Constraining WACCM6 Cirrus Cloud Microphysics with CALIPSO (IIR-CALIOP) Effective Diameter Retrievals

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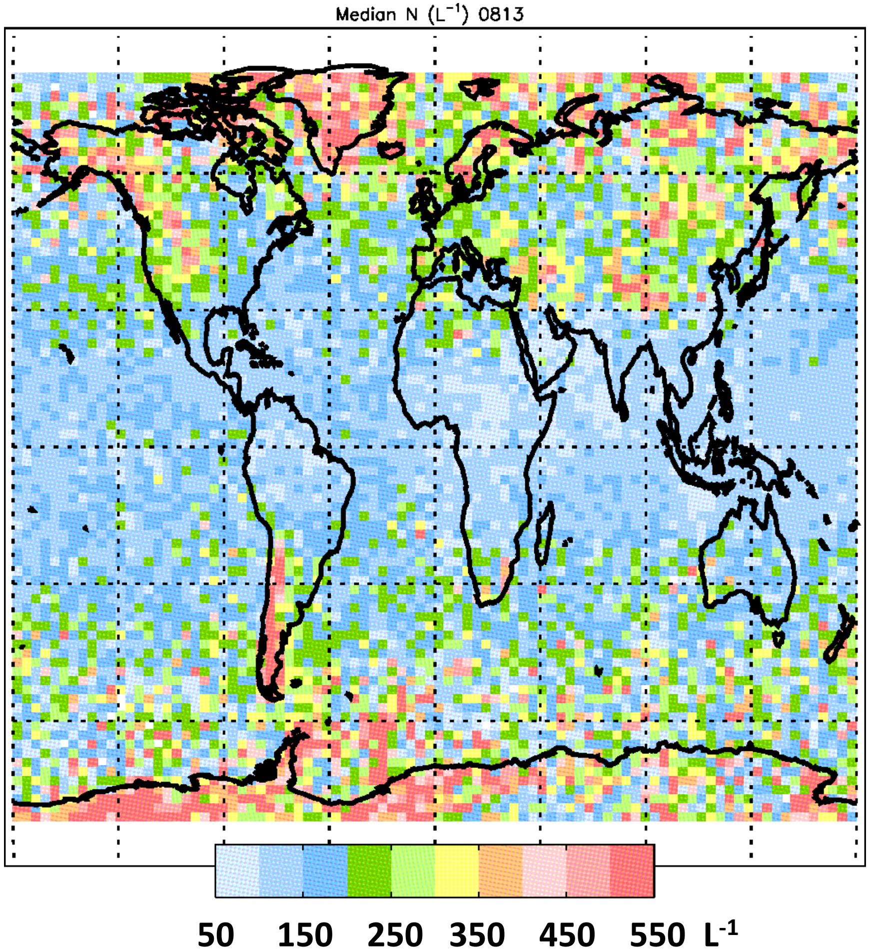
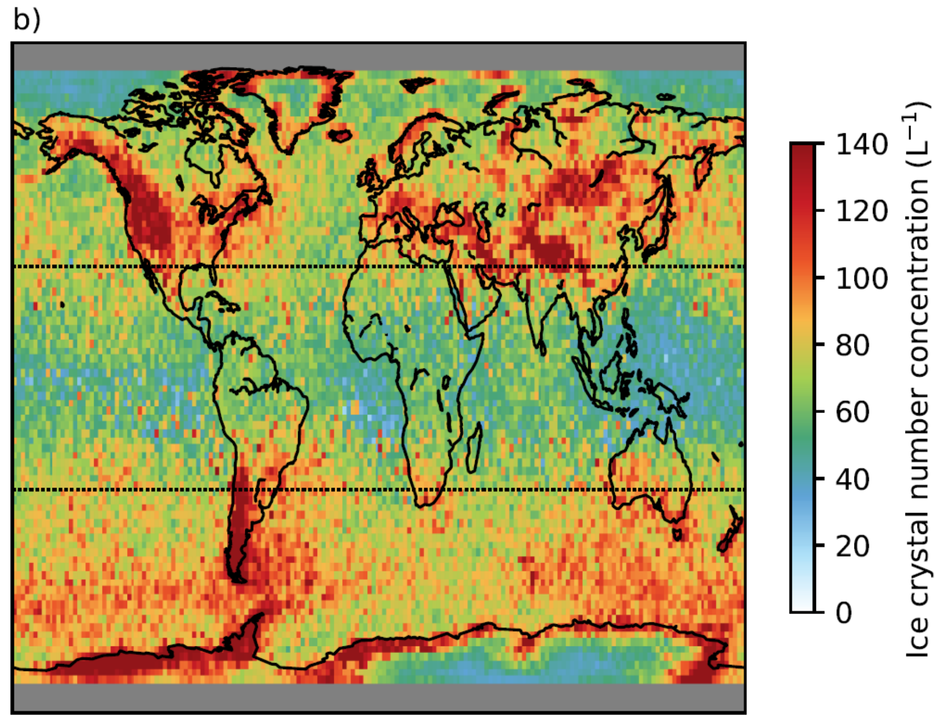
Photo courtesy of Grzegorz Swistak

Left: Our CALIPSO retrieval (Mitchell et al., 2018, ACP), median N (L^{-1}) for 2008 & 2013, -45 to -55°C. Right: From Gryspeerdt et al. (2018, ACP), using a lidar-radar CALIPSO-CloudSat retrieval for N (L^{-1}) at -50°C near cloud top. Their results are similar to our study in terms of the N dependence on latitude, topography and season.

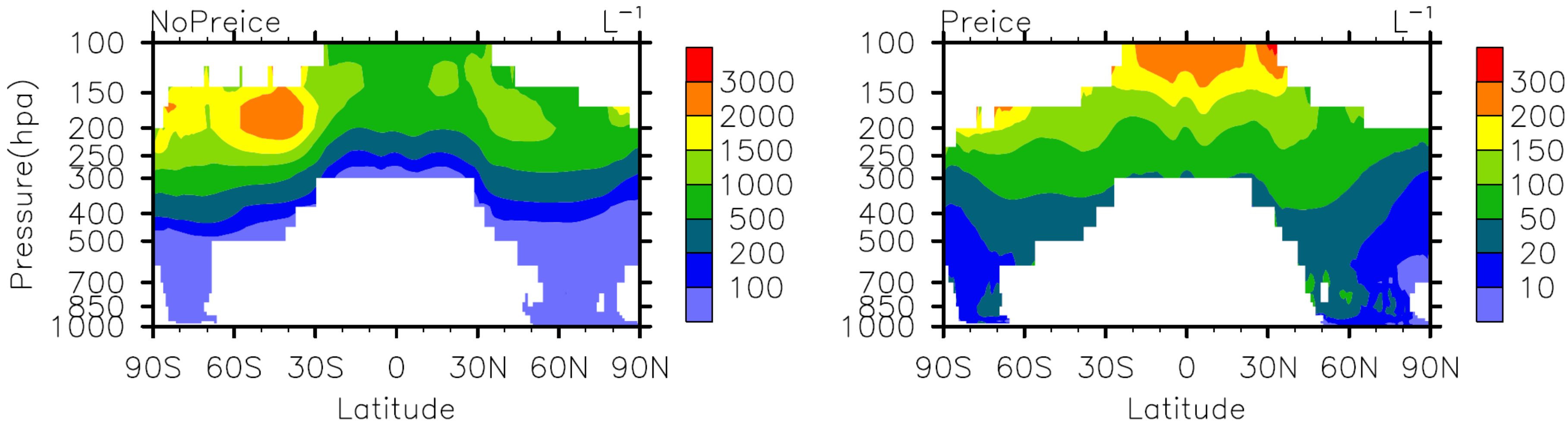




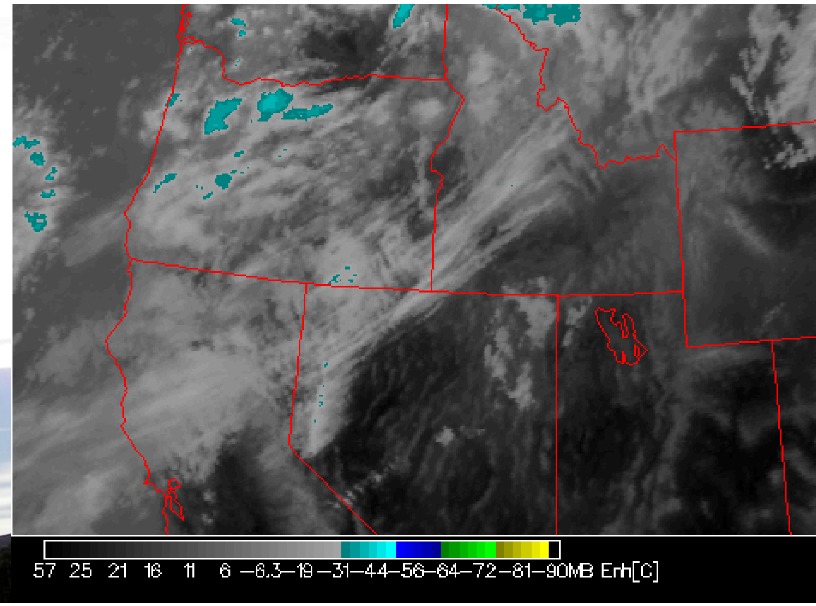
Homogeneous ice nucleation (hom) appears responsible for higher N outside the tropics.

Treatment of ice nucleation in CAM5.3, without and with pre-existing ice

From Shi et al., 2015, ACP

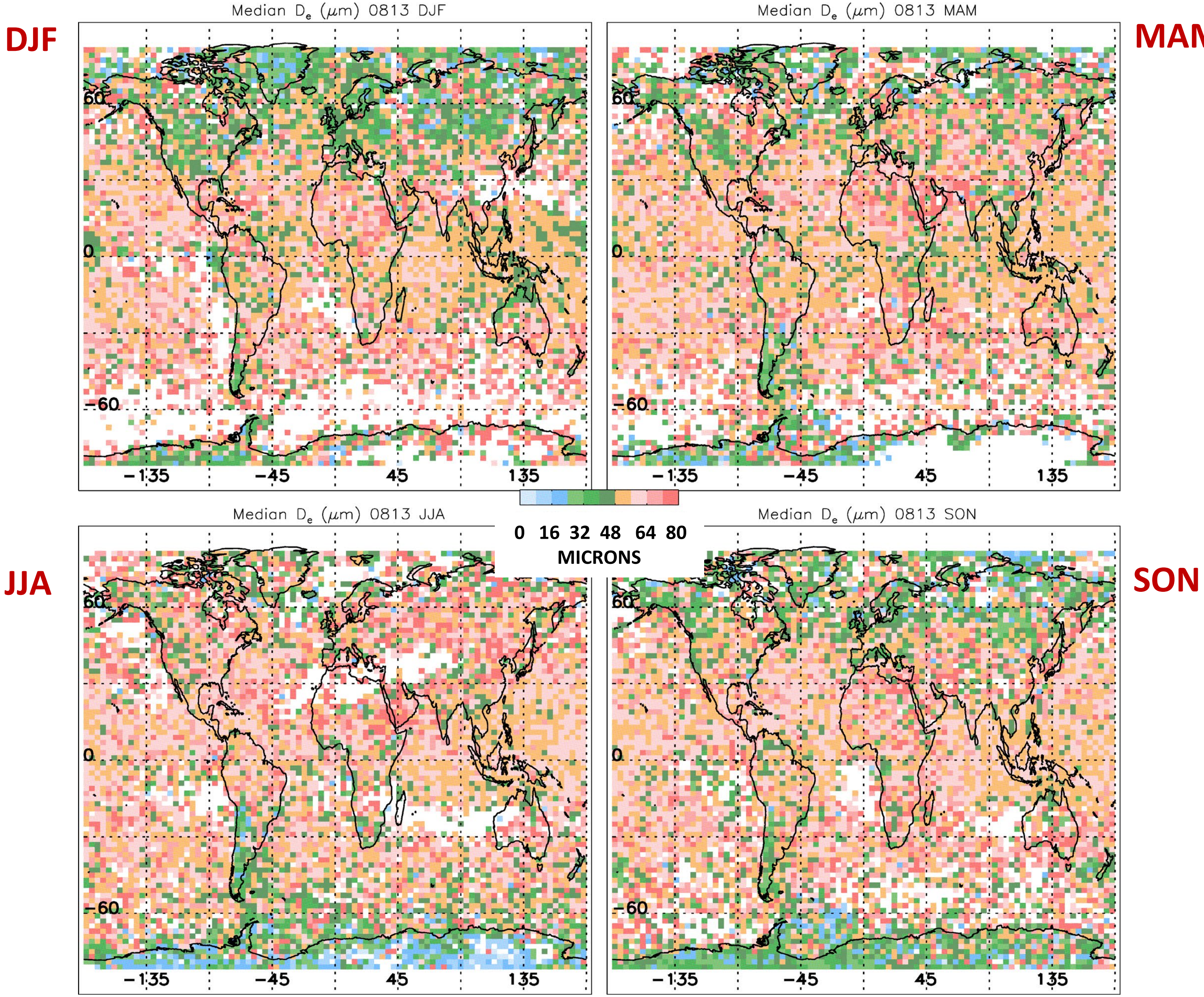


Annual zonal mean for in-cloud ice particle number concentration, N_i, from NoPreice (left) and Preice (right) experiments. Note the different color bars.



Effective diameter is smallest at high latitudes and over high terrain

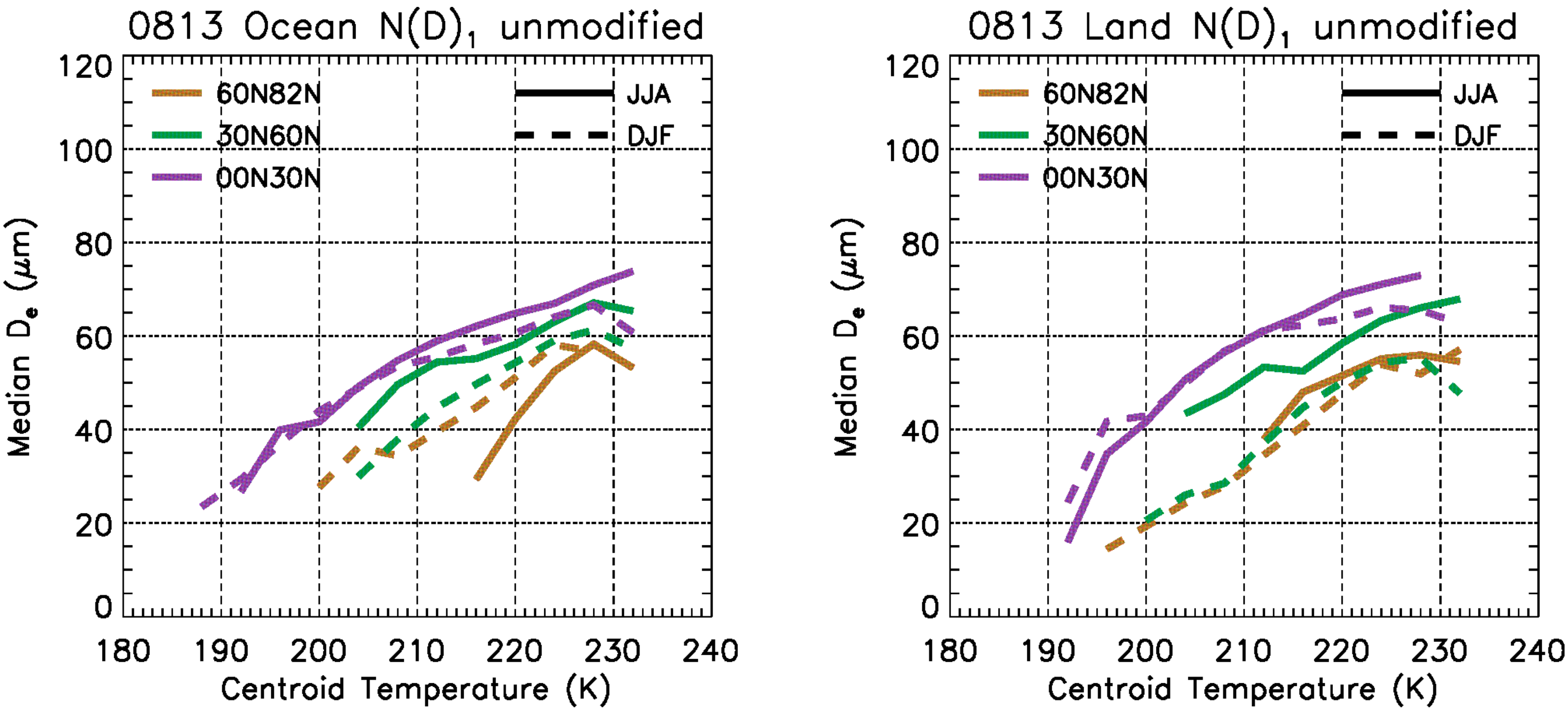
Plots show D_e for T < 235 K for 2008 and 2013



WACCM6 Experiment: 10-years (1975-1984)

CALIPSO simulation: $D_e(T)$ based on CALIPSO observations

Het simulation: based on tropical (30 °S – 30 °N) cirrus $D_e(T)$ only



D_e for Het (purple) is usually larger than CALIPSO D_e outside the tropics, with Het having larger ice fall speeds and lower IWC, optical depth and coverage, resulting in weaker cloud radiative forcing.

…WACCM6 Experiment

- Cirrus microphysics in WACCM6 was constrained by CALIPSO retrieved D_e:

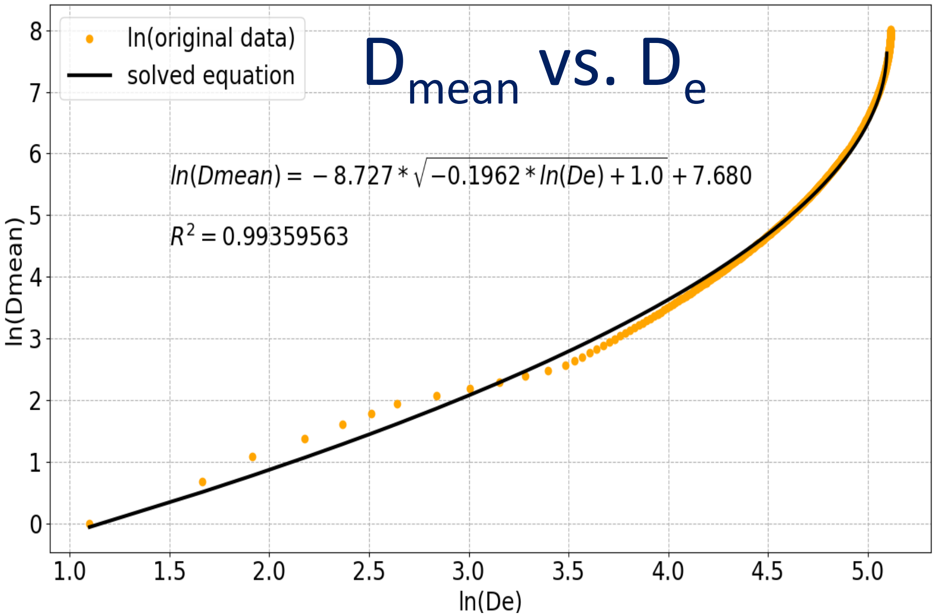
  $$D_e = f(T, \text{latitude, season, surface(land vs. ocean)}) \Rightarrow 48\ D_e(T)$$

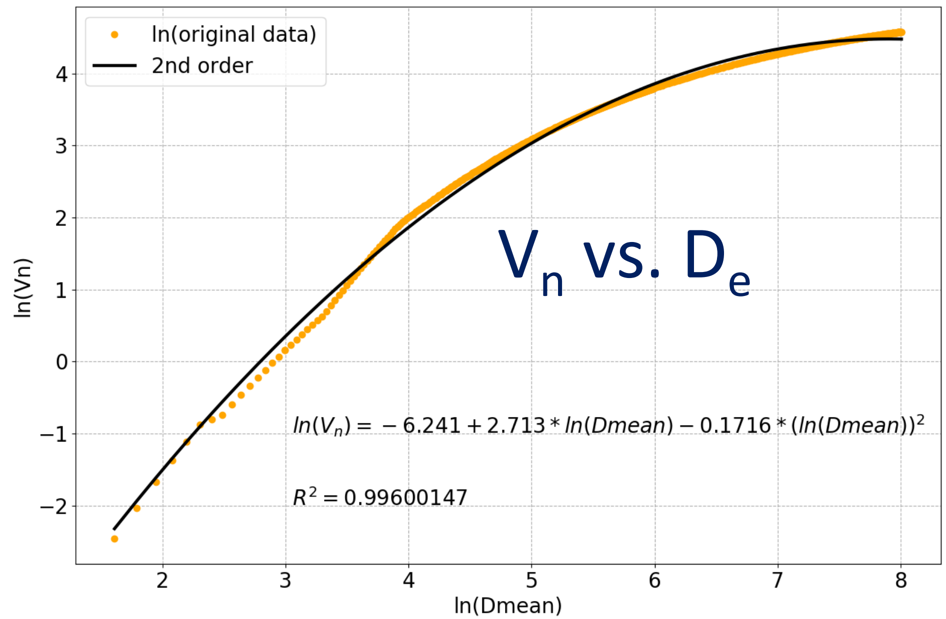
- Implemented new physics to make the microphysics consistent with this D_e constraint, and a more accurate treatment of ice fall speeds, which affects the ice water content and cirrus cloud coverage:

  $$V_{\text{mass-weighted}}\ \&\ V_{\text{number-weighted}} = f(D_e, T, p)$$

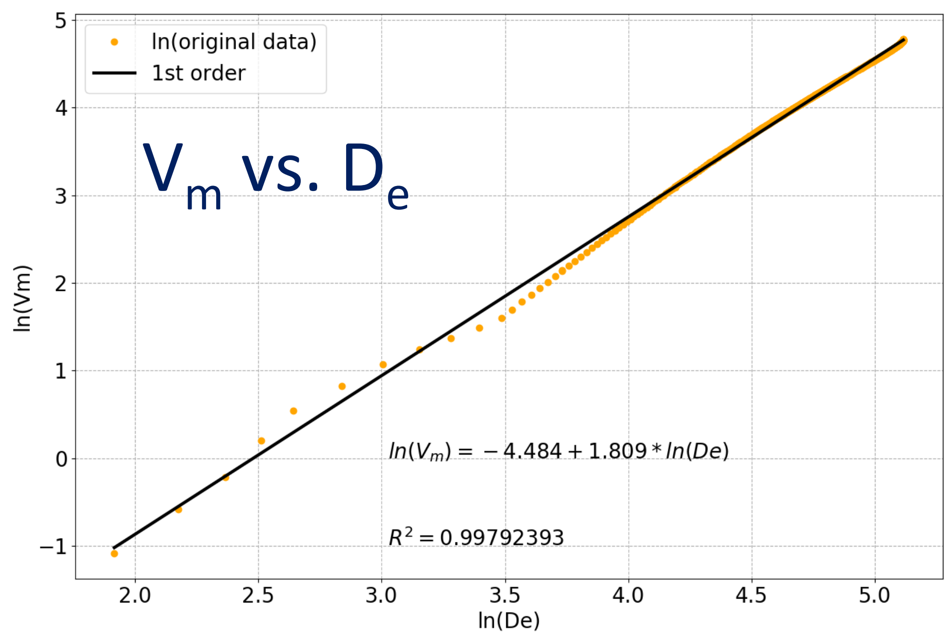
- Assume tropical D_e – T relations are representative of heterogeneous ice nucleation. Note that retrieved N was lowest in tropics (~ 50-100 L^{-1}).
- Resolution: O.9° lat. x 1.25° lon. with 70 vertical levels
- Climatological SSTs and using balanced (spun up) initial conditions

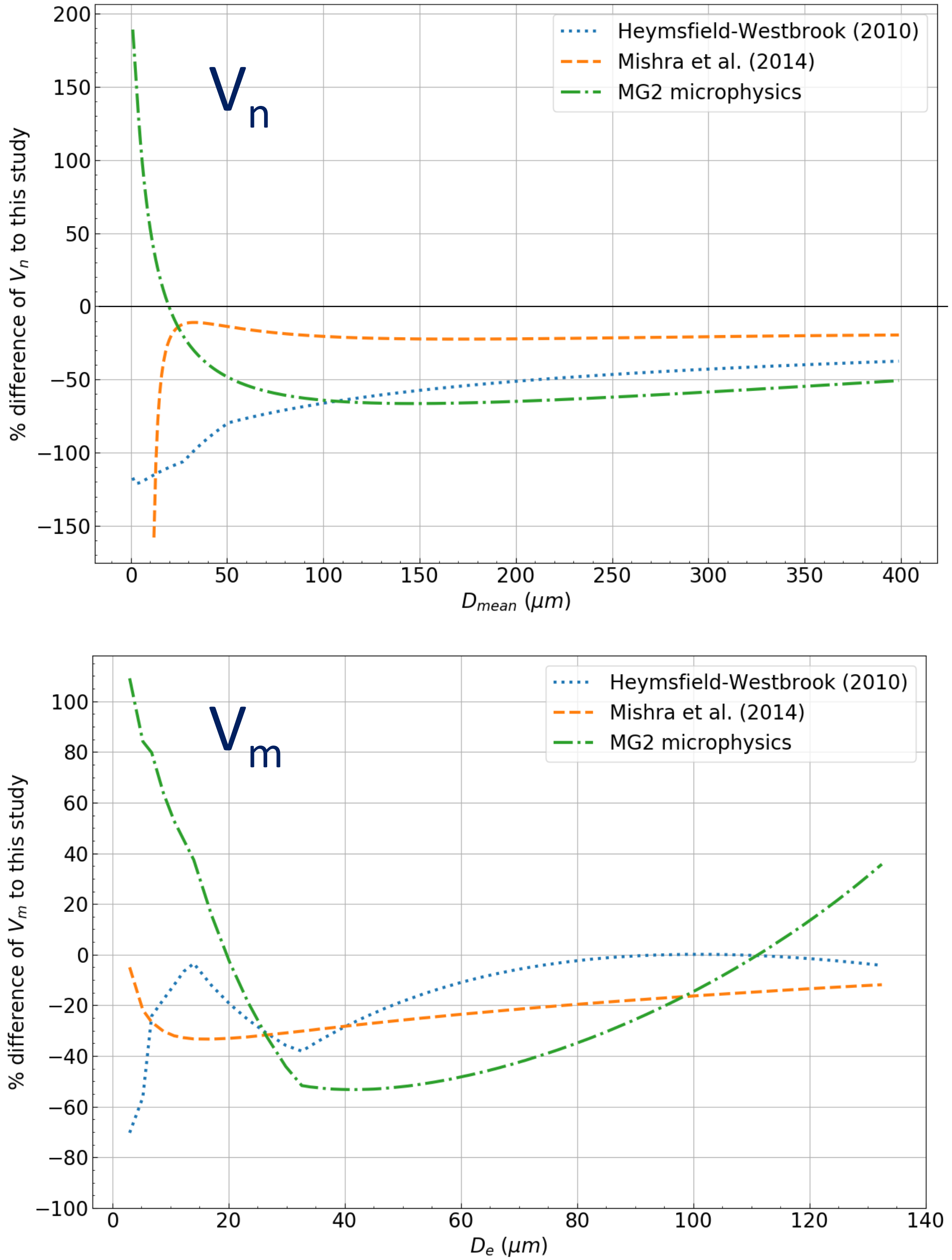
Cloud Microphysical Changes Made to WACCM6





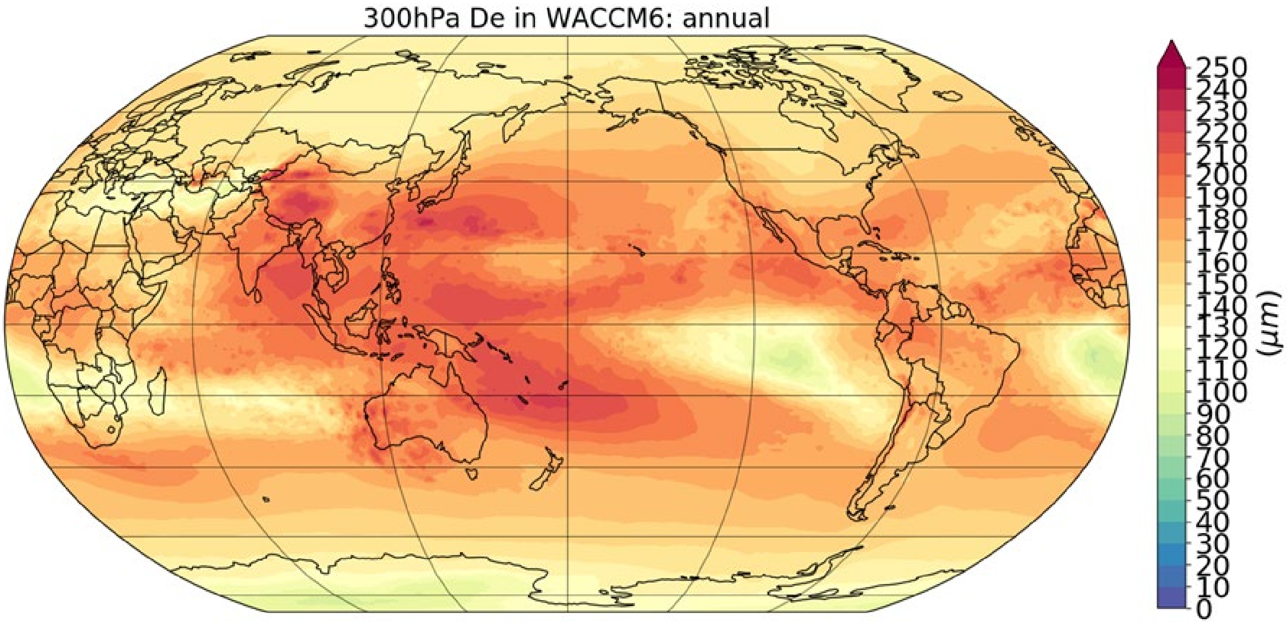
Mean ice particle size D_{mean} = 1/Λ where Λ = PSD slope, and D_{mean} is calculated from CALIPSO D_e based on Erfani and Mitchell (2016, ACP). The number- and mass-weighted ice fall speeds are calculated from D_{mean} and D_e, respectively, using EM (2016) again. In this way the ice PSD in the MG2 microphysics module and associated processes are consistent with CALIPSO D_e.



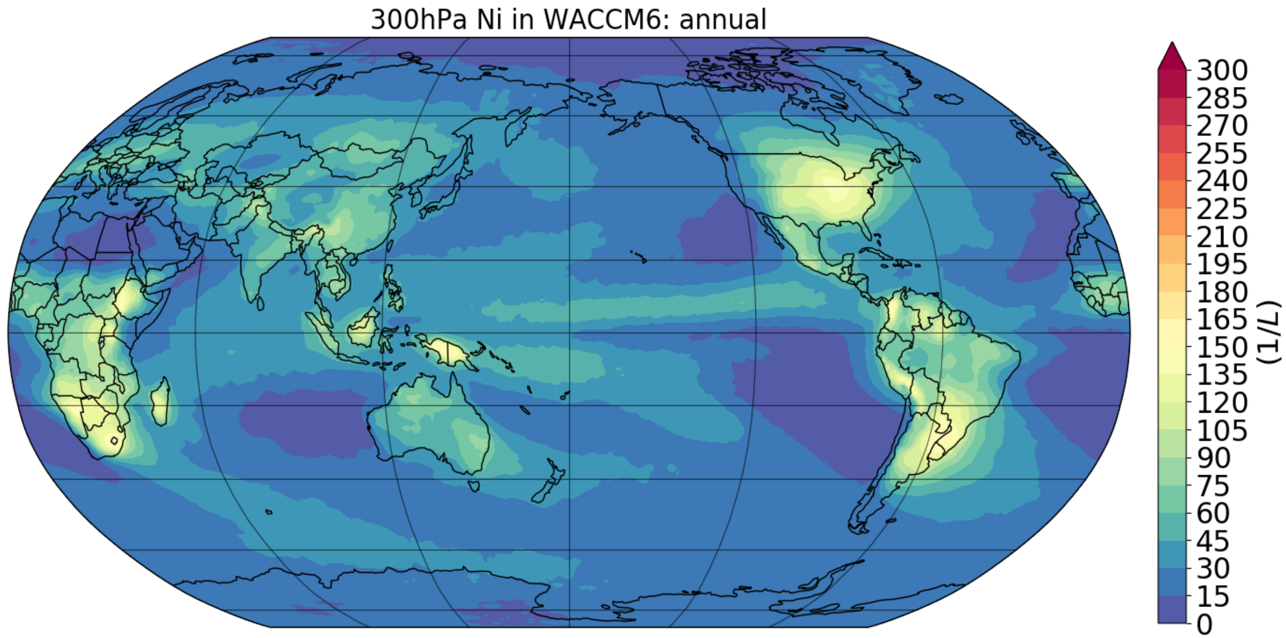


Comparisons of three ice fall speed schemes (including the scheme used in CAM6; MG2) against the scheme developed for this study. Both mass- and number-weighted fall speeds, V_m and V_n, are calculated in each scheme. The closer to the zero line, the closer the agreement is. The Mishra et al. scheme generally agrees within 20% and 30% for V_n and V_m, respectively, while the Heymsfield-Westbrook scheme generally agrees with V_m within 30%.

Annual means for std. WACCM6 D_e and N (in-cloud) at 300 hPa

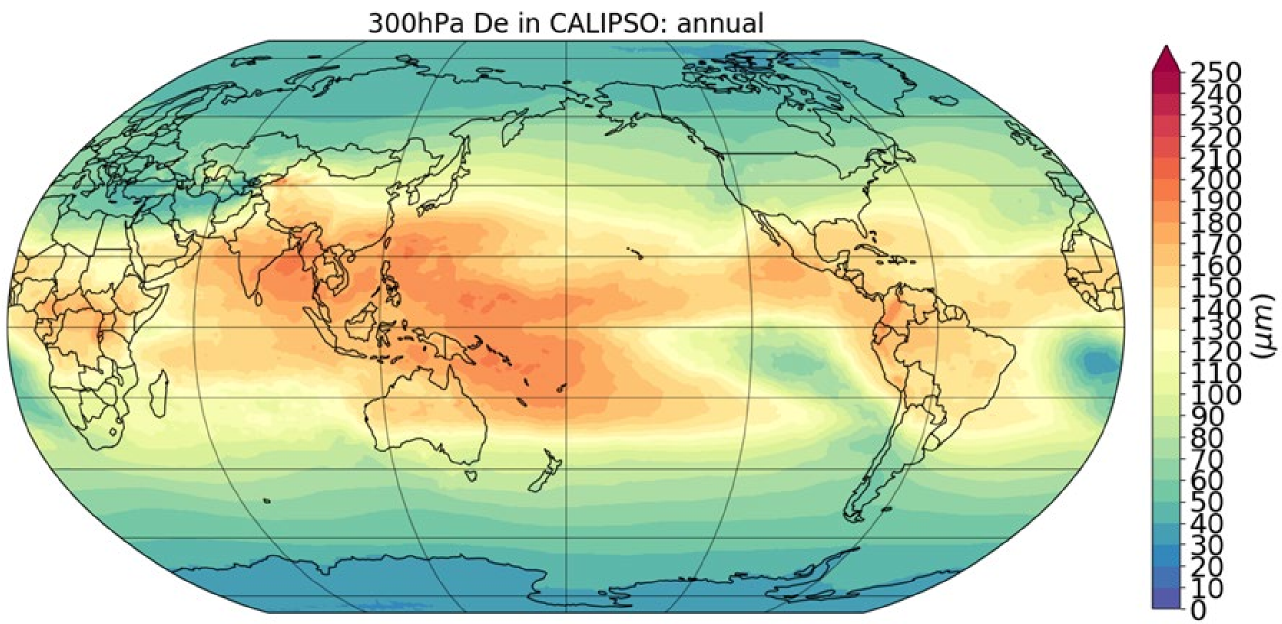


D_e

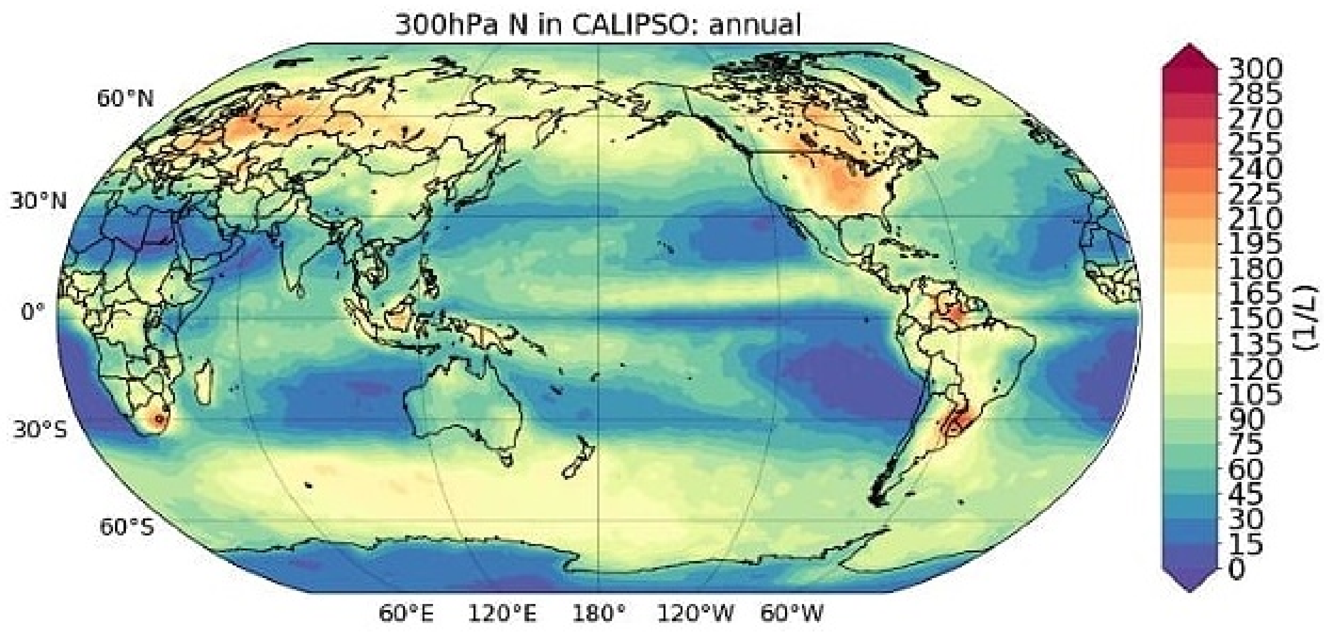


N

Annual means for CALIPSO D_e and N (in-cloud) at 300 hPa



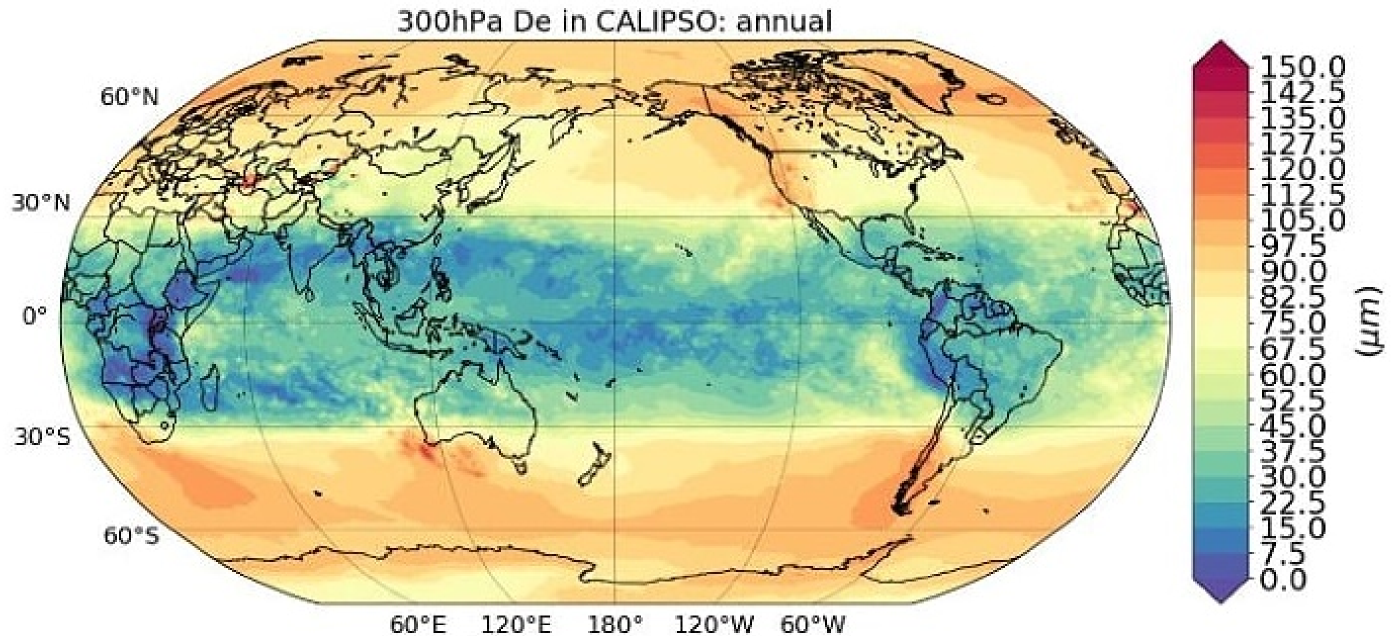
D_e



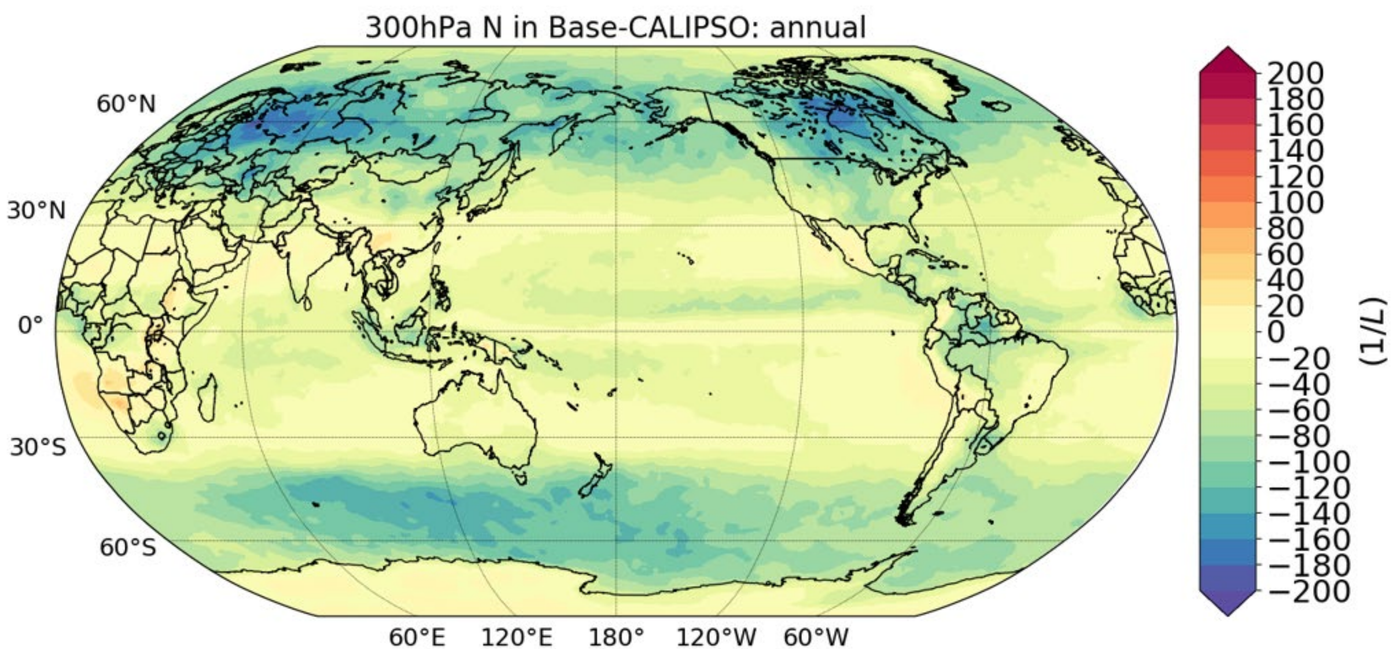
N

Standard WACCM6 – CALIPSO D_e and N differences (in-cloud) at 300 hPa

D_e



N

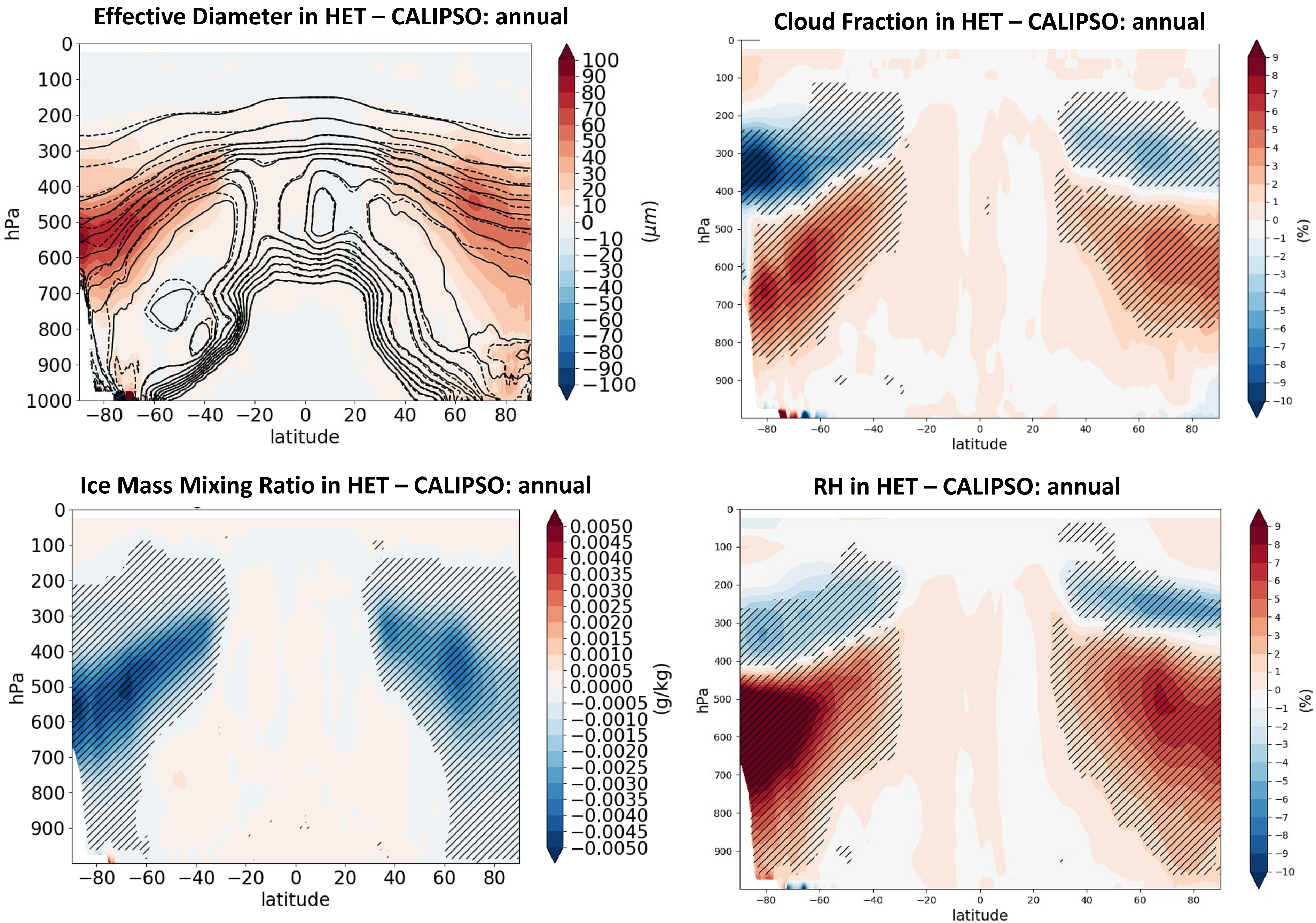


Comparing the standard, CALIPSO and Het versions of WACCM6 for CRE differences (CRE = LWCF + SWCF): Global annual means and for outside the tropics (W m^{-2})

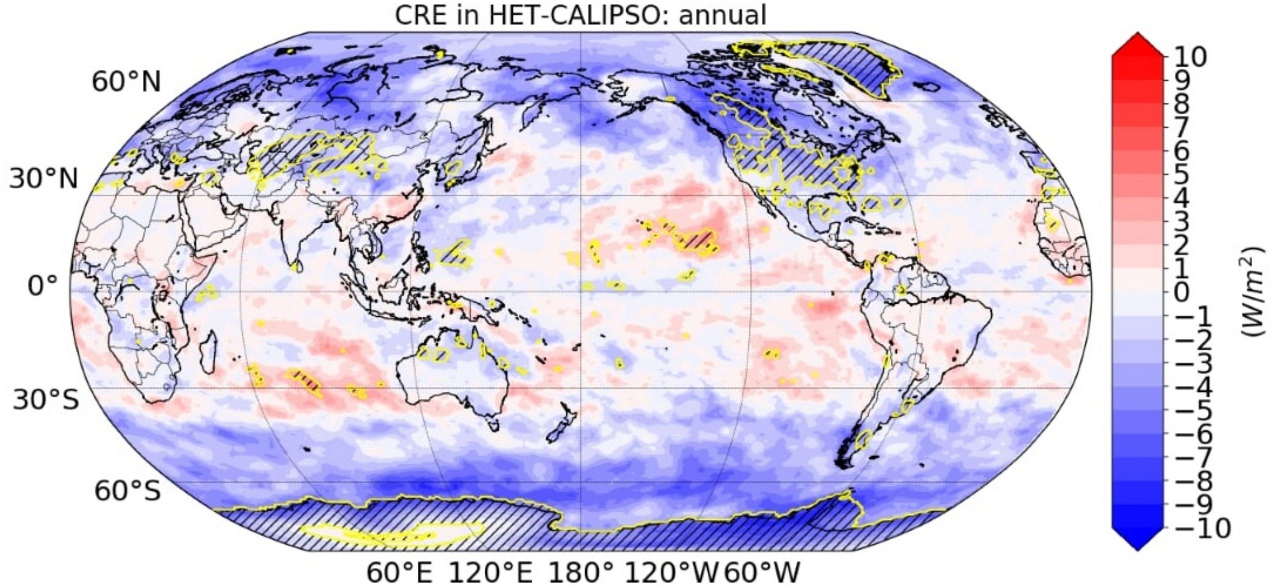
N.H. is Northern Hemisphere 30N – 90N

S.H. is Southern Hemisphere 30S – 90S

	WACCM6 – CALIPSO	WACCM6 – Het	Het – CALIPSO
Global	-1.16	0.67	-1.83
N.H.	-2.22	0.33	-2.55
S.H.	-3.11	-0.10	-3.01

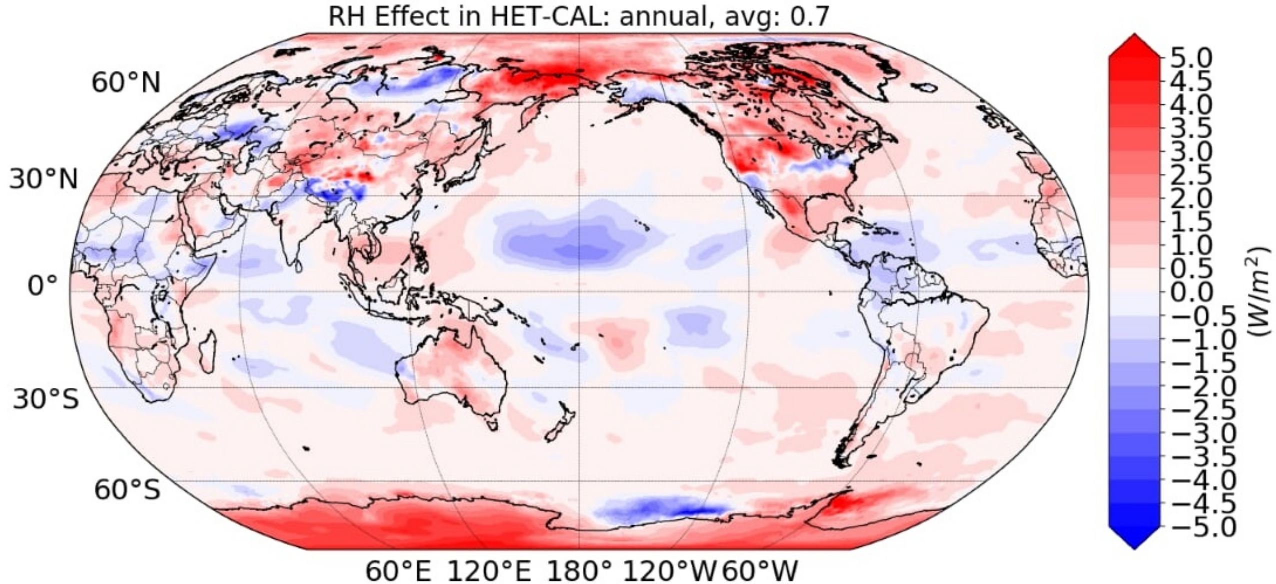

Effective Diameter in HET – CALIPSO: annual
hPa
latitude
(μm)
Cloud Fraction in HET – CALIPSO: annual
hPa
latitude
(%)
Ice Mass Mixing Ratio in HET – CALIPSO: annual
hPa
latitude
(g/kg)
RH in HET – CALIPSO: annual
hPa
latitude
(%)

Het – CALIPSO net CRE (LWCF + SWCF), annual mean



Net all-sky flux HET – CALIPSO difference at TOA minus CRE difference, annual mean

This is the relative humidity TOA net radiative forcing difference



Het – CALIPSO net CRE, net RH forcing and total net forcing at TOA for annual means and means excluding summer (W m^{-2})

N.H. is Northern Hemisphere 30N – 90N
S.H. is Southern Hemisphere 30S – 90S

	Δnet CRE		Δnet RH forcing		Δ total net forcing	
	Annual	No-summer	Annual	No-summer	Annual	No-summer
Global	-1.83	-2.13	0.706	0.660	-1.12	-1.47
N.H.	-2.55	-2.68	0.536	0.213	-2.01	-2.47
S.H.	-3.01	-3.74	0.876	1.11	-2.13	-2.63

Note: No-summer applies to both hemispheres, meaning JJA omitted for NH, and DJF omitted for SH.

Summary and Conclusions

1. D_e in the Morrison-Gettelman microphysics version 2 (MG2) in WACCM6 was constrained using CALIPSO D_e retrievals. Results were compared with std. WACCM6 and the "HET" simulations.

2. D_e (N) in WACCM6 was much larger (lower) than in the CALIPSO simulation outside the tropics during non-summer months.

3. Orographic gravity wave trains appear important to hom cirrus formation. Refined mesh might better represent these?

4. In WACCM6, CAM6, ECHAM6 and CESM2, the "pre-existing ice" assumption is universally applied. These results suggest this is misguided, with relatively high N (from wave-induced cirrus?) outside the tropics (± 30° latitude).

5. CALIPSO differs from HET and WACCM6 for TOA annual mean forcing outside the tropics by ~ 2 W m^{-2}.

EXTRA SLIDES

CALIPSO (IIR-CALIOP) Retrieval Specifications

Resolution is 1km
IIR quality flag= good
IIR pixels co-located with CALIOP track

Types of scene => single-layered clouds not opaque to CALIOP lidar
Cloud base temperature < 235K
CALIOP Integrated Attenuated Backscatter > 0.01 sr^{-1}
=> $\sim 0.3 < OD_{vis} < \sim 3$

Cloud layer « centroid » temperature = temperature at height dividing the CALIOP attenuated backscatter profile into equal parts.

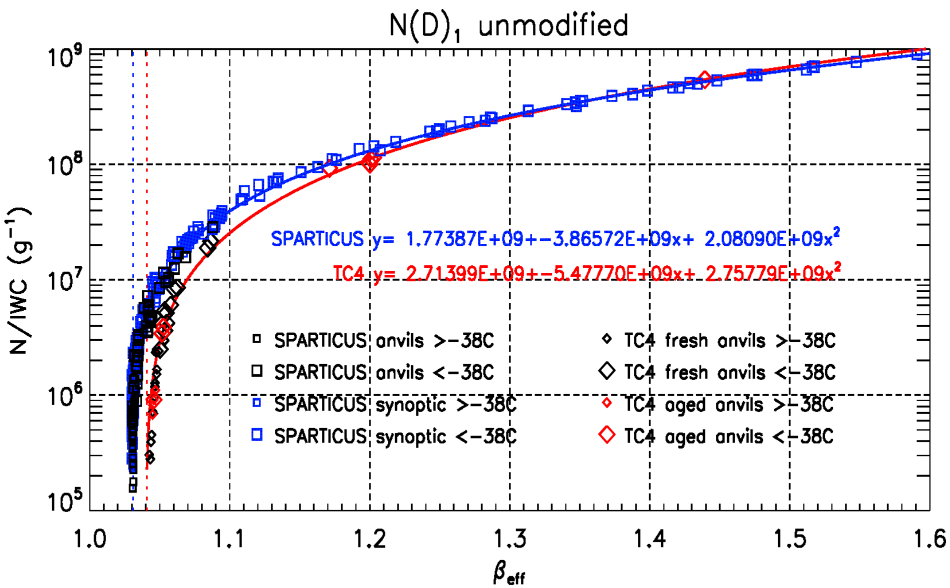
Reference – Blackbody BTD > 20K

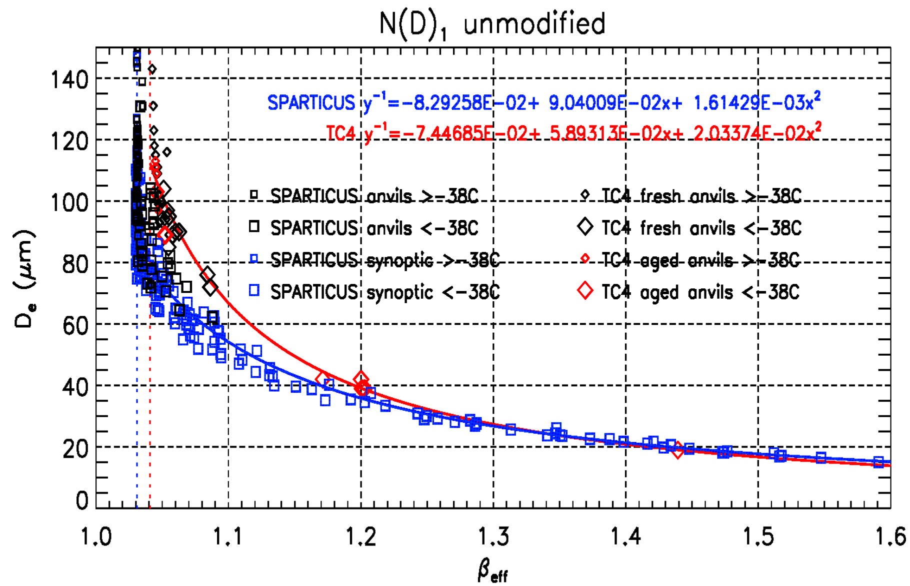
Error estimates (not shown) => measurements ± 0.3 K, reference ±1K, blackbody ±2K

Effective absorption optical depth ratio: $\beta = \tau(12\ \mu m) / \tau(10.6\ \mu m)$

The N Retrieval Equation

$$N = \frac{\rho_i \ [2/\ \bar{Q}_{abs}(12\ \mu m)]\ \tau_{abs}(12\ \mu m)\ D_e}{3\ \Delta z_{eq}} \left(\frac{N}{IWC}\right)$$



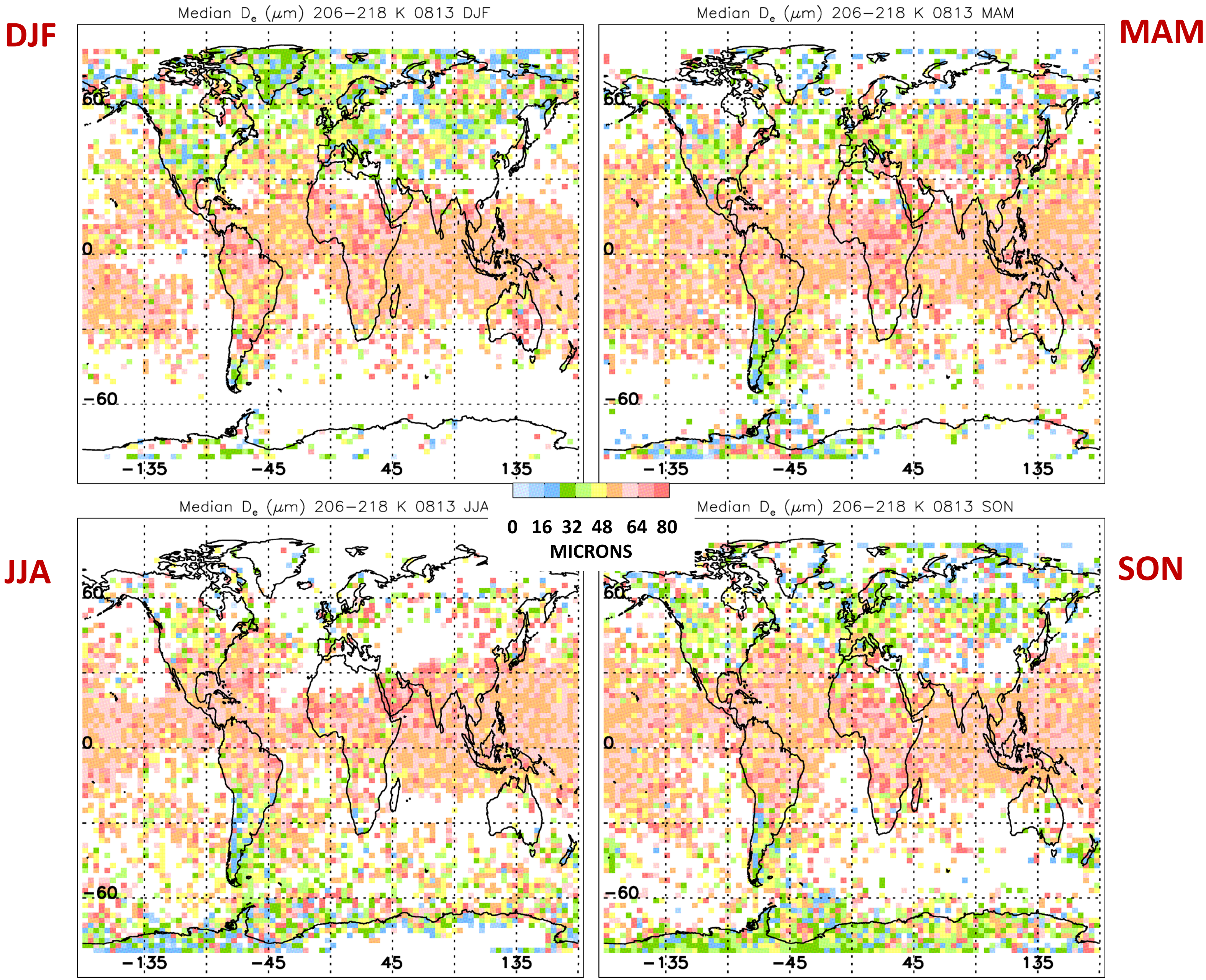


The quantities N/IWC, D_e , area-weighted Q_{abs} and β_{eff} are determined from measured ice particle size distributions (PSDs) and, for the retrieval, empirical fits as shown above.

The retrieval formulation depends on what field campaign it is based on (SPARTICUS or TC4) and whether the 1^{st} size-bin of the 2D-S probe (5-15 μm) was used to represent the PSDs measured in these campaigns.

Effective diameter is smallest at high latitudes and over high terrain

Plots show D_e between 206 and 218 K for 2008 and 2013



Calculation of ice particle number concentration

Cirrus cloud ice particle size distribution (PSD) has a single slope (λ) determined from D_e (instead of different λ for cloud ice & snow).

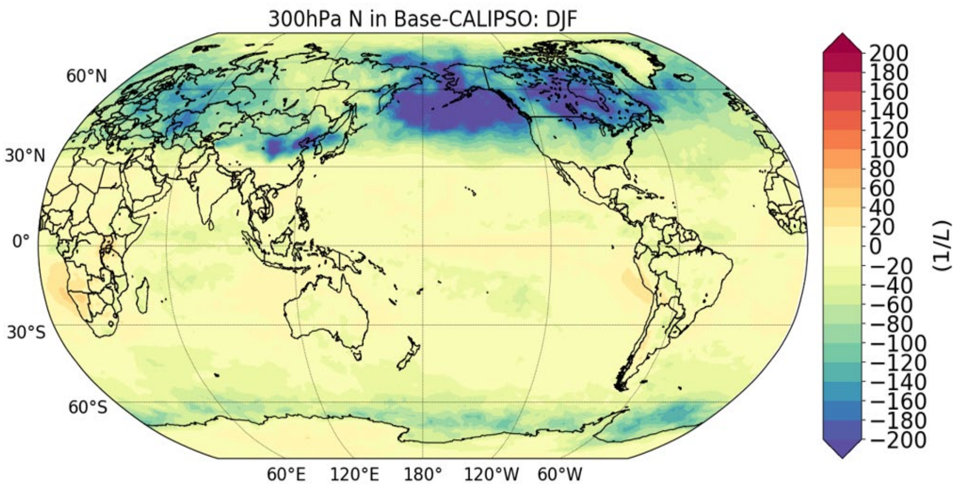
$$N = \frac{IWC \;\; \lambda^{\beta}}{\alpha\, \Gamma(\beta + 1)} = \frac{q_{ice} \;\; \rho_{air} \;\; \lambda^{\beta}}{\alpha\, \Gamma(\beta + 1)}$$

IWC = ice water content, q_{ice} = ice mass mixing ratio, ρ_{air} = air density, ice particle mass = m = $\alpha\, D^{\beta}$, D = particle maximum dimension. Constants α and β are representative of cirrus cloud ice particles.

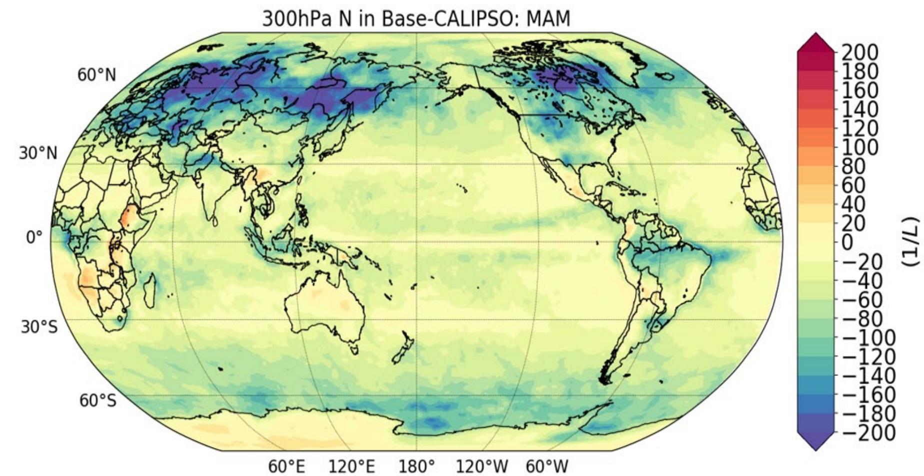
Constraining D_e with CALIPSO observations allows N to be calculated from PSD moments invoking conservation of mass. This avoids many uncertainties associated with ice nucleation. The PSD y-intercept parameter $N_0 = \lambda N$; N_0 affects PSD vapor deposition rates.

Standard WACCM6 – CALIPSO N differences for in-cloud N at 300 hPa

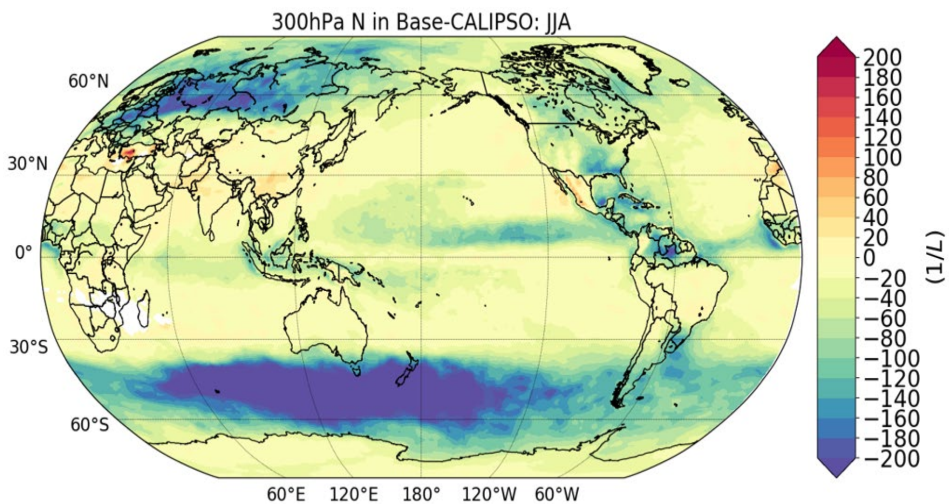
DJF



MAM



JJA



SON