Explicit Retrieval of Cloud and Atmospheric Properties from CrIS, IASI, and AIRS

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Presentation outline

- Motivations
- Principal Component-based Radiative Transfer Model (PCRTM)
- PCRTM retrieval algorithm (PCRTM-RA) and applications
- 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 spectral channels are used in satellite data assimilations
  - 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
- Need a forward model that can treat cloud radiative transfer accurately and efficiently
  - Most of the sounder footprints contain cloud signatures
  - Cloudy radiance data assimilation is a big challenge
  - Current Cloud Clearing algorithm has limitations
    - Need to make assumptions about the inhomogeneity of the scene
    - Hard to characterize the error of the cloud cleared radiances and products
- PCRTM (Principal Component-based Radiative Transfer model) was developed to satisfy the need listed above
  - Initially developed in 2004
  - Extends from 50 cm^{-1} (200 μm) to 33333 cm^{-1} (300 nm)
  - Milliseconds per spectrum in IR
  - 2-3 orders of magnitude faster than MODTRAN in solar spectral region
  - 10% extra computation to include multiple scattering clouds

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

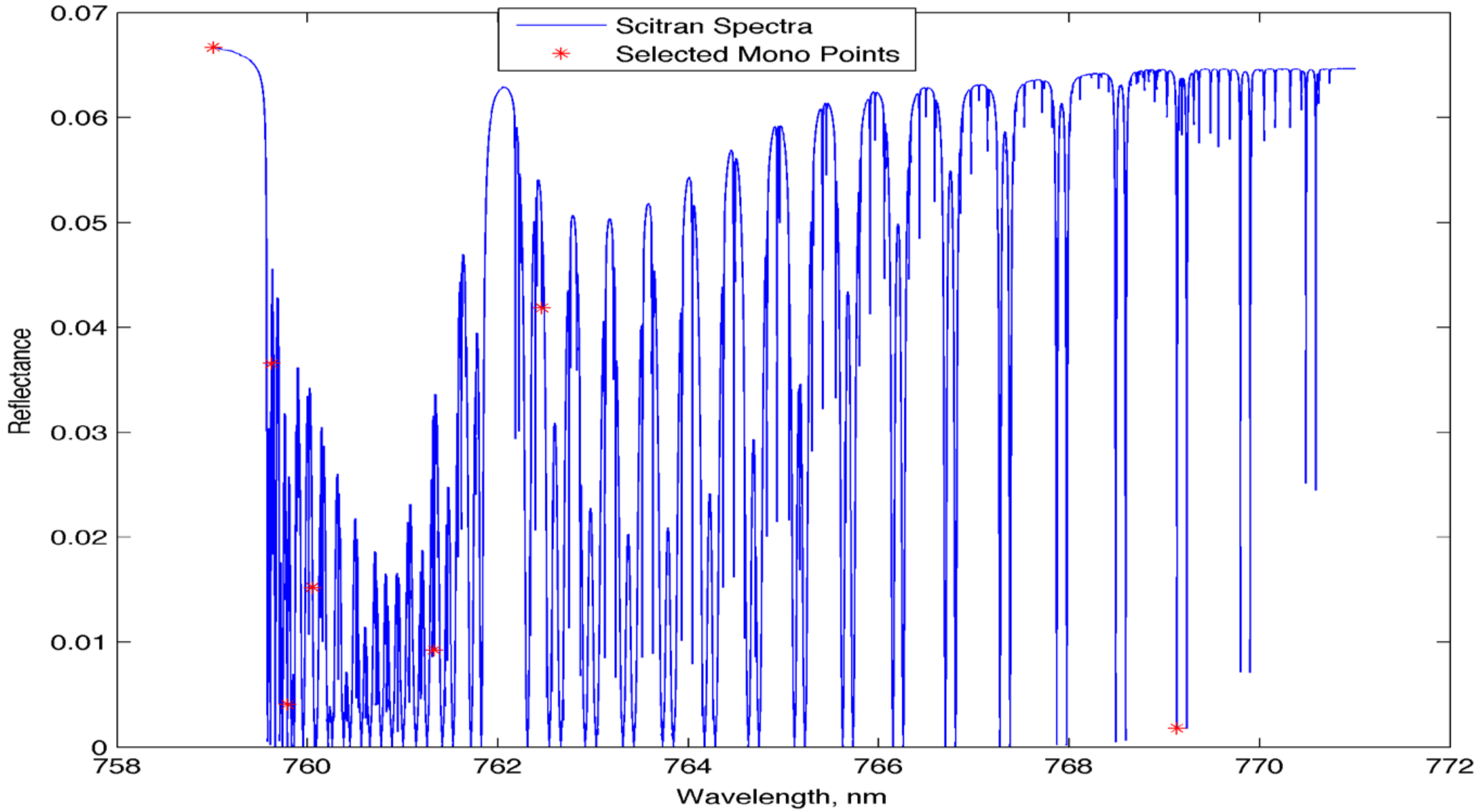
$$y_i = \vec{R}^{ch} \times U_i = \sum_{j=1}^{N_{mono}} \phi_j R_j^{mono} \vec{U}_i = \sum_{j=1}^{N_{mono}} A_j R_j^{mono}$$

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

  - 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

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



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 years 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

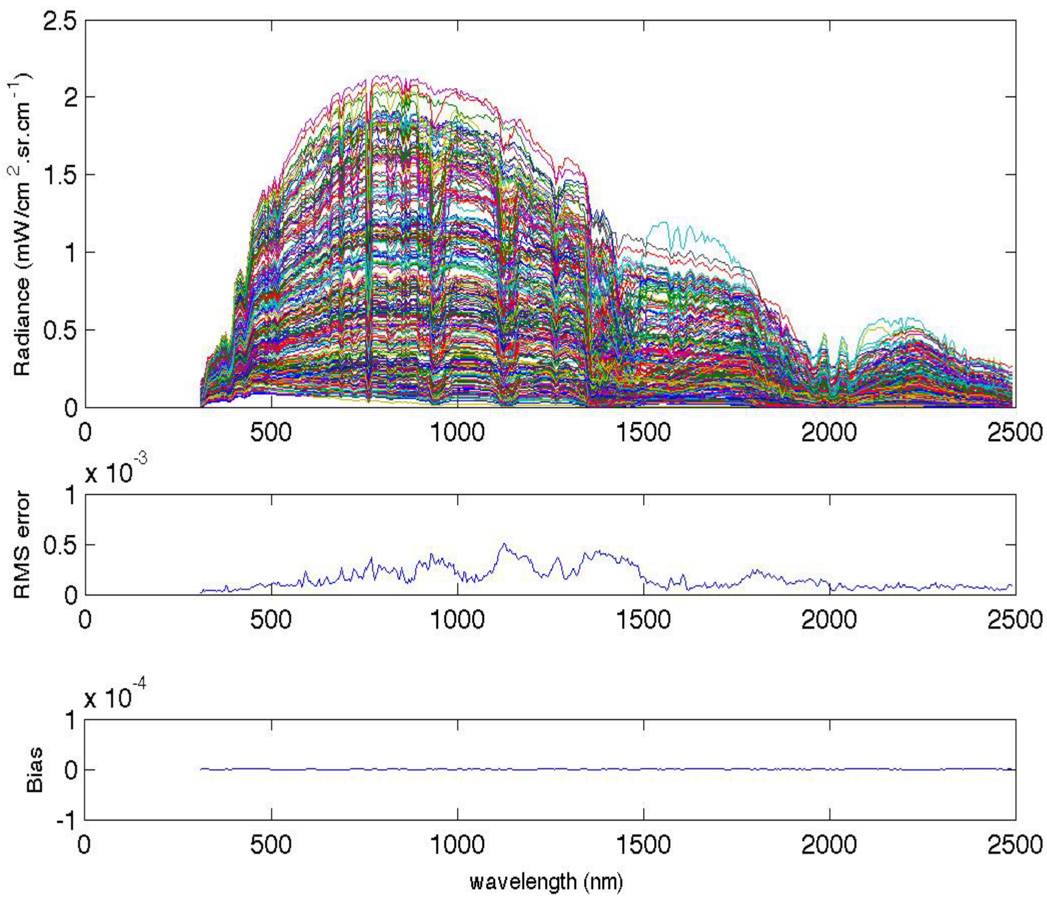
Computational Speed in IR Spectral Region

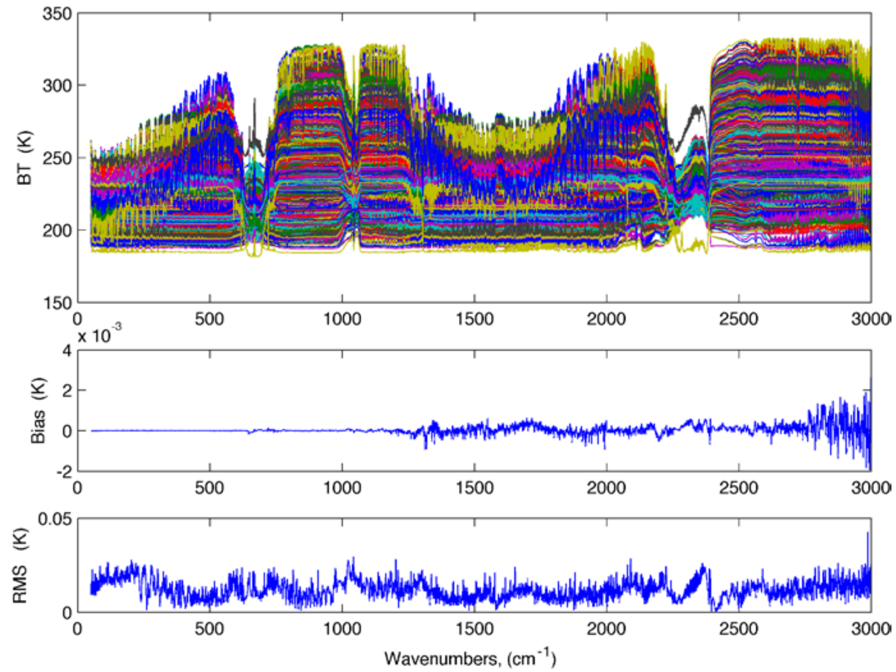
Sensor	Channel Number	PC score (seconds)	PC score + radiance	PC score + PC Jacobian
CLARREO, 0.1 cm^{-1}	19901	0.014 s	0.022 s	0.052 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s	0.013 s	0.039 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s	0.012 s	0.036 s
IASI, 0.25 cm^{-1}	8461	0.011 s	0.012 s	0.044 s
AIRS, 0.5-2.5 cm^{-1}	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

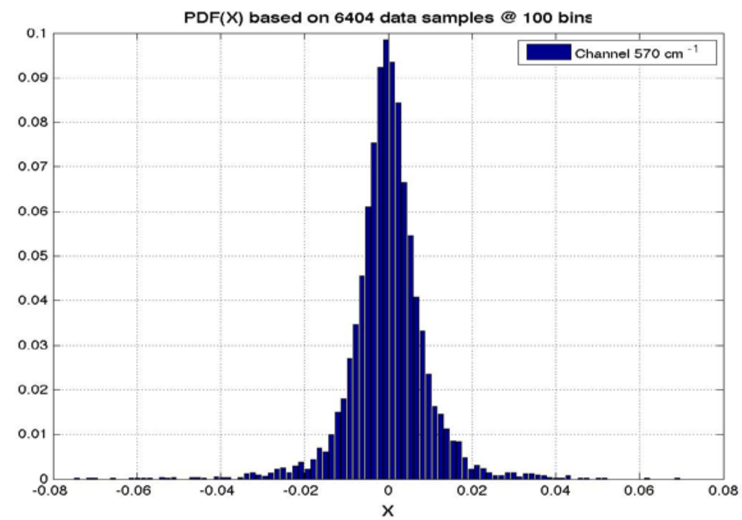
- CrIS, CrIS-full-res, IASI, NAST-I and S-HIS have multiple databases corresponding to different apodization functions including unapodized spectra
- Spectral coverage (50-3000 cm^{-1})
- Multilayer, multiple scattering clouds included
- 15 variable trace gases
- It provide radiative kernel/Jacobian with minimum additional computations
- Non-LTE included

Accuracy of PCRTM is very good relative to reference RT models

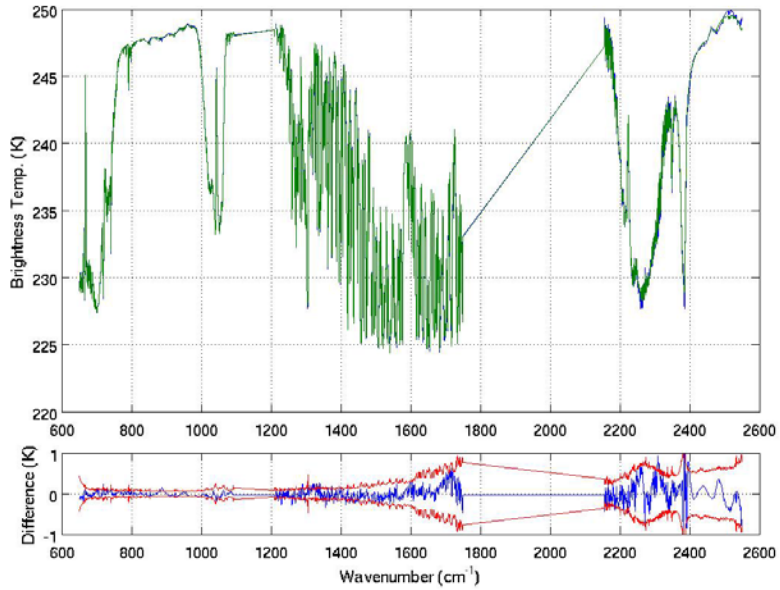
- Bias error relative to LBL is typically less than 0.002 K
- The PDF of errors at different frequencies are Gaussian distribution
- RMS error < 0.03K for IR and < 5×10^{-4} mW/cm^2/sr/cm^{-1} for solar (< ~0.02%)

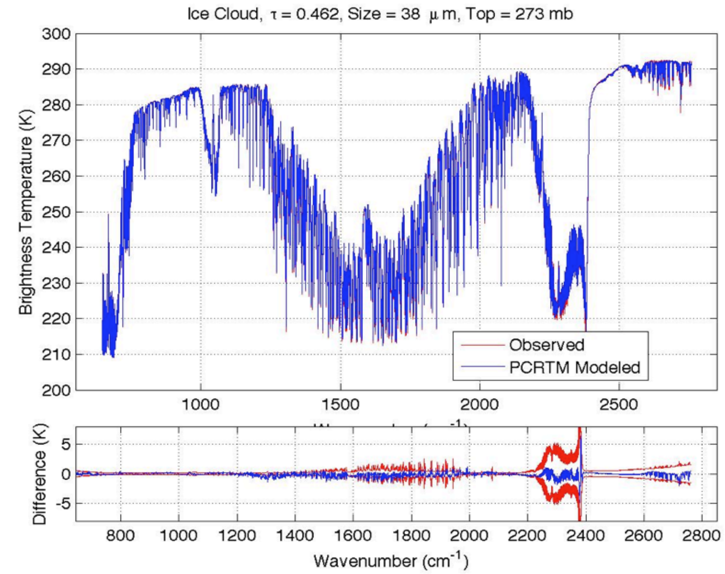


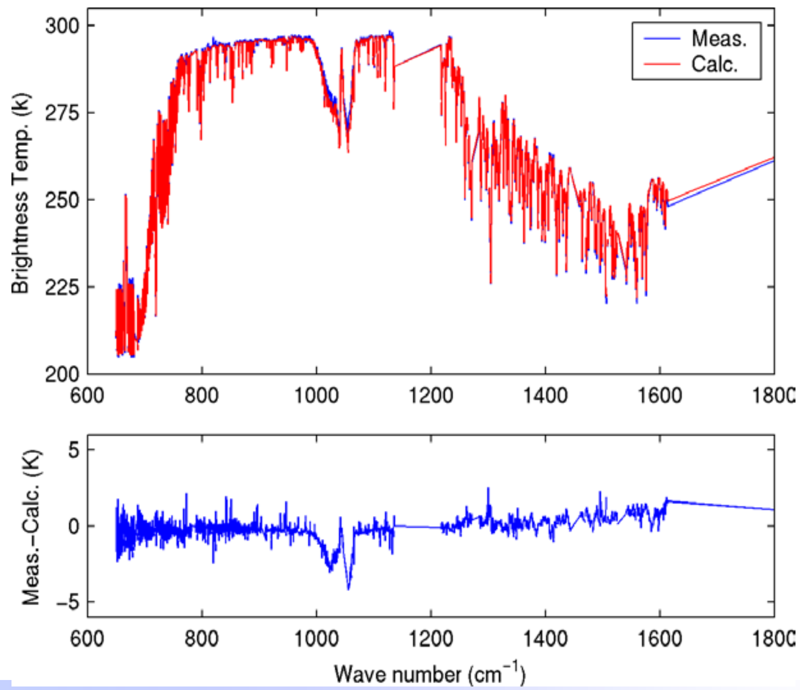


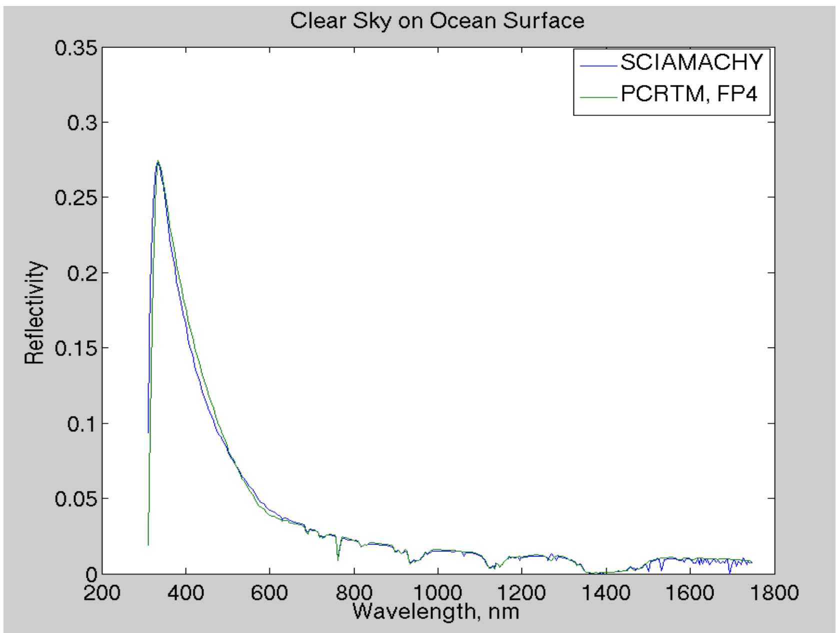


PCRTM has been validated using CrIS, IASI, AIRS, NAST-I, and SCIAMACHY real data

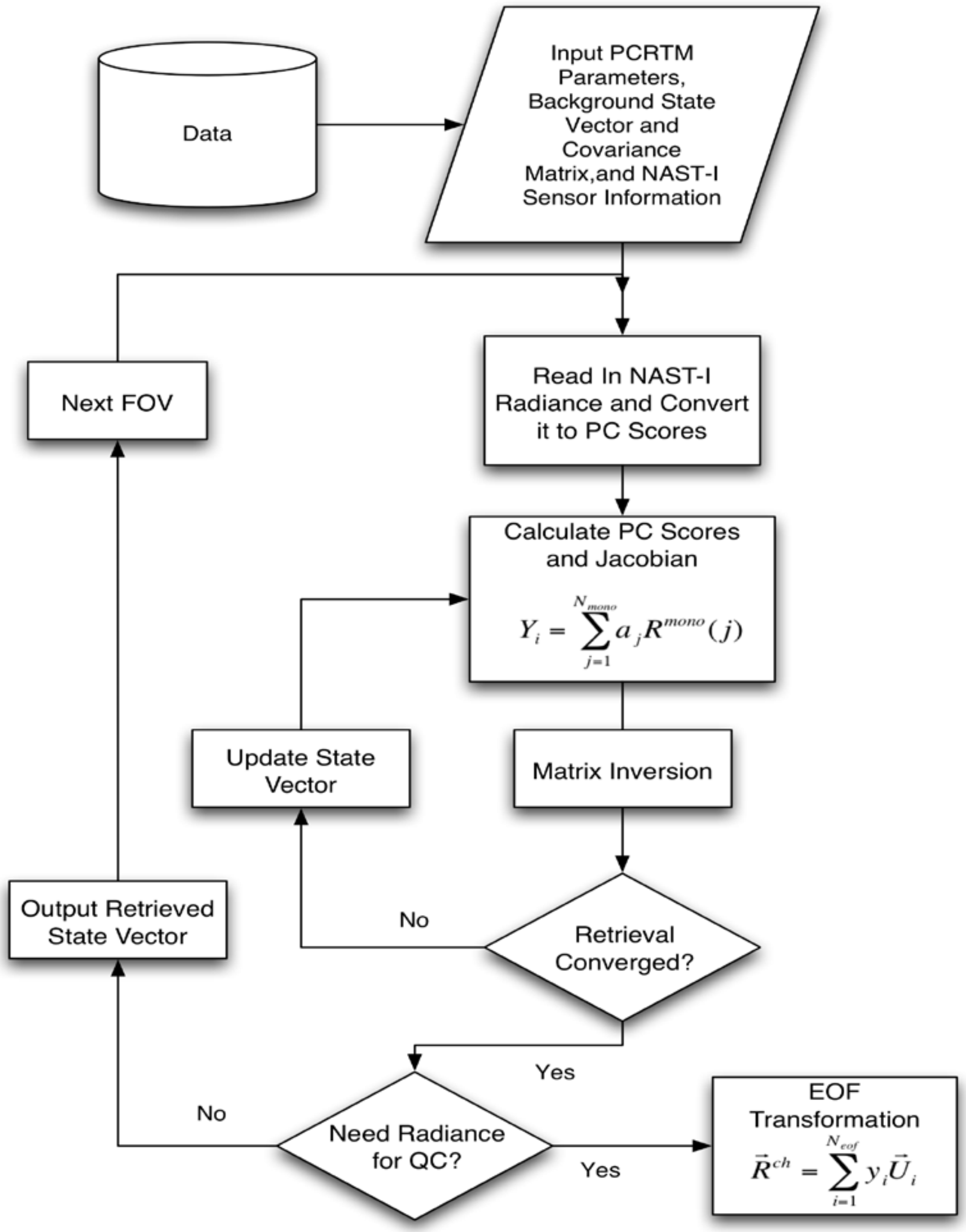








A brief description of the Optimal Estimation PCRTM Retrieval Algorithm (PCRTM-RA)



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

PCRTM models PC scores directly
- Small matrix and vector dimensions
- 100 super channels instead of thousands of channels
- Simply minimizing cost function
- Channel-to-channel correlated noise handled
- A Climatology covariance and background used as OE constraint
- Climatology background used as first guess

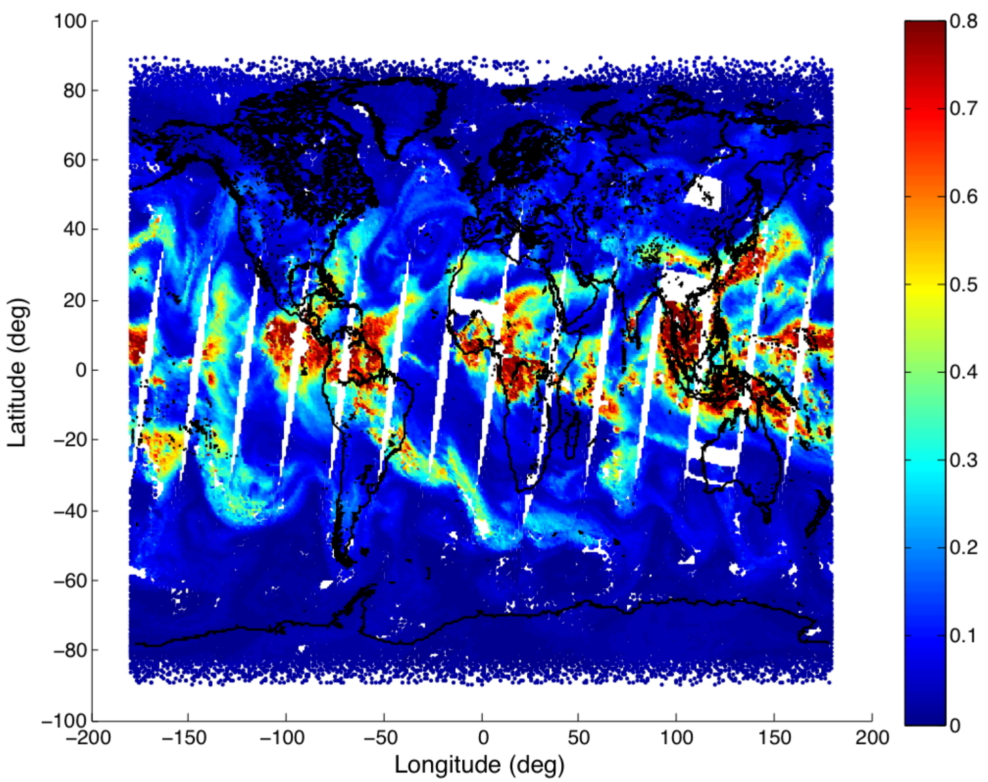
All parameters retrieved simultaneously
- No need to estimate errors of non-retrieved parameters
- Temperature
- Water
- Trace gases (CO2, CO, CH4, O3, N2O)
- Surface temperature and emissivities
- Cloud optical depth/size/phase/height/temperature
- Product error covariance and averaging kernel provided for each retrieval at not extra computational cost

MW retrieval capability added
- CRTM used as forward model
- PCRTM-RA can operate in 3 Modes
  - MW-only, IR-only, MW+IR

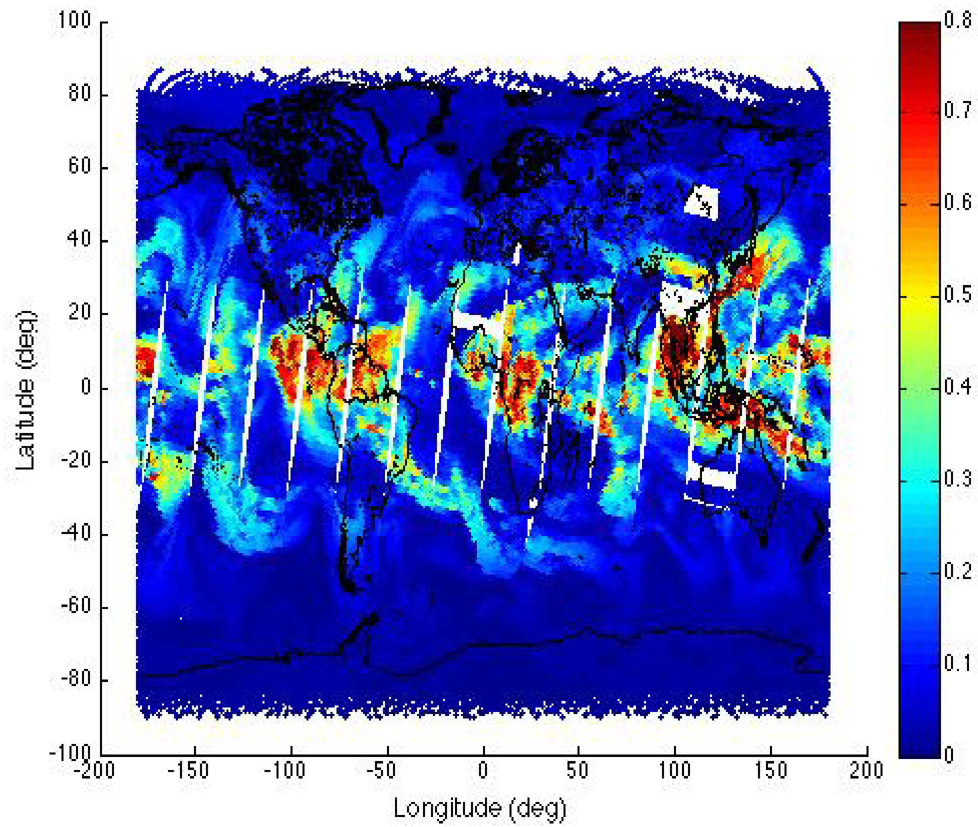
Example of Appying PCRTM-RA to CrIS/ATMS data

Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Water Vapor from 5-15-2012 focus day CrIS/ATMS data 90% convergence rate.

Retrieved 300 hPa from CrIS/ATMS using PCRTM-RA

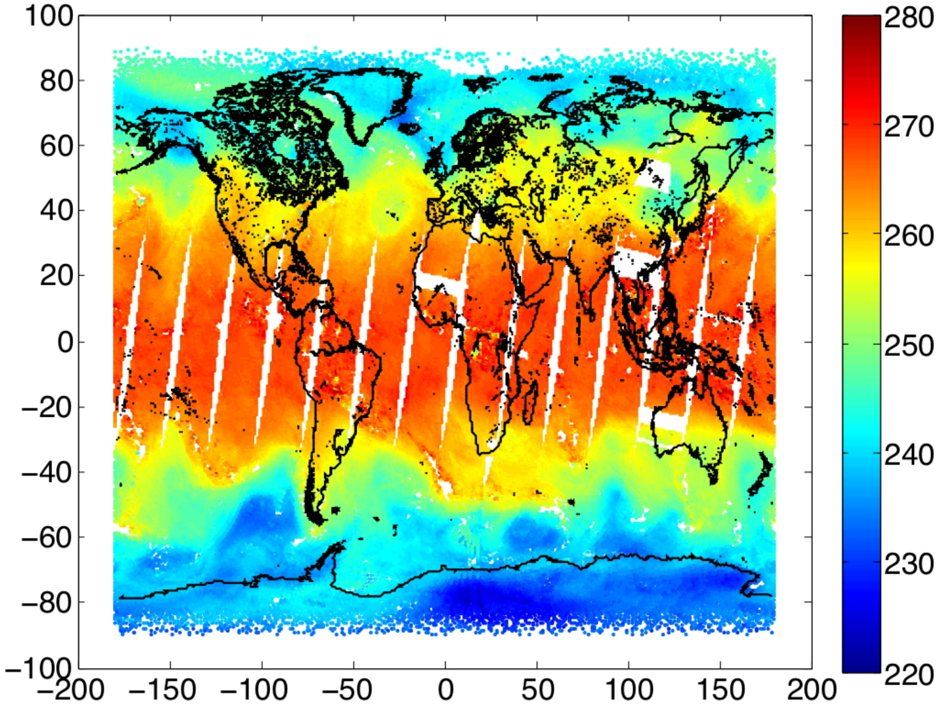


300 hPa from ECMWF

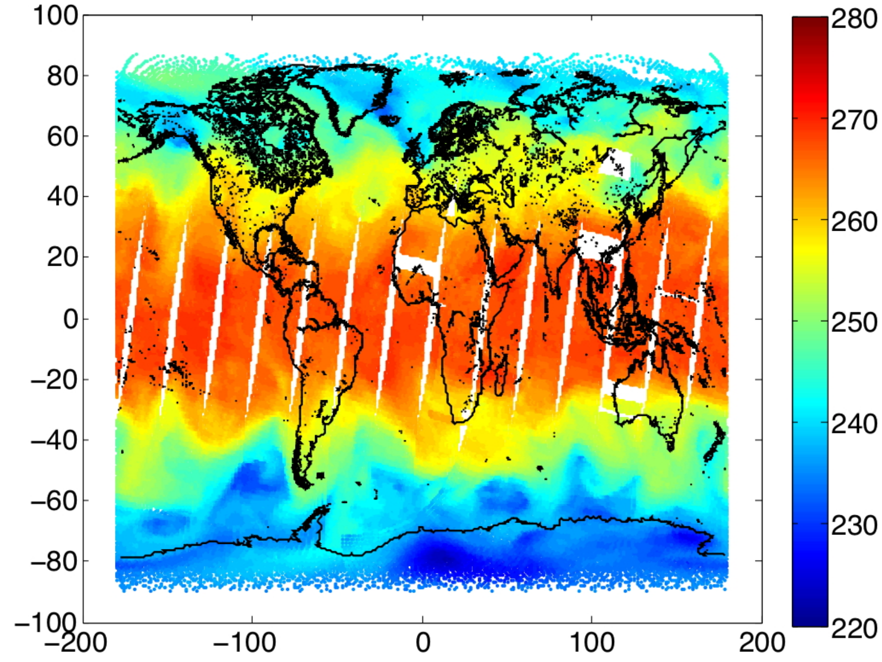


Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Temperature from 5-15-2012 focus day CrIS/ATMS data

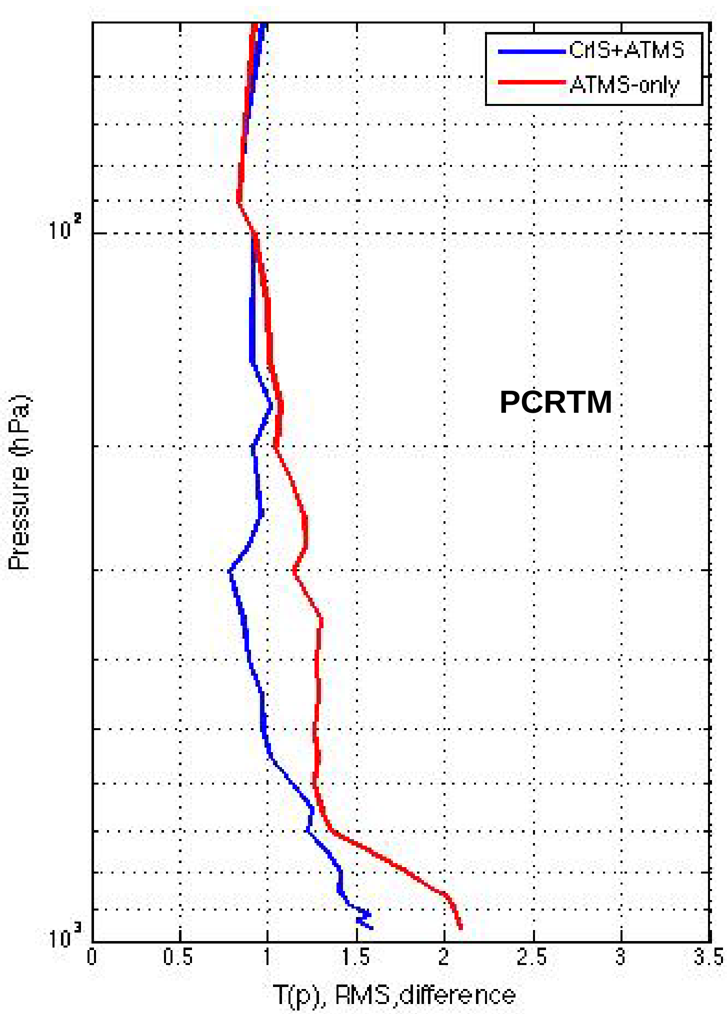
500 hPa Retrieved from ATMS/CrIS using PCRTM_RA

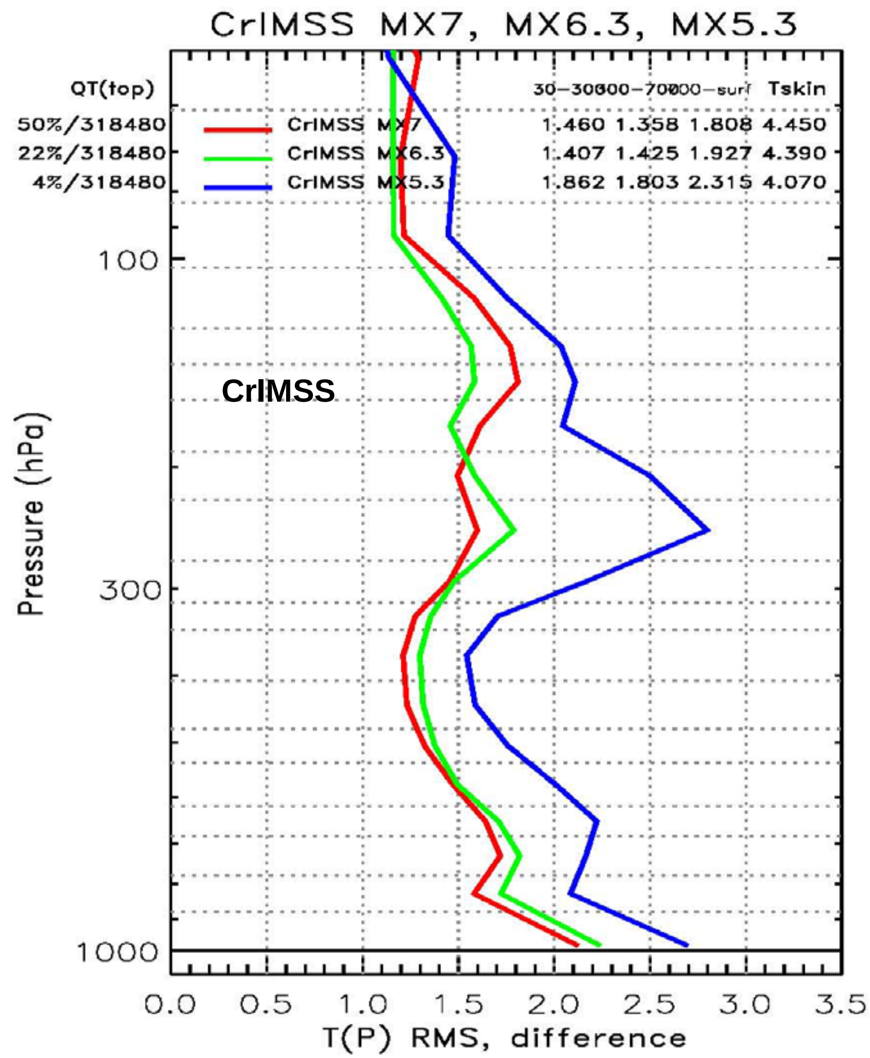


500 hPa Temperature from ECMWF



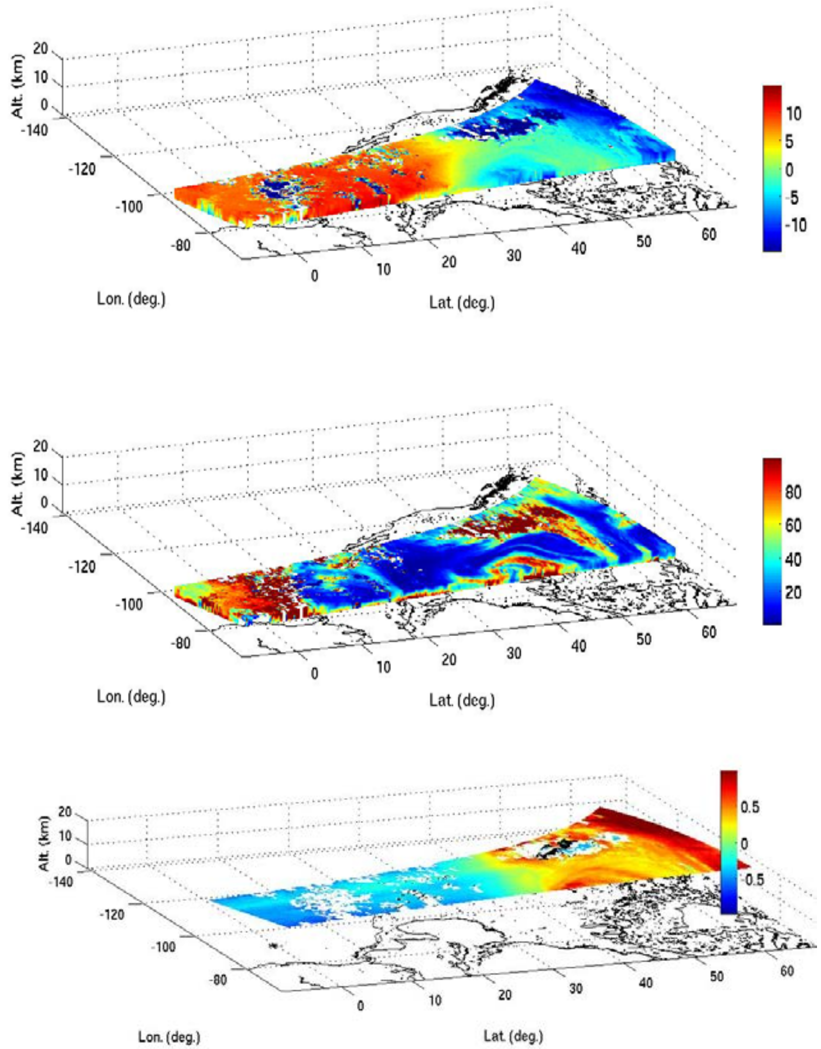
Comparison of PCRTM Temperature Retrieval with IDPS Operational CrIMSS EDR Algorithm

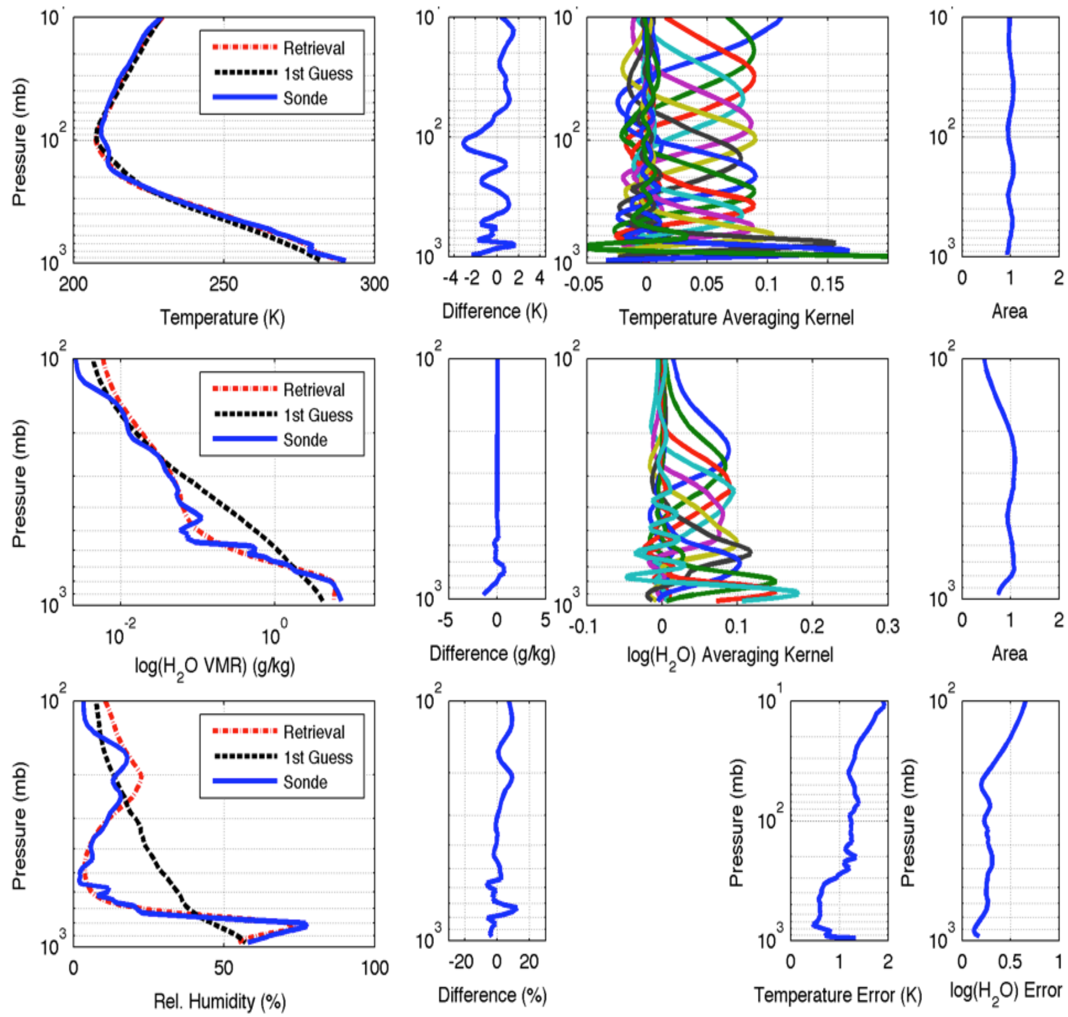




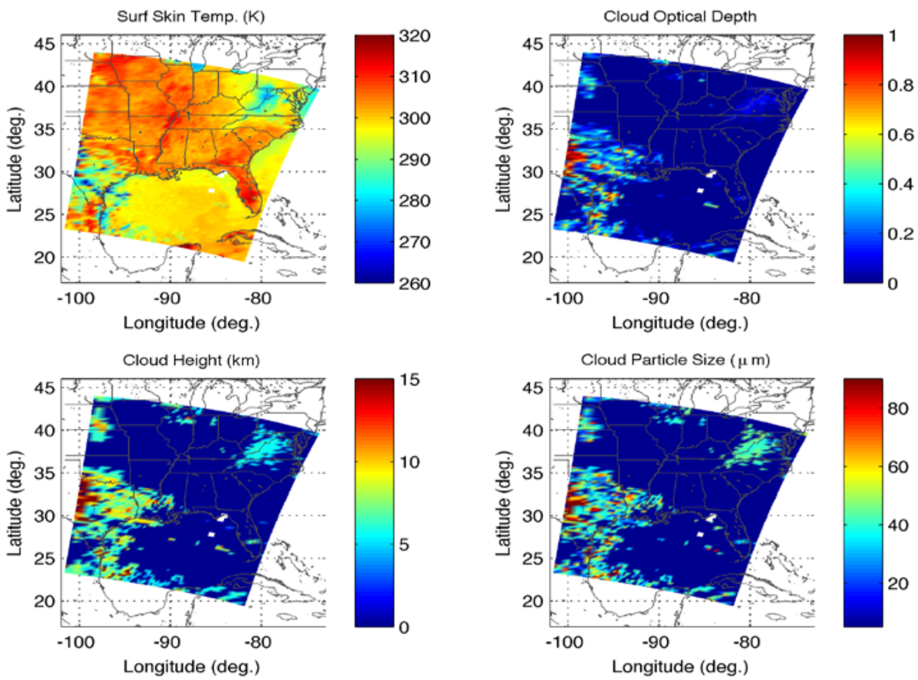
Comparison of PCRTM retrieval with radiosondes

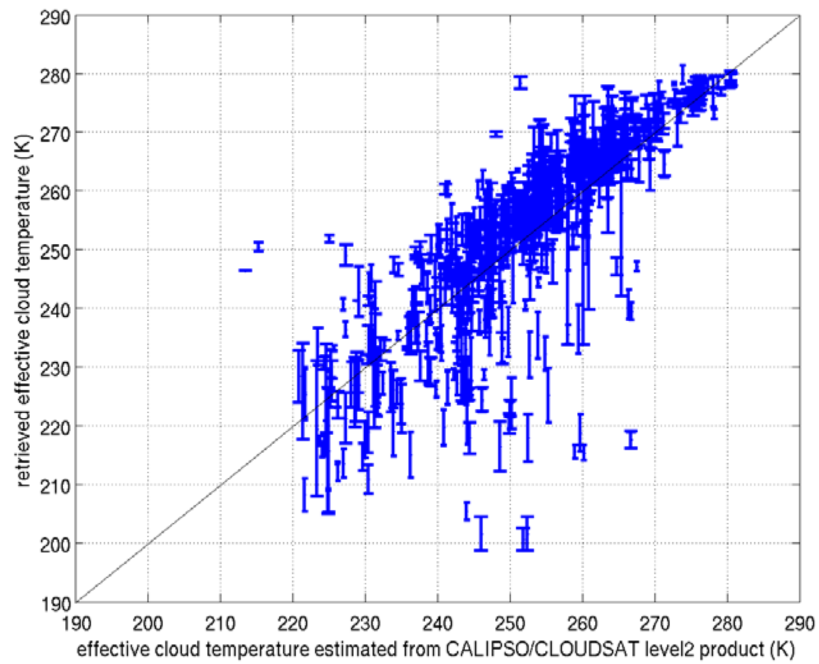
- Temperature, moisture, and ozone cross-sections
- Plots are deviation from the mean
- Fine water vapor structures captured by the retrieval system
- A very cloudy sky condition



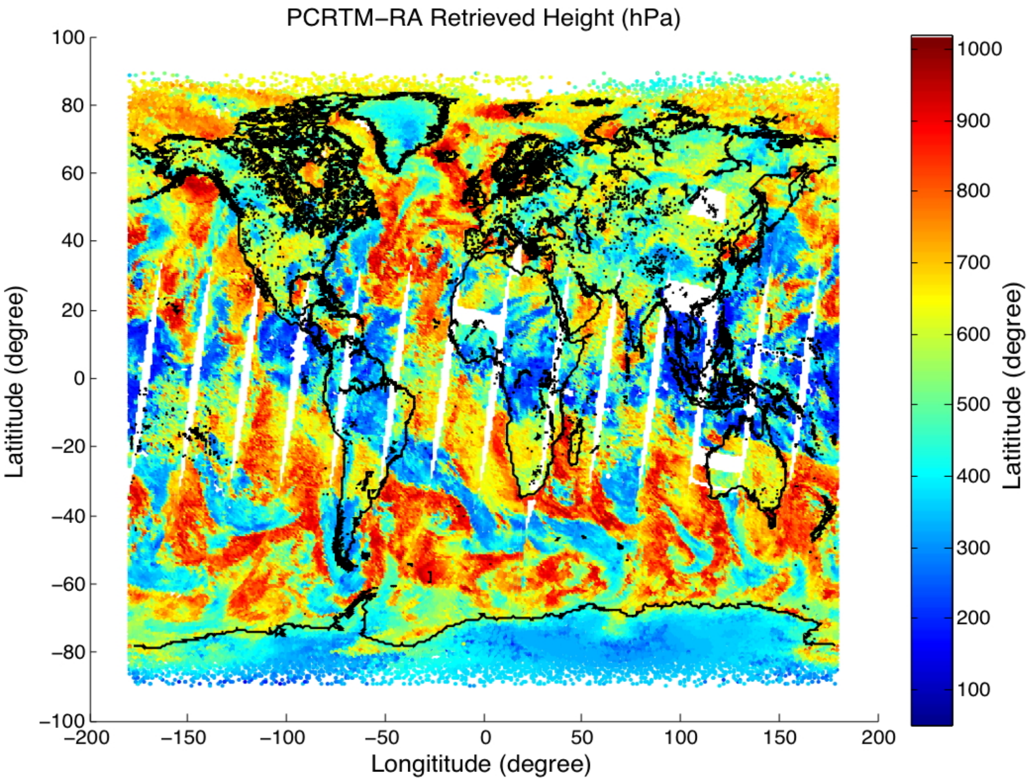


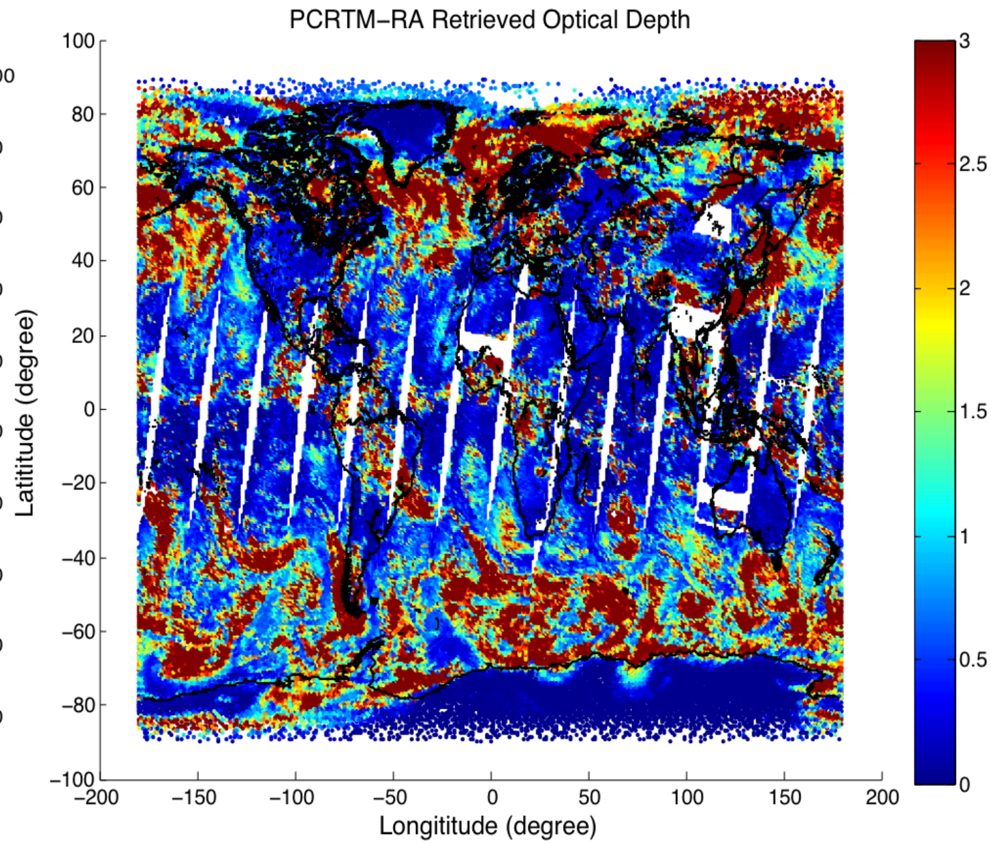
Example of retrieved cloud properties





PCRTM-RA Retrieved Cloud Top Pressure and Optical Depth from 5-15-2012 CrIS/ATMS focus day data



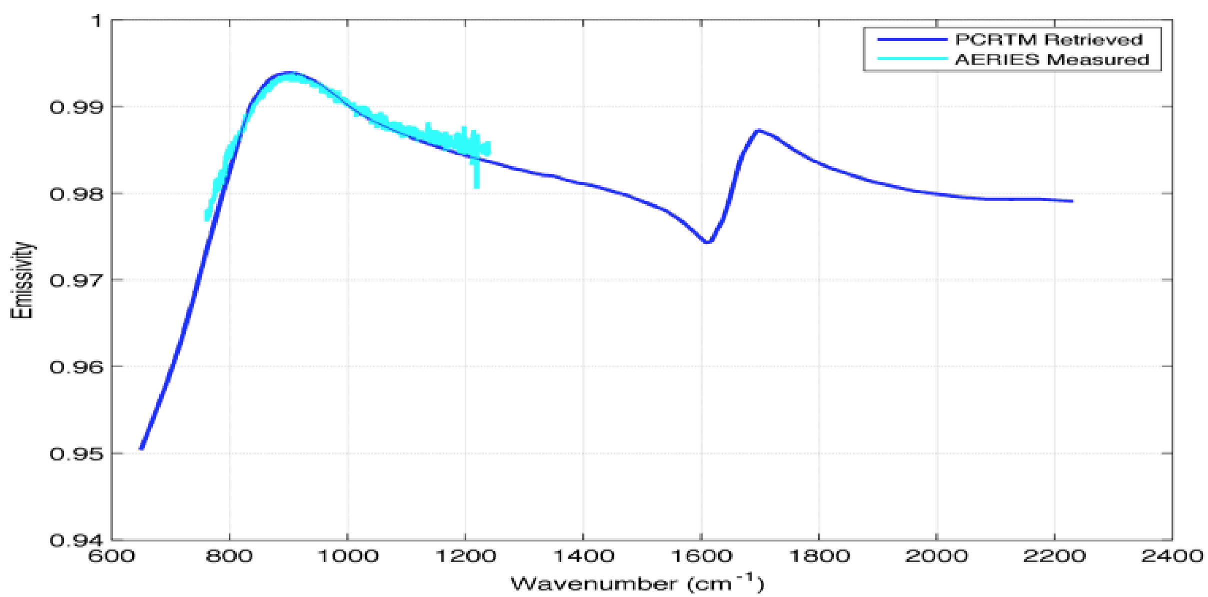


Example of retrieved surface temperature and emissivity and comparison with field validation data

Comparison of PCRTM retrieved surface skin temperature with ARIES measured Tskin

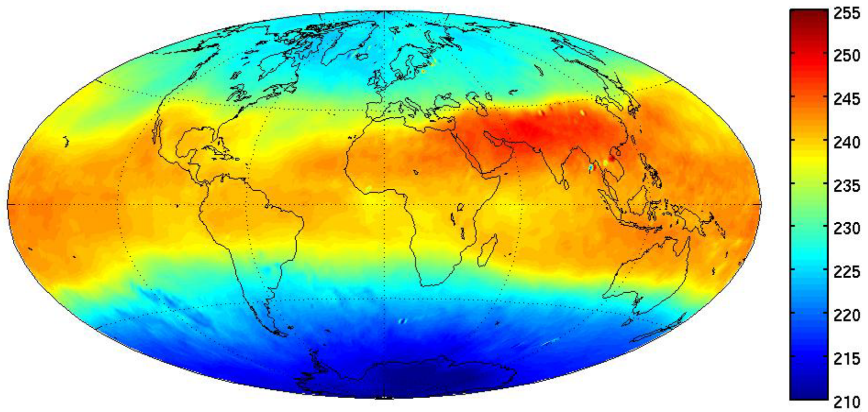
Date	Location	Surface Pressure (hPa)	ARIES Measured skin temperature (K)	IASI-retrieved surface skin temperature (K)
19 April 2007	ARM CART site	972.0	284.7	284.8
29 April 2007	Gulf of Mexico	1021.7	297.8	297.6
30 April 2007	Gulf of Mexico	1017.5	298.6	298.1
4 May 2007	Gulf of Mexico	1009.9	297.4	297.1

Comparison of retrieved ocean emissivity with ARIES aircraft measurements

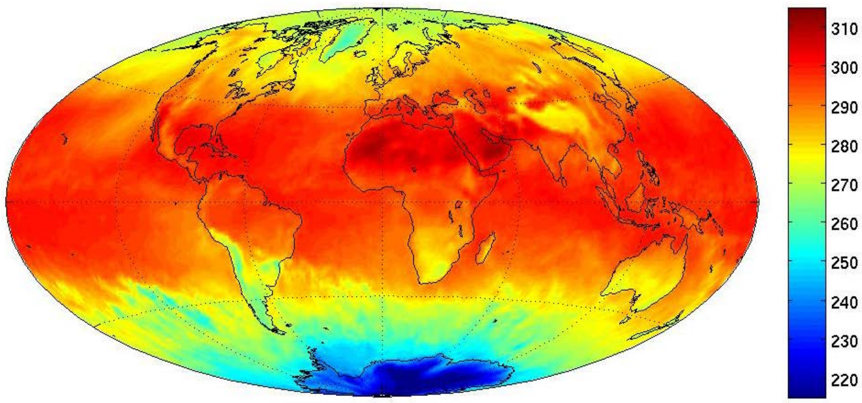


Example of retrieved global distribution of climate related properties retrieved using the PCRT-RA

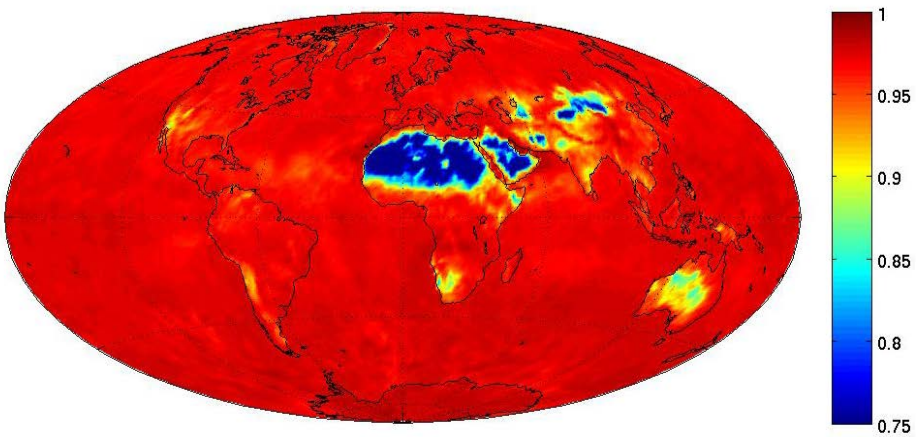
Atmospheric temperature at 9 km for July 2009



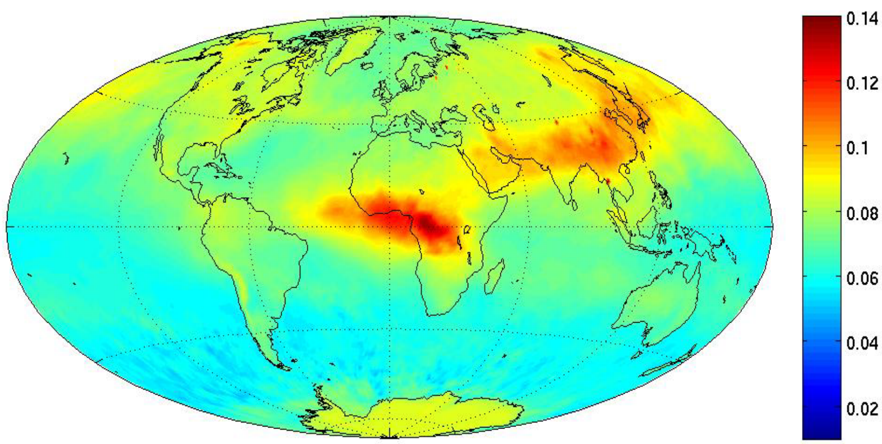
Surface skin temperature for July 2009



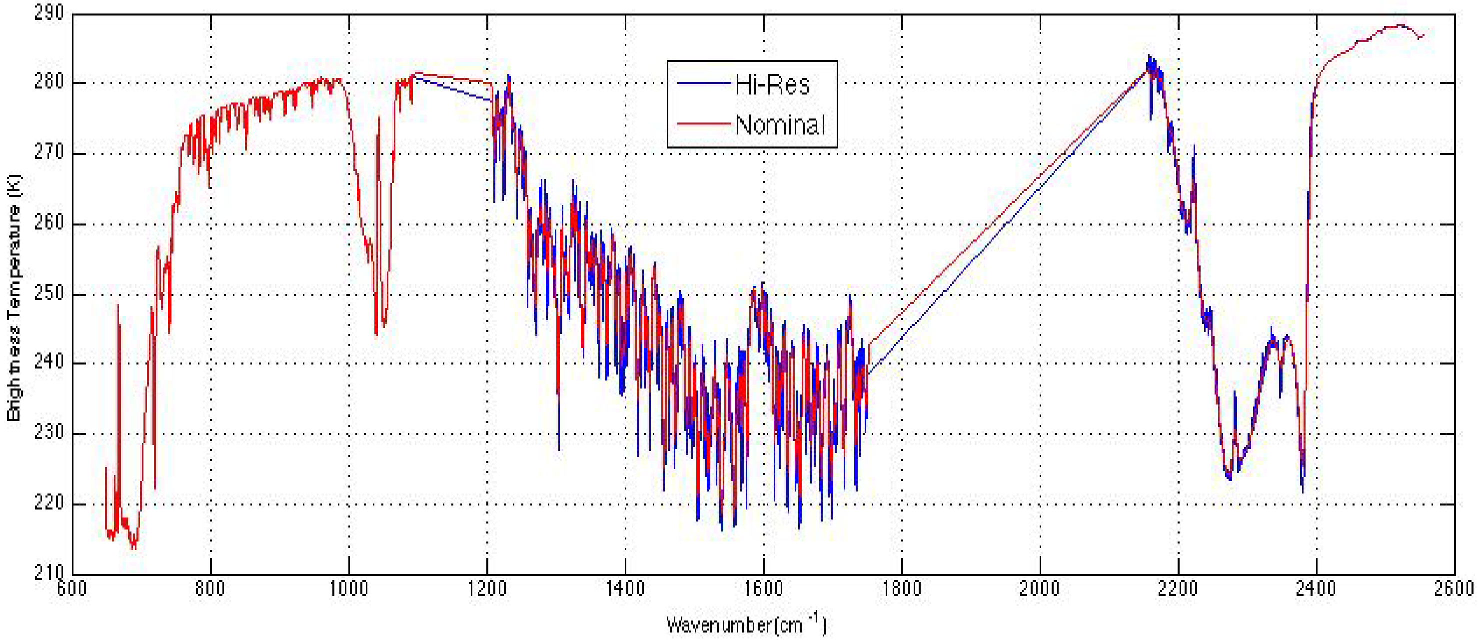
Surface emissivity for July 2009



Atmospheric carbon monoxide mixing ratio for July 2009



Application of PCRTM-RA to Full Resolution CrIS Data



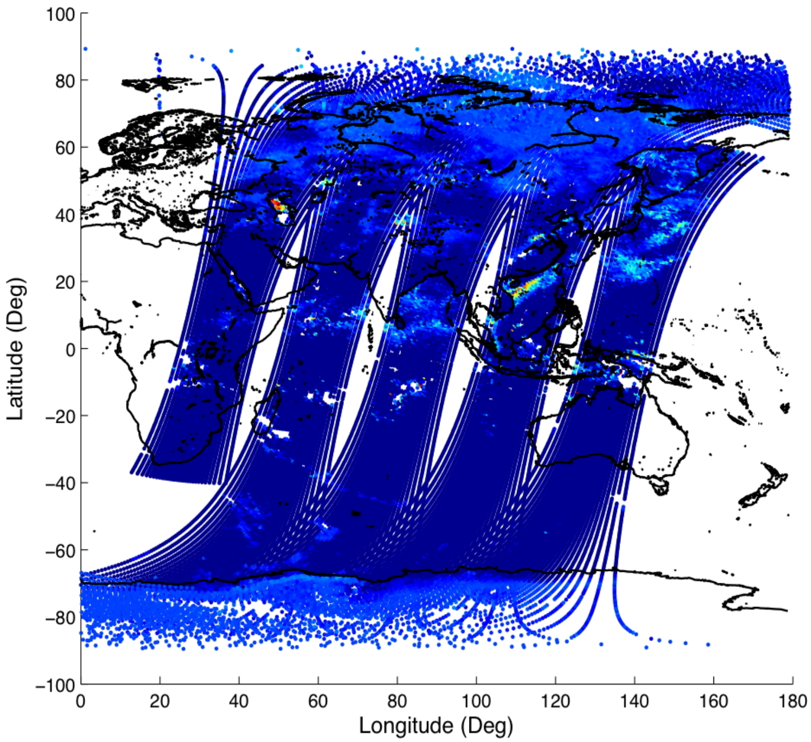
	CrIS (LW)	CrIS (MW)	CrIS (SW)
Nominal Res	0.625 cm^{-1}	1.25 cm^{-1}	2.5 cm^{-1}
High Res.	0.625 cm^{-1}	0.625cm^{-1}	0.625cm^{-}

Switching between nominal and full resolution CrIS/ATMS retrieval is very easy

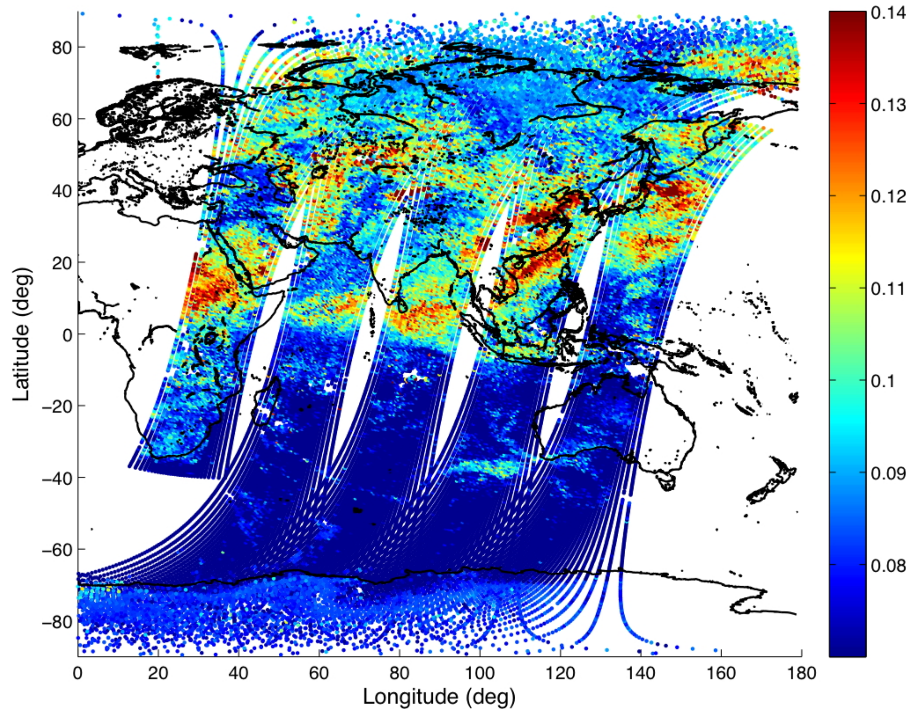
- **change instrument ID**
- **change observational error covariance matrix**

CO retrieved from full-resolution CrIS data (3-12-2013)

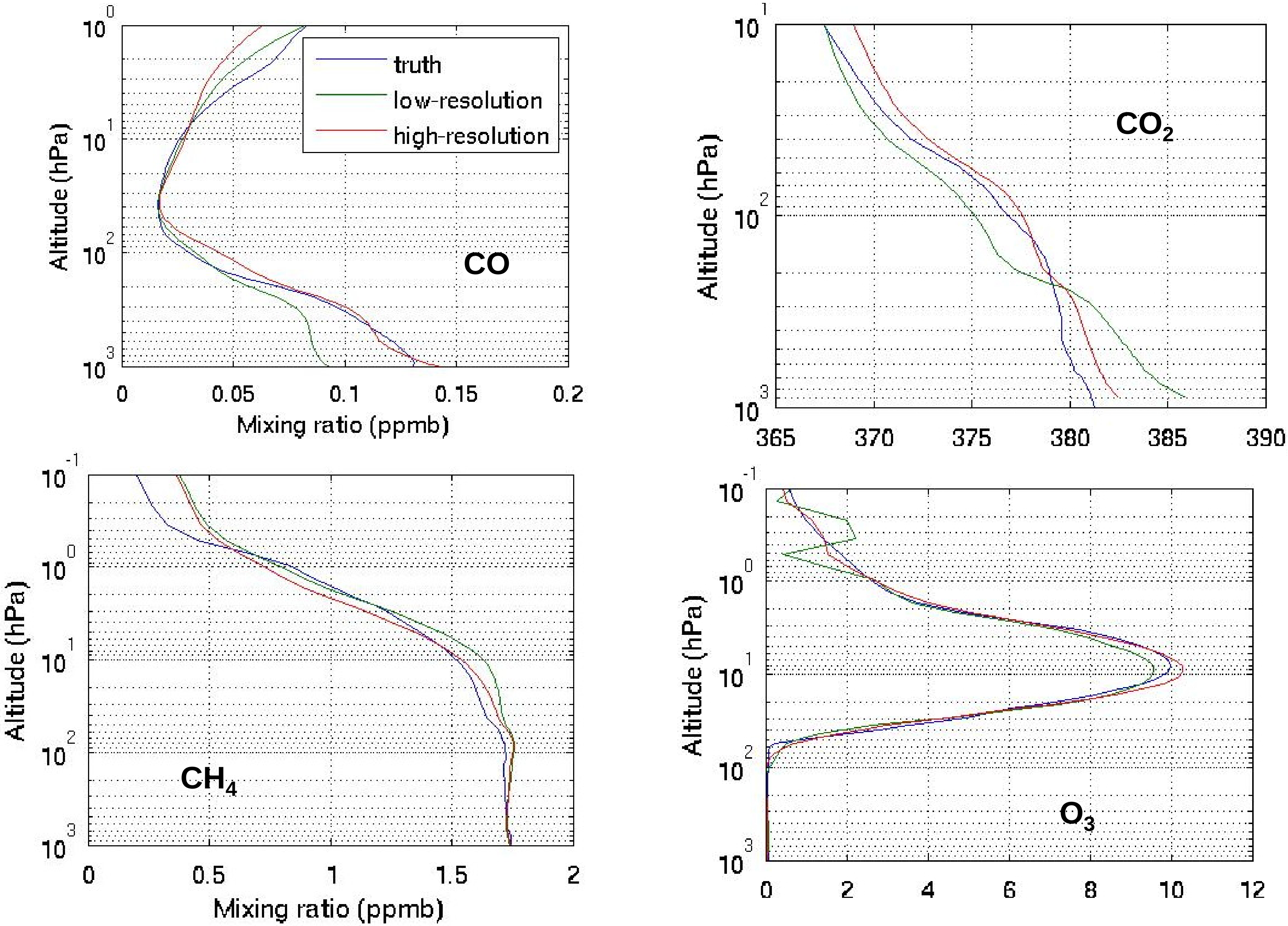
From nominal resolution CrIS using PCRTM-RA



From high resolution CrIS using PCRTM-RA

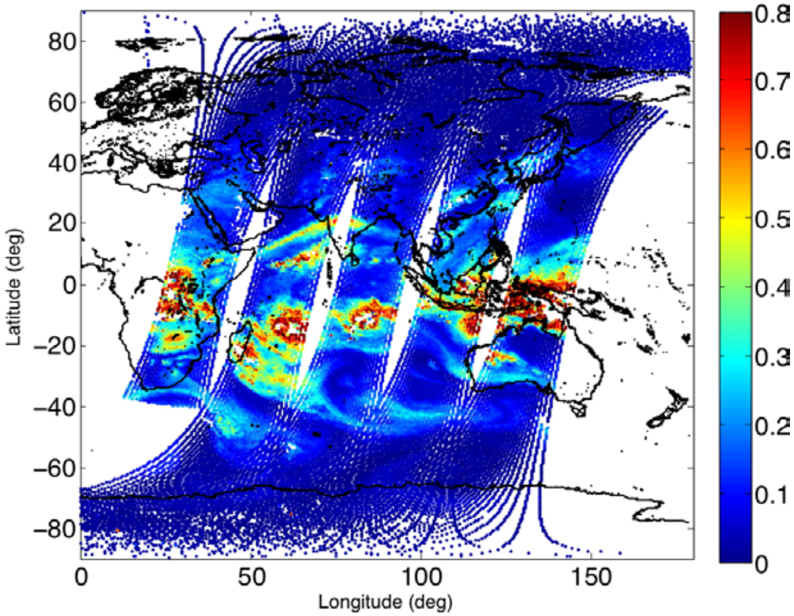


Trace gas retrievals from CrIS with different spectral resolutions

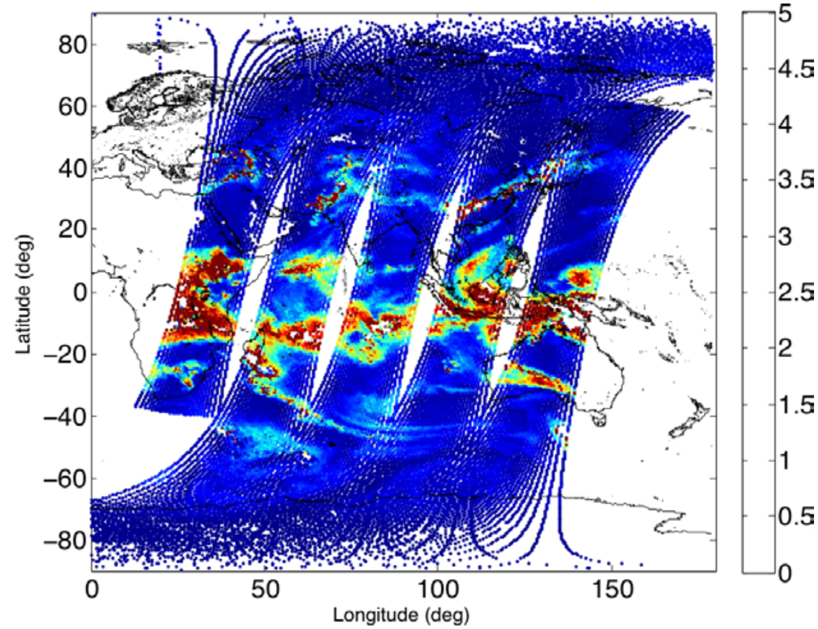


PCRTM-RA Retrieved Atmospheric Temperature from High Resolution CrIS/ATMS

Retrieved 300 hPa H2O from CrIS/ATMS using PCRTM-RA

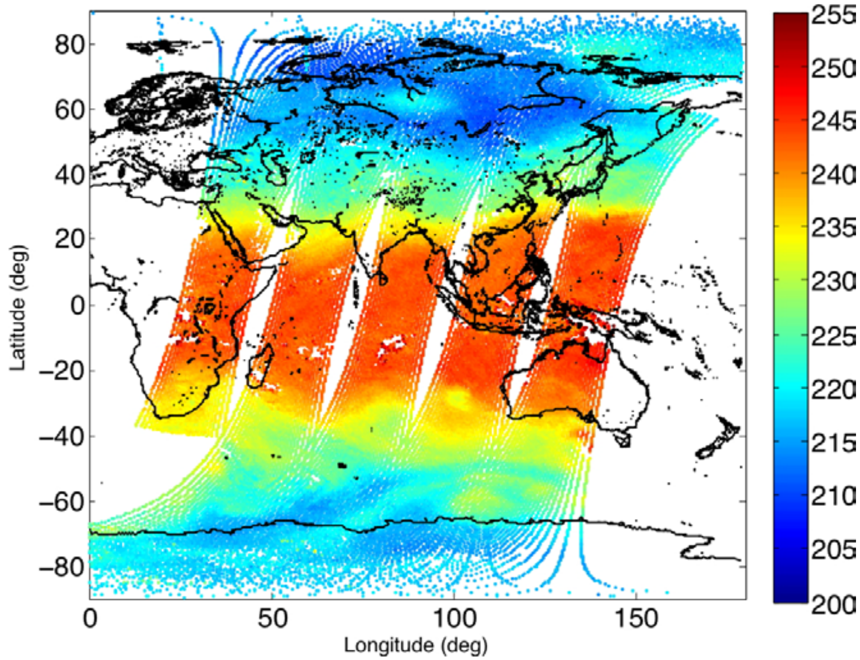


Retrieved 500 hPa H2O from CrIS/ATMS using PCRTM-RA

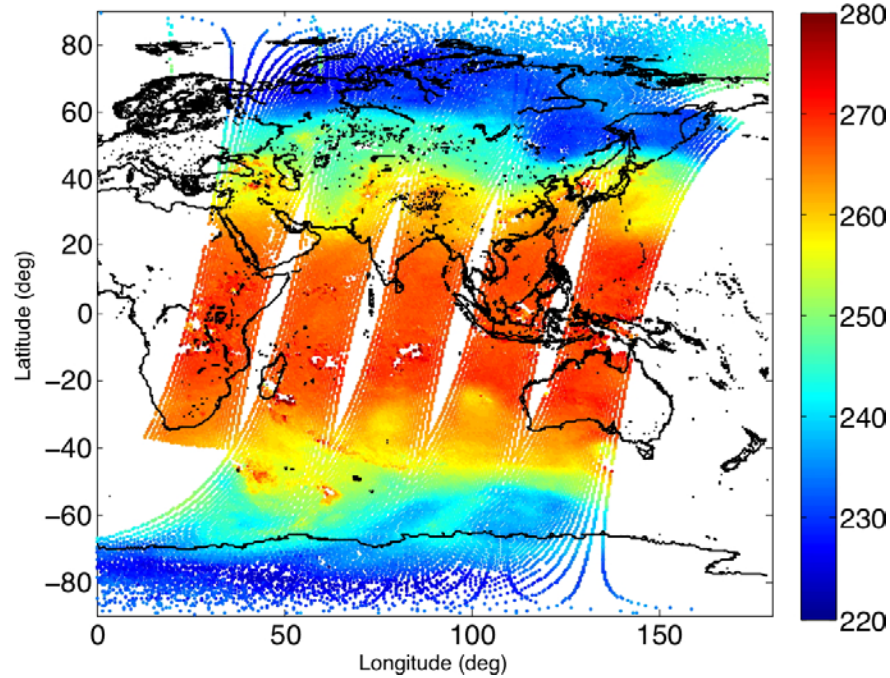


PCRTM-RA Retrieved Atmospheric Temperature from High Resolution CrIS/ATMS

Retrieved 300 hPa Temperature from CrIS/ATMS using PCRTM-RA



Retrieved 500 hPa Temperature from CrIS/ATMS using PCRTM-RA



Summary and conclusions

- Forward model is a key component in analyzing hyperspectral data
  - PCRTM has been applied: AIRS, IASI, CrIS, NAST-I, S-HIS, SCIAMACHY
  - Covers spectral range from 0.3 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
- PCRTM-RA 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 …)
- PCRTM-RA system now includes MW channels
  - CRTM used as forward model
  - Improves performance below thick clouds
  - Designed for ATMS/CrIS, ATMS/Hi-Res CrIS, AMSU/AIRS, AMSU/IASI, CLARREO
  - Can do MW-only, IR-only, or MW+IR
- Advantages over existing methods
  - Full spectral channels used with all relevant parameters retrieved simultaneously
  - No need to estimate cloud-clearing error or errors due fixing some parameters
  - Cloud properties explicitly retrieved
  - Product error estimates and averaging kernels provided