Advanced cloud products from the NASA PACE mission and their relevance for other missions

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Netherlands Institute for Space Research

NASA

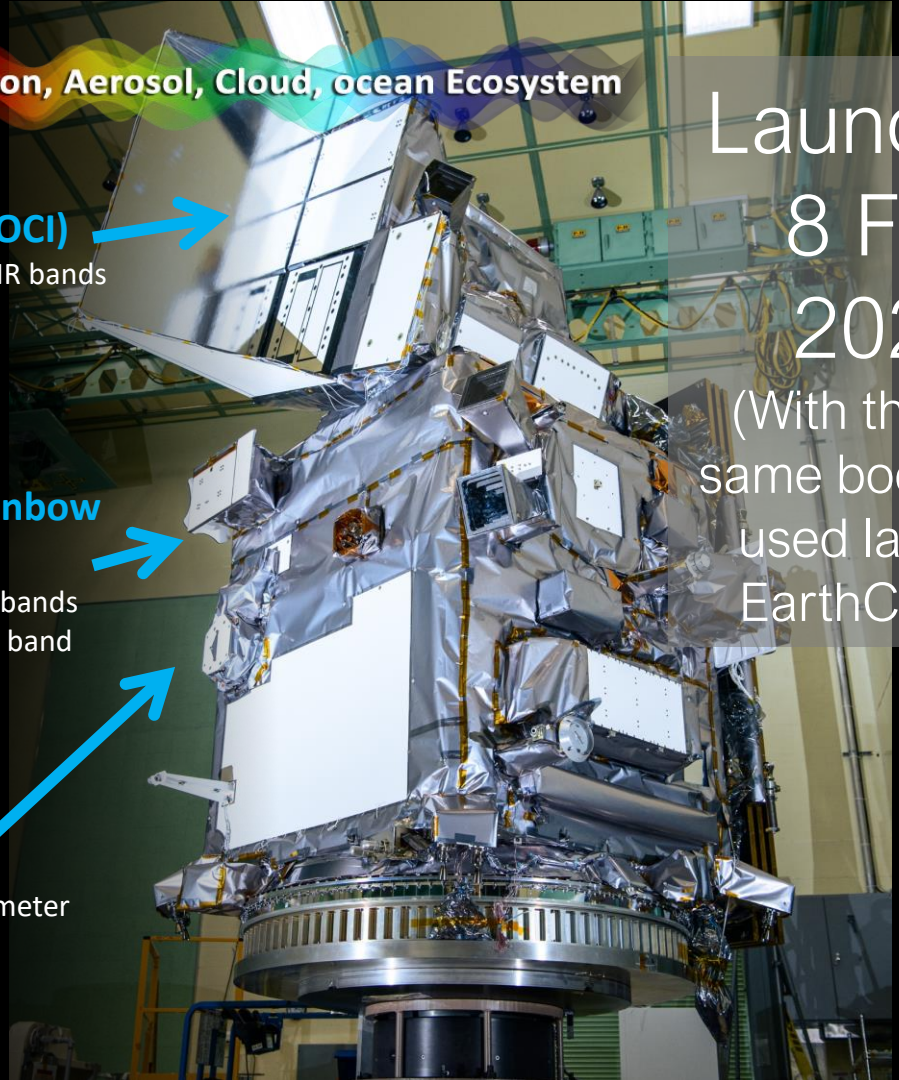
AIRSENSE

CleanCloud

Netherlands Organisation for Scientific Research (NWO)

PACE

Plankton, Aerosol, Cloud, ocean Ecosystem



Ocean Color Imager (OCI)

UV-NIR hyperspectral + 7 SWIR bands
~1 km resolution

Hyper angular Rainbow Polarimeter (HARP2)

Multi-angle polarimetry in VIS 3 bands
+ hyper-angular polarimetry in 1 band
~5 km resolution

SPEXone

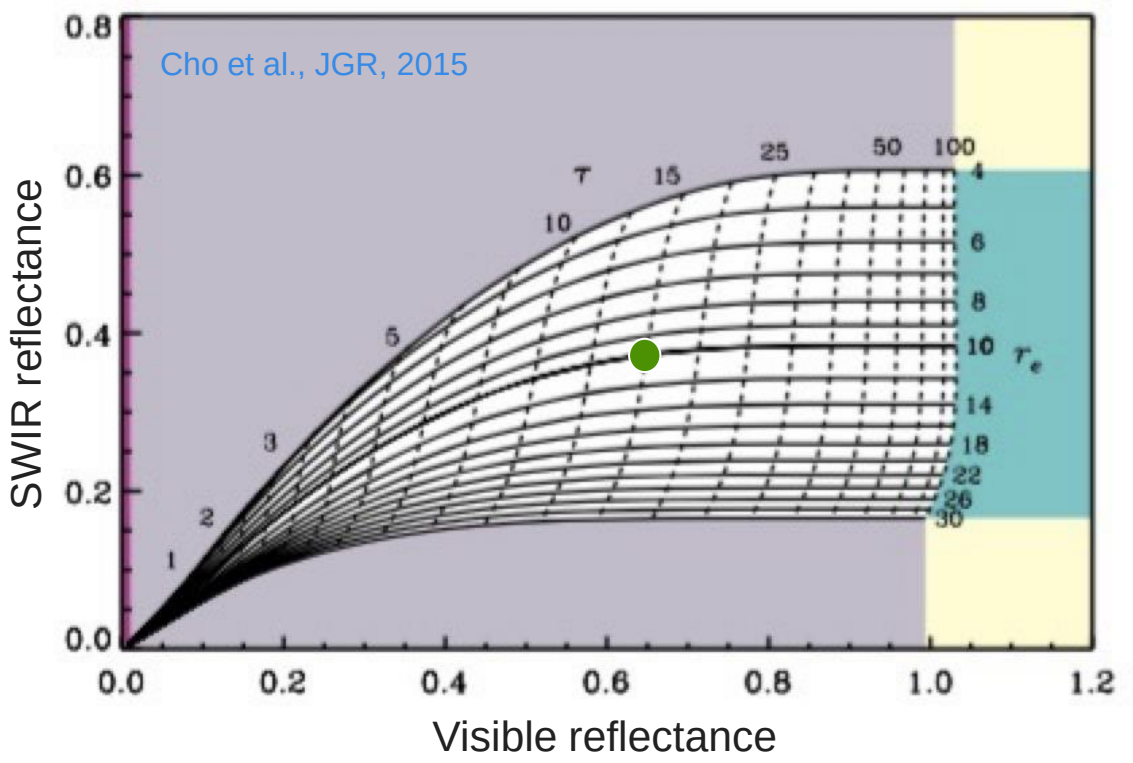
UV-NIR hyperspectral polarimeter
5 viewing angles
~5 km resolution

Launched 8 Feb 2024

(With the very same booster as used later for EarthCARE!)

Cloud product	OCI	HARP-2	SPEXone
Detection	Implemented	Planned later	Implemented
Cloud top height	Implemented (O2 A band)	Possibly later	Ongoing (apparent pressure O2 A band)
Cloud top phase	Implemented (SWIR)	Ongoing	N/A
Cloud optical thickness	Implemented (VIS)	Not planned	Not planned
Particle effective radius (liquid/ice)	Implemented (SWIR)	N/A	N/A
Polarimetric drop effective radius and variance	N/A	Ongoing	Possibly later
Ice crystal shape and scattering properties	N/A	Planned later	Possibly later
Drop number concentrations	Not planned	Ongoing (OCI+HARP2)	Possibly later
Cloud water path	Implemented	Ongoing (OCI+HARP2)	Possibly later

OCI bi-spectral cloud optical thickness and effective radius retrievals: MODIS heritage code

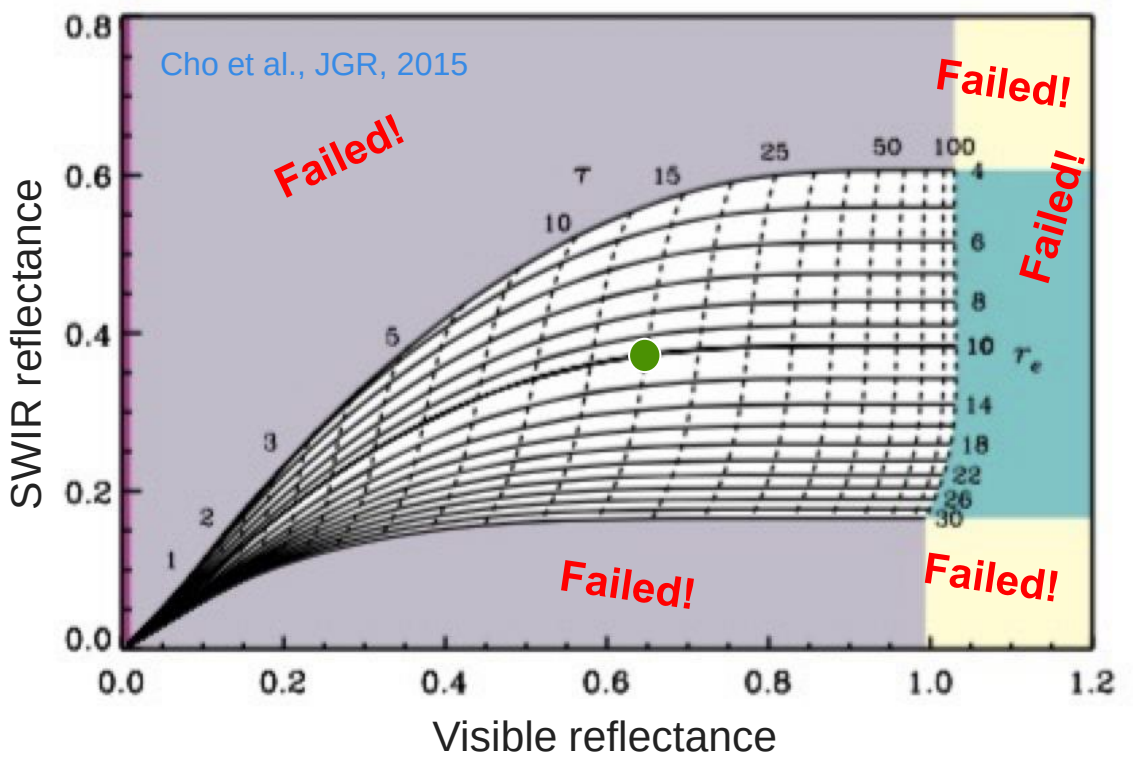


OCI SWIR bands:
1.6 µm
2.13 µm
2.25 µm

Overlapping with:
MODIS
VIIRS
MSI- EarthCARE
SEVIRI
FCI, AHI, ABI,
……

OCI bi-spectral cloud optical thickness and effective radius retrievals: MODIS heritage code

Globally 16% MODIS retrievals fail; locally >40%



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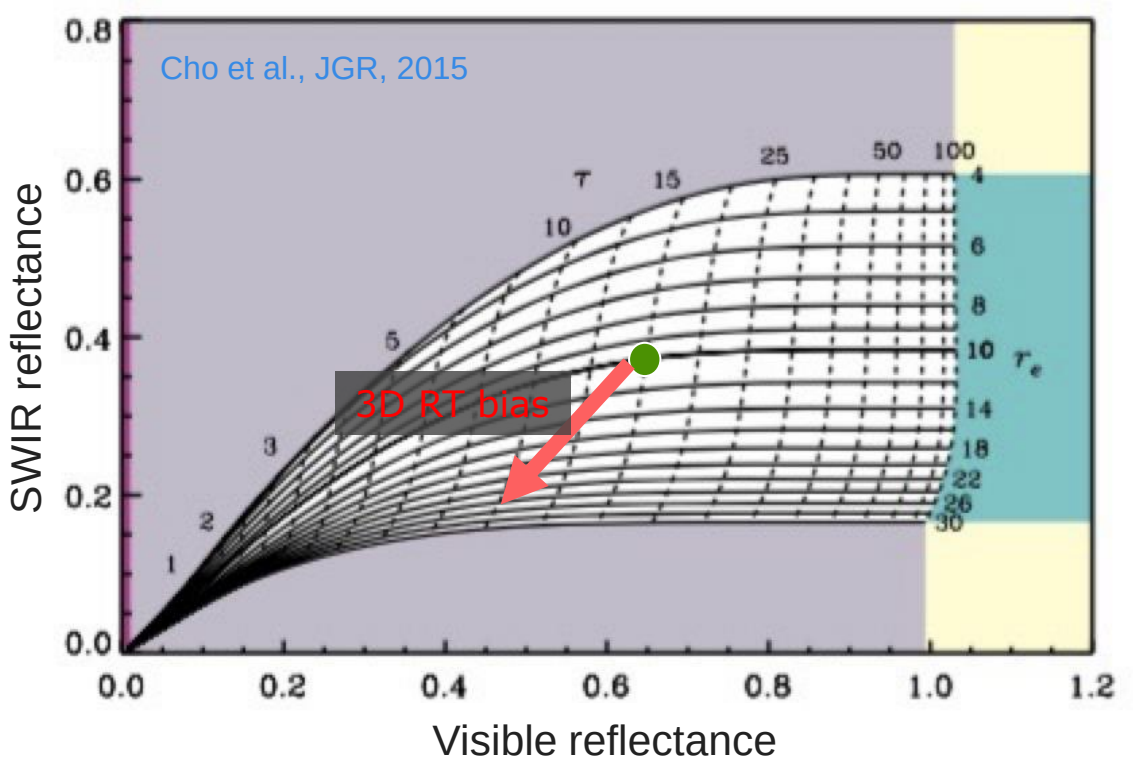
OCI bi-spectral cloud optical thickness and effective radius retrievals: MODIS heritage code

DiGirolamo et al, 2010:

Globally only 24% of MODIS observation comply with 1D assumption; locally ~0%

3D effects depend on wavelength



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……

Hyperangular polarimetric cloudbow retrievals of drop size distribution

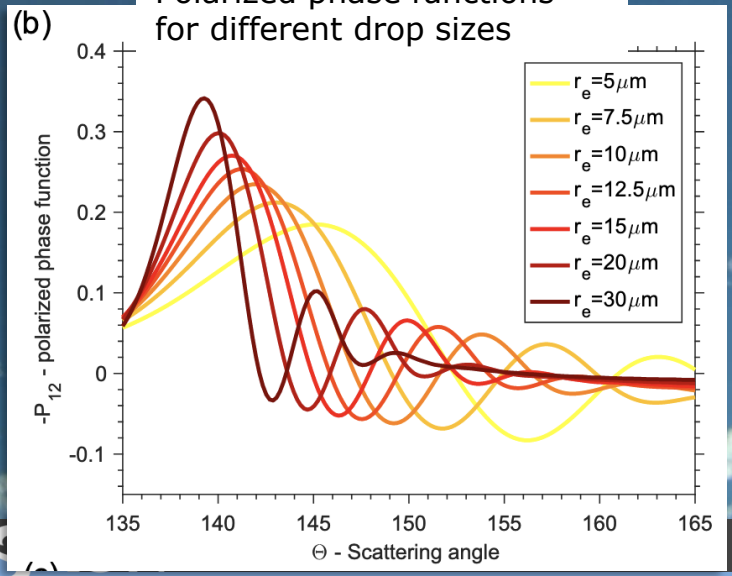
2020–02–13 12:31:22.458

specMACS
on HALO aircraft
(DLR/LMU)

Total reflectance

Polarized reflectance

Polarized phase functions for different drop sizes

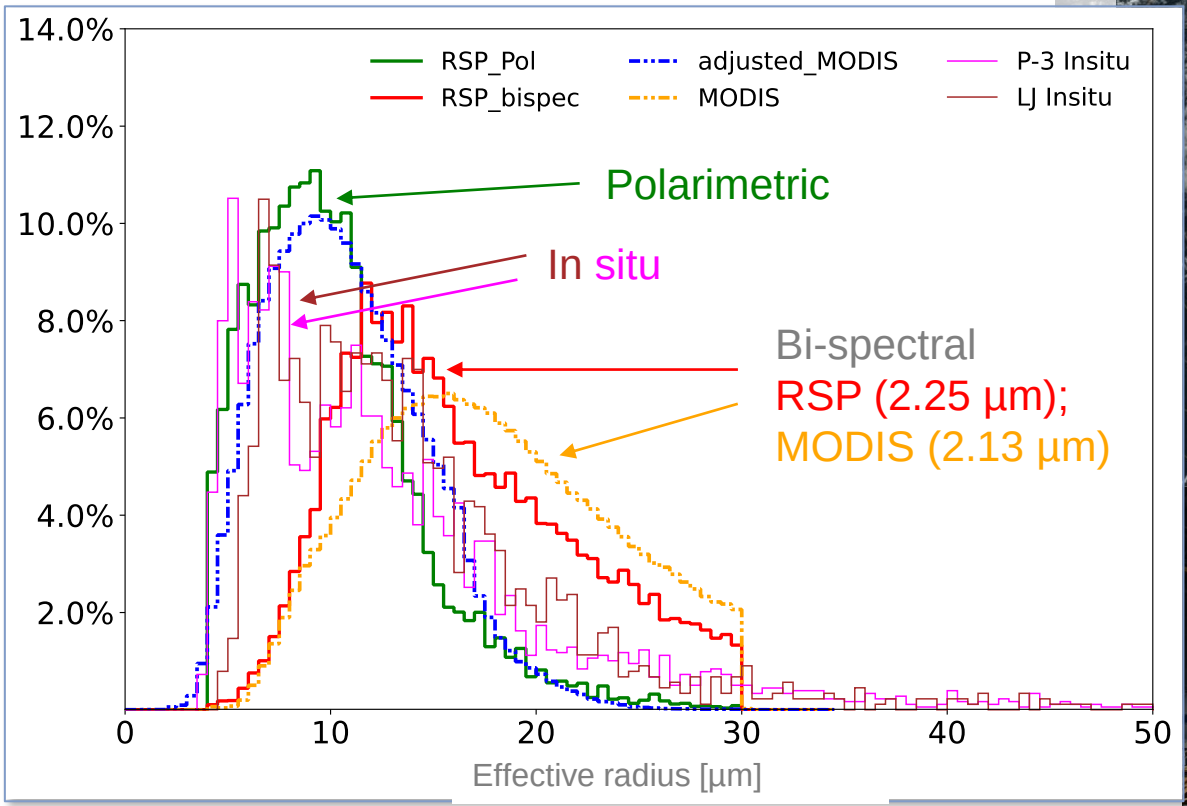


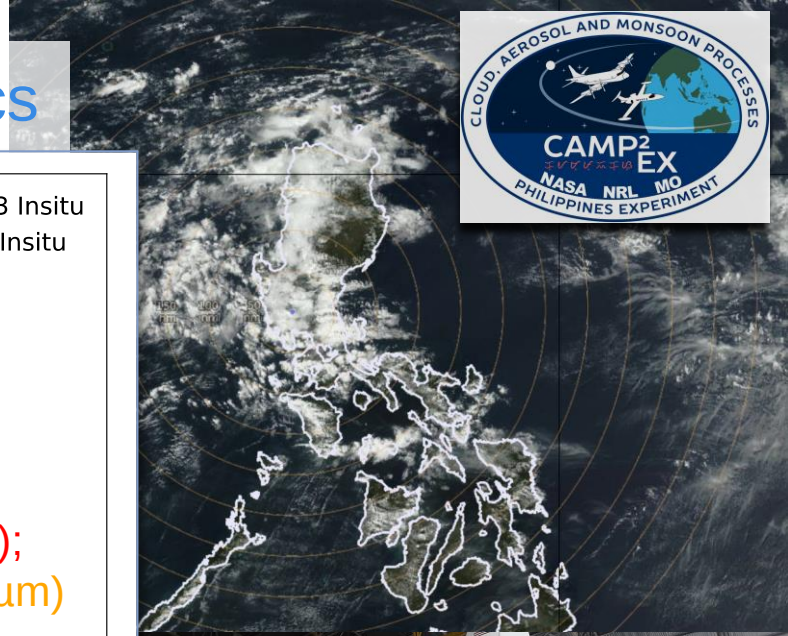
- Very simple retrievals only using Mie calculations and *relative* measurements
- Accurate for broken, small and/or inhomogeneous clouds, mixed-phase, etc.
- Needs hyper-angular (~2°) observations resolving cloud bow structure

HARP-2 polarimetric algorithm heritage: Airborne Research Scanning Polarimeter (RSP)

- **Polarimetric** drop size distributions
- Also **Bi-spectral** effective radius
  - 1.64 µm
  - 2.25 µm
- SPEXone-like aerosol products
- Many, diverse campaigns

CAMP²Ex RSP effective radius statistics





(From Fu et al. ACP 2022)

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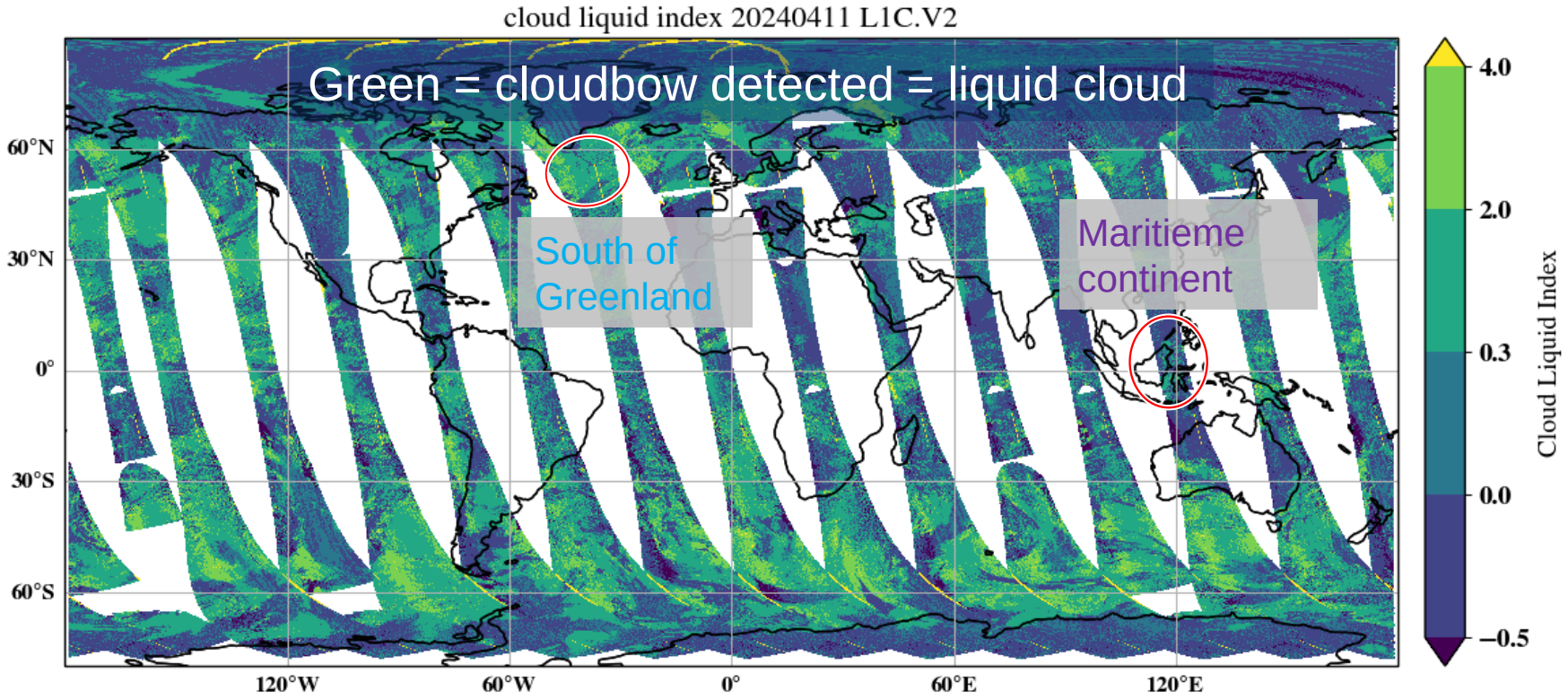
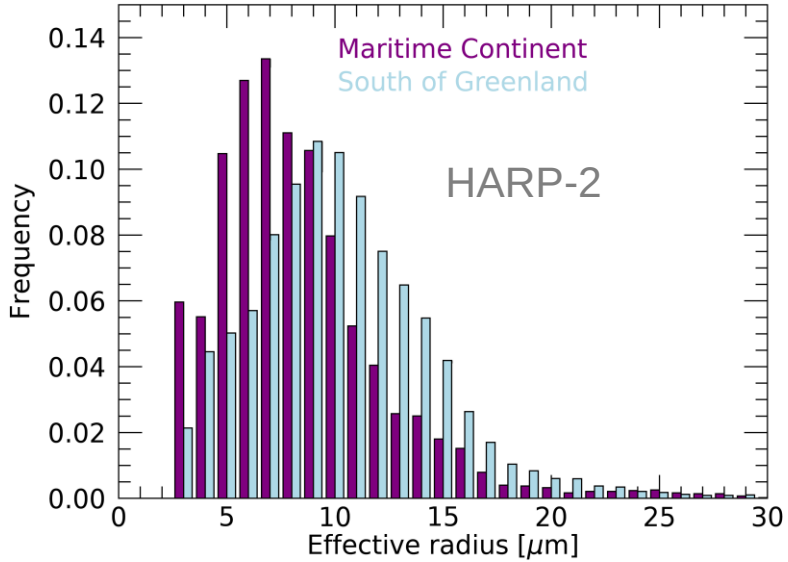
HARP-2 Liquid index (van Diedenhoven et al., JAS, 2012)



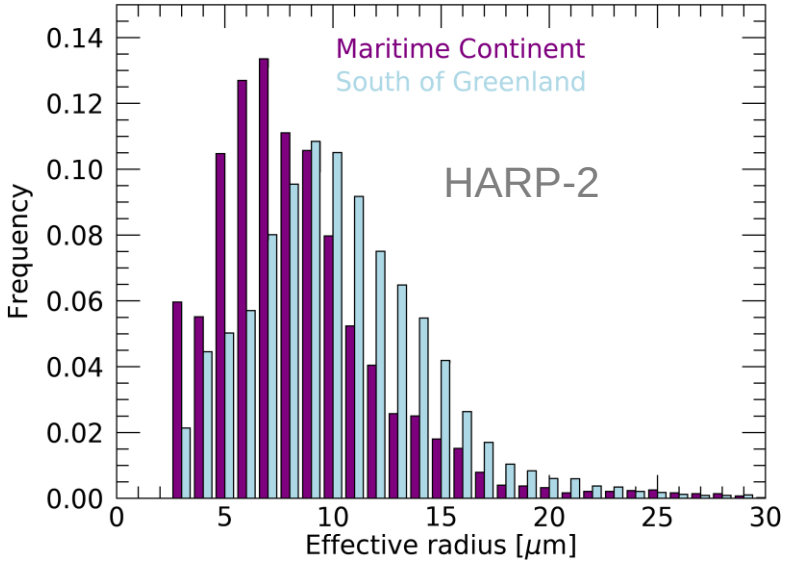
HARP-2 polarimetric drop effective radius retrievals

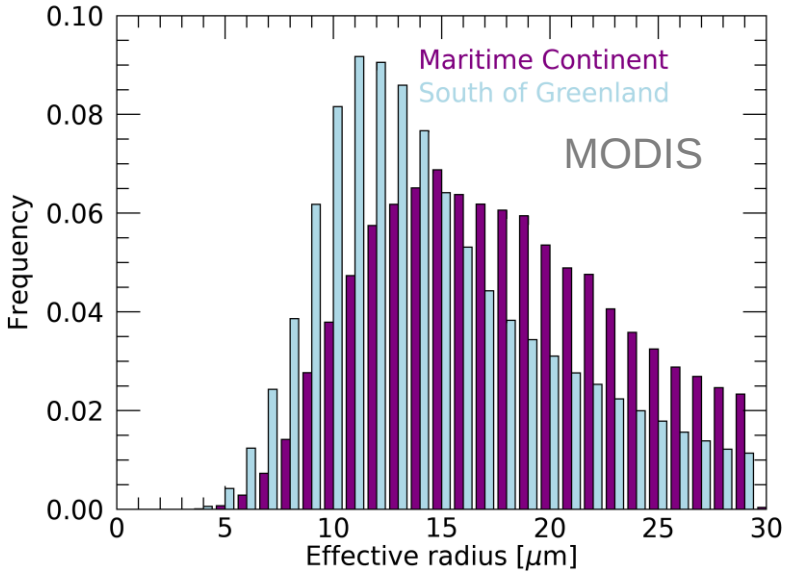
- HARP-2 5x5 km^2 pixel-level retrievals
- HARP-2 gets smaller drops at Maritime cont. compared to South Greenland
- Consistent with Maritime continent being more polluted



HARP-2 polarimetric drop effective radius retrievals

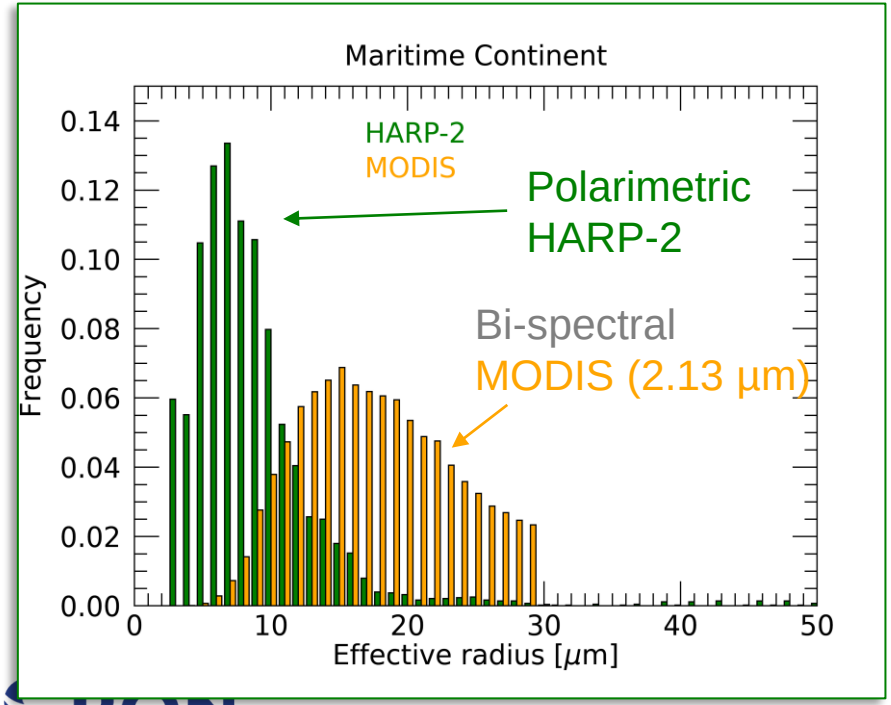
- MODIS bi-spectral (2.13 um) shows larger effective radius than HARP-2
- MODIS bias is especially large at Maritime continent

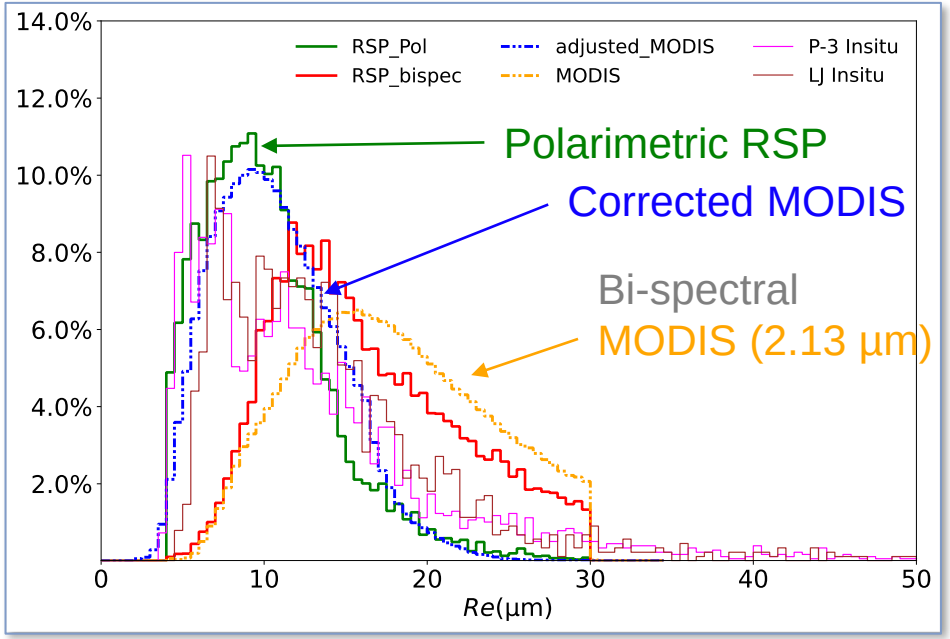




HARP-2 polarimetric drop effective radius retrievals

HARP-2 effective radii and difference with MODIS are similar to those seen in this region during CAMP2Ex

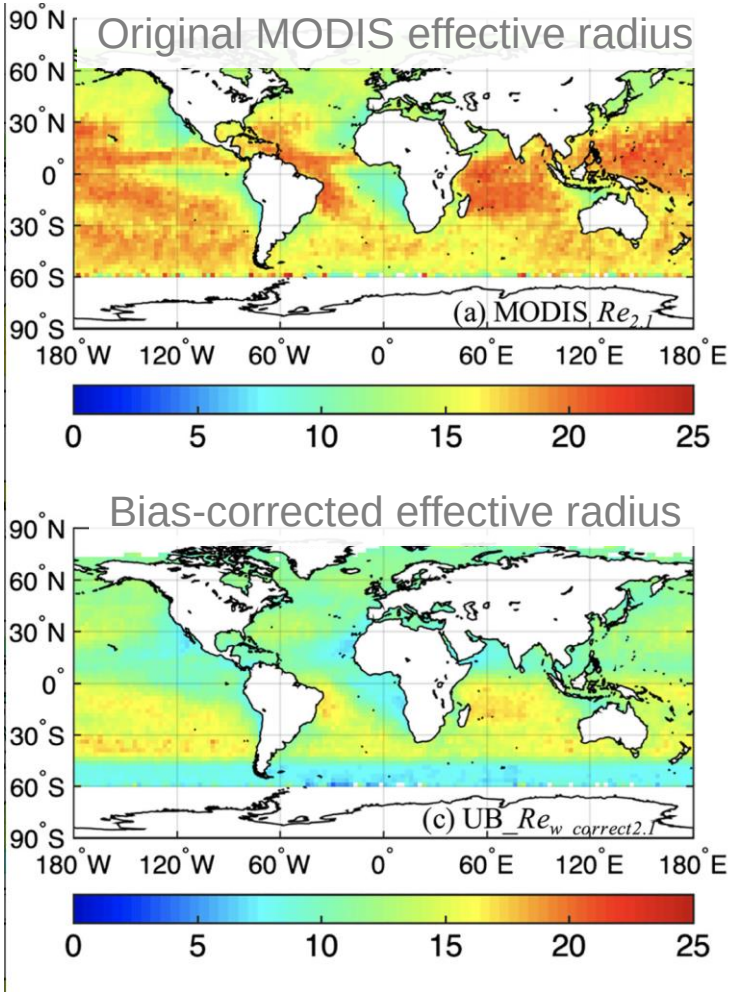




(From Fu et al. ACP 2022)

PACE HARP-2 and OCI

- Fu et al., JGR 2019: MODIS Bi-spectral correction factors
  - based on multi-angle data (MISR)
  - As function of location, solar-viewing geometry, inhomogeneity metrics
- PACE provides opportunity to
  - evaluate corrections
  - expand to land and other SWIR bands
  - make them applicable to essentially any other multi-spectral imager



Recommendations

- Invest in satellite studies on cloud microphysical processes
  - Synergy of multiple observations
  - Model-data integration
  - Instrument concepts
- Explore cloudbow retrievals application to CO2M-MAP (+CLIM+COI2 SWIR)
- Explore high resolution (~50 m) multi-angle cloud polarimetry for cloud 3D shape and microphysical process studies

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Conclusion and Outlook

- First HARP-2 pixel-level polarimetric drop size retrievals promising
- OCI cloud products expected this month; HARP-2 products later this year
- HARP-2 products to evaluate and expand bi-spectral bias corrections for essentially all multi-spectral imagers
- PACE cloud *and* aerosol products to be used in EC CleanCloud project to evaluate aerosol-cloud interactions and improve models
- PACE cloud and aerosol to be validated with PACE-PAX and ORCHESTRA
- Cloudbow retrieval may also be applicable to CO2M-MAP!

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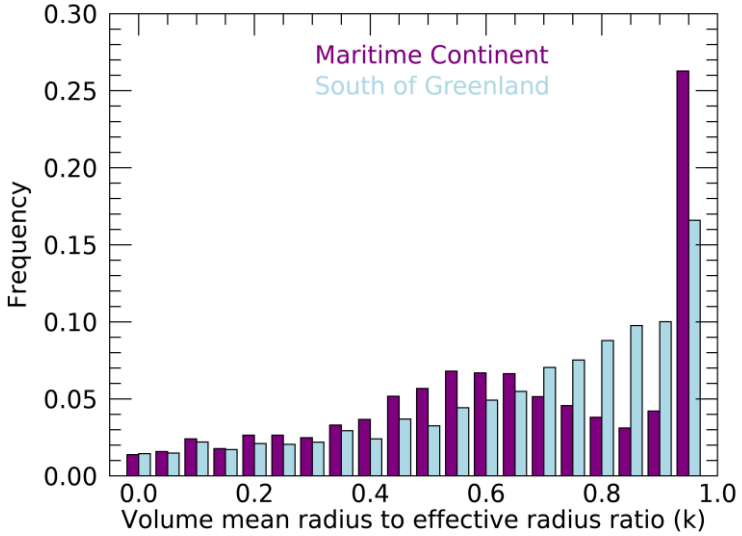
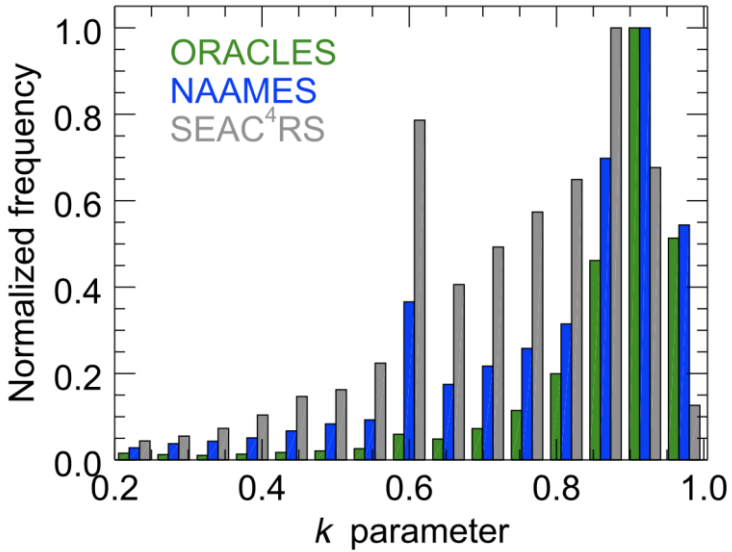
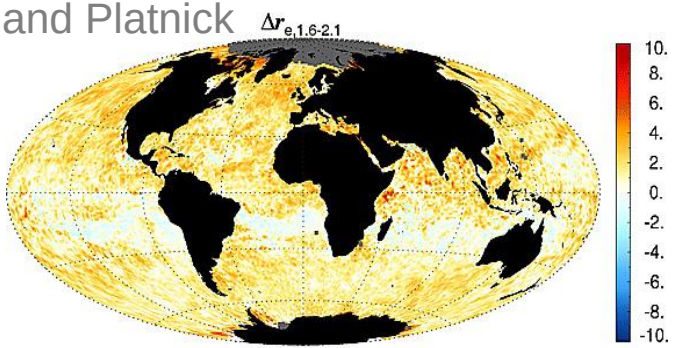
Retrieval of drop size distribution effective variance (V_{eff})

- V_{eff} values converted to k parameter look reasonable and comparable to RSP results (Grosvenor et al. 2018) with peak near 1.

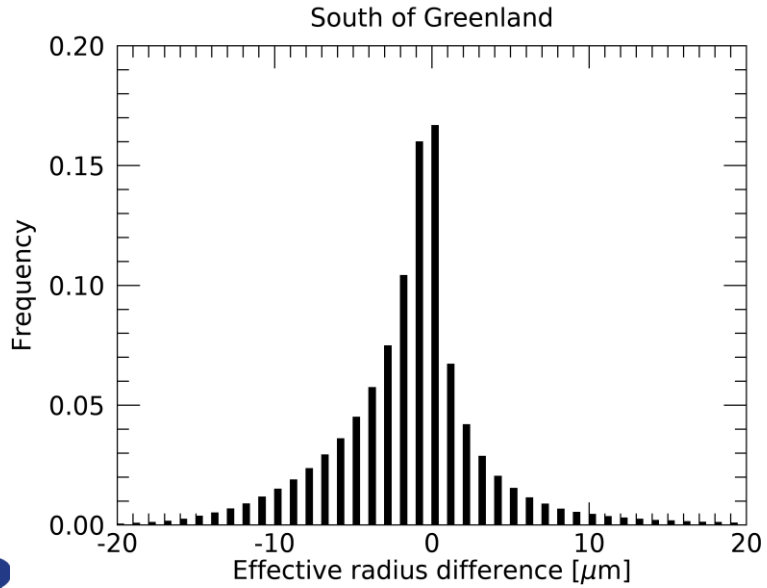


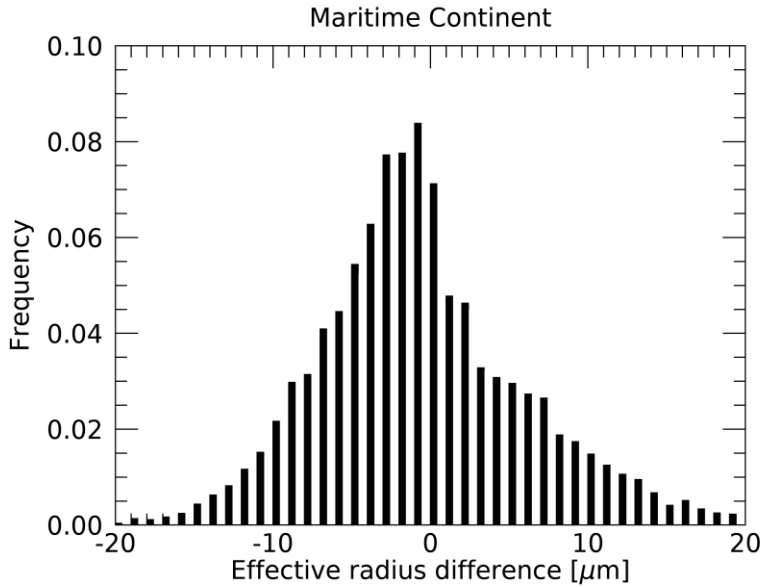


Zhang and Platnick



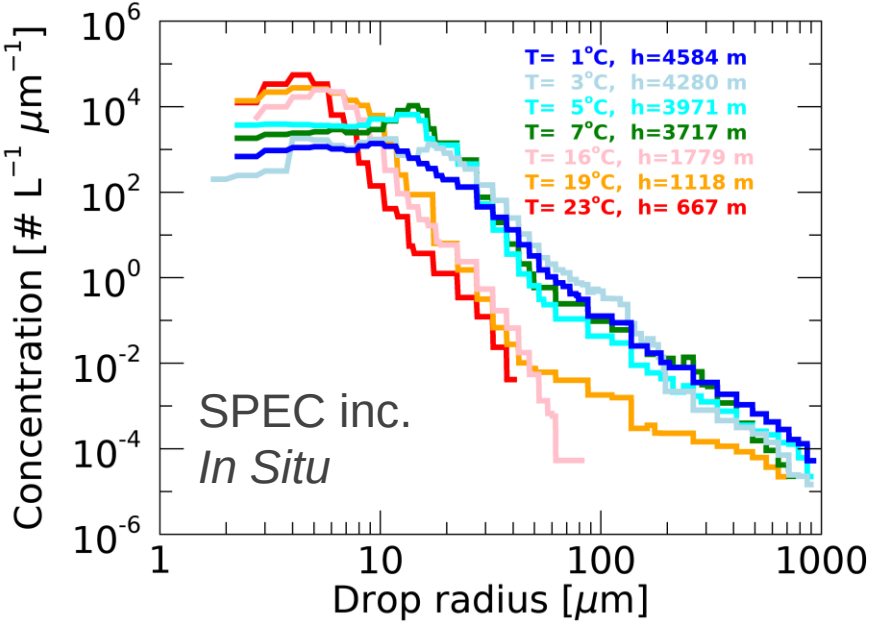
- MODIS [2.13 um -1.64 um] difference is larger for MC, as expected if 3D effects are an issue. Most of the time 2.13 < 1.64



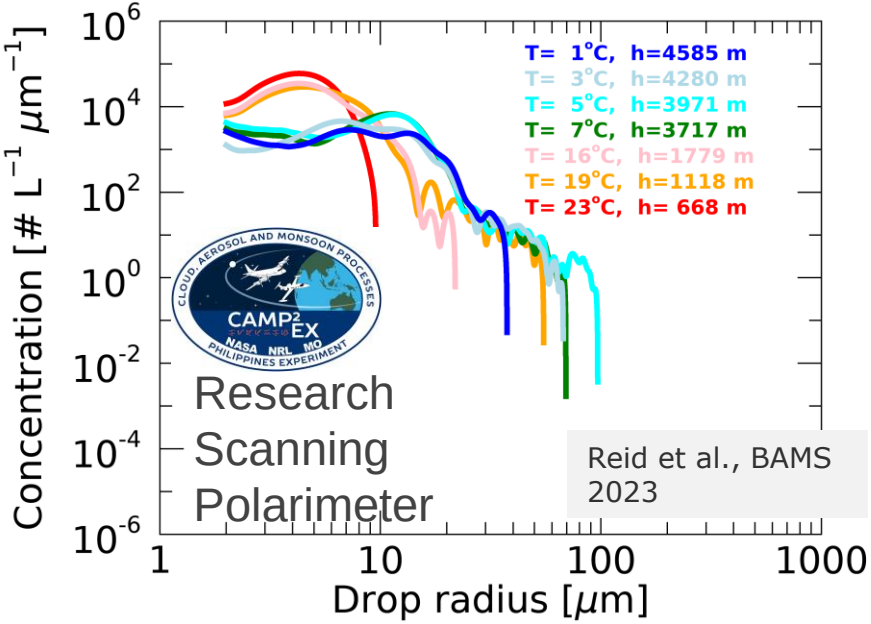


Remote sensing of full droplet size distributions using "Rainbow Fourier Transform" method (Alexandrov et al. 2012)

Average *in situ* size distributions for various flight altitude bins



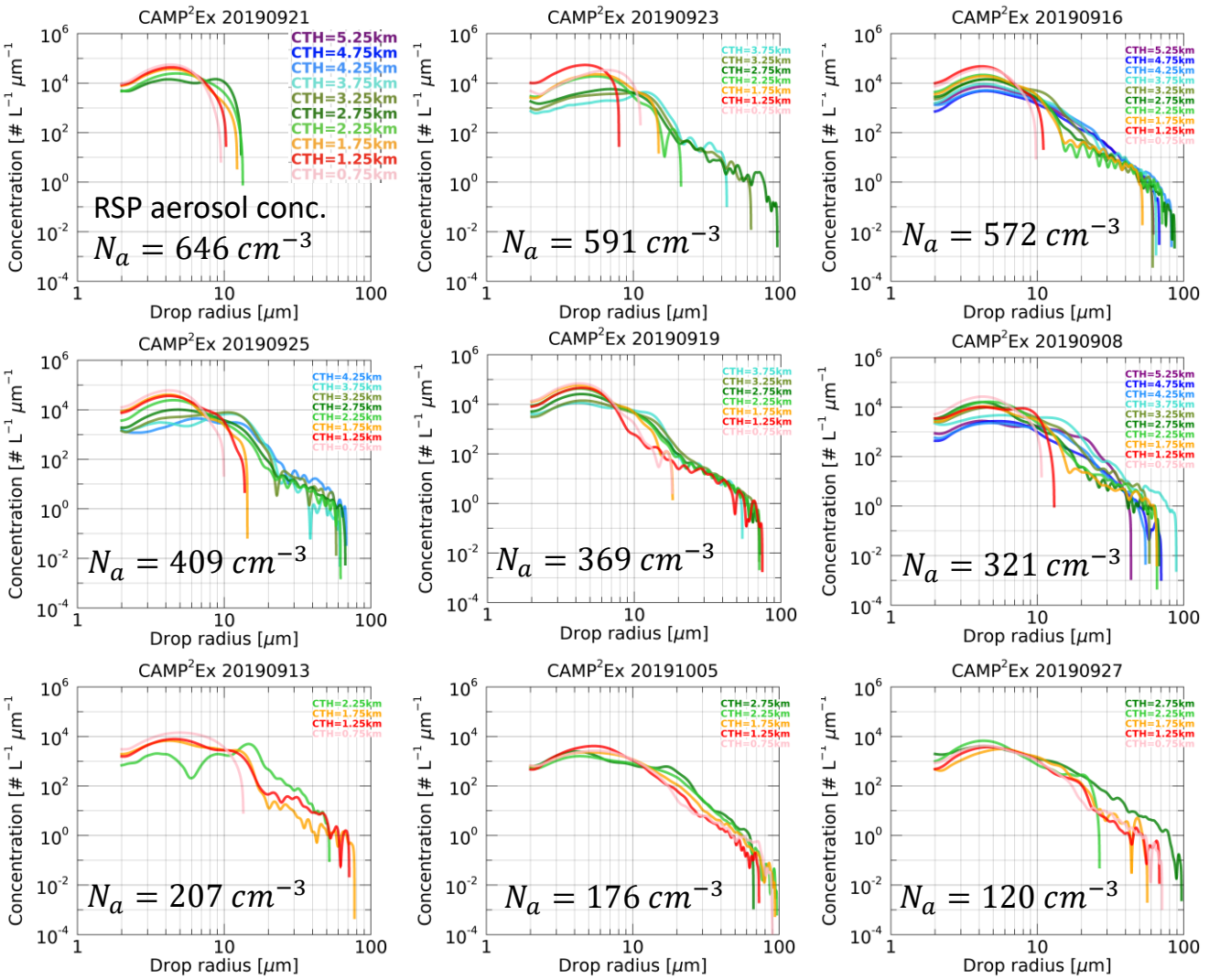
Average RSP size distributions for various cloud top height bins



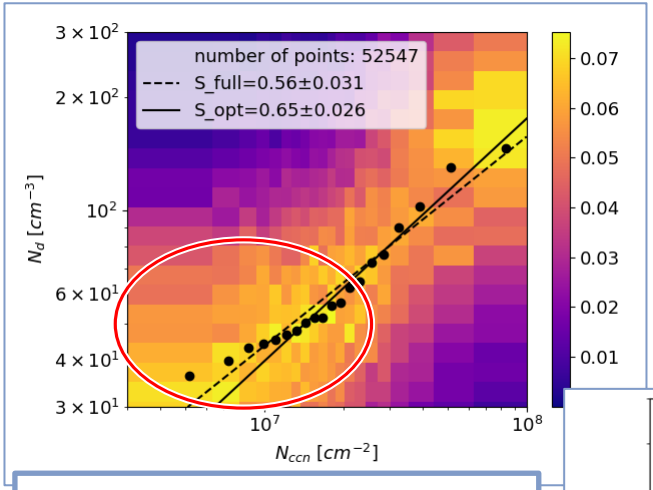
Droplet size distribution development in various aerosol conditions

- N_a = aerosol concentration from RSP in surrounding air
- Each panel shows results for given day, ordered by N_a

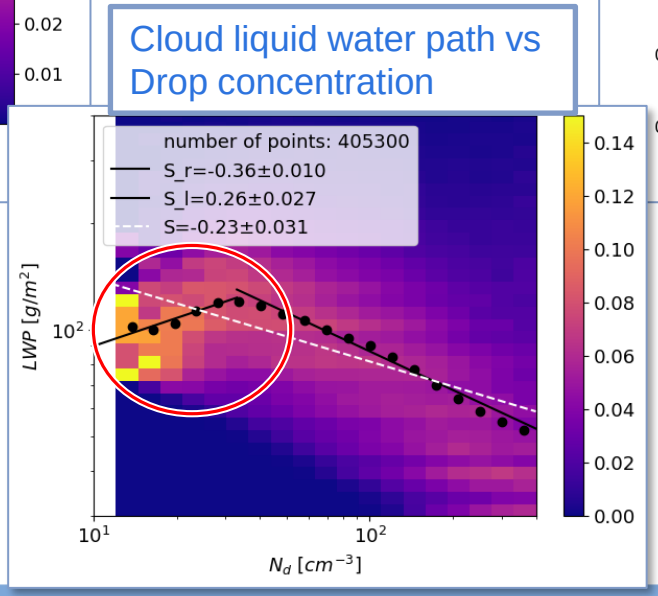
- Large drop mode develops as clouds grow
- Appearance of large drop mode at lower height for low N_a



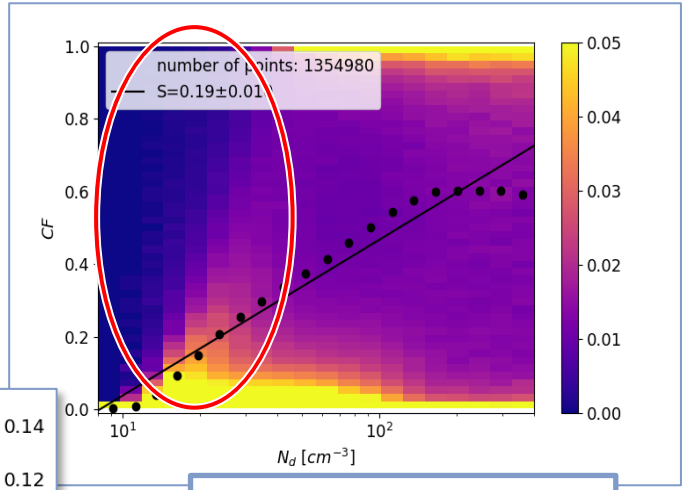
Aerosol-cloud interactions + adjustments



Drop concentration vs cloud condensation nuclei column number concentration



Cloud liquid water path vs Drop concentration



Cloud fraction vs Drop concentration

Using 1-year of MODIS + POLDER data. Work by Willem Kroese (TU Delft/Utrecht), based on Hasekamp et al. Nat. comm 2019

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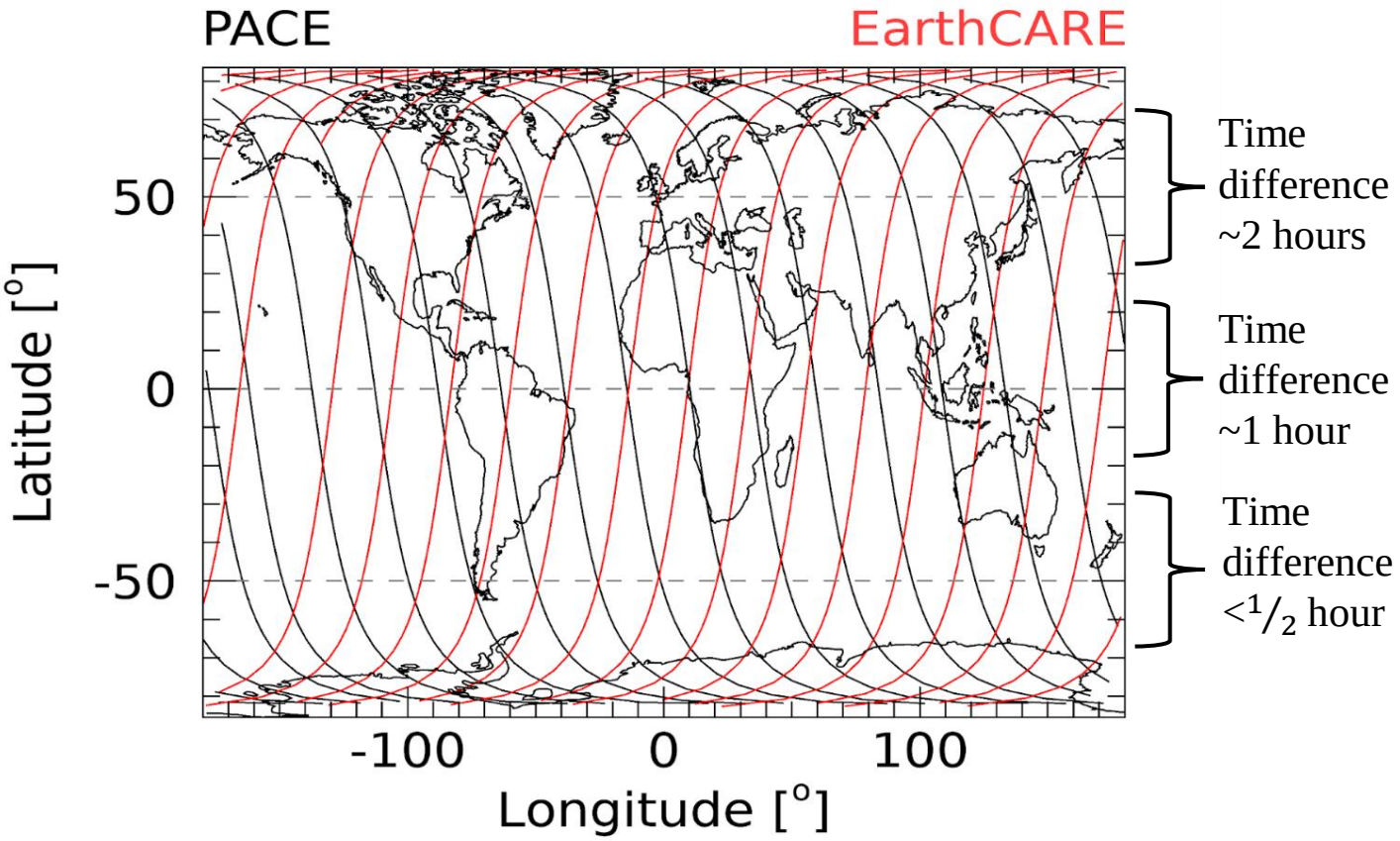
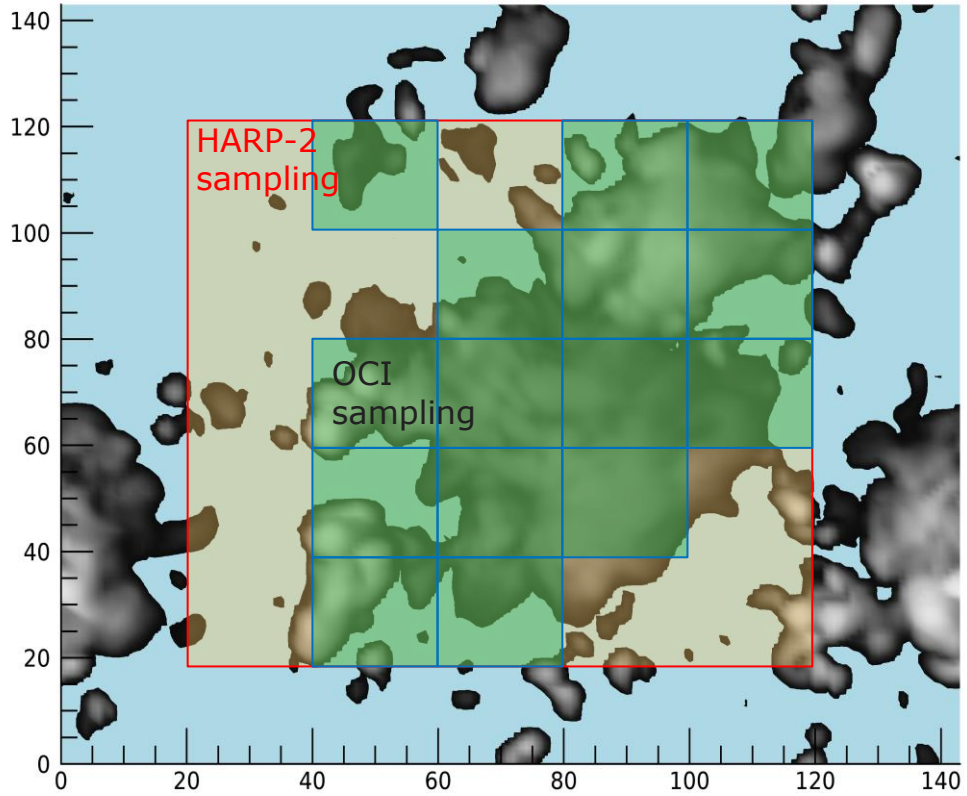

PACE
EarthCARE
50
0
-50
Latitude [°]
-100
0
100
Longitude [°]
Time difference ~2 hours
Time difference ~1 hour
Time difference <1/2 hour

PACE sampling of clouds

- HARP-2 polarimetry:
  - Size distribution for all drops in tops of liquid clouds in 5x5 km^2 field of view
- OCI bi-spectral:
  - Optical thickness of all cloudy 1 km^2 pixels
- Combined:
  - Number concentrations estimate for liquid clouds in 5x5 km^2 pixels

$$N_d = \frac{\sqrt{5}}{2\pi}\left(\frac{f_{ad}\, c_w}{Q_e\, \rho_w}\right)^{1/2}\left(\frac{\tau_c}{k^2\, r_e^5}\right)^{1/2}$$

LES+3D radiative transfer of ~7x7 km^2 field at 50 m resolution



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