A Novel Cirrus Cloud Retrieval Method for GCM High Cloud Validations

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ABSTRACT

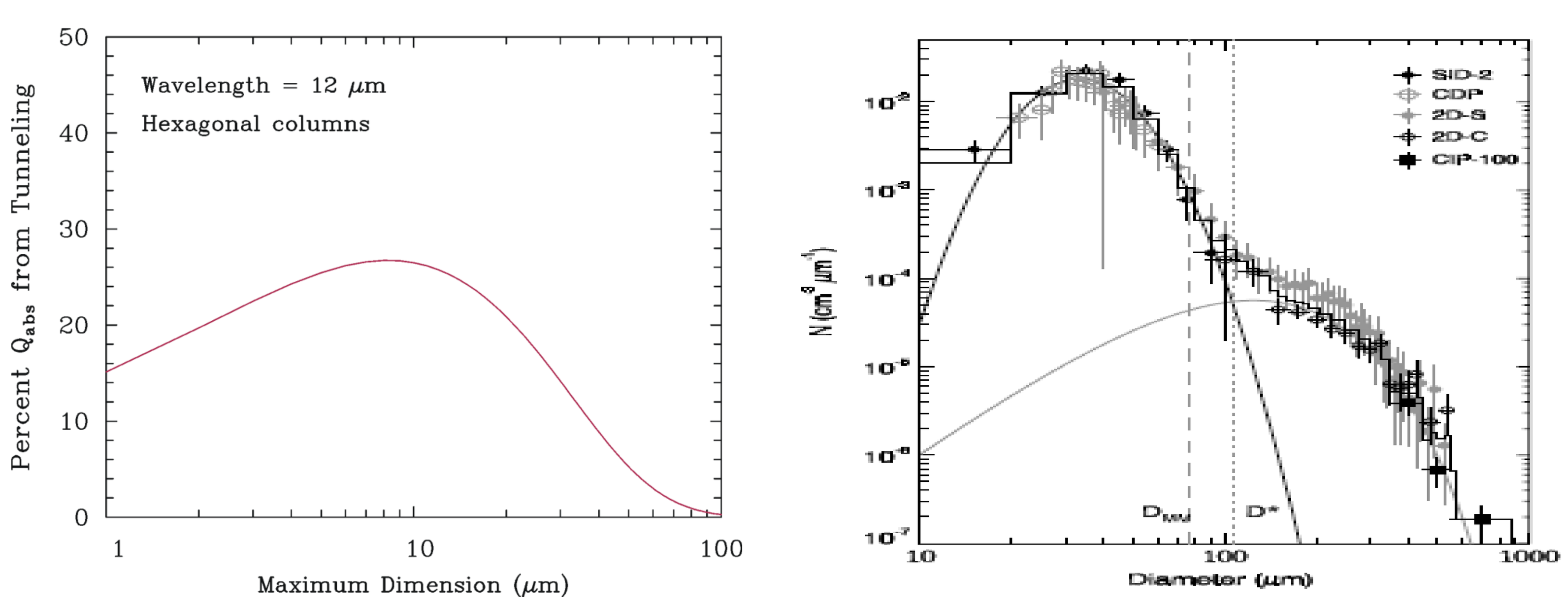
A new understanding of absorption differences in satellite split-window channels has resulted in a new retrieval method for semi-transparent cirrus clouds (0.3 < OD < 3.0). Using the Imaging Infrared Radiometer (IIR) aboard CALIPSO, ice particle number concentration N, D_e, IWC, IWP and visible optical depth (OD) are retrieved for single-layer cirrus having cloud base temperature T < 235 K.

These retrievals show a pronounced cirrus seasonal cycle in the N. Hemisphere over land north of 30°N latitude in terms of both cloud amount and microphysics, with greater cloud cover, higher N and smaller D_e during the winter season. We postulate that this is partially due to the seasonal cycle of deep convection that replenishes the supply of ice nuclei (IN) at cirrus levels, with homogeneous ice nucleation (henceforth hom) prevailing during boreal winter north of 30°N when deep convection is relatively absent and snow often covers the ground, resulting in lower IN and higher N concentrations. In addition, hom cirrus tend to occur over mountainous terrain, possibly due to stronger, more sustained updrafts in orographic waves.

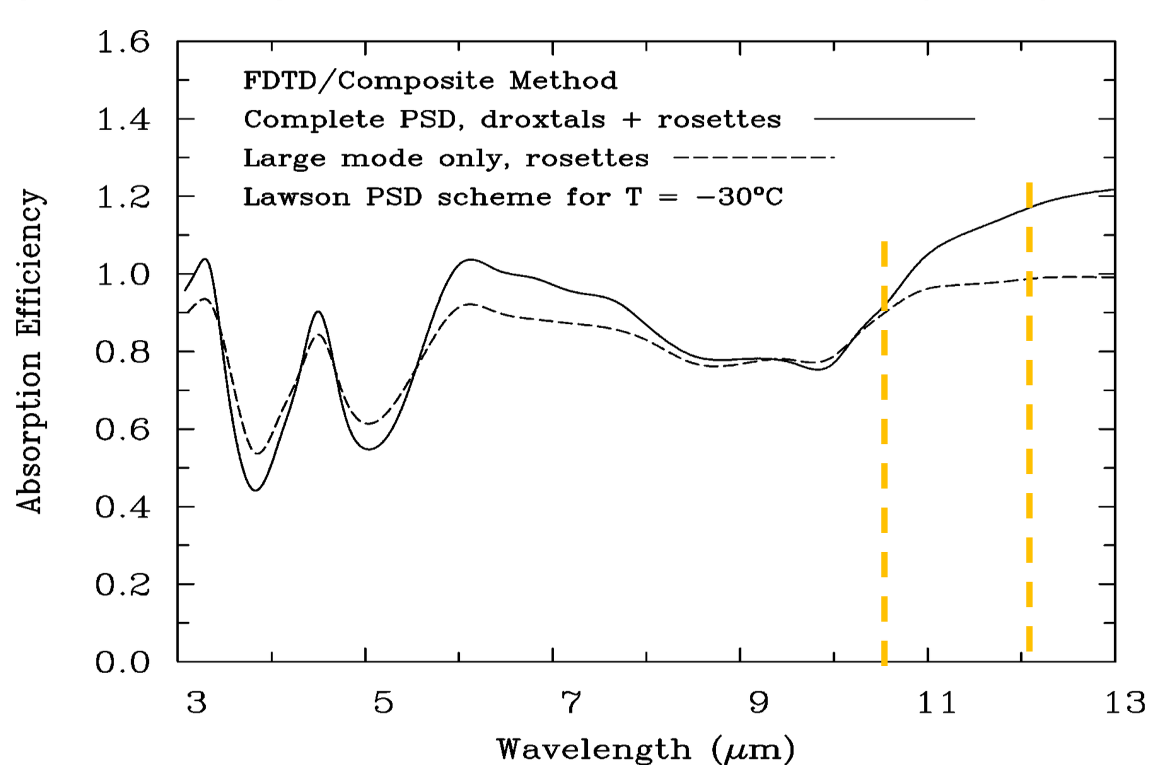
Over oceans, heterogeneous ice nucleation appears to prevail based on the lower N and higher D_e observed. Due to the relatively smooth ocean surface, lower amplitude atmospheric waves at cirrus cloud levels are expected.

Over pristine Antarctica, IN concentrations are expected to be minimal, allowing hom to dominate. Accordingly, over Antarctica cirrus clouds exhibit relatively high N and small D_e throughout the year.

THEORY



Cloud emissivity differences between 11 & 12 μm are primarily due to differences in the contribution of wave resonance (i.e. tunneling) to absorption. Resonance contributions are important when wavelength and particle size are comparable. Right panel from Cotton et al. (2012, QJRMS), with cirrus over N. Scotland sampled by several state-of-the-science probes.



PSD absorption efficiencies for large mode only (dashed) and for the complete PSD.

Cirrus cloud microphysics: Discriminating regions of homo- and heterogeneous ice nucleation.

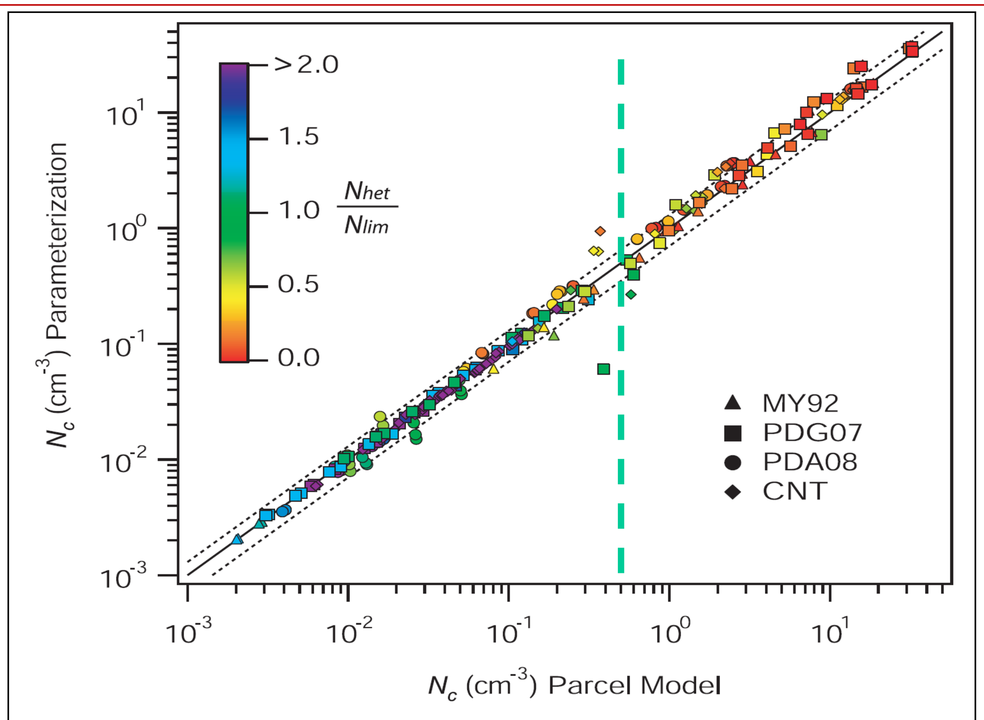


Fig. 4. Comparison between N_c from combined homogeneous and heterogeneous freezing predicted by the parameterization and the parcel model for simulation conditions of Table 2 and freezing spectra of Table 1. Dashed lines represent the ±30% difference. Colors indicate the ratio $\frac{N_{het}}{N_{lim}}$.

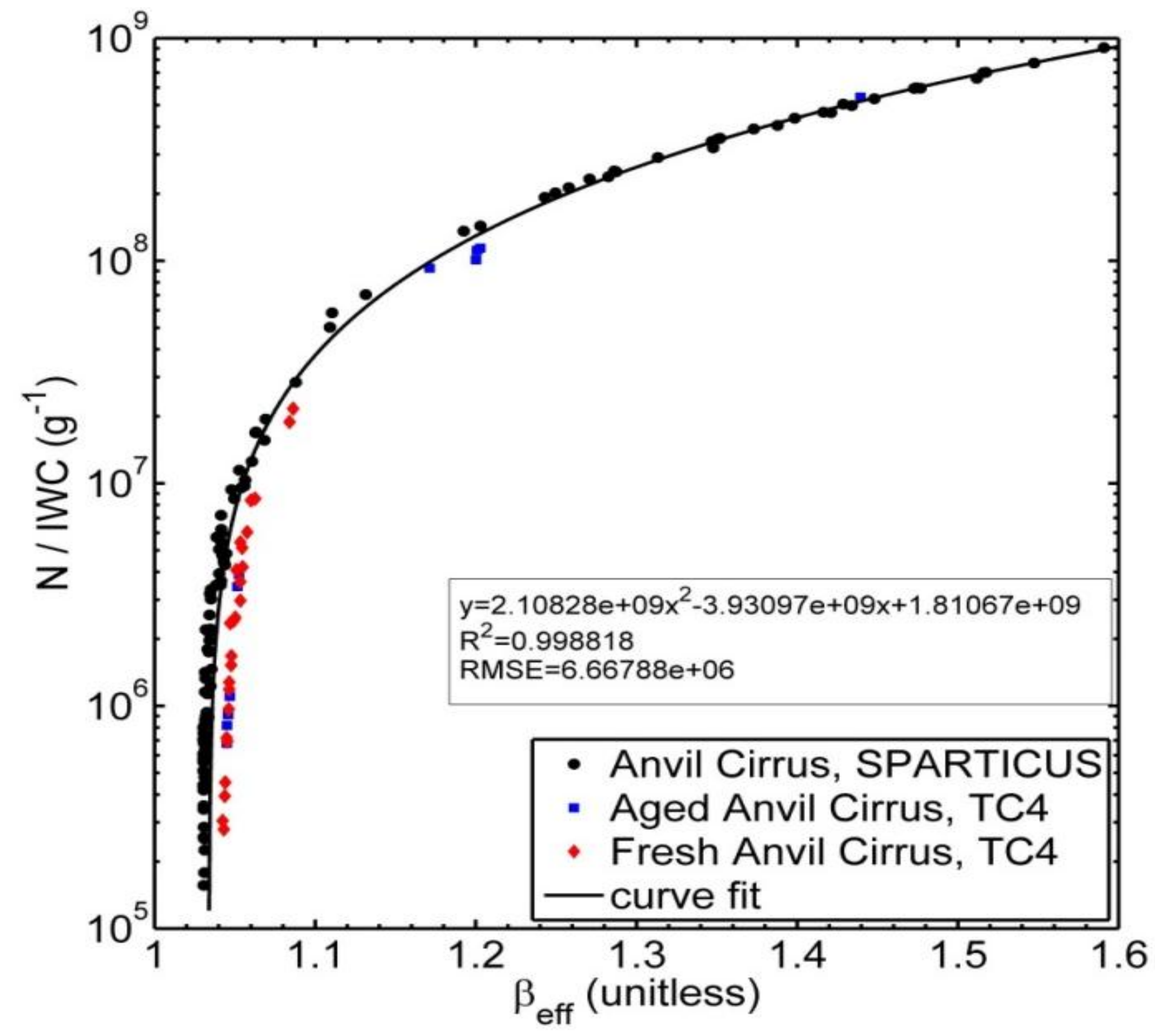
Cloud formation conditions & aerosol characteristics used to produce this figure from Barahona & Nenes (2009, ACP).

Property	Values
T_o (K)	205–250
V (m s^{-1})	0.04–2
α_d	0.1, 1.0
$\sigma_{g,\mathrm{dry}}$	2.3
N_o (cm^{-3})	200
$D_{g,\mathrm{dry}}$ (nm)	40
N_{dust} (cm^{-3})	0.05–5
N_{soot} (cm^{-3})	0.05–5
θ_{dust}	16°
θ_{soot}	40°
$s_{h,\mathrm{dust}}$	0.2
$s_{h,\mathrm{soot}}$	0.3

N_{lim} is the limiting IN concentration that completely inhibits homogeneous freezing.

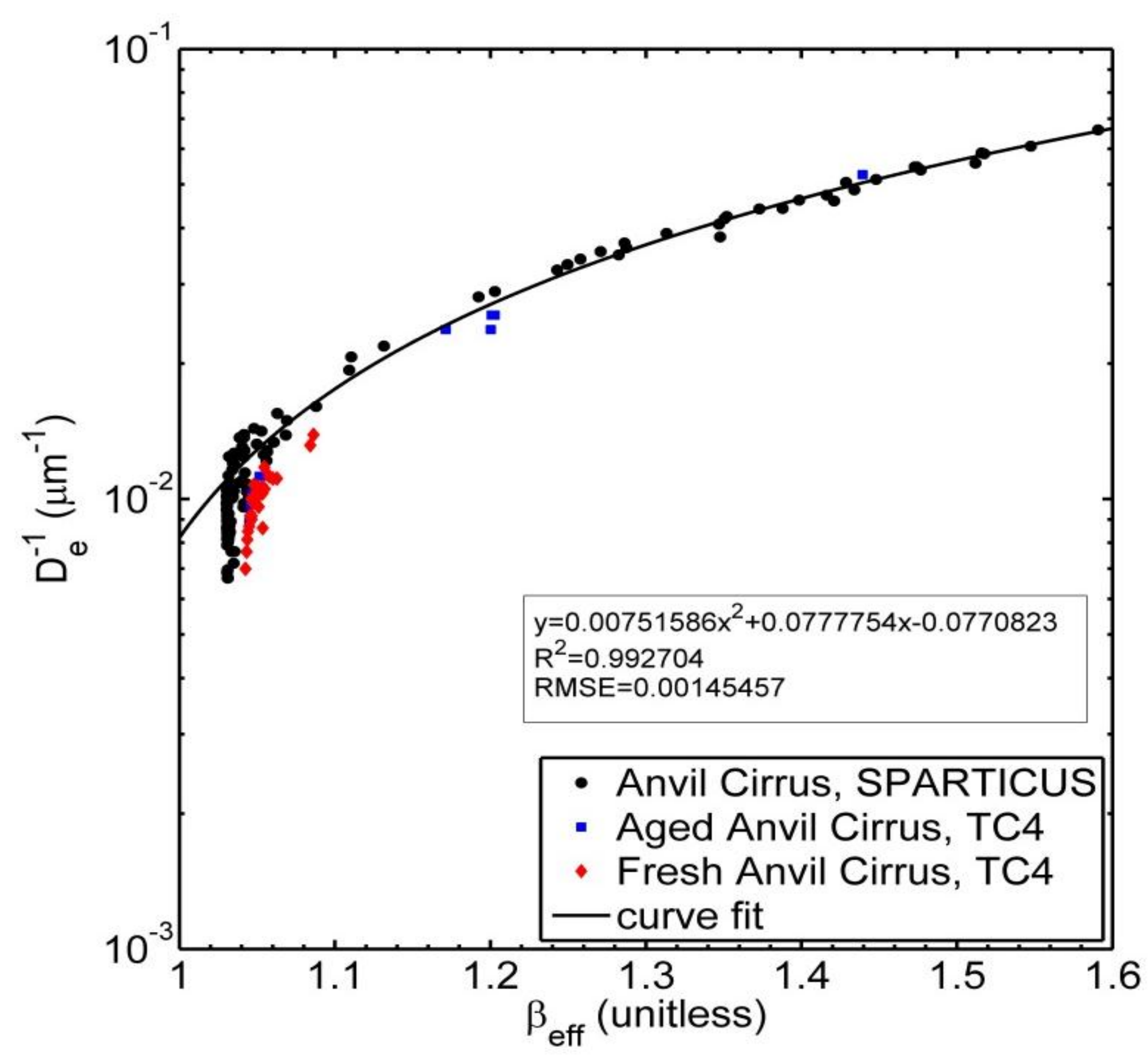
Components of the retrieval method that are sensitive to wave resonance absorption

β_{eff} is the effective absorption optical depth ratio measured by the IIR, based on channels at 10.6 and 12.05 μm. β_{eff} is a standard CALIPSO retrieval product that is a measure of wave resonance absorption and includes the effects of scattering.

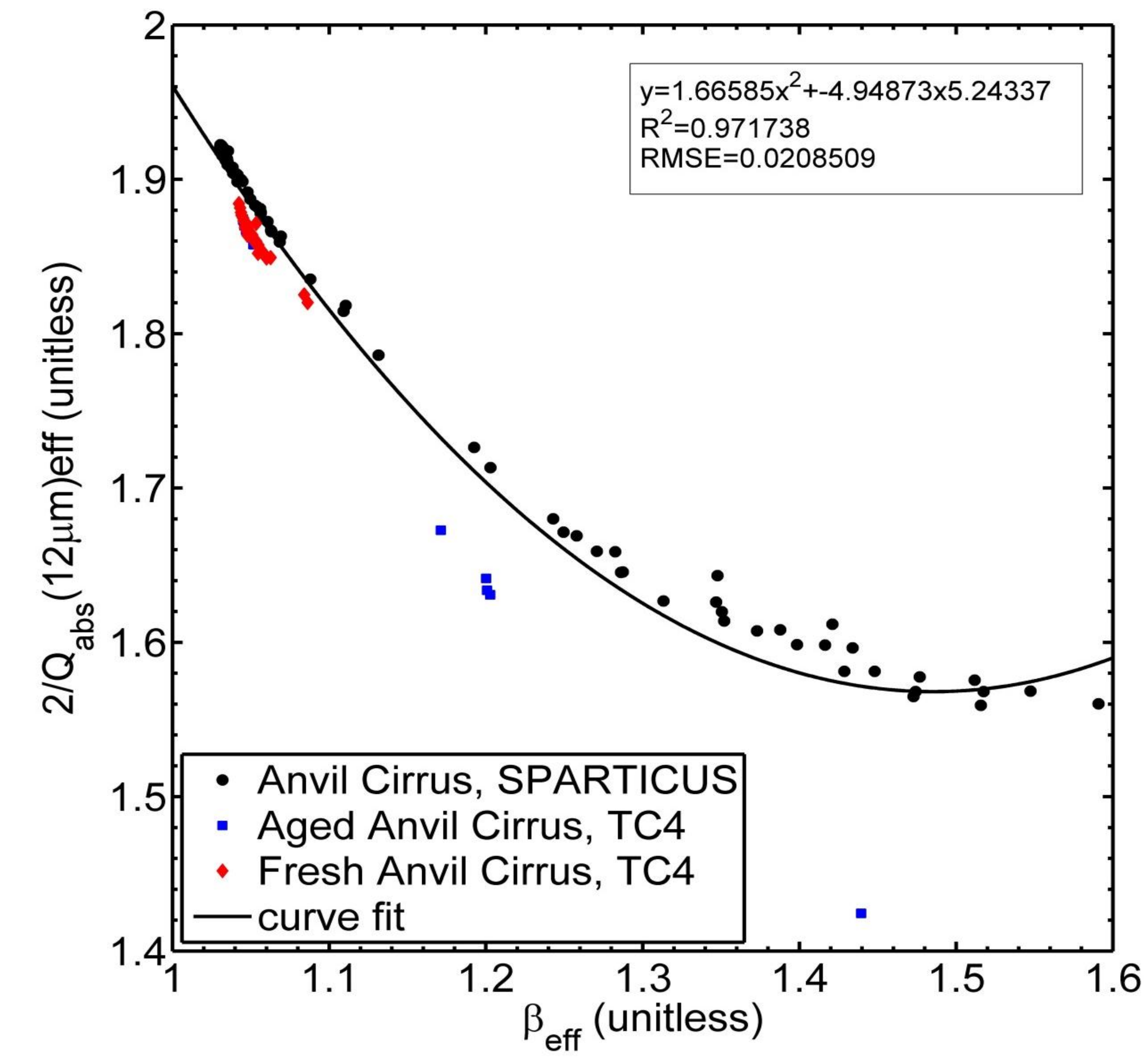


Relationship between β_{eff} and N/IWC based on measurements from two field campaigns. The curve-fit is used in the CALIPSO retrieval.

Retrieving effective diameter D_e from β_{eff}



Relationship between β_{eff} and D_e based on measurements from two field campaigns. The curve-fit is used in the CALIPSO IIR retrieval.



Relationship between β_{eff} and 2/ $\bar{Q}_{abs}$(12 μm) based on measurements from two field campaigns. The curve-fit is used in the CALIPSO IIR retrieval. 2/ $\bar{Q}_{abs}$(12 μm) converts the absorption optical depth τ_{abs} to a visible optical depth. When β_{eff} > 1.485, then 2/ $\bar{Q}_{abs}$(12 μm) = 1.57 in the retrieval algorithm. $\bar{Q}_{abs}$ = particle size distribution (PSD) absorption coefficient/PSD projected area.

The Retrieval Equation

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

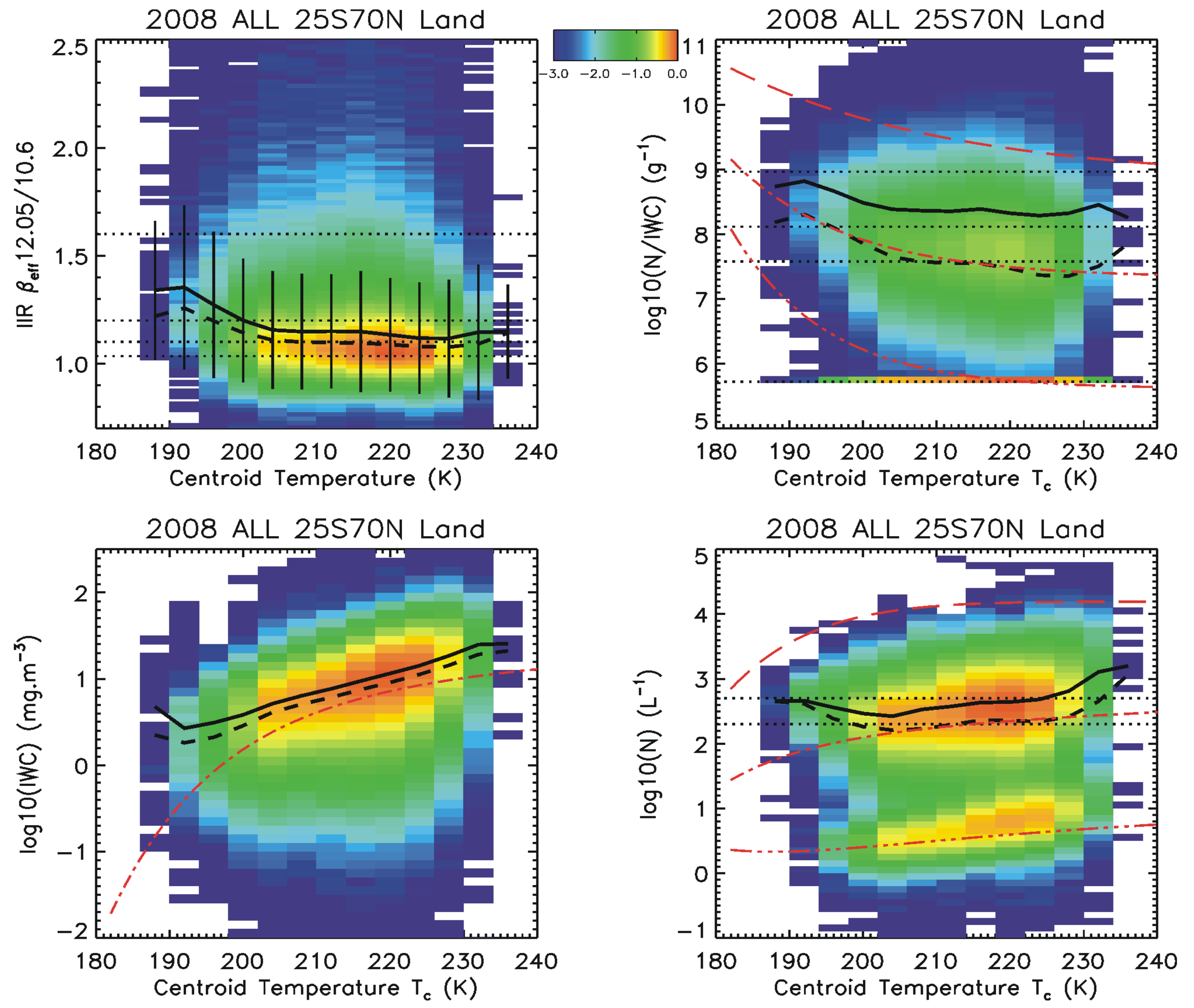
The quantities N/IWC, D_e and $2/\ \bar{Q}_{abs}(12\ \mu m)$ are retrieved from β_{eff} as already described. ρ_i is the density of bulk ice and τ_{abs} is the effective absorption optical depth from the IIR 12 μm channel, a standard retrieval product. The terms on the RHS excepting N/IWC determine the ice water content (IWC), and ice water path (IWP) is IWC · Δz_{eq} where Δz_{eq} = equivalent cloud thickness (typically 30-90% of geometric cloud thickness; calculated from principles described in Garnier et al. 2015, AMT).

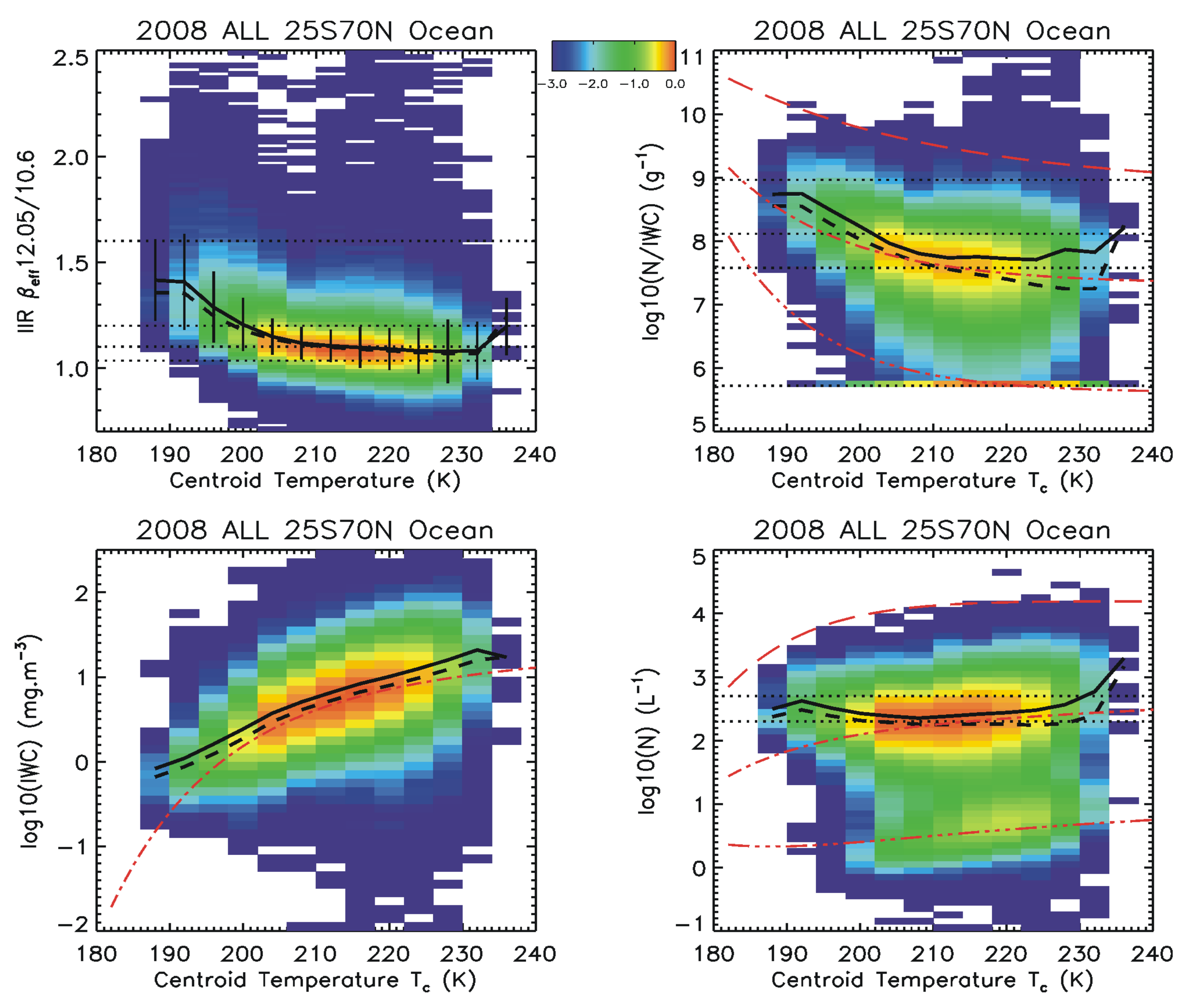
Application of Theory

The retrieval equation was applied to single-layer cirrus (having no cloud below) where the integrated attenuated backscatter (IAB) from the CALIOP lidar aboard CALIPSO was greater than 0.01 sr^{-1} and the lidar could always detect cloud base (< 235 K). This resulted in a visible OD range of ~ 0.3 to 3.0. Cloud temperature was estimated as the cloud centroid temperature, which is the temperature near the center of the CALIOP attenuated backscatter profile. As shown from Fig. 4 of Barahona and Nenes (2009, ACP), cirrus having N > 200 $liter^{-1}$ are likely formed through hom, and they are very likely formed through hom when N > 500 l^{-1}. Therefore we use N > 500 l^{-1} as a threshold indicating that the cirrus cloud was most likely formed through hom.

Retrieval Results

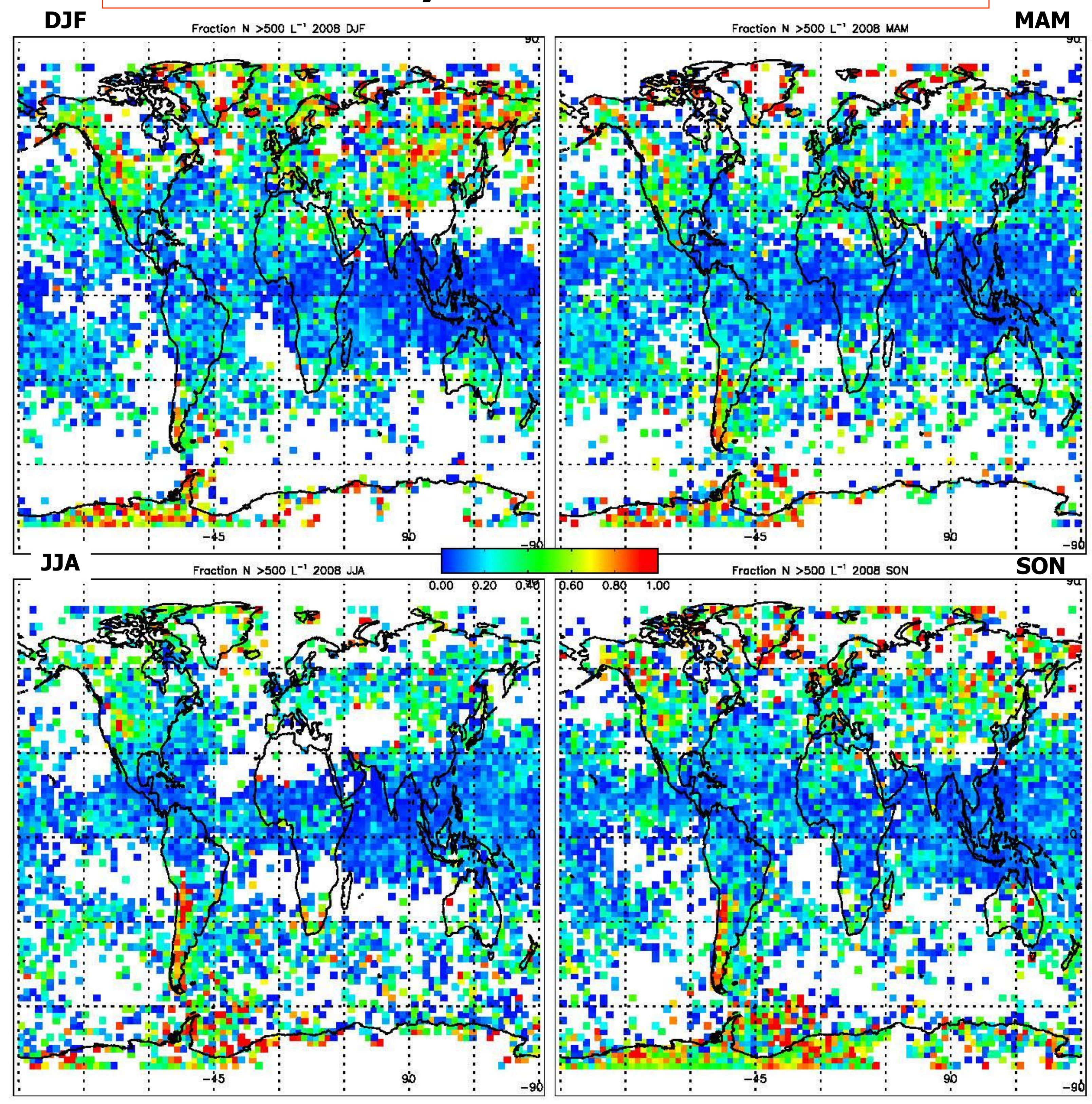
Krämer et al. (2009, ACP) compiled coincident in situ measurements of N and IWC from 5 field campaigns (10 flights) where N was measured by the FSSP probe and IWC was directly measured by various probes. These measurements were made at T < 240 K where PSD tend to be relatively narrow and ice particle shattering upstream of particle detection is less of a problem. Moreover, the FSSPs used did not use a flow-straightening shroud in front of the inlet.



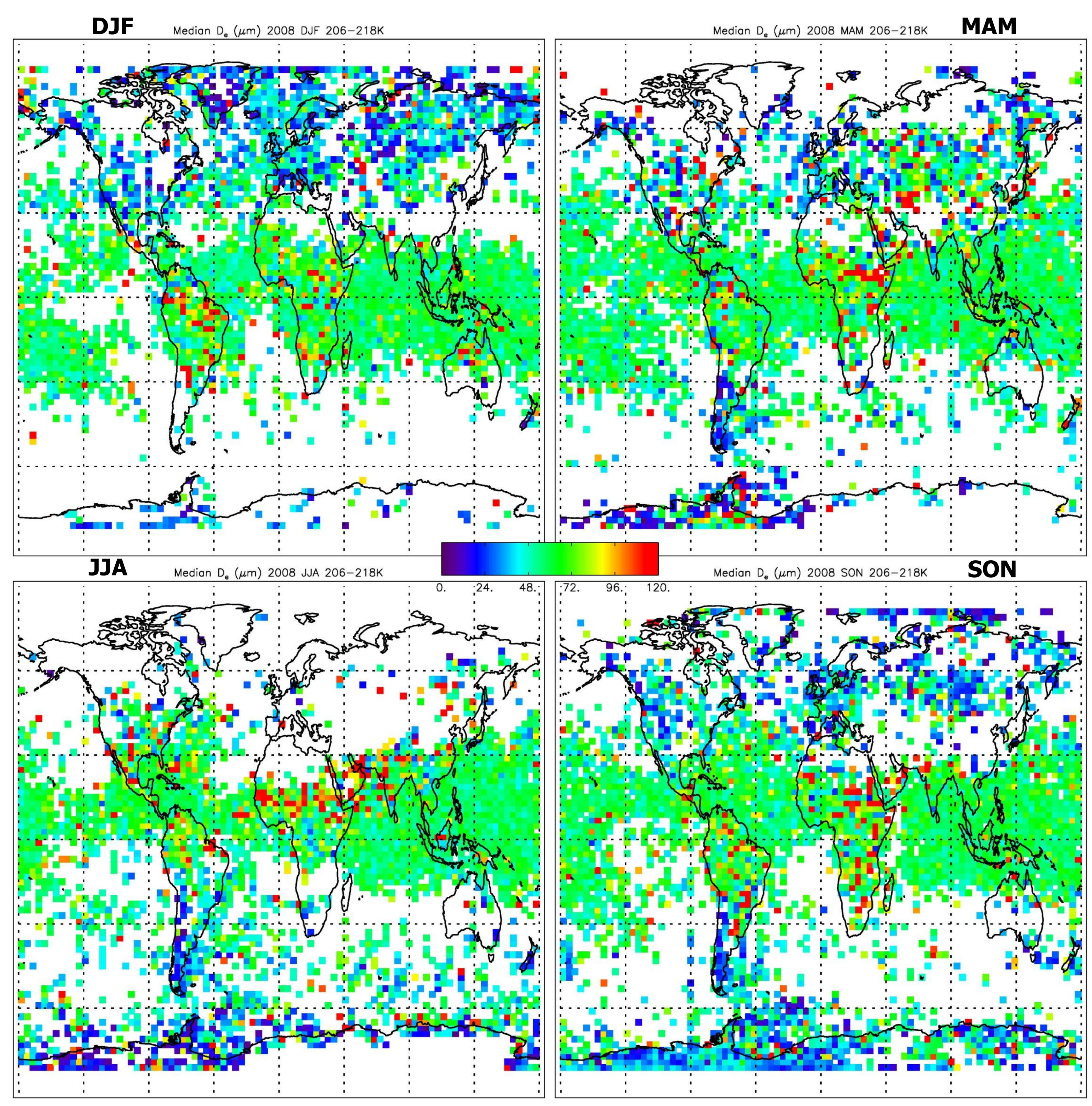


Comparisons of the means (solid curves) and medians (black dashed) of retrieved N/IWC, IWC and N with corresponding in situ measurements from Krämer et al. (2009) shown by the red dashed curves; top and bottom being maximum and minimum values and middle red curve being the middle value. Retrievals are over the land and ocean for latitudes spanning the range of field campaigns for all seasons. The black dotted horizontal lines in the panel for N correspond to 200 and 500 l^{-1}. The divergence between the retrieved and in situ medians for IWC and N for T < 200 K is believed due to subvisual cirrus whose thermal IR signal is too weak for the IIR instrument to retrieve. Color code: number of samples were normalized to the maximum value (log scale).

The Seasonal Cycle of Hom and Het Cirrus



Cirrus clouds having N > 500 $liter^{-1}$ are most likely formed through homogeneous ice nucleation (hom), and the fraction of these cirrus are shown above for each season. A possible explanation of this observed seasonal cycle of hom and het cirrus is given in the abstract. Legend: winter, spring, summer & fall => DJF, MAM, JJA, & SON.



The median effective diameter D_e is plotted above for cirrus clouds residing in the temperature range of 206-218 K. The color bar shows the D_e value in microns. Each panel shows one season as defined by the months DJF, MAM, JJA & SON. Relatively few cirrus exist at these temperatures north of 30°N during summer, although more exist (but still relatively few) at warmer temperatures.

CLOSING COMMENTS

Cziczo et al. (2013, Science) found that heterogeneous ice nucleation was the dominant formation mechanism for cirrus clouds, but the field campaigns that the study was based on were between the equator and south of 37°N latitude. Considering the seasons and locations of the sampling, the Cziczo et al. results appear consistent with the findings of this CALIPSO study.

A GCM climate intervention study by Storelvmo et al. (2015, Phil. Trans. RMS) assumed that cirrus clouds at high latitudes during winter (or when sun-angles are lower) were formed primarily by hom, which appears consistent with these findings. When the formation mechanism was changed to het in the GCM, a net cooling occurred from escaping longwave radiation, with surface temperatures in the Polar Regions dropping by 2 to 5°C. These CALIPSO results indicate that some amount of cooling is possible if the high latitude cirrus clouds were seeded with efficient ice nuclei when the sun is relatively low in the sky or absent.

The Storelvmo et al. results have been contested by Penner et al. (GRL, 2015). One possible way to resolve this conundrum might be to improve the parameterization of sub-grid processes in a GCM that govern hom and het ice nucleation, using retrievals like these to test the parameterizations. Then a more realistic appraisal of the cooling potential of cirrus cloud seeding appears likely.

ACKNOWLEDGEMENT:
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