Boundary Layer Cloud Characterization with Passive Satellite Imagers: Capabilities, Limitations, Future Needs

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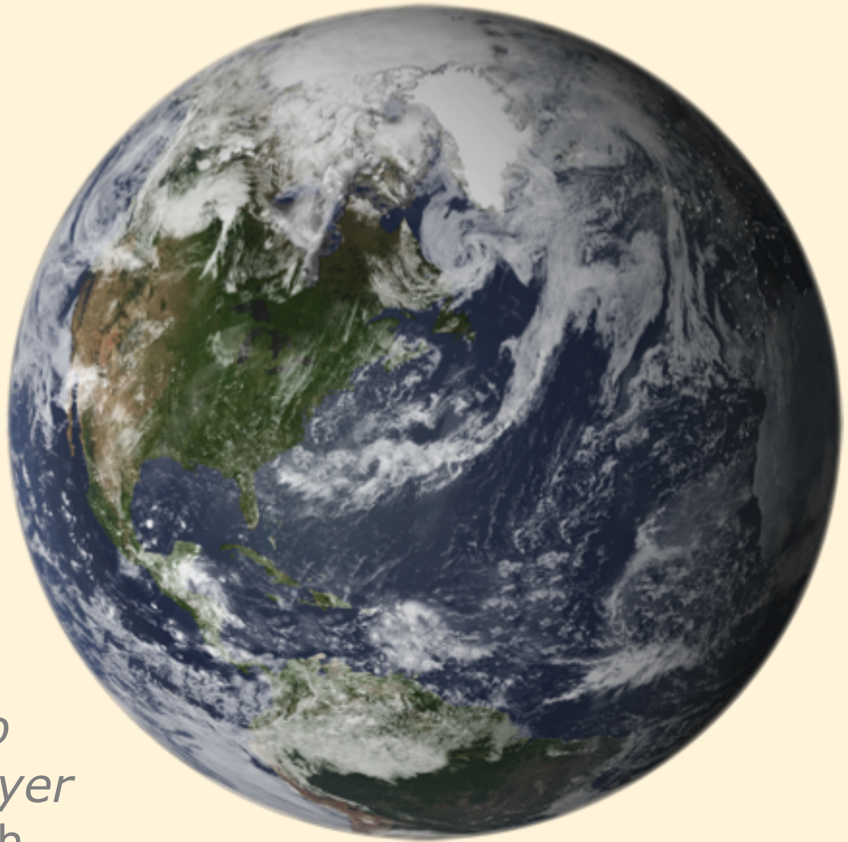
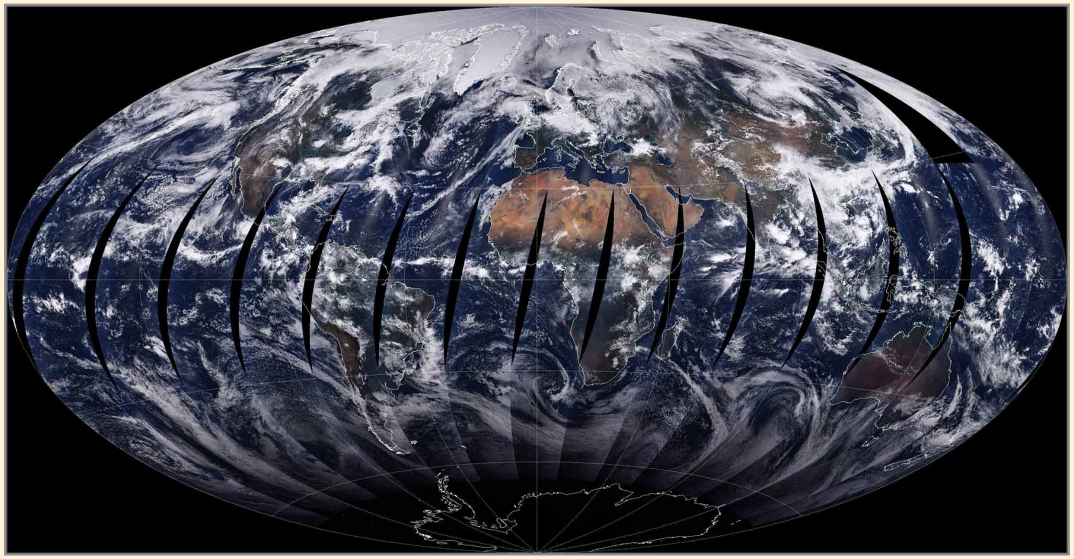


Innovative Satellite Observations to Characterize the Cloudy Boundary Layer
Keck Institute for Space Studies, Cal Tech
21-24 September 2010



MODIS true-color daily composite

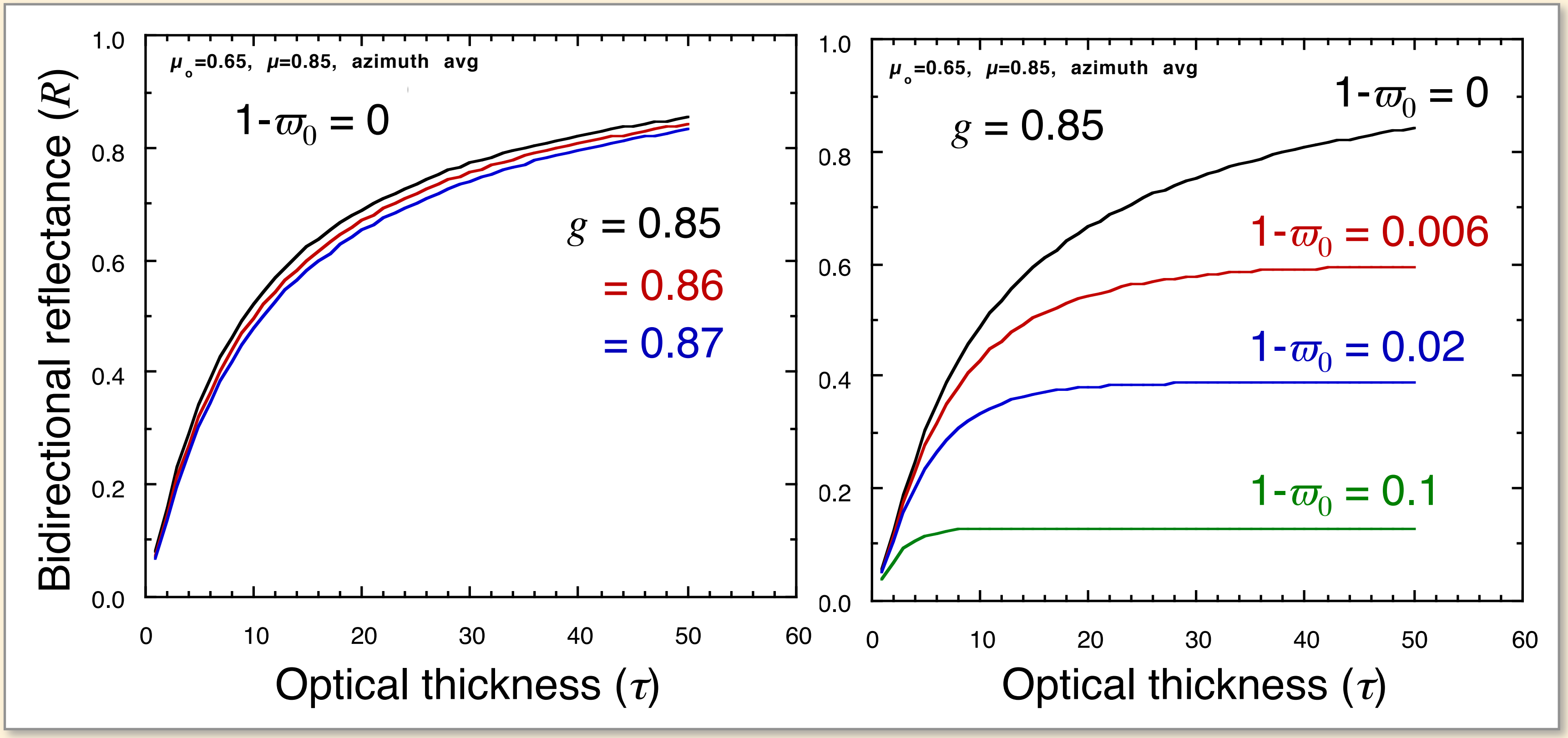
Outline

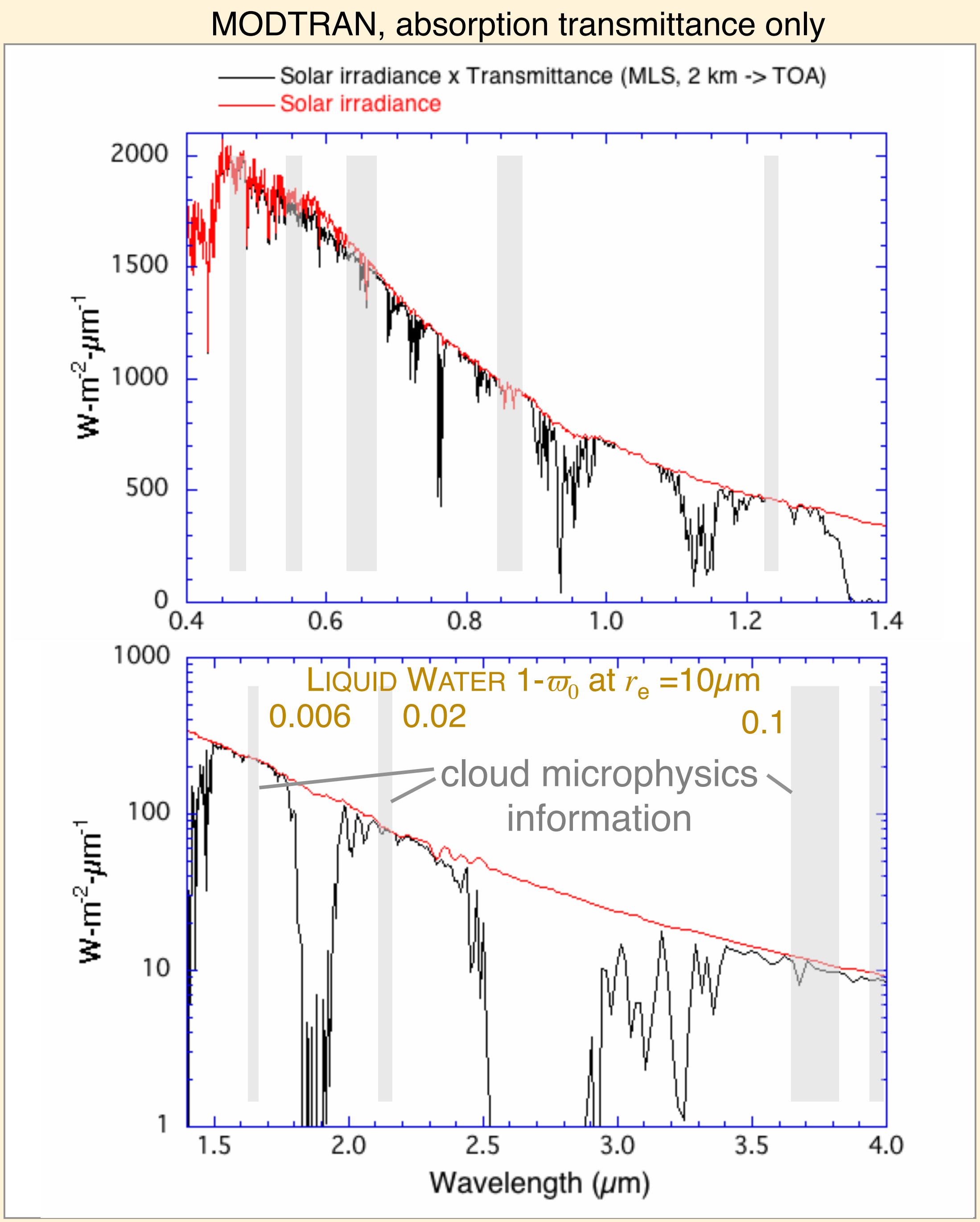
1. Imager cloud retrieval overview
2. Examples from MODIS: Capabilities
3. Examples from MODIS: Issues
   - What do we mean by a “cloudy pixel” and why does it matter?
   - Effective radius sensitivity to choice of spectral bands
   - Geometric sensitivities/biases
   - Clouds/BL height
   - Trend detection
4. Future needs and discussion

1. Imager Cloud Retrieval Overview

Water Cloud Reflectance: $R = R\,(\tau,\, g,\, \varpi_0,$ geometry)

conservative scattering, $R \approx R((1\text{-}g)\tau)$ reflectance vs. $1\text{-}\varpi_0$, $R \approx R(1\text{-}\varpi_0)$





MODIS nominal solar reflectance band locations

– general purpose window bands (land, aerosol, clouds)

Cloud optical vs. microphysical properties?

For <u>homogeneous cloud</u> and Mie scattering (water droplets), 3 optical variables can be reduced to 1 optical & 1 microphysical:

$$R_\lambda = R\left(\tau_\lambda, \varpi_{0,\lambda}, g_\lambda\right) \Rightarrow R_\lambda \approx R\left(\tau_{\lambda_0}, r_e\right)$$

$$r_e \equiv \frac{\int_0^\infty r^3 n(r)\,dr}{\int_0^\infty r^2 n(r)\,dr} = \frac{3}{4}\frac{\langle V \rangle}{\langle A_{cs} \rangle}$$

$$WP = \frac{2}{3}\,\tau\, r_e$$

Cloud optical vs. microphysical properties?

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$$R_\lambda = R\left(\tau_\lambda, \varpi_{0,\lambda}, g_\lambda\right) \Rightarrow R_\lambda \approx R\left(\tau_{\lambda_0}, r_e\right)$$

and v_e or more generally $n(r)\mathrm{d}r$

WARNING!

$$r_e \equiv \frac{\int_0^\infty r^3 n(r)\,dr}{\int_0^\infty r^2 n(r)\,dr} = \frac{3}{4}\frac{\langle V\rangle}{\langle A_{cs}\rangle}$$

column-integrated quantities

$$WP = \frac{2}{3}\tau\, r_e$$

local parameter in general $r_e = r_e(x,y,z)$

Residual example for 5 wavelength retrieval: 0.75, 1.0, 1.2, 1.6, 2.1 μm

obvious causes for the r_e discrepancy "found wanting"

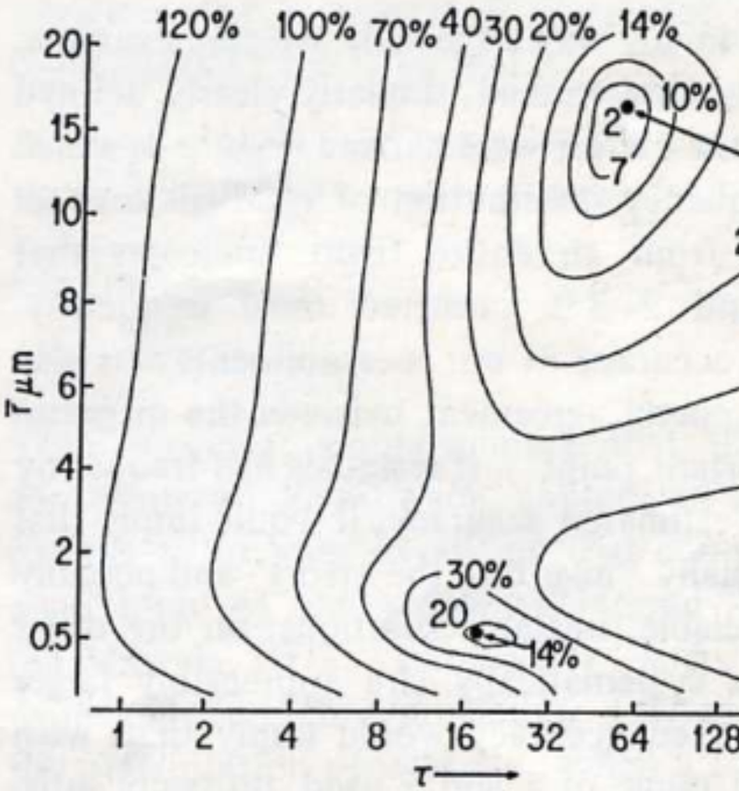


Figure 3 Isopleths of the residual in $\bar{r}$, τ space
measured spectral reflectances).

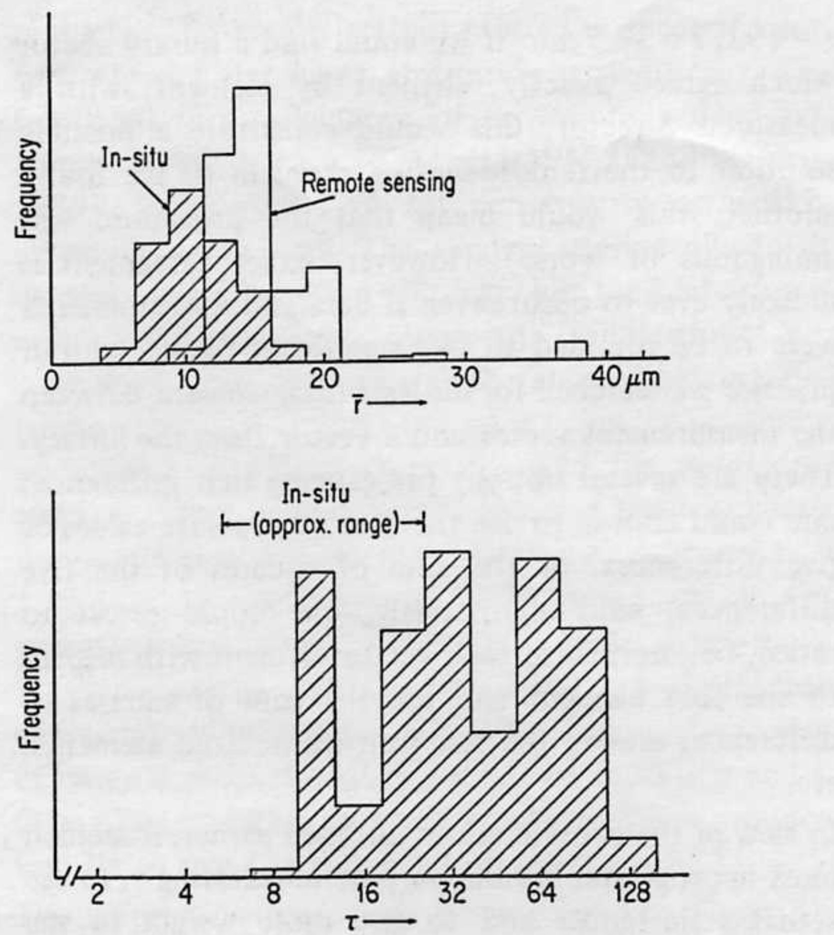


Figure 5 Histogram plot of the frequency distribution of inferred $\bar{r}$ (upper) from one day's flight data and (lower) frequency distribution of $\bar{r}$ from cloud physics (*in-situ*) instruments.

Twomey & Cocks (1982, 1989)
Clouds downwind from
Cane fires, Australia

Nakajima & King (1990)

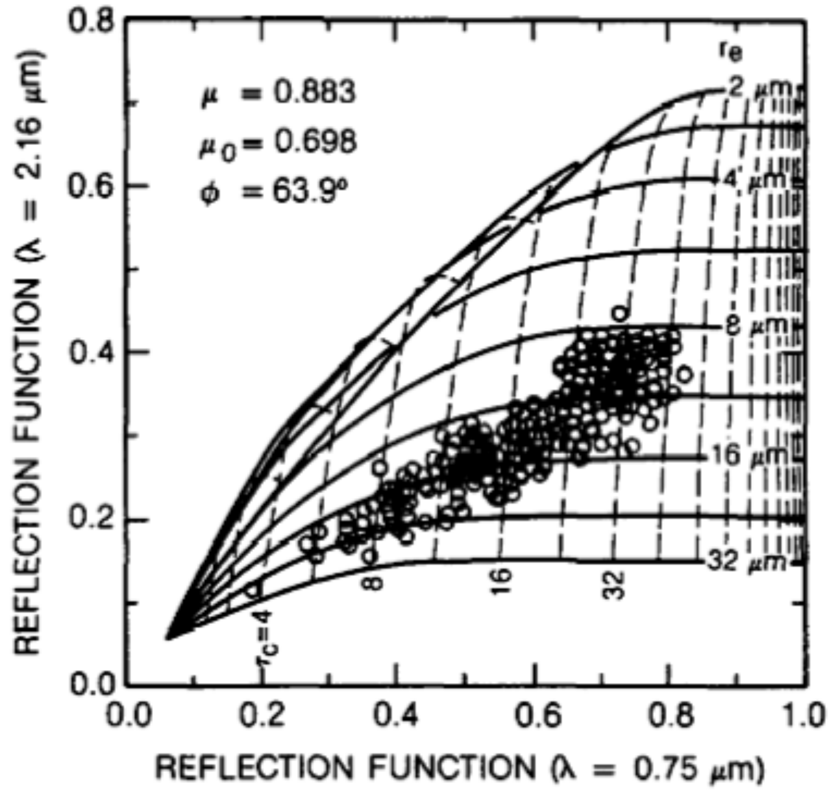


FIG. 2. Theoretical relationships between the reflection function at 0.75 and 2.16 μm for various values of the cloud optical thickness (at $\lambda = 0.75$ μm) and effective particle radius for the case when $\theta_0 = 45.7°$, $\theta = 28.0°$ and $\phi = 63.9°$. Data from measurements above marine stratocumulus clouds during FIRE are superimposed on the figure (10 July 1987).

2. Capabilities: Examples from MODIS

MODIS Cloud Product Overview

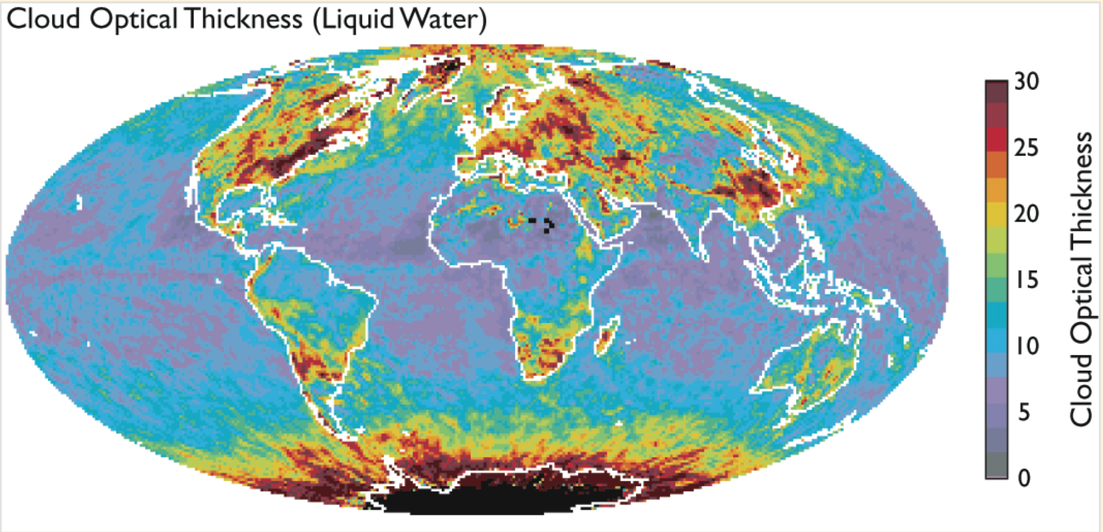
Main pixel-level products (Level-2), Collection 5

- Cloud mask. U. Wisconsin/CIMSS. *1km, 48-bit mask/11 spectral tests, clear sky confidence given in 4 levels*
- Cloud top properties: pressure, temperature, effective emissivity. U. Wisconsin/CIMSS. *5 km, CO_2 slicing high clouds, 11 µm for low clouds*
- Cloud optical & microphysical properties**:** optical thickness, effective particle size, water path, thermodynamic phase. NASA GSFC
  - *1 km, 2-channel solar reflectance algorithm. Standard retrievals are non-absorbing band (depends on surface type) + 1.6, 2.1, 3.7 µm*
  - *1 τ, 3 r_e retrievals*
  - *2.1 µm combination is the "primary" retrieval r_e (used in L3 aggregations)*
  - *Retrieval uncertainties*
  - *Various QA including, "Clear Sky Restoral" (CSR): Used to help eliminate cloudy pixels not suitable for retrievals or incorrectly identified cloudy pixels spatial (edge removal, use of 250m bands over water surfaces, and spectral tests).*

Monthly Mean Cloud Optical Thickness & Effective Radius
April 2005, Aqua Collection 5

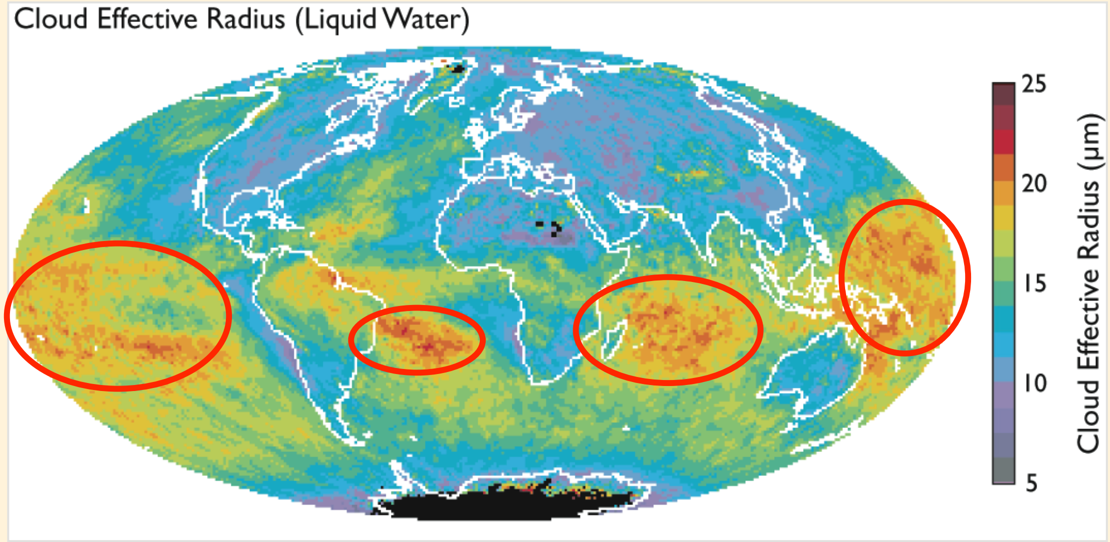
Monthly Mean Cloud τ
(MYD06 Cloud Mask)

"Cloud_Optical_Thickness _QA__Mean_Mean"



Monthly Mean r_e (MYD06)

"Cloud_Effective_Radius_ Liquid_QA_Mean_Mean"

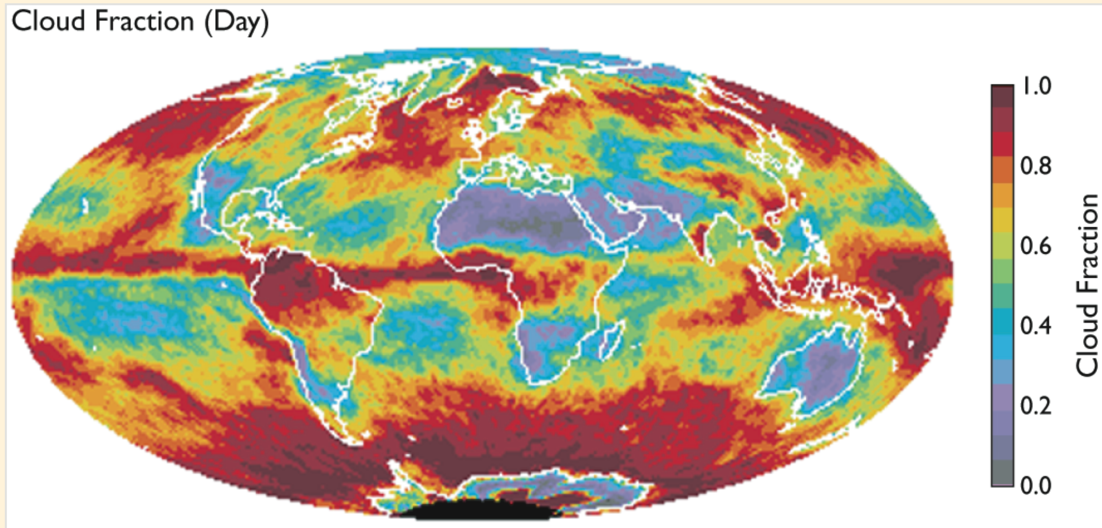


Monthly Mean Cloud Fraction & Effective Radius

April 2005, Aqua Collection 5

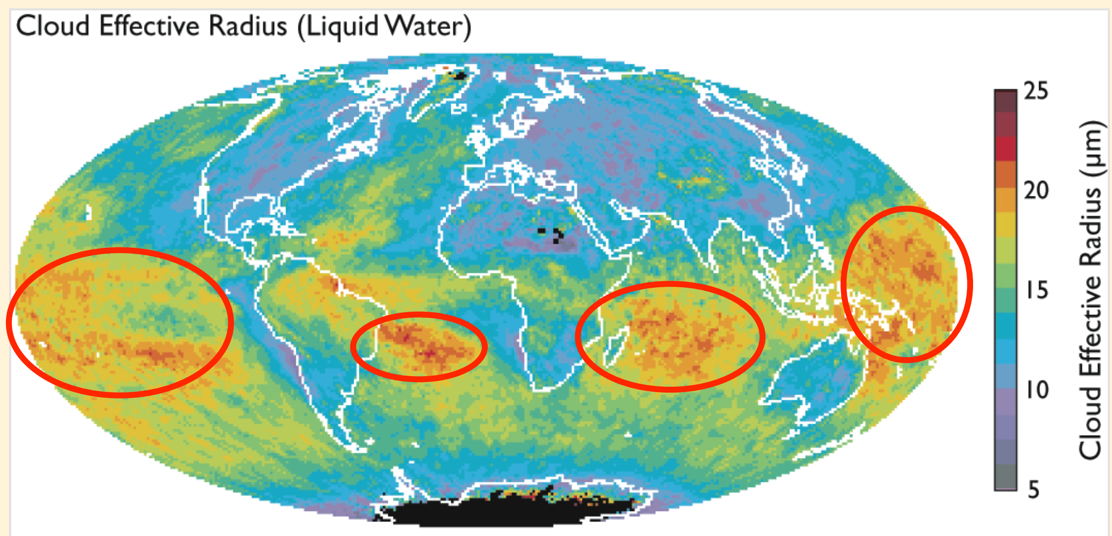
Monthly Mean Cloud Fraction (MYD35 Cloud Mask)

“Cloud_Fraction_Day_Mean_Mean”



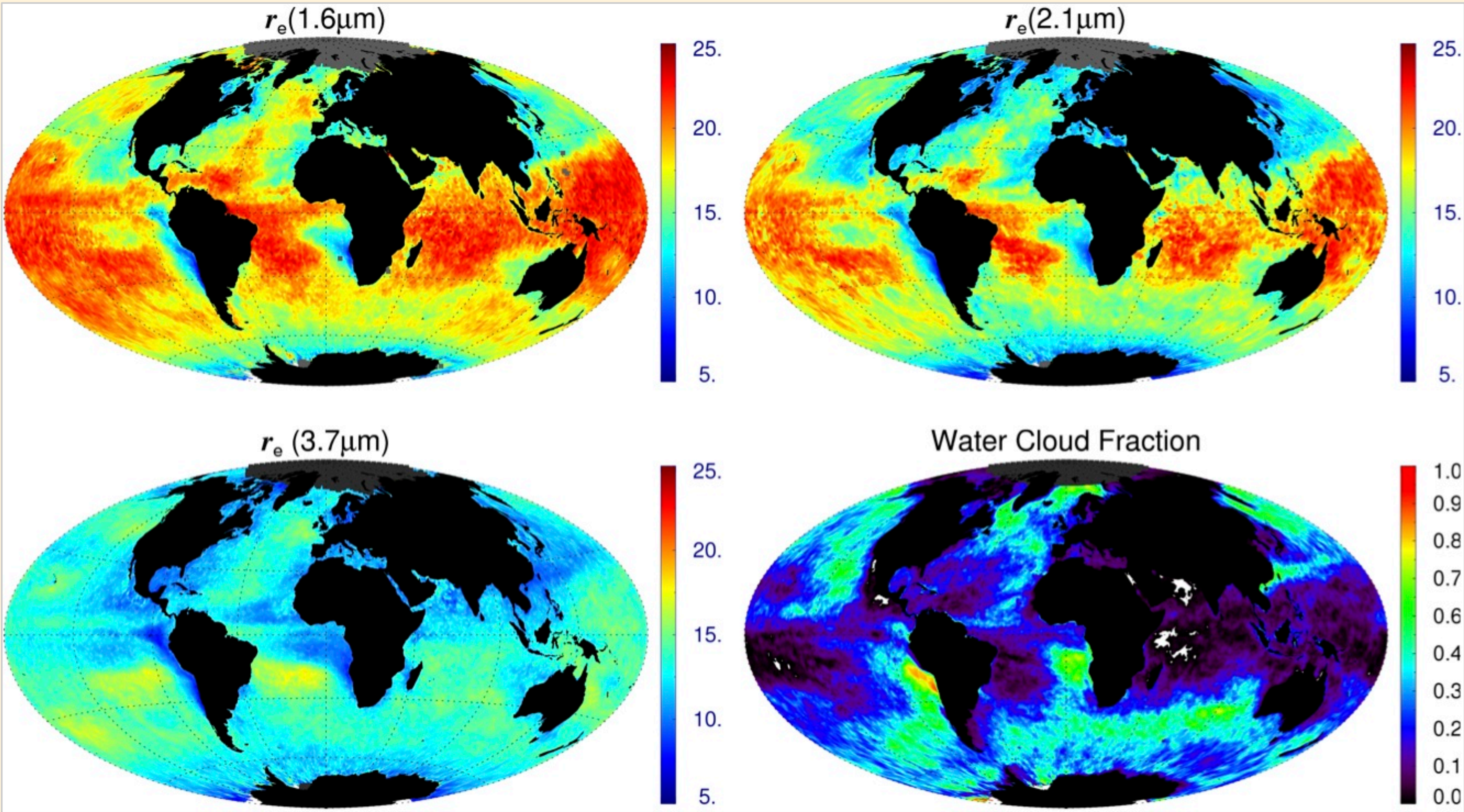
Monthly Mean r_e (MYD06)

“Cloud_Effective_Radius_Liquid_QA_Mean_Mean”

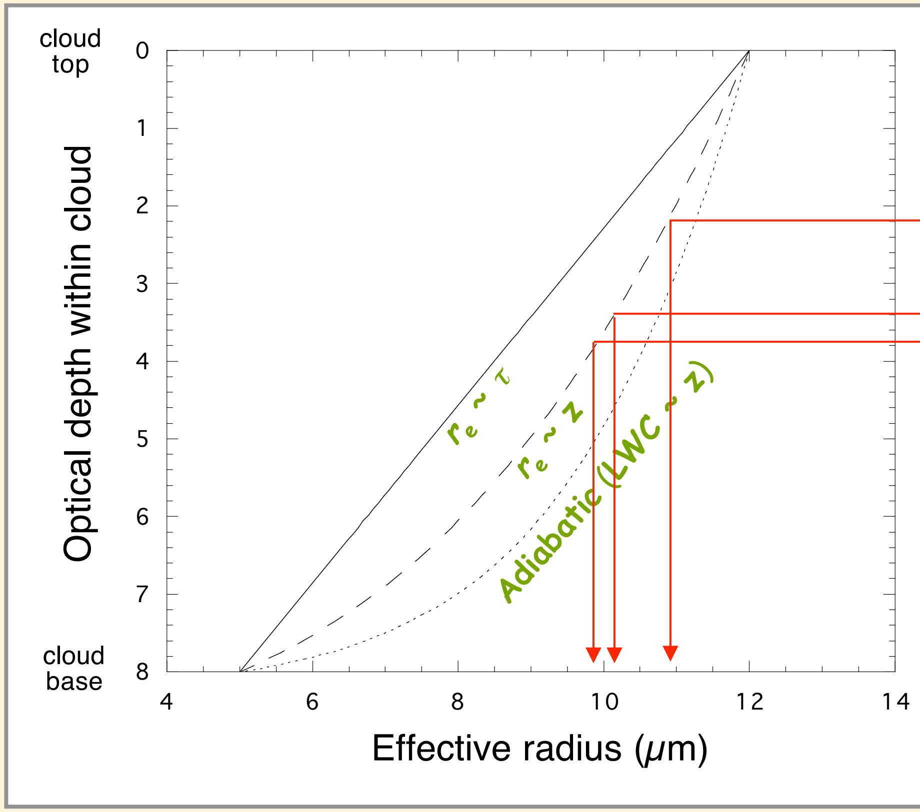


Monthly Mean Cloud Effective Radius: 2.1 vs. 3.7 µm

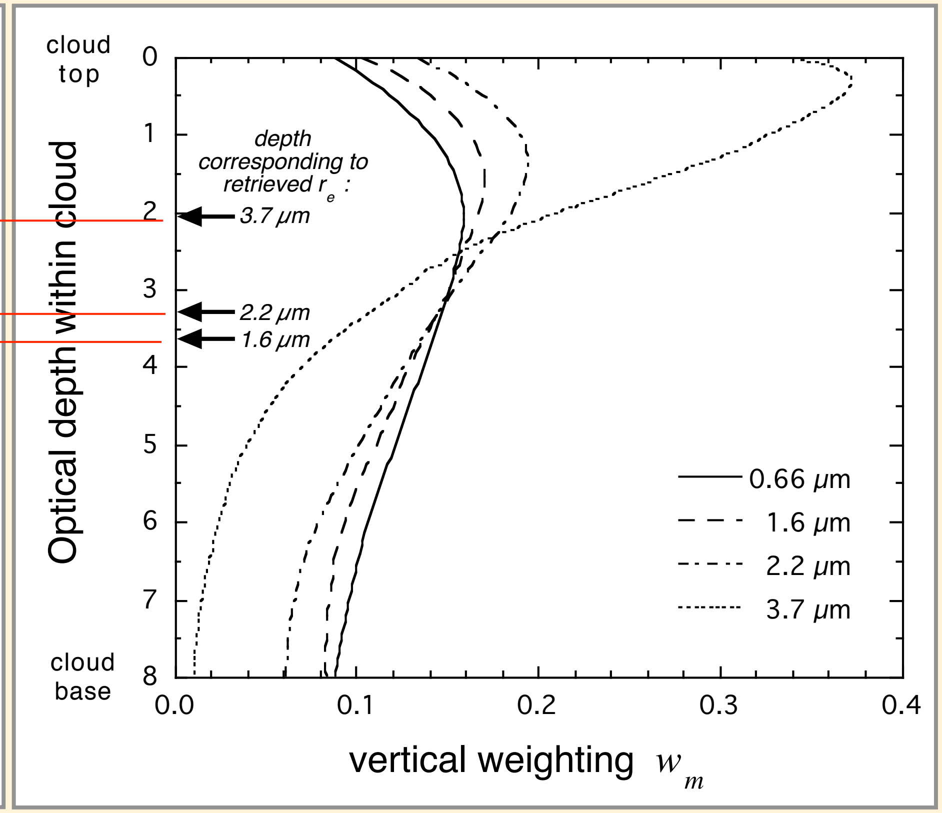
(Terra MODIS April 2005, C6 Test3, L3 unweighted means, liquid water clouds)



Effective radius (r_e) retrieval differences - *theoretical*



example analytic profiles



approx. vertical weighting
(based on photon penetration depth)

Platnick (2000)

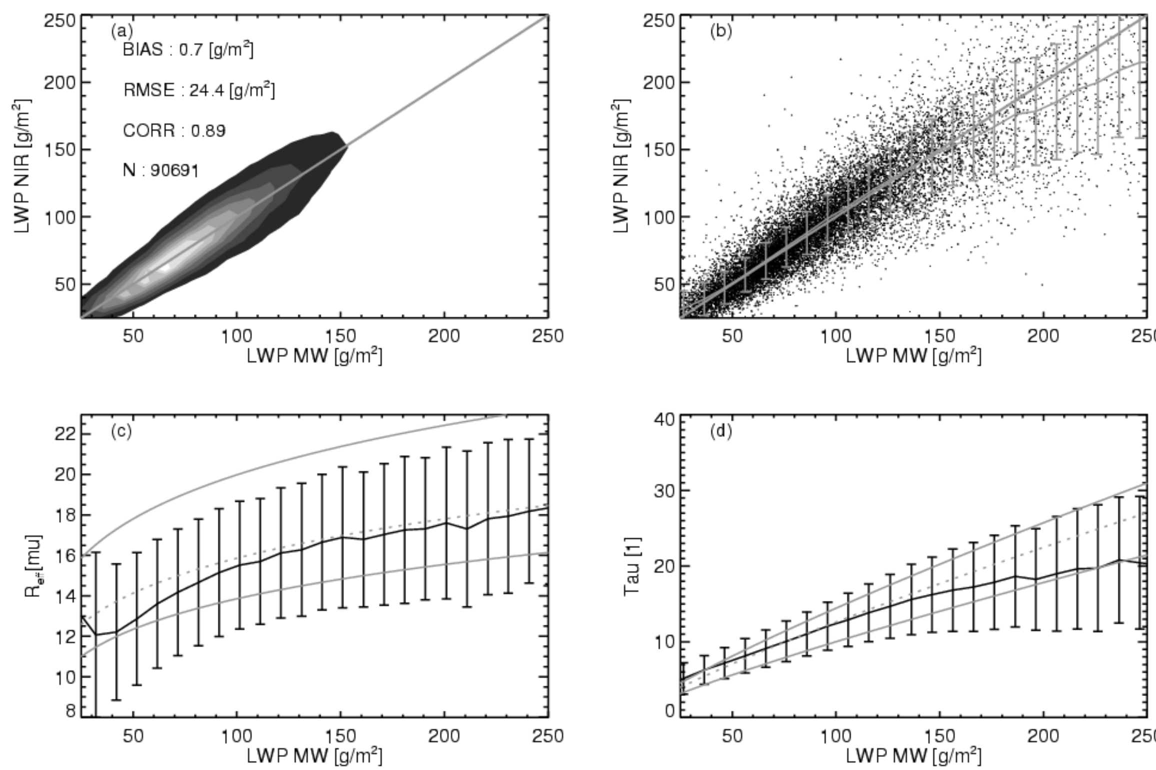
Example Liquid Water Path: MODIS vs. AMSR-E

(from Borg and Bennartz, 2007; see also dry bias Greenwald 2007, Horvath and Genteman, 2007)

Adiabatic cloud $W = \frac{5}{9}\rho_L \tau r_{eff}$ Vert. homog. cloud $W = \frac{2}{3}\rho_L \tau r_{eff}$

Global comparison with microwave data show excellent agreement of LWP for stratiform marine BL clouds

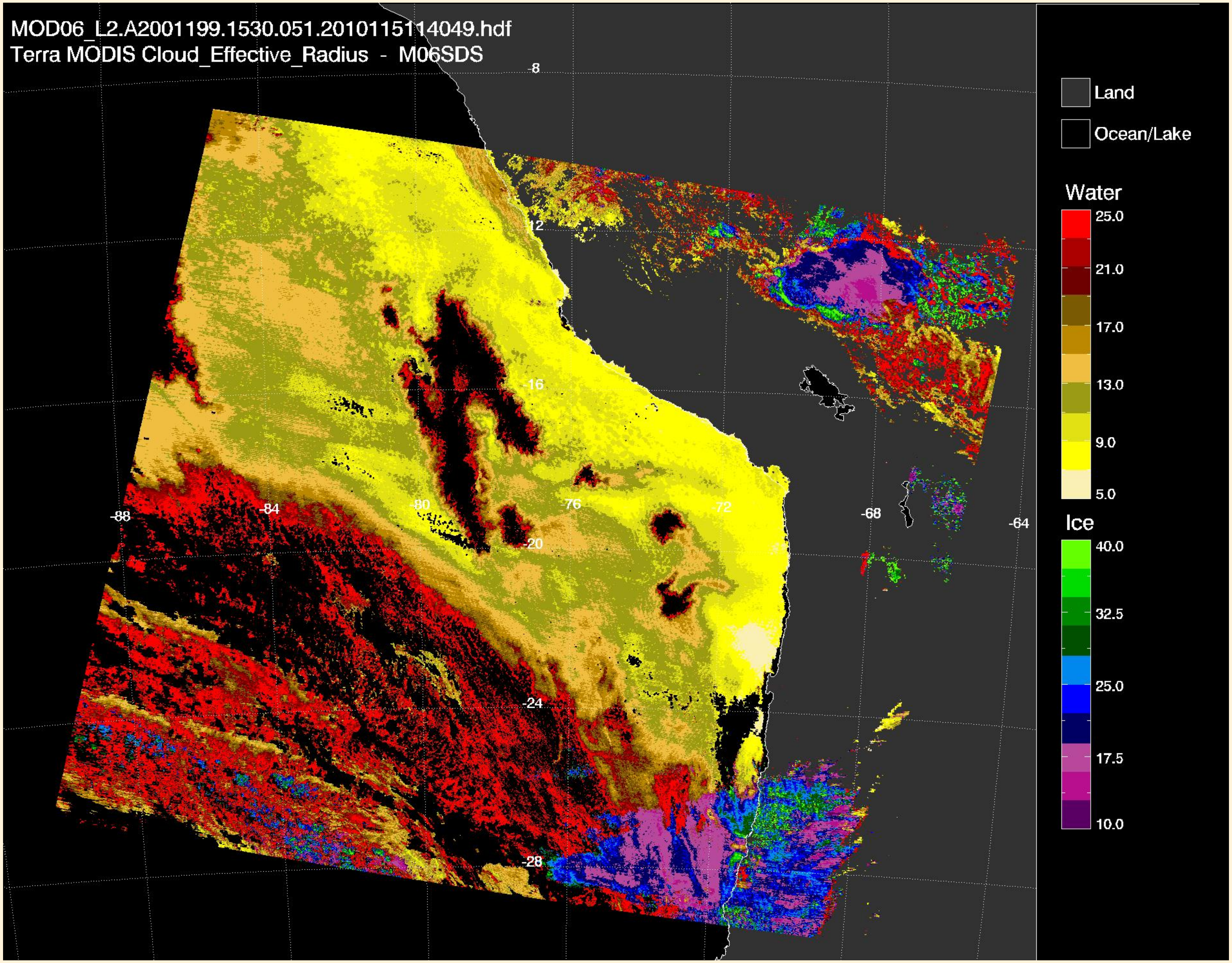
No indication of systematic errors for marine BL clouds



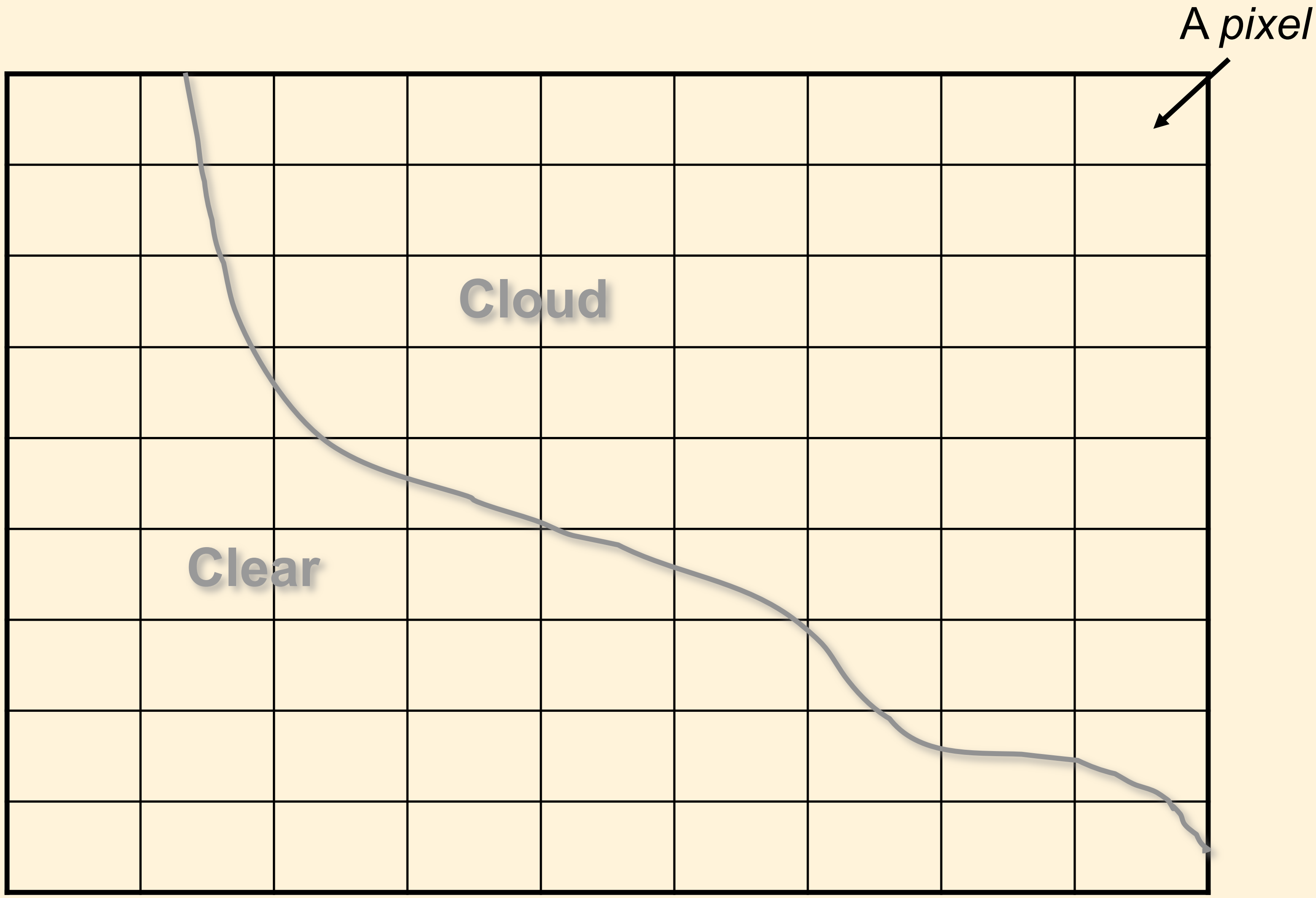
3. Issues: Examples from MODIS

- What do we mean by a “cloudy pixel” and why does it matter? Rationale for “Clear Sky Restoral” and impact on retrievals
- Analysis of effective radius sensitivity to choice of spectral bands
- Geometric sensitivities/biases
- BL Cloud-Top Pressure: sensitivity to lapse rate
- Trend detection

Granule Example – Peru/Chile Sc (Terra, 18 July 2001)



What Do We Mean by a Cloud Mask?



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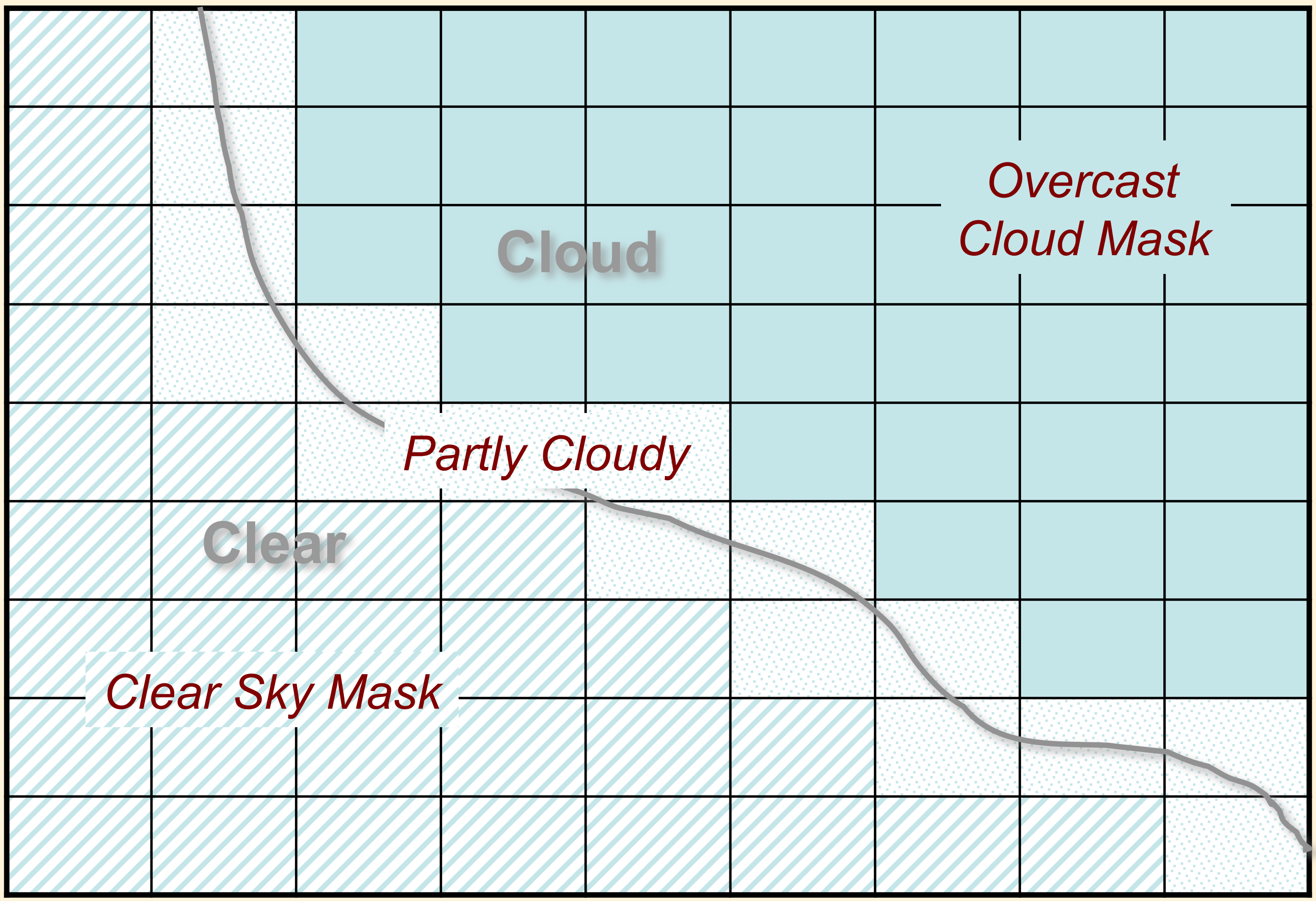
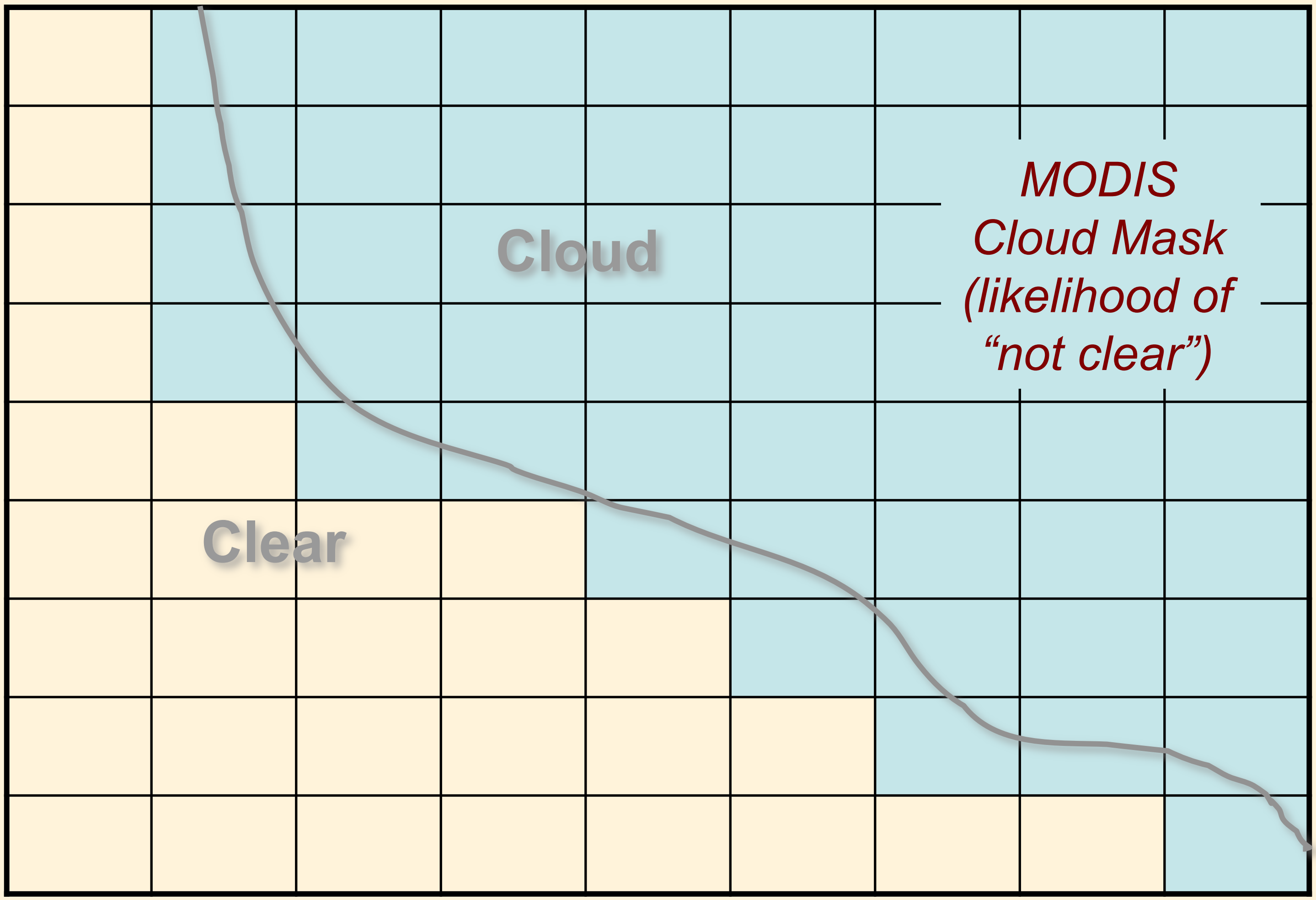
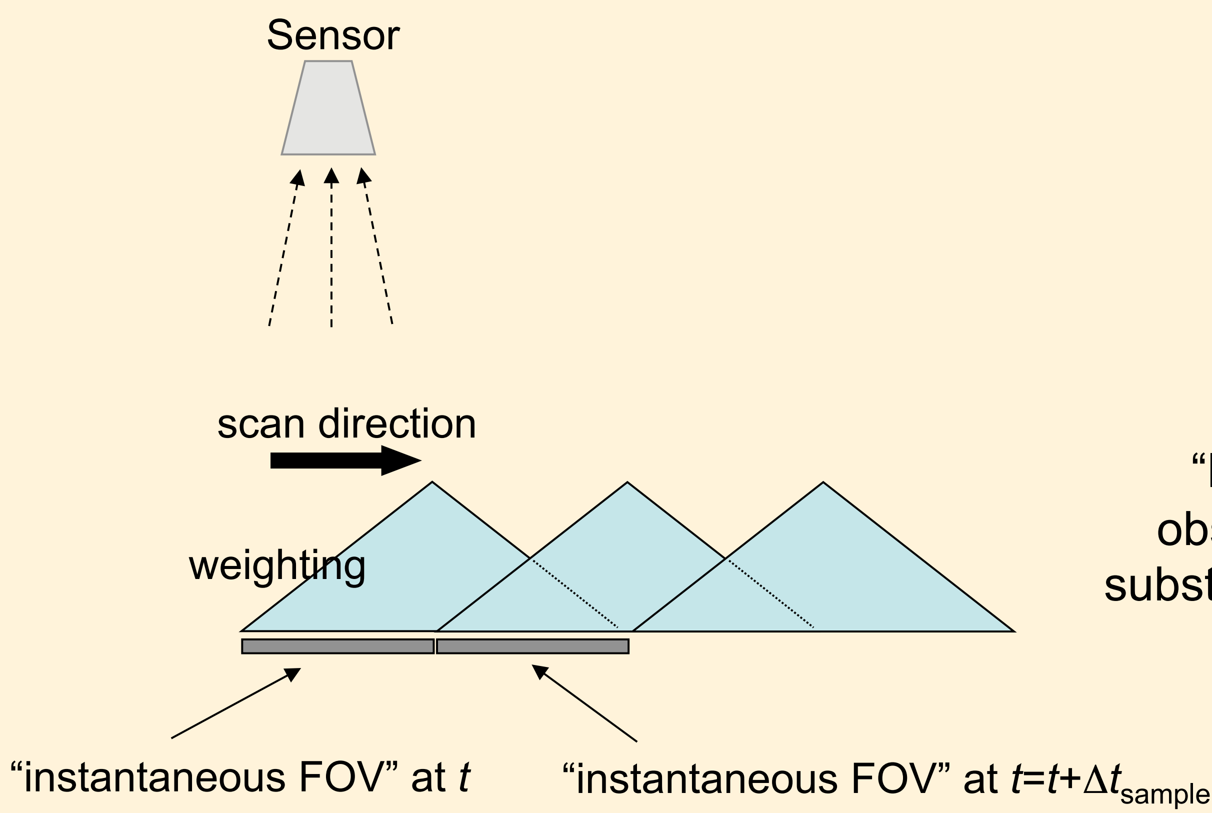


What Do We Mean by a Cloud Mask?

Most cloud masks are Clear Sky Masks



Another Issue: What is a Pixel?



“Pixels” (individual observations) overlap substantially in the across-track direction

<u>Moral of this story</u>:

(1) “Pixels” are rarely distinct elements.

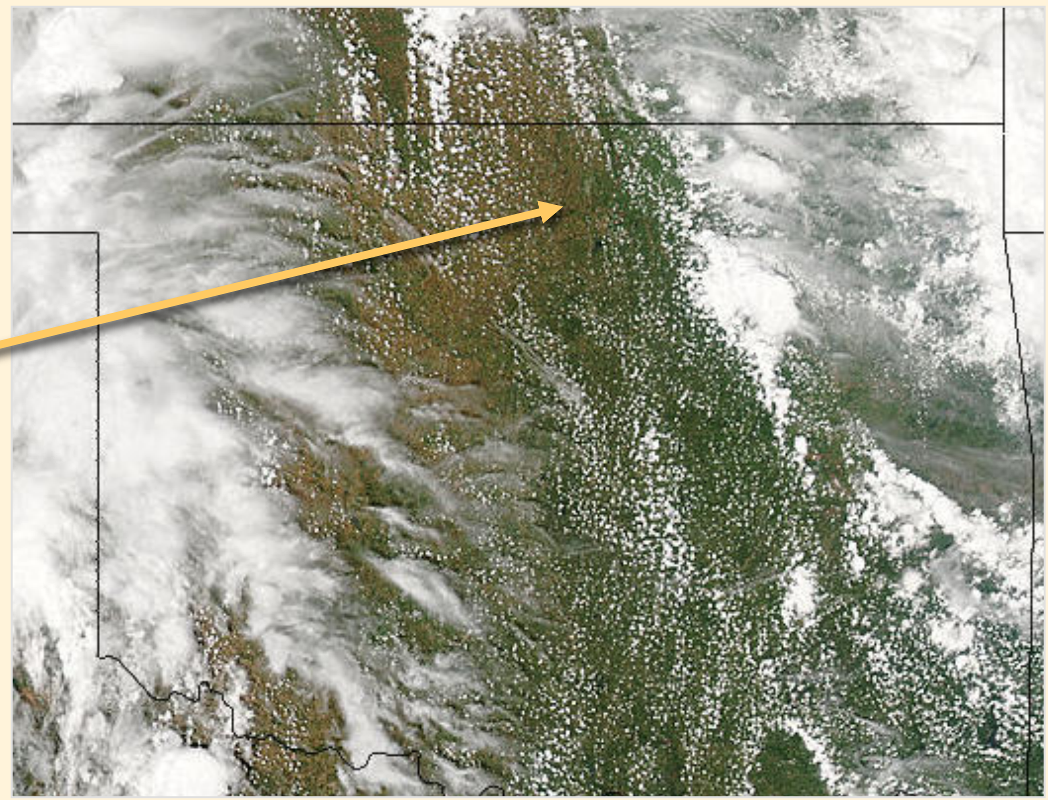
(2) It is dangerous to treat non-clear pixels from detection algorithms as “cloudy”.

CLASIC MAS vs. MODIS Cloud Fraction Comparison

Effect of imager spatial resolution for low cloud portion of track:

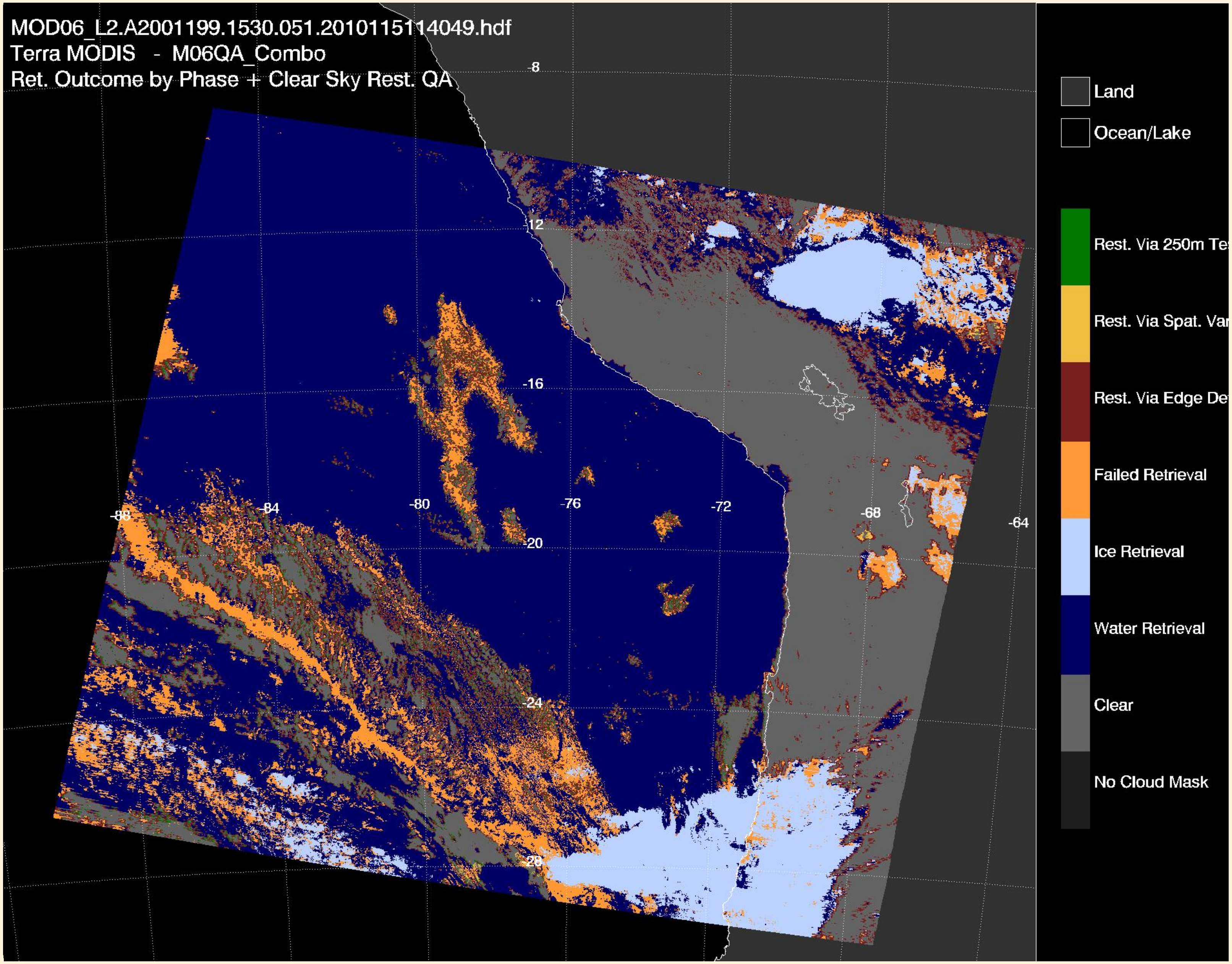
MAS cloud fraction (50m) = **20.1%**

MODIS cloud fraction (MYD35 1km cloud mask) = **47%**



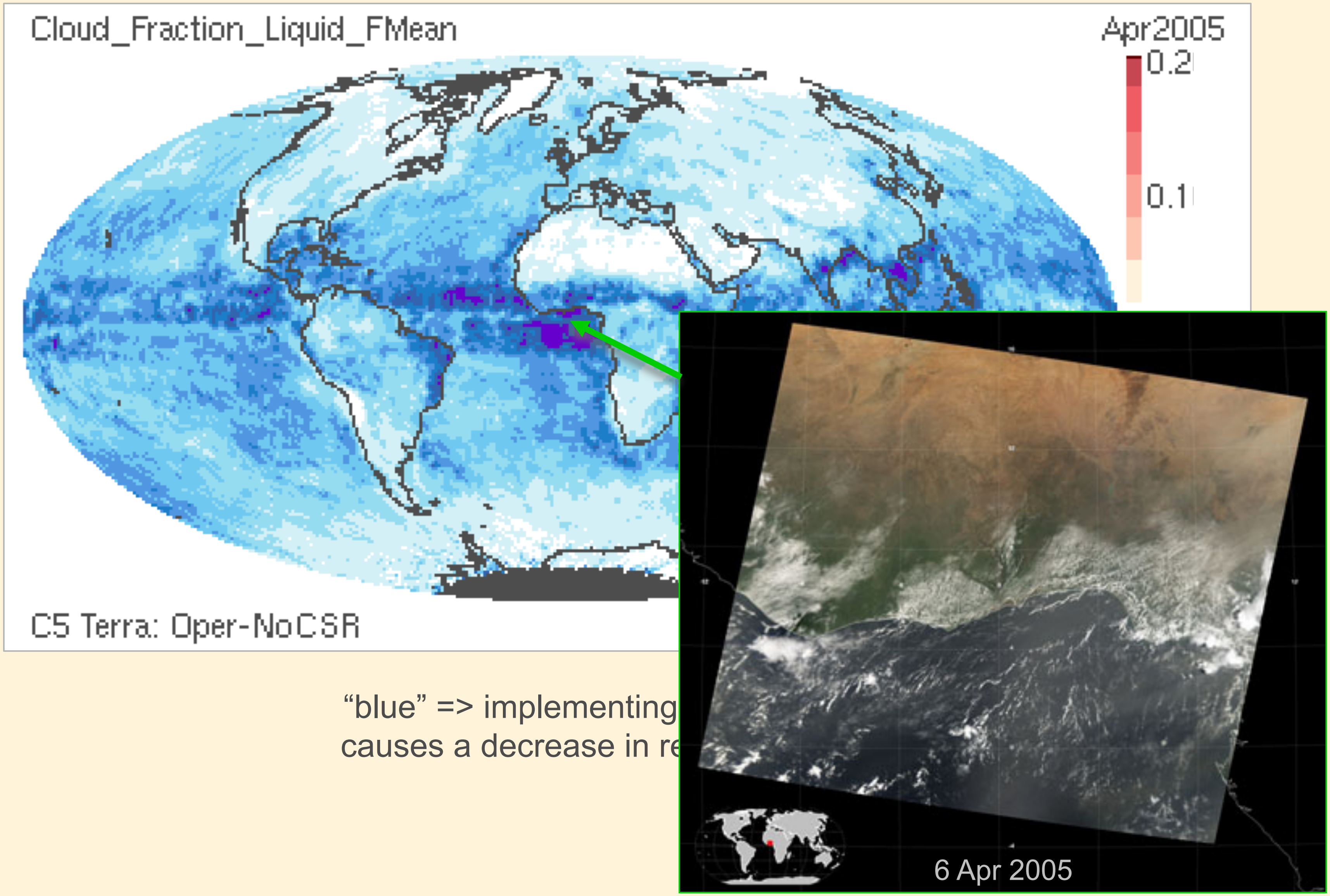
(see Ackerman et al, *JAOT*, 2007 for other lidar comparisons)

Granule Example – Peru/Chile Sc (Terra, 18 July 2001)



Difference: C5 run w/out Clear Sky Restoral - C5

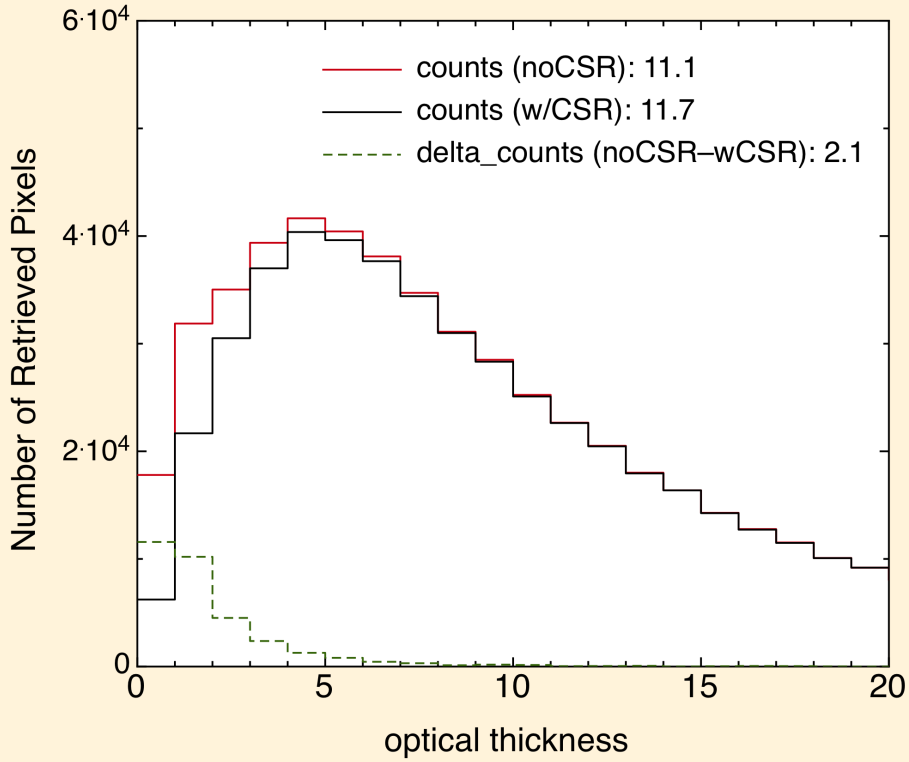
Retrieval Fraction, Terra 8-Day Aggregation, 30 March - 6 April 2005



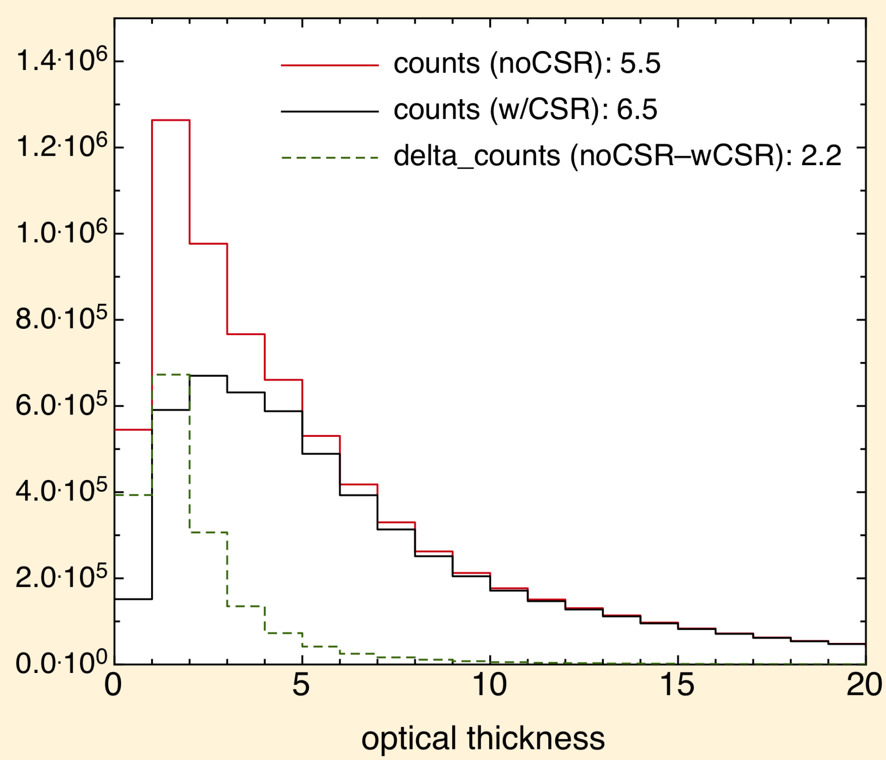
"blue" => implementing
causes a decrease in re

Sensitivity to Clear Sky Restoral: Histograms

Optical Thickness, liquid water clouds (April 2005)



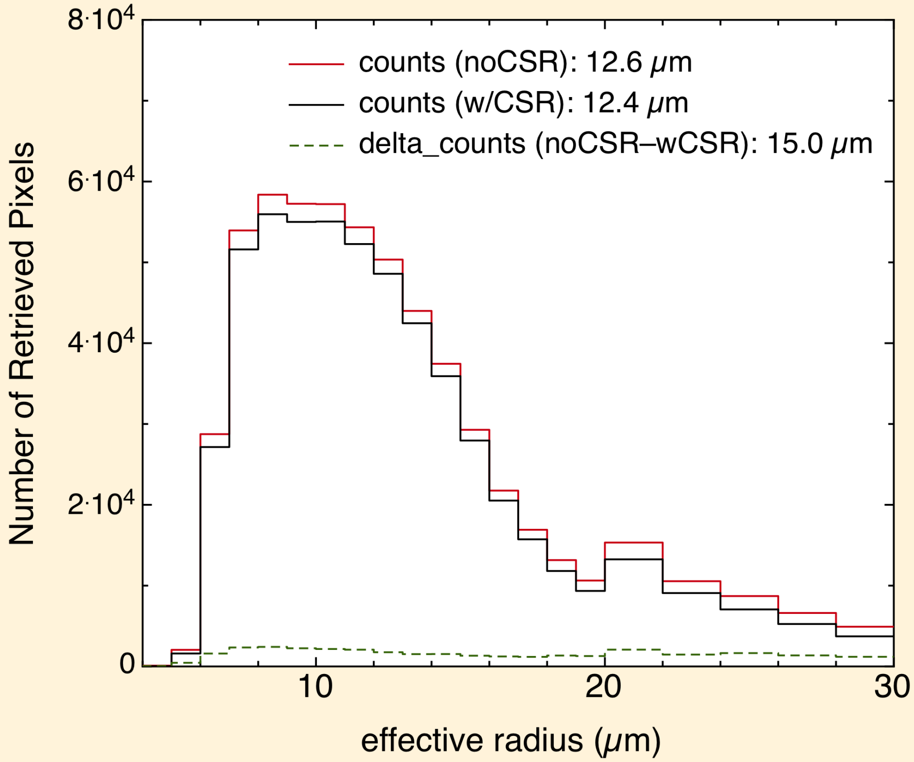
Peru Sc (10S–20S, 70W–85W)



Tropical Pacific (±25°)

Sensitivity to Clear Sky Restoral: Histograms

Optical Thickness, liquid water clouds (April 2005)



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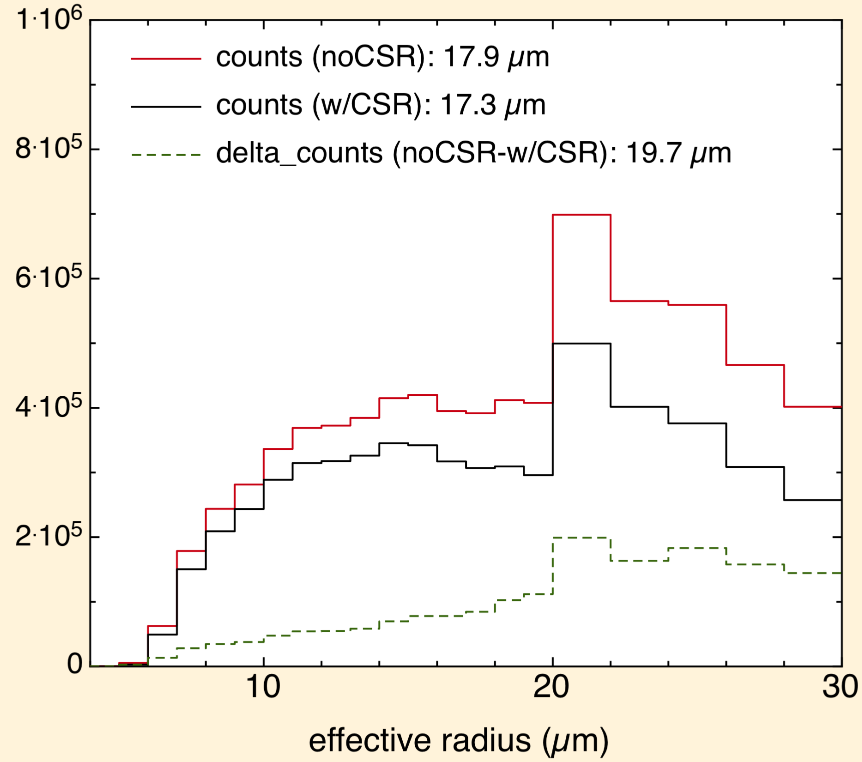
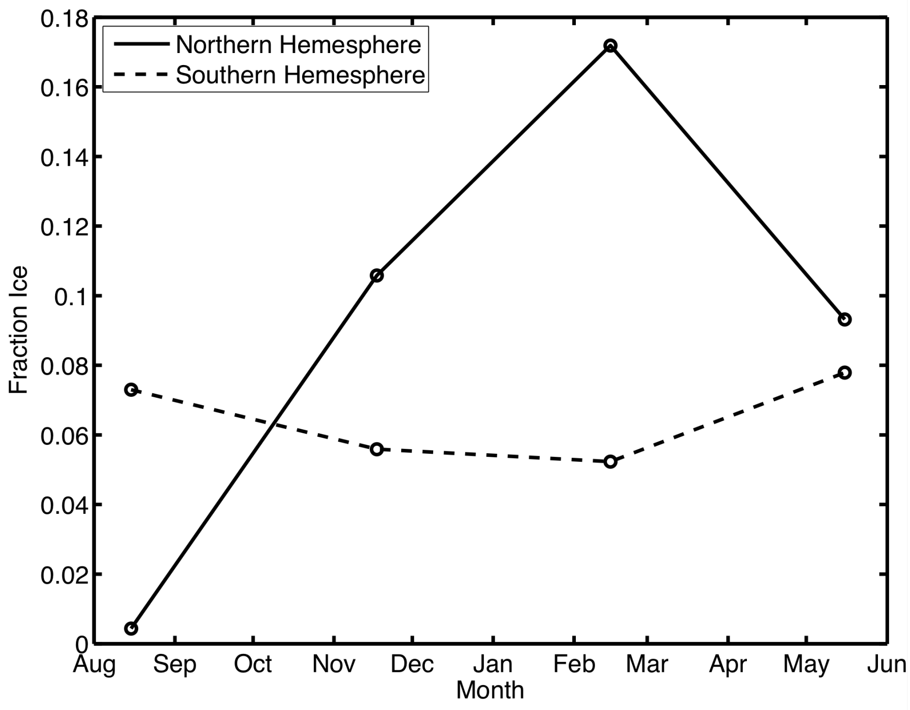


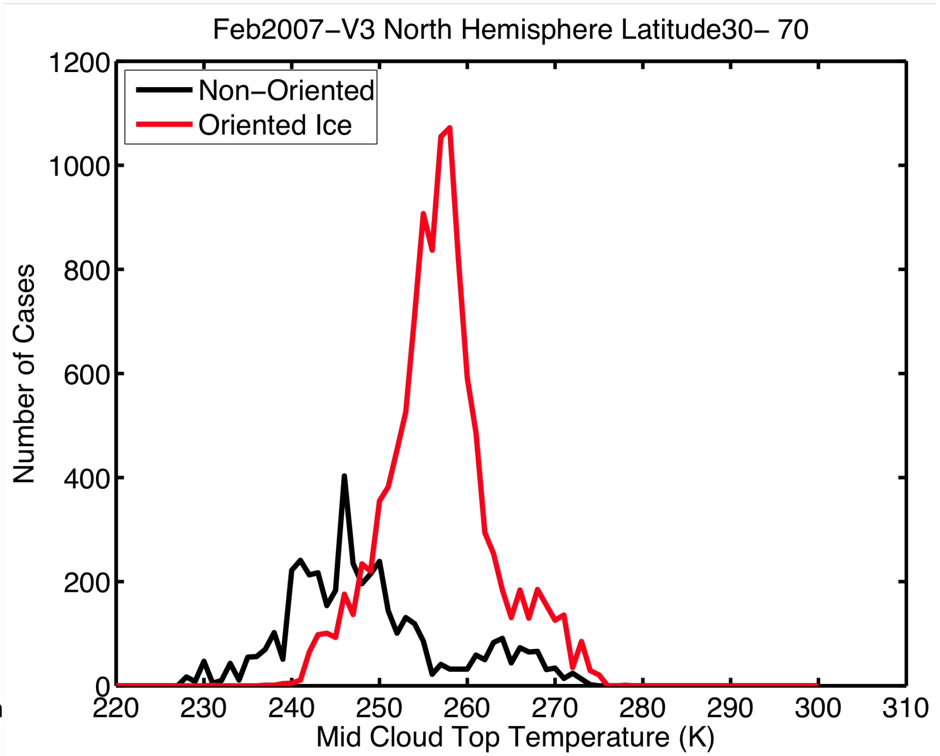
Tropical Pacific (±25°)

BL Phase In Broken Cloud Regimes (B. Holz)

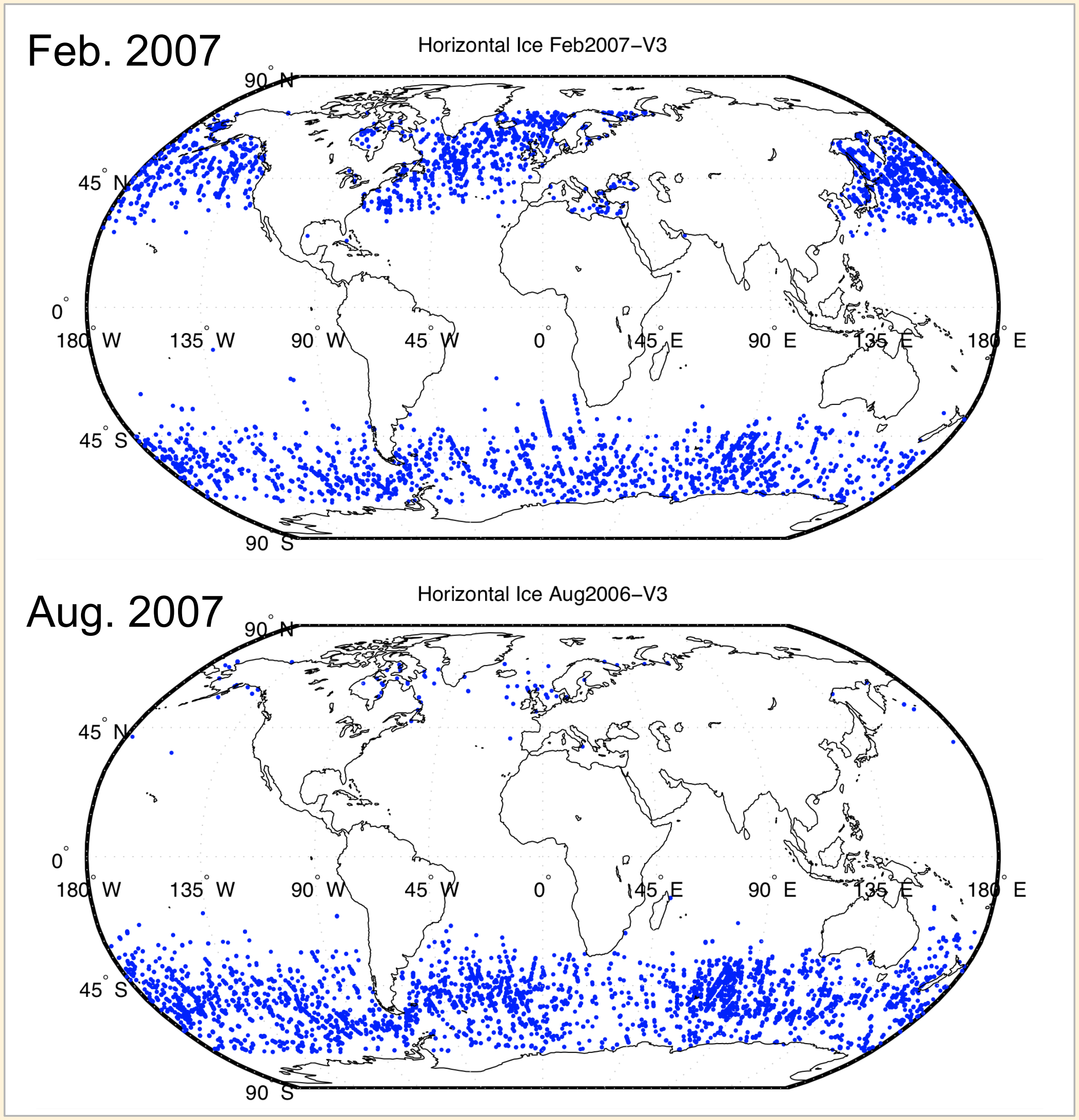
- Analysis: Fraction of non-tropical low clouds detected by CALIOP that are/have ice (early Yong Hu algorithm, applied before off-nadir pointing)

- Restricted to: Height<3km, ±30-70° latitude, isolated clouds w/spatial scales <20 km (max diameter from MODIS)





BL Phase In Broken Cloud Regimes, cont. (B. Holz)



Summary: Cloud Retrieval Fraction and Issues

Cloud Detection/Cloud Fraction: Ill-defined but nevertheless impacts those pixels considered for optical/microphysical retrievals, and a useful metric for trend studies if consistent instruments/algorithms are available.

MODIS "Clear Sky Restoral" Algorithm

- As expected:
  - algorithm removes more liquid than ice cloud (not shown) from the retrieval space
  - algorithm increases mean τ as expected (e.g., eliminates broken cloud or aerosol portion of PDF)
- Not expected:
  - algorithm does not in general have a significant effect on mean r_e !
- **Cloud Phase:** Midlatitude BL clouds w/ice appear relatively common in broken regimes.

3. Issues: Examples from MODIS

- What do we mean by a “cloudy pixel” and why does it matter? Rationale for “Clear Sky Restoral” and impact on retrievals
- Analysis of effective radius sensitivity to choice of spectral bands
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- BL Cloud-Top Pressure: sensitivity to lapse rate
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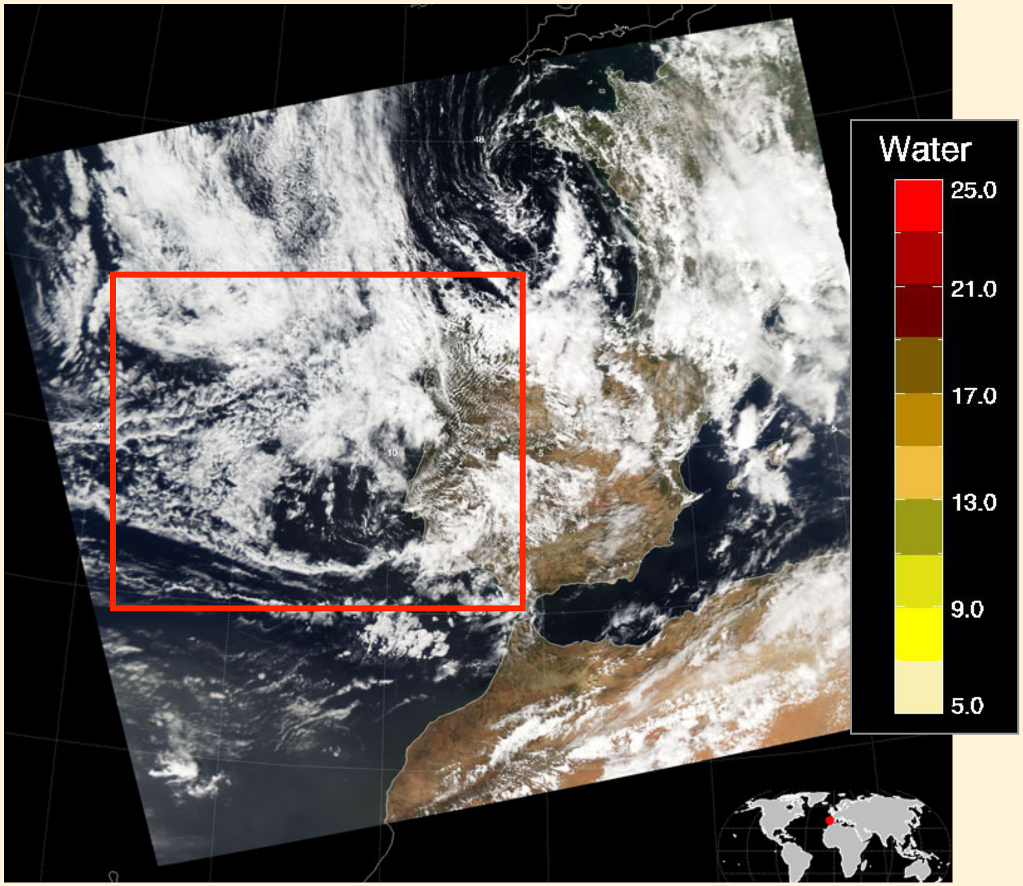
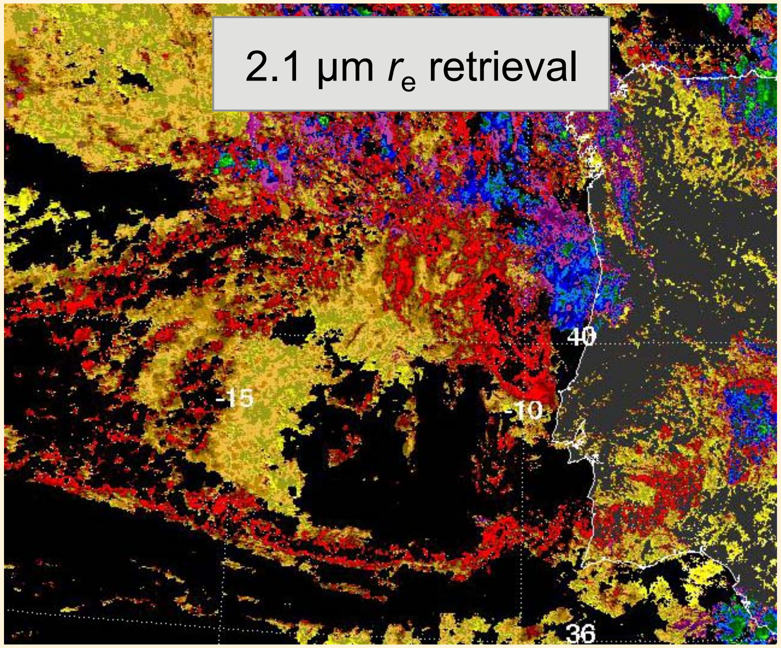
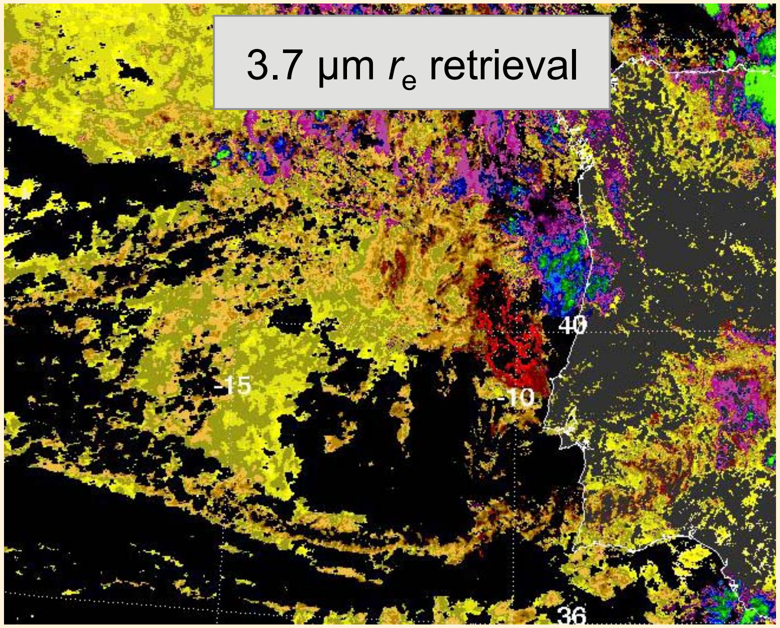
MODIS Aqua, Collection 5
9 September 2005

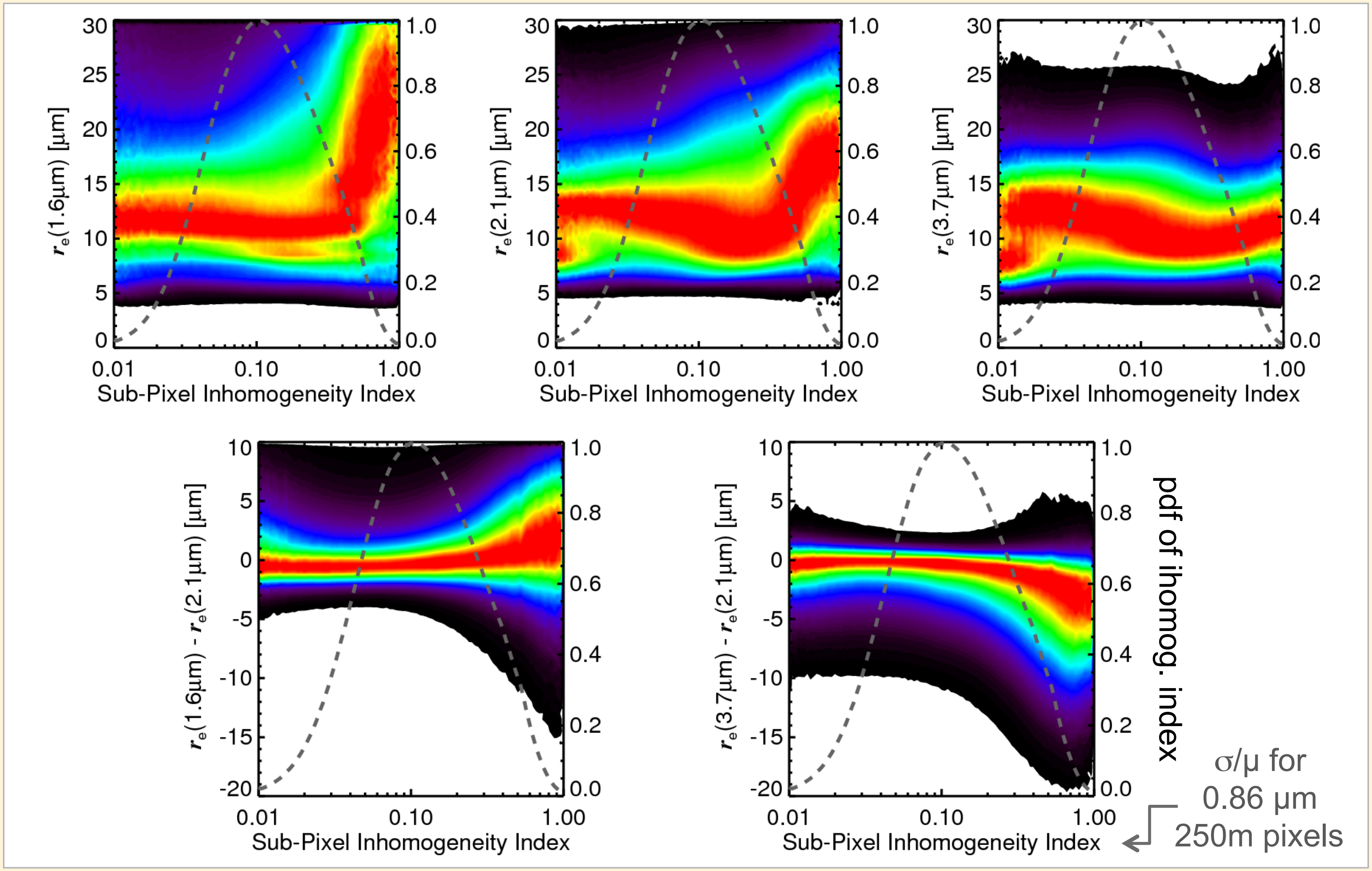






r_e Differences Correlated w/250m spatial inhomogeneties

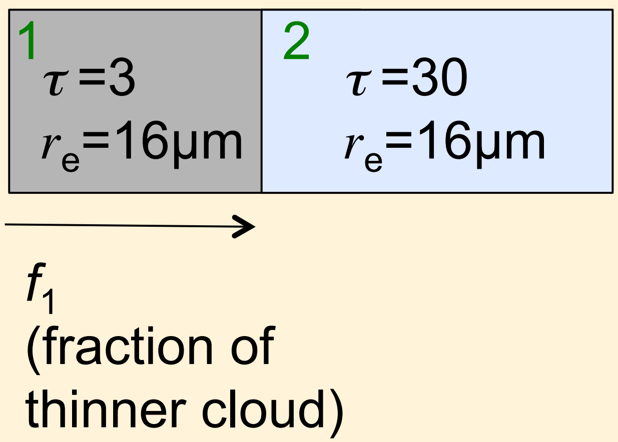
Global Ocean, ±60°, April 2005, Terra (Zhibo Zhang, et al.)

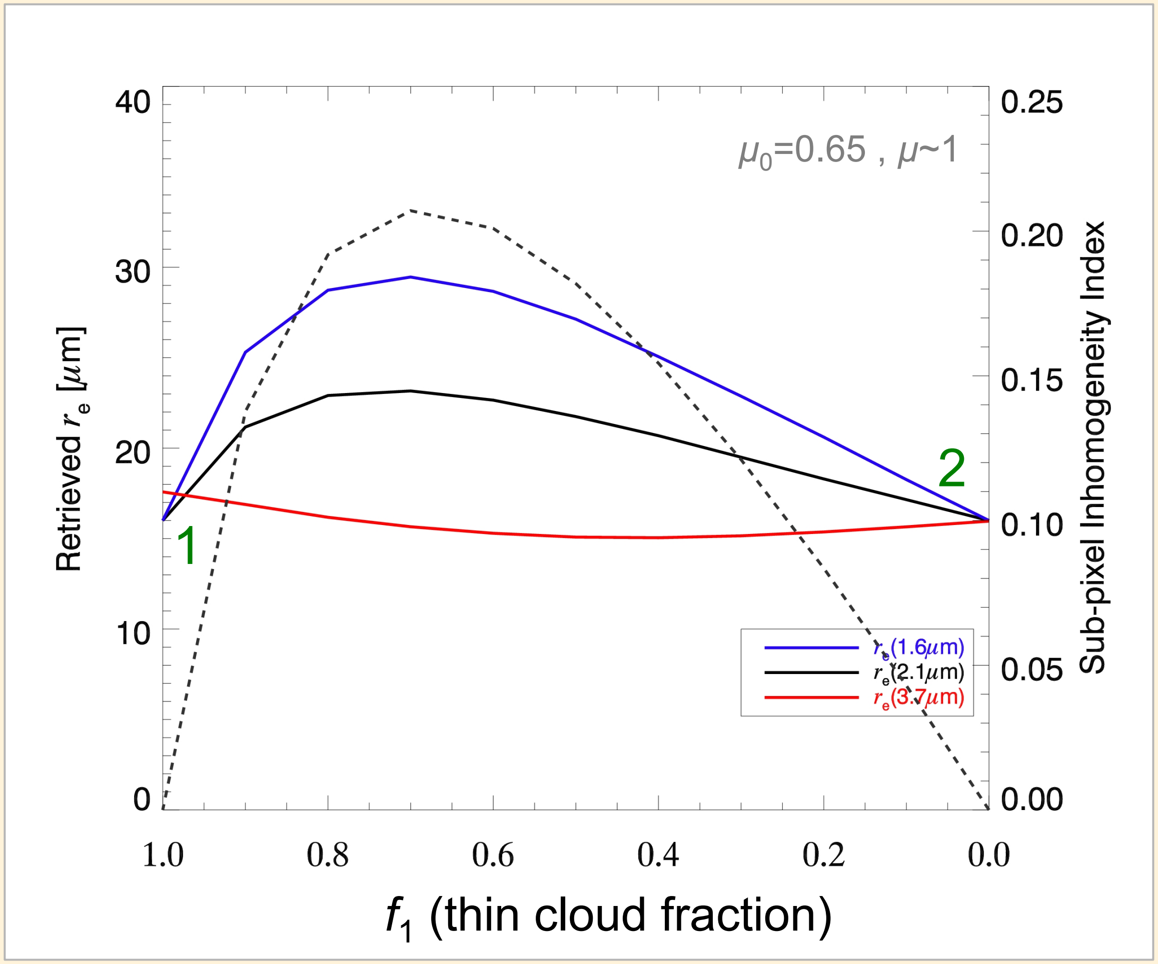


r_e Differences and Spatial Inhomogeneties: Back-of-Envelope Example (no 3D RT)

(Zhibo Zhang, et al.)

“pixel” over dark ocean





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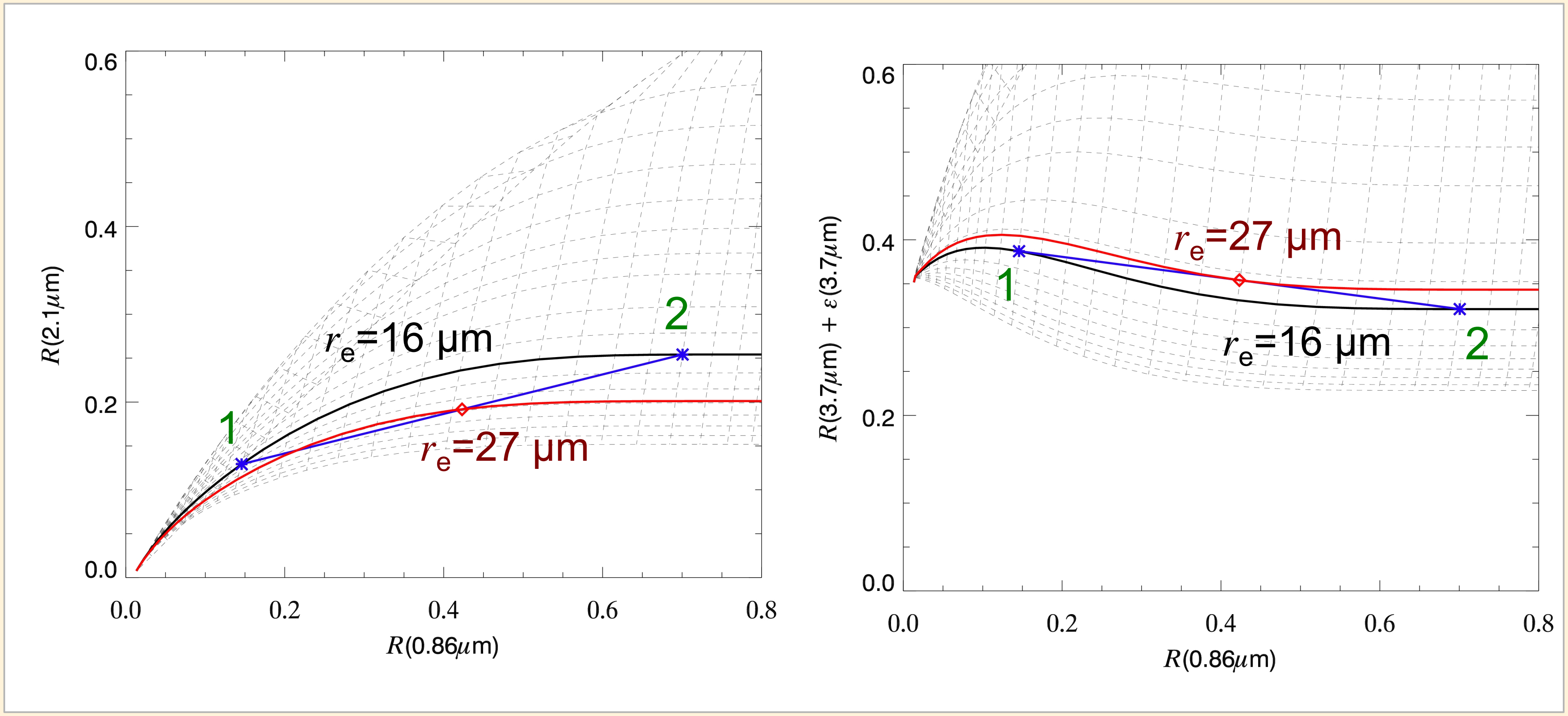
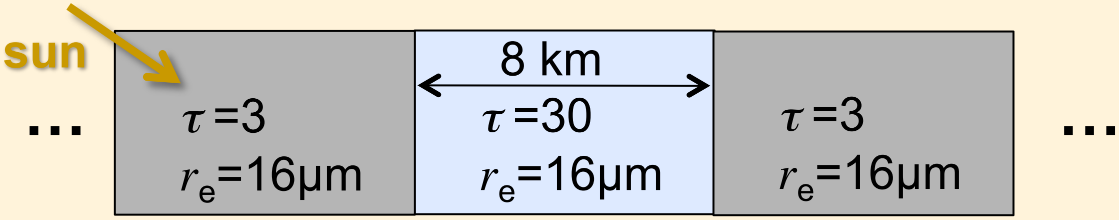
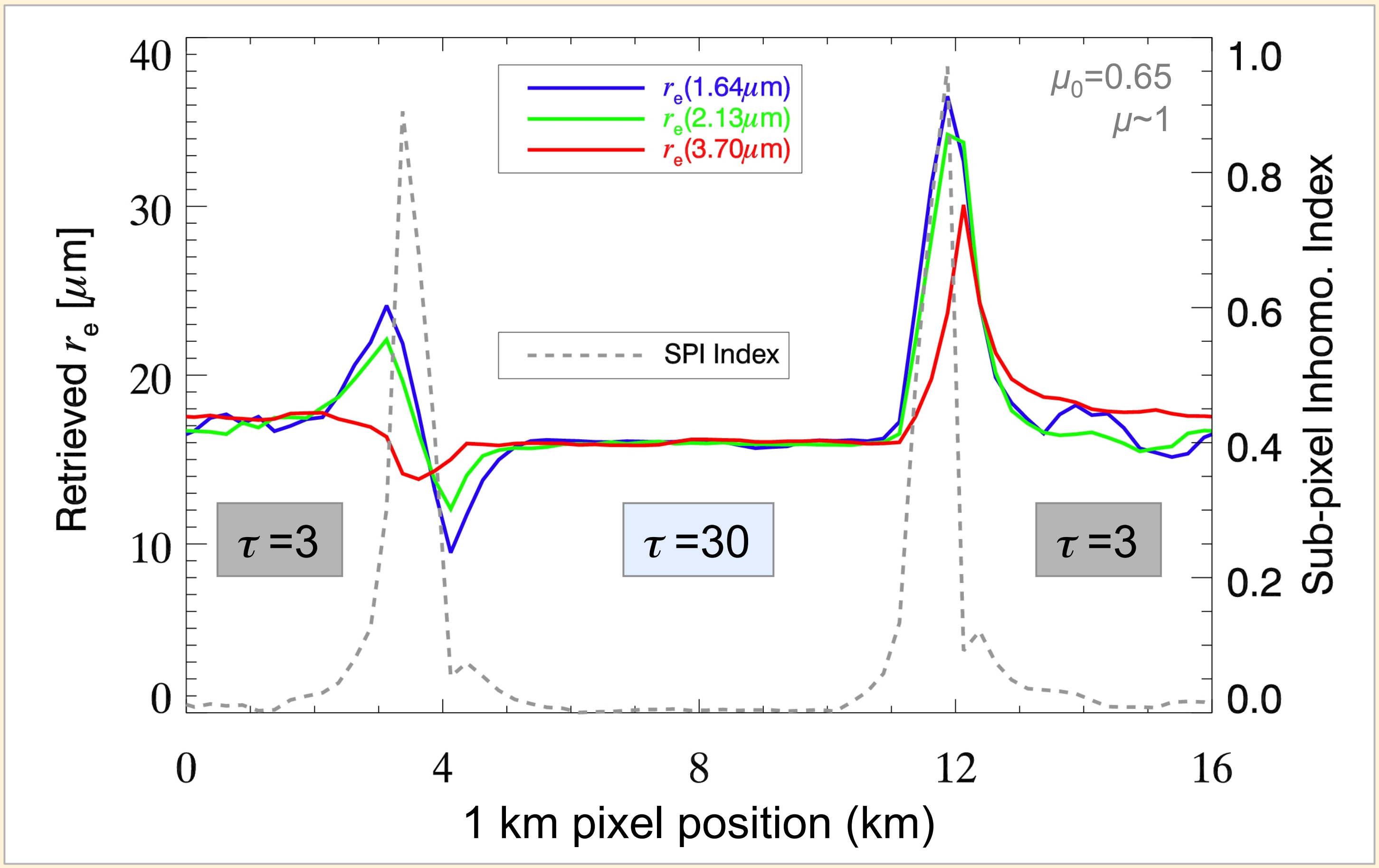


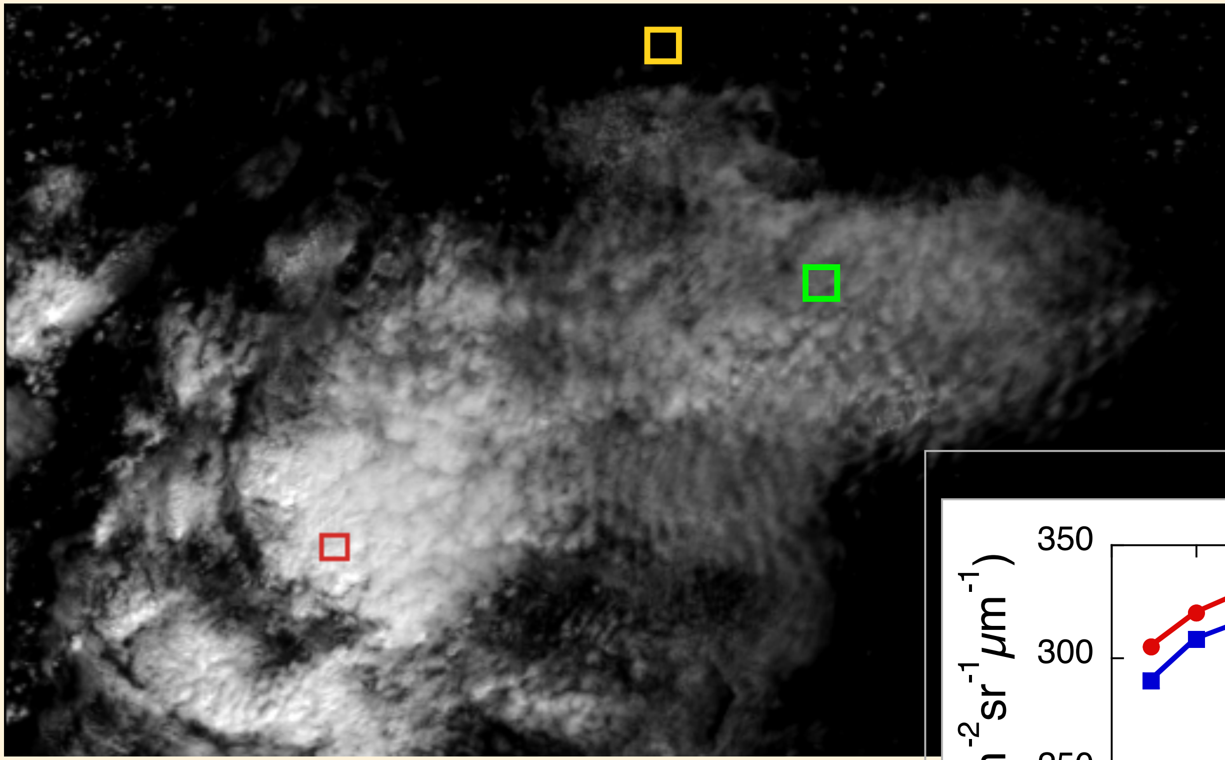
r_e Differences and Spatial Inhomogeneties: 3D RT Results

(Zhibo Zhang, et al.)

periodic 8 km cloud elements over Cox-Munk ocean sfc.

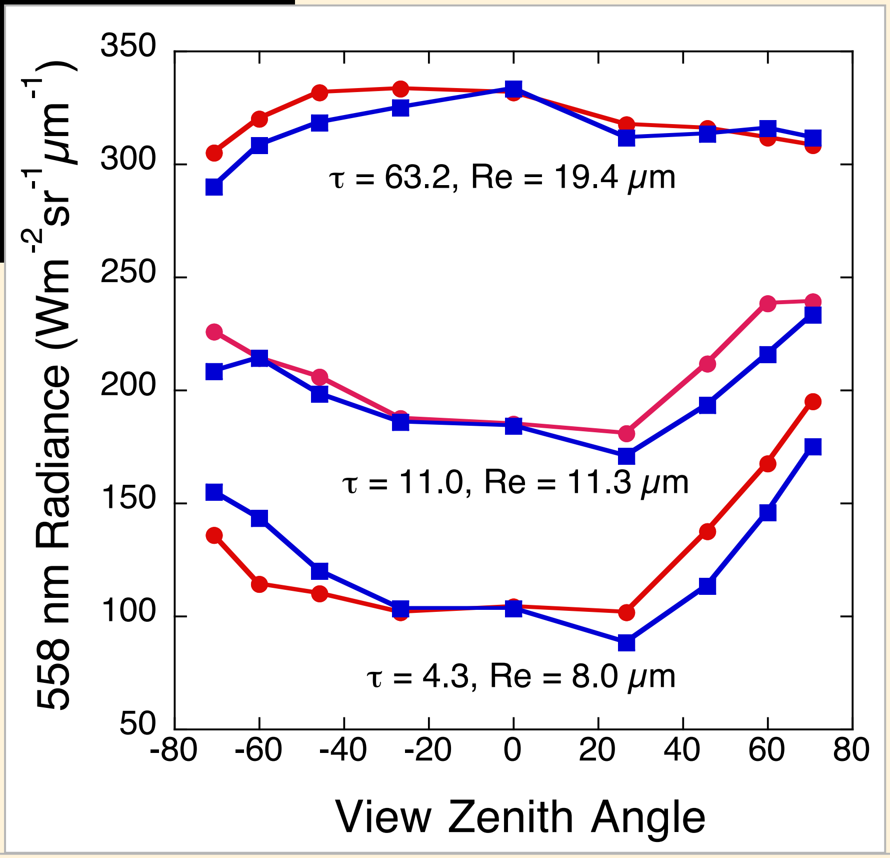






Example, RICO region
October 29, 2003
(Di Girolamo et al.)

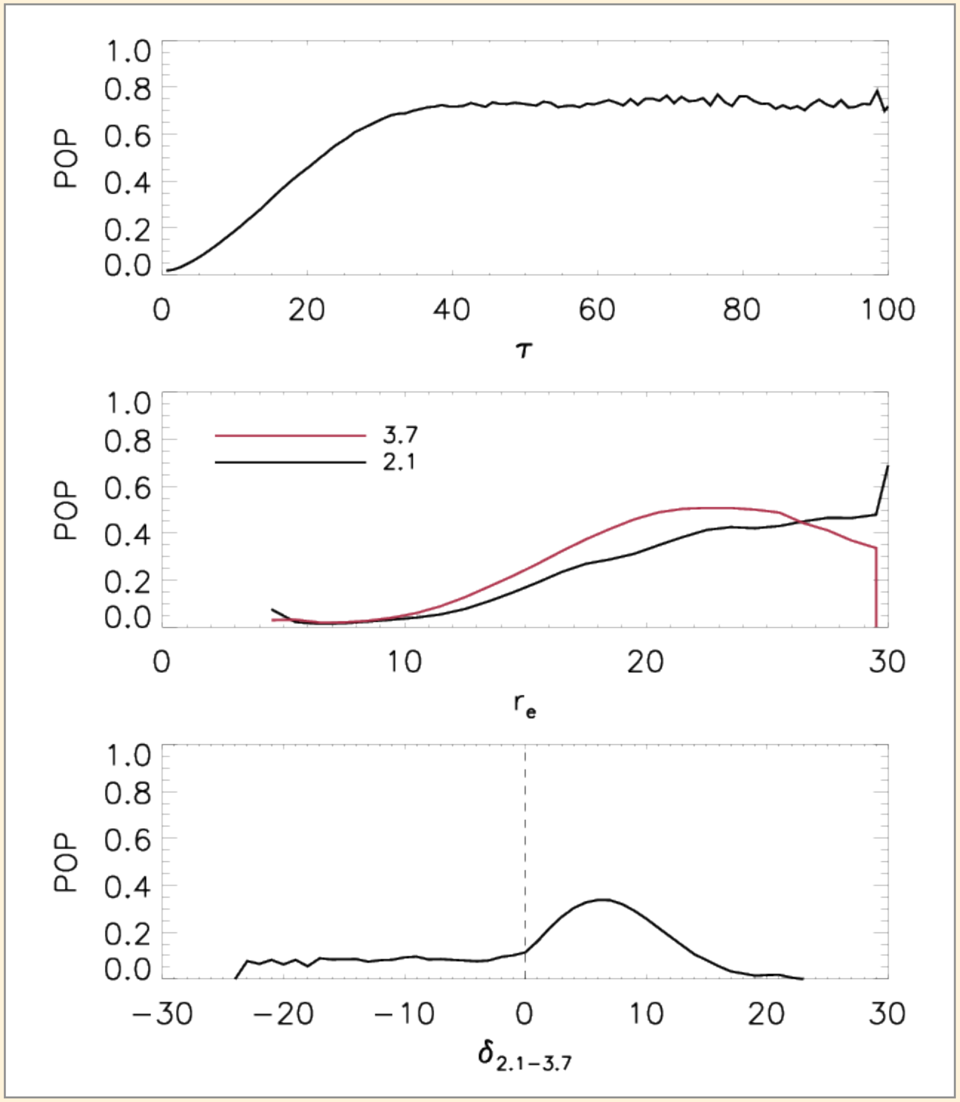
MISR observations
DISORT Simulations from MODIS retrievals



Global Oceanic Low Cloud Results

- MODIS 250m cloud heterogeneity metric (dispersion in 3x3 sq. km region)
- For metric < 0.1 (~40% of all retrievals are less than this value): Angular consistency in the MODIS-retrieved cloud optical properties are within 10% of their plane-parallel values for various angular consistency metrics.

Relationship Between MODIS Retrievals and CloudSat Probability of Precipitation (Matt Lebsock et al.)

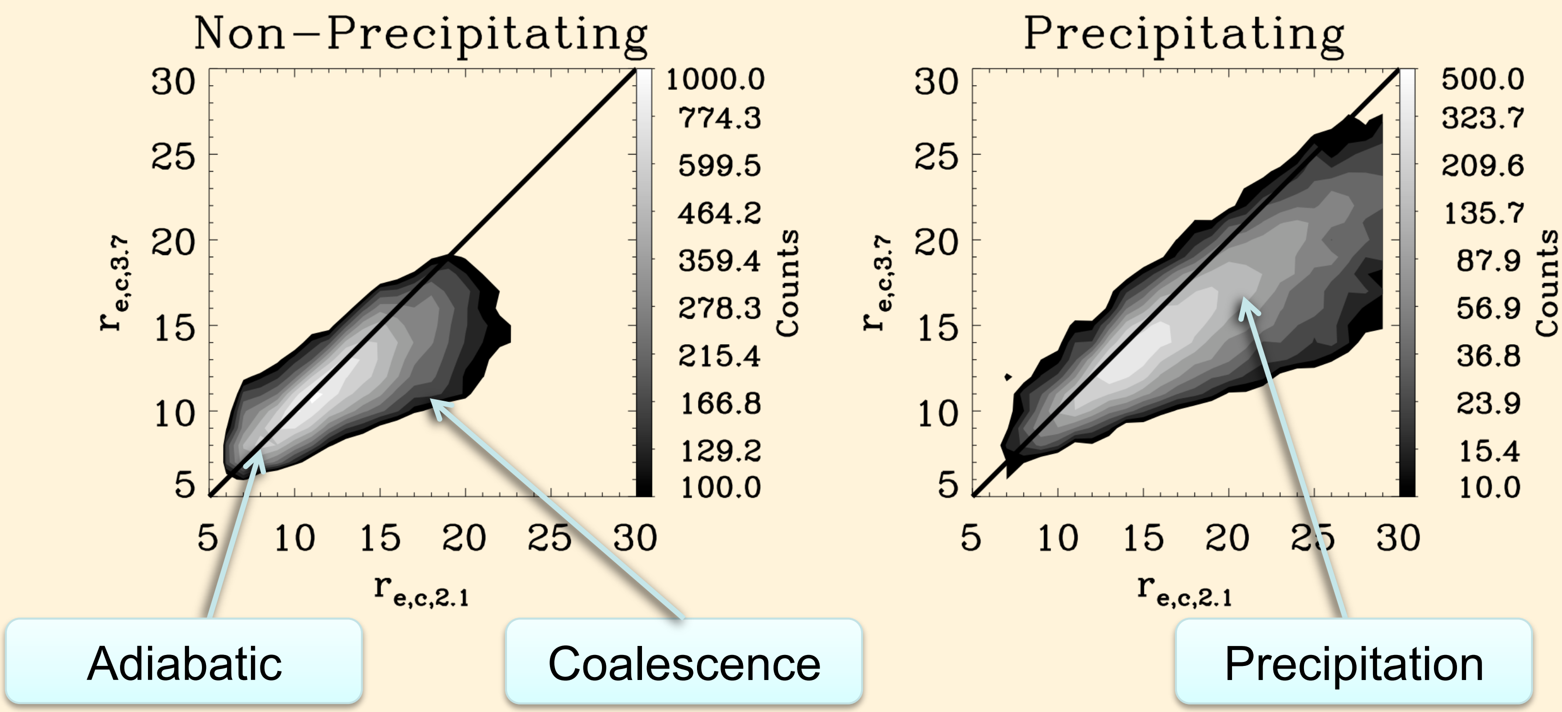


Three MODIS parameters are related to the POP:

1. τ
2. r_e
3. δr_e

MODIS r_e Joint Distributions vs. CloudSat Precipitation

(Matt Lebsock et al.)



- $r_{e,3.7}$ appears to show less precipitation influence
- r_e or δr_e alone can't predict precipitation
- $r_{e,2.1}$ extends beyond 30 μm

Summary of Water Cloud Δr_e Results

- Global r_e statistics between 1.6/2.1 and 3 7 µm retrievals are significantly different.
  - Can't directly compare MODIS standard retrieval (2.1 µm) with AVHRR or MODIS/CERES 3.7 µm derived data sets.
  - Differences between these data sets are due to choice of bands uses, not algorithmic.
  - Oceanic differences correlated with absolute r_e and inhomogeneities reflectance (σ/μ) and precip. (Lebsock et al., 2008; Takashi Nakajima et al., 2010)
  - But drizzle/precip may also be correlated with clouds inhomogeneities. Which is the tail and which is the dog (both)?
  - Some/more significant positive (2.1–3.7) bias with VZA (beyond pixel level uncertainties) in broken oceanic regions.
- Pursuing MOD06 retrievals from marine BL LES runs

4. Summary & Discussion

- All retrievals (w/out exception) have issues with portions of the retrieval pdf space.
- Spatial Resolution is a key issue for BL cloud studies.
- Issues related to broken clouds and/or strong inhomogeneities/ precip:
  - Inability to retrieve cloud amount and physical cloud information (temperature/height biases, optical property "failed" retrievals)
  - Interpretation of large r_e and large Δr_e from different spectral channels
  - Vertical (non-adiabatic) as well as horizontal structure
  - Deviations from plane-parallel models with view angle (instantaneous differences may be large, but aggregated statistics appear less so)
  - Significant presence of ice in midlatitude low clouds. Must have the ability to detect ice and discern mixed phase to (a) understand BL energy budget and affect on dynamics/microphysics, (b) have any hope of understanding retrieval uncertainties.

Summary & Discussion, cont.

- Cloud processes occur across the gamut of spatial/temporal scales, are complex, and require a full understanding of cloud properties (in addition to aerosol and dynamic/thermodynamic properties, model analysis, ancillary data, etc.).
  - Synergistic sensor approaches are required (e.g., A-Train, ACE)
  - To maintain/monitor climatologies (trends), need to continue to invest in instruments that can maintain data continuity.
  - Not everything can be learned from satellites. Strong in situ and modeling efforts are necessary. Inability to retrieve cloud amount and physical cloud information (temperature/height biases, optical property “failed” retrievals)
- ACE BL
  - Imager: narrow swath (selected high res bands), multiple views, wide swath Solar reflectance + IR (w/spectral heritage)
  - Polarimeter
  - Active: Radar (dual frequ.), HSRL