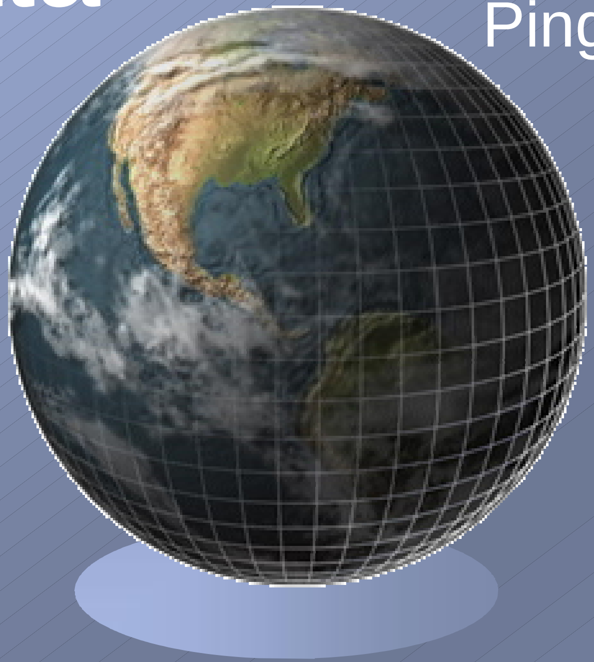
Study of Tropical Cirrus Clouds using MODIS Data



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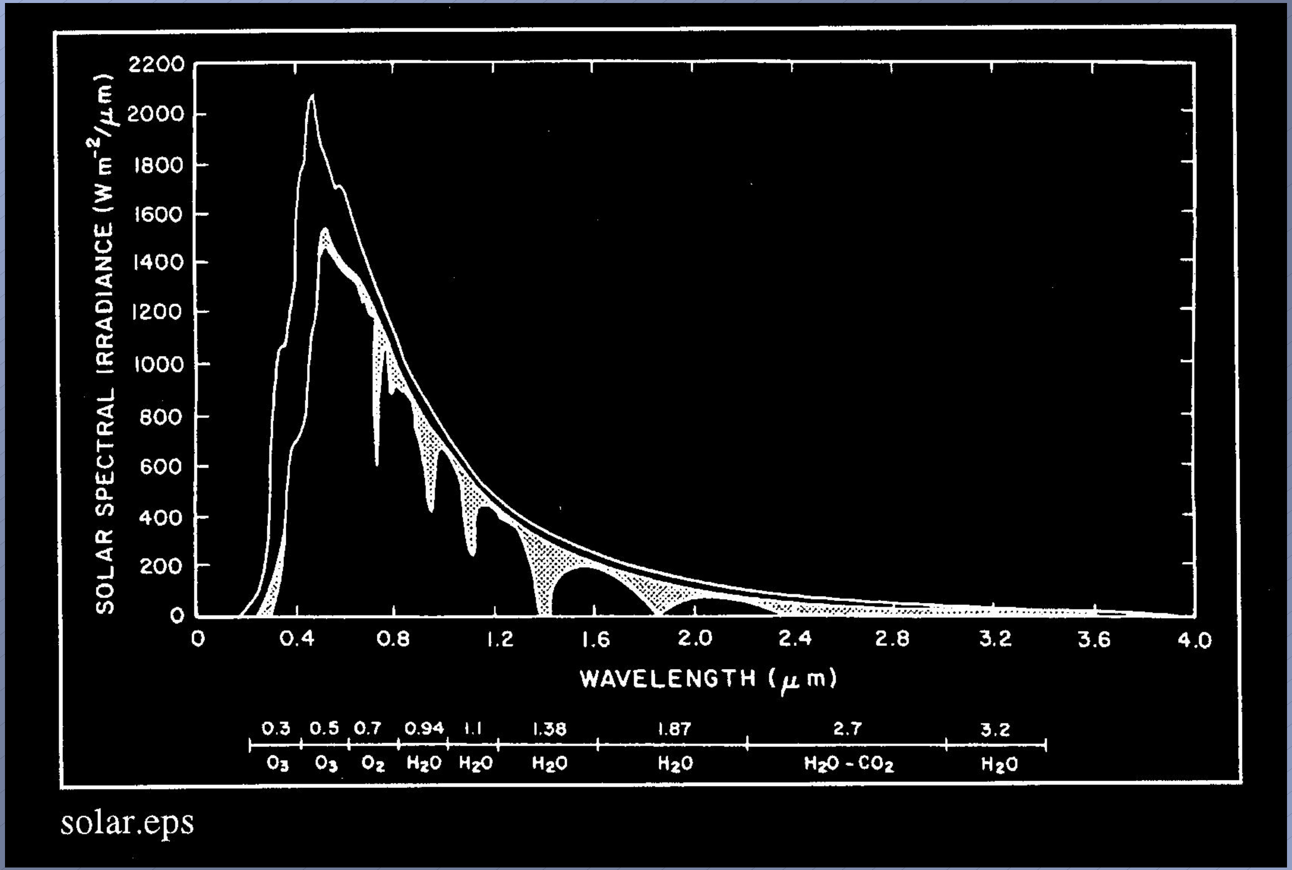
Cirrus Importance

- One of the most uncertain components in climate research because of high locations, optically thin nature, and nonsphericity of ice crystals.
- May substantially regulate the long-wave radiative energy exchange in the vicinity of the tropical tropopause (Hartmann et al., 2001; Hartmann and Larson, 2002).
- Total cirrus cover has been found to be over 50% for the entire tropics (Chepfer et al., 2000), and a thin cirrus layer may be present as much as 80% of the time in this region (Wang et al., 1994).
- Cirrus clouds also significantly impact the water vapor distribution near upper troposhere and low stratosphere (Jensen et al., 1996; Holton and Gettlemen, 2001)
- The important roles that cirrus clouds have been recognized through various studies (e.g., Lynch, D. K., K. Sassen, D. O. Starr, Cirrus, Oxford University Press, New York, 2002)
- Cirrus microphysical and optical properties (optical thickness, ice crystal effective size, etc.) are of great importance.

Cirrus Detection

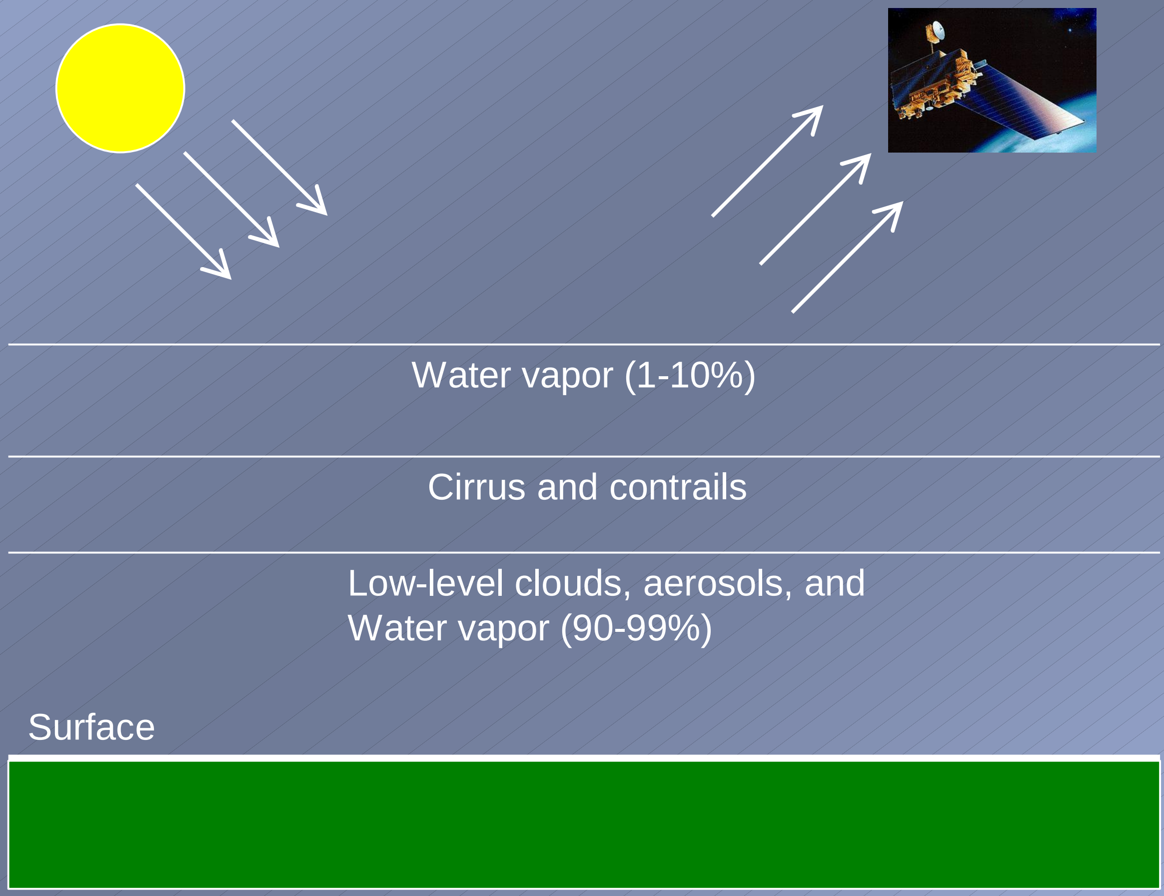


Adopted from Liou, 1980: An Introduction To Atmospheric Radiation

Visible Cirrus Reflectance

- Method reported by Gao et al. (Gao, B.-C., P. Yang, W. Han, R.-R. Li and W. J. Wiscombe: An algorithm using visible and 1.375-µm channels to retrieve cirrus cloud reflectances from aircraft and satellite data, IEEE-TGRS, 40, 1659-1688, 2002)
- Use a combination of a visible channel (here, 0.66-µm) and the 1.375-µm “cirrus detection” channel.
- Surface and atmospheric effects (the “virtual surface” removed from reflectance data in the visible spectrum (0.4-1.0 µm).
- Isolated visible cirrus reflectance is derived for the visible spectrum, which can be used to retrieve tropical cirrus optical thickness.

Atmosphere Configuration



Deriving Cirrus Reflectance

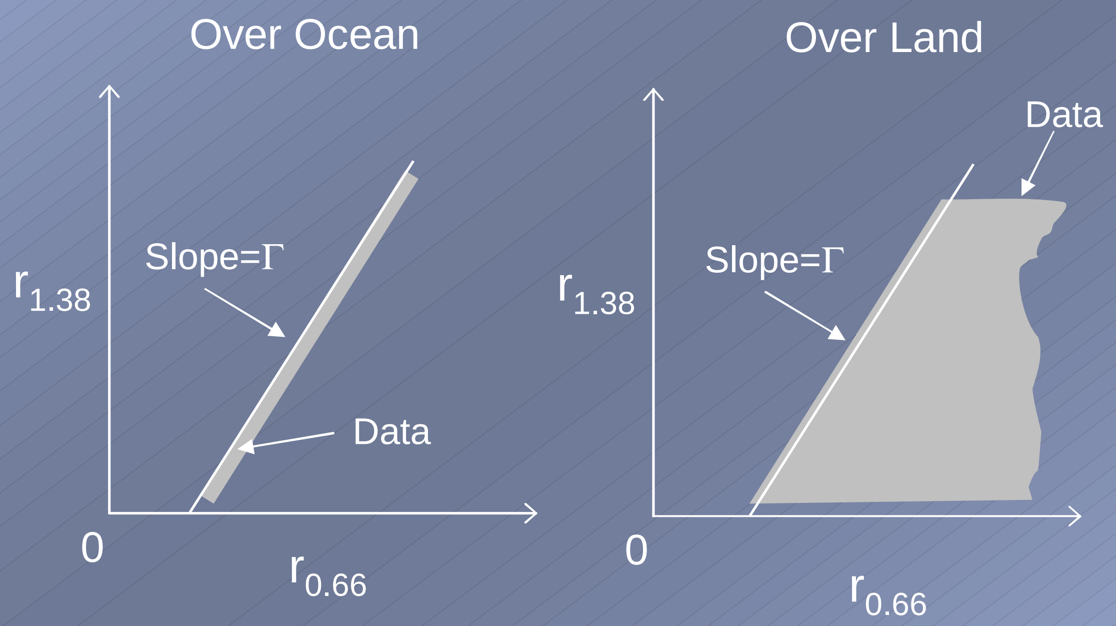
Cirrus cloudy condition: $r_{1.38}(\mu_0, \ _0, \mu, \ ) = \Gamma r_{0.66}(\mu_0, \ _0, \mu, \ )$

Isolated 0.66-μm cirrus reflectance: $r_{c,0.66}(\mu_0, \ _0, \mu, \ ) = \frac{r_{1.38}(\mu_0, \ _0, \mu, \ )}{\Gamma}$

Visible cirrus reflectance: $r_\lambda(\mu_0, \ _0, \mu, \ ) = r_{c,0.66}(\mu_0, \ _0, \mu, \ )$

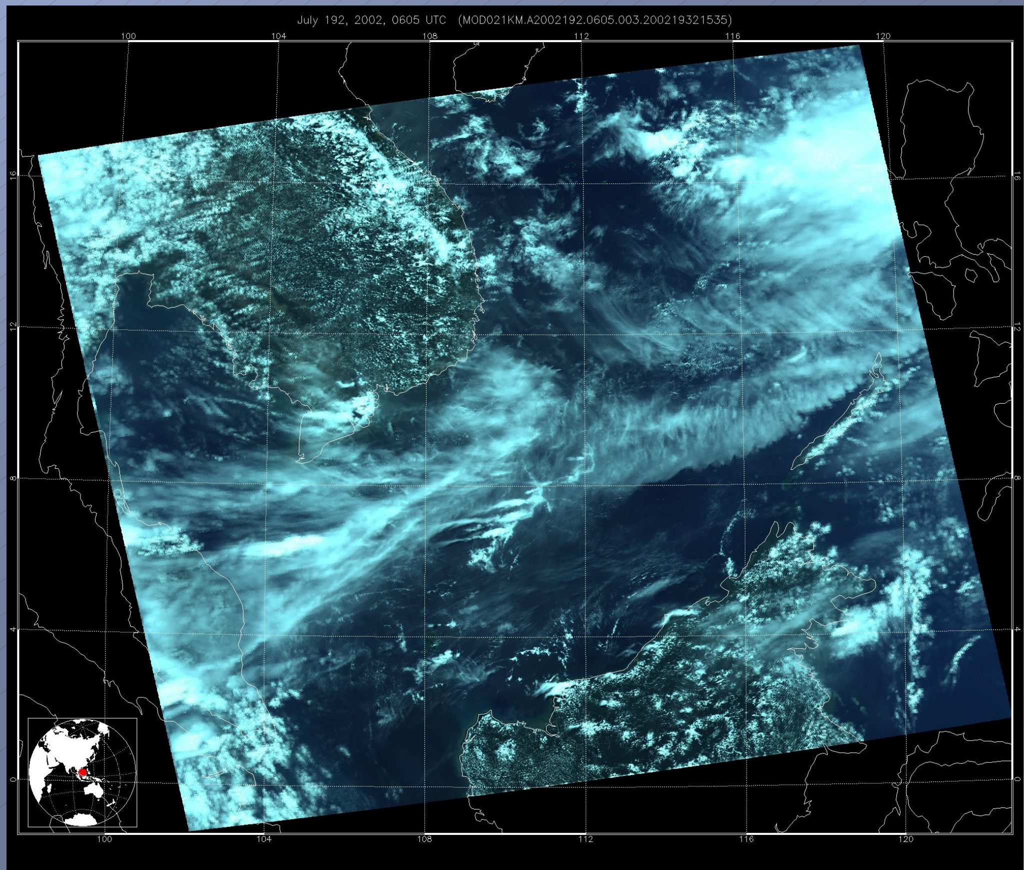
Gao, B.-C., P. Yang, W. Han, R.-R. Li, and W. J. Wiscombe 2002: An algorithm using visible and 1.375-μm channels to retrieve cirrus cloud reflectances from aircraft and satellite data, IEEE-TGRS, 40, 1659-1688.

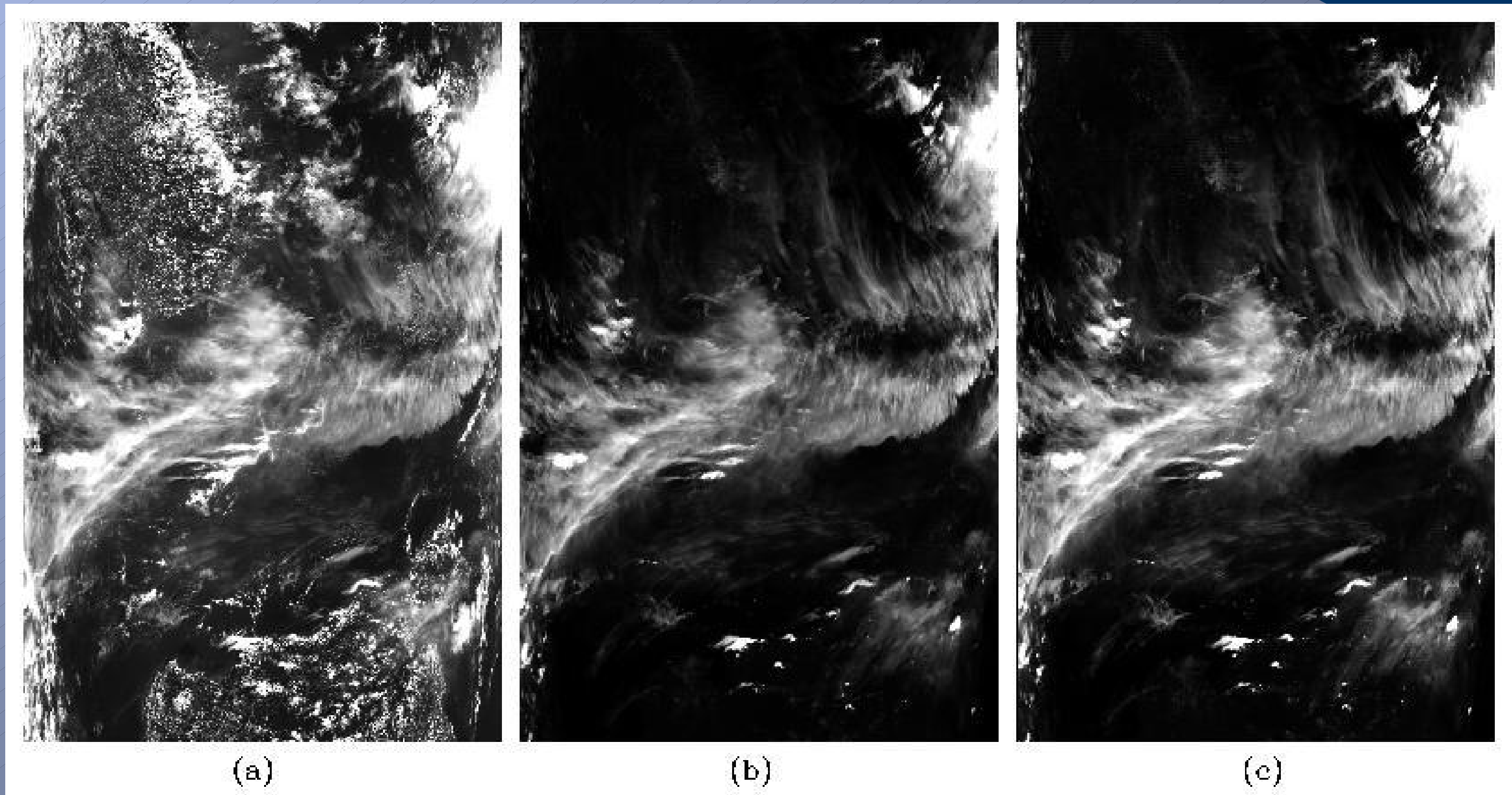
Derivation of Γ



Cirrus Reflectance Example

Terra MODIS: 0605 UTC, July 10, 2002





a) 0.66-µm MODIS reflectance image.

b) 1.375-µm MODIS reflectance image.

c) Derived isolated cirrus reflectance.

Tropical Cirrus Retrieval

- Tropical cirrus optical thickness is inferred from visible cirrus reflectance.
  - Follow a look-up table approach.
  - Use scattering properties of nonspherical ice crystals, averaged over nine size distributions from Central Equatorial Pacific Ocean Experiment (CEPEX).
  - Assume that cirrus clouds are composed of 41.6% aggregates, 24.7% bullet rosettes, 33.7% solid columns (McFarquhar 2000).
  - Simulate the radiative transfer process using DISORT (Stamnes et al. 1988).

Tropical Cirrus Retrieval (cont.)

- MODIS level-1b data (0.66- and 1.375 μm reflectance for “virtual surface” removal, solar/satellite geometries) used for optical thickness retrieval.
  - Only consider granules between ±30° latitude.
- Method described in detail in Meyer et al. (Meyer, K., P. Yang, and B.-C. Gao, 2004: Optical thickness of tropical cirrus clouds derived from MODIS 0.66- and 1.375 -μm channels, IEEE-TGRS, 42, 833-841).

Optical Properties Database

- Single-scattering properties computed from the computational models developed by Yang and Liou (1995,1996,1998) for individual ice crystal habits

Bulk Optical Properties of Ice Clouds

- Database is input for DISORT calculations.
- Pre-computed single-scattering database for individual ice crystal habits are averaged for various size distributions
- Averaging completed over 3 habits and 24 size bins.
- Include 9 tropical size distributions.

Database Definitions

Effective diameter:

$$D_e = \frac{3}{2}\frac{\sum_{D=D_{\min}}^{D_{\max}}\left[\sum_{h=1}^{3} V(h,D)\,f(h,D)\,n(D)\Delta(D)\right]}{\sum_{D=D_{\min}}^{D_{\max}}\left[\sum_{h=1}^{3} A(h,D)\,f(h,D)\,n(D)\Delta(D)\right]},$$

Extinction coefficient:

$$\overline{\ }_{ext} = \sum_{D=D_{\min}}^{D_{\max}}\left[\sum_{h=1}^{3} f(h,D)\,\sigma_{ext}(h,D)\,n(D)\Delta(D)\right]$$

Single-scattering albedo:

$$\bar{\omega}_o = \frac{\bar{\sigma}_{sca}}{\bar{\sigma}_{ext}}$$

Phase function:

$$\bar{P}(\Theta) = \frac{\sum_{D=D_{\min}}^{D_{\max}}\left[\sum_{h=1}^{3} f(h,D)\,P(\Theta,h,D)\,\sigma_{sca}(h,D)\,n(D)\Delta(D)\right]}{\sum_{D=D_{\min}}^{D_{\max}}\left[\sum_{h=1}^{3} f(h,D)\,\sigma_{sca}(h,D)\,n(D)\Delta(D)\right]},$$

Particle Size Distribution (PSD)

$$N(D) = N_0 D^u \exp(-\lambda D)$$

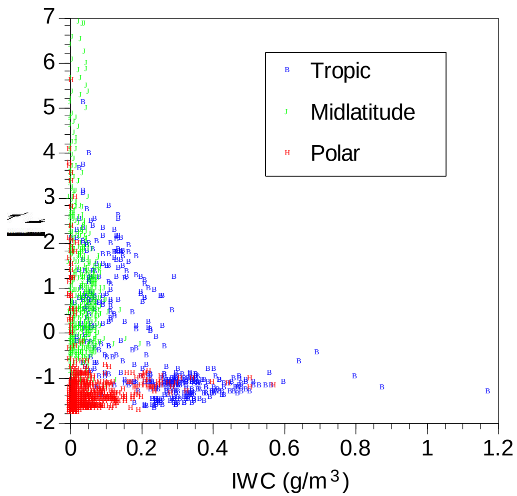


Fig.1 μ as a function of IWC for ice clouds in different latitudes

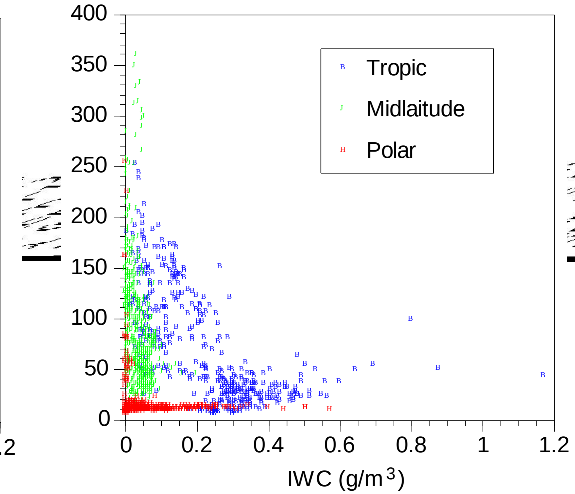


Fig.2 λ as a function of IWC for ice clouds in different latitudes

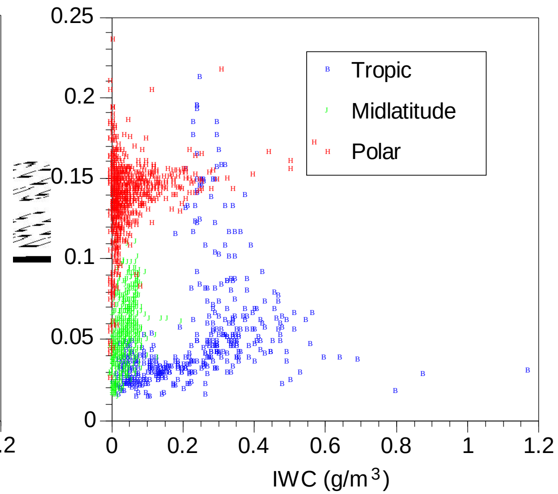


Fig.3 Median mass Diameter as a function of IWC for ice clouds in different latitudes

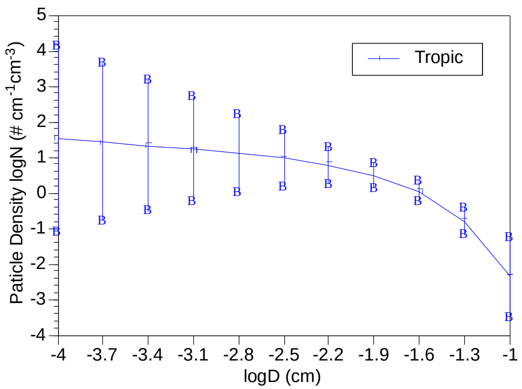


Fig.4 Particle size distribution range of tropic Ice clouds

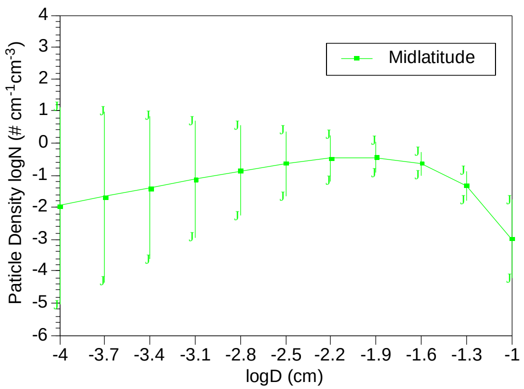


Fig.5 Particle size distribution range of mid-latitude Ice clouds

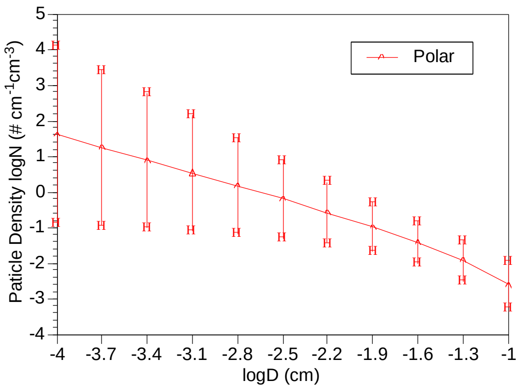
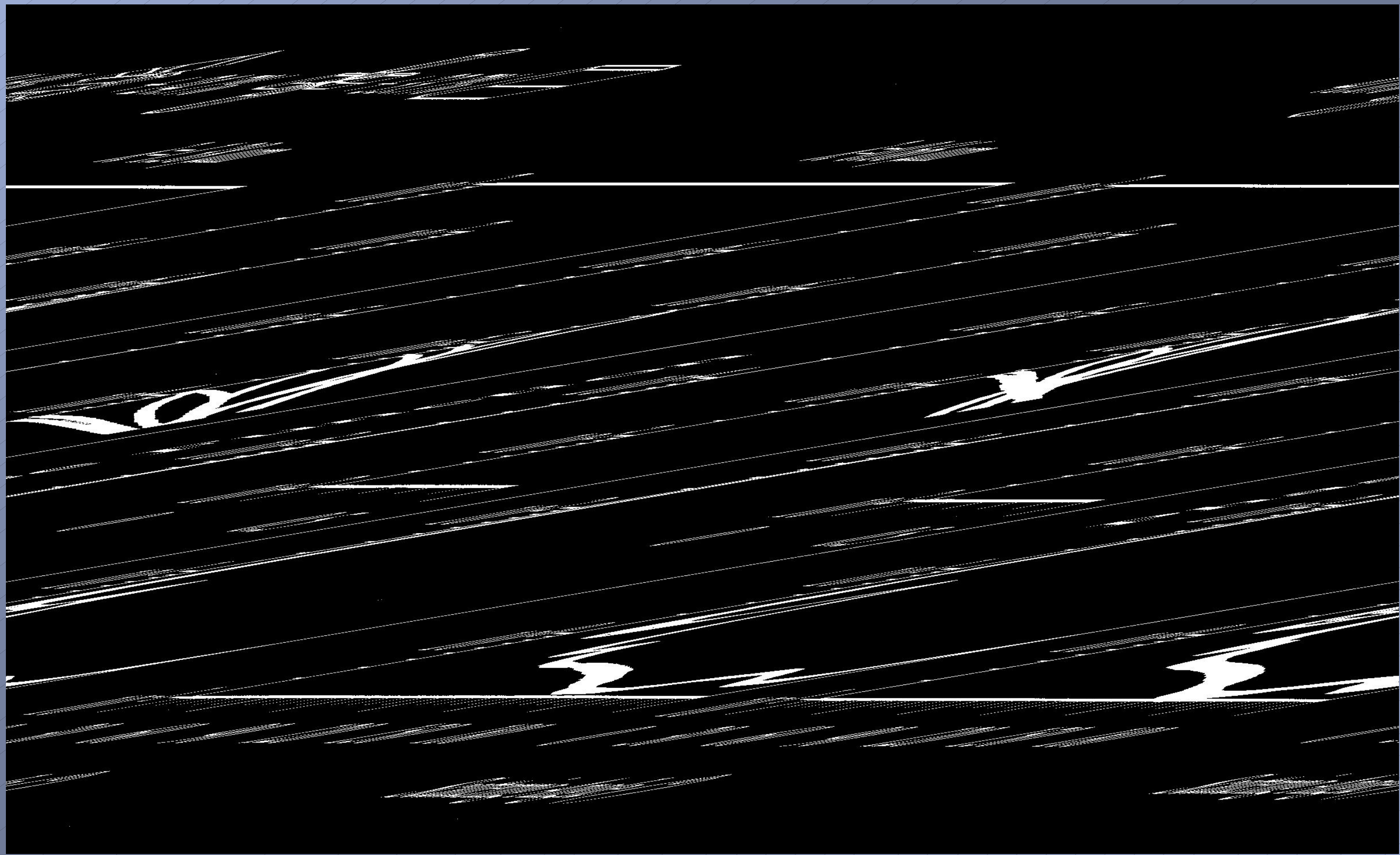


Fig.6 Particle size distribution range of polar Ice clouds

Datasets provided by Andrew Heymsfield, NCAR

Phase Function



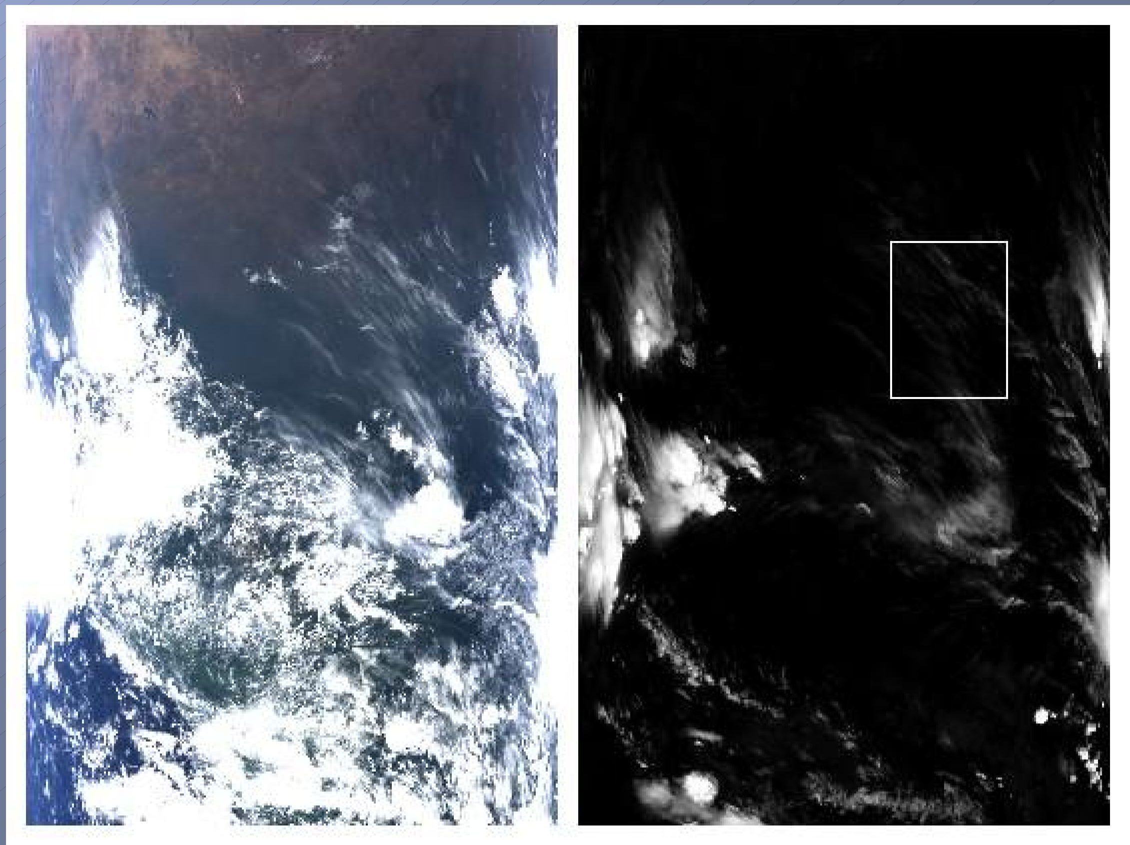
Look-up Tables

Retrieval Method

- Uses 4864 look-up tables (one for each solar/satellite geometry).
- Visible cirrus reflectance is derived from level-1b 0.66- and 1.375-µm data using method of Gao et al. (2002).
- Matches the visible cirrus reflectance values with the corresponding optical thickness values.

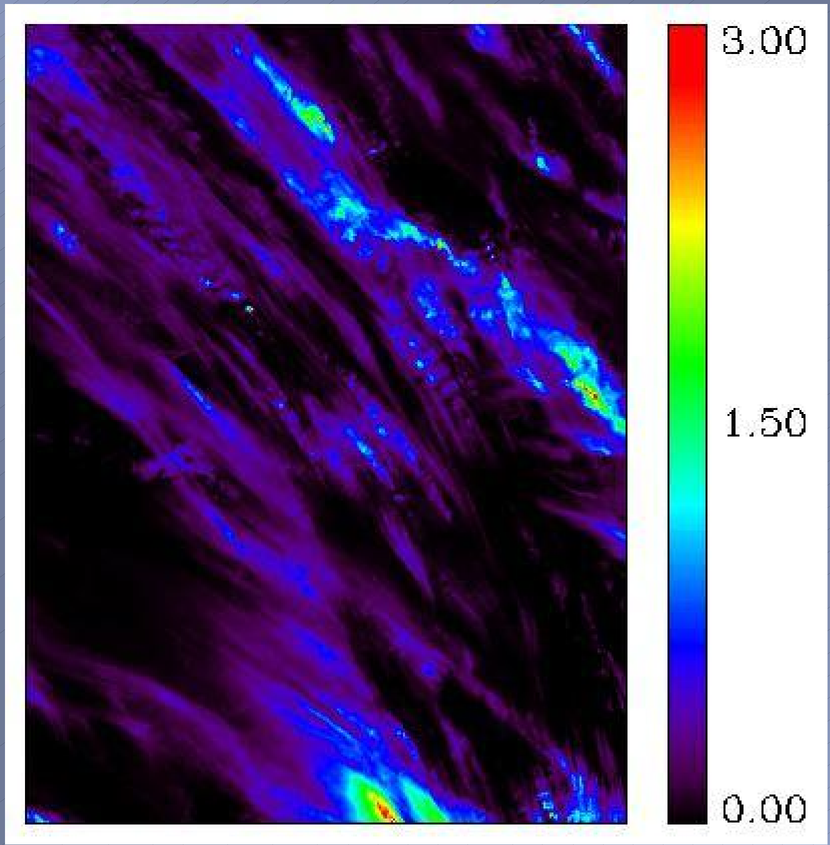
Retrieval Example: Land

Terra MODIS: 0925 UTC, January 30, 2003, Africa



Visible 1.375-µm

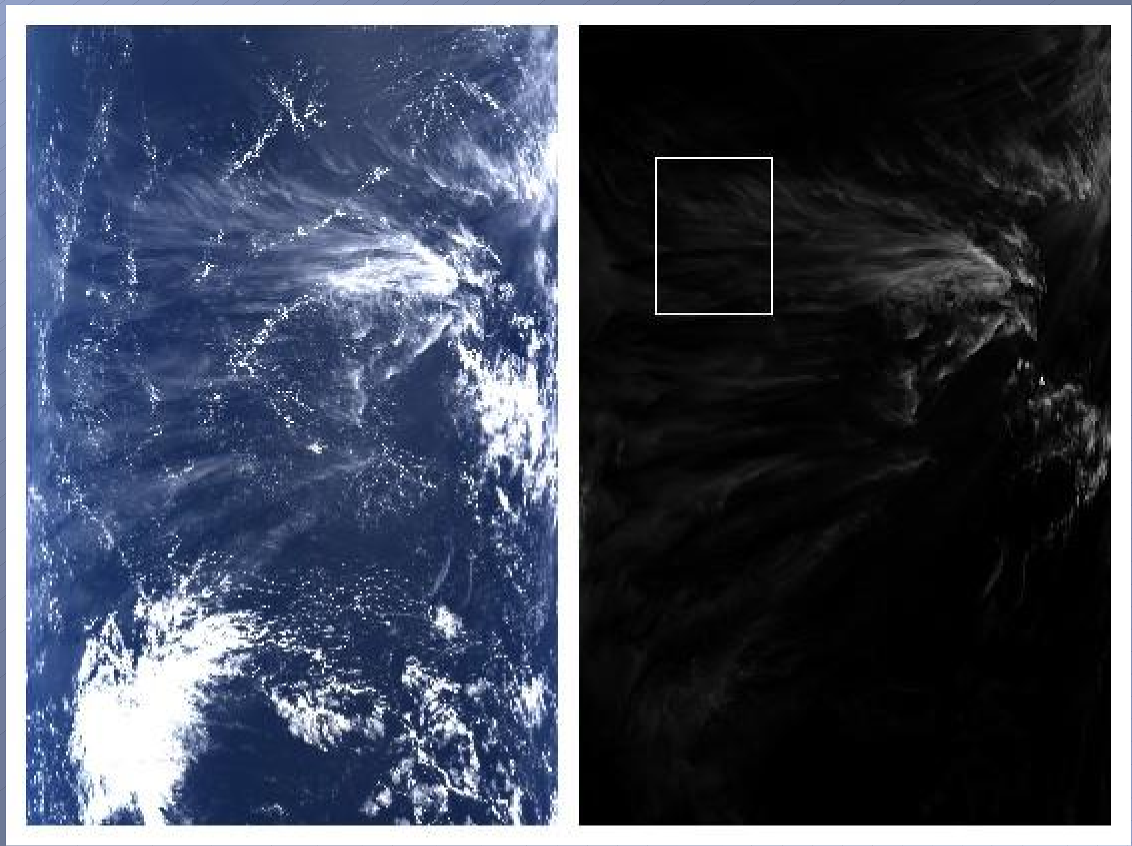
Retrieval Example: Land



Cirrus optical thickness

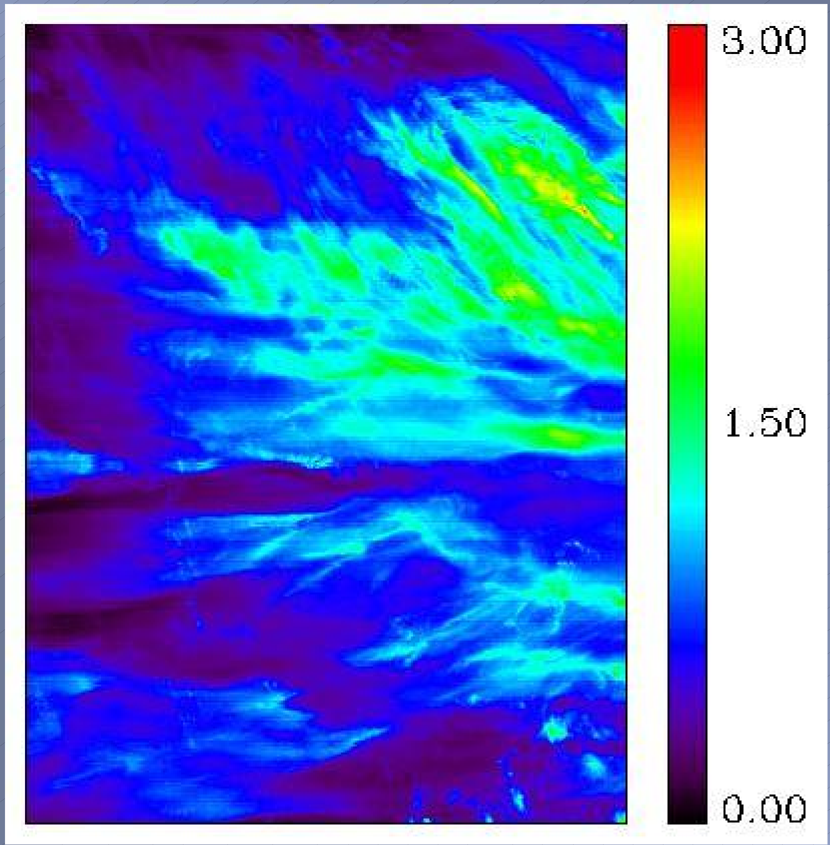
Retrieval Example: Ocean

Terra MODIS: 0615 UTC, July 13, 2002, Indian Ocean



Visible 1.375-µm

Retrieval Example: Ocean



Cirrus optical thickness

Tropical Cirrus Level-3 Analysis

- Aqua MODIS level-3 daily data (MOD08_D3).
  - July, 2002, to December, 2004.
- Use modified level-1b algorithm for optical thickness retrieval.
- Consider only high clouds (cloud top pressure < 440 hPa), following ISCCP definition.
- Include frequency of occurrence, average optical thickness, as well as seasonal and zonal averages.

Tropical Cirrus Level-3 Analysis

Frequency of occurrence: $F_{occc} = \left(N_c / N_t\right) \times 100$

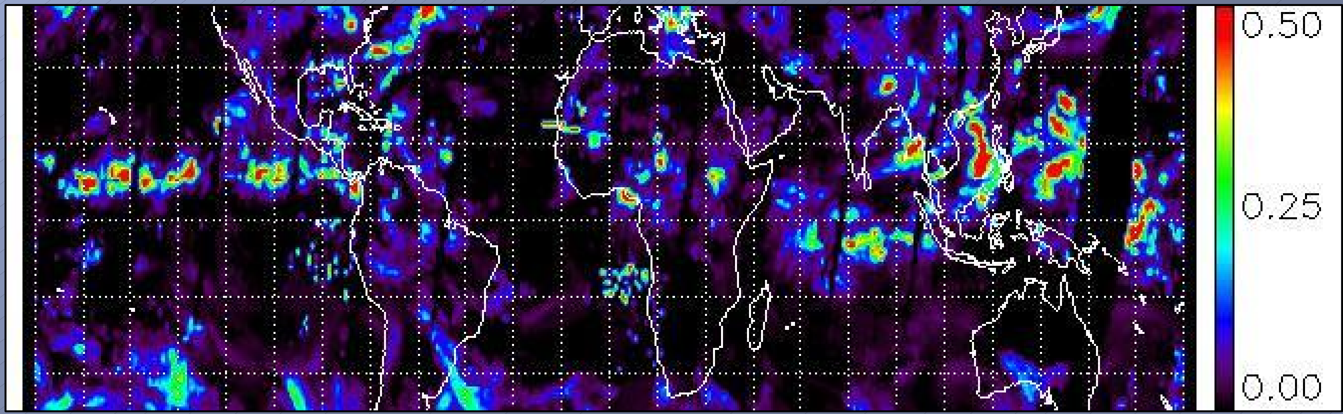
Average optical thickness: ${}_{ave} = {}_{c} / N_c$

N_c: number of days with cirrus clouds
N_t: total number of days
${}_{c}$: sum of optical thickness for days with cirrus clouds

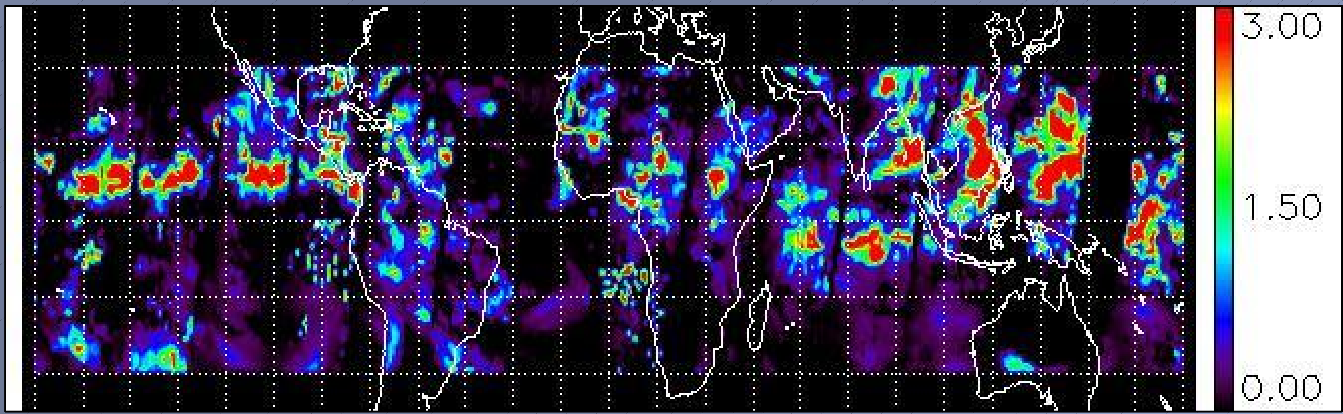
Level-3 Example

Terra MODIS: July 27, 2002

Cirrus Reflectance

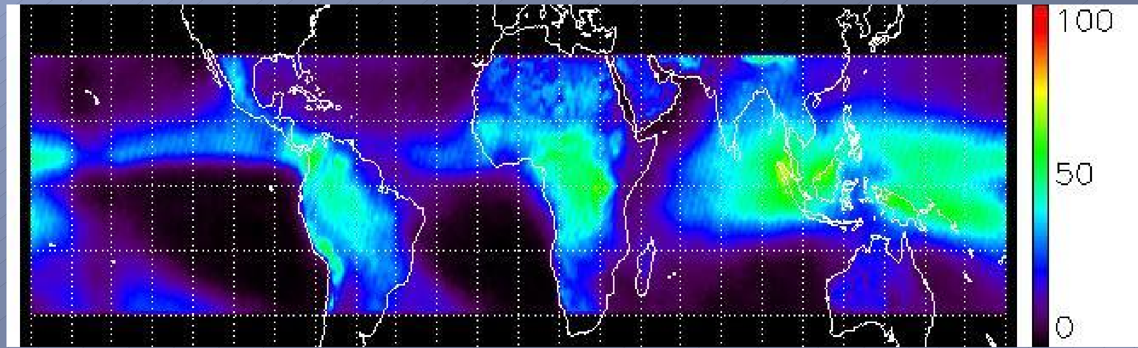


Cirrus Optical Thickness

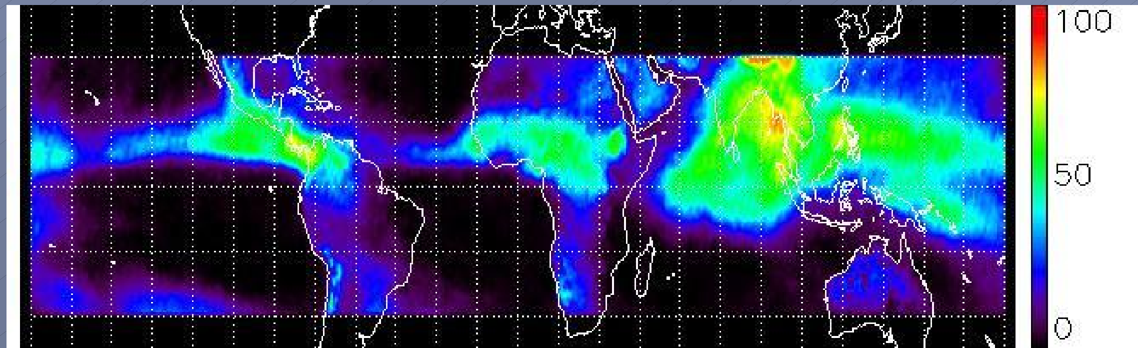


Frequency of Occurrence

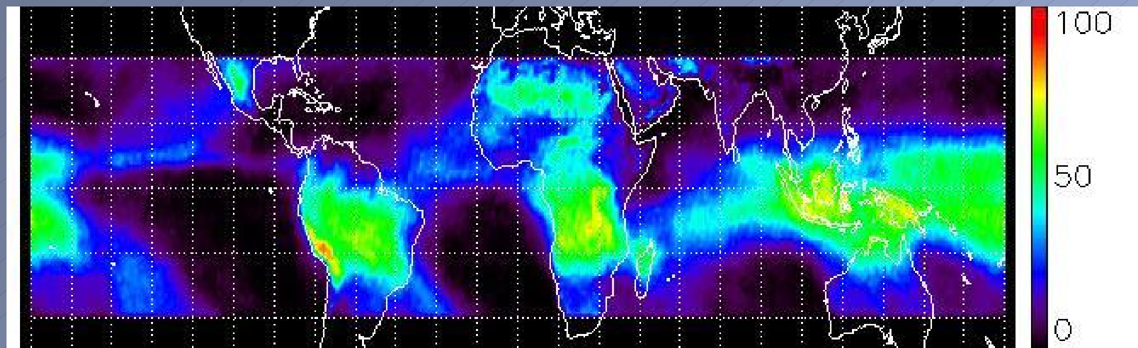
Entire Period:



Summer (JJA):

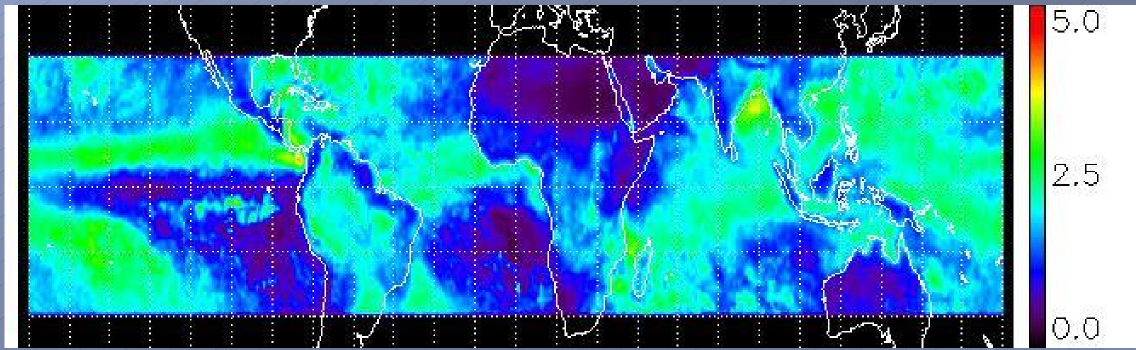


Winter (DJF):

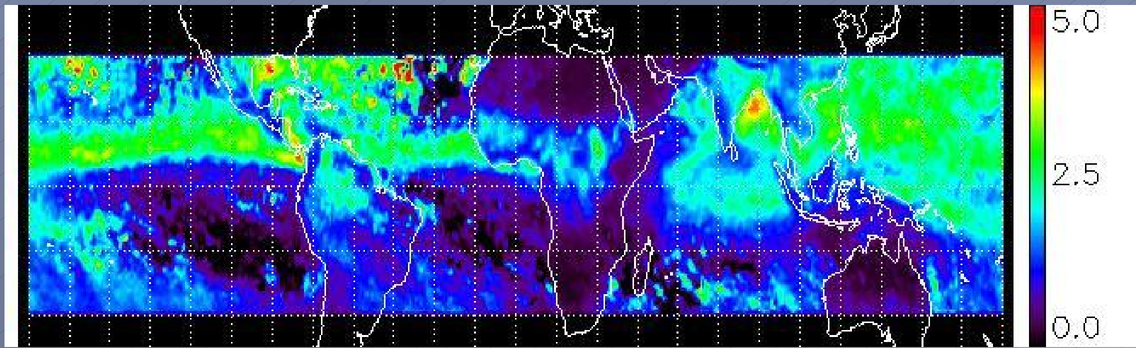


Average Optical Thickness

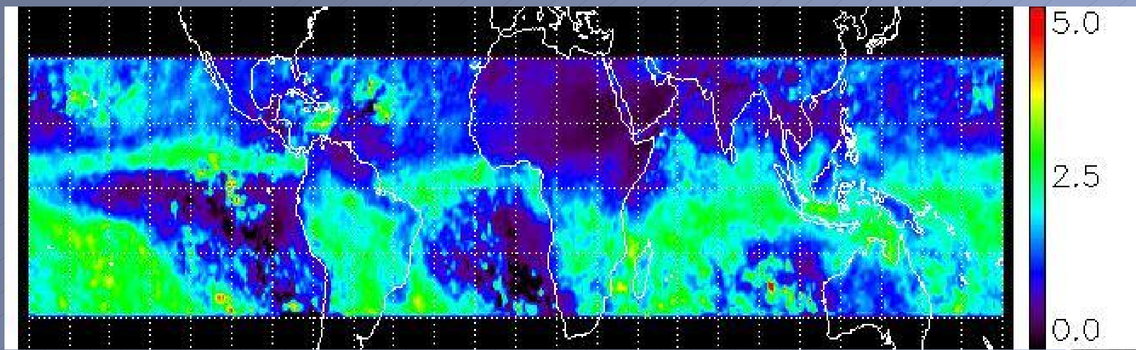
Entire Period:



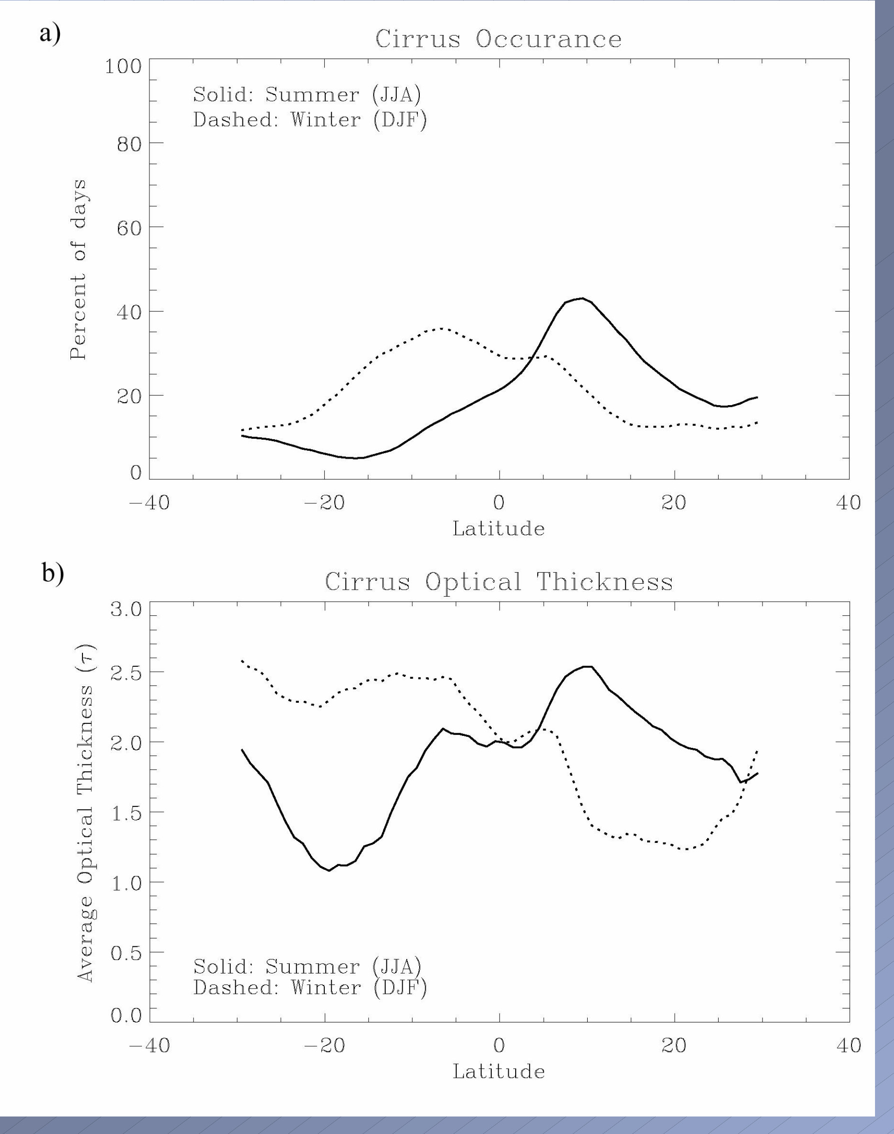
Summer (JJA):



Winter (DJF):



Analysis - Latitude

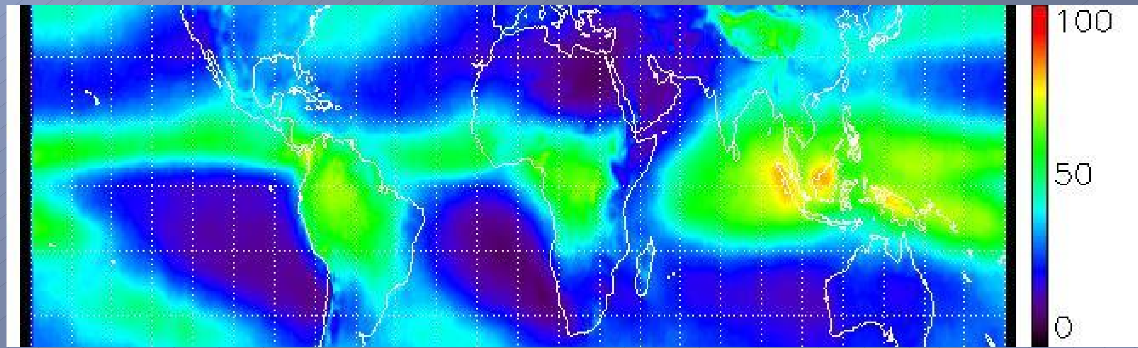


HIRS Comparison

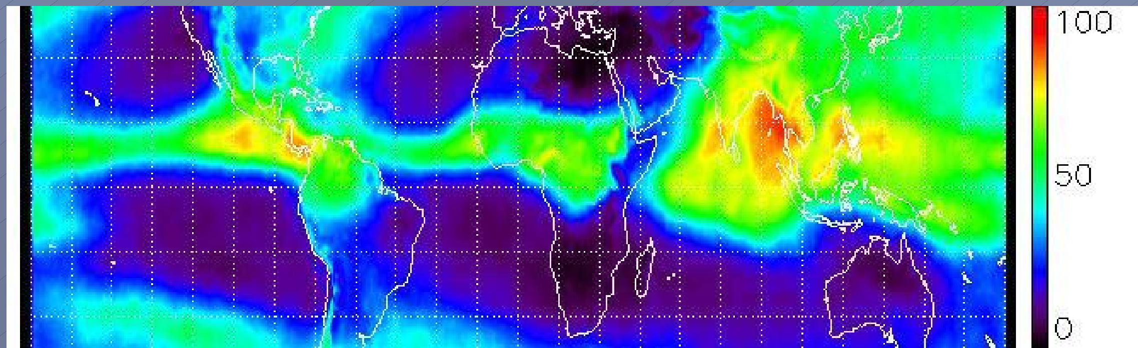
- High resolution Infrared Radiation Sounder.
- Compare level-3 cirrus results with those from HIRS (Wylie et al., 2004).
  - HIRS retrieval uses CO_2 slicing method with channels from 13- to 15-µm.
  - Data covers 22 years, from 1979-2001.
  - Includes only high cloud frequencies (cloud top pressure <440 hPa).

HIRS High Clouds: Frequency of Occurrence

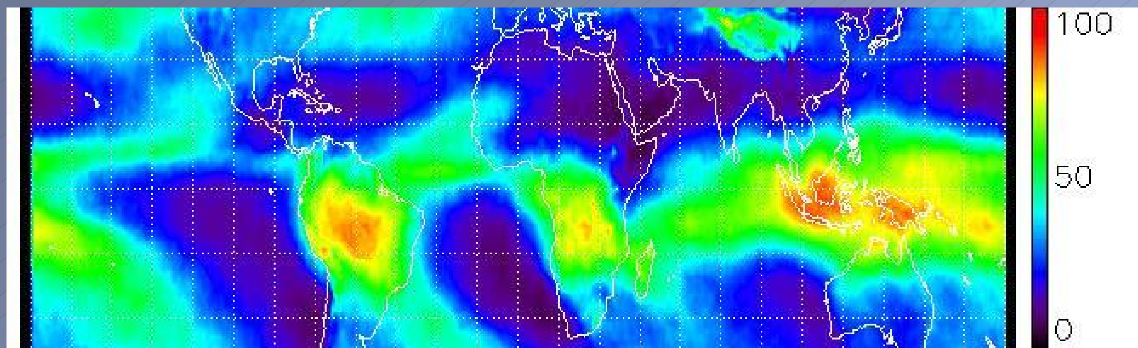
Entire Period:



Summer (JJA):

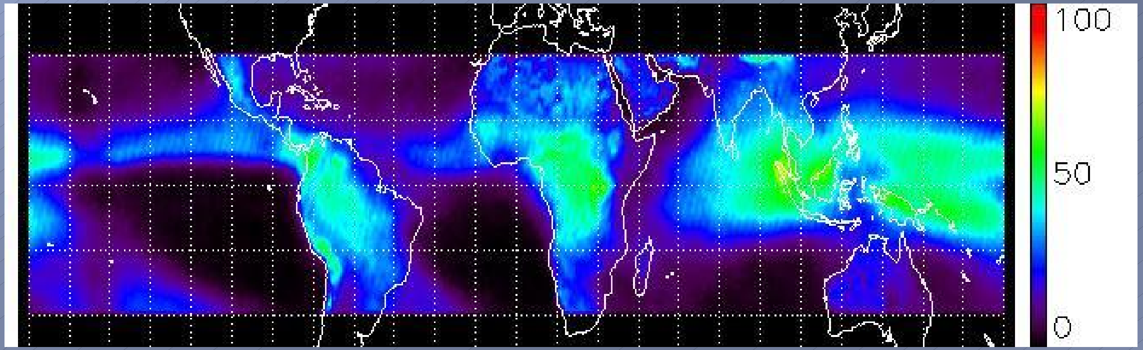


Winter (DJF):

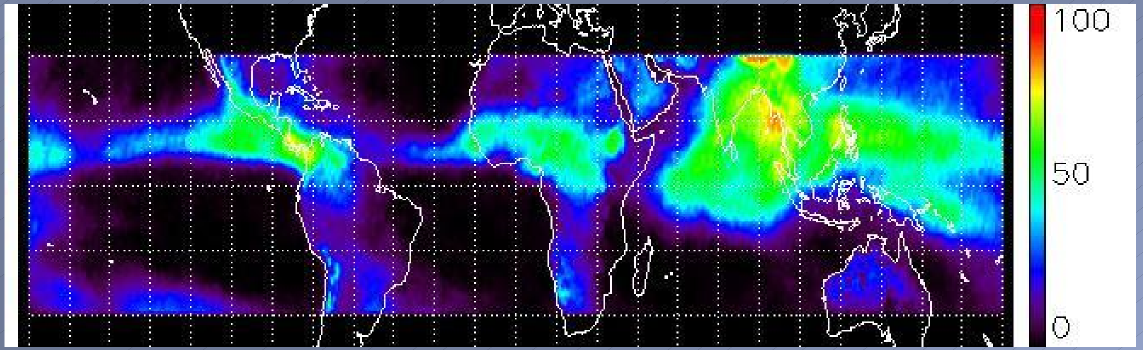


Frequency of Occurrence (MODIS)

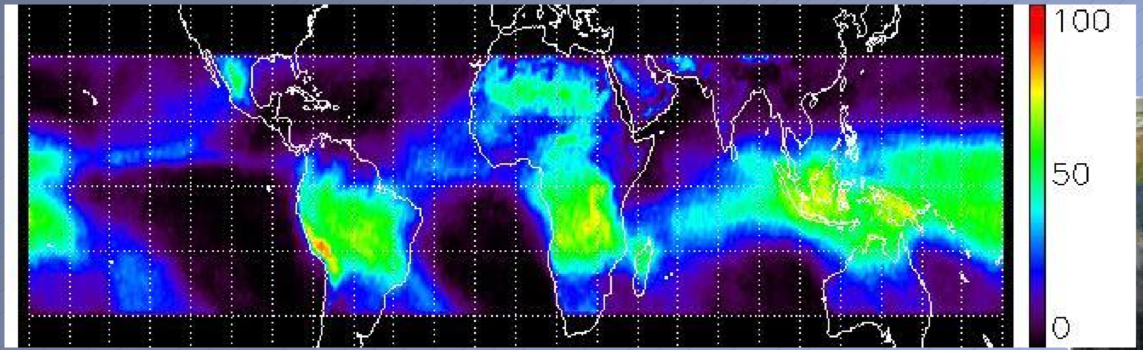
Entire Period:



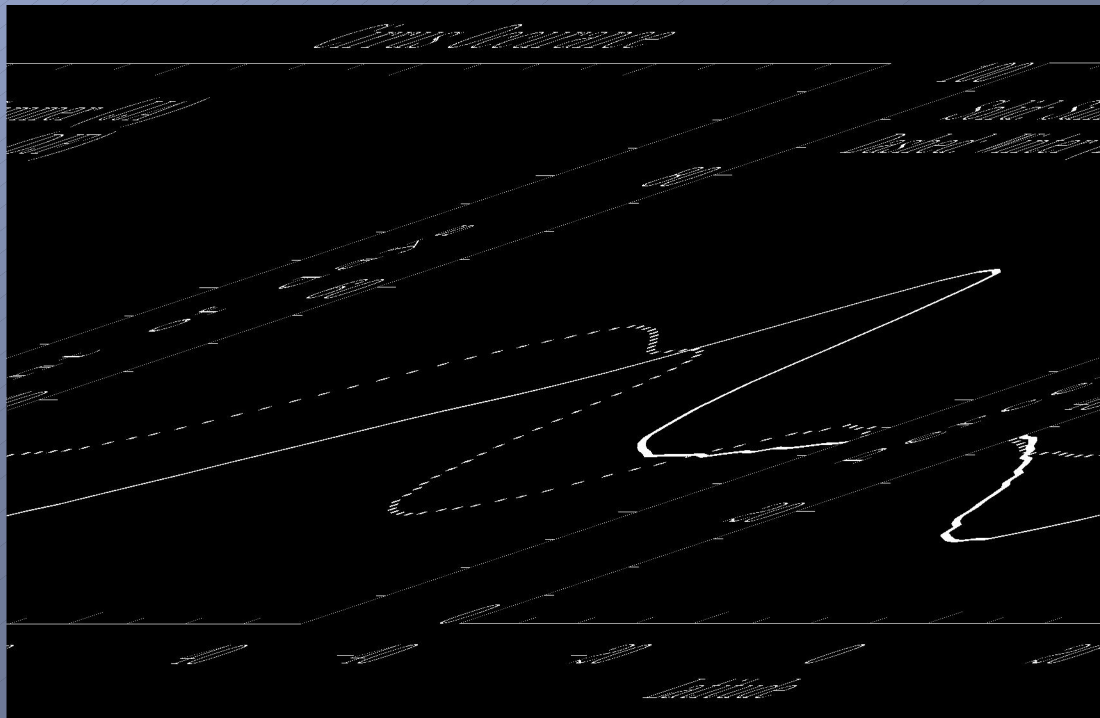
Summer (JJA):



Winter (DJF):



HIRS High Clouds: Latitude



HIRS/MODIS Comparison

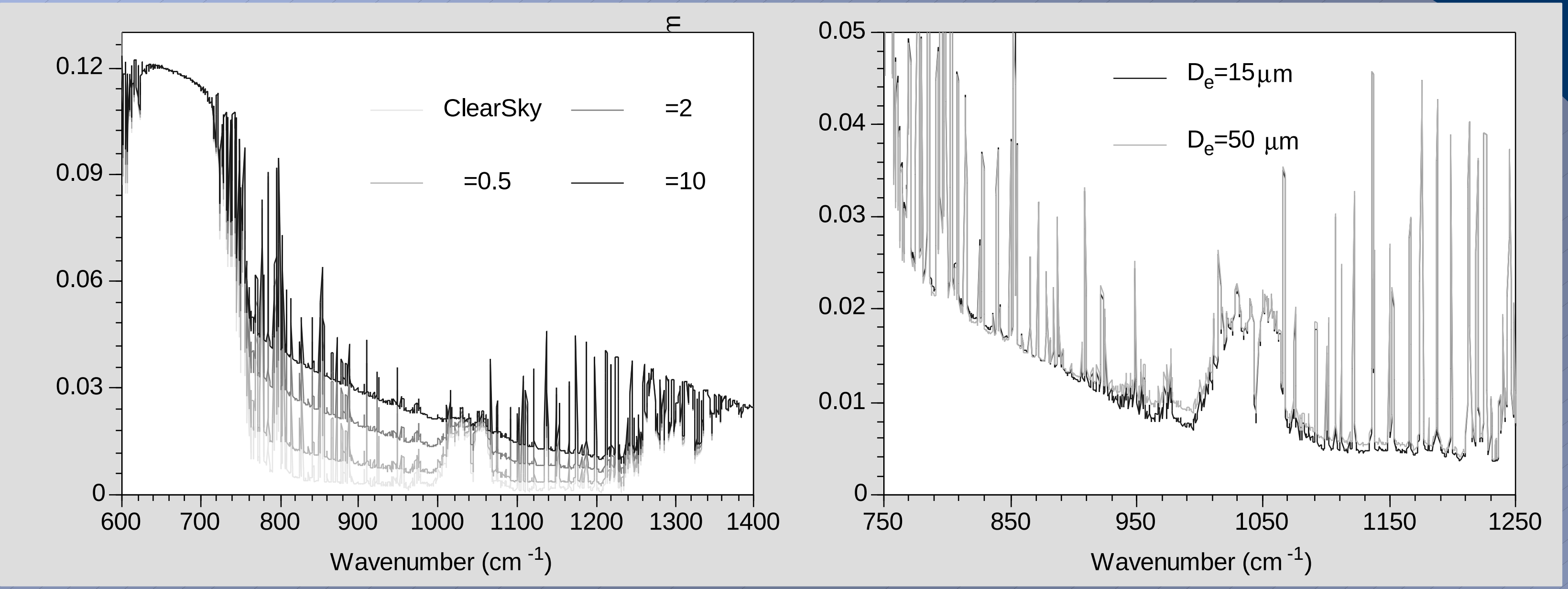
- The general trends found using both methods are quite similar.
- Discrepancies do exist between our MODIS retrieval and the HIRS high cloud frequencies
  - HIRS reports greater frequencies than our MODIS method.
- Possible explanations:
  - Different retrieval methods. HIRS products are based on the IR channels, whereas MODIS cirrus products are based on the visible and near-IR channels
  - Lower threshold (threshold for reflectance=0.01) on MODIS level-2 cirrus reflectance values may exclude thin cirrus cloudy pixels during level-3 averaging (underestimation by MODIS).

Comparison of Ground-based Retrieval and MOD06 Cloud Products

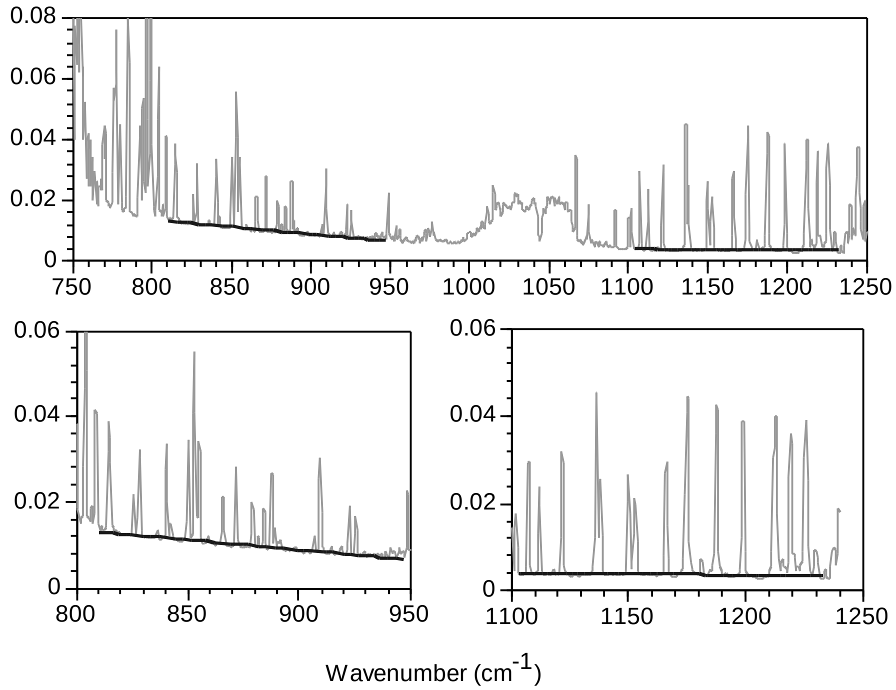
P. Yang, S.-C. Tsay, Q. Ji, G. Guo, and H. Wei

Yang, P., S.-C. Tsay, H. Wei, G. Guo, and Q. Ji, 2005: Remote sensing of cirrus optical and microphysical properties from ground-based infrared radiometric measurements. Part I: A new retrieval method based on mmicrowindow spectral signature, IEEE GRL (in press, 4/2005).

G. Guo, Q. Ji, P. Yang, and S.-C. Tsay, 2005: Remote sensing of cirrus optical and microphysical properties from ground-based infrared radiometric measurements. Part II: Retrievals from CRYSTAL-FACE Measurements, IEEE GRL (in press, 4/2005).



Sensitivity of the downward radiance at the surface to the cloud optical thickness (left panel) and effective size (right panel). Note that an effective size of 50 µm is assumed for the left panel and an optical thickness of 1 is assumed for the right panel.

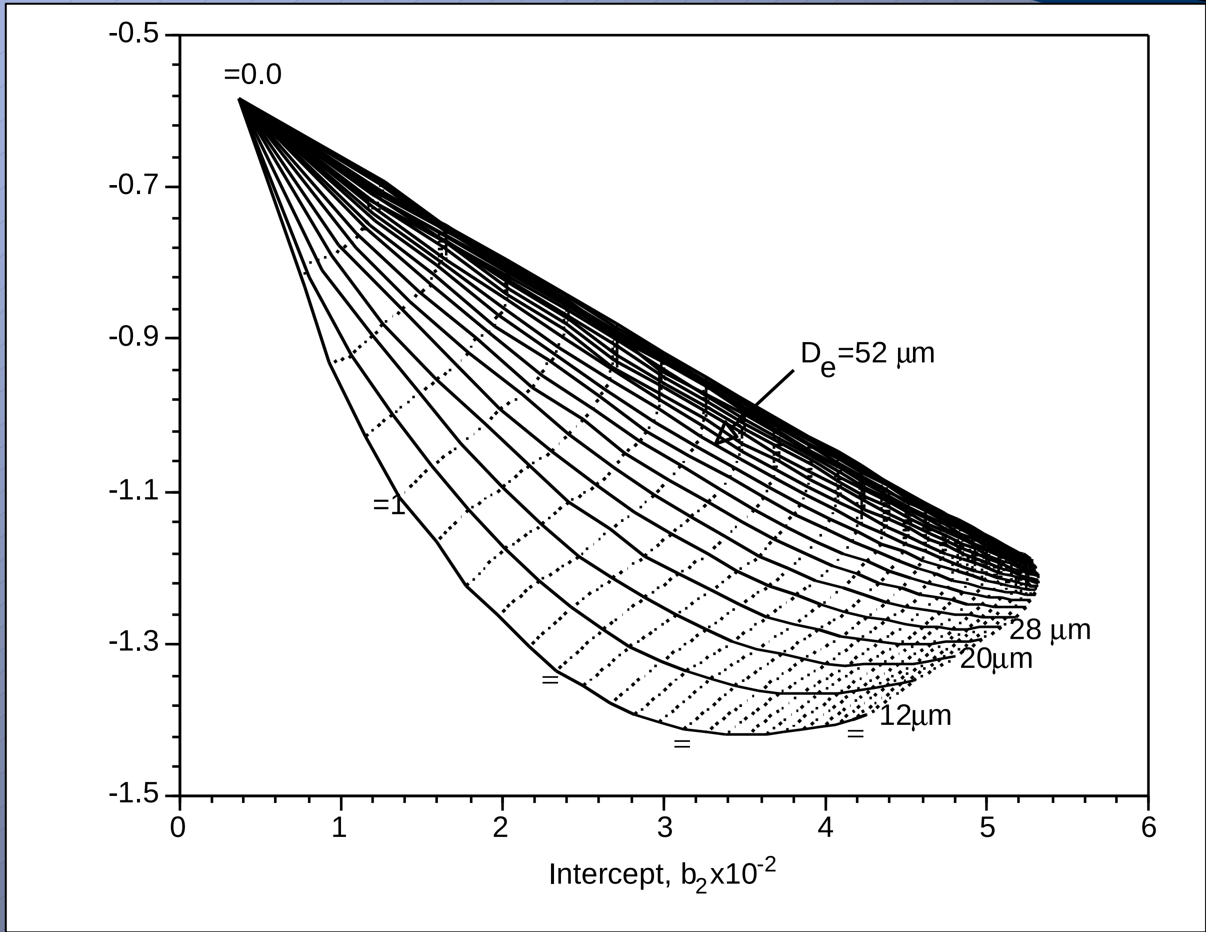


Enveloping profiles (the linear lines in the diagram) that fit the microwindows of the downward radiance within the spectral regimes of 810-940 cm^{-1} and 1100-1240 cm^{-1}. These lines can be described in terms of the following linear equations:

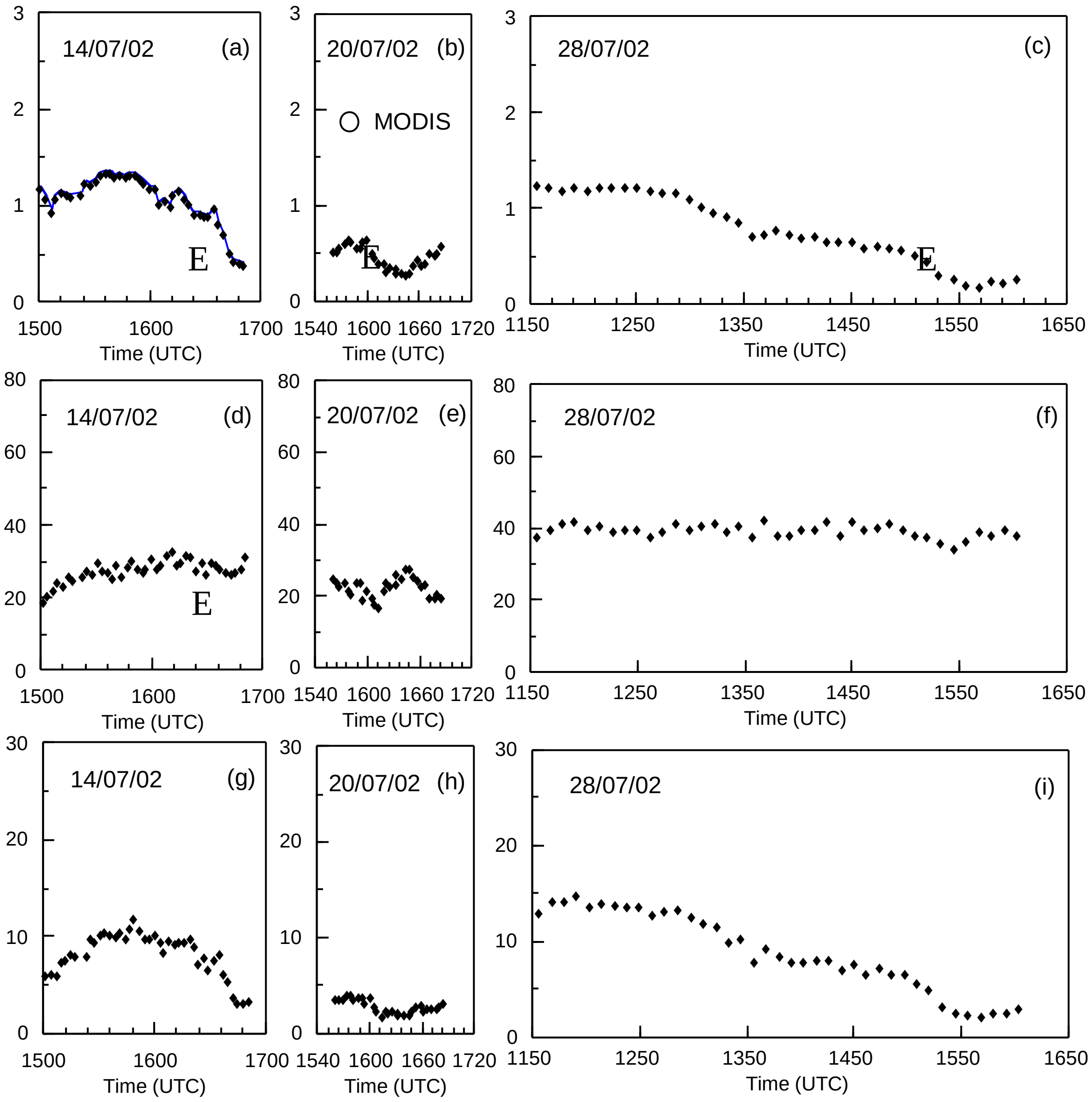
$$r(\ ,D_e,\upsilon) = a_1(\ ,D_e)\upsilon + b_1(\ ,D_e), \text{ for } \ \in 810-940cm^{-1}$$

$$r(\ ,D_e,\upsilon) = a_2(\ ,D_e)\upsilon + b_2(\ ,D_e), \text{ for } \ \in 1100-1240cm^{-1}$$

where r and indicate the fitted minimum radiance (i.e., microwindows) and wavenumber, respectively.



Correlation between the slope in Eq. (1) and the intercept in Eq. (2) for various effective sizes and optical thickness values of cirrus clouds.



MODIS cloud products:
King et al (2003)
Platnick et al. (2003)

Retrieved optical thickness and effective particle size of ice crystals within cirrus clouds for three selected cases. Also shown is the ice water path derived from the retrieved optical thickness and effective particle size.

Conclusions

- Tropical cirrus cloud optical thickness can be inferred from visible (here, 0.66-µm) cirrus reflectance.
  - The sensitivity to habit percentage still needs to be explored.
- Cirrus trends are established using Aqua MODIS data.
- Aqua MODIS cirrus coverage patterns compare well to HIRS, although frequency magnitudes differ.
- MOD06 cloud products agree with surface-based retrieval, according to a case study based on CRYSTAL-FACE data.