single-layered cloud systems, identify overcast pixels and determine altitude of cloud layer.**
- **For each pixel, radiances are given by**

$$I = (1 - A_C) I_S + A_C I_C (z_C, \tau, R_e)$$

A_C **= Fractional cloud cover within a pixel**

I_S **= Average cloud-free radiance within a pixel**

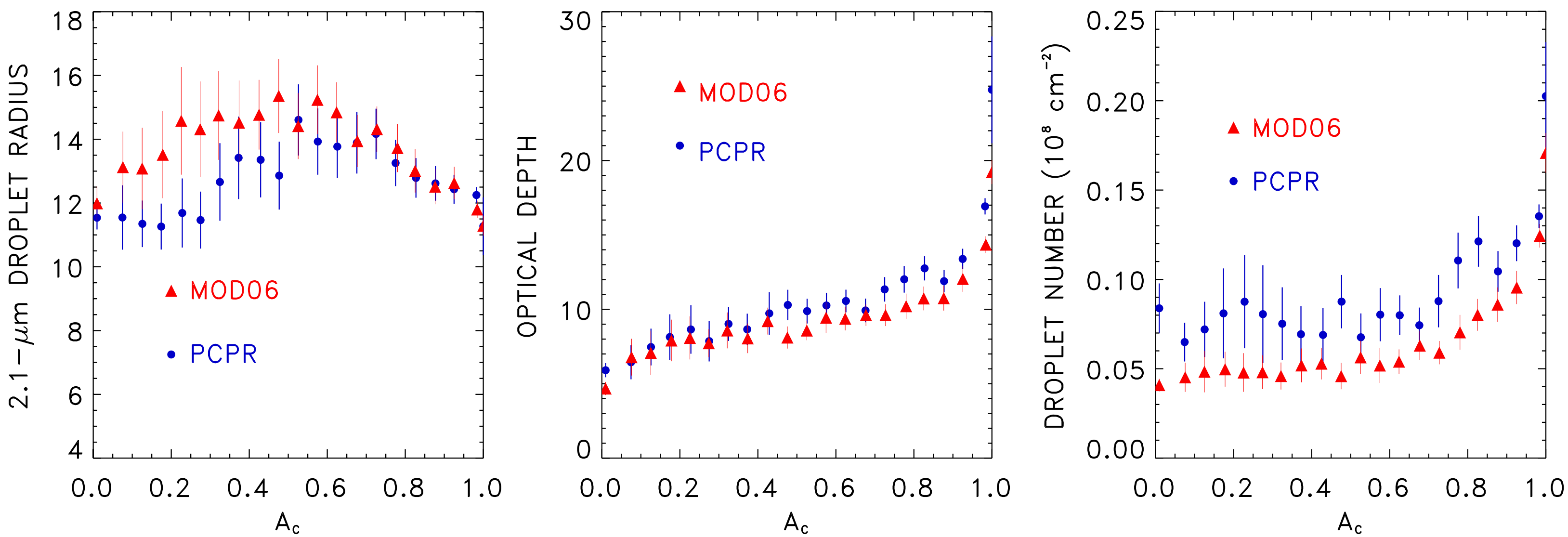
$I_C(z_C, \tau, R_e)$ **= Average overcast radiance within a pixel**

z_C **= Average cloud altitude obtained from nearby overcast pixels**

- **For each pixel, adjust A_C, τ, R_e so that calculated radiances at 0.64, 1.6, 2.1, 3.7, and 11 μm match those observed.**

Regional Cloud Properties and Regional Cloud Cover

50-km Scale Regions of Marine Stratocumulus

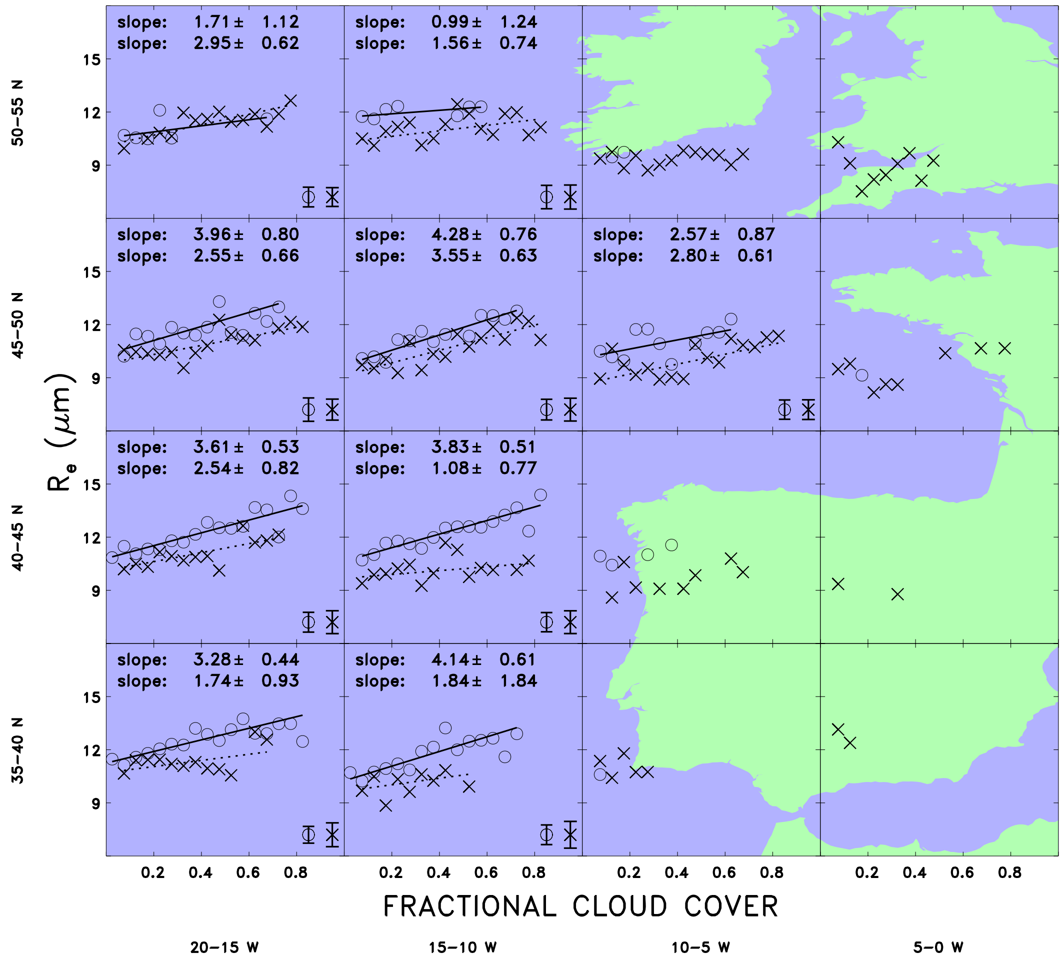


Droplet radius in MOD06 product biased so that as regional cloud cover increases from 0.2 to 1.0, droplet radius decreases.

Droplet number concentrations increase as regional cloud cover increases.

Cloud Droplet Radius and Fractional Cloud Cover for “Clean” and “Polluted” Days

NOAA-14 AVHRR, Summers 1995-1999

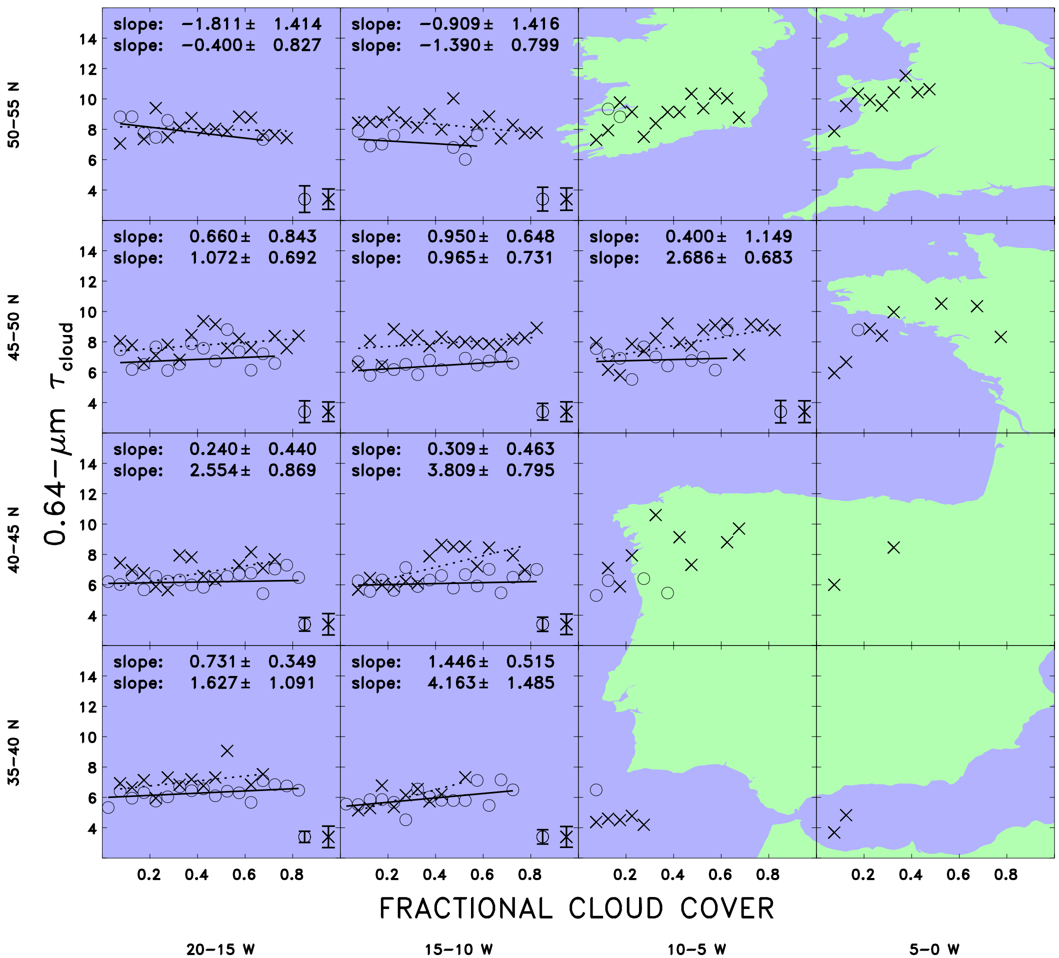


- **Data separated according to aerosol optical depths. Optical depths less than the 40th percentile (○) identified as “clean” and optical depths greater than the 60th percentile (×) identified as “polluted.”**
- **Droplet radius increases as cloud cover increases.**
- **Regardless of cloud cover fraction, droplet radius decreases as aerosol optical depth increases.**

Source: Matheson et al. (2006)

Cloud Optical Depth and Fractional Cloud Cover for "Clean" and "Polluted" Days

NOAA-14 AVHRR, Summers 1995-1999



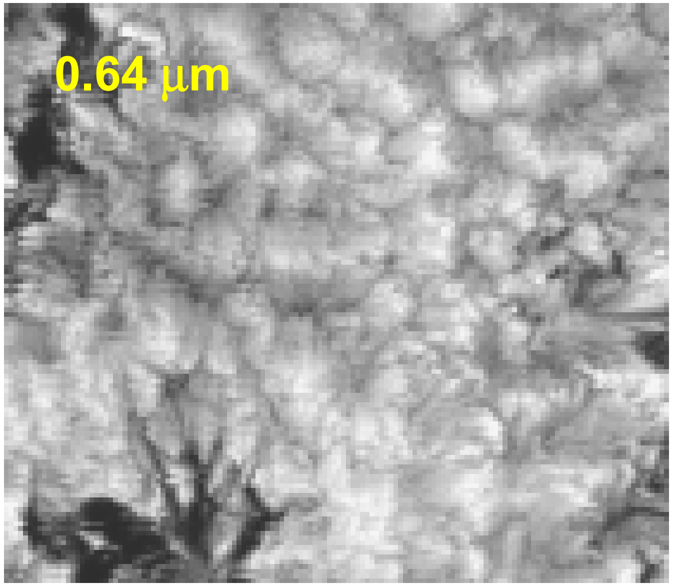
Source: Matheson et al. (2006)

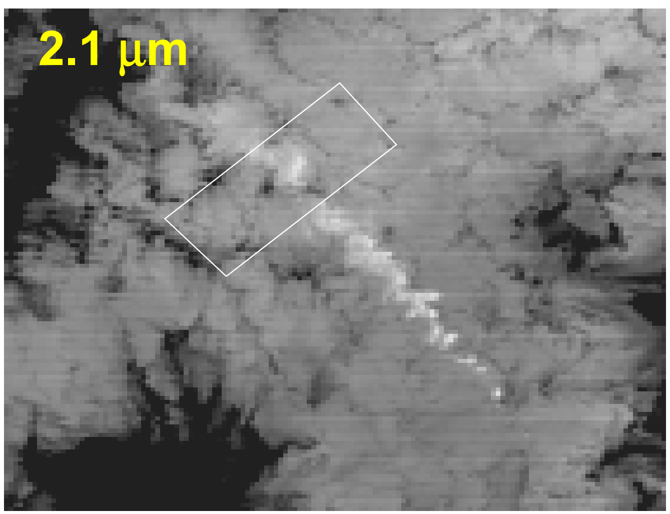
- Cloud optical depth increases slightly with increasing cloud cover.
- Cloud optical depth increases with aerosol optical depth.

Lessons Learned from Ship Tracks

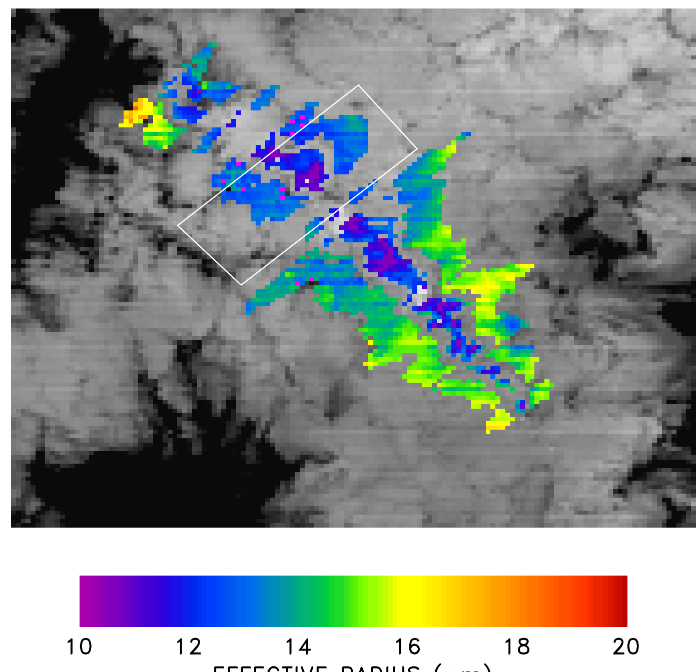
Automated Identification and Analysis of Ship Tracks

- Ship track positions logged by hand using 2.1, 3.7, and 11-µm images.
- Based on logged position, automated routine selects, regardless of fractional cloud cover, 1-km pixels “polluted” by ships and nearby control pixels.





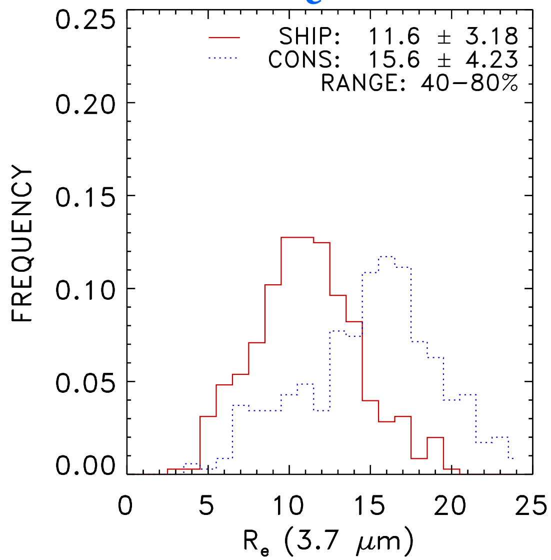
Droplet Radius



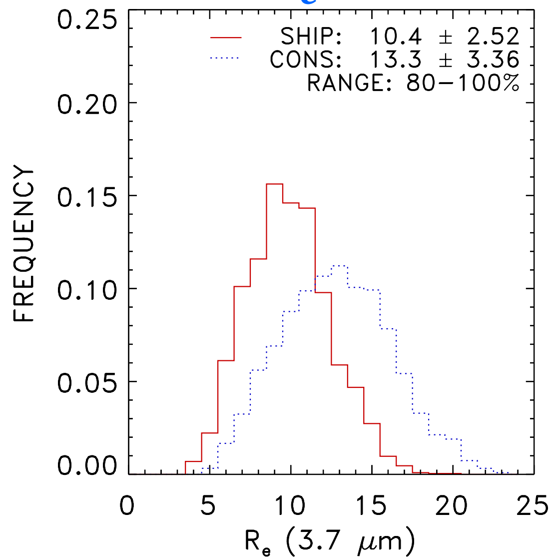
Droplet Radius

Aqua MODIS—Afternoon Clouds
Derived from 3.7-µm reflectances

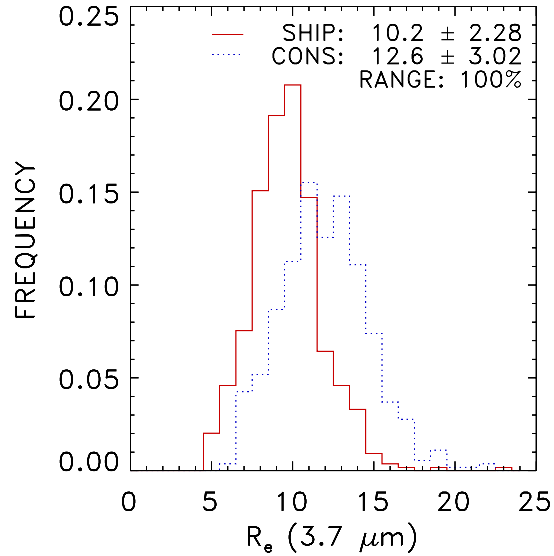
$0.4 < A_c < 0.8$



$0.8 < A_c < 1.0$



Overcast

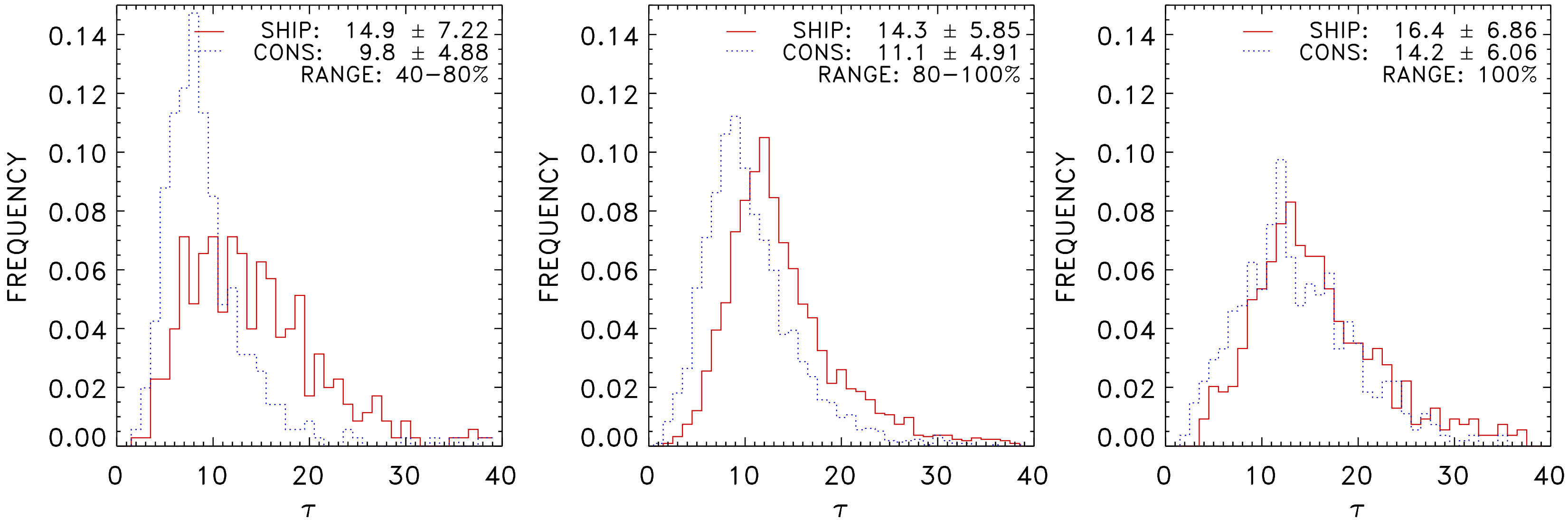


- **Averages for 20-pixel long segments aligned along the ship tracks for three years of summertime observations from both Terra and Aqua.**
- **Terra droplet radii are nearly identical except for $0.4 < A_c < 0.8$, for which morning clouds have droplets with radii that are about 1 µm larger.**
- **Droplets in polluted clouds exhibit much narrower distributions→*droplet growth inhibited in polluted clouds*.**
- **Droplets larger in clouds that only partially cover 1-km pixels→*dissipation is through drizzle*.**

Optical Depth

Aqua MODIS—Afternoon Clouds

$0.4 < A_c < 0.8$ **$0.8 < A_c < 1.0$** **Overcast**



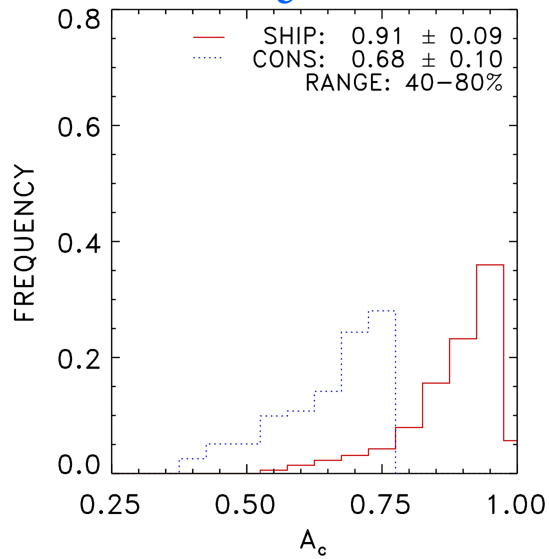
- **Terra optical depths are larger by ~2 for A_c > 0.8→***morning clouds are thicker than afternoon clouds***.**
- **Difference between optical depths for polluted and nearby unpolluted clouds increases as the fractional cloud cover of the unpolluted clouds decreases→***bigger clouds have larger optical depths***.**

The aerosol indirect effect is not only an increase in fractional cloud cover but also the optical depths of the polluted clouds are larger because the clouds cover larger areas.

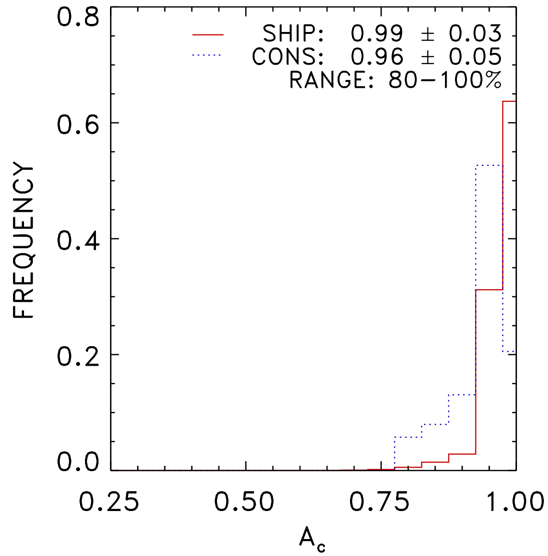
Cloud Cover Fraction

Aqua MODIS—Afternoon Clouds

0.4 < A_c < 0.8



0.8 < A_c < 1.0

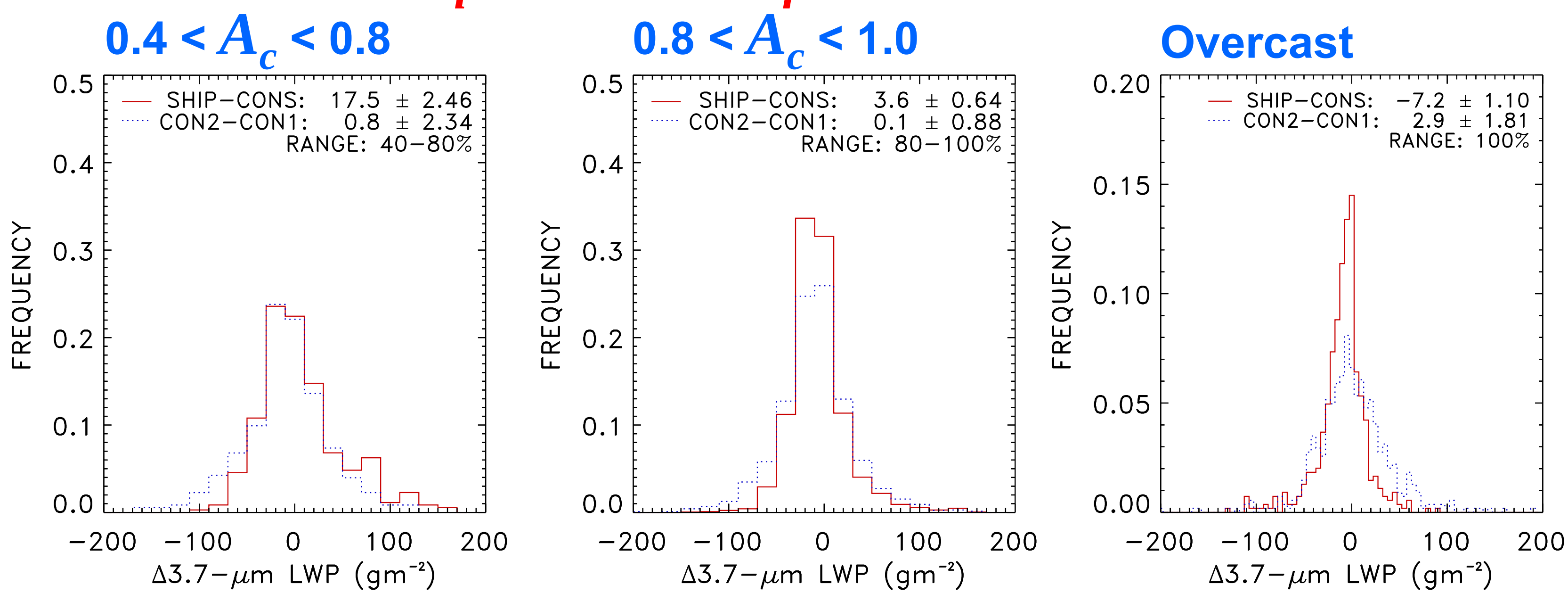


- **Cloud cover fractions nearly identical for Terra.**
- **For broken cloud conditions, polluted clouds have greater pixel-scale cloud cover than nearby unpolluted clouds, qualitatively consistent with LES model results reported by Ackerman et al. (2003).**

Differences in Liquid Water Amounts

(Polluted − Controls and Control 2 − Control 1)

Aqua MODIS—Afternoon Clouds



- **Liquid water amount changes for Terra are about 20 − 40% larger so that loss of liquid water is greater for overcast clouds and gain of liquid water is greater for clouds that only partially cover the 1-km pixels→*morning clouds have larger rates of entrainment than afternoon clouds*.**

- **Overcast pixels lose liquid water while partially cloudy pixels gain liquid water when polluted→*dissipation is through drizzle and is supported by a relatively moist overlying troposphere*.**

Where is this Heading?

- Characterize clouds in heavily cloudy region and aerosols in cloud-free regions and model the apparent behavior of aerosols in the transition regions adjacent to clouds.
  - INDOEX aircraft combined with CALIPSO lidar observations suggest that enhancement in relative humidity within 1 km of cloud edge would have little impact on aerosol forcing.
  - Illumination of cloud-free columns by nearby clouds is likely to have a greater effect on retrieved aerosol properties.
- Watch out for biases in cloud property retrievals. Biases in retrieved properties for water clouds can be misinterpreted as aerosol indirect effects.
- Results of ship track studies indicate that how clouds respond depends on cloud cover fraction, so that *modeling* changes in clouds will be essential to estimating the aerosol indirect effects. Observations can be used to assess the fidelity of the model results.

Study polluted clouds to learn about cloud-feedbacks in the climate system.

Acknowledgment: NASA CERES and CALIPSO Projects and EOS and Radiation Sciences Programs and NOAA Climate Program Office.

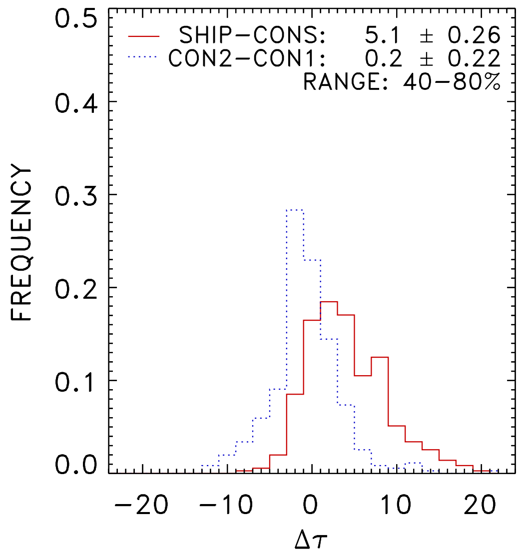
Backups

Differences in Optical Depths

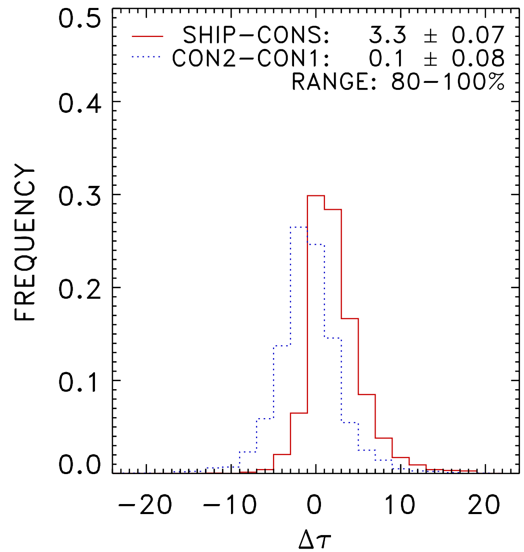
(Polluted − Controls and Control 2 − Control 1)

Aqua MODIS—Afternoon Clouds

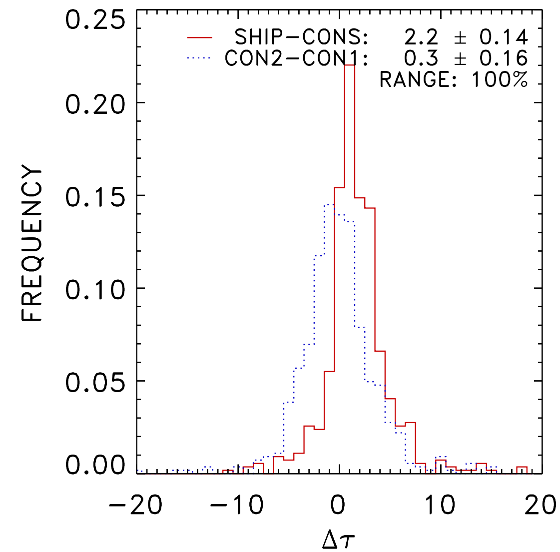
0.4 < A_c < 0.8



0.8 < A_c < 1.0



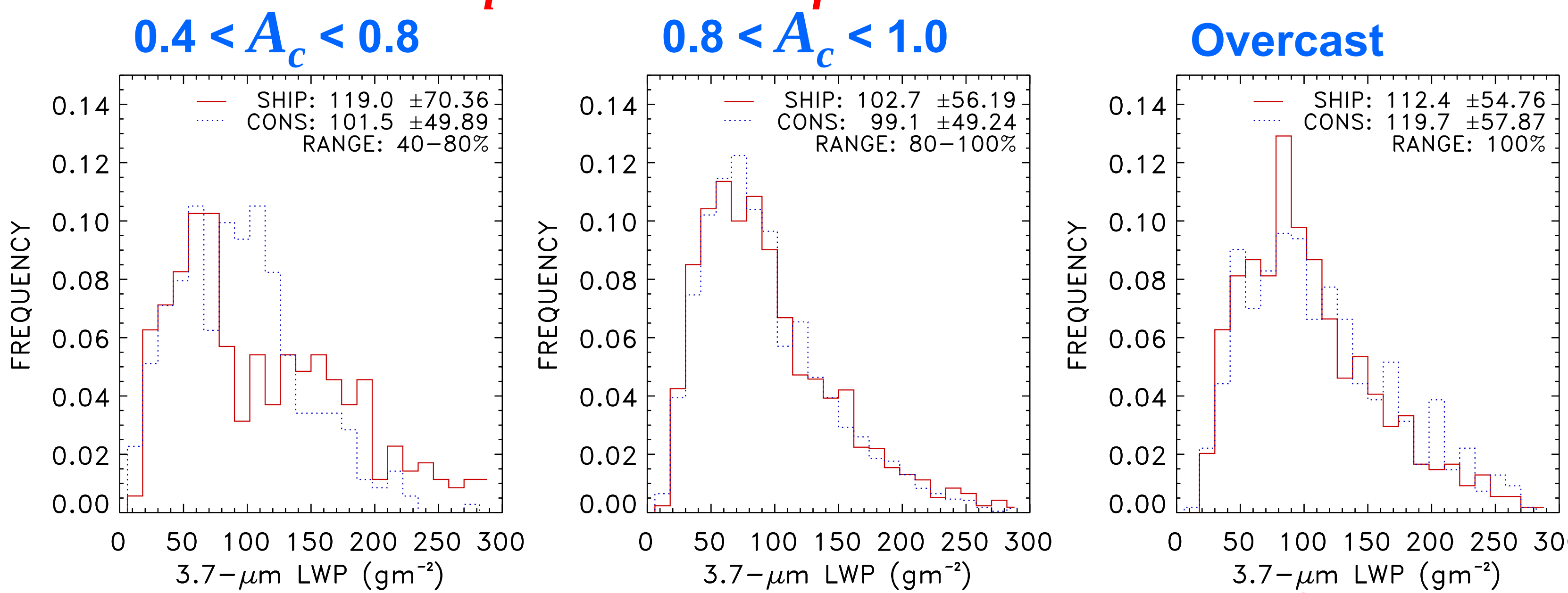
Overcast



- **Optical depth changes for Terra about ~10% smaller→*morning clouds are less sensitive to pollution than the thinner afternoon clouds*.**
- **Increase in optical depths caused by pollution highly significant, the changes increasing as pixel-scale cloud cover fraction decreases→*bigger clouds have larger optical depths*.**

Cloud Liquid Water Amount

Aqua MODIS—Afternoon Clouds



- **Terra liquid water amounts ~10% larger→*morning clouds are thicker than afternoon clouds*.**
- **For overcast conditions, polluted clouds have less liquid water than nearby unpolluted clouds→*overlying free trosposhpere sufficiently dry that the increased entrainment in clouds with smaller droplets leads to the drying of polluted clouds as suggested by results of LES model results reported by Ackerman et al. (2004)*.**
- **For broken cloud conditions, polluted clouds have more liquid water than nearby unpolluted clouds and 20-pixel track segments with A_c < 0.8 have clouds with larger liquid water amounts than those in segments with 0.8 < A_c < 1.0 →*dissipation of clouds is through drizzle and suggests that regions with broken clouds have moisture support in the overlying troposphere.***