Meridional and vertical variations of cloud properties over the Southern Ocean

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Motivation

- Low level cloud is most common over the Southern Ocean
- Low level cloud is very difficult to simulate by models and cause the largest uncertainties in CMIP6 (Zelinka et al., 2020)
- Coexistence of supercooled liquid and ice clouds under relative pristine environments with aerosol-cloud interaction primarily linked to ocean productivity and sea salt production
- Retrieving cloud properties from satellite measurements are complicated, especially difficult under high solar zenith angle

Data and Method

Measurements of Aerosol, Radiation and Cloud over Southern Ocean (MARCUS) during October 2017 to March 2018

- **W-band radar➔cloud profile, H_{top}**
- **MWR → LWP/PWV**
- **Ceilometer –H_{base}**
- **Radiosonde- T_{base}/T_{top}**
- **Navigation-latitude and longitude**
- **Cloud/drizzle particle sizes and number concentration (Wu et al. 2019)**

1-hour averaged centered at overpass time

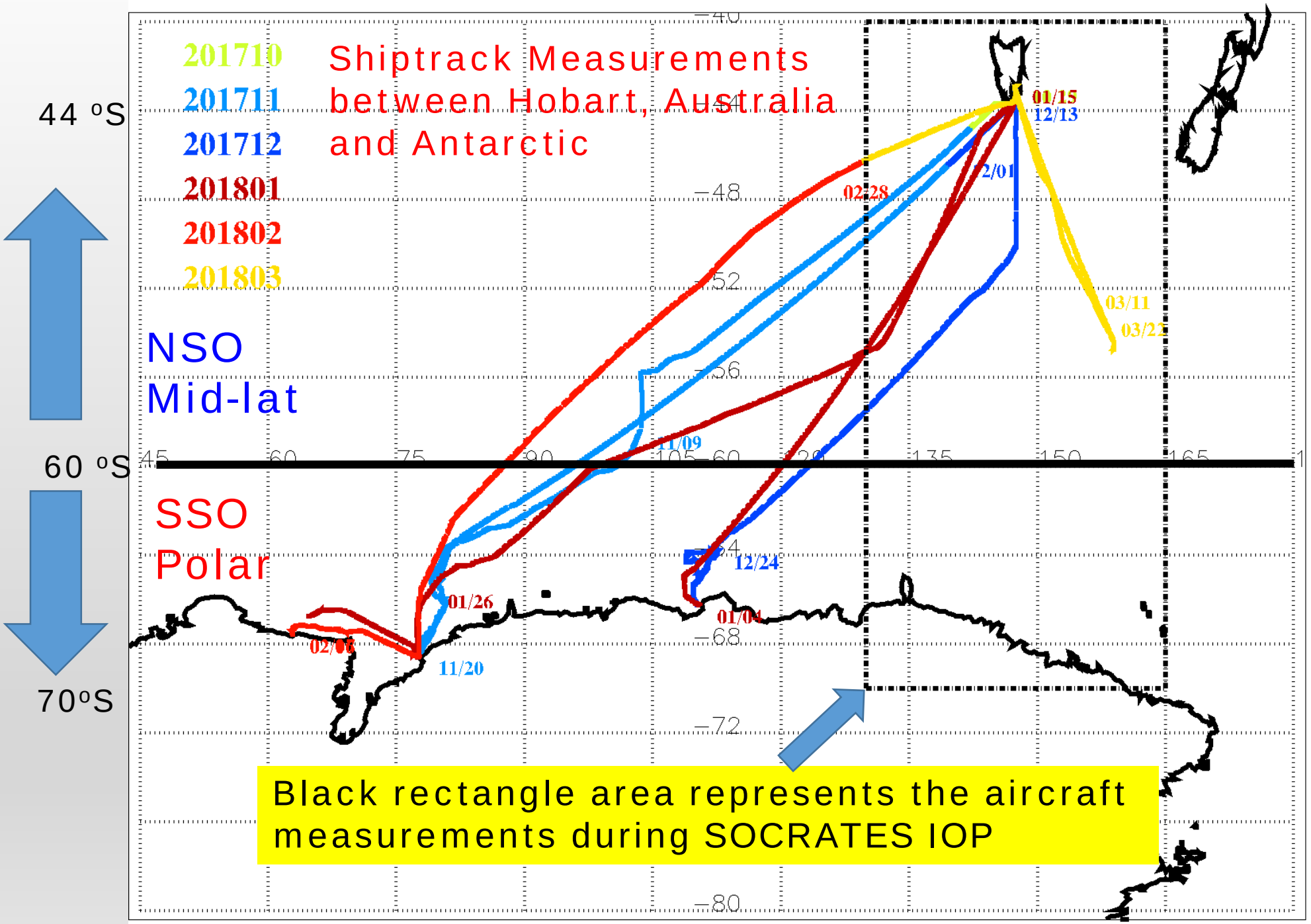
CERES-MODIS SSF data

- **H_{top}/T_{top}**
- **R_e at 3.7 and 2.1 um**
- **LWP**
- **TAU and TAU2.1 (for calculating N_c)**
- **N_c (Painemal and Zuidema, 2011)**

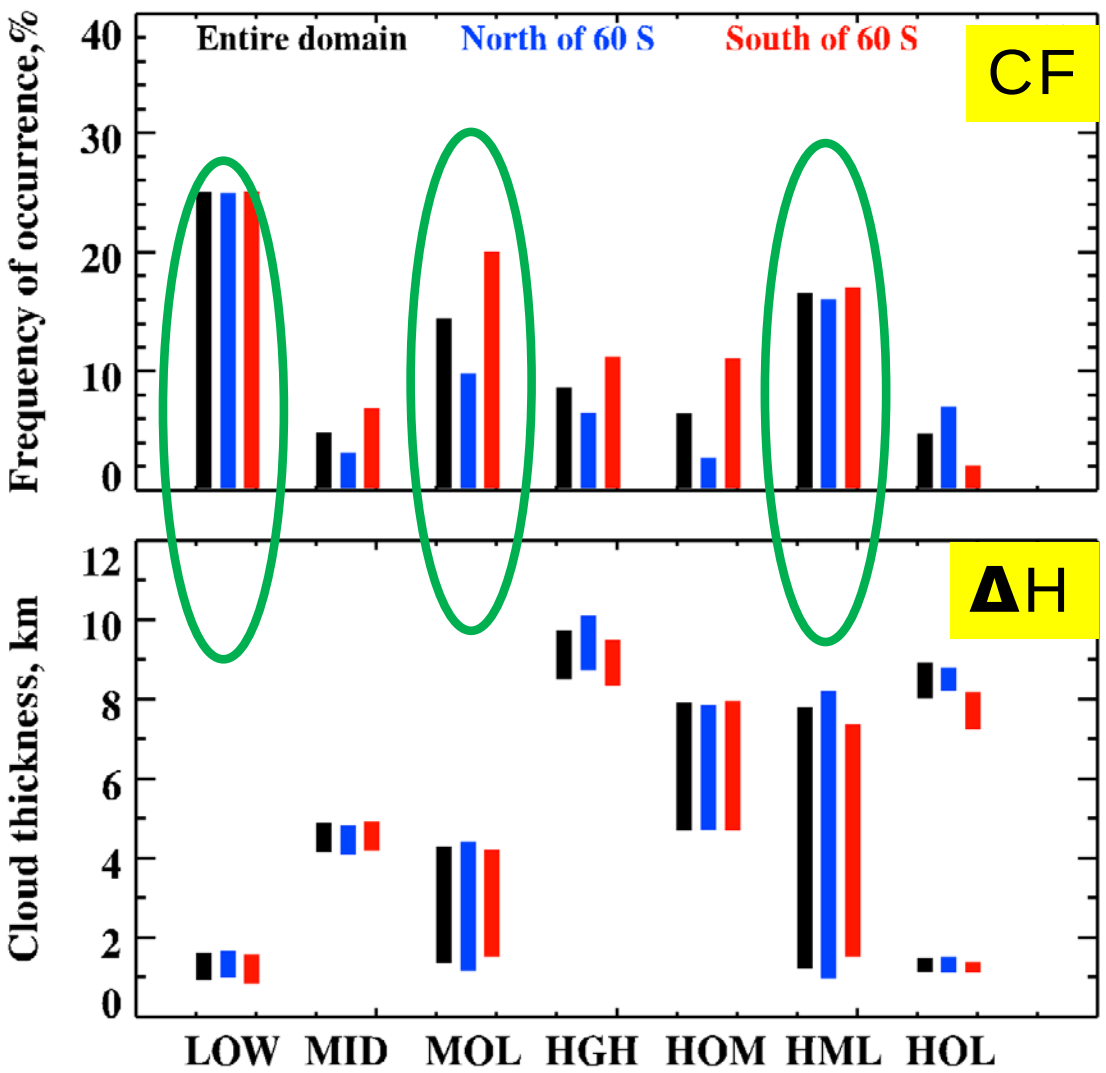
Selected the pixels bounded by the ship track lat-lon within a grid box of 0.2ºx0.2º

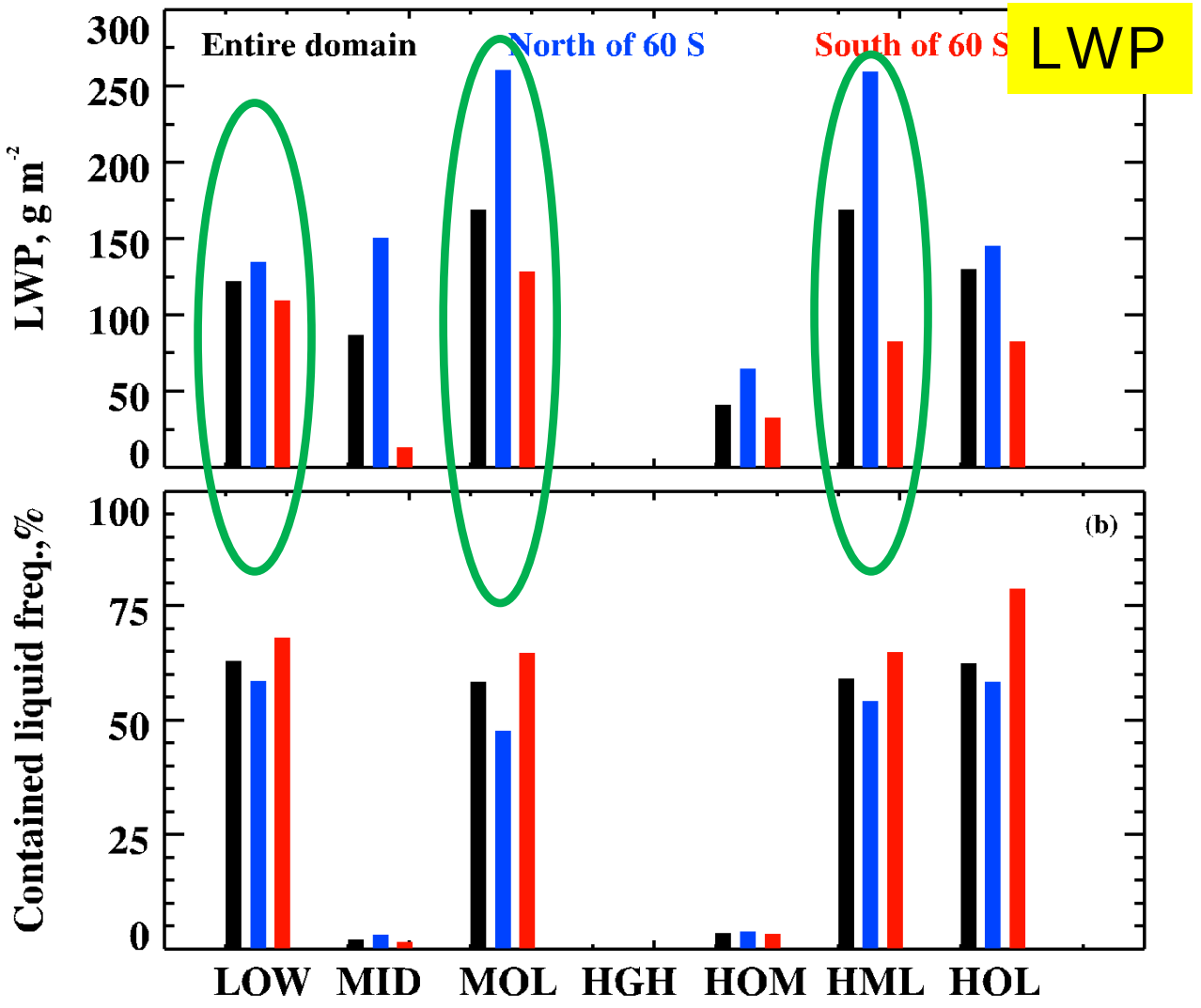
The Southern Ocean Clouds, Radiation, Aerosol Transport Experimental Study (SOCRATES) during January to February 2018

- **CDP – Cloud droplet size distribution**
- **2DS – Drizzle / Ice size distribution**


201710
201711
201712
201801
201802
201803
Shiptrack Measurements between Hobart, Australia and Antarctic
44 ºS
60 ºS
70ºS
NSO
Mid-lat
SSO
Polar
01/15
12/13
02/28
2/01
03/11
03/22
11/09
12/24
01/26
01/04
02/06
11/20
Black rectangle area represents the aircraft measurements during SOCRATES IOP

Cloud types and properties from shiptrack measurements (Xi et al. 2020)



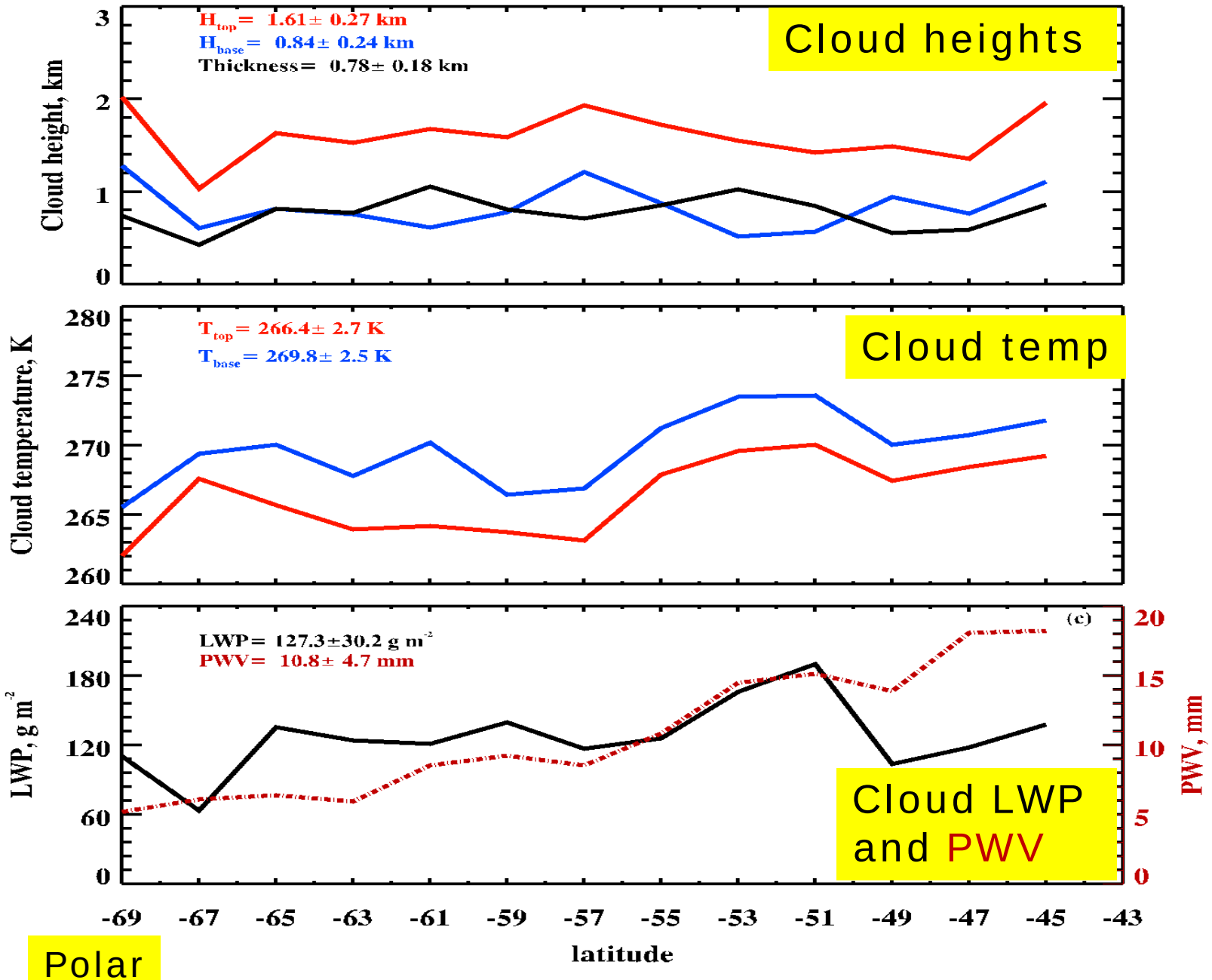


LOW (L): H_{top}≤3km; MID (M) H_{base}>3km & H_{top}≤6km; HGH (H): H_{base}>6km (Xi et al. 2010)

→The dominant cloud types are LOW, MOL, and HML with a slightly higher H_{top} over NSO than SSO;

→MOL and HML LWPs over NSO are 2-3 times higher than those over SSO, their LOW LWPs comparable

Meridional variations of cloud properties during MARCUS



- H_{top}, H_{base} and ΔH have minor meridional variations;
- Both T_{top} and T_{base} slightly increase northward;

→No strong relationship between cloud heights and temperatures.

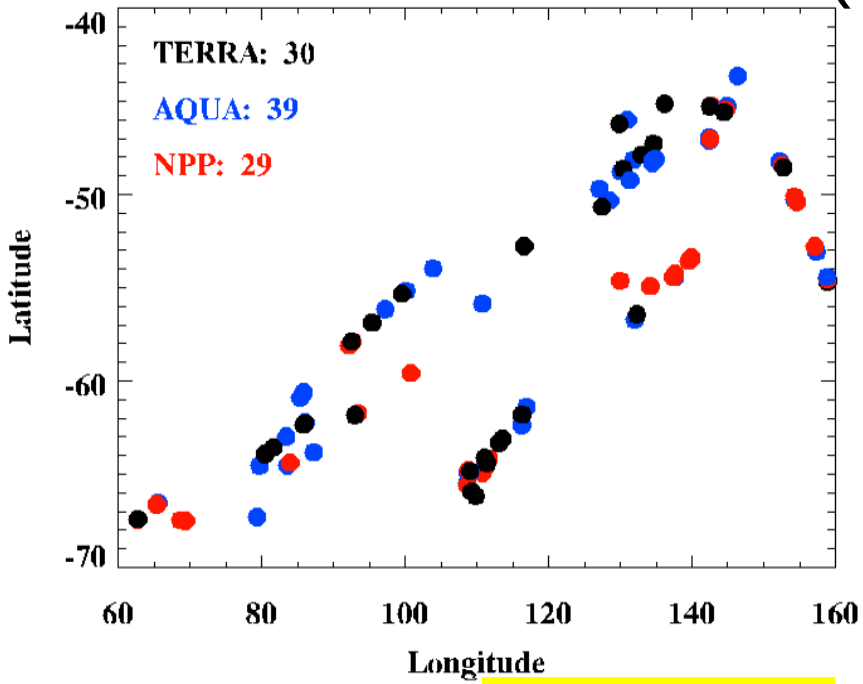
- The PWV increases with latitude;
- LWP increases with latitude except ,decreasing from 51°S to 49°S

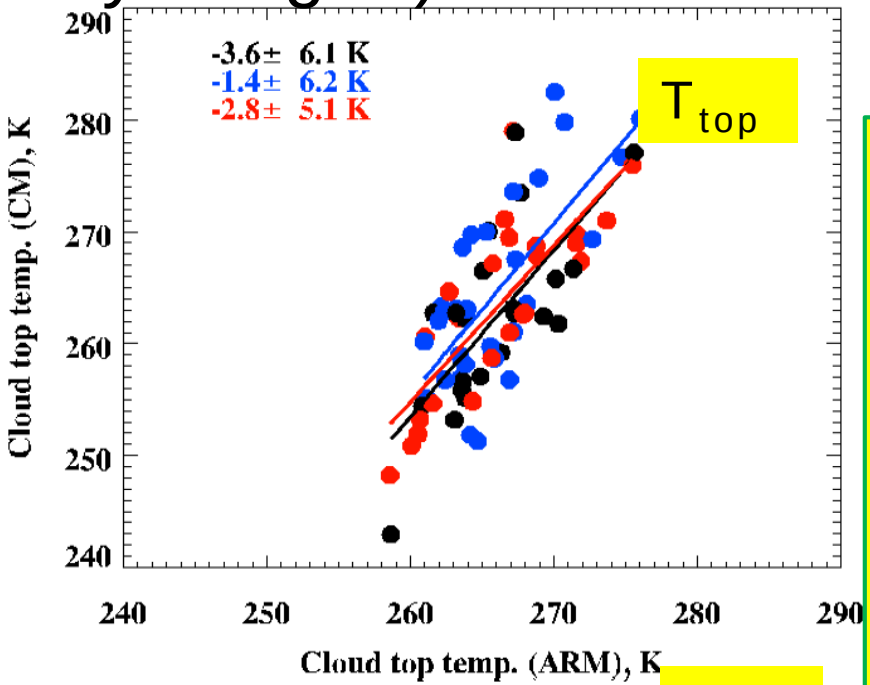
→Positive correlations between LWP and ΔT

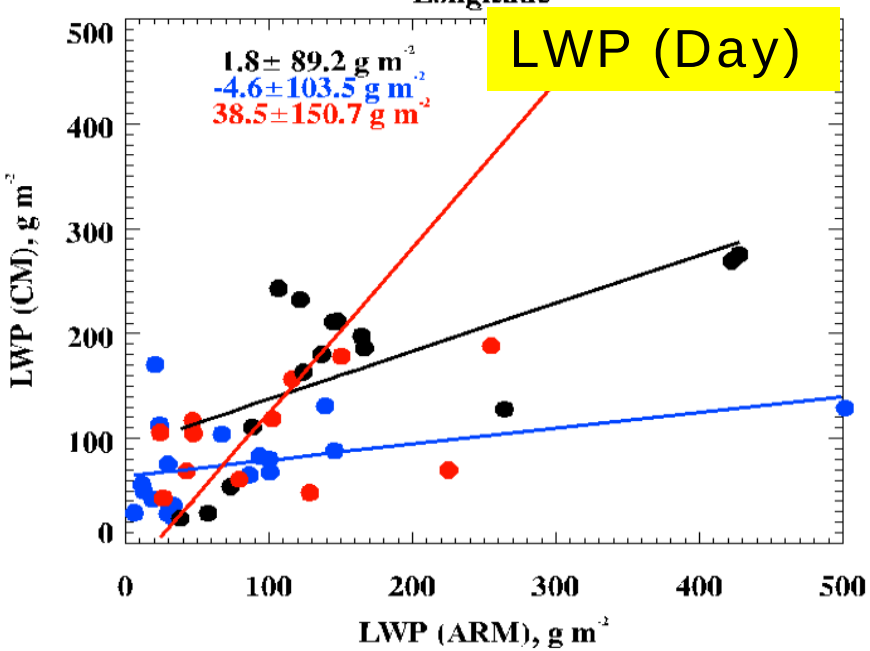
Comparison between CERES-MODIS (CM) and Ship-based results

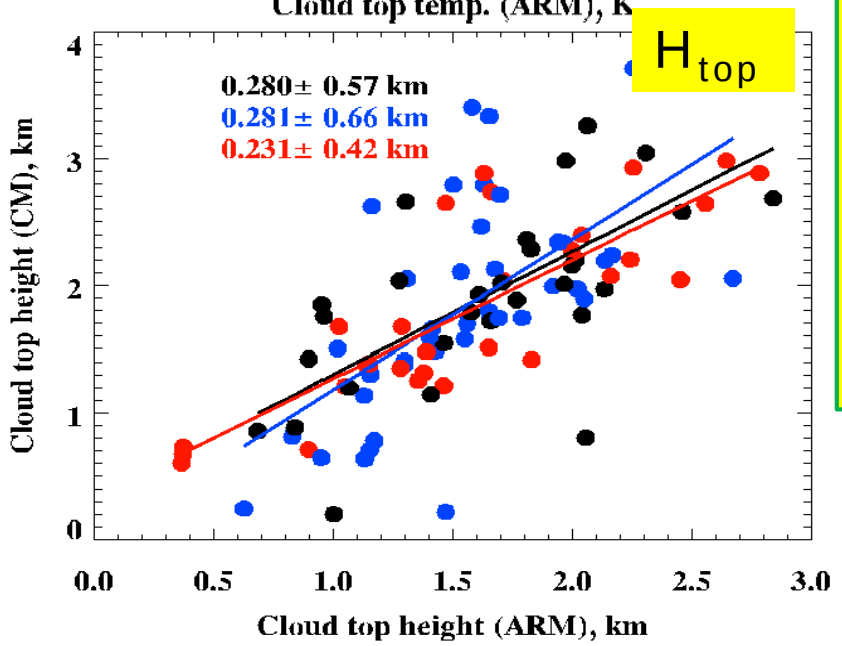
- **Cloud macrophysics and LWP for LOW cloud;**
- **Daytime: CM r_e retrievals at 3.7 and 2.1 µm and N_c; their meridional variations; Δr_e vary with SZA;**
- **[illegible] microphysical retrievals;**
- **Validation using in-situ measurements during SOCRATES: focused on effective radius and number concentration; drizzle effect on the effective radius.**

Low-level clouds (Day+Night)







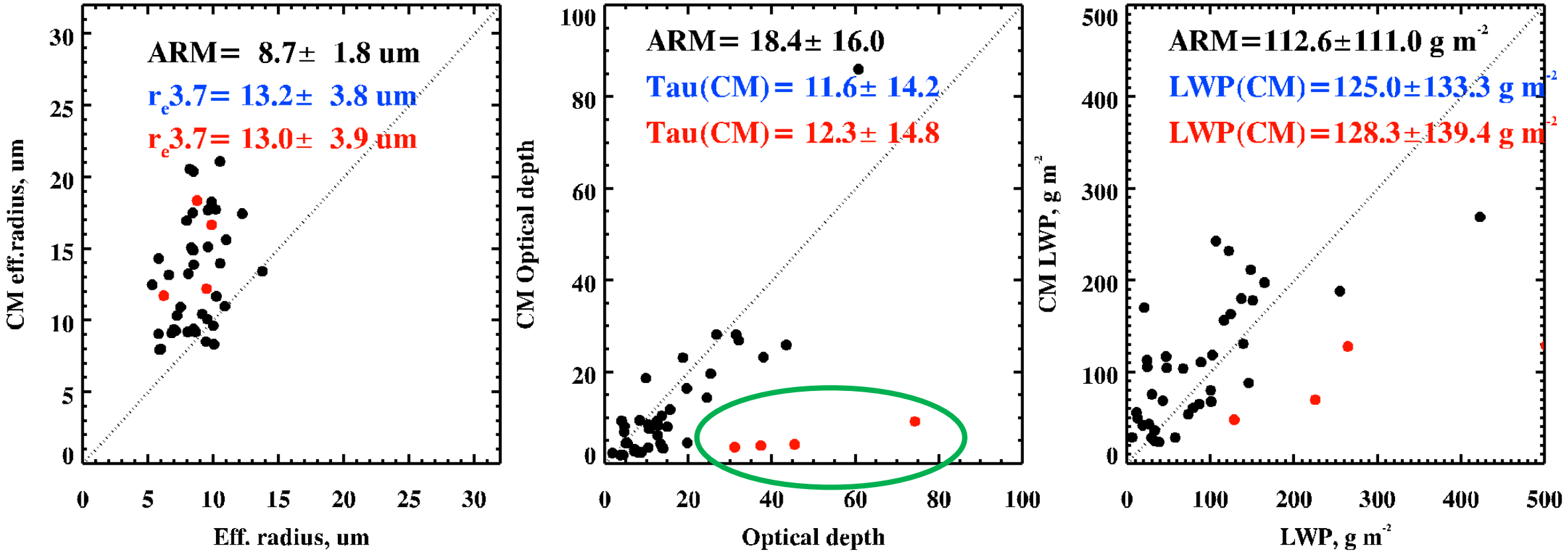


- There are a total of 98 samples and the T_{top} and H_{top} agree well with ARM measurements.
- LWP (daytime): The differences between CERES-MODIS and ARM fall within the uncertainties of ARM retrievals (~ 10 gm^{-2}) except for a few NPP samples.

Comparison between CERES-MODIS (CM) and Ship-based results

- **Cloud macrophysics and LWP for LOW cloud;**
- **Daytime: CERES-MODIS r_e retrievals at 3.7 and 2.1 µm and N_c; their meridional variations; Δr_e vary with SZA;**
- **microphysical retrievals;**
- **Validation using in-situ measurements during SOCRATES: focused on effective radius and number concentration; drizzle effect on the effective radius.**

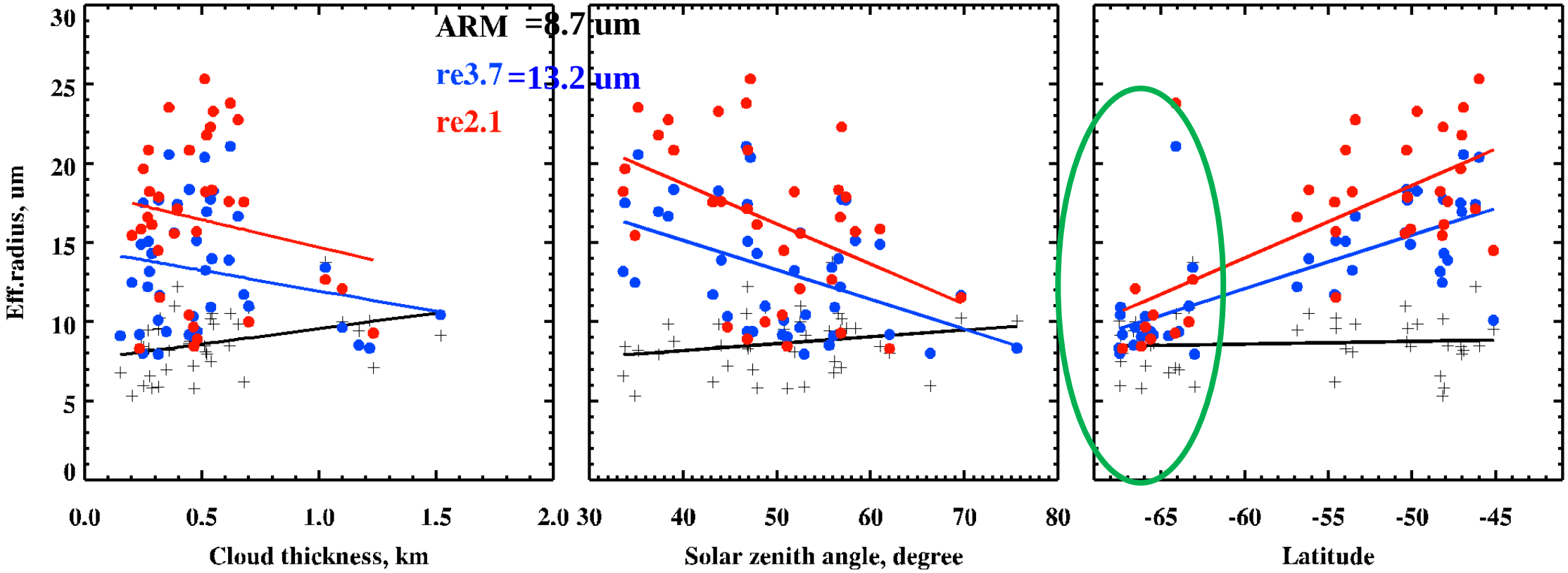
Comparison of r_e, τ and LWP between CERES-MODIS(CM) and ARM



- Δr_e (CM-ARM) and $\Delta\tau$ have large difference, but LWP just has 11% difference between CM and ARM.
- **When we exclude the outliers from small CM optical depth, then both r_e and τ difference between CM and ARM decrease.**

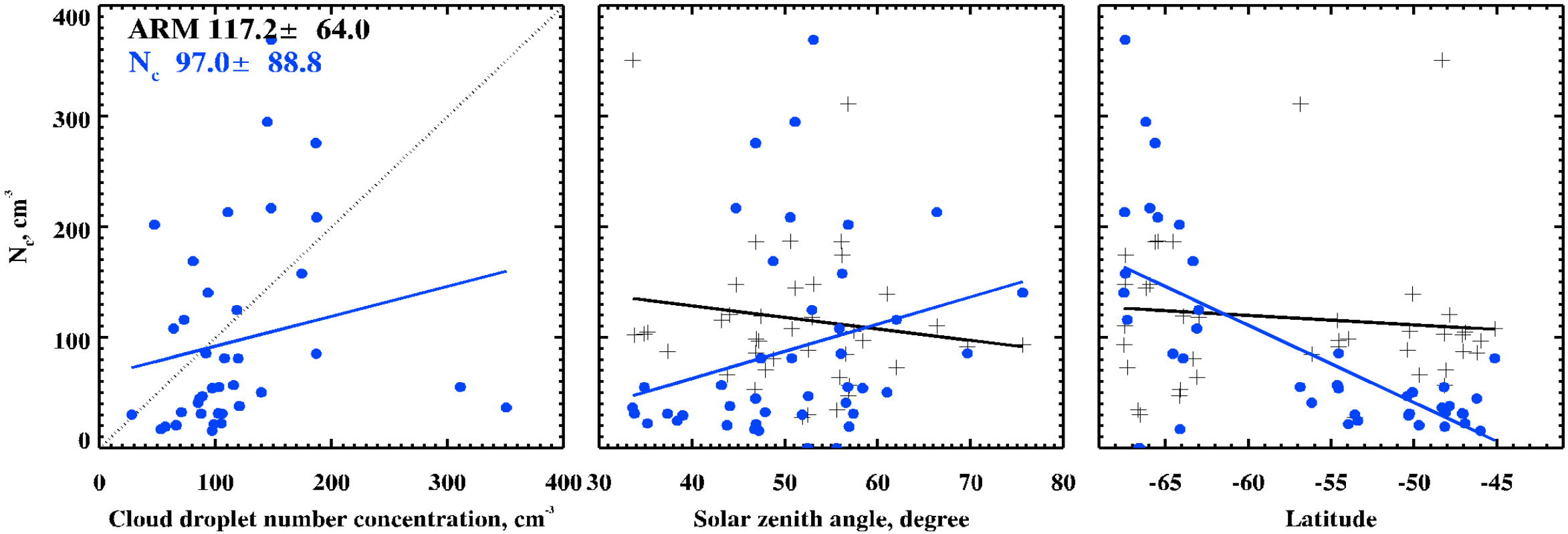
Four red points are from Terra, Aqua, and 2NPP. The means represent excluding these red points

Dependence of r_e retrievals on ΔH, SZA, and Latitude



- **Ship-based (ARM): r_e increases slightly with ΔH and SZA but no change in latitude.**
- **CM r_e retrievals at 3.7 and 2.1 um decrease with ΔH and SZA but increase with latitude. Again $r_e(2.1) > r_e(3.7)$, non-adiabatic?**
- **r_e (ARM) and $r_e(2.1)$ and $r_e(3.7)$ agree well over high latitudes (see green oval).**

Daytime N_c Comparison [CM (y) vs ARM (x)]



ARM	N_c (3.7 um)	N_c (2.1 um)
117.2±64.0	97.0±88.8	77.9±98.0

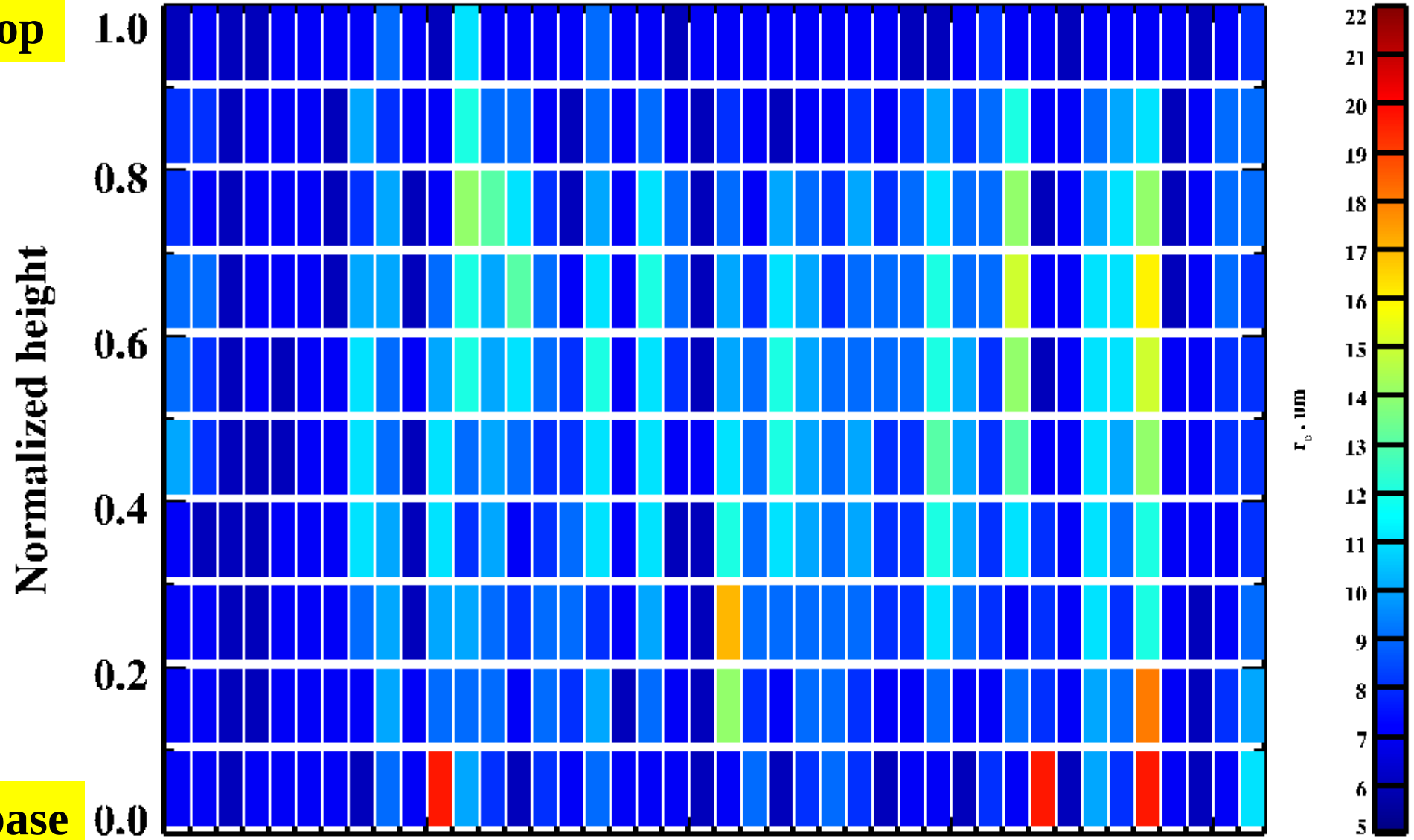
ARM N_c slightly changes with SZA and latitude, while CM N_c strongly depends on its r_e retrievals (negative correlate)

Comparison between CERES-MODIS (CM) and Ship-based results

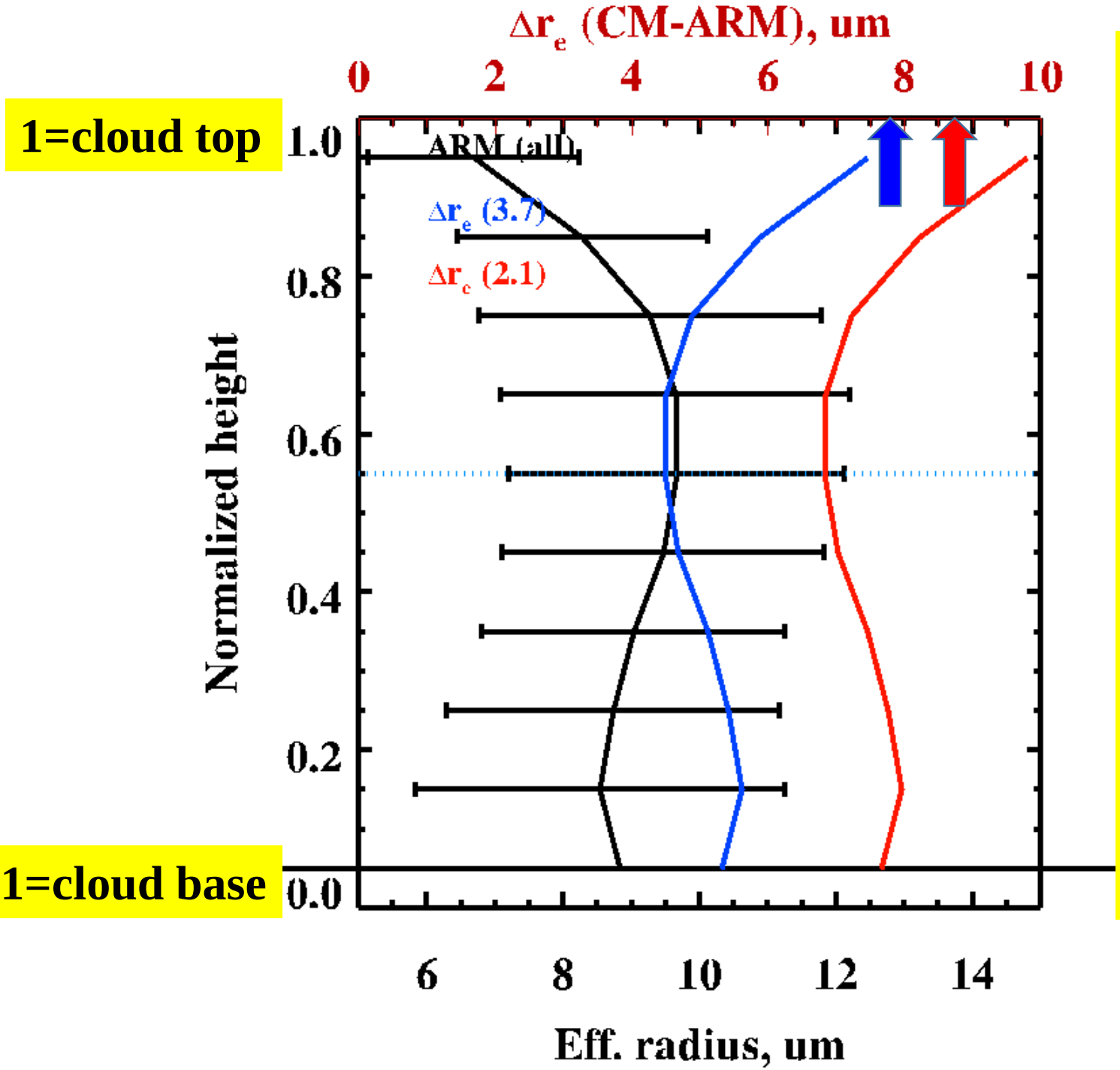
- **Cloud macrophysics and LWP for LOW cloud;**
- Daytime: micro-physical properties, r_e at 3.7, and 2.1 um and N_c; Meridional variations; Ar_c vary with SZA;
- **The profiles of r_e with and without rain → drizzling effect on the microphysical retrievals;**
- **Validation using in-situ measurements during SOCRATES: focused on effective radius and number concentration; drizzle effect on the effective radius.**

The profiles of retrieved cloud particle sizes using ARM measurements

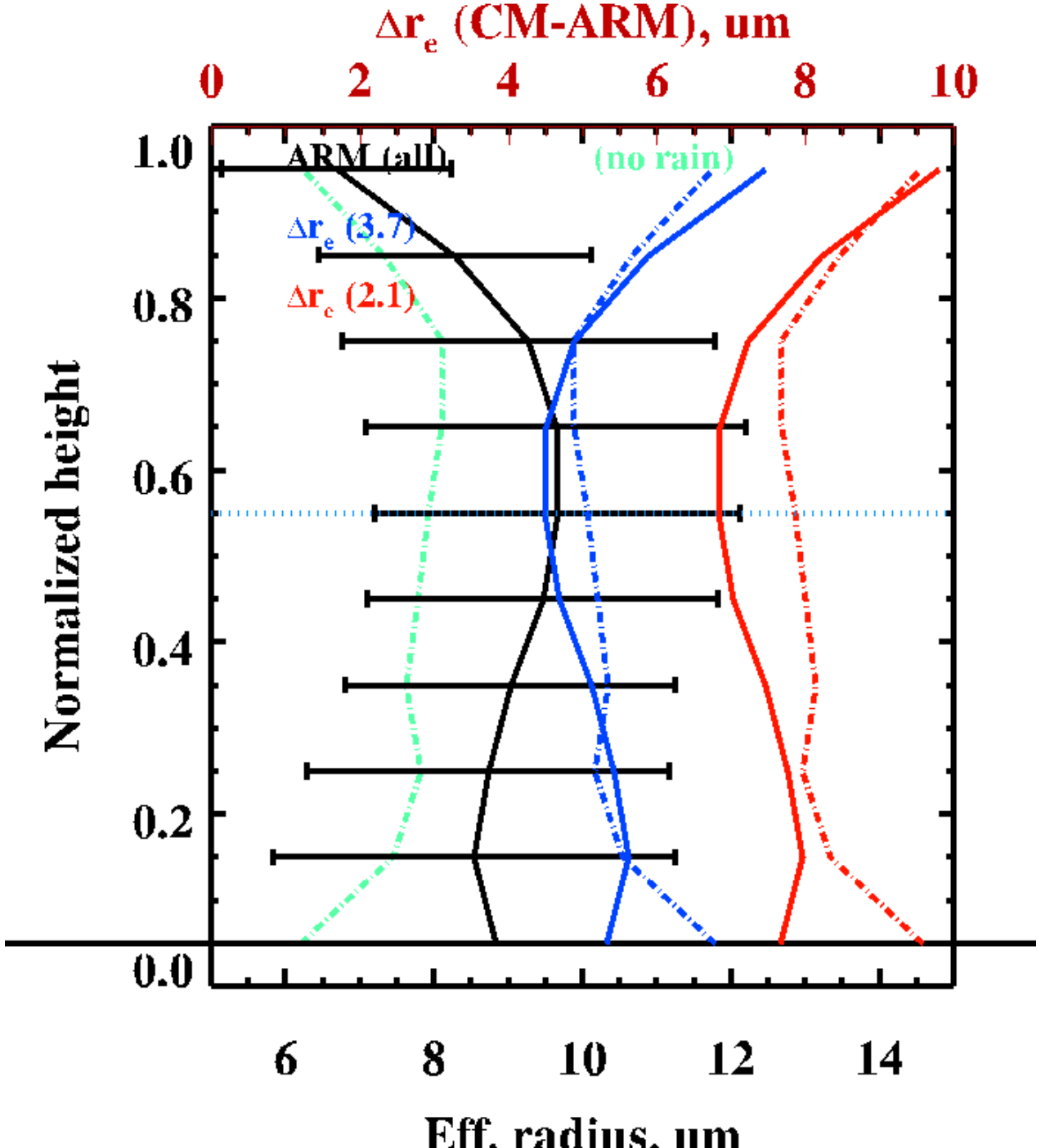
1=cloud top



0=cloud base



- Ship-based retrieved r_e profile has a max. at slightly above middle of the clouds and the min. Δr_e happens there, too.
- Very large variation of ship-based retrieval happens near the H_{base} because there are large drizzle particles there.
- The $\Delta r_e(2.1)$ is even larger than $\Delta r_e(3.7)$



Dotted lines relate to selected samples without rain:

- **Ship-based retrieved r_e profile without rain (13 samples), has maximum at 75% of the cloud thickness from H_{base}.**
- **Relative differences can reach ~2 um between all samples and these without drizzle size particles.**
- **The minimum between r_e(3.7) and r_e(ARM) is at the same place as the maximum of the r_e profile.**

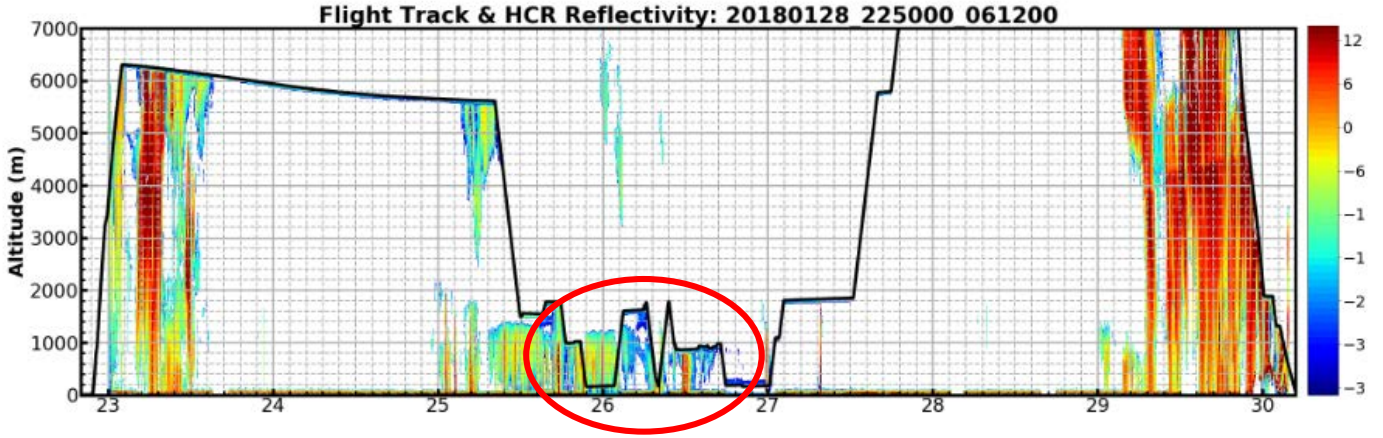
Comparison between CERES-MODIS (CM) and ship-based results

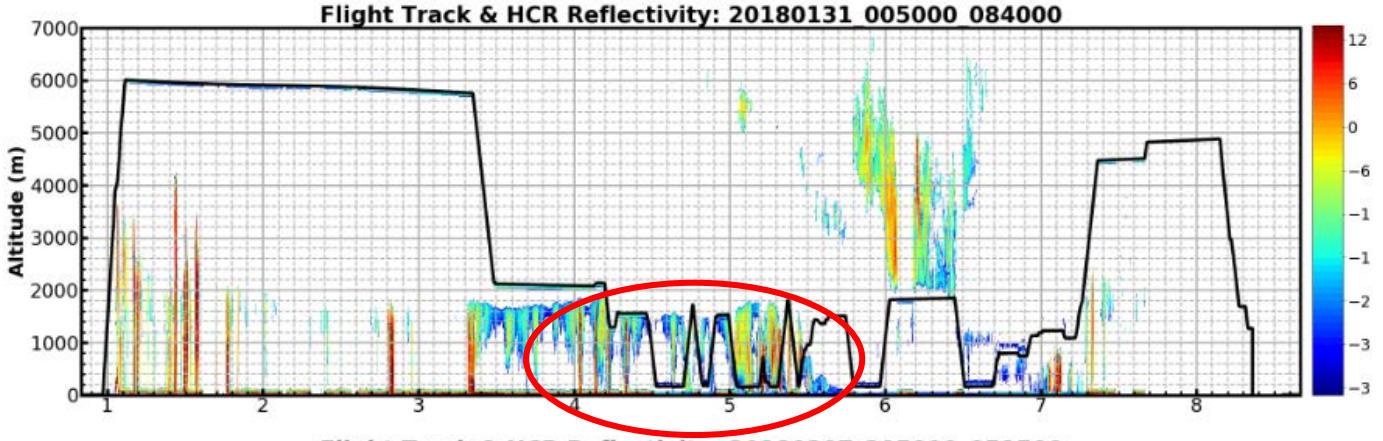
- **Cloud macrophysics and LWP for LOW cloud;**
- Daytime: micro-physical properties, r_e at 3.7, and 2.1 um and N_c; Meridional variations; Δr_e vary with SZA;
- [illegible] **microphysical retrievals;**

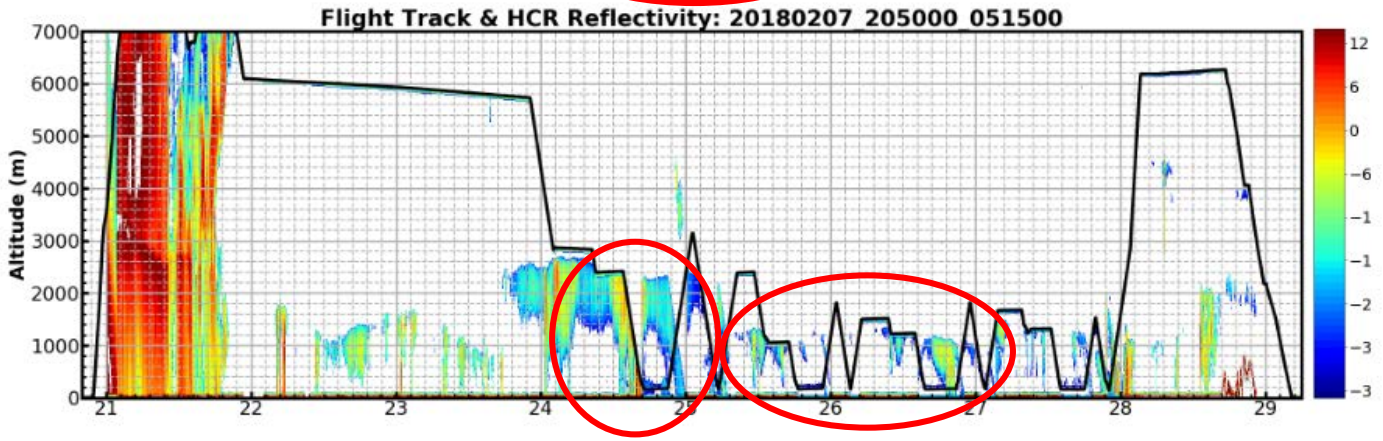
- **Validation using in-situ measurements during SOCRATES: focused on effective radius and number concentration; drizzle effect on the effective radius.**

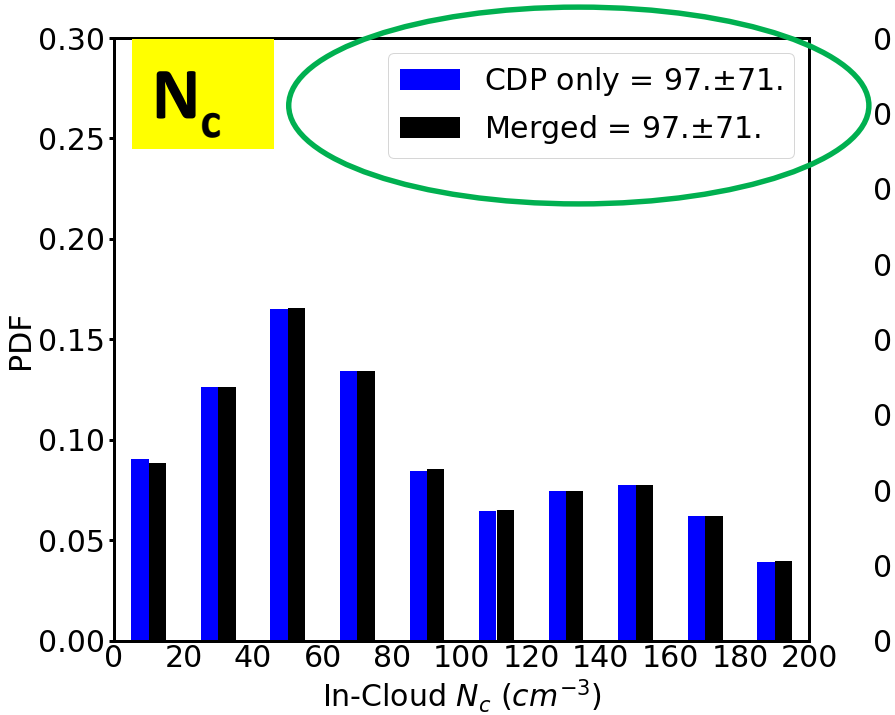
SOCRATES Low Cloud Sampling Periods (~18.4 hours)

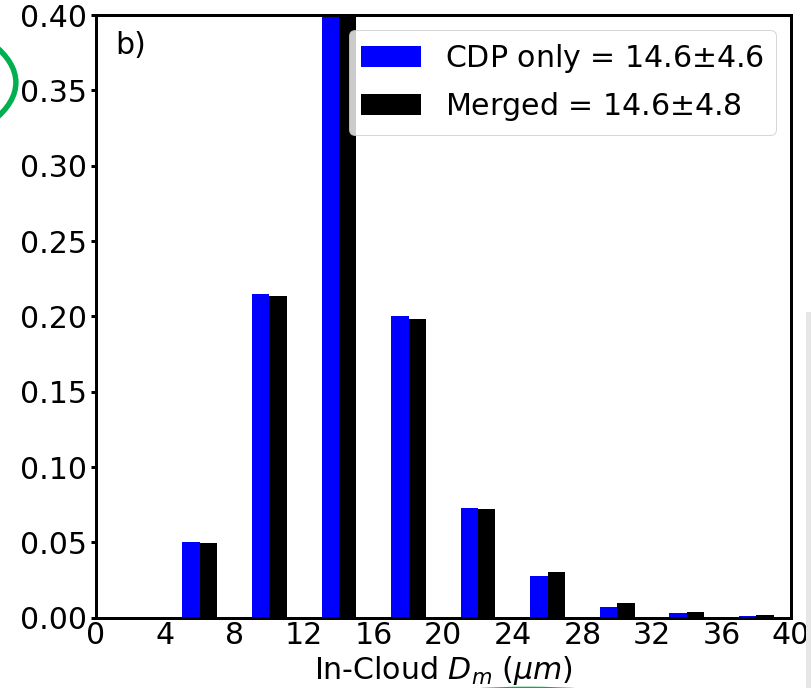
RF No.	Date	UTC Start	UTC End
1	**20180116**	**1.8**	**2.8**
5	**20180126**	**2.0**	**2.9**
6	**20180129**	**1.4**	**2.8**
7	**20180131**	**3.4**	**5.9**
8	**20180204**	**2.9**	**5.8**
9	**20180205**	**2.6**	**4.7**
10	**20180208**	**0.0**	**1.1**
10	**20180208**	**1.4**	**3.2**
11	**20180217**	**3.0**	**4.9**
12	**20180218**	**2.8**	**5.2**
13	**20180220**	**1.8**	**5.6**
14	**20180222**	**3.2**	**5.1**



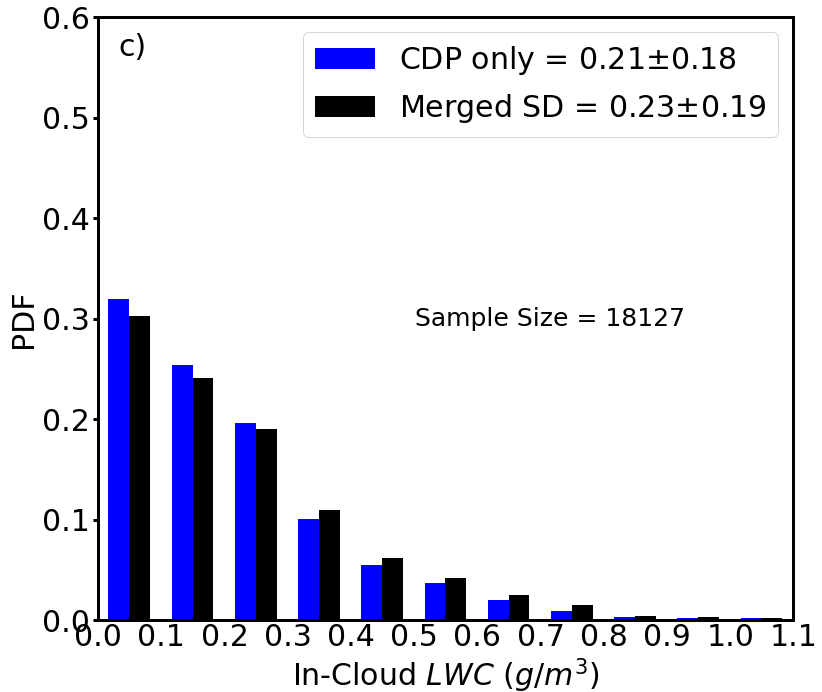


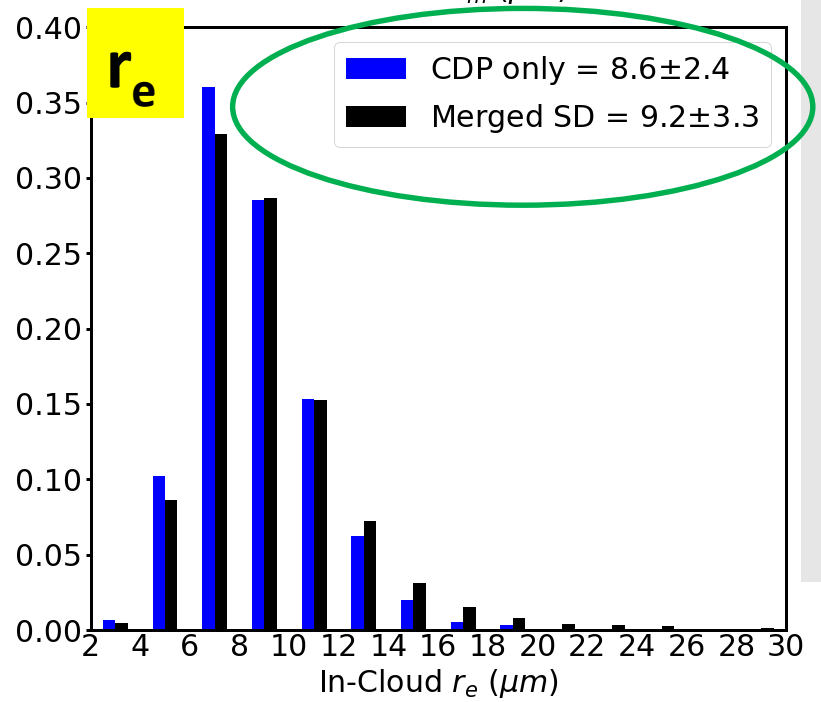






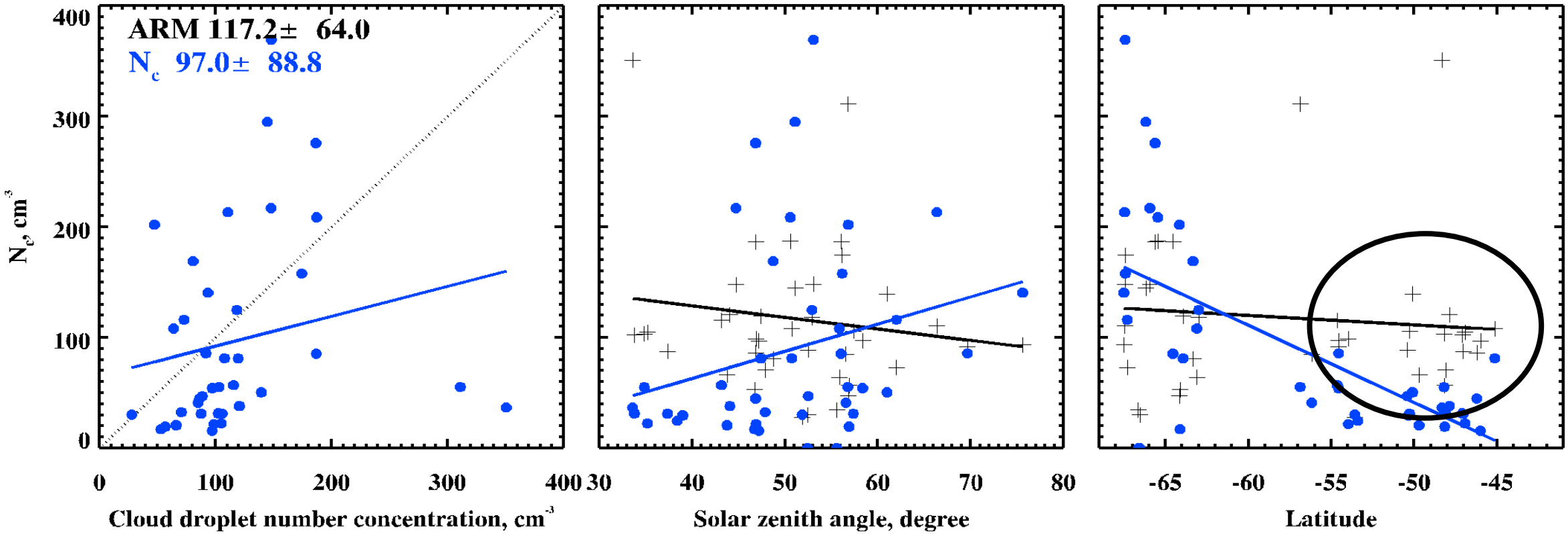
CDP: 2 - 50µm
Merged:
2 - 5000 µm (CDP+2DS)





- **In-situ CDP measured r_e is close to the value (8.7um) of ship-based retrieval during MARCUS;**
- **The merged r_e from CDP+2DS indicates little contribution of drizzle to overall particle size.**
- **The in-situ N_c is almost the same as ARM retrievals over NSO and CM mean.**

Daytime N_c Comparison [CM (y) vs ARM (x)]



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117.2±64.0	97.0±88.8	77.9±98.0

ARM N_c slightly changes with SZA and latitude, while CM N_c strongly depends on its r_e retrievals (negative correlate)

Summary

- **The most frequent cloud types are LOW, HML and MOL over the southern ocean;**
- **For low clouds, the CERES-MODIS (CM) T_{top}, H_{top} and LWP have reasonable agreements with the ship-based measurements. These are encouraging results at high latitudes over the southern ocean where verification data have been scarce;**
- **The mean differences (CM-ARM) of r_e, LWP, N_c and τ are 4.5 um, 12.4 gm^{-2}, -20 cm^{-3}, and -6.8, respectively. CM r_e agrees well at SSO with ARM r_e. The CM N_c is higher at SSO and lower at NSO than ARM N_c;**
- **The ship-based r_e slightly increases with ΔH and SZA, no variation with latitude; CM N_c increases with SZA and decreases with latitude. The CM r_e(3.7 and 2.1) decrease with ΔH and SZA, and increase with latitude;**
- **The max. ship-based $r_e(Z)$ and min. $\Delta r_e(3.7)$ occur in between 55% of ΔH above H_{base}. Without rain, the $r_e(Z)$ is constantly less than these with rain, and its max. occurs at 75% of ΔH above H_{base};**
- **The in-site (CDP) measured r_e and N_c during SOCRATES are very closed to ship-based retrievals during MARCUS. r_e from CDP+2DS is ~6% larger than ship-based retrieval, which may help us to explain the contribution of the drizzle size particles to the effective radius, but not much contribution on the cloud number concentration.**