The ratio of absorption optical depth:

$$\beta = \frac{\tau(12 \mu m)}{\tau(10.6 \mu m)} = \frac{\bar{Q}_{\text{abs}}(12 \mu m)}{\bar{Q}_{\text{abs}}(10.6 \mu m)}$$

is primarily determined by photon tunneling absorption and is thus sensitive to the concentration of small ice crystals. An effective $\beta$ that includes scattering effects, $\beta_{\text{eff}}$, is a standard retrieval product from the imaging infrared radiometer aboard the CALIPSO satellite.
The Retrieval Equation

\[ N = \rho_i \left[ \frac{2}{Q_{\text{abs}}(12 \, \mu m)} \right] \tau_{\text{abs}}(12 \, \mu m) \frac{D_e \left( \frac{N}{IWC} \right)}{3 \, \Delta z_{eq}} \]
Cloud formation conditions & aerosol characteristics used to produce this figure from Barahona & Nenes (2009, ACP).

<table>
<thead>
<tr>
<th>Property</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_o$ (K)</td>
<td>205–250</td>
</tr>
<tr>
<td>$V$ (m s$^{-1}$)</td>
<td>0.04–2</td>
</tr>
<tr>
<td>$\alpha_d$</td>
<td>0.1, 1.0</td>
</tr>
<tr>
<td>$\sigma_{g,\text{dry}}$</td>
<td>2.3</td>
</tr>
<tr>
<td>$N_o$ (cm$^{-3}$)</td>
<td>200</td>
</tr>
<tr>
<td>$D_{g,\text{dry}}$ (nm)</td>
<td>40</td>
</tr>
<tr>
<td>$N_{\text{dust}}$ (cm$^{-3}$)</td>
<td>0.05–5</td>
</tr>
<tr>
<td>$N_{\text{soot}}$ (cm$^{-3}$)</td>
<td>0.05–5</td>
</tr>
<tr>
<td>$\theta_{\text{dust}}$</td>
<td>16°</td>
</tr>
<tr>
<td>$\theta_{\text{soot}}$</td>
<td>40°</td>
</tr>
<tr>
<td>$s_{h,\text{dust}}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$s_{h,\text{soot}}$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

$N_{\text{lim}}$ is the limiting IN concentration that completely inhibits homogeneous freezing.
CALIPSO IIR 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
=> ~ 0.3 < OD_{vis} < ~ 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
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 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. Color code: number of samples were normalized to the maximum value (log scale). For T < 200 K, sampled cirrus is not TTL cirrus with OD < 0.3.
Testing the Retrieval with SPARTICUS Synoptic Cirrus Data; 15 flights & 229 PSDs CALIPSO retrievals confined to SPARTICUS spatial and temporal domain
The Seasonal Cycle of Hom and Het Cirrus for 2008

Results for 2008: Fraction of cirrus clouds having $N > 500$ liter$^{-1}$. Such cirrus are most likely formed by homogeneous ice nucleation (hom), and the fraction of these cirrus are shown for each season.

Legend: winter, spring, summer & fall => DJF, MAM, JJA, & SON.

Results are consistent with Cziczo et al. (2013, Science).
For 2008: Median effective diameter $D_e$ for cirrus clouds residing in the temperature range of 206-218 K. The color bar shows the $D_e$ value in $\mu$m. 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.
CAM5 predictions of mineral dust number concentration at 200 hPa for each season, averaged over 4 years.

From Storelvmo & Herger, 2014, JGR.
Annually averaged relative contributions to cirrus ICNC from 3 processes; from Gasparini & Lohmann, 2016, JGR

\[ w \propto \text{large scale vertical motion} + (TKE)^{1/2} \text{ or } w \propto \text{large scale vertical motion} + \text{orographic forcing} \]
Detrained ice dominating mid- and high-latitudes between -35 & ~ -60°C does not appear consistent with column integrated retrievals ($T < -38°C$) during winter.

**Figure 4.** Annually averaged relative contributions of the three ice nucleating processes. Color coding is the same as in previous slide.
Method for Determining Fraction of Hom Cirrus

Fraction:
0.324
0.232
0.316

N > 500 L⁻¹
N > 500 L⁻¹ & β_{eff} > 1.15
D_e < 45 μm
Observational evidence that pre-existing ice is a poor assumption for orographic wave-induced cirrus clouds

During high winds, jet stream wave cirrus on lee side of Sierra Nevada Mtns. was observed from ground and space on 17 June 2016 at 18:30 local time. New cirrus manifested in clear sky along leading edge of orographically-induced cirrus, obviously without pre-existing ice.
CAM5 Experiment: Contrasting an all het-cirrus world (with pre-existing ice) with a CALIPSO cirrus world

Treatment of ice fall speeds:

\[ V_m = f(D_e, T, p) \] based on Mishra et al. (2014, JGR)

Cirrus cloud radiative forcing differs due to both \( D_e \) and \( V_m \)
CAM5 4-year simulation results: $D_e(T)$ based on CALIPSO retrievals minus $D_e(T)$ based on pre-existing ice ($\pm 30^\circ$ latitude zone)
CAM5 Experiment CALIPSO – Het Cloud Radiative Forcing Results
Findings & Working Hypotheses

• In the N. Hemisphere over land, mid-latitude cirrus exhibit a seasonal cycle where hom cirrus comprise ~ 37% of total cirrus during winter, based on a conservative threshold for hom cirrus (N > 500 L⁻¹).

• In the high latitudes, the hom cirrus fraction is ~ 43% and 50% in the Arctic and Antarctic, respectively, averaged over all seasons. Ice nuclei (IN) concentrations are expected to be minimal here, promoting hom.

• The above seasonal cycle may be linked to the seasonality of deep convection that replenishes the IN supply at cirrus levels and also provides pre-existing ice during nucleation, lowering the RHi.

• Over land outside the tropics during winter, hom cirrus tend to occur over mountainous terrain, possibly due to stronger updrafts in the mountain-induced waves and lower IN concentrations (less mixing).

• Assuming pre-existing ice in GCMs may produce cloud forcing errors on the order of 1 W m⁻² outside the ± 30 ° latitude zone.
Frequency of cirrus occurrence for each 30° lat. Zone

Arctic cirrus cloud cover is greater in winter by factor of ~ 2

| Occurrence of selected conditions (%) during 2008 (Dec 2007 to Nov 2008) |
|-----------------|---|---|---|---|
| Season          | DJF | MAM | JJA | SON |
| 60N-84N         | 0.49 | 0.2 | 0.21 | 0.22 |
| 30N-60N         | 0.74 | 0.96 | 0.60 | 0.73 |
| 0N-30N          | 1.58 | 1.90 | 2.02 | 1.70 |
| 30S-0S          | 1.58 | 1.46 | 0.75 | 1.07 |
| 60S-30S         | 0.25 | 0.39 | 0.47 | 0.36 |
| 84S-60S         | 0.16 | 0.19 | 0.31 | 0.72 |
| Full globe      | 0.81 | 0.86 | 0.73 | 0.80 |

| Occurrence of selected conditions (%) during 2013 (March 2013 to Feb 2014) |
|-----------------|---|---|---|---|
| Season          | DJF | MAM | JJA | SON |
| 60N-84N         | 0.61 | 0.31 | 0.16 | 0.24 |
| 30N-60N         | 0.90 | 0.98 | 0.56 | 0.65 |
| 0N-30N          | 1.43 | 1.82 | 1.86 | 1.76 |
| 30S-0S          | 1.58 | 1.47 | 0.79 | 1.05 |
| 60S-30S         | 0.30 | 0.36 | 0.46 | 0.35 |
| 84S-60S         | 0.09 | 0.20 | 0.42 | 0.61 |
| Full globe      | 0.82 | 0.86 | 0.71 | 0.78 |
Radiative Impact at High Latitudes

Cirrus cloud net radiative forcing should be strongest for a combination of relatively low $D_e$, high cloud cover and low noontime sun angles (LW forcing dominates). Such conditions occur during the cold season at high latitudes. Moreover, any changes in these conditions may affect Arctic Amplification (enhanced warming of Arctic).

Figures here are from Hong & Liu (2015, J. Clim.), showing net forcing for all ice clouds wrt latitude zone and season (e.g. HL = high latitude; C = cold season). Net forcing was calculated from a RT model having ice cloud microphysical properties and coverage based on CloudSat-CALIPSO retrievals (DARDAR scheme).
The Seasonal Cycle of Hom and Het Cirrus for 2013

Similar to 2008, but in DJF, there is more hom cirrus over Greenland & less over Siberia. Also, there is less hom cirrus over the Andes and Antarctica during 2013. Are dust concentrations increasing in the Southern Hemisphere?
CAM5 simulation with pre-existing ice and 0.1% of secondary organic aerosols acting as IN; from Penner et al., 2015, GRL. Hom dominates in TWP with het dominating in N. Hemisphere, mid- & high latitudes.
Testing the Retrieval with SPARTICUS Synoptic Cirrus Data; 15 flights & 229 PSDs

2008 DJF Land SPAR3

2008 MAM Land SPAR3

Centroid Temperature (C)

N Fraction

N±ΔN >250 L⁻¹
N±ΔN >500 L⁻¹
N±ΔN >500 L⁻¹
N±ΔN >500 L⁻¹

2008 DJF Land SPAR3

2008 MAM Land SPAR3

Centroid Temperature (C)

N Fraction

N±ΔN >250 L⁻¹
N±ΔN >500 L⁻¹
N±ΔN >500 L⁻¹
N±ΔN >500 L⁻¹
CALIPSO – Het for $D_e$ annual mean
CALIPSO – Het for seasonal $D_e$

winter

spring

summer

fall
CALIPSO – Het for cloud cover annual mean
CALIPSO – Het for changes in seasonal cloud cover

winter

spring

summer

fall
CALIPSO – Het for changes in cloud ice, annual mean
CALIPSO – Het for changes in seasonal cloud ice

winter

spring

summer

fall
CALIPSO – Het for changes in relative humidity, annual mean
CALIPSO – Het for seasonal changes in relative humidity

- Winter
- Spring
- Summer
- Fall
CALIPSO – Het for changes in meridional wind component (v), annual mean
CALIPSO – Het for changes in zonal wind component (u), annual mean
CALIPSO – Het for seasonal changes in $u$
CALIPSO – Het for changes in vu, annual mean
CALIPSO – Het for seasonal changes in vu