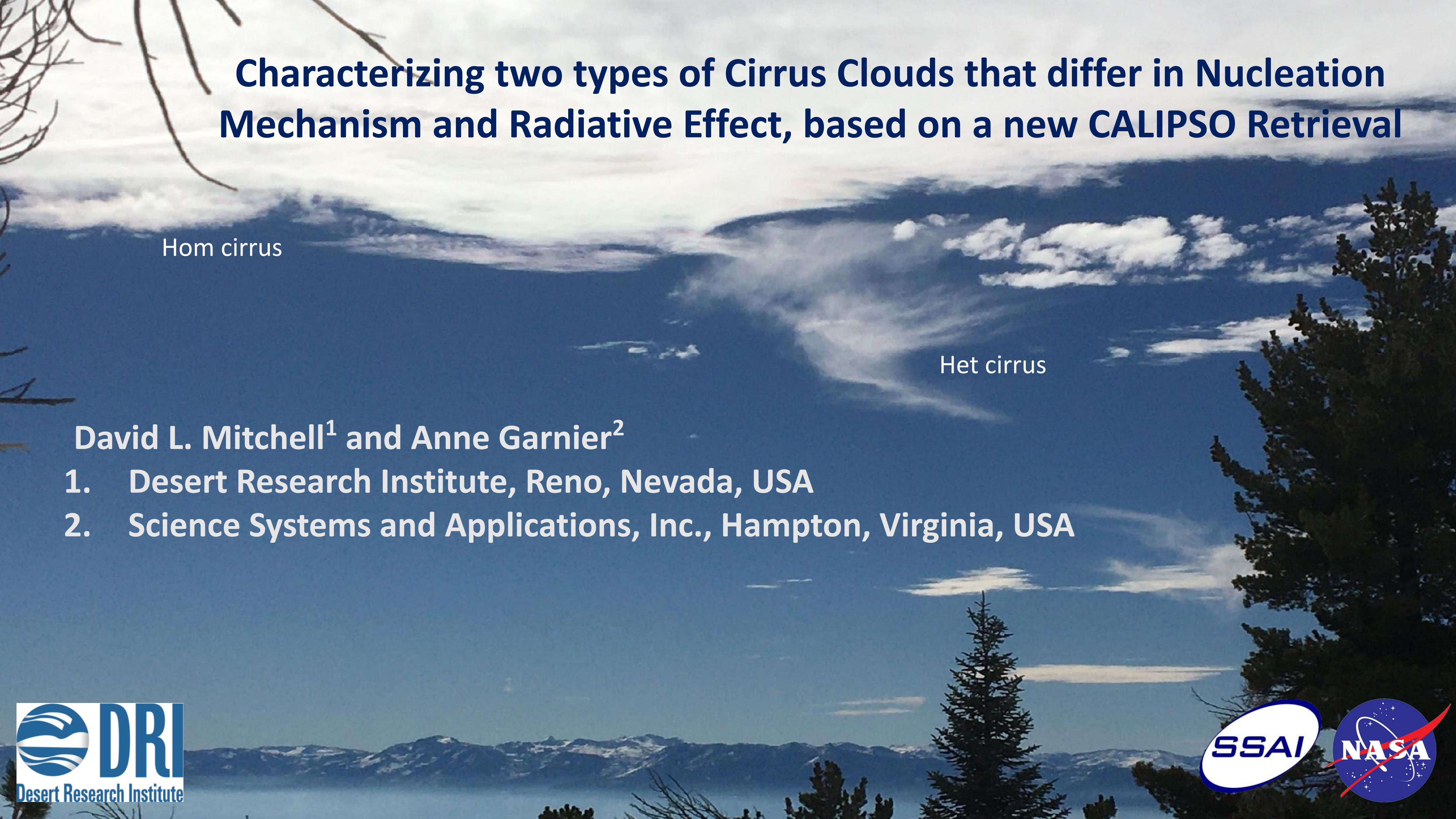
Characterizing two types of Cirrus Clouds that differ in Nucleation Mechanism and Radiative Effect, based on a new CALIPSO Retrieval



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Since last year's talk covered the methodology of this new CALIPSO satellite retrieval, this year's talk will cover only the results (i.e., time is too limited to cover both). However, a few fundamentals can be mentioned:

1. Only single-layer ice clouds are sampled that are semi-transparent to the CALIOP lidar.

2. Most of the clouds have a visible optical depth < 3.

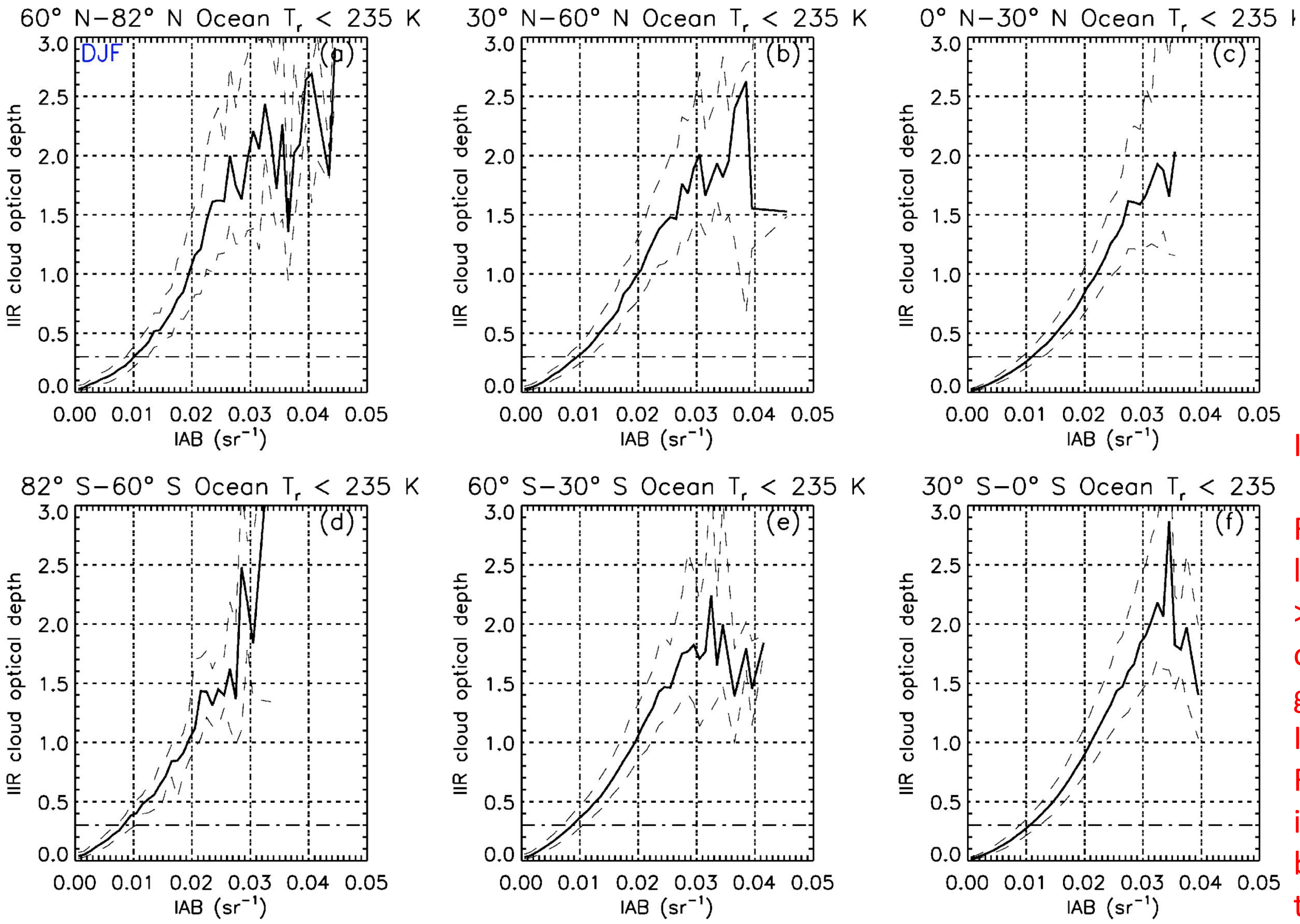
3. Retrieved cloud properties correspond to cloud layers and not in-cloud profiles.

4. Sampled clouds have a radiative temperature of ≤ 235 K (-38 °C).

5. The following analysis is based on 4 years of CALIPSO data.

Comparing cloud optical depth (OD) with integrated attenuated backscatter (IAB): OD uncertainty

OCEANS
DJF
4 years



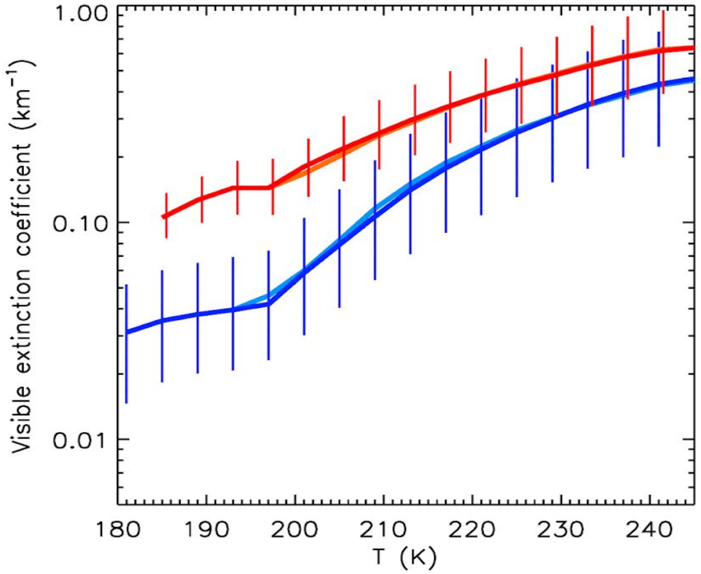
Solid: median
Dashed: 25th and 75th percentiles

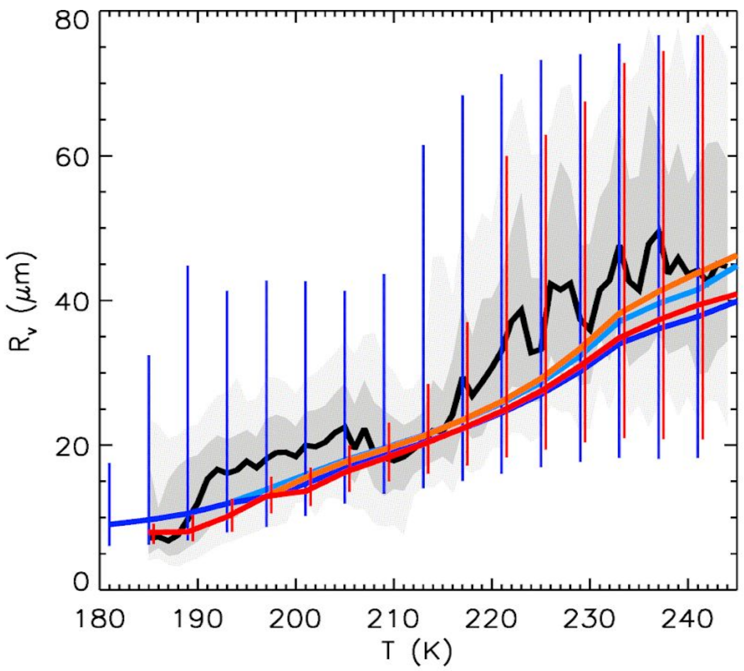
IAB ≈ 0.01 for OD ~ 0.3

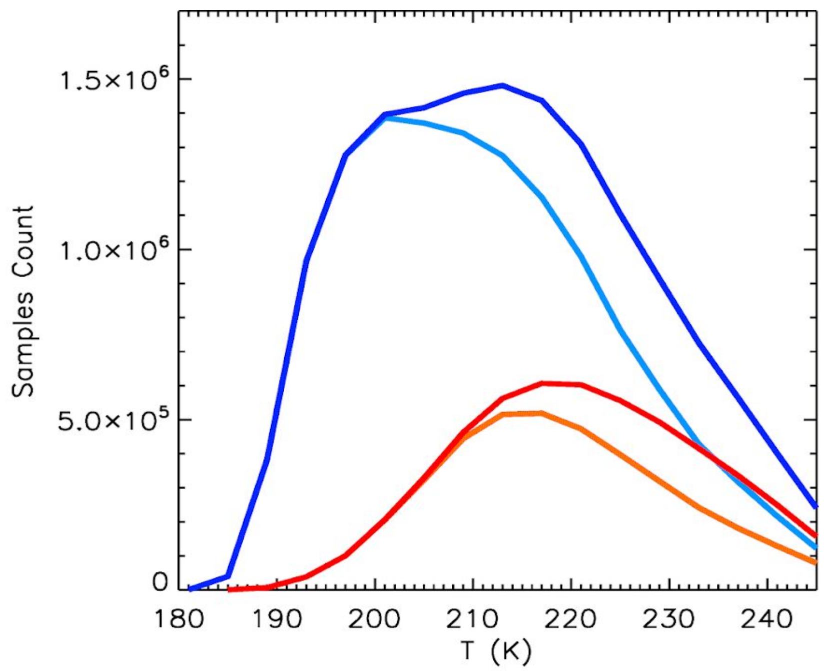
Retrievals are valid over land and ocean for IAB > 0.01 sr^{-1}, while valid only over oceans with greater uncertainty for IAB < 0.01 sr^{-1}. Retrievals are grouped into two categories based on this IAB threshold.

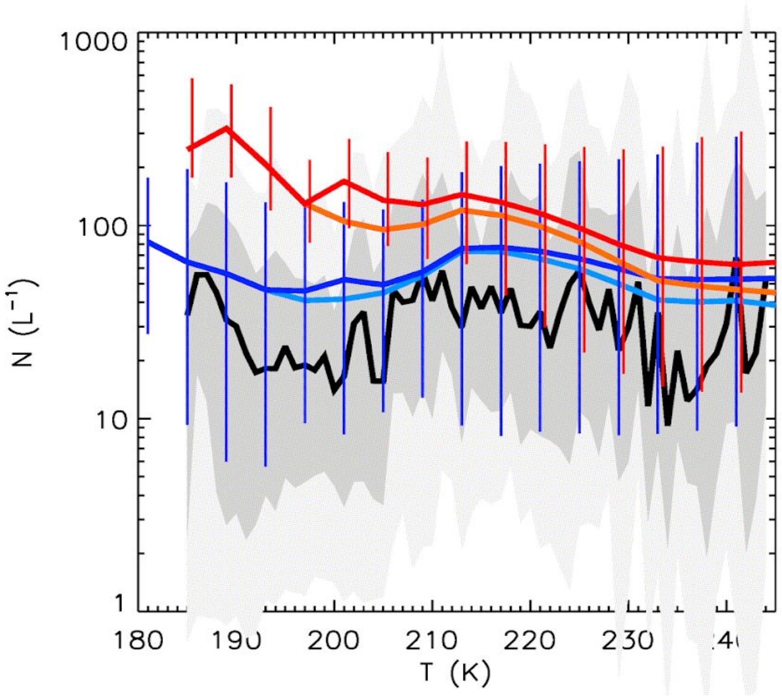
Comparison with global cirrus cloud climatology of Krämer et al. (2020, ACP) based on aircraft measurements (black curves).

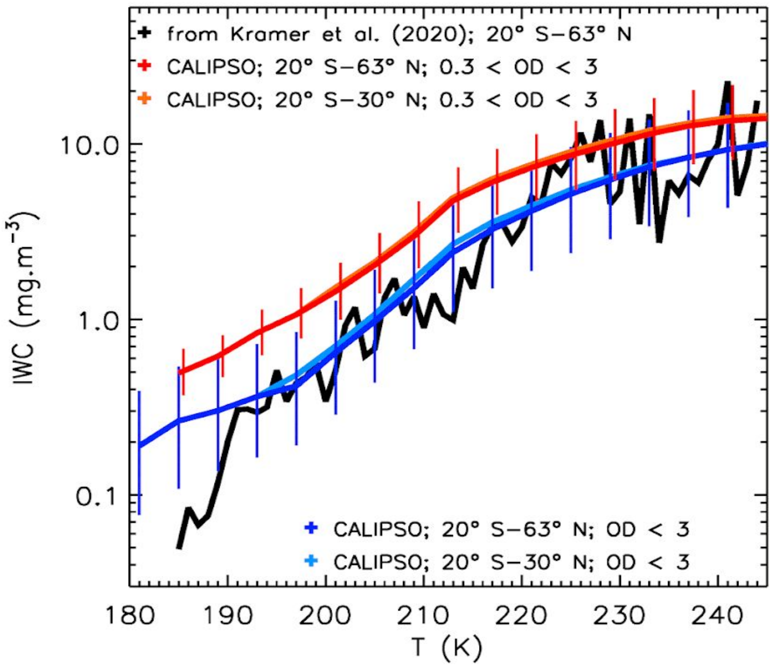
Reasonable agreement for all IIR samples (~ 0.005 < OD < ~ 3; OD = cloud optical depth) => blue curves; less agreement for 0.3 < OD < 3.0 where uncertainty is lowest => orange & red curves. Orange & light-blue curves are for tropics only. Bars & shading give percentiles (10%, 25%, 75% & 90%).

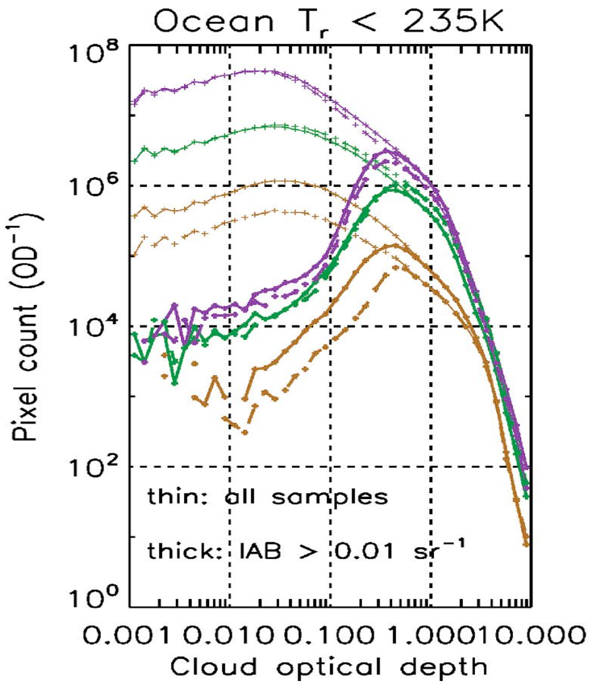


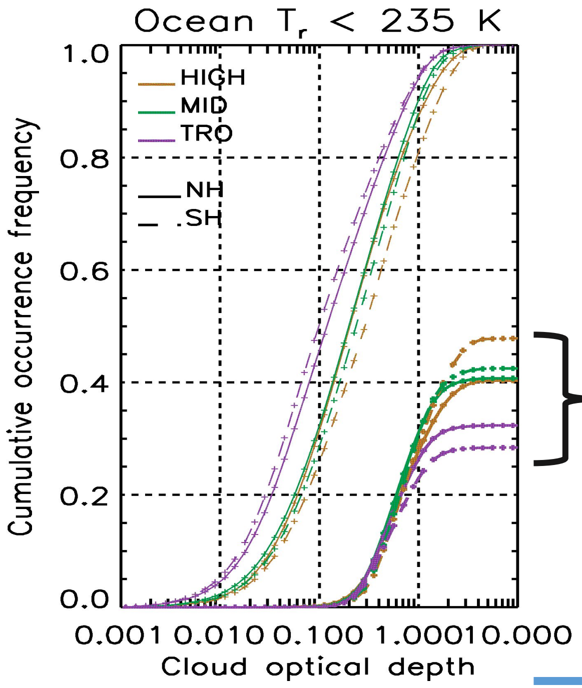








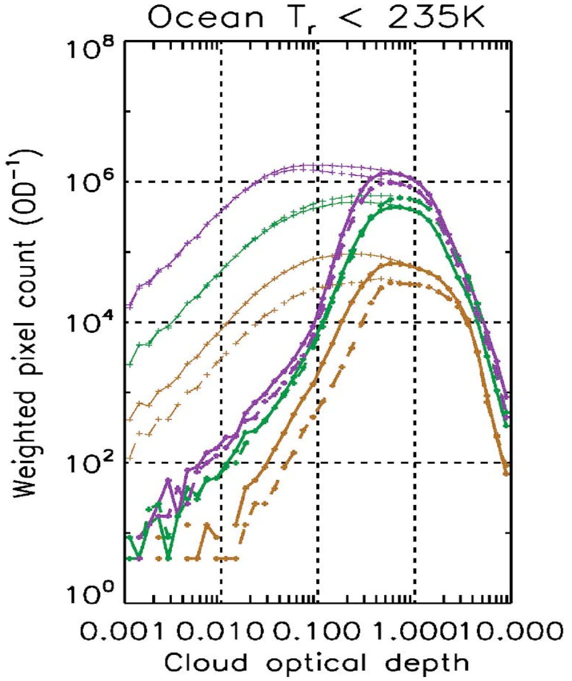


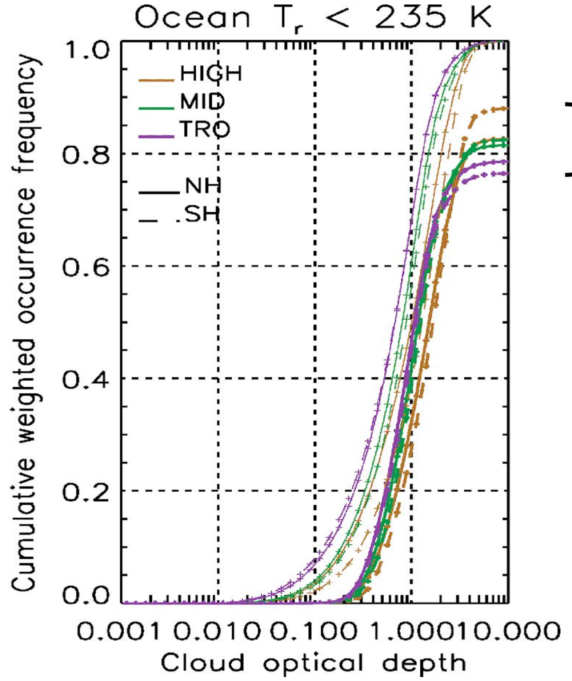


Normalized to total number of samples for all sampled cirrus

Samples with IAB > 0.01 sr^{-1} represent 28 to 48 % of all samples.

Looking at occurrence frequencies of cirrus samples having the lowest uncertainty (IAB> 0.01 sr^{-1})





76% to 88% of total weighted samples for all cirrus samples

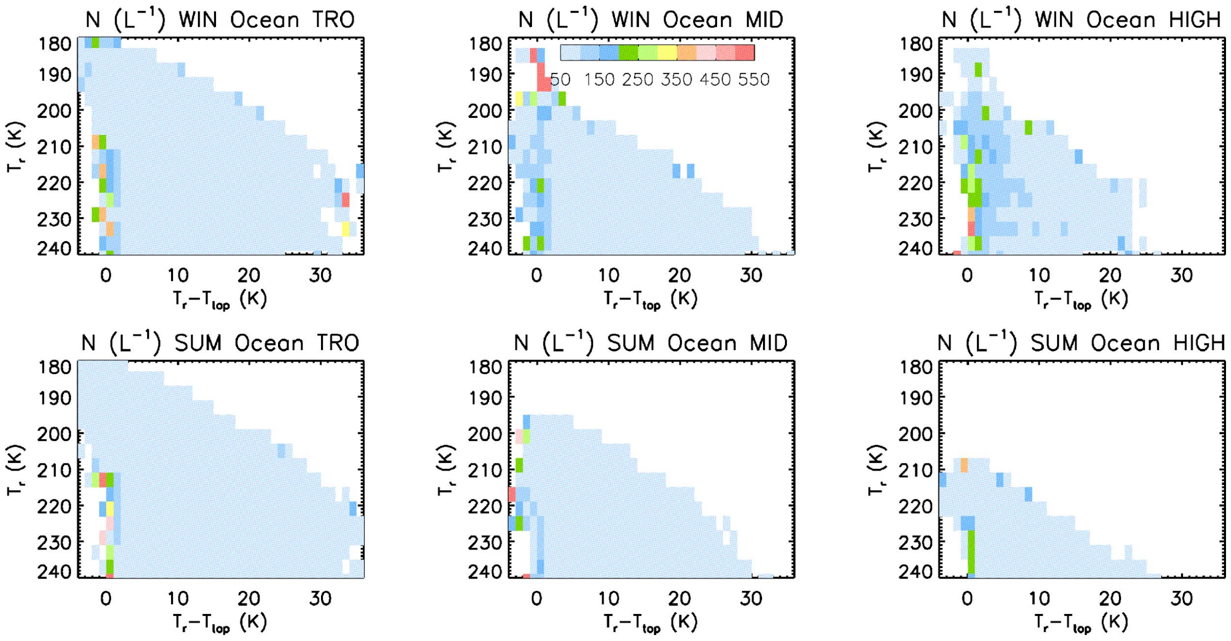
Normalized to total number of weighted samples for all sampled cirrus clouds

Net cloud radiative effect or CRE is approximated as pixel count x optical depth = weighted pixel count

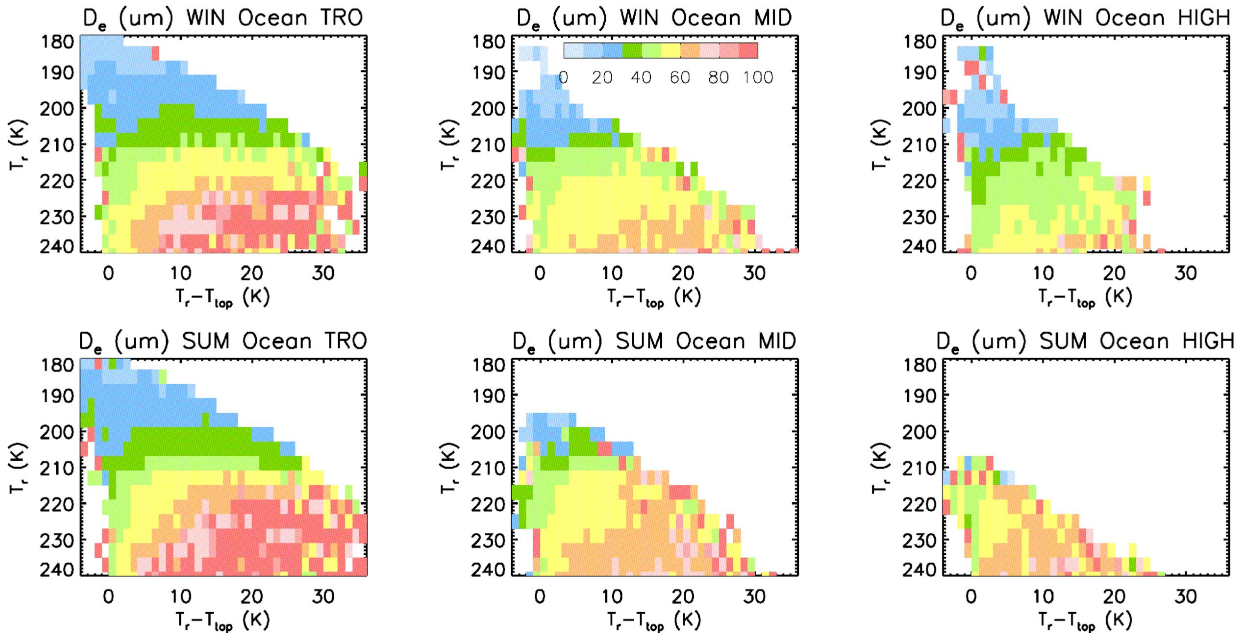
76% to 88% of the net cloud radiative effect for all cirrus clouds appears to be associated with IAB > 0.01 sr^{-1}, or OD > ~ 0.3.

In situ and liquid origin cirrus combined – **IAB < 0.01 sr^{-1} (OD < ~ 0.3)**

Number concentration N (L^{-1})



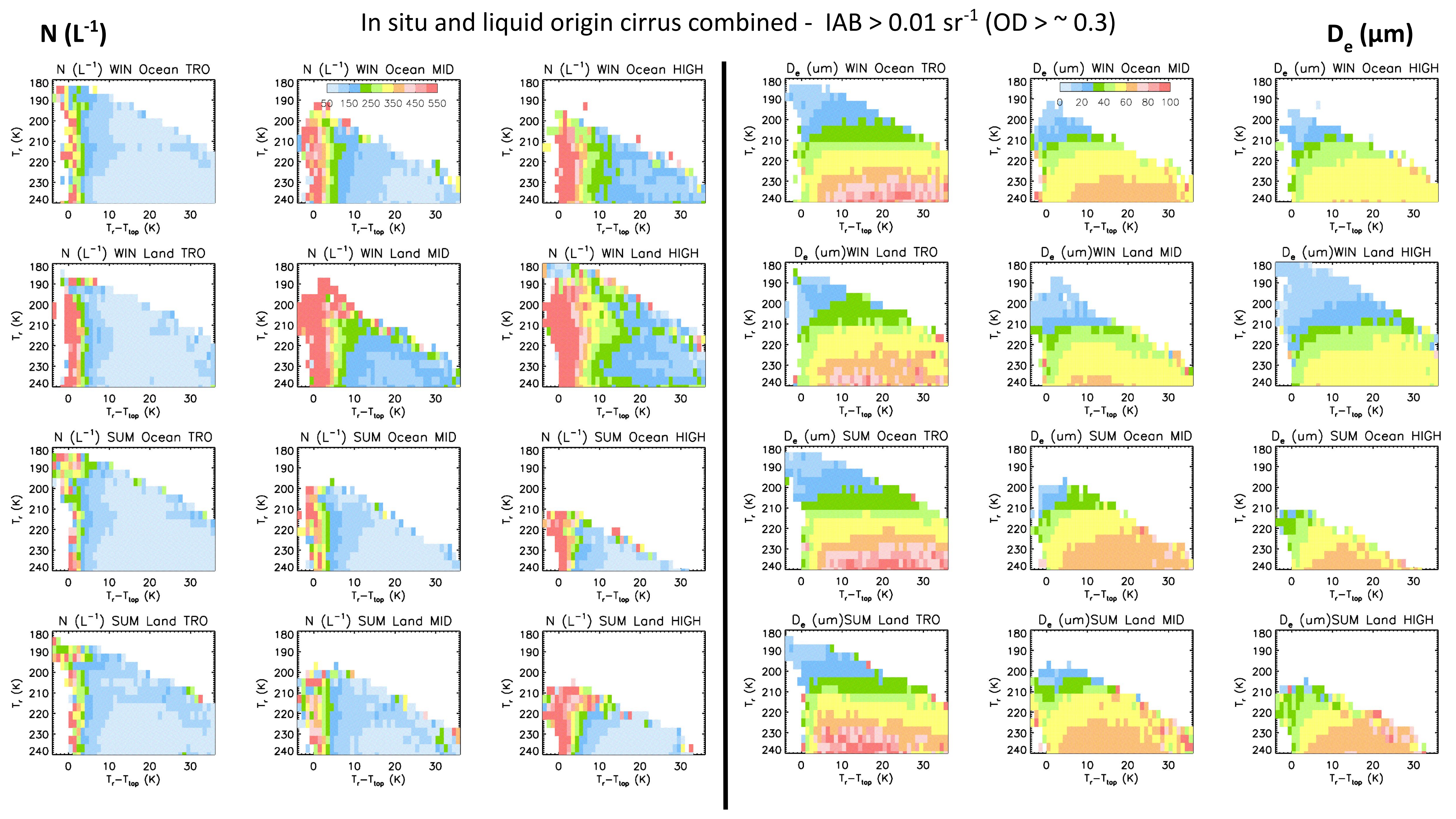
Effective diameter D_e (μm)



T_r = radiative temperature of cloud

T_{top} = cloud top temperature

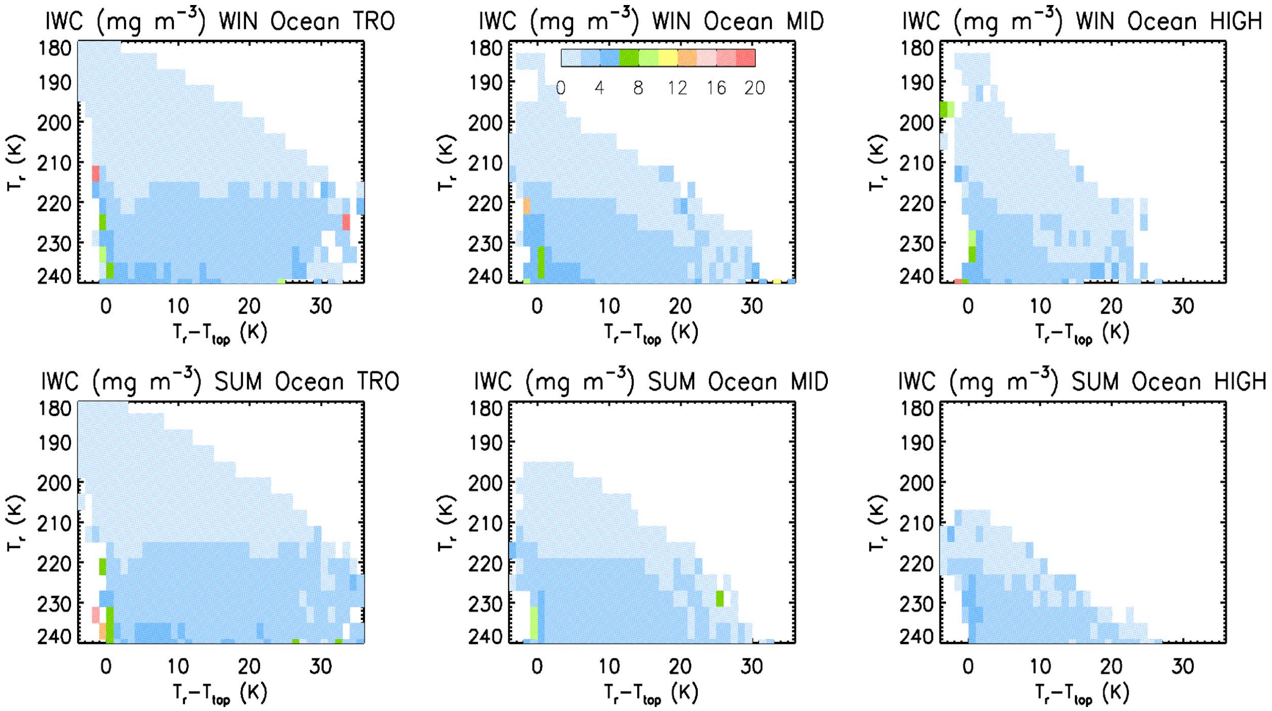
$T_r - T_{top}$ = related to the cloud geometric thickness because T_r is most of the time near mid-cloud.



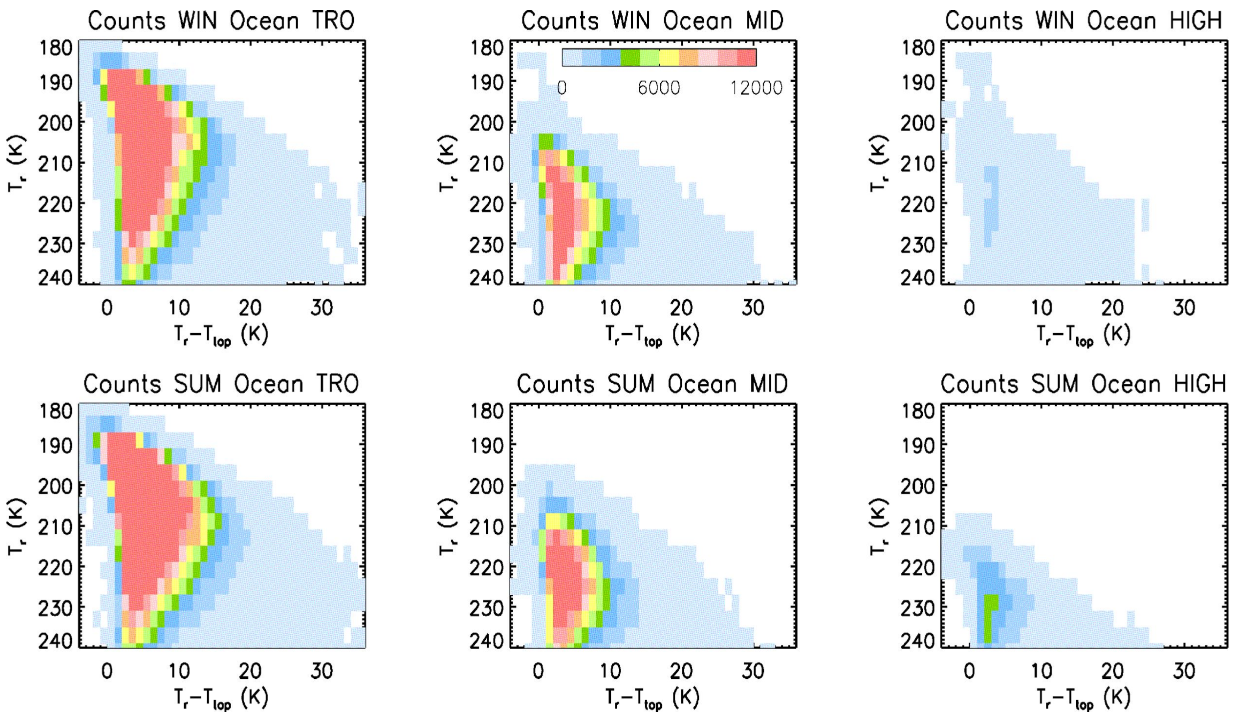
In situ and liquid origin cirrus combined - IAB > 0.01 sr^{-1} (OD > ~ 0.3)
N (L^{-1})
D$_e$ (μm)
N (L^{-1}) WIN Ocean TRO
N (L^{-1}) WIN Ocean MID
50 150 250 350 450 550
N (L^{-1}) WIN Ocean HIGH
D$_e$ (um) WIN Ocean TRO
D$_e$ (um) WIN Ocean MID
0 20 40 60 80 100
D$_e$ (um) WIN Ocean HIGH
N (L^{-1}) WIN Land TRO
N (L^{-1}) WIN Land MID
N (L^{-1}) WIN Land HIGH
D$_e$ (um)WIN Land TRO
D$_e$ (um)WIN Land MID
D$_e$ (um)WIN Land HIGH
N (L^{-1}) SUM Ocean TRO
N (L^{-1}) SUM Ocean MID
N (L^{-1}) SUM Ocean HIGH
D$_e$ (um) SUM Ocean TRO
D$_e$ (um) SUM Ocean MID
D$_e$ (um) SUM Ocean HIGH
N (L^{-1}) SUM Land TRO
N (L^{-1}) SUM Land MID
N (L^{-1}) SUM Land HIGH
D$_e$ (um)SUM Land TRO
D$_e$ (um)SUM Land MID
D$_e$ (um)SUM Land HIGH
T$_r$ (K)
T$_r$−T$_{top}$ (K)

In situ and liquid origin cirrus combined – **IAB < 0.01 sr^{-1}**

Ice water content or IWC (mg m^{-3})

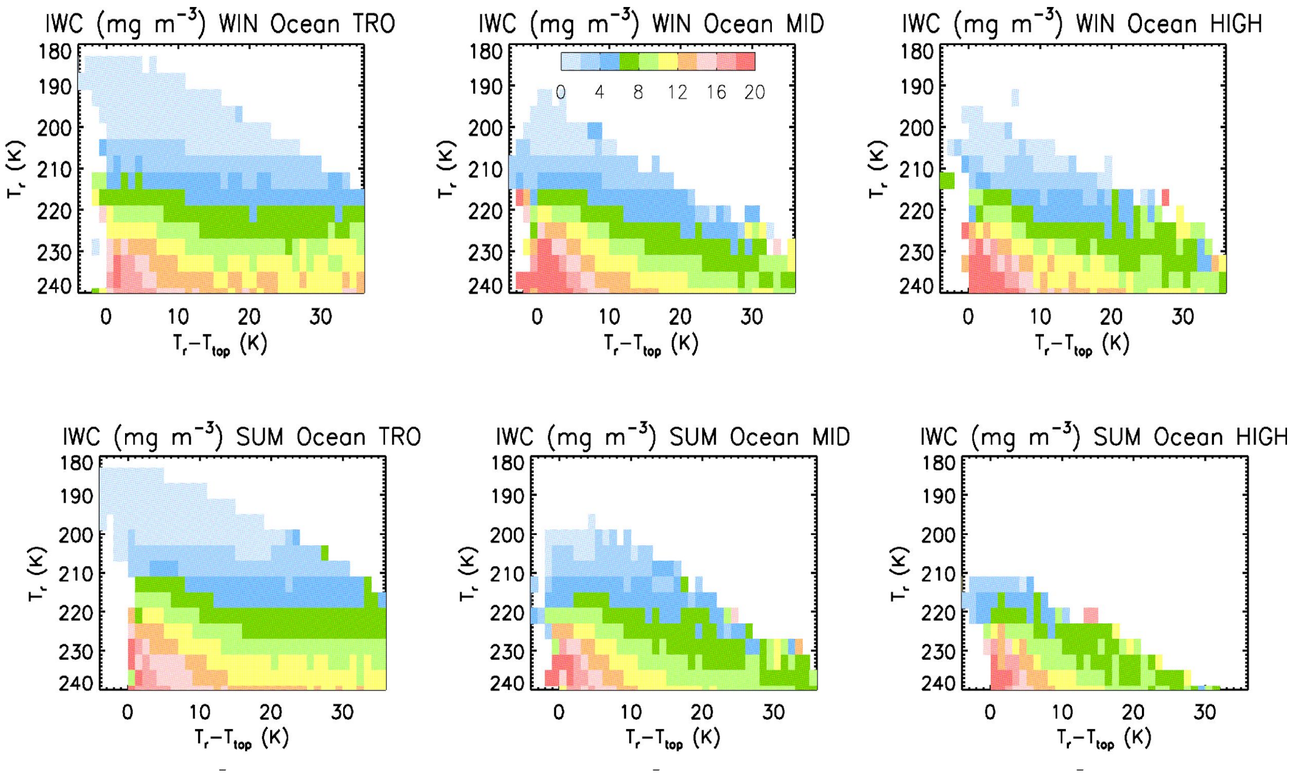


Samples Count

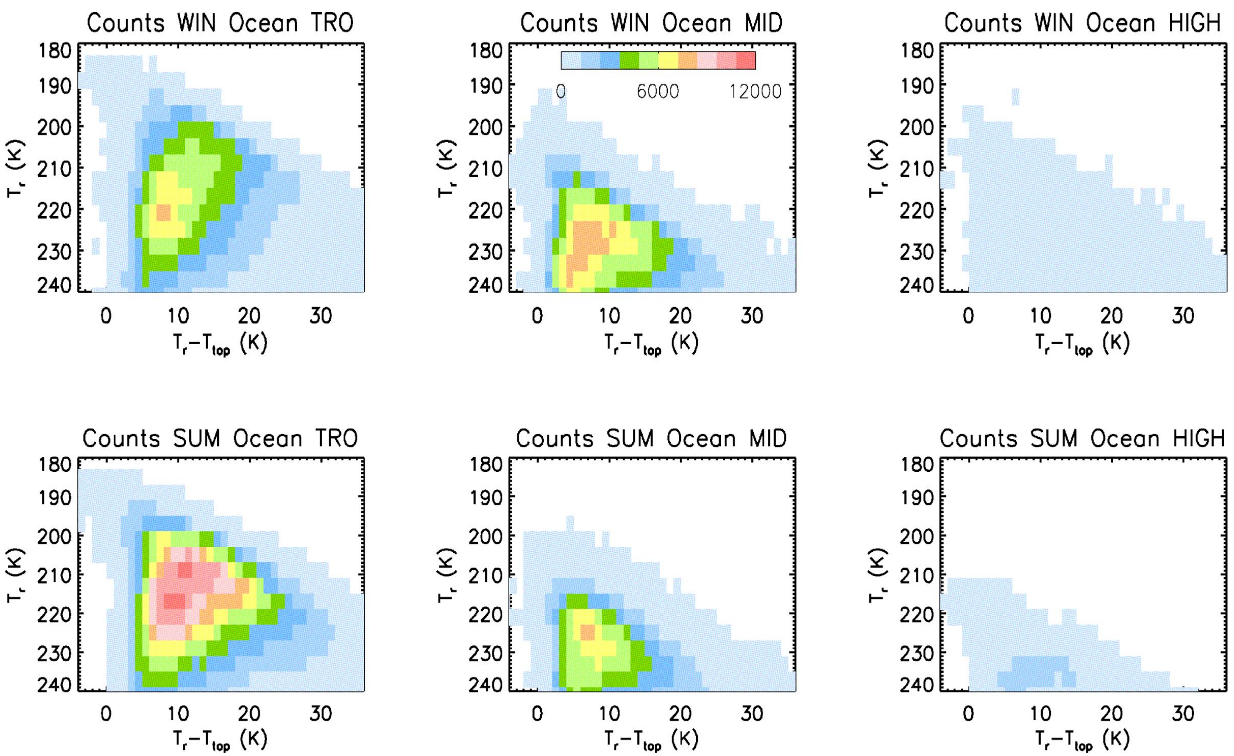


In situ and liquid origin cirrus combined - **IAB > 0.01 sr^{-1}**

IWC (mg m^{-3})



Samples Count



Summary of these results:

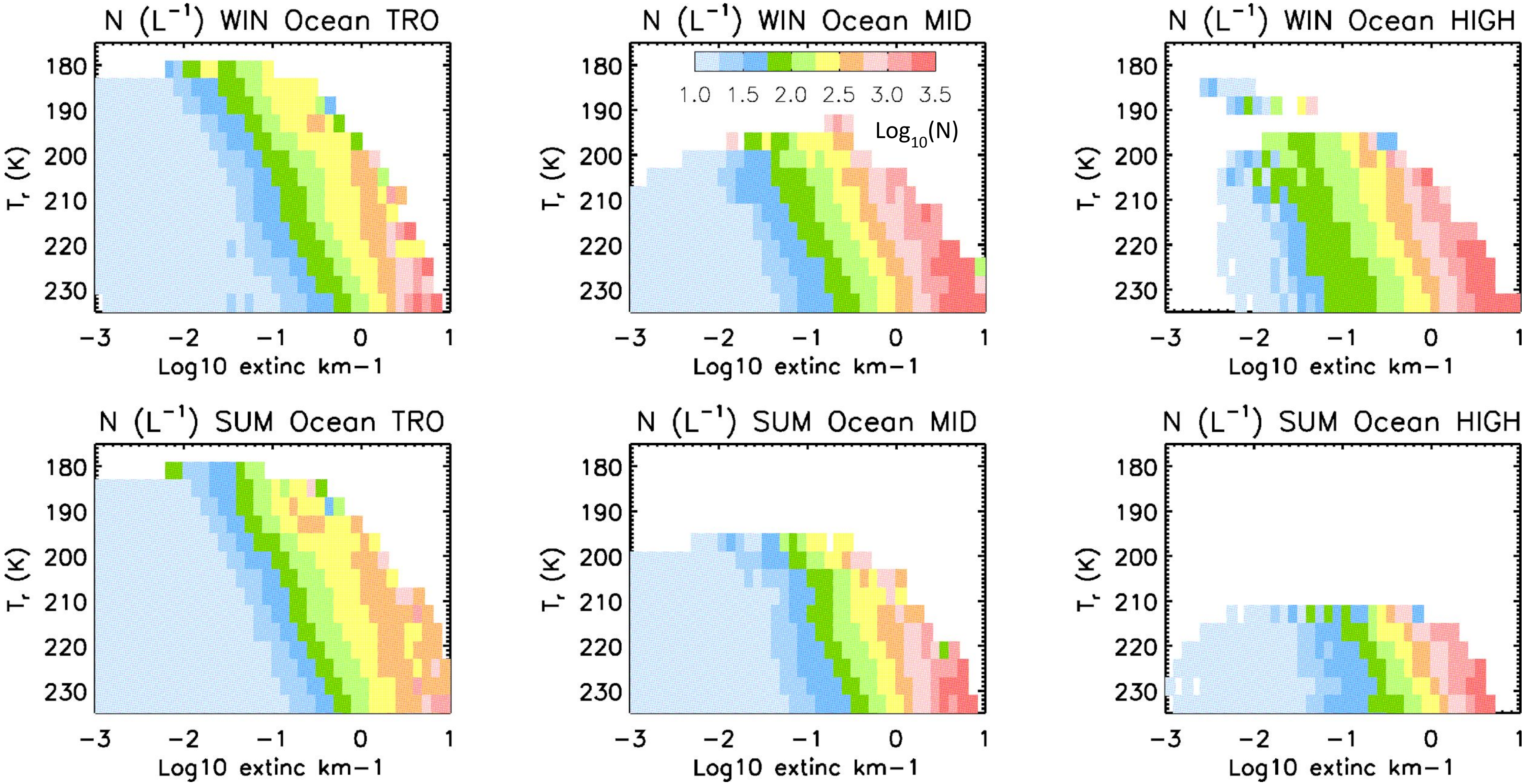
1. **When homogeneous ice nucleation (i.e., hom) is relatively active (i.e., N is higher), IWC is higher and D_e tends to be smaller.**

2. **Therefore, to distinguish between these two types of cirrus clouds, where one is formed primarily through heterogeneous ice nucleation (i.e., het) while hom is also active in the other type, use the cloud visible extinction coefficient defined as:**

$$\alpha_{ext} = \frac{3\ IWC}{\rho_i\ D_e}$$

where ρ_i is the bulk density of ice.

All Cirrus Clouds: Analysis shows two types of cirrus



To understand these results, a very simple model was used and is described below:

Clausius-Clapeyron Equation:

$$e_{si} = e_{s0} \exp\left[\frac{L_s}{R_g}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$

e_{si} = water vapor pressure at ice saturation, L_s = latent heat of sublimation
R_g = gas constant

Supersaturation required for homogeneous ice nucleation:

$$e_s / e_{si} = \exp\left[\frac{L_f}{R_g}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

e_s = water vapor pressure at water saturation, L_f = latent heat of fusion

$$S_i^f = 1.0 + 0.305\,(e_s/e_{si})$$

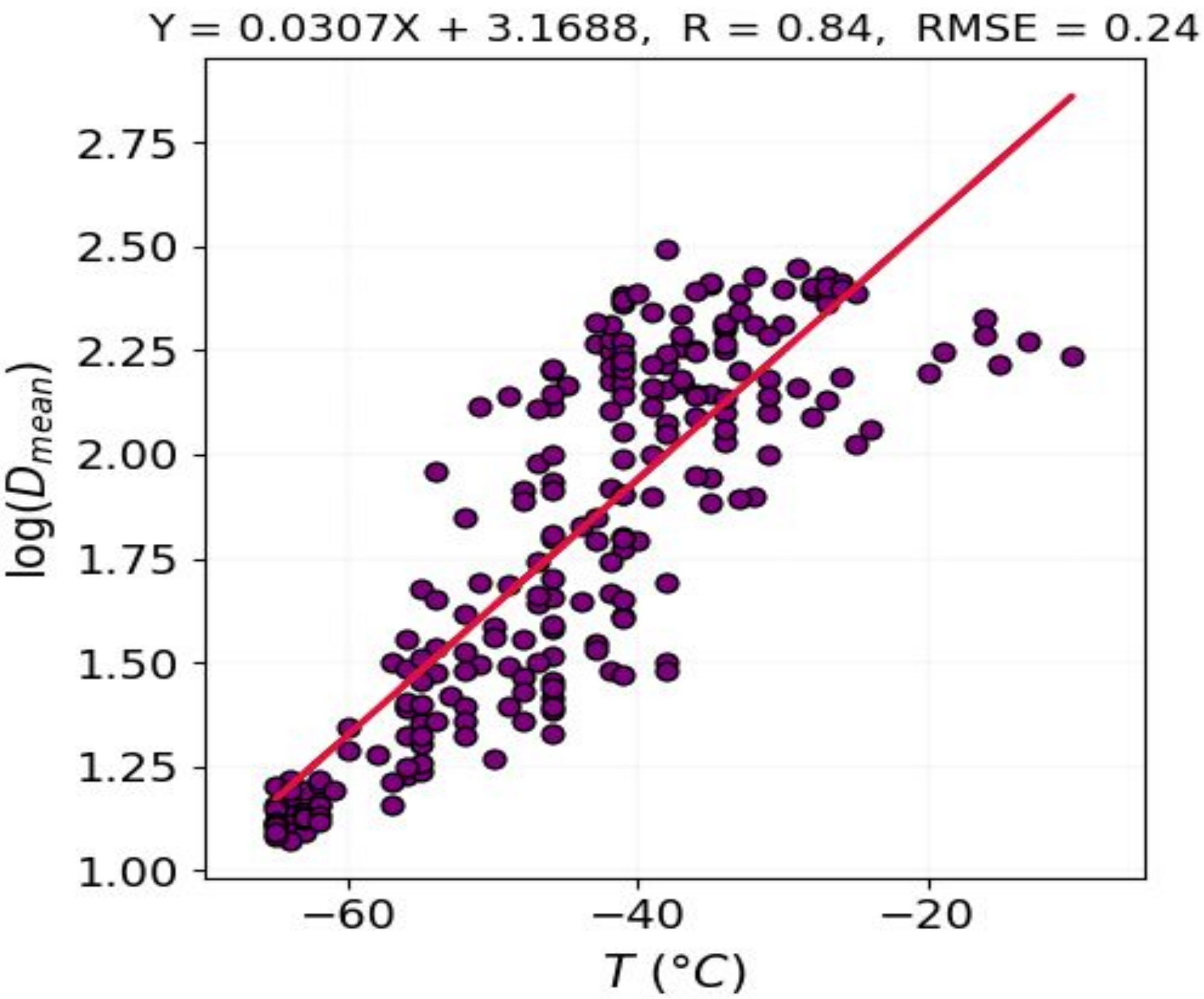
S_i^f = supersaturation where homogeneous ice nucleation occurs

$$e_{hom} = S_i^f \, e_{si}$$

e_{hom} = water vapor pressure at S_i^f

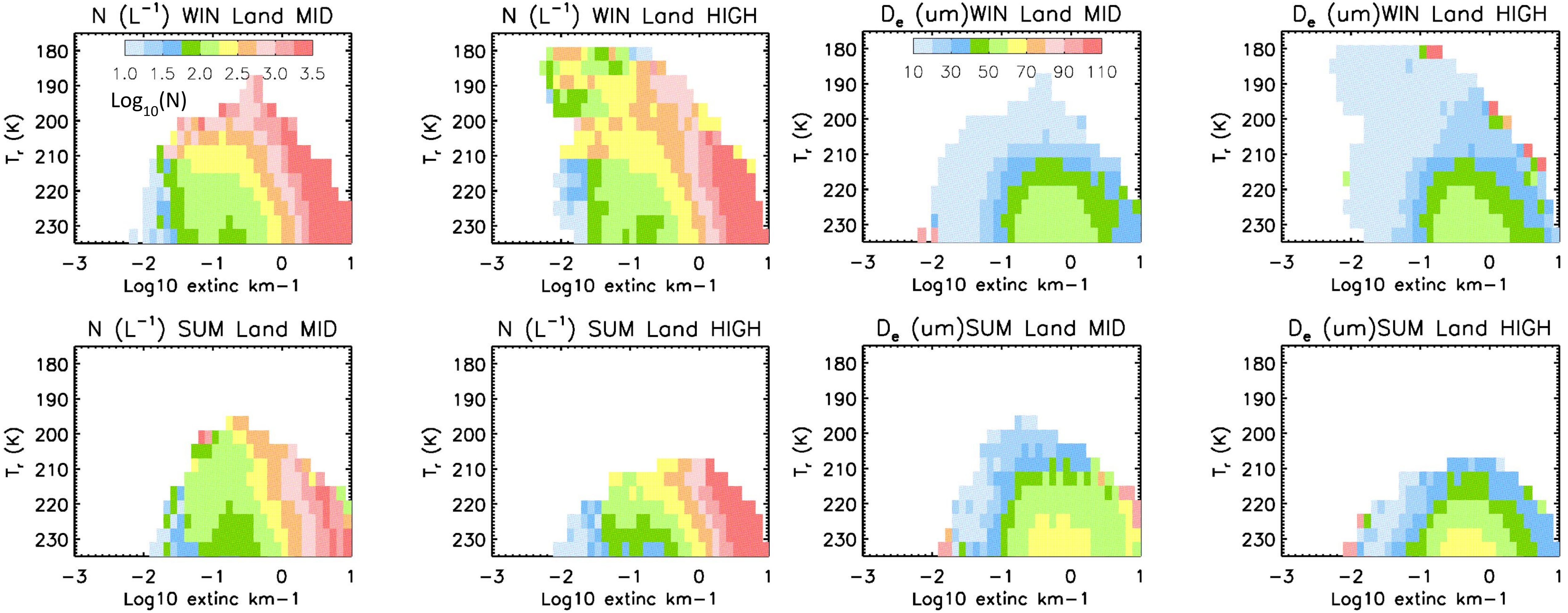
Vapor densities are obtained from the gas law.
Maximum IWC resulting from homogeneous ice nucleation (hom):

$$IWC_{hom} = \rho_{hom} - \rho_{si}$$



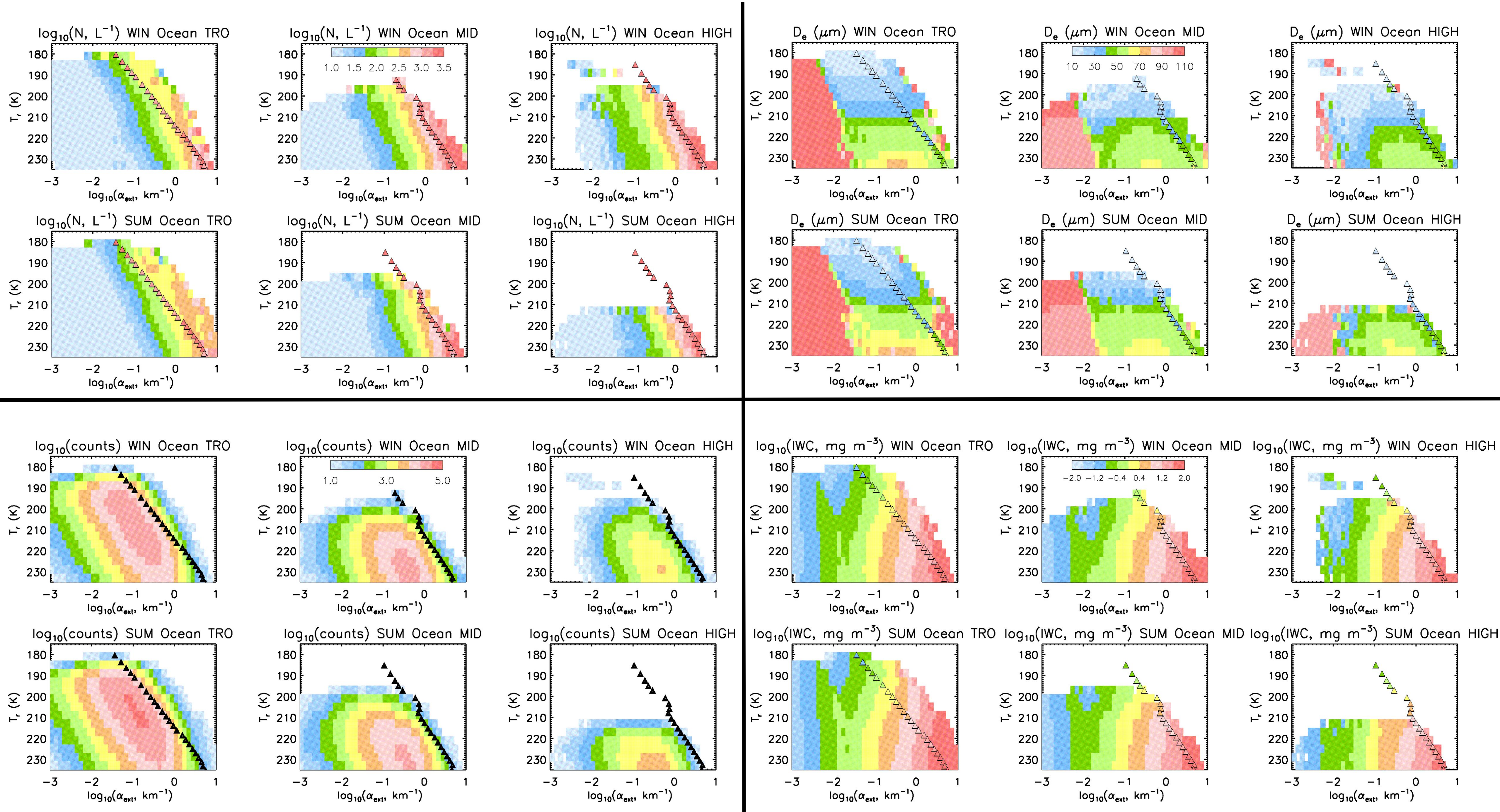
The mean maximum dimension of ice particle size distributions from the SPARTICUS field campaign were related to temperature. This D_{mean}, combined with ice particle mass and area expressions in Erfani and Mitchell (2016, ACP), were used to estimate D_e and relate D_e to temperature. For T < 235 K, this D_e was reduced by a factor of 0.636 based on the impact of hom on D_e as deduced from D_e retrievals shown next.

Land IAB > 0.01 sr^{-1}



In regions most affected by hom (i.e., high N), D_e decreases from ~ 55 µm to ~ 35 µm, or by a factor of 0.636.
The N plots also show that an IAB of 0.01 sr^{-1} roughly separates the two types of cirrus clouds.

All IABs Oceans with data from hom_max_IWC_2.txt (TRO) and SPART1.txt files (MID, HIGH) overplotted using the same color code for the color inside the triangles



Summary and Conclusions

1. Cirrus clouds having IAB > 0.01 sr^{-1} (or optical depth > ~ 0.3) account for roughly 80% of the net radiative effect of all cirrus clouds, but their frequency of occurrence comprises 28% to 48% (depending on latitude) of the occurrence frequency for all cirrus clouds.

2. For these optically thicker cirrus clouds, ice nucleation by both het and hom occur, while only het is important for the optically thinner cirrus clouds. Based on the N-gradient in the extinction analysis, the transition between these cirrus types tends to occur ~ N = 55 L^{-1}.

3. While aircraft in situ measurements are critical for testing satellite retrieval methods, the existence of two cirrus modes complicates these comparisons. In addition, satellite measurements can estimate the radiative importance of each cirrus mode which should be consistent with GCM predictions of cirrus clouds.

Improvements to the CALIPSO cirrus cloud retrieval of Mitchell et al. (2018, ACP)

1. **Ice particle number concentration** no longer depends on estimates of IWC but rather depends on optical probe measurements of ice particle projected area:

New empirical function N and A_{PSD} are directly measured by aircraft PSD probes.

$$N = \left(\frac{N}{A_{PSD}}\right)_{\beta_{eff}} \times \frac{\left(1/Q_{abs,eff}(12\mu m)\right)_{\beta_{eff}} \times \tau_{abs}(12.05\mu m)}{\Delta z_{eq}} \quad (1)$$

2. **Estimation of in situ IWC has been improved**, with better estimates of small ice **particle mass** (Erfani & Mitchell, 2016, ACP), better agreement **between calculated (from in situ PSD measurements) and IIR β_{eff}**, and a recent laboratory study on ice particle masses (D < 100 µm; Weitzel et al., 2020, ACP).

3. **Improved retrieval equation for effective diameter** based on theory and two strong empirical relationships:

$$D_e = \frac{3}{2} \times \frac{IWC}{\rho_i \cdot A_{PSD}} = \frac{3}{2 \cdot \rho_i} \times \left(\frac{N}{A_{PSD}}\right)_{\beta_{eff}} \times \left(\frac{IWC}{N}\right)_{\beta_{eff}} \quad (2)$$

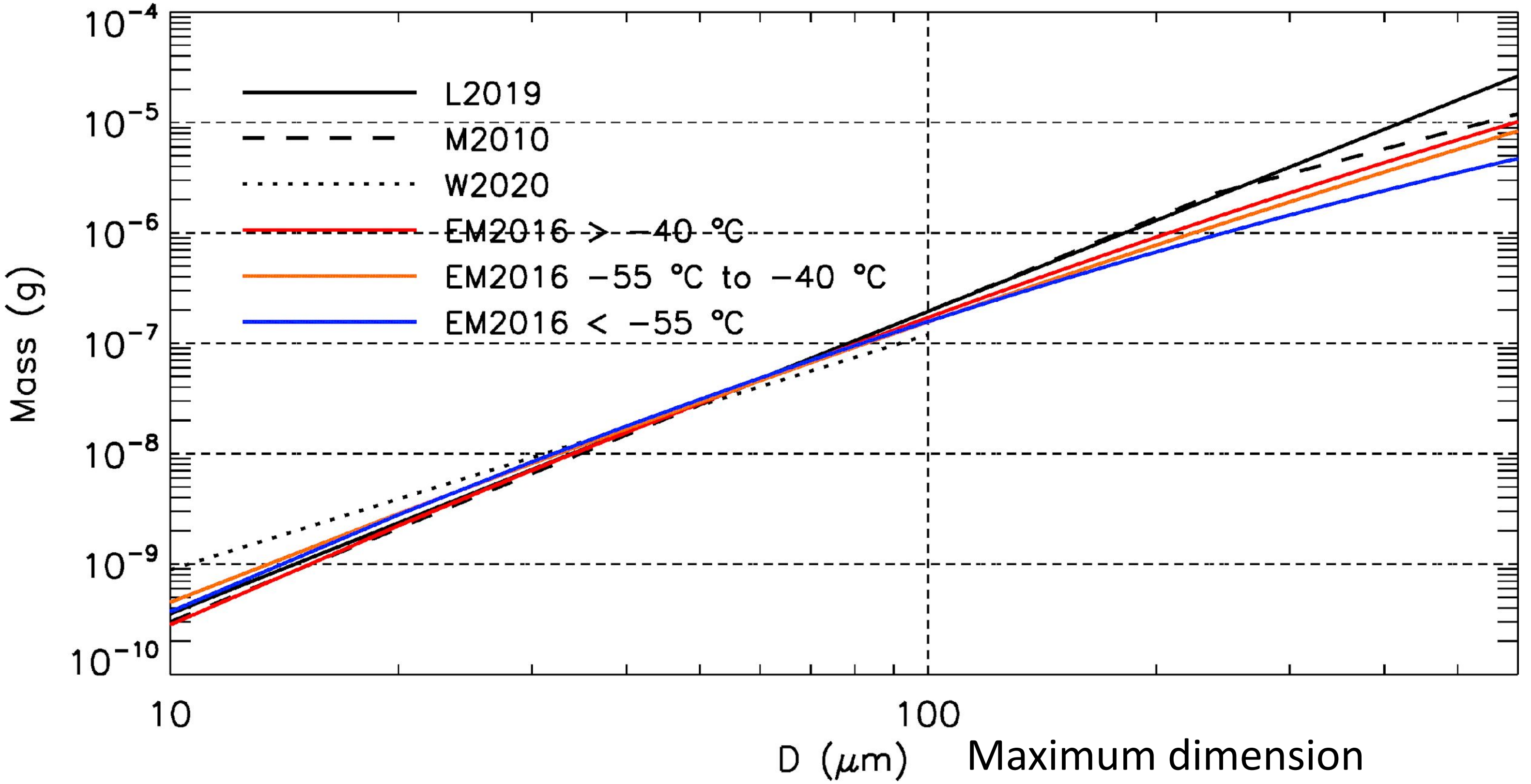
Theory, Mitchell, JAS, 2002

From which we derive $$IWC = \frac{\rho_i}{3} \times \alpha_{ext} \times D_e \quad \text{with} \quad \alpha_{ext} = \frac{2.\left(1/Q_{abs,eff}(12\mu m)\right)_{\beta_{eff}} \times \tau_{abs}(12.05\mu m)}{\Delta z_{eq}} \quad (3)$$

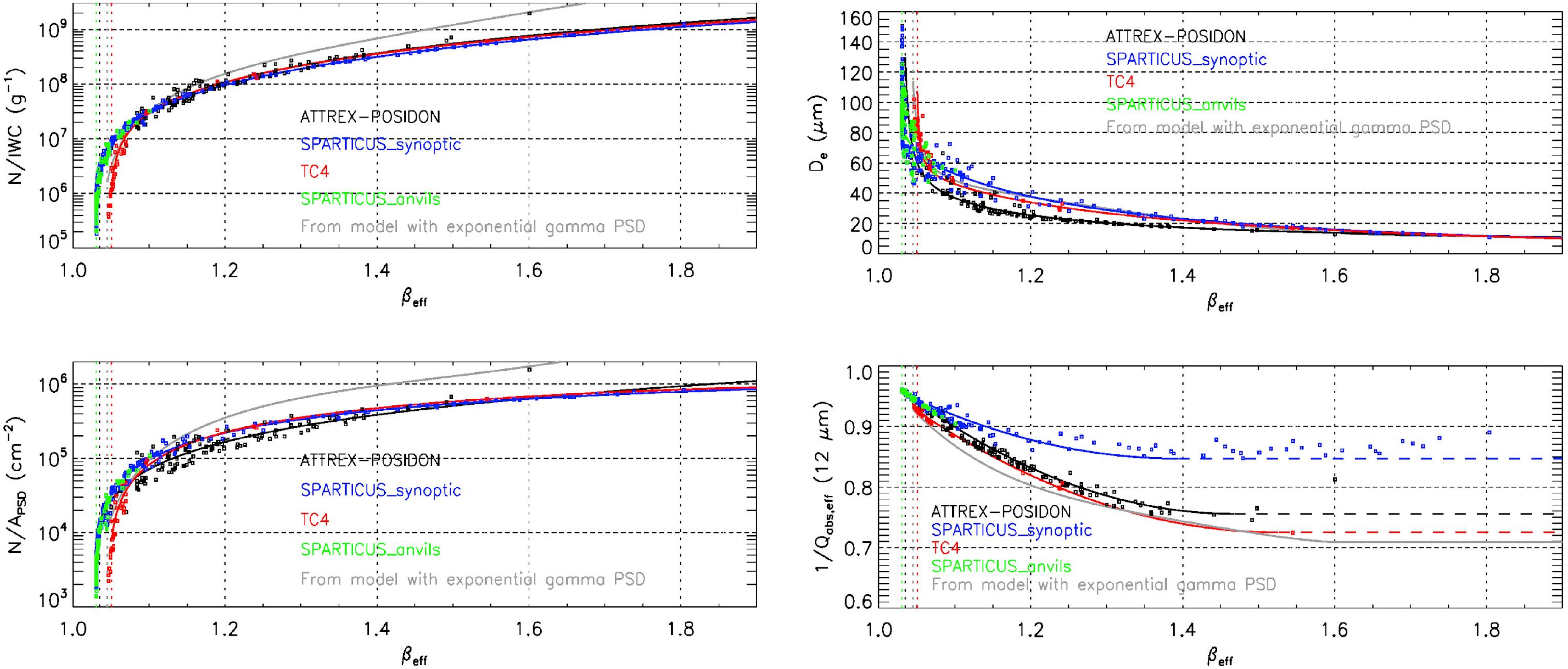
The N/A_{psd}-β_{eff}, N/IWC-β_{eff}, and 1/ $Q_{abs,eff}$(12 µm)- β_{eff} relationships were developed from cirrus cloud PSD measurements from several field campaigns using the same methodology as in Mitchell et al. (2018, ACP).

Evaluation of ice particle m-D expressions from:

- Lawson et al. (2019, JGR), *L2019*
- Mitchell et al. (2010, JAS), *M2010*
- Erfani and Mitchell (2016, ACP) for anvils, *EM2016*
- Weitzel et al. (2020, ACP, based on maximum 2-D projected dimension), *W2020*



❑ These m-D relationships change both PSD IWC **and PSD β_{eff}**



XX - β_{eff} relationships

This CALIPSO retrieval is based on these empirical XX – β_{eff} relationships where XX is the cirrus cloud property or property ratio shown on the y-axis. A_{PSD} is the size distribution projected area concentration.

TC4 is shown for discussion but not used in the retrievals.