Evaluation of satellite cloud retrievals against airborne observations in heterogeneous cloud fields and near the scan edge

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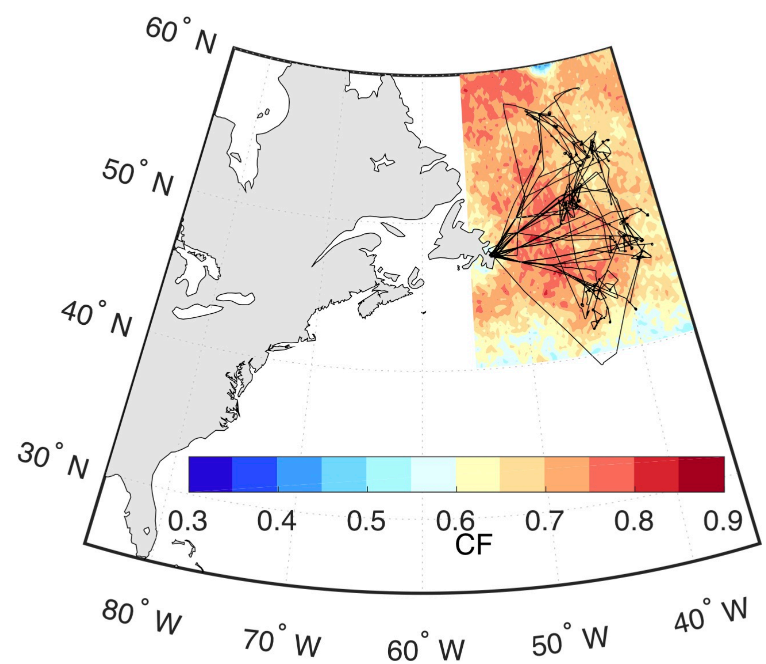
Motivation

- VIS/IR satellite cloud retrievals compare well with observations in marine overcast stratiform clouds.
    - Plane parallel assumption is reasonable
- However, multiple error sources make the retrievals less reliable for:
    - Partially cloudy scenes, high latitudes, and near the edge of the scan
- We take advantage of two NASA funded field campaigns to **evaluate CERES-MODIS and SatCORPS geostationary cloud retrievals** of cloud optical depth and effective radius in liquid clouds.

ORACLES 2016-2017

NAAMES 2015-2016-2017

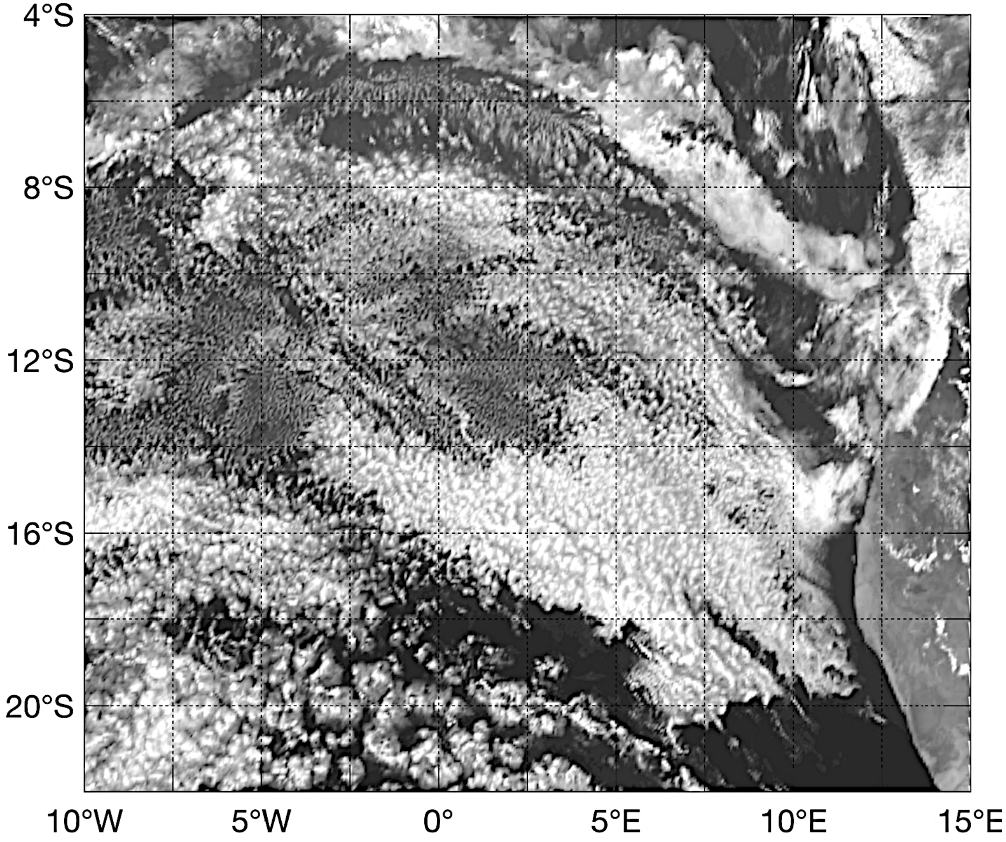


Dataset

- Both field campaigns deployed the airborne NASA GISS Research Scanning Polarimeter (RSP):
  - Polarimetric-based 2.26-μm cloud effective radius (r_e). Insensitive to 3D radiative effects. Footprint resolution ~ 70 m
  - 0.865-μm Cloud optical depth (τ): Reflectance-based constrained with polarimetric r_e.
- In-situ cloud probes for NAAMES
- **Meteosat-10 SEVIRI** cloud retrievals over the SE Atlantic
  - 3.9-μm r_e and 0.64-μm τ
- **GOES-13** cloud retrievals over the North Atlantic.
  - 3.9-μm r_e and 0.65-μm τ
- Terra and Aqua **MODIS:** 3.79-μm r_e and 0.64-μm τ

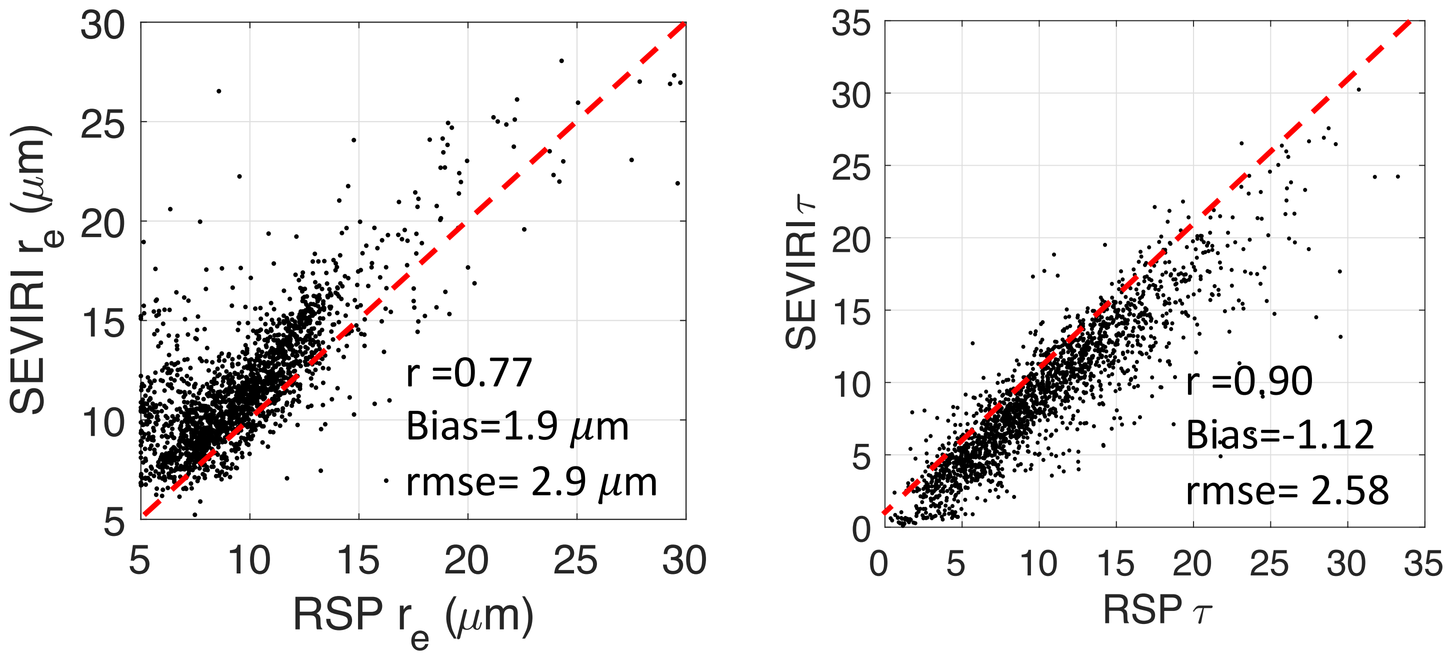
Meteosat evaluation during ORACLES

- ORACLES primarily sampled stratocumulus clouds
- Broken scenes (open cell) were often observed



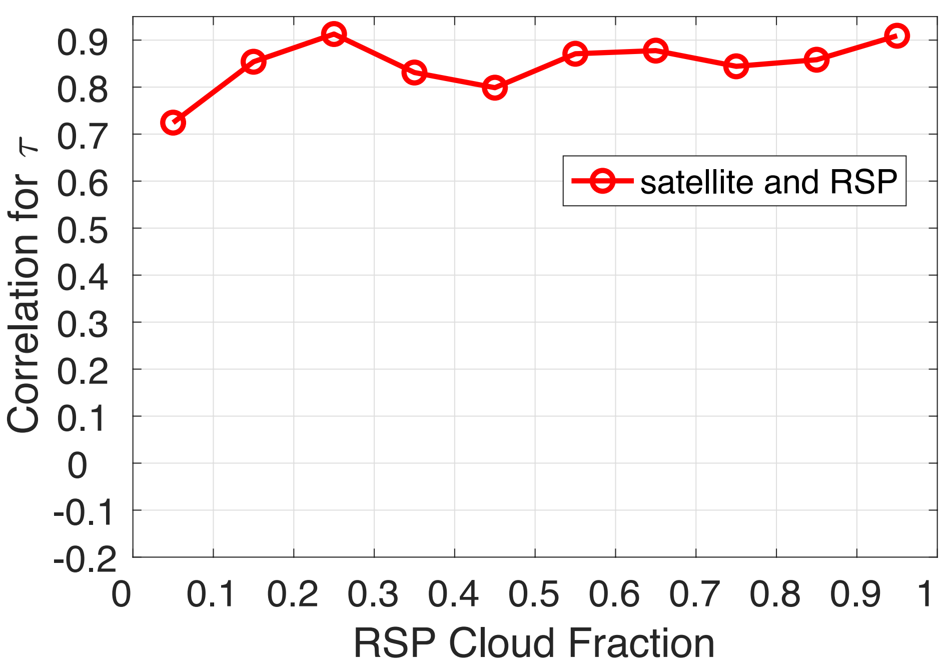
Initial assessment

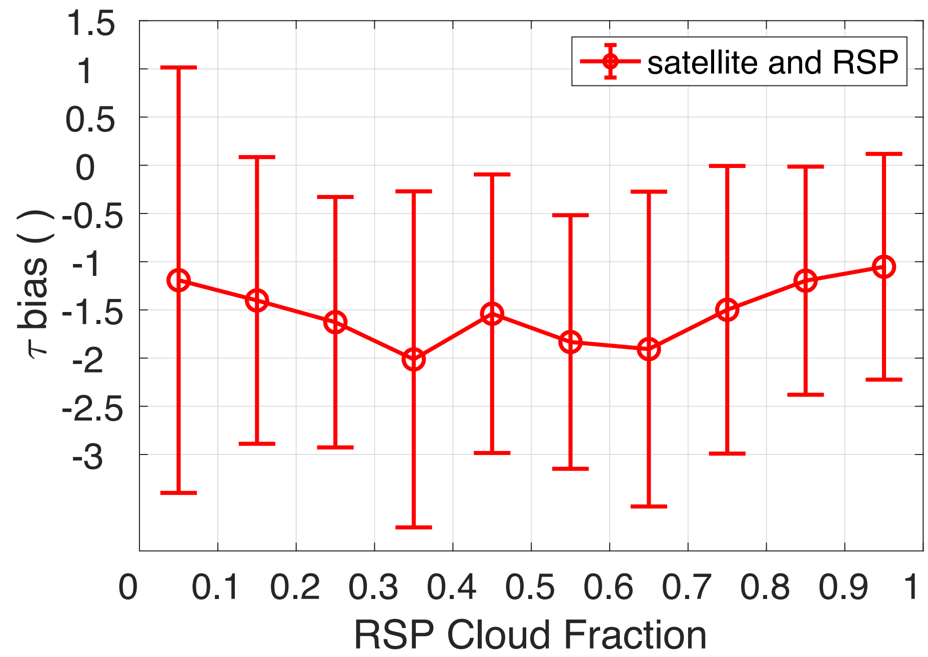
- RSP data are averaged every 90s (~18 km).
- Similarly, SEVIRI retrievals are collocated with RSP with a mismatch <15 min, and further averaged over a circle with 18-km diameter.



- All-sky correlations and biases similar to MODIS assessments over the SE and NE Pacific (e.g. Painemal and Zuidema 2011; Noble and Hudson 2015 JGR).
- Statistics mainly driven by overcast scenes. How about broken scenes?

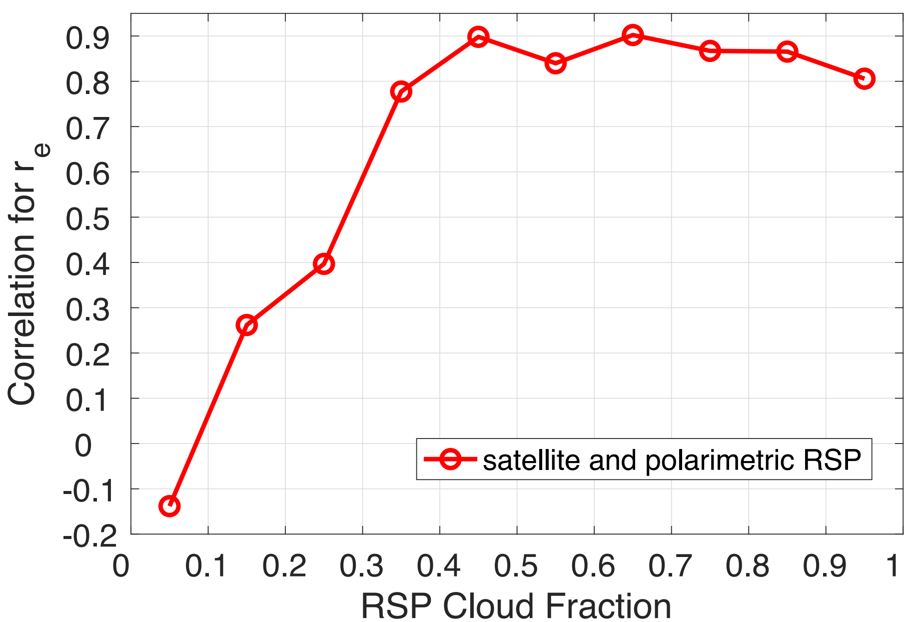
Dependence of cloud optical depth (τ) on CF

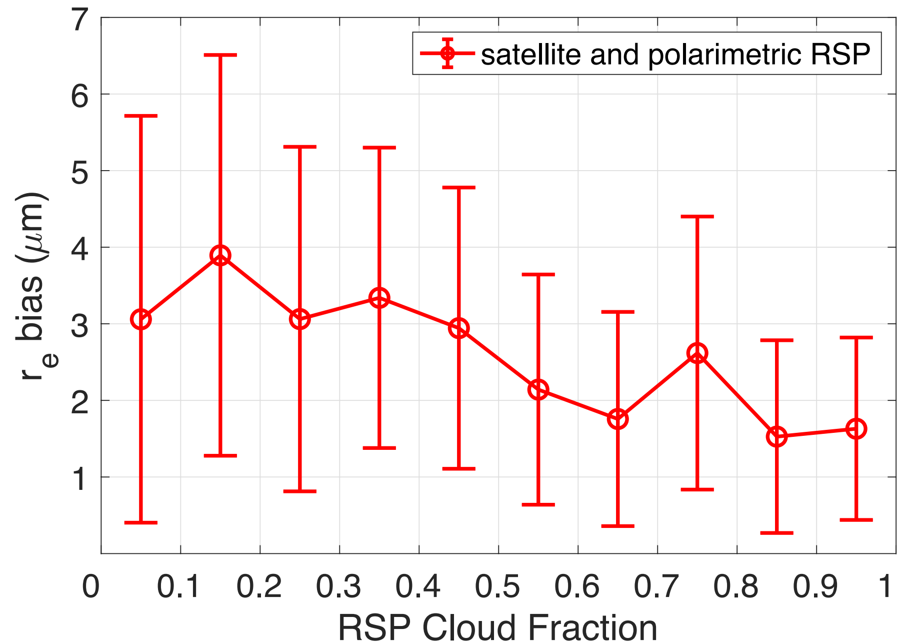




- Both airborne and satellite τ are highly correlated regardless of CF.
- A negative bias of SEVIRI τ is not dependent on CF.

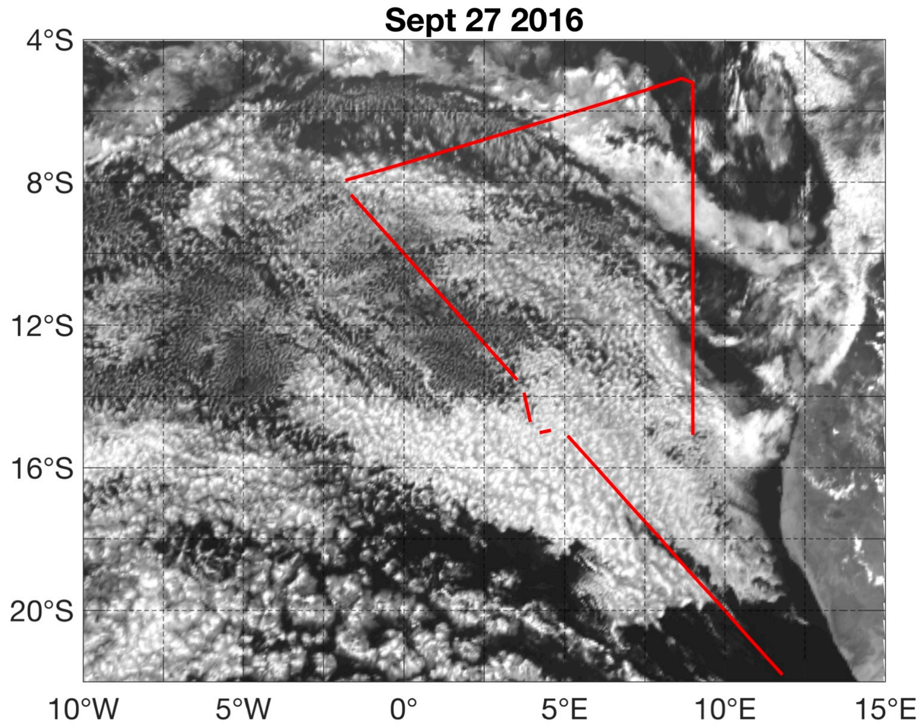
Dependence of SEVIRI r_e on cloud cover

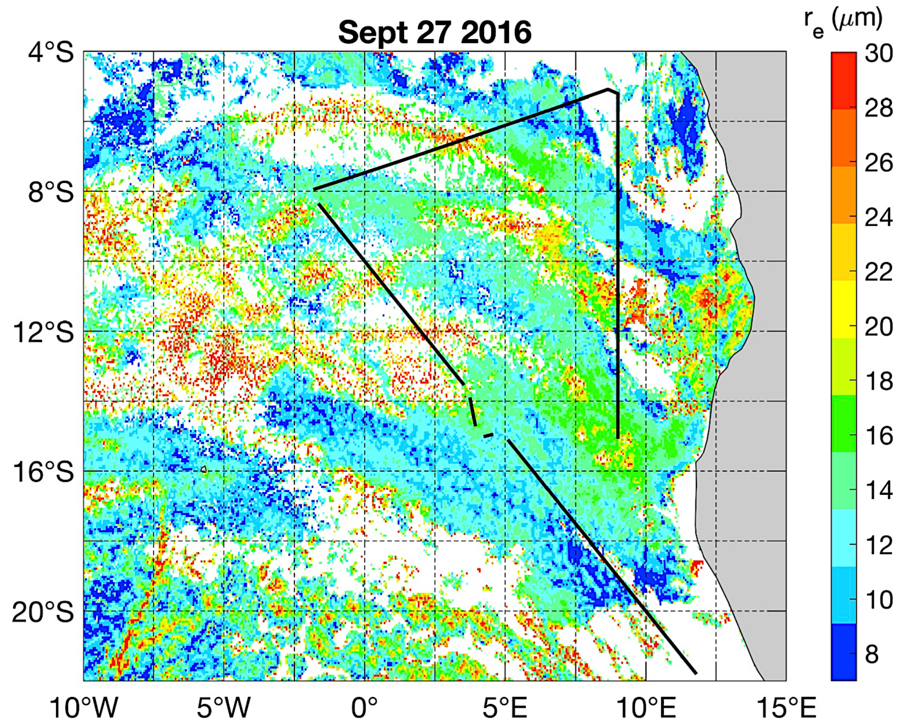




- SEVIRI r_e correlates well with RSP for cloud fraction (CF) >0.3.
- SEVIRI positive bias ~ [1.5 μm 3 μm] for CF>0.3.
- **Given these results, can we trust SEVIRI retrievals in open cell (partially cloudy) regions?**

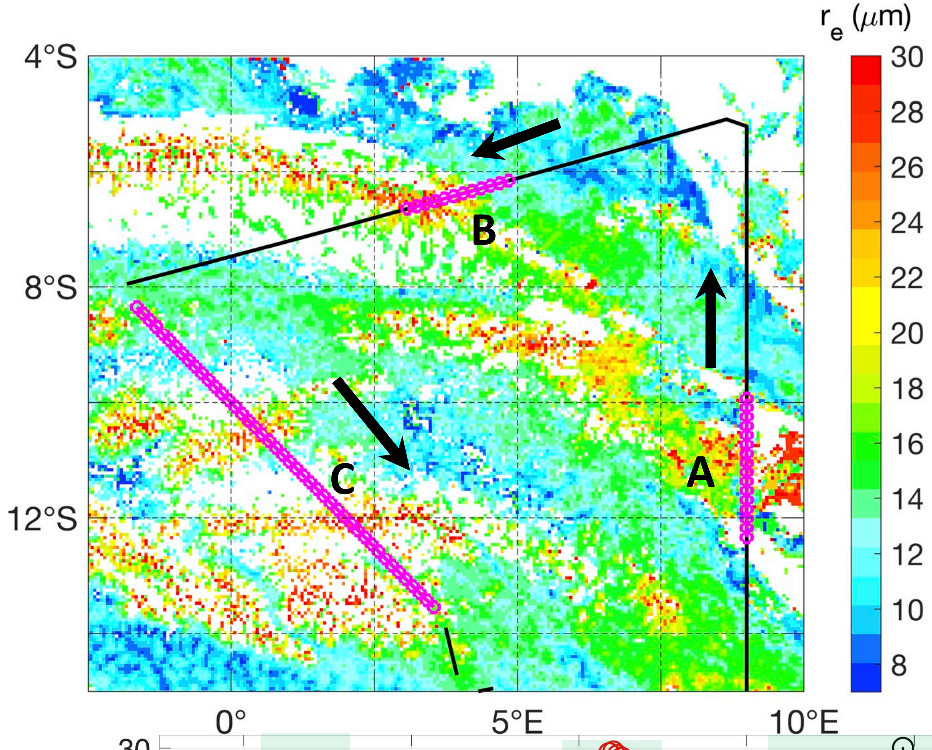
Open Cell case: Sept 27 2016



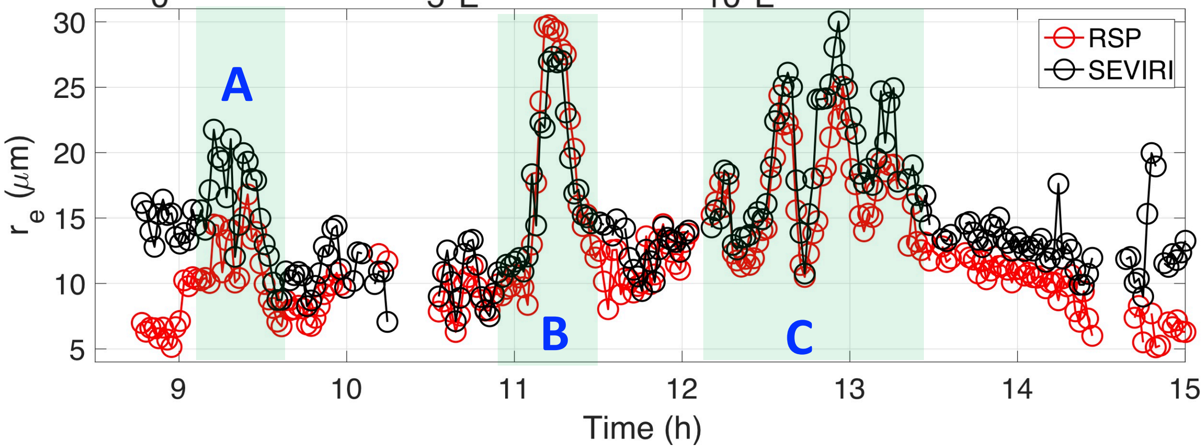


- Aircraft sampled three cloud-clear transitions, including two open cell areas.
- Note the strong SEVIRI r_e increase in open cell regions.

Open Cell case: Sept 27 2016



- Open cells B and C show a dramatic increase in droplet size in both RSP (airborne) and SEVIRI.
- SEVIRI is able to reproduce the r_e spatial gradient.
- Large r_e for open cells likely associated with precipitation.

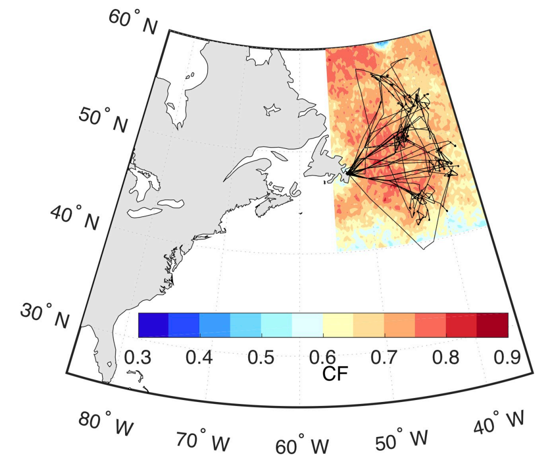


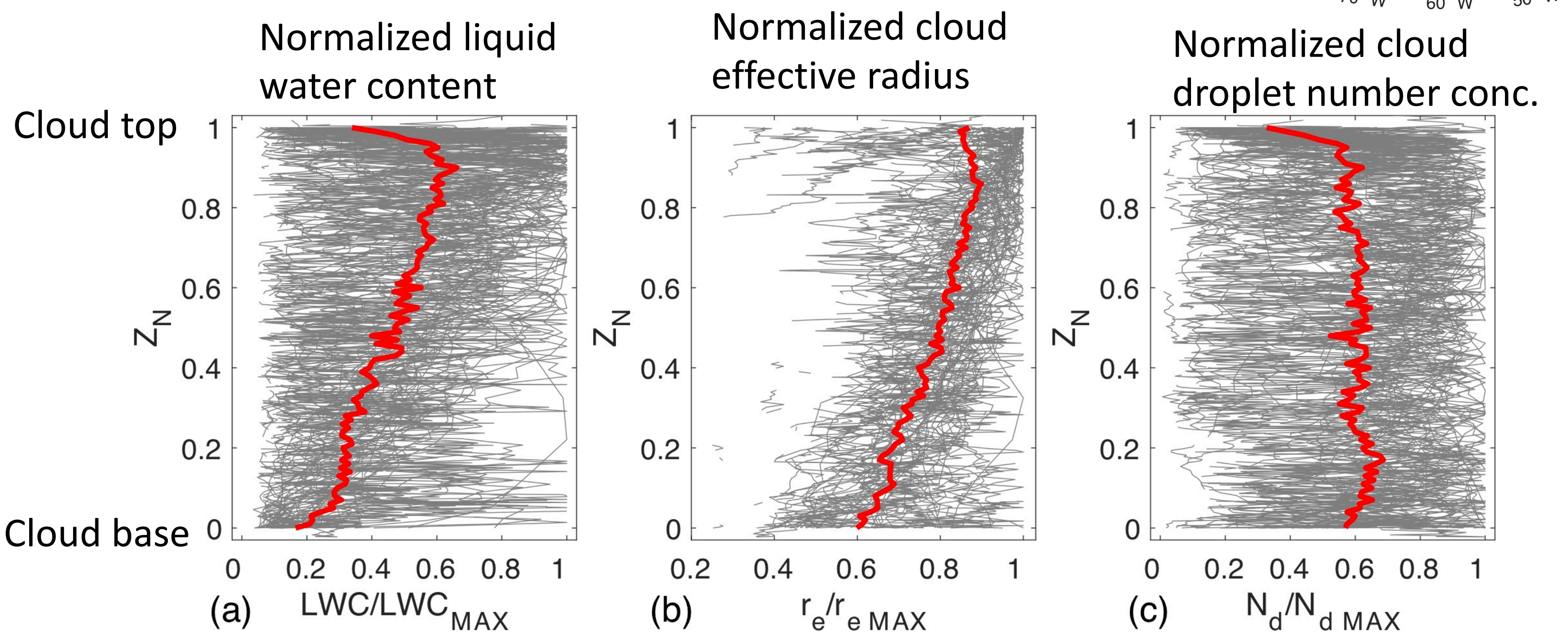
Concluding remarks for ORACLES analysis

- Satellite cloud retrievals reproduce the microphysical transitions observed in open cells.
- The substantial increase in r_e (up to 30 μm) for open cell regions is validated with airborne polarimetric observations (transition is not drive by 3D radiative transfer effects).
- r_e and $\boldsymbol{\tau}$ correlate well with airborne retrievals for cloud fraction > 0.3 (30%).

MODIS/GOES evaluation in midlatitudes

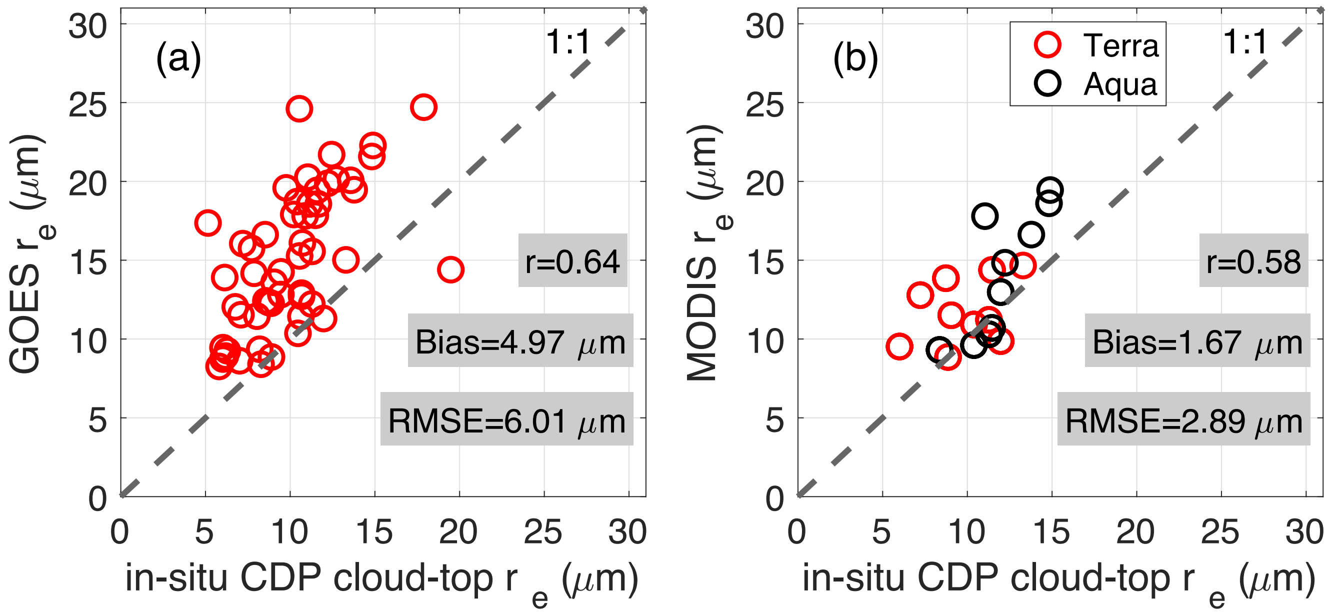
- NAAMES observations collected during three campaigns: Nov 2015, May 2016, Sept 2017, north of 40˚N.
- Overcast scenes
- Warm and supercooled boundary layer clouds





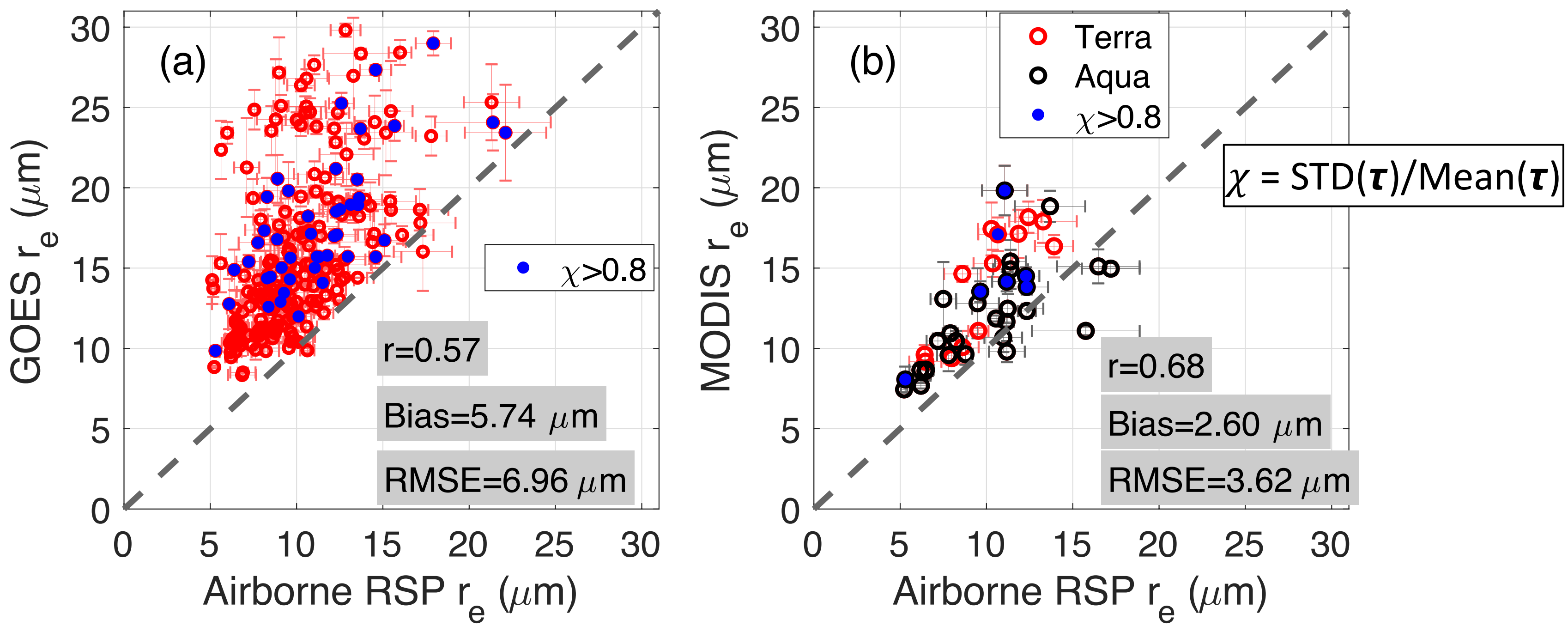
Evaluation of GOES-13 and MODIS against NAAMES in-situ data

- Assessment of GOES and MODIS cloud effective radius against their cloud top counterpart from the in-situ Cloud Droplet Probe (CDP)



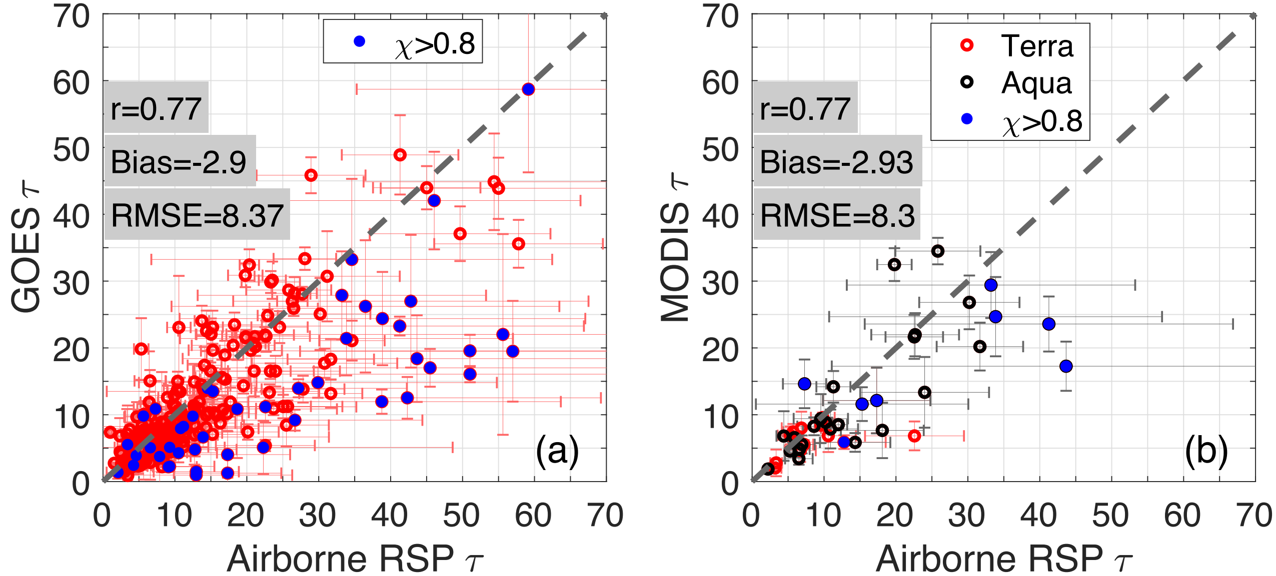
- Both GOES and MODIS overestimates the in-situ r_e.
- GOES bias is more than twice that for MODIS.

Evaluation of GOES-13 and MODIS r_e against NAAMES airborne RSP r_e



- Positive bias for both satellite instruments, with larger biases for GOES-13 (consistent with the in-situ comparison).
- Bias in heterogenous cloud scenes (blue circles) is not statistically different from the rest of the dataset.

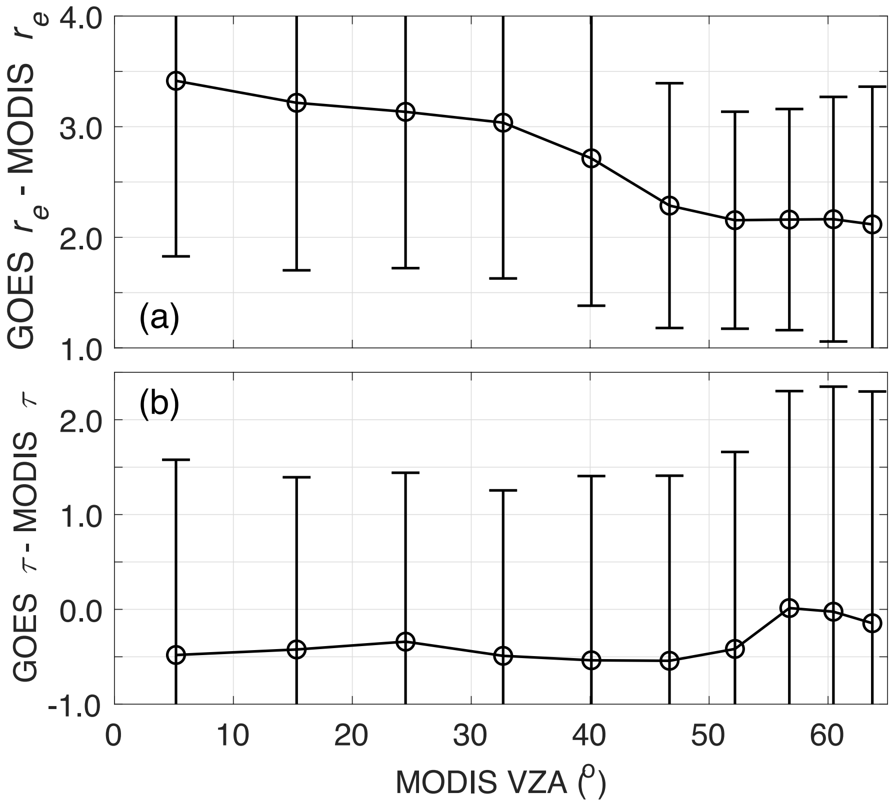
MODIS/GOES optical depth (τ) evaluation against RSP τ



- Nearly identical negative bias for GOES-13 and MODIS
- Negative bias is primarily explained by spatial (subpixel) heterogeneity effects (blue circles).

Discrepancies between GOES and MODIS

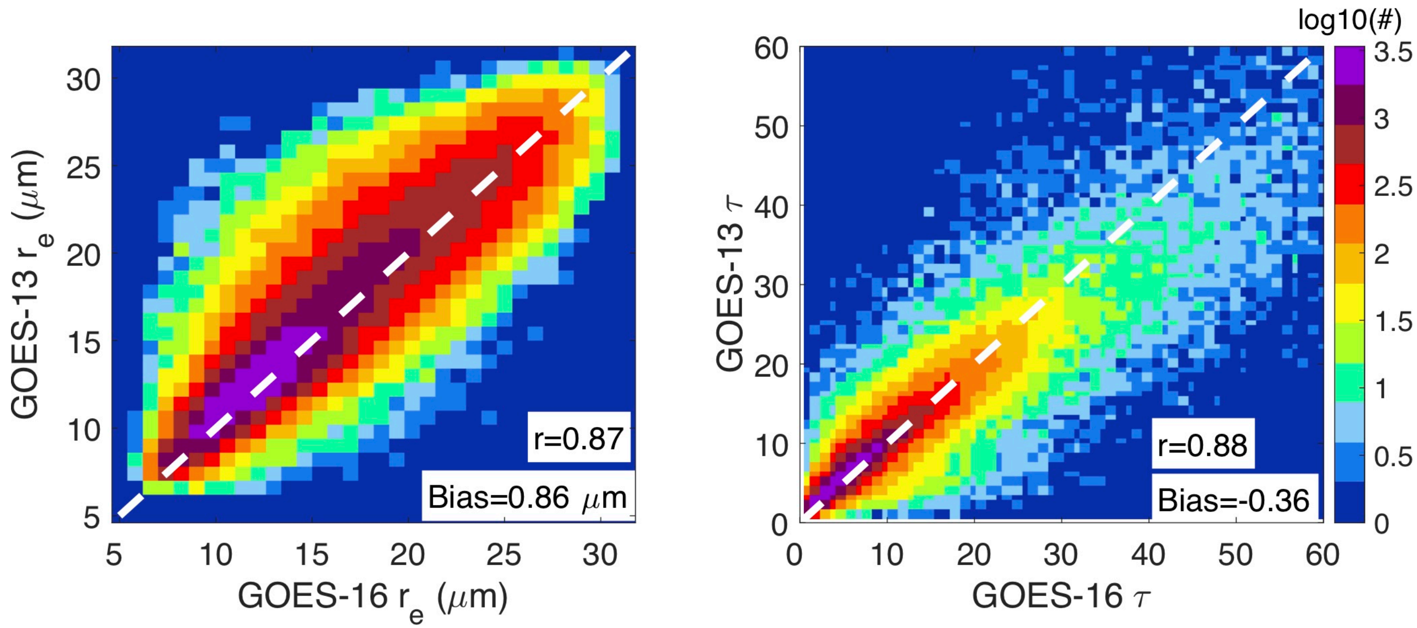
- An important discrepancy source is the viewing zenith angle (VZA):
  - NAAMES domain was close to GOES-13 scan edge, (VZA)~ 65˚
  - Sun-synchronous operation of Aqua/Terra implies that viewing geometry is variable.
- To address the VZA effect we intercompare MODIS and GOES as a function of MODIS VZA:



- Retrievals compare better when GOES and MODIS VZA are similar.
- However, a r_e difference of at least 2.0 μm persists when comparing GOES and MODIS with similar VZA (GOES>MODIS).
- Inconsistency between GOES r_e and airborne data is not fully explained by the edge-of-the-scan effect.

Could we get better agreement if we had used GOES-16 instead of GOES-13?

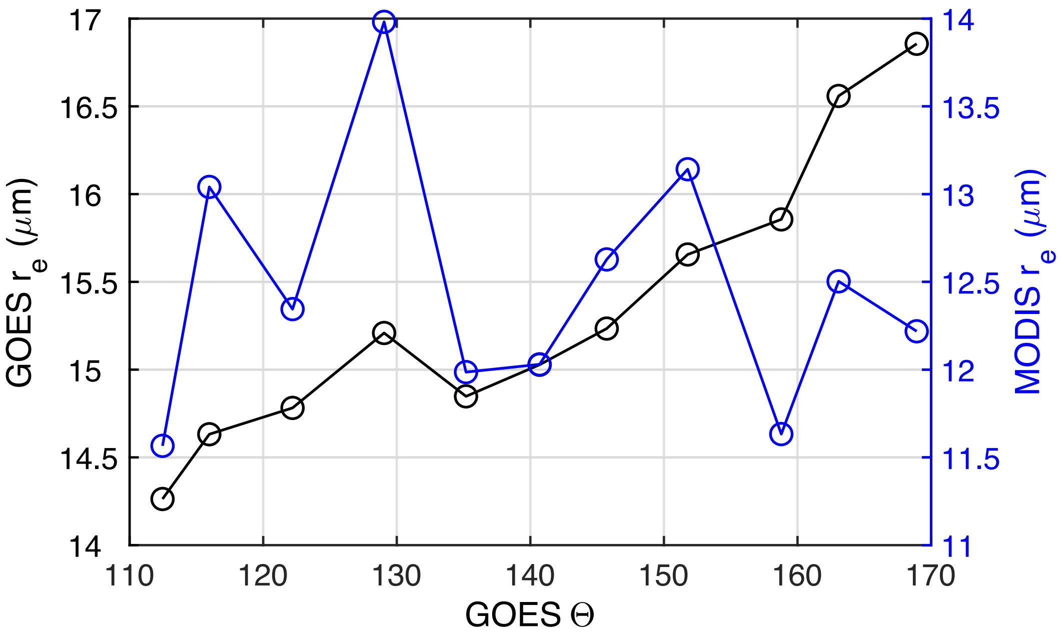
- Rather than comparing GOES-16 with NAAMES aircraft data, we intercompare both GOES-13 and GOES-16 retrievals during November 2017.



- GOES-16 τ > GOES-13 τ, GOES-16 r_e< GOES-13 r_e . Results qualitatively consistent with pixel resolution effects.
- Comparison suggests that **GOES-16 would agree better with the aircraft data than GOES-13**
- However, the large positive bias for r_e would persist.

Discrepancy: Satellite scattering angle

- We found that the effect of VZA and pixel resolution cannot fully explain the GOES-13 r_e positive bias.
- We also take at look at GOES scattering angle ($\boldsymbol{\Theta}$). $\boldsymbol{\Theta}$ provides information about the cloud sides: shadow and illuminated side.



- As expected, GOES $\boldsymbol{\Theta}$ is unrelated to changes in MODIS r_e.
- Interestingly, GOES r_e increases with $\boldsymbol{\Theta}$. I.e. GOES r_e increases toward the backscattering scattering direction.

Concluding remarks for NAAMES

- MODIS r_e and τ compare well with in-situ and airborne RSP data
  - Bias in τ largely explained by spatial heterogeneity effects
  - Positive bias of MODIS r_e, in agreement with previous assessments in the subtropical Pacific.
- GOES-13 correlate well with the airborne data
- A large positive bias in GOES-13 r_e is in part the effect of high VZA and pixel resolution.
- Intriguing relationship between GOES-13 r_e and scattering angle: r_e increases toward the forward scattering direction.
- The dependence on scattering angle appears to be unrelated to the illumination effect expected toward the forward scattering.
- Work by Arduini et al. (2005) and Benas et al. (2019) indicate that r_e is sensitive to the shape of the droplet size distribution near the rainbow and glory.
- In-situ observation shows that the effective variance of the DSD is smaller than that used in the retrieval algorithm.
- Future work will explore the sensitivity of the retrievals to changes in effective variance for forward scattering angles.

Summary (ORACLES+NAAMES)

- We assessed CERES/SatCORPS cloud retrievals in challenging conditions:
  - Heterogeneous clouds, high SZA, edge of the scan
- **Good news:**
  - Spatially variability of r_e and τ in broken scenes are properly captured by the satellite retrievals in the subtropics.
  - MODIS retrievals in high latitudes are comparable to other studies in the subtropics.
- **Complicated news:**
  - We identified large r_e biases in geostationary retrievals near the edge of the scan and for backscattering angles.
  - The overestimation is not entirely explained by VZA and pixel resolution effects.
  - Increase of r_e with satellite scattering angle needs more analysis.
  - **Future uncertainty analysis of geostationary cloud retrievals will provide insight into the viewing geometry effects and will evaluate possible methods to remediate systematic biases.**

  - NAAMES comparison to be submitted to JGR in May.
  - ORACLES analysis to be submitted as an ORACLES overview paper or standalone work (GRL).

Extra slides

NAAMES Cloud vertical structure overview

- NAAMES observations collected during three campaigns: Nov 2015, May 2016, Sept 2017
- Warm and supercooled boundary layer clouds