Observations of the Aerosol Indirect Radiative Forcing

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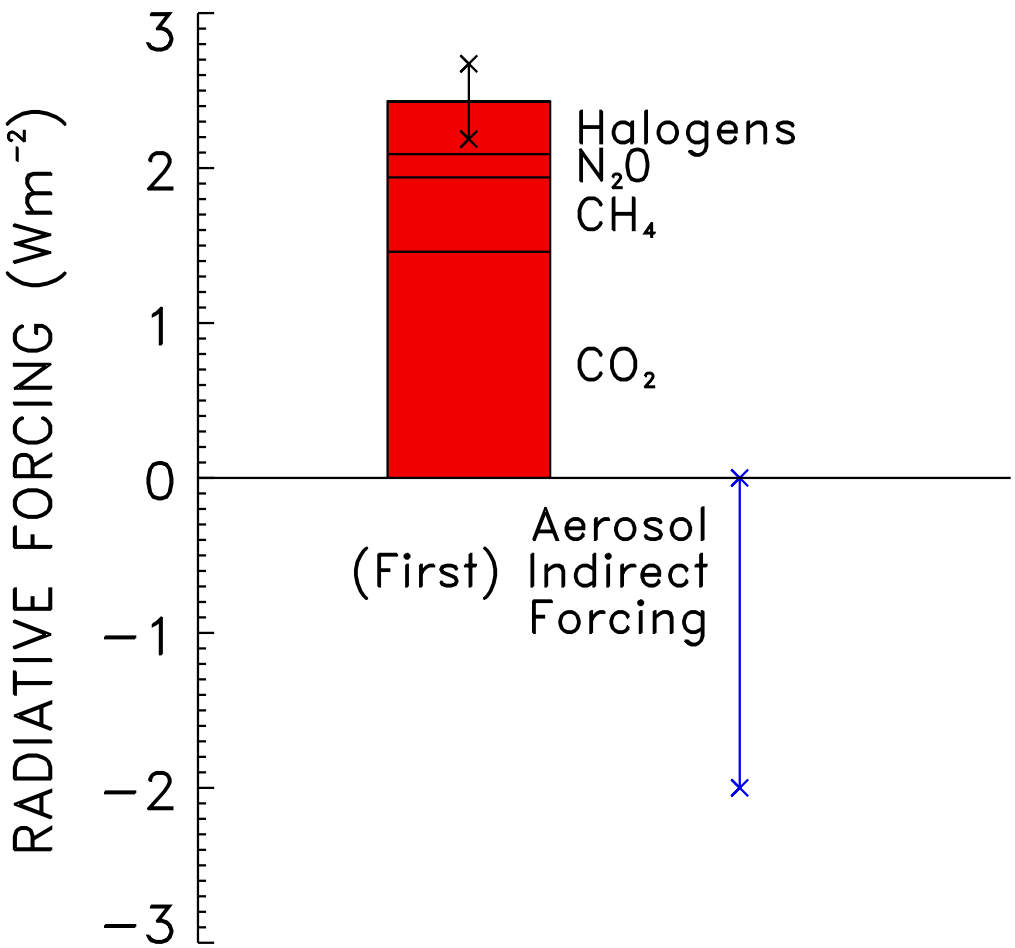
Goal: **Assess the status of using observations to determine the aerosol indirect radiative forcing.**

IPCC Aerosol Indirect Radiative Forcing



Source: IPCC (2001)

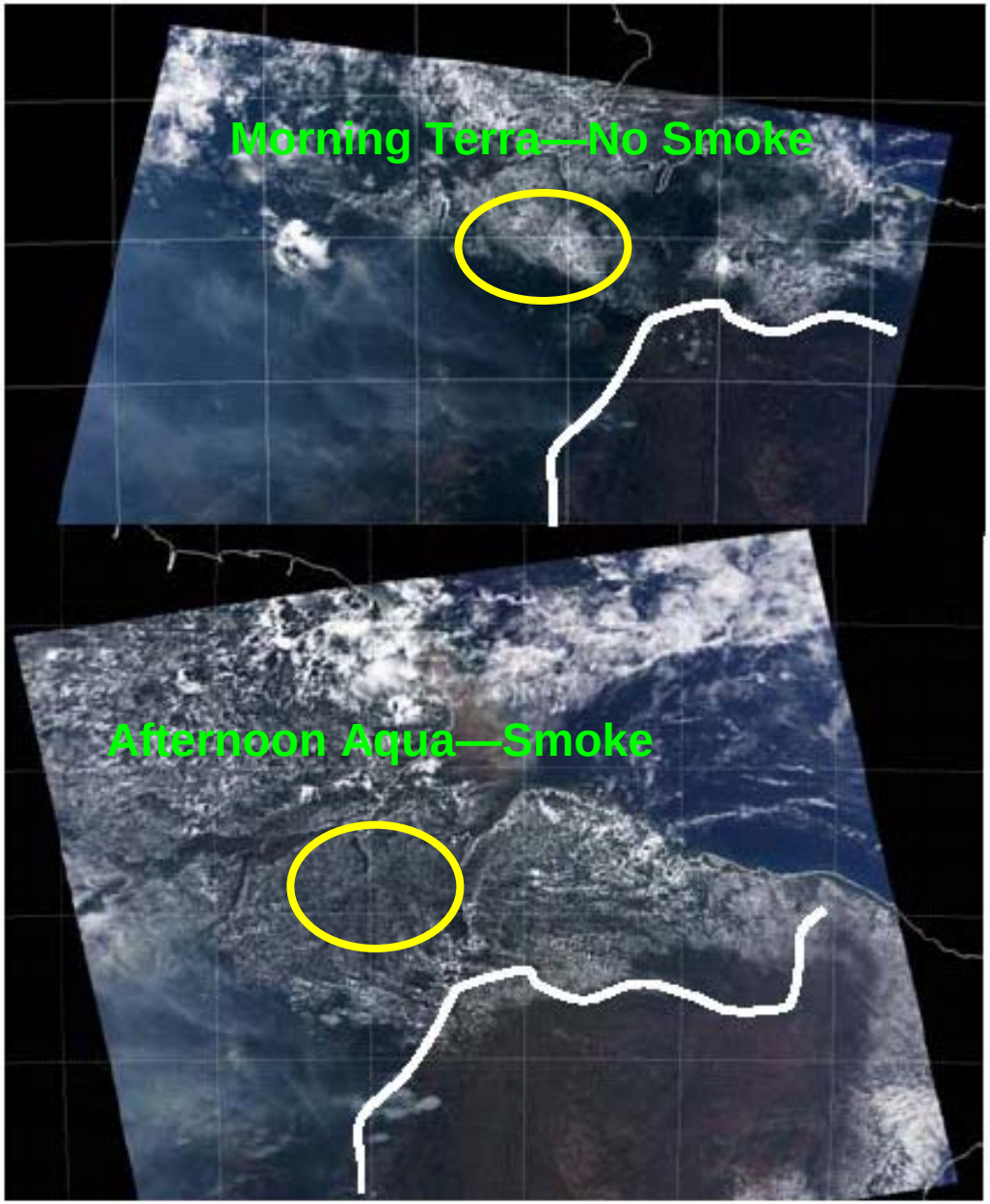
- ***Nothing but uncertainty*…** **(model driven).**
- **"First" aerosol indirect forcing is a misnomer.**
- **To correctly estimate the aerosol indirect radiative forcing, models will have to correctly account for cloud-climate feedbacks.**
- **To correctly "measure" the aerosol indirect effect, the response of the clouds to the thermodynamics of the air bringing the pollution will have to be accounted for.**

"*First*" and "*Second*" Aerosol Indirect Radiative Forcing

- *First* Indirect Forcing—number of droplets increases while liquid water remains constant → droplet size decreases accordingly.
- *Second* Indirect Forcing—drizzle suppressed, clouds have more liquid water, cloud lifetime, and consequently, cloud amount increases. In many climate models, the second forcing almost doubles the total forcing.
- Observationally, there is no such thing as "*First*" and "*Second*." Clouds respond quickly (~minutes to ~hour) to changes in droplet sizes. All observations see the clouds after they have responded to these changes.
- The *CHIEF GOAL* of observations, aside from identifying the indirect effect, is to determine how the clouds have changed, and especially how cloud liquid water has changed.

Semi-Direct Aerosol Forcing

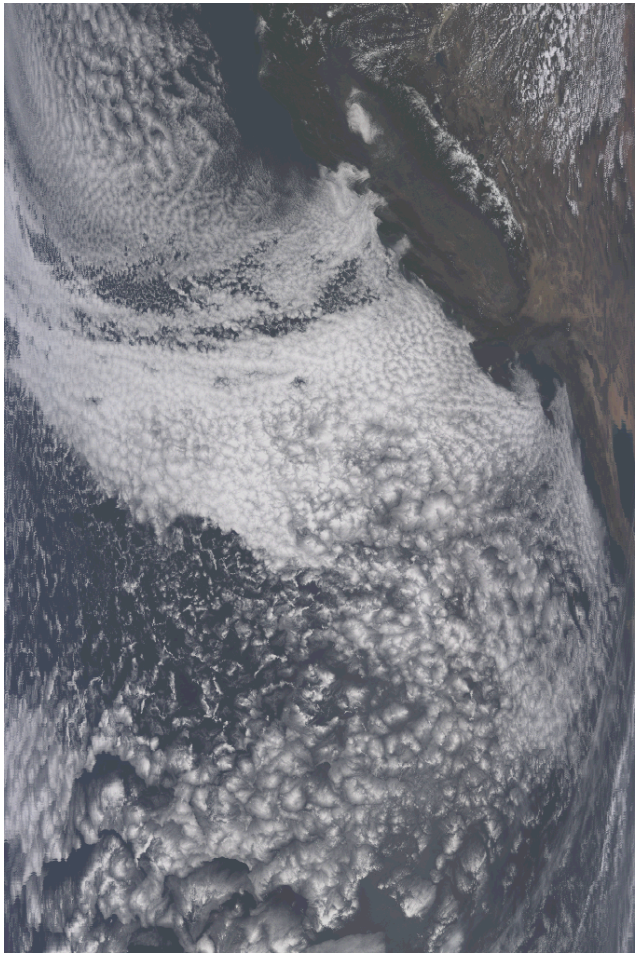
- Absorption of sunlight by aerosols inhibits cloud growth (Hansen et al. 1997; Ackerman et al. 2000).
- Smoke from biomass burning inhibit growth of clouds in the Amazon basin (Koren et al. 2004).



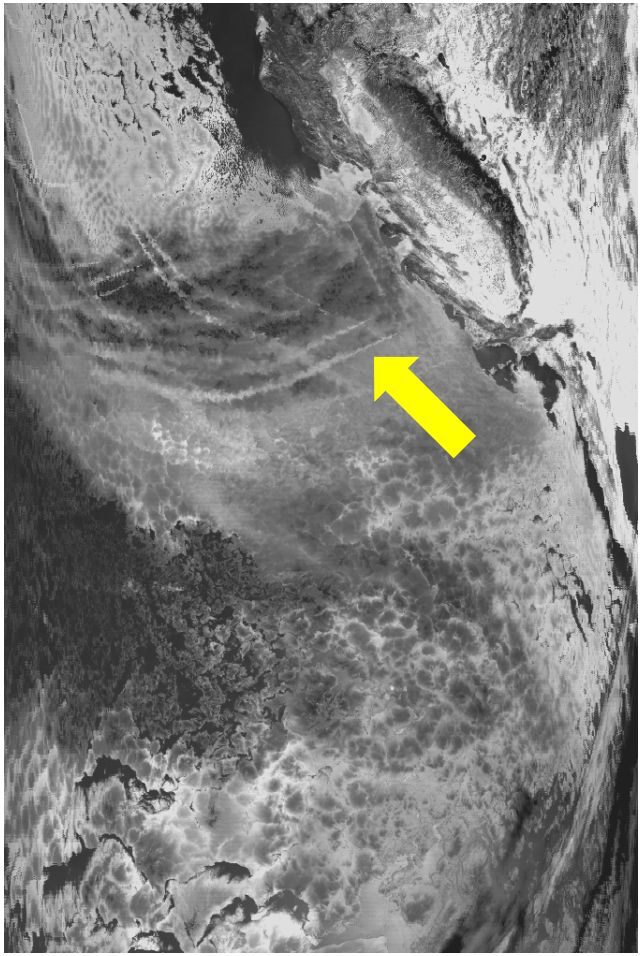
Ship Tracks

Terra, 1-km MODIS 2 May 2002 1910 Z

Visible-True Color



3.7-μm



Automated Comparison of Polluted and Unpolluted Clouds

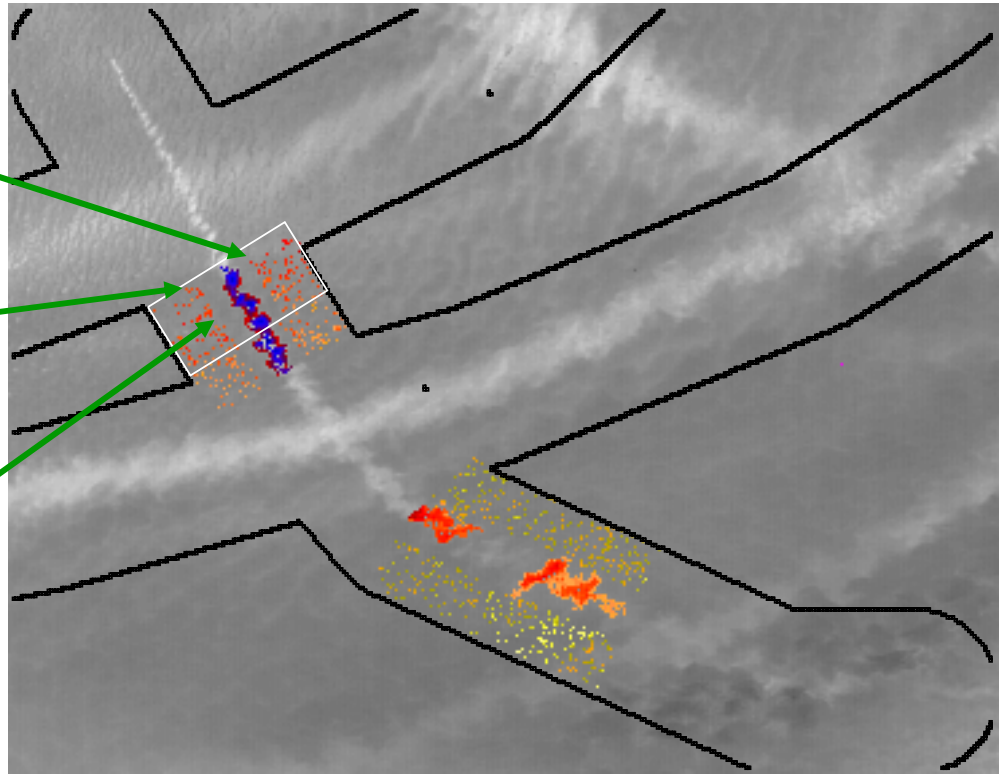
NOAA-14 1 July 1999 2256 Z

3.7 μm

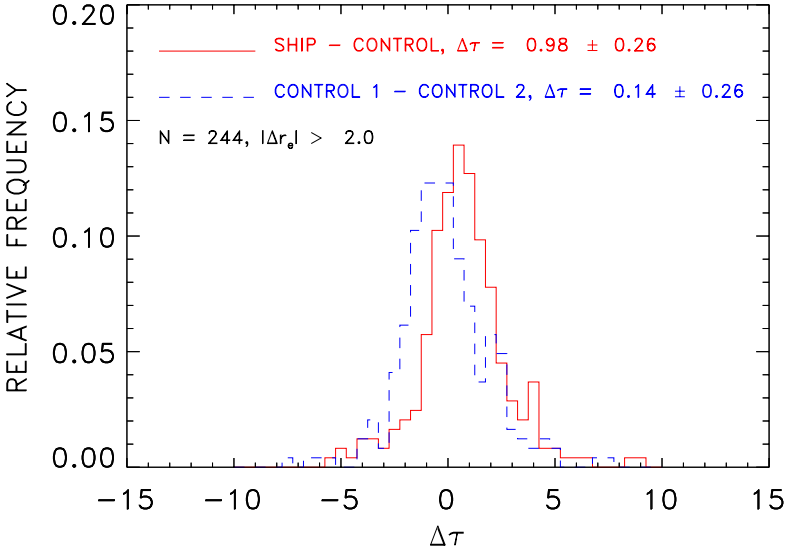
Automated selection of polluted clouds

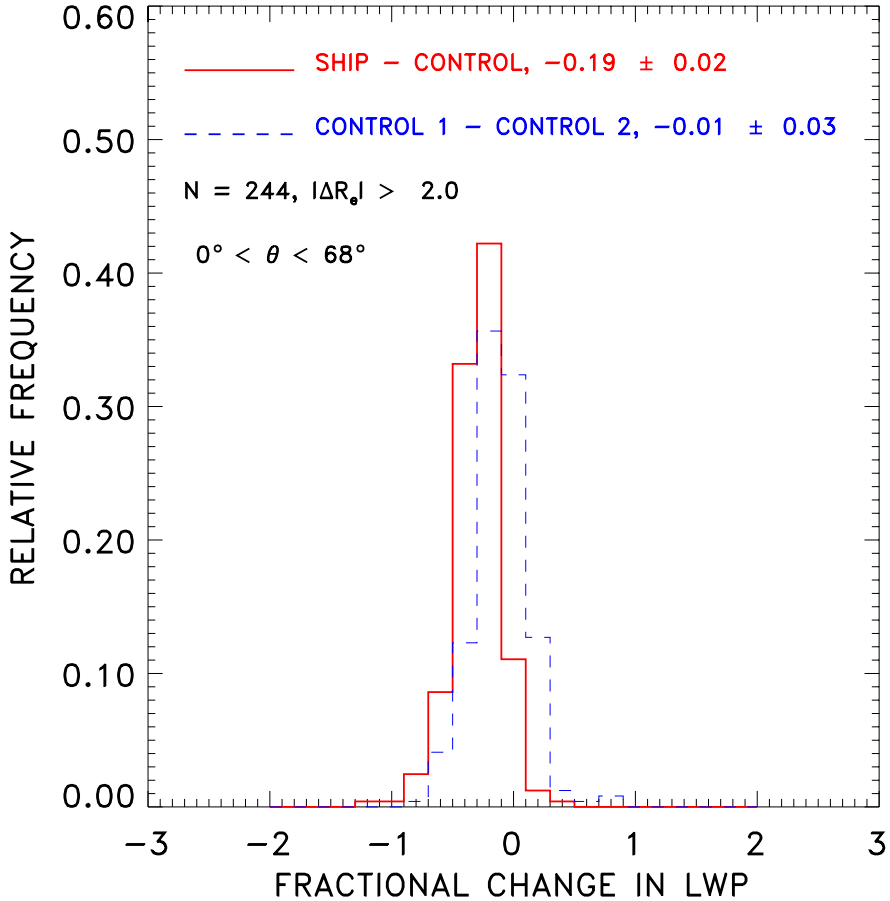
Automated random selection of nearby unpolluted clouds

Ship track segment: 30 km along track and 30 km either side of the track



Changes in Optical Depth and Liquid Water Amount

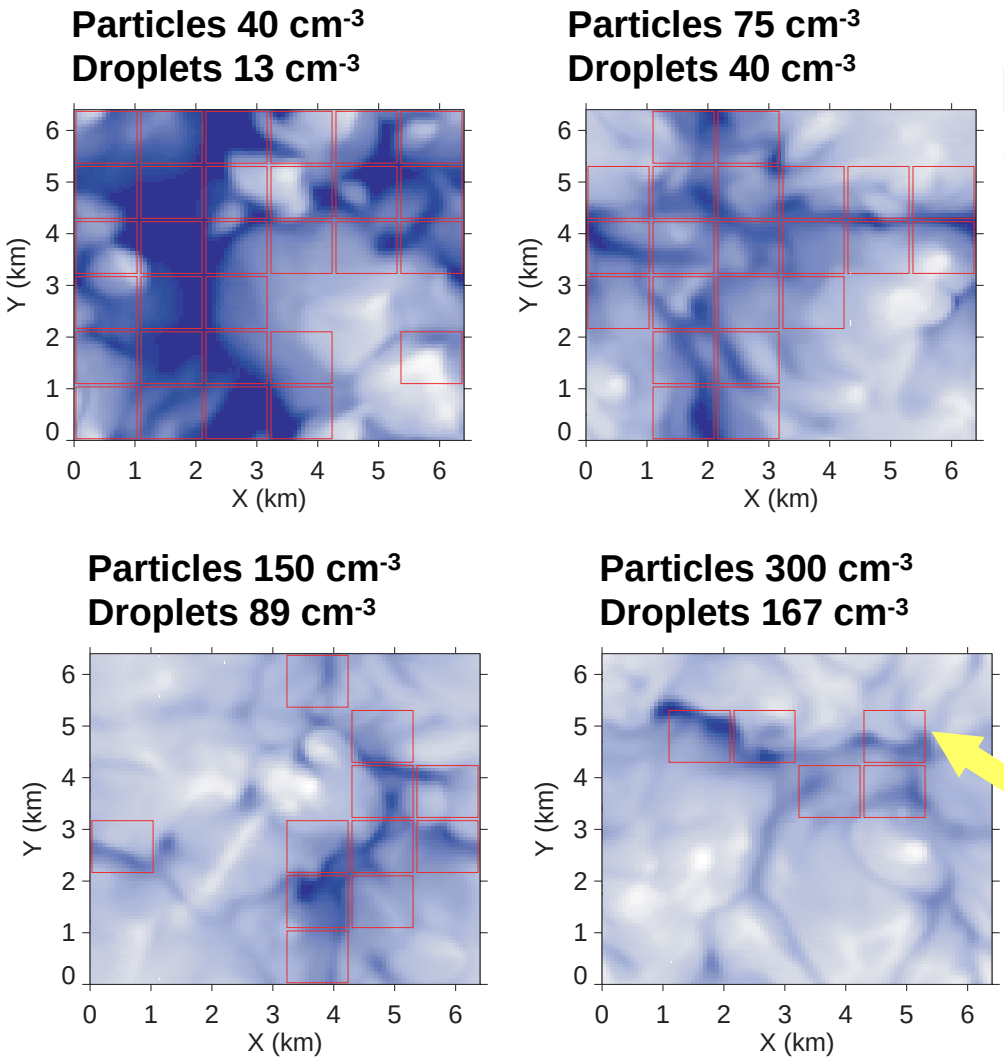




- Clouds polluted by ships have higher reflectivities than nearby unpolluted clouds.
- Polluted clouds also lose liquid water (~20%).

Source: Coakley and Walsh (2002)

Simulated Cloud Albedos



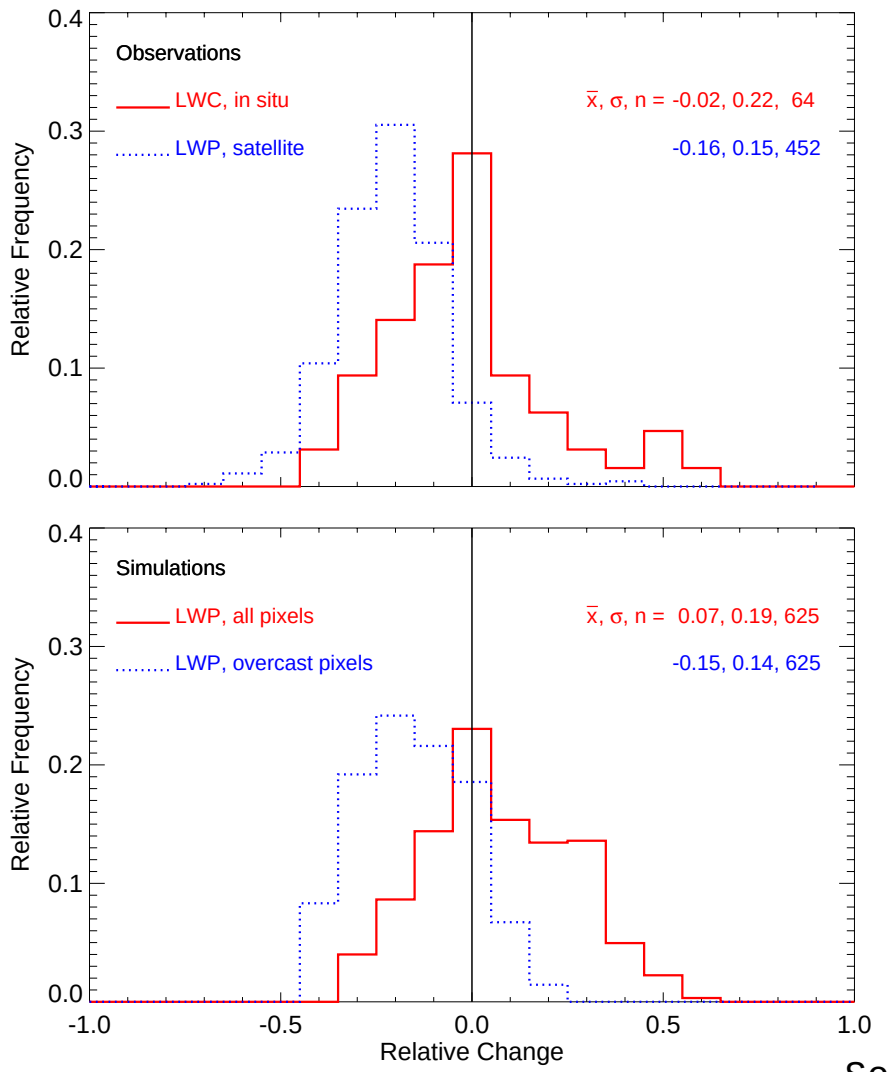
Large eddy simulation of marine stratocumulus.

- **6.5 × 6.5 × 1.5 km³ domain**
- **50 m resolution**
- **droplet number and sizes calculated**
- **radiative heating incorporated**

Partly cloudy 1-km field of view

Source: Ackerman et al. (2003)

Simulated and Observed Liquid Water Paths



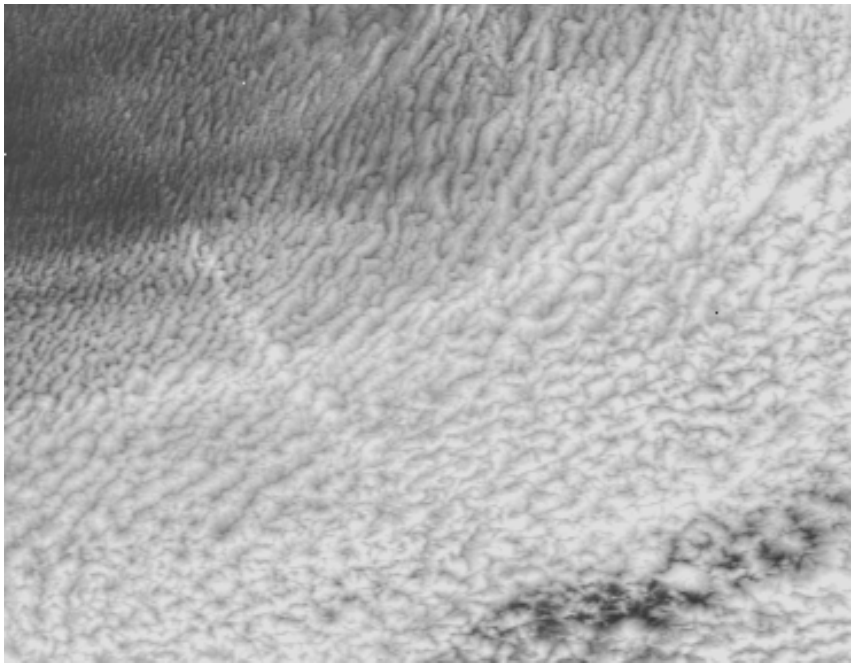
- **Liquid water remains constant by increasing cloud cover**
- **Liquid water in overcast fields of view diminished in both satellite observations and model simulations.**

Source: Ackerman et al. (2003)

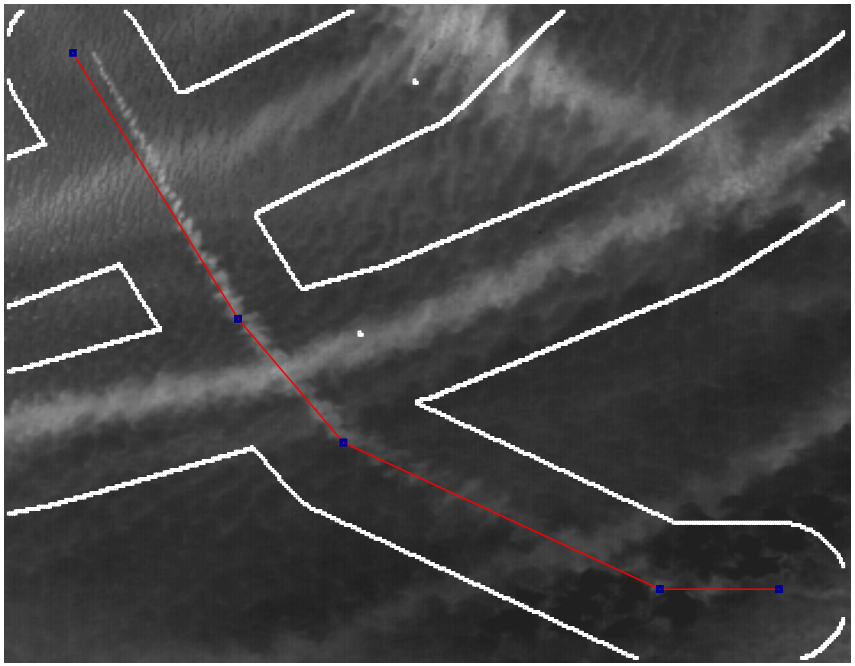
Analysis of Ship Tracks

NOAA-14 1 July 1999 2256 Z

0.64 μm

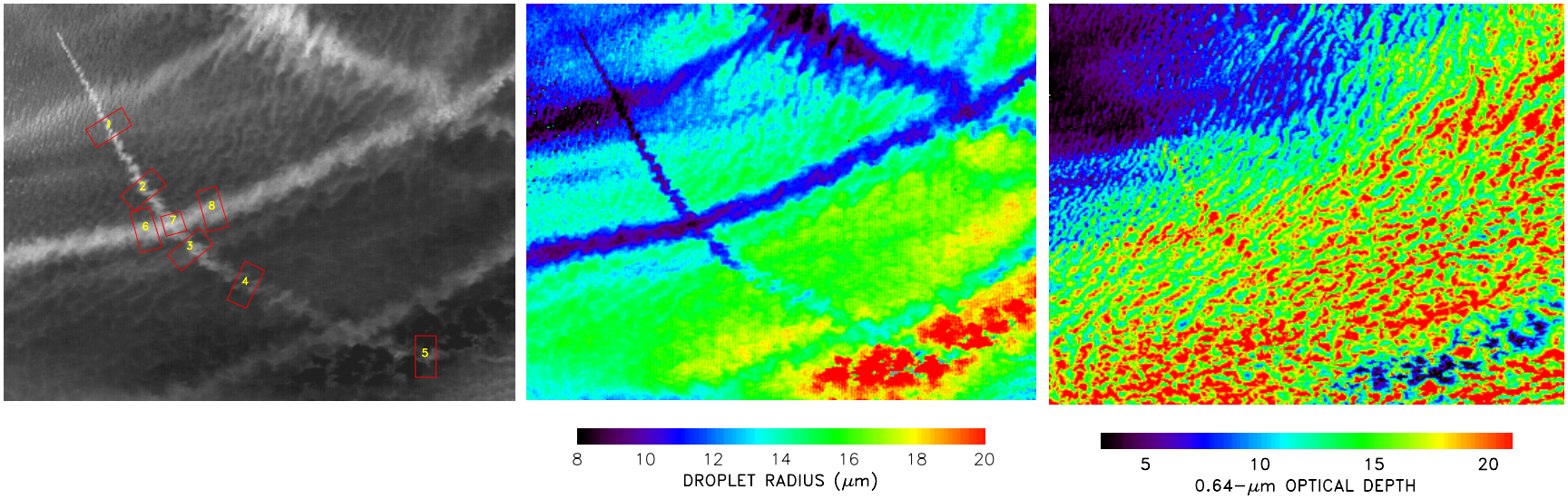


3.7 μm



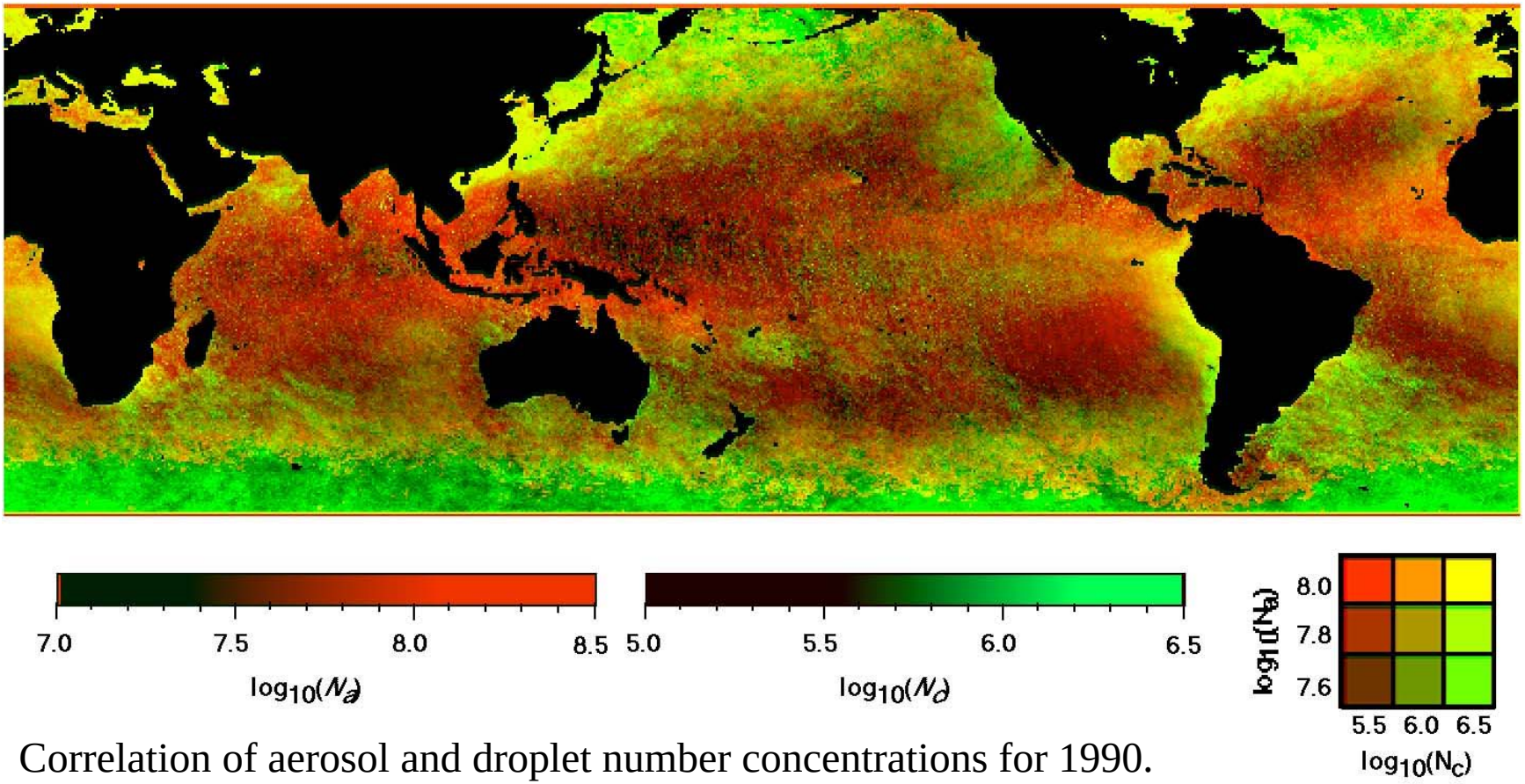
New Analysis of Ship Tracks

3.7-μm **Droplet Effective Radius** **0.64-μm Optical Depth**



Cloud properties now retrieved for partially covered 1-km fields of view.

Correlation of Aerosol and Droplet Number Concentrations

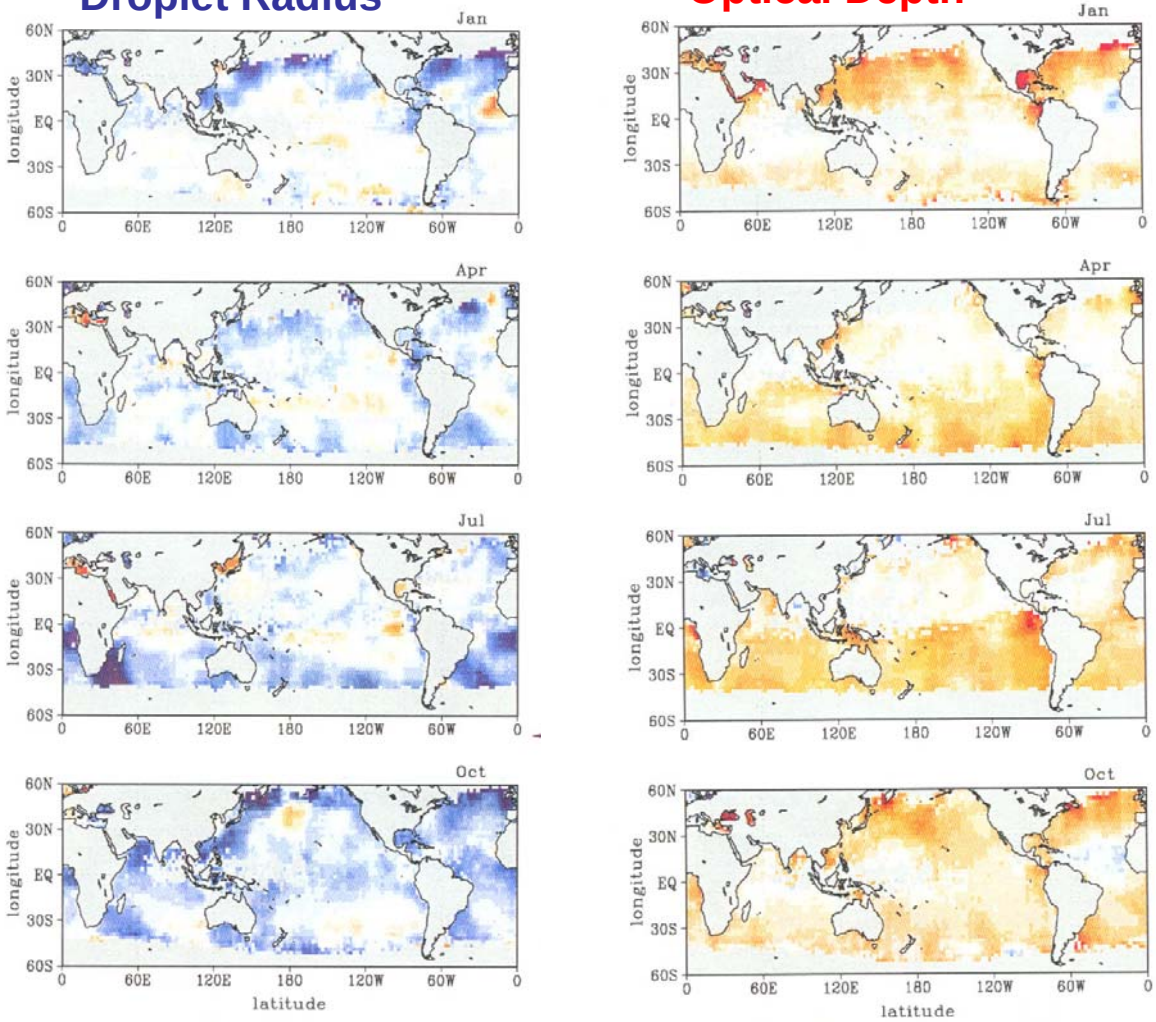


Correlation of aerosol and droplet number concentrations for 1990.

Source: Nakajima et al. (2001)

Cloud Droplet Radius and Optical Depth and Aerosol Column Number

Droplet Radius **Optical Depth**

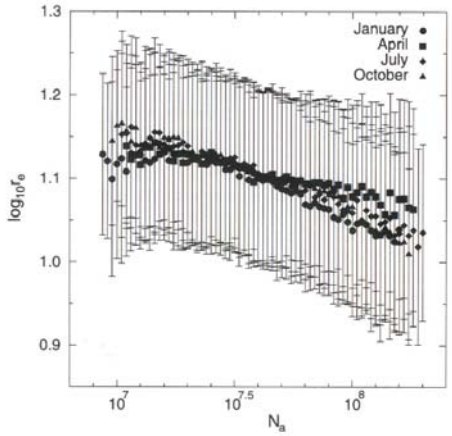


- **4-km AVHRR data for 1990.**
- **Correlations shown for month of daily average values composited for 17.5° × 17.5° latitude-longitude regions.**
- ***Blues* indicate negative and *Reds* positive correlations.**

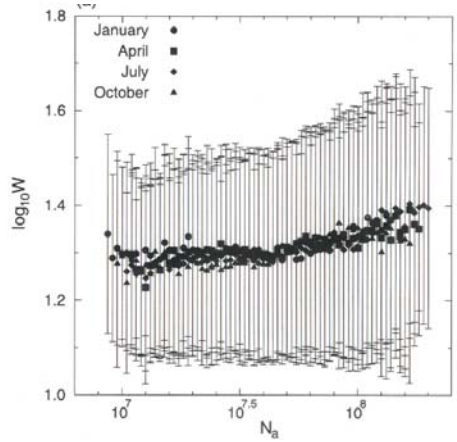
Source:
Sekiguchi et al. (2003)

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

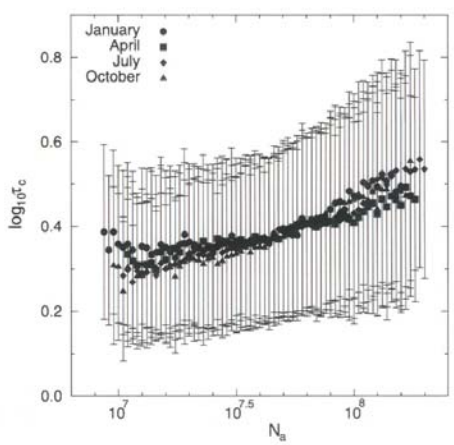
Droplet Radius



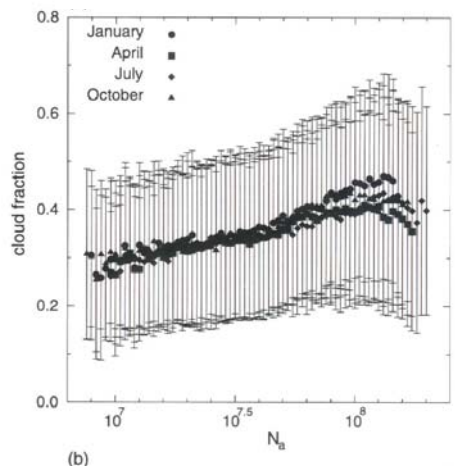
Liquid Water



Optical Depth

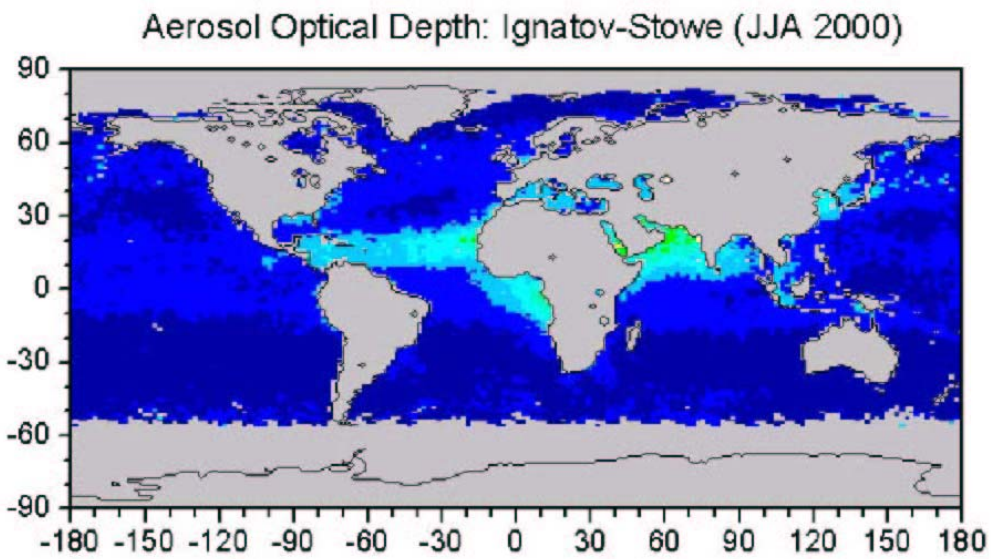


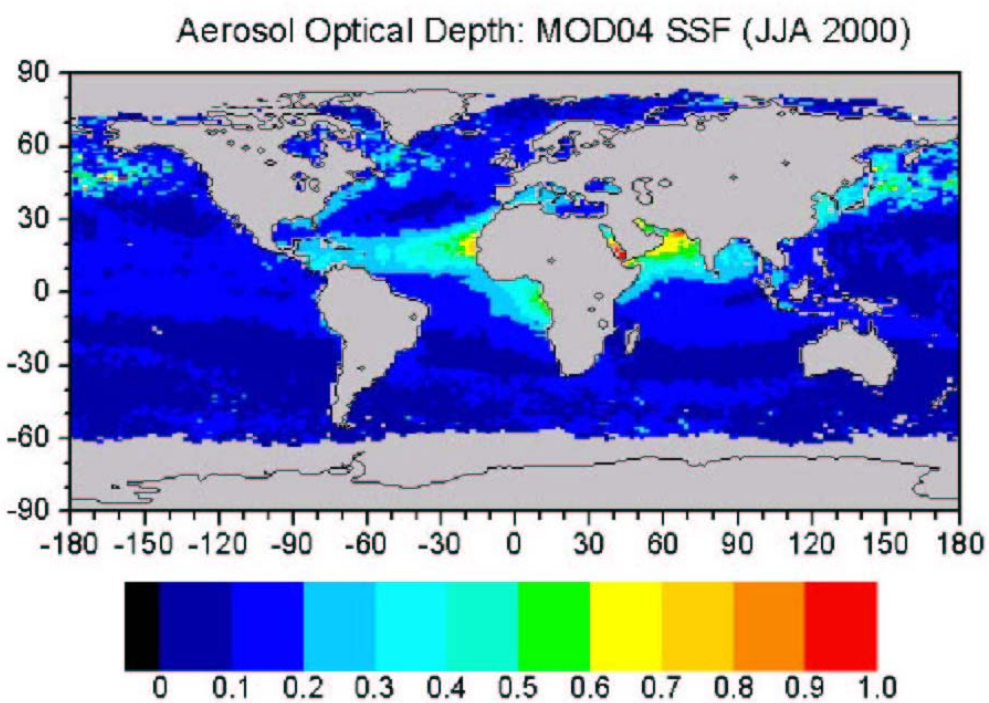
Cloud Cover



- **Daily averages for 2.5° × 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)



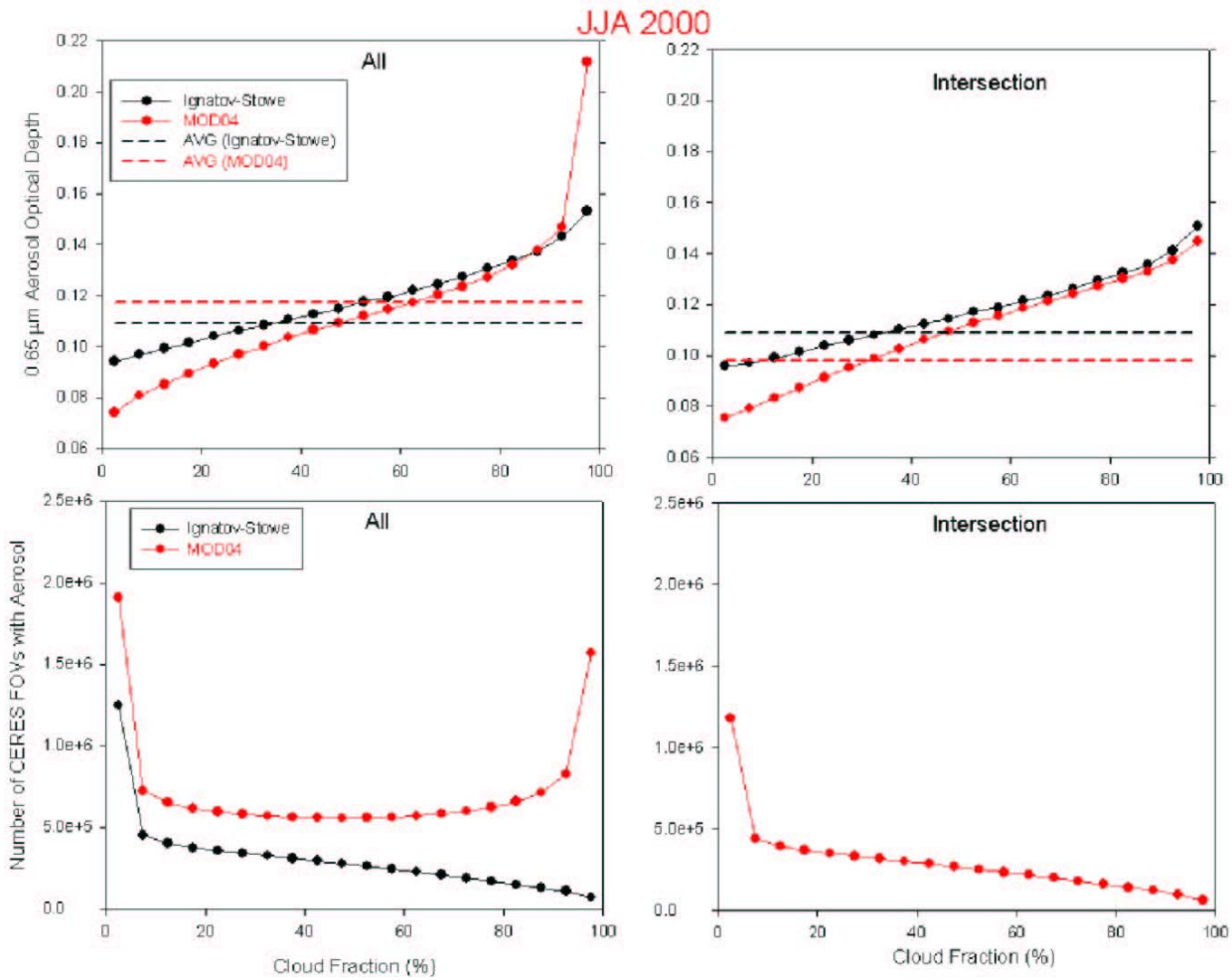


Aerosol Optical Depths from CERES SSF

- **Each CERES footprint (~25 km) has associated with it aerosol optical depths derived from cloud-free MODIS pixels within the CERES FOV.**
- **Results show optical depths for the multiwavelength MOD04 MODIS operational algorithm and a single-channel NOAA-like Ignatov-Stowe Algorithm.**
- **Differences arise from 1) different cloud-screening applied to the MODIS pixels and 2) different aerosol models used in the retrievals.**

Source: N. Loeb, CERES SSF for Terra.

Aerosol Optical Depth and Cloud Cover

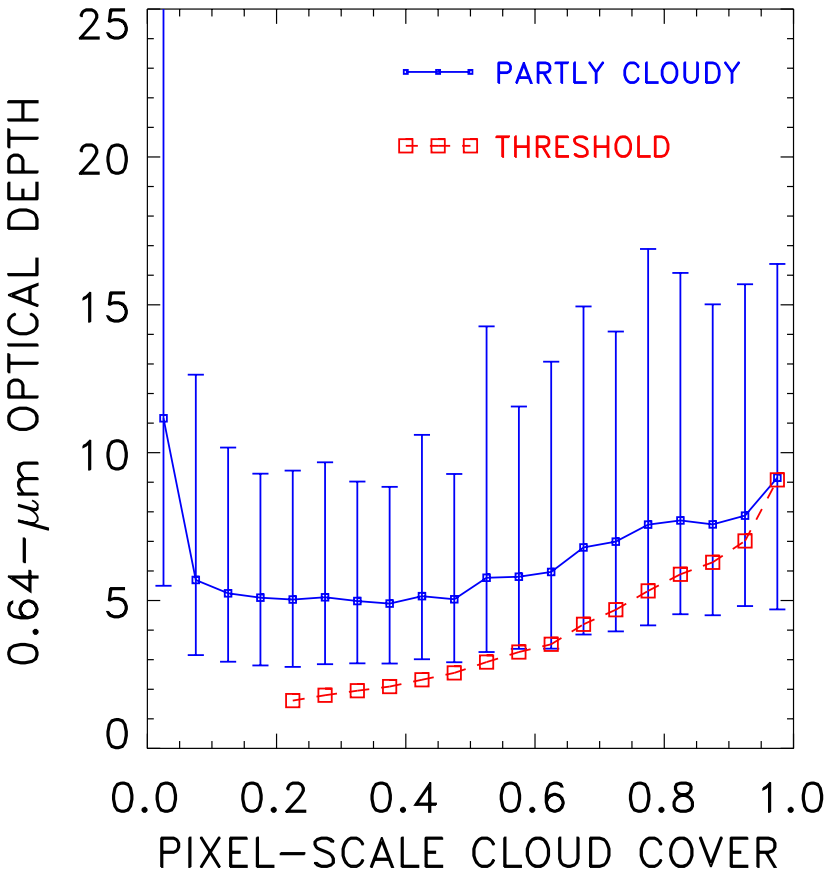


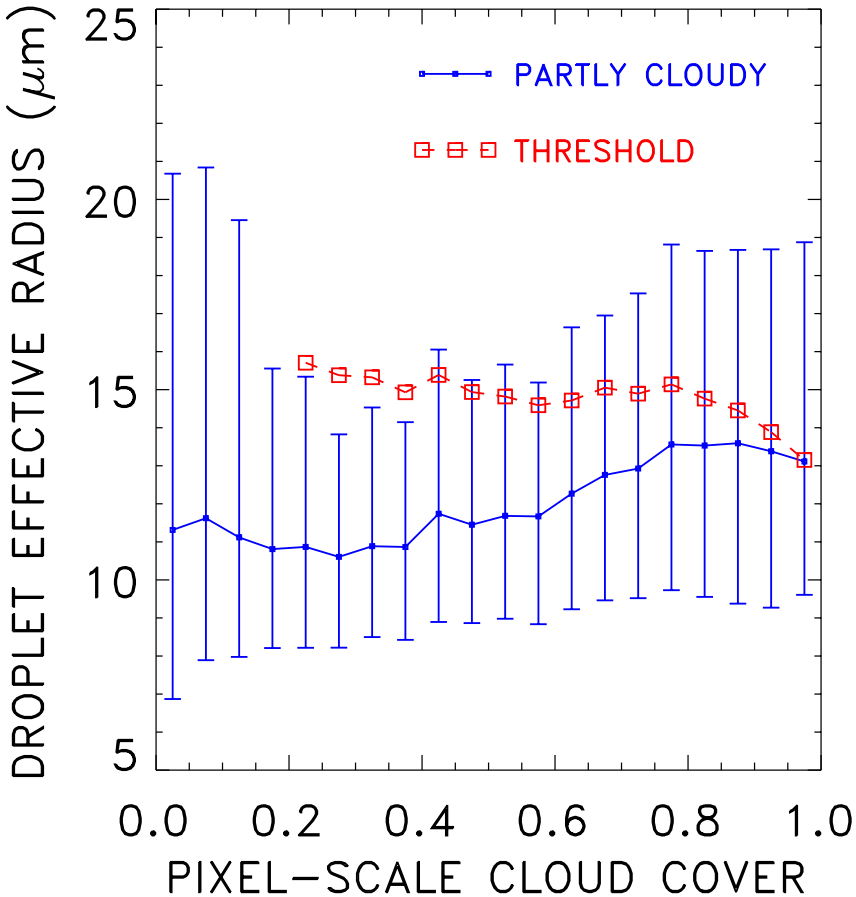
CERES fields of view with either MODIS or Ignatov-Stowe aerosol optical depth retrievals.

CERES fields of view with both MODIS and Ignatov-Stowe aerosol optical depth retrievals.

- Aerosol optical depth increases as cloud cover within CERES field of view increases.
- Aerosol optical depths could increase because of
  1) growth of particle size with increasing relative humidity in cloudy environment,
  2) additional illumination by sunlight from the sides of clouds, and 3) cloud contamination in the pixels used to perform the aerosol retrievals.
- Cloud screening more stringent in Ignatov-Stowe retrievals. Distribution of fractional cloud cover for MODIS retrievals is typical of cloud cover fractions for 25-km scales.
- Difference in aerosol direct radiative forcing ~ 0.4 Wm^{-2} due to differences in the cloudiness of the regions, and ~0.4 Wm^{-2} due to differences in the aerosol models used in the retrievals.

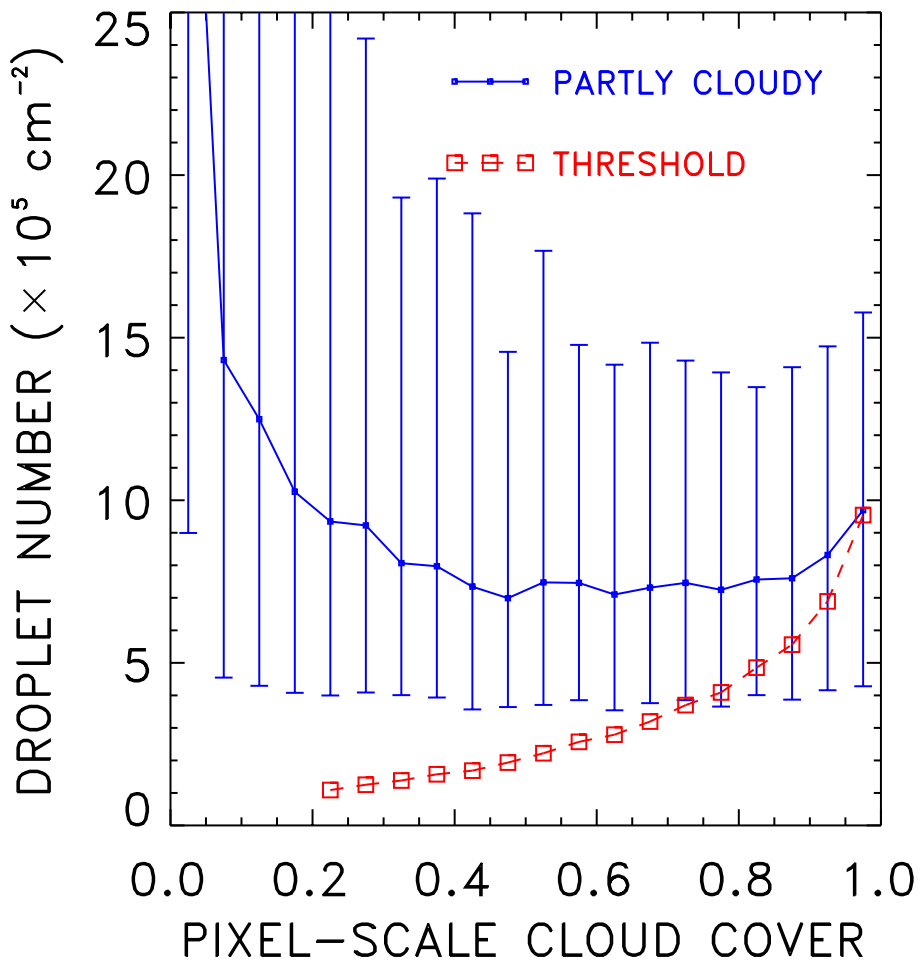
Aerosol Indirect Effect?





Threshold derived cloud optical depth increases with decreasing droplet radius. ***In contrast, partly cloudy pixel derived optical depths and droplet radii are positively correlated, except at large cloud cover fractions.***

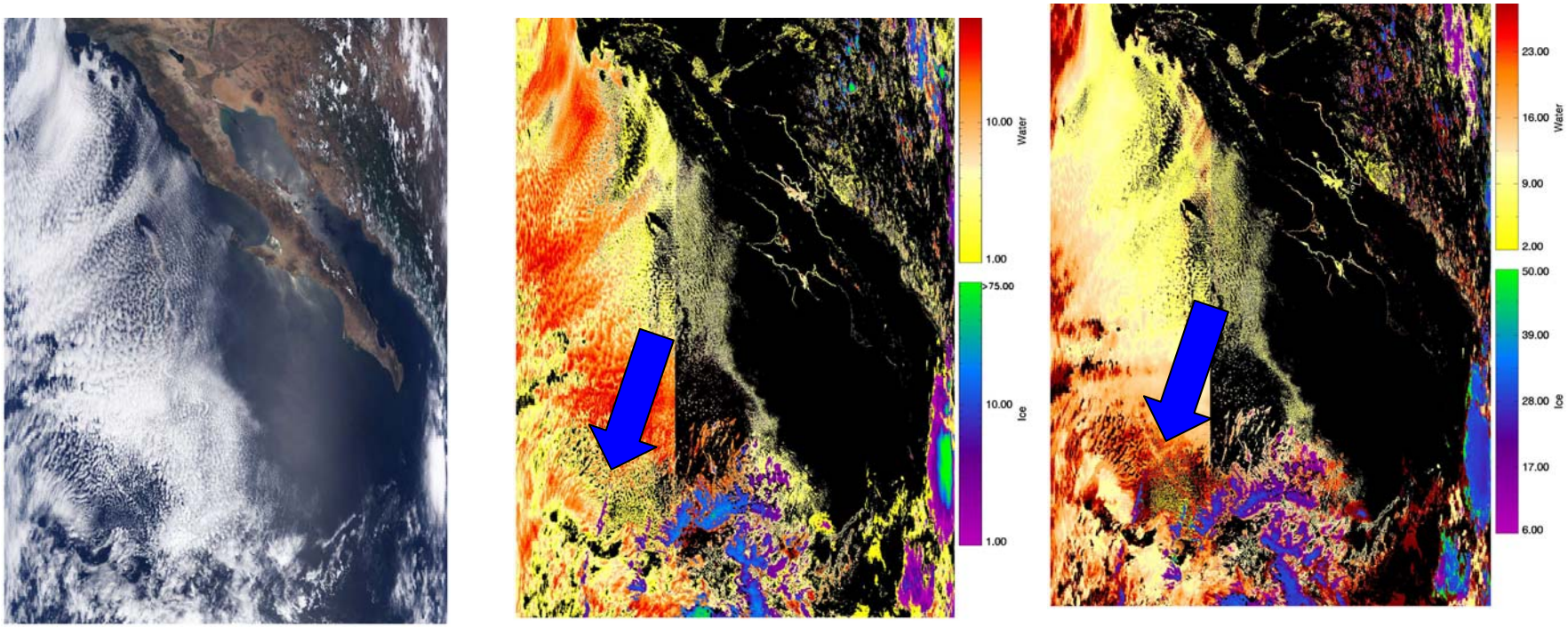
Droplet Number Concentration



- **Column droplet number concentration only slightly smaller for clouds in partly cloudy pixels than for clouds in overcast pixels.**
- **For Ac < 0.2 Column number concentration is fairly constant regardless of pixel-scale cloud cover fraction.**
- **In contrast, threshold retrievals produce droplet column numbers that support the impression that clouds are responding to effects of increased aerosol concentrations.**

Partly Cloudy Pixels in 1-km MODIS Retrievals

Visible Optical Depth **Droplet Radius**

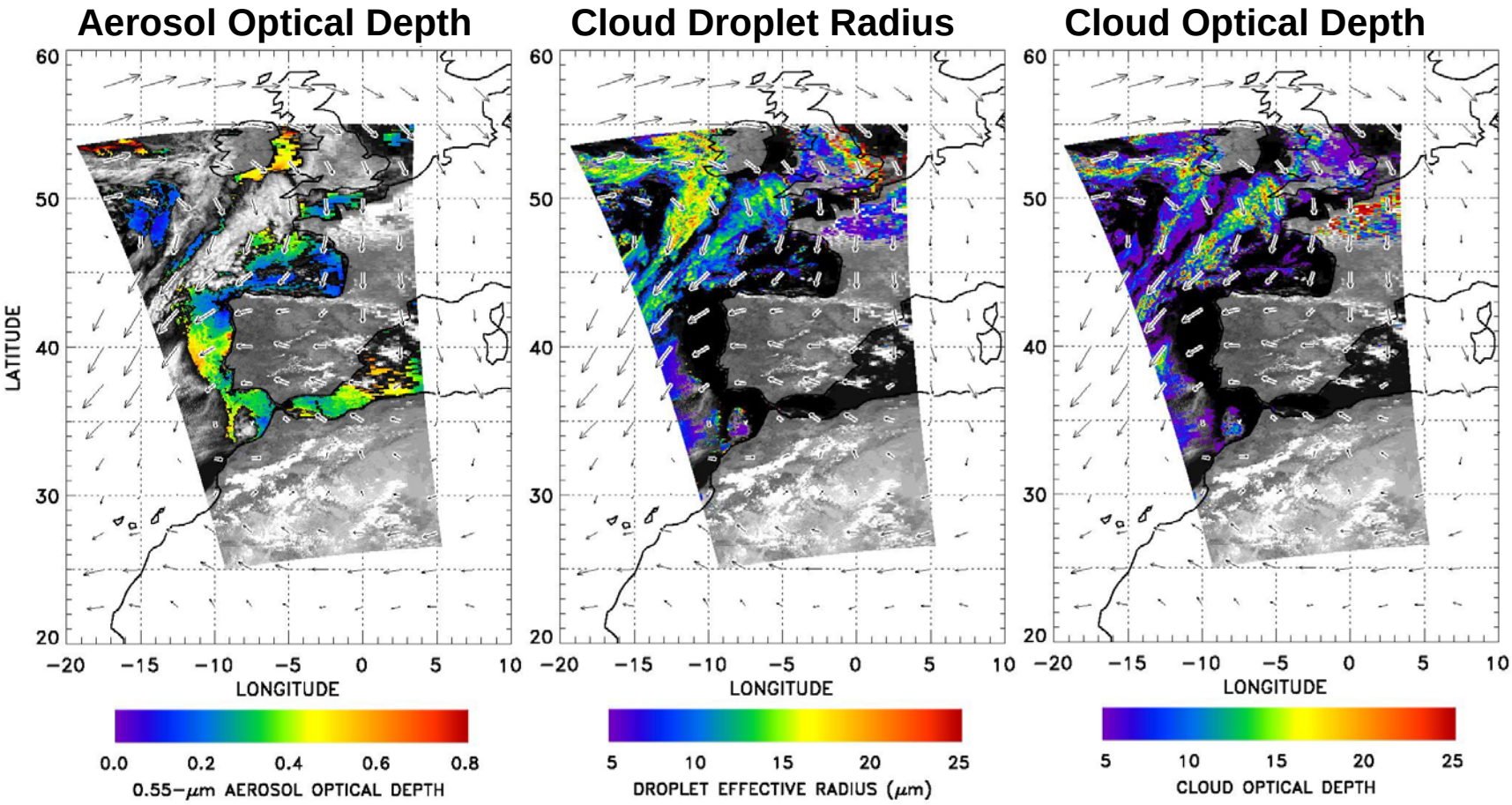


Terra 1-km MODIS data off the coast of California.

Where clouds break up, optical depths become small and droplet radii become large.

Aerosol and Cloud Optical Depth and Droplet Effective Radius

14 August 1995 1407 Z

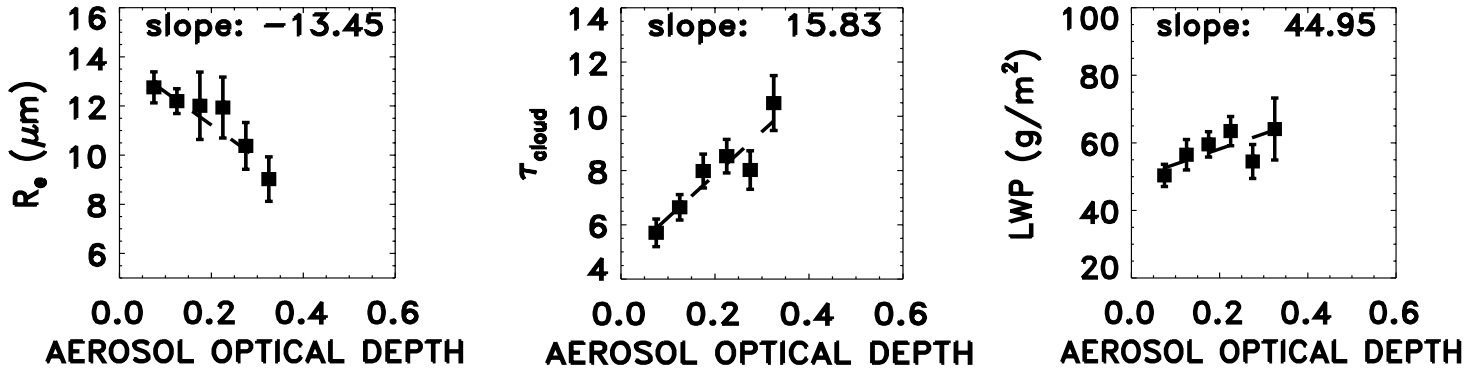


Source: Matheson et al. (2004)

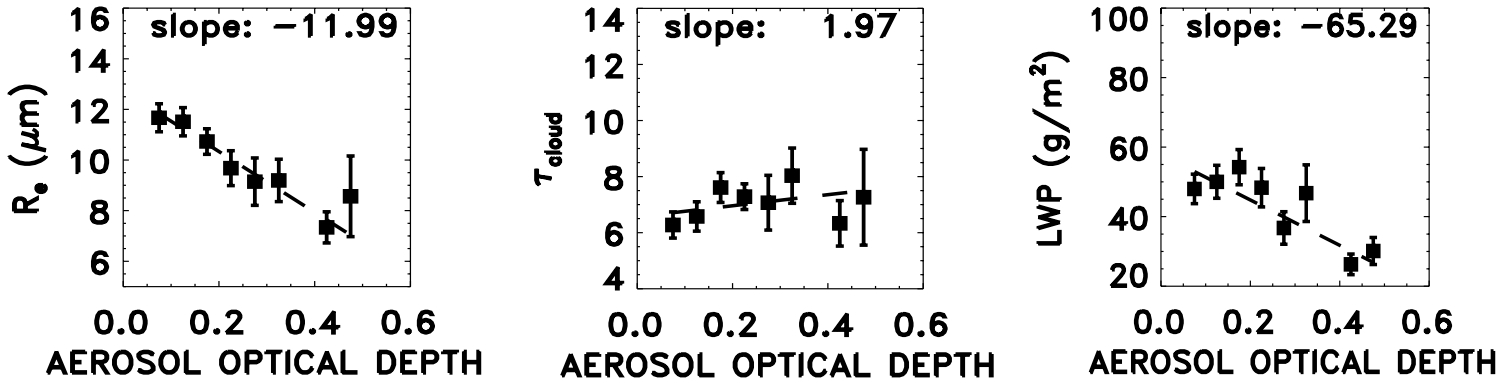
Composite Cloud Properties and Aerosol Optical Depth

5° × 5° Latitude – Longitude Regions, Summer 1995

Small Aerosol Burden, Maritime – 47.5N, 17.5W



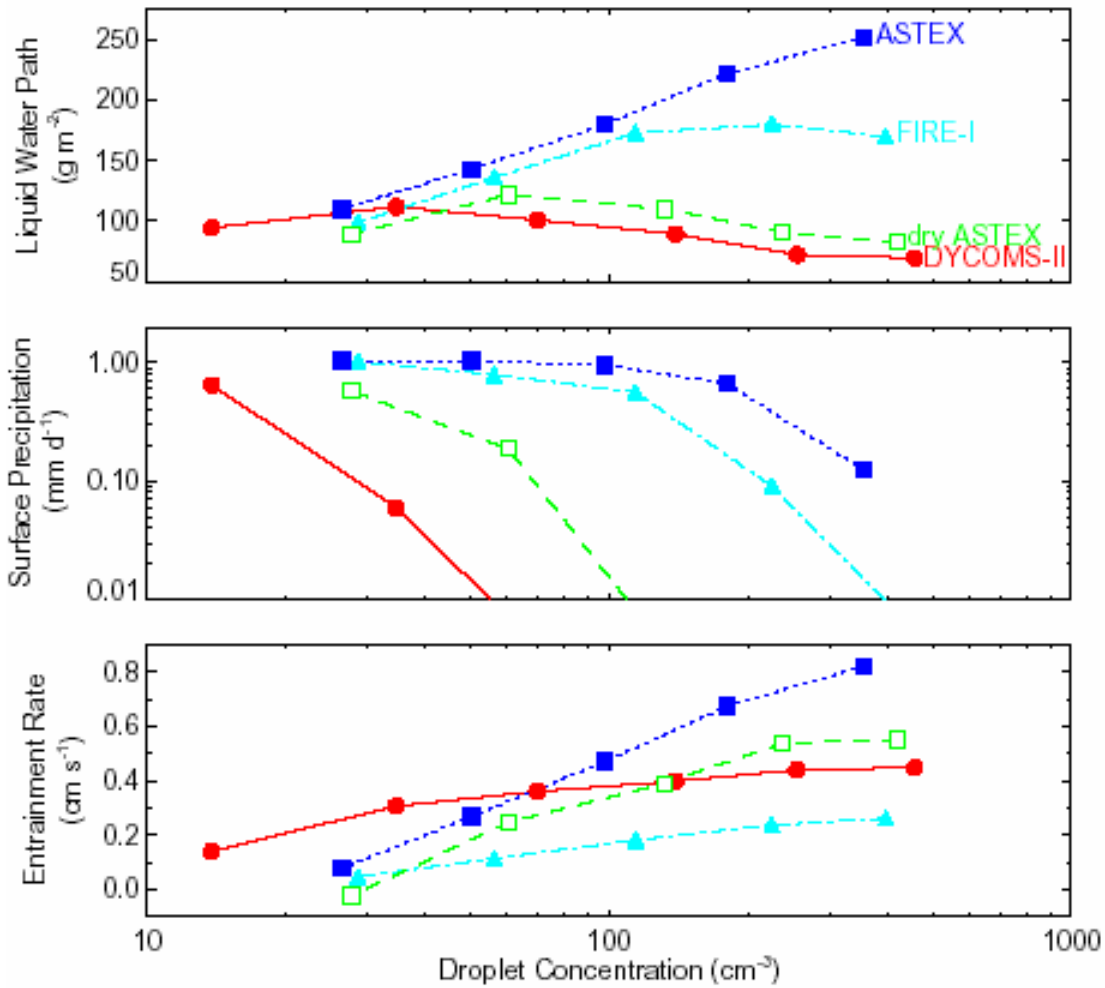
Large Aerosol Burden, Coastal – 42.5N, 12.5W



Source: Matheson et al. (2004)

Large Eddy Simulations

- **Simulations performed for different environmental conditions: *dry air aloft*, as in DYCOMS-II and *moist air aloft* as in ASTEX.**
- **When air aloft is sufficiently dry, entrainment of the dry air can be sufficient to dry out the cloud and boundary layer. The polluted clouds lose liquid water.**



Source: Ackerman et al. (2004)

Summary: Aerosol Indirect Radiative Forcing

- The key is learning what happens to cloud liquid water when clouds are polluted.
- Possible changes in fractional cloud cover as a response to the pollution will have to be accounted for.
- Existing observations and LES model simulations show that cloud liquid water can either increase or decrease with increasing particle concentrations.
- The response of clouds to the thermodynamics of their environment (i.e. cloud-climate feedback) will have to be understood to obtain reliable assessments of the aerosol indirect forcing from either model calculations or observations.

Summary of Current Status

Estimates of the aerosol indirect

AND

direct forcing…

- **… are hampered by the inability to distinguish between cloud contamination, growth of particles with increasing relative humidity, and extra illumination of aerosols by sunlight from the sides of clouds.**
- **… will require *both surface-based and space-based* observing systems for *both aerosols and clouds*.**
- **… will require better understanding of the effects of thermodynamics on cloud properties (cloud-climate feedback problem).**