Presentation outline

- Motivations
- Approach: Principal Component-based Radiative Transfer Model (PCRTM)
- Examples of PCRTM Applications
- Summary and Conclusions

Motivations

- Radiative Transfer (RT) model is a component in satellite remote sensing
  - $y = F(x, \nu, \theta ....)$
  - Observation System Simulation Experiment (OSSE)
  - Sensor performance end-to-end simulations or sensitivity studies
  - Retrieval and data assimilations
- Line-by-line RT model is too slow
  - Over a million RT needed to cover infrared spectral region
- Traditional Channel-based RT models deal with one channel at a time
  - 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
  - Too slow for climate OSSE
- It is essential to have a RT model
  - Accurate and fast
  - Works in all spectral regions
  - Includes as accurate physics as possible
  - Takes advantage of spectral correlations
  - Can handle cloud and aerosols

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
• GIFTS	1827 x 128 x 128
• FIRST	~1500x10 (or more)
• CLARREO	thousands

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

Approach

- 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
  - Only the first ~50-100 leading eigenvectors are used for optimal fingerprinting
  - 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

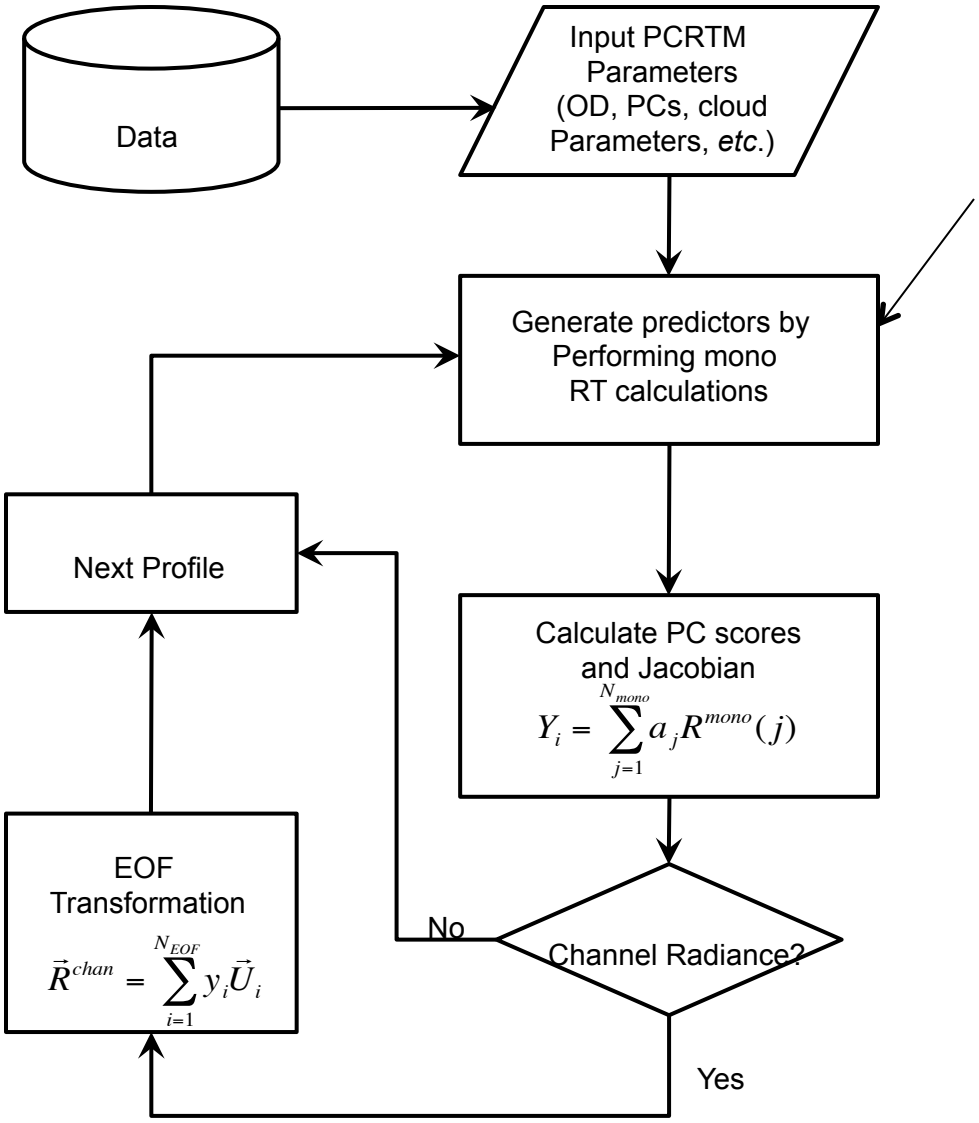
$$y_i = \vec{R}^{ch} \times U_i = \sum_{j=1}^{N_{mono}} \phi_j R_j^{mono} \vec{U}_i = \sum_{j=1}^{N_{mono}} A_j R_j^{mono}$$

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

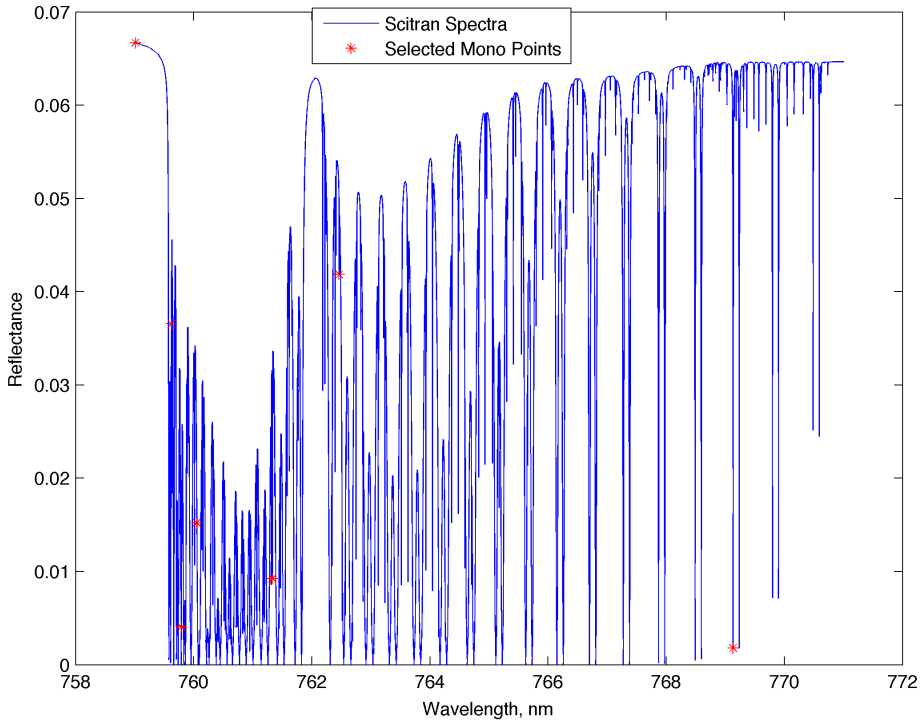
  - Radiative transfer done monochromatically at very few frequencies
  - Very accurate relative to line-by-line (LBL) RT model (< 0.05K or 0.05%)
  - 3-4 orders of magnitude faster than LBL RT models
  - A factor of 2-100 times faster than channel-based RT models
  - Provide Jacobian or radiative kernel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

How does PCRTM work?

Flow diagram of the PCRTM forward model



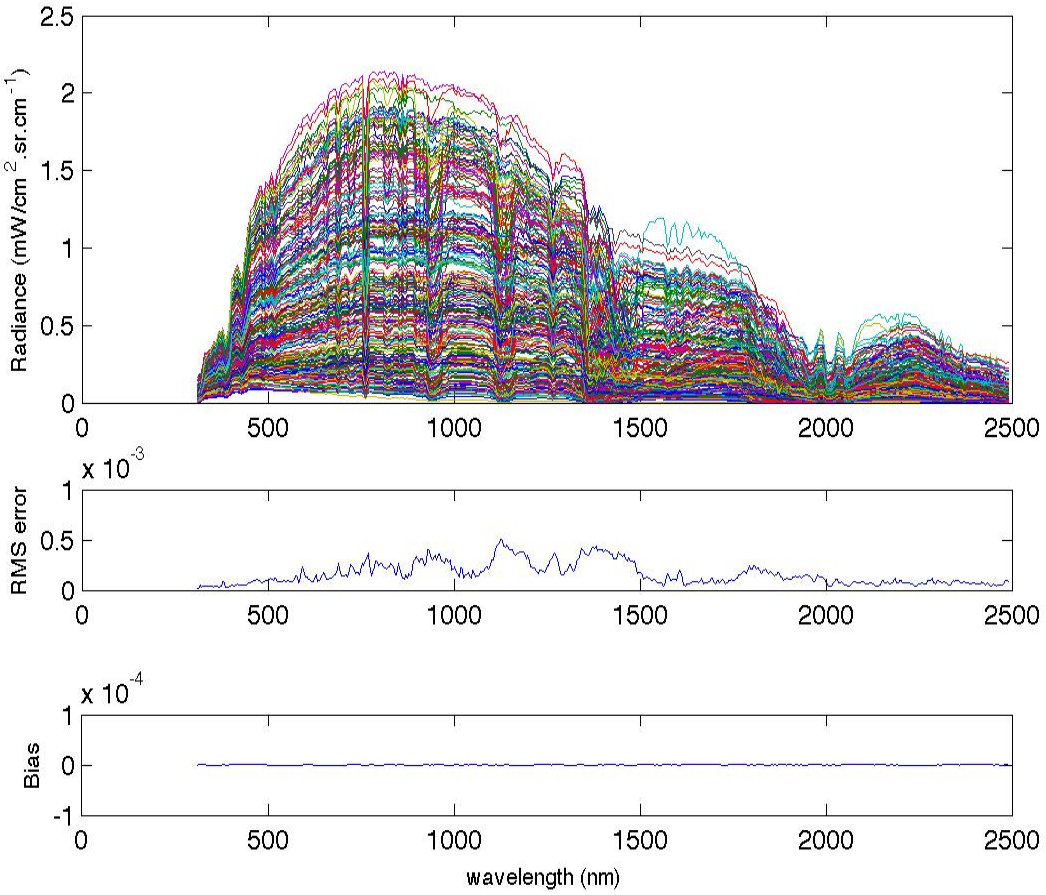
- Regular Monochromatic RT performed
  - This function can be performed by LBL, MODTRAN…
  - Can use lookup table and fast parameterization if needed
- RT needs to be done at minimum number of frequencies
  - Orders of magnitude smaller than LBL and MODTRAN

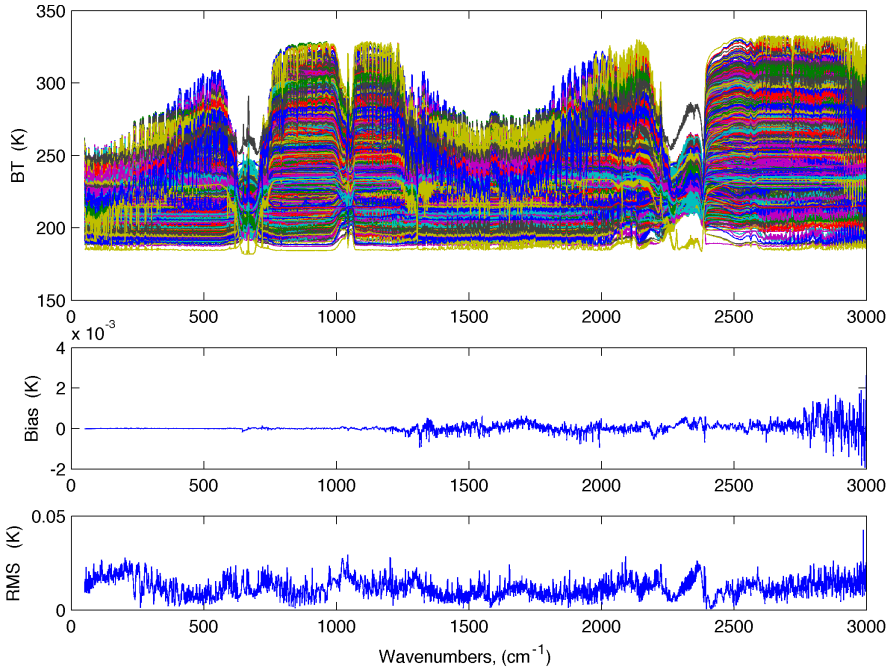


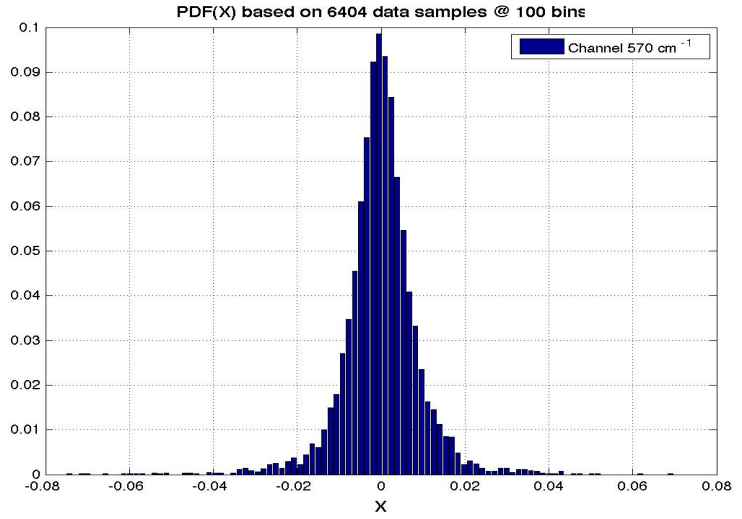
- O_2 A-band (12000 mono RT calculations using LBL)
- Only 7 Mono frequencies are essential when modeling at the OCO and SCIAMACHY spectral resolution

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 < 5E-4 mW/cm^2/sr/cm^{-1} for solar (<0.2%)







Very Fast computation speed for PCRTM

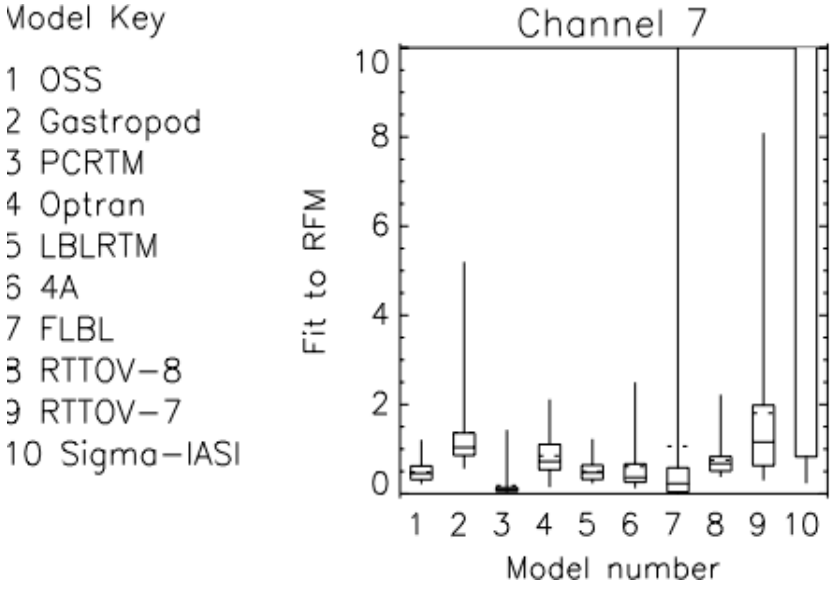
- **Milliseconds to fraction of seconds for IR, fraction of second to seconds for sola**
- **CrIS, CrIS-full-res, IASI, NAST-I and S-HIS have multiple databases corresponding to different ILS**
- **Spectral converage from 310 nm to 200000 nm**

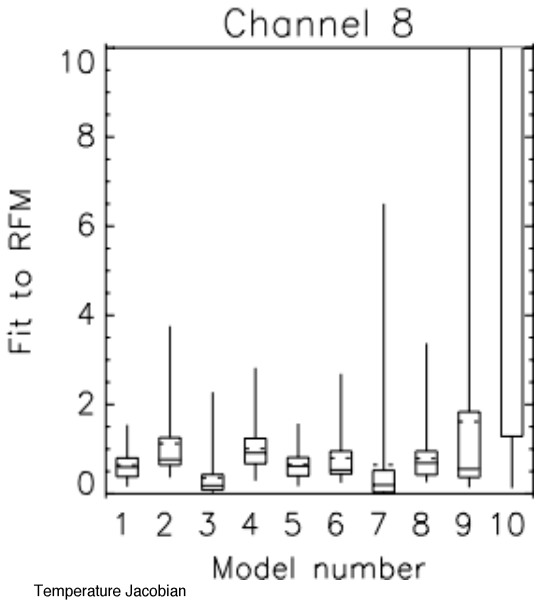
Sensor	Channel Number	PC score (seconds)	PC score + Channel radiance	PC score + PC Jacobian
CLARREO, 0.1 cm^{-1}	19901	0.014 s	0.022 s	0.052 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s	0.013 s	0.039 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s	0.012 s	0.036 s
IASI, 0.25 cm^{-1}	8461	0.011 s	0.012 s	0.044 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s	0.0074 s	0.031 s
CrIS, Blackman, 0.625-2.5 cm^{-1}	1317	0.0050 s	0.0060 s	0.021 s
CrIS, Boxcar, 0.625-2.5 cm^{-1}	1317	0.0050 s	0.0060 s	0.022 s
CrIS, Hamming, 0.625-2.5 cm^{-1}	1317	0.0050 s	0.0058 s	0.022 s
NAST-I, 3 bands, 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, Hamming Full resolution	2211	0.009 s	0.009 s	0.033 s

	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
Oc/ld 10 nm	109	3079	28

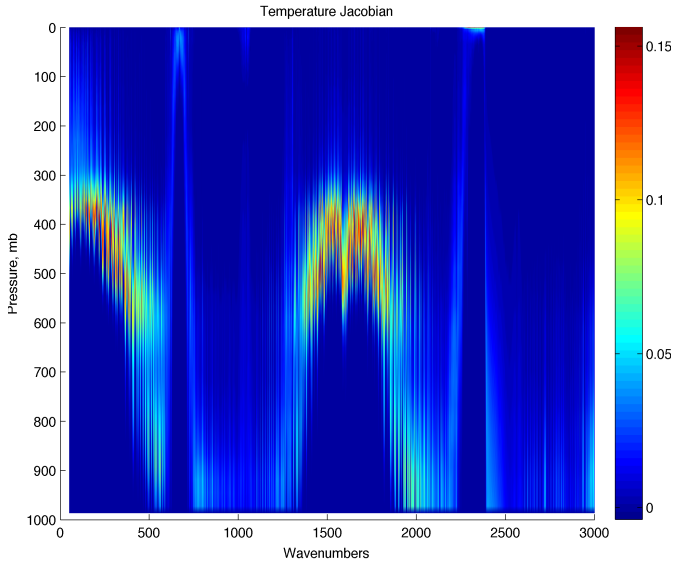
Example of Jacobian from PCRTM

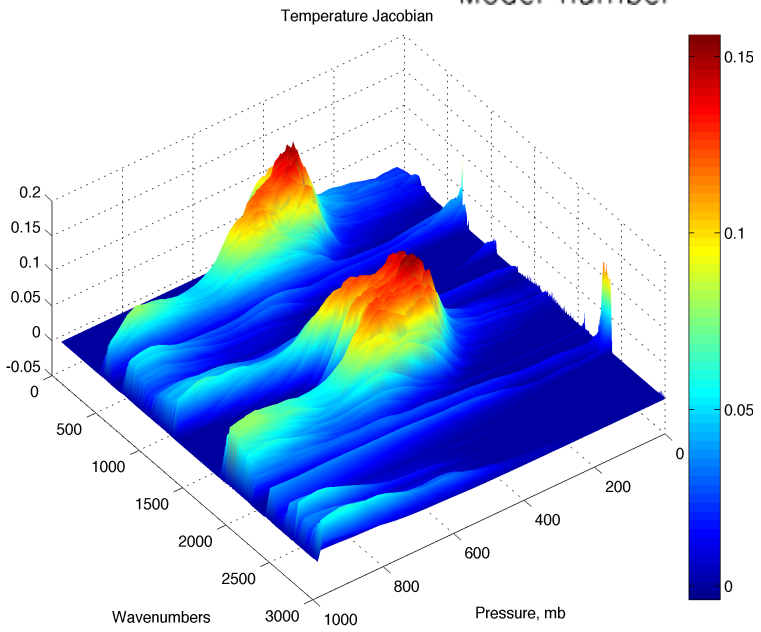
- Comparison of ozone Jacobian from different models (*Saunders et al. JGR, 2006*)



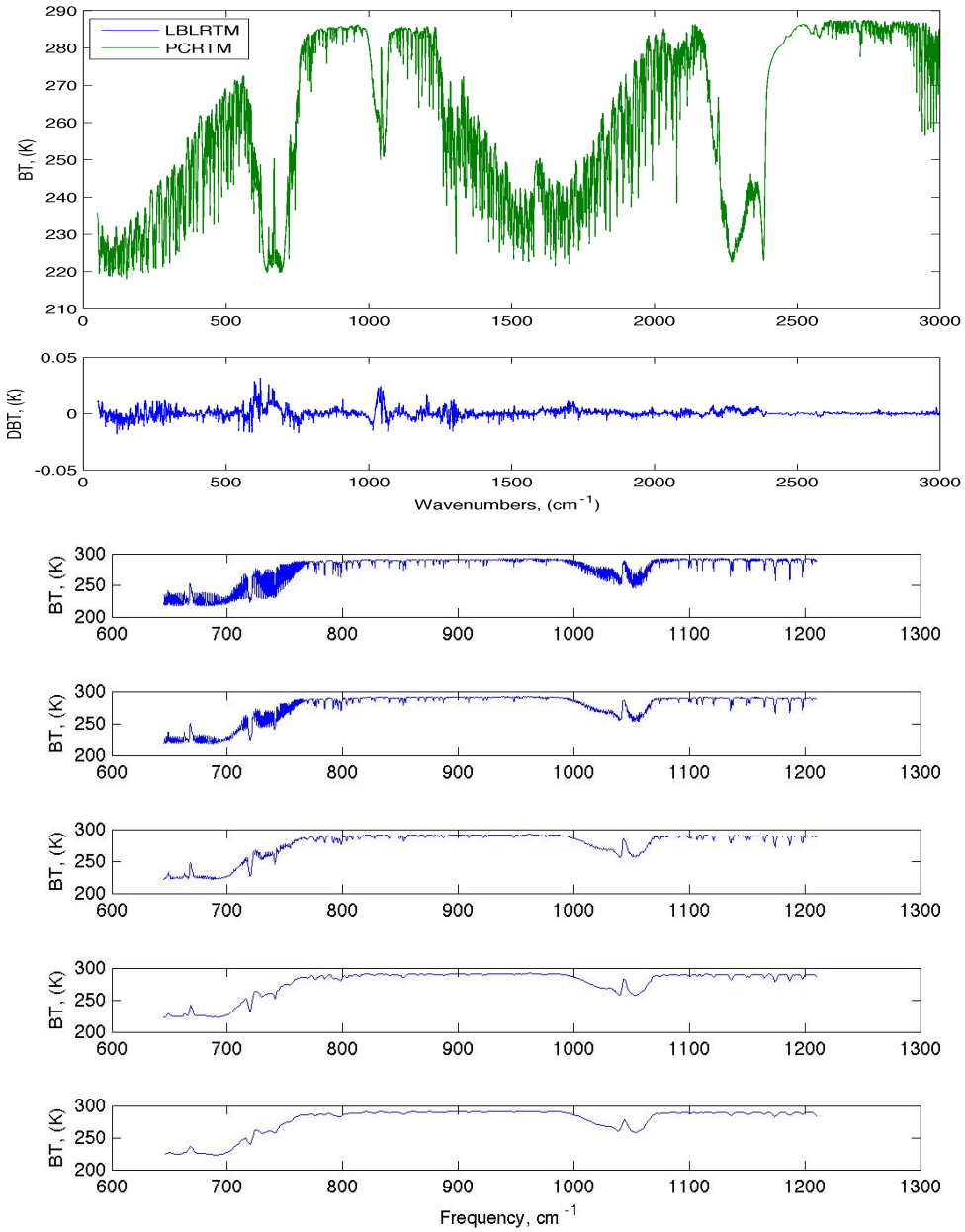


- Temperature Jacobian calculated from PCRTM (see Brian's talk for details)

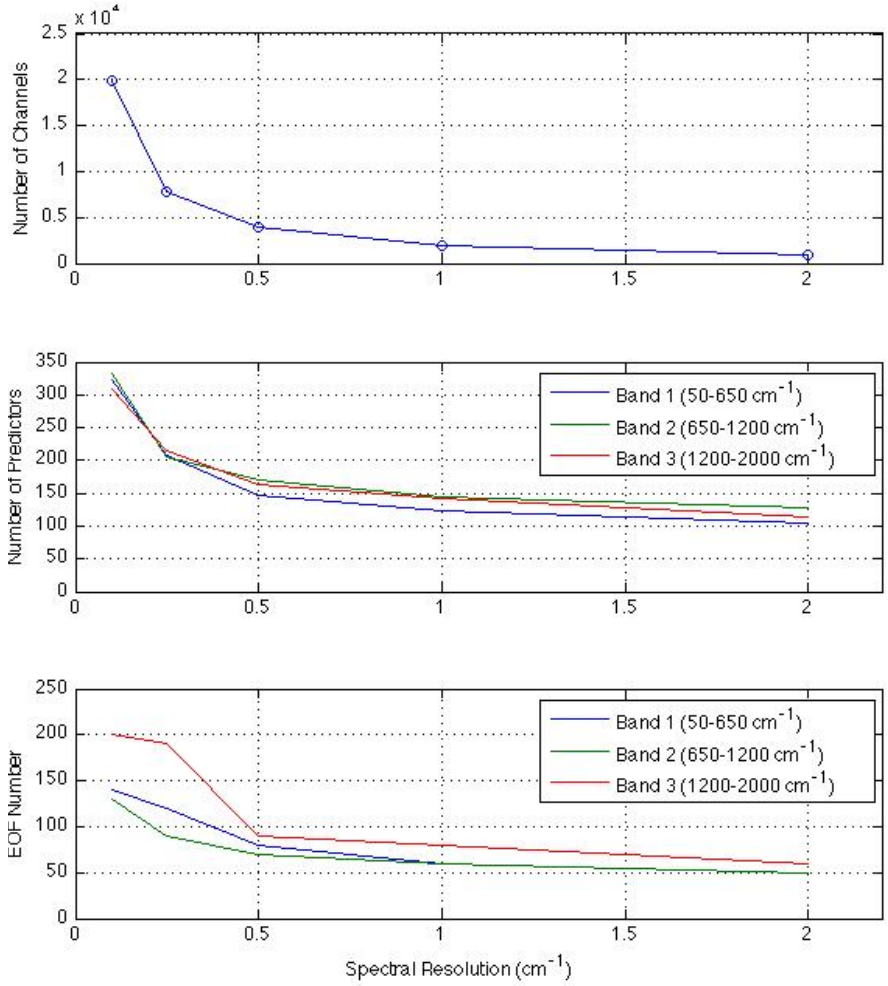




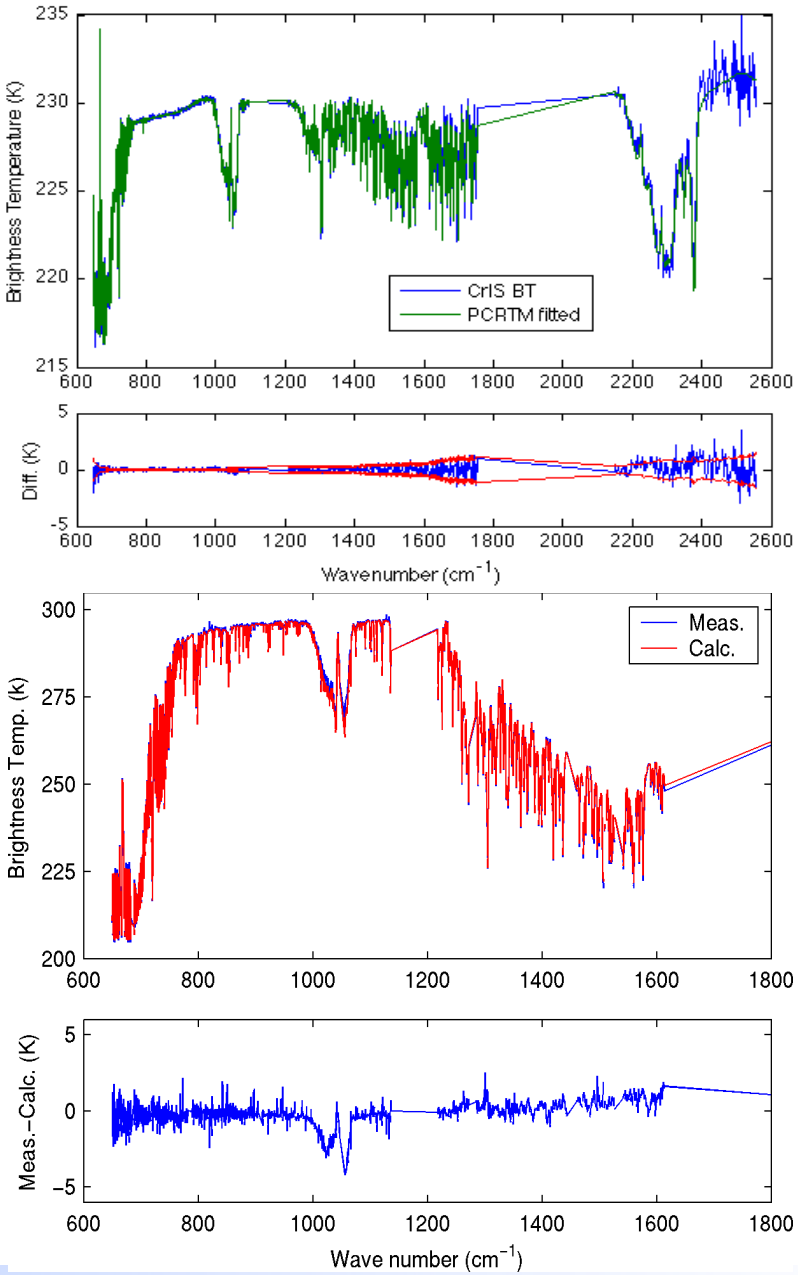
Examples of CLARREO PCRTM in IR spectral region

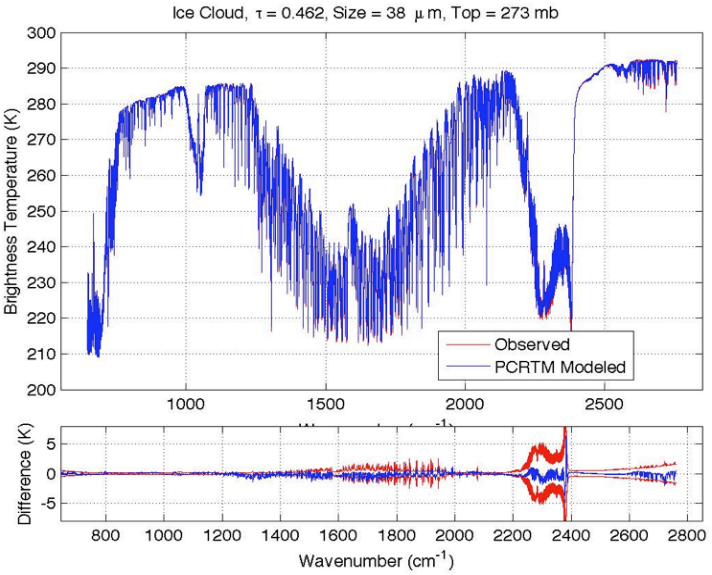


- 0.1 cm^{-1}, 0.25 cm^{-1}, 0.5 cm^{-1}, 1.0 cm^{-1}, and 2.0 cm^{-1}
- 0.1 cm^{-1} model can be used to generate lower spectral resolution instrument forward models
- Reduce >1 million mono RT to < 1000
- EOF and mono numbers decrease with resolution



PCRTM has been successfully used on real hyperspectral data (CrIS, IASI, AIRS, NAST-I)

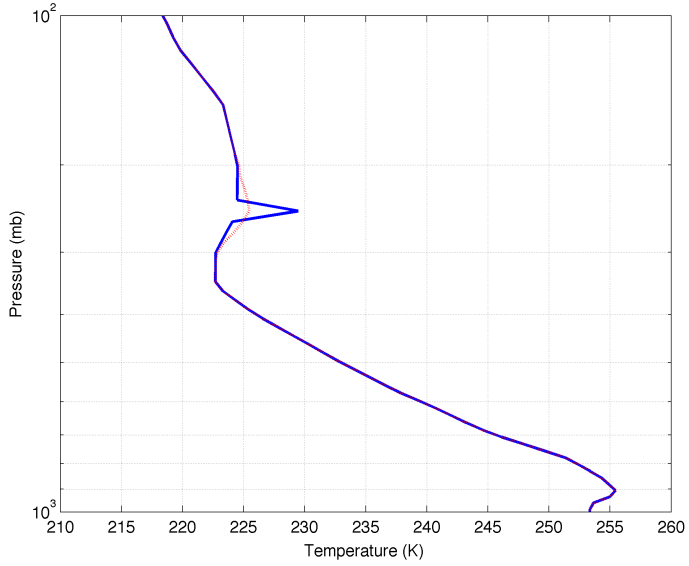


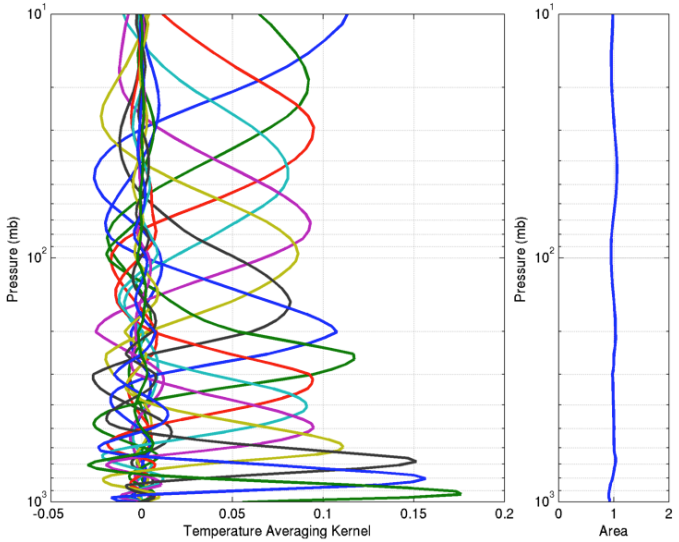


PCRTM has been successfully trained for

- Metop-A IASI
- NASA Aqua AIRS
- Suomi NPP CrIS (unapodized and apodized)
- NAST-I (NASA airborne instrument)
- CLARREO IR (50-3000 cm^{-1}, 0.1-2.0 cm^{-1} resolution)
- CLARREO Solar (300-2500 nm, 4 nm resolution)

CLARREO Information Content Analysis (methodology)



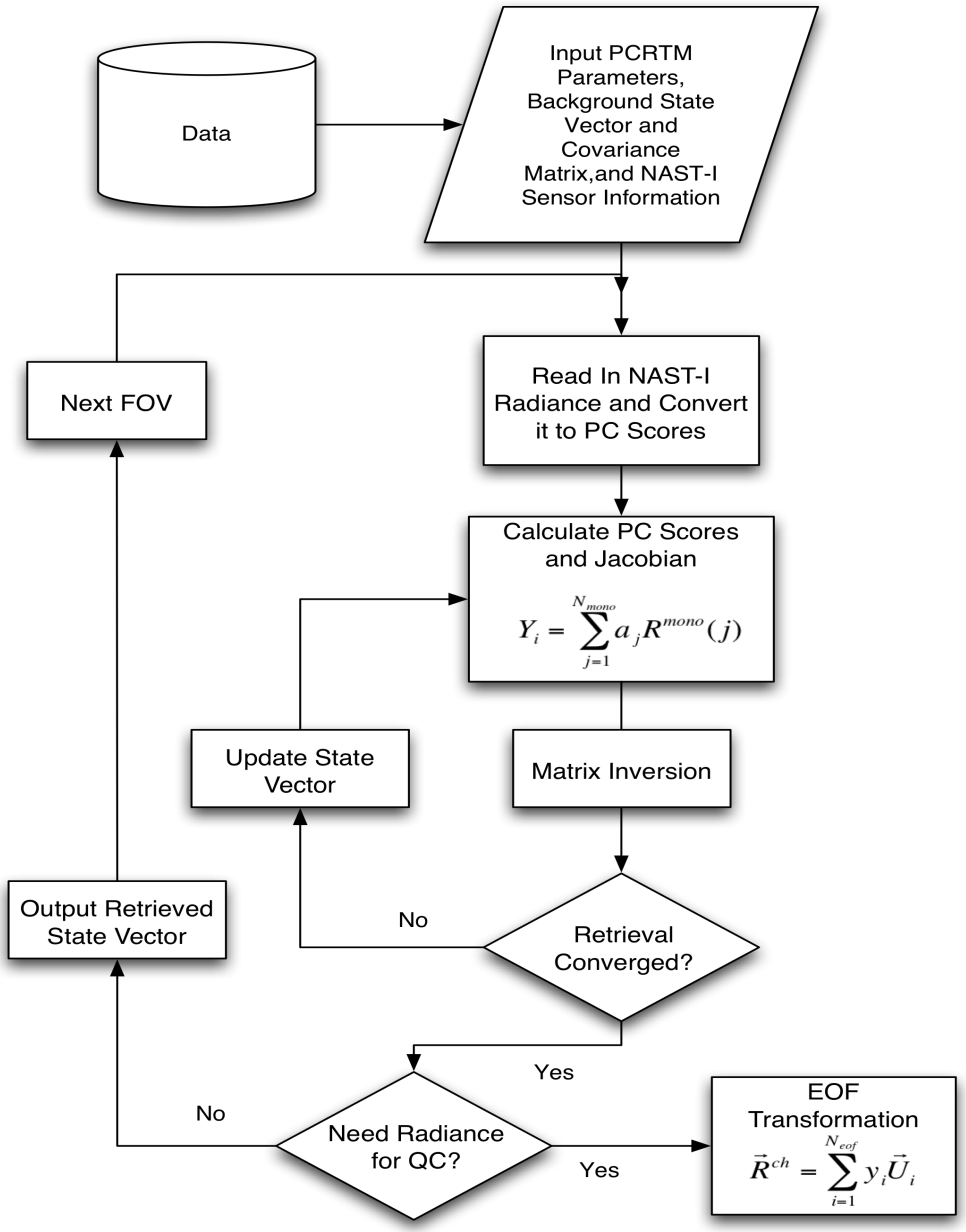


$$A_x = \frac{\partial x_n}{\partial x} = (K^T S_y^{-1} K + S_a^{-1})^{-1} K^T S_y^{-1} K$$

$$H_x = -\frac{1}{2}\sum_i \ln\left|I - A_x\right|, \quad d_x = tr(A_x)$$

- Averaging kernel provide information on retrieval system
  - Location and magnitude of the peaks relate to information at a particular height
  - Width of the peaks relate to vertical resolution
  - Integrated area of the averaging kernel provides relative contribution from a priori and measurements
  - Trace of A_x provides degree of freedom
- Averaging kernel is profile dependent
  - Generate CLARREO spectra with hundreds of atmospheric profiles
  - Probability Density Function (PDF) or mean of the A_xFor different instrument configurations (K)
    - Different noise (S_y)
    - Different spectral resolution (K)
    - Different band coverage (K)
    - With and without Far IR band (K)

A brief description of the PCRTM cloud retrieval algorithm



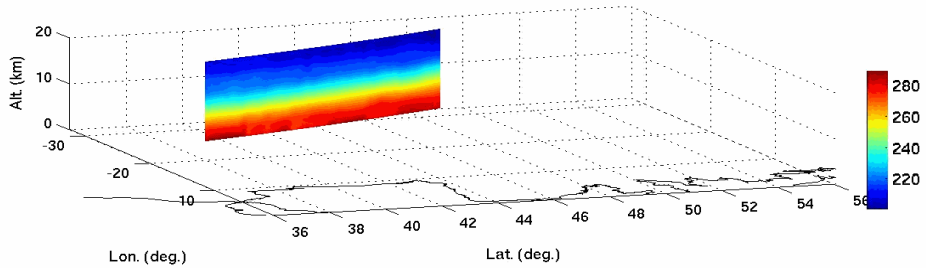
$$X_{n+1} - X_a = (K^T S_y^{-1} K + \lambda I + S_a^{-1})^{-1} K^T S_y^{-1} [(y_n - Y_m) + K(X_n - X_a)]$$

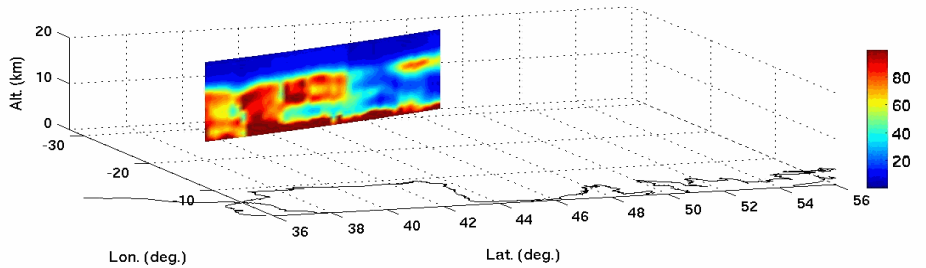
- PCRTM models PC scores directly
  - Small matrix and vector dimensions
  - All 8000 channels from IASI and NAST-I used
- Both y and x vectors are in EOF domain
  - Small matrix and vector dimensions
  - 100 super channels instead of thousands of channels
  - Simply minimizing cost function
  - Channel-to-channel 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

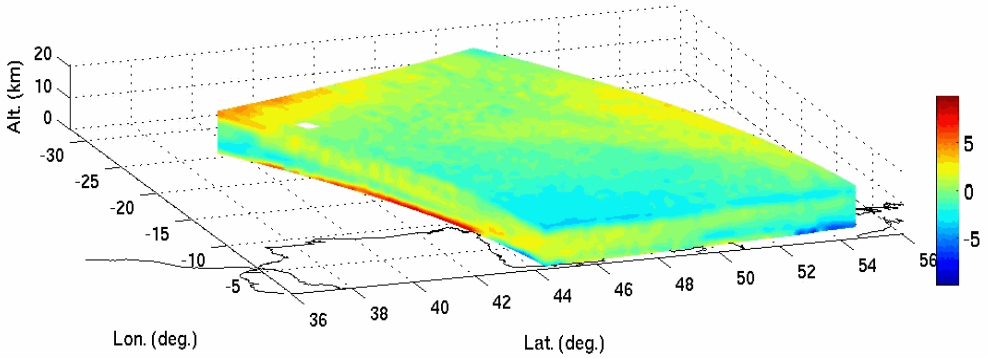
Retr. Config/ Matrix Dimension	Radiance/ Profle	Subset Radiance/ Profile	Radiance PC/ Profile PC
Y	~8400	300	100
X	100	100	41
K	8400x100	300x100	100x41
S_y^{-1}	8400x8400	300x300	100x100
S_x	100x100	100x100	41x41

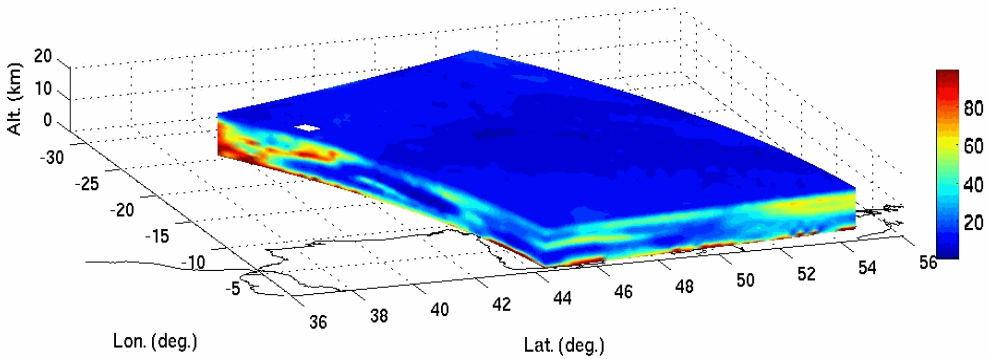
Example of retrieved atmospheric parameters from IASI data

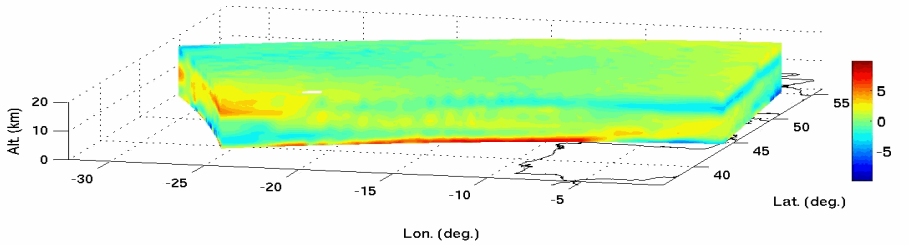
- 3 movies showing IASI temperature and moisture cross-sections on 11/04/2007 over Anglet France
  - T and H_2O as a function of altitude
  - T and H_2O along satellite track
  - T and H_2O x-track
- Note fine atmospheric features capture
- Coherent spatial features

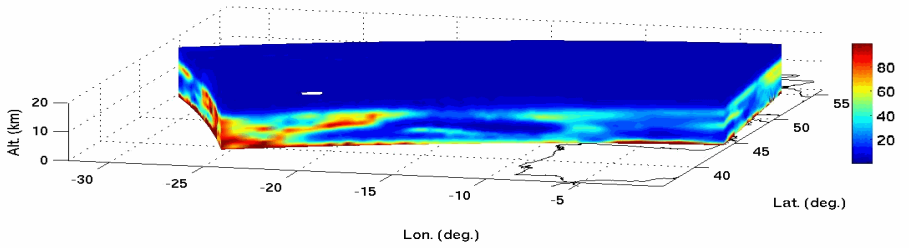






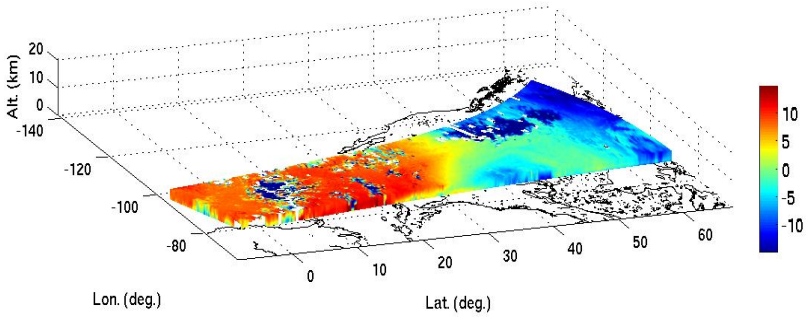


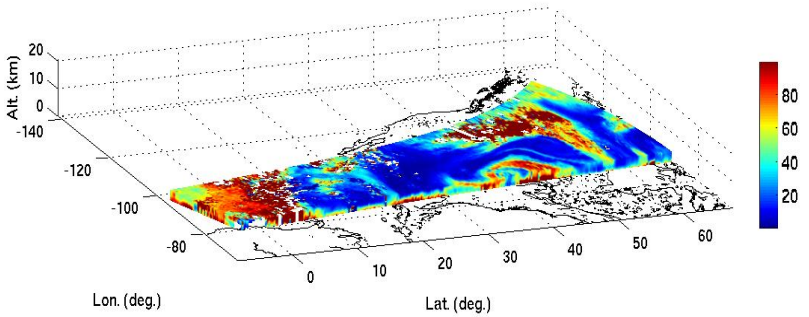


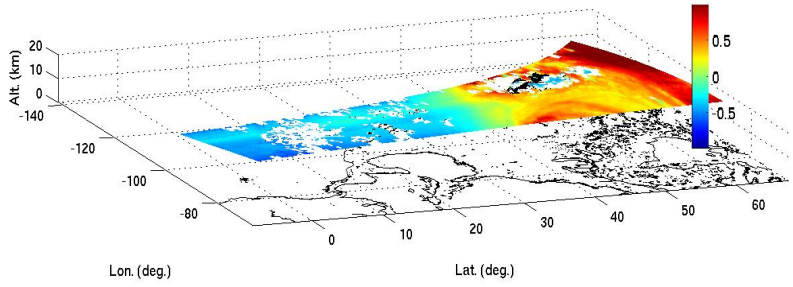


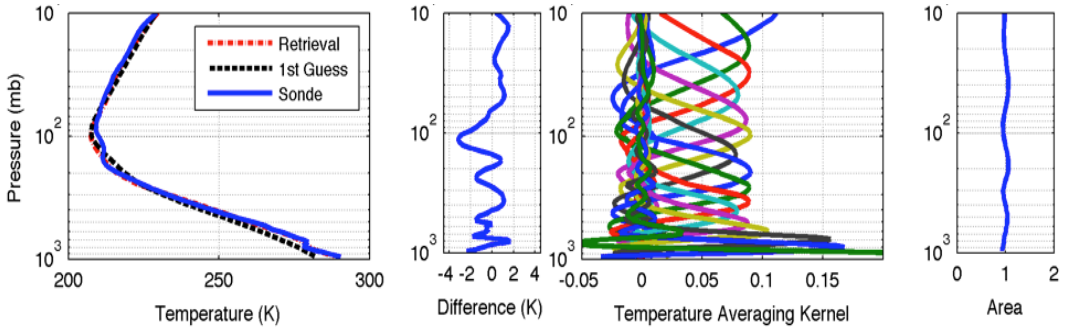
Comparison of PCRTM retrieval with radiosondes

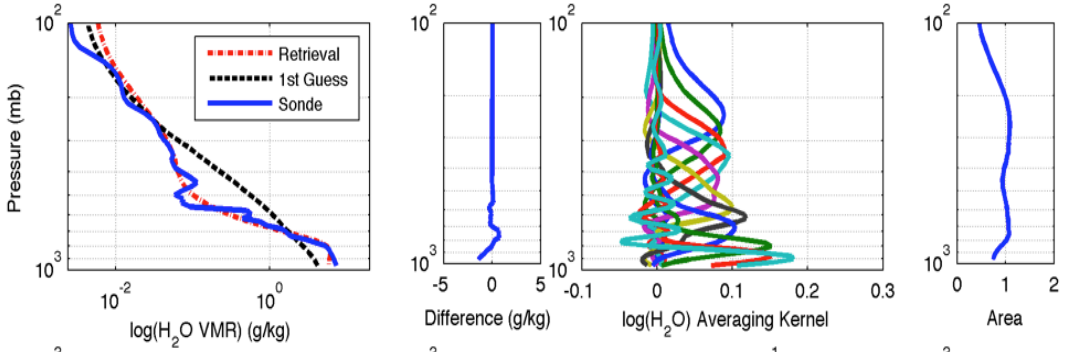
- Temperature, moisture, and ozone cross-sections
- Plots are deviation from the mean
- Fine water vapor structures captured by the retrieval system
- A very cloudy sky condition

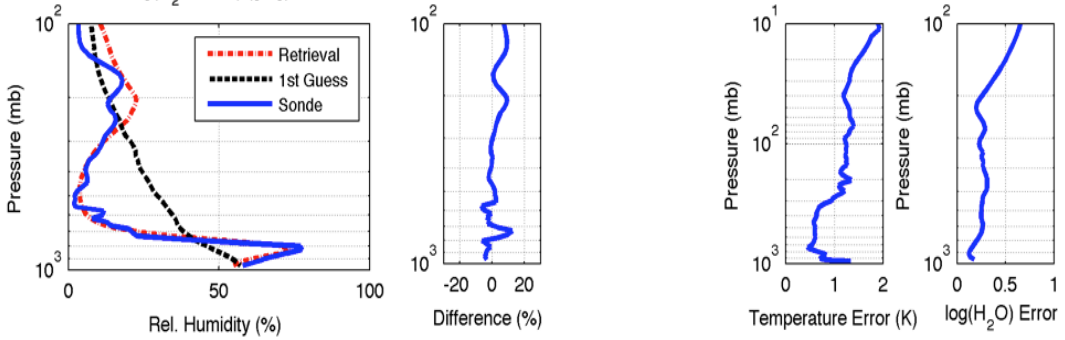




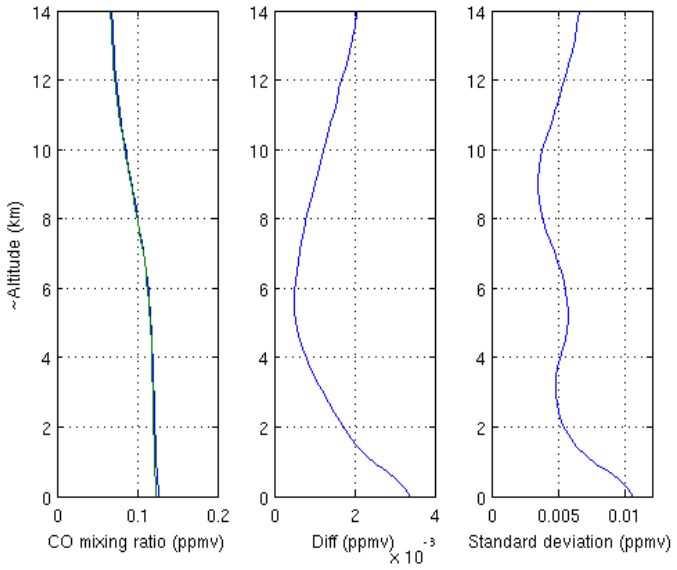


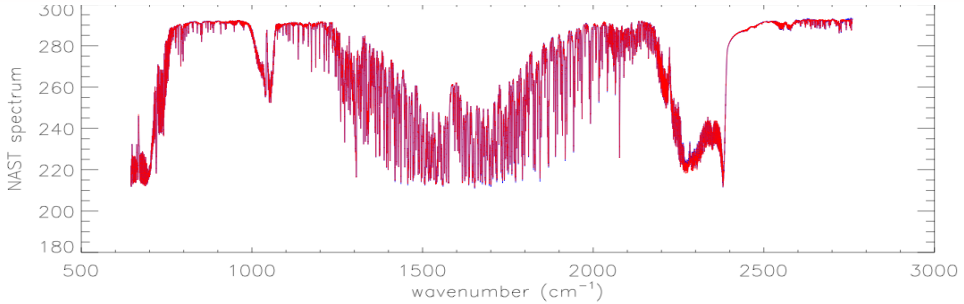


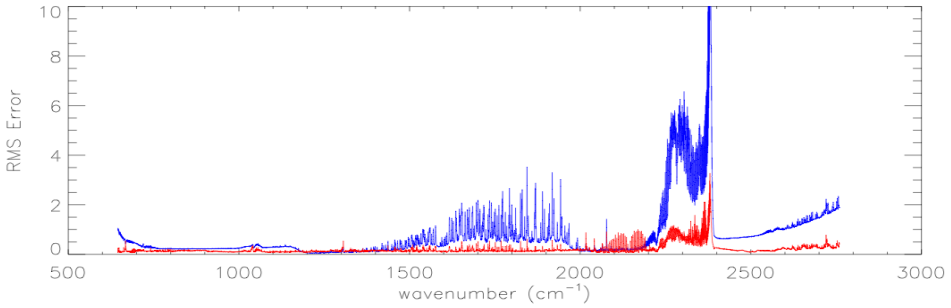


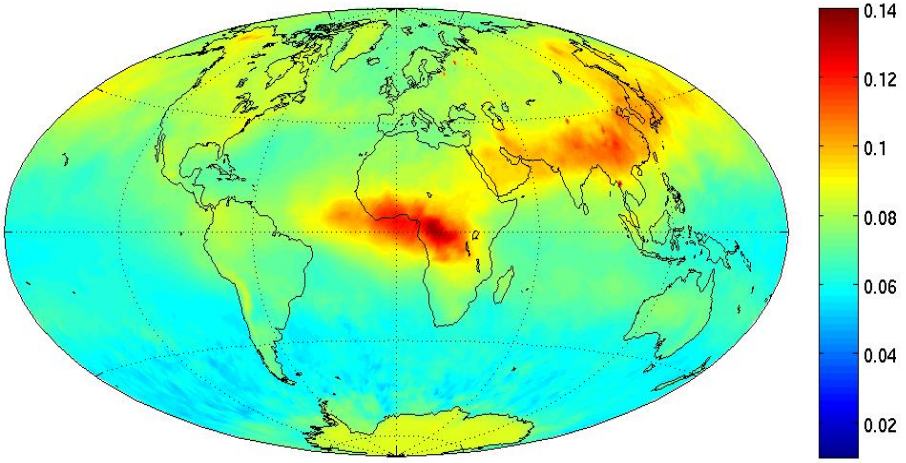


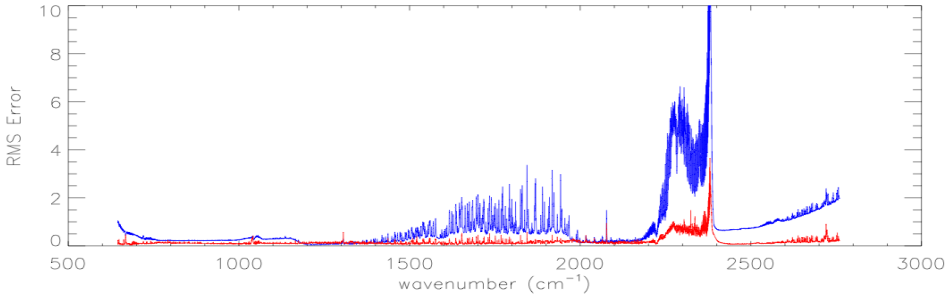
Example of trace gas retrievals (CO retrieval sensitivity study and global CO retrieved from real IASI data





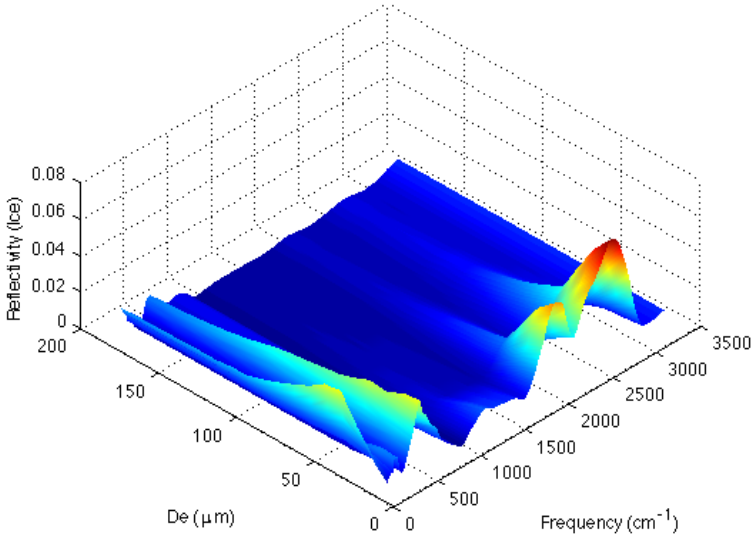


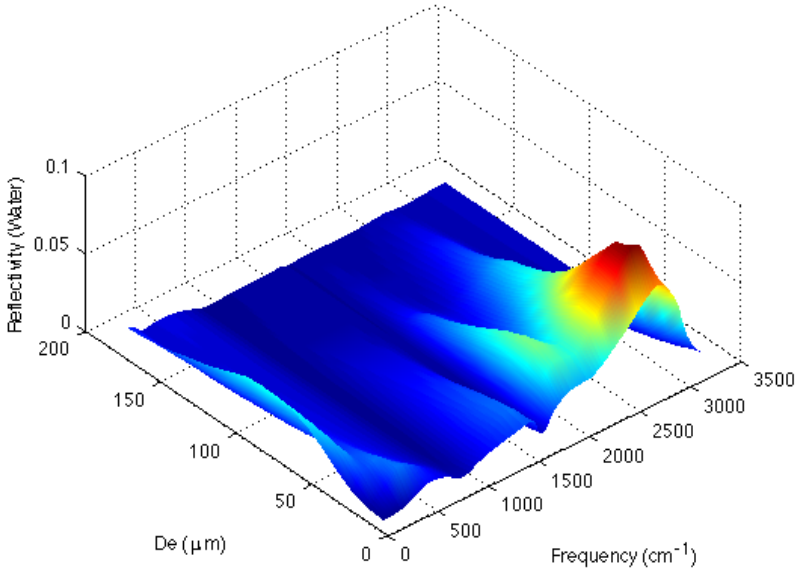


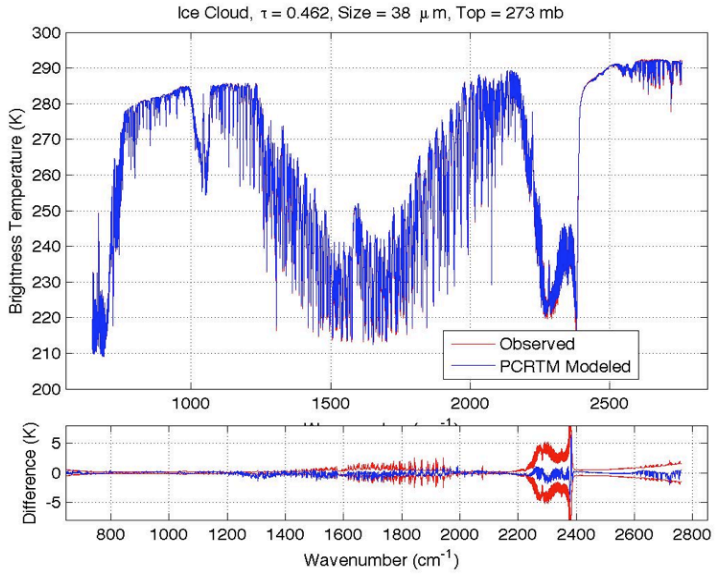


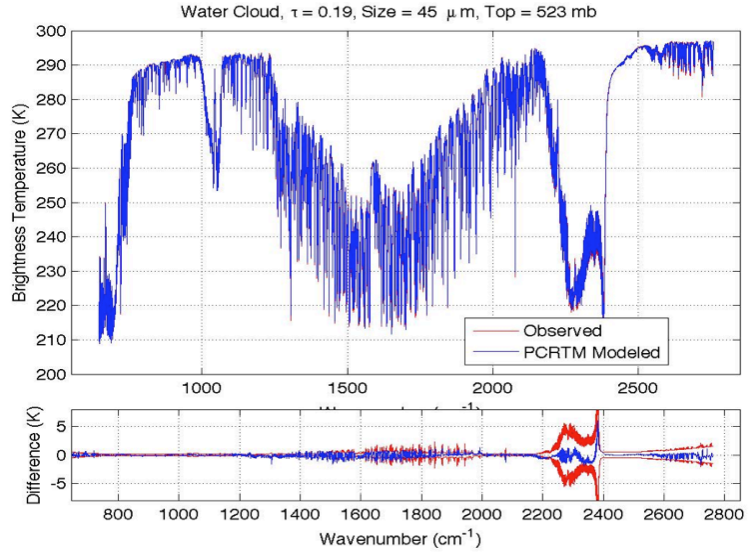
- Notice that the feature near 2020-2250 cm-1 are removed when CO profile is explicitly retrieved in the inversion algorithm

Effective cloud transmissivity and reflectivity are good ways to model clouds

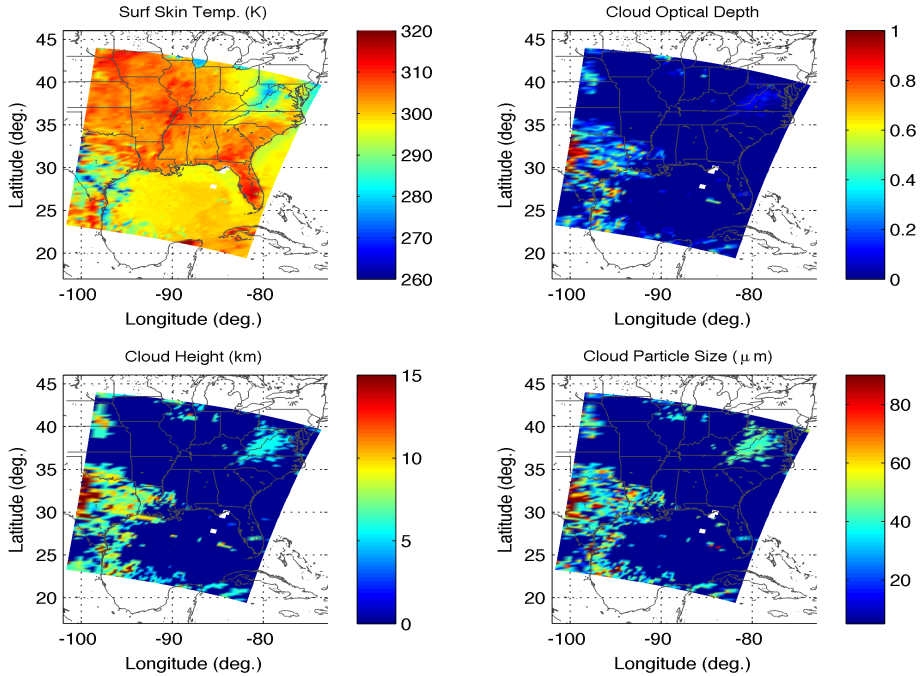


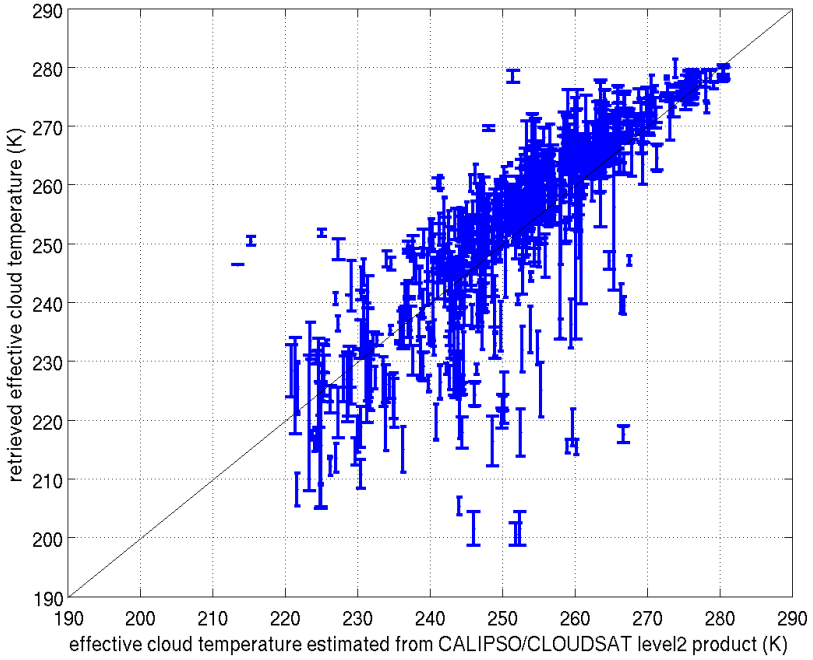


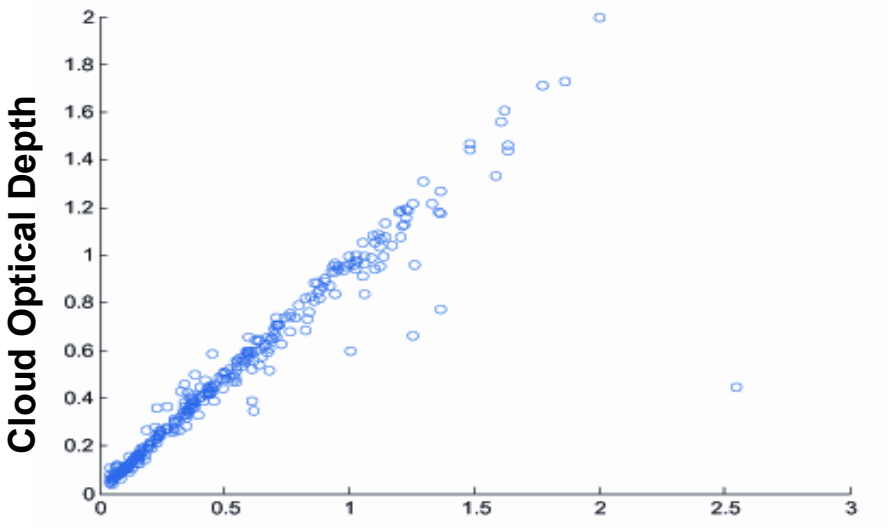


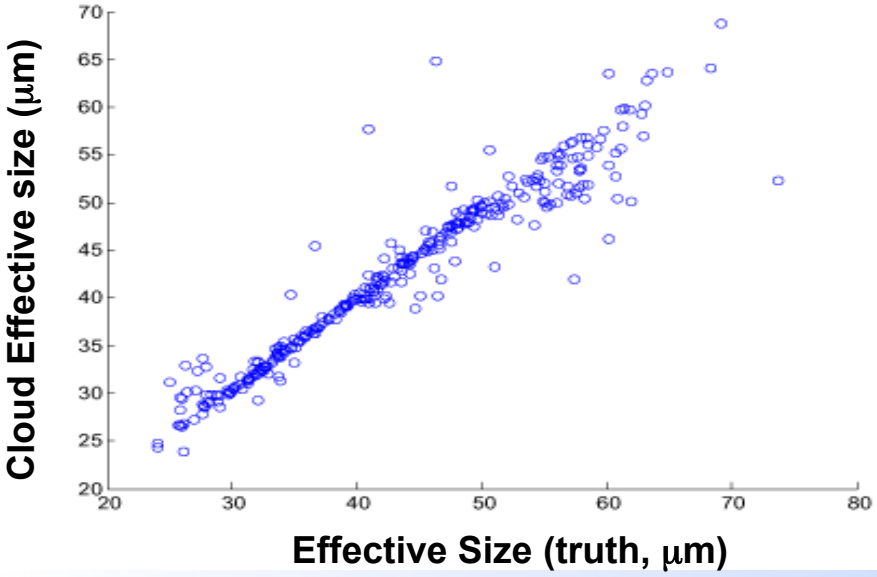


Example of retrieved cloud properties



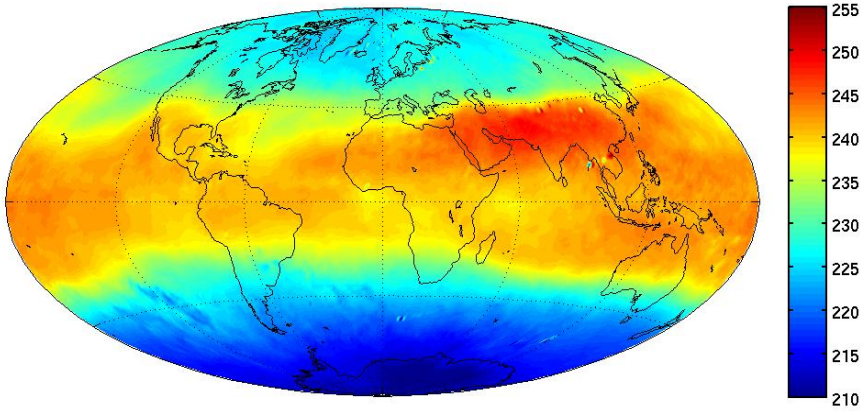




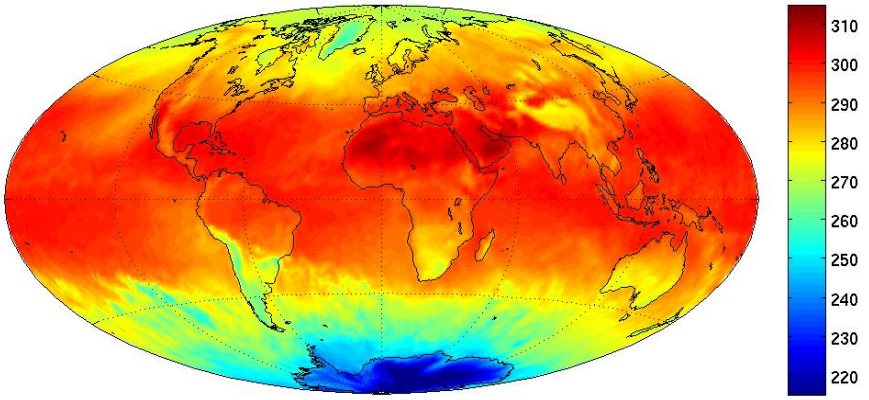


Example of retrieved global distribution of climate related properties retrieved using the PCRTM algorithm

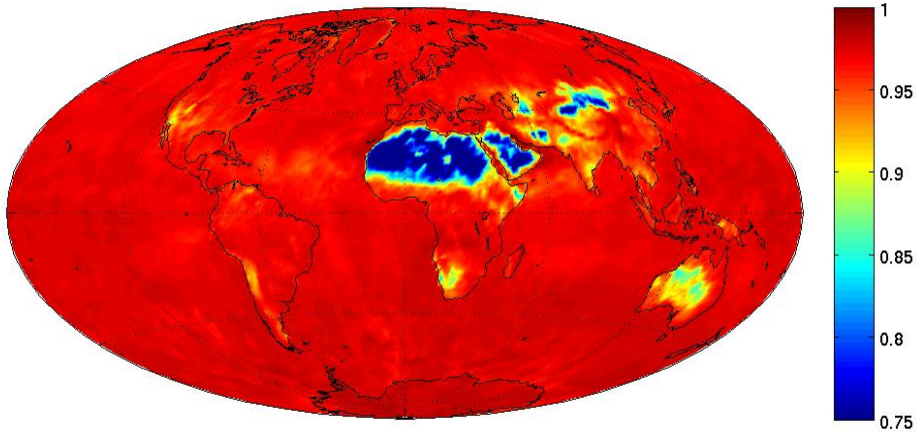
Atmospheric temperature at 9 km for July 2009



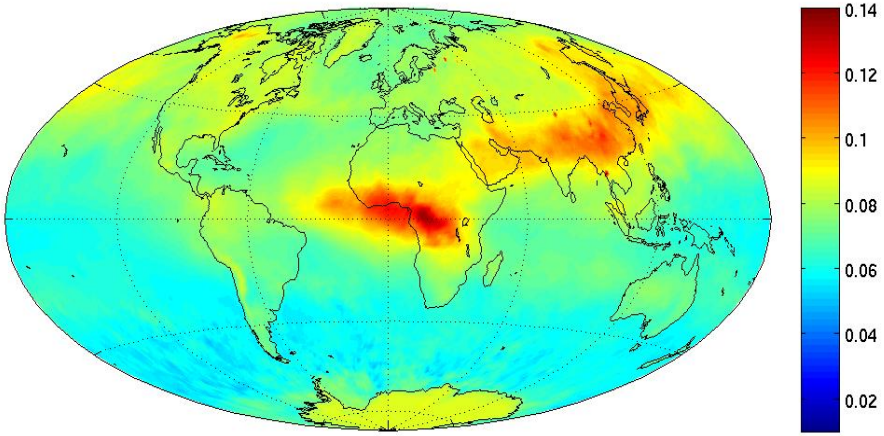
Surface skin temperature for July 2009



Surface emissivity for July 2009



Atmospheric carbon monoxide mixing ratio for July 2009

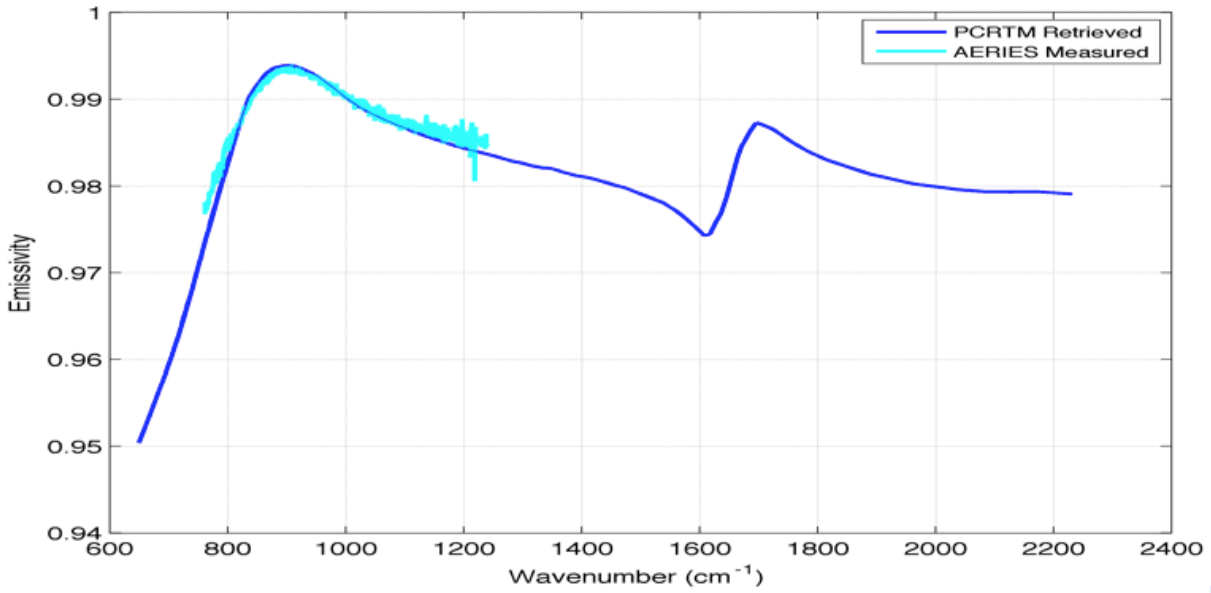


Example of retrieved surface temperature and emssivity and comparison with field validation data

Comparison of PCRTM retrieved surface skin temperature with ARIES measured Tskin

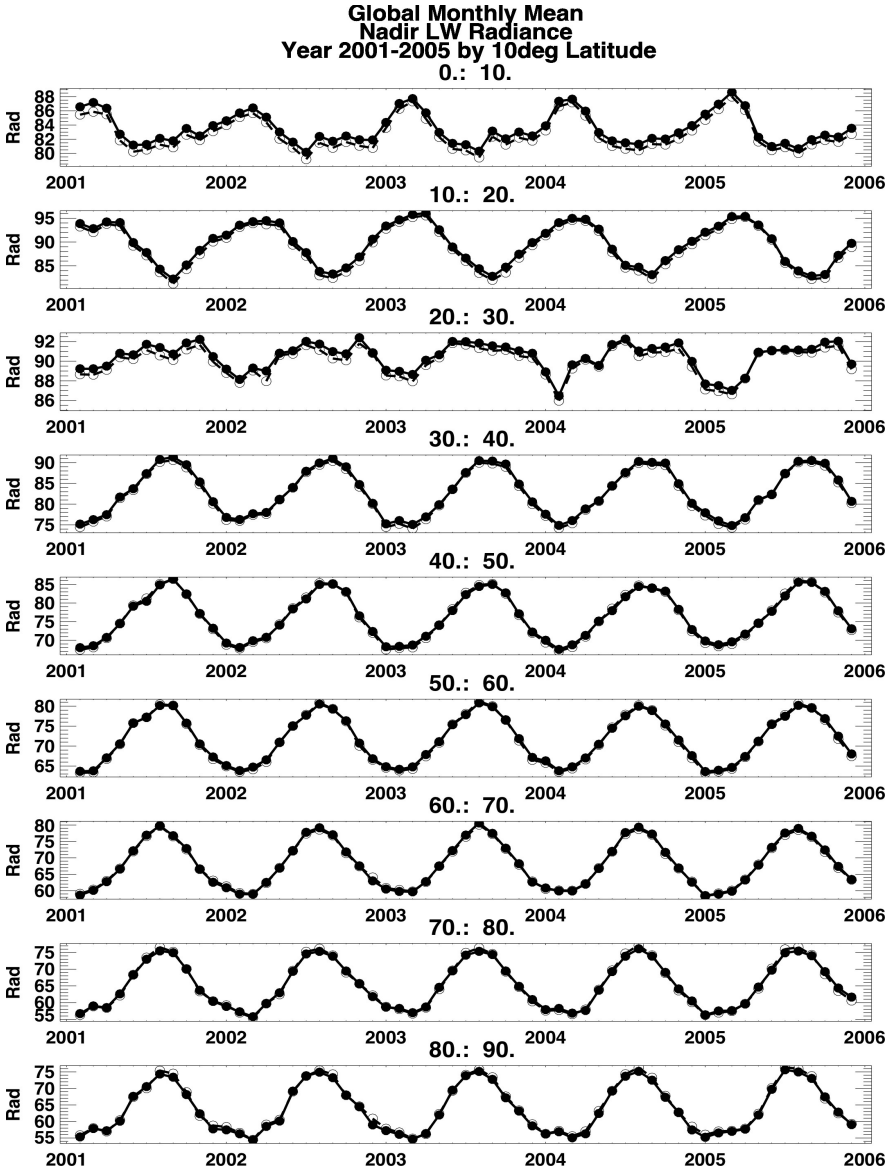
Date	Location	Surface Pressure (hPa)	ARIES Measured skin temperature (K)	IASI-retrieved surface skin temperature (K)
19 April 2007	ARM CART site	972.0	284.7	284.8
29 April 2007	Gulf of Mexico	1021.7	297.8	297.6
30 April 2007	Gulf of Mexico	1017.5	298.6	298.1
4 May 2007	Gulf of Mexico	1009.9	297.4	297.1

Comparison of retrieved ocean emissivity with ARIES aircraft measurements

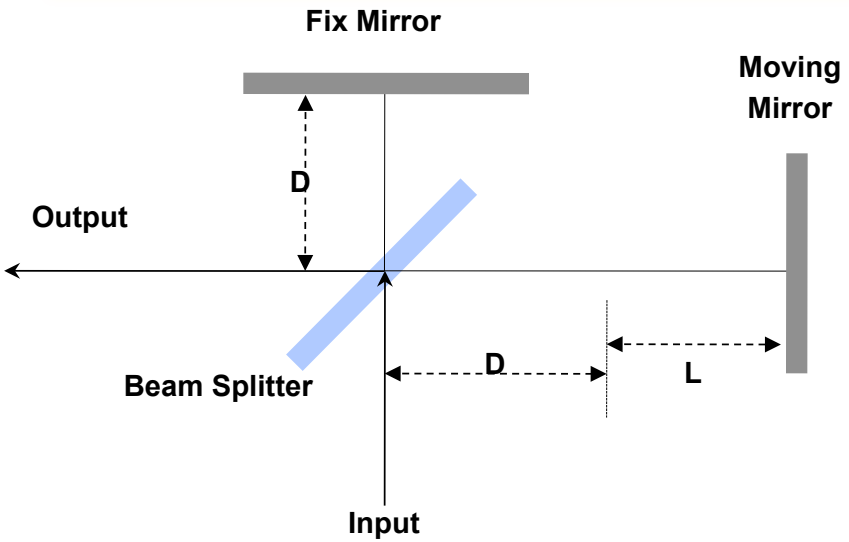


Applying PCRTM to calculate the OLR and comparison with CERES observations

- Work done by Fred Rose and Seiji Kato at NASA Langley
- PCRTM used to calculate cloudy radiance from 50 cm-1 to 2800 cm-1 using MODIS/CERES cloud fields and model atmospheres
- PCRTM OLRs are compared with CERES observations
- Orders of magnitude faster than Modtran
- Good agreement for 6 years of record

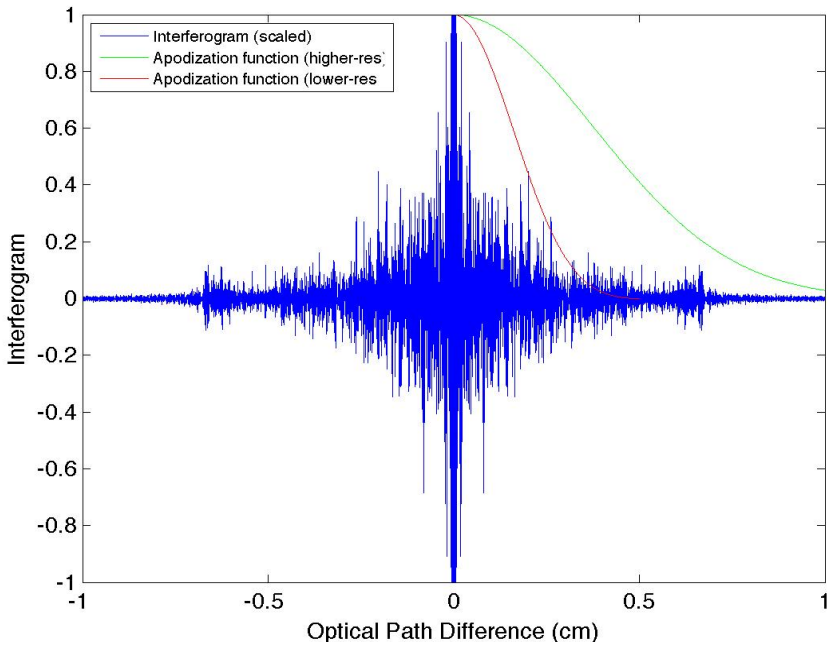


Application of PCRTM to S-NPP CrIS data

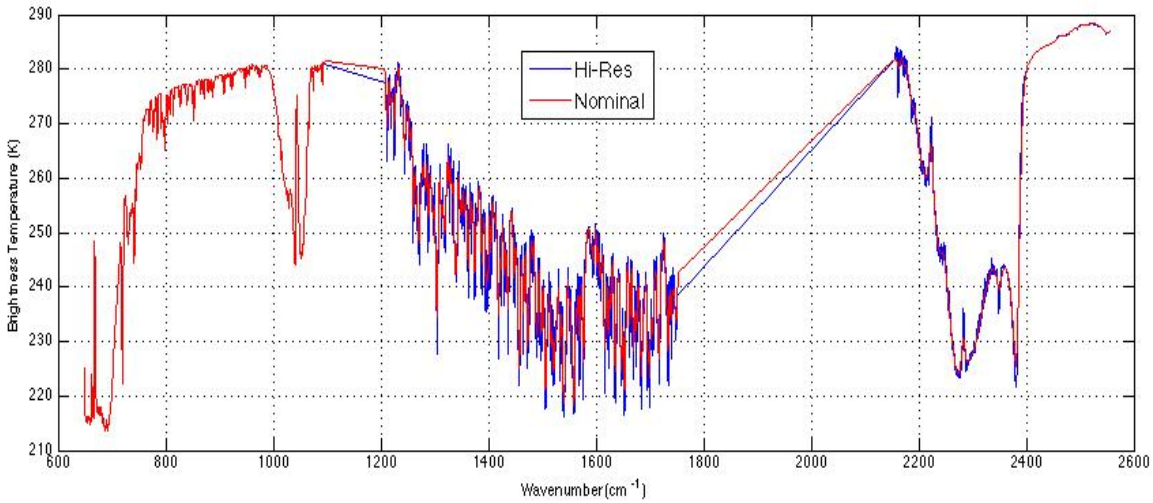


	CrIS (LW)	CrIS (MW)	CrIS (SW)
MOPD	0.8 cm	0.4 cm	0.2 cm
Spectral spacing	0.625 cm^{-1}	1.25 cm^{-1}	2.5 cm^{-1}
Apodized spectral resolution	0.88 cm^{-1} Hamming	1.76 cm^{-1} Hamming	3.53 cm^{-1} Hamming

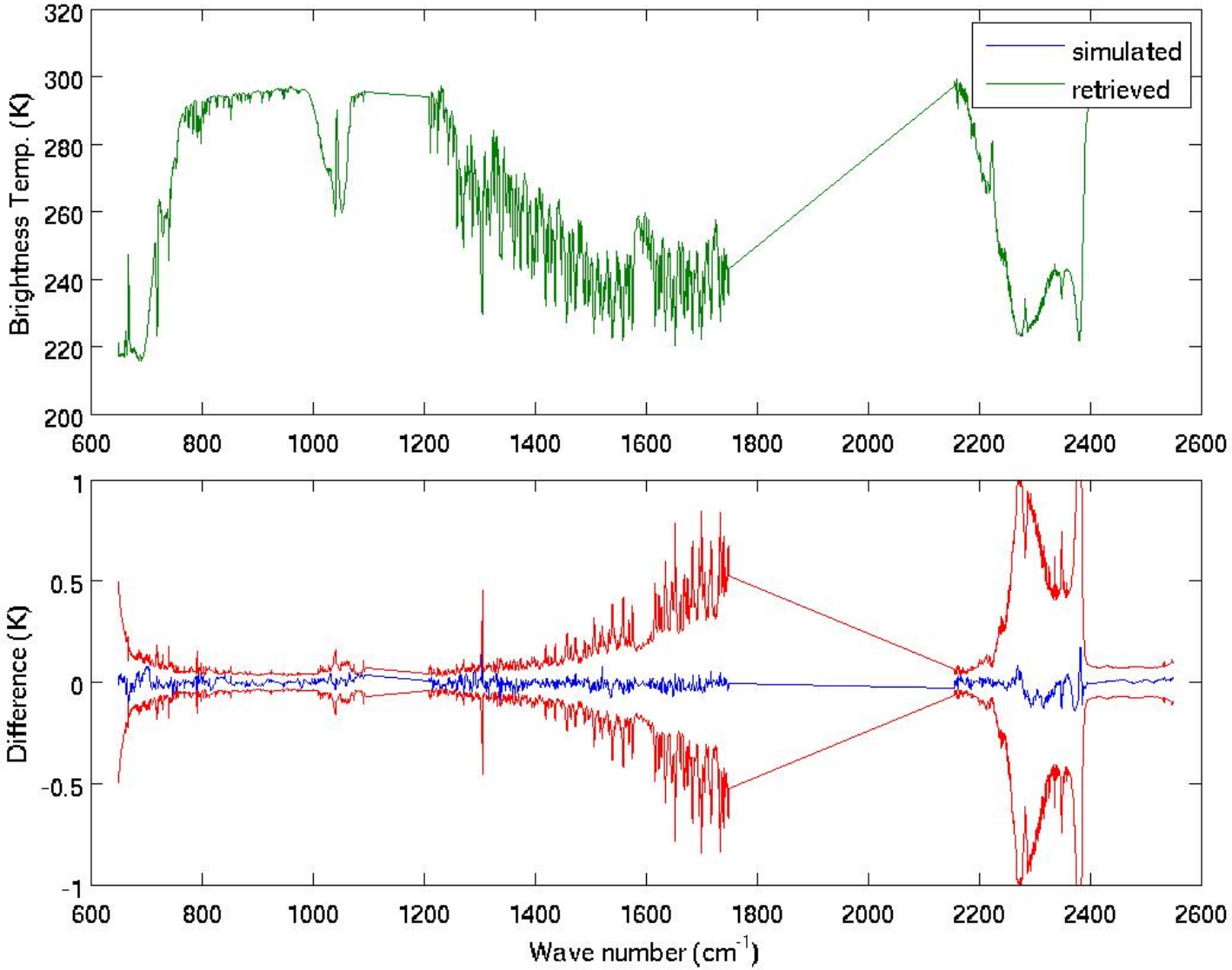
MOPD=2*L (L physical mirror displacement relative to zero optical path difference)



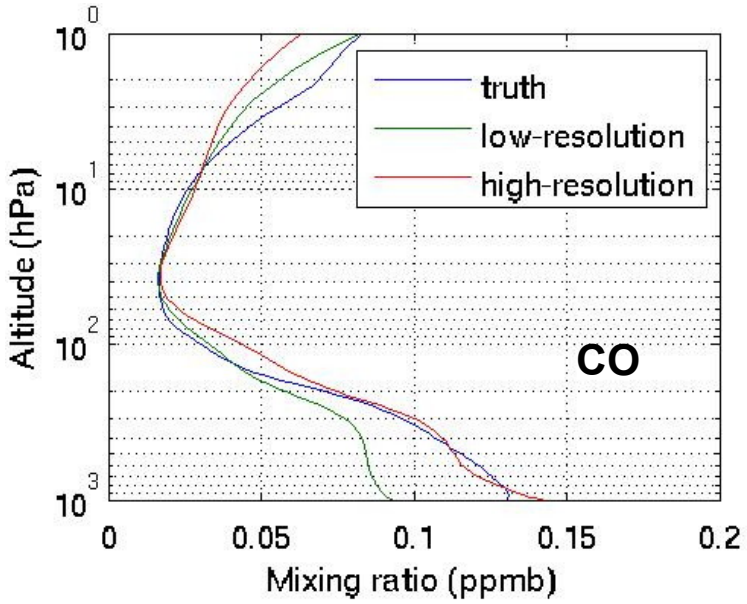
- Nominal CrIS spectrum has 1317 spectral channel (unapodized)
- Hi-Res CrIS spectrum has 2211 spectral channels

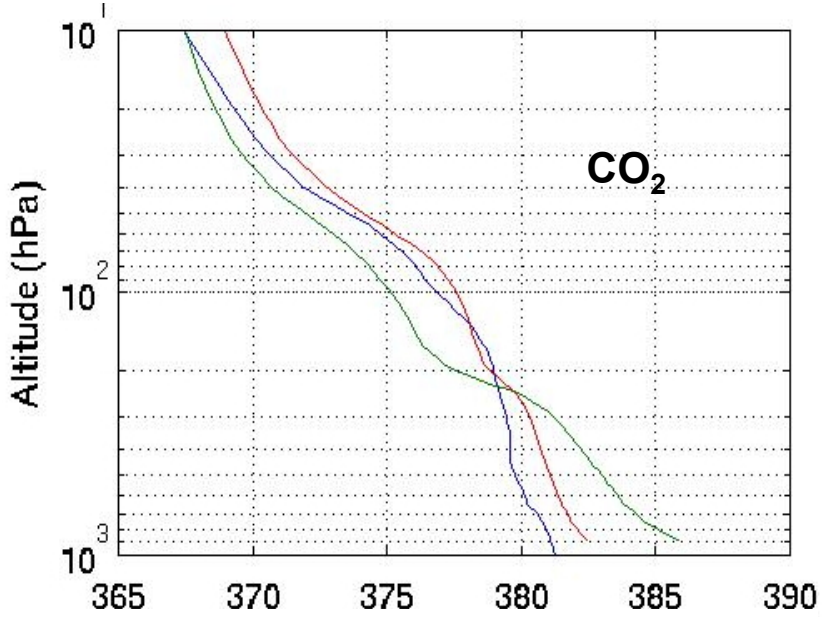


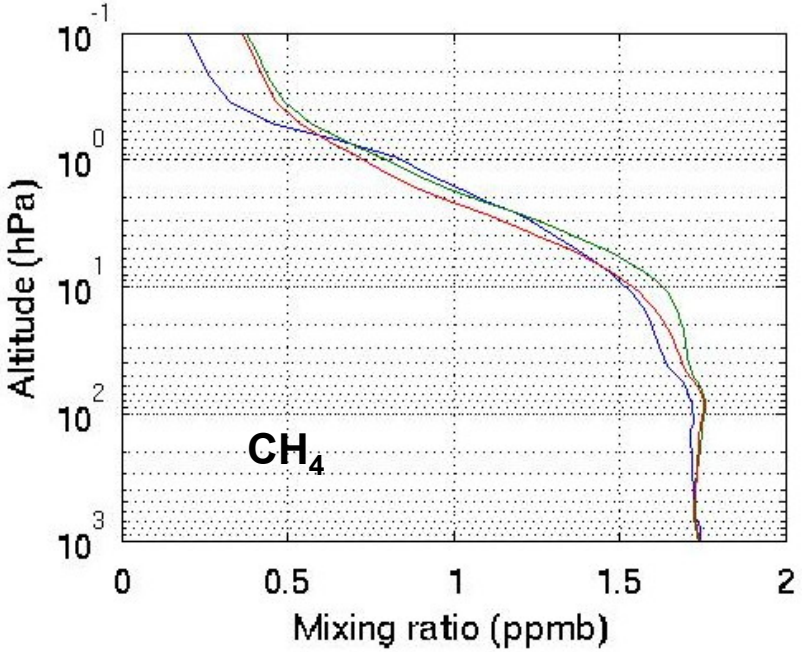
Spectral residues from simulation-retrieval studies

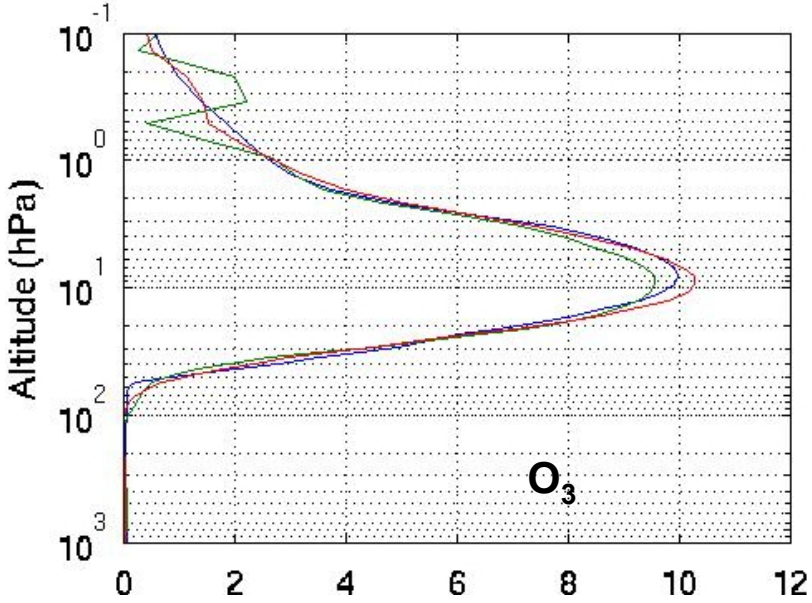


Trace gas retrievals from CrIS with different spectral resolutions (from simulation studies)

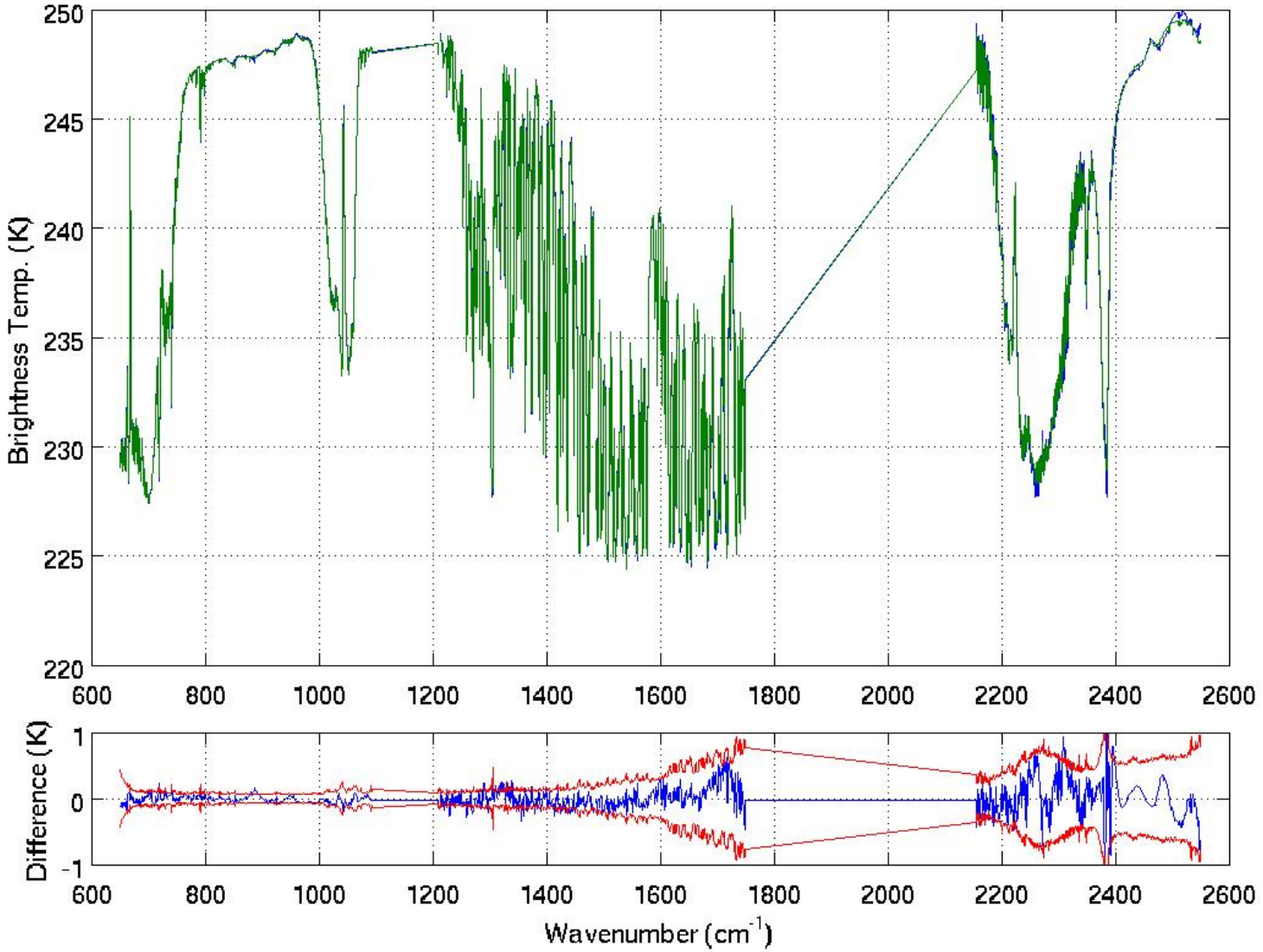






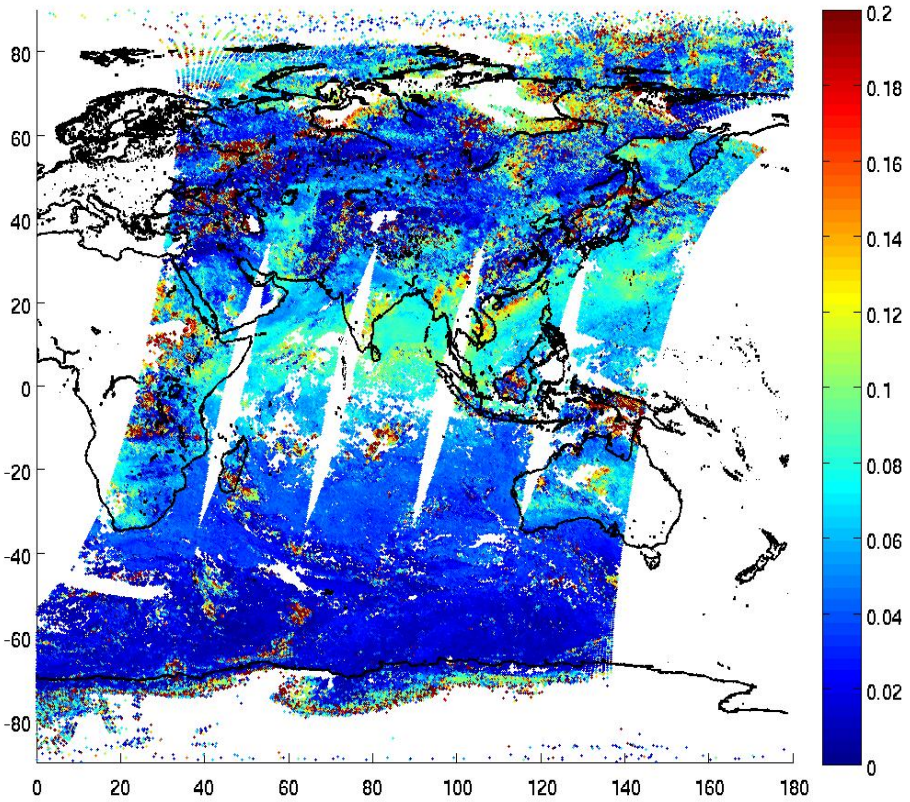


Spectral residues from real CrIS Hi-Res data

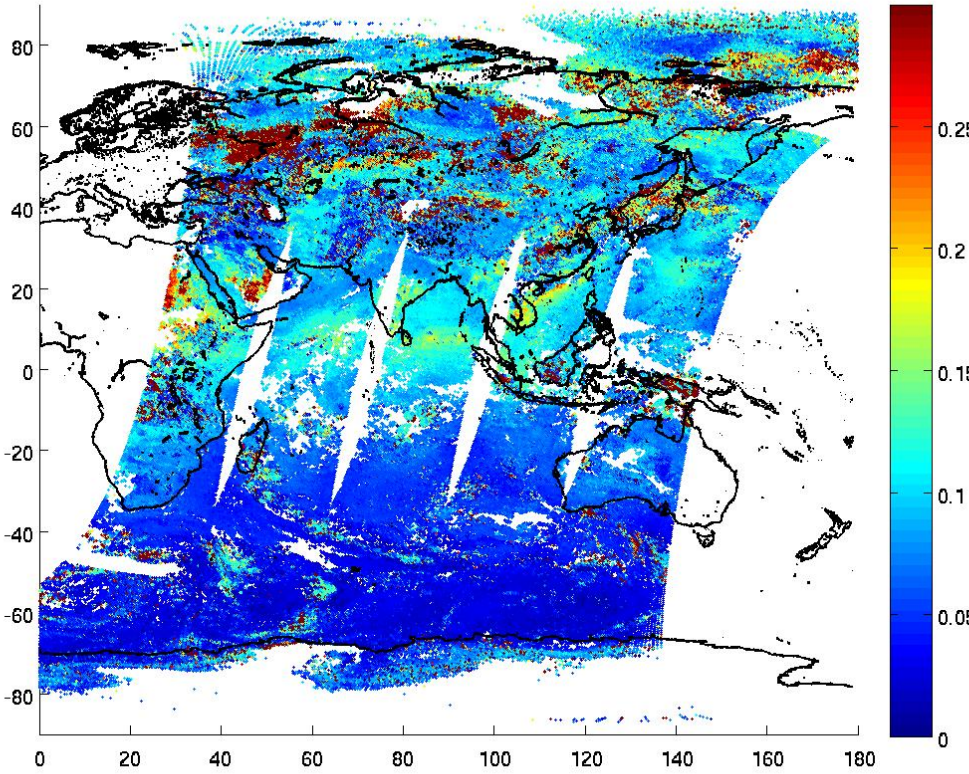


CO retrieved from full-resolution CrIS data

From nominal resolution CrIS

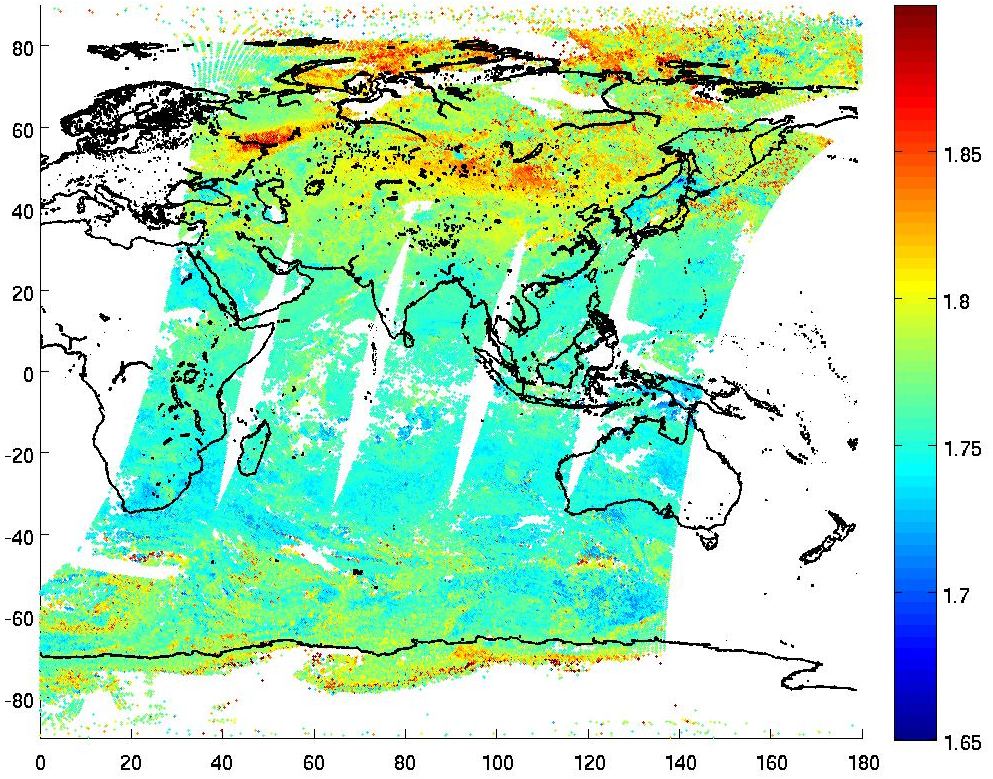


From high resolution CrIS

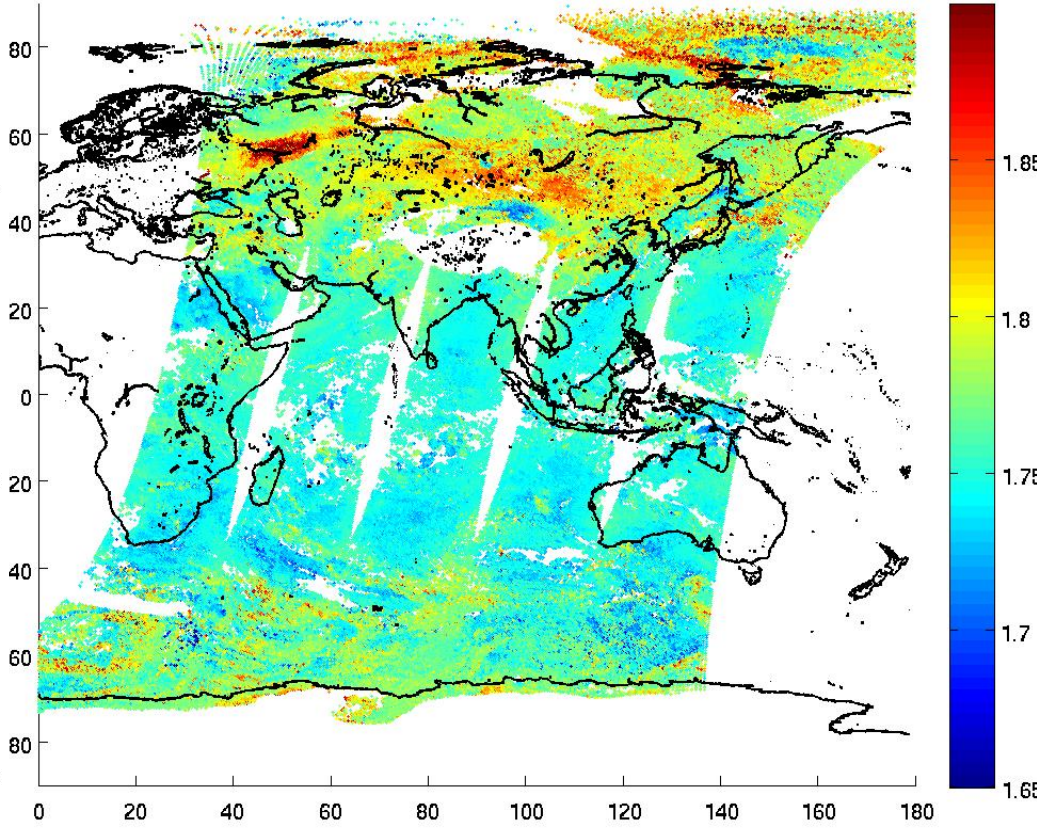


Tropospheric CH4 (500 mb) from CrIS

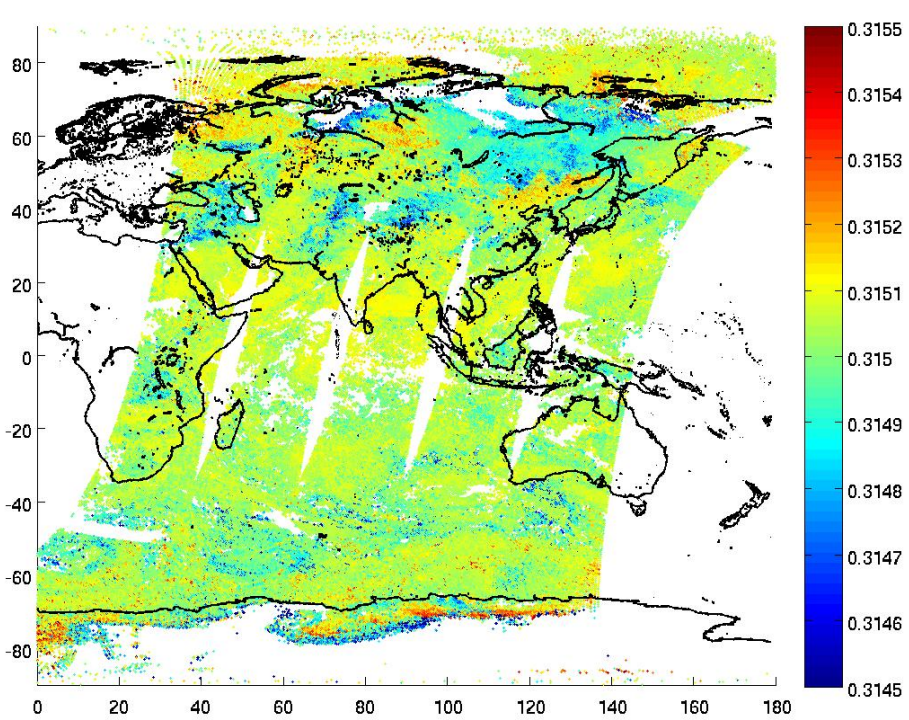
From nominal resolution CrIS

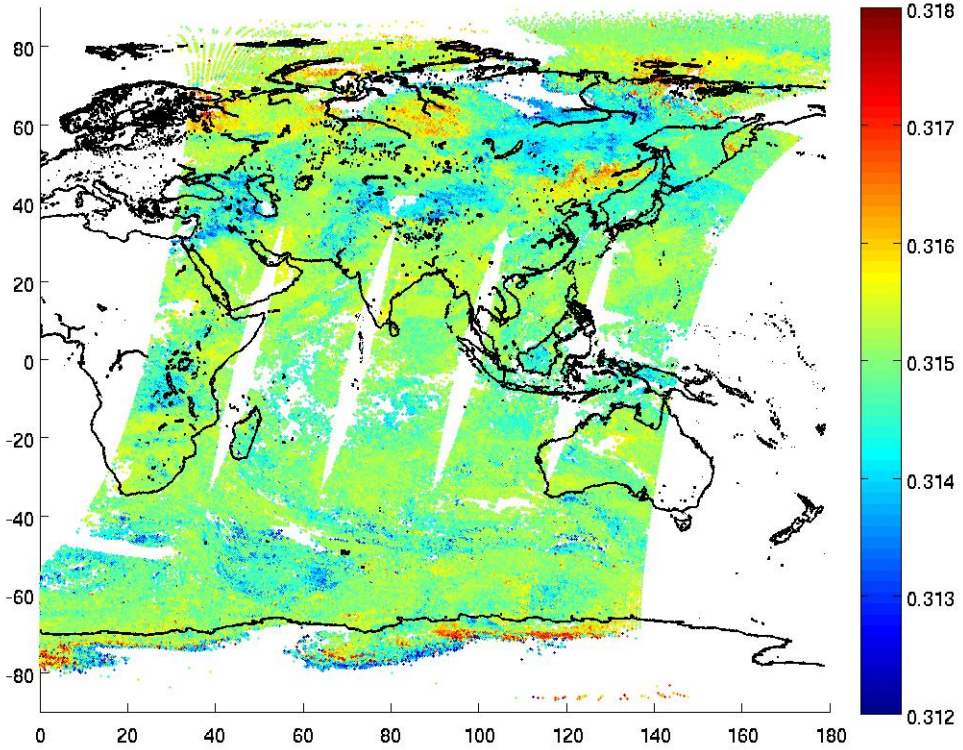


From high resolution CrIS



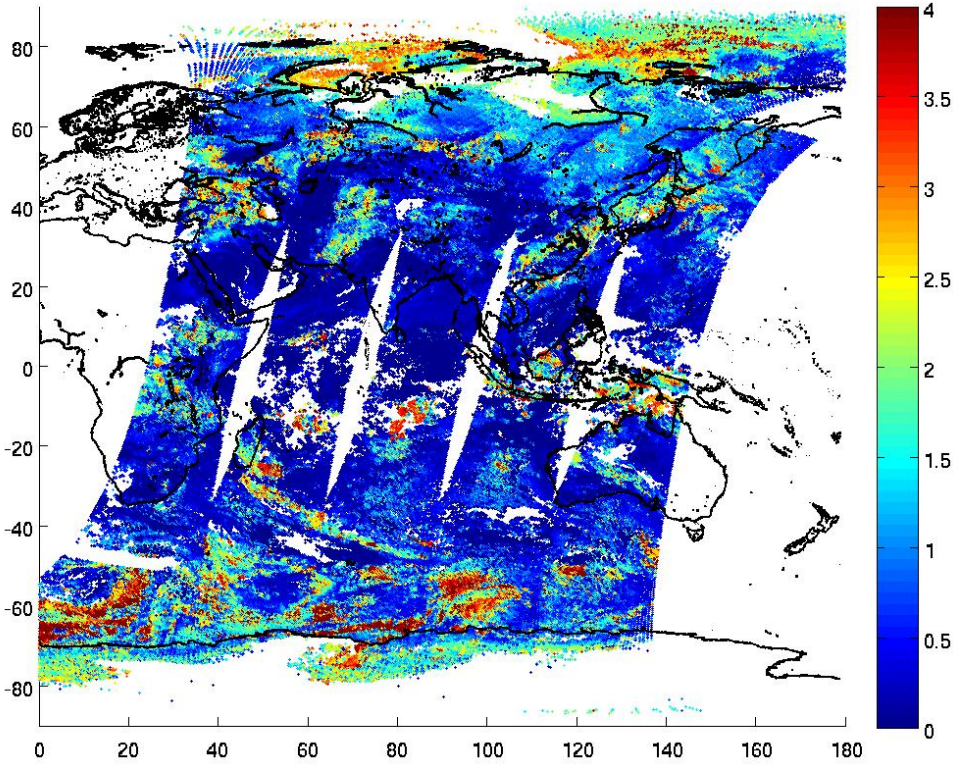
N2O at 500 mb Retrieved from CrIS



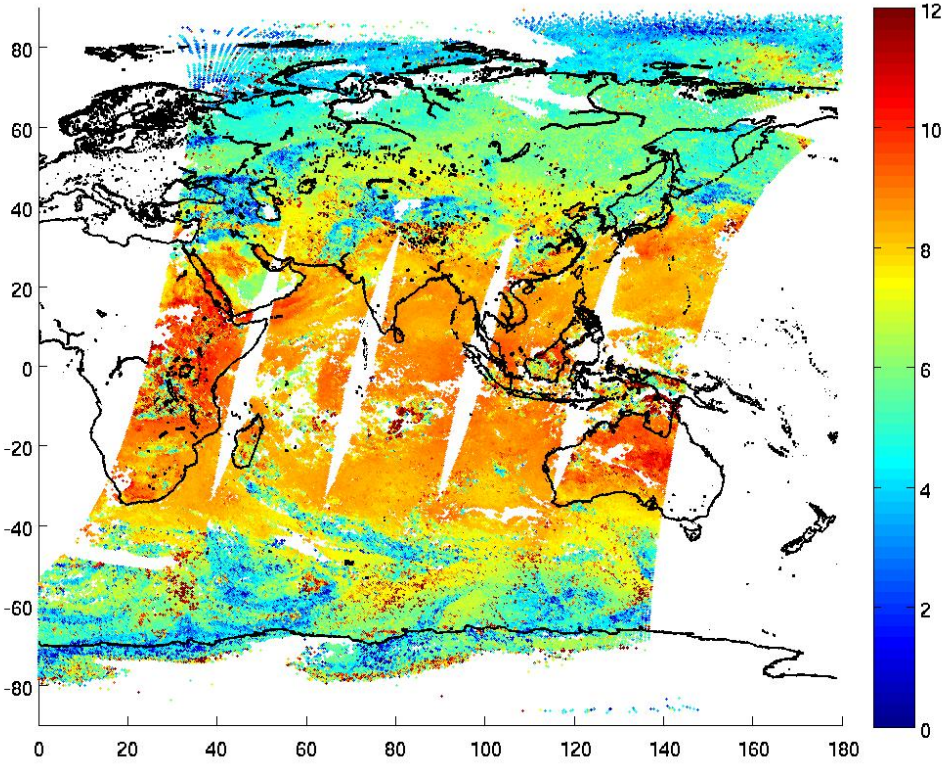


Cloud optical depth and O3 from CrIS

Cloud optical depth

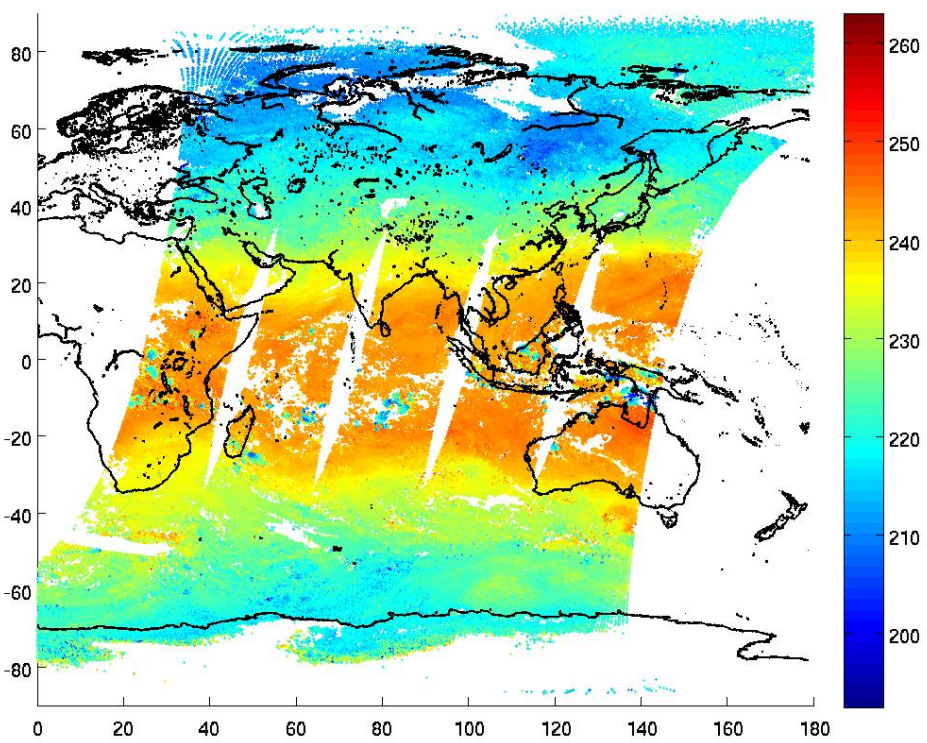


O3 (10 mb)

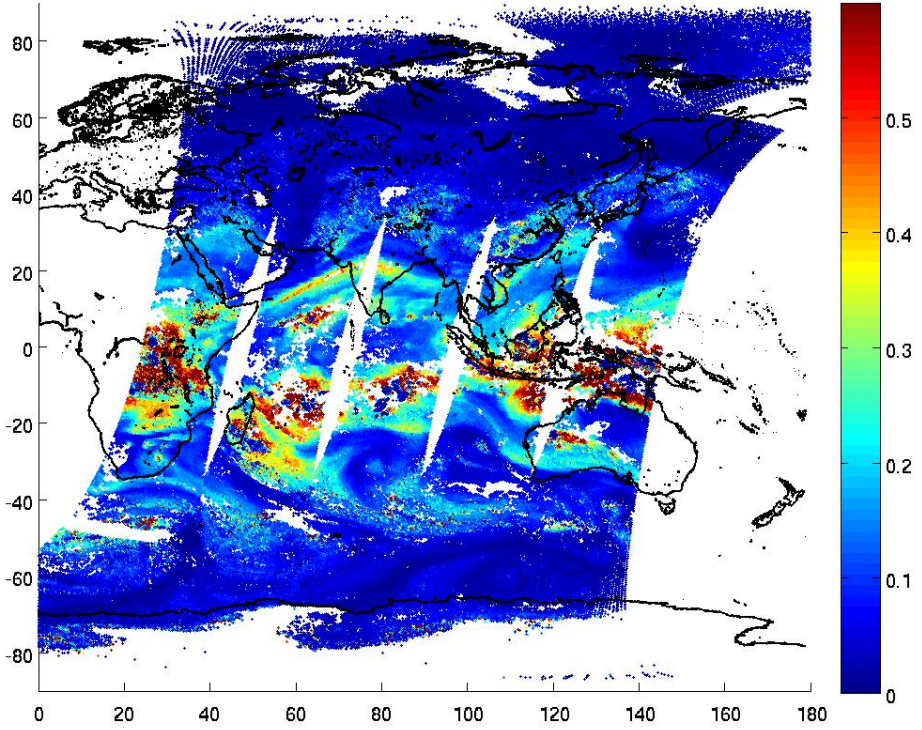


Retrieved Temperature and Moisture From CrIS

300 mb Temperature



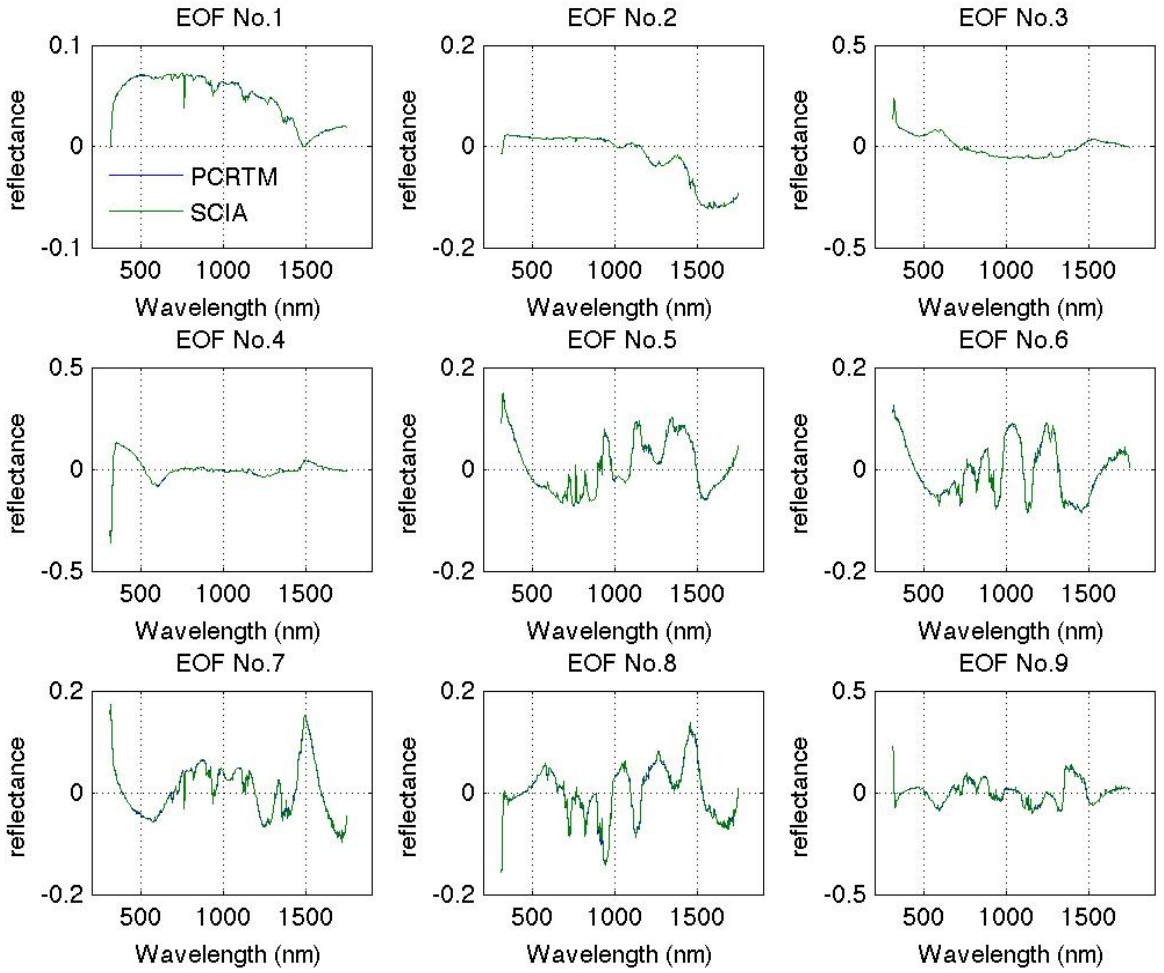
300 mb H2O



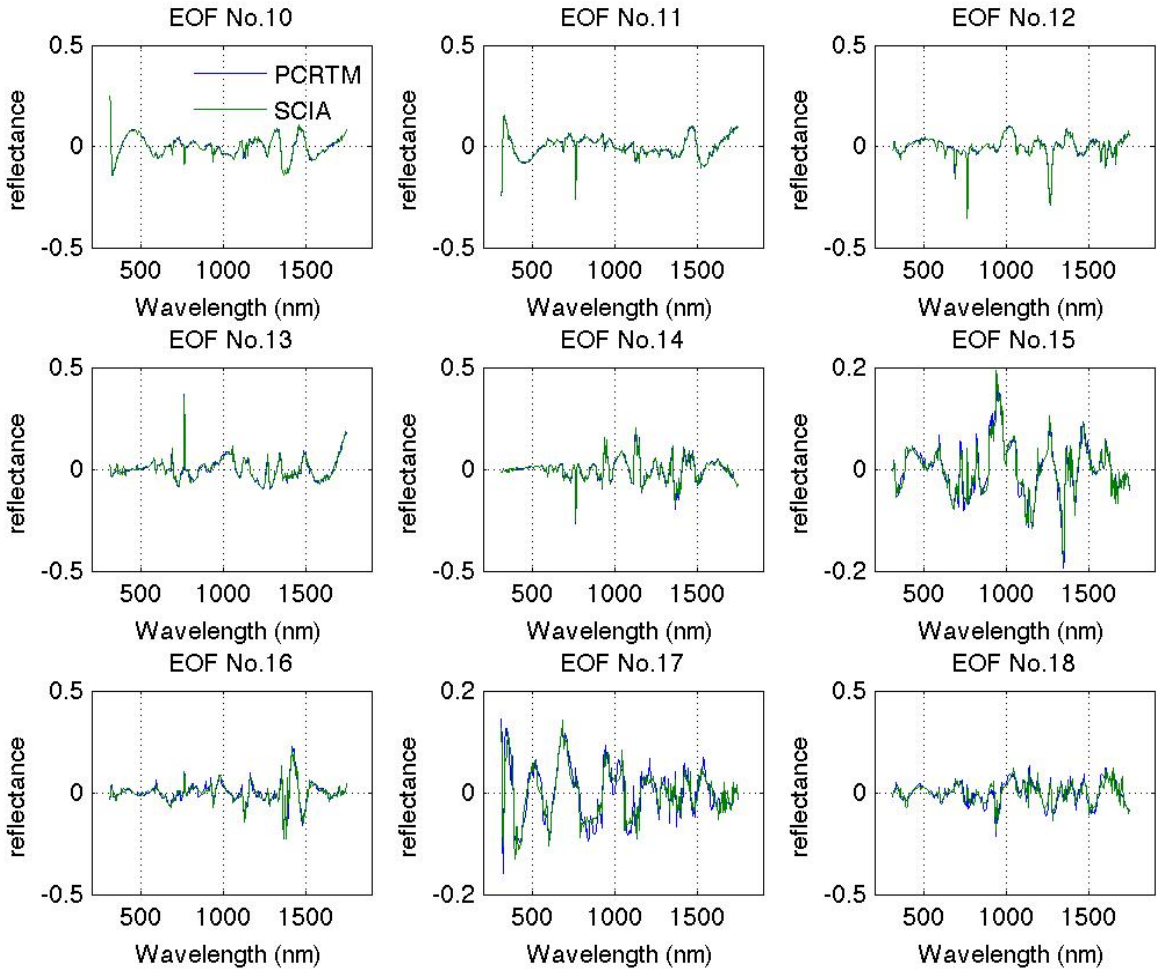
Intersection PCA analysis of observed and simulated SCIAMACHY reflectance spectra

- One year of SCIAMACHY observed reflectance spectra
- One year of PCRTM simulated reflectance spectra
  - 214769 ocean spectra, 56019 land spectra
  - CERES and MODIS products are used as PCRTM inputs
- PCA analysis done for land and ocean separately
  - EOF obtained from PCRTM simulated spectra
  - EOF obtained from real SCIAMACHY spectra
  - Perform intersection PCA analysis
  - Very high correlations between the two transformed eigenvectors

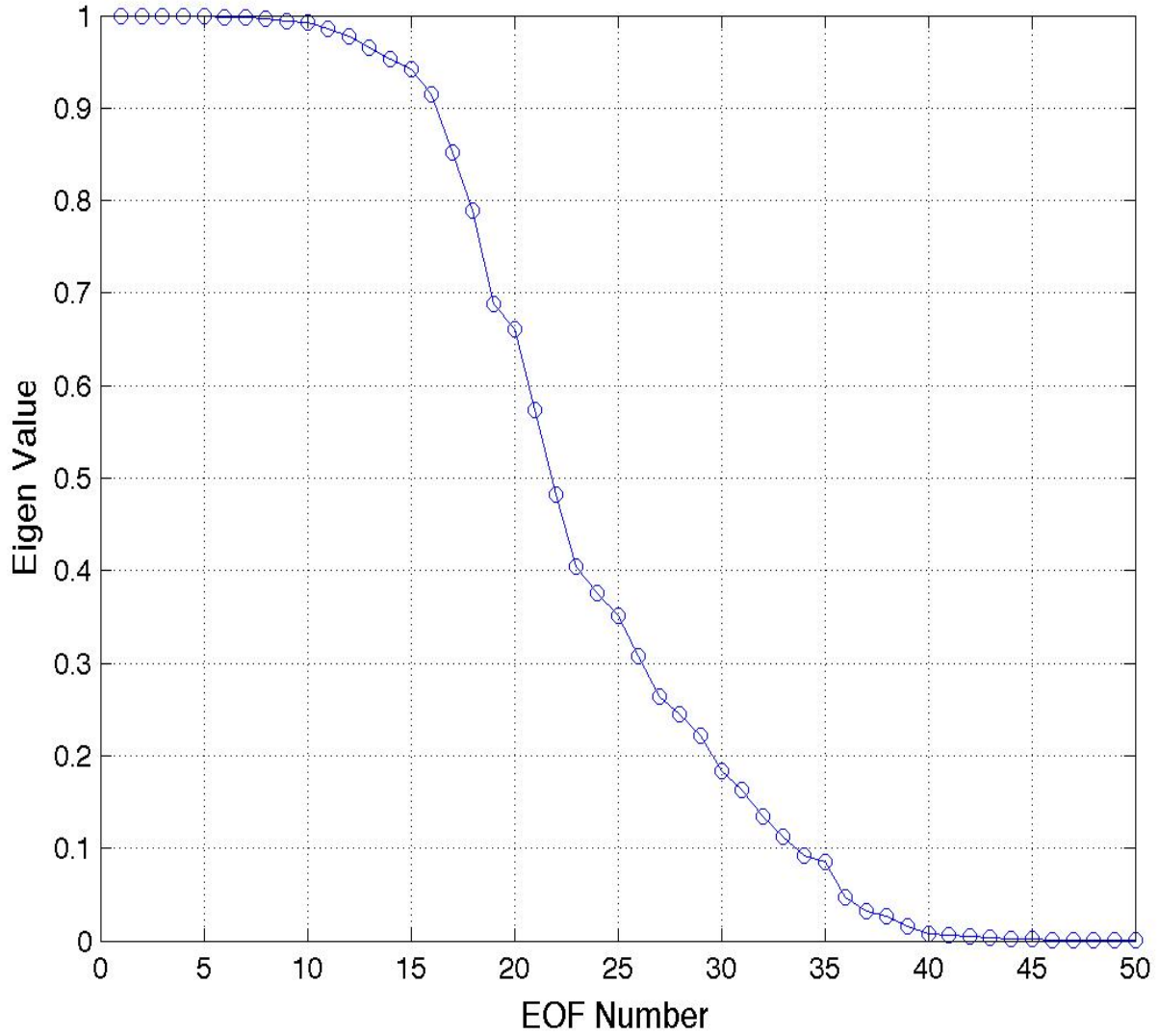
Intercept EOFs from both SCIAMACHY and PCRTM



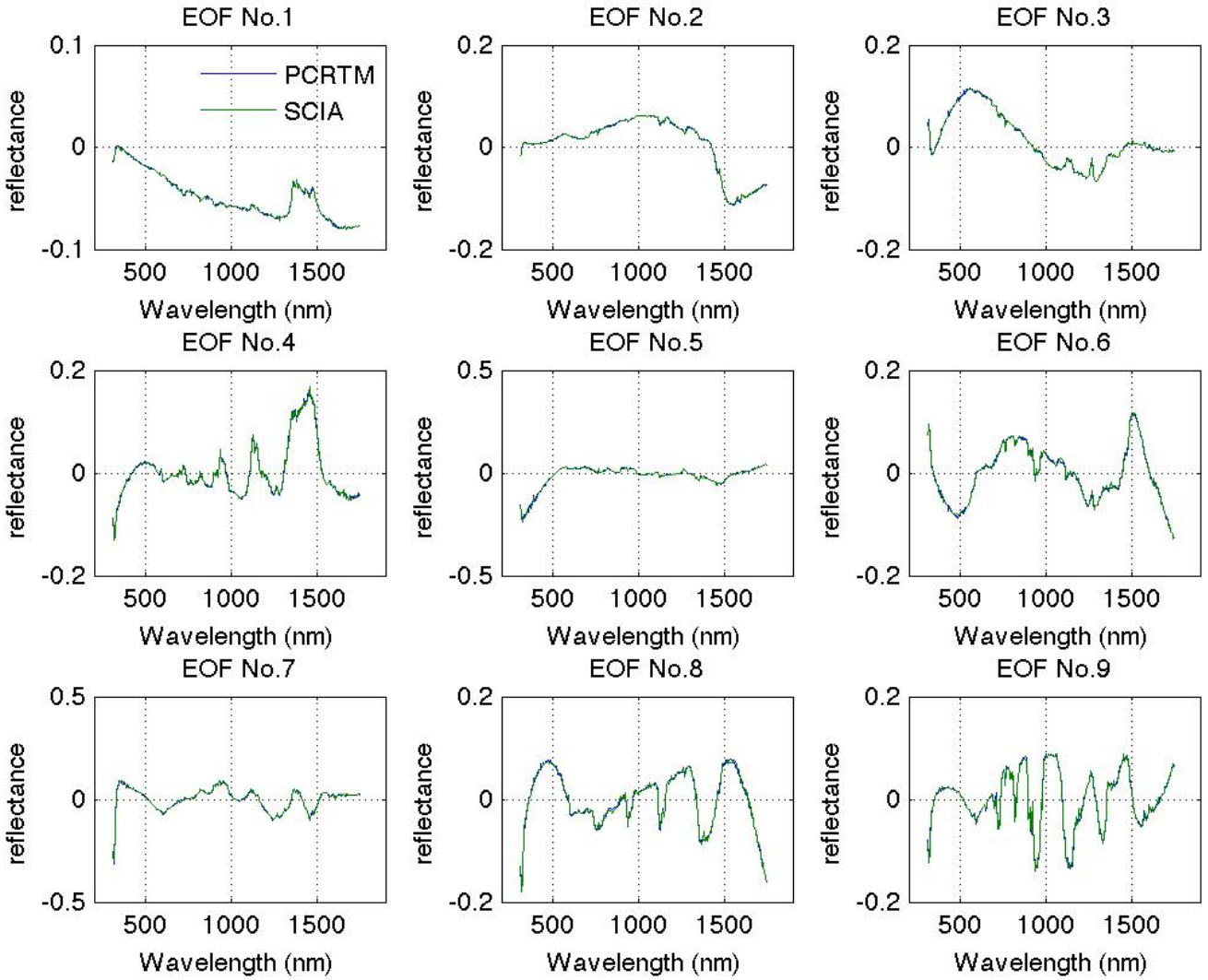
Intercept EOFs from both SCIAMACHY and PCRTM



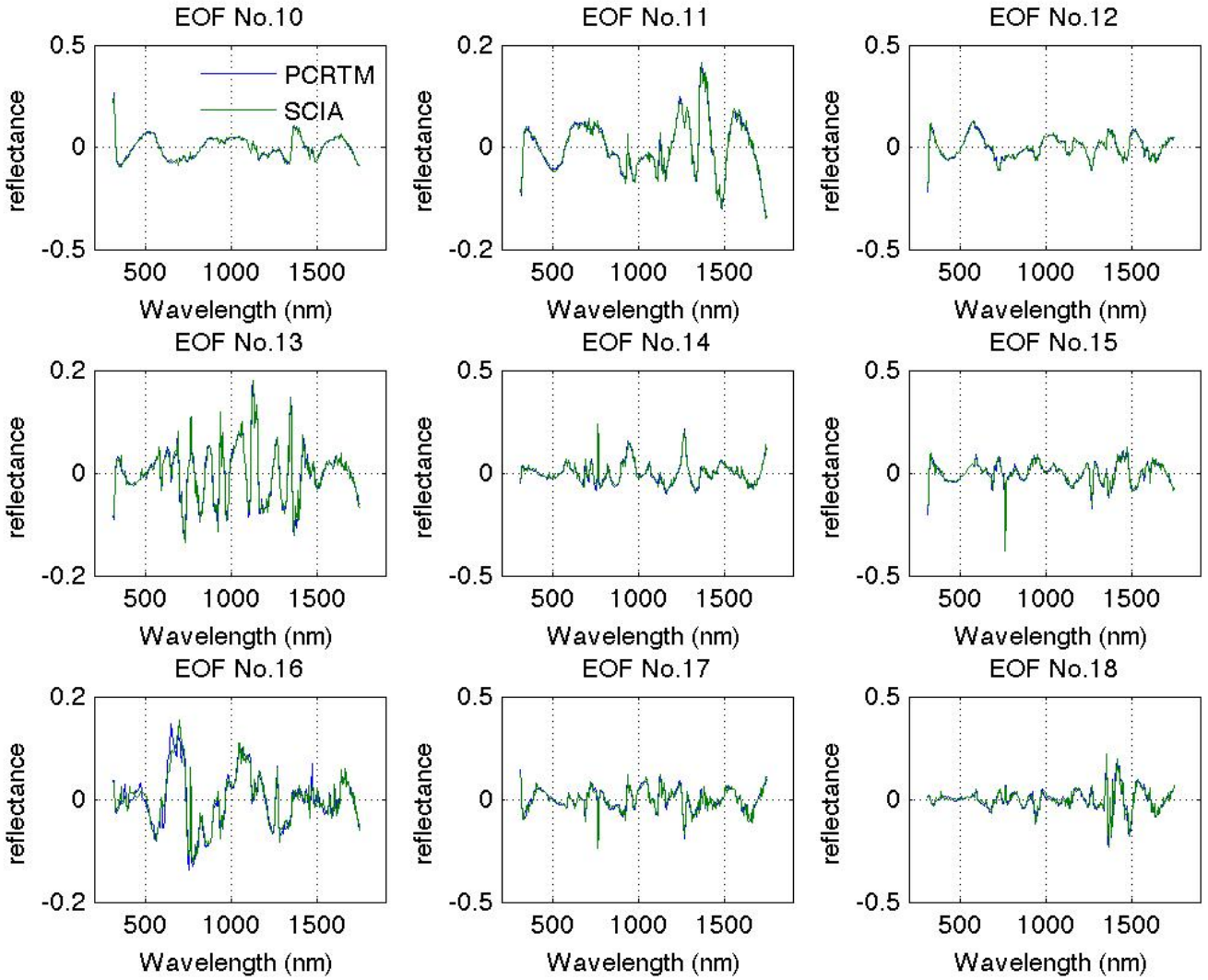
Eigenvalues from intercept PCA analysis



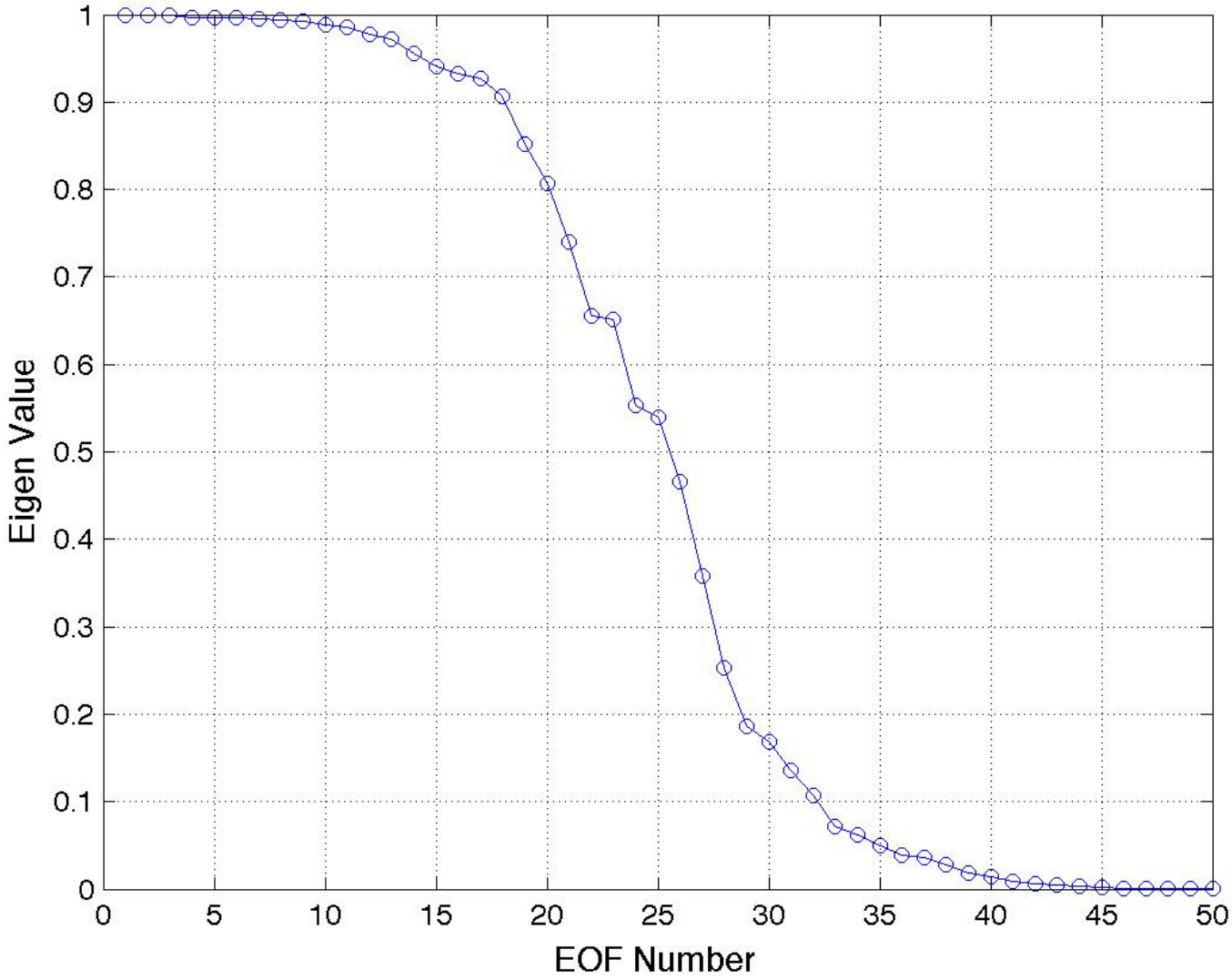
Intercept EOFs from both SCIAMACHY and PCRTM



Intercept EOFs from both SCIAMACHY and PCRTM



Eigenvalues from intercept PCA analysis



Summary and conclusions

- Forward model is a key component in analyzing hyperspectral data
  - End-to-end sensor trade studies
  - Realistic global long term data simulations and OSSE experiment
  - Satellite data analysis and data assimilationstrace gas profiles, cloud and surface properties
  - PCRTM has been applied to numerous existing and planned hyperspectral sensors: AIRS, IASI, CrIS, NAST-I, CLARREO..
- PCRTM can be used for other applications
  - Generate climate data record from multiple sensors (AIRS/IASI/CrIS)
  - Expand PCRTM applications (e.g. satellite data assimilations)
  - Use multi-spectral regions to improve retrieval information