Radiative Transfer Model Under Cloudy Conditions

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Presentation Outline

- **Introduction to PCRTM**

- **Cloud radiative transfer modeling**

- **Example of applying cloudy PCRTM to forward modeling**

- **Examples of applying cloudy PCRTM to retrievals**

- **Conclusions**

Overview of PCRTM

- PCRTM calculates channel radiances by linearly combine a set of pre-stored EOF:

$$\vec{R}^{ch} = \sum_{i=1}^{N_{EOF}} c_i \vec{U}_i + \vec{\varepsilon} = \sum_{i=1}^{N_{EOF}} \left(\sum_{j=1}^{N_{mono}} a_j R_j^{mono} \right) \vec{U}_i + \vec{\varepsilon}$$

- EOFs $\vec{U}_i$ are obtained by performing a Principal Component Analysis (PCA) of channel radiances under a wide range of atmospheric and observation conditions

- Coefficient C_i are predicted from a few monochromatic radiances which depends on (T, T_s, H_2O and trace gases....)

- C_i can be treated as supper channels which contain all the essential information on a spectrum

- PCRTM provides Jacobians for both C and R

Theoretical Basis of PCRTM

- There are a lot of redundant information in the channel radiances for high spectral resolution spectra
- PCA is an efficient way to compress the information content
  - EOF are orthonormal to each other

$$R^{ch}_{N_{ch} \times N_s} = U_{N_{ch} \times N_s} W_{N_s \times N_s} V^T_{N_s \times N_s}$$

- Only small number (N_{eof}) U are needed to capture information content

$$R^{ch}_{N_{ch} \times N_s} = U_{N_{ch} \times N_{eof}} W_{N_{eof} \times N_{eof}} V^T_{N_s \times N_{eof}} + \varepsilon_{N_{ch} \times N_s}{'}$$

- Any radiance spectrum can be generated using the following formula:

$$\overset{\rho}{R}^{ch} = R^{ch}_{N_{ch} \times 1} = U_{N_{ch} \times N_{eof}} \left(U^T_{N_{ch} \times N_{eof}} R^{ch}_{N_{ch} \times 1} \right) = \sum_{i=1}^{N_{eof}} c_i \overset{\rho}{U}_i$$

Theoretical Basis of PCRTM

- C_i is the projection coefficient (EOF amplitude) for the *ith* EOF (dot product of R and U):
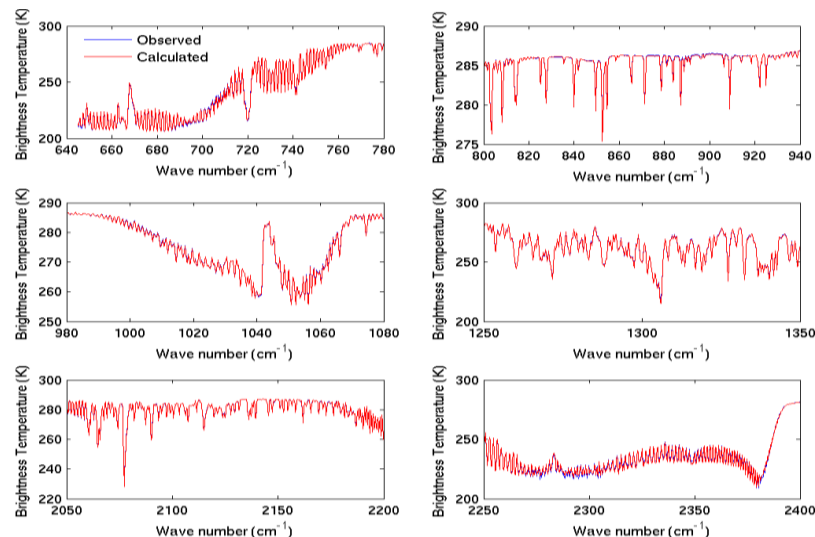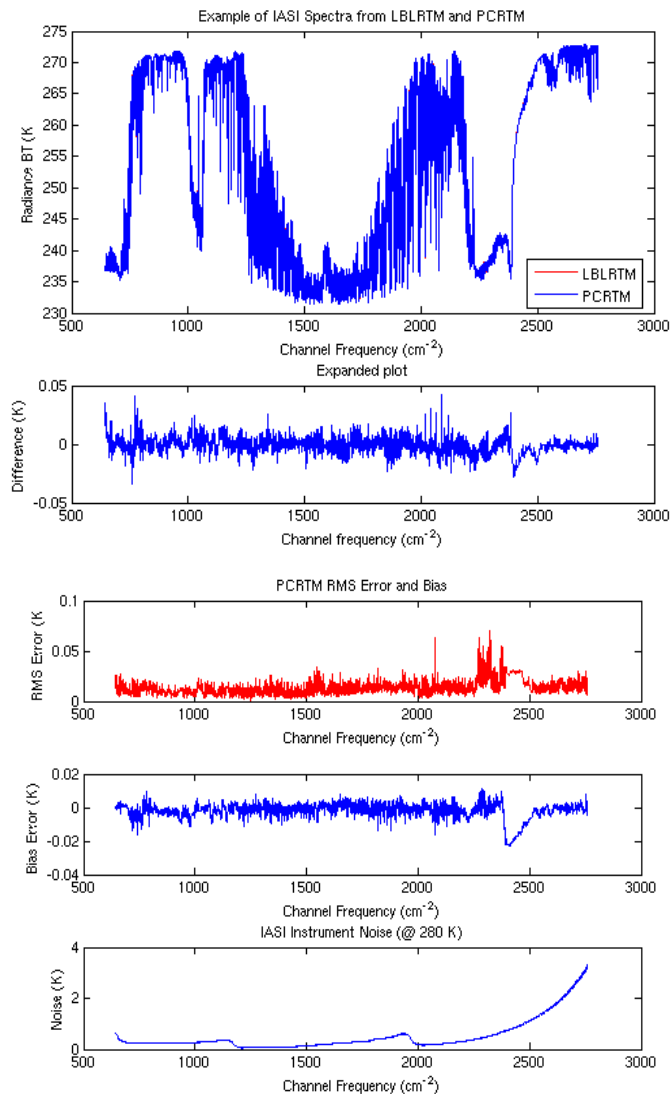
$$C_i = U_{N_{ch} \times 1}^{T} R_{N_{ch} \times 1}^{ch} = \sum_{j=1}^{N_{ch}} U(j,i) \times R^{ch}(j)$$

- It contains essential information about the spectrum and can be treated as super channels in a physical retrieval algorithm
- It can be obtained by linearly combined a few monochromatic radiances:

$$C_i = \sum_{j=1}^{nch} U(j,i) \times \left| \sum_{k=1}^{N} b_k R^{mono}(k) \right| = \sum_{l=1}^{N_{mono}} a_l R^{mono}(l)$$

$$\frac{\partial C_i}{\partial x_j} = \sum_{l=1}^{N_{mono}} a_l \frac{\partial R^{mono}(l)}{\partial x_j}$$

PCRTM accuracy for IASI

- PCRTM can be train as accurate as one wishes relative to line-by-line model
- Much smaller error relative instrument noise
- Compare well with satellite observed spectra

Examples of Eigenvectors in PCRTM
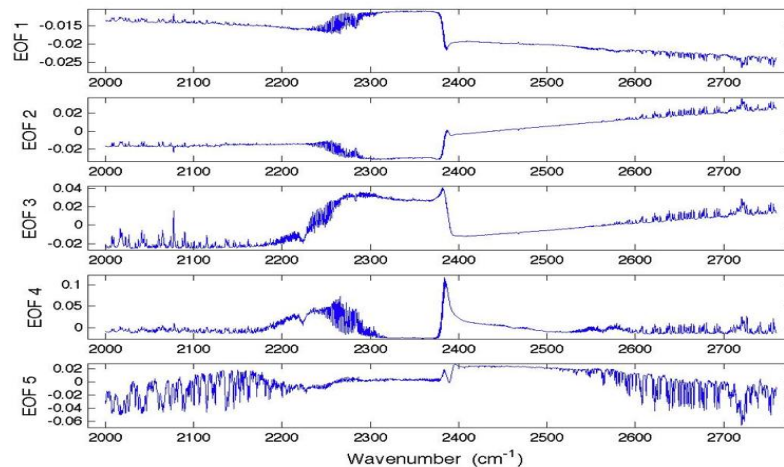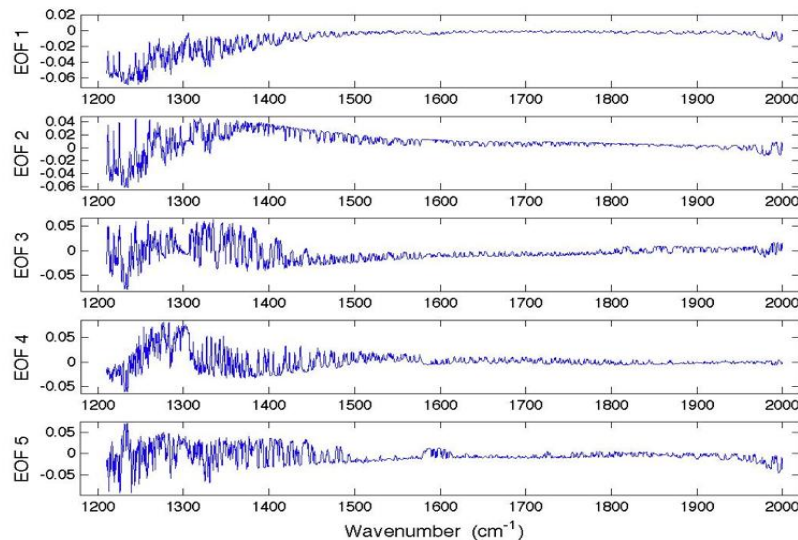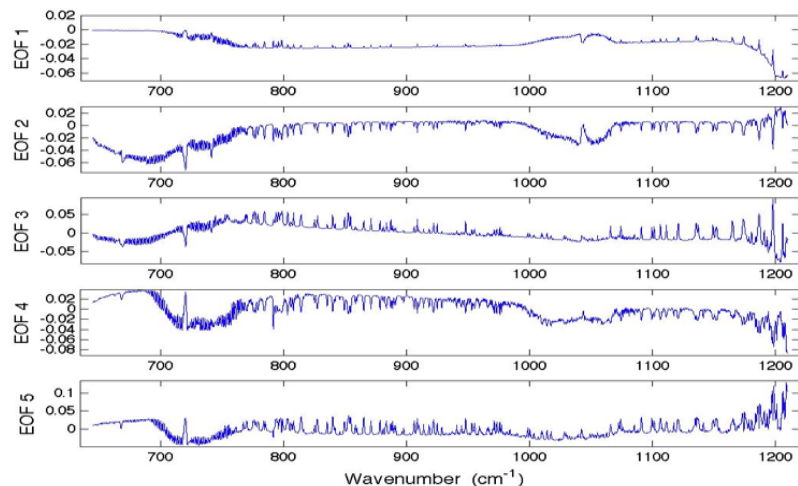
- Eigenvectors capture correlated spectral information of hyperspectral data
  - Remove redundant information
  - Average out random instrument noises
- PC scores capture information content of the observations
  - Atmospheric profiles, cloud, and surface properties are a function of the PC scores
- Doing radiative transfer and inversion in EOF domain
  - Reduces dimension and time for data processing

Effective cloud property calculation

$$\mu \frac{dR(\tau,\mu)}{d\tau} = R(\tau,\mu) - \frac{1}{2}\omega \int_{-1}^{1} R(\tau,\mu')P(\mu,\mu')d\mu' - \frac{\omega}{4\pi}F_0 P(\mu,-\mu_0)e^{-\tau/\mu_0} + (1-\omega)B[(T(\tau)]$$

- Cloud reflectivity (*a*) and transmissivity (*t*) look-up tables are calculated using DISORT
- Both reflectivity and transmissivity are functions of frequency, particle size, optical depth and emergent zenith angle.
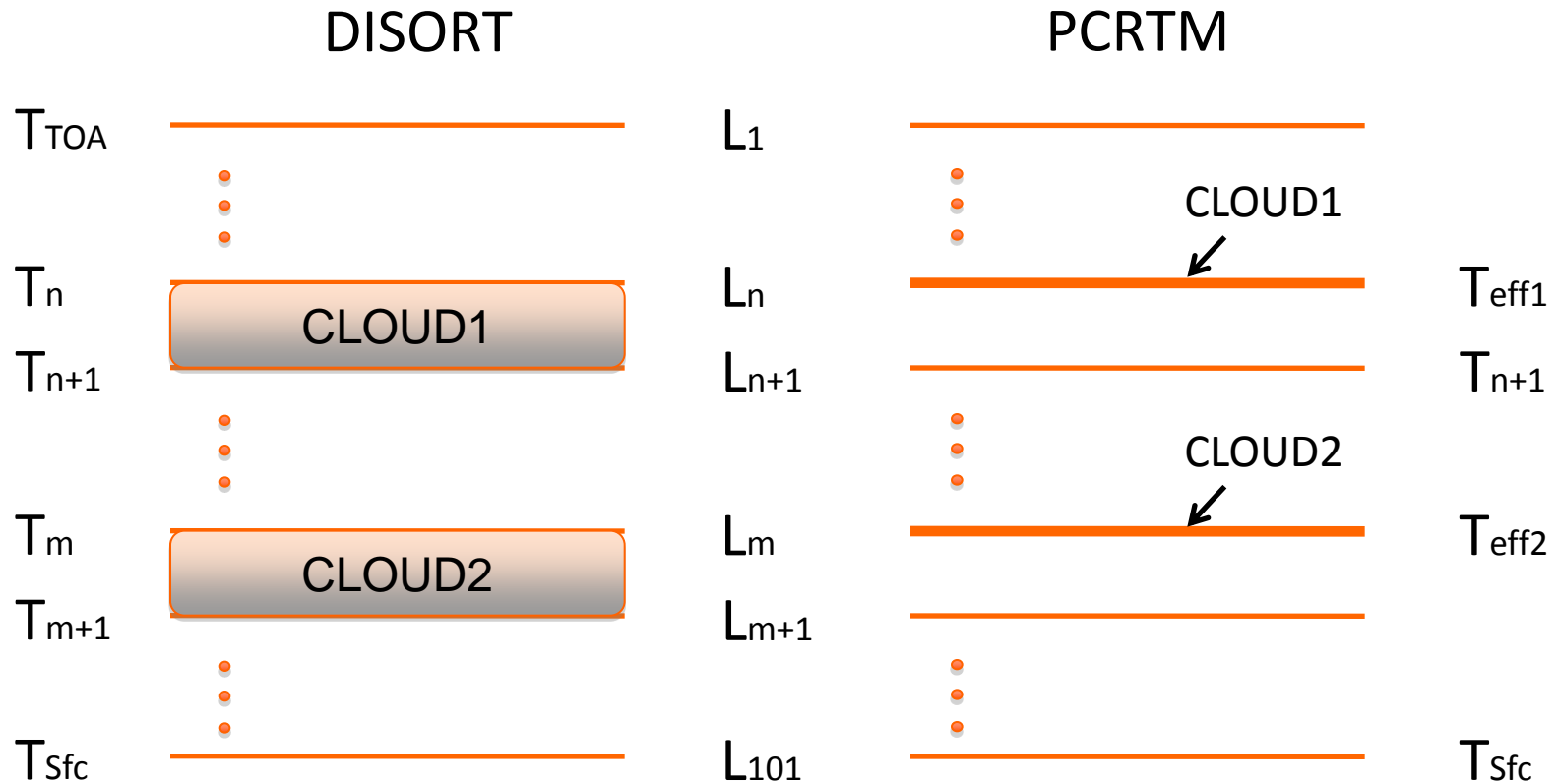- Reflectivity and transmissivity are azimuthally averaged.

I(0,μ)   I$_{inc}$

CLOUD

I(| ,-μ)
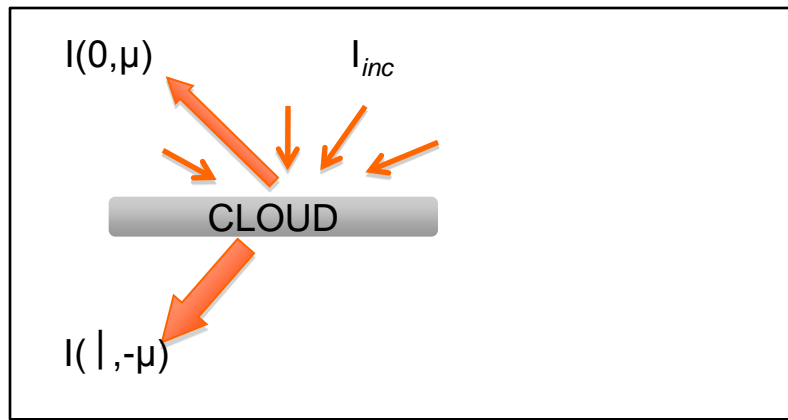
Clear sky condition - -RT done recursively :
$$R_{l+1,v} = R_{l,v}t_{l,v} + (1-t_{l,v})B(T_l,v)$$

Under cloudy condition :
$$R_{l+1,v} = R_{l,v}t_{l,v} + (1-t_{cloud,v}-r_{cloud,v})B(T_{cloud},v) + r_{cloud,v}R_{down}$$

Cloud layering and modeling

DISORT

PCRTM

T_{TOA}

T_n

CLOUD1

T_{n+1}

T_m

CLOUD2

T_{m+1}

T_{Sfc}

L_1

L_n

L_{n+1}

L_m

L_{m+1}

L_{101}

CLOUD1

CLOUD2

T_{eff1}

T_{n+1}

T_{eff2}

T_{Sfc}
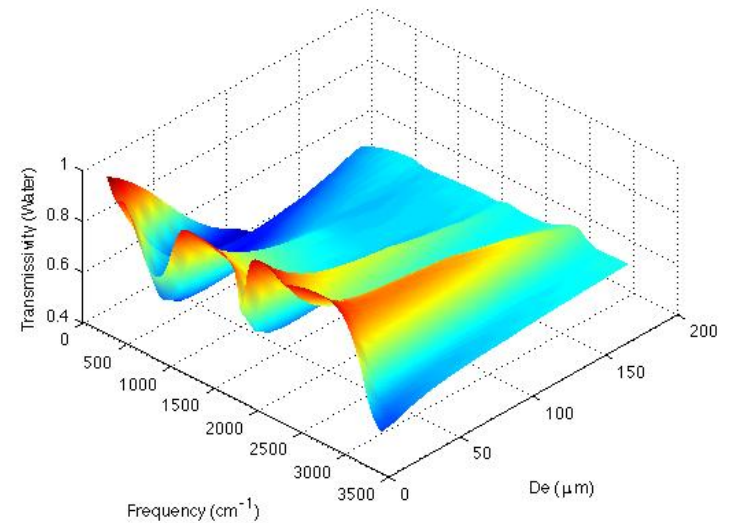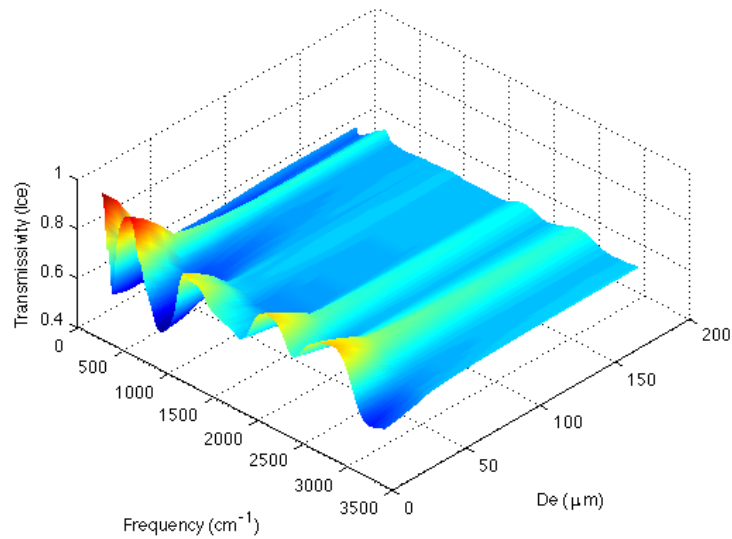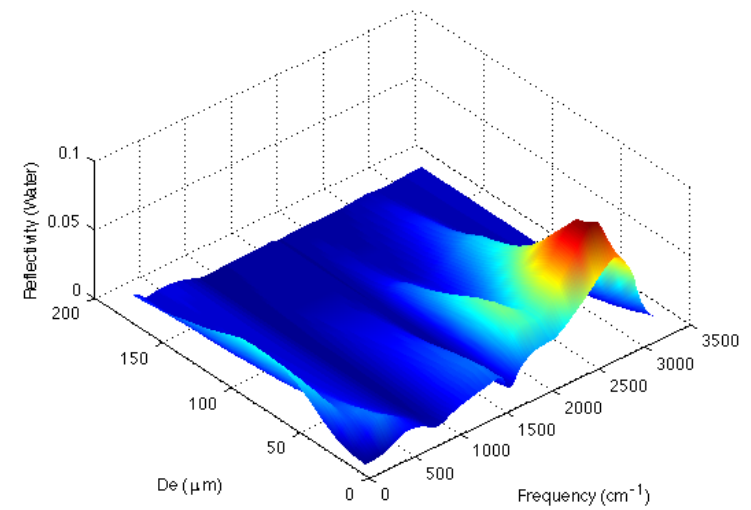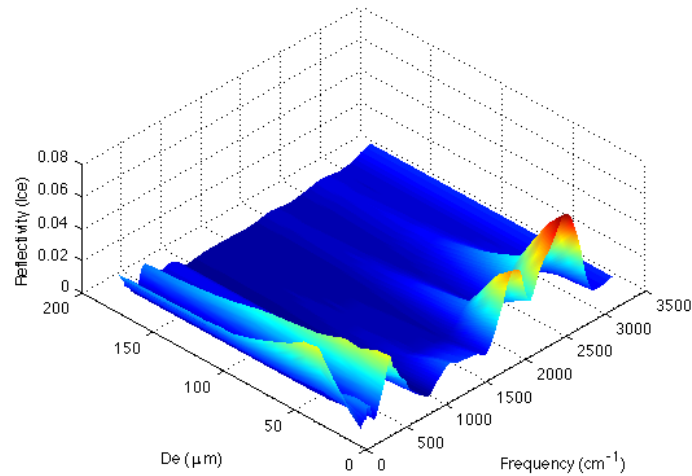
T_{eff} is a function of cloud optical depth and cloud thickness

Forward Model Flowchart

Atmospheric (T, H2O, O3, N2O, CO, CH4), surface (,ε, ρ,Ts), cloud (tau,Pcld, De, phase), and observation Geometry…..

PCRTM parameters Principal components Cloud lookup table

Calculate layer property (layer T, trace gas amounts, cloud effective Temperature….)

Next profile

Calculate super Channel and Jacobian

$$C_i = \sum_{l=1}^{N_{mono}} a_l R^{mono}(l), \qquad \frac{\partial C_i}{\partial x_j} = \sum_{l=1}^{N_{mono}} a_l \frac{\partial R^{mono}(l)}{\partial x_j}$$

Yes　　　　　**No**

Channel Radiance

Super channel generation

Cloud properties

Comparison between PCRTM and DISORT for ice clouds

- DISORT and PCRTM treat layer Planck function differently
  - Result in differences even when cloud optical depth is zero
- The cloud height are purposely chosen high for two layer ice cloud case
  - Large temperature gradient
  - Test our effective cloud temperature scheme
- Better effective cloud temperature scheme is under development
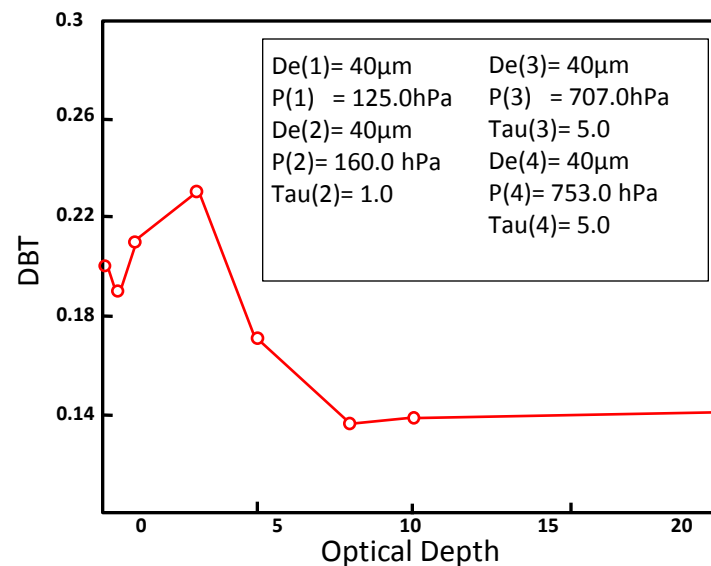
Single layer of ice cloud

De= 40μm
P   = 125.0hPa

Two layers of ice cloud

De(1)= 40μm
P(1)   = 9.0hPa
De(2)= 40μm
P(2)= 11.0 hPa
Tau(2)= 10.0
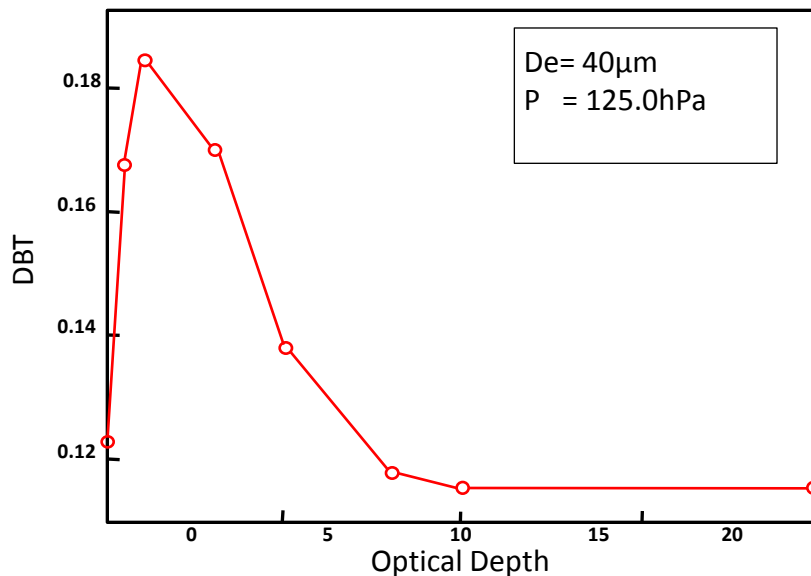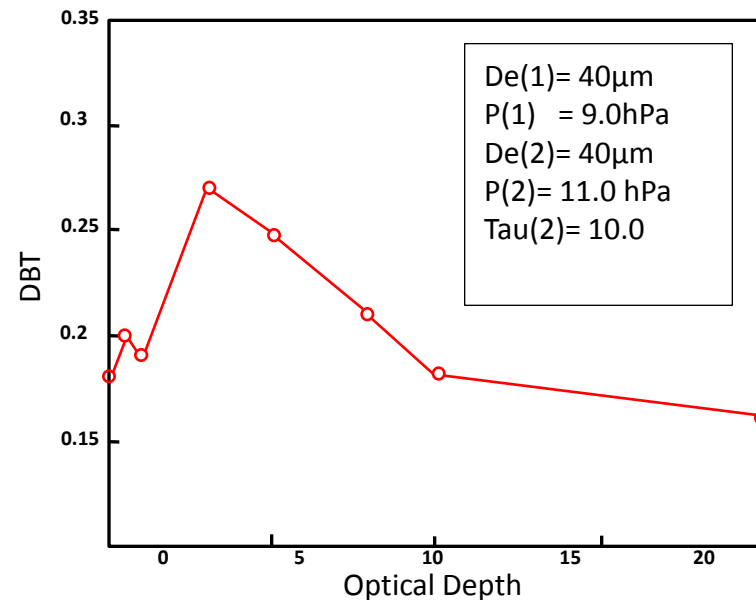
Comparison between PCRTM and DISORT for mixed ice and water clouds

- Up to 4 layers of clouds are tested
  - Code can handle as many as 100 layers of clouds
  - Errors are small considering errors in cloud properties
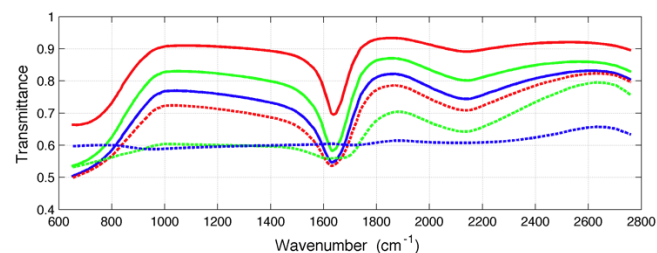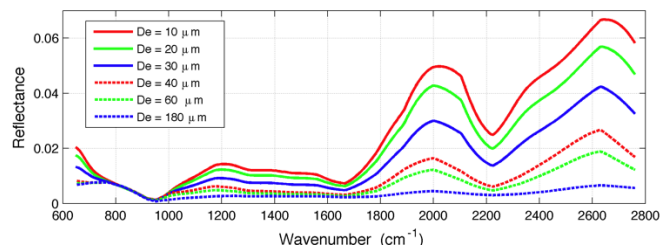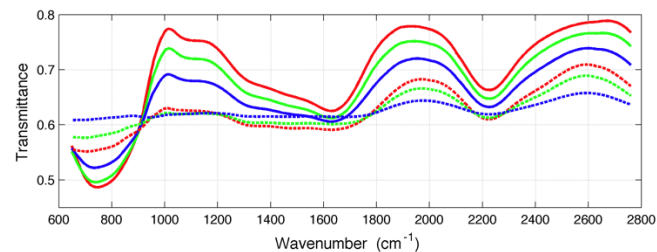 - Much faster speed relative to full multiple scattering calculations
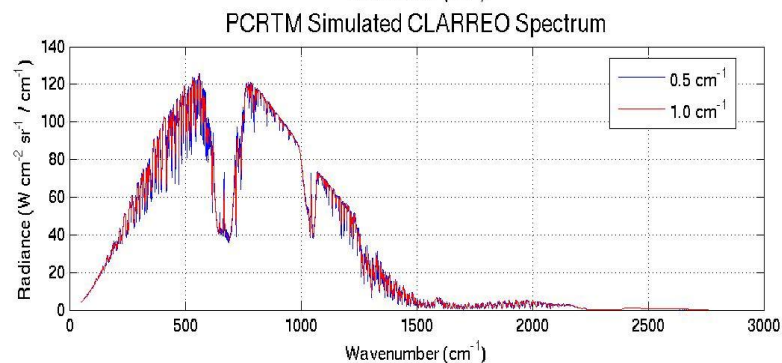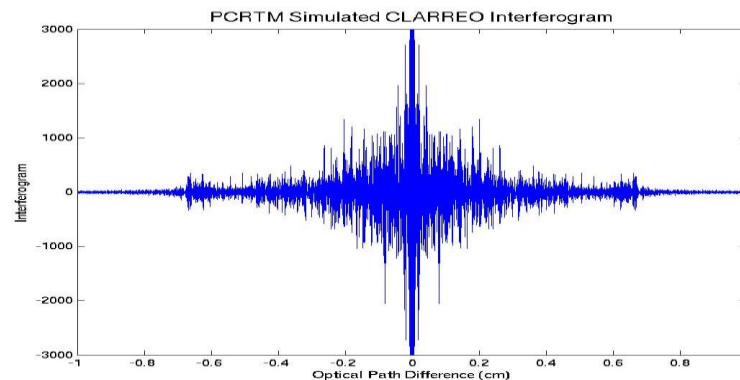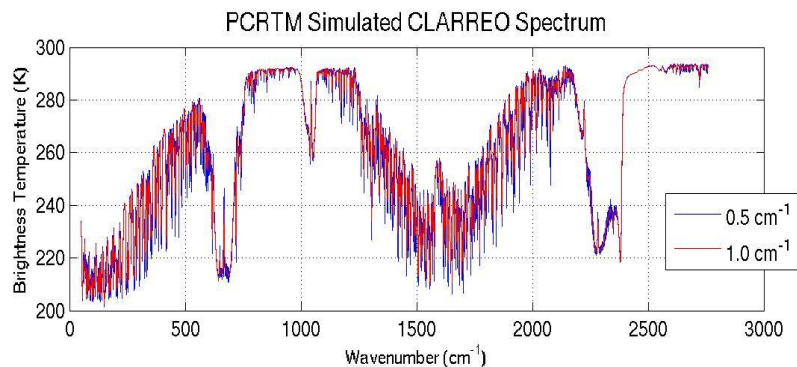
Ice cloud on top of water cloud
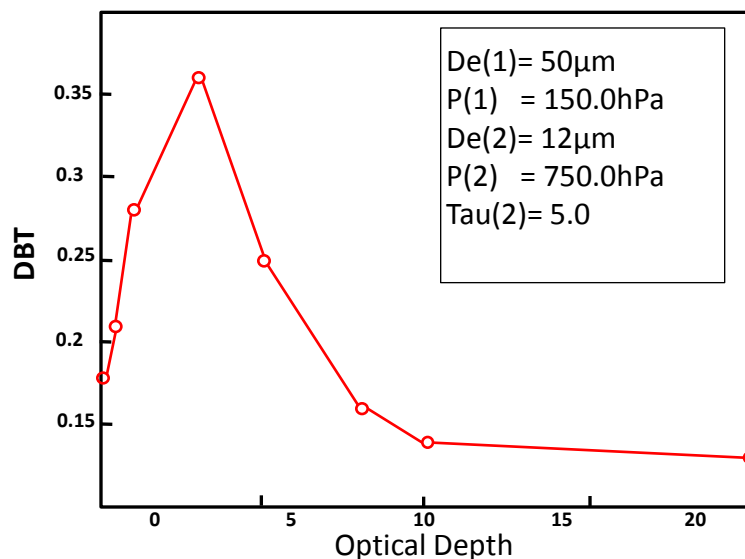
Two layers of ice cloud on top of two layers of water cloud

De(1)= 50μm
P(1)   = 150.0hPa
De(2)= 12μm
P(2)   = 750.0hPa
Tau(2)= 5.0

De(1)= 40μm   De(3)= 40μm
P(1)   = 125.0hPa   P(3)   = 707.0hPa
De(2)= 40μm   Tau(3)= 5.0
P(2)= 160.0 hPa   De(4)= 40μm
Tau(2)= 1.0   P(4)= 753.0 hPa
                 Tau(4)= 5.0

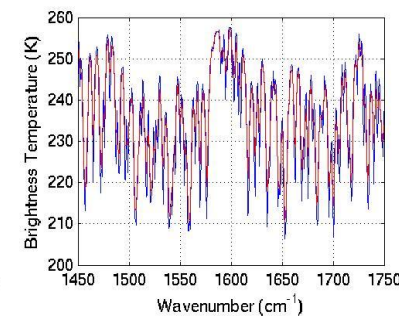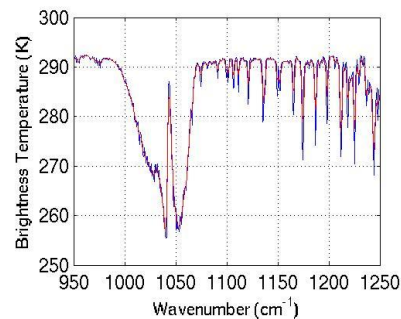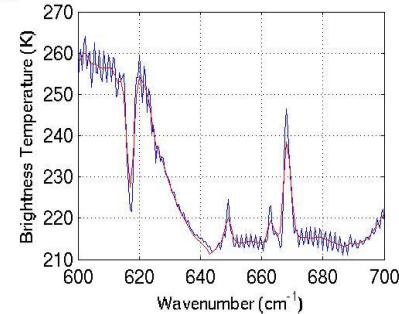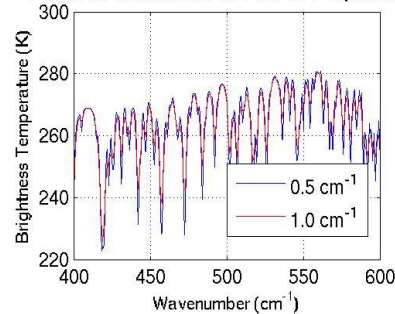# Examples of Observed and fitted IASI cloudy radiances
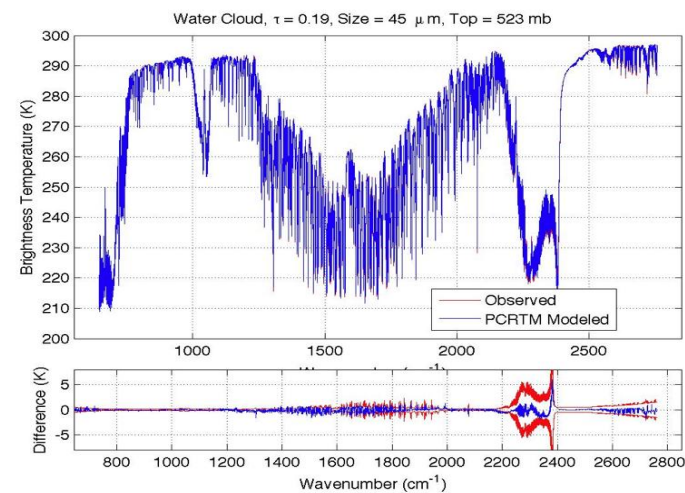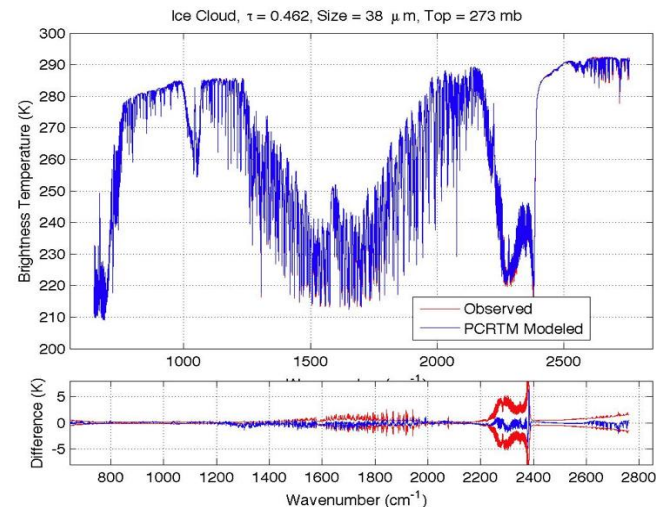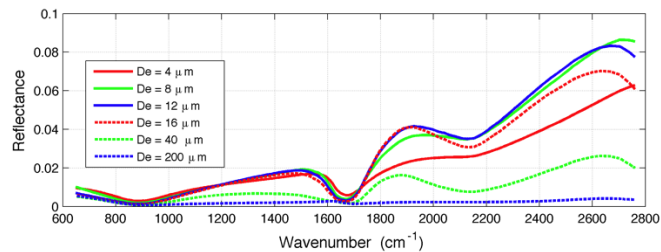
Applying PCRTM to Simulate CLARREO

- Simulated CLARREO Spectra
  - 0.5 cm-1 resolution, maximum OPD=1.0 cm
  - 1.0 cm-1 resolution, maximum OPD=0.5 cm
- Capable of two cloud layers
- Covers Far IR and Mid IR

Applying PCRTM to calculate the whole LW radiances

- Work done by Fred Rose and Seiji Kato at NASA Langley
- PCRTM used to calculate cloudy radiance from 50 cm^{-1} to 3000 cm^{-1} using MODIS/CERE cloud fields and model atmospheres
- Integrated LW radiances are compared with CERES observations
- Good agreement for 6 years of record

Global Monthly Mean
Nadir LW Radiance
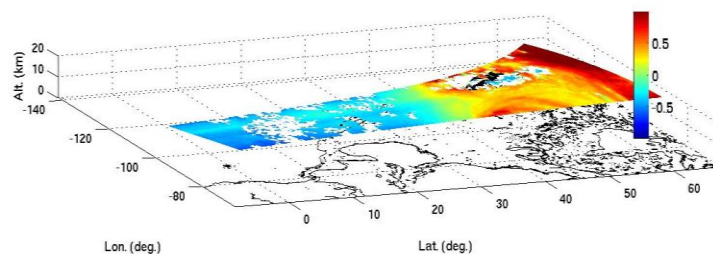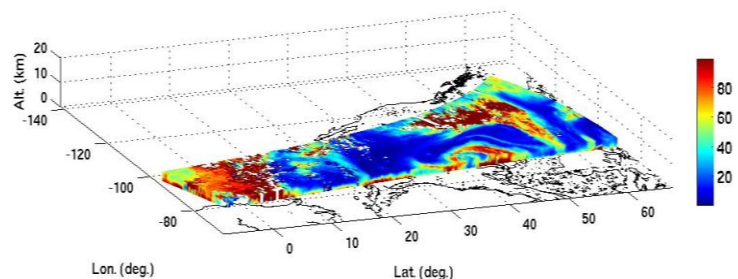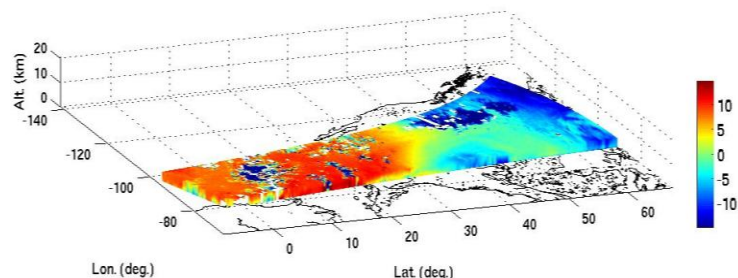Year 2001-2005 by 10deg Latitude
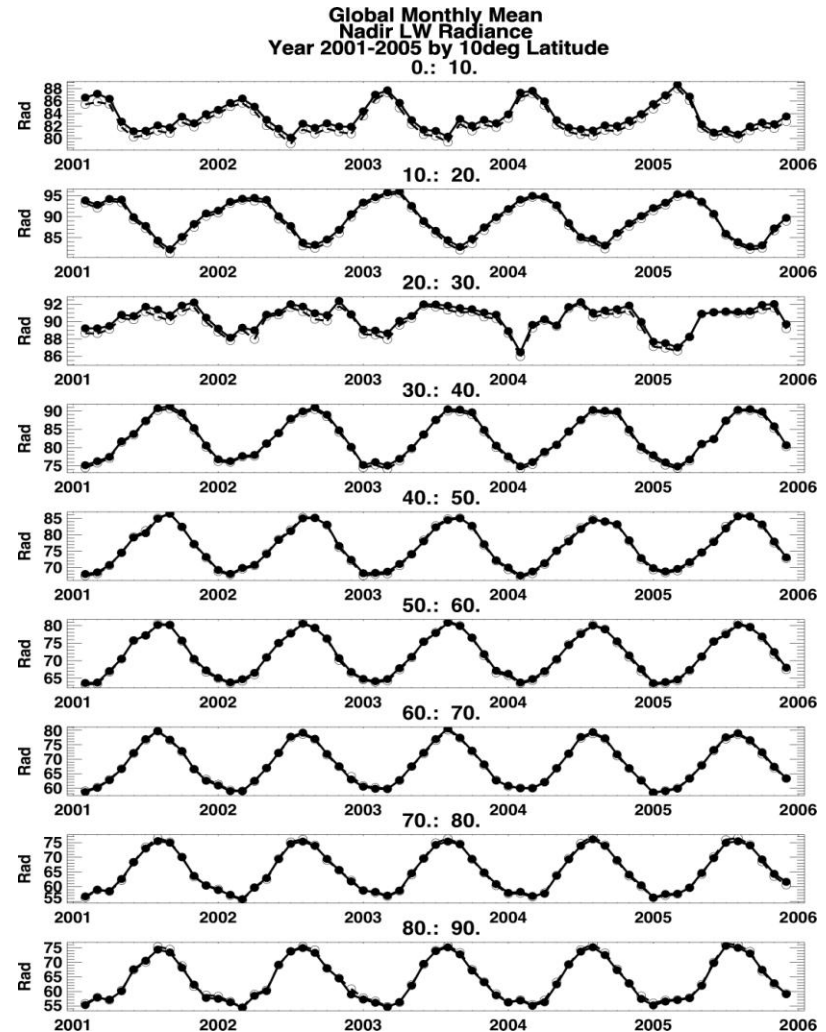
# Example of retrieved cloud properties from IASI observations
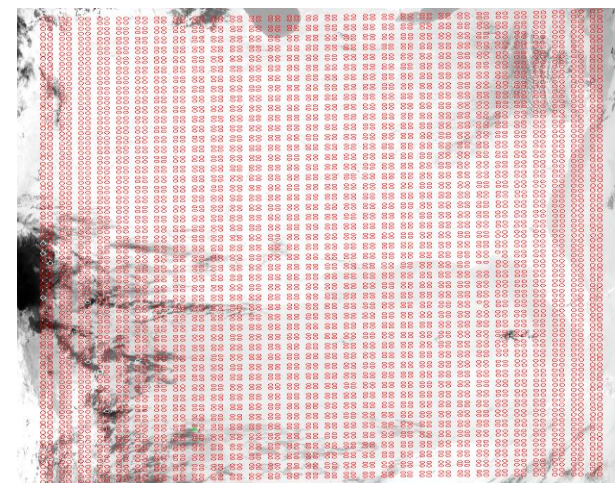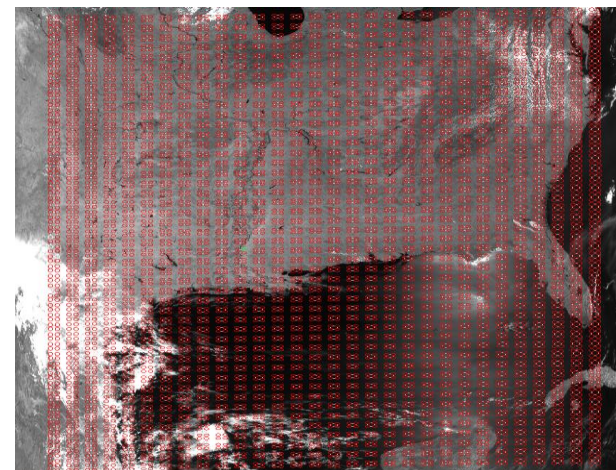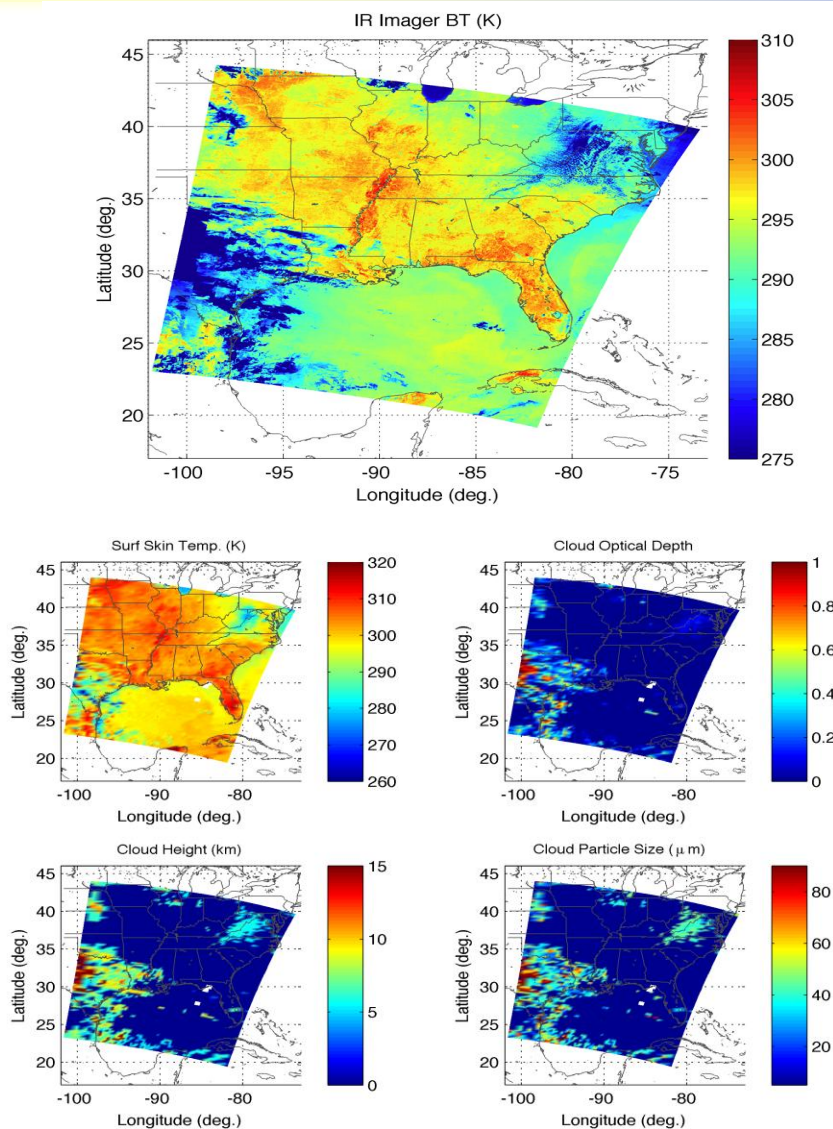
Example of the Fine Spatial and Vertical Resolutions of Retrieved Atmospheric Profiles

- Temperature, moisture, and ozone cross-sections
- Plots are deviation from the mean
- Fine water vapor structures captured by the retrieval system
- A very cloudy sky condition

- Retrieved temperature, moisture, and relative humidity profiles retrieved from April 19th, 2007 JAIVEx campaign
- Averaging kernels and expected retrieval errors are shown
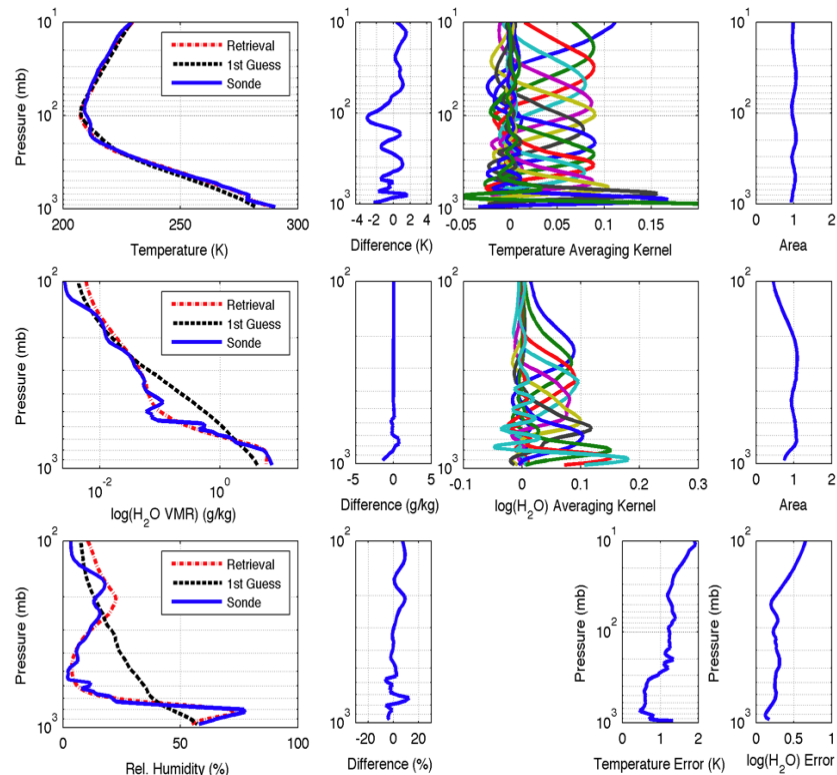
Example of Retrieved Surface Properties

Date	Location	Surface Pressure (hPa)	ARIES Measured skin temperature (K)	IASI-retrieved surface skin temperature (K)
19 April 2007	ARM CART site	972.0	284.7	284.8
29 April 2007	Gulf of Mexico	1021.7	297.8	297.6
30 April 2007	Gulf of Mexico	1017.5	298.6	298.1
4 May 2007	Gulf of Mexico	1009.9	297.4	297.1
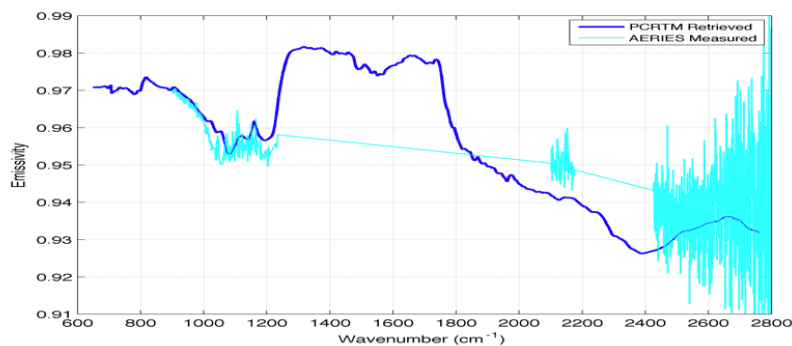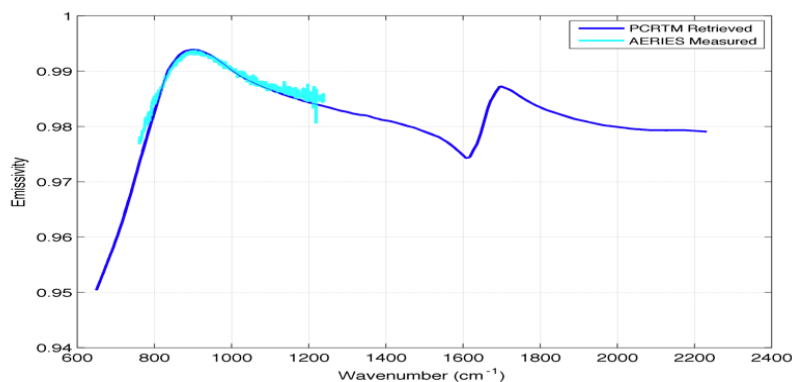
- Retrieved surface skin temperature
  - mean error of 0.18 K
- Retrieved ocean emissivity agrees well with
  - Masuda Emissivity model
  - ARIES measurements
- Retrieved land emissivity agree with ARIES measuremtn
  - There are some spatial coverage between the aircraft measurements and the satellite observations

Retrievals from Simulated IASI spectra

Cloud Optical Depth (truth)

Effective Size (truth, μm)
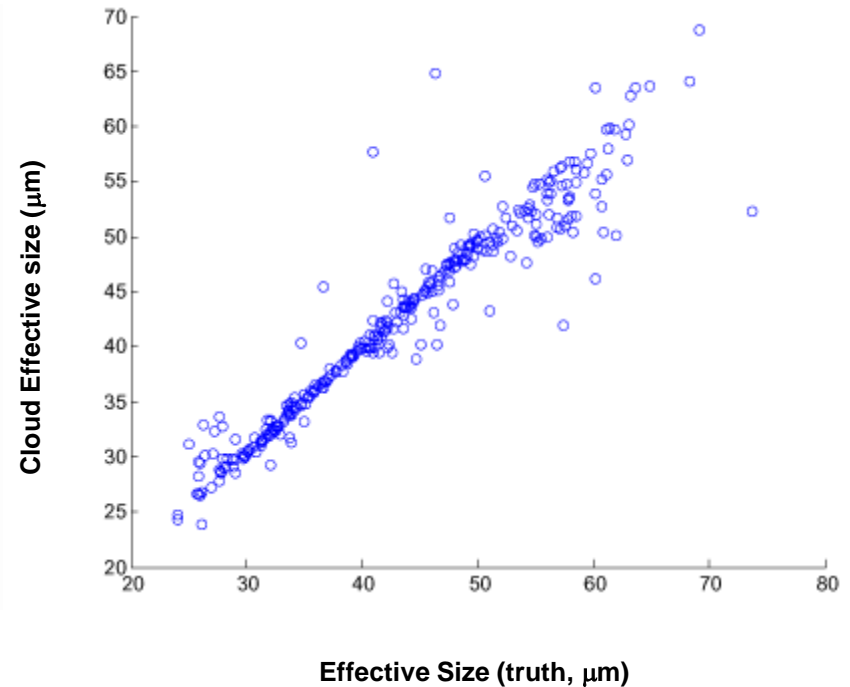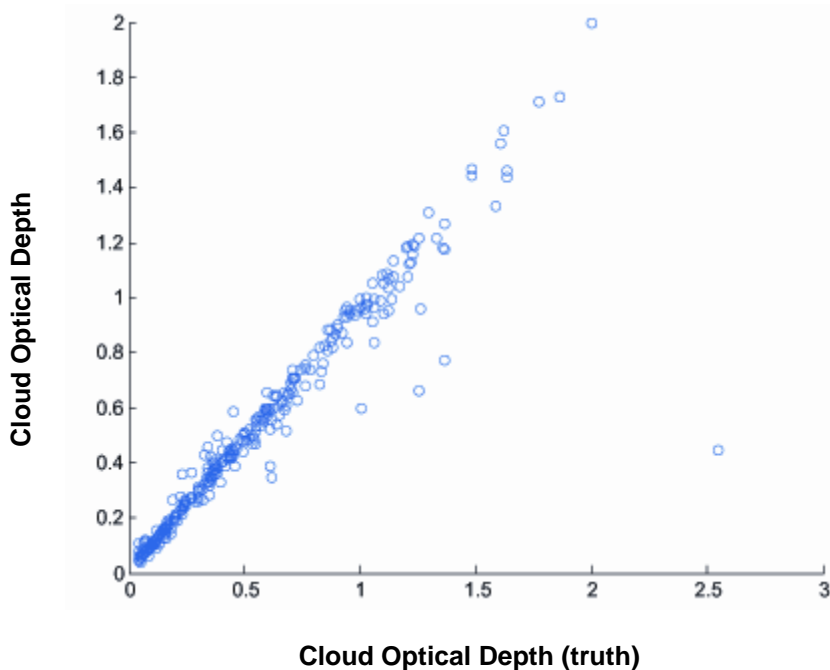
- Simulate IASI spectra from known state vector
- Perform PCRTM physical retrieval for T, H_2O, O_3, CO, cloud, and surface properties simultaneously
- Results are preliminary

Conclusions

- PCRTM model is accurate relative to LBL

- PCRTM can handle up to 100 layers of clouds

- Multiple scattering calculations are done off-line

- Results compare well with DISORT

- Have applied the method to simulate CLARREO radiances

- Calculated LW TOA radiances and compares well with CERES

- Performed retrieval for IASI observation under cloudy sky conditions

- Will continue the work to quantify the retrieval errors under cloudy condition