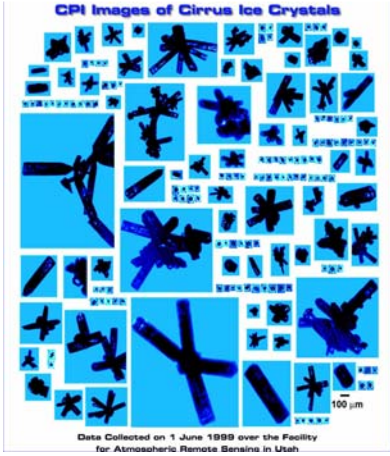

Satellite Remote Sensing of Small Ice Crystals in Cirrus Clouds

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ABSTRACT

In situ instruments have not been able to characterize the concentrations of small (D < 60 µm) ice crystals in cirrus clouds although the 2DS probe appears promising. Some instruments indicate small crystal concentrations are orders of magnitude greater than the larger crystals in a size distribution, while other instruments indicate no anomaly. Therefore we have developed a method for detecting the relative concentration of these small crystals from satellites.

Some in situ measurements indicate small crystals may account for about half of the optical depth of cirrus clouds and the nature of the cirrus cloud feedback in GCM simulations depends strongly on their concentration. Thus simulations of future climate may be highly uncertain until their concentrations are adequately characterized.

General Approach

Parameterize measurements of the ice particle size distribution (PSD) that include small ice crystals as a function of temperature and IWC. Incorporate this parameterization into a retrieval algorithm that calculates the relative concentration of small mode ice crystals using radiances measured from satellites. Combining in situ and satellite measurements in this way, the PSD is retrieved for a given IWC, even if the PSD is bimodal. Also retrieved are the small-to-large mode number concentration ratio, the IWP and effective size D_e.

How Photon Tunneling Can be Used to Remotely Detect Small Ice Crystals in Cirrus

Photon Tunneling is the process by which radiation beyond the physical cross-section of a particle is either absorbed or scattered outside the forward diffraction peak. Tunneling is strongest when:

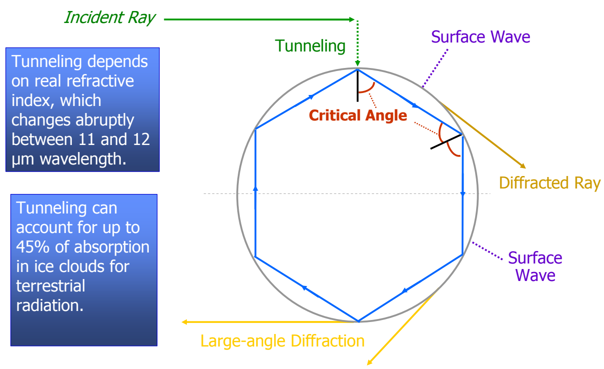
1) Effective size and wavelength are comparable

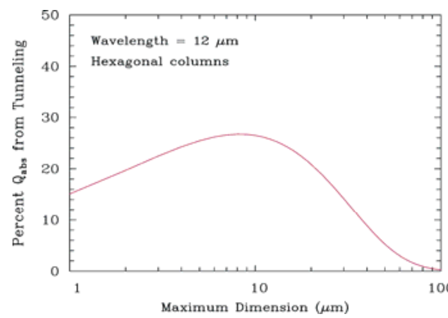
2) Particle shape is spherical or quasi-spherical

3) The real refractive index is relatively large

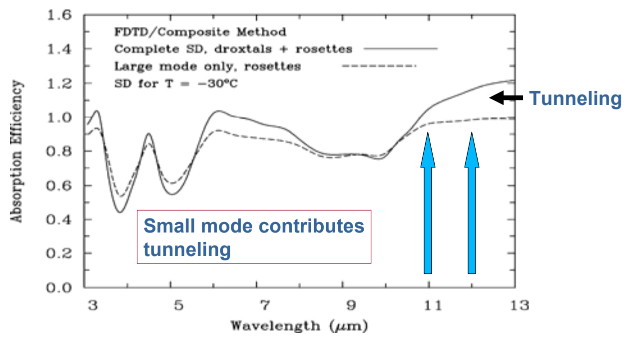
Therefore tunneling contributions at terrestrial wavelengths are greatest for smallest (D < 60 µm) ice crystals. To detect the tunneling signal is to detect small ice crystals.

Tunneling Phenomena





Size dependence of photon tunneling



Wavelength dependence of photon tunneling

Retrieval of Cirrus Temperature and Emissivity

1. For two CO_2 channels A and B, cirrus emissivity ε will be the same due to similar refractive indices. Solving for ε using the simple non-scattering formulation, and equating $\varepsilon_A = \varepsilon_B$,

$$I_{OBS} = (1 - \varepsilon)\, I_{CLR} + \varepsilon\, B(T_{CLD})$$

and

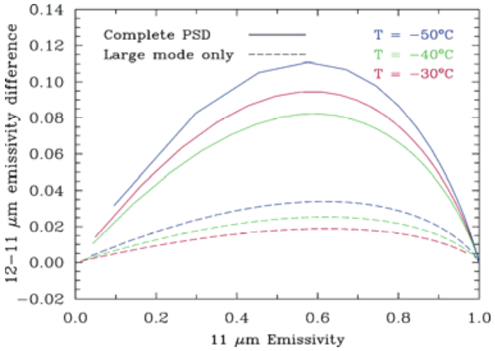
$$\frac{I_{A,OBS} - I_{A,CLR}}{B_A(T_{CLD}) - I_{A,CLR}} = \frac{I_{B,OBS} - I_{B,CLR}}{B_B(T_{CLD}) - I_{B,CLR}}\,.$$

We then solve for the one unknown, cirrus temperature T_{CLD}.

2. With T_{CLD} retrieved and I_{CLR} and I_{OBS} directly measured, we can solve for ε at 11 & 12 µm, where ε_{11} and ε_{12} are solved independently:

$$\varepsilon_{11} = \frac{I_{11,OBS} - I_{11,CLR}}{B_{11}(T_{CLD}) - I_{11,CLR}} \qquad \varepsilon_{12} = \frac{I_{12,OBS} - I_{12,CLR}}{B_{12}(T_{CLD}) - I_{12,CLR}}$$

Method for Estimating Small Crystal Concentrations



1. Begin with satellite retrievals of cloud temperature and cloud emissivity (ε) at 11 and 12 µm wavelength channels.

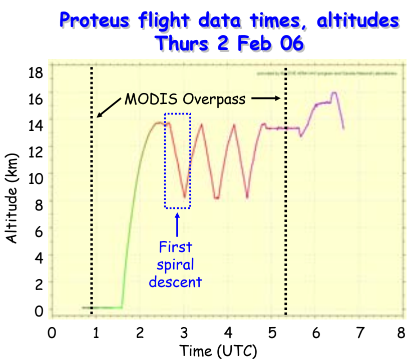
2. Use retrieved temperature to estimate PSD mean size $\bar{D}$ and dispersion (ν) for large and small mode. Difference between the solid and dashed curves above results primarily from differences in contribution of small PSD mode to the ice water content (IWC). This also determines the effective diameter, D_e. Dispersion ν has little influence on above curves.

3. Locate the retrieved Δε and the 11 µm ε by (1) incrementing the modeled ice water path (IWP) to increase ε(11 µm) and (2) incrementing the small mode contribution to the cloud IWC, which elevates the curve.

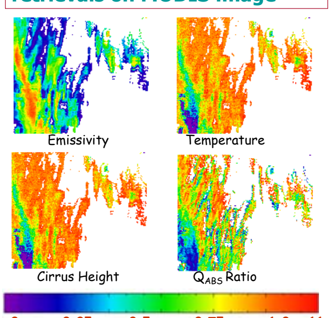
4. If retrieved point lies below the "large mode only" curve (e.g. a dashed curve), then systematically decrease $\bar{D}$ for large mode until a match is obtained. Negative Δε values correspond to maximum allowed D values.

5. This method retrieves IWP, D_e, the small-to-large mode ice crystal concentration ratio, and the PSD and N for a given IWC.

TWP-ICE Case Study: 2 February 2006

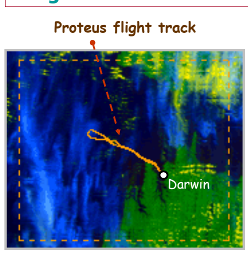


Temperature-emissivity related retrievals on MODIS image



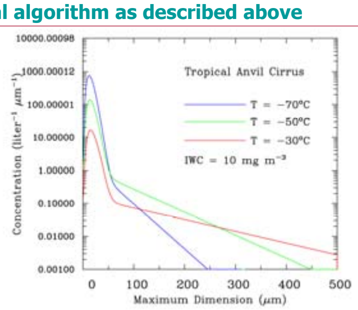
0	0.25	0.5	0.75	1.0	11-µm Emissivity
200	209	218	227	235	Cirrus Temperature (K)
15	14	13	12	11	Cirrus Height (km)
0.98	1.02	1.07	1.11	1.15	12/11-µm Q_{ABS} Ratio

Sampled region of MODIS image at 0520 UTC

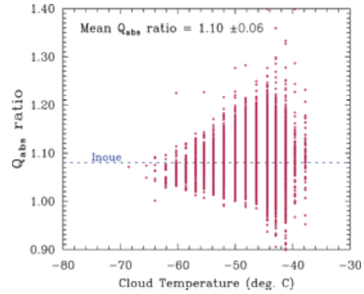


0.47 0.86 11.03-µm Composite

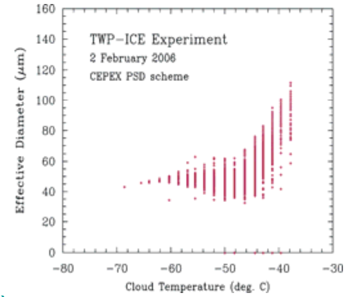
PSD scheme based on CEPEX data (anvil cirrus), used in the retrieval algorithm as described above



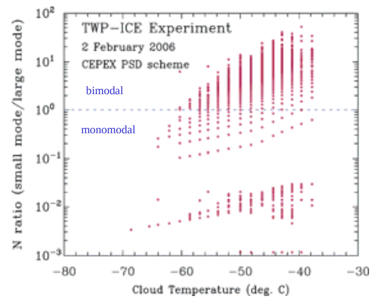
TWP-ICE Case Study: 2 February 2006 - Continued -



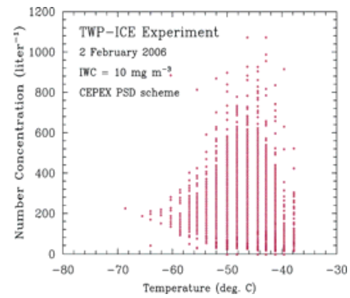
12/11 µm absorption optical depth (AOD) ratios with temperature. Blue-dashed line is mean ratio (1.08) from literature.



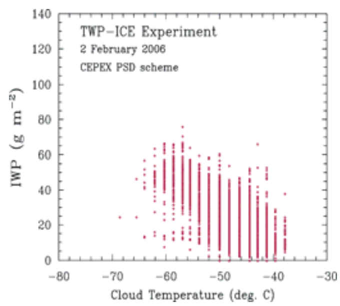
Mean AOD ratio of 1.08 produces retrieved D_e trend since AOD ratio depends on D_e and wavelength



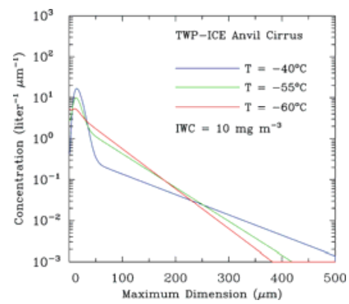
Degree of bimodality in retrieved PSD shown by the small-to-large mode number concentration ratio.



Total number concentrations assuming an IWC of 10 mg m^{-3}

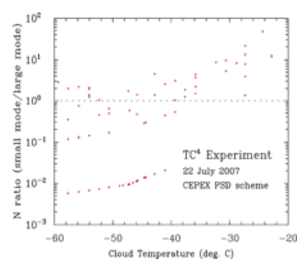


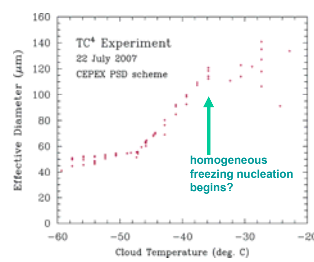
Retrived IWP, with colder, higher emissivity cirrus having higher IWP

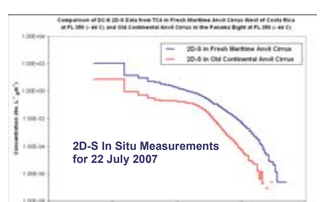


Representative retrieved PSD for the indicated temperatures and assumed IWC.

TC4 Case Study: 22 July 2007, Costa Rica







Retrieval results from TC4 case study and comparisons with in situ measurements involving the new 2DS probe which minimizes ice artifacts from shattering. Note that the D_e-T relationship is consistent with TWP-ICE.