Hyperspectral Radiatve Transfer Modeling and its Applications

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Presentation outline

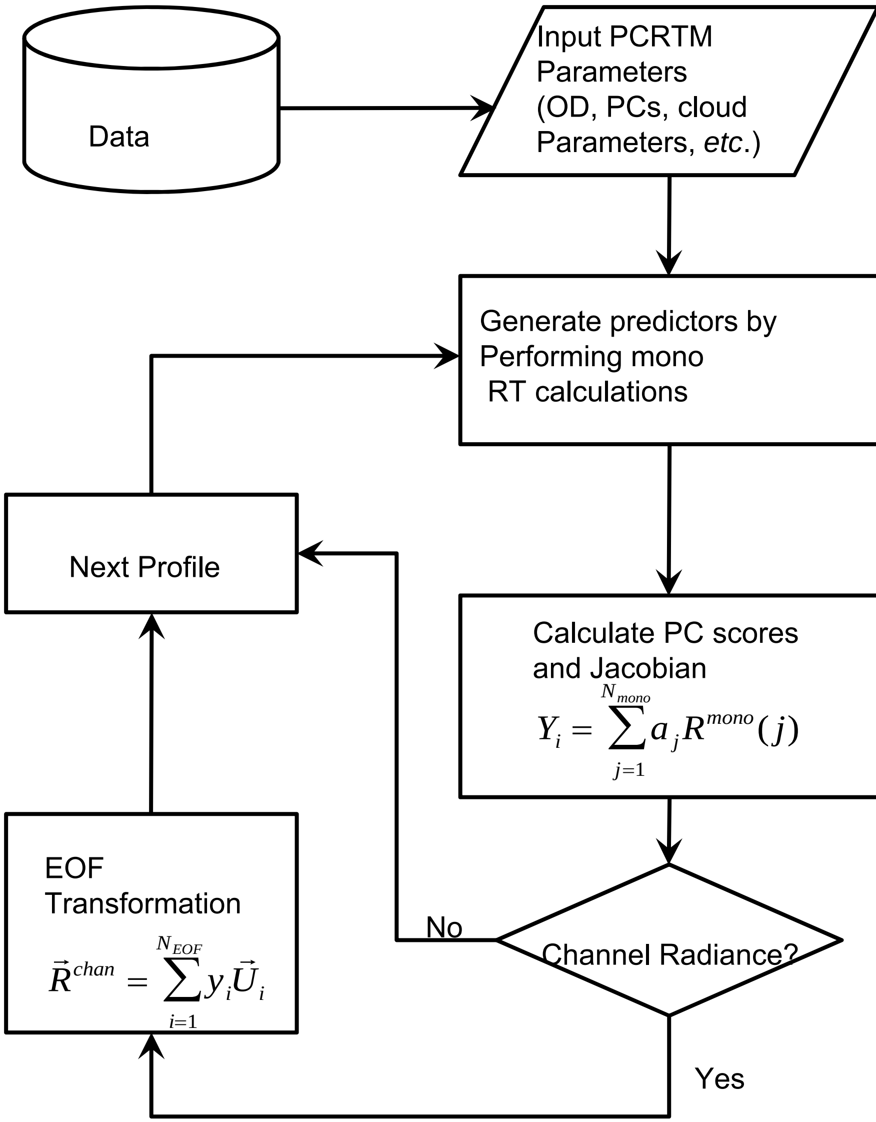
- Overview of a Principal Component (PC) base radiative transfer model
- Applications of PCRTM
  - Information content analysis
  - OSSE/proxy data generation
  - Inversion of atmospheric and surface properties
  - Study the impact of calibration accuracy on climate variable retrievals
- Summary and Conclusions

What is a Principal Component based Radiative Transfer Model (PCRTM)

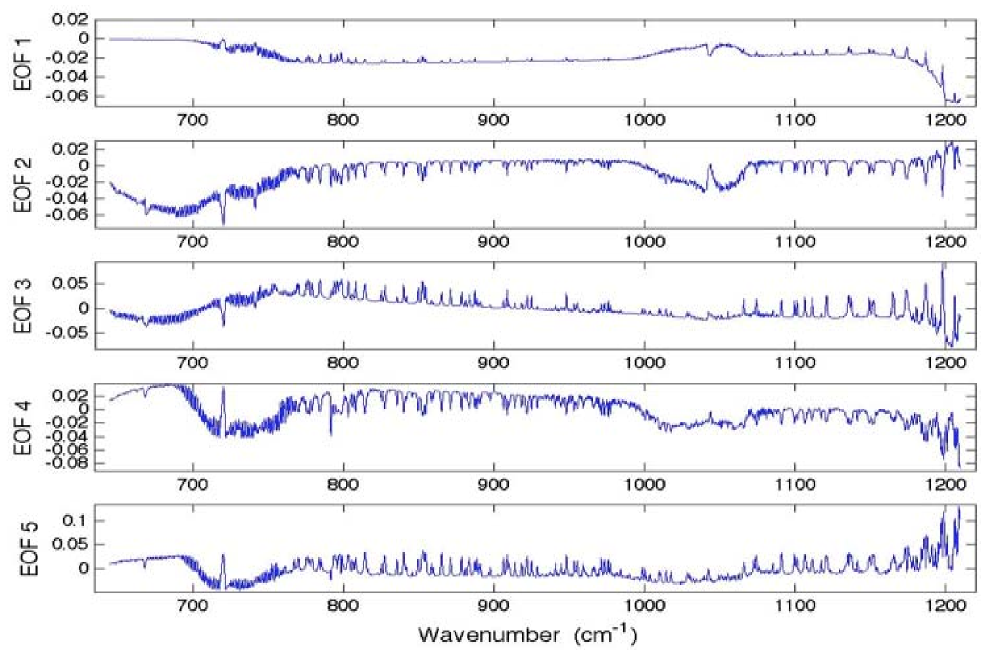
- PCRTM is different from a conventional radiative transfer model
  - Instead of performing RT calculation one channel at a time, PCRTM compresses original spectrum into a set of PC scores
    - Radiative transfer done monochromatically at very few frequencies for all spectral channels
  - It provides channel radiance and associated Jacobian by simple EOF transformation
- PCRTM is more efficient than conventional channel base RTM
  - Spectral information are captured by eigenvectors and PC scores
    - Reduces dimensionality of original spectrum by a factor of 10-90
  - Very accurate relative to line-by-line (LBL) RT model
    - < 0.05K for IR and <0.05% for solar
  - Every fast computational speed
    - 3-4 orders of magnitude faster than LBL RT models
    - A factor of 2-100 times faster than channel-based RT model
- Both forward and inverse calculations can be done in PC domain
  - Save space and computational time

How does PCRTM work?

Flow diagram of the PCRTM forward model

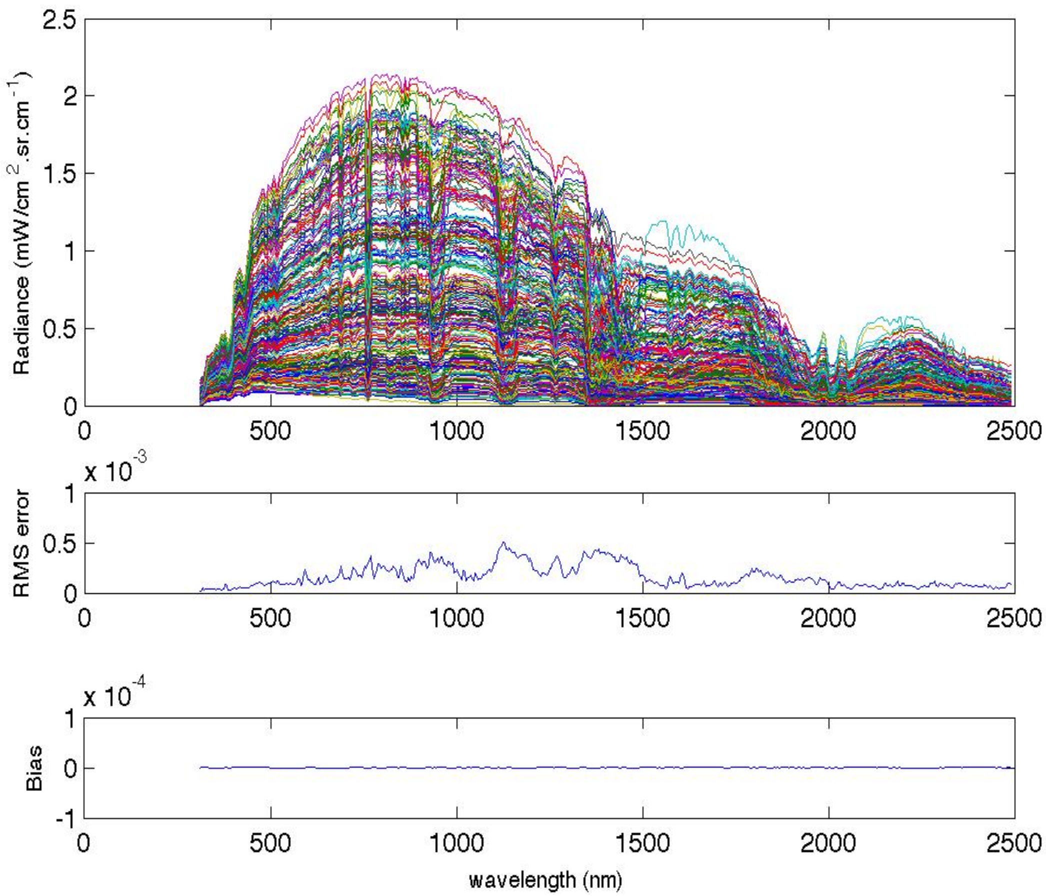


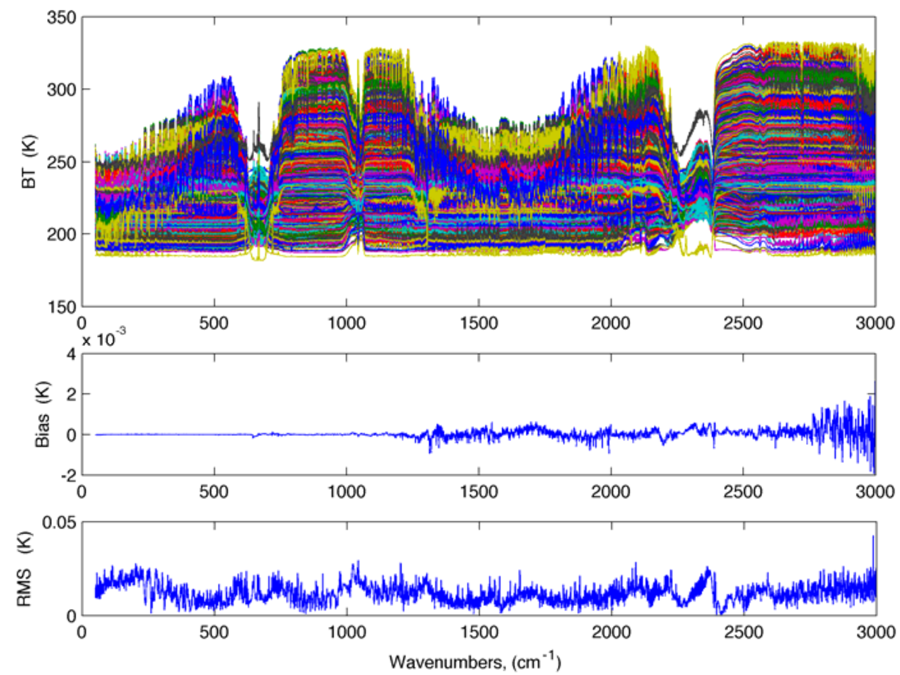
- Monochromatic RT assures Beer's law apply
- RT needs to be done at minimum number of frequencies
  - Orders of magnitude smaller than LBL

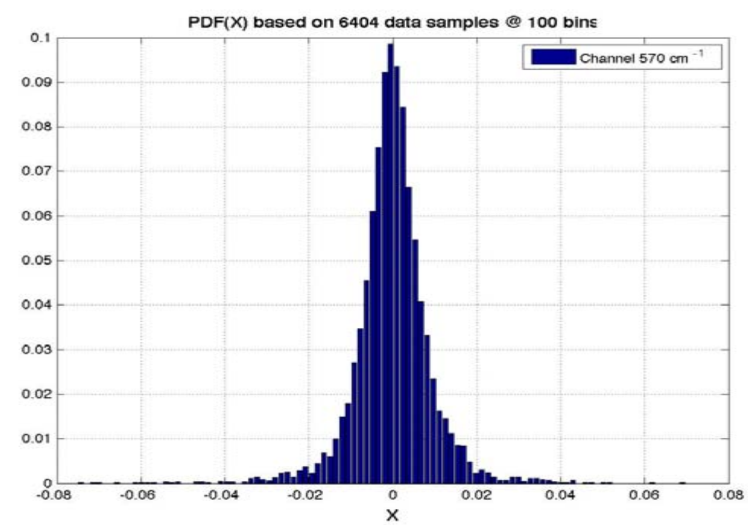


Accuracy of PCRTM is very good relative to reference RT models

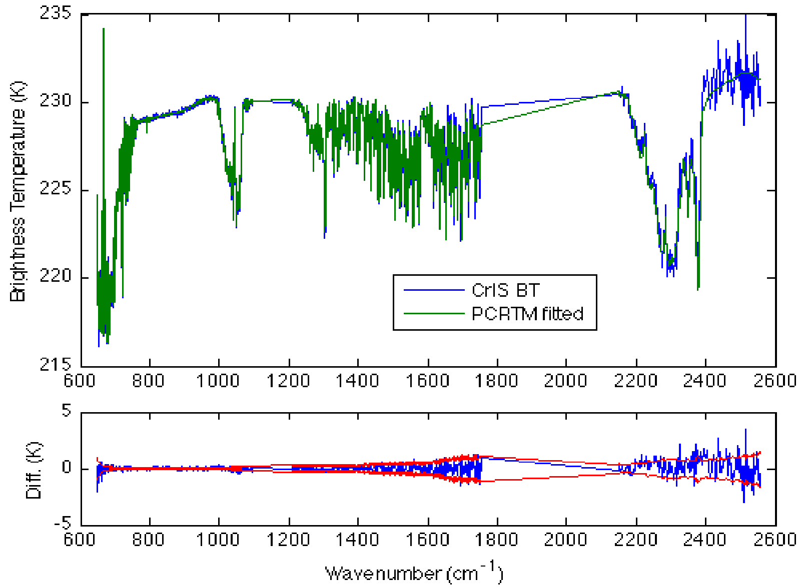
- Bias error relative to LBL is typically less than 0.002 K
- The PDF of errors at different frequencies are Gaussian distribution
- RMS error < 0.03K for IR and < 5×10^{-4} $mW/cm^2/sr/cm^{-1}$ for solar (< ~0.02%)

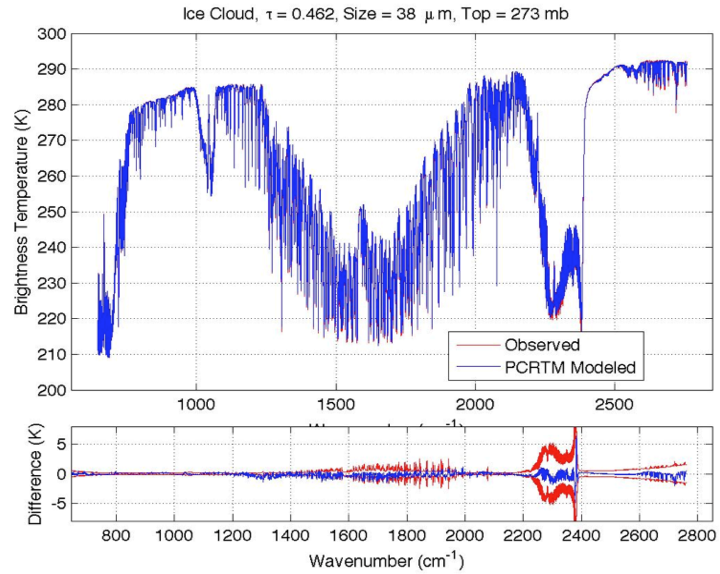


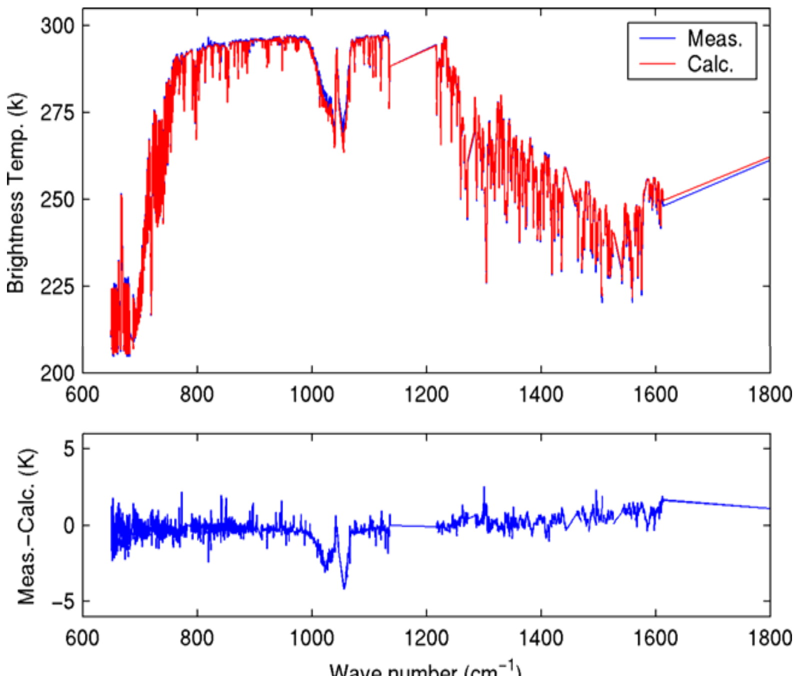




PCRTM has been successfully used on real hyperspectral data (CrIS, IASI, AIRS, NAST-I)







PCRTM has been successfully used to perform forward radiative transfer modeling and geophysical parameter retrievals of the following on orbit instruments:

- Metop-A IASI
- NASA Aqua AIRS
- Suomi NPP CrIS
- NAST-I (NASA airborne instrument)

PCRTM computational speed benchmark

- Miliseconds computational time for each spectrum in IR spectral region

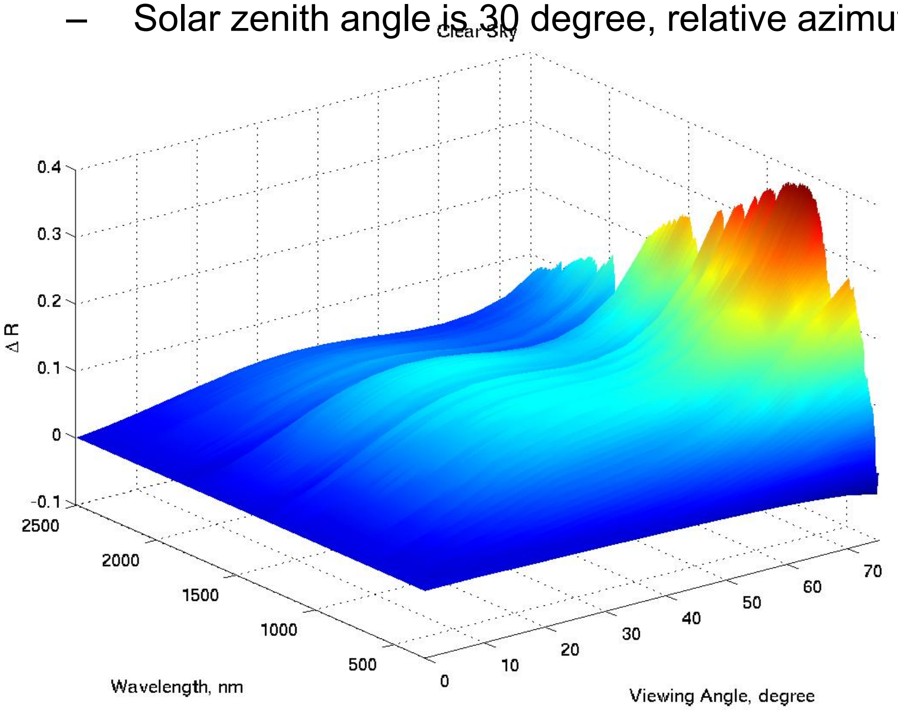
Sensor	Channel Number	PC score (seconds)	PC score + Channel radiance	PC score + PC Jacobian
CLARREO, 0.5 cm^{-1}	5421	0.011 s	0.013 s	0.039 s
IASI, 0.25 cm^{-1}	8461	0.011 s	0.012 s	0.044 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s	0.0074 s	0.031 s
CrIS, Hamming, 0.625-2.5 cm^{-1}	1317	0.0050 s	0.0058 s	0.022 s
NAST-I, 3 bands, 0.25 cm^{-1}	8632	0.010 s	0.013 s	0.045 s

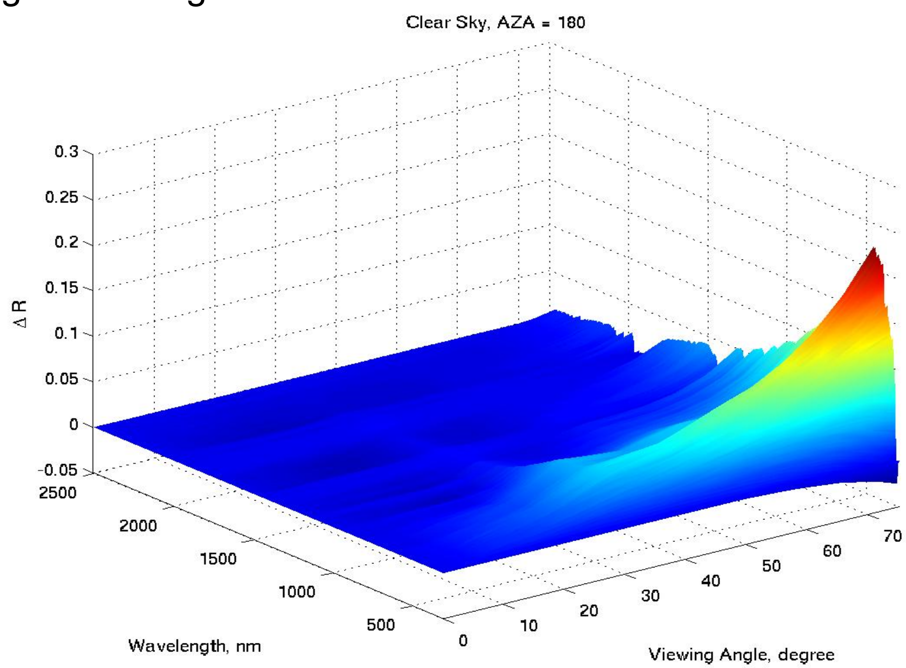
- Fractional of seconds to a few seconds in solar reflected spectral region
  - Table below shows the speed up relative to channel-based MODTRAN model

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

Information Content Analysis

- Due to its computational speed and accuracy, PCRTM can be used to study the TOA radiance (or reflectance) as a function of:
  - Wavelength and spectral resolution
  - Solar zenith angle, satellite viewing angle, relative azimuth angle
  - Cloud optical depth, particle size, cloud height….
  - Atmospheric and surface conditions
- Left figure shows clear sky TOA radiance (Nadir radiance subtracted) as a function of satellite viewing angle
  - Solar zenith angle is 30 degree, relative azimuth angle=0 degree
- Right figure shows clear sky TOA radiance as a function of satellite viewing angle
  - Solar zenith angle is 30 degree, relative azimuth angle=180 degree

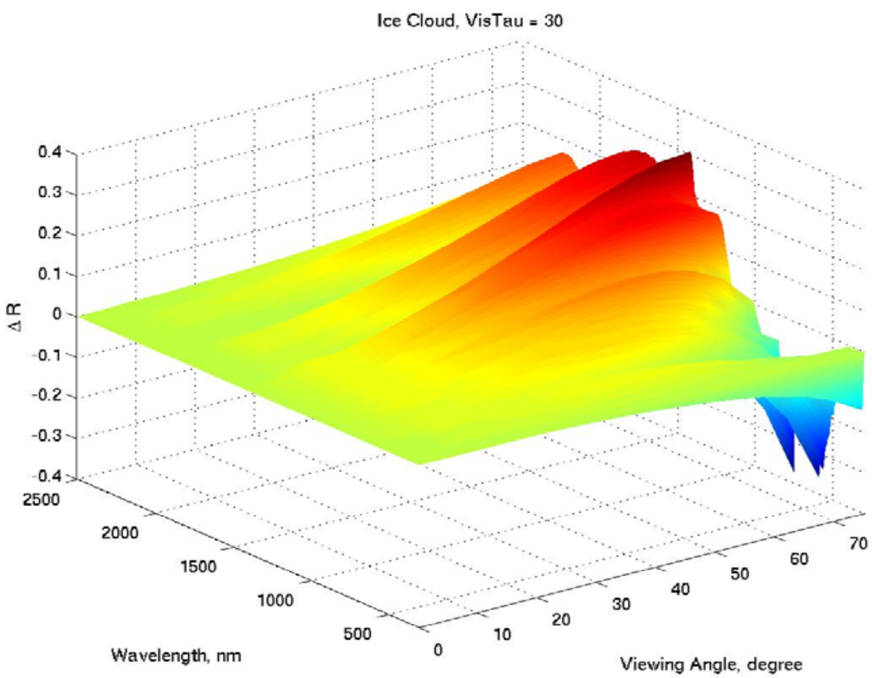


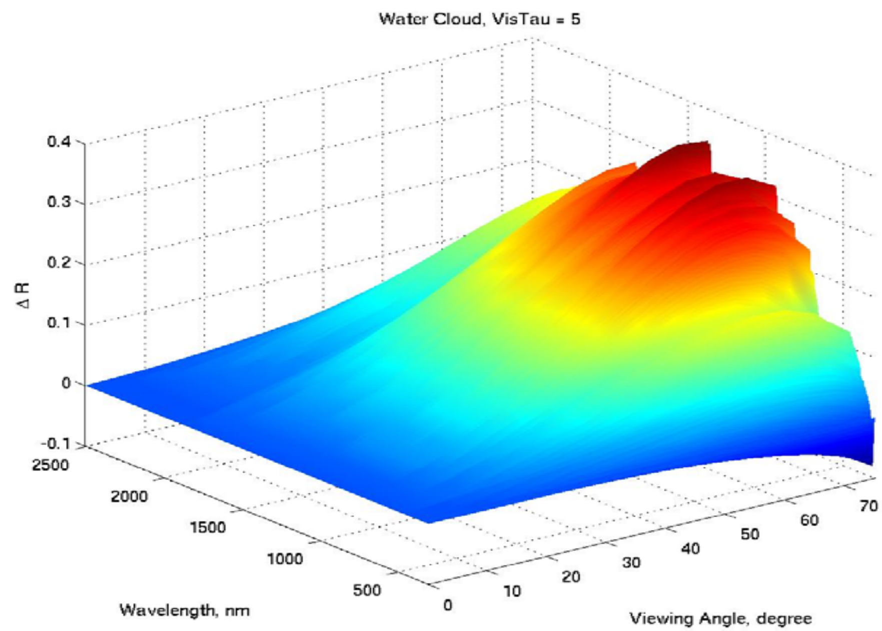


Another example of sensitivity study

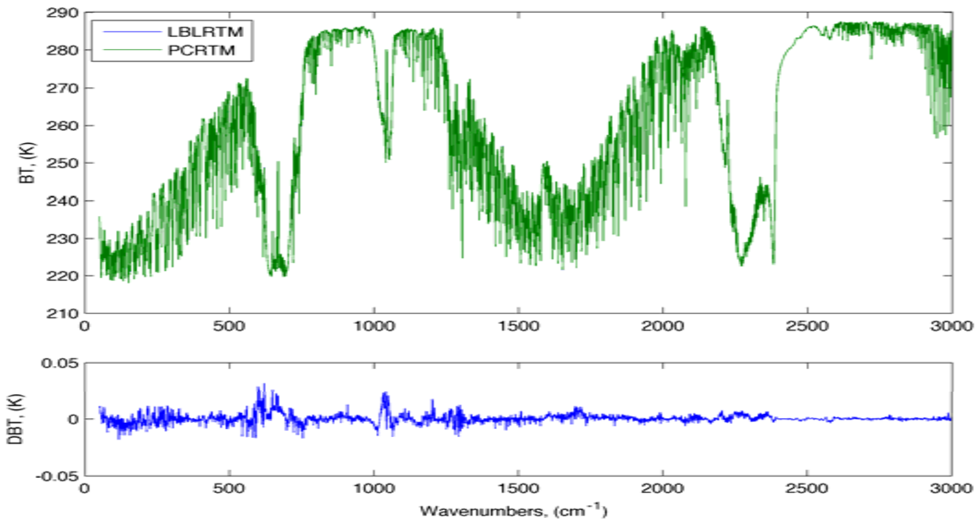
- Left figure shows TOA radiance as a function of satellite viewing angle and wavelength
  - Solar zenith angle is 30 degree, relative azimuth angle=0 degree
  - Ice cloud (cloud height 11 km, optical depth: 30)
  - ΔR represents the difference between the TOA radiance at various viewing angles and at Nadir

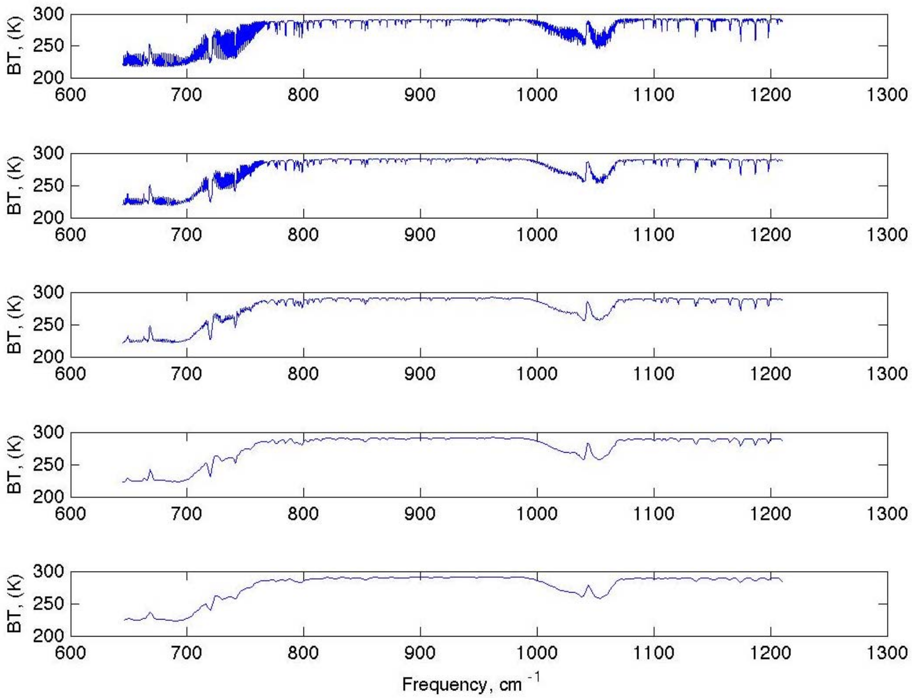
- Right figure shows TOA radiance as a function of satellite viewing angle and wavelength
  - Solar zenith angle is 30 degree, relative azimuth angle=0 degree
  - water cloud (cloud height 10 km, optical depth: 5)
  - ΔR represents the difference between the TOA radiance at various viewing angles and at Nadir



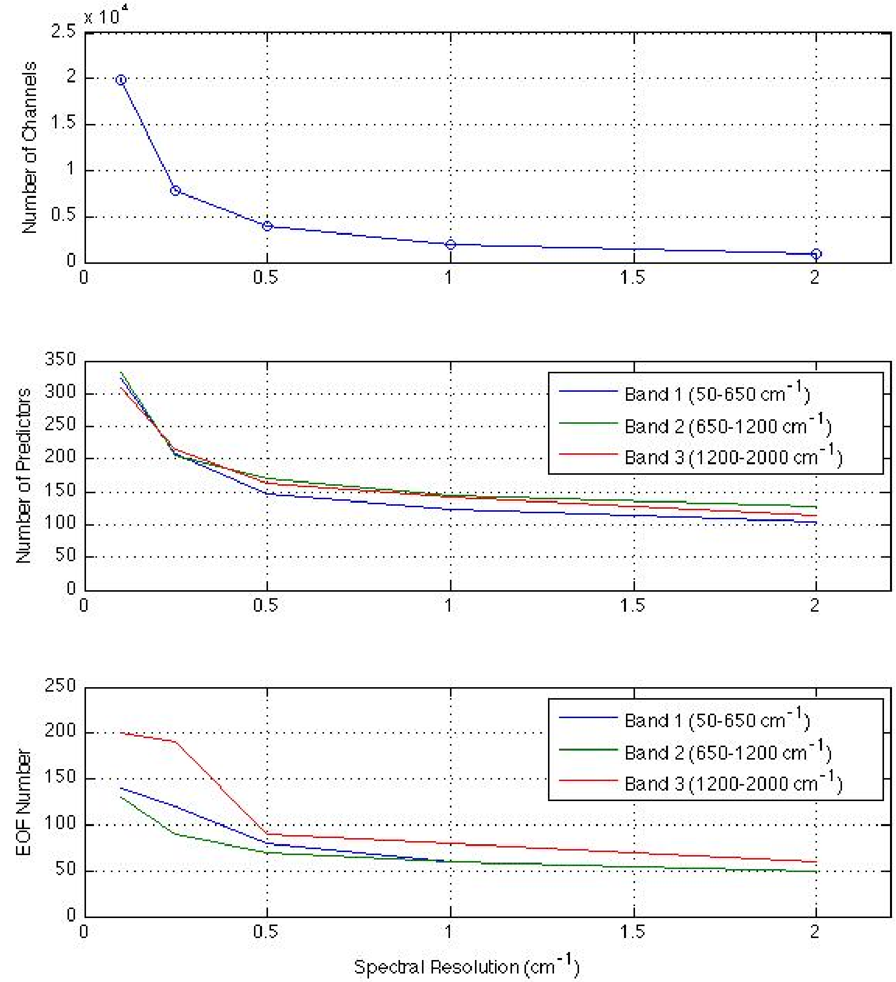


Information content as a function of spectral resolution



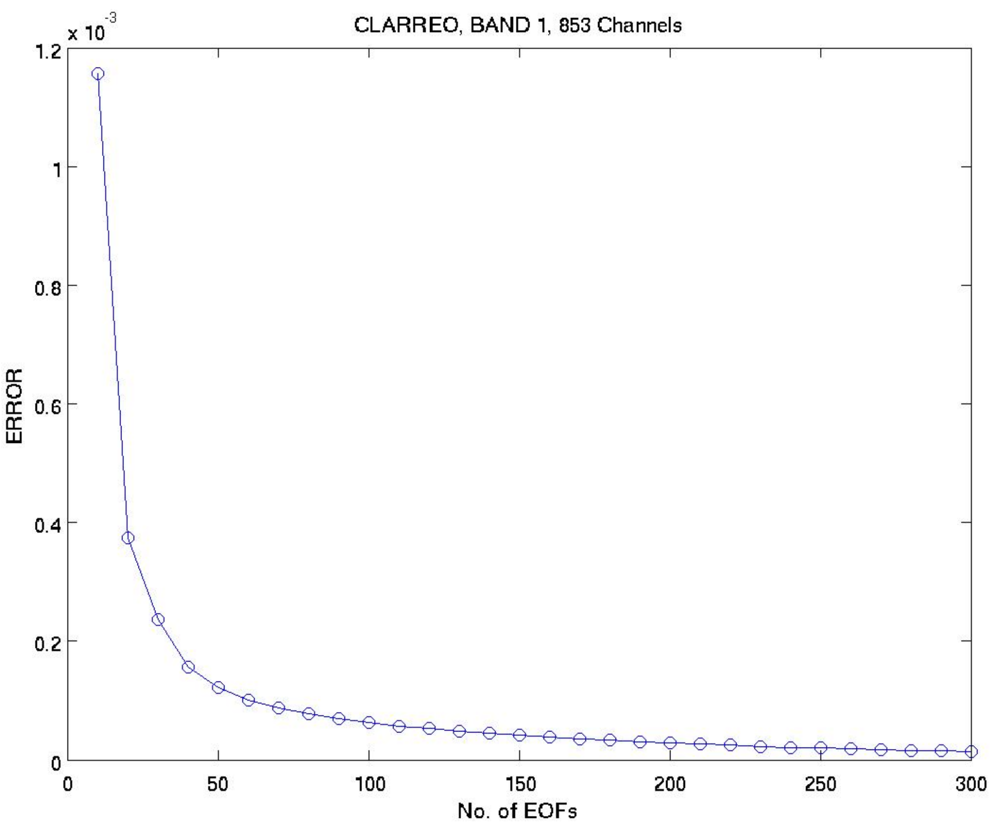


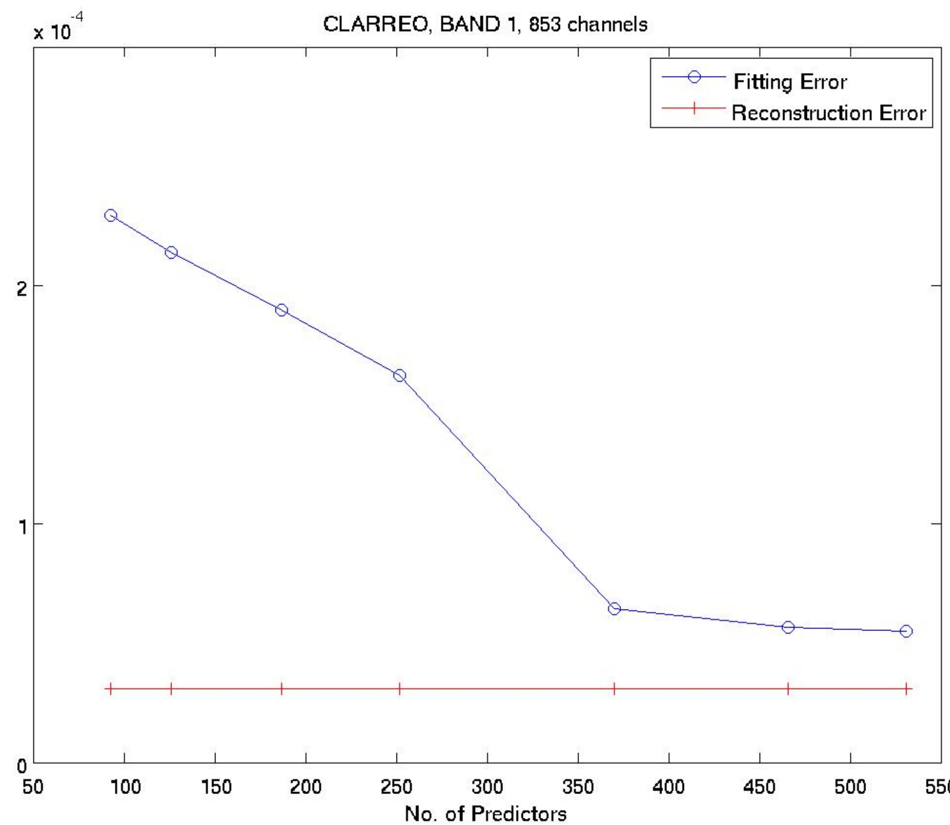
- 0.1 cm^{-1}, 0.25 cm^{-1}, 0.5 cm^{-1}, 1.0 cm^{-1}, and 2.0 cm^{-1}
- 0.1 cm^{-1} model can be used to generate lower spectral resolution instrument forward models
- Reduce >1 million mono RT to < 1000
- EOF and mono numbers decrease with resolution



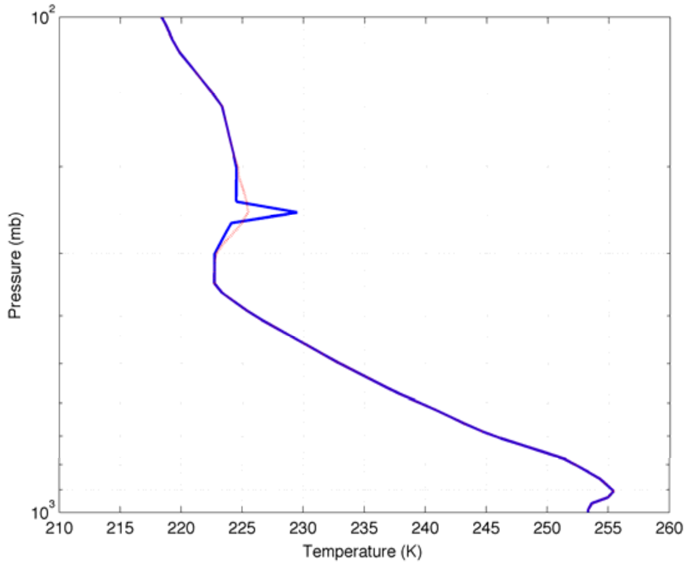
Information content as functions of EOF number and predictor number

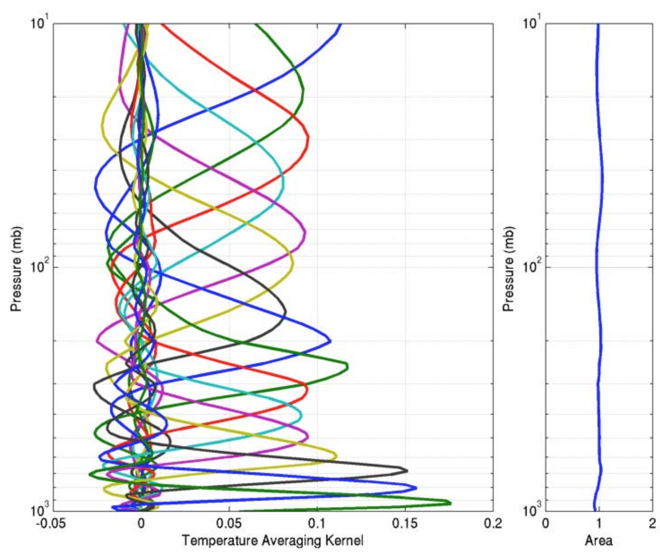
- For a given spectral resolution, the number of EOFs needed depends on your applications
- The first few leading EOFs contains most of the information content
- The PCRTM accuracy increases with the number of predictors
- Only small number of predictors are needed relative to the original monochromatic radiances





CLARREO Information Content Analysis
(methodology)





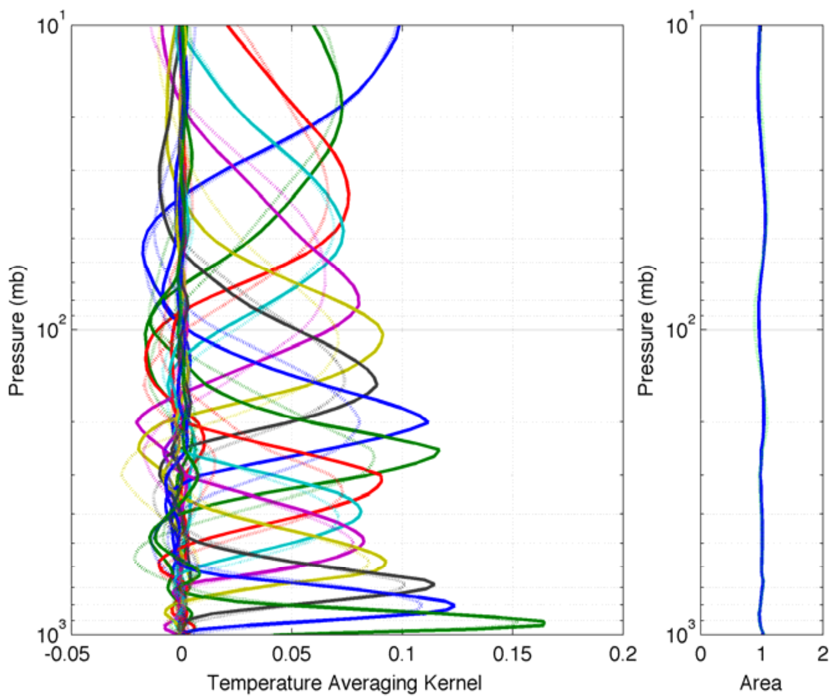
$$A_x = \frac{\partial x_n}{\partial x} = (K^T S_y^{-1} K + S_a^{-1})^{-1} K^T S_y^{-1} K$$

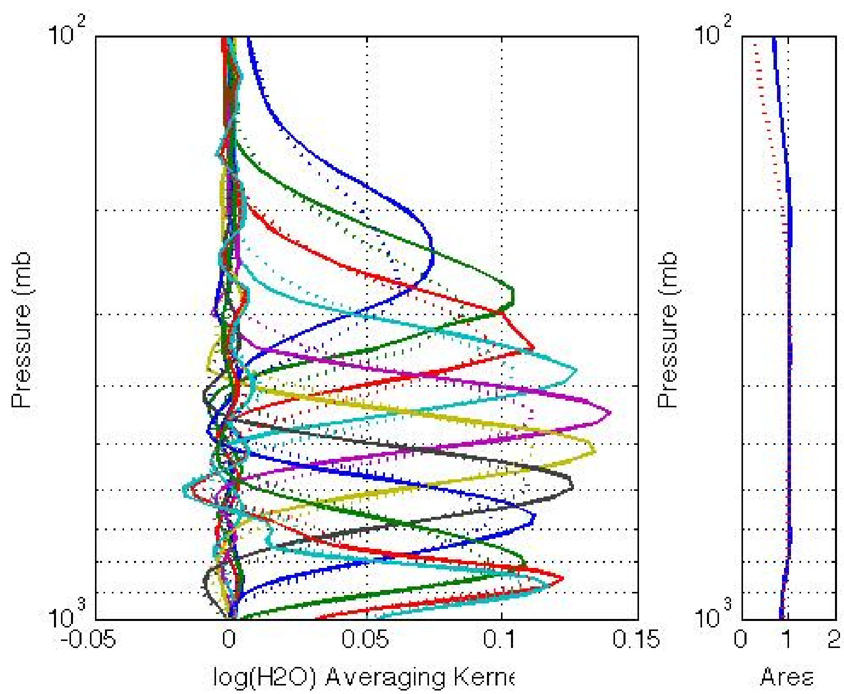
$$H_x = -\frac{1}{2}\sum_i \ln|I - A_x|, \quad d_x = tr(A_x)$$

- 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)

CLRREO Information Content Analysis
(Impact of Far IR band)

- The baseline spectral resolution for this study is 1.0 cm^{-1}
  - Need more realistic CLARREO instrument noise
- Far-IR impact on atmospheric vertical temperature information
  - The vertical resolution decreases without far-IR portion of the spectrum (dotted lines, DOF: 8.11 vs. 9.34)
- Far-IR impact on atmospheric vertical water information
  - The vertical resolution decreases without far-IR portion of the spectrum (dotted lines, DOF: 4.48 vs 6.13)
  - The far-IR band provide more information for higher altitude moisture
- There are other things to consider for Far-IR
  - Far-IR spectral region is essential in TOA long-wave radiance flux calculation
  - Far-IR provides more constraints on atmospheric clouds

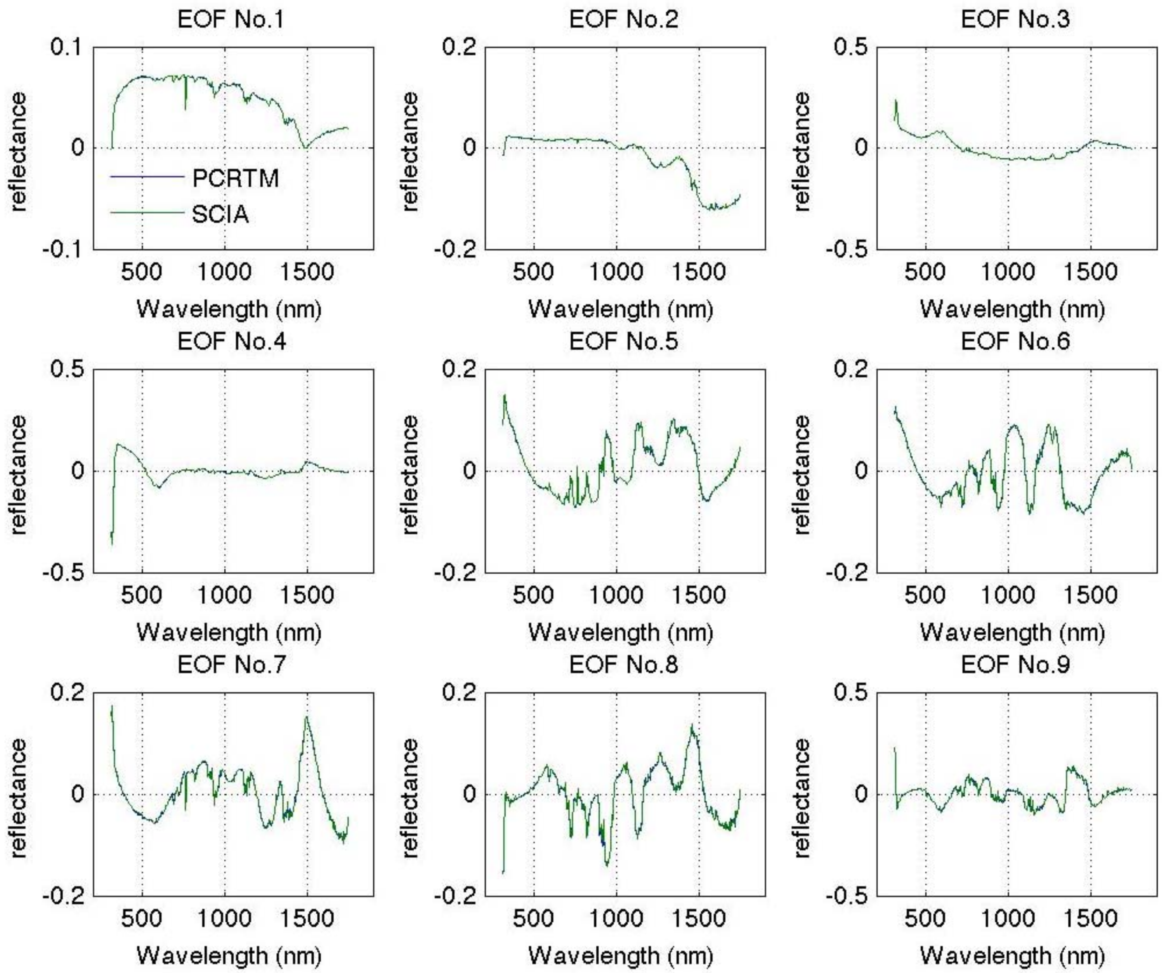




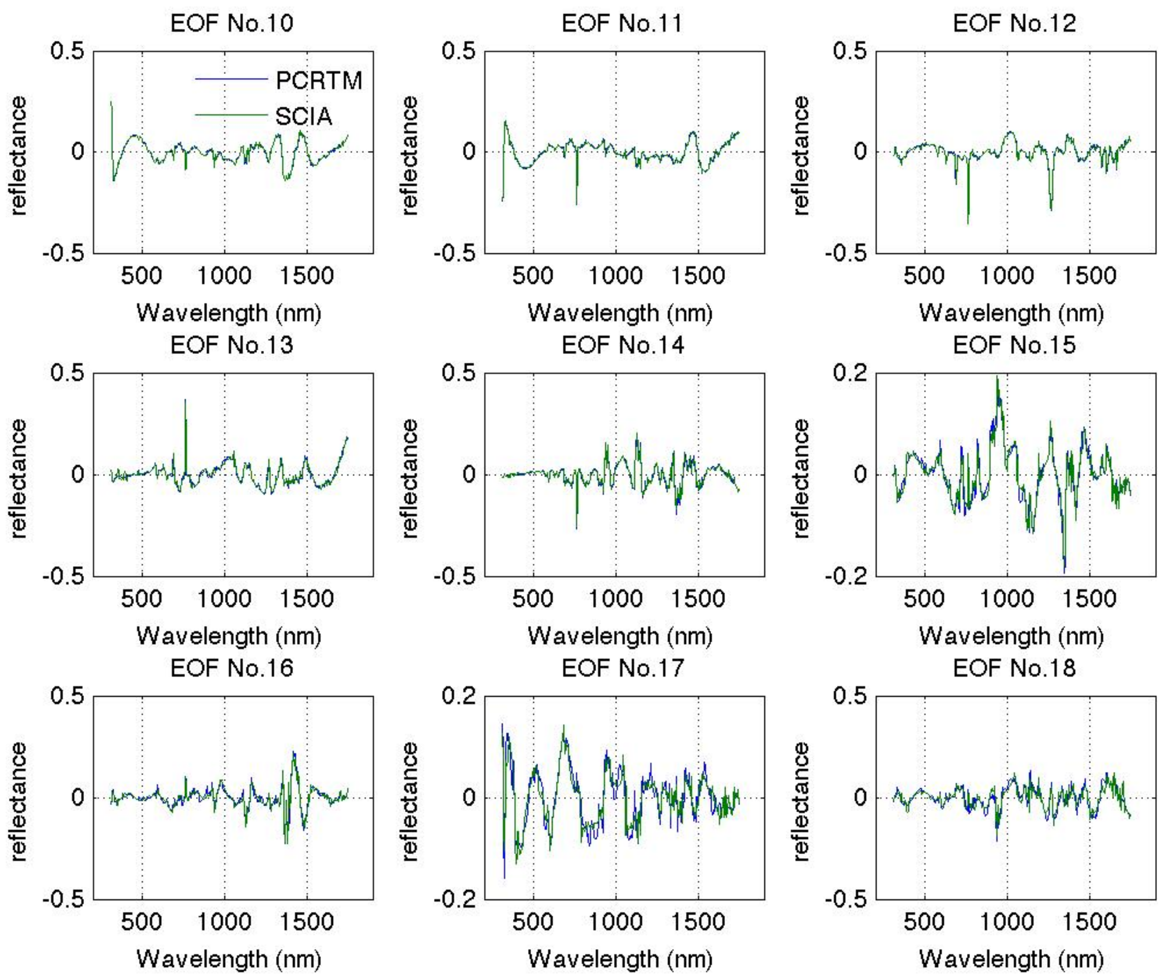
CLARREO proxy data generation

- 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

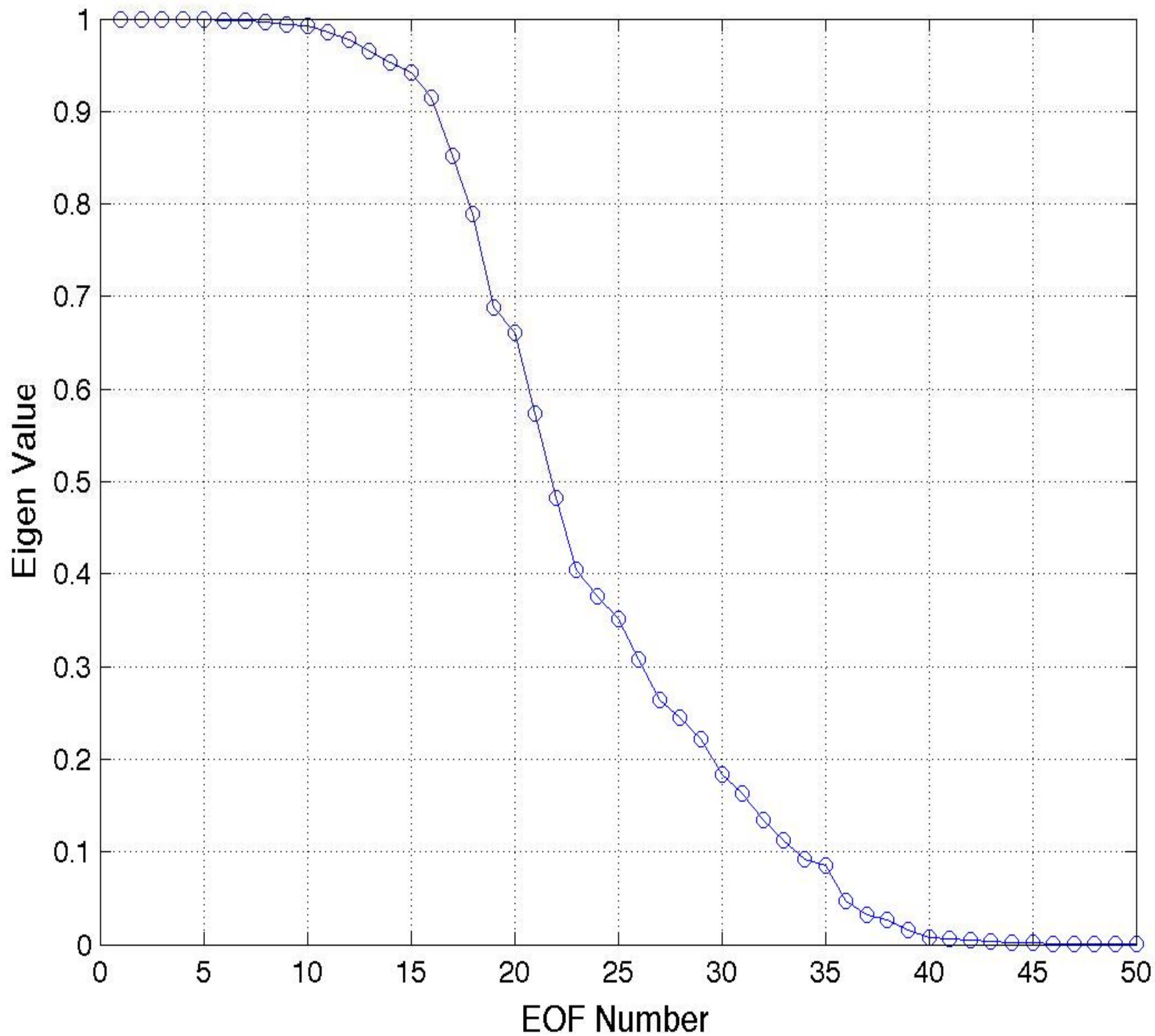
EOFs from both SCIAMACHY and PCRTM



EOFs from both SCIAMACHY and PCRTM

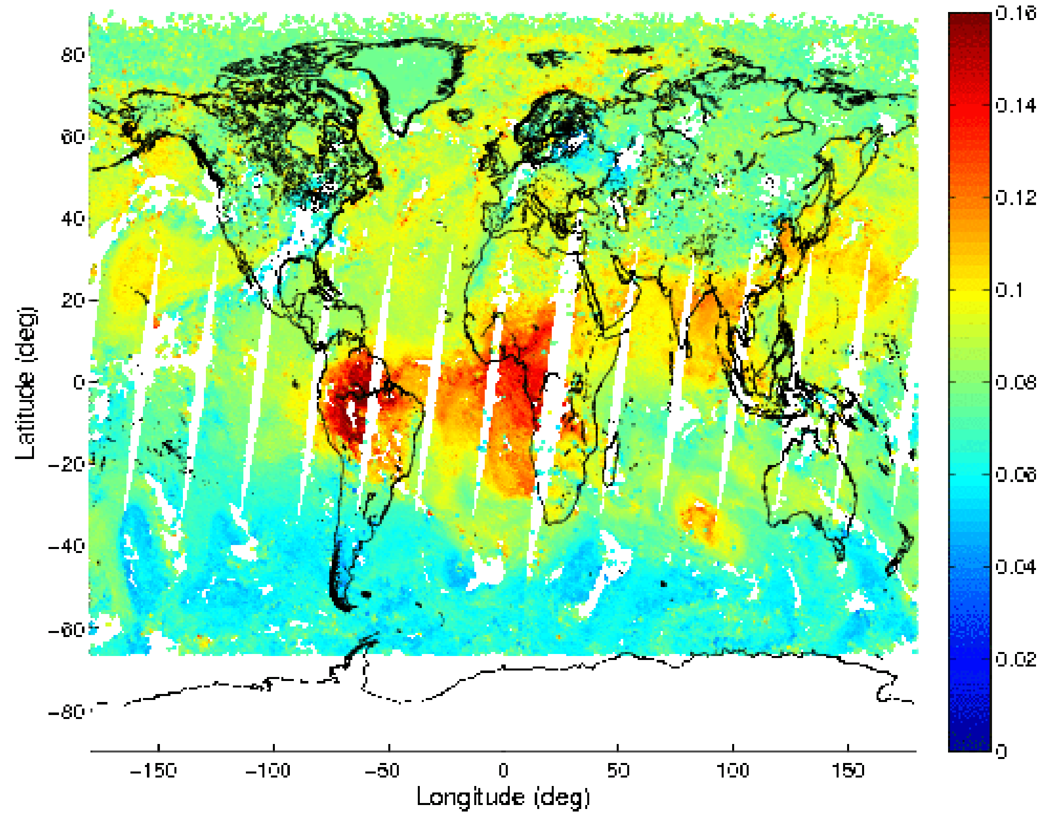


Eigenvalues from intercept PCA analysis



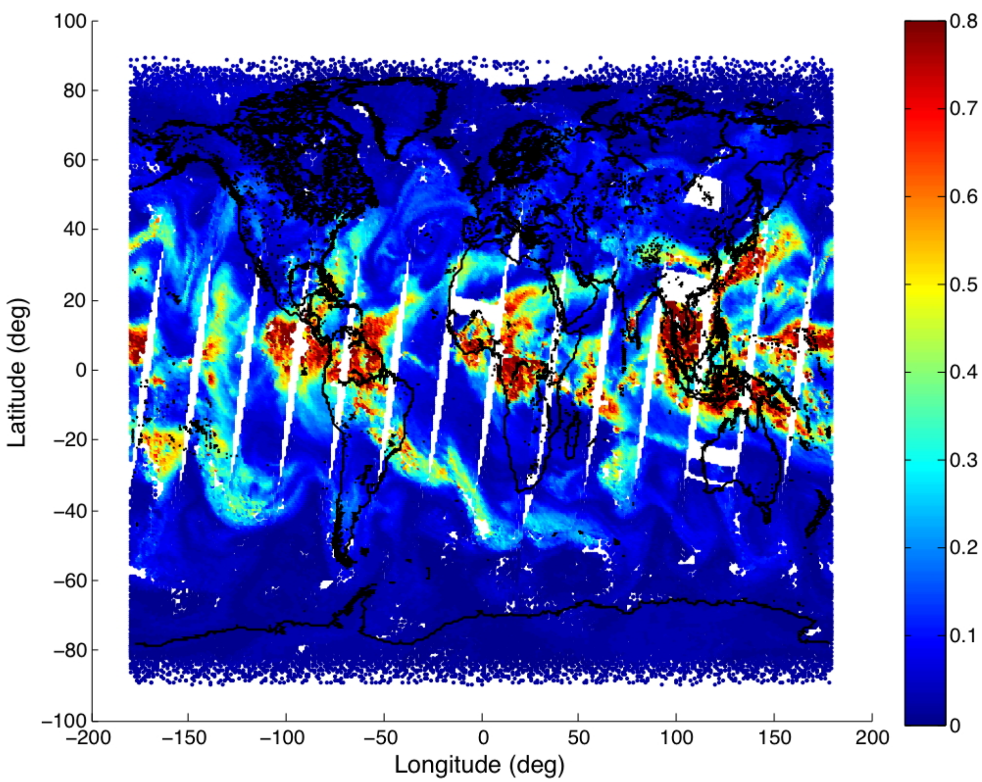
Atmospheric and Surface Property Retrieval using PCRTM

- PCRTM can be used to retrieve
  - Atmospheric temperature, water, O3, CO2, CO, CH4, and N2O vertical profiles
  - Cloud phase, height, temperature, particle size, optical depth
  - Surface emissivity, skin temperature
- The movie below shows global CO retrievals from December 21-27, 2016
  - CO mixing ratio at 300 mbar
  - Full spectral resolution CrIS data used

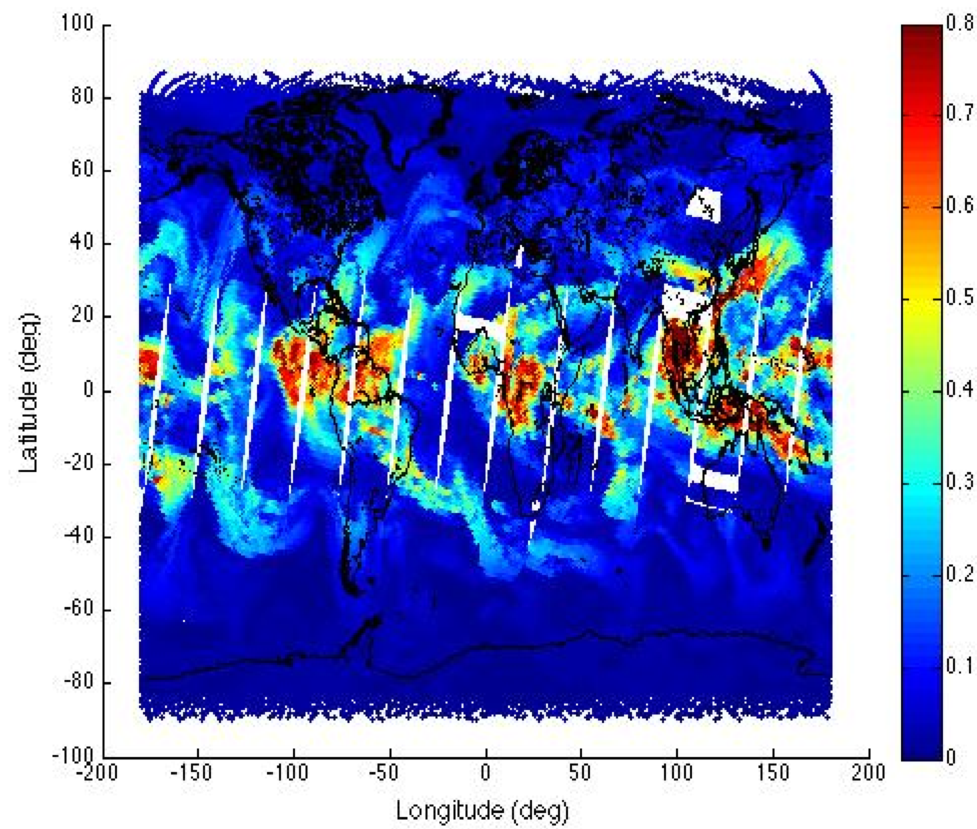


Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Water Vapor from focus day CrIS/ATMS data

Retrieved 300 hPa from CrIS/ATMS using PCRTM-RA

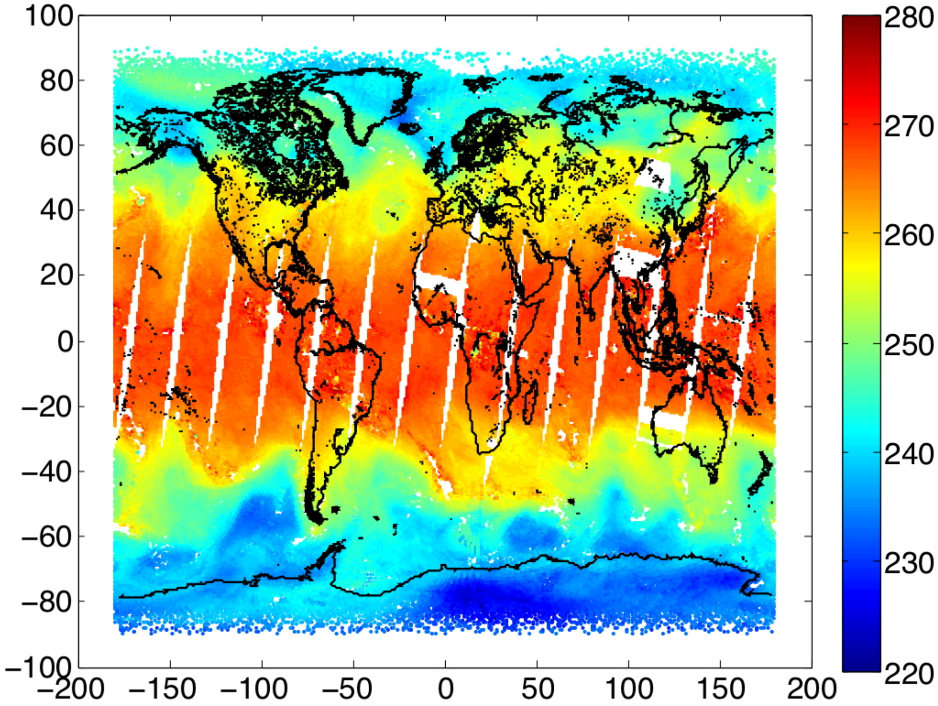


300 hPa from ECMWF

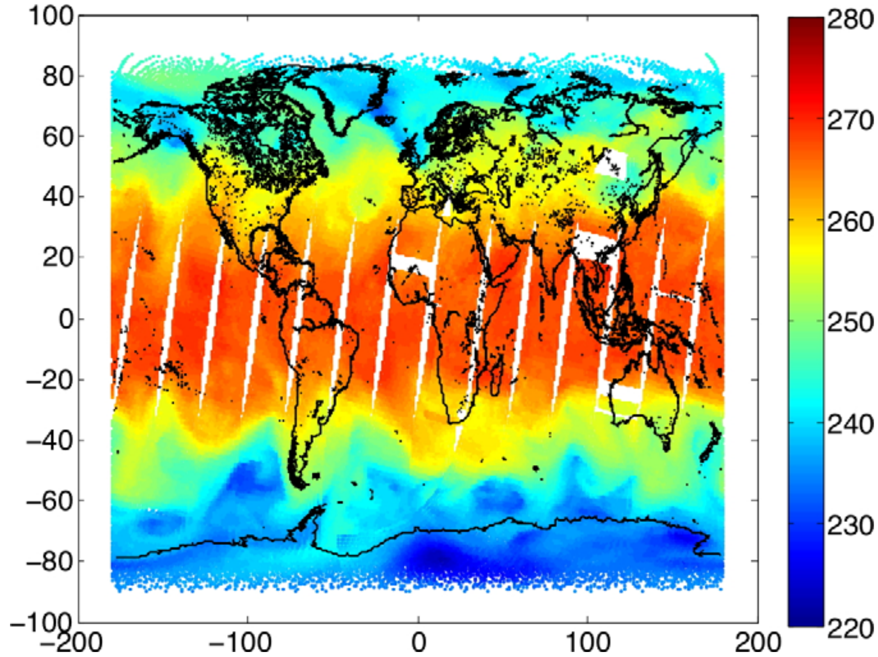


Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Temperature from focus day CrIS/ATMS data

500 hPa Retrieved from ATMS/CrIS using PCRTM_RA



500 hPa Temperature from ECMWF



Deriving Instrument Calibration Requirement based on spectral fingerprinting

- Quantify natural variability and derive the calibration requirement for geophysical constituents observation
  - Methodology outlined in BAMS paper by Wielicki et al.
  - Derive Natural variability of T(p) and H_2O(p) from MERRA and ECMWF reanalysis data
  - Climate model (CMIPS-5) provides additional validation
  - Derive vertical T(p) and H_2O(p) accuracy required for trend detection using natural variability and autocorrelation length
- Derive spectral dependent instrument requirement using fingerprinting method and the required actuary for T(p) and H_2O(p)
  - Frame work of the fingerprint method used
  - Fast radiative transfer model (PCRTM) is suitable for simulation study
  - Null space vertical error minimized by using EOF representation of the vertical profile.

Calibration requirement

Calibration requirement is established base on how the measurement uncertainty affect the climate trend detection uncertainty

$$U_a^2 = 1 + (\sigma_{cal}^2 \tau_{cal} + \sigma_{instru}^2 \tau_{instru} + \sigma_{orbit}^2 \tau_{orbit})/(\sigma_{var}^2 \tau_{var})$$

$$\sigma_{cal} = \sqrt{\frac{(U_a^2 - 1)\sigma_{var}^2 \tau_{var} - \sigma_{instru}^2 \tau_{instru} - \sigma_{orbit}^2 \tau_{orbit}}{\tau_{cal}}}$$

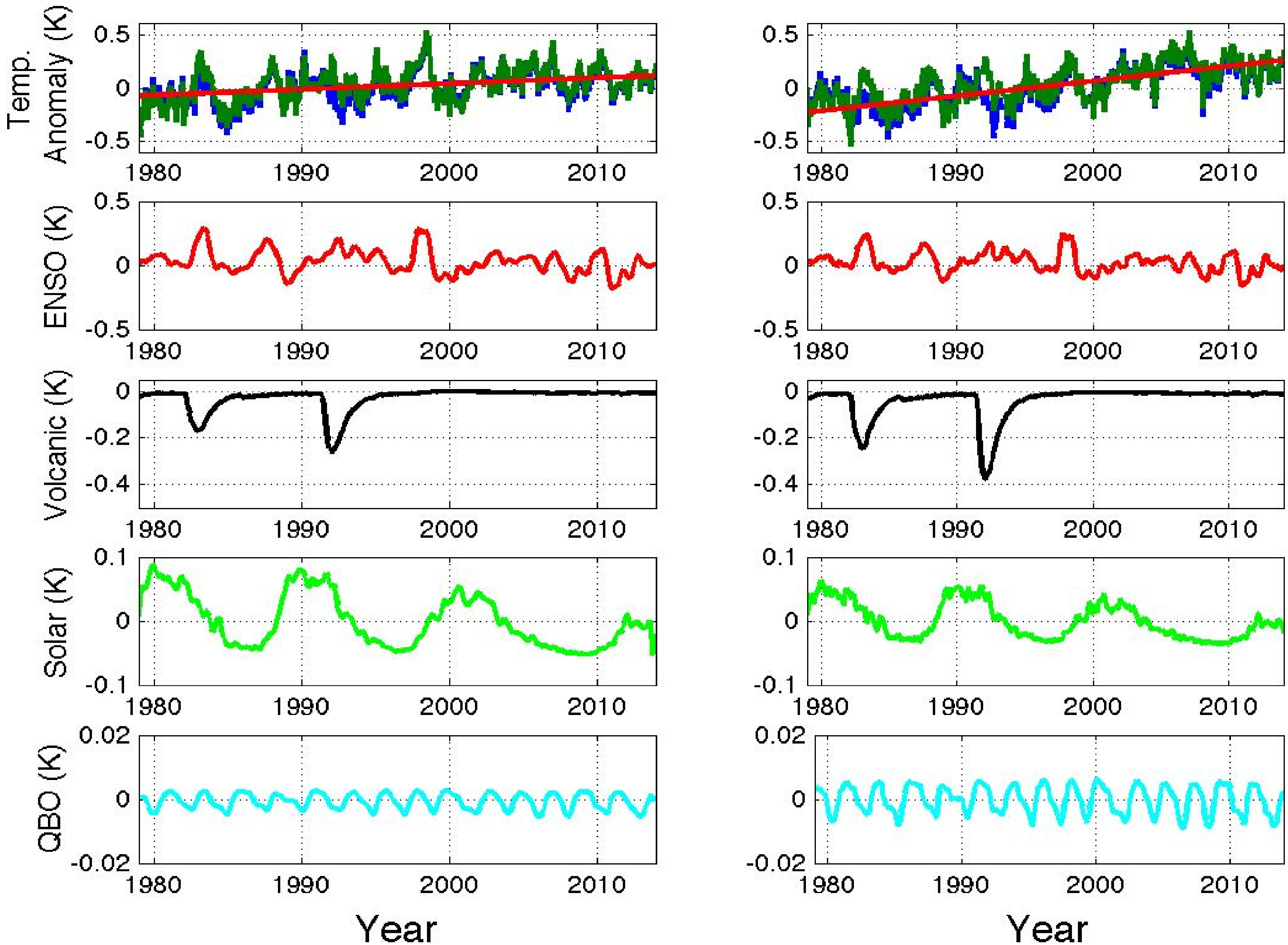
$$\sigma_{cal} = \sqrt{\frac{(U_a^2 - 1)\tau_{var}}{\tau_{cal}}}\ \sigma_{var}$$

- instrument noise contribution σ_{instru}, is small due vertical averaging
- orbit sampling error σ_{orbit}, is also neglected

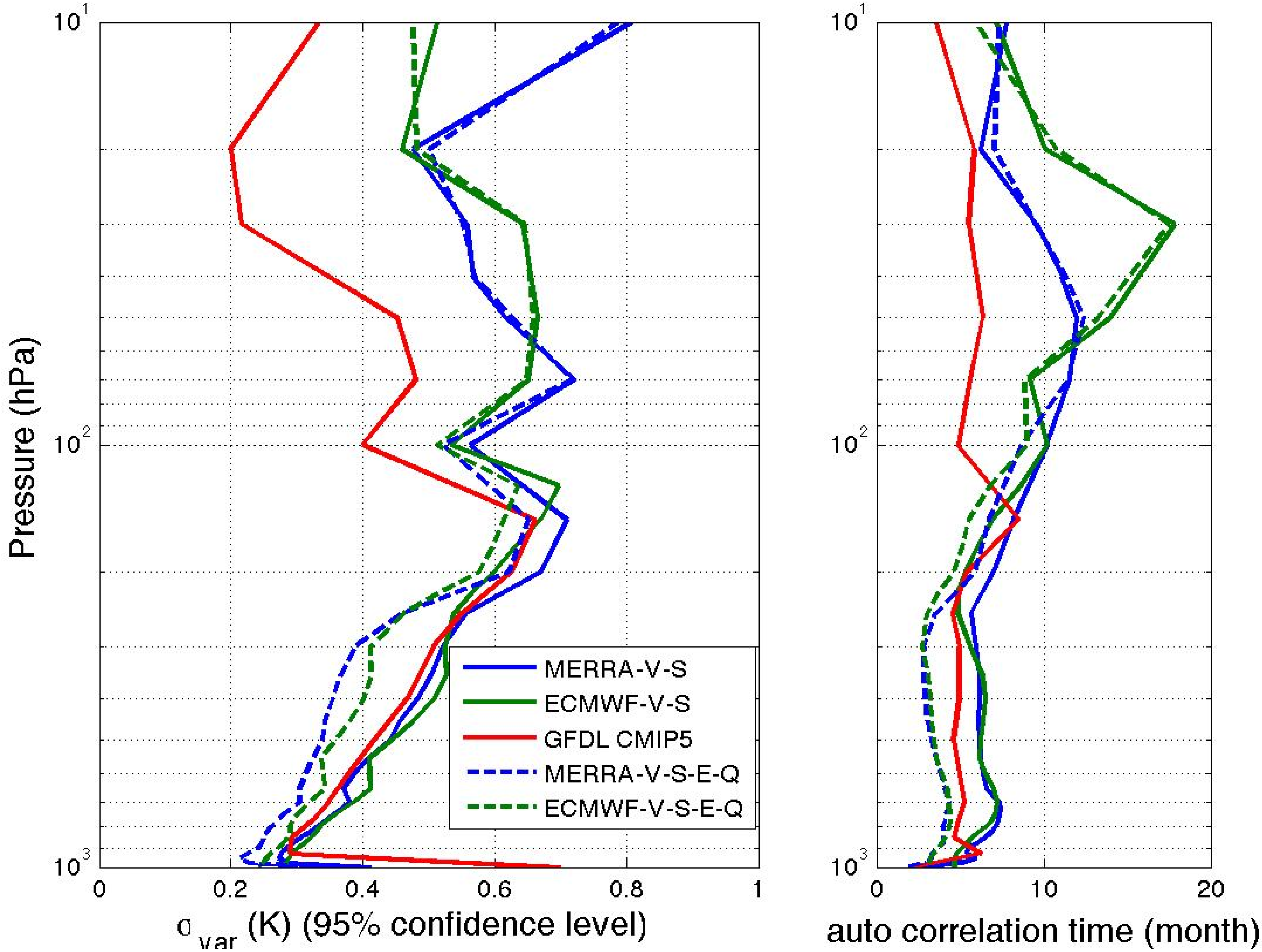
Accuracy uncertainty factor U_a (Wielicki et al. 2013) defines how CLARREO's observation accuracy for climate trends deviates from the accuracy of a perfect system

Bruce A. Wielicki, et al., 2013: Achieving Climate Change Absolute Accuracy in Orbit. *Bull. Amer. Meteor. Soc.*, 94, 1519–1539.

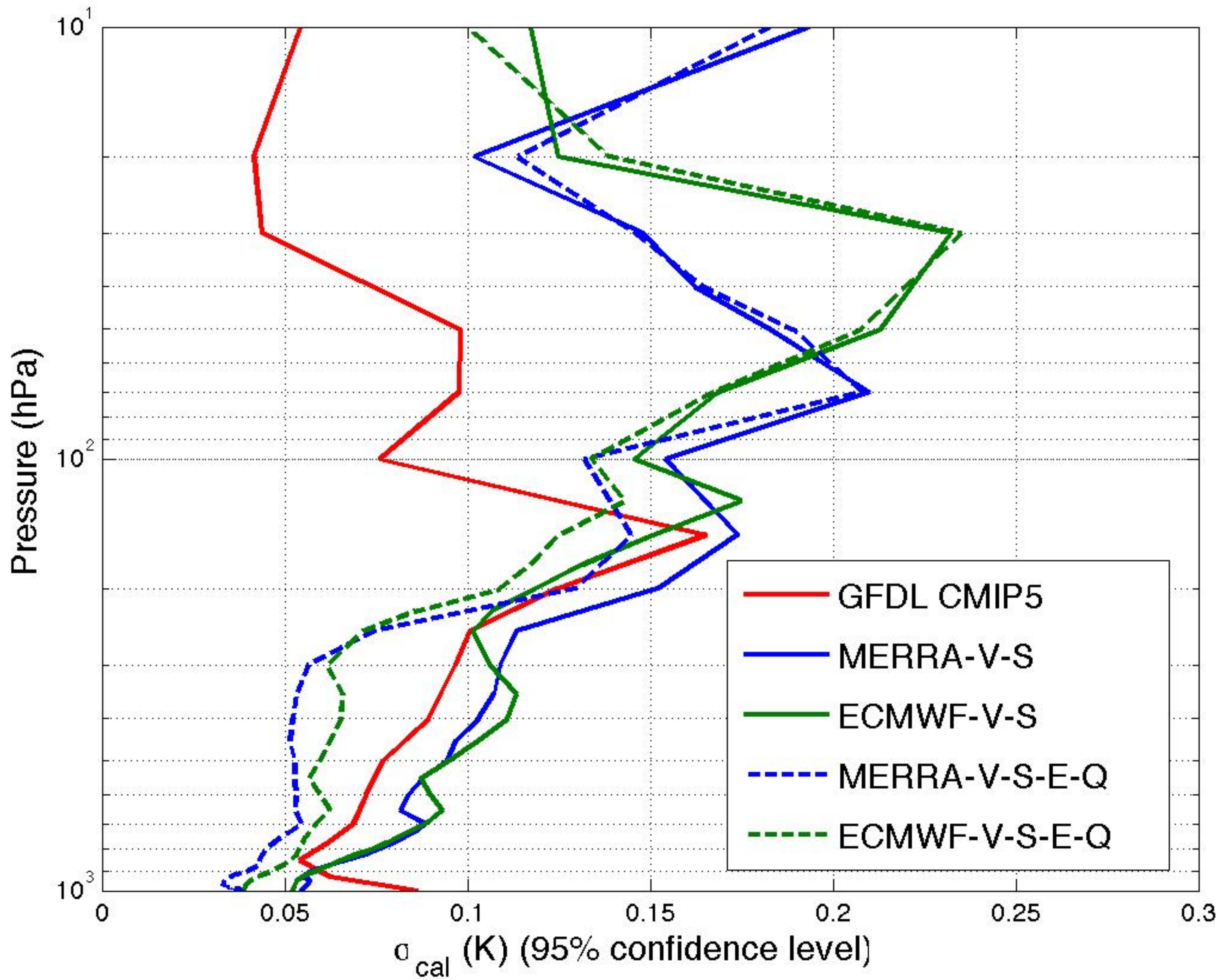
Temperature anomaly and linear trend @ 975hPa from MERRA and ECMWF



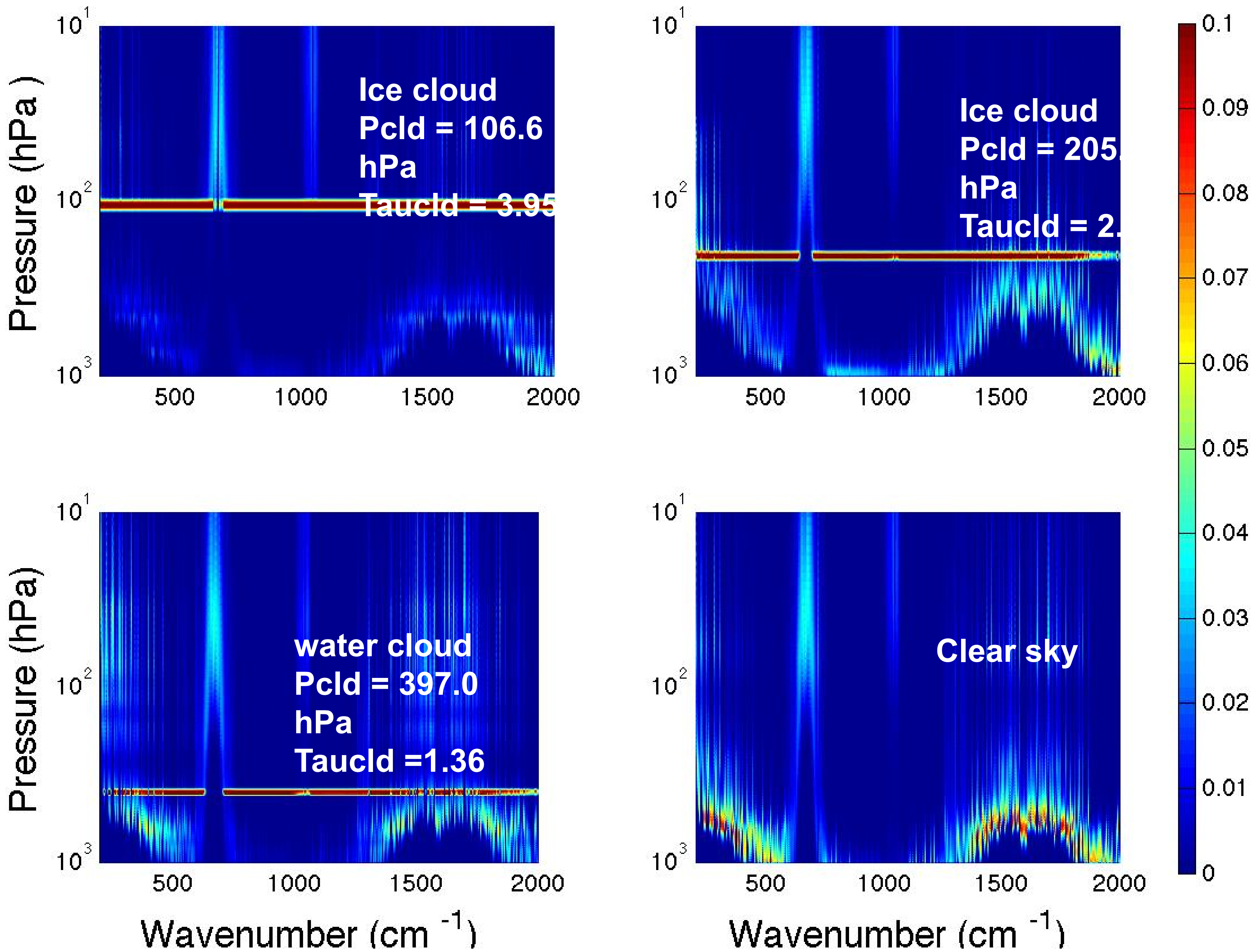
Temperature variability derived from MERRA, ECMWF and GFDL CMIP5



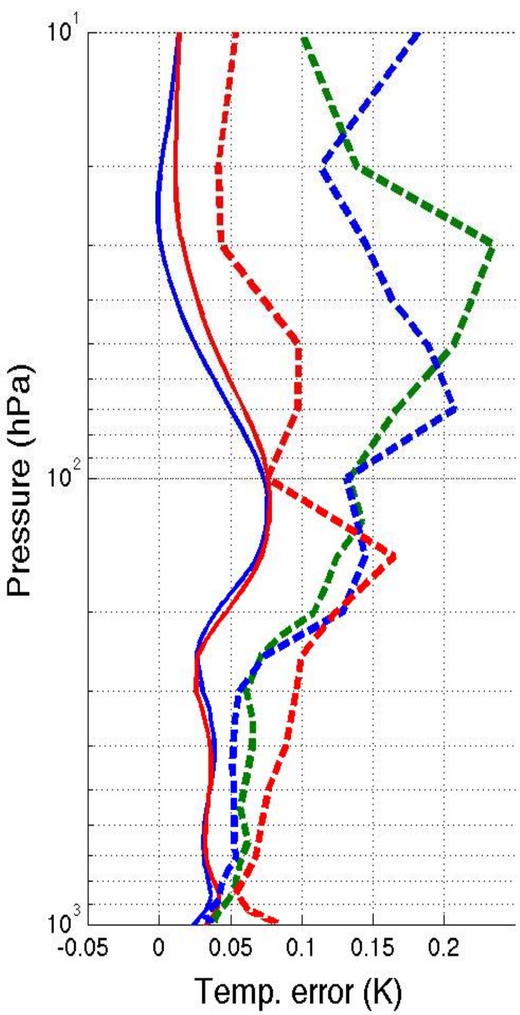
Temperature calibration requirement $U_a = 1.2$, $\tau_{cal} = 5$ years

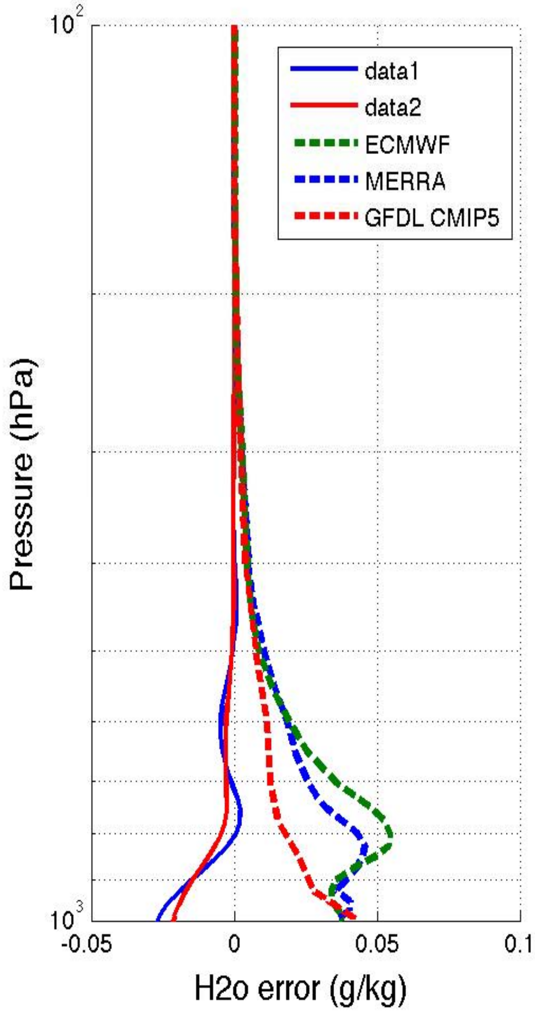


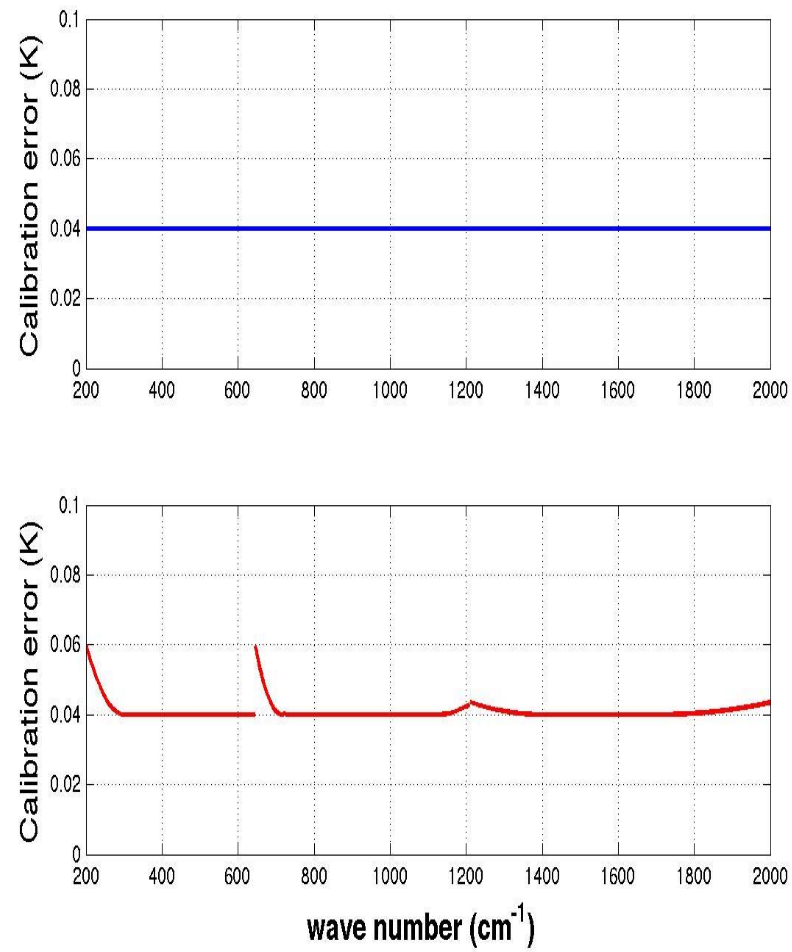
Temperature kernel matrix (Jacobian)



Spectral calibration errors and the associated error in temperature and humidity observation







Summary and conclusions

- PCRTM is different from channel-base forward models
  - Spectral correlations captured
  - Whole spectral information can be calculated efficiently
  - Both forward and inverse model can be done in EOF domain
  - It has capability of handling multiple scattering calculations
  - Accurate relative to line-by-line models
  - PCRTM has been trained to work from far-IR to UV-Vis spectral regions
- PCRTM has been applied to numerous existing and planned hyperspectral sensors: AIRS, IASI, CrIS, NAST-I, SCIAMACHY,CLARREO..
  - Information content analysis and sensor trade studies
  - Realistic global long term data simulations and OSSE experiment
  - Satellite data analysis and data assimilations
  - Retrieved parameters include
    - Atmospheric emperature, Water, CO_2, CO, CH_4, O_3, and N_2O profiles
    - Cloud phase, height, temperature, size, optical dpeth
    - Surface emissivity spectrum and skin temperature