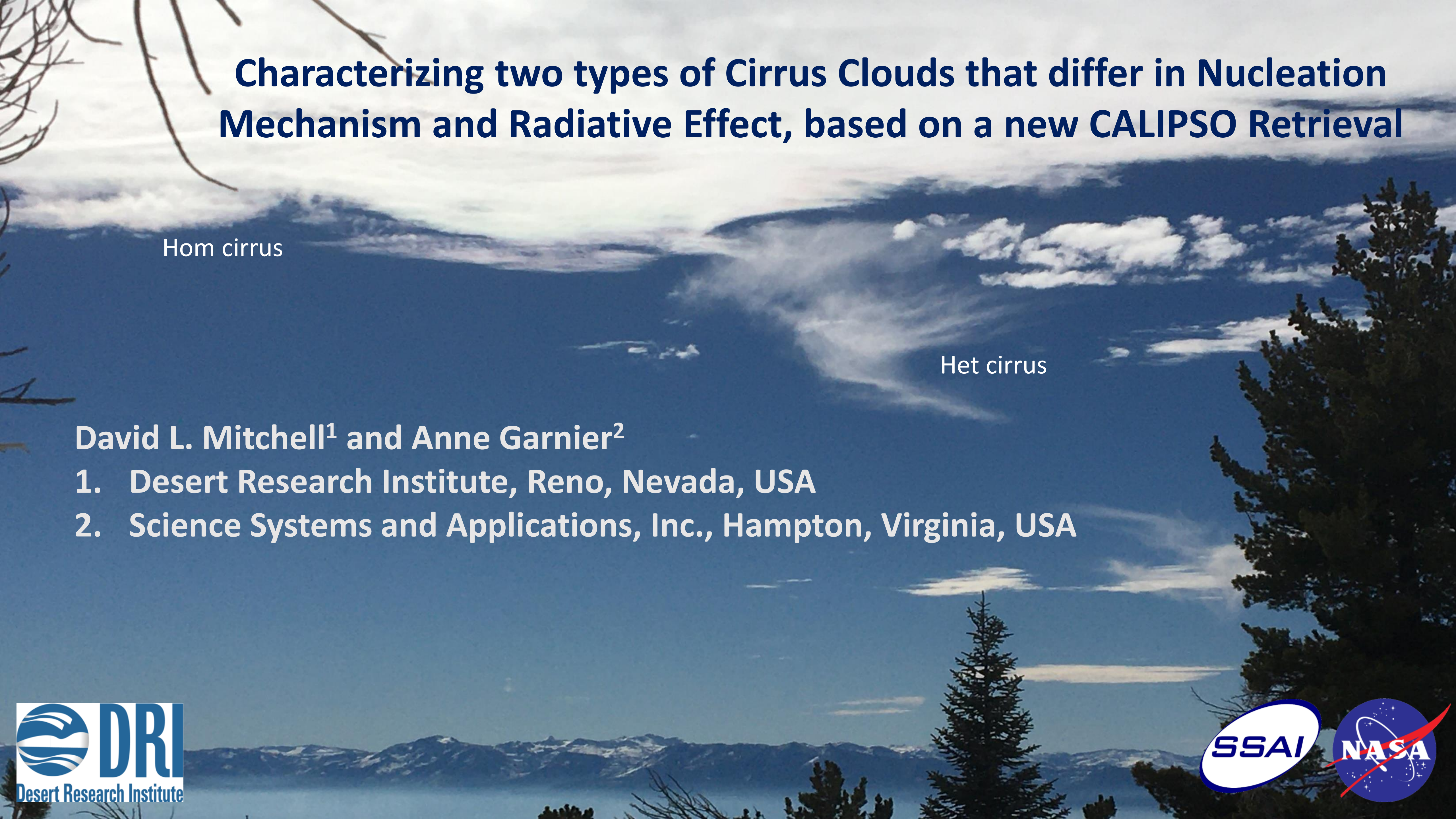
Characterizing two types of Cirrus Clouds that differ in Nucleation Mechanism and Radiative Effect, based on a new CALIPSO Retrieval



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The research findings discussed here are based on a new CALIPSO satellite retrieval, and due to the limited time, the development of this retrieval will not be discussed. 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 sampled have a visible optical depth < 3.

3. Retrieved cloud properties from CALIPSO Infrared Imaging Radiometer (IIR) correspond to cloud layers and not in-cloud profiles. Larger uncertainties at small optical depth.

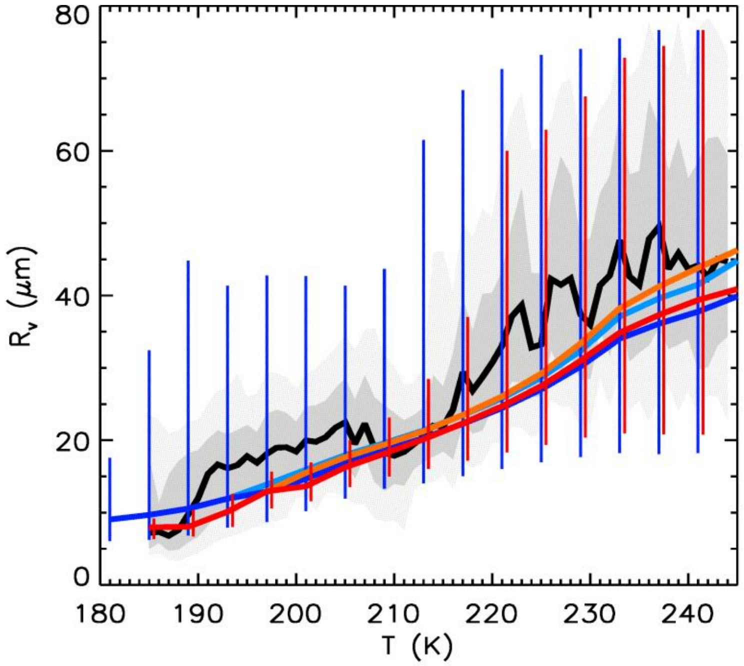
4. Sampled clouds have a radiative temperature ≤ 235 K (-38 °C).

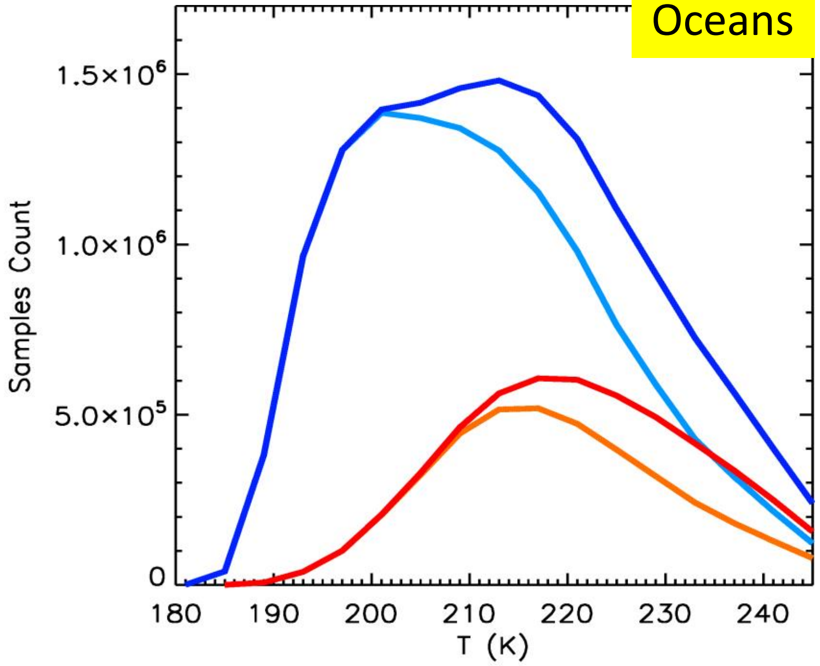
5. The following analysis is based on 4 years of CALIPSO data.

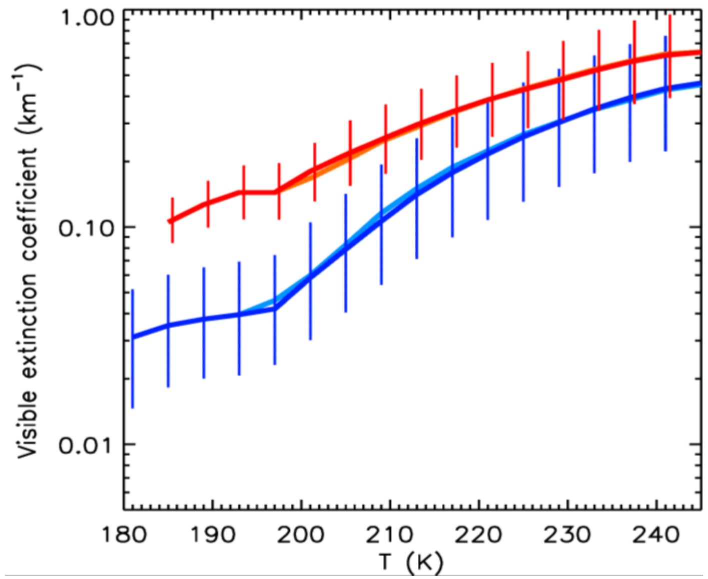
Comparison with global cirrus cloud climatology of Krämer et al. (2020, ACP) based on aircraft measurements (black curves).

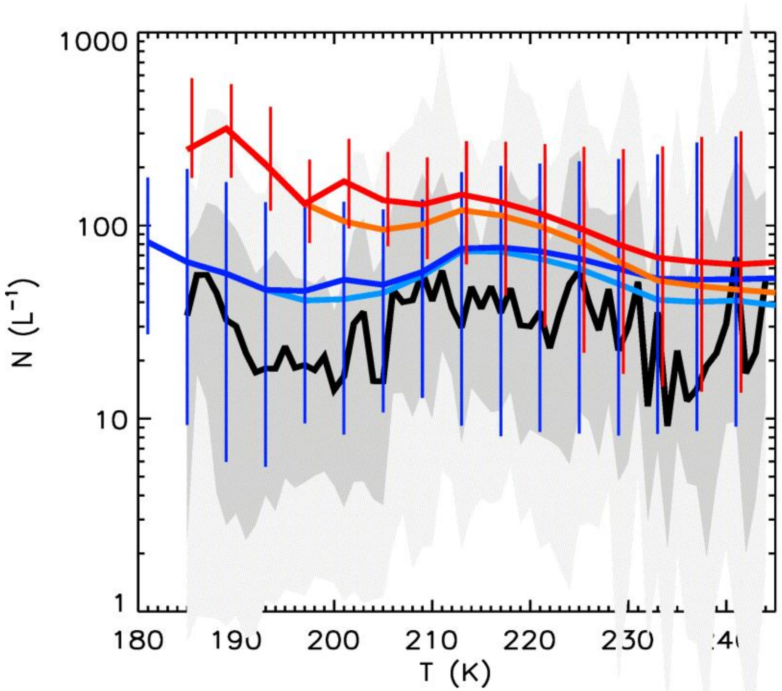
Reasonable agreement for all IIR samples (OD < ~ 3; OD = cloud optical depth) => blue curves; less agreement for OD > ~ 0.3 where uncertainty is lowest => orange & red curves. Orange & light-blue curves are for tropics only. Bars & shading give percentiles (10%, 25%, 75% & 90%).

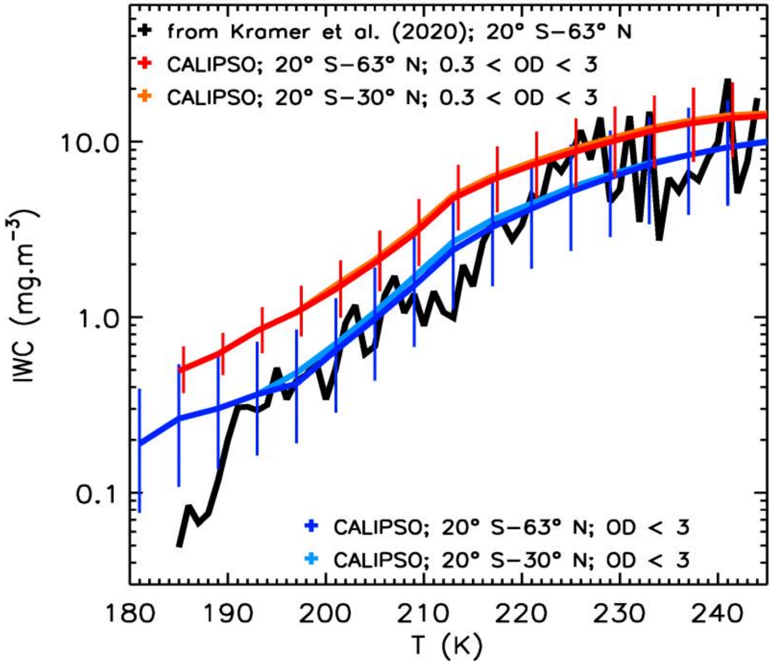
Oceans





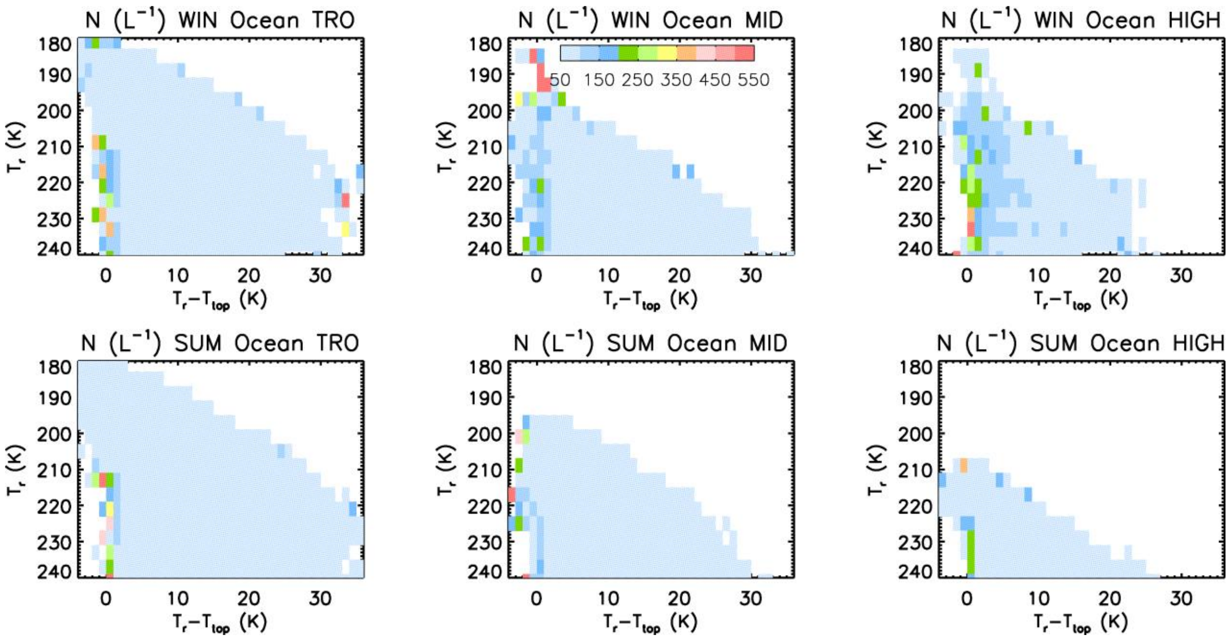






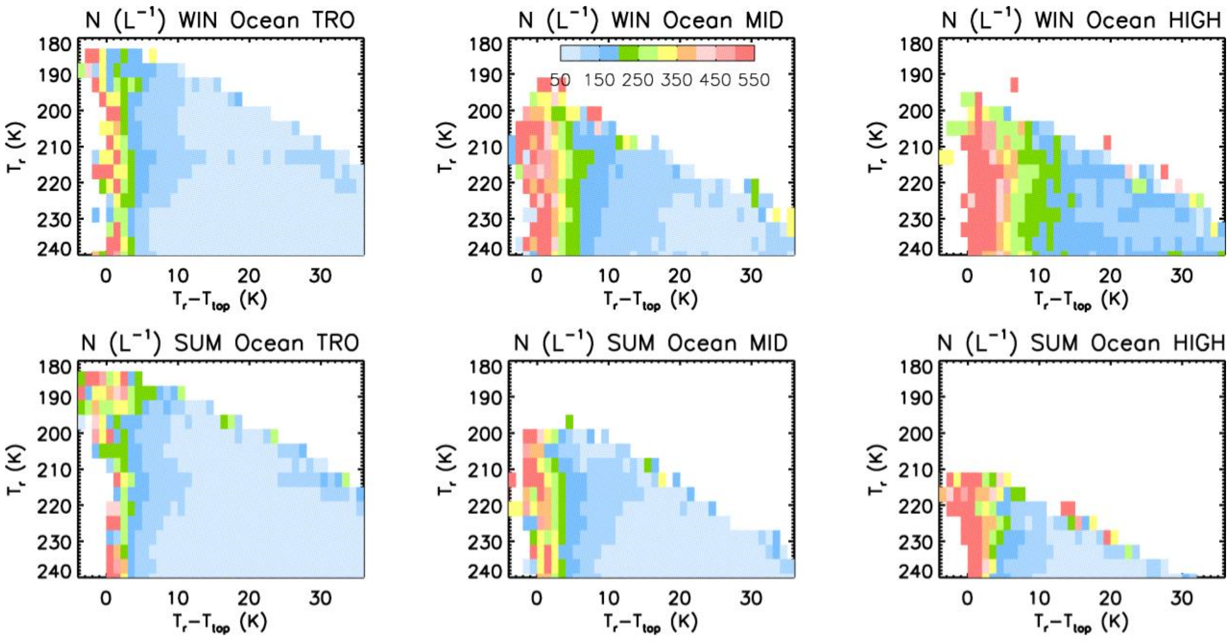
OD < ~ 0.3

Number concentration, N (L^{-1})



OD > ~ 0.3

Number concentration, N (L^{-1})



T_r = radiative temperature of cloud

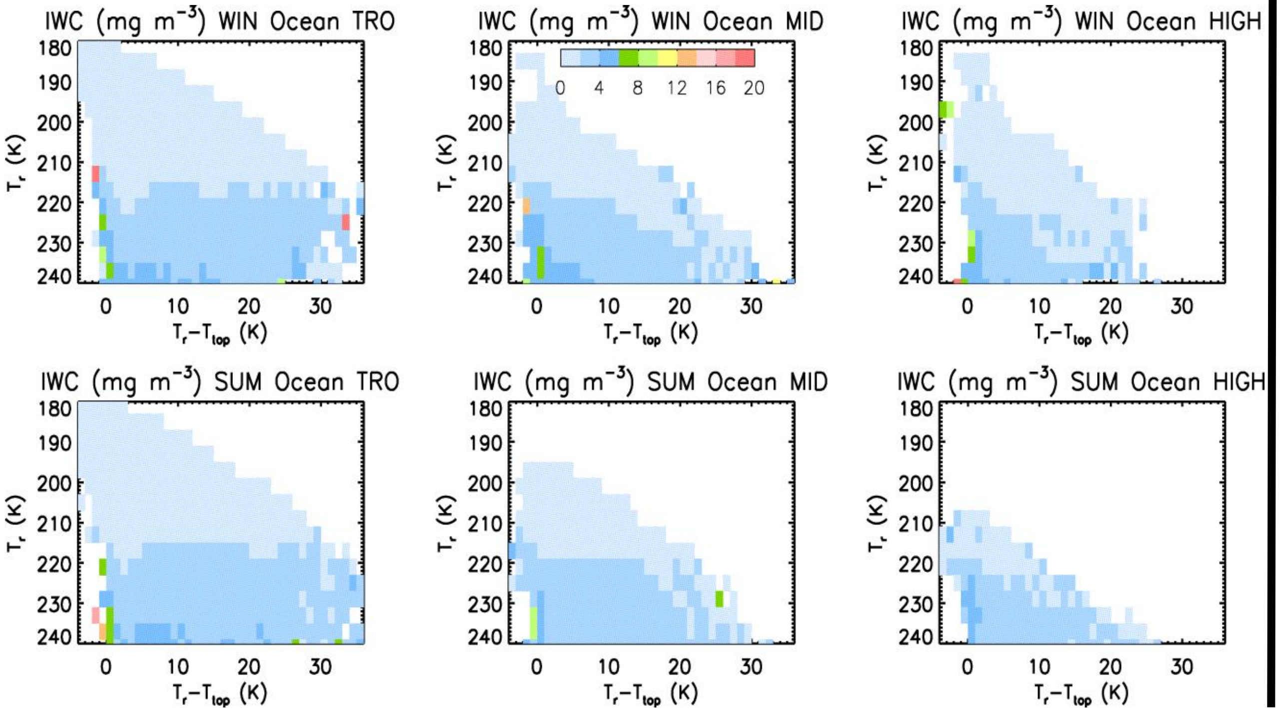
T_{top} = cloud top temperature

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

Oceans

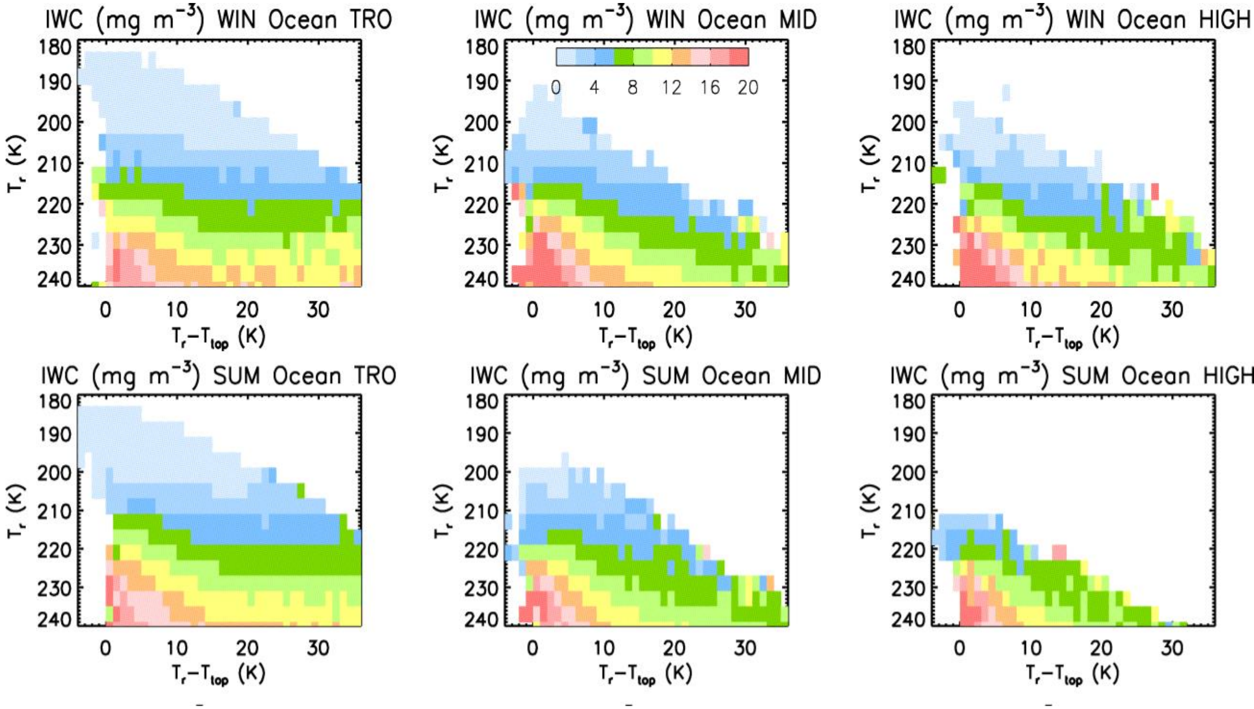
OD < ~ 0.3

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



OD > ~ 0.3

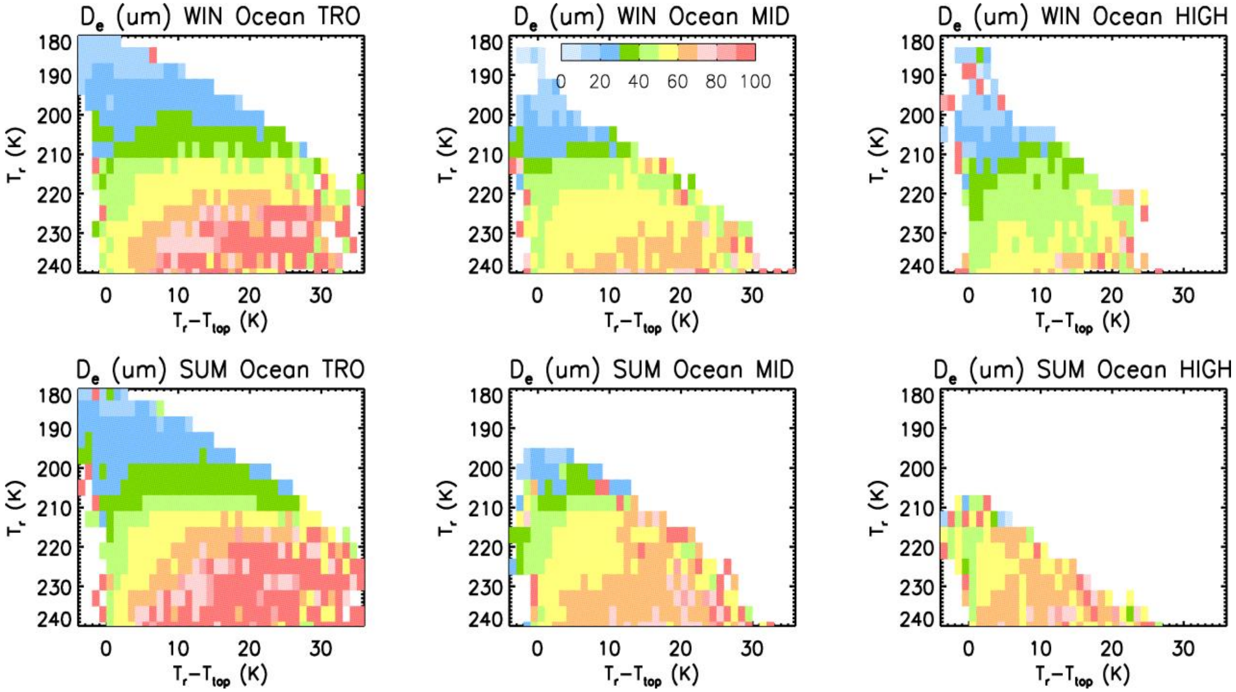
Ice water content, IWC (mg m^{-3})



Oceans

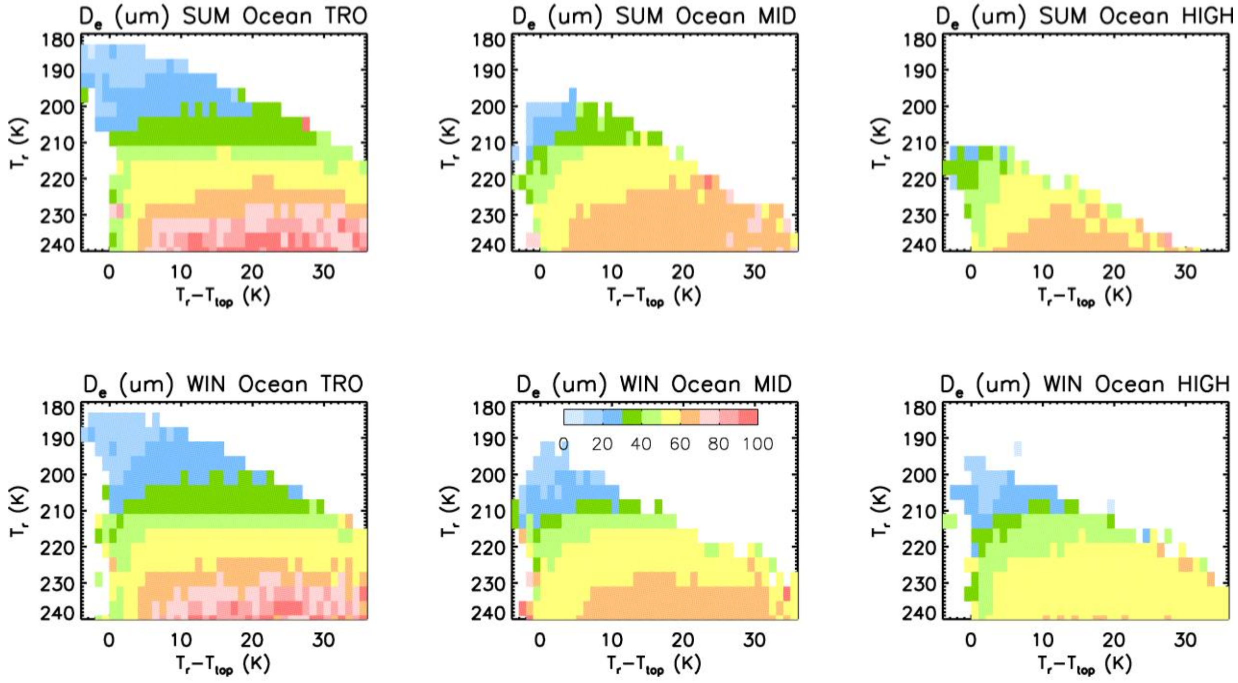
OD < ~ 0.3

Effective diameter, D_e (μm)



OD > ~ 0.3

Effective diameter, D_e (μm)



Differences between these two cloud classes are less obvious for D_e.

Summary of these results:

1. **When homogeneous ice nucleation (i.e., hom) is relatively active (based on higher N), N and IWC are most affected with relatively high values. When hom is most active (as observed over land; not shown), D_e decreases.**

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

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

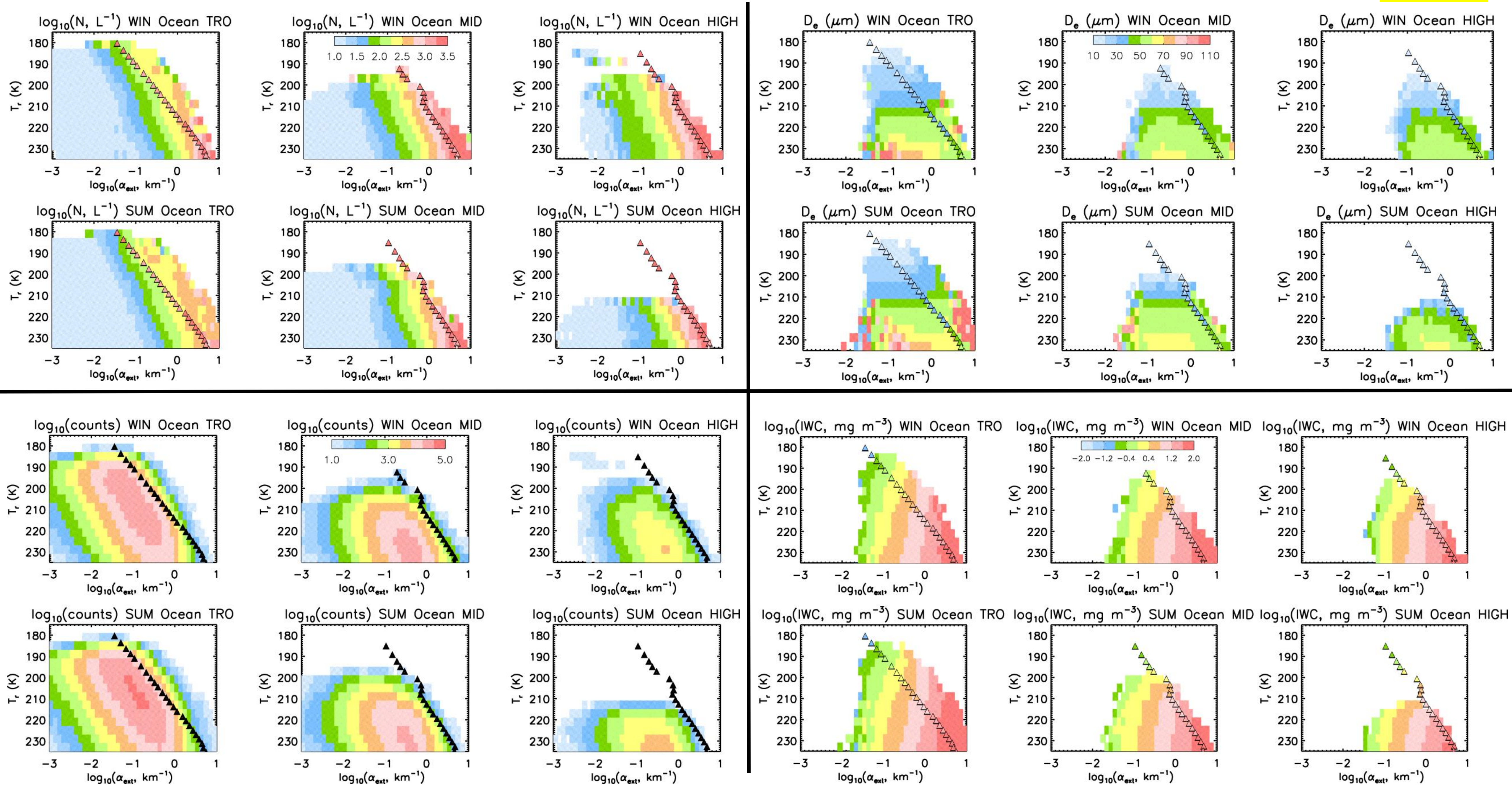
where ρ_i is the bulk density of ice.

All samples

Color inside the triangles (from model) uses the same color code.

OD > ~ 0.3

Oceans

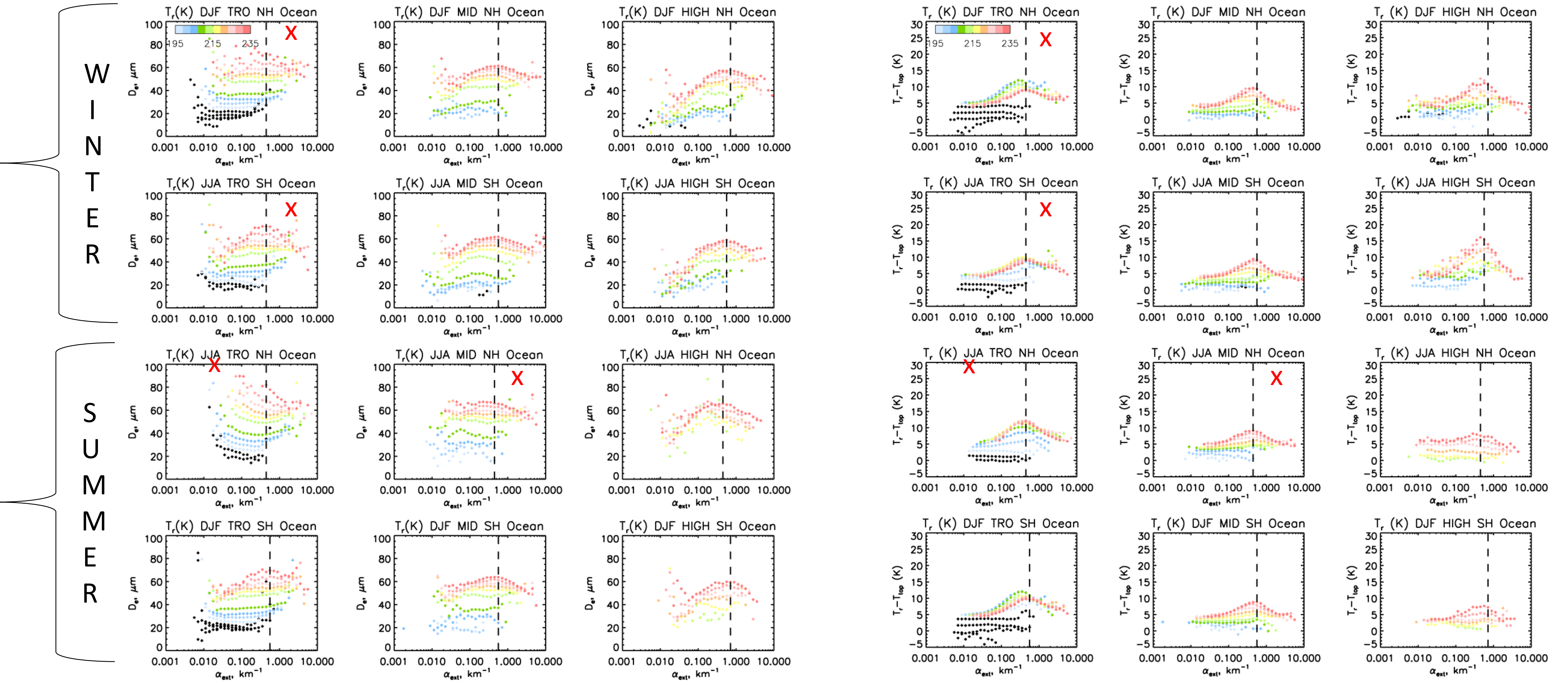


METHODOLOGY FOR MAPPING THE FRACTION OF HOM CIRRUS RELATIVE TO ALL SAMPLED CIRRUS (1/2)

Oceans

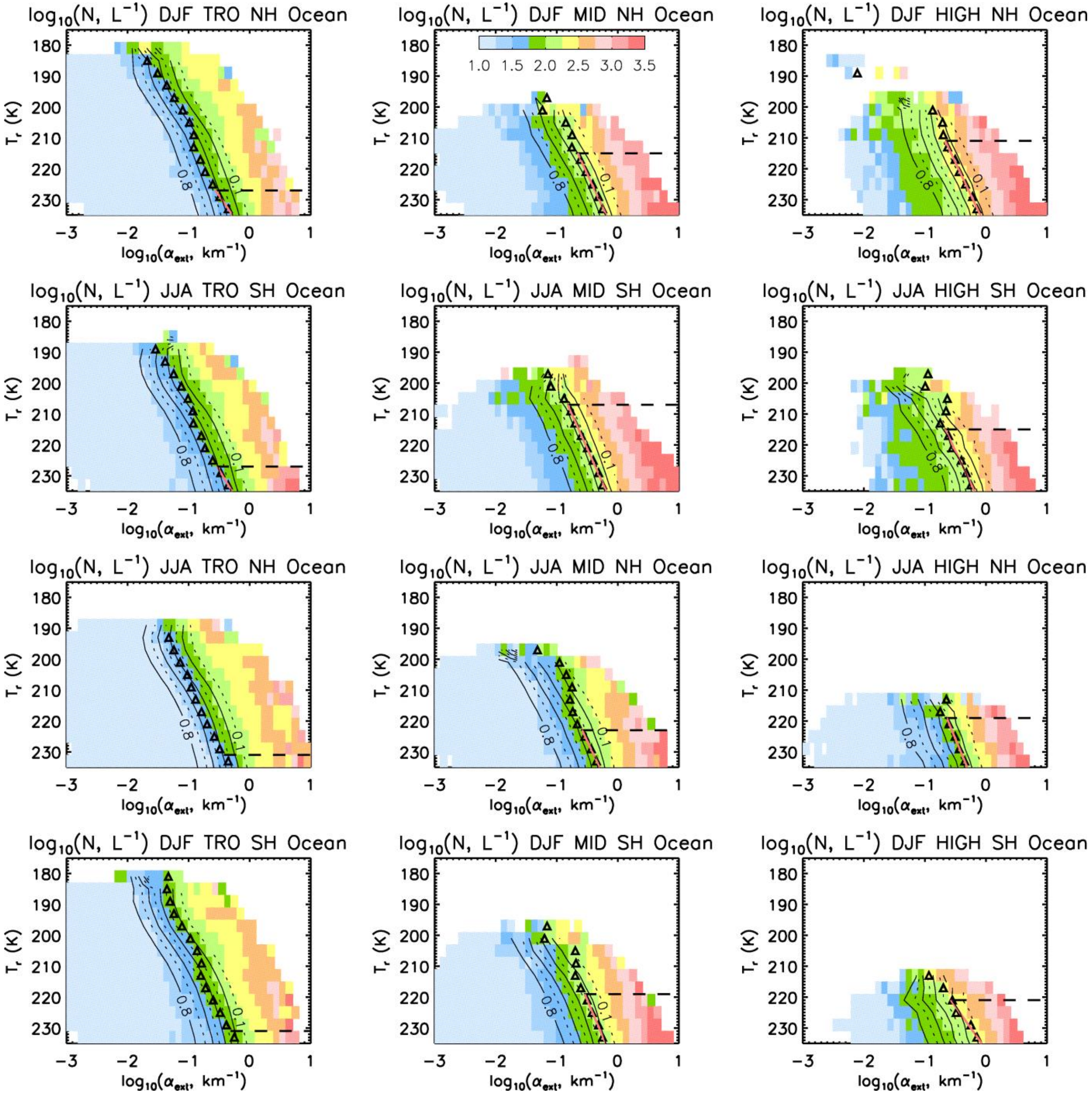
Vertical lines: maximum D_e at 231-235 K. α_{ext} > dashed line => evidence of strong microphysical impact by hom (recall hom impacts IWC more than D_e)

Four exceptions (red crosses): α_{ext} threshold ~ 233 K determined by maximum in $T_r - T_{top}$ since this maximum almost always coincides with the maximum D_e.



METHODOLOGY FOR MAPPING THE FRACTION OF HOM CIRRUS RELATIVE TO ALL SAMPLED CIRRUS (2/2)

Oceans

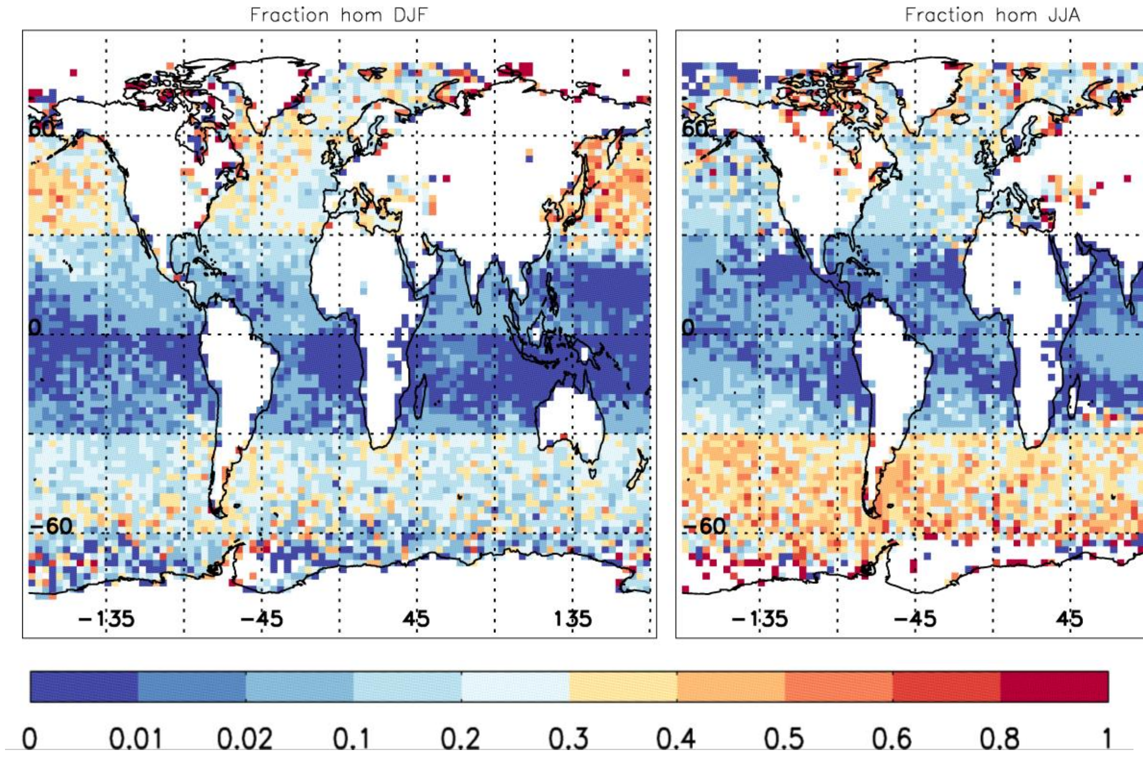


- Horizontal lines: temperature T_r_lim above which no hom evidence, i.e. no maximum D_e
- Triangles: where N = N at 233 K α_{ext} threshold
- Red lines: α_{ext}-T_r equations for hom-het threshold:

  => $\log_{10}(\alpha_{ext}) = a_0 + a_1 T_r$, $T_r \geq T_r$_lim

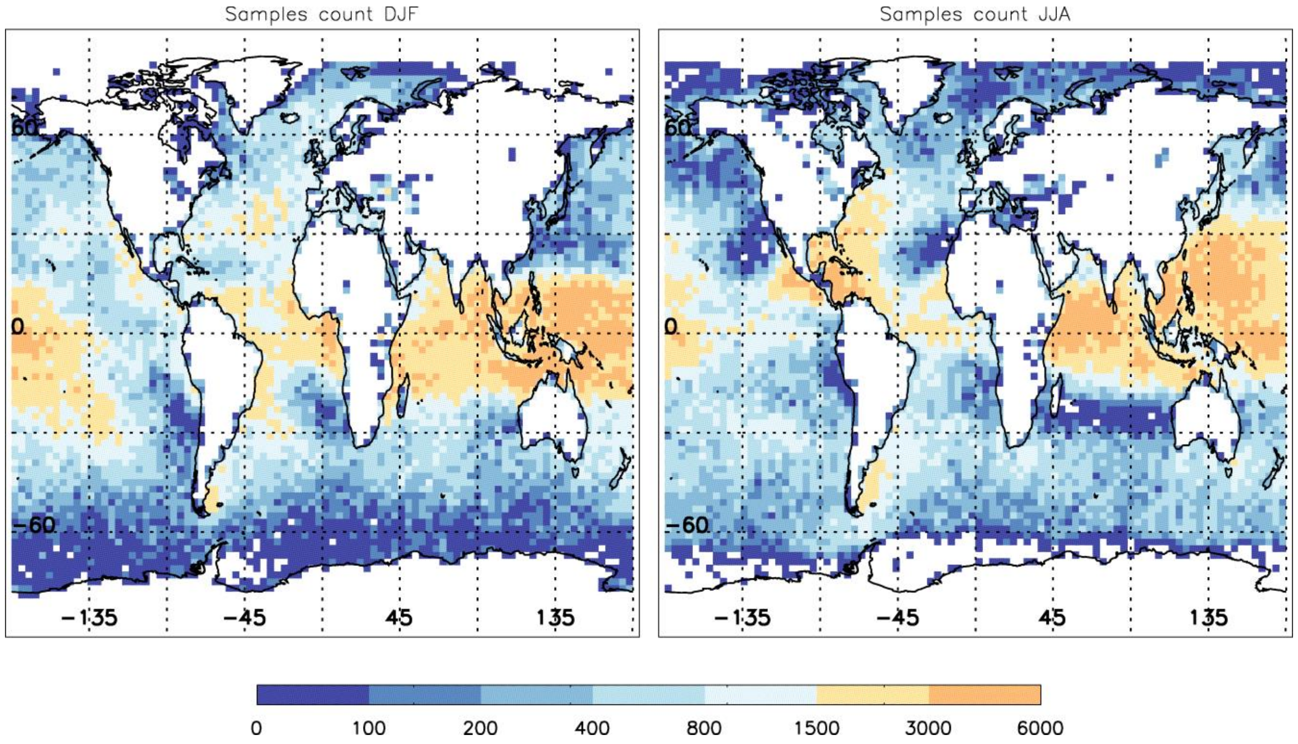
  => one per season (DJF or JJA) and 30° latitude band

- Contours: fraction of samples of larger extinction. Shown are fractions between 0.1 and 0.8.



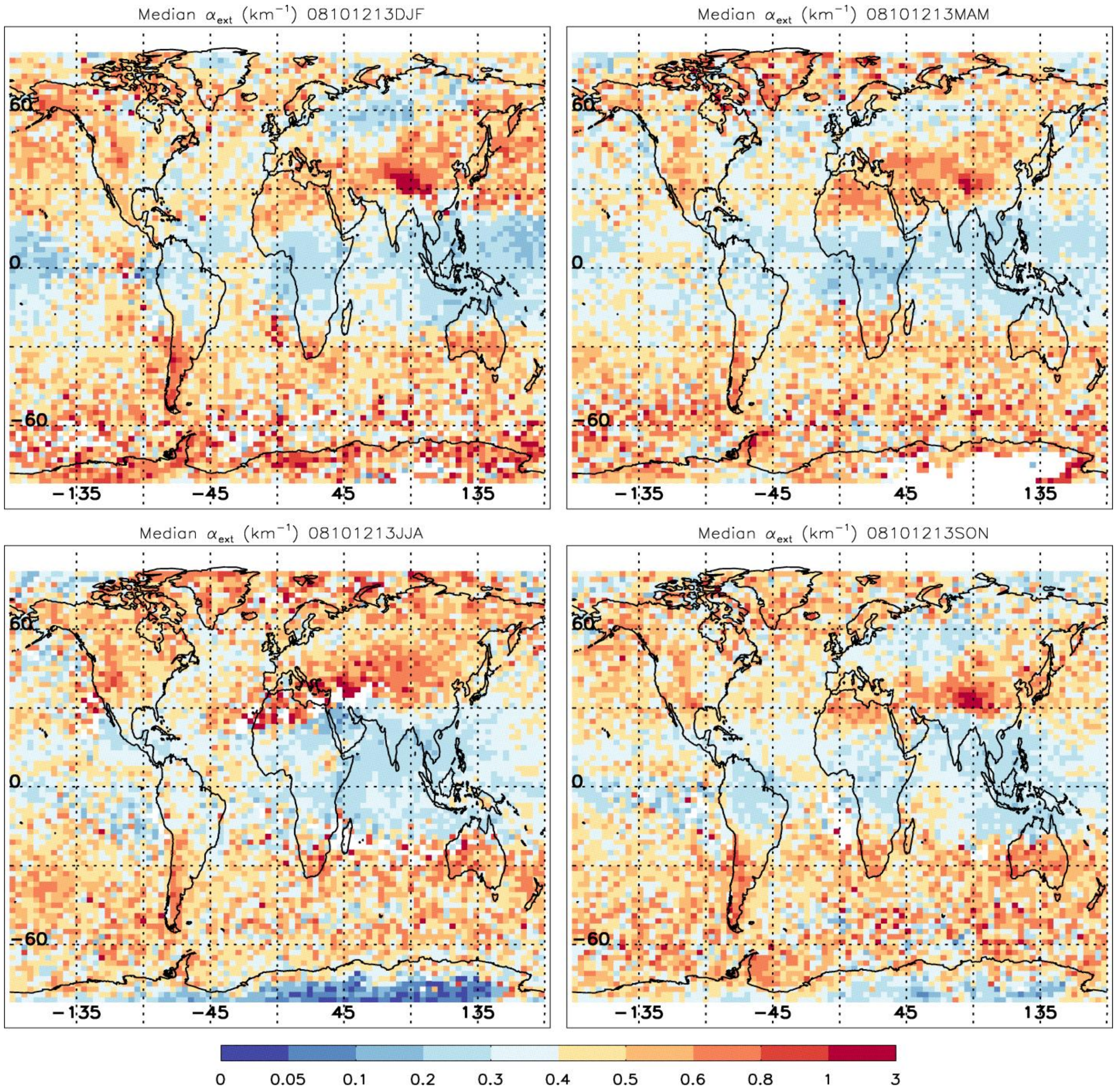
Fraction of hom-cirrus clouds relative to all sampled cirrus clouds over liquid water (oceans and lakes), but no sea ice.

Density of CALIPSO samples over oceans and lakes (all samples).



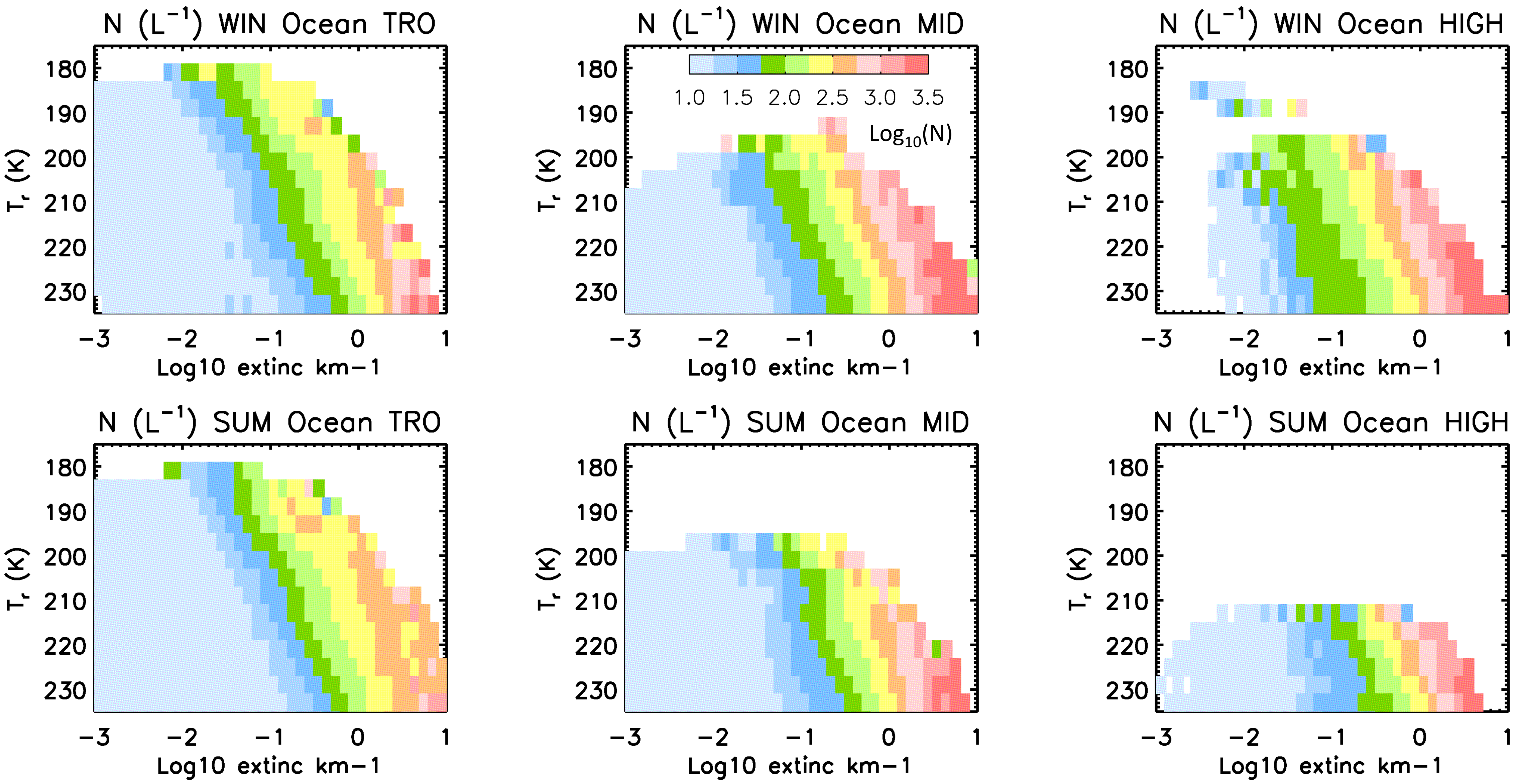
END OF TALK

THANK YOU FOR LISTENING



Seasonal change in the median extinction coefficient

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

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

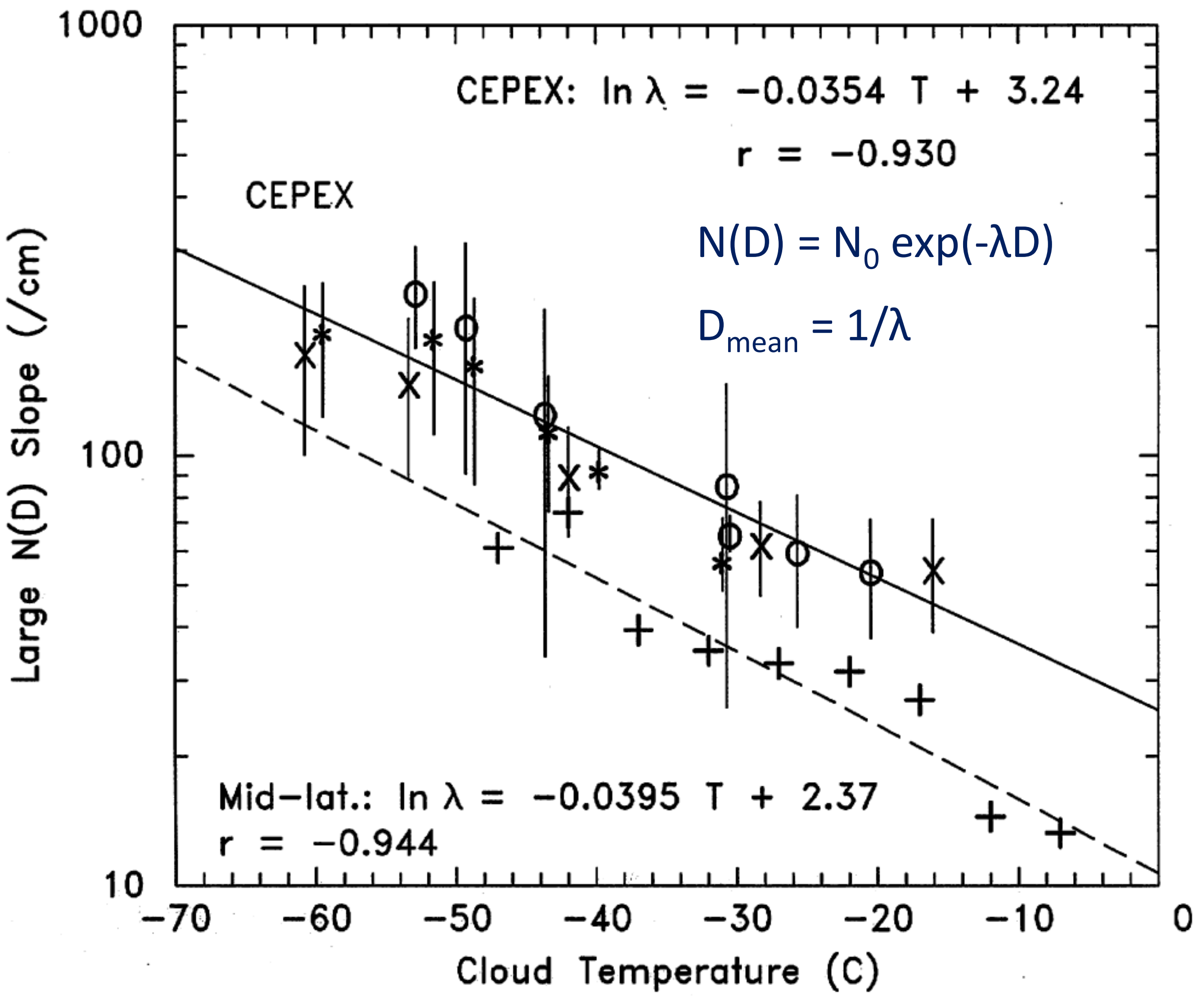
S_i^f = supersaturation where homogeneous ice nucleation occurs

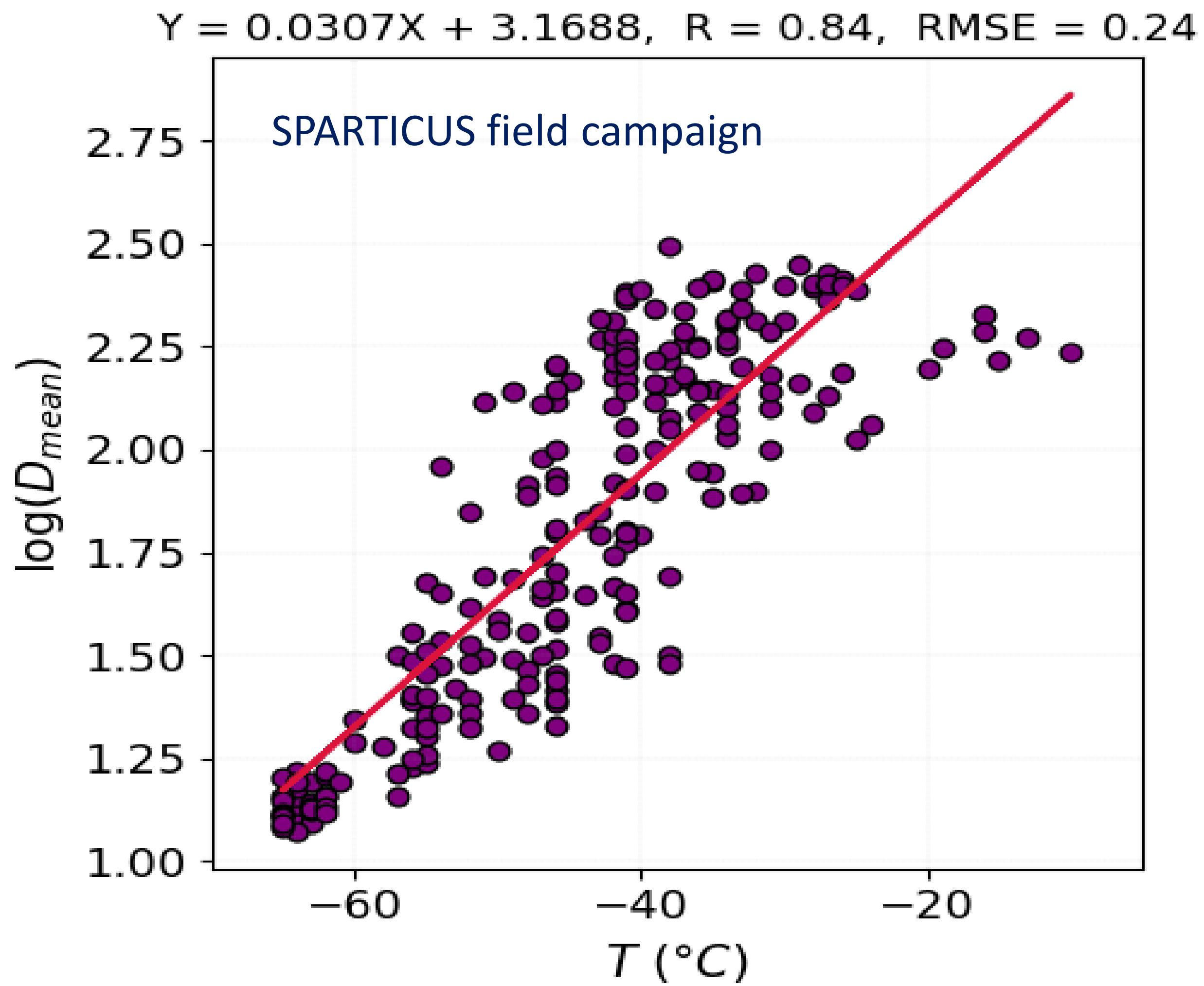
$$e_{hom} = S_i^f\, e_{si}$$

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):

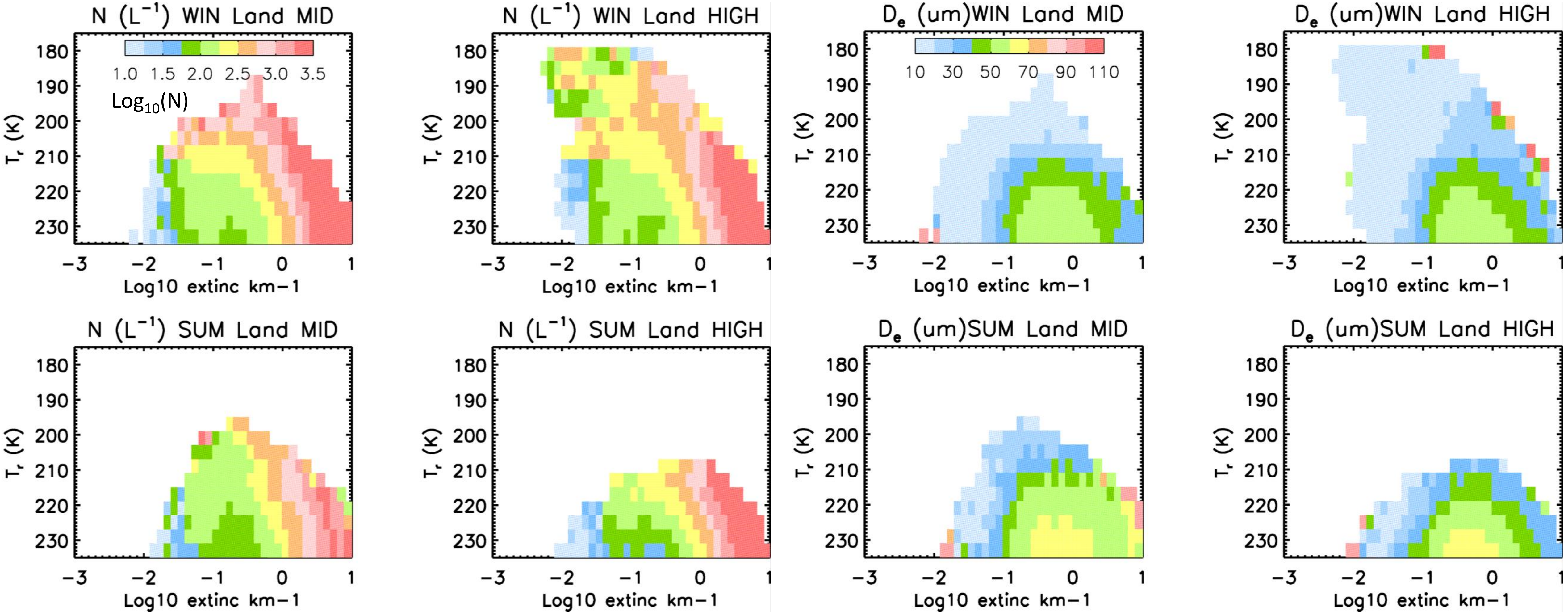
$$IWC_{hom} = \rho_{hom} - \rho_{si}$$





The mean maximum dimension of ice particle size distributions from the CEPEX and SPARTICUS field campaigns were related to temperature to calculate D_e and N. 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.

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.

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:

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

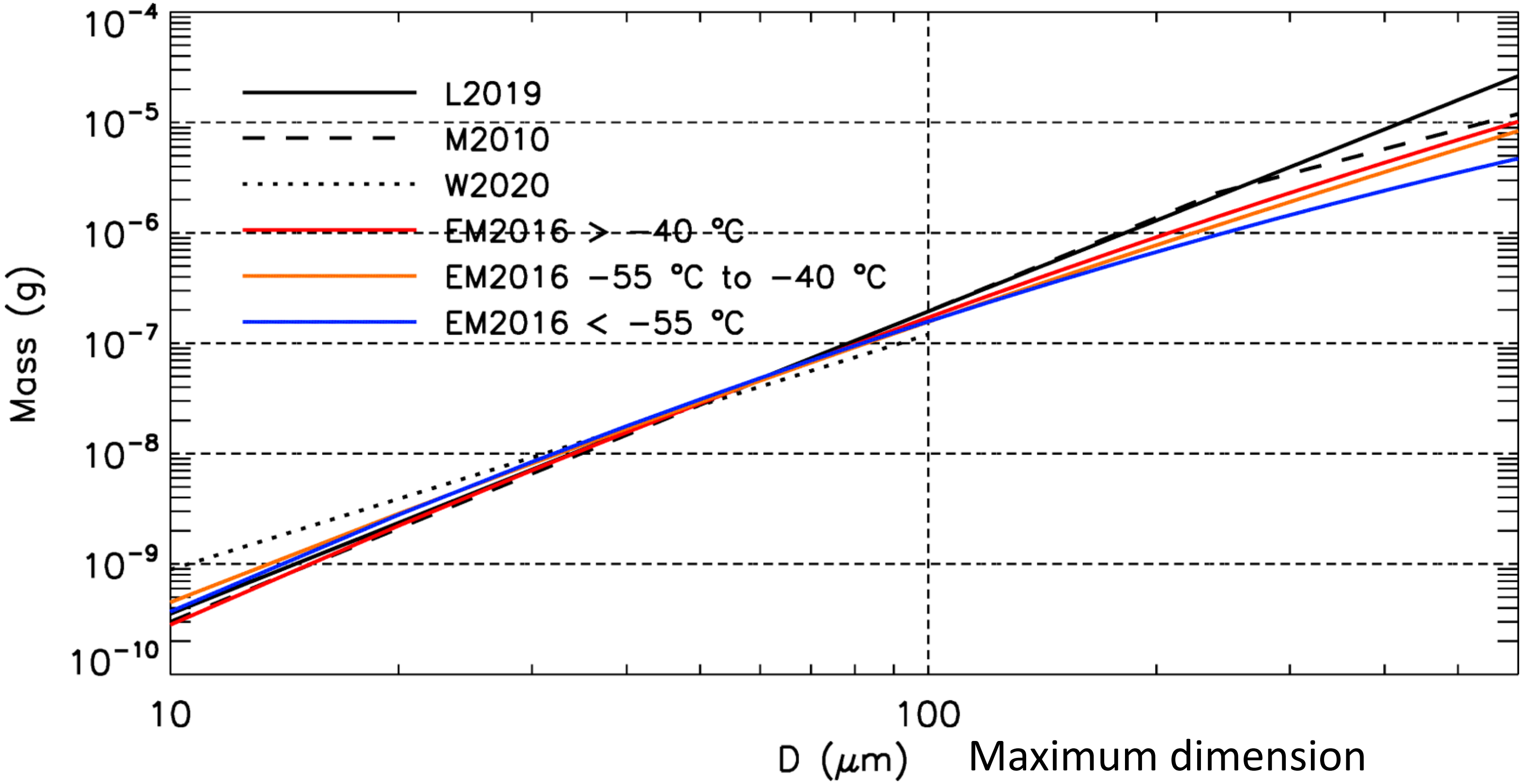
Theory, Mitchell, JAS, 2002

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

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).

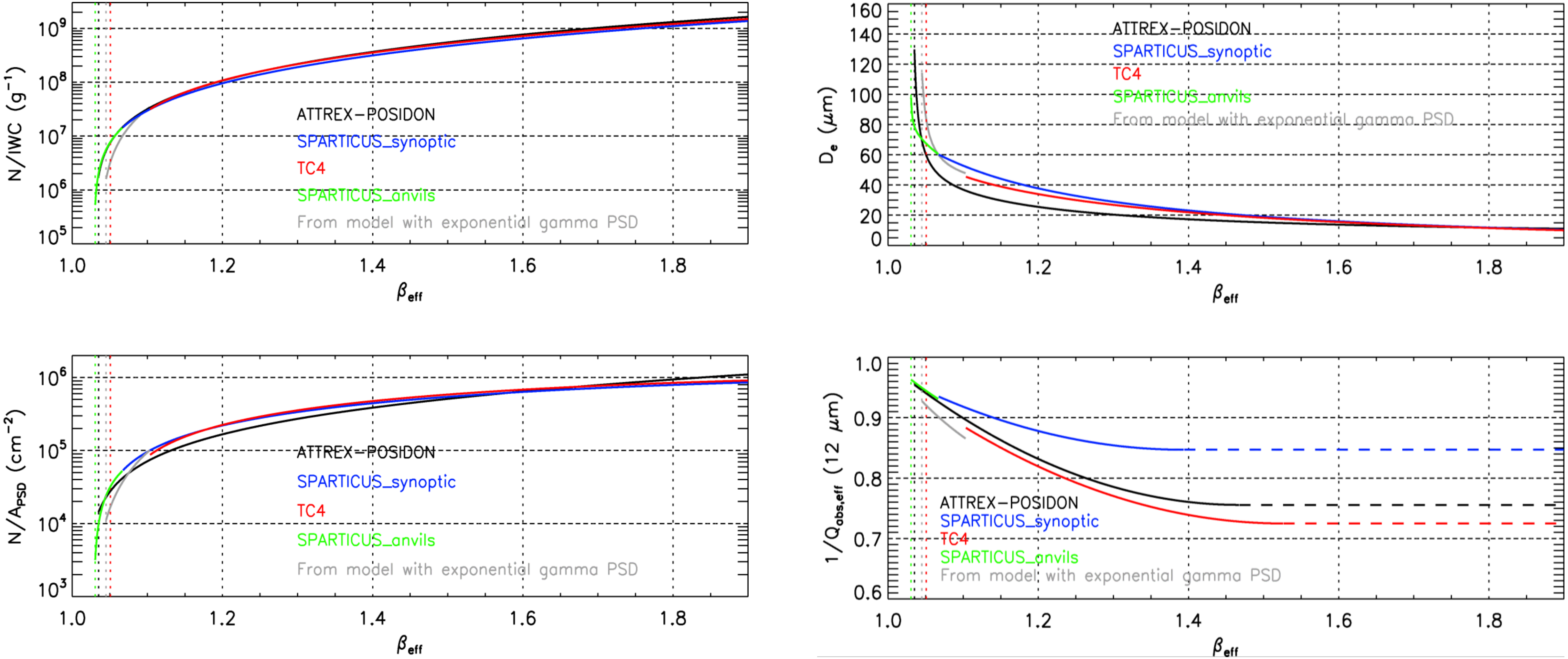
Evaluation of ice particle m-D expressions from:

- 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*



Maximum dimension

❑ 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.