Main Points

Why this panel?

- Satellite data are often *misinterpreted* or *over-interpreted* (my view)
  - -- MODIS 'anthropogenic' aerosol; MISR 'SSA'; AERONET SSA

Some Measurement-related Strengths

- Satellites can measure aerosol amount and 'type' (away from cloud & sometimes above cloud)
- Satellites can measure aerosol layer & near-source plume elevation
- Satellites can measure cloud fraction, cloud phase, α_c, τ_c, p_c, N_c, r_c, LWP, $q_v(z)$, $T(z)$, cloud height
- Aerosols tend to concentrate in layers, even when transported long distances
- Special cases: Ship tracks, Aircraft Contrails, Stratus over smokestacks (perturbation + control)

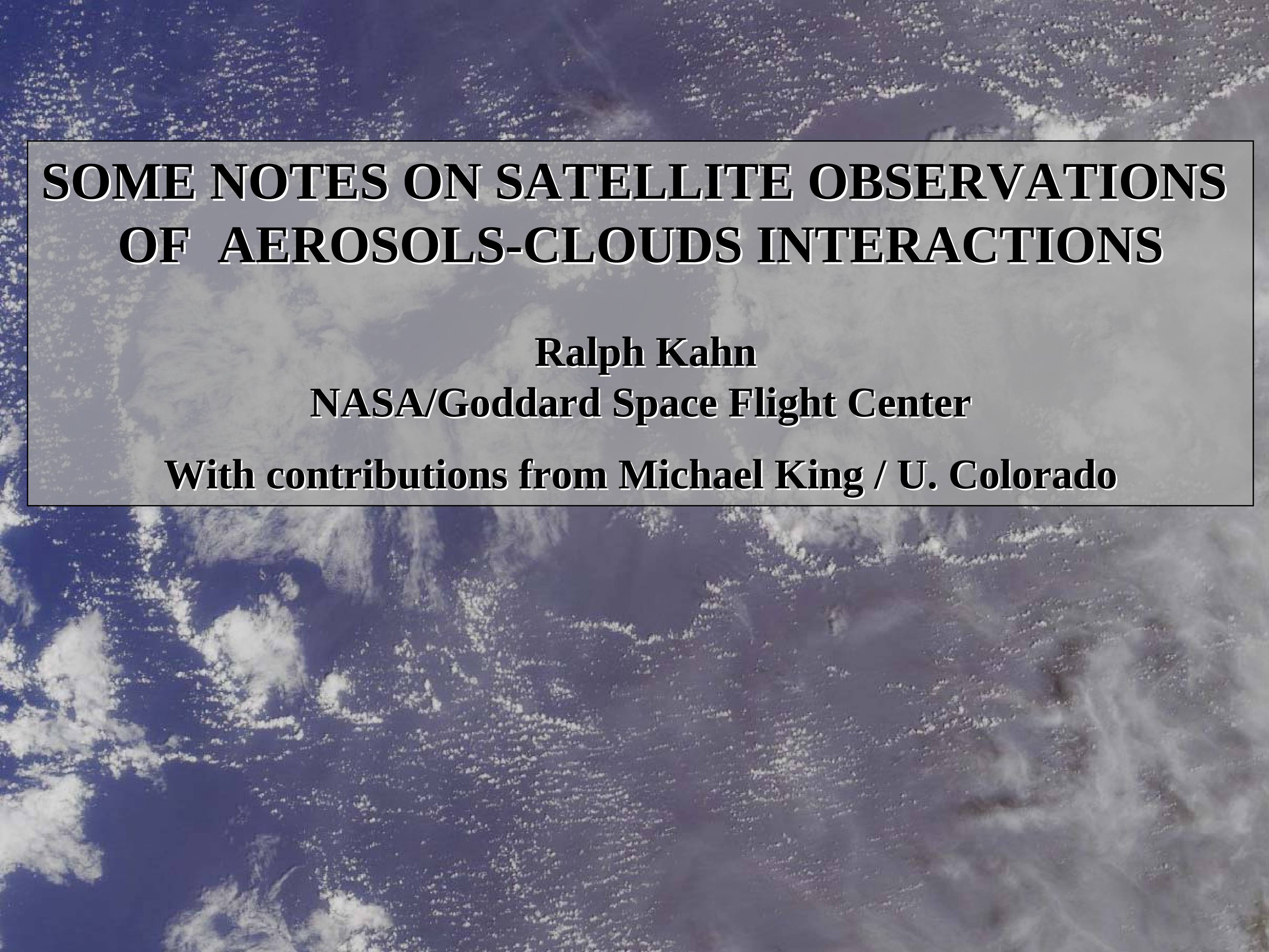
Some Measurement-related Issues – Please Read and Take Seriously the Quality Statements

- Difficult to retrieve aerosols when they are collocated (especially in 3-D) with cloud
  - -- Cloud-scattered light & cloud "contamination" can affect near-cloud aerosol retrievals
- Not always easy to distinguish cloud from aerosol particles (particle hydration; cloud-processing)
- Remote-sensing cannot retrieve particles smaller than about 0.1 μm diameter (most CCN)
- Factors can co-vary
  - -- LWP can decrease as aerosol number concentration increases (also depends on atm. stability)
- Remote sensing usually sees only some weighted vertical average of cloud particle properties
- Time & spatial scales of many aerosol-cloud interactions do not match satellite sampling

What Next?

- *Kaufman* {*AOD; FMF*}; *Matsui* {τ_c, r_c, LWP; stab.}; *Oreopoulos-Platnick* {α_c, r_c}; *Nakajima* {τ_c, r_c};
  - -- *McComiskey & Feingold* {PDFs of N_a, w;*LWP*} in cloud parcel model
- Need <u>quantitative</u> tests of mechanisms
- Identify where, when, and what combinations of ***new*** measurements are most needed

Backup Slides

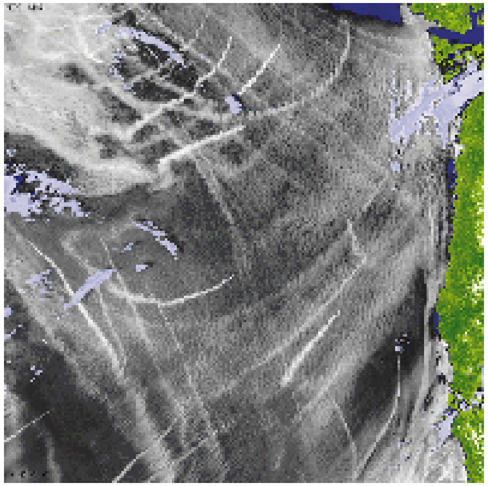


SOME NOTES ON SATELLITE OBSERVATIONS OF AEROSOLS-CLOUDS INTERACTIONS

Ralph Kahn
NASA/Goddard Space Flight Center

With contributions from Michael King / U. Colorado

SATELLITES DEMONSTRATE EFFECT OF AEROSOLS ON CLOUDS – IN SPECIAL CASES (1)



AVHRR, US W. Coast
(from Toon, *Science* 2000)

Ship Tracks – Test of Cloud Albedo Effect

Coakley et al., *Science* 1987

- **Statically stable** AVHRR scenes
- Fairly **uniform** low-level marine stratus ~ few 100 km
- **No** ship-track signal at **11** microns
- **Weak** effect at **0.67** microns – 1.6% ± 0.7%
  Scattering important but not absorption, and ***LWP*** & ***r_c* vary**
- **Significant** effect at **3.7 microns** – 3.9% ± 0.4%
  Smaller, more numerous particles → **Scattering/Absorption ratio increases**

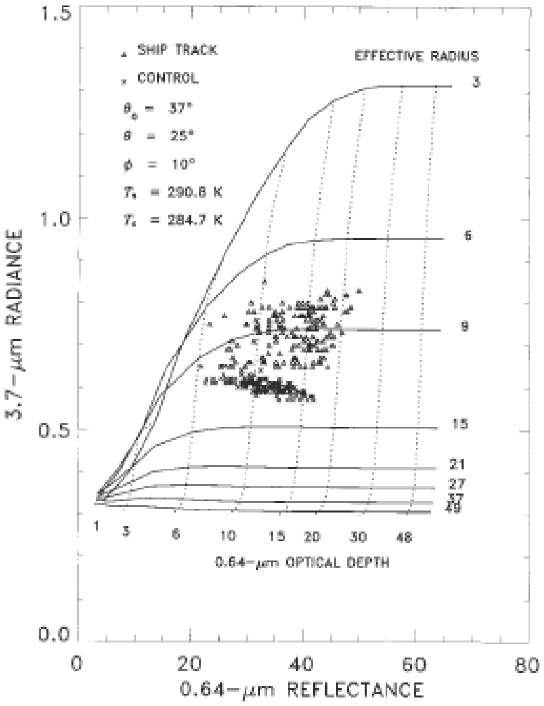
- The right **combination of meteorological conditions** and **measurements** is needed to observe the effect

- **Quantitatively, expect** ΔRefl(3.7) / ΔRefl(0.67) **~ 0.6 to 2.6**
  Observed 0.4 → Increased **absorption** and/or decreased ***LWP*** occur (*opposite LWP* effect)

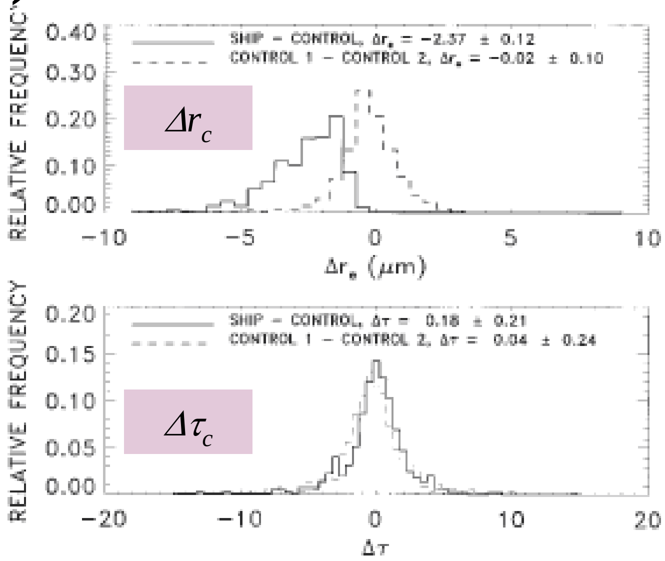
SATELLITES DEMONSTRATE EFFECT OF AEROSOLS ON CLOUDS – IN SPECIAL CASES (1)

Ship Tracks – Test of Cloud Albedo Effect (Cont’d)

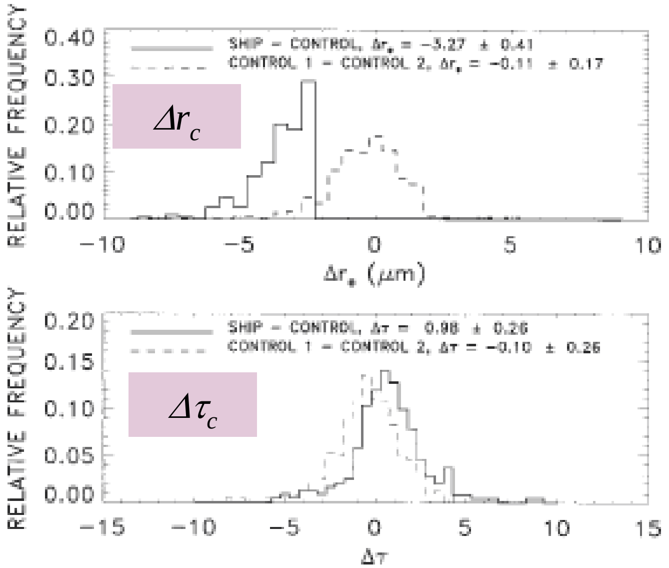
Coakley and Walsh *JAS* 2002



τ_c and r_c from 0.64 and 3.7-micron AVHRR (plane-parallel RT)



All 452 cases -- solid = polluted



224 cases where Δr_c > 2 micron

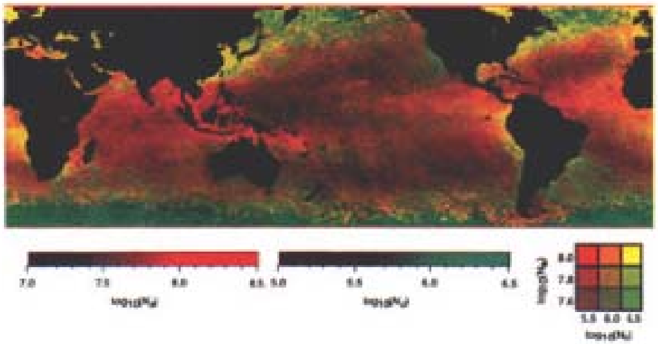
Observed $\Delta\tau_c$ --> ***15-20% reduction in LWP***, even accounting for aerosol *SSA*

Satellites Demonstrate Effect of Aerosols on Clouds – Correlation Studies (1)

Over Global Ocean – Test of Cloud Radius Effect

Nakajima et al., *GRL* 2001

- **AVHRR scenes** for Jan, Apr, Jul, & Oct 1990
- Assume **bi-modal aerosol** dist. of **fixed** r_a and σ
- 0.67 and 3.4 micron channels for τ_a and **coarse/fine**
- Use AI (= *Ang.* x τ_a) + fixed sizes to estimate N_a
- 0.67, 3.4, and 11 micron channels for τ_c and r_c
- **Negative** correlation between **fine-mode** N_a and r_c in **low-cloud** areas (yellow color)
- **Positive** correlation between N_a and τ_c
- Cloud **Liquid Water Path** ($2r_c\tau_c/3$) **~ Independent** of N_a



Log N_a vs. Log N_c
Yellow= N_a, N_c large
Red= N_a large, N_c small
Green= N_a small, N_c large

- **N_c not correlated with N_a in tropics** (red color) – aerosol-cloud interactions vary with aerosol type, cloud type, vertical distribution

[*Sekiguchi et al*, *JGR* 2003] extend this approach to $N_a \sim \{N_c, r_c, \tau_c, T_c$, cld. fraction$\}$; global & regional correlations aggregated from near-coincident observations

Satellites Demonstrate Effect of Aerosols on Clouds – Correlation Studies (2)

POLDER – Cloud Radius Effect

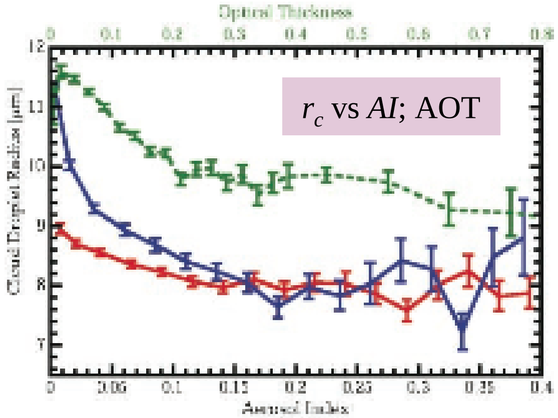
Bréon et al., *Science* 2002

- March-May 1997; 60˚N to 45˚S
- **Aerosol Index** (*AI*= τ_a x *Ang*) ~ aerosol column number
- **r_c over land & water** from polarized signal angular shape
- **Uniform cloud** and **narrow size dist.** required
- **Seasonal Mean** *AI* and r_c from near-coincident obs.
- 1-day **Back-trajectory** to get *AI* in cloudy regions

- **r_c inversely correlated with *AI***
- Infer: More aerosols → smaller cloud drops
- **Steeper slope over water** than land
- Infer: Greater susceptibility over water
- Water & land **r_c same for large *AI***
- Uncertain sampling biases → difficult to quantify

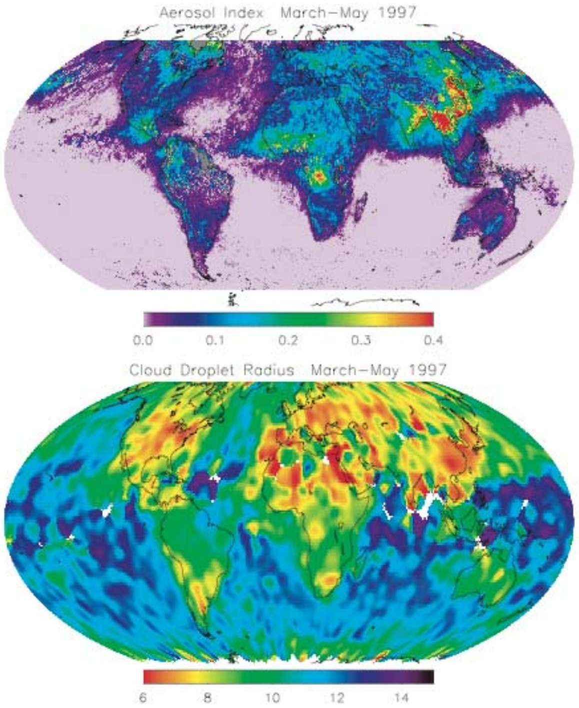
[*Quaas et al*., *JGR* 2004]

- *Half* the r_c vs *AI* slope over land; sampling differences?
- ***LWP*** (~ r_c x τ_c) **increased** with ***AI*** (i.e., with ***decreased r_c***) for *AI*>0.1 (N. mid-lat.) → cloud lifetime *LWC* effect?



r_c vs *AI*; AOT

Red=Land; Blue=Ocean; Green=Ocean AOT; (error bars indicate variability)



Global *AI* (top) and r_c

CORRELATION STUDIES (3): AEROSOL CONVECTIVE CLOUD "INVIGORATION" HYPOTHESIS

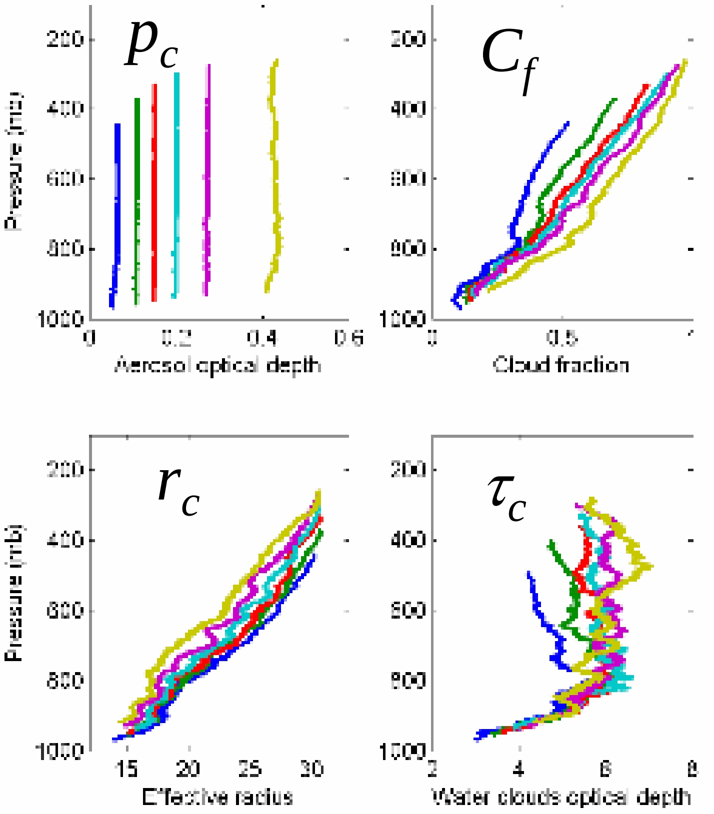
Kaufman, *Koren*, *Rosenfeld*, *Remer*, *Rudich*, articles published and submitted

- **$1/r_c \sim N_c \sim N_a \sim \tau_a$** [Cloud Radius Effect]
- **r_c decrease → early precipitation inhibited → stronger updrafts →**

higher cloud tops, **higher cloud fraction**, **glaciation and heat release at higher elevations**

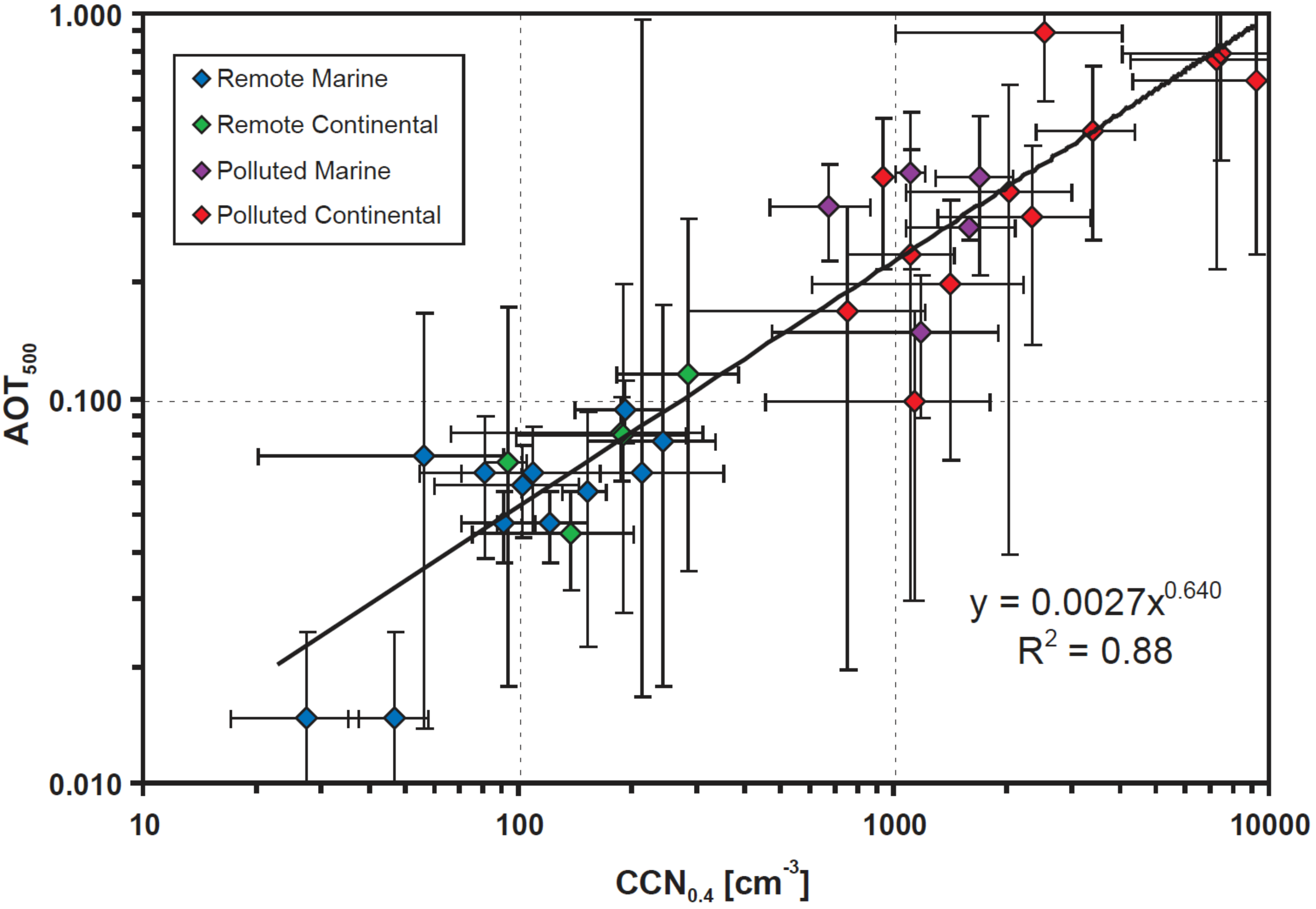
- **MODIS data** $\{\tau_a, C_f, \tau_c, r_c, T_c, p_c\}$
- Aggregated to 1° x 1° from higher-resolution daily measurements, so ***aerosol and cloud information are treated as "simultaneous"***
- **NCEP wind and *RH* profiles** to test correlations w/meteorological factors

- **C_f, T_c, τ_c(water clouds)** all **increase w/τ_a**
- **τ_c(ice clouds)** decreases or is unchanged Infer anvils grow, which increases C_f at the expense of τ_c



Colors show τ_a

Correlation Between AOD from Space and CCN in Remote & Polluted Regions



Andreae ACP 2009

ISSUES (5): USING *AI* (= τ_a x *Ang*) to Estimate *CCN*

Kapustin, Clarke, et al., JGR 2006

- <u>Test</u> <u>Idea</u>: Smaller particles more likely to become *CCN*; ***Ang*** is a smaller quantity for larger particles
- ACE-Asia, Trace-P *in situ* **field data** – *CCN* proxy

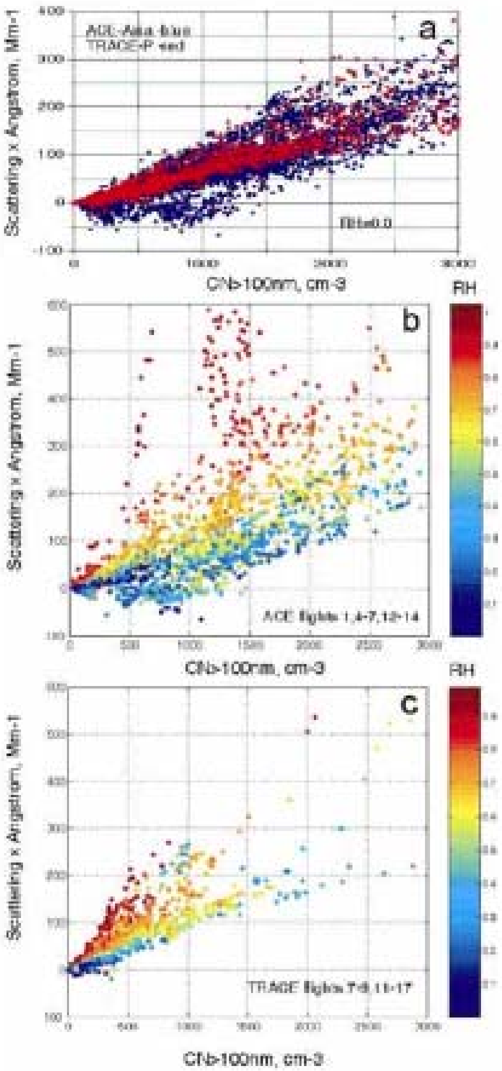
- **AI does not work quantitatively in general**, but can **<u>if the data are stratified</u>** by:

-- ***RH*** in the aerosol layer(s) observed by satellites
-- **Aerosol Type** (hygroscopicity; pollution, BB, dust)
-- **Aerosol Size** (*Ang* is not unique for bi-modal dist.)

Practically, in addition to τ_a and *Ang*, this requires:

-- Vertical **humidity structure**
-- **Height-resolved** aerosol **type**
-- **Height-resolved size** dist.
[extrapolated to small sizes(?)]

This study includes enough detail to assess *AI ~ N_a* *<u>and</u>* *AI ~ CCN*



AI vs. *in situ CCN* proxy
(a) all ACE (blue) & Trace-P, **<u>dry</u>**
(b) ACE - OPC-only, amb. *RH*
(c) TP - OPC-only, amb. *RH*

Cloud Optical & Microphysical Properties

(M. D. King and S. Platnick)

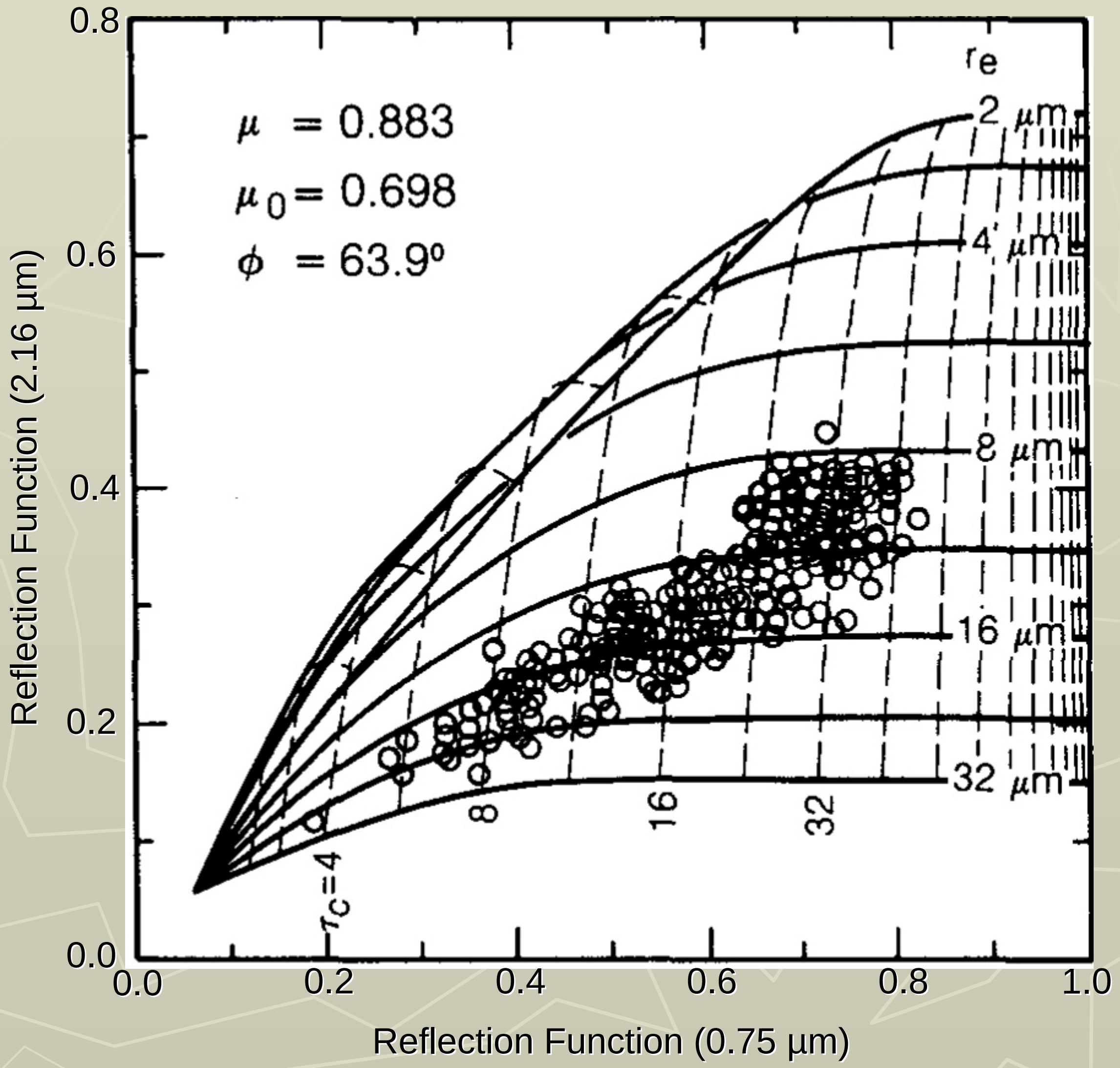
- Pixel-level cloud product during daytime at 1 km
  - Daytime defined as $\theta_0 < 81.4°$ to be consistent with cloud mask
- Critical input (especially for global processing):
  - Cloud mask: to retrieve or not to retrieve?
  - Cloud thermodynamic phase: liquid water or ice libraries?
  - Cloud top temperature, ancillary surface temperature: needed for 3.74 µm emission characterization (band contains solar and emissive signal), *T*(sfc) from NCEP, Reynolds SST
  - Atmospheric correction: requires cloud top pressure, ancillary information regarding atmospheric moisture & temperature (e.g., NCEP, other MODIS products)
  - Surface albedo: for land, ancillary information regarding snow/ice extent (e.g., NISE)

Retrieval of τ_c and r_e

(T. Nakajima and M. D. King)

Cloud Optical Properties

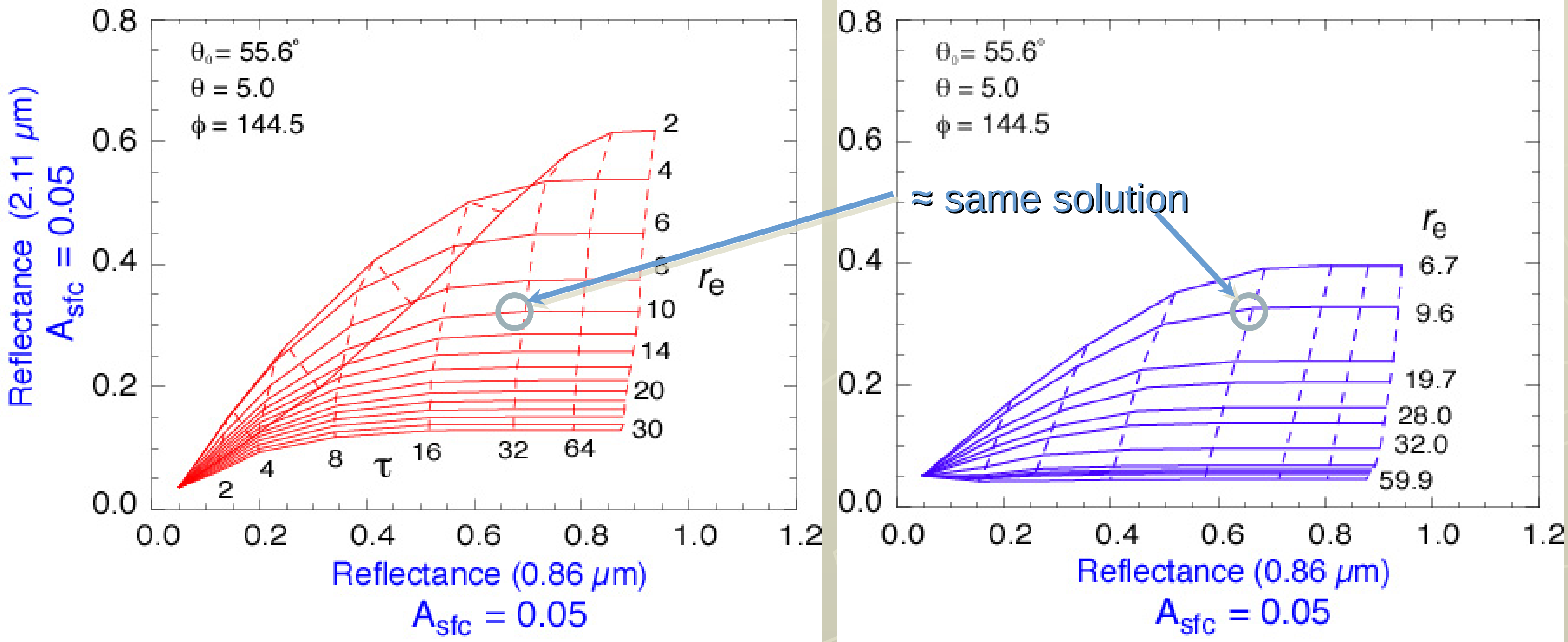
- The reflection function of a nonabsorbing band (e.g., 0.75 µm) is primarily a function of optical thickness
- The reflection function of a near-infrared absorbing band (e.g., 2.16 µm) is primarily a function of effective radius
  - clouds with small drops (or ice crystals) reflect more than those with large particles
- For optically thick clouds, there is a near orthogonality in the retrieval of τ_c and r_e using a visible and near-infrared band



Nakajima and King
King et al. (1992)

Cloud Optical & Microphysical Retrievals

Retrieval space examples



≈ same solution

Liquid water

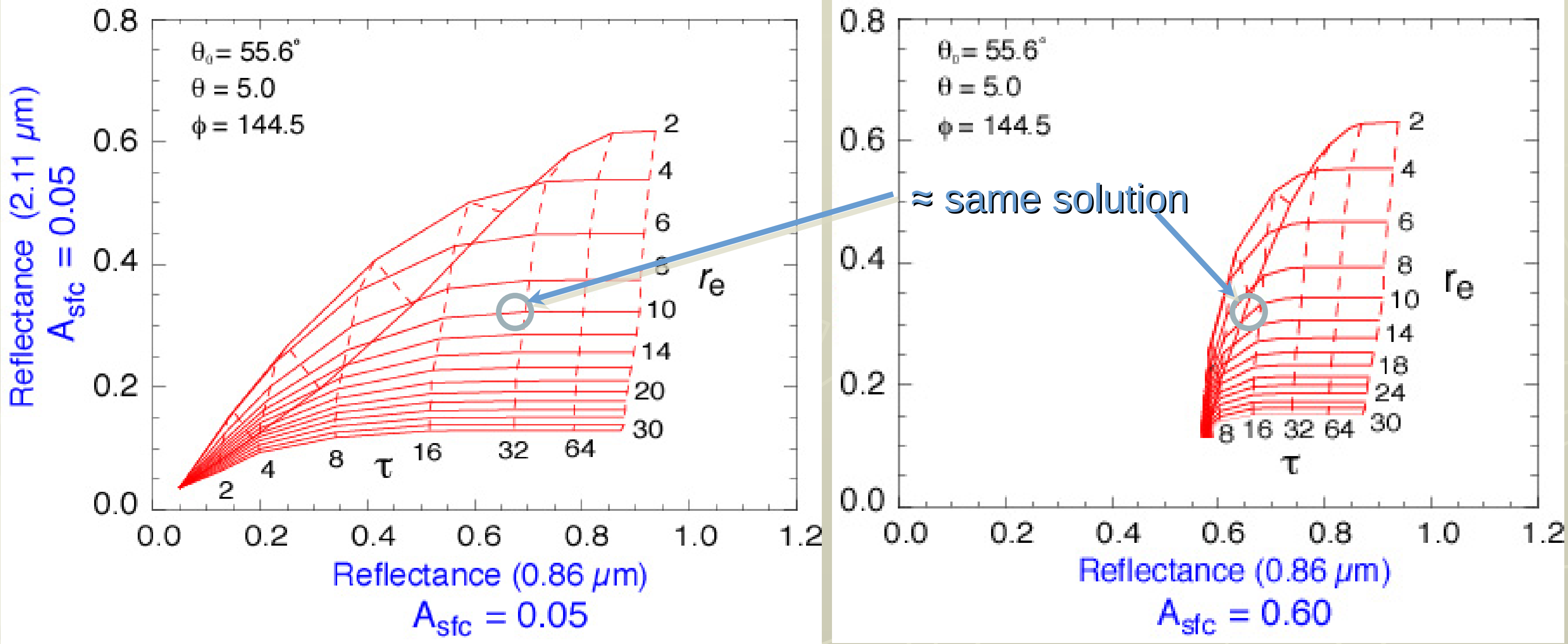
ocean surface

Ice cloud

ocean

Cloud Optical & Microphysical Retrievals

Retrieval space examples



≈ same solution

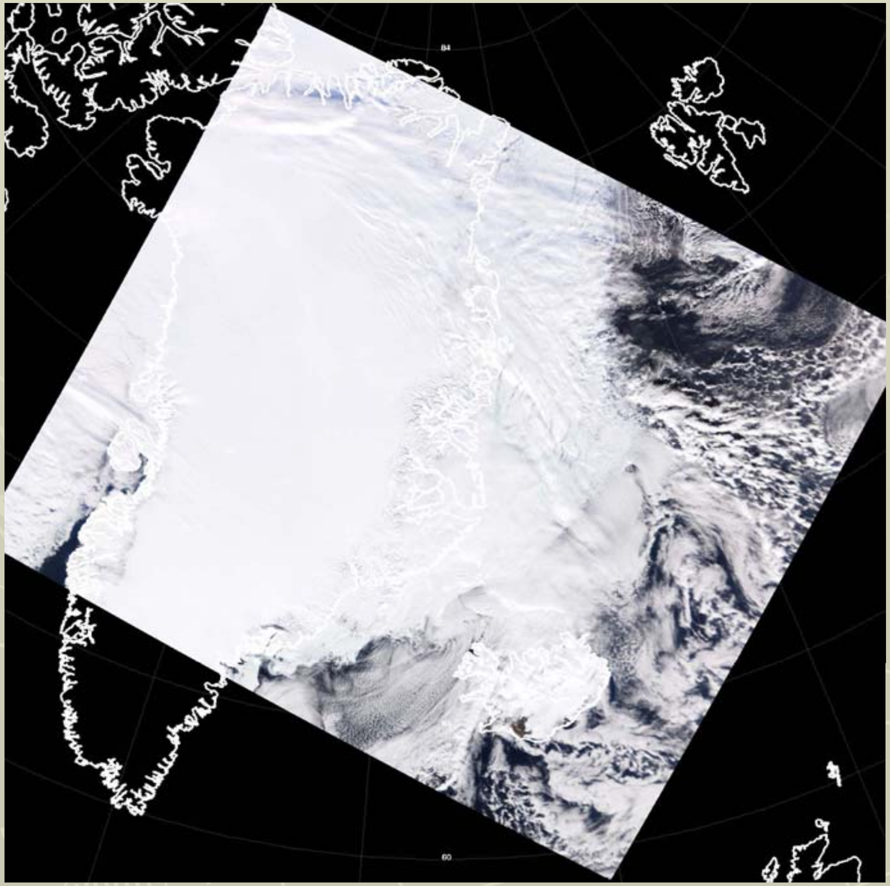
Liquid water
ocean surface

Liquid water
ice surface

Terra/MODIS Cloud Thermodynamic Phase

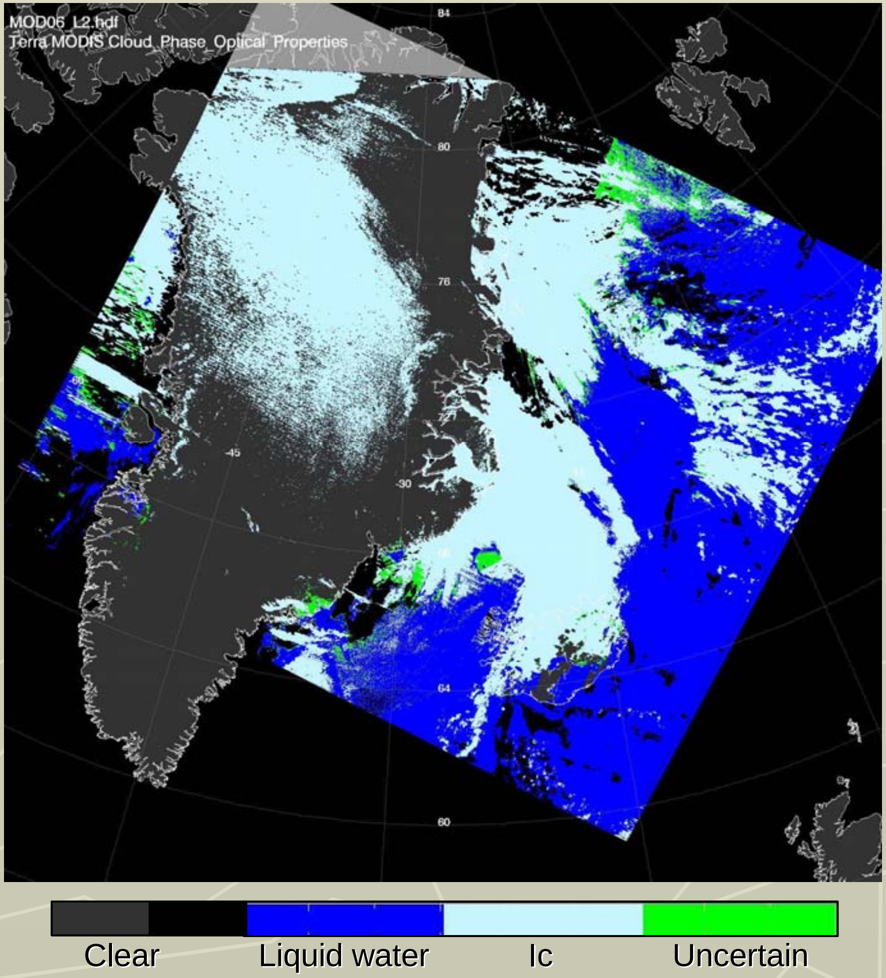
(M. D. King, S. Platnick, J. Riedi et al. – NASA GSFC, U. Lille)

True Color Composite (0.65, 0.56,



March 22, 2001

Thermodynamic

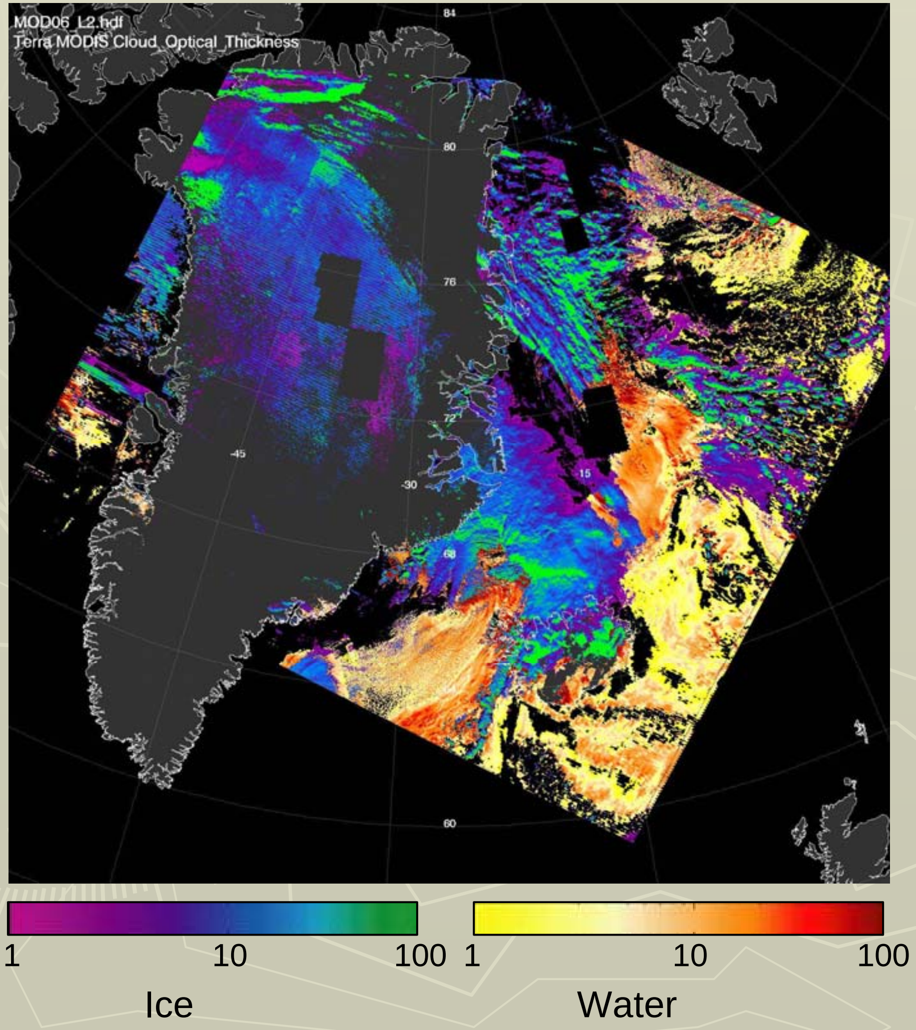


Collection 5

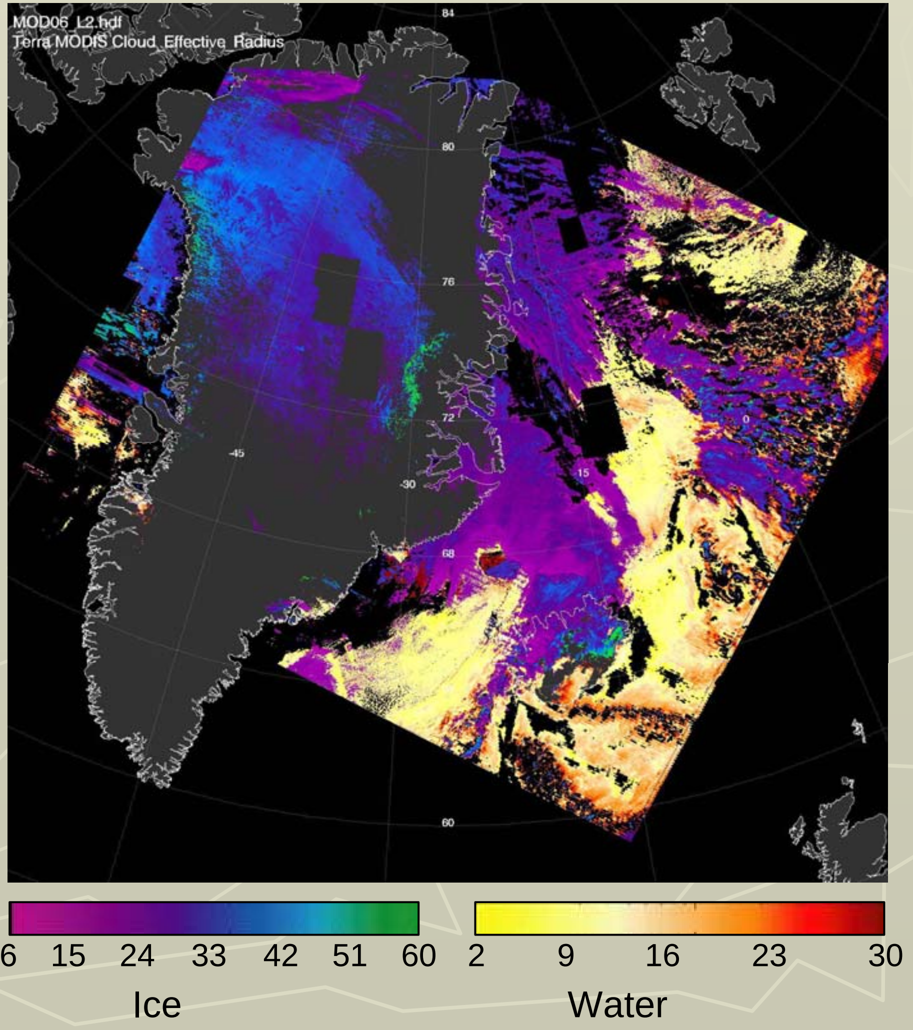
Cloud Optical Thickness and Effective Radius

(M. D. King, S. Platnick – NASA GSFC)

Cloud Optical



Cloud Effective Radius



Monthly Mean Cloud Fraction by Phase

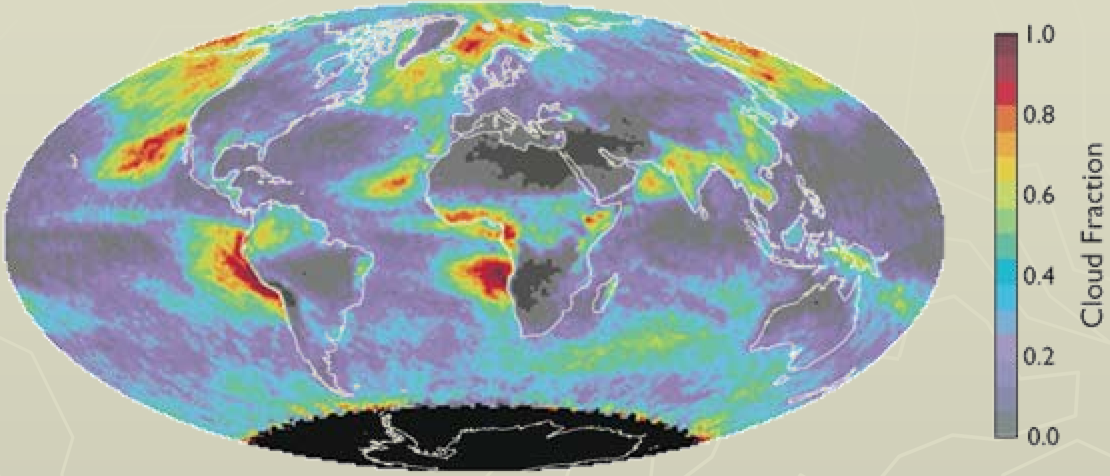
(M. D. King, S. Platnick et al. – NASA GSFC)

July 2006 (Collection 5)

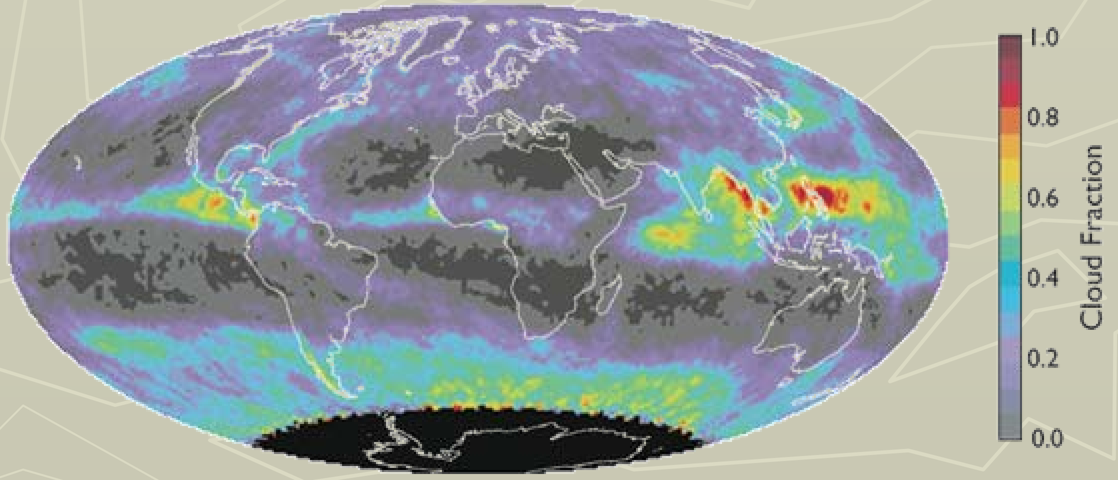
Terra

- Liquid water clouds
  - Marine stratocumulus regions
    - ✓ Angola/Namibia
    - ✓ Peru/Ecuador
    - ✓ California/Mexico
- Ice clouds
  - Tropics
    - ✓ Indonesia & western tropical Pacific
    - ✓ ITCZ
  - Roaring 40s

Cloud Fraction (Liquid Water)



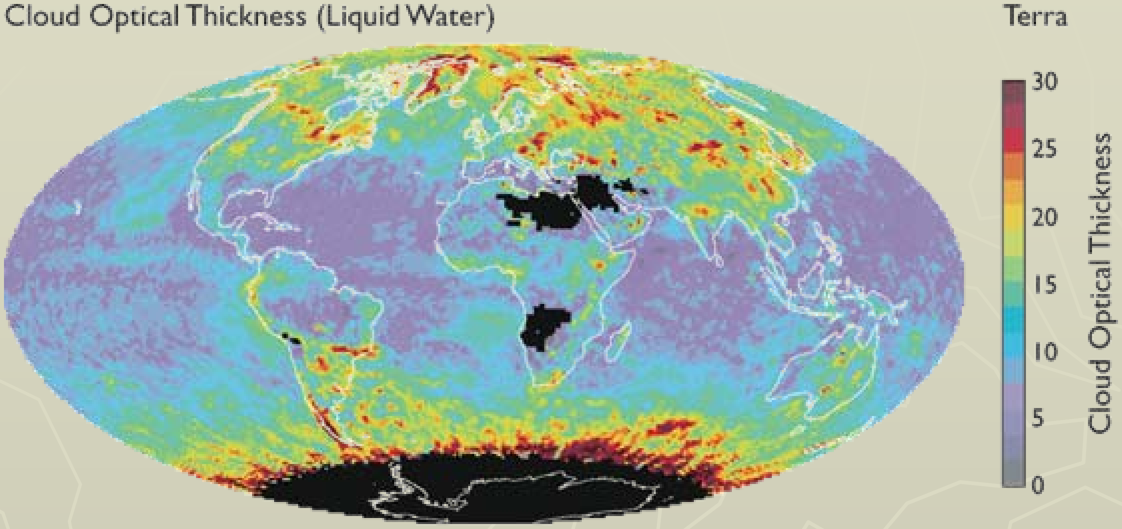
Cloud Fraction (Ice)

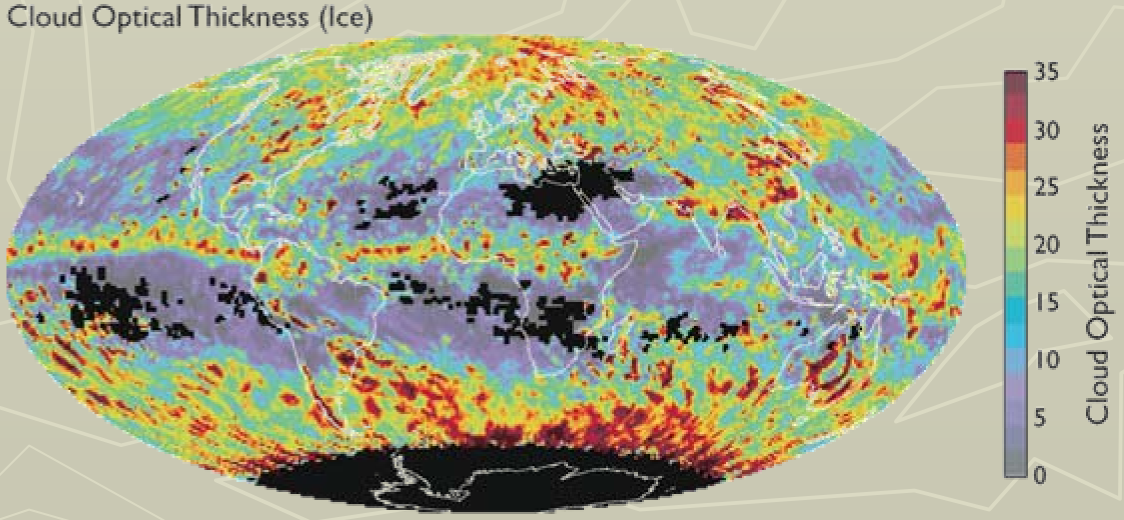


Monthly Mean Cloud Optical Thickness
(M. D. King, S. Platnick et al. – NASA GSFC)

July 2006 (Collection 5)
Terra (QA Mean)

- Liquid water clouds
  - Marine stratocumulus $\tau_c \sim 15$
  - Higher optical thickness over land than ocean
    - ✓ Cloud optical thickness near 5 in Indian Ocean
  - High optical thickness around roaring 40s
- Ice clouds
  - Larger in tropics (ITCZ)
  - High where deep convection occurs
    - ✓ Congo basin
    - ✓ Amazon basin
  - High optical thickness around roaring 40s
  - Higher over land than ocean


Cloud Optical Thickness (Liquid Water)

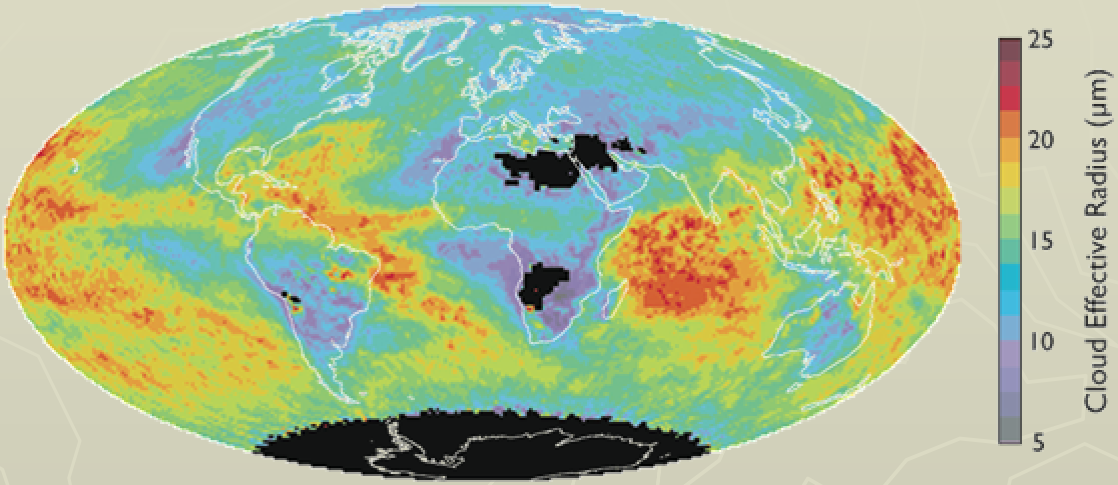

Cloud Optical Thickness (Ice)

Monthly Mean Cloud Effective Radius
(M. D. King, S. Platnick et al. – NASA GSFC)

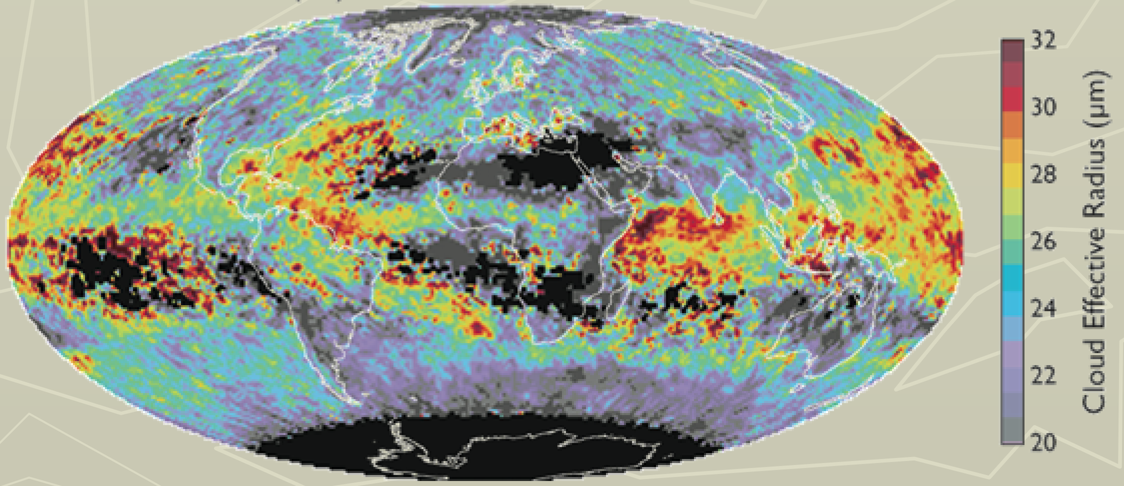
July 2006
Terra (QA Mean)

- Liquid water clouds
  - Larger drops in SH than NH
  - Larger drops over ocean than
    - ✓ Due to cloud condensation nuclei (aerosols)
- Ice clouds
  - Larger in tropics than high latitudes
    - ✓ Anvils
  - Small ice crystals at top of deep convection

Cloud Effective Radius (Liquid Water)



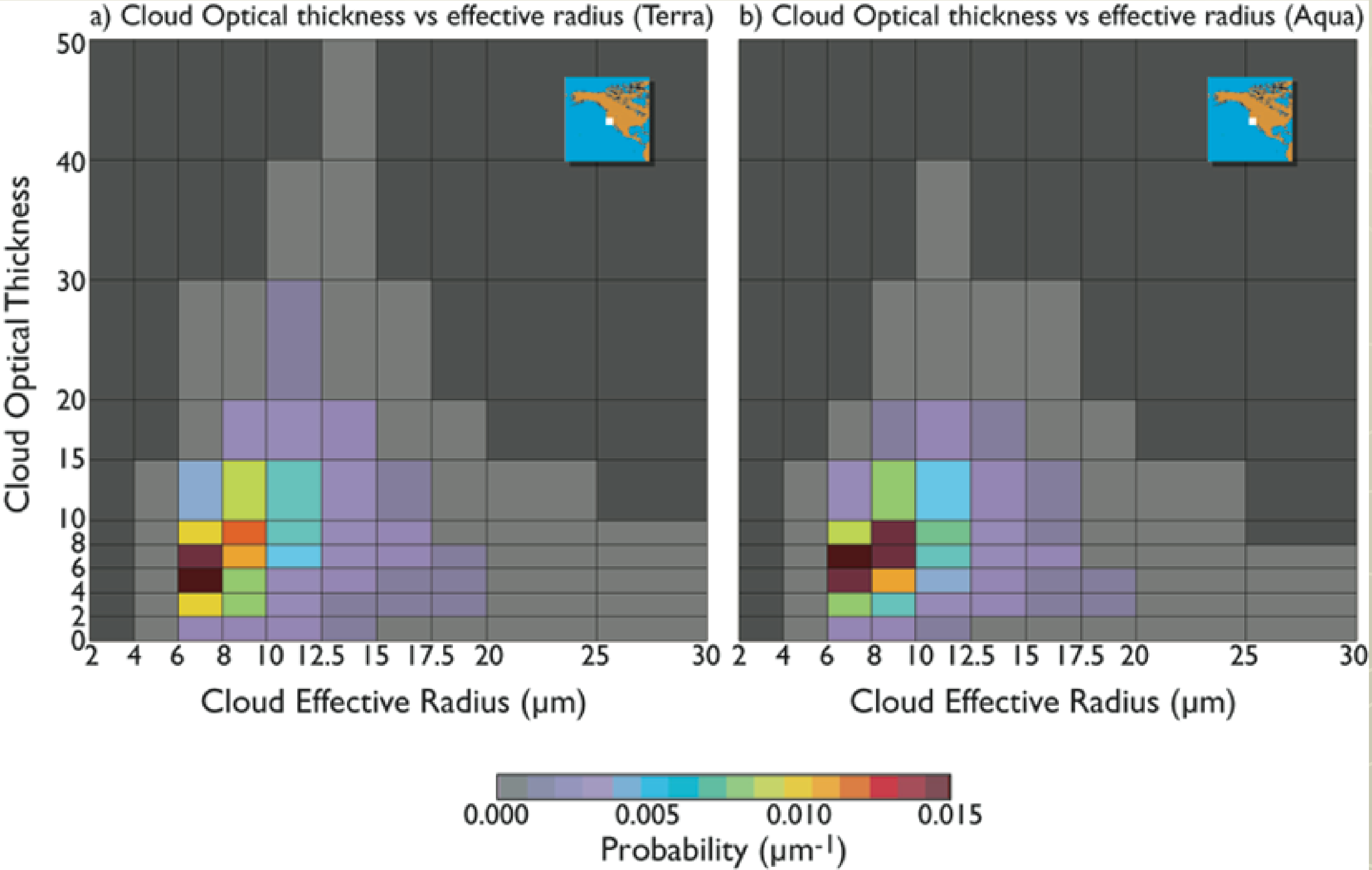
Cloud Effective Radius (Ice)



MODIS τ_c vs r_e Joint Histograms

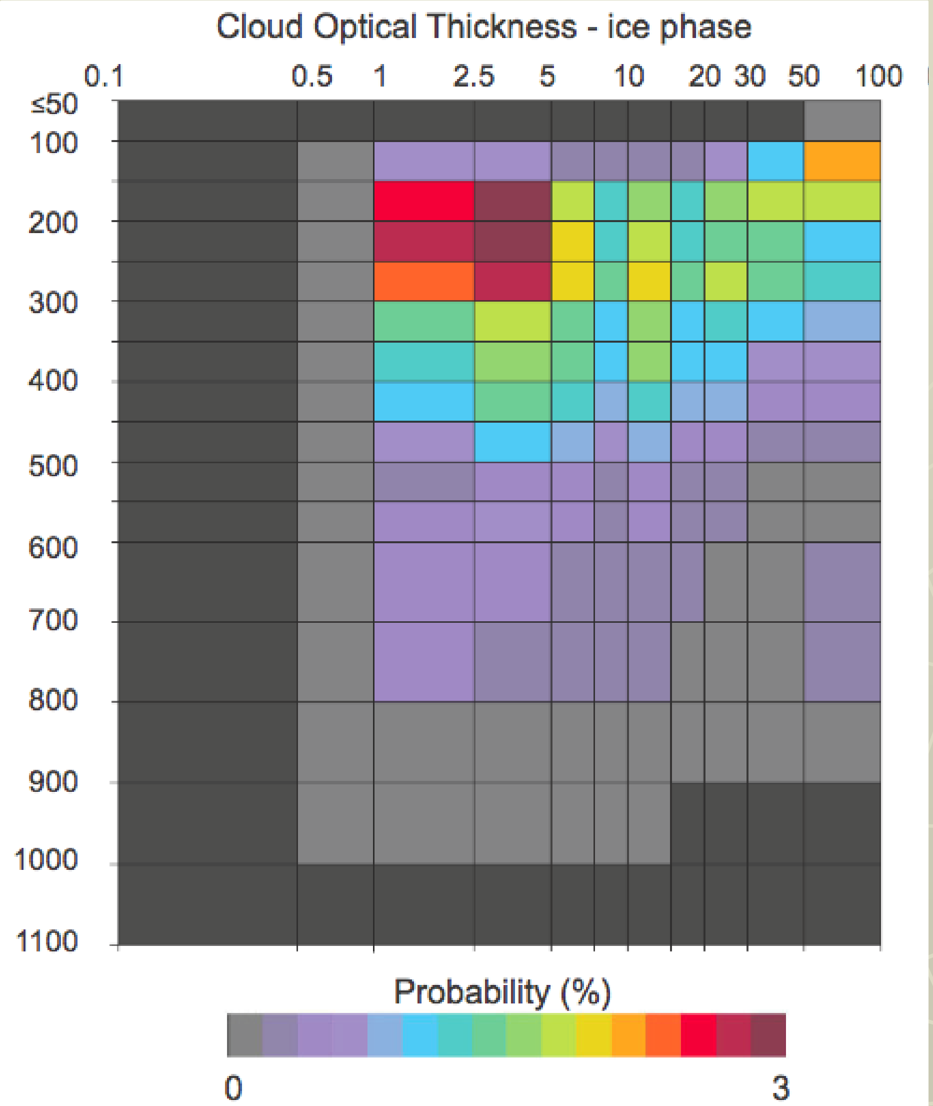
Liquid Water Clouds over Ocean

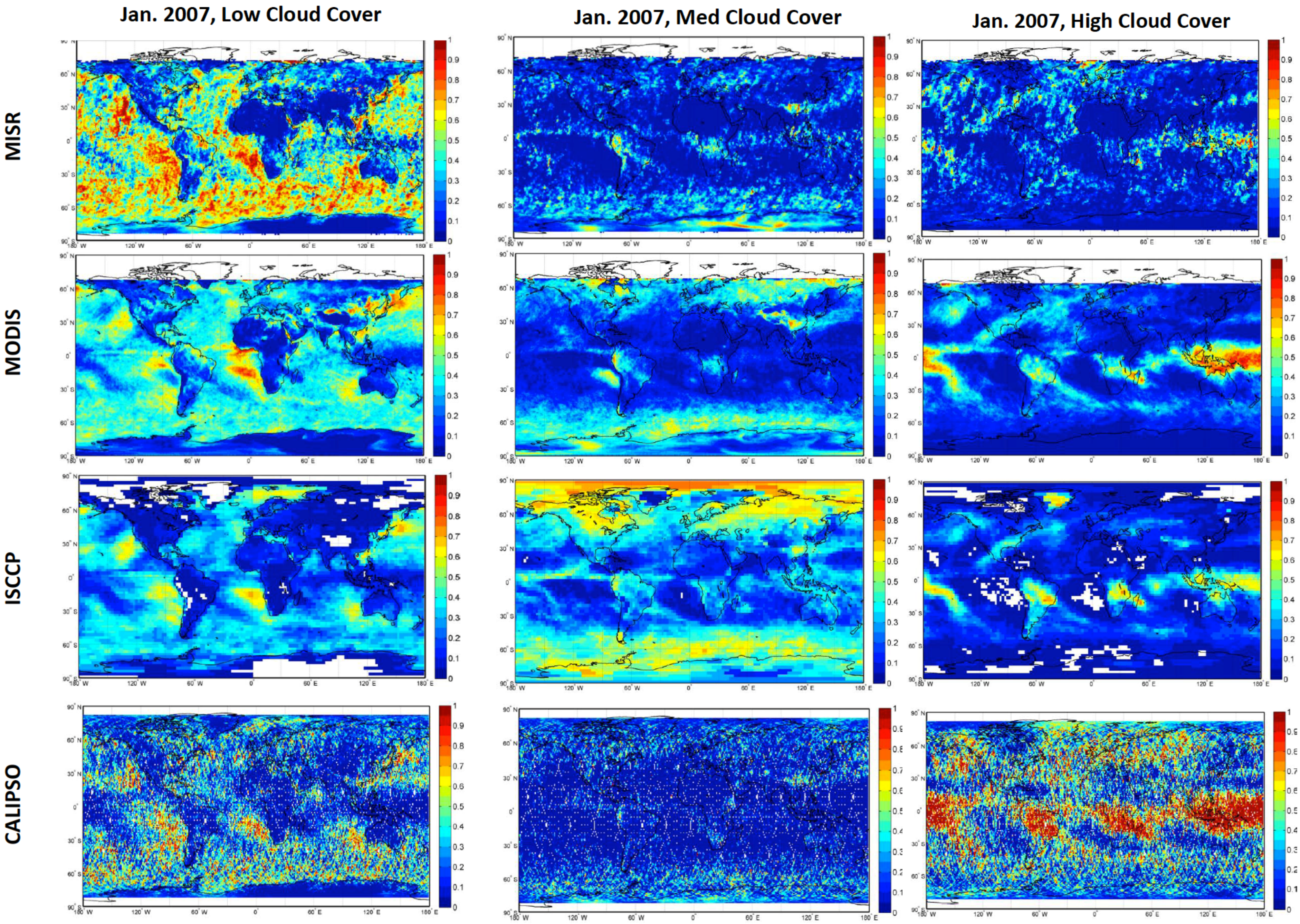
32°-40°N, 117°-125°W
July 2006



MODIS and ISCCP-like τ_c vs p_c Joint Histograms

50°N-50°S
Terra
August

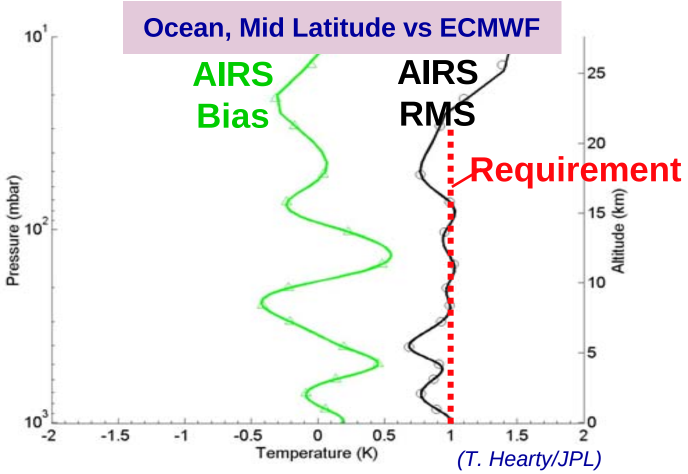




GEWEX Project

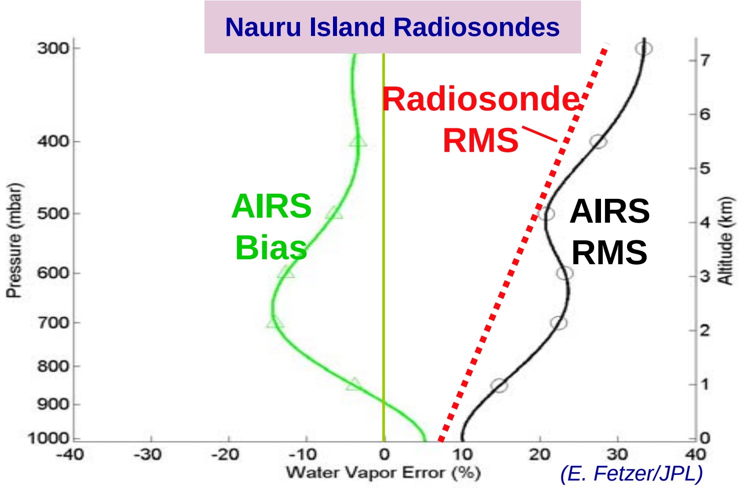
AIRS - Temperature & Water Vapor Profiles

Temperature Profiles
Accurate to 1K/km to 30 mb

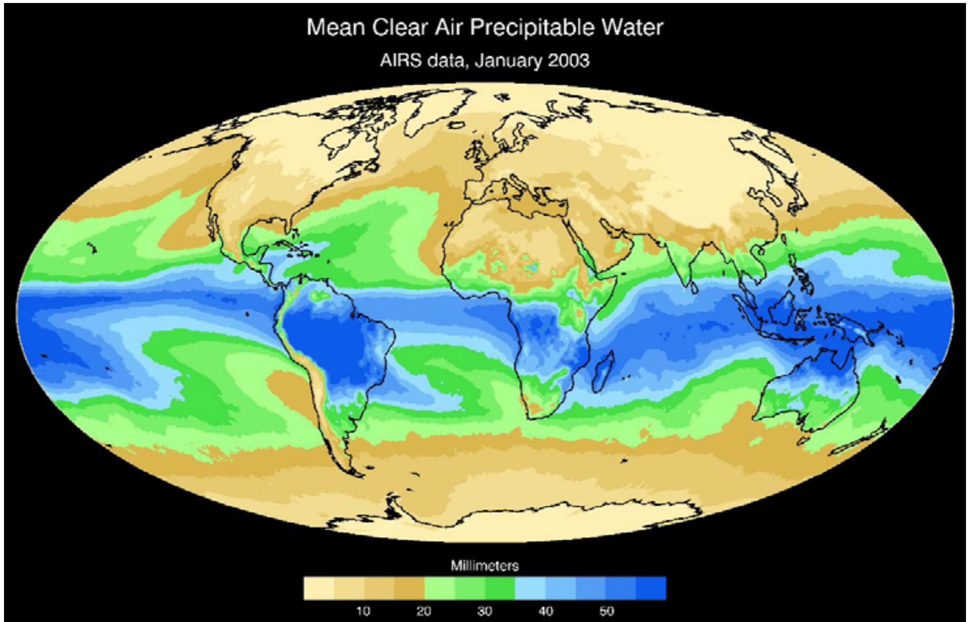


(T. Hearty/JPL)

Water Vapor Profiles
Match Observations 15%/2km



(E. Fetzer/JPL)

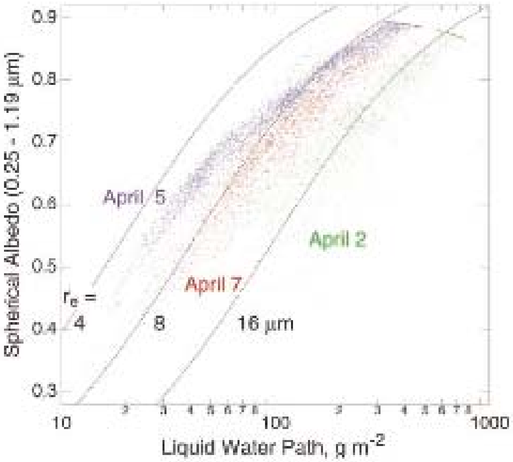


ISSUES (1) – CLOUD ALBEDO EFFECT W/ VARYING *LWP*

Synoptic-Scale Clouds – Combined Satellite & Model Analysis

Schwartz et al., *PNAS* 2002

- Two **week-long events** in April 1987
- **Low-level** (T_c)-cloud-filled (σ_{min}) pixels used
- **AVHRR 0.67** & **3.7 micron** bands for τ_c and $\boldsymbol{r_c}$
- $\boldsymbol{LWP}$ = 2/3 ρ_w τ_c $\langle \boldsymbol{r_c} \rangle$; with $\langle \boldsymbol{r_c} \rangle$ = 0.82 r_c
- α_c (cloud top spherical albedo) ~ **(**τ_c; $\boldsymbol{g}$) g=assym. factor
- **Aerosol Transport Model** predicts sulfate aerosol loading



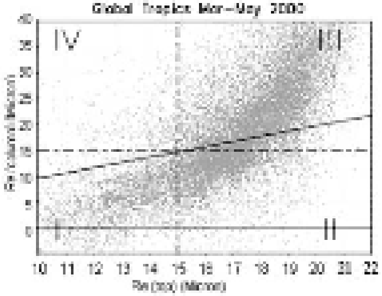
Cloud albedo vs. *LWP*, stratified by date (~r_c) [Most aerosol on April 5]

- $\boldsymbol{r_c}$ **decreased by ~ half** at the peak of each event
- τ_c and α_c show **no systematic change**
- ***LWP* decrease** with r_c (though *LWP* ~ cloud dynamics)
- α_c **increased by 0.02 to 0.15** with decreased r_c, for data **stratified by *LWP*** [i.e., comparing only perturbed & unperturbed having same *LWP*]. Sensitivity greatest for intermediate *LWP* (~ 100 gm/m^2)

ISSUES (2): VERTICAL STRUCTURE
r_c – CLOUD 'TOP' VS. CLOUD COLUMN, & *LTS*

Matsui et al., *GRL* 2004

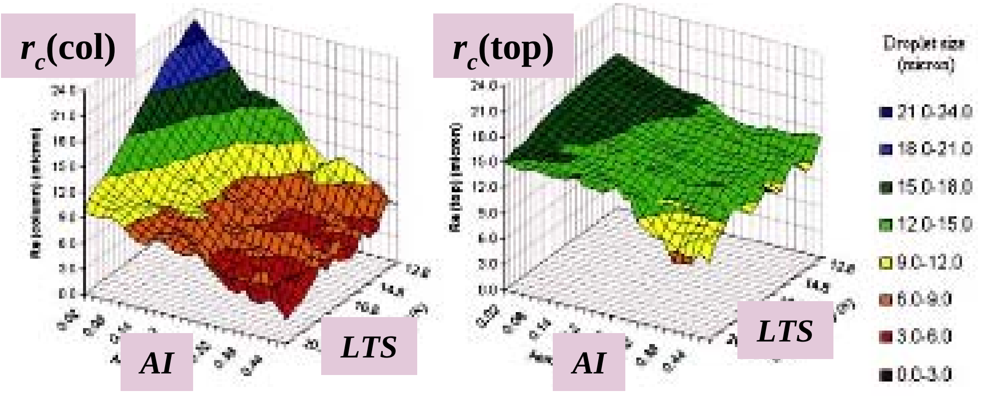
- **TRMM** data, March-May, 2000; 37°N to 37°S
- Vis-IR Radiance Imager (**VIRS**) for r_c**(top),** τ_c
- Microwave Imager (**TMI**) for r_c**(col),** ***LWP*** (19, 37GHz)
- Warm clouds only ($T_c > 273$ K)
- VIRS to find cloud-filled TMI pixels
- ***AI*** from **MODIS**
- **Lower Trop. Stability** (***LTS***) from **NCEP**



	r_c(top) vs.	r_c(col) (microns)	
I.	<15	<15	[non-ppt.]
II.	>15	<15	[transition]
III.	>15	>15	[ppt.]

- ***IE*** appears **larger** for r_c**(col)** than r_c(top)
- **Higher *LTS*** and/or ***AI*** ~ **reduced** r_c and **suppressed rain conditions**
- **Aerosol effect ~ 50% larger** than *LTS* effect
- TMI ***LWP*** **decreases with reduced** r_c → **net change in cloud albedo SMALL**

[dα_c/d*LTS* ~9%; *LTS* effect dominates]

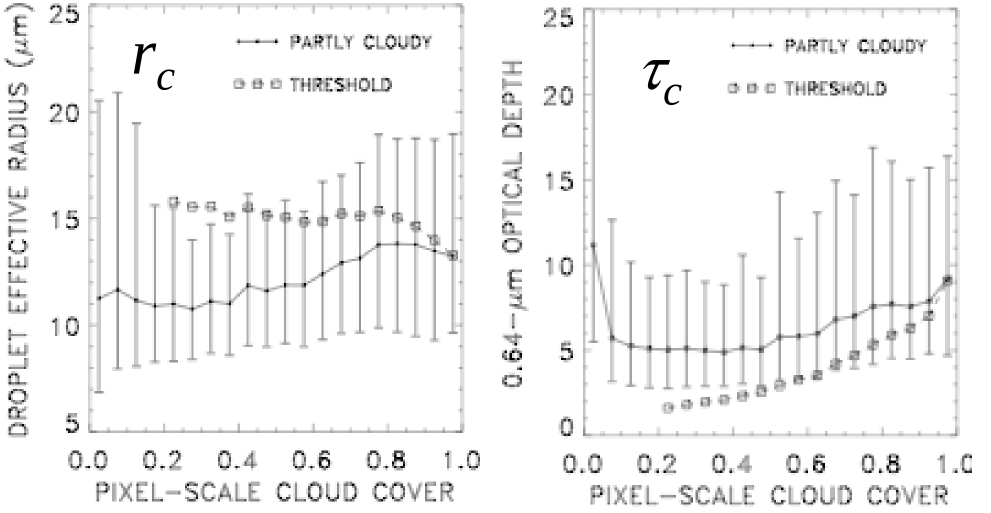


r_c vs. *AI* vs. *LTS*

ISSUES (3): PARTLY-FILLED PIX, SCATT. LIGHT BIASES

Coakely et al., J. Atmosph. Sci. 2005, JAOTech 2005; Loeb&Manalo-Smith, J Clim 2005

- VIRS 0.64, 1.6, 3.7, 11 *μm*
- **Low-level, single-layer** clouds
- Identify **cloud-free** pixels: ***land/water*** (0.64/1.6 'NDVI') + (for 3x3) σ (0.64 & 11) + ***threshold*** (0.64 & 11)
- Find remaining pixels that are **overcast**: σ (0.64 & 11) + ***threshold*** (0.64 & 11)
- Remaining are **partly cloudy** except if T_{11}> cloud-free pixels; or T_{11}< overcast pixels



r_c, τ_c, <u>vs</u>. Fraction of pixel cloudy

- Broken cloud found in **40% of 2 km pixels**
- A simple threshold approach **overestimates r_c**, C_f, and **underestimates τ_c**, z_c, N_c compared to *Partly Cloudy Pixel* [MODIS cloud algorithm flags large r_c, small τ_c pixels as uncertain]
- **C_f, τ_c, r_c, N_c decrease** with increasing fraction cloud-free
- Results depend on cloud type, weakly on spatial resolution

ISSUES (4): LARGER-SCALE SAMPLING BIASES

Example: *Rosenfeld and Feingold, GRL* 2003

First Indirect Effect: $IE \sim -d\, ln\, r_c / d\, ln\, \tau_a$

AVHRR – [*IE* ~ 0.17] over ocean

- **partly filled pixels, surface contributions → r_c *errors***
- **biased against thin & broken cloud, especially over land**

POLDER – [*IE* ~ 0.085] over ocean; [*IE* ~ 0.04] over land

- **"glory" to get r_c → favors monodisperse, uniform clouds**
- **biased against: thicker clouds, variable top height & r_c**

Thinner clouds → smaller updrafts, less activation, smaller *IE*
So POLDER may produce artificially low regional *IE* estimates

Brief Highlights of *Some* More Satellite-Related Recent Work

Indirect Effects Observed

Lebsock et al JGR 08 – [high aerosols ~ reduced LWP] for non-ppt. **warm oceanic clouds**, especially less stable cases; ***not*** for almost-ppt. clouds

L'Ecuyer et al. JGR 09 – More CSU multi-satellite confirmation of 1st and 2nd indirect effects for **warm maritime clouds**

Jiang et al. GRL 08 – S Am. dry season **polluted ice clouds** have smaller r_c and precipitate less (TRMM; MODIS; MLS CO and LWP data used)

Gasso, JGR 08 – Weak **volcanic activity** increases BL cloud brightness and decreases r_c and LWP.

Bell, Rosenfeld, et al. JGR & GRL 08 – Higher TRMM & maybe surf. rainfall **mid-week in SE US**; lower in adjacent Atlantic → arsl. effect(?)

Satellite Retrieval Issues

Wen, Marshak, et al. JGR 08 – **Aerosol** retrieval **3-D Radiative** effects, bluing due to cloud → Rayleigh scattering (theory + field observations)

Zhao, Di Girolamo, et al. GRL 09 – RICO: **sub-pixel (<1.1 km) tropical cumulus** biases MISR AOD less than 10^{-2} in regional average

Tackett & Di Girolamo GRL 10 – nighttime CALIPSO show enhanced aerosol size and number concentration near cloud

Su et al. JGR 08 – Near-cloud **RH &/or cloud processing**: AOD 8%–17% higher within 100 m of E US clouds based on HSRL

Twohy, Coakley, Tahnk JGR 09 – INDOEX: 5% RH increase approaching clouds → *observed* ~50% aerosol scattering increase

Horvath & Davies GRL 04, Di Girolamo et al. GRL 10 – Maritime **Cloud** retrieval **3-D Radiative** effects on r_c and τ_c

CCN Characterization from Space

Dusek et al. Sci 06 – **Size matters** more than chemistry for CCN (84-96% of total for the 06 study),

Hudson GRL 07 & Dusek et al. GRL 10 – **Chemistry** is more difficult to measure, but it matters too

Clarke & Kapustin Sci 10 – Aircraft **CO**, volatile and non-volatile AOD, which can be measured from space, as region-specific CCN concentration proxies

SATELLITE CONTRIBUTION: WHERE WE’VE BEEN

→ Need to measure **both** **Causes** (Aerosols) and **Effects** (Clouds)

[My Opinion]	**Special Cases**	**Global Scale***
• **First Indirect Effect**		
– **Cloud Radius**	**quantitatively**	**qualitatively**
– **Albedo**	**quantitatively**?	**qualitatively**?
• **Second Indirect Effect**		
– **Cloud Lifetime**	**qualitatively**	**qualitatively**?
– ***LWP***	**quantitatively**	**qualitatively**?
→ **Sign apparently depends on conditions** not yet well-understood		
• **Semi-direct Effect**		
– **Cloud Darkening**	**qualitatively**	??
– **Thinning**	**qualitatively**	??

*Primarily or exclusively for single-layer, stratiform water clouds