Validation of Cloud Parameters Derived from Geostationary Satellites, AVHRR, MODIS, and VIIRS Using SatCORPS Algorithms

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Challenge of Validation

- **Provide reliable uncertainty estimate of a given cloud parameter retrieved from satellite imagery**
  - algorithm uncertainties rely on idealized model computations
  - need comparisons with independent measurements of known(?) certainty

- **Develop basis for algorithm improvement**
  - what are conditions giving rise to error? e.g., small Cu
  - what is source of error? e.g., background, calibration…

INDEPENDENT MEASUREMENT SOURCES*

Platform	parameters	pros	cons
• In situ	CF, Zt, Zb, COD, Re, CWC, Habit, phase	most physical, integratable?	sparse, 1 level at a time, μ-physics guys disagree☺
• surface or ship sites	CF, Zt, Zb, COD, Re, CWC, Habit, phase, CWP	transmission or active sensors, diurnal cycle	spatially sparse, requires in situ valid, sometimes trouble with Zt
• other satellites	CF, Zt, Zb, COD, Re, CWC, Habit?, phase, CWP	assess θ depend, same/different methods	same probs as target, mostly cloud top only

• Quality and number of parameters depend on instruments available!

• All measurements have their own uncertainties, which can be large

Langley (LaRC) Imager Cloud Retrievals Considered

Satellites / Imagers

- Aqua MODIS: CERES Ed4, **1 km** subsampled 2x4 => 2.8 km
- SNPP VIIRS: CERES Ed1, **0.75 km** subsampled 2x4 => 2.4 km
- GEOSats: GOES-E, GOES-W, Meteosat, MTSAT (**4 km**), Himiwari-8
- AVHRR: GAC **4 km**, NOAA-18 JAJO

Methodology

- VISST: 0.65, 3.8, 11, 12 µm (daytime)
- SIST: 3.8, 11, 12 µm, or 3.8 & 11 µm (night SZA > 82°)
- SINT: 1.24, 3.8, 11, 12 µm (day over snow, MODIS & VIIRS)

- Minnis et al. (2010, 2011)

Retrieval Methodologies

- Use updated VISST, SIST, & SINT from Minnis et al. (2011)

Updates

- Estimation of Ztop from Zeff for thick ice clouds (COD > 8)
  - *parameterization of Minnis et al. (GRL 2008)*
- Use of regionally dependent lapse rate for boundary-layer Ztop
  - *parameterization of Sun-Mack et al. (2014)*
- Rough ice crystal model (hexagonal columns)
  - *results of Yang et al. (TGRS, 2008)*
- Multispectral retrievals of Re and COD
  - *1.24 and 2.1 µm Re from VISST*
  - *1.24 COD from SINT over snow*

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LaRC Cloud Products*

Standard, Single-Layer VISST/SIST

	Cloud
0.65, 1.2, 1.6, 2.1 µm Reflectances	
3.7, 6.7, 10.8 µm Temp	**Mask, Phase**
12 or 13.3 µm Temp	**Optical Depth**, IR emissivity
Broadband Albedo	**Droplet**/Xtal effective radius
Broadband OLR	**Liquid/Ice Water Path**
Clear-sky Skin Temperature	**Effective Temp**, height, pressure
Icing Potential	Top/ Bottom Pressure
Pixel Lat, Lon	**Top**/ Bottom Height
Pixel SZA, VZA, RAZ	Overshooting top (OT)

Multi-Layer, CIRT, CO_2 channel only (BTD11-12 for VIIRS)

Upper & lower cloud

Multilayer ID (single or 2-layer)

effective temperature	optical depth, thickness
effective particle size	ice or liquid water path
height, top/base height	pressure

Minnis et al., SPIE 2008; TGRS 2011)

* Available parameters depend on sensor complement

Validation (Reference) Data

- Aircraft in situ data
  - VOCALS T_{top}, Z_{top}, LWP, N_d
- Surface observations – ARM sites
  - Azores (*Xi et al., next talk*)
  - MAGIC ship observations (ceilometer, sonde) T_{top}, Z_{base}, Z_{top}, ΔZ
- Satellite data, A-Train: CALIPSO, AMSR-E
  - CALIPSO Vertical Feature Mask (VFM) CF, phase
  - CALIPSO 5-km Cloud Layers Product (05kmCLay) COD, IWP
  - CALIPSO 333-m Cloud Layers Product (333mCLay) Z_{top}
    - *pixel within 2.5 km & 15 min of CALIPSO 5-km center is match after parallax correction*
  - AMSR-E/2 Level 2 Ocean Product (Wentz Algorithm) LWP (12 km)

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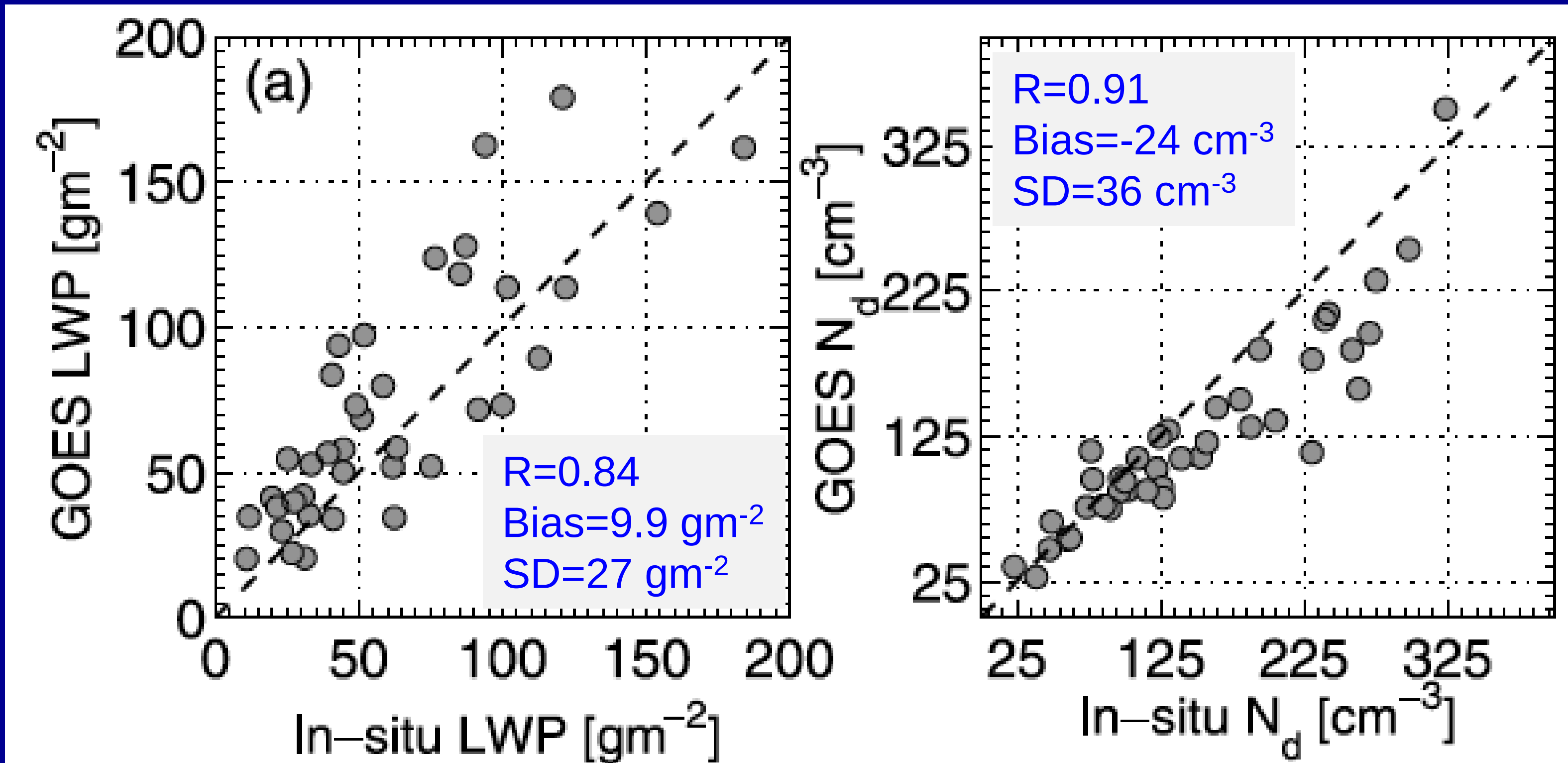
Surface Example

In Situ μ-physics & Optical Properties VOCALS-REx (SE Pacific 2008)

Painemal et al.(JGR,2012)



- *C-130 flights during VOCALS: Re near top; τ & LWP from vertical profiles*

  - Painemal & Zuidema (JGR, 2011)

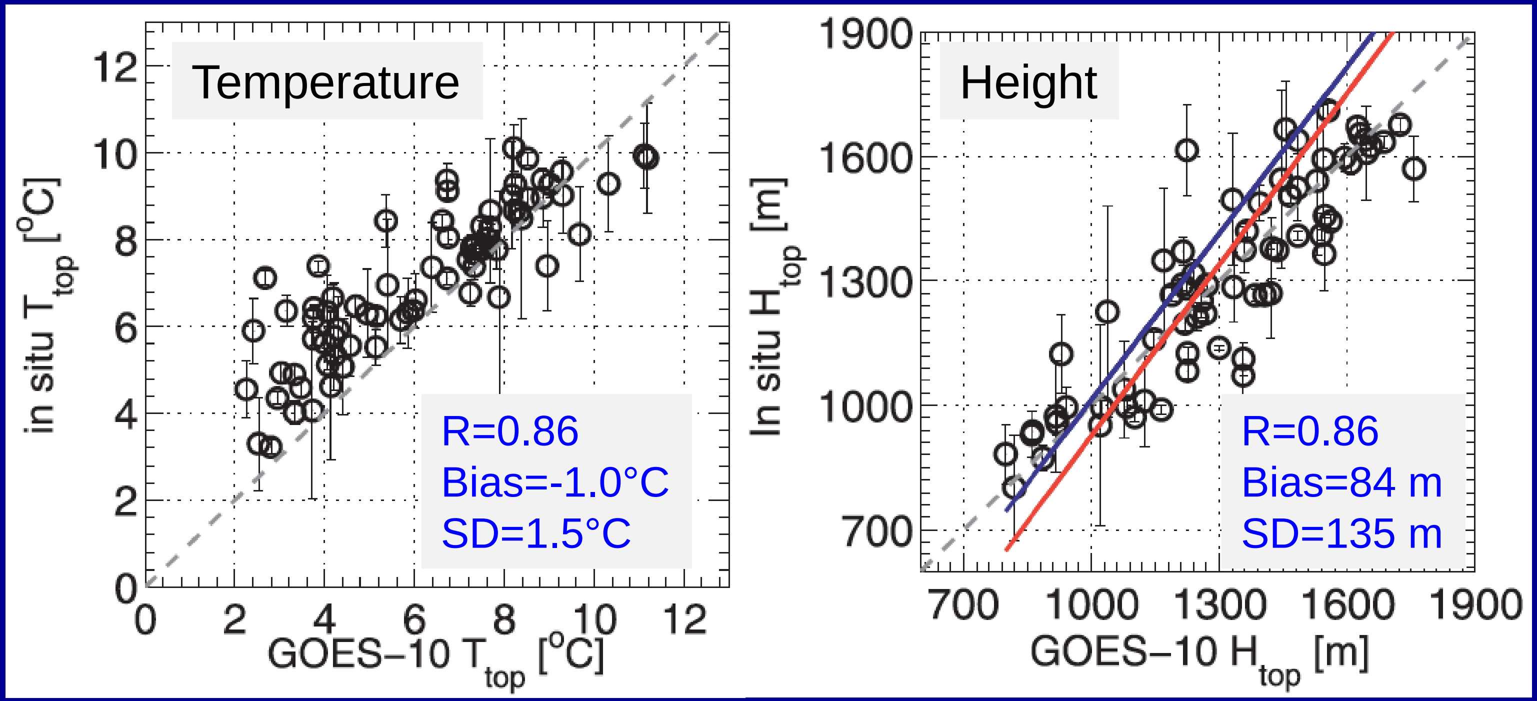
- *GOES-10 4-km VISST retrievals, LWP = 5/9 τ * Re*

  - Overestimate of Re typical, why?; probably drives Nd bias

  - Overall results provide some uncertainty guidance for assimilation

Cloud-Top Height & Temperature VOCALS-Rex, GOES vs in situ (SE Pacific 2008)

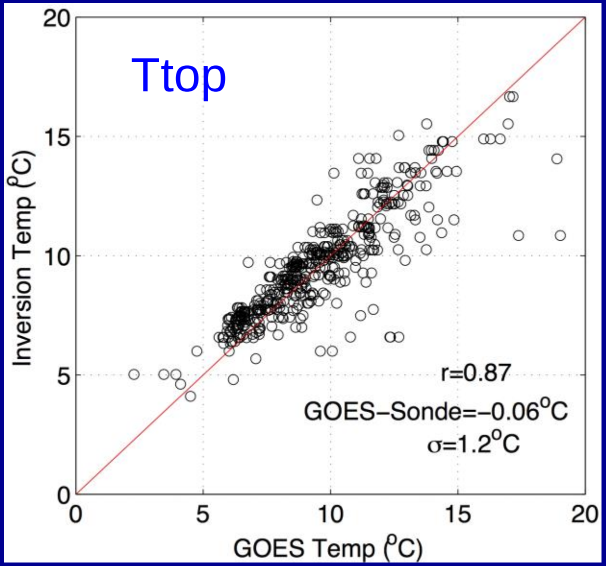
Painemal & Minnis (JAS,2013)

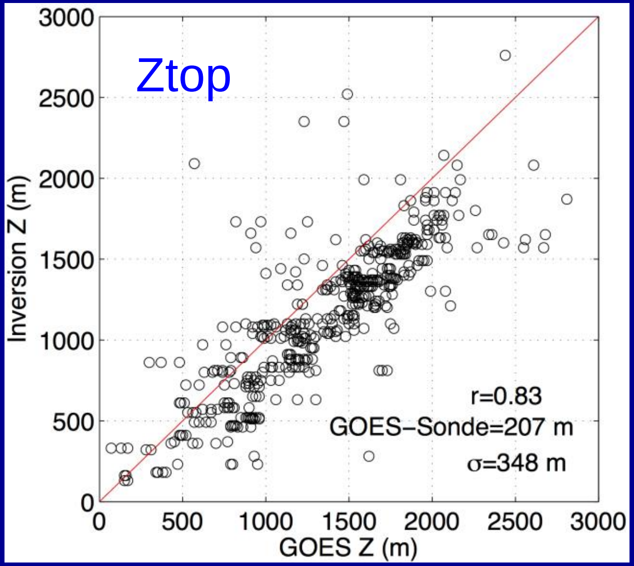


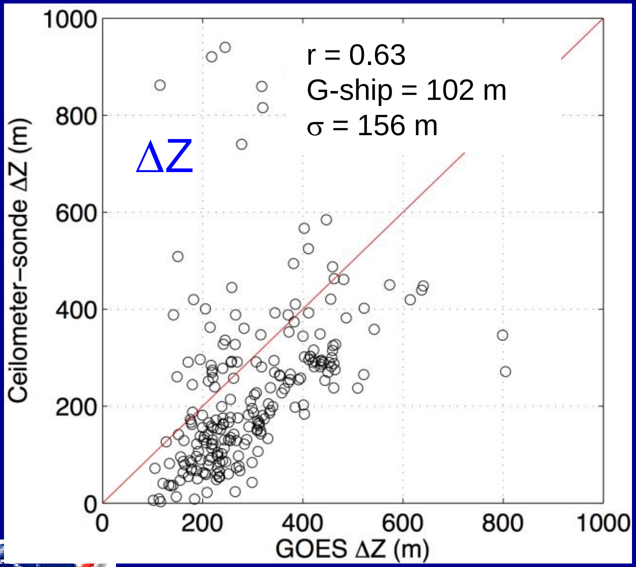
- Ttop colder than air; seen in other marine Sc areas with MODIS data
  - drops colder than air?
- Heights very close with both techniques (lapse rate & new technique)
- 1 region, 1 satellite, 1 season

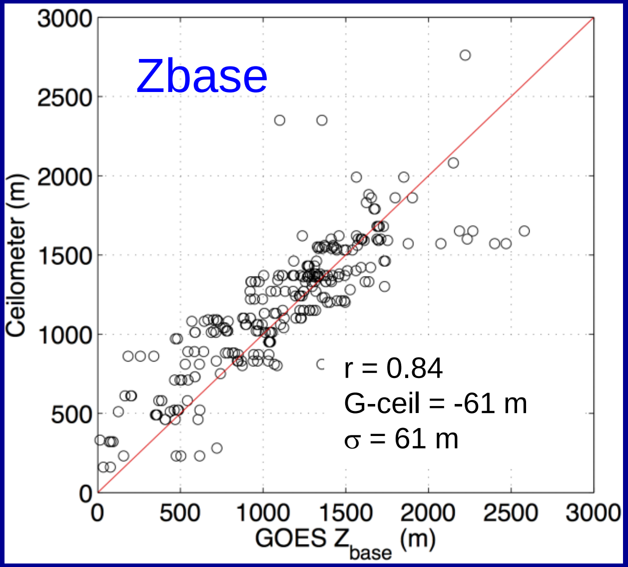
Surface Example

Cloud Heights & Temperatures, MAGIC vs GOES-15
(California-Hawaii, July 2013)









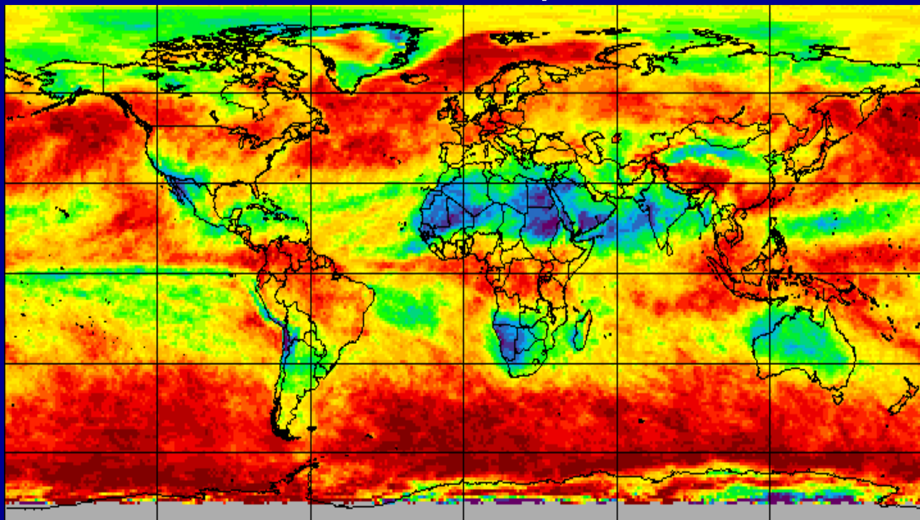
Preliminary Results

- Ttop close on average, but GOES mostly colder
- Ztop too high relative to Inv height
  - radar will clarify
- ΔZ parameterization too thick but generally proportional
  - no Ci screening
- Zbase fairly close due to compensating errors

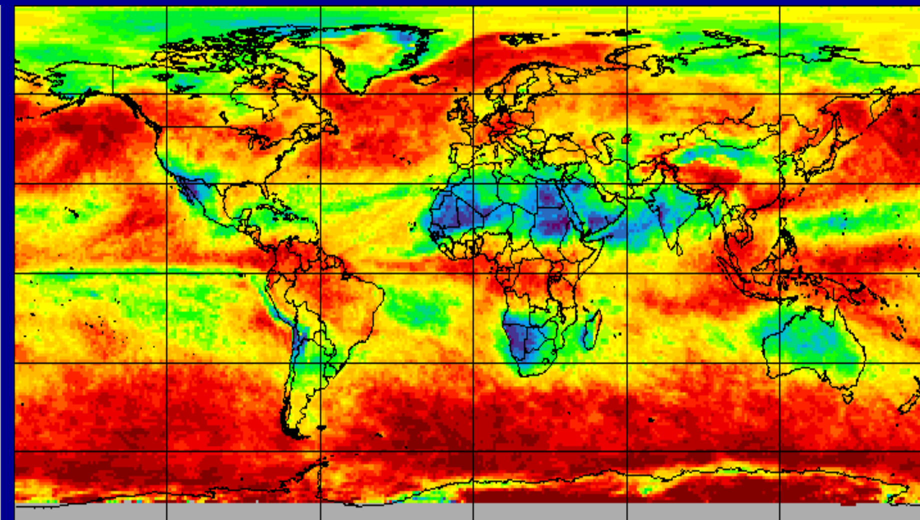
Satellite to Satellite

Mean Cloud Fraction, April 2013, day

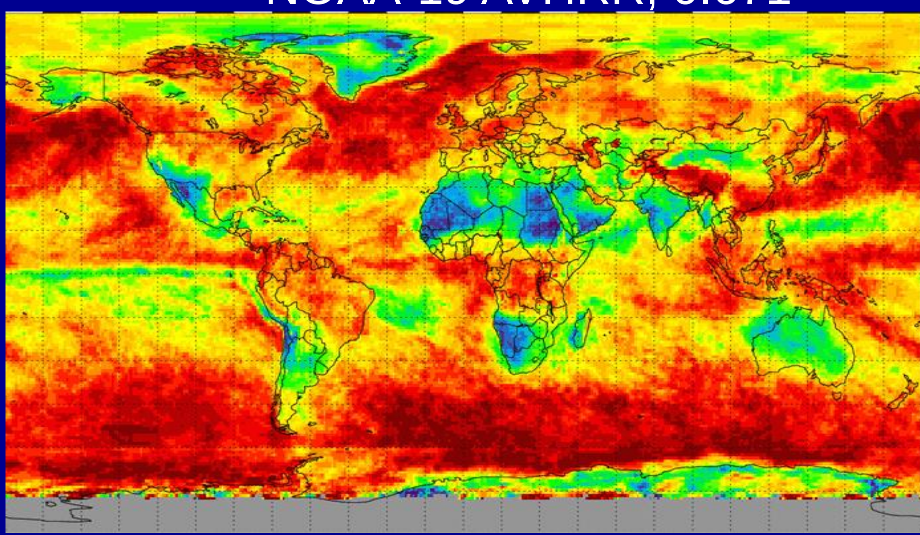
CM Ed4 – Aqua 0.644



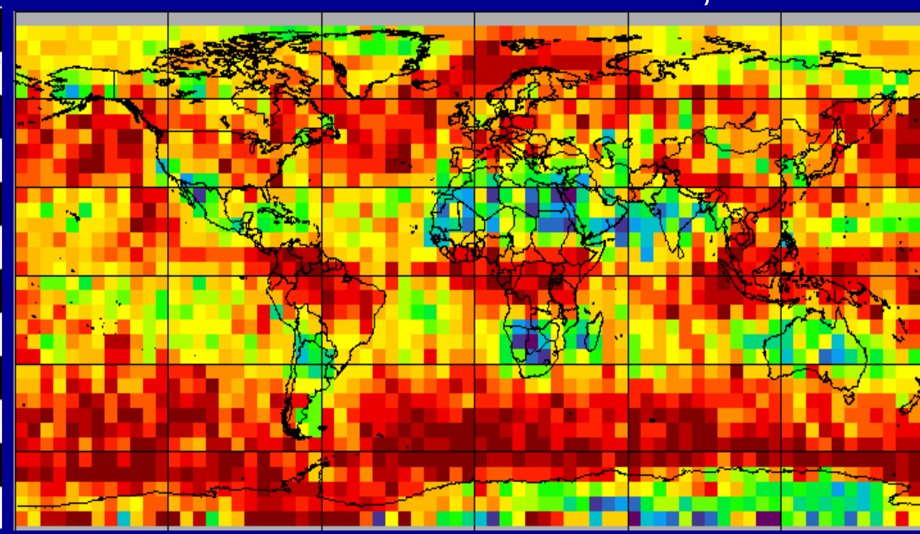
NPP VIIRS Ed1, 0.649



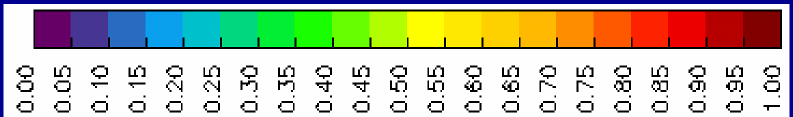
NOAA-19 AVHRR, 0.671



CALIPSO VFM – no 80 km, 0.684



Day periods different in polar regions



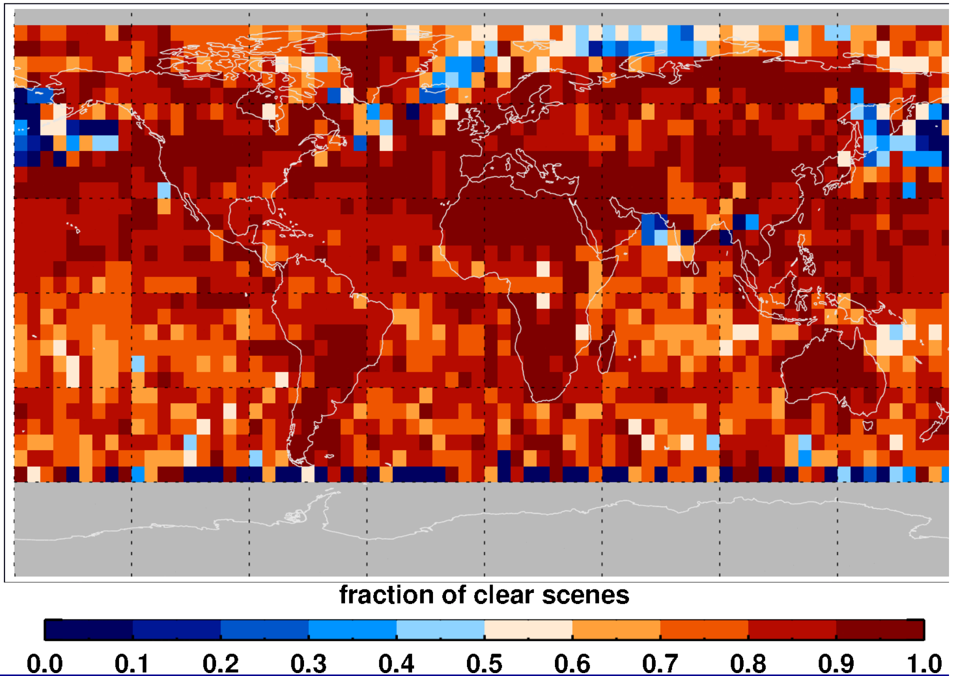
Fraction Correct Identification, VISST vs CALIPSO

DAY (SZA < 82°)	Aqua (July 2013)	VIIRS (July 2013)	NOAA-18 (JAJO 2008)	GEO* (10/08, 1/10)
Land, Snow/Ice-free	**0.885**	**0.858**	**0.851**	**0.854**
Ocean, Snow/Ice-free	**0.907**	**0.878**	**0.873**	**0.859**
Global, Snow/Ice-covered	**0.887**	**0.871**	**0.818**	
NIGHT				
Land, Snow/Ice-free	**0.873**	**0.856**	**0.861**	**0.859**
Ocean, Snow/Ice-free	**0.912**	**0.883**	**0.893**	**0.867**
Global, Snow/Ice-covered	**0.765**	**0.732**	**0.689**	

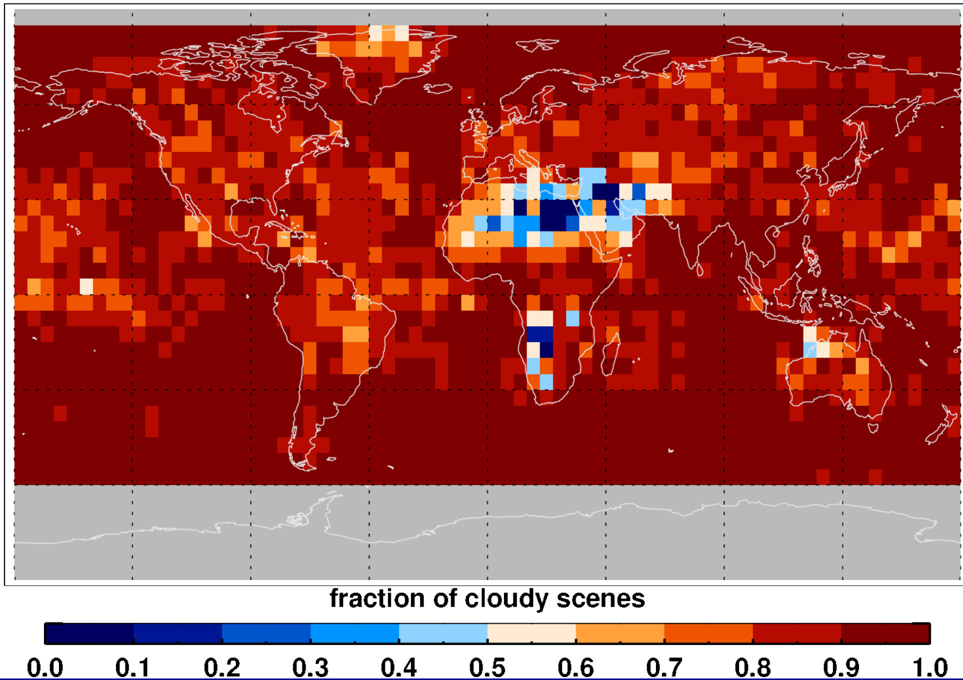
- Aqua results best in all categories
  - *results always best for ocean for all satellites*
  - *polar night worst case*
- Collocation of CALIPSO with other satellites not as good as Aqua
  - *Up to 15-min time difference*

Regional Errors in Cloud Detection, Aqua vs CALIPSO, July 2013

Number of correctly identified clear scenes divided by number of clear scenes



Number of correctly identified cloudy scenes divided by number of cloudy scenes



Problem Areas

- Clear scenes in mostly cloudy areas
- Clouds over bright surfaces (deserts) & sparse cloud regions (trade Cu)

Cloud Phase, VISST vs CALIPSO
Single-layered clouds only

DAY (SZA < 82°)	Aqua (July 2013)	VIIRS (July 2013)	NOAA-18 (JAJO 2008)	GEO* (10/08, 1/10)
Land, Snow/Ice-free	0.949	0.921	0.895	0.891
Ocean, Snow/Ice-free	0.971	0.949	0.928	0.902
Global, Snow/Ice-covered	0.914	0.897	0.786	
NIGHT				
Land, Snow/Ice-free	0.897	0.878	0.904	0.892
Ocean, Snow/Ice-free	0.946	0.946	0.920	0.905
Global, Snow/Ice-covered	0.876	0.911	0.875	

- Aqua results best in daytime
  - *extra channels*
- Aqua VIIRS & AVHRR results best in daytime
  - *extra channels help less*
  - *GEO phase least accurate in snow-free categories*
- Collocation of CALIPSO with other satellites not as good as Aqua
  - *Up to 15-min time difference*

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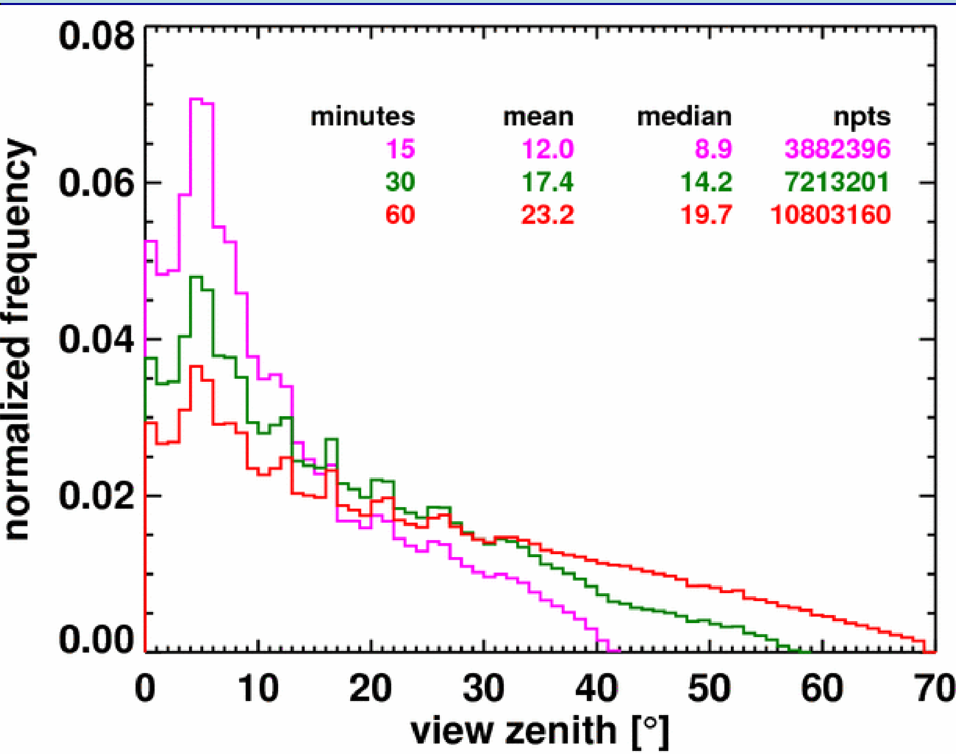
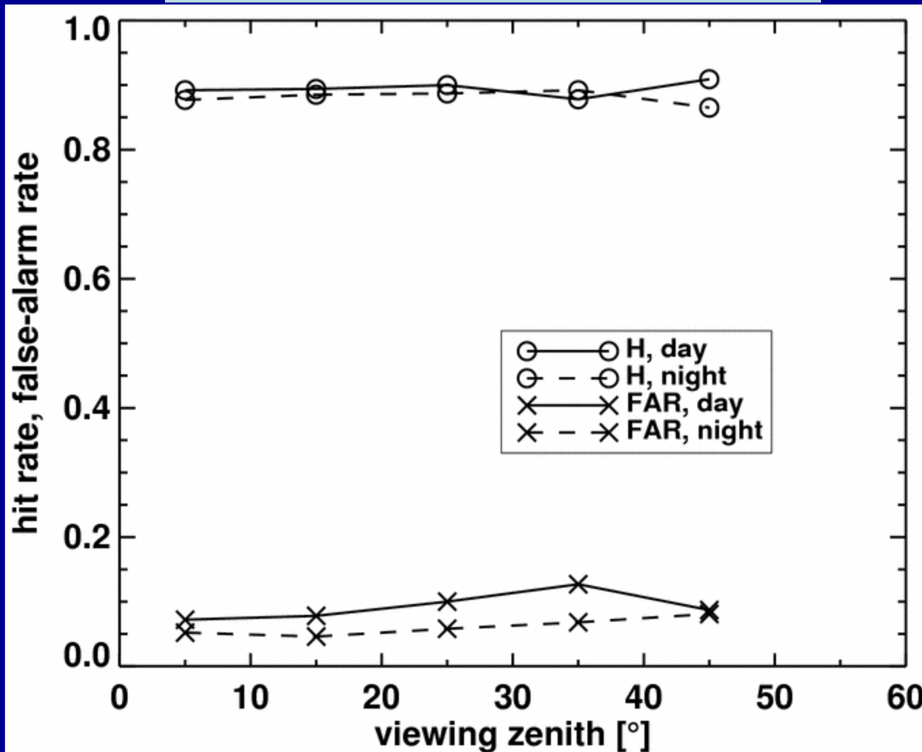
Cloud Fraction & Phase Correct With Viewing Zenith Angle
AVHRR (variable VZA) vs CALIPSO (near nadir)

Frequency of AVH-CAL matches w/VZA



Cloud Hit & false alarm rates

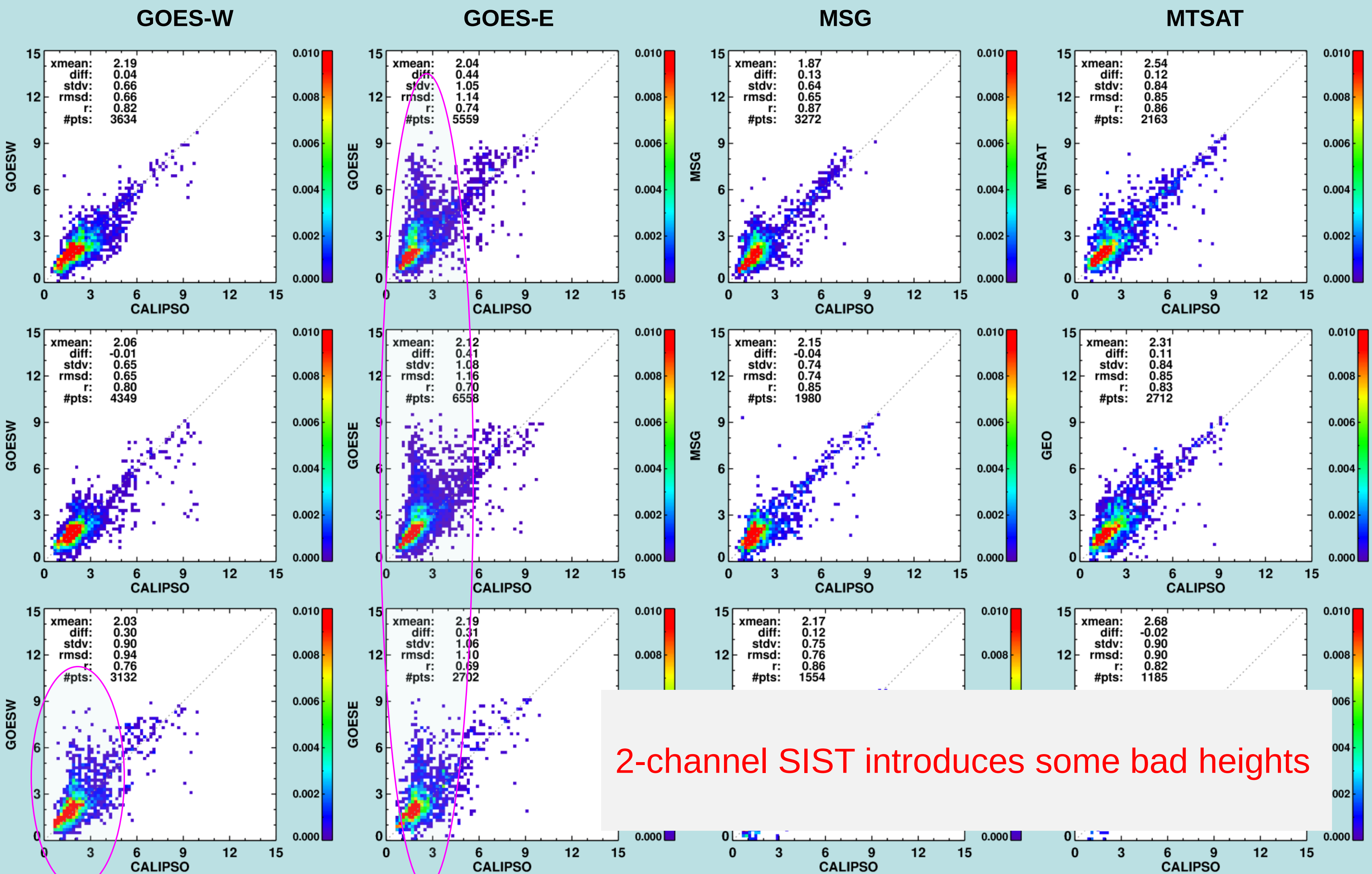


- Matches constrained to ±15 min window, limits angular range
  - greater range possible with GEO data
- Very small changes in accuracy with VZA up to 40°
  - hint that it will decrease for VZA > 40°

Top: Oct 2008
Middle: Jan 2010
Bottom: Apr 2013

Cloud **Top Altitude, GEOSat vs CALIPSO**

water phase, nighttime, opaque



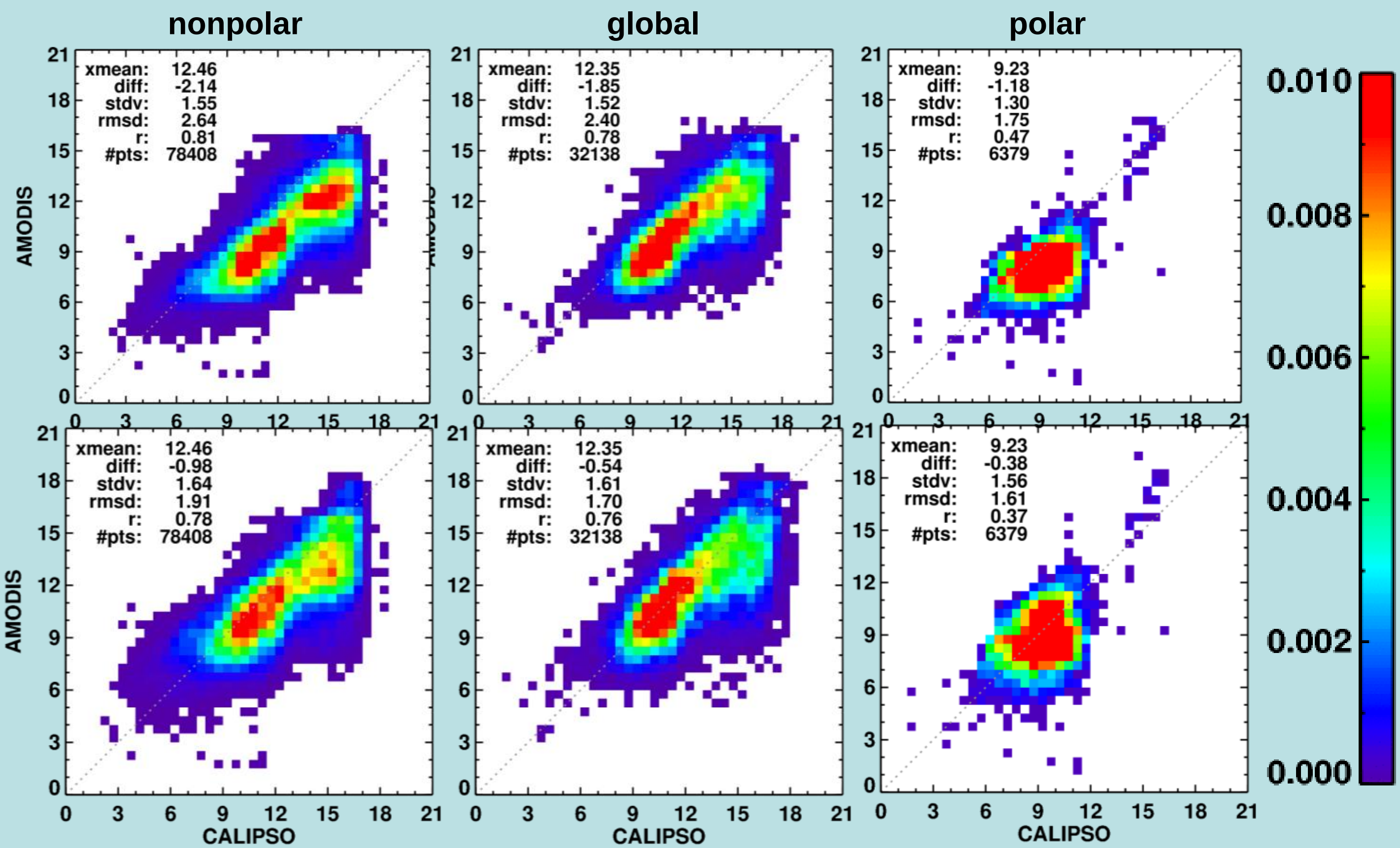
2-channel SIST introduces some bad heights

Cloud Top Altitude, Aqua MODIS vs CALIPSO, July 2013

ice phase, nighttime, opaque with & without height correction

On file

After correction



- Biases w/o correction
  - 1.2 – 2.1 km underestimate
- Biases w/ correction
  - 0.4 – 1.0 km underestimate
- Correction increases STD by ~6%

Users!
Apply the correction.
In Ed4 Data Quality Summary.

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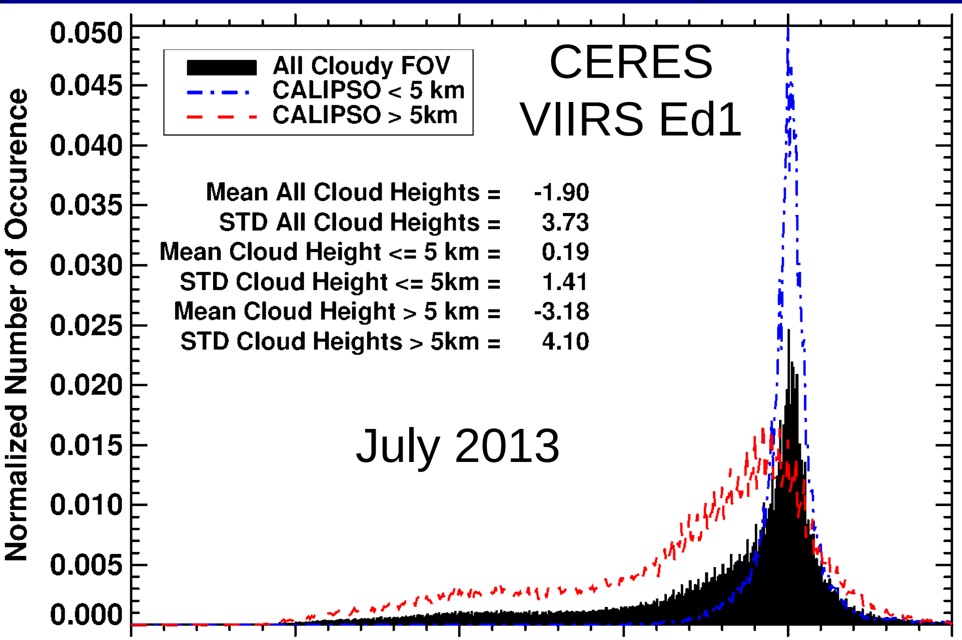
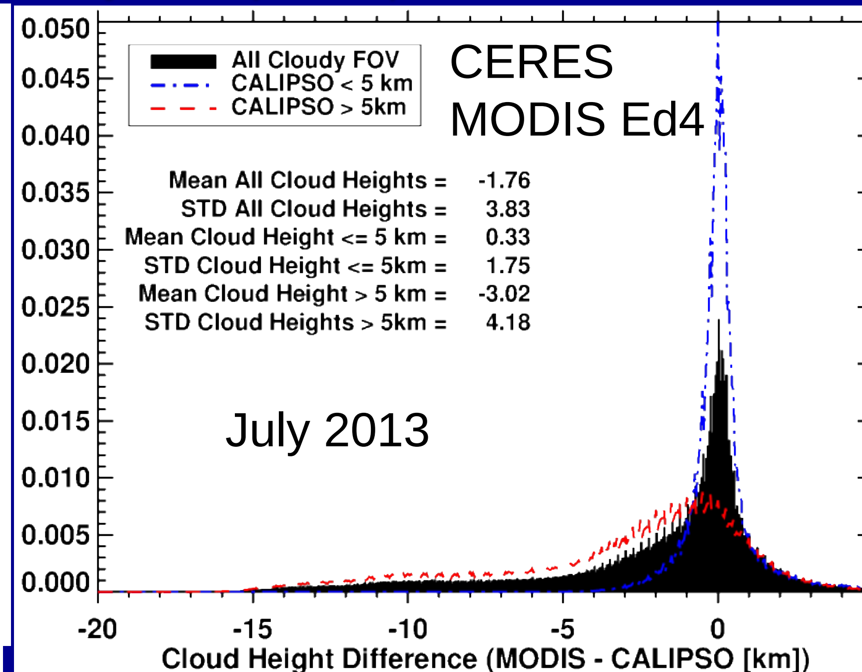
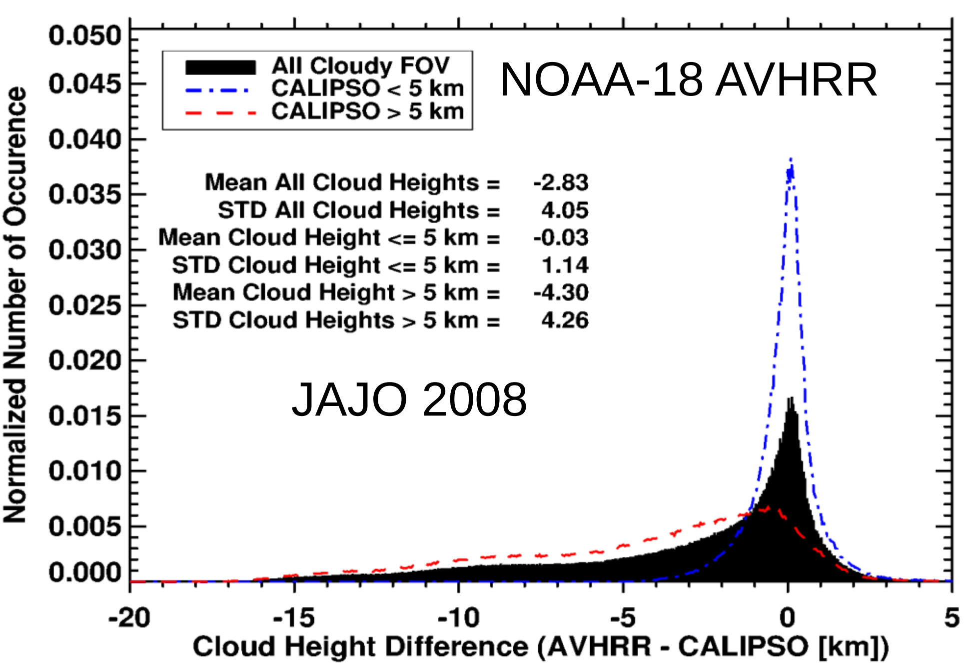
Distribution of Cloud Height Differences (Satellite – CALIPSO)
All clouds (use highest for multilayered pixels), 60° - 60°S

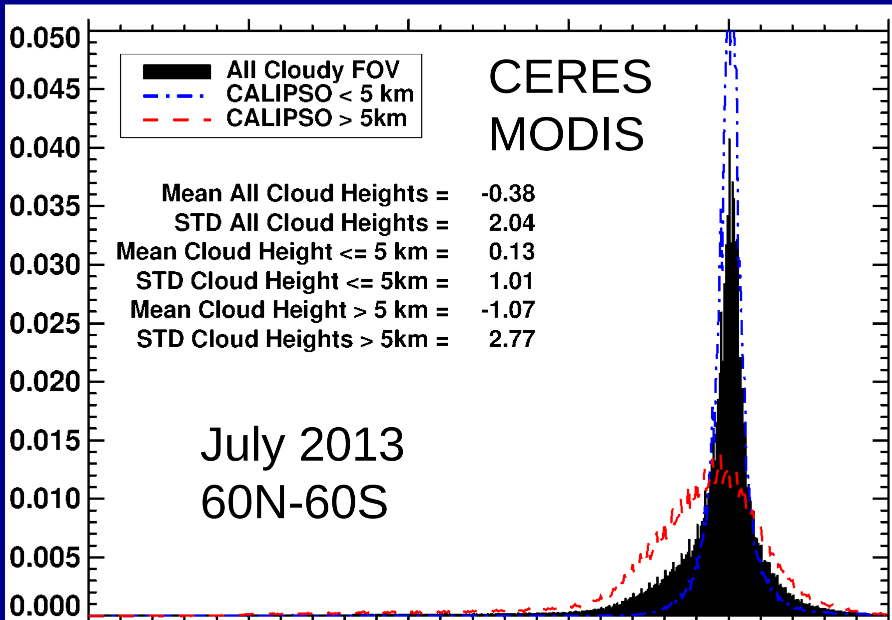


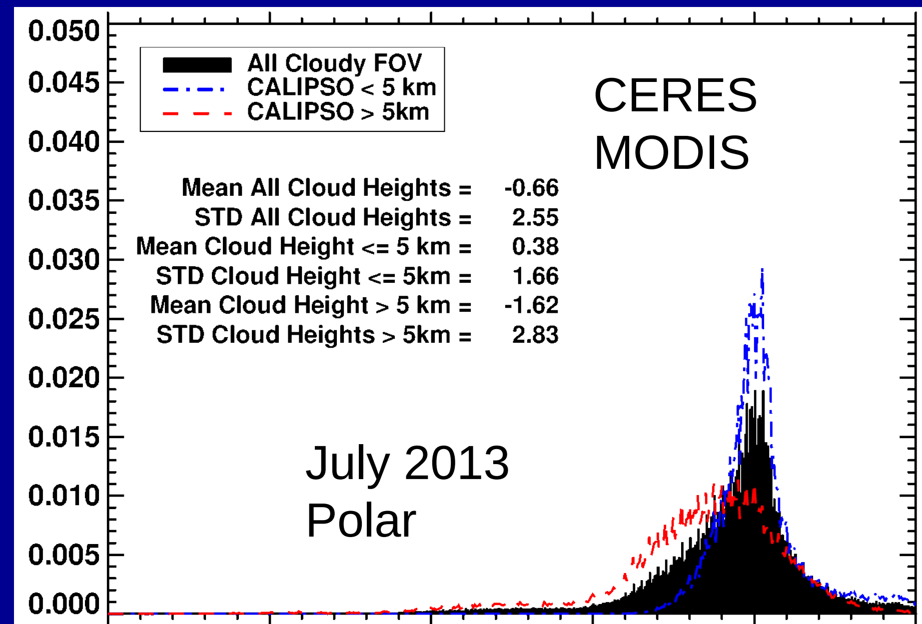


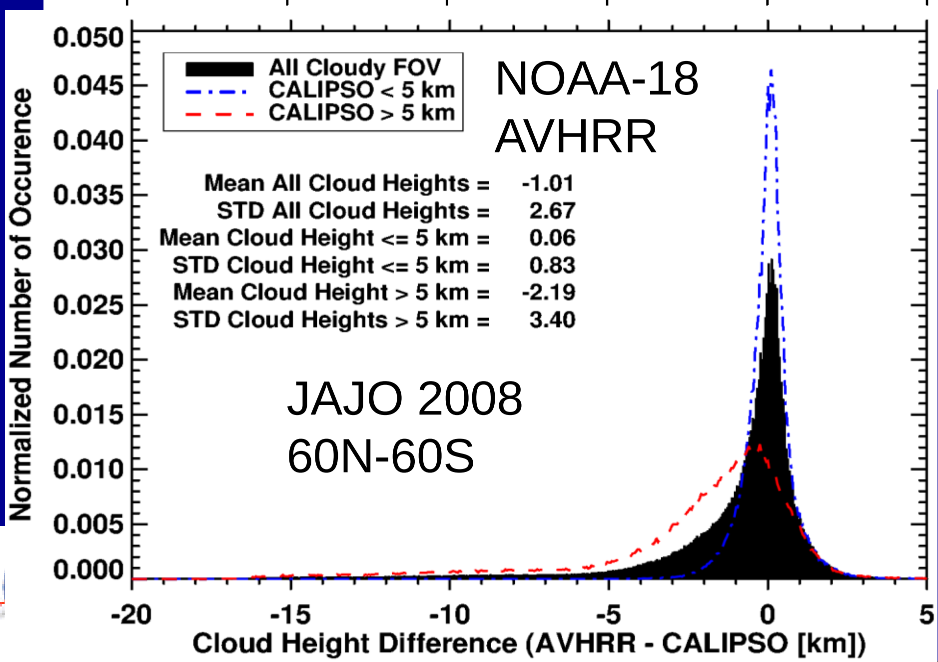


- Low cloud diffs narrowly distributed
  - bias: -0.03 to 0.33 km
  - STD: 1.14 to 1.75 km
- High cloud (ZCAL > 5 km) difference
  - bias: -4.30 to -3.02 km
  - STD: 4.10 to 4.26 km

Distribution of Cloud Height Differences (Satellite – CALIPSO)
Single-layered or single phase pixels





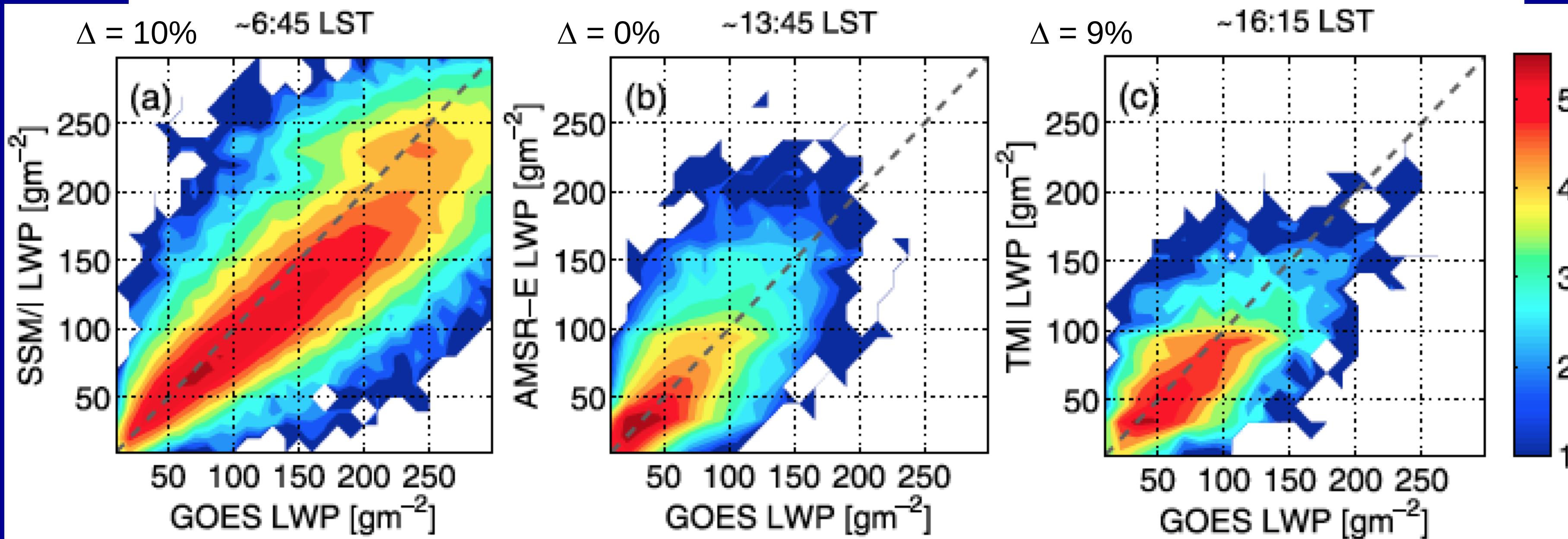


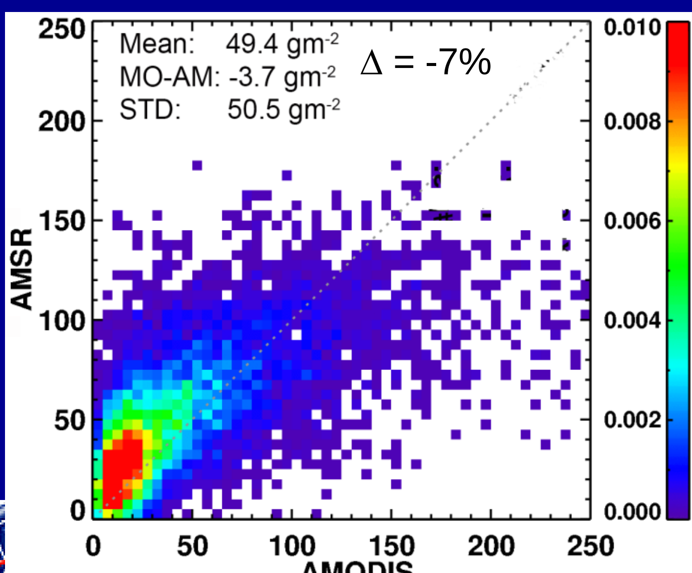
- CERES nonpolar SL low cloud diffs
  - bias is smaller: 0.06 from 0.13 km
  - STD reduced: 0.83 to 1.01 km
- CERES nonpolar SL hi cloud diff
  - bias: -2.19 to -1.07 km
  - STD: 2.77 to 3.40 km
- Polar lo clds biased by 0.38 ±1.66 km
- Polar hi clds biased by -1.62 ± 2.83 km

Cloud LWP (VISST vs Satellite μ-wave Radiometer)

VOCALS GOES-10 vs SSM/I, AMSR-E, & TMI

Painemal et al. (JGR, 2012)

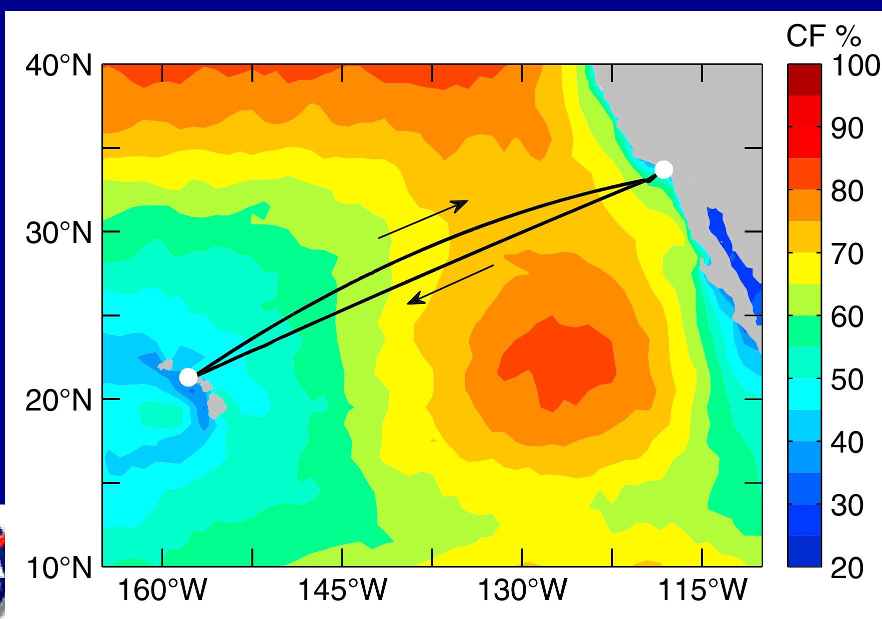




LWP = 5/9 Re * τ

- Adiabatic approx works fairly well for stratus
  - bias: -0.7% to +10%
  - STD: up to 100%
- Constant Re(z) approx may be better for Cu?
- MWR errors vary, ~50% for LWP < 50 gm^{-2}, decreasing for larger LWP

- ARM Mobile Facility (AMF2): radars, lidars, microwave and visible radiometers, sondes, and aerosol probes
- Nine months of measurements
  - Oct-Jan 2012-2013, May-Sept 2013, 6 days/leg
  - L.A.-Honolulu: More than 30 transects



Dataset

- ***MAGIC data***:
  - Clouds: microphysics from a Cimel sun-photometer (Chiu et al. 2013 ACP): cloud optical depth (τ) and effective radius (r_e)
  - Three-channel microwave liquid water path (Cadeddu et al., 2013, AMT)
  - Cloud radar and radiosondes: cloud height and temperature
- **Satellites**:
  - CERES Ed4 1-km Terra/Aqua MODIS retrievals
  - Daytime GOES-15: 4-km pixel, every 30 min, SZA < 60°
  - C-MODIS & GOES liquid water path (LWP): adiabatic-like assumption: $LWP=5/9 \cdot \rho_w \cdot r_e \cdot \tau$
  - Satellite microwave liquid water path from AMSR2 (0.25°x 0.25°)

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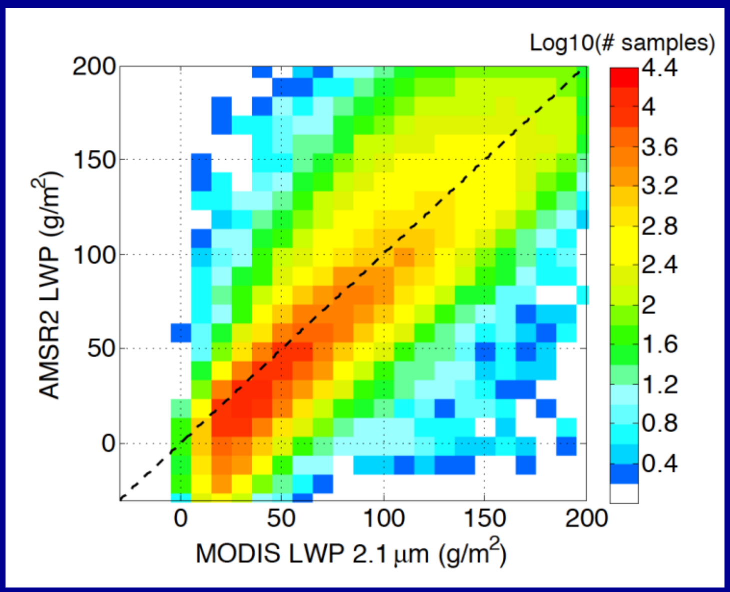
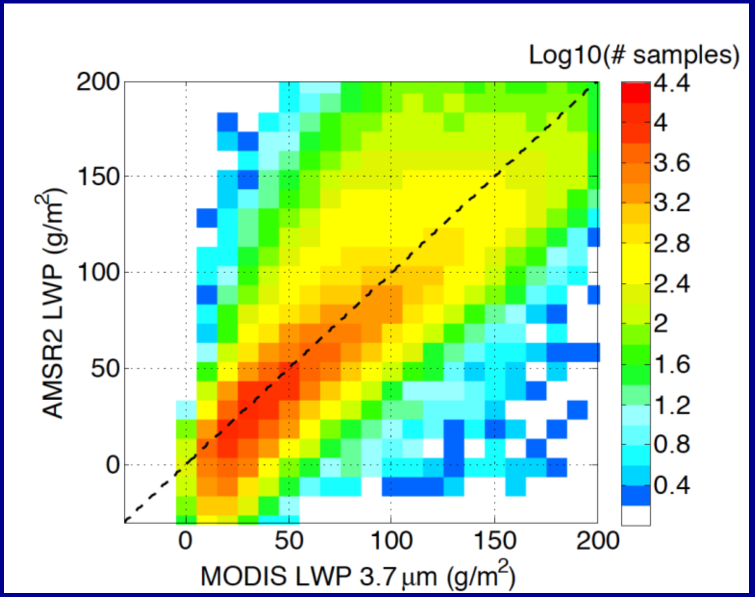
Satellite vs Satellite: AMSR2-MODIS

- Afternoon pass ~ 1:30 pm, overcast scenes
- AMSR2, Wentz algorithm at 0.25˚x 0.25˚
- LWP estimates based on 3.7 μm and 2.1 μm effective radius

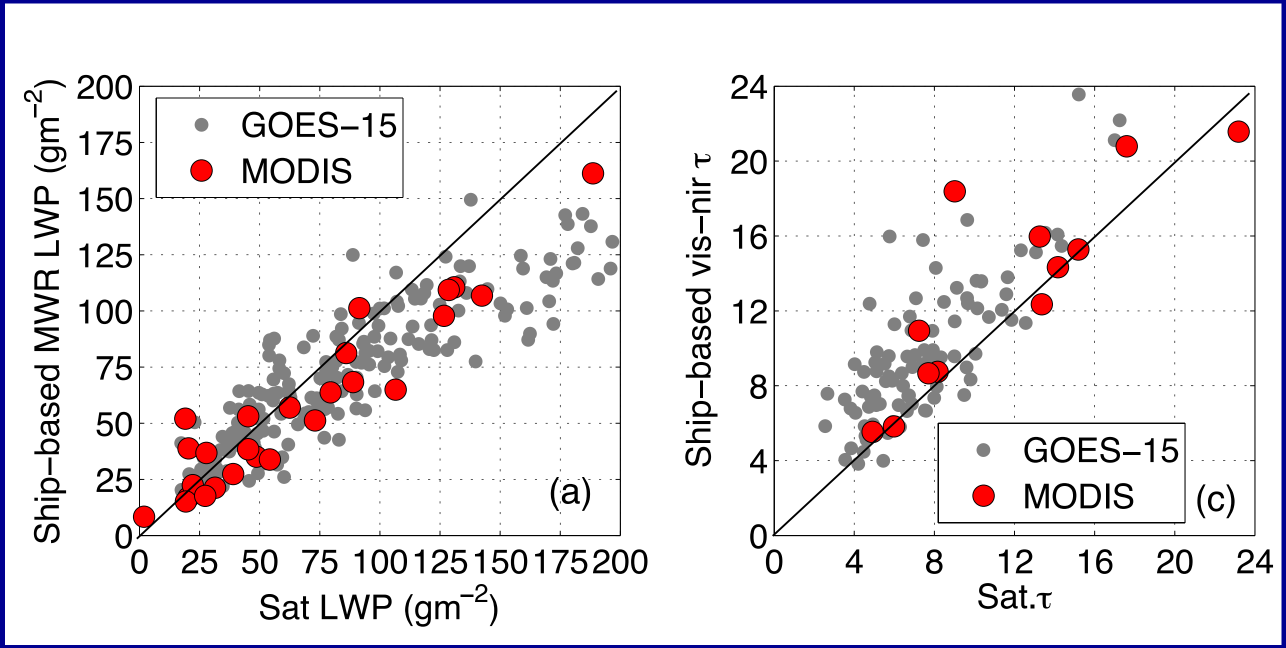




- AMSR2 –MODIS 2.1μm: r=0.89, bias=5.5 g/m^2 (9.3%)
- AMSR2 –MODIS3.7μm: r=0.85, bias=0.81 g/m^2 (**1.3 %**), nearly unbiased!!

Ship-based data: Cloud microphysics and liquid water path

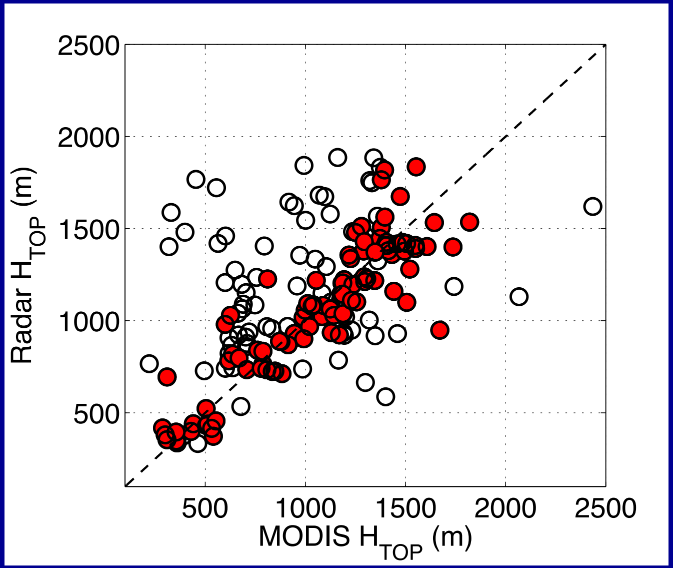
- LWP: Ship-based 3-channel μ–wave radiometer
- Cloud optical depth (τ): sun-photometer (Chiu et al., 2012)

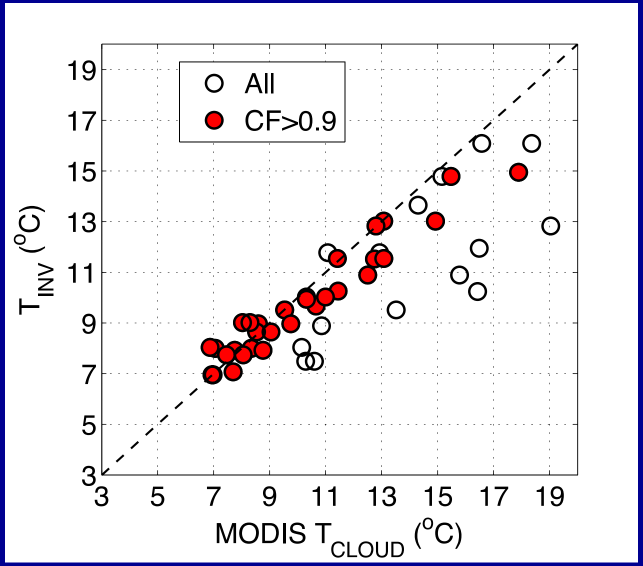


- Cloud effective radius? Comparison is uncertain, ground-based r_e is less robust than τ.

Cloud temperature and height

- C-MODIS cloud temperature vs inversion temperature (radiosonde)
- C-MODIS cloud height (linear fit from Painemal et al. 2013, T_{top} and SST) and k-band radar (three months)
- CTT r=0.96, bias=0.4K
- CTH, r=0.89, bias=37 m

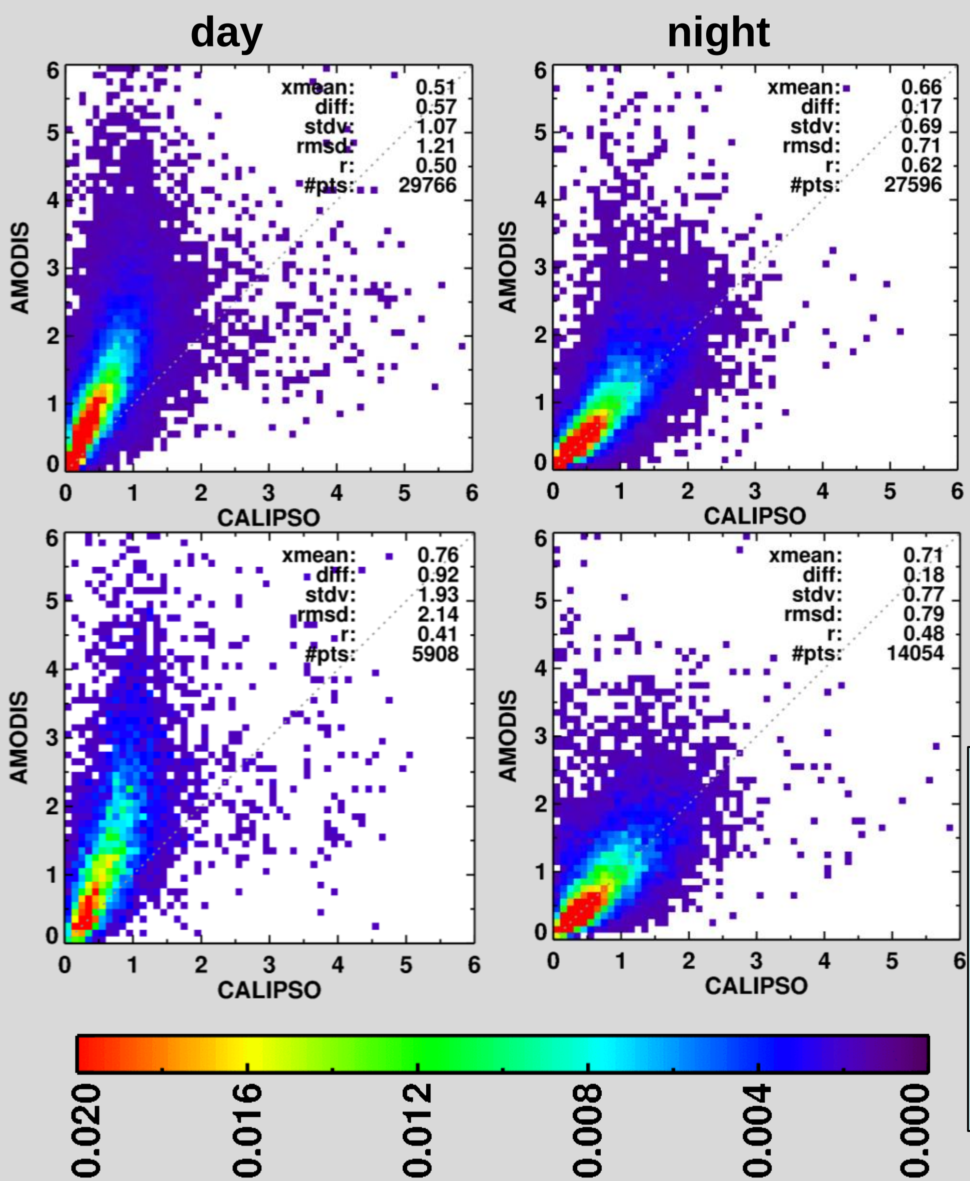




Ice cloud optical depth, non-opaque, no snow/ice
Aqua CM vs CALIPSO, July 2013

ocean

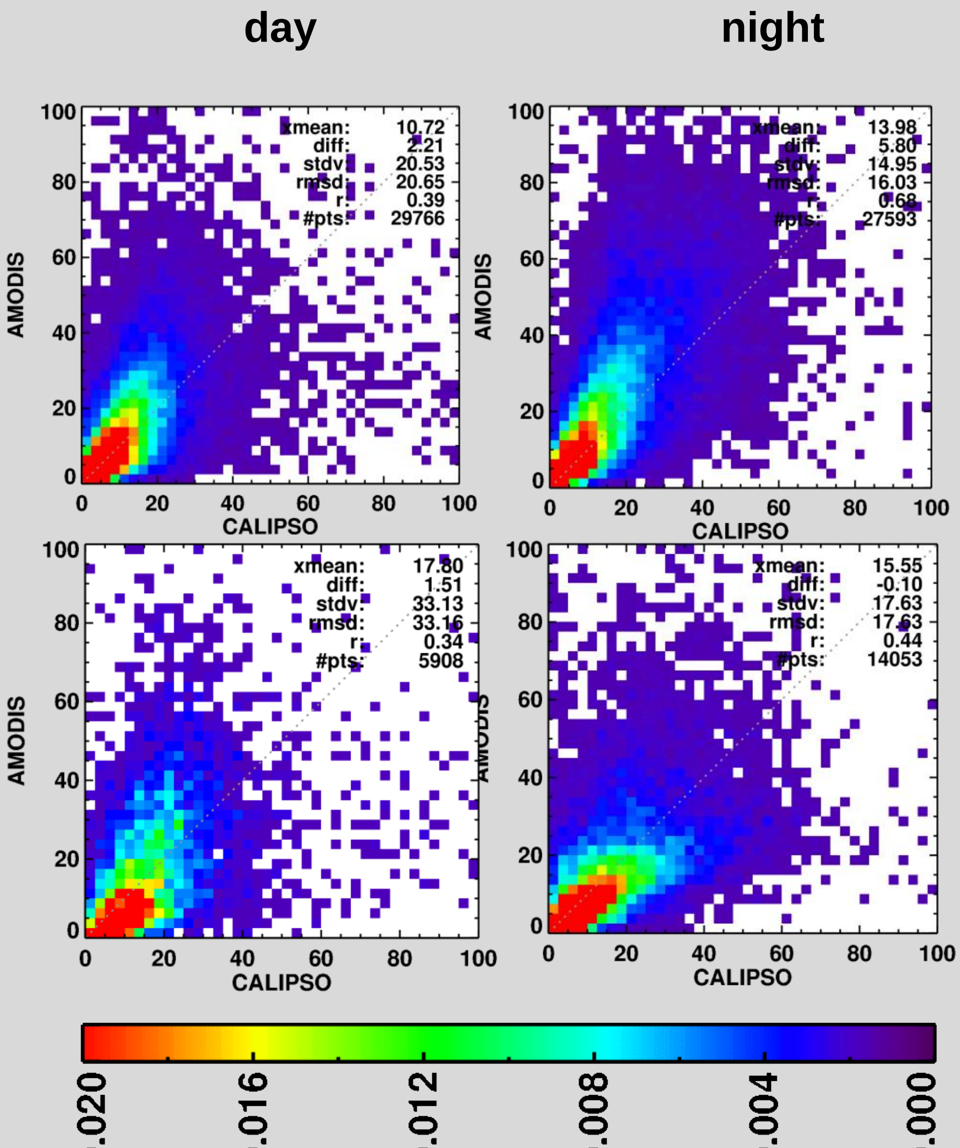
land



- **Day:** $COD_{CM} = 2*COD_{CAL}$
  - new ice xtal model no help
  - yields Zeff underestimate
- **Night:** $COD_{CM} = 1.25*COD_{CAL}$
  - mostly $COD_{CM} = COD_{CAL}$
  - SIST very effective
  - scatter large
- **VIIRS:** Results nearly identical

- Apply SIST during day?
  - testing soon
- Try new scattering model?
  - *Liu et al. (ACP, 2014)*
  - testing soon

Ice water path, non-opaque, no snow/ice, Aqua CM vs CALIPSO, July 2013



- **Day:** $IWP_{CM} = 1.2*IWP_{CAL}$
  - most points around 1:1 over ocean
  - Re must balance COD bias
- **Night:** $IWP_{CM} = 1.25*IWP_{CAL}$ -
  - most points around 1:1 line over ocean
  - land points below 1:1 line
  - Re probably very good
    - *bias same as COD*
- **VIIRS:** Results nearly identical

Concluding Remarks

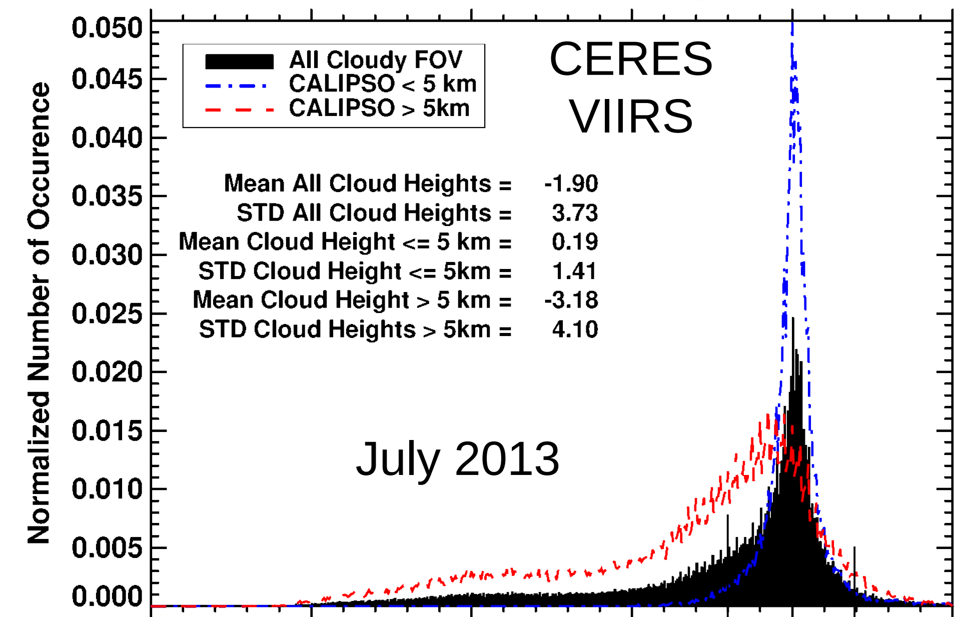
• Many approaches are available for validating satellite cloud retrievals

- land sea, air, and space; theoretical
- essential for quantifying errors and guiding improvements
  - *need large number of comparisons to cover the variables*
  - *need algorithm uncertainties*
- careful comparisons and understanding of reference datasets are critical
  - *need to quantify uncertainties in reference datasets to fully assess satellite errors*
- many other techniques available but not discussed here
  - *closure, angle dependencies, etc.*

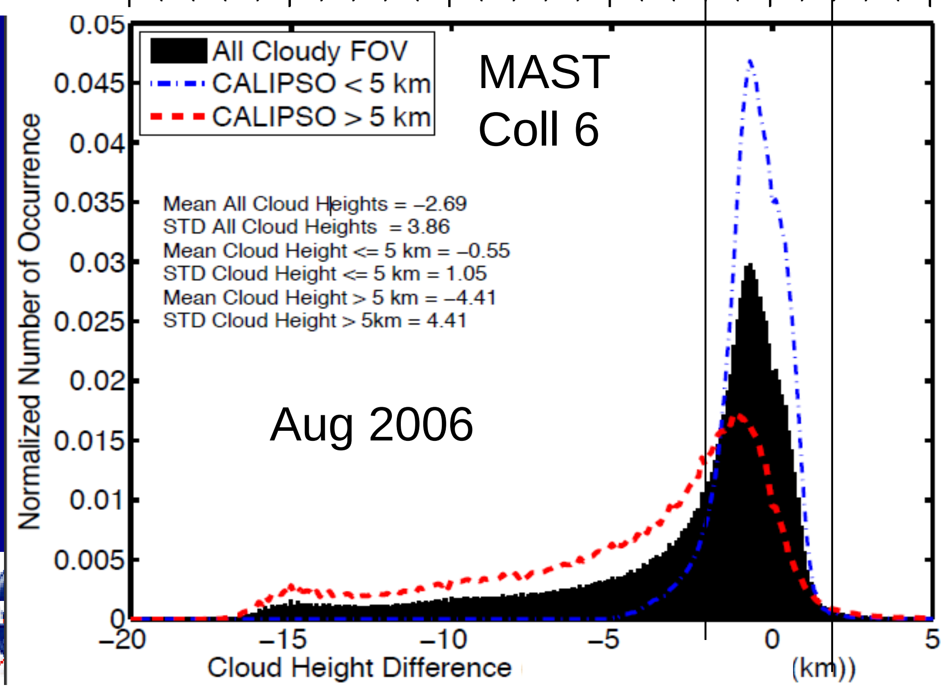
• Current versions of VISST & SIST algorithms produce relatively consistent results across platforms

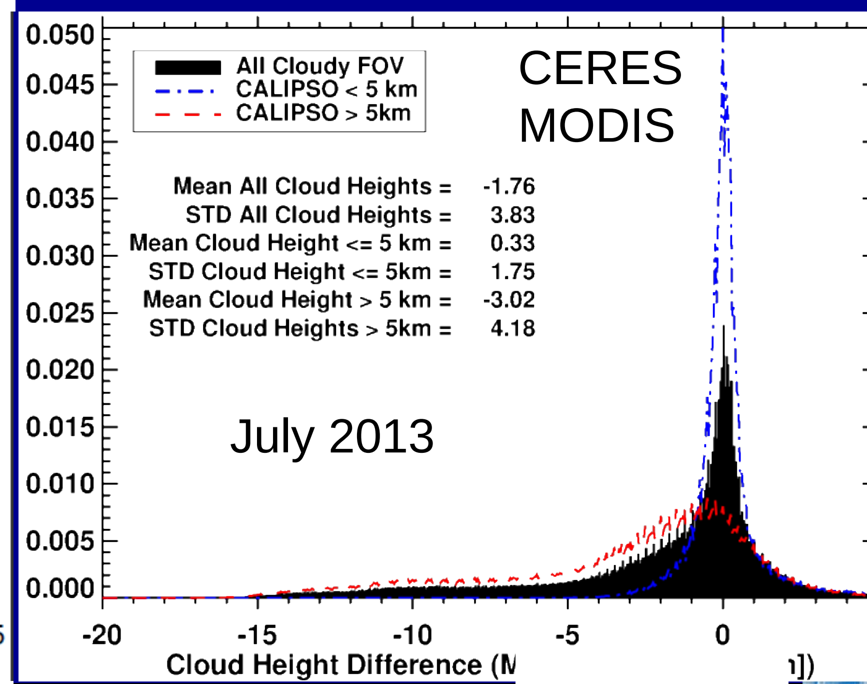
- validation comparisons indicate Ed4 MODIS yields highest accuracy
  - *must account for angular dependence in comparisons*
- need continued improvement in several areas
  - *cloud detection of thin cirrus, tropical Cu, night*
  - *height determination: 2-chan SIST, day thin cirrus, ML*
  - *formula for LWP: depends on type?*
  - *new scattering phase function*

Distribution of Cloud Height Differences (Satellite – CALIPSO)
All clouds (use highest for multilayered pixels), 60° - 60°S

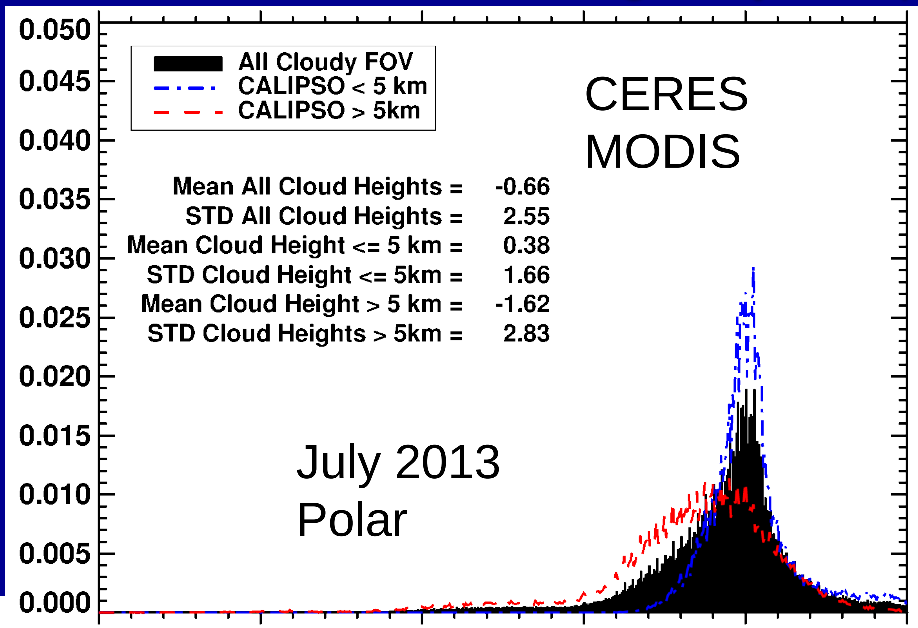


- CERES low cloud differences narrowly distributed
  - STD > Coll 6? ~1.75 vs 1.05
  - bias is smaller, ~0.33 vs -0.55
- CERES hi cloud difference
  - STD = Coll 6 – 0.2 km
  - bias smaller by ~1.3 km

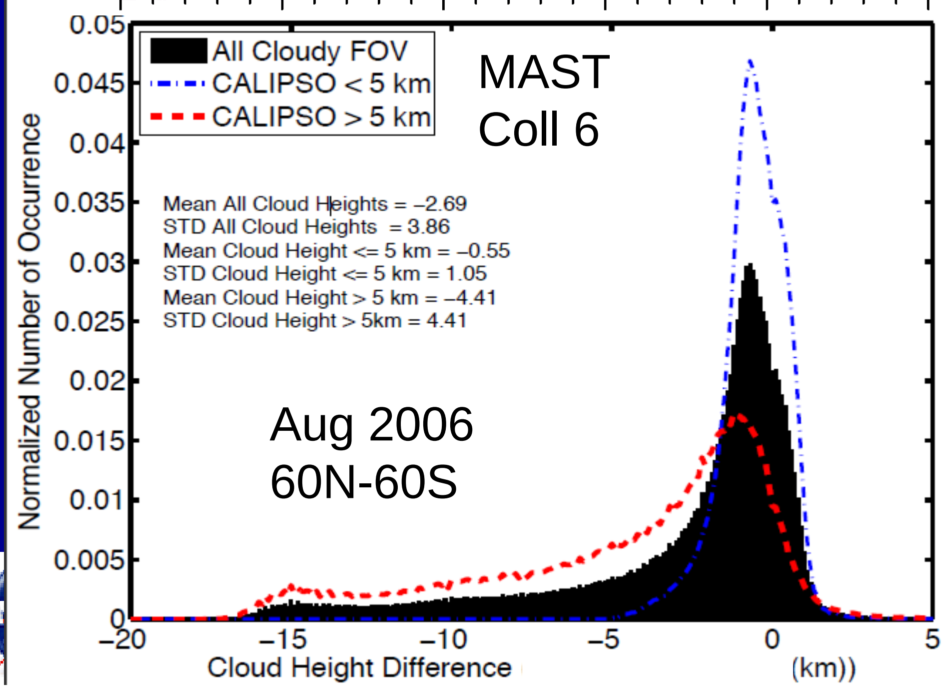


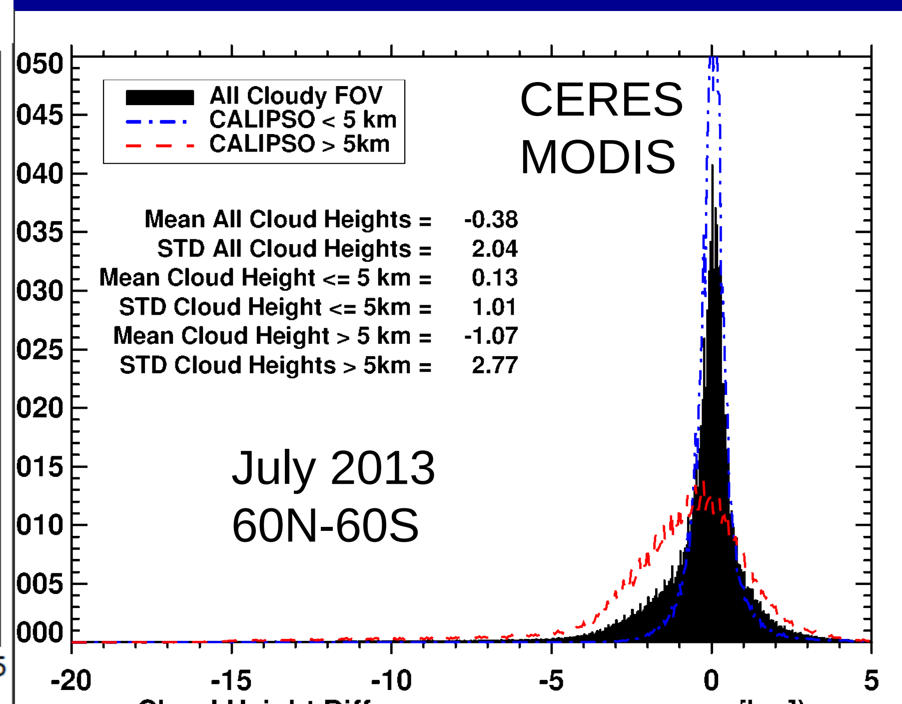


Distribution of Cloud Height Differences (Satellite – CALIPSO)
Single-layered pixels, 60° - 60°S

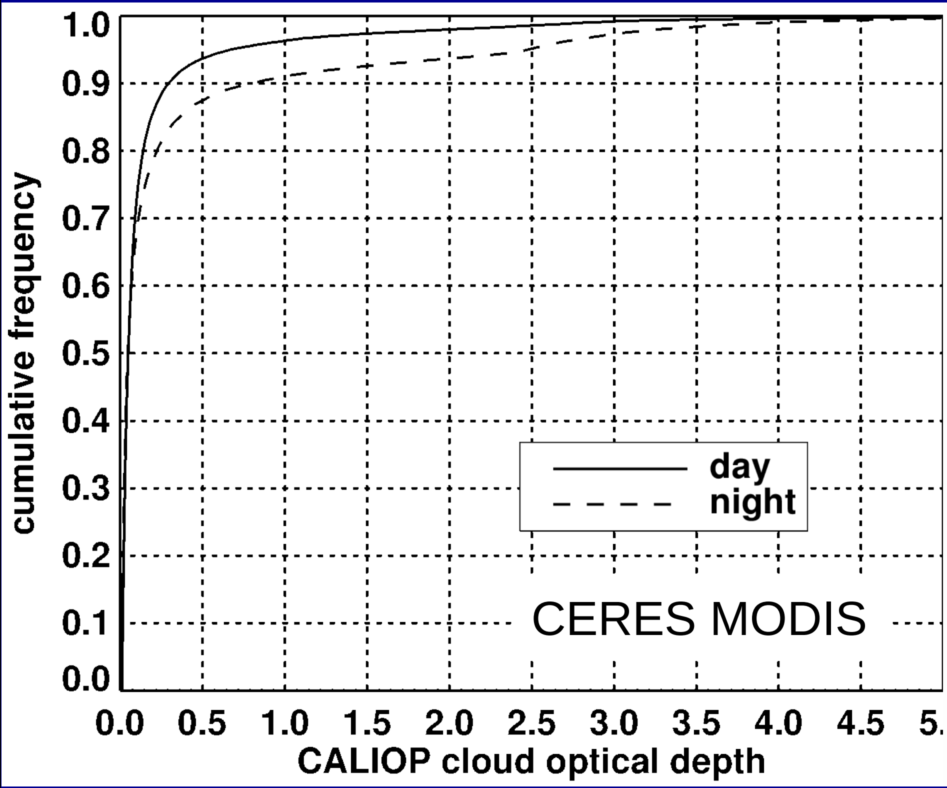


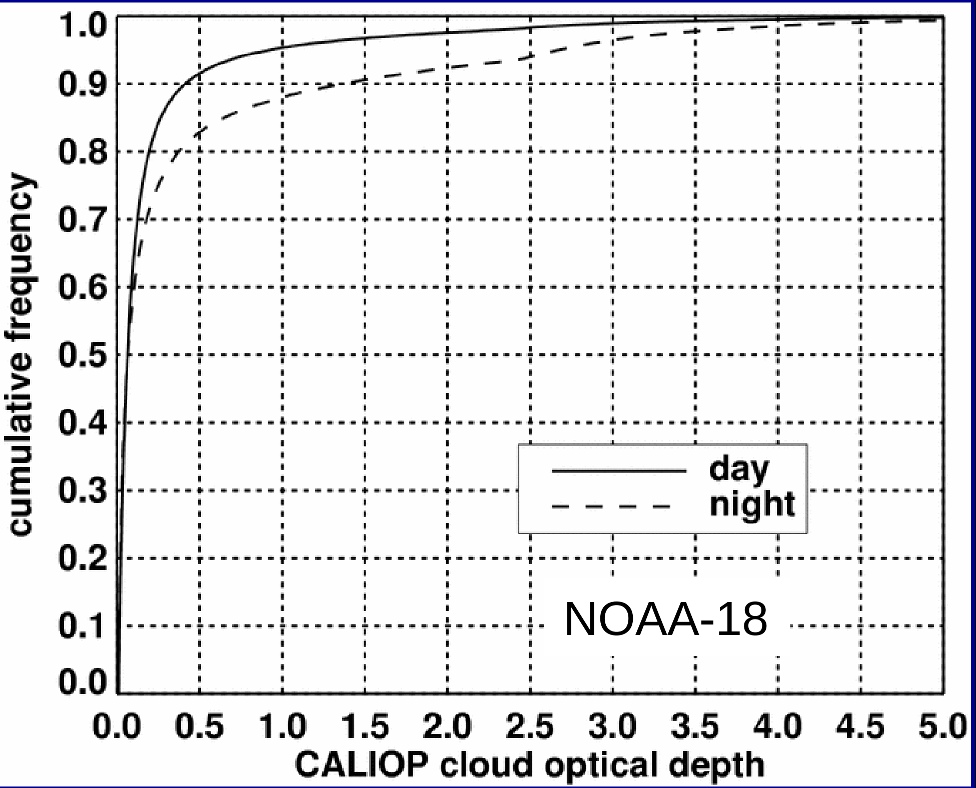
- CERES low cloud differences narrowly distributed
  - STD reduced ~1.75 to 1.01 km
  - bias is smaller, ~0.13 from 0.33 km
- CERES hi cloud difference
  - STD = Coll 6 – 0.2 km
  - bias smaller by ~1.3 km
- Not clear if MAST used 5 or 1 km pixel





Cloud Detection vs CALIPSO COD
60° - 60°S





- MODIS mask more sensitive than AVHRR
  - bias: -0.7% to +10%
  - STD: up to 100%
- Cloud detection more difficult at night