Inter-comparison of cloud observations from CALIOP and passive sensors

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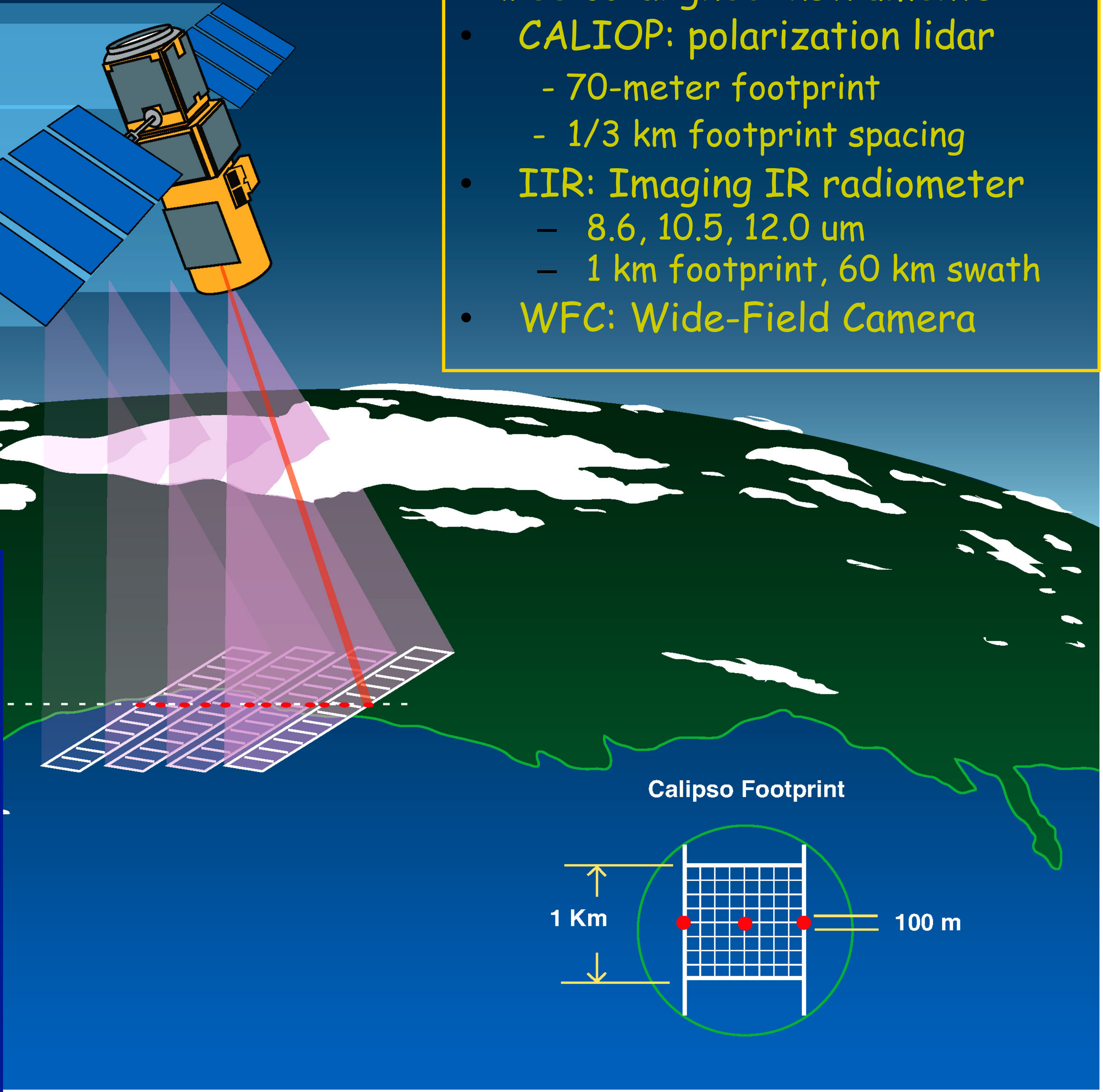
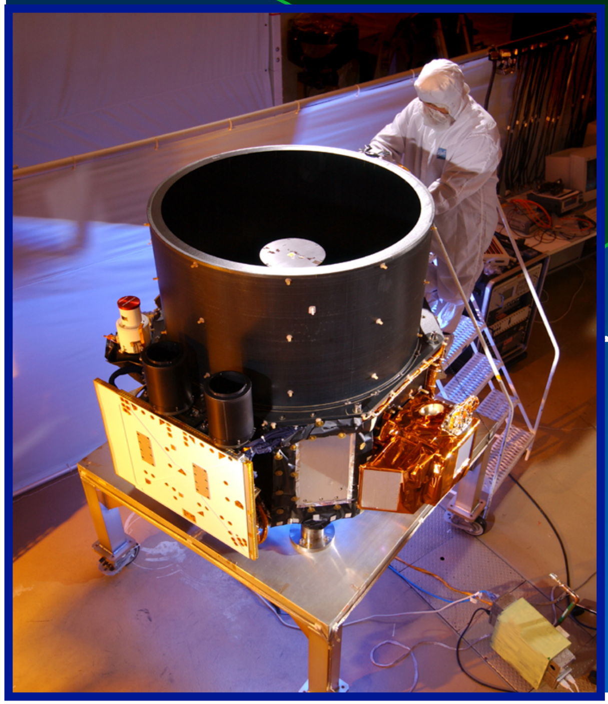
1) NASA Langley Research Center, Hampton, VA
2) LATMOS, U. Pierre et Marie Curie, Paris

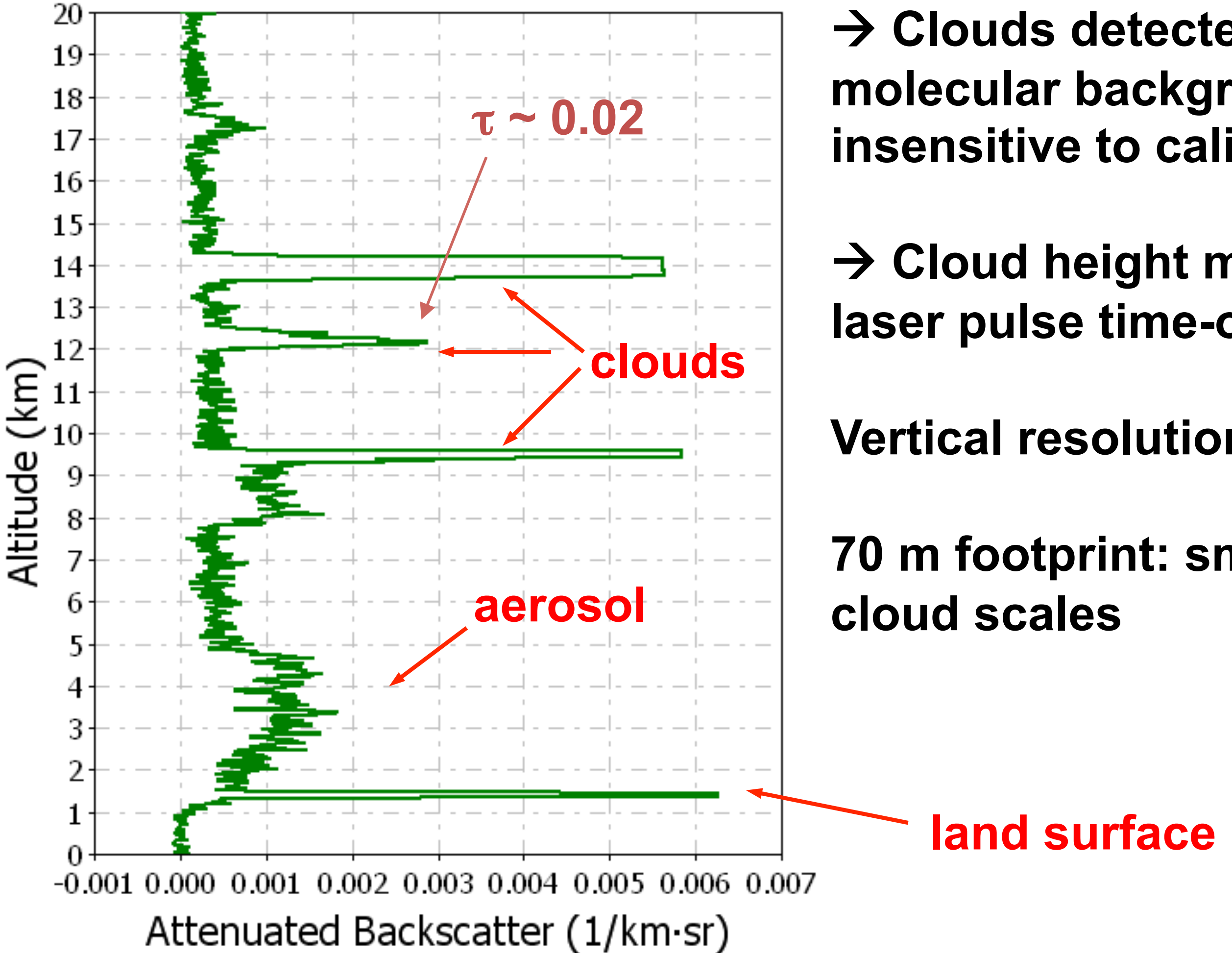
First light: 7 June 2006

Three co-aligned instruments:

- CALIOP: polarization lidar
  - 70-meter footprint
  - 1/3 km footprint spacing
- IIR: Imaging IR radiometer
  - 8.6, 10.5, 12.0 um
  - 1 km footprint, 60 km swath
- WFC: Wide-Field Camera







(profile averaged over 20 km)

→ Clouds detected via contrast with the molecular background, thus inherently insensitive to calibration error

→ Cloud height measured directly from laser pulse time-of-flight

Vertical resolution: 30-60 m

70 m footprint: small compared to most cloud scales

CALIPSO Cloud Products

1. **Cloud occurrence** (contrast with molecular background)
2. **Cloud height** (time of flight)
3. **Ice/Water phase** (depolarization)

Numerous published intercomparisons

- **MODIS cloud tops/mask: Holz and Ackerman (JGR, 2009)**
- **Small biases on single-layer clouds when CO2 slicing can be used**
- **Large biases for high thin clouds, multi-layer clouds**

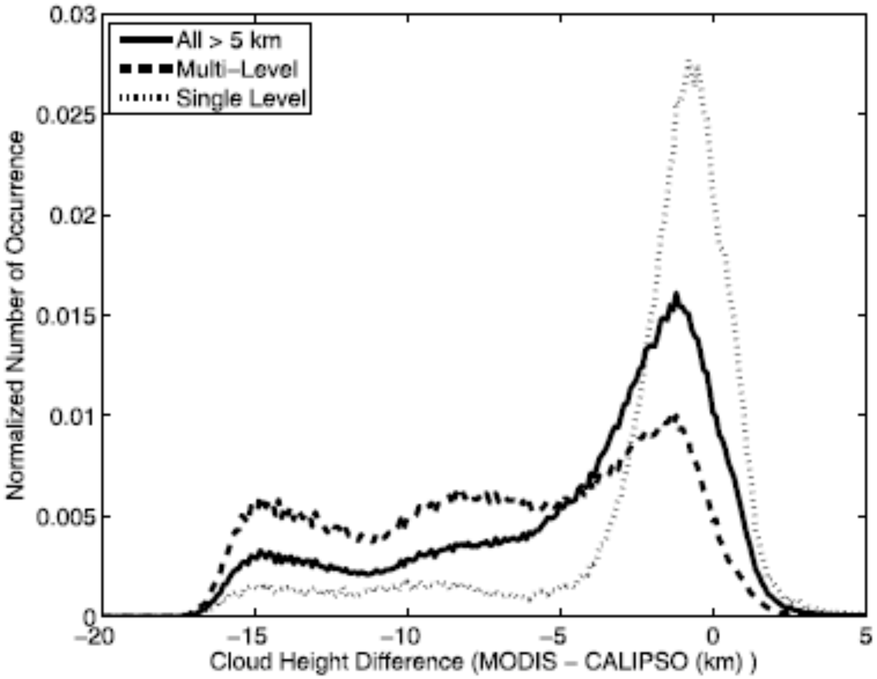


Figure 13. Histogram of global cloud height differences for August 2006 are presented filtered by single and multilayer clouds using CALIOP. A multilayer cloud is defined using CALIOP and requires that maximum cloud top height be greater than 5 km and the separation between the top cloud layer base and cloud top height of the bottom layer be greater than 4 km.

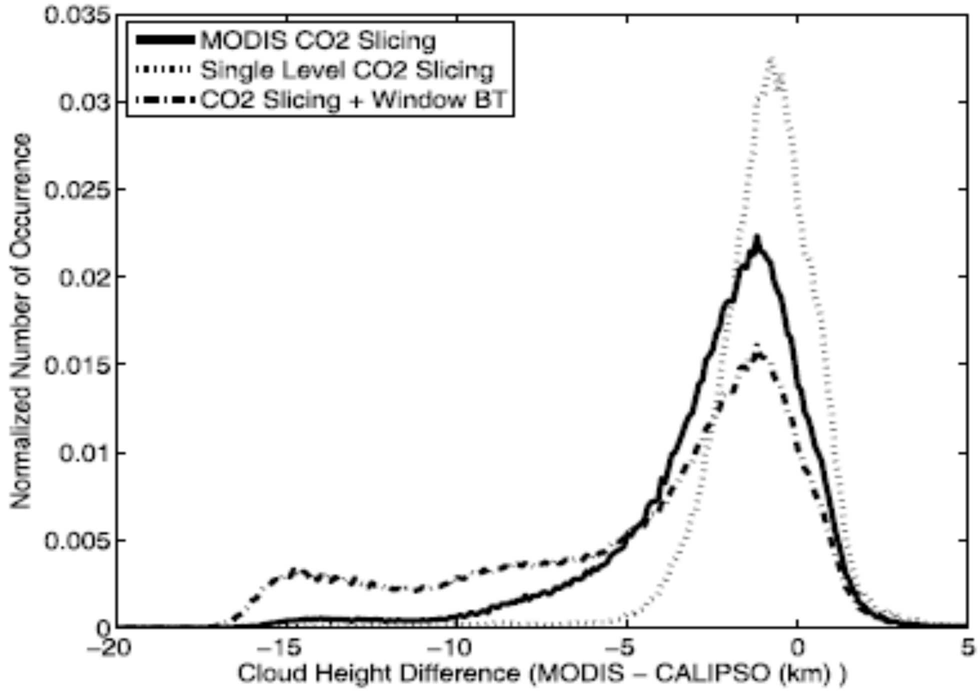
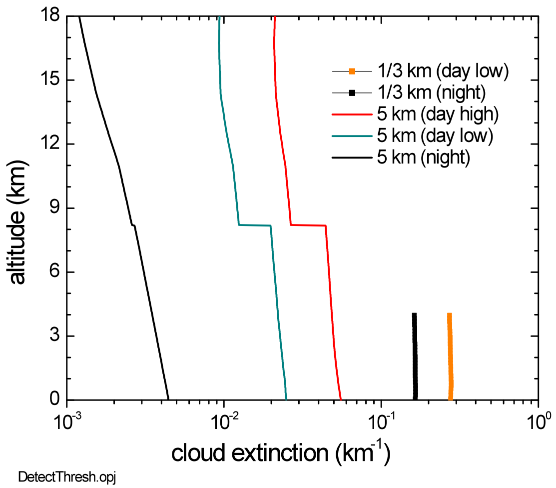


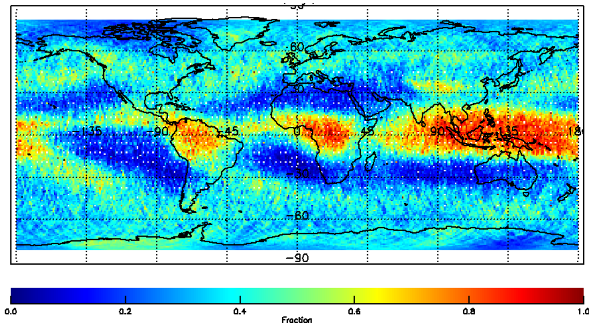
Figure 14. Histogram of the global cloud height differences during August 2006 for CALIOP determined high clouds (>5 km) filtered for cases where the MODIS retrieval applied CO_2 slicing (solid line) and CALIOP determined single level clouds (dotted line). The distribution for all high clouds (combined CO_2 slicing + window BT retrieval) is also presented.

Very sensitive to high, thin cloud

CALIOP used as reference for cloud occurrence and height in GEWEX Cloud Assessment:

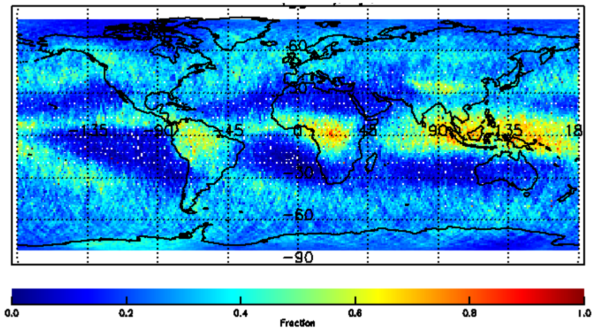


All, 0.381

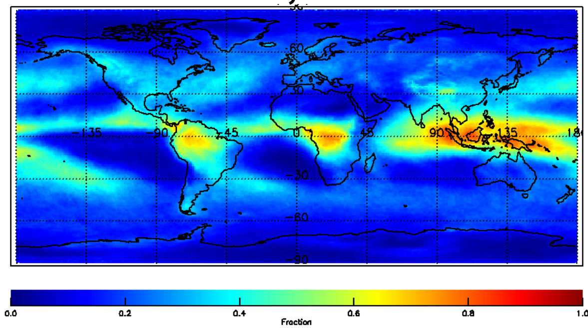


Annual mean cloud fraction of high cloud (> 6.5 km) from CALIOP, with various thresholds applied.

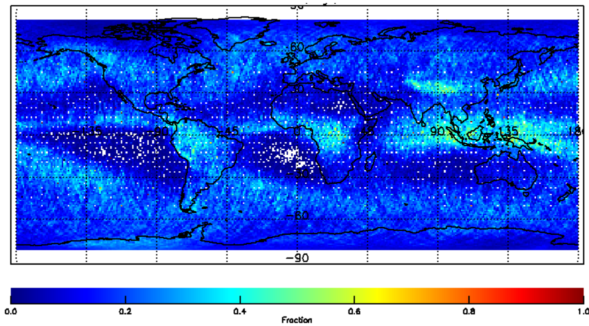
OD > 0.03 , 0.288



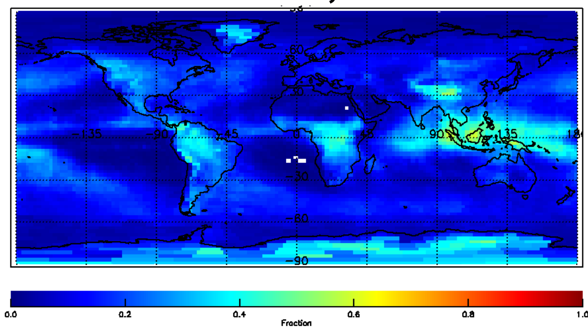
AIRS, 0.228



OD > 0.3, 0.170



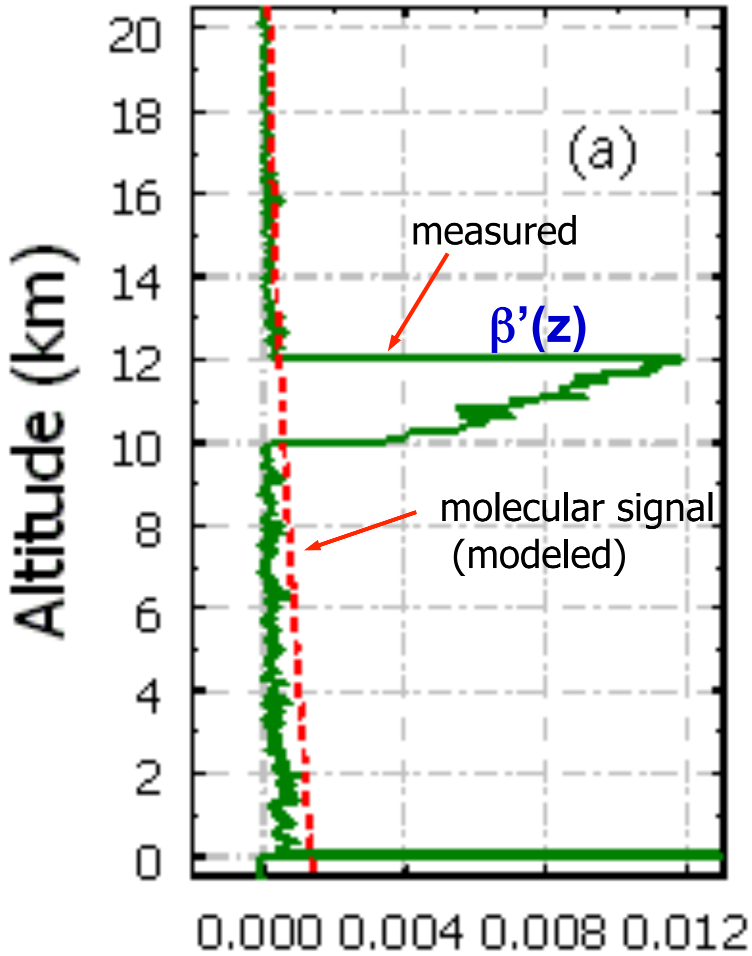
ISCCP, 0.144



CALIPSO Cloud Products

1. **Cloud occurrence** (contrast with molecular background)
2. **Cloud height** (time of flight)
3. **Ice/Water phase** (depolarization)
4. **Optical depth, extinction profile**
    1. Two different CALIOP retrievals
5. **De and IWP**
    1. IR retrieval constrained by CALIOP

Two CALIOP Cirrus Retrievals



1) Forward ("unconstrained") retrieval

$$\beta_c(z) = \beta'(z)\, e^{+2\tau^*(z)} - \beta_m(z)$$

Depends on:

a priori lidar ratio: $S = \sigma_c / \beta_c$

multiple scattering factor $\eta = \tau^* / \tau$

2) "Constrained" retrieval

Measure cloud transmittance from clear air returns above and below

Transmittance provides constraint on extinction retrieval:

$$S_a^* = \frac{1 - T^2}{2\gamma'}$$

If we properly correct for multiple scattering, can also retrieve lidar ratio S

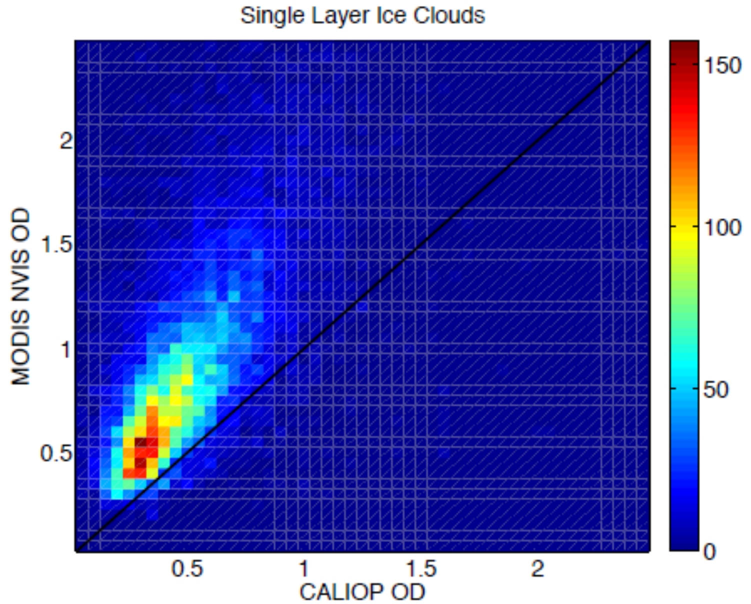
CALIPSO Cloud Products

1. **Cloud occurrence** (contrast with molecular background)
2. **Cloud height** (time of flight)
3. **Ice/Water phase** (depolarization)
4. **Optical depth, extinction profile**
   1. Currently for ice cloud only, water cloud possible
   2. Two retrievals: from two-way transmittance or forward retrieval
5. **De and IWP**
   1. IR retrieval constrained by CALIOP
6. **IWC**
   1. Two retrievals: from CALIOP extinction or from IIR IWP and CALIOP Δz
   2. New mass/extinction parameterization (Heymsfield et al., 2014)

Cirrus Optical Depth (OD) Validation

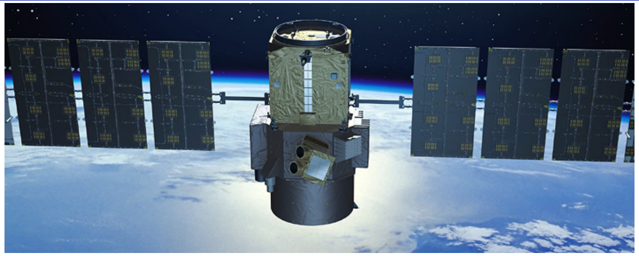
- Initial CALIOP-MODIS comparisons (~2008) indicated significant discrepancies
  - Daytime only
  - Mostly unconstrained retrievals
- MODIS team concerns (Collection 6) led to formation of an informal working group to investigate the discrepancy
- Intercomparison of multiple retrievals:
  - CALIOP constrained, unconstrained
  - MODIS C5
  - 3 different IR retrievals

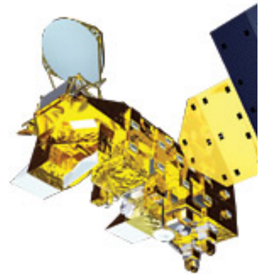
CALIOP vs. MODIS



Bob Holz will say more at 12:00 today

Retrieval Approaches



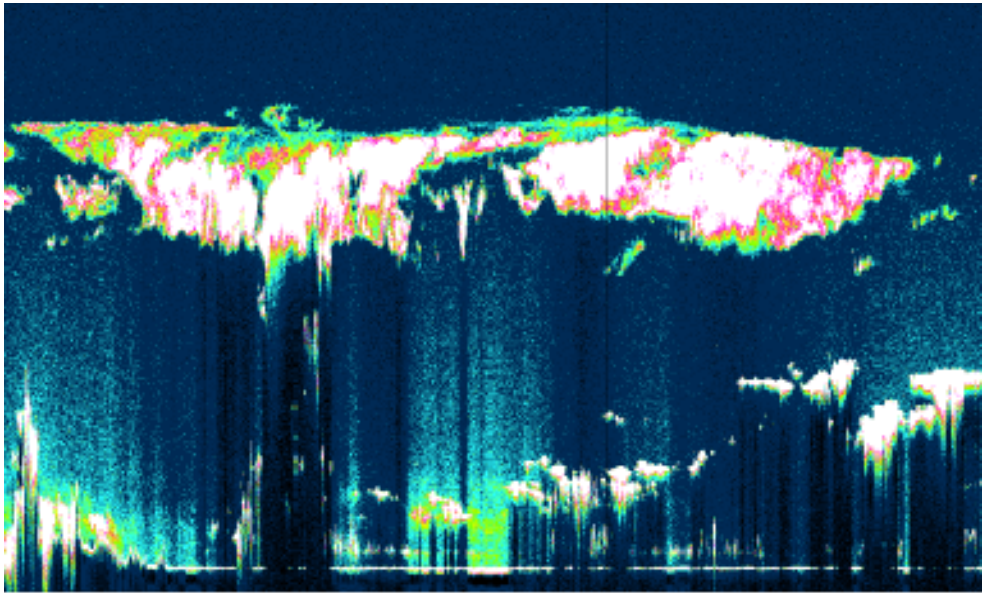


(1)

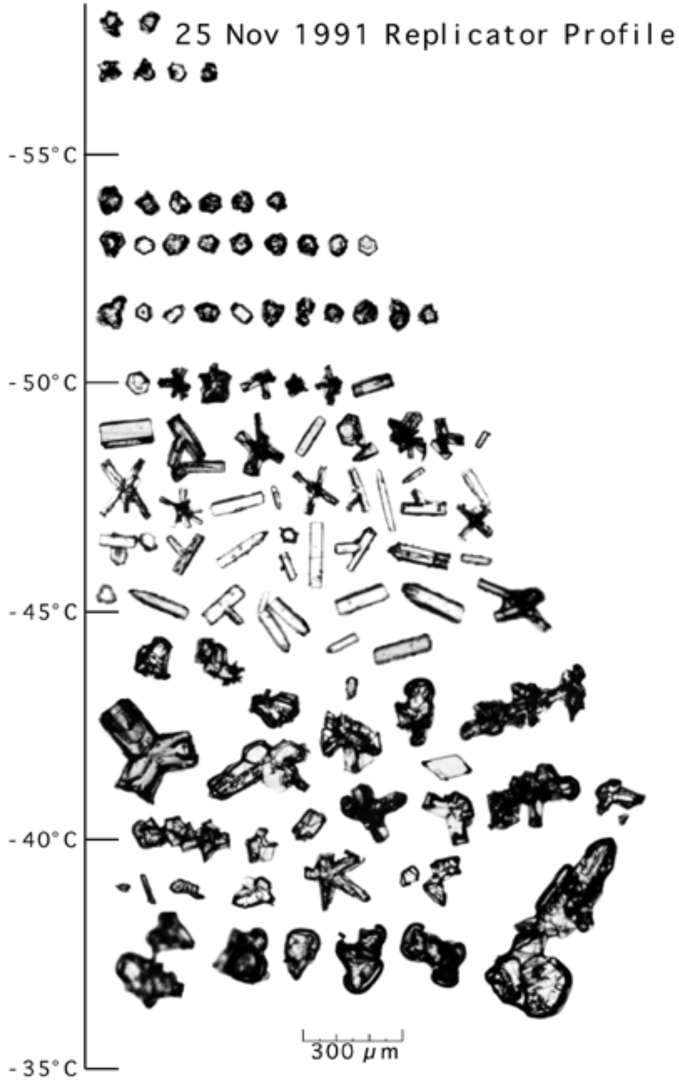
(2) lidar attenuation

Reflectance $\sim \tau^* = \tau[1-g(r_e)]$

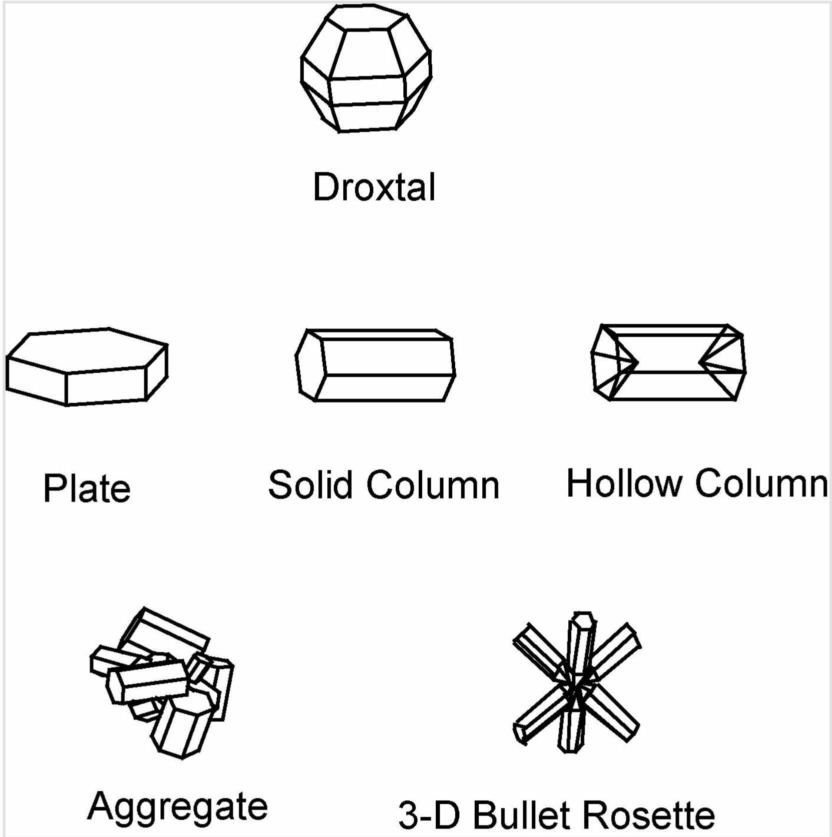
(3) thermal emission



Models can only approximate the real world



ice crystal shapes from FIRE II
(Miloshevich and Heymsfield)



Geometric Scattering Theory

<u>Anatoli Borovoi and co-authors:</u>

- several papers show lidar backscatter from ice crystals is mostly due to internal corner reflections.
- Backscatter is produced at preferential tilt angles, involves only partial facets.

So backscatter cross-section
is decoupled from extinction

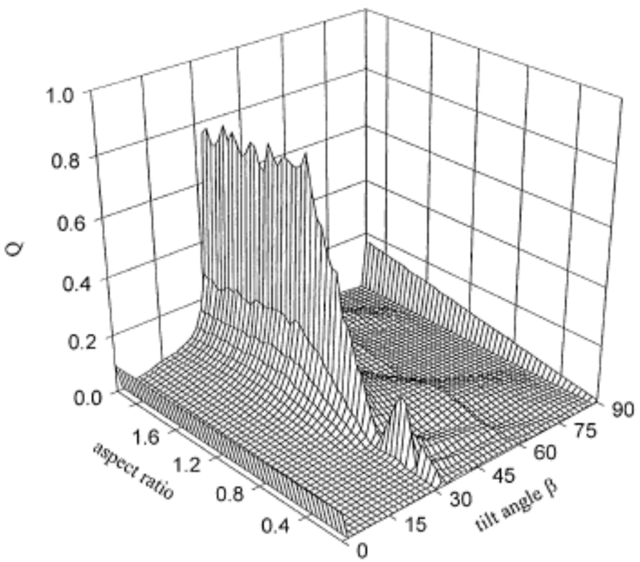
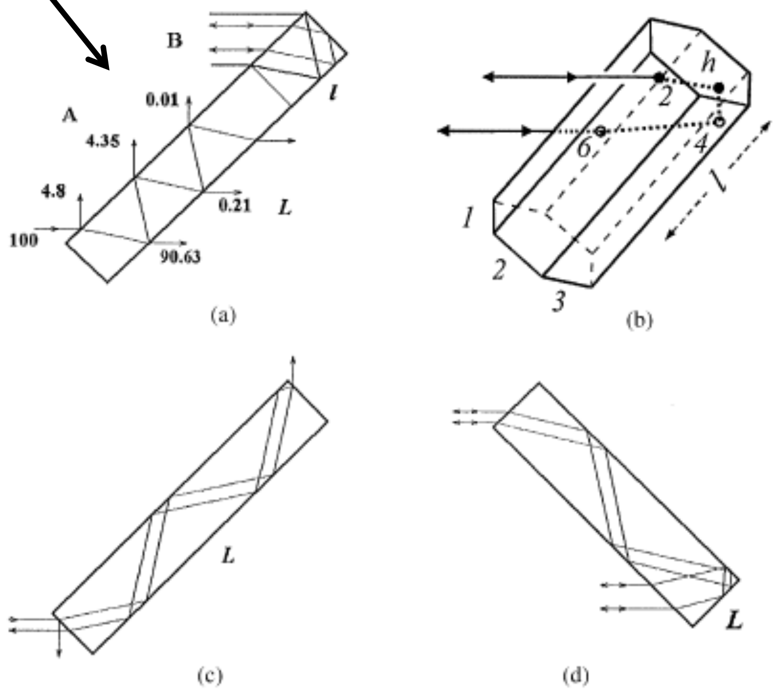
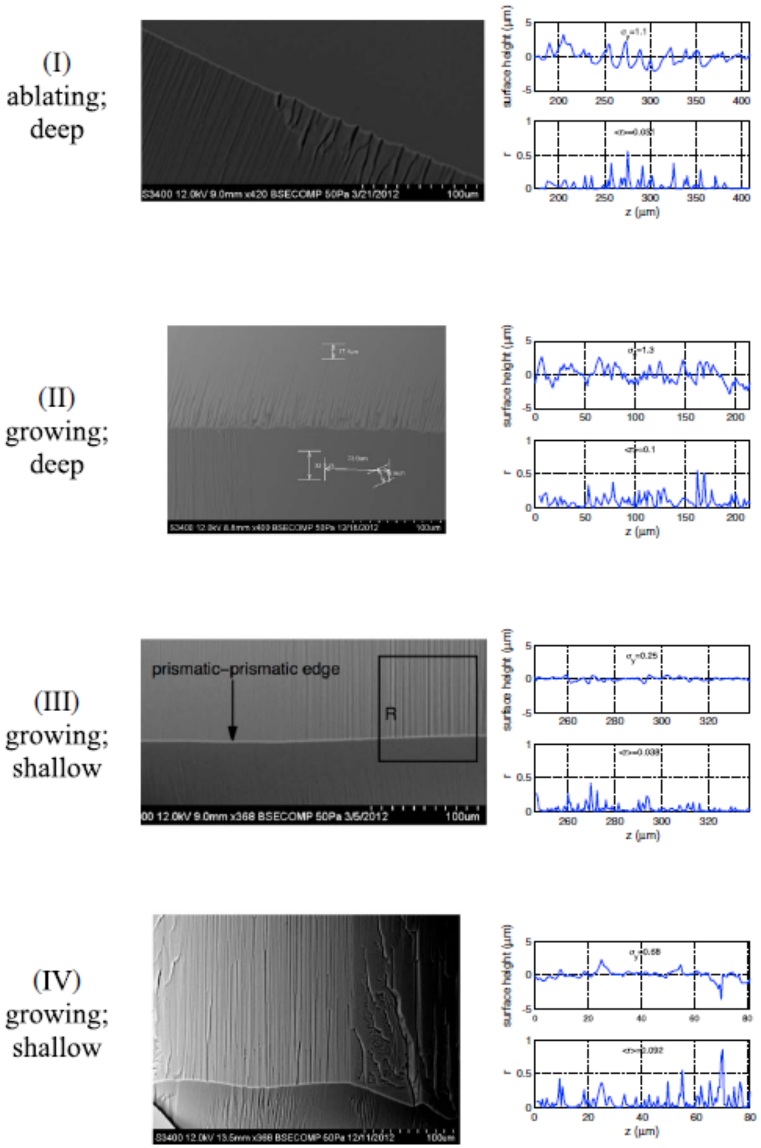


Fig.8. Backscattering efficiency, Q, vs.aspect ratio L/2a for hexagonal columns and plates

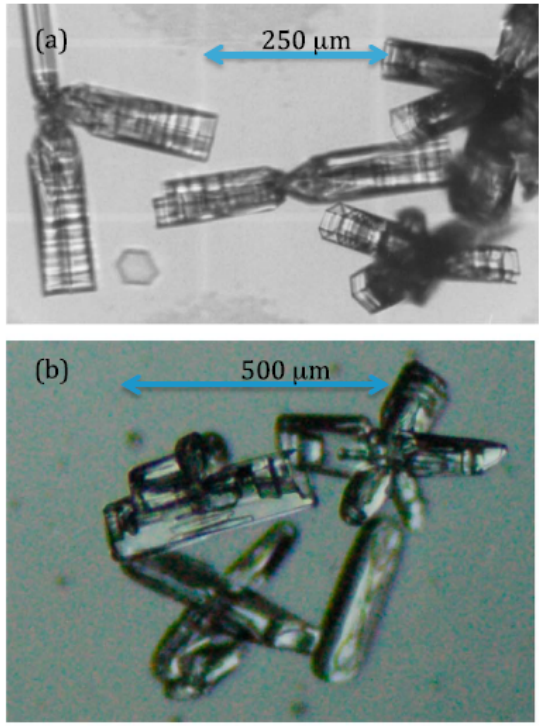


Plus, crystals have microscale irregularities



VPSEM images of ice at low pressure: growing at -45 C, ablating at T = -32 C (Neshyba et al, 2013)

Ice crystals captured during winter at South Pole and Summit stations



- Summary of what we learn from consideration of the physics of lidar backscatter:
  - Lidar backscatter appears to be highly sensitive to details of crystal habit, aspect ratio, and micro-scale surface roughness
  - Theory currently not capable of accounting for all these factors
    - Must also account for diffraction
    - Coherent effects may also be important
  - Lidar ratio could be highly variable, but must rely on experimental approaches to evaluate
- Constrained retrievals avoid all these issues, but are not always possible, especially during day

New IR Cirrus Optical Depth Retrieval

- Development of the CALIPSO IR retrieval was inspired by Martin Platt's LIRAD work in the 1970's
  - Thanks to Jacques Pelon and many others

- IIR retrieval is basically a split window technique
  - Parol, et al. (1991)
  - With CALIOP used to constrain the IR forward model
  - Garnier et al, JAMC (2012, 2013)

- The use of lidar profiles constrains significant uncertainties in traditional split-window IR retrievals

Level 2 IIR Products

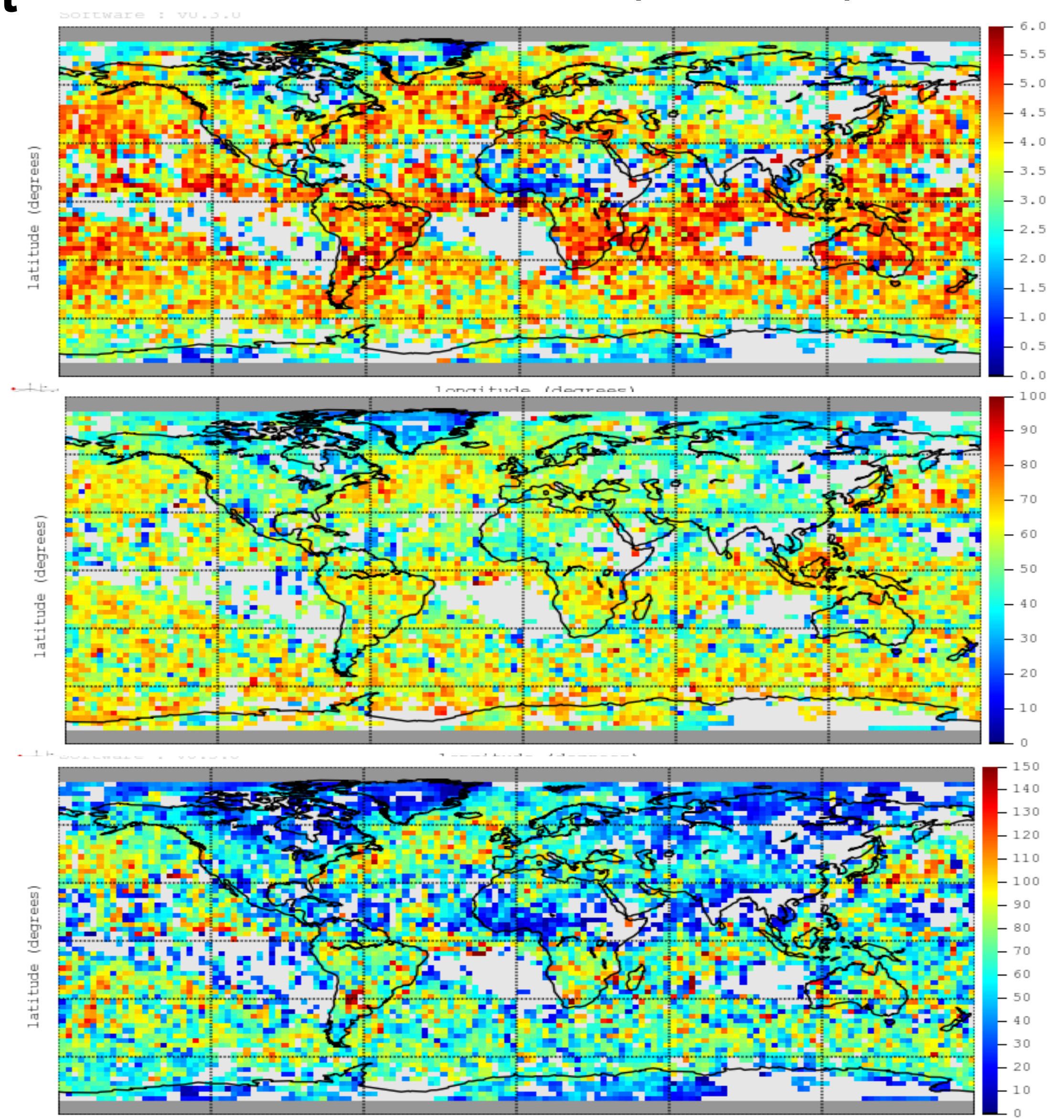
From cloud emissivity at
8.65, 10.5, 12.05 um

for clouds > 7 km (Jan 2009)

Cloud Optical Depth

Effective Diameter

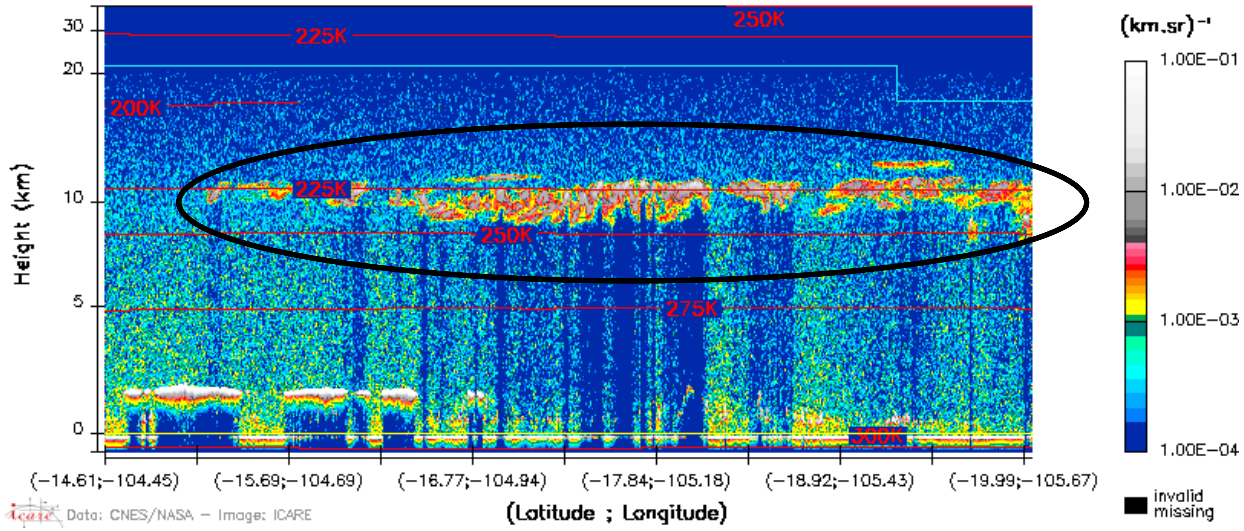
Ice Water Path



effective optical depth retrieval

$$\varepsilon_{eff} = \frac{R_m - R_{ref}}{R_{Tcloud} - R_{ref}}$$

$$OD_{eff} = -\ln(1 - \varepsilon_{eff})$$



R_m, radiance at 12.05 μm, measured

R_{ref}, reference radiance at 12.05 μm, measured or computed

- CALIOP used to identify clear-sky for reference measurements

R_{Tcloud}, blackbody radiance from cloud equivalent altitude

- cloud altitude derived from CALIOP

Garnier et al, JAMC, 2012

IIR scene types derived from CALIOP

TABLE 2: IIR scene classification for high altitude clouds (>7km)

Scene	Target description	Reference
21	1 high STC layer and no aerosol layer	surface
30	1 high STC layer and non- depolarizing aerosols	surface
40	1 high opaque cloud layer, vol_depol_ratio_max >40%	surface
80	1 high opaque cloud layer, vol_depol_ratio_max < 40%	surface
22	2 high STC layers	surface
26	3 high STC layers	surface
31	1 high STC layer	low opaque cloud
32	2 -5 high STC layers	low opaque cloud
37	1 high STC layer	low opaque aerosol
41	1 high STC layer	high opaque cloud
42	2 high STC layers	high opaque cloud

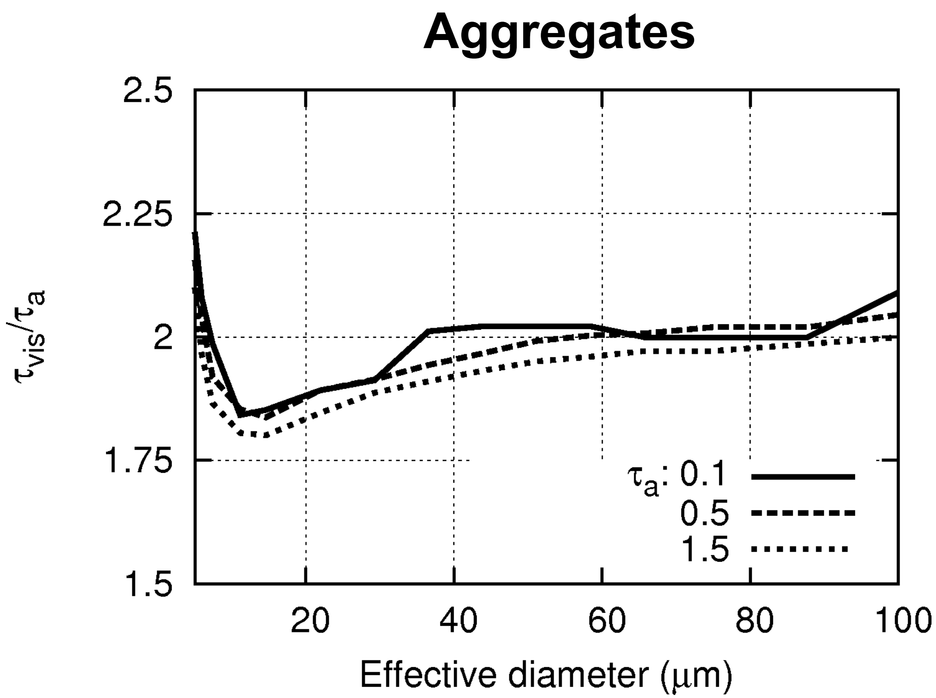
From CALIOP:

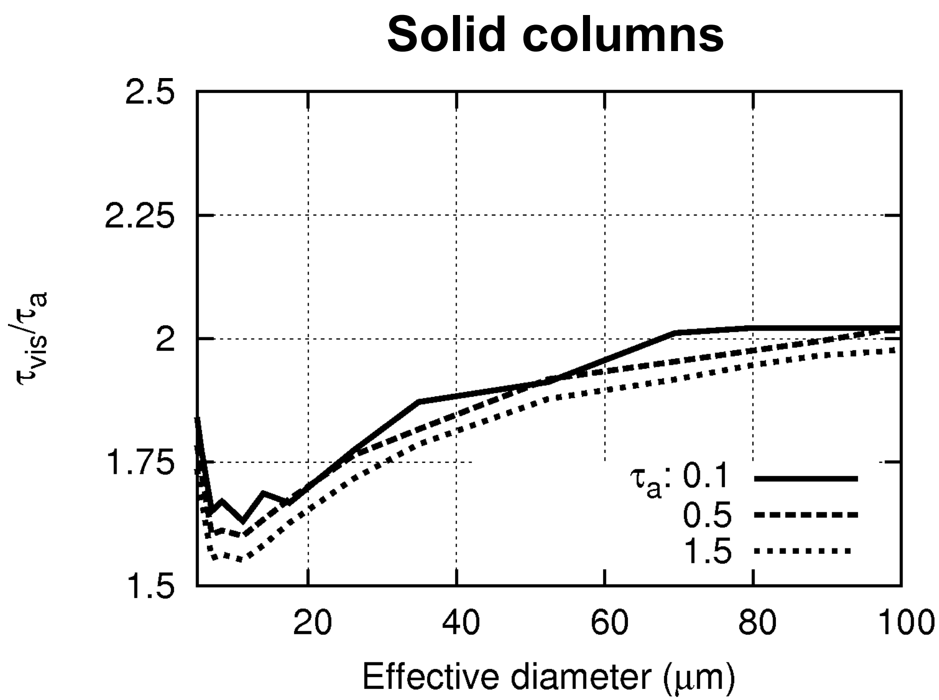
- scene type: R_{ref} (clear or low opaque)
- eff cloud height: R_{Tcloud}

RT Simulations

Ratio of visible OD to effective absorption OD at 12 μm
(from atmospheric radiative transfer calculations)

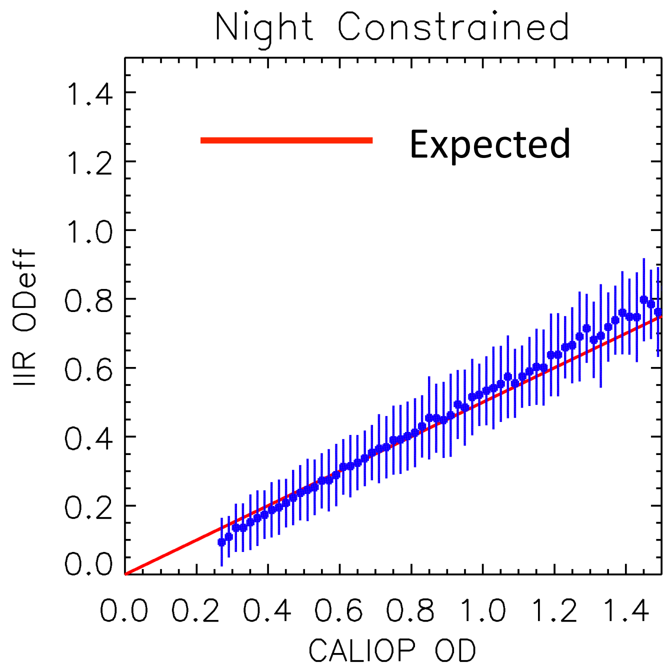
For large particles: theory predicts ratio is approximately 2 and independent of habit





IIR OD_{eff} vs. constrained OD

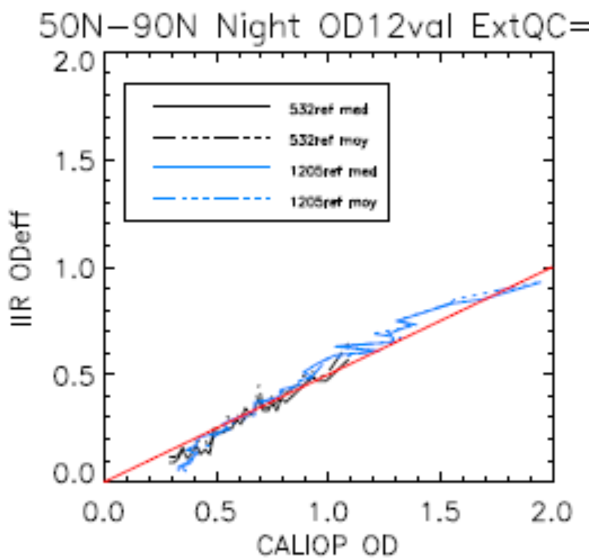
Single-layer semi-transparent clouds, tops > 7km, randomly oriented ice, global ocean

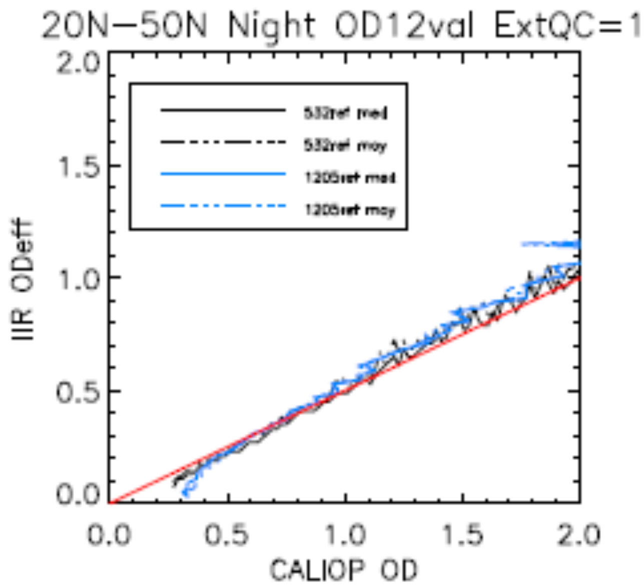


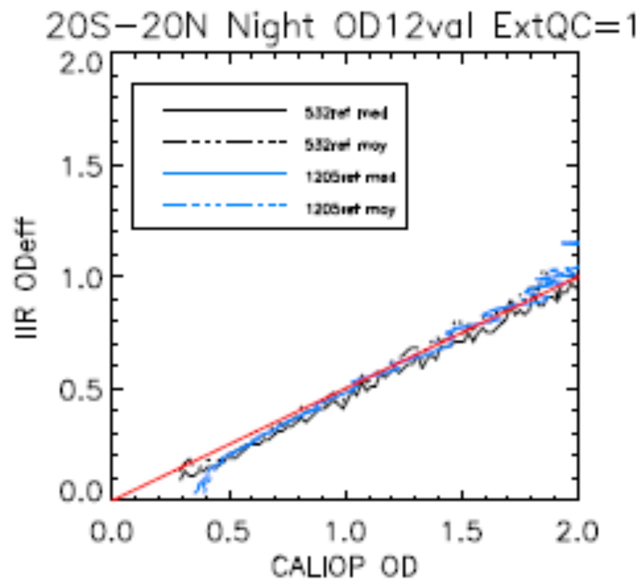
← CALIOP 'constrained' OD from direct transmittance measurement

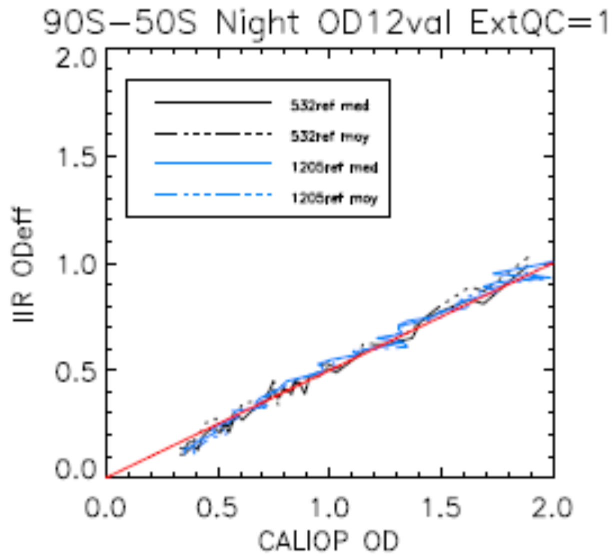
- CALIOP constrained OD/IIR OD_{eff} = 2.0 +/-10% in agreement with expectations and sensitivity studies.

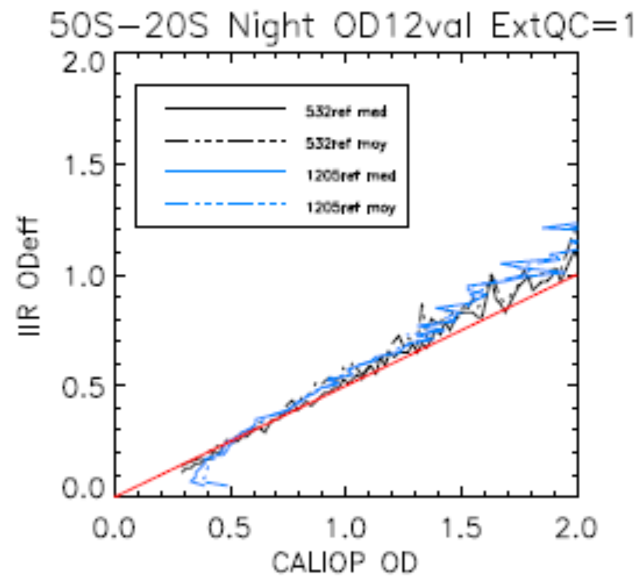
IIR OD$_{eff}$ vs. constrained OD
by latitude







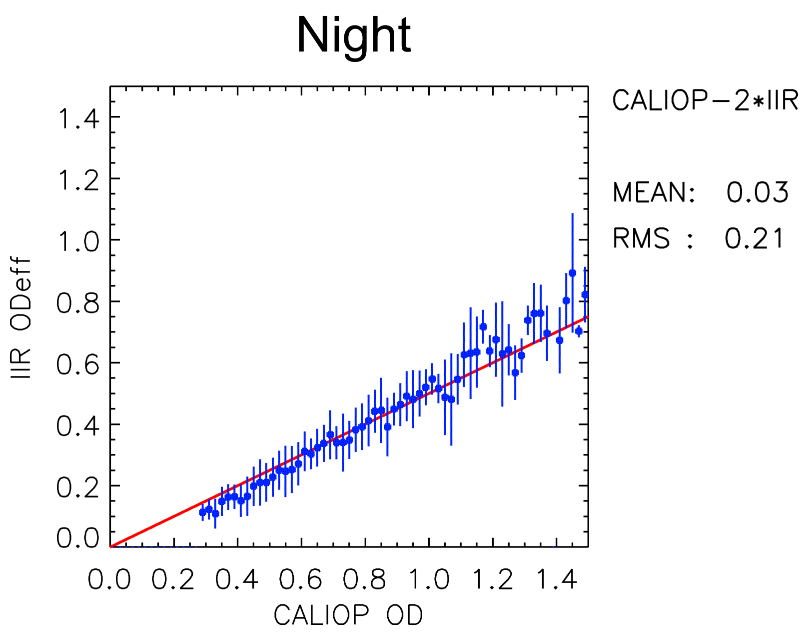


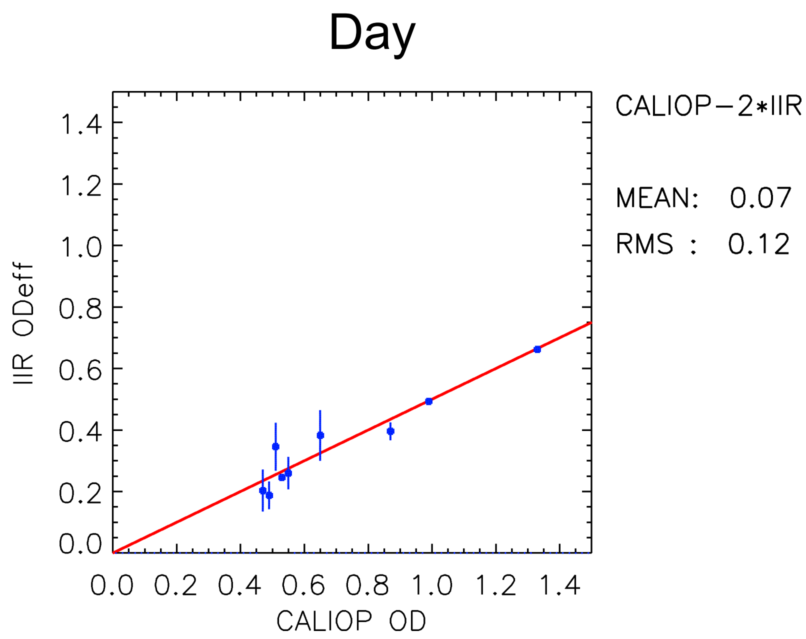


IIR OD_{eff} vs. constrained OD

Thin cirrus above low opaque cloud

January 2011, all latitudes

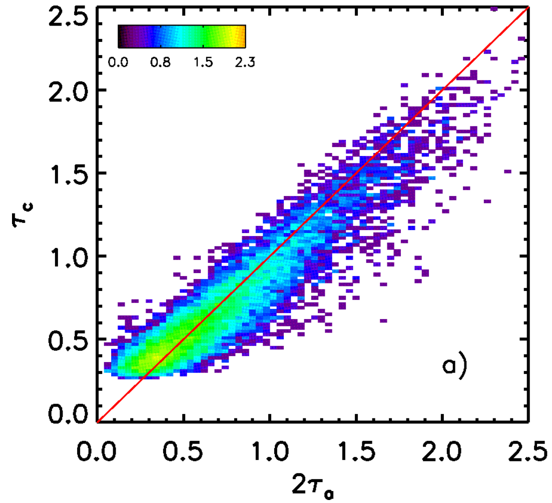




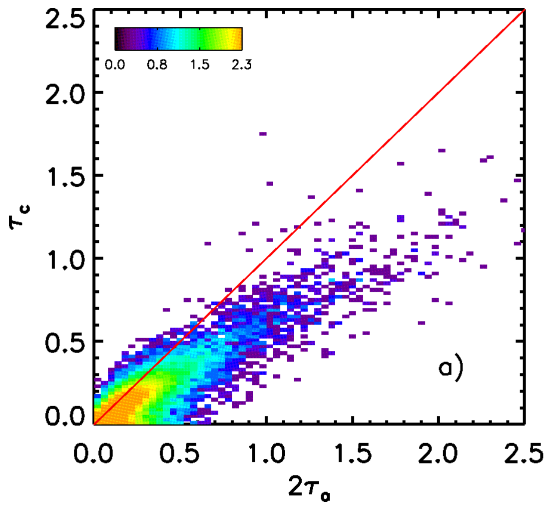
Single-layered ST clouds over low opaque cloud, alt > 7km (type 31)
Measured reference from neighboring pixels, ROI high confidence

IR OD vs. Constrained, Unconstrained retrievals

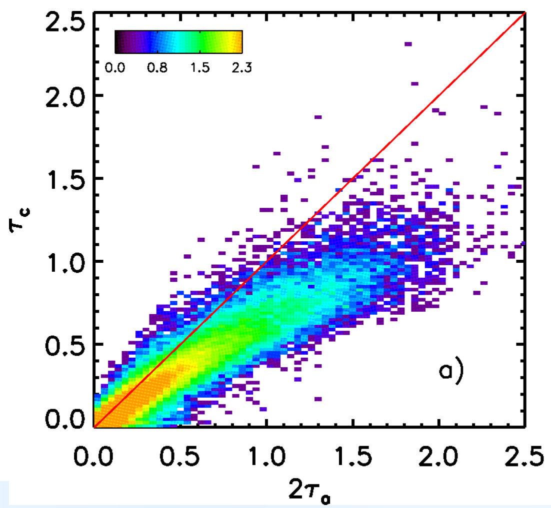
Night, constrained, Qc=1



Unconstrained, Qc=0

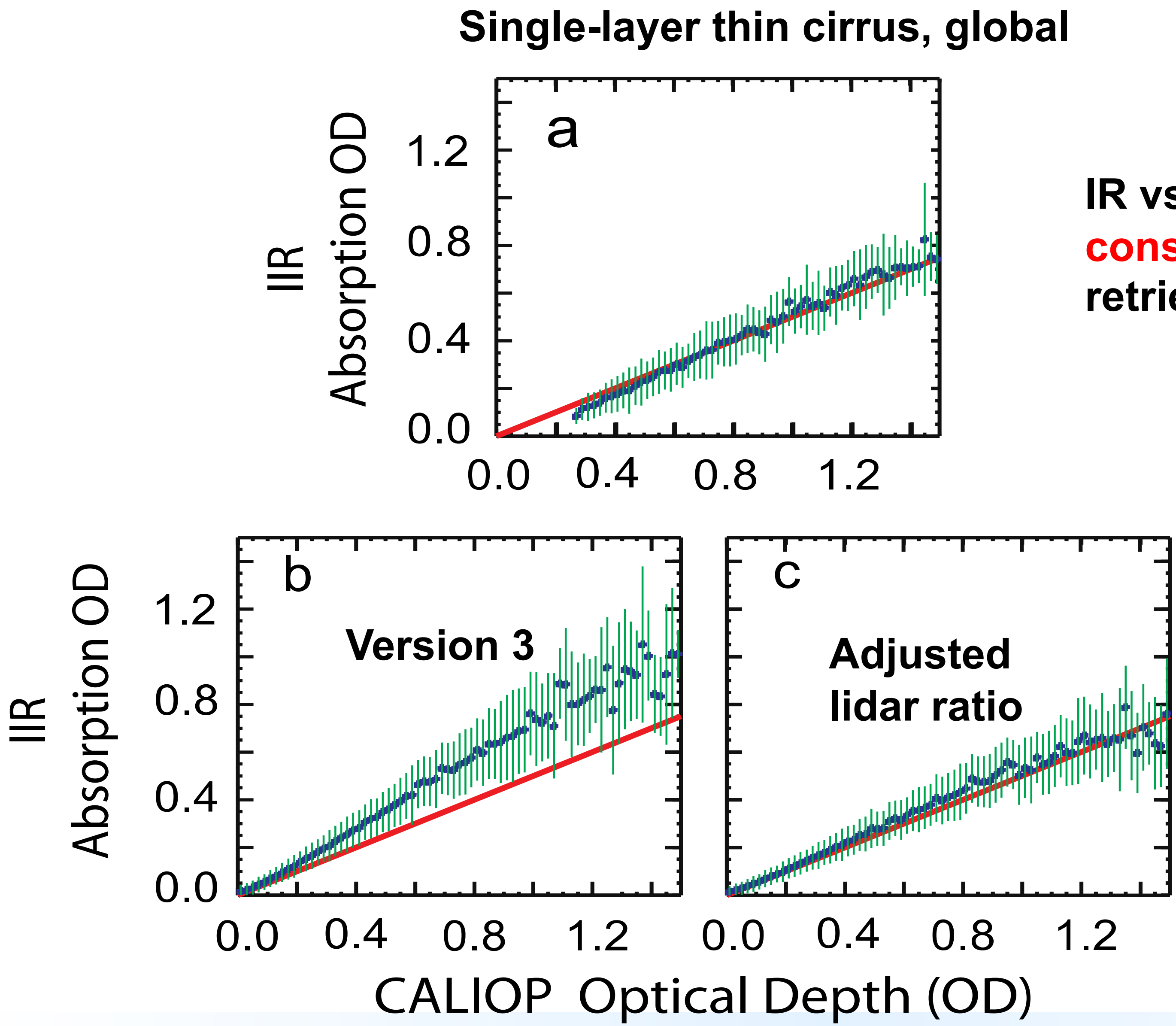


Night, **Sc=25**



Day, **Sc=25**

CALIOP cirrus OD vs. IIR 12 um eff. OD

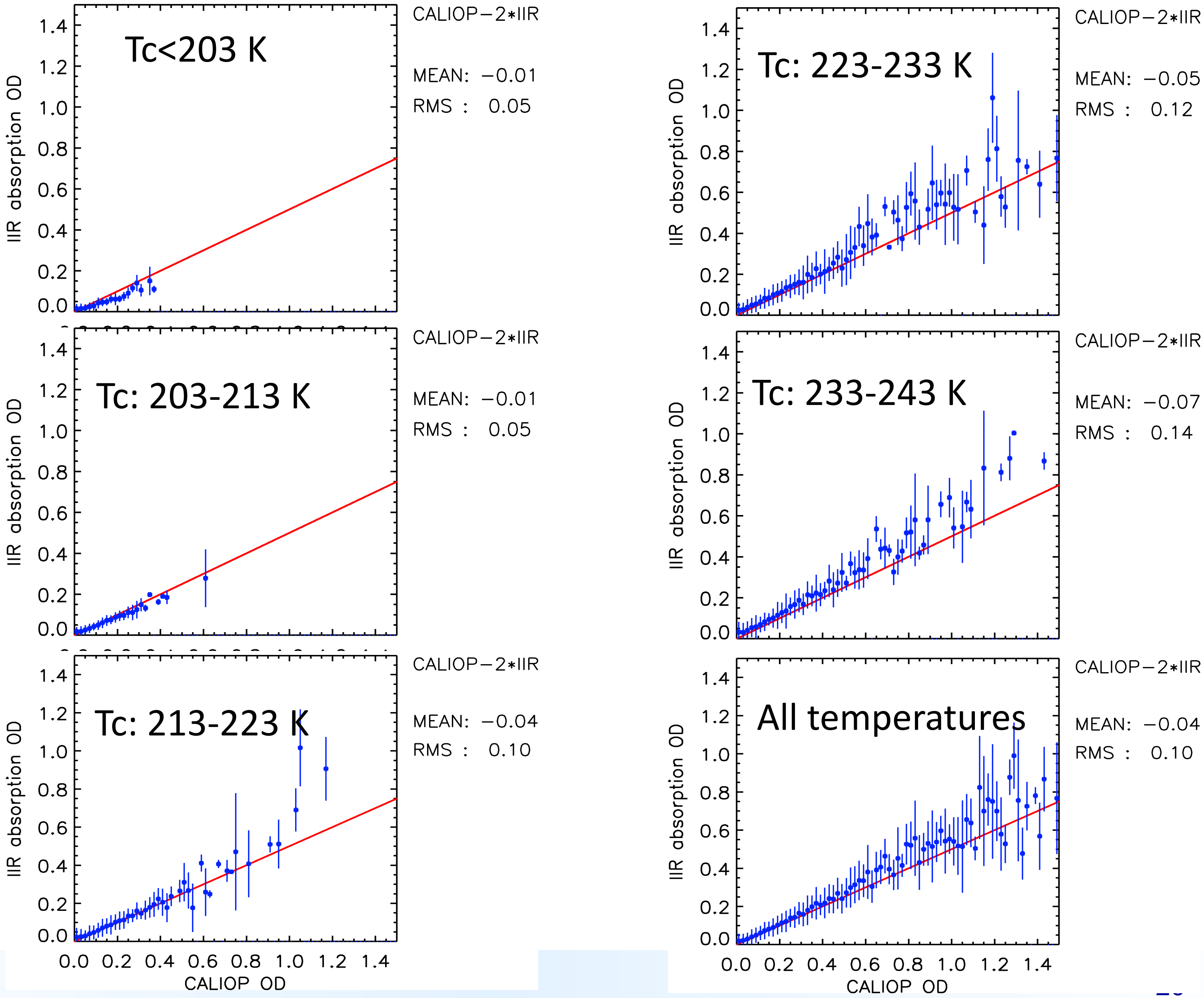


IR vs. CALIOP **constrained** retrievals

IR vs. CALIOP **unconstrained** retrievals

IR vs. Unconstrained OD

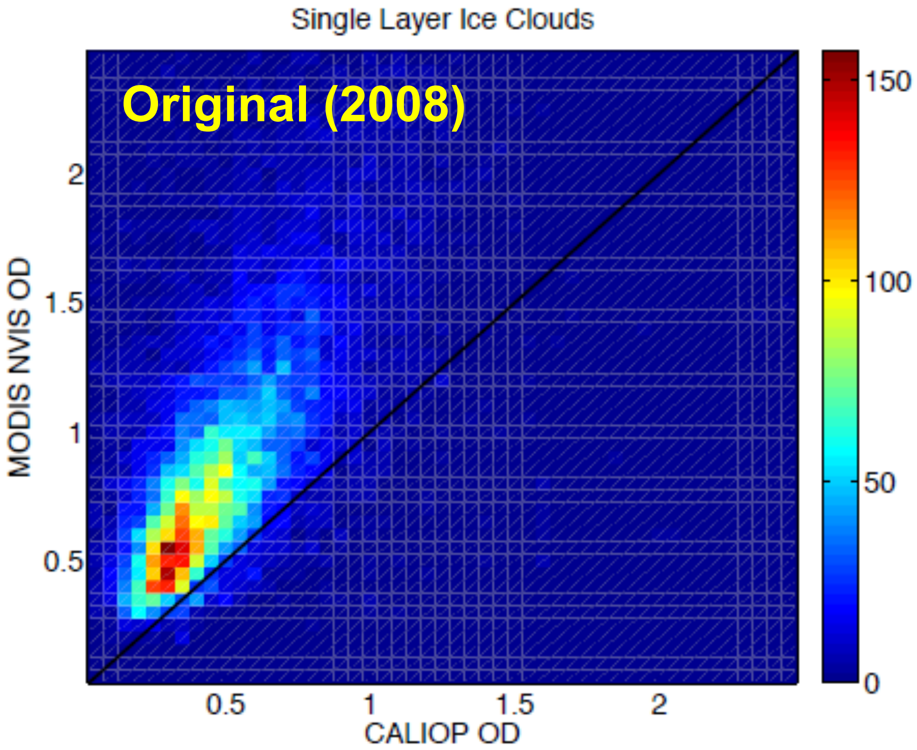
Unconstrained
Night, Sc=29.9

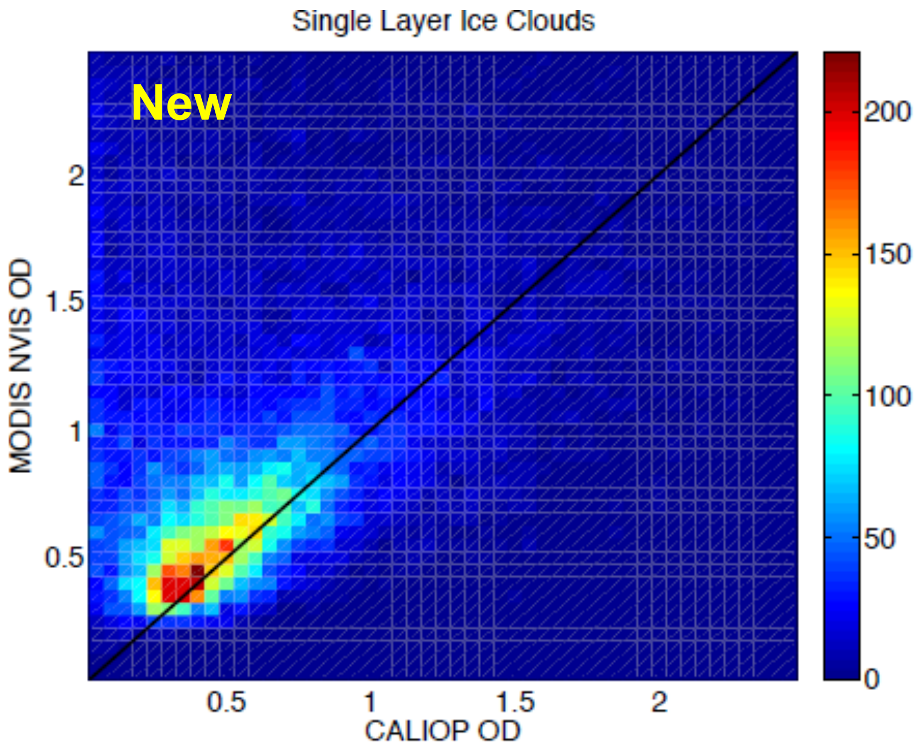


Resolution of Original Discrepancy

- **New ice model adopted for MODIS Collection 6**

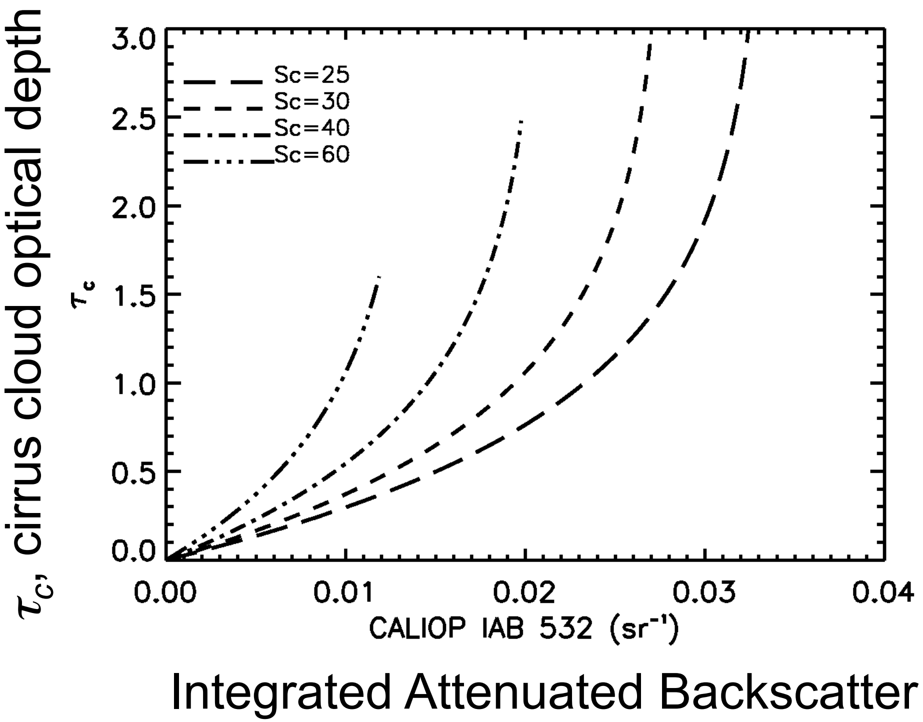
- **Larger lidar ratio brings CALIOP unconstrained retrieval into agreement with MODIS Collection 6**





MODIS = ACOL
CALIOP lidar ratio = 31

Theoretical Relations Between Lidar IAB and OD

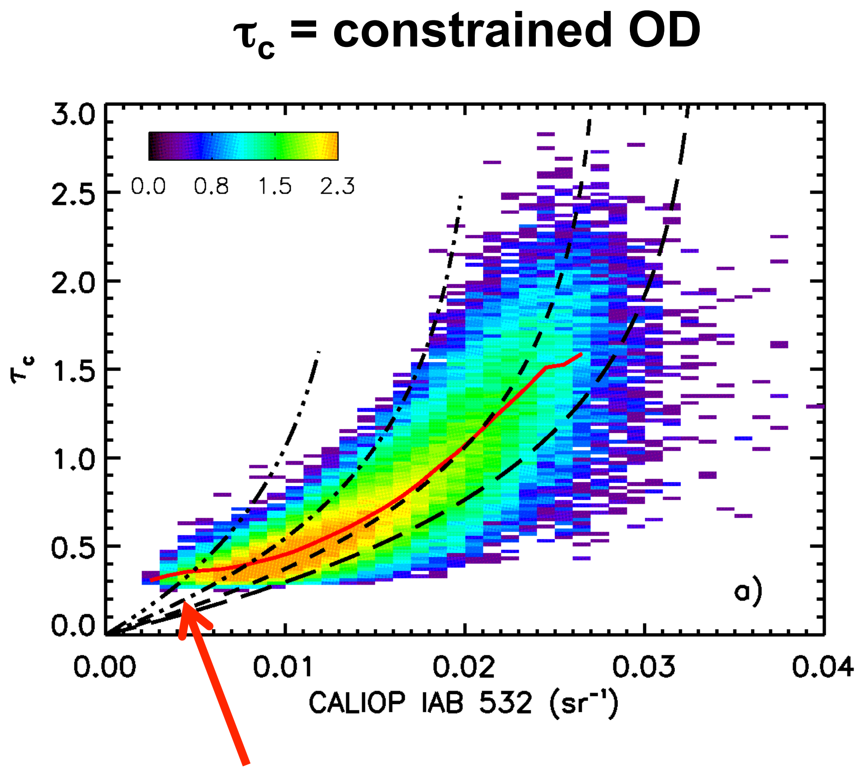


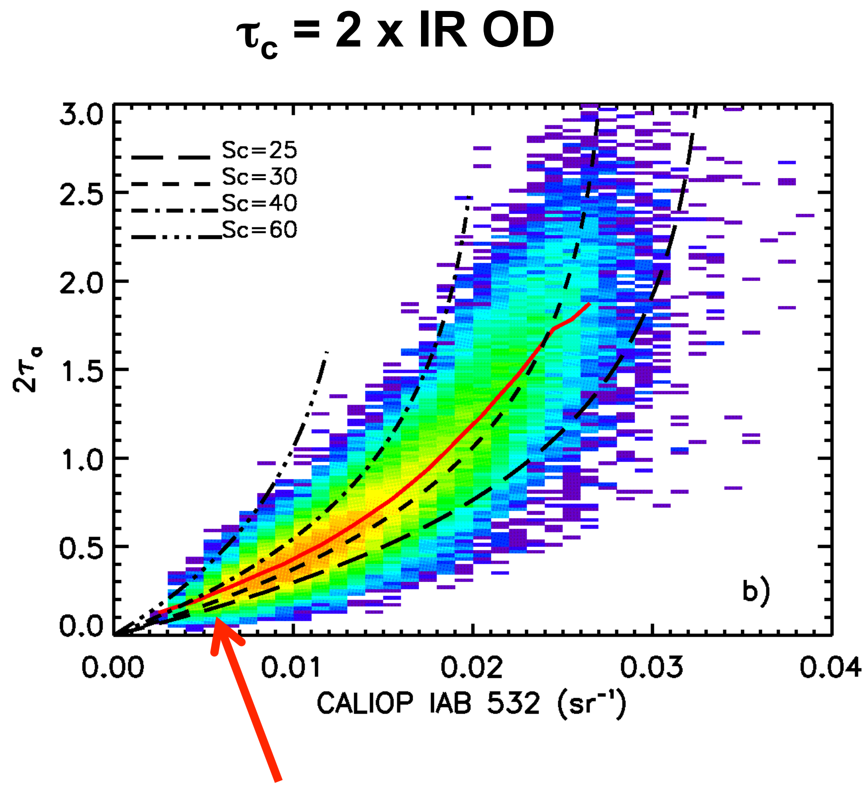
$$IAB = \frac{1 - e^{-2\eta\tau_c}}{2\eta S_c}$$

η, multiple scattering factor: 0.6

S_c, *cirrus cloud lidar ratio (sr)*

Discovered bias in constrained retrievals at small optical depths





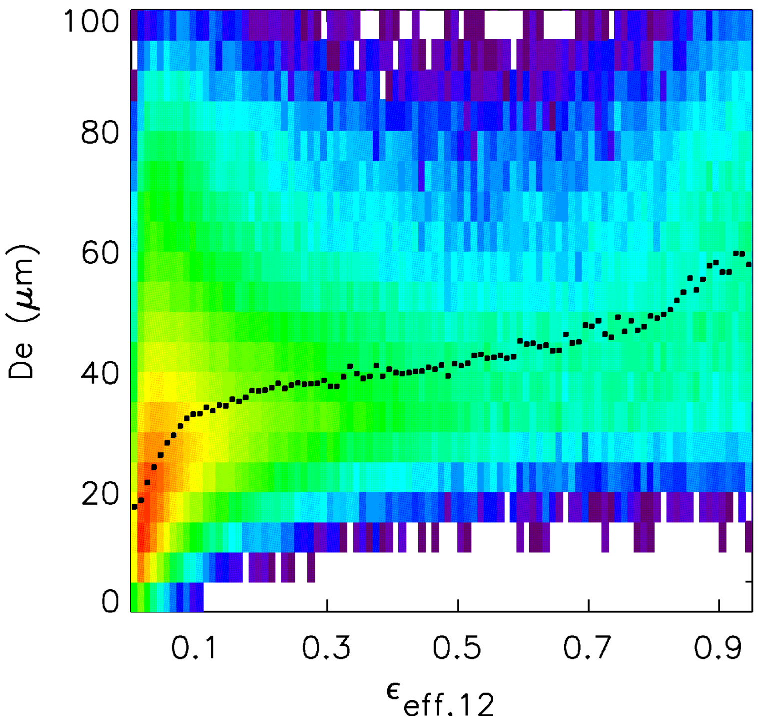
D_e and IWP

Basic approach (Parol, 1991):

$\beta_{eff}12/10 = OD_{eff}\_12 \;/\; OD_{eff}\_10$

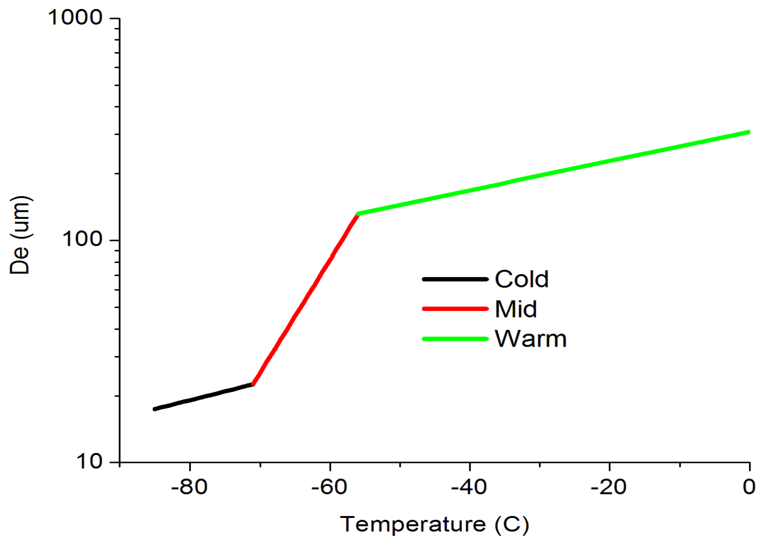
$\beta_{eff}12/08 = OD_{eff}\_12 / \; OD_{eff}\_08$

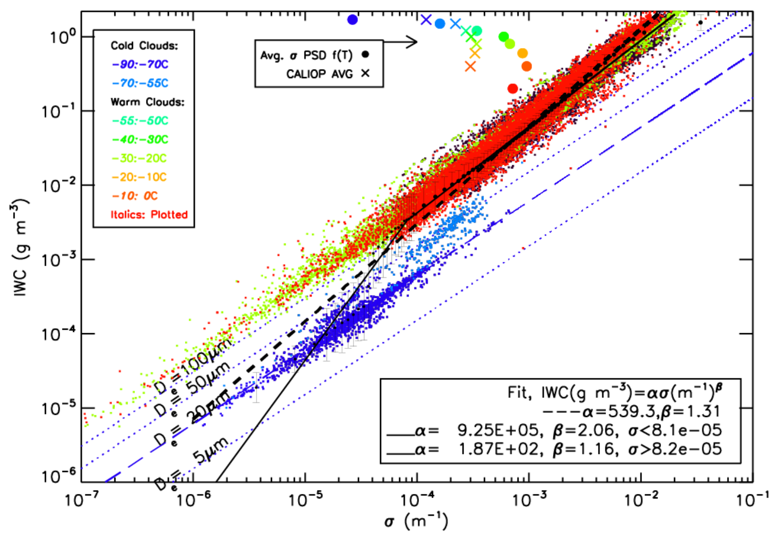
... and lookup tables



Single-layered cloud, altitude > 7km, T° < 233K, sea, all latitudes, Day+Night

Garnier et al, JAMC, 2013





Heymsfield et al, JAMC, 2014

D_e and IWP

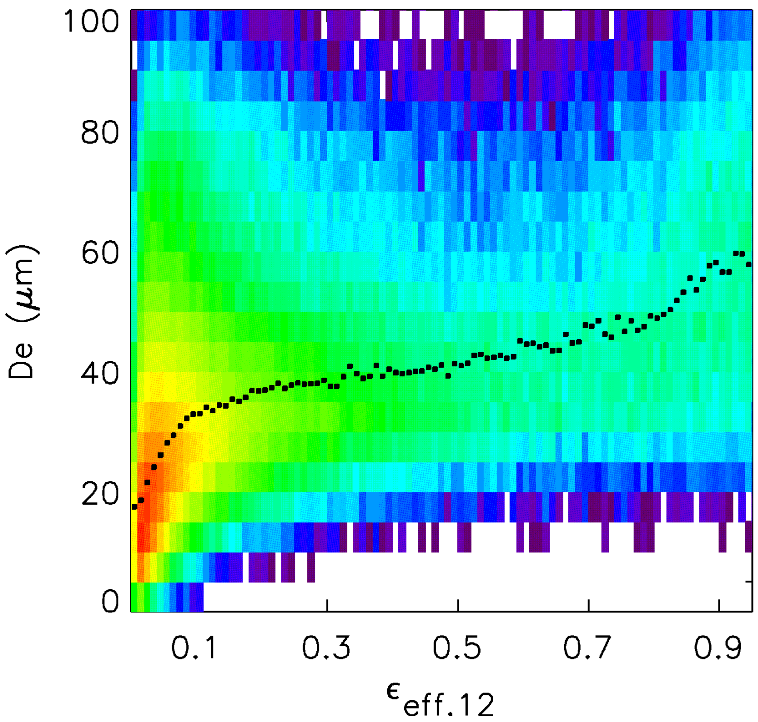
January 2011

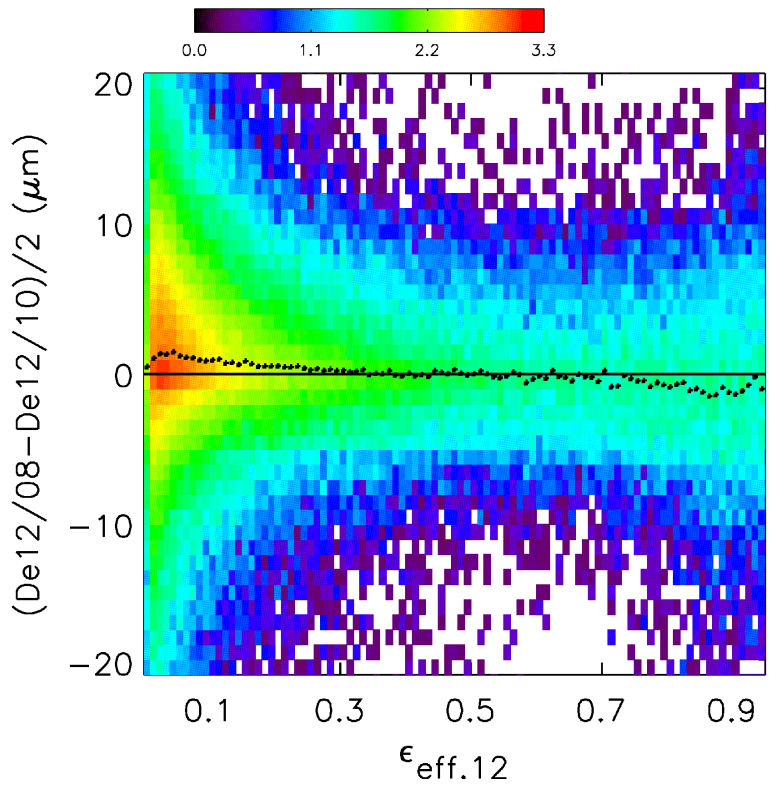
Basic approach (Parol, 1991):

$\beta_{eff}12/10 = OD_{eff}\_12 / OD_{eff}\_10$

$\beta_{eff}12/08 = OD_{eff}\_12 / OD_{eff}\_08$

... and lookup tables





Single-layered cloud, altitude > 7km, T ° < 233K, sea, all latitudes, Day+Night

Garnier et al, JAMC, 2013

Summary and Next Steps

- Constrained cirrus OD and 12 μm OD agree within 10% rms
  - Implies τ_{vis}/τ_{IR} is well behaved, and multiple scattering correction is reasonably good
  - Bias in constrained OD for $\tau < 0.3$ can be easily corrected
- Version 3 unconstrained OD biased low by 20% at small OD
  - Increasing the *a priori* lidar ratio should significantly reduce V3 bias
    - Final value depends on new Version 4 calibration
  - Mean lidar ratio varies ≤ 10%, much less than might be expected
    - But represents a large error for OD > 2
  - Evidence that variations in lidar ratio are mostly related to temperature
- Opaque cirrus
  - Currently unconstrained, very sensitive to choice of lidar ratio
  - Beginning to explore CALIOP-IIR comparisons in opaque clouds
  - Can improve using constraints from either integrated lidar return signal or IIR 12 um emissivity

Recommendations to CREW

- By comparing retrievals based on independent physics, have been able to quantify random and systematic uncertainties

- Clouds discussed here represent a small subset of all clouds
  - Single-layer, semi-transparent ice cloud
  - Ice cloud over low opaque water cloud

- But, retrievals are well-constrained and (relatively) well understood

- Could be used more extensively for CREW intercomparisons

- In any case, comparison of independent retrievals is essential for evaluating uncertainties (on both sides)

END