Presentation outline

- Motivations
- Principal Component-based Radiative Transfer Model (PCRTM)
- PCRTM retrieval algorithm and applications to CrIS and IASI data
- Summary and Conclusions

Motivations

- Need fast radiative transfer model to handle hyperspectral data
  - Modern sensors have thousands of channels and 0.1-1 million spectra per day
  - Only 4-10% of data are used in satellite data assimilations
- Need retrieval algorithm to take advantage of hyperspectral data
  - Retrieve all parameters that contribute to the TOA radiance
  - No need to to perform retrieval on cloud-cleared radiances
  - No need to make assumptions about the inhomogeneity of the scene
  - Provide realistic error estimate for the retrieved parameters
  - More physical cloud parameters can be retrieved

Examples hyperspectral sensors:

• AIRS	2378 x 1 x1
• CrIS	1305 x 3 x 3
• NAST-I	8632 x 1 x 1
• IASI	8461 x 2 x 2
• FIRST	~1500x10 (or more)
• CLARREO	thousands

- PCRTM (Principal Component-based Radiative Transfer model) was developed to satisfy the need listed above

Introduction to PCRTM Forward Model

- Explore spectral correlation in hyperspectral data
  - No need to calculate spectrum one channel at a time
  - Compress spectra into compact form using PCA, wavelet, Fourier Series etc
  - Reduce dimension of the data
- PCA is a good approach for compressing spectra and capture information
  - Leading EOFs captures all essential information of thousands of channels
  - PCA has been used to reduce instrument noise and to compress spectra
- PCRTM parameterization is physical-based fast model

$$y_i = \vec{R}^{ch} \times U_i = \sum_{j=1}^{N_{mono}} \phi_j R_j^{mono} \vec{U}_i = \sum_{j=1}^{N_{mono}} A_j R_j^{mono}$$

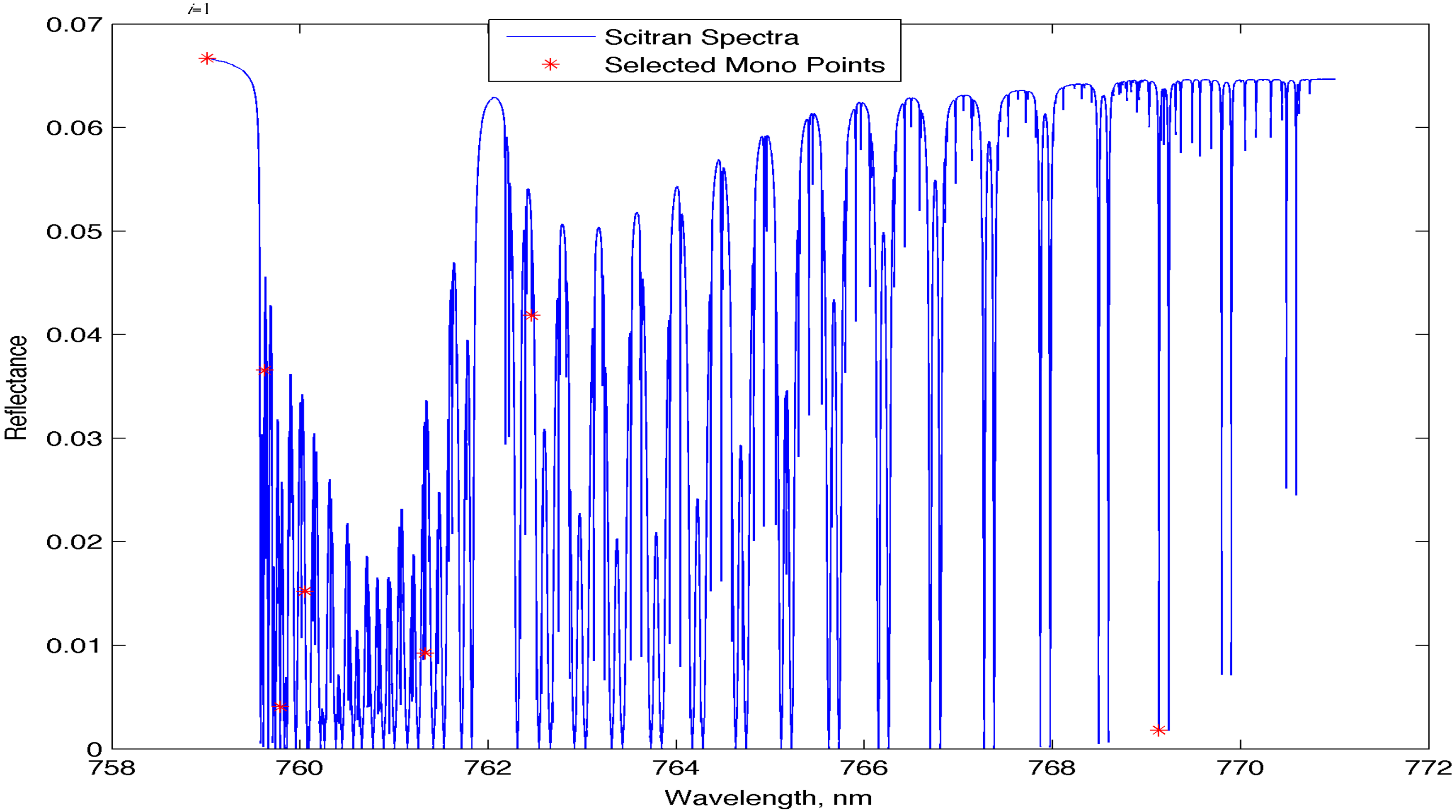
$$\vec{R}^{ch} = \sum_{i=1}^{N_{EOF}} y_i \vec{U}_i + \vec{\varepsilon}$$

  - Radiative transfer done monochromatically at very few frequencies
  - Very accurate relative to line-by-line (LBL) RT model (< 0.05K or 0.05%)
  - 3-4 orders of magnitude faster than LBL RT models
  - A factor of 2-100 times faster than channel-based RT models
  - Provides Jacobian or radiative kernel needed for retrievals and climate studies
  - Includes accurate cloud RT: multiple layers and multiple scattering up to 101 layers

PCRTM is Physical and Fast

- Example of O_2 A-band
  - 12000 monochromatic RT LBL calculations needed to covr 759-771 nm spectral region
- PCRTM reduces monochromatic RT calculation to 7
  - 1700 times faster than LBL
  - Been trained for OCO (~0.04 nm) and SCIAMACHY (~0.2 nm) spectral resolutions

$$\vec{R}^{chan} = \sum_{i=1}^{N_{EOF}} y_i \vec{U}_i$$



Computational Speed up in Solar Spectral Region

- PCRTM reduces MODTRAN RT calculation by a factor or 28-928 depending on spectral resolution and MODTRAN accuracy chosen
  - PCRTM can handle ice and water clouds
  - Aerosols
  - Various trace gases
  - Land and ocean surfaces
  - Multiple scattering calculation uses 4-32 streams
- It takes 1 day to simulate 1 year of all sky SCIAMACHY spectra using PCRTM with 30 CPUs
- It will take more than 2 years for the MODTRAN to do the same

0.3 μm-2.0 μm	PCRTM RT	MODTRAN RT	speed up
Ocean 1cm^{-1}	956	259029	270
Land 1cm^{-1}	1339	259029	193
Ocean 4nm	279	259029	928
Land 4nm	354	259029	731

Computational Speed in IR Spectral Region

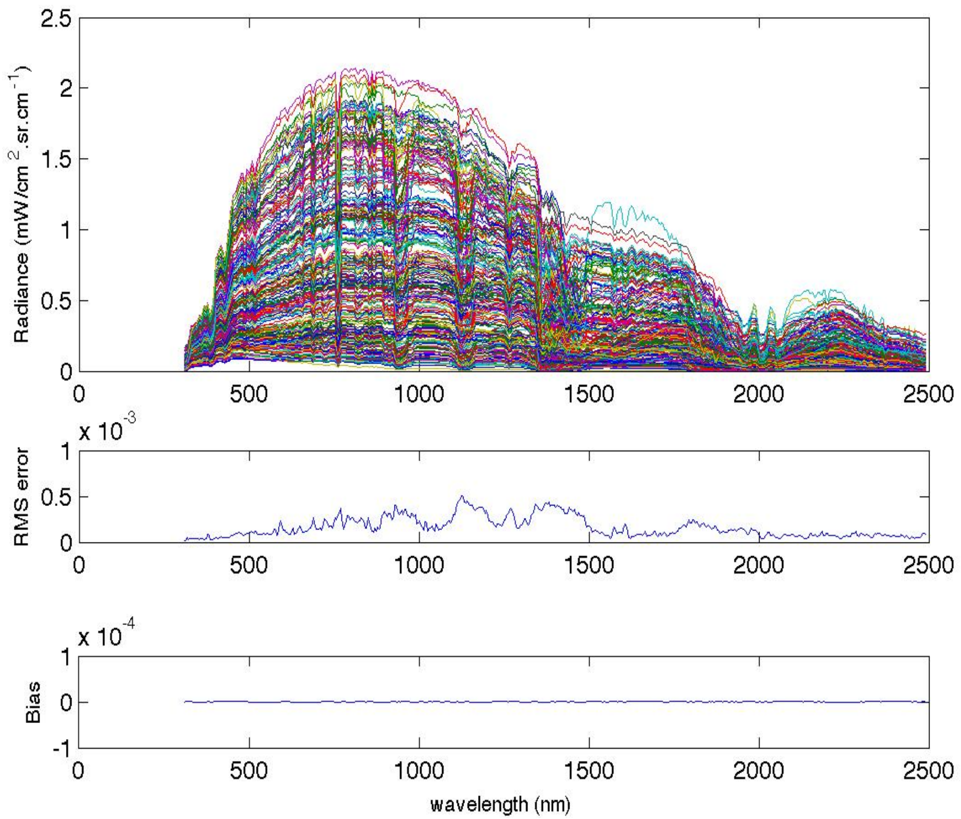
Sensor	Channel Number	PC score (seconds)	PC score + radiance	PC score + PC Jacobian
CLARREO, 0.1 cm^{-1}	19901	0.014 s	0.022 s	0.052 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s	0.013 s	0.039 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s	0.012 s	0.036 s
IASI, 0.25 cm^{-1}	8461	0.011 s	0.012 s	0.044 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s	0.0074 s	0.031 s
CrIS,0.625-2.5 cm^{-1}	1317	0.0050 s	0.0060 s	0.021 s
NAST-I, 0.25 cm^{-1}	8632	0.010 s	0.013 s	0.045 s
S-HIS, 0.5 cm^{-1}	4316	0.008 s	0.008 s	0.038 s
CrIS, 0.625 cm^{-1}	2211	0.009 s	0.009 s	0.033 s

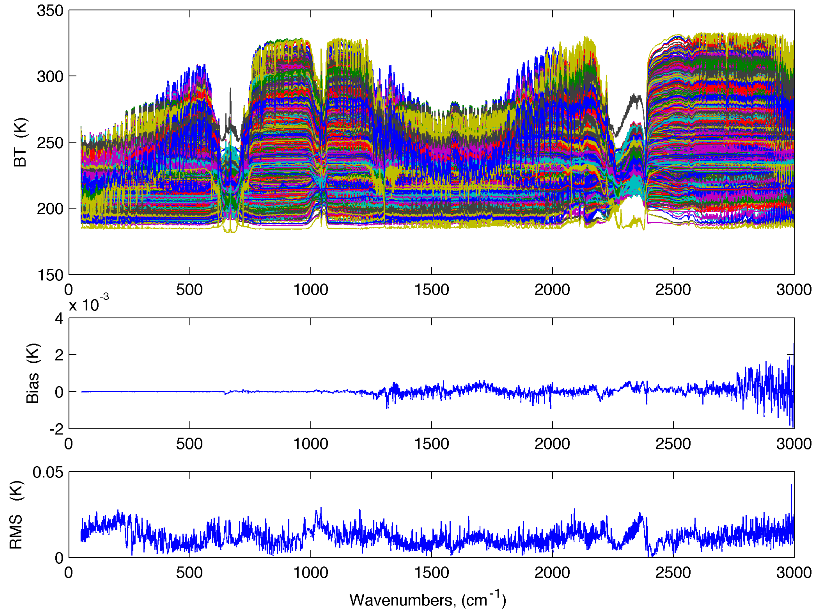
NAST-I Spectral Band	Number of Channels	No. of RT Calc. for All NAST Channels	Predictors per Channel
PCRTM	8632	310-900	0.04-0.1
PFAST	8632	8632	~40
OSS	8632	22316	2.59

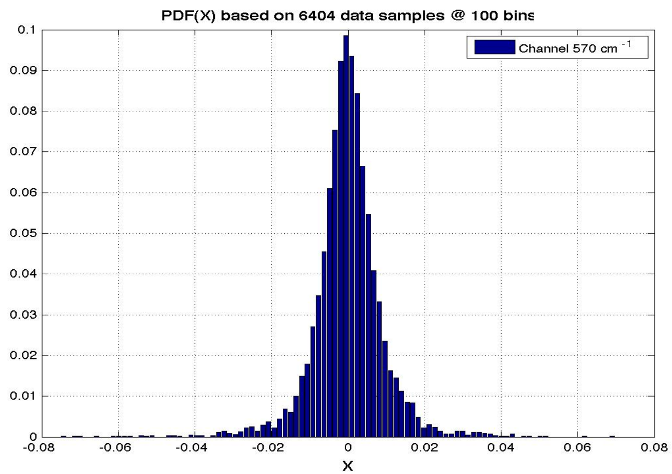
- Milliseconds to fraction of seconds in IR
- CrIS, CrIS-full-res, IASI, NAST-I and S-HIS have multiple databases corresponding to different instrument lineshape function
- Spectral coverage (50-3000 cm^{-1})
- Multilayer, multiple scattering clouds included
- 15 variable trace gases
- It provide radiative kernel /Jacobian with minimum additional computations.

Accuracy of PCRTM is very good relative to reference RT models

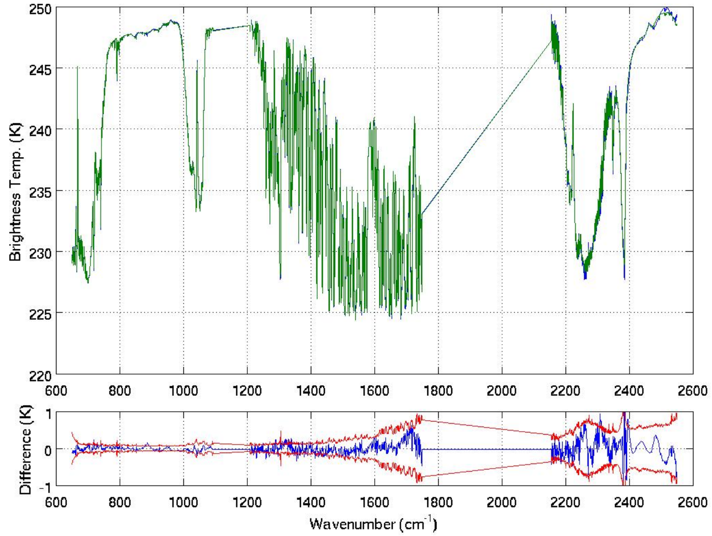
- Bias error relative to LBL is typically less than 0.002 K
- The PDF of errors at different frequencies are Gaussian distribution
- RMS error < 0.03K for IR and < $5x10^{-4}$ $mW/cm^2/sr/cm^{-1}$ for solar (< ~0.02%)

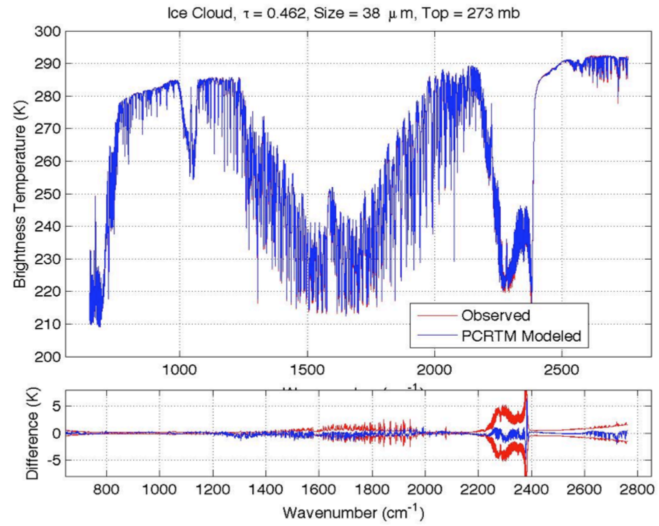


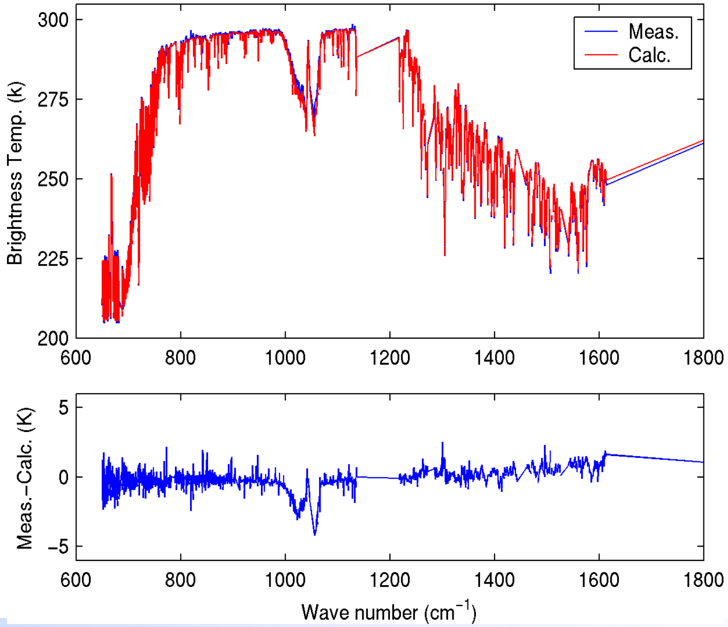


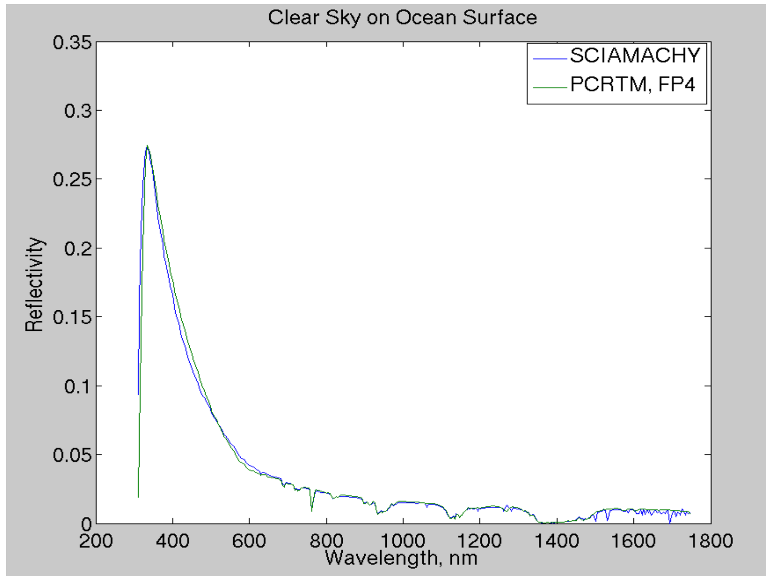


PCRTM has been validated using CrIS, IASI, AIRS, NAST-I, and SCIAMACHY real data



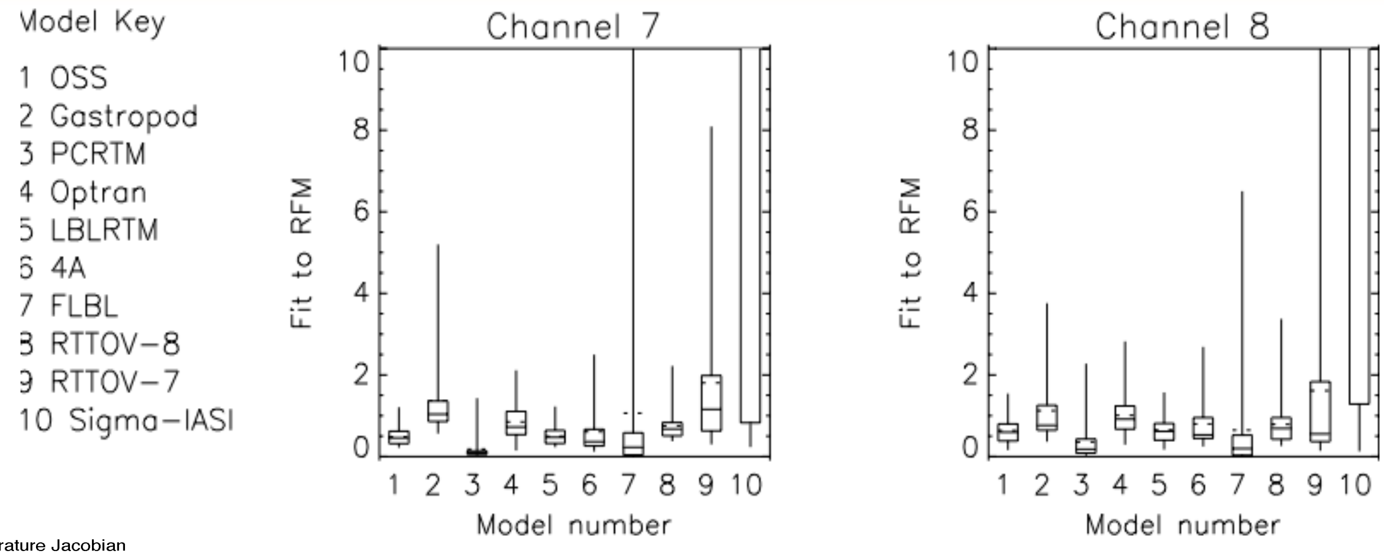


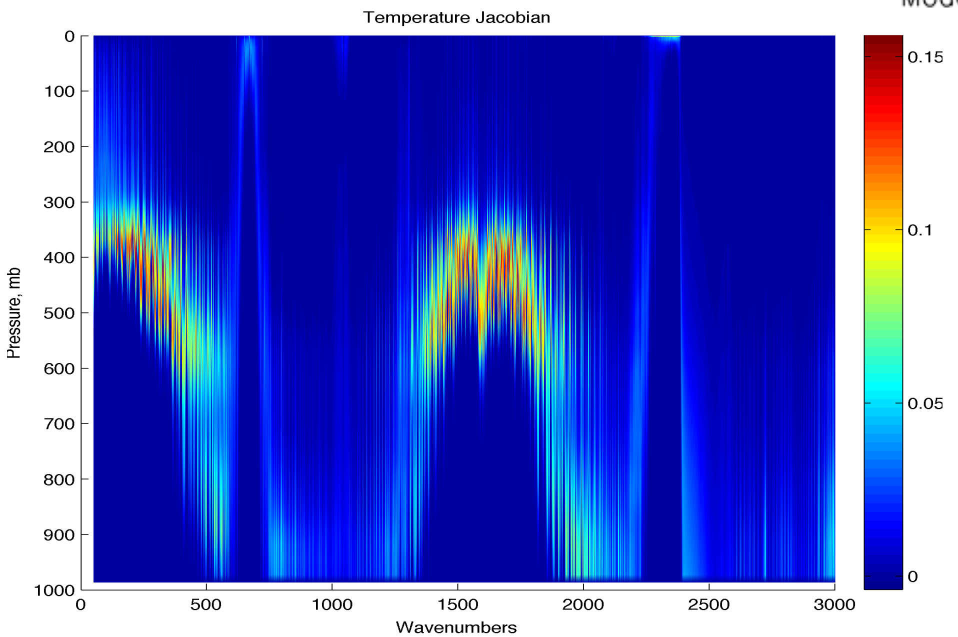




Example of Jacobian from PCRTM

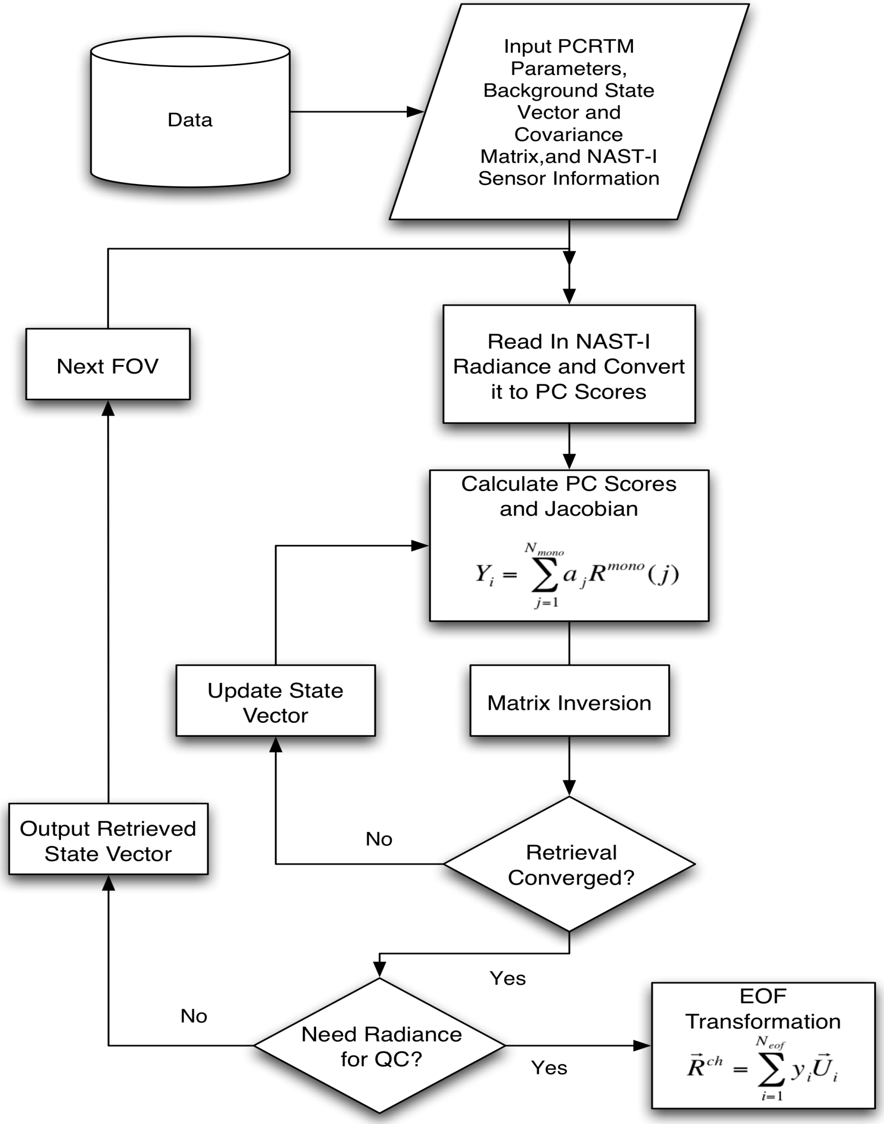
- Comparison of ozone Jacobian from different models (*Saunders et al. JGR, 2006*)





Temperature Jacobian calculated from PCRTM

A brief description of the PCRTM Optimal Estimation Retrieval Algorithm



$$X_{n+1} - X_a = (K^T S_y^{-1} K + \lambda I + S_a^{-1})^{-1} K^T S_y^{-1} [(y_n - Y_m) + K(X_n - X_a)]$$

PCRTM models PC scores directly
- Small matrix and vector dimensions
- All 8000 channels from IASI and NAST-I used

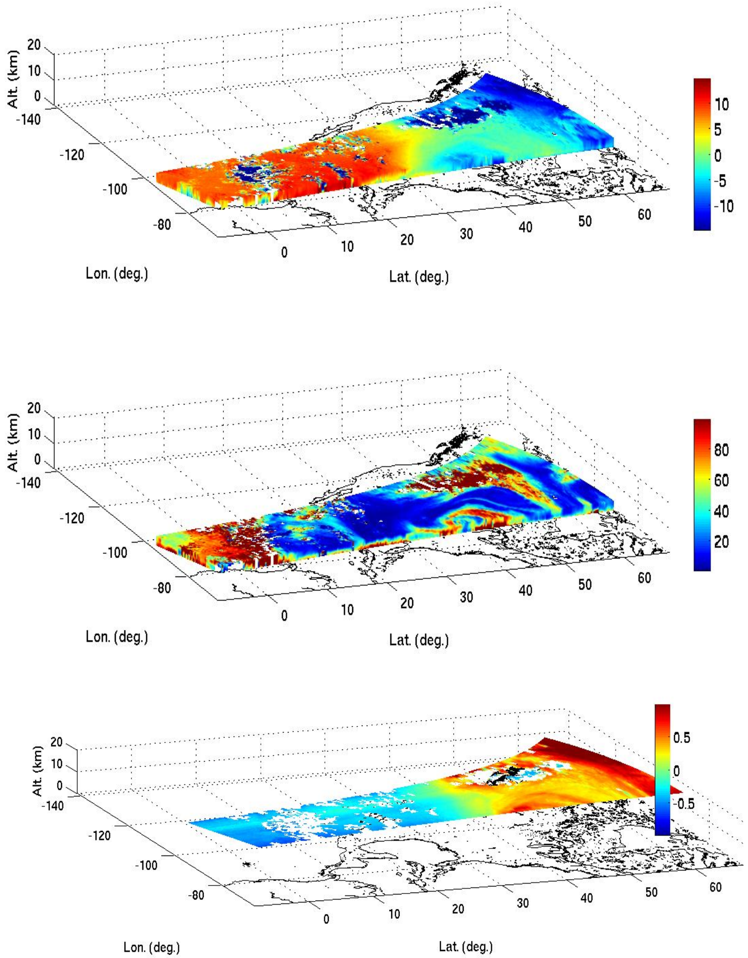
Both y and x vectors are in EOF domain
- Small matrix and vector dimensions
- 100 super channels instead of thousands of channels
- Simply minimizing cost function
- Channel-to-channel correlated noise handled

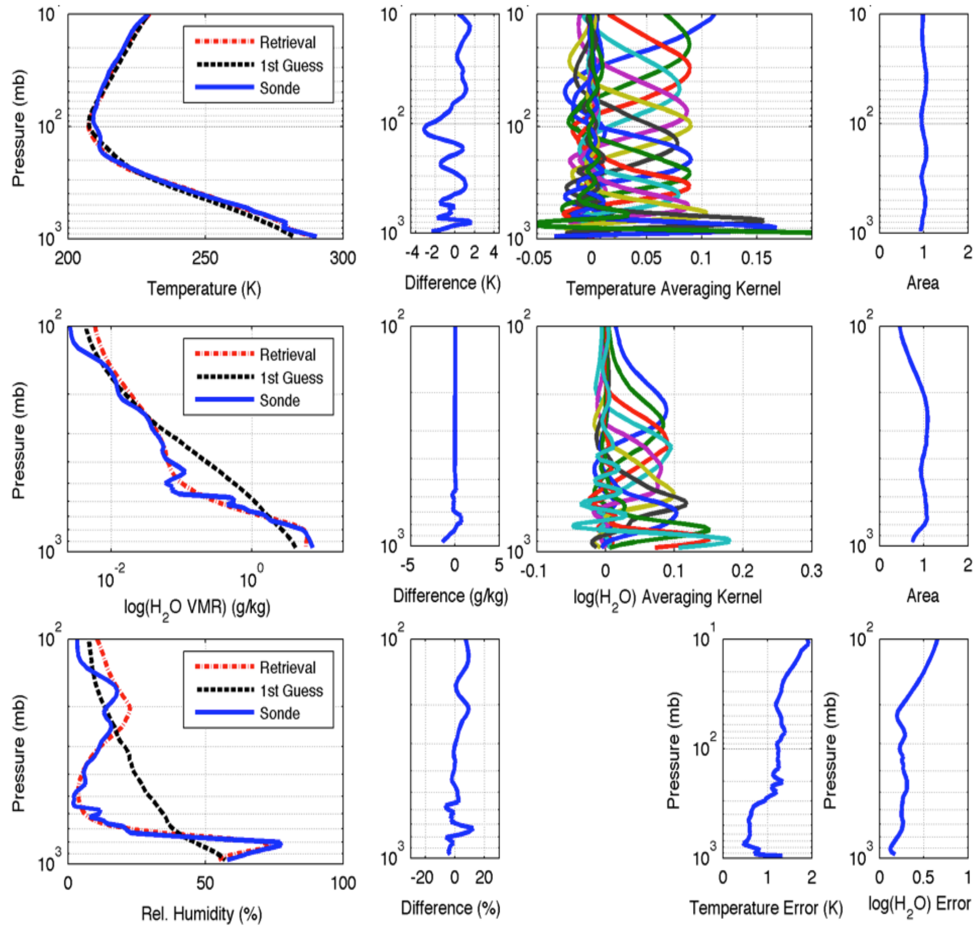
All parameters retrieved simultaneously
- No need to estimate errors of non-retrieved parameters
- Temperature
- Water
- Trace gases (CO2, CO, CH4, O3, N2O)
- Surface temperature and emissivities
- Cloud optical depth/size/phase/height

Retr. Config /Matrix Dimension	Radiance /Profle	Subset Radiance /Profile	Radiance PC/ Profile PC
Y	~8400	300	100
X	100	100	41
K	8400x100	300x100	100x41
S_y^{-1}	8400x8400	300x300	100x100
S_x	100x100	100x100	41x41

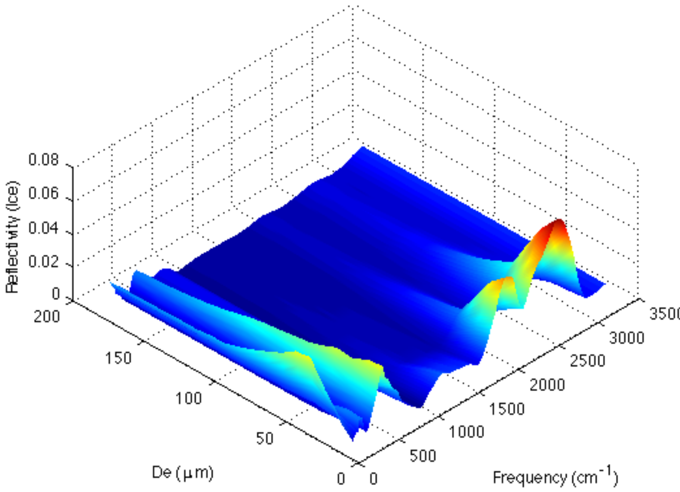
Comparison of PCRTM retrieval with radiosondes

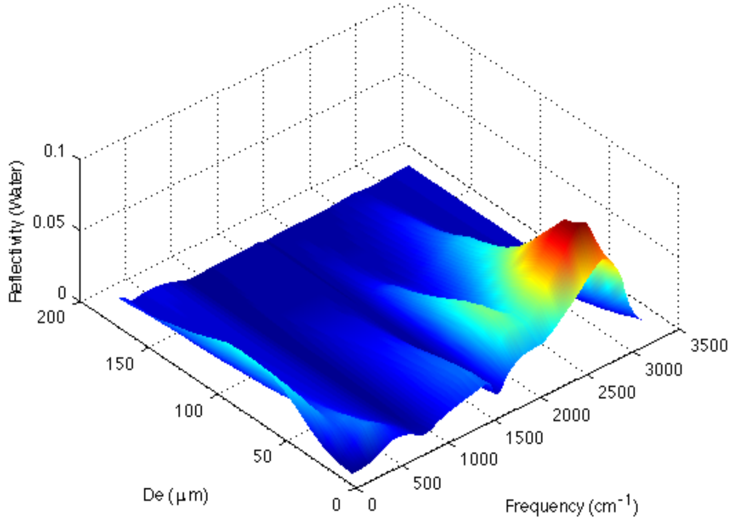
- Temperature, moisture, and ozone cross-sections
- Plots are deviation from the mean
- Fine water vapor structures captured by the retrieval system
- A very cloudy sky condition

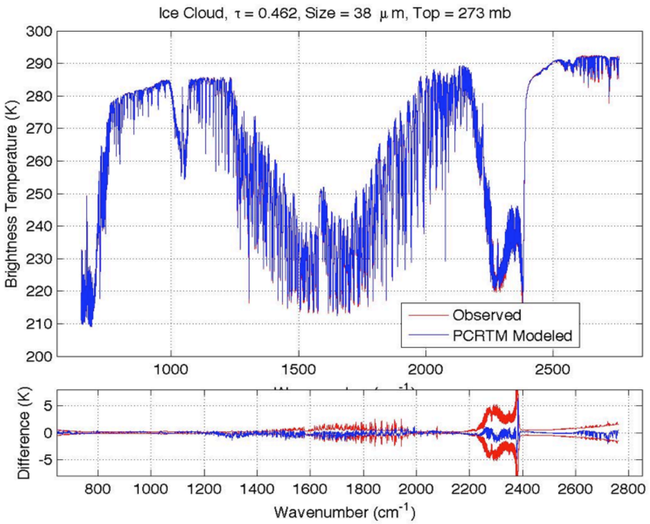


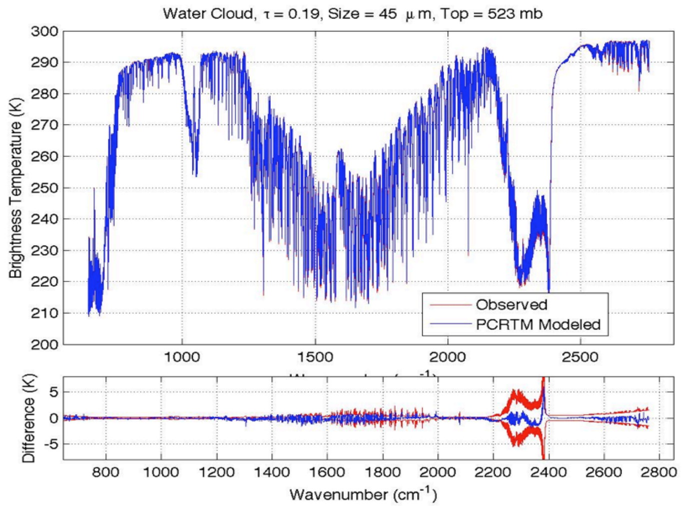


Effective cloud transmissivity and reflectivity are good ways to model clouds

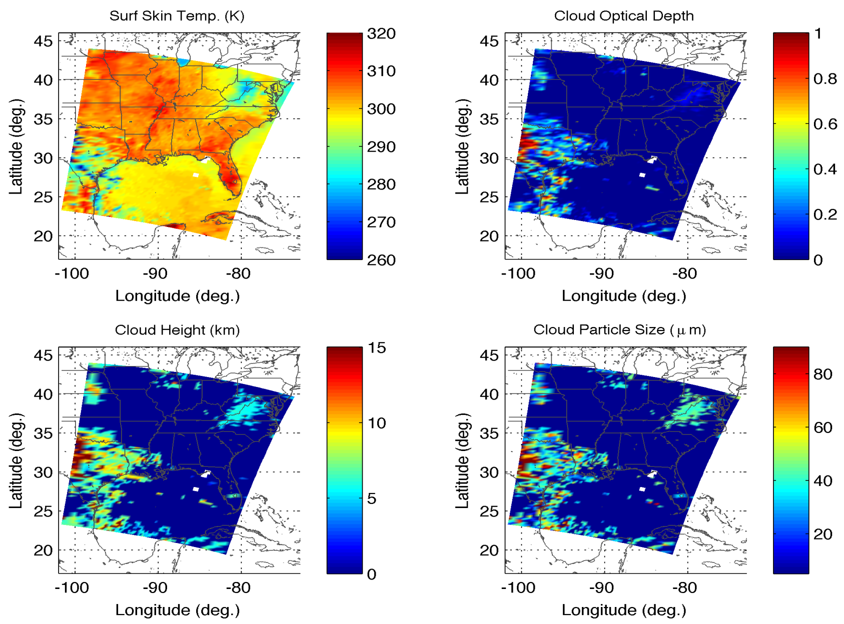


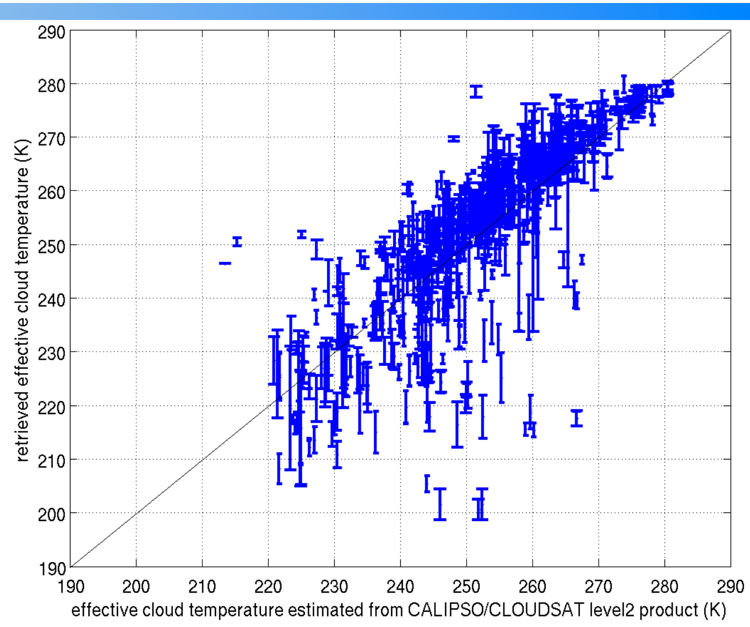


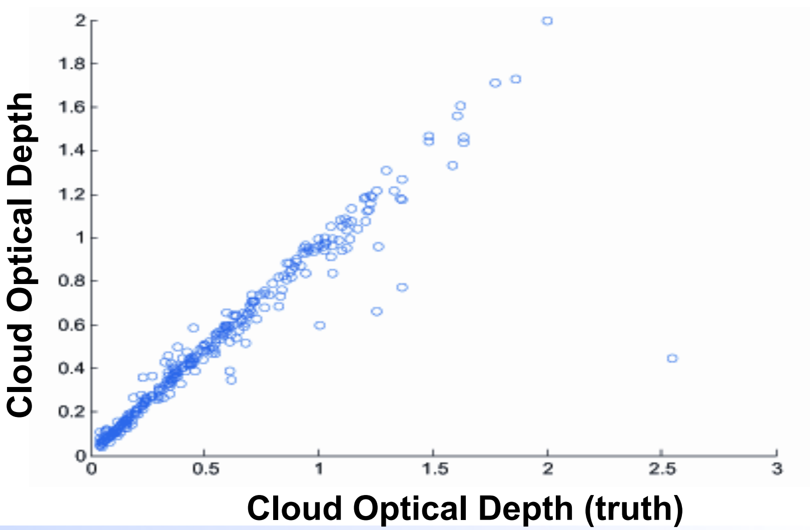


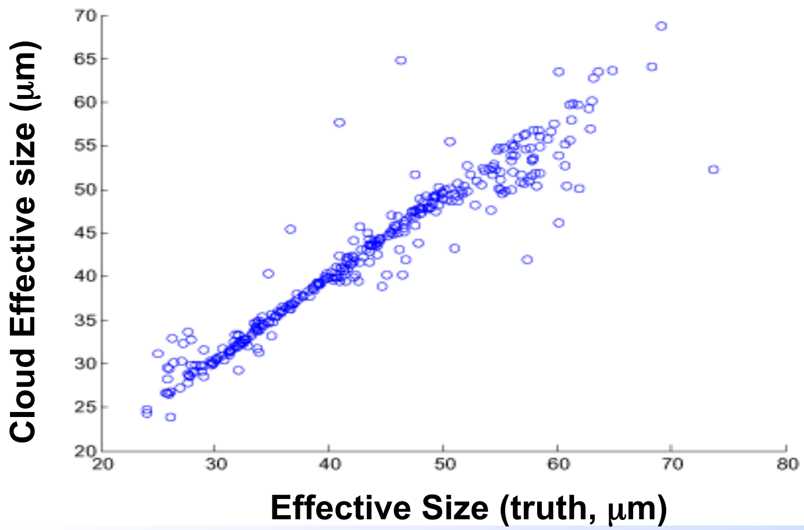


Example of retrieved cloud properties







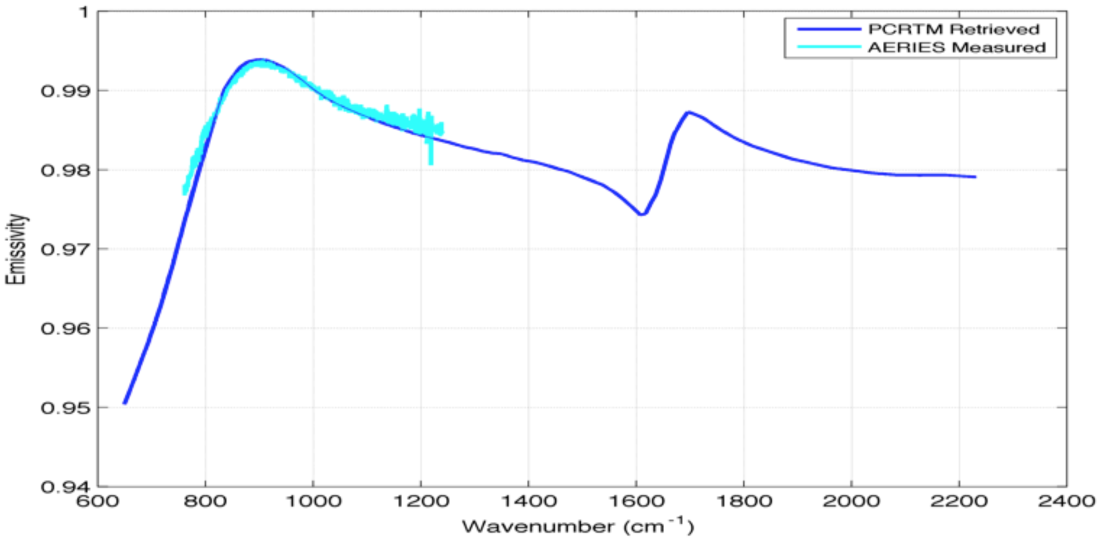


Example of retrieved surface temperature and emssivity and comparison with field validation data

Comparison of PCRTM retrieved surface skin temperature with ARIES measured Tskin

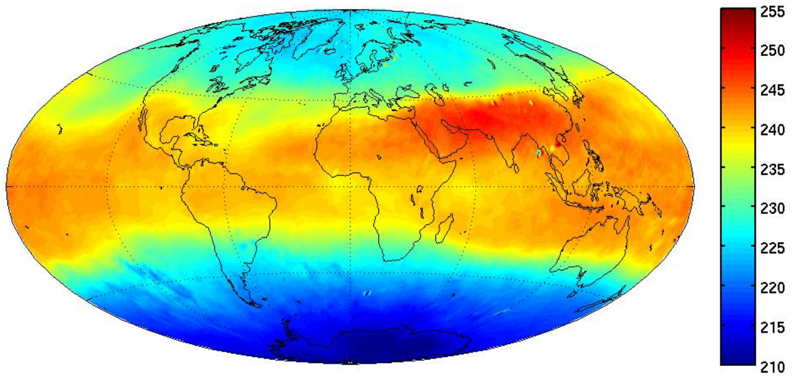
Date	Location	Surface Pressure (hPa)	ARIES Measured skin temperature (K)	IASI-retrieved surface skin temperature (K)
19 April 2007	ARM CART site	972.0	284.7	284.8
29 April 2007	Gulf of Mexico	1021.7	297.8	297.6
30 April 2007	Gulf of Mexico	1017.5	298.6	298.1
4 May 2007	Gulf of Mexico	1009.9	297.4	297.1

Comparison of retrieved ocean emissivity with ARIES aircraft measurements

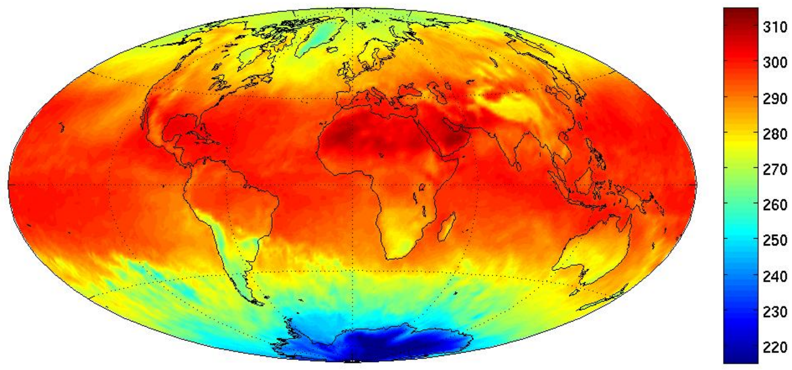


Example of retrieved global distribution of climate related properties retrieved using the PCRTM algorithm

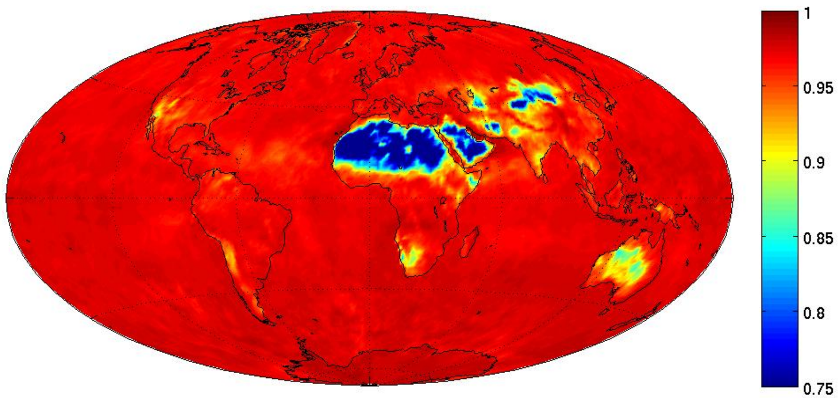
Atmospheric temperature at 9 km for July 2009



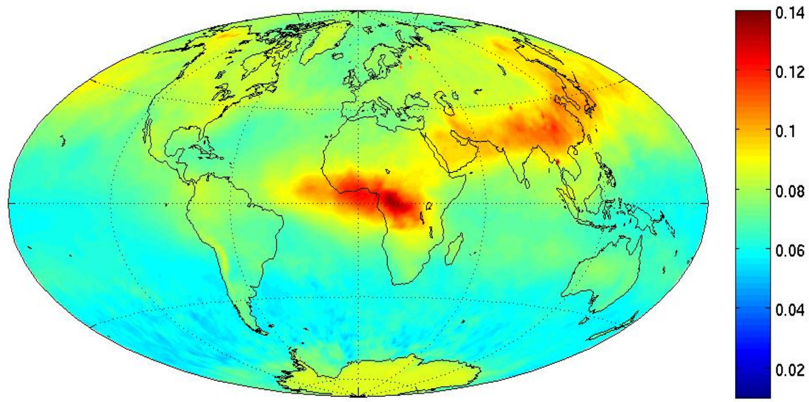
Surface skin temperature for July 2009



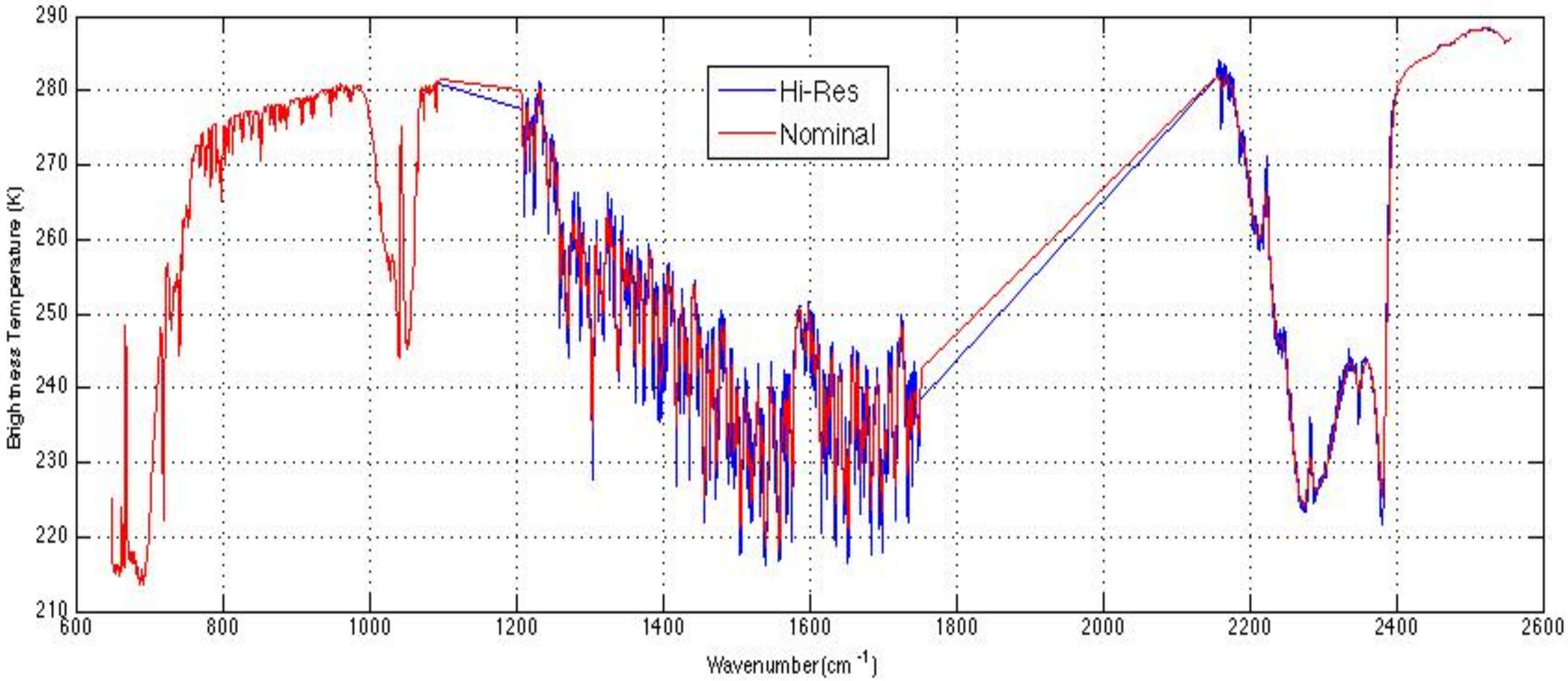
Surface emissivity for July 2009



Atmospheric carbon monoxide mixing ratio for July 2009

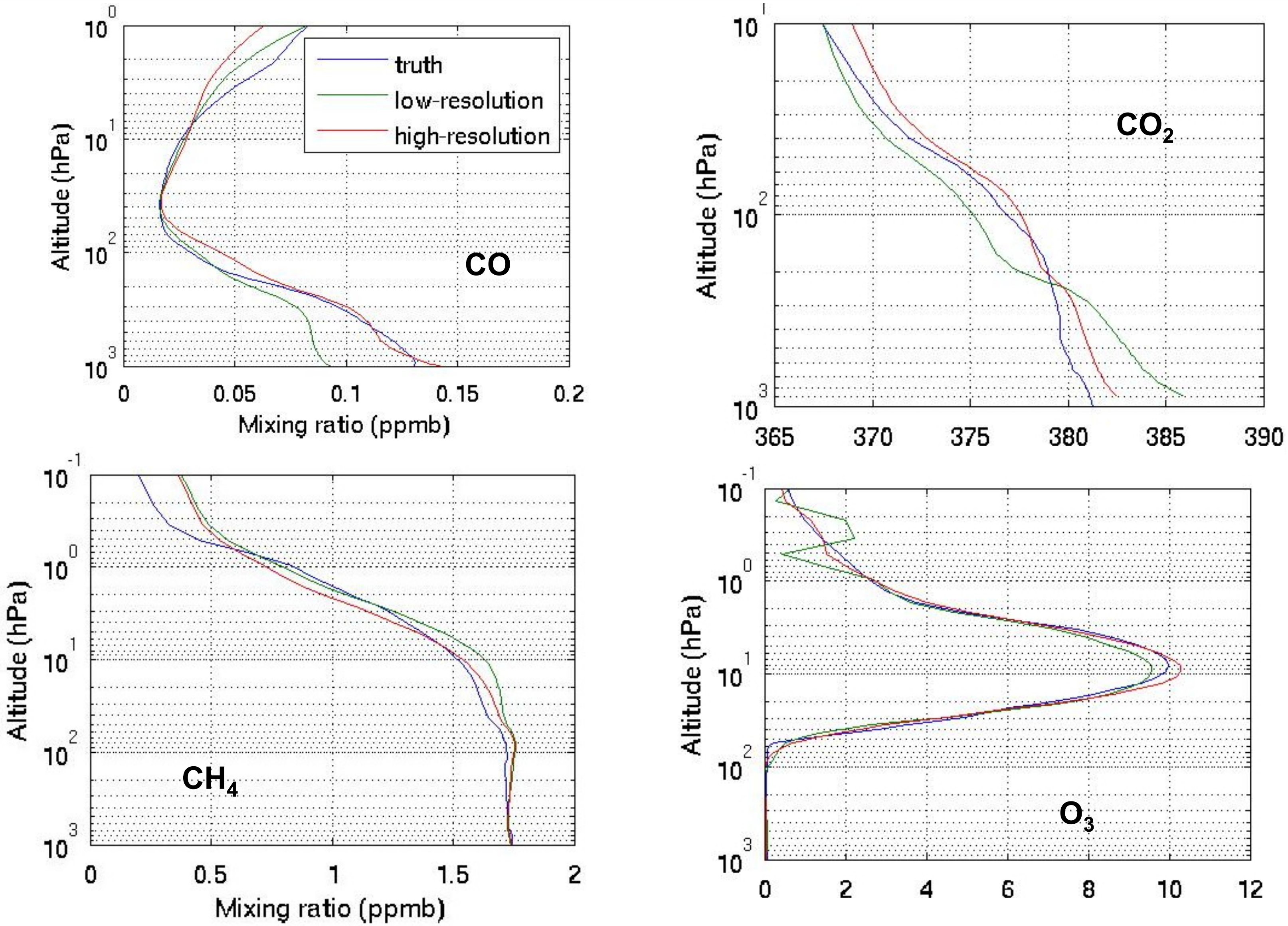


Recent Application of PCRTM to S-NPP CrIS data



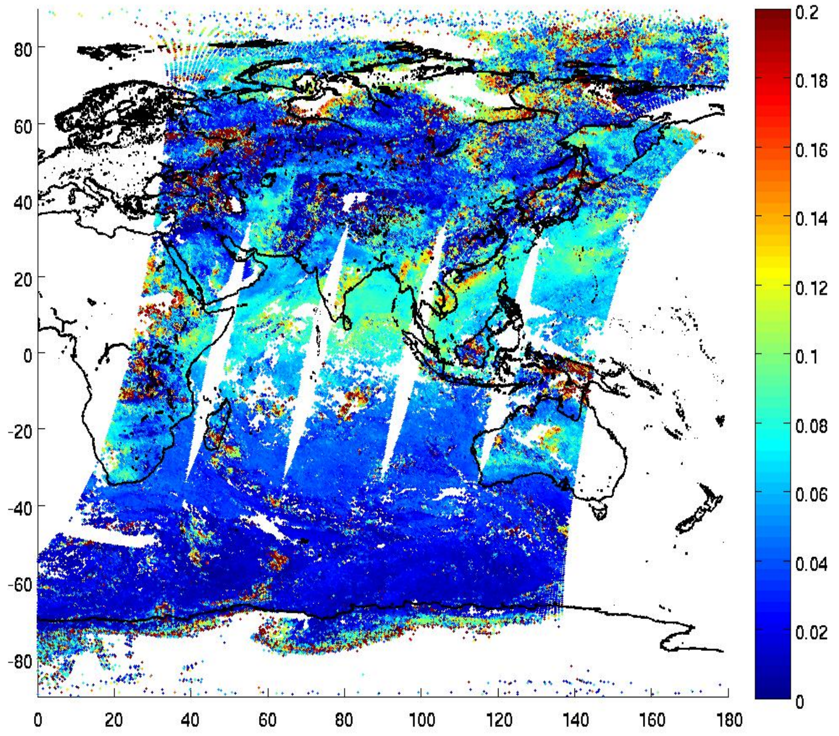
	CrIS (LW)	CrIS (MW)	CrIS (SW)
Nominal Res	0.625 cm^{-1}	1.25 cm^{-1}	2.5 cm^{-1}
High Res.	0.625 cm^{-1}	0.625cm^{-1}	0.625cm^{-}

Trace gas retrievals from CrIS with different spectral resolutions

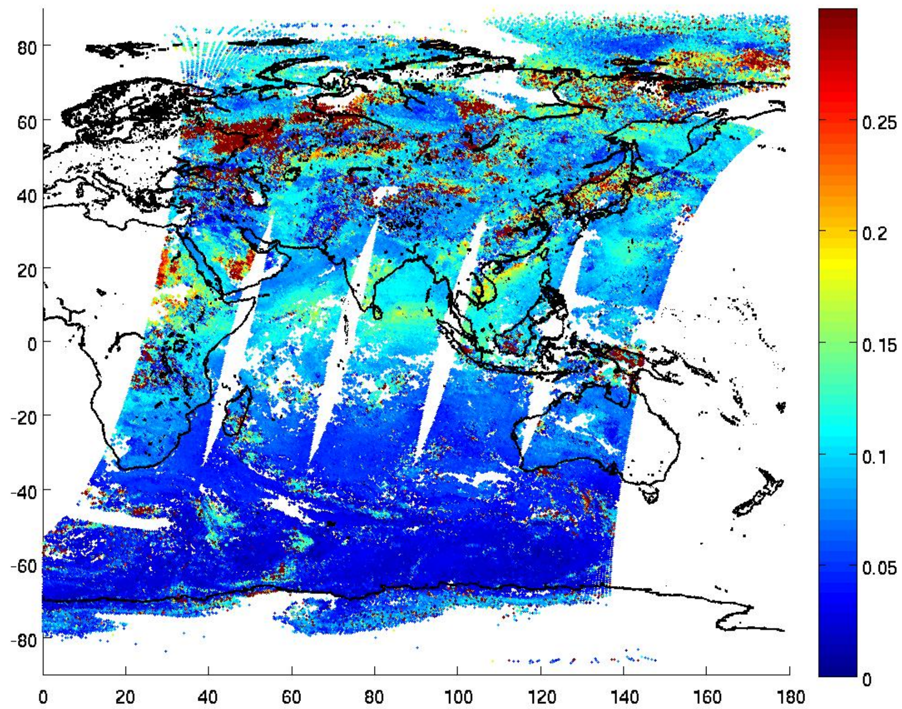


CO retrieved from full-resolution CrIS data

From nominal resolution CrIS



From high resolution CrIS



Summary and conclusions

- Forward model is a key component in analyzing hyperspectral data
  - PCRTM has been developed for numerous satellite and airborne sensors
  - Covers spectral range from 0.31 μm to 200 μm
  - With 15 variable trace gases
  - Multiple scattering clouds included
  - Physical and accurate
  - Very fast relative to LBL and traditional fast RT models
  - Been applied to numerous hyperspectral sensors: AIRS, IASI, CrIS, NAST-I, SCIAMACHY
- PCRTM retrieval algorithm developed to use full spectral information
  - Atmospheric temperature profile
  - Atmospheric water vertical profiles
  - Trace gas profiles,
  - Cloud height, particle size, phase, effective temperature, optical depth
  - Surface properties (Tskin, emissivity …)
- Advantages over existing methods
  - No need to assume the scene inhomogeneity and estimate cloud-clearing error
  - Full multiple scattering effect account for through a fast parameterization
  - Full spectral channels used with all relevant parameters retrieved simultaneously
  - Good error estimate on retrieved variables