Dependence of Homo- and Heterogeneous Ice Nucleation on Latitude and Season and Climate Implications

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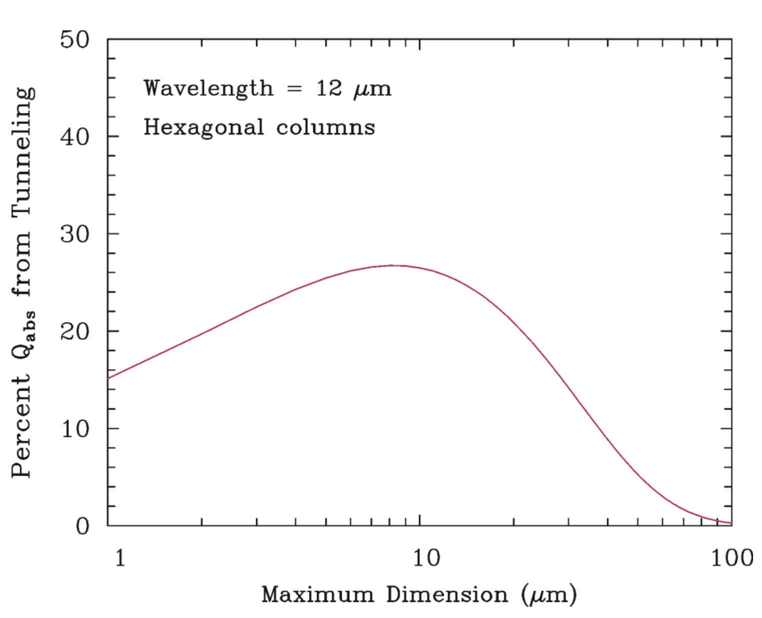
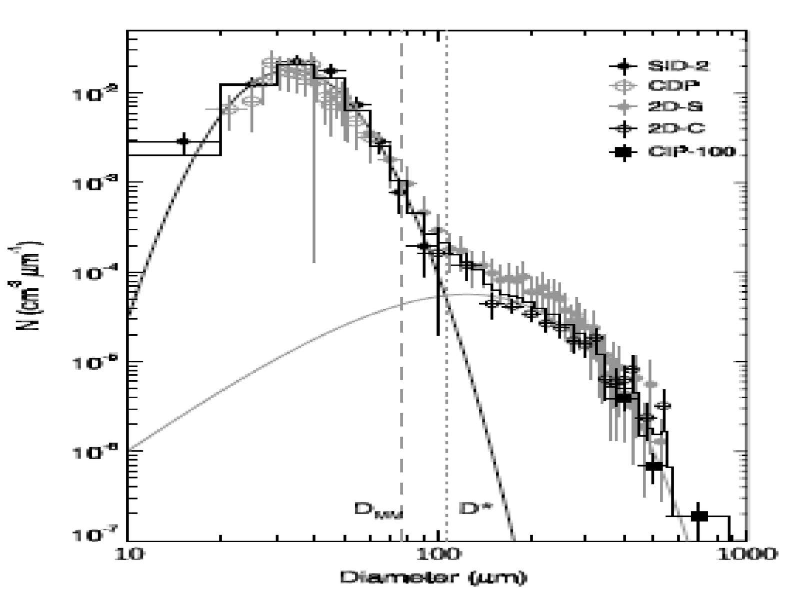
ABSTRACT

The 12-to-11 μm absorption optical depth ratio, or β, is extremely sensitive to the concentration of small ice crystals (D < 50 μm) due to its dependence on wave resonance contributions to absorption. For this reason it is strongly correlated with the N/IWC ratio, where N = total ice particle number concentration and IWC = ice water content. Using theory and in situ measurements, we show how N/IWC can be an index for ice nucleation rates. The imaging infrared radiometer (IIR) aboard the CALIPSO satellite retrieves an effective β, or β_{eff}, where β_{eff} includes scattering effects. Retrieved β_{eff} are compared with β_{eff} derived from co-located coincident in situ measurements, revealing differences that can be expected and how to interpret the retrievals (vertically integrated quantities).

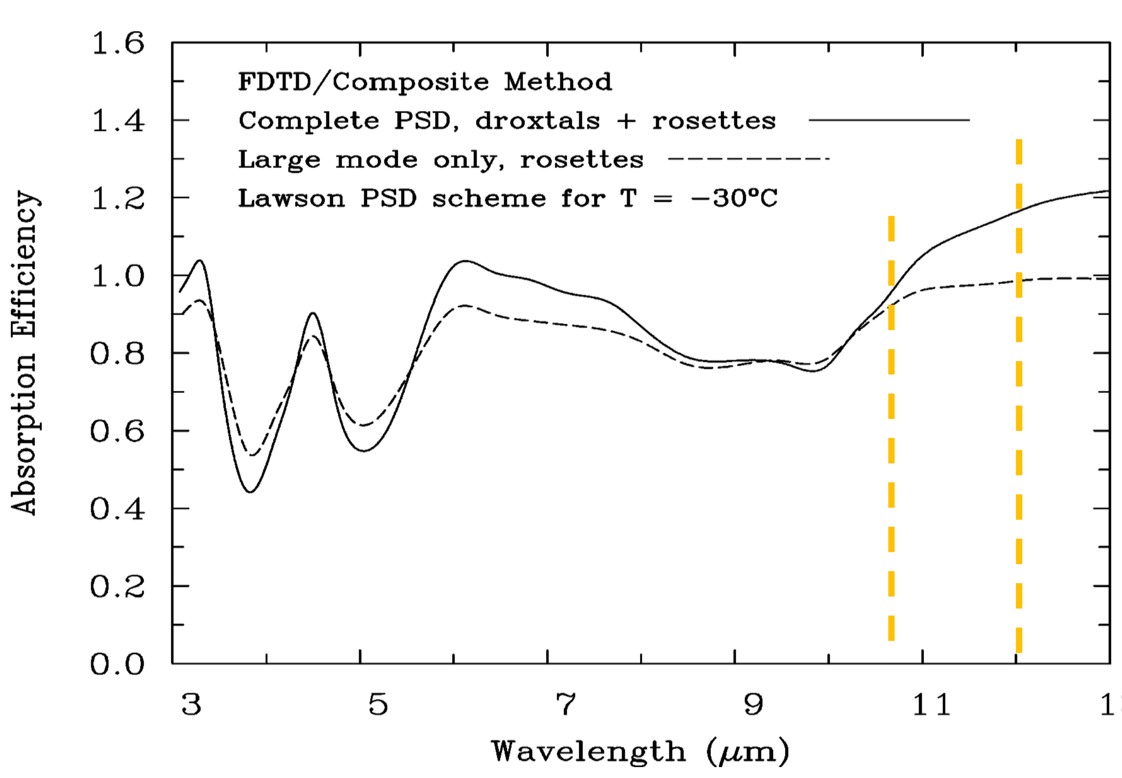
Retrieval results show that β_{eff} (or N/IWC) is lower in the tropical eastern Pacific relative to the tropical western Pacific, consistent with in situ measurements from TC4 and ATTREX. Moreover, β_{eff} at the coldest temperatures is relatively high in wintertime at high latitudes, suggesting that homogeneous ice nucleation is more common in cirrus at high latitudes during winter. This interpretation is further supported by GCM predictions of the latitude and seasonal dependence of mineral dust concentrations. This result also indicates that cirrus cloud climate engineering may be feasible. Finally, β_{eff} is often higher over land than over oceans.

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 (hom & het) and relating β_{eff} to these regions

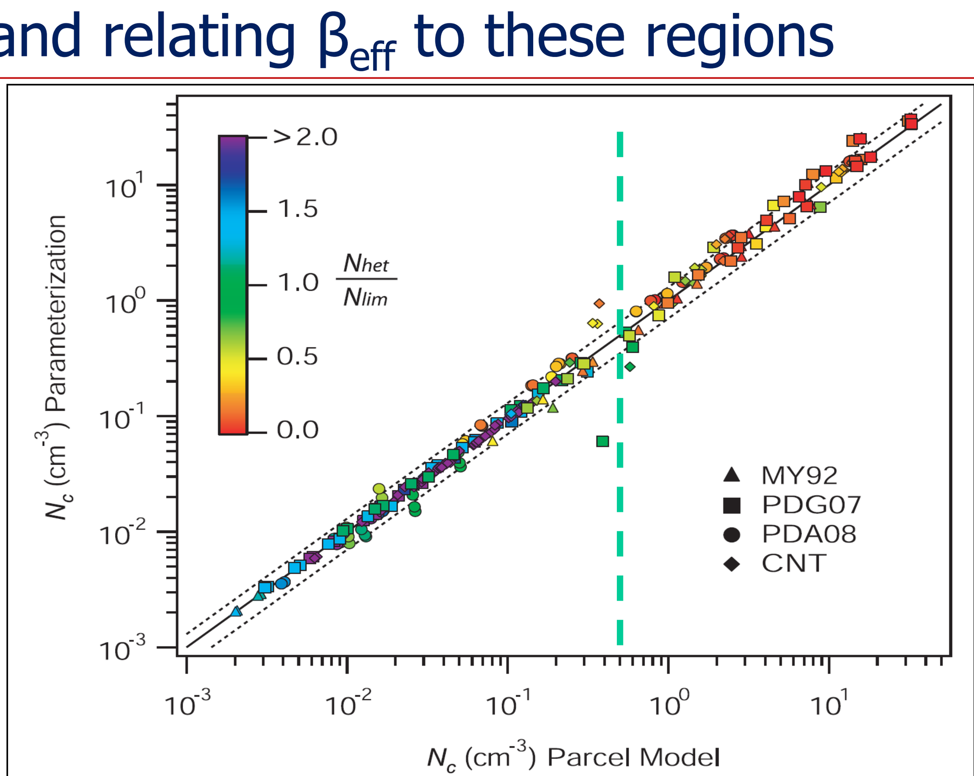
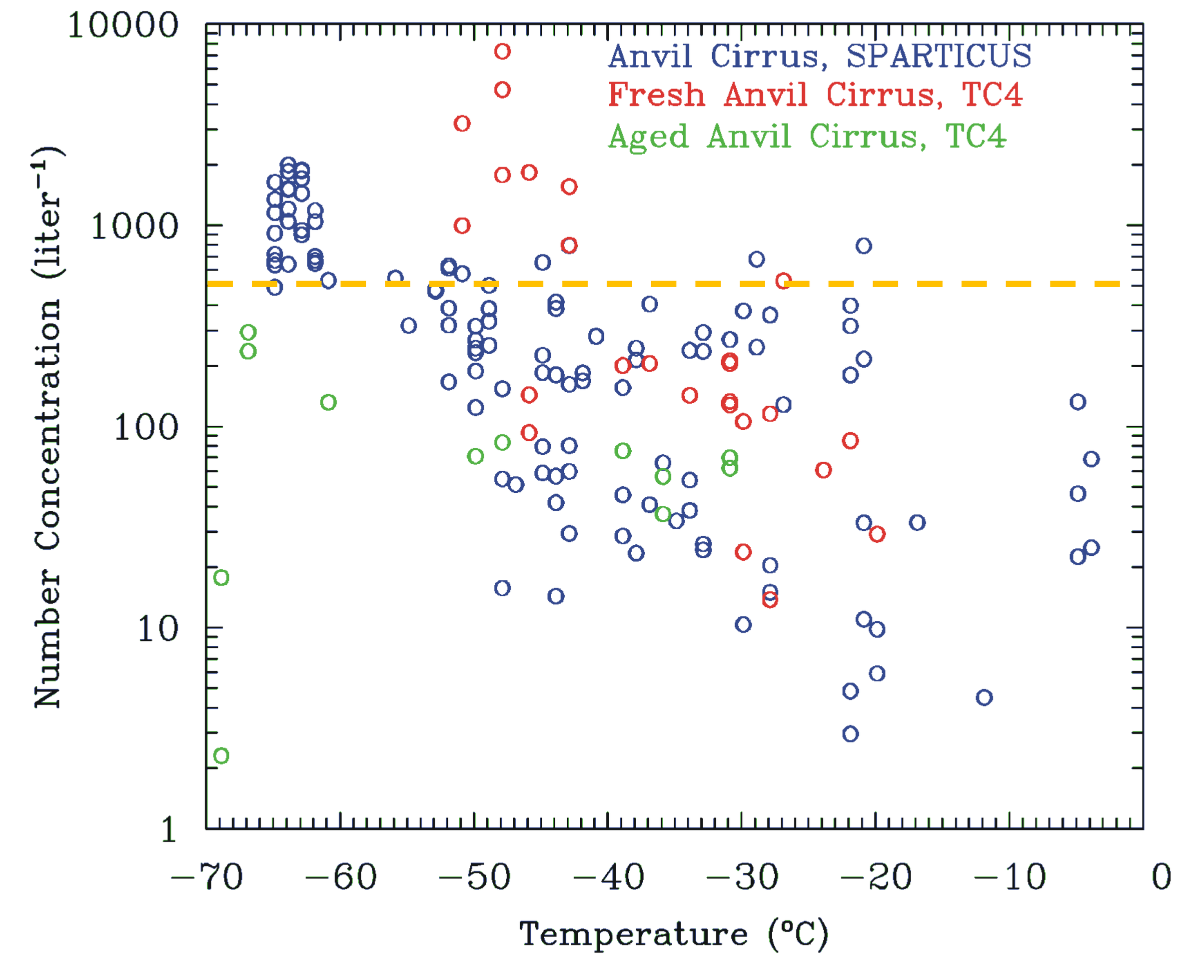


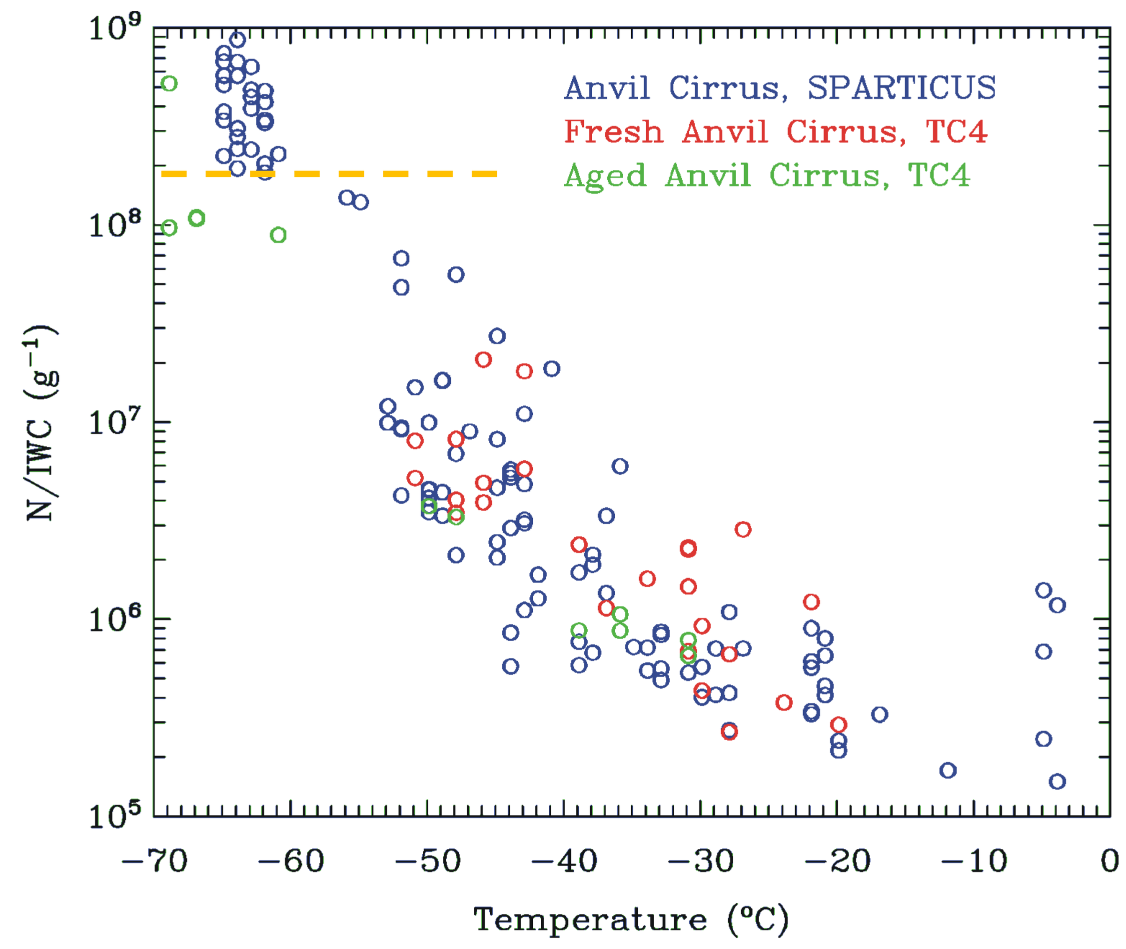
Fig. 4. Comparison between N_c from combined homogeneous and heterogeneous freezing predicted by the parameterization and the parcel model for simulation conditions of Table 2 and freezing spectra of Table 1. Dashed lines represent the ±30% difference. Colors indicate the ratio $\frac{N_{het}}{N_{lim}}$.

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

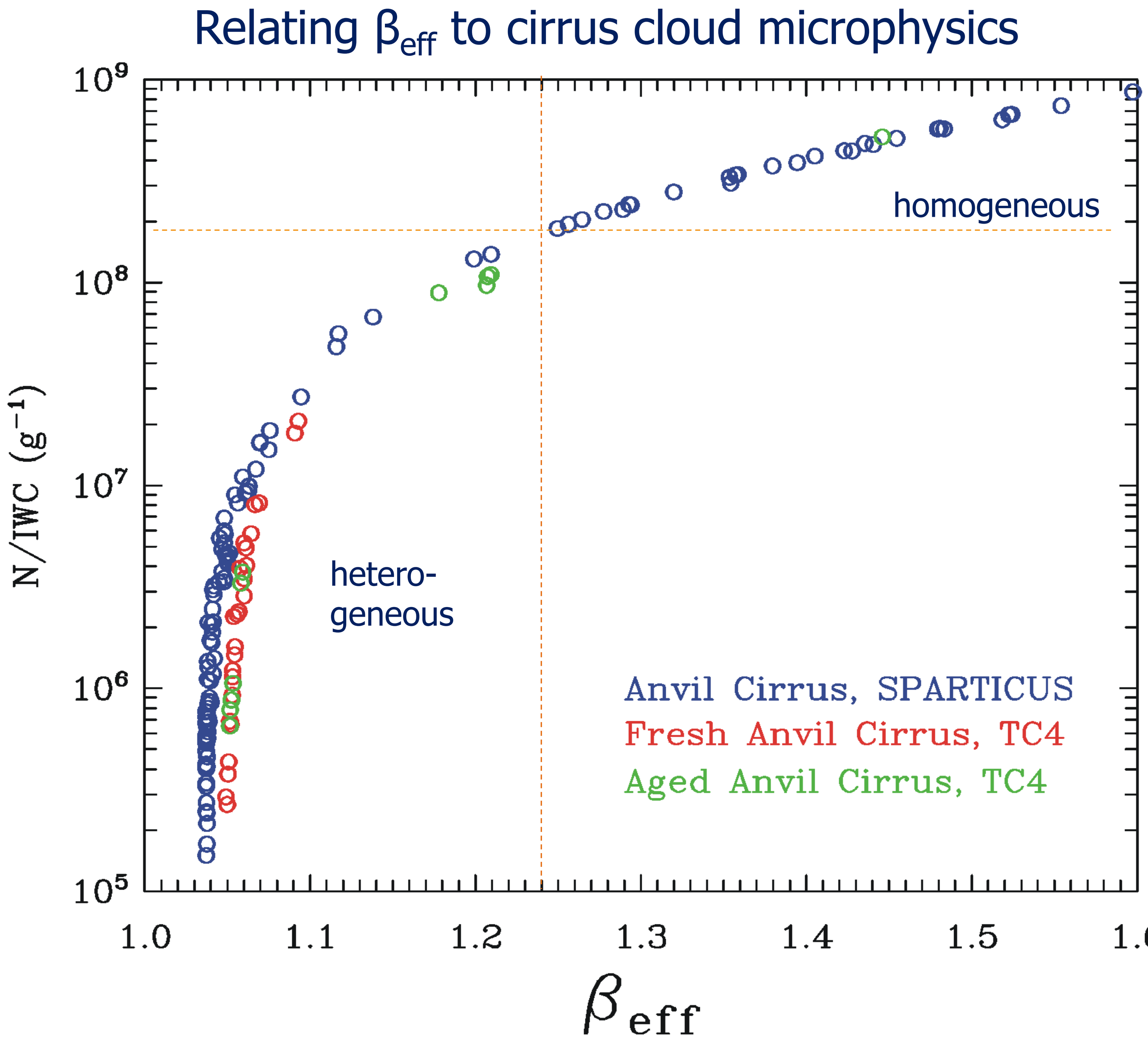
Property	Values
T_o (K)	205–250
V (m s^{-1})	0.04–2
α_d	0.1, 1.0
$\sigma_{g,dry}$	2.3
N_o (cm^{-3})	200
$D_{g,dry}$ (nm)	40
N_{dust} (cm^{-3})	0.05–5
N_{soot} (cm^{-3})	0.05–5
θ_{dust}	16°
θ_{soot}	40°
$s_{h,dust}$	0.2
$s_{h,soot}$	0.3

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

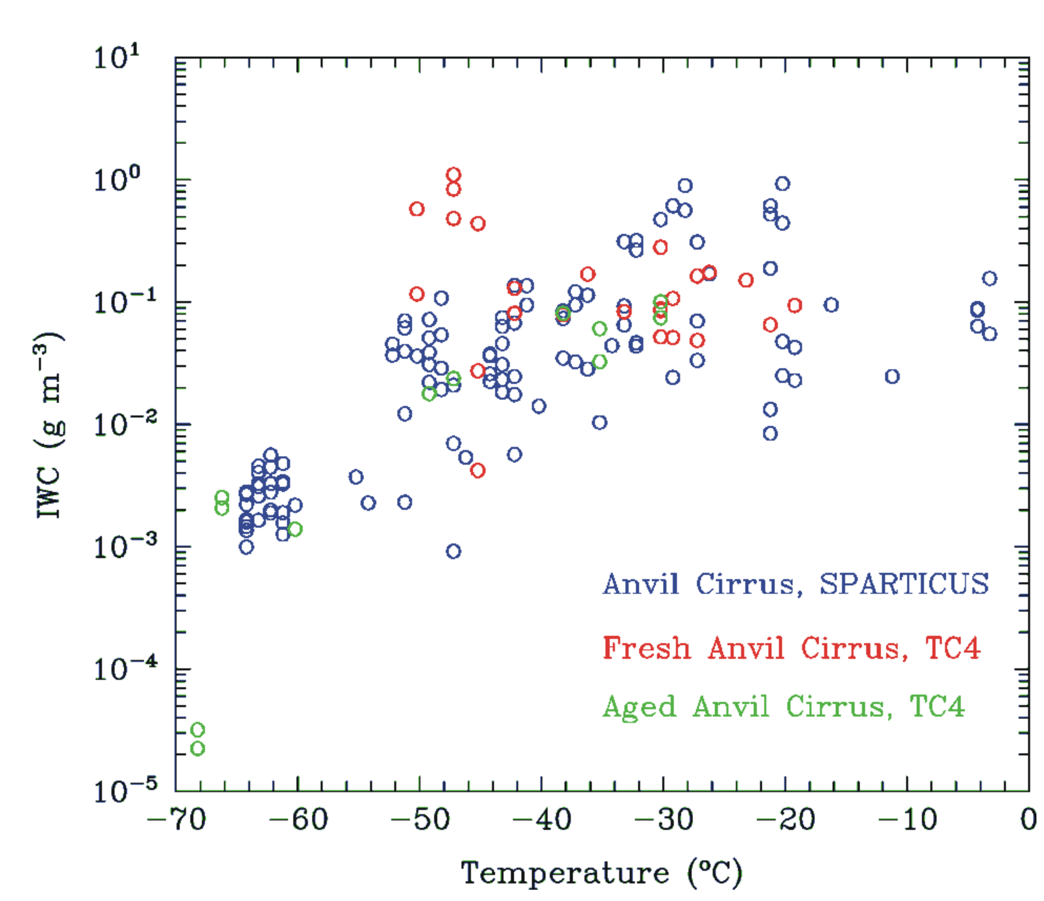




Relating β_{eff} to cirrus cloud microphysics

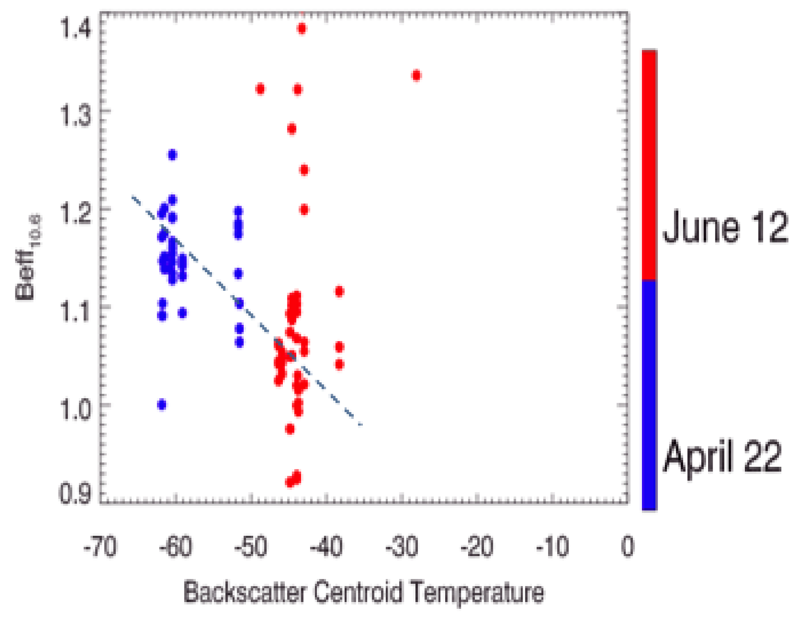


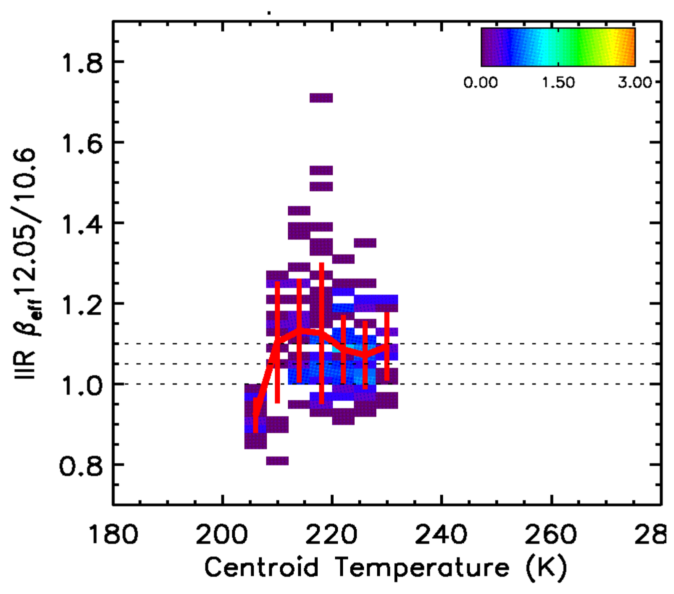
Relationship between β_{eff} and N/IWC based on measurements from two field campaigns. The estimated β_{eff} threshold for homogeneous freezing is shown by the dashed orange line, based on CALIPSO IIR channels at 10.6 and 12.05 μm..



The dependence of IWC on temperature for the two field campaigns. Very low IWC near -70°C contributes negligible thermal emission.

Comparing in situ and co-located/coincident retrieved β_{eff} for the SPARTICUS anvil cirrus previously evaluated





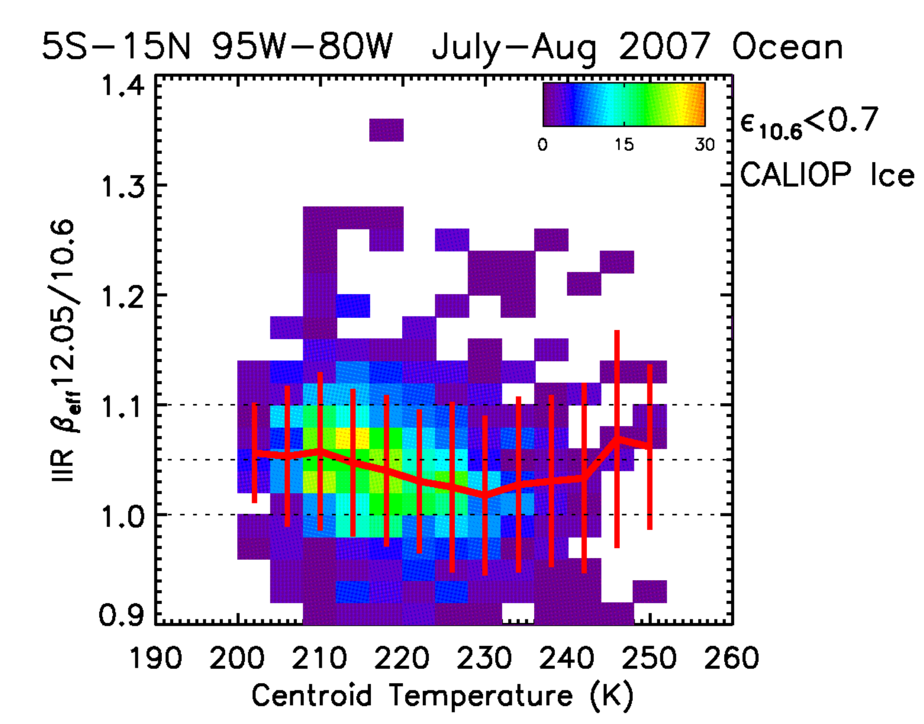
Left panel: IIR 1 km β_{eff} for cloud emissivities between 0.1 & 0.7 that correspond to the in situ sampling shown previously.
Right panel: IIR 5 km β_{eff} for 10.6 µm cloud emissivities between 0.15 & 0.4 for temperatures < 230 K. The color code is the decimal logarithm of the number of samples.

β_{eff} differences between the eastern and western tropical Pacific

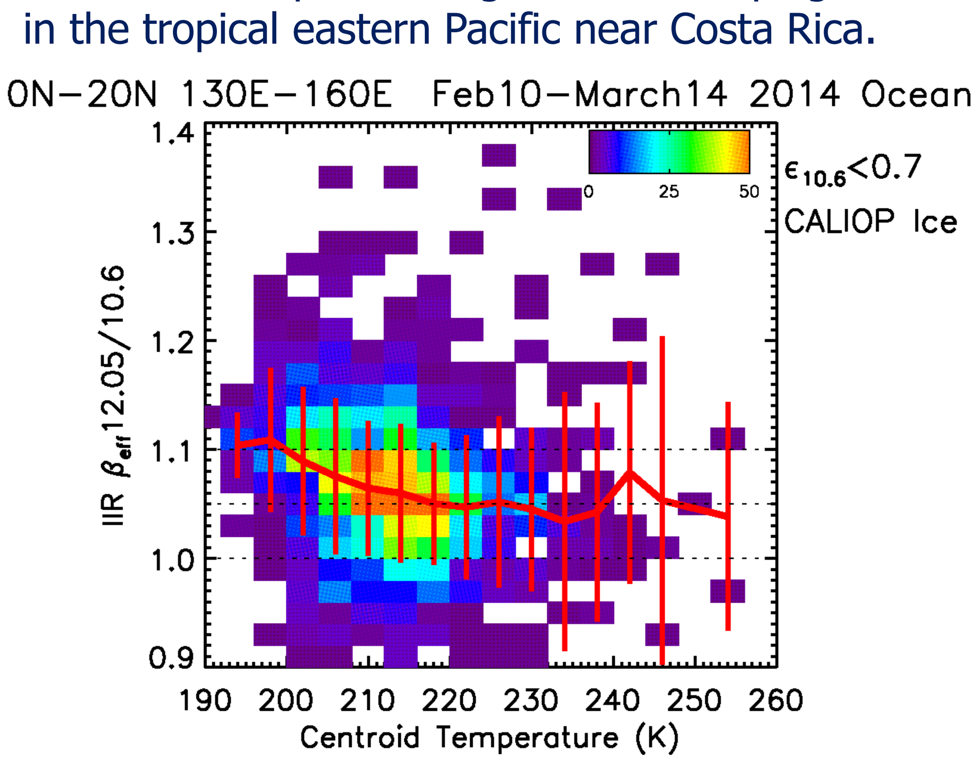
Single layered clouds; IRR pixels co-located with CALIOP track. CALIOP Ice: layers classified as ice by CALIOP, randomly oriented ice and horizontally oriented ice, high and medium confidence.

Color code: number of samples
In red: mean values and standard deviations

Centroid temperature: temperature at the centroid altitude of the CALIOP attenuated backscatter profile.

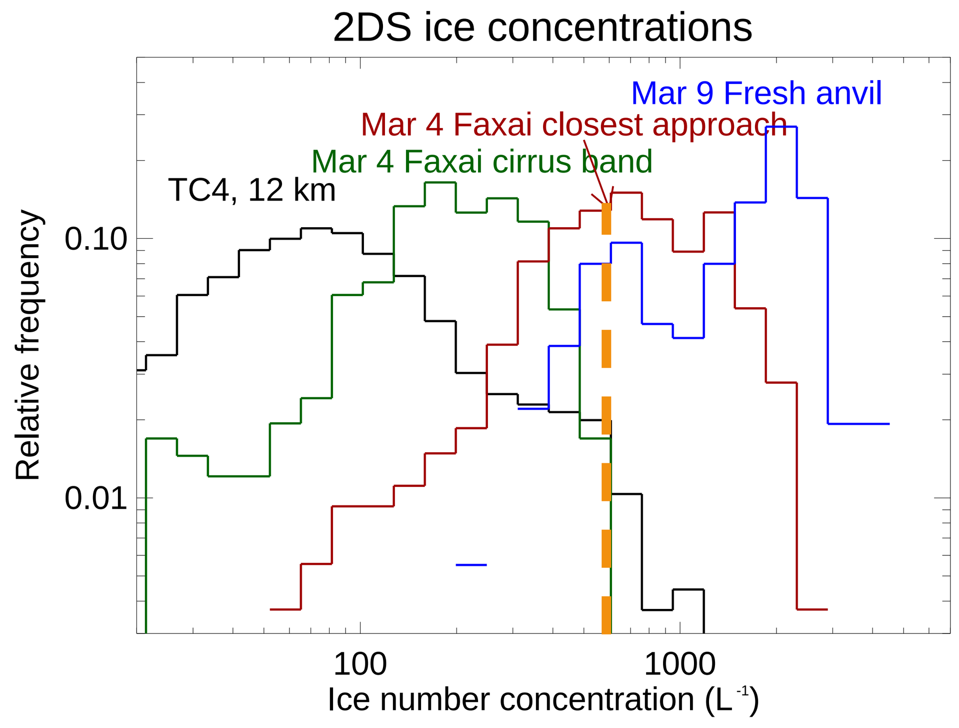


Retrievals sampled during the TC4 campaign in the tropical eastern Pacific near Costa Rica.



Retrievals sampled during the ATTREX campaign in the tropical western Pacific near Guam.

Slide below is courtesy of E. Jensen, P. Lawson, S. Woods, S. Lance, B. Gandrud; from NASA ATTREX Science Team Meeting

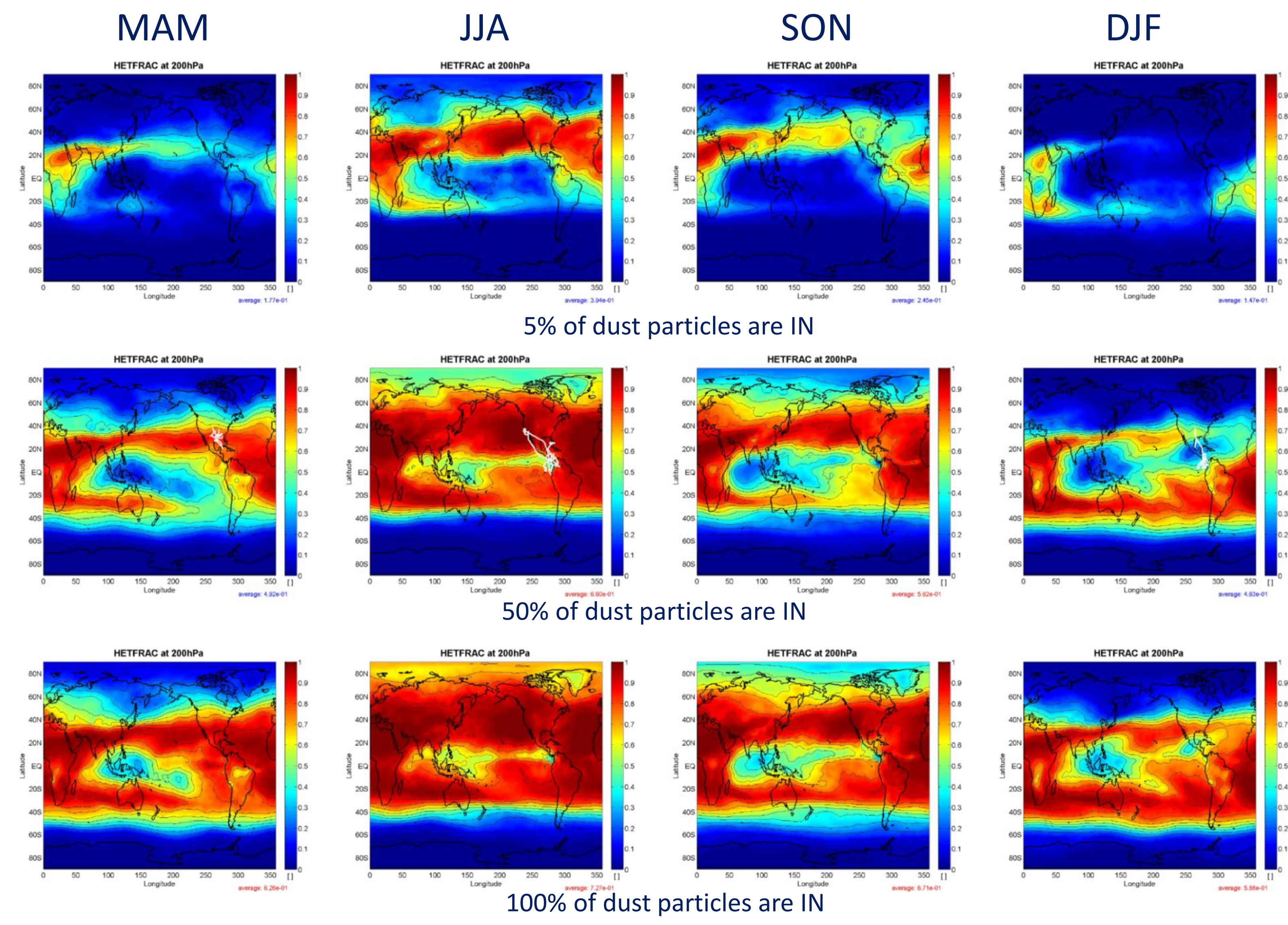


- ATTREX anvils (14–16 km) generally have larger ice concentrations than lower TC4 anvils (<12 km) [1]
- Differences between ATTREX cases likely attributable to location in cloud, cloud age, etc.

[1] Differences between TC4 2DS and ATTREX 2DS (Hawkeye) cannot be ruled out

Summary: N/IWC is generally higher for T < -40°C in the TWP during ATTREX, with cirrus reaching colder temperatures in the TWP. This is consistent with in situ sampling during TC4 & ATTREX. N for ATTREX anvils suggests contributions from both hom & het, suggesting that β_{eff} > 1.10 or 1.15 might correspond to hom. The SPARTICUS analysis suggests a similar β_{eff} threshold range.

CAM5 predictions of fraction of ice crystals formed by heterogeneous ice nucleation/total number of ice crystals nucleated (HETFRAC) at 200 hPa



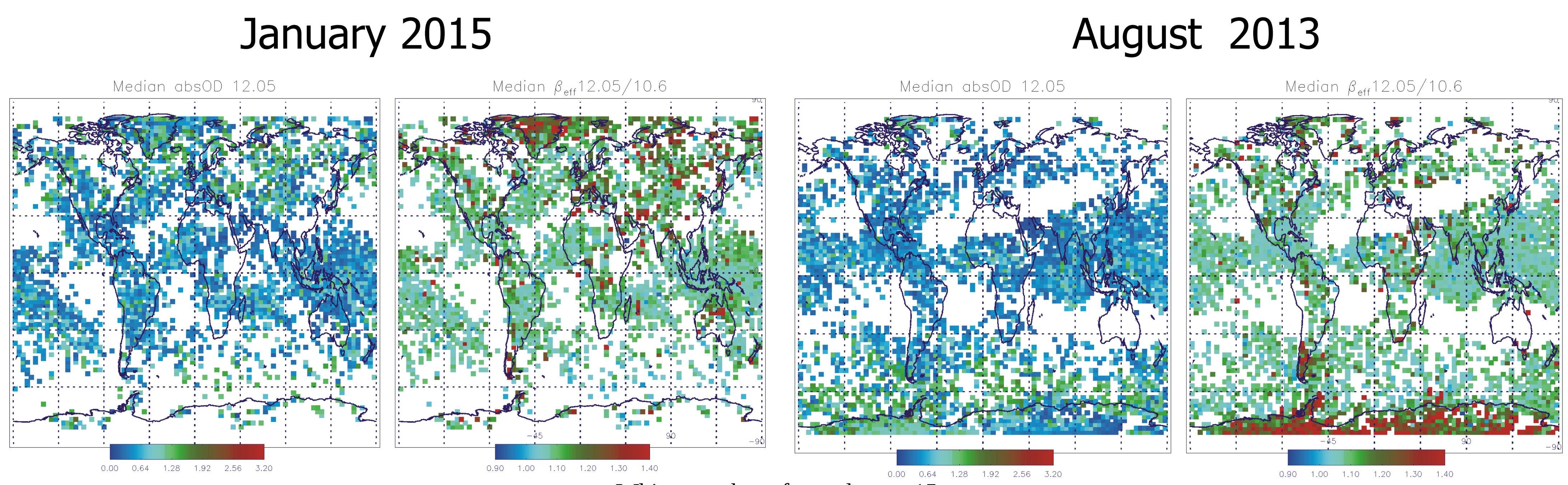
Adapted from Storelvmo & Herger, 2014, JGR

CALIPSO IIR Retrieval Specifications

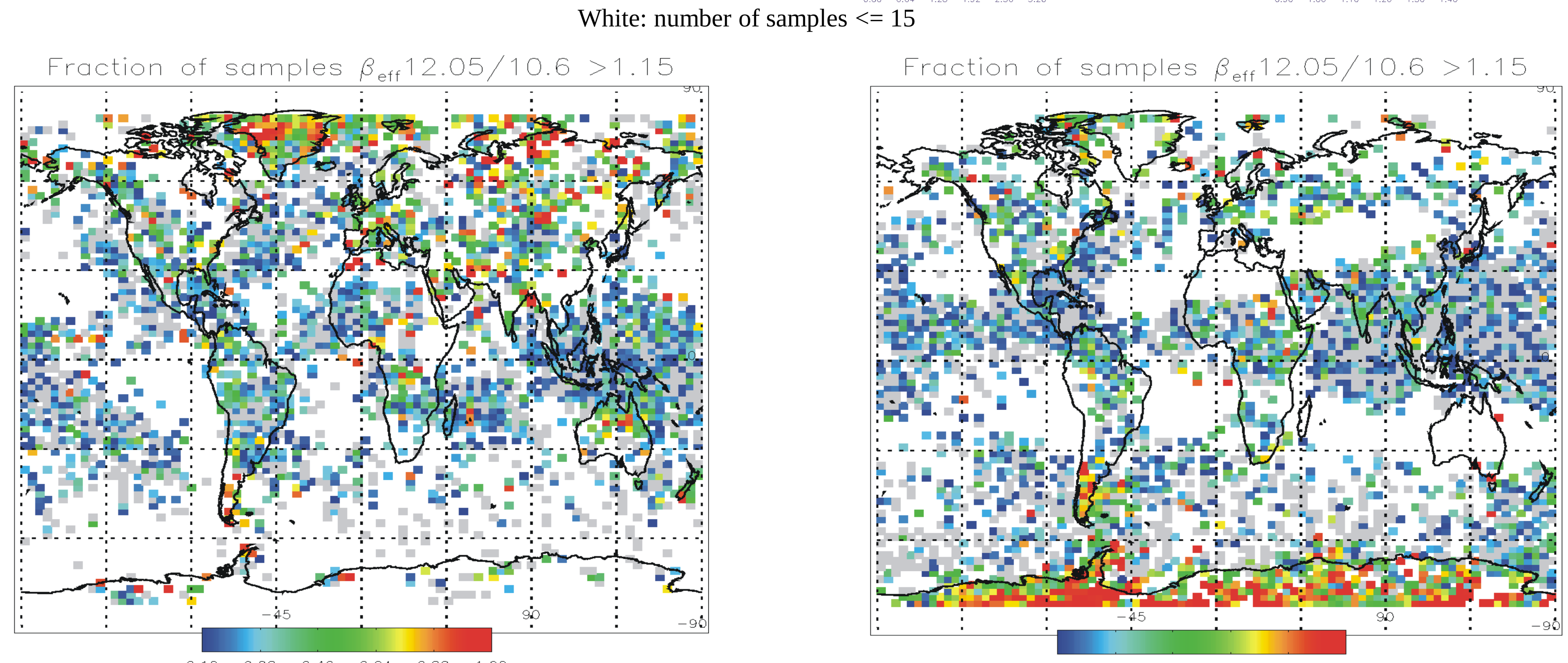
Resolution is 1km; Types of scene => single-layered clouds; cloud base temperature < 235K; IIR quality flag= good

CALIOP Integrated Attenuated Backscatter > 0.012 sr-1 (optical depth > about 0.5) & emissivity @10.6 mm < 0.8

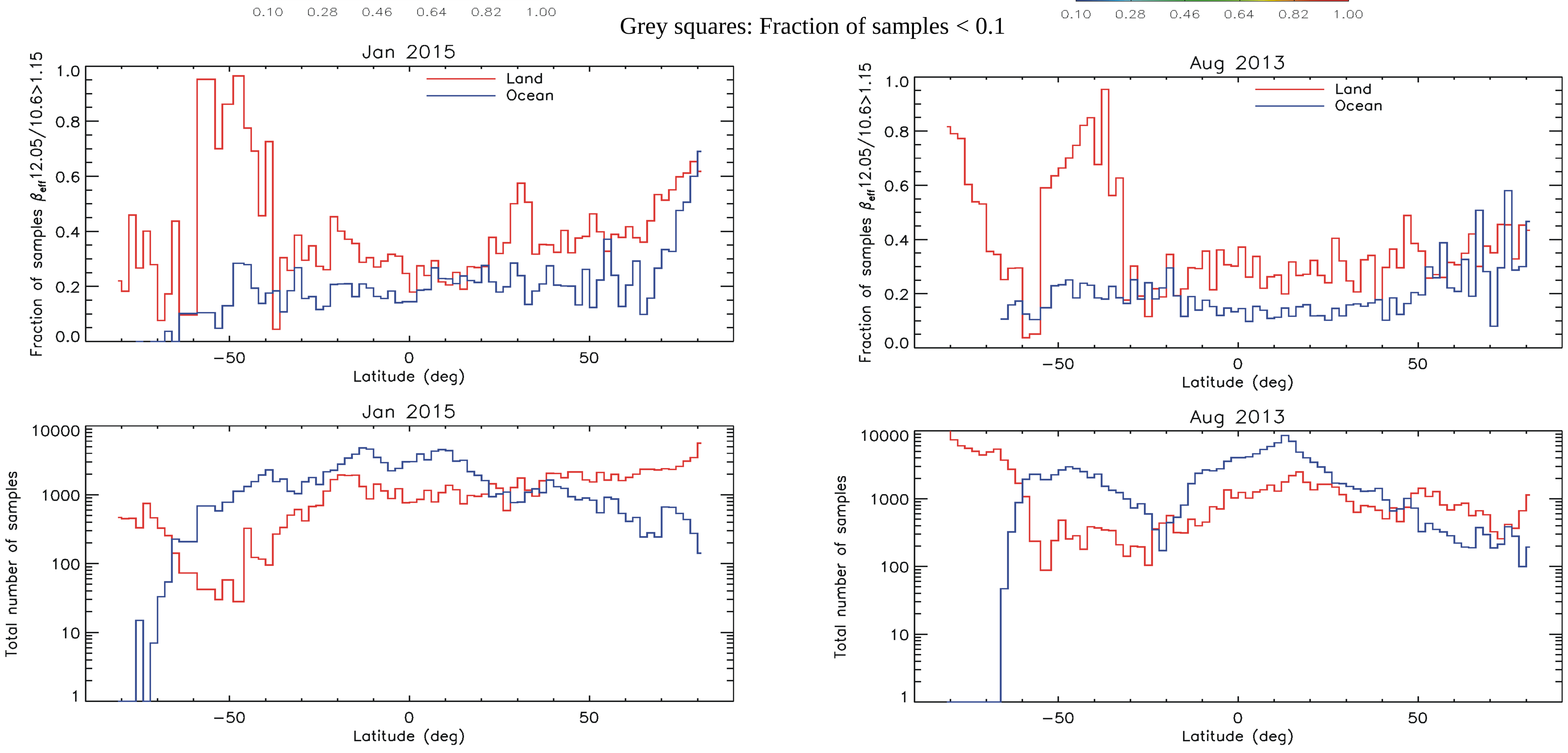
Reference – Blackbody BTD > 10K; Error estimates (not shown) => measurement only, random noise 0.3 K



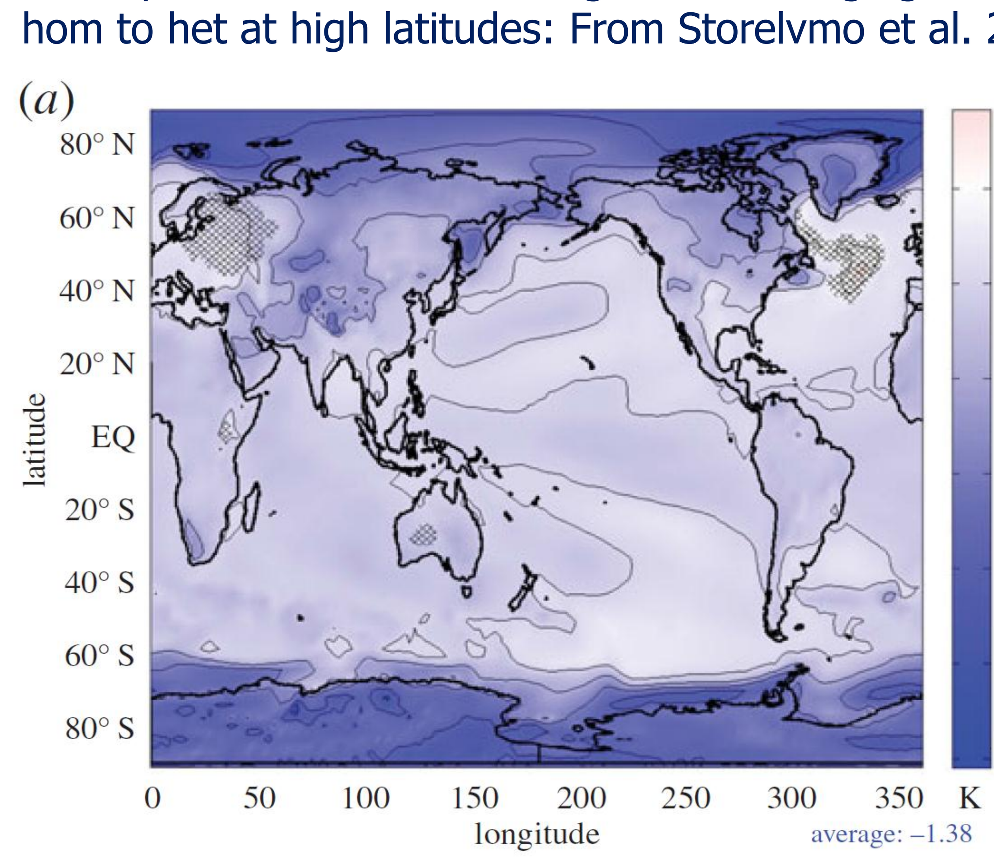
White: number of samples <= 15



Grey squares: Fraction of samples < 0.1



CAM5 predicted surface cooling due to changing from hom to het at high latitudes: From Storelvmo et al. 2014



Conclusions:

The N/IWC ratio depends on latitude and season, largely consistent with predicted concentrations of mineral dust. This can be explained by a similar dependence of homo- and heterogeneous ice nucleation on latitude and season. More research is needed to determine the fraction of ice crystals formed through hom during polar winter (60-90°lat). GCM simulations indicate this dependence of hom & het may have an impact on polar surface temperatures.