PACE Cloud Team

- *GSFC*
  Steve Platnick (PI), Kerry Meyer
- *U. Wisconsin/CIMSS*
  Steve Ackerman, Rich Frey*, Andy Heidinger [NOAA], Andi Walther
- *U. Colorado/LASP*
  - Odele Coddington*, Peter Pilewskie, Sebastian Schmidt
- *UMBC*
  - Zhibo Zhang*, Frank Werner, Dan Miller
- *GISS/Columbia University*
  - Bastiaan Van Diedenhoven
    (ice cloud polarimeter expertise but not part of funded proposal)

* Attending the Science Team Meeting

PACE Cloud Team Proposed Efforts

- Investigate OCI cloud information content and retrieval uncertainty vs. VIIRS/MODIS legacy products. Leverage VIIRS/MODIS algorithm funding and the SNPP Atmosphere SIPS infrastructure.

    A. Cloud mask/detection [Leads: *Ackerman, Frey* (U. Wisconsin/CIMSS)]

    B. Cloud-top retrievals w/A-band and 940/1380 nm (OCI) water vapor bands [Leads: *Heidinger* [NOAA/CIMSS], *Meyer* [GSFC]

    C. Cloud thermodynamic phase discrimination information content [Leads: *Coddington, Schmidt, Pilewskie*] and impact on cloud optical thickness and effective particle radius retrievals [Leads: *Platnick, Coddington*]

    D. Liquid water cloud optical retrieval sensitivity to spatial resolution using obs. (eMAS, ASTER) and model (LES) data [Leads: *Zhang, Meyer*]

- As needed, assist Project on OCI instrument specs, trade studies, etc. pertaining to cloud products [Lead: *Platnick*]

PACE Cloud Team Status

- Final version of cloud chapter for AC report delivered summer 2017 (authors: S. Platnick, O. Coddington, S. A. Ackerman, R. Frey, A. Heidinger, A. Walter, K. G. Meyer, Z. Zhang, B. van Diedenhoven); input on exec. summary provided fall 2017.
  - In addition to OCI studies proposed as part of ROSES 2013, added LES-based marine boundary layer liquid cloud polarimetric retrieval studies (Z. Zhang, D. Miller, et al.) and overview of ice cloud polarimetric capabilities (van Diedenhoven).
  - Main supporting publications: Coddington et al. (2017), Miller et al. (2016, 2017), Werner et al. (2016, 2018), Zhang et al. (2016), …
- Product-specific algorithm study recommendations provided in cloud chapter and in following slides. Broad recommendations/thoughts:
  - Next science team needs to include focused work on synergistic OCI/polarimeter retrievals (cloud-top, cloud phase, cloud microphysics).
  - Greatest challenge for product continuity/legacy remains lack of IR observations. Supplement IR information w/constellation flying and/or use of GEO imager assets? Also, sun-sync time potentially inconsistent with previous missions.

A. Cloud Masking/Detection (1)

Year 3 Work

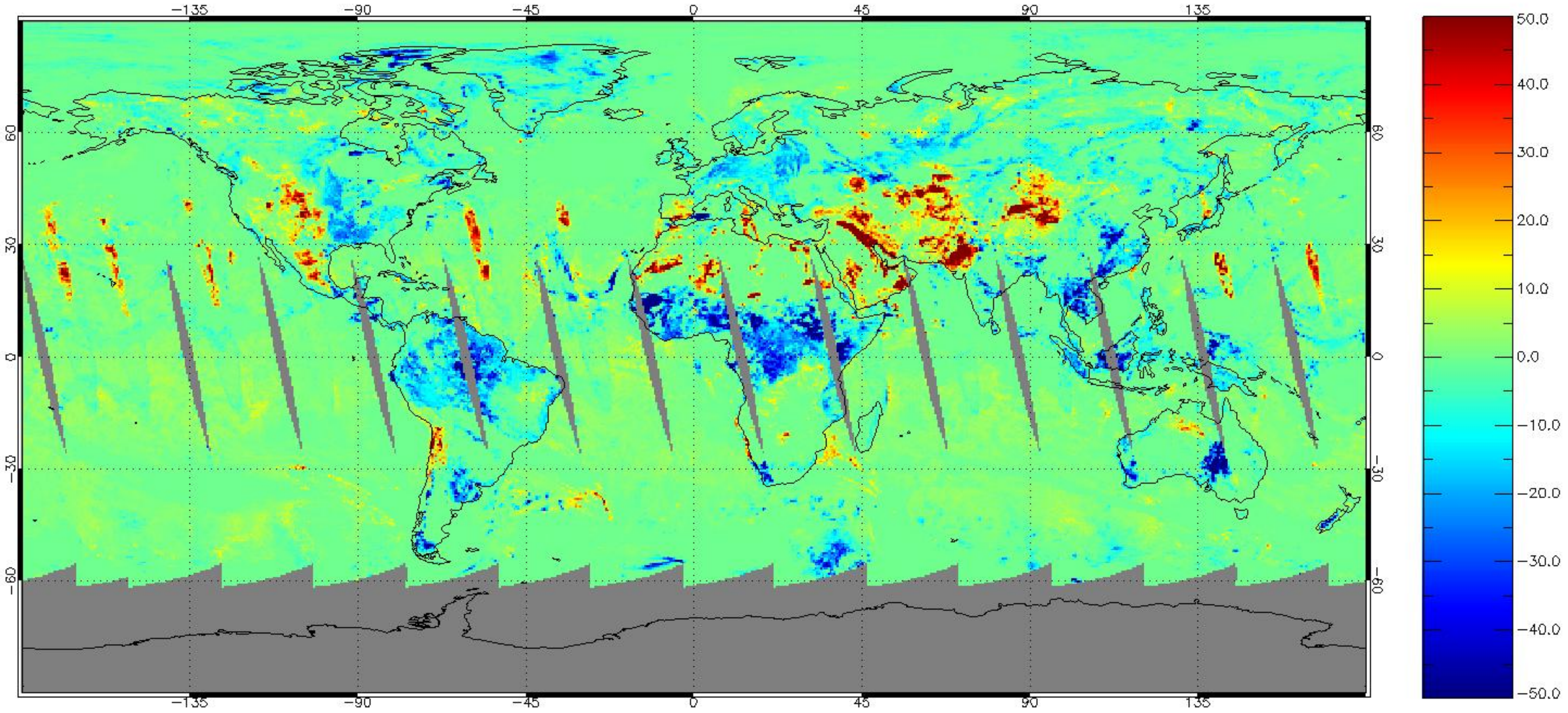
- Using MODIS Aqua and SNPP VIIRS input radiances as proxies for PACE, tested VNIR-only cloud detection on global daytime scenes.
- Implemented new VNIR-only cloud detection over land surfaces, including snow/ice.
- Tuned cloud test and clear sky restoral test thresholds for better clear/cloudy sky discrimination given no LWIR observations available for PACE.

Future Recommendations

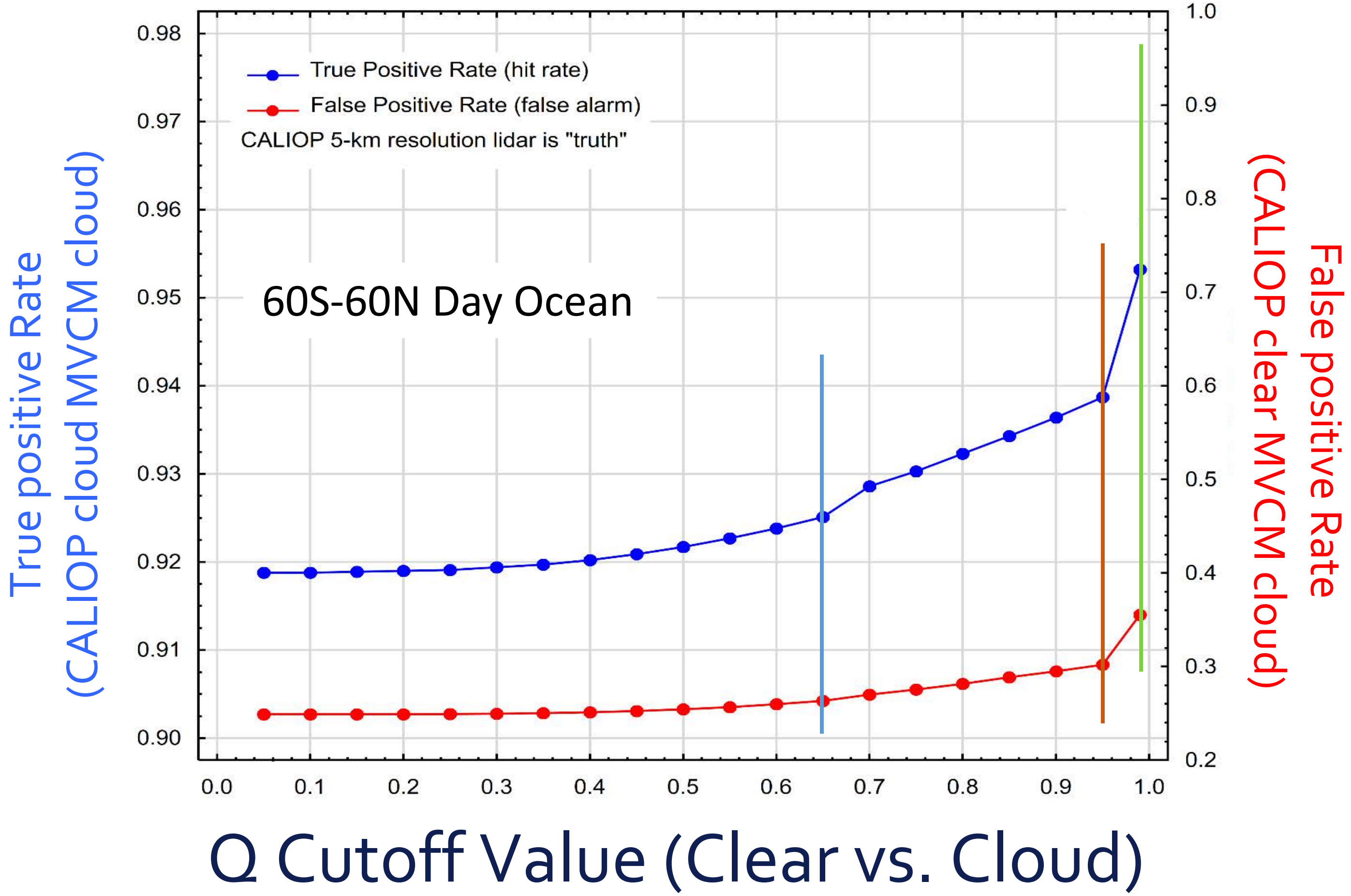
- General assessment of cloud test thresholds and Q values. Land scenes may need Q adjustments due to lesser information content (no LWIR), especially deserts.
- More work needed on deserts and semi-arid regions with regard to existing test thresholds; are there additional useful cloud tests?
- Determine if LWIR data from geostationary instruments would be helpful. Also, any new/updated ancillary data?
- Given no LWIR information for cloud detection, what are downstream algorithm priorities? For example, trade fewer detected thin clouds and cloud edges for less false alarms?

A. Cloud Masking/Detection (2)

01 July 2013 MVCM PACE Minus MVCM Aqua Day Cloud Fraction



A. Cloud Masking/Detection (3)



$$Q = \sqrt[N]{\prod_{i=1}^{N} \min(F_i)}$$

Q <= a threshold value (e.g., 0.99, 0.95, 0.66, vertical bars) **indicates cloud was found**

We typically recommend Q = 0.95 as the cutoff between clear and cloud for daytime ocean.

B. Cloud Top Properties (1)

Year 3 Work

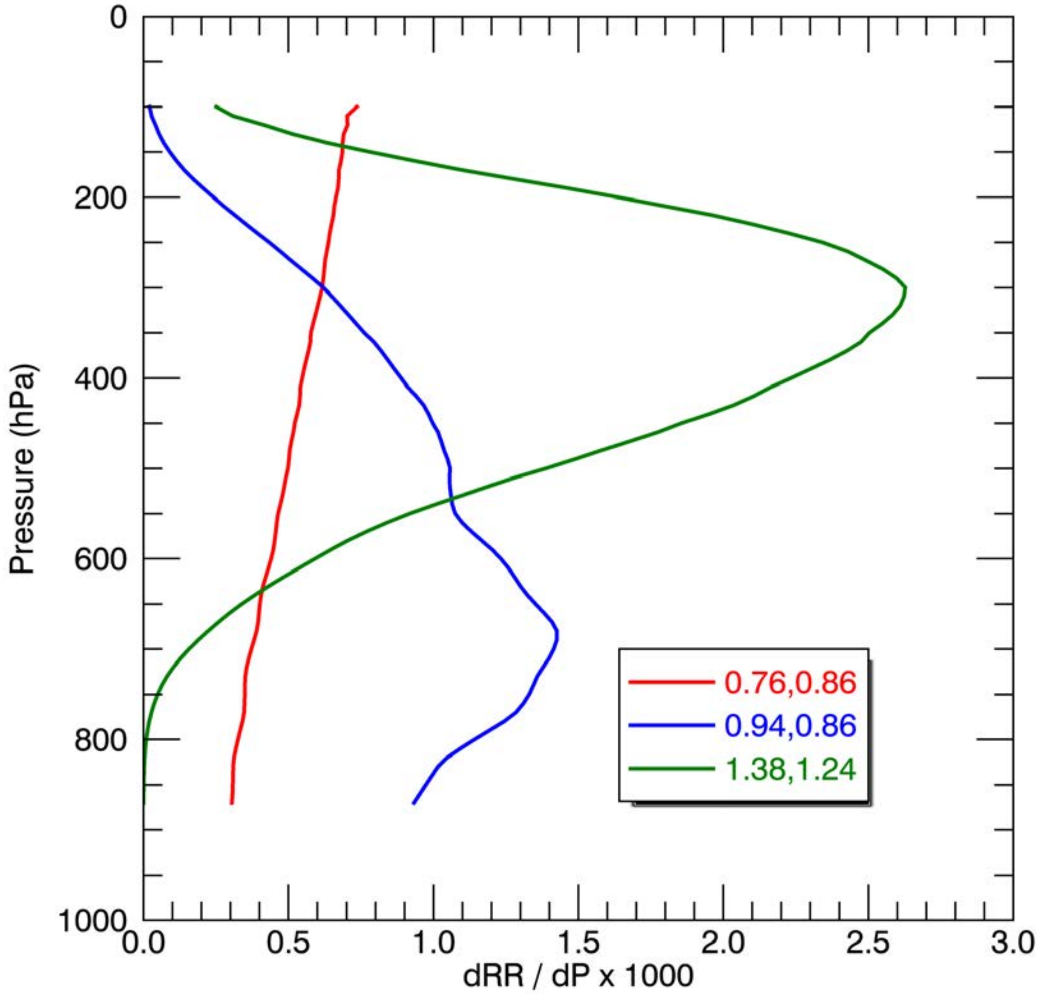
- Preliminary synthetic retrievals developed using an optimal estimation algorithm applied to OCI-like water vapor channels (940, 1380 nm) and O_2 A-band observations.
- CIMSS Correlated-K Radiative Transfer modified to simulate two layers of cloud from OCI channels.
- Developed Baseline Optimal Estimation retrieval to probe skill in cloud height/pressure estimation.
- Explored the benefits of using a Cloud Top Pressure constraint from nearby IR sensors.

Future Recommendations

- Need to expand simulated case studies to include more difficult scenes (multiple layers/phases inconsistent with first guess).
- Overcome convergence difficulties by exploring alternative LUT approach.
- Use OCO-2 A-band spectral observations as proxy data and compare with other A-Train assets.
- Current studies based on notional OCI A-band location/bandpass; need to build on these studies with more specific A-Band specifications.
- Expand work to include synergistic polarimetric observations (e.g., Rayleigh-derived cloud-top).
- Do we need an OSSE to better quantify non-polarimetric vapor/A-band capabilities?

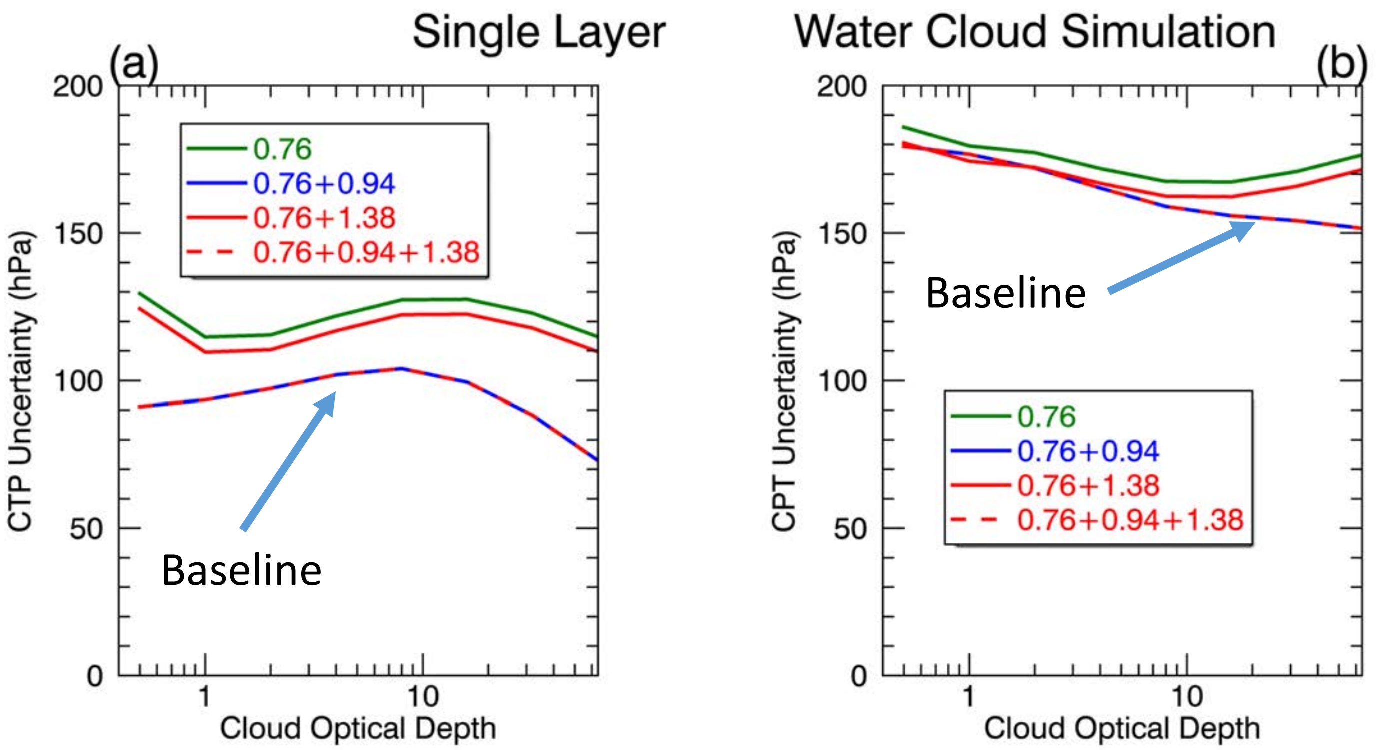
B. Physics of the Baseline OCI CTP (2)

- Baseline OCI Cloud-top Pressure (CTP) algorithm uses the 0.76, 0.94 and 1.38 μm OCI channels that fall in gaseous absorption bands.
- These channels provide sensitivity that spans the Troposphere.
- Algorithm uses Reflectance Ratios (RR). RR values should reduce impact of uncertainties in calibration and microphysical model assumptions.
- Image on the right shows the sensitivity of the Reflectance Ratios (RR) to changes in CTP as a function of CTP. Simulation assumed a cloud of optical depth of 4 in a Tropical Atmosphere.
- 0.76 / 0.86 Reflectance Ratio sensitivity is nearly linear since O_2 is a well-mixed gas.
- 1.38 / 1.24 Reflectance Ratio sensitivity peaks in upper Troposphere because since the 1.38 channel is in a strong absorption feature.



B. Baseline OCI Results – Single Layer Water (3)

- Images show the O.E. uncertainty of CTP and CPT for a low level water cloud.
- To highlight channel contributions, several channel combinations were run.
- Prior information assumed to have uncertainty of 200 hPa – so this is the max value of retrieved uncertainty.
- ***Simulations show 0.94 adds considerably to the 0.76 channel. 1.38 provides little benefit.***
- ***For high clouds, situation reverses. 1.38 adds considerably while 0.94 does not.***

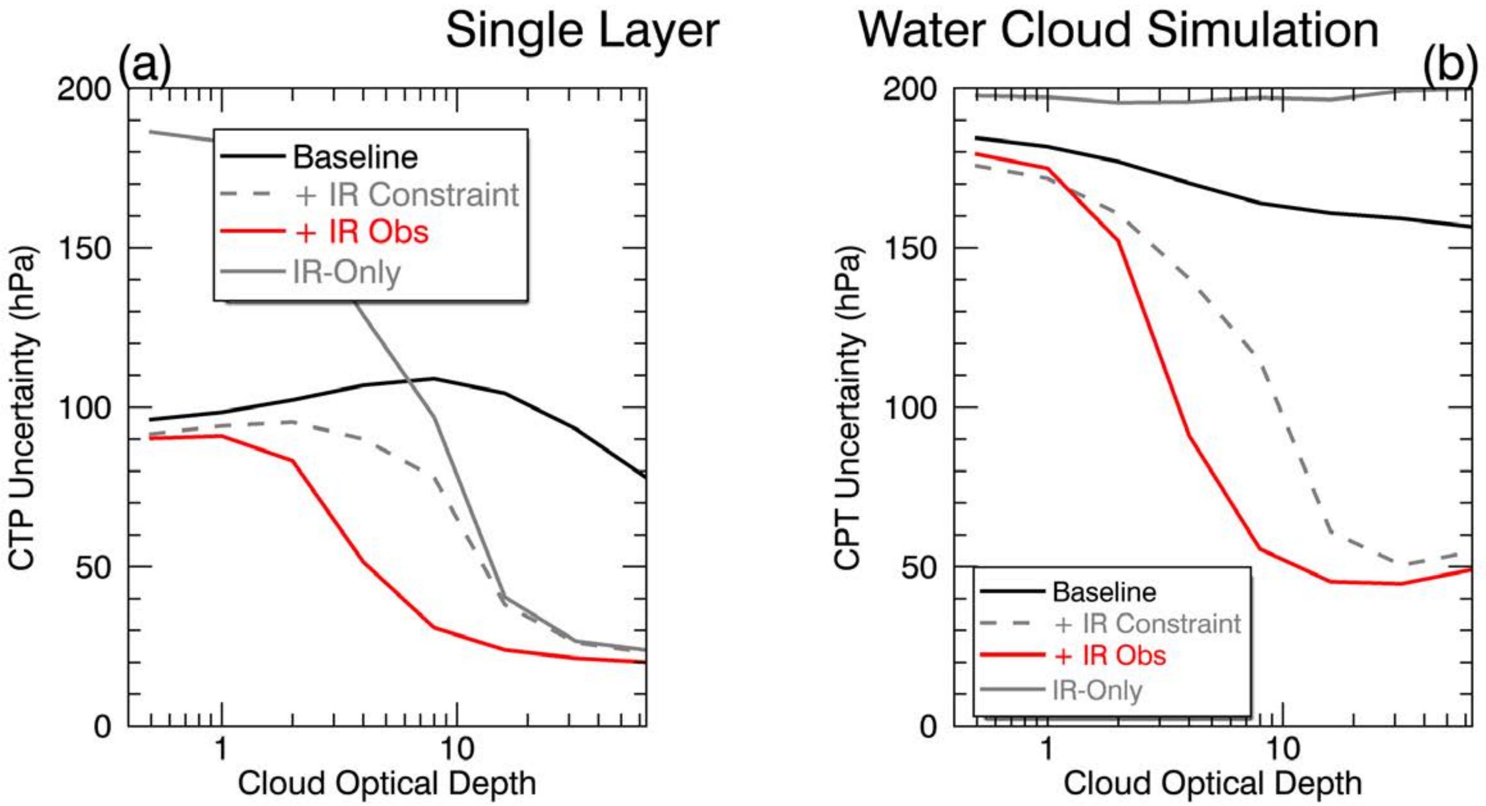


Terms:
CTP = Cloud Top Pressure
CPT = Cloud Pressure Thickness (*not a MODIS legacy/continuity product)
“Baseline” = approach that includes all channels (dashed red line)

CPT retrievals are a challenge for low clouds but easier for higher clouds (not shown).

B. Impact of Using IR Information (4)

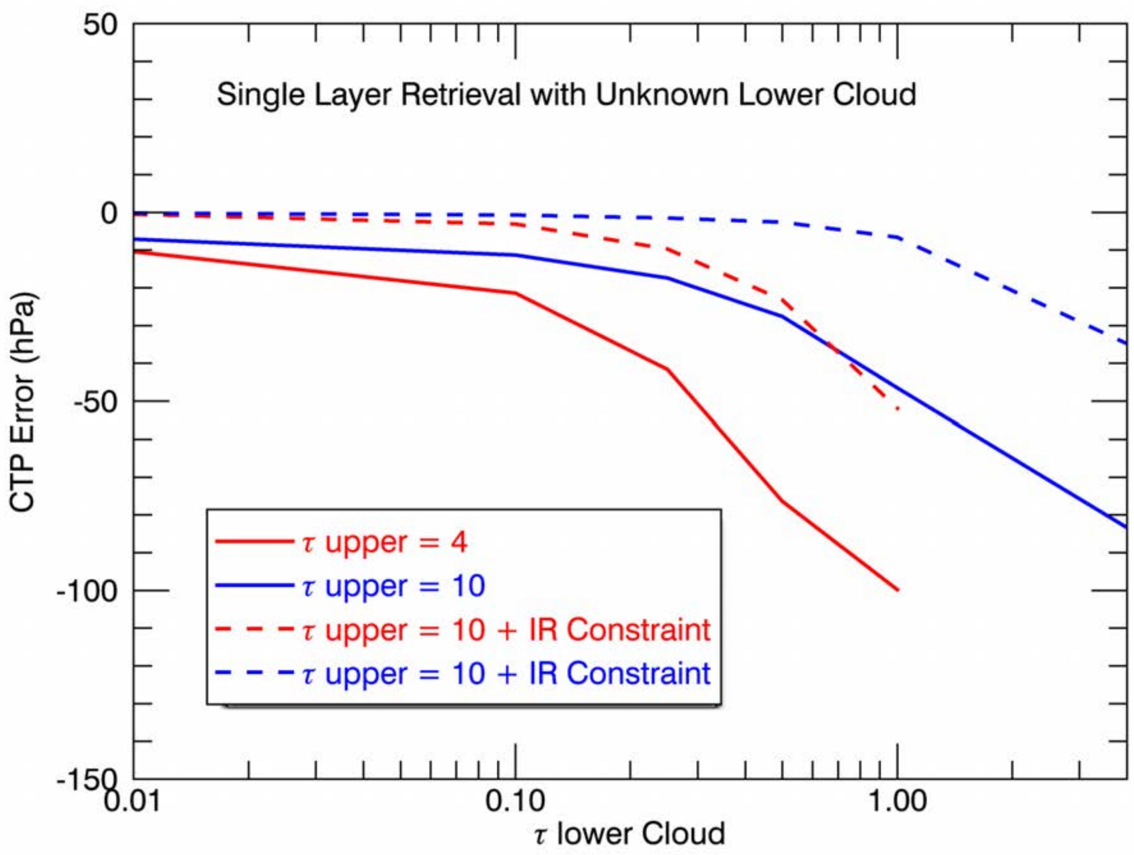
- IR observations and retrievals from other sensors may often be available to complement OCI observations.
- OCI O.E. Retrieval can easily incorporate other IR retrievals as a new constraint.
- Here we demonstrate this for a water cloud simulation using an IR constraint and using IR observations.
- Note using IR-only observations give no skill for CPT. All skill comes from OCI.
- Images show impact of using an IR retrieval of CTP as constraint in OCI Baseline OE. (dashed grey).



IR improves CTP estimation and significantly improves CPT retrieval compared to OCI Baseline. OCI complements IR.

B. Sensitivity to Multi-Layer Clouds (5)

- OCI retrieval is sensitive to the presence of lower cloud layers.
- If lower cloud layer is unknown, retrievals of upper cloud are impacted.
- Image shows impact on CTP as a function of lower and upper cloud optical thickness.
- IR constraint (if available) does mitigate this error.
- Retrieval of 2-layers with OCI Baseline is a challenge. Retrieval may require synergy with other PACE sensors.
- Prior knowledge of presence of multiple layers would be helpful.



OCI retrieval will be sensitive to unknown lower clouds.

B. LUT-based Alternative to CTP Retrievals (6)

Initial Retrieval set-up approach: Optimal estimation technique with three reflectance ratio inputs.
+ Optimal solution with physically-based uncertainty in case of convergence.
- Set-up of observation uncertainty (uncertainty of reflectance ratios) and background a-priori are challenging. Solution space is small ➔ High likelihood of non-convergence due to retrievals with observation slightly outside expected range fails.

Alternative set-up: Pre-computed Multi-dimensional LUTs for CTP and CPT

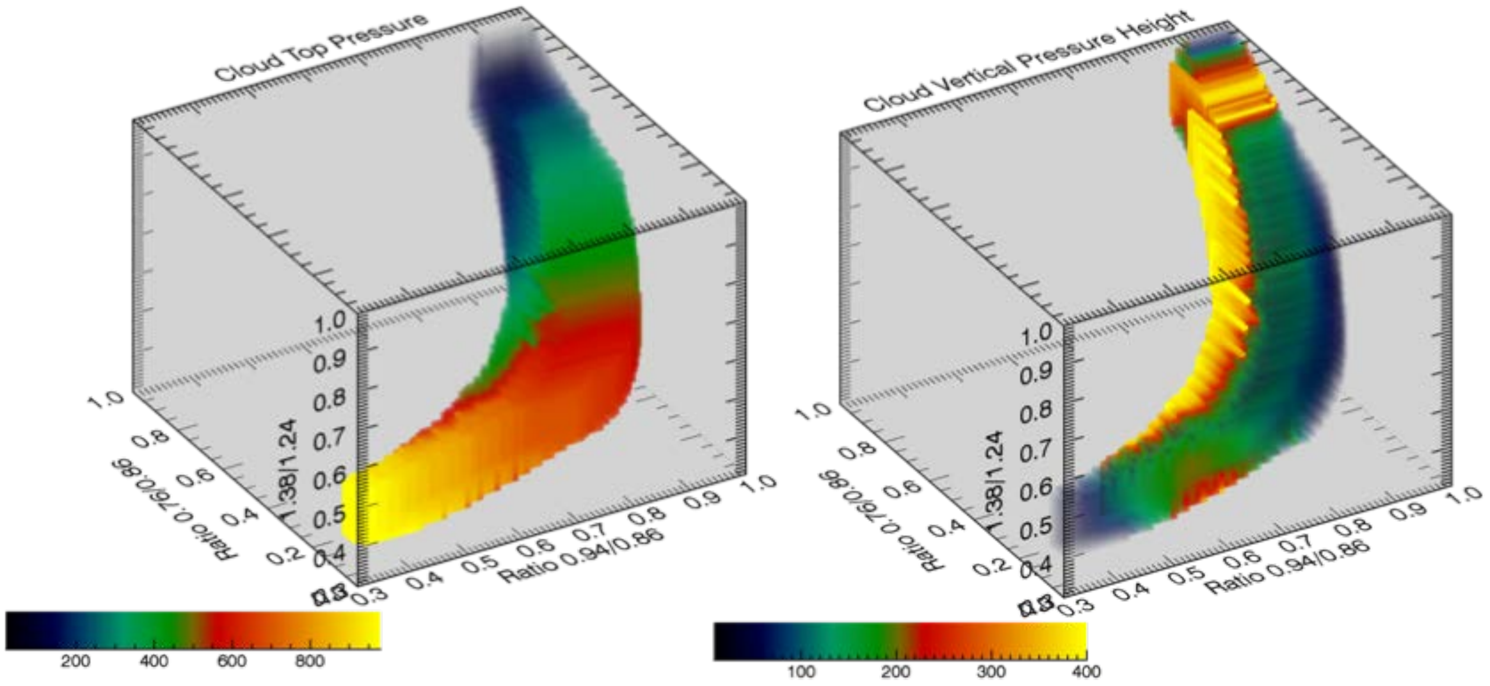


Fig. shows single-layer cloud LUT for an ice cloud with COD=10 and REFF=20.

LUTs created separately for *single/multi-layer* and *ice/water phase* and for a wide range of COD/REF

+ Very fast retrieval possible
+ LUT data size is acceptable
+ No Convergence fail problem
- *No* direct *solution uncertainty* estimates (but possible by considering local homogeneity of region in the LUT cube). No consideration of different input and model uncertainties.

C. Cloud Retrieval Info. Content Studies (1)

Thermodynamic Phase Discrimination, Optical Thickness & Effective Particle Radius

Year 3 Work

- Extended information content analysis to benefit cloud team objectives by assessing:
  - Sensitivity in retrieved optical thickness and effective ice particle radius to different assumptions in ice crystal habits.
- Further Investigated information content in thermodynamic phase [Coddington et al., 2017] and cloud optical properties to changing surface albedo
- Laid out an approach for to integrate the "GENRA" software code with MODIS software cloud algorithms for utilization in research analysis/testing.

Future Recommendations

- Expand information content work to include synergistic polarimetric observations.
- Need to understand PACE sun-view geometry and need to build on information content studies with specific geometry specifications.
- Need to expand/modify information content analysis for PACE-specific OCI imager measurement uncertainties.
- Expand information content analysis to a broader range in land surface types.
- Expand sensitivity analysis to ice optical model to a broader range in optical thickness, ice particle radius values.

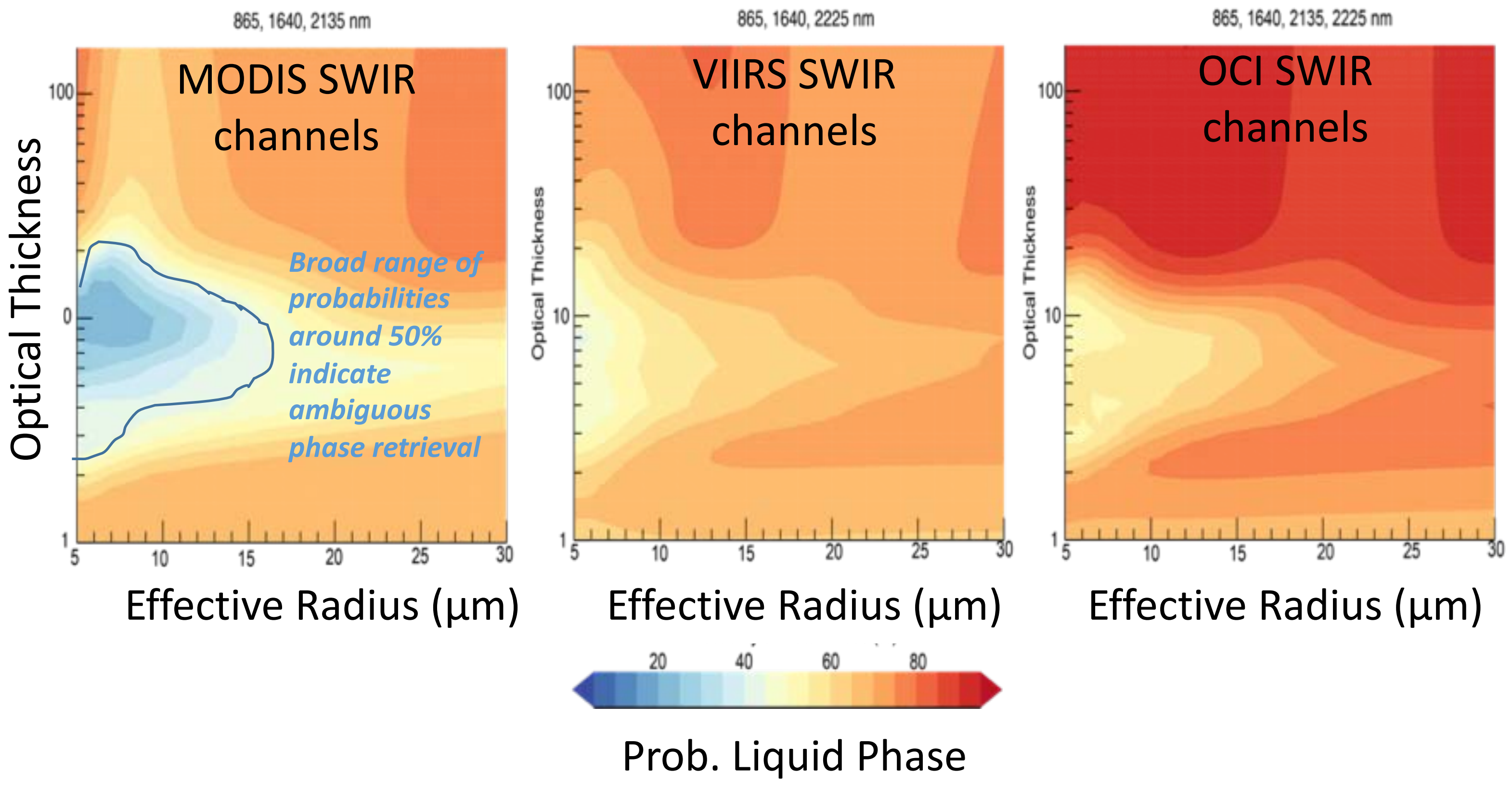
C. Cloud Retrieval Info. Content Studies (2)

Thermodynamic Phase Discrimination, Optical Thickness & Effective Particle Radius

Approach: GEneralized Nonlinear Retrieval Analysis (GENRA) methodology with extension to different land surface types. Results reported in *Coddington et al., JGR* [2017]. Contributions of realistic Lambertian surfaces added to MODIS, VIIRS, and PACE cloud reflectances.

Figures: Phase information content example for liquid cloud over snow/ice surface.

Findings: An OCI 2.25 μm channel in addition to a 2.13 μm channel always improves probability of successful cloud phase discrimination.

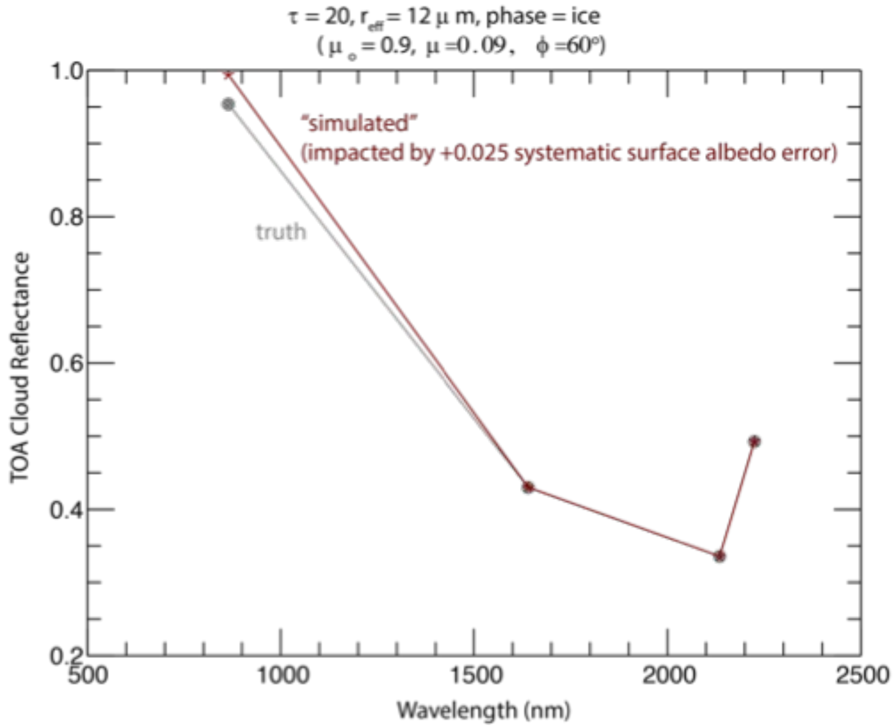


Example: Uncertainties in retrieved snow surface albedo propagate into retrieved cloud properties such that the best-fit solution is obtained for a thinner cloud (of the same droplet effective radius).

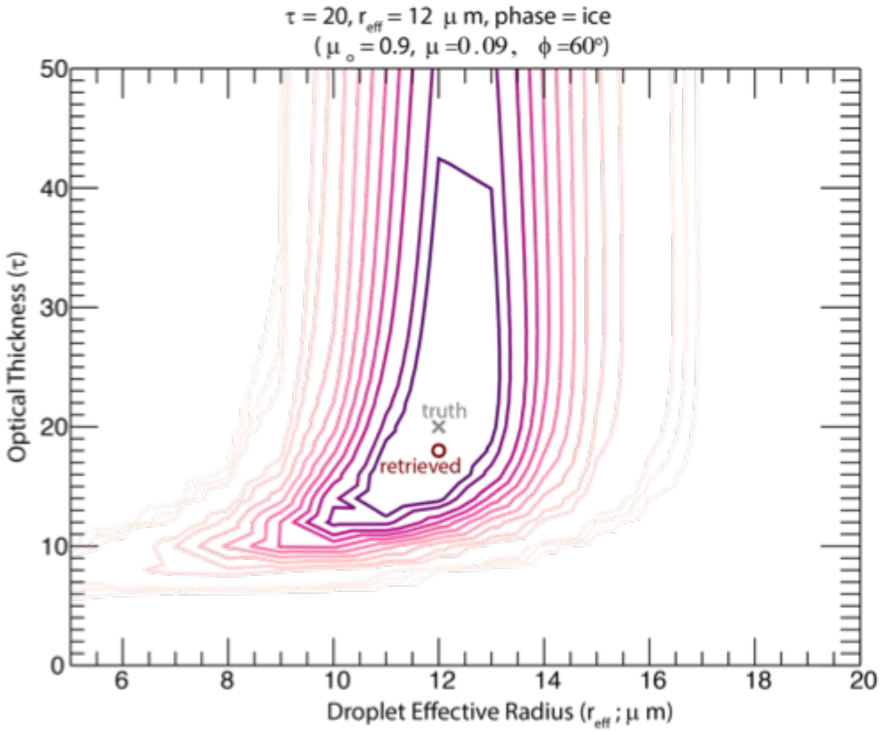
Results (cont.)

Surface albedo is an essential, non-retrieved, forward model input.

Uncertainties in prescribed surface albedo can propagate into uncertainties in retrieved cloud properties.



Simulated Cloud Reflectance for 2 different snow surface assumptions (grey = assuming "true" surface albedo; maroon = assuming "retrieved" surface albedo with +0.025 unit magnitude bias).



Maximum Likelihood solution for Cloud optical thickness and droplet effective radius given different snow surface values ("x" = retrieval given "true" surface albedo value; "o" = retrieval given "biased" surface albedo.

C. Cloud Retrieval Info. Content Studies (4)

Sensitivity of Ice Cloud Optical Thickness & Effective Particle Radius to Ice Optical Model

Approach: GEneralized Nonlinear Retrieval Analysis (GENRA) methodology with extension to different MODIS/VIIRS ice optical models. The ice optical models are represented by different approximations of single scattering albedo (ratio of absorption to extinction) and asymmetry parameter (average cosine of scattering angle) dependent upon ice crystal habit and surface roughness. Therefore, retrieved cloud optical thickness & effective radius pairs are sensitive to assumptions in the ice optical models.

"Truth"
Ice crystal habit: *Columns*, severely-roughened

(Optical Thickness, Effective Radius (μm))
(4,11)
(10,11)
(10,50)
(30,40)

"Retrieved": Here, cloud reflectances for ice crystals with a *solid bullet rosette* (severely-roughened) habit are matched to simulated ice cloud reflectances based on an ice optical model that assumed crystal habit = *columns* (severely-roughened). Differences in (tau, ref) pairs relative to the "Truth" indicate a retrieval sensitivity.

λ = MODIS SWIR	λ = VIIRS SWIR	λ = PACE SWIR
(3,5)	(4,12)	(4,11)
(10,11)	(10,11)	(10,11)
(10,51)	(10,48)	(10,49)
(30,39)	(30,38)	(30,38)

For these selected cases, assumptions in ice optical model primarily impacted ice crystal effective radius to a magnitude of 1-2 μm. Thin clouds show potentially greater sensitivity. Analysis is ongoing.

**** A polarimeter would provide constraints on the variation of ice scattering properties.***

D. Spatial resolution for liquid water retrievals (1)

Framework & Numerical Test-bed for Assessing Total/Polarized Radiance Retrievals

Year 3 Work

- Used the ASTER-based testbed to investigate the sensitivity of cloud masking to instrument spatial resolution (Werner et al., 2018)
- Further Investigated the impacts of partly-cloudy pixels and inhomogeneous pixels on the quality and statistics of cloud optical and microphysical property retrievals.
- Investigate the impacts of sub-pixel inhomogeneity and 3-D radiative transfer effects on bi-spectral and polarimetric cloud property retrievals (Miller et al. 2017).

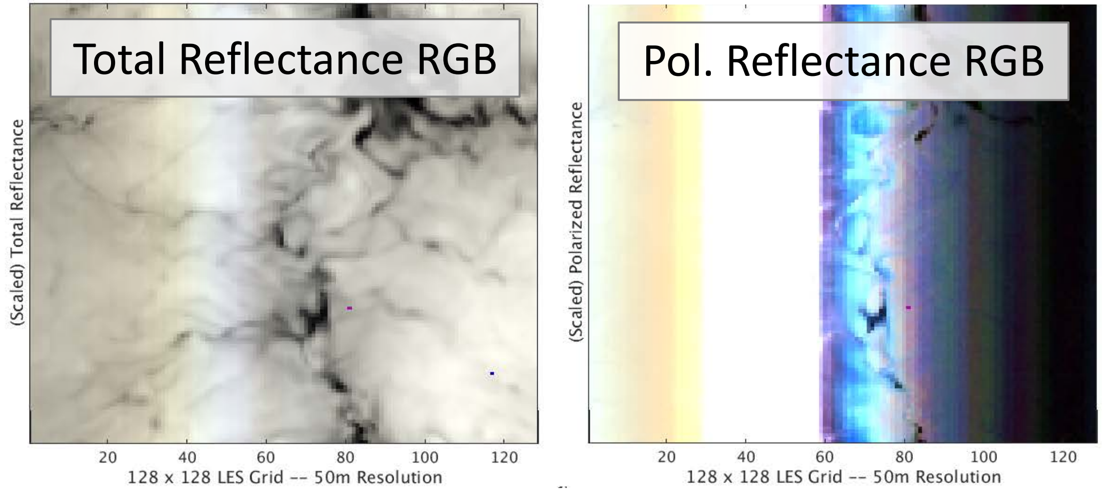
Future Recommendations

- Need to understand sun-view geometry of PACE polarimeter-observed scattering angles, as well as the angular/spectral resolution (affects cloud and aerosol retrievals)
- Need to understand the angular collocation method/algorithm of PACE polarimeter (e.g., collocate at cloud top or ground; parallax effect)
- Need to understand the spatial and angular collocation/alignment of OCI and polarimeter (important for cross calibration and synergistic retrievals)
- Need theoretical understanding of how 3D radiative effects influence polarimetric cloud retrievals

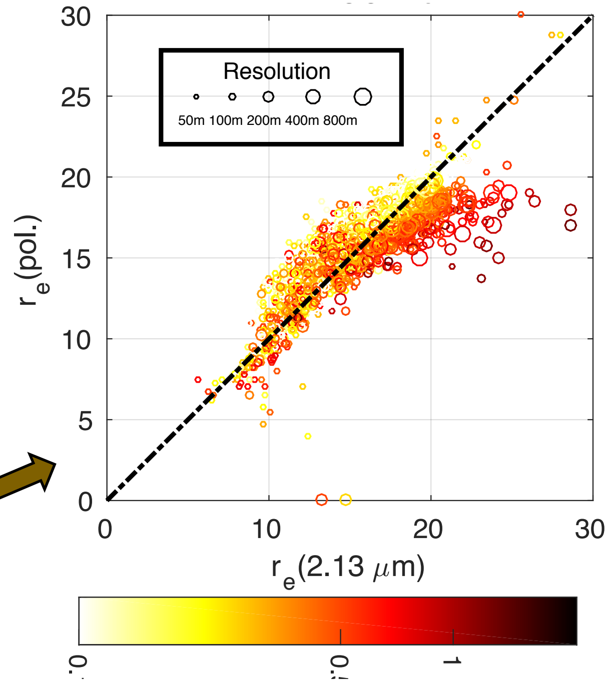
D. Spatial resolution for liquid water retrievals (2)

Approach: Synthetic (LES marine BL models w/Monte Carlo RT) and empirical (ASTER) studies to asses sub-pixel 3D heterogeneity sensitivities. Results reported in *Miller et al.* [2017] for model studies of total reflectance (e.g., OCI) and polarimetric retrieval sensitivities, and *Zhang et al.* [2016] and *Werner et al.* [2016, 2017 (in review)] for ASTER 15m studies.

Example reflectances from LES model output



Polarimetric vs. Total Reflectance Eff. Radius Retrievals vs. Spatial Resolution Sensitivity



Log$_{10}$ (subpixel sdev/mean)

Polarimetric CER retrievals less sensitive to LES heterogeneity than total reflectance method but sample shallower into cloud. Both techniques can be synergistic.