High Spatial Resolution Sounding Products from AIRS and CrIS

Xu Liu, W. Wu, and Q. Yang

NASA Langley Research Center, Hampton, VA, USA
Xu.Liu-1@nasa.gov

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Motivations

- Why PCRTM high spatial-spectral resolution retrieval?
  – Avoid cloud clearing errors by fitting observed AIRS/CrIS radiances directly
  – High spatial resolution products
  – Use full spectral information
  – All geophysical parameters that affect TOA radiances are retrieved
  – Derive self-consistent radiative kernel form sounder observation directly
- Introduction to PCRTM radiative transfer model
  – Trained to work from far-IR to UV-Vis spectral regions
  – Accurate multiple cloud/aerosol multiple scattering calculation
  – Trained for polarized RT calculation (I, Q, U)
- PCRTM Single FOV cloud retrieval algorithm is capable of retrieving
  Optimal Estimation with very loose a priori and background covariance
  – Atmospheric Temperature, Water, CO2, CO, CH4, O3, and N2O profiles
  – Cloud phase, height, temperature, size, optical depth
  – Surface emissivity spectrum and skin temperature
- Climate spectral fingerprinting using CrIS/ATMS and AIRS/AMSU data
  – Spectral Fingerprinting methodology
  – Radiative kernel calculations
- Summary and Conclusions

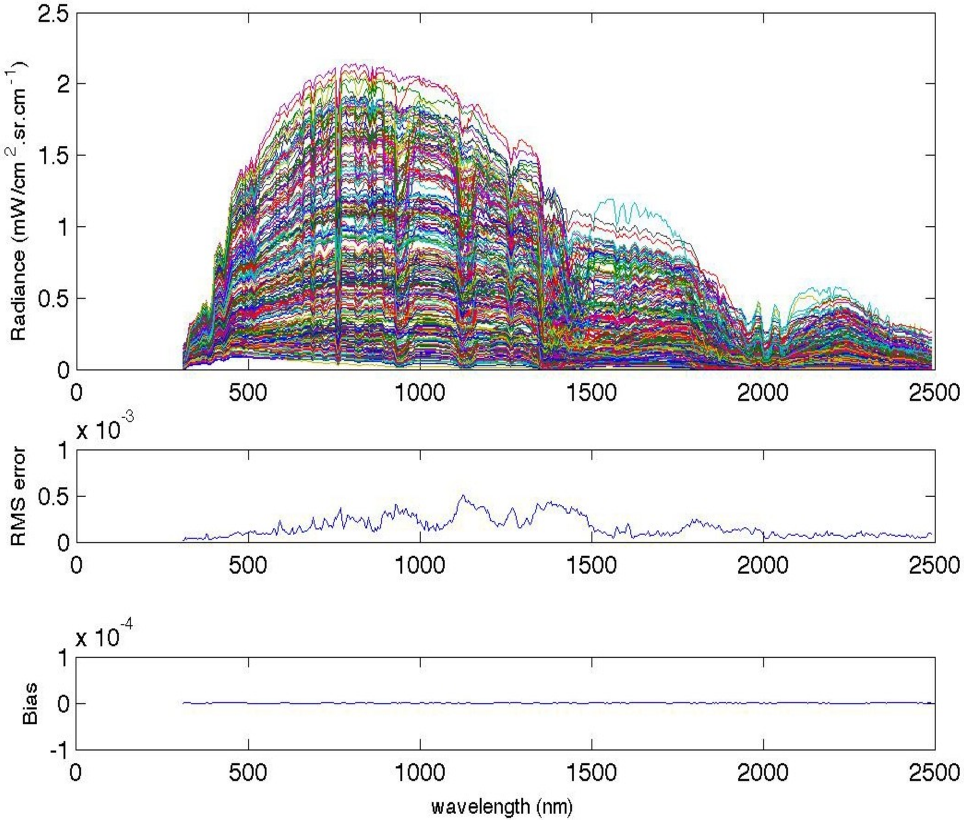
Introduction to a Principal Component-based Transfer Model (PCRTM)

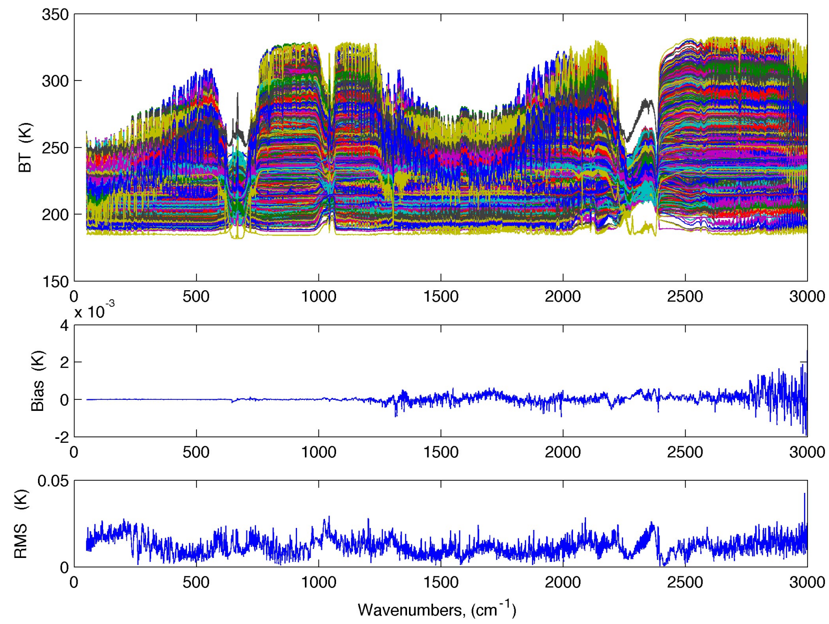
- PCRTM was first developed in 2004 to handle hyperspectral data
  - 1 million LBL RT needed for IR spectral region
  - Channel-based RT still too slow (thousands of spectral channels)
  - Compress spectral into Principal Component (PC) domain
  - Performs minimum number of monochromatic calculations
  - Handles clouds efficiently
  - Extended to include polariziations
  - Covers spectral range from far infrared to UV-Vis spectral regions
- Very fast parameterizations
  - Achieved by both reduction in spectral domain and in multiple scattering domain
  - A few miliseconds per spectrum in IR
  - 2-4 orders of magnitude faster than MODTRAN (depends on spectral resolution)
- Very accurate relative to reference models
  - Better than 0.03 K accuracy from far-IR to near-IR
  - Better than 0.02% accuracy from near-IR to UV-vis
- Recent publication related to PCRTM
  - Liu et al. App. Optics, 2016, Yang et al. Optic Express 2016, Liu et al , Wu et al 2017, Chen et al 2013, Pan et al. 20 Seiji et al 2011, 2014, Liu et. al 2007, 2009, 2017, Huang et. al. 2014. Pan et al. 2015, 2017, Feldman et al.2013, Bantges et al. 2016, Rose et al. 2013, Sergio et al AMT 2017, Aunman et al. JGR, 2018, Wu et al. 2018.

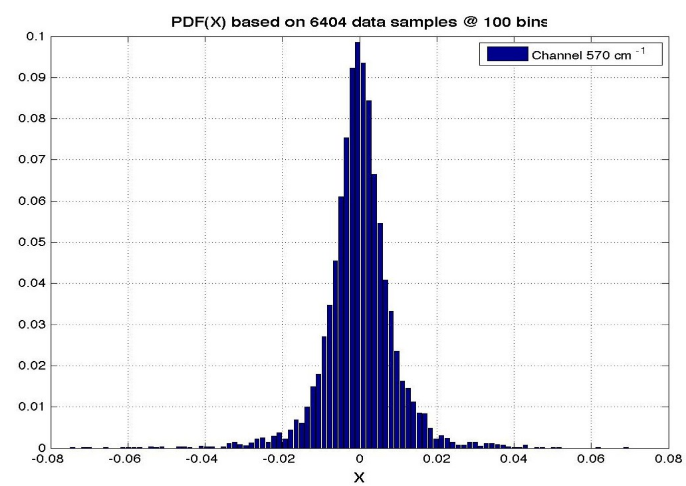
(Xu.Liu-1@nasa.gov)

PCRTM covers spectral range from 0.3 μm to 100 μm

- 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%)







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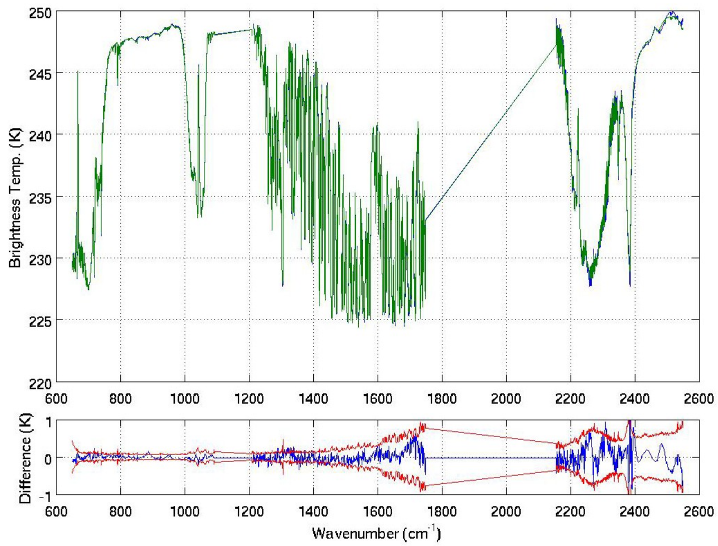
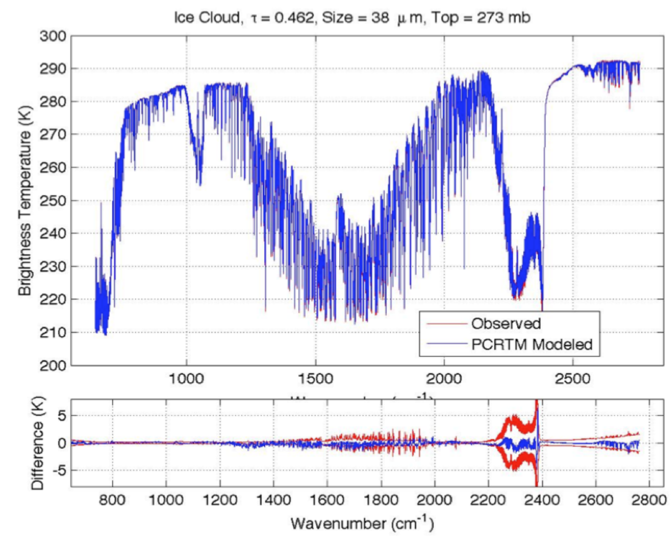
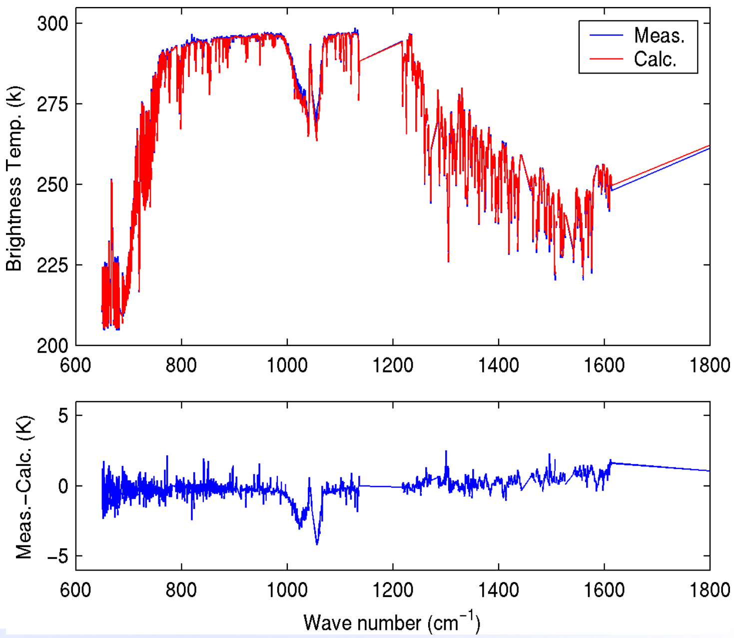
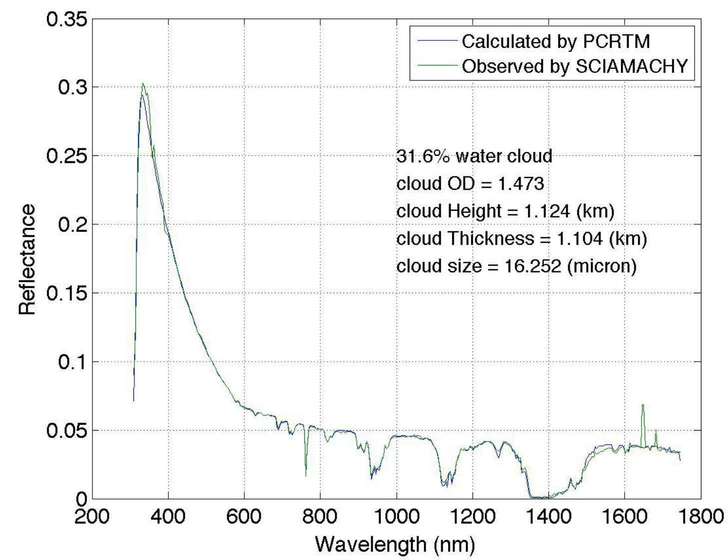
Examples of PCRTM Simulations of CrIS, IASI, AIRS, NAST-I, and SCIAMACHY real data









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Computational Speed in IR Spectral Region

Sensor	Channel Number	PC score (seconds)	PC score + radiance	PC score + PC Jacobian
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

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.

PCRTM is very fast relative to MODTRAN

Number of radiative transfer calculations for PCRTM are reduced by 3 orders of magnitude relative to modtran for spectral range from 300 nm to 2500 nm

PCRTM	*nmo*	*nch*	*npc*	*nsmo*	*speed up*
Land (8 nm)	259,029	546	220	262	988
Ocean (8 nm)	259,029	546	267	240	1079

Hybrid Stream method further speed up PCRTM-SOLAR by another factor of 5-10 relative to 32-stream PCRTM

	M1	M2	Speedup to Regular PCRTM-SOLAR	Speedup to MODTRAN5
Land 8 nm	263	49	5	5286
Ocean 8 nm	241	23	10	11,262

PCRTM handle NLTE and solar scattering properly

- Figure 1 shows the calculated hyper spectra for night time, day time without NLTE and daytime with NLTE
- Figure 2 shows PCRTM calculated and observed day-time IASI spectra during SNPP-2 field campaign

Fig. 1

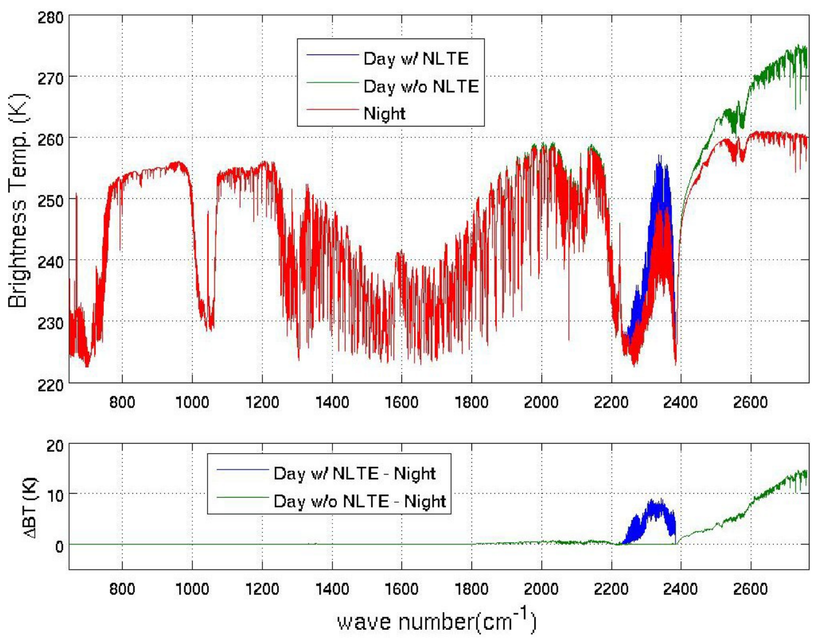
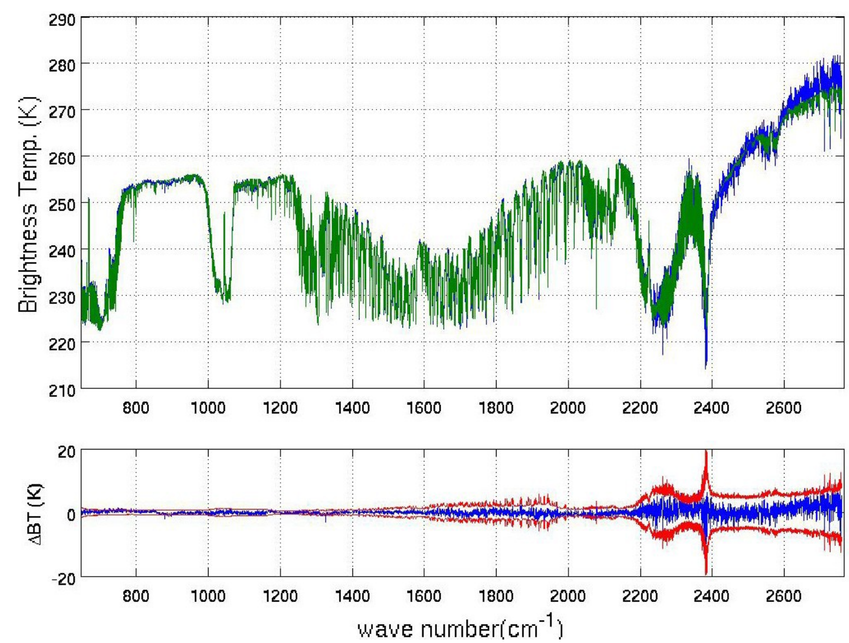


Fig. 2



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Recent Results on Simulating AIRS spectra in the using ECMWF cloud fields (Aunman et al, 2018 JGR)

- **PCRTM was able to match with ARIS observation well during day time**

bt2616 (AIRS observed –calculated)	day PDF correlation	day bias ± stddev [K] 1437 cases		night PDF correlation	night bias ± stddev [K]1377 cases	day-night [K]
SARTA_pM1	0.8744	+5.00±14.79		0.9738	-3.06±18.40	8.0
SARTA_p999	0.8779	+7.05±15.57		0.9746	-0.37±19.45	7.4
PCRTM_ERO	0.9855	+1.55±15.90		0.9371	-0.29±19.23	1.84
PCRTM_MRO	0.9846	+0.73±15.84		0.9334	-1.88± 18.84	2.61
PCRTM_ERO2	0.9804	+2.52±16.79		0.9543	+0.58± 20.56	1.94
PCRTM_MRO4	0.9766	+0.91±16.22		0.9446	-1.25±19.47	2.1
HT_CMO	0.6669	+15.04±20.11		0.9075	-2.53±20.49	17.5
HT_CRO	0.6492	+15.97±19.76		0.9809	-1.43±20.12	17.4
HT_CMRO	0.6653	+15.13±20.10		0.9074	-2.46±20.47	17.5
HT_SMO	0.9215	+3.69±15.86		0.9791	-2.11±20.59	5.7
HT_SRO	0.9628	+3.87±15.83		0.9736	-0.83±20.14	4.7
HT_SMRO	0.9245	+3.65±15.88		0.9799	-2.02±20.56	5.7
RTTOV_MRO	0.8948	+4.81±15.86		0.9574	-6.48±19.85	11.3
RTTOV_CMSS	0.8803	+8.07±15.26		0.9605	-2.38±19.02	10.5
σ-IASI_as	0.4809	+20.94±18.94*		0.8739	+5.37±19.50	15.6
CRTM2_tcc	0.3991	+20.55±17.60		0.6623	+6.38±20.52	14.1
CRTM_mro	0.6680	+13.90±18.74		0.9604	-2.16±19.58	16.1
CRTM_2col	0.6410	+15.33±18.59		0.9486	-1.04±19.63	16.4

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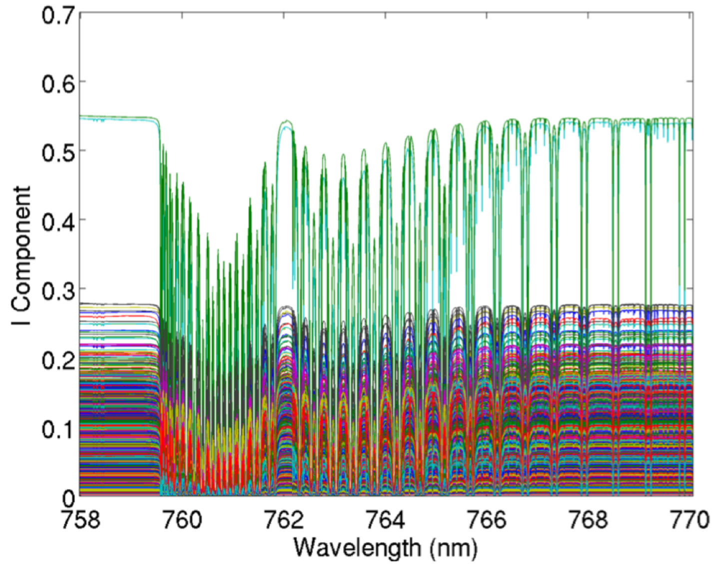
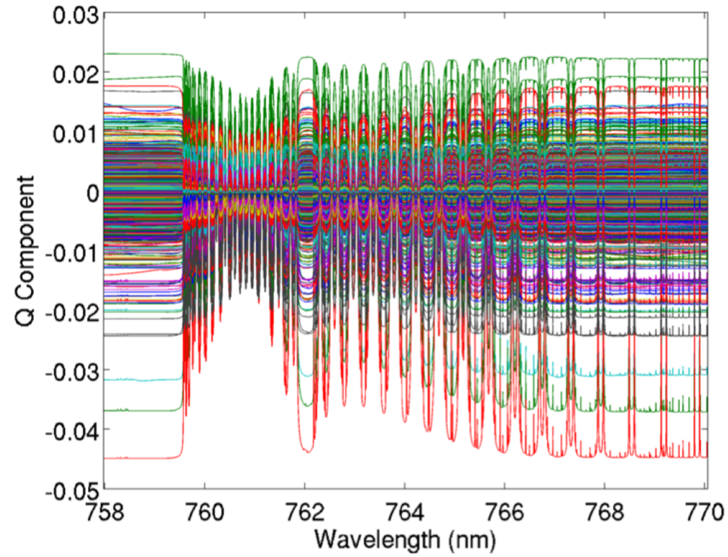
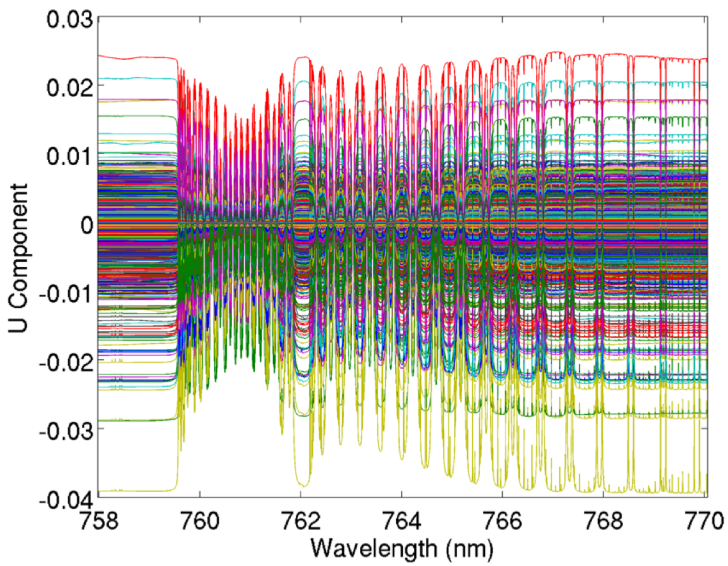
PCRTM for high spectral resolution polarized O_2-A band







- **The I, Q, and U are monochromatic radiances normalized to solar irradiance.**
- **The values of I are always positive**
- **The values of Q and U may be either positive or negative**
- **The magnitudes of Q and U are at least one-order smaller than that of I.**

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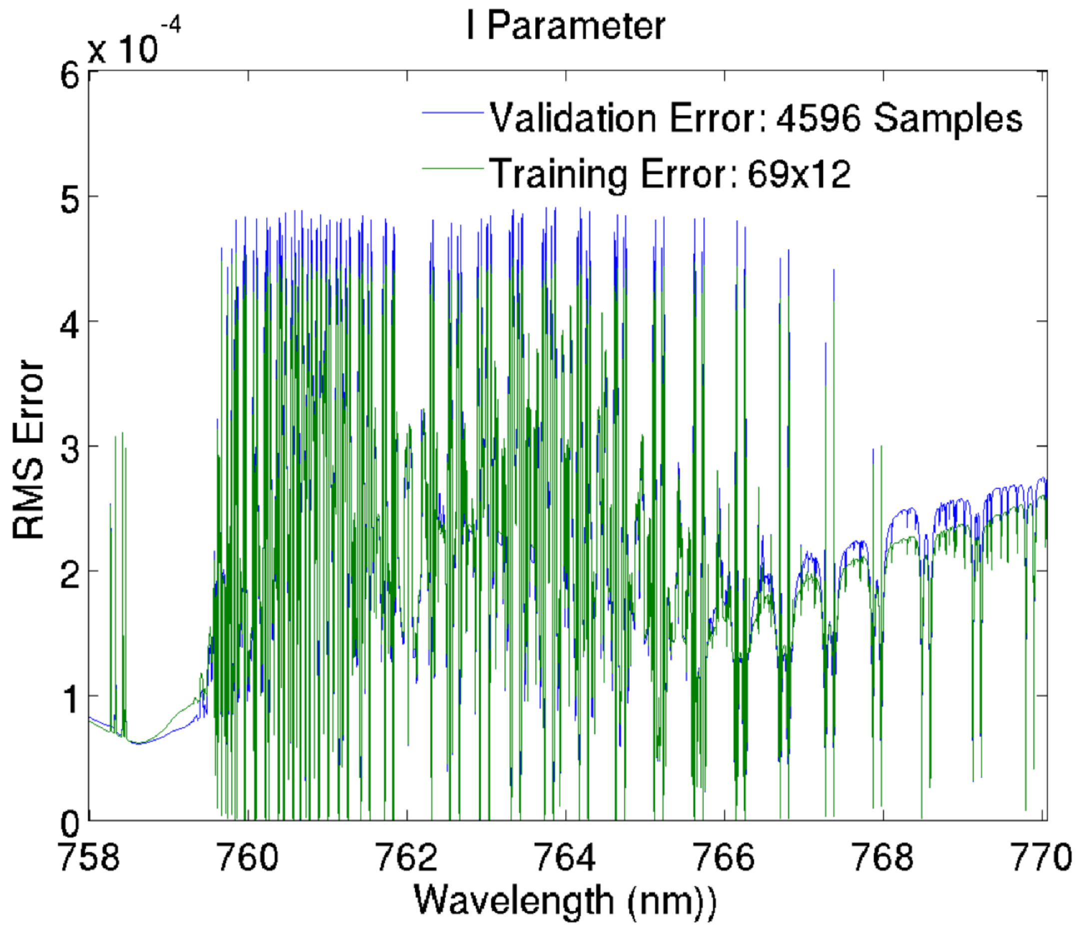
Training Results for Total Radiance (I) Alone



- Only 69 EOFs needed
- Only 12 mono radiances needed
- About 690 times faster than LBL model.

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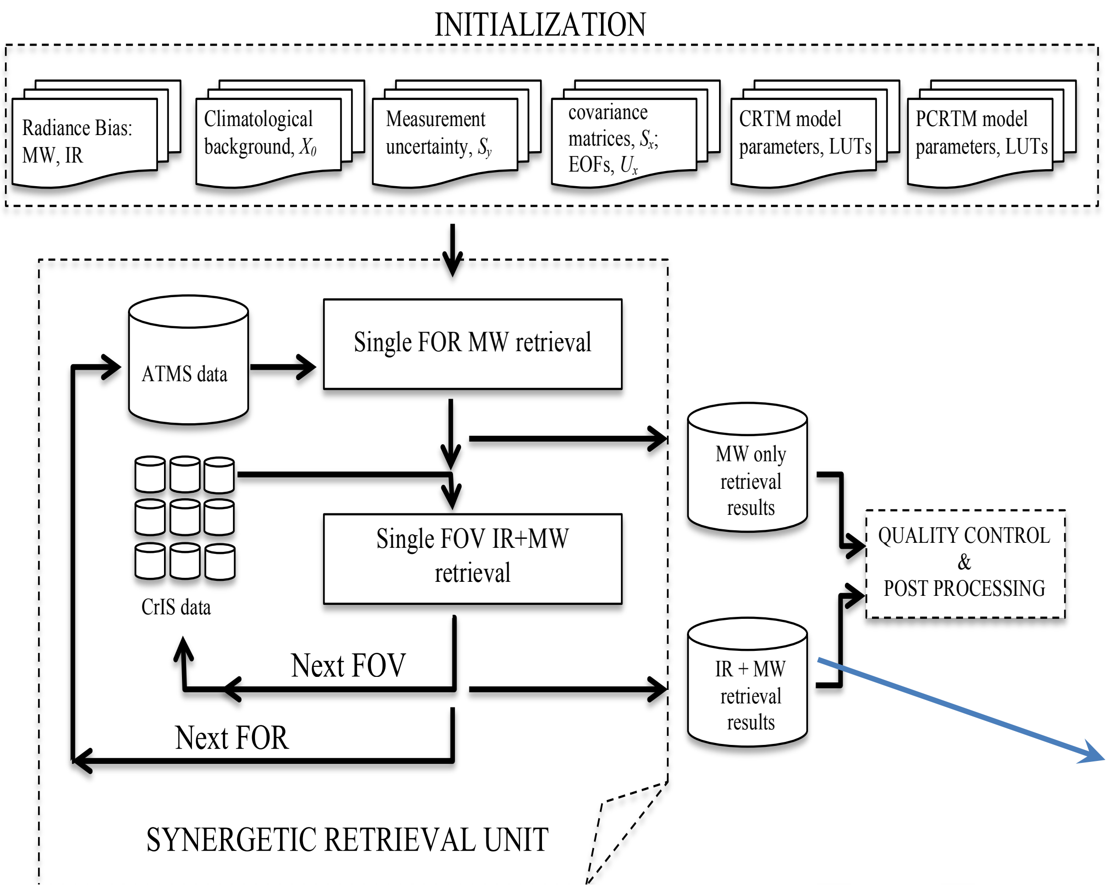
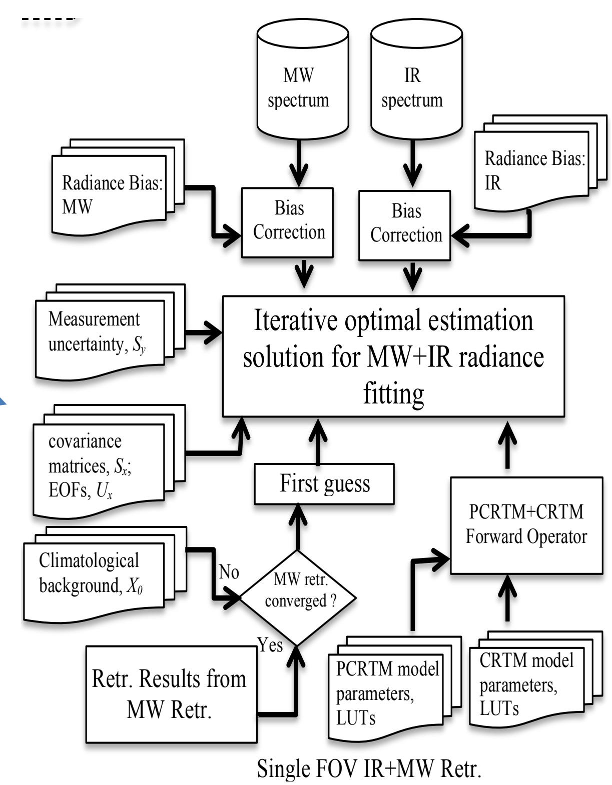
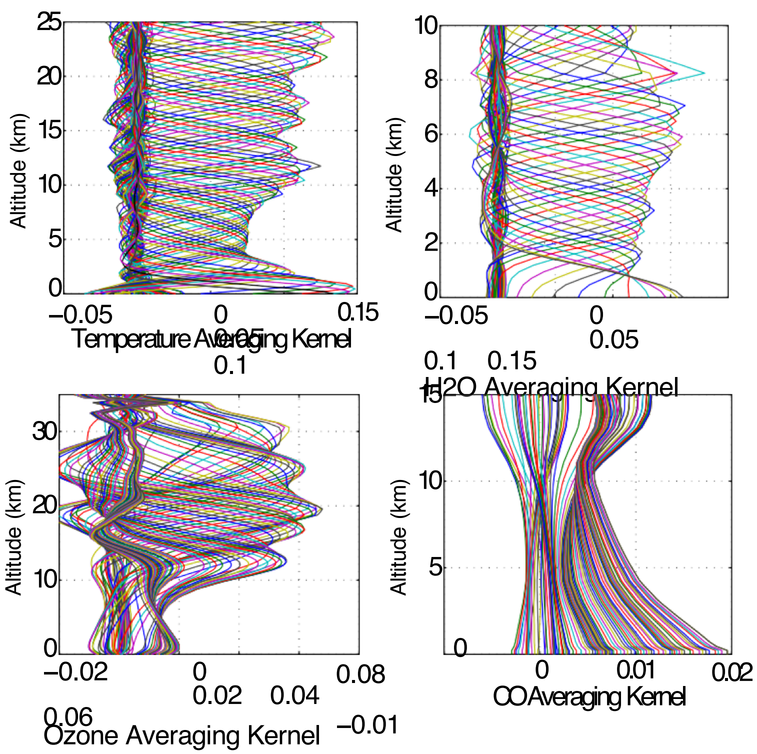
IR+ MW retrieval algorithm using PCRTM+CRTM

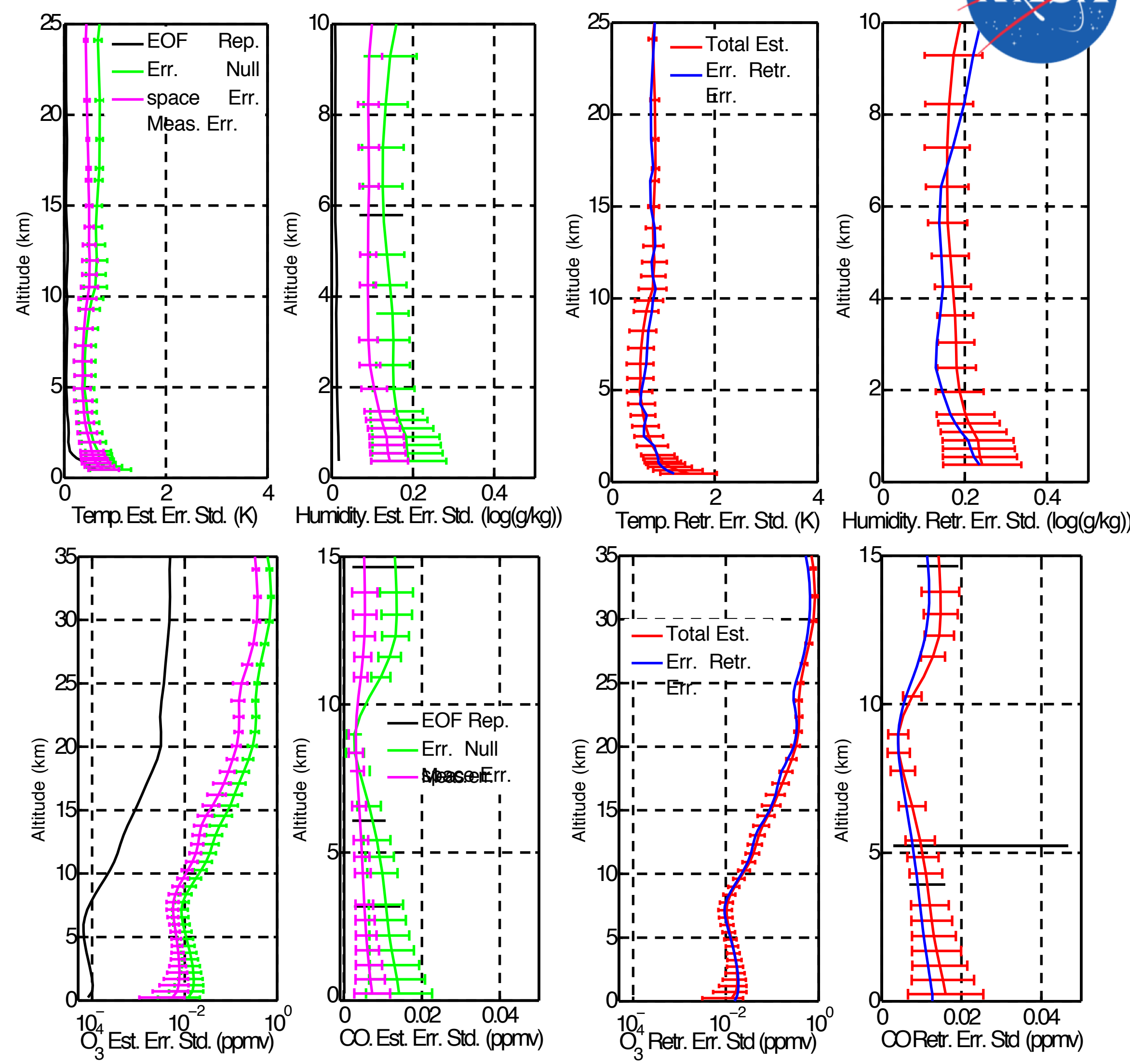




- Both PCRTM and CRTM are sensor based forward models, providing the application flexibility (can be used for CrIS/ATMS, AIRS/AMSU/HSB, IASI/AMSU/MHS)

End-to-End Closure Experimental Study for IR only retrieval using Single FOV IASI spectra





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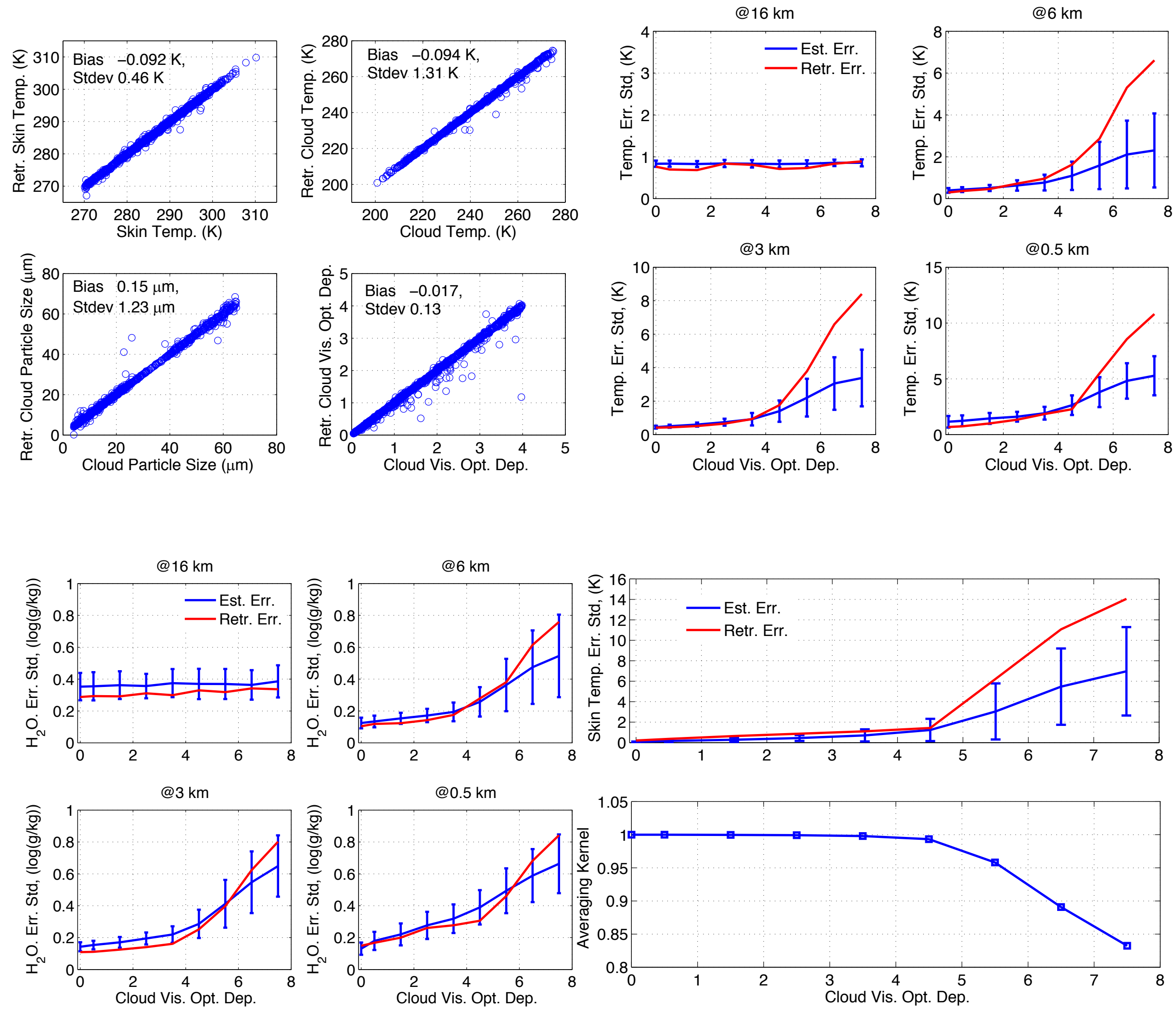
End-to-End simulation study – evaluation for IASI retrieval capability under all-sky condition

- The accuracy of the IR only retrieval for below-cloud properties decreases as cloud optical depth increases, which can be compensated by using MW+IR combined retrieval.

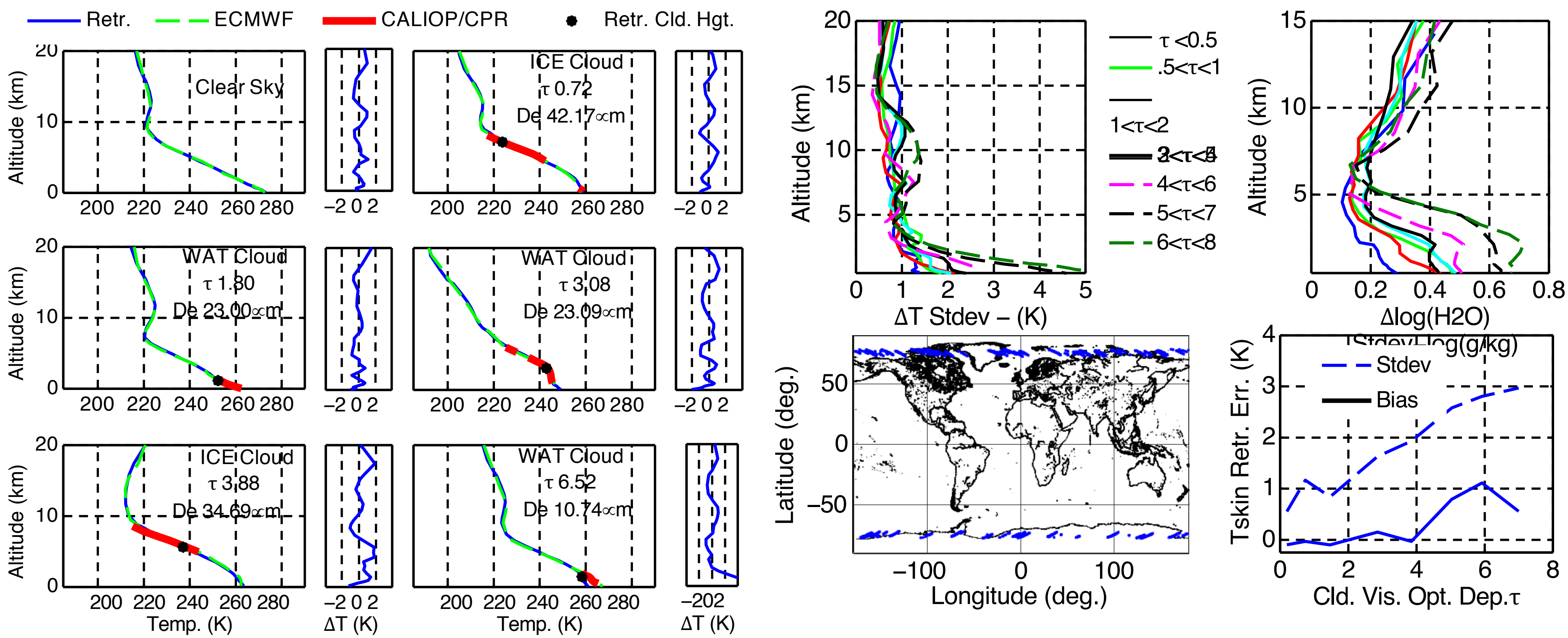
Confusion Matrix for Cloud Phase Retrieval

Output Class		Ice Cloud	Water Cloud	
	Ice Cloud	47.98% [1]50.15% [2]47.18% **A**	0.58% [1]0.31% [2]0.68% **B**	Sensitivity 98.81% [1]99.39% [2]98.58% **C**
	Water Cloud	0.91% [1]2.77% [2]0.23% **D**	50.53% [1]46.77% [2]51.91% **E**	Sensitivity 98.24% [1]94.54% [2]99.56% **F**
		Precision 98.15% [1]94.77% [2]99.51% **G**	Precision 98.87% [1]99.34% [2]98.71% **H**	Accuracy 98.52% [1]96.92% [2]99.09% **I**
	Target Class			

[1] over land, [2] over ocean



Validation using real satellite data



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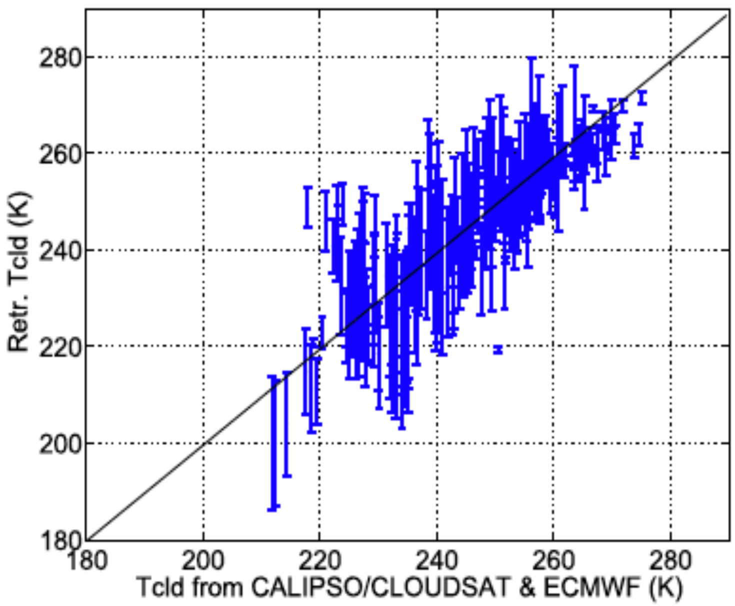
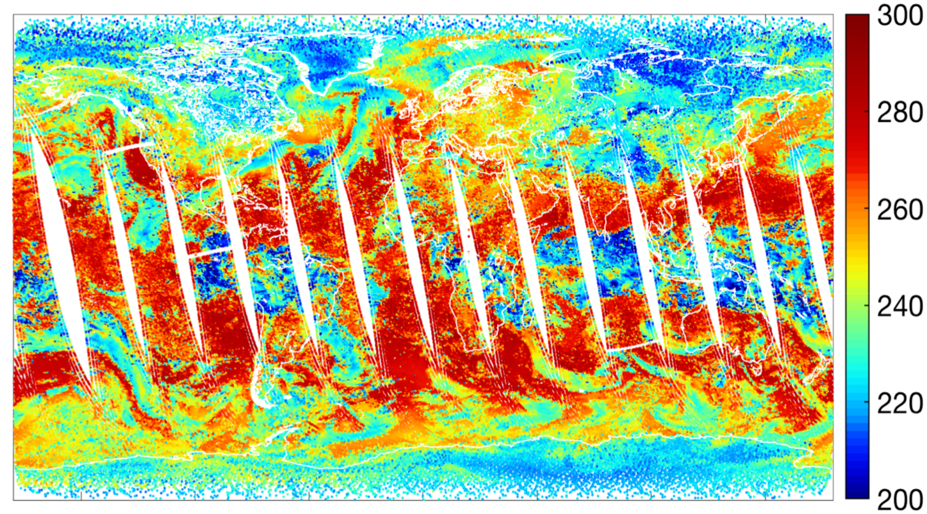
Cloud top Temp., particle size, optical depth

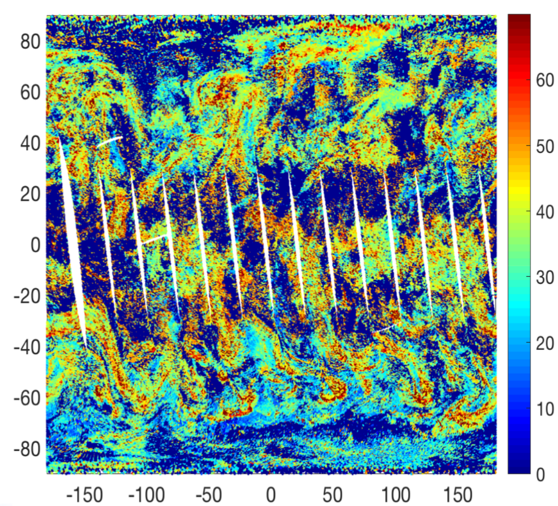
Cloud top Temp. retrieval validation using IASI + CALIOP/CLOUDSAT/ECMWF



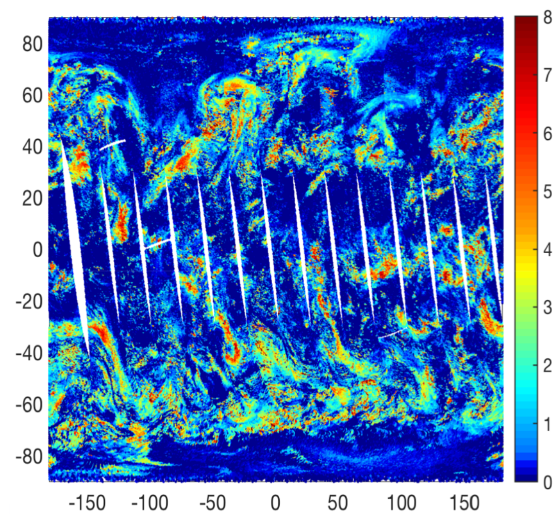
Cloud top pressure (hPa)



Cloud effective diameter (μm)



Cloud optical depth @550nm



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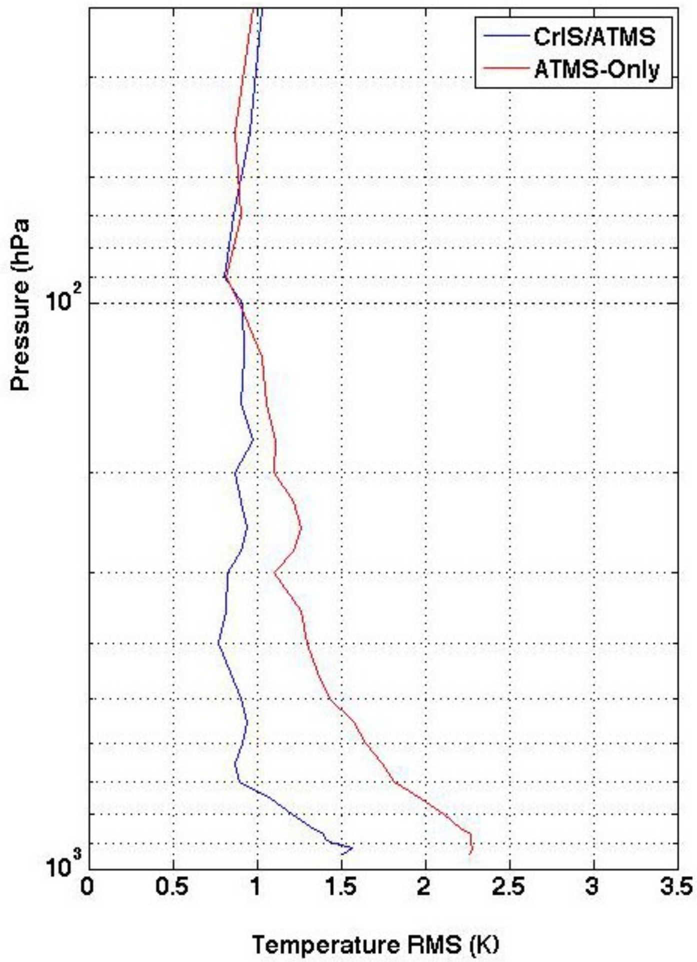
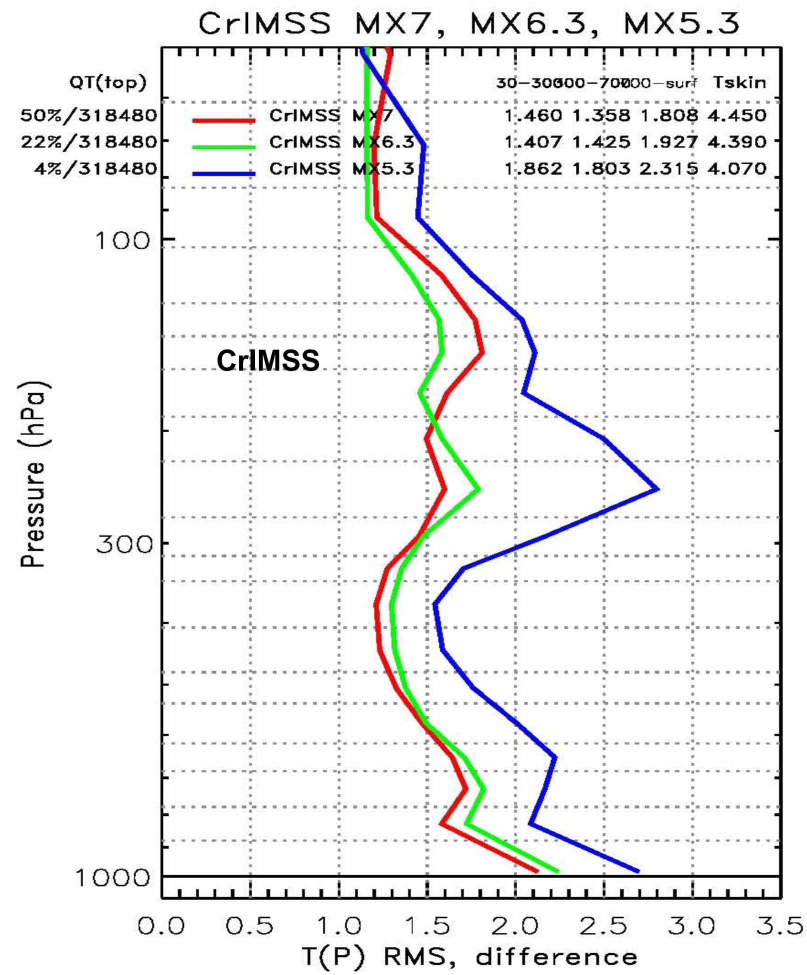
Atmospheric temperature profile retrieval with and without multiple spectral regions





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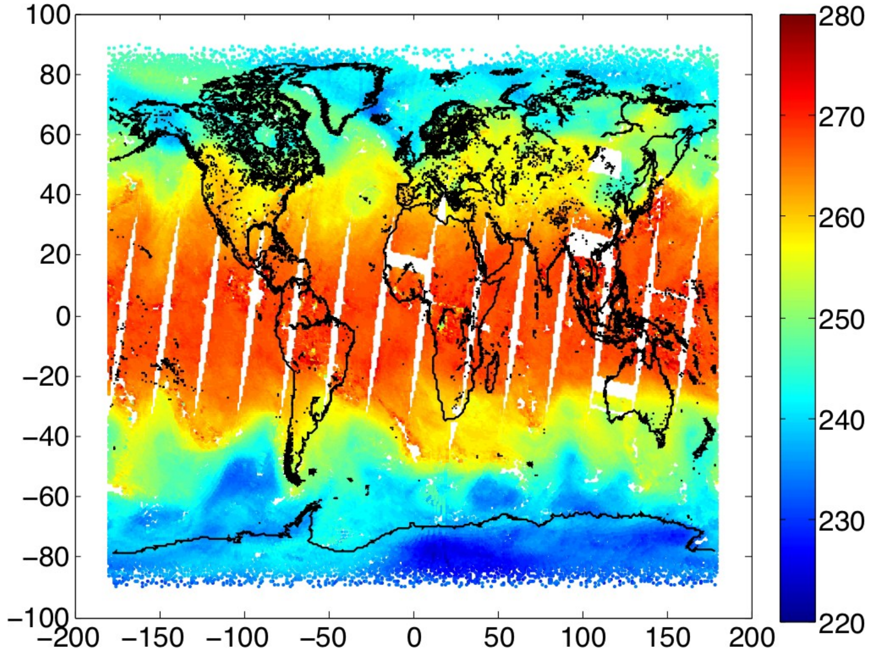
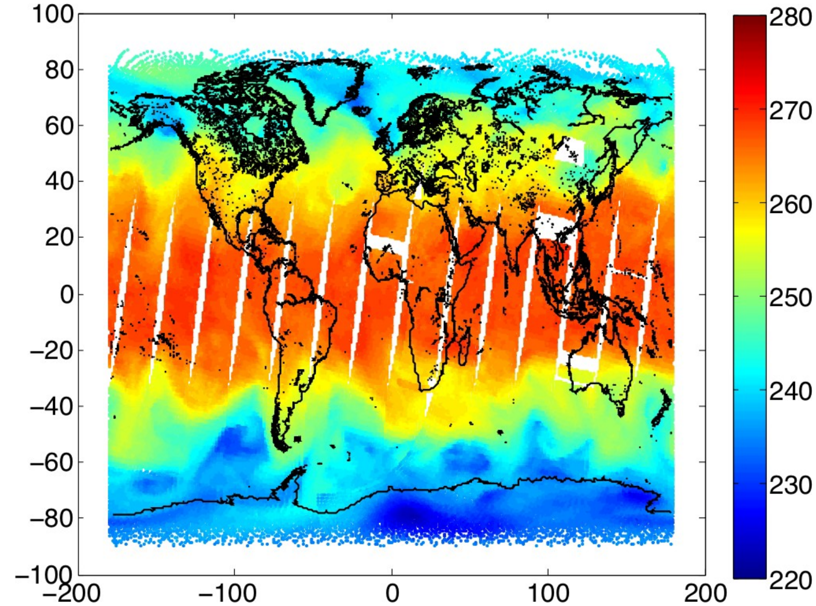
Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Temperature from focus day CrIS/ATMS data

500 hPa Retrieved from ATMS/CrIS
using PCRTM_RA

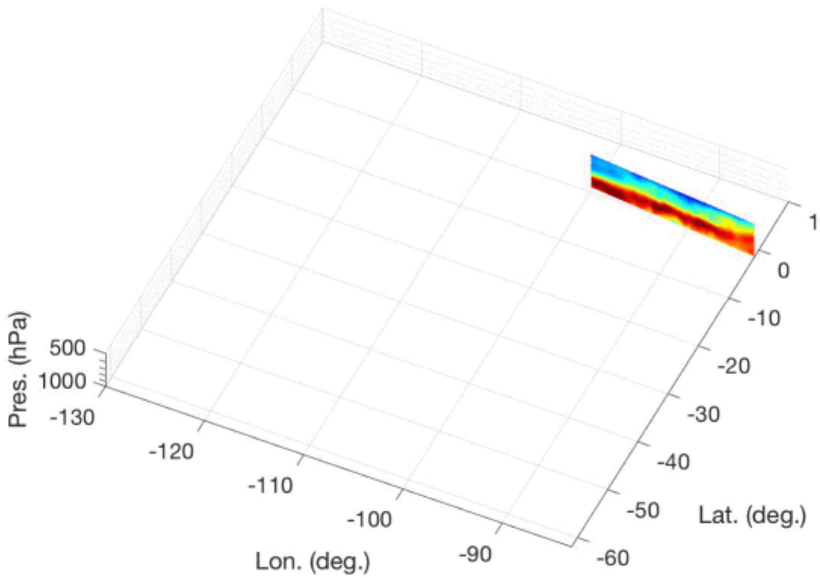


500 hPa Temperature from ECMWF

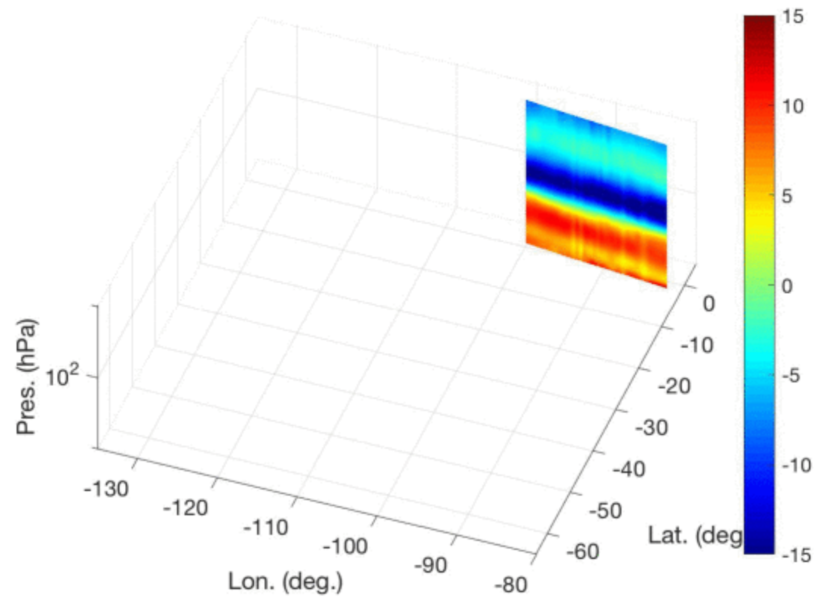


PCRTM Retrieval Algorithm can capture detailed 3-D atmospheric features

Retrieved Atmospheric Relative Humidity from combined CrIS/ATMS(12/21/2015) PCRTM algorithm

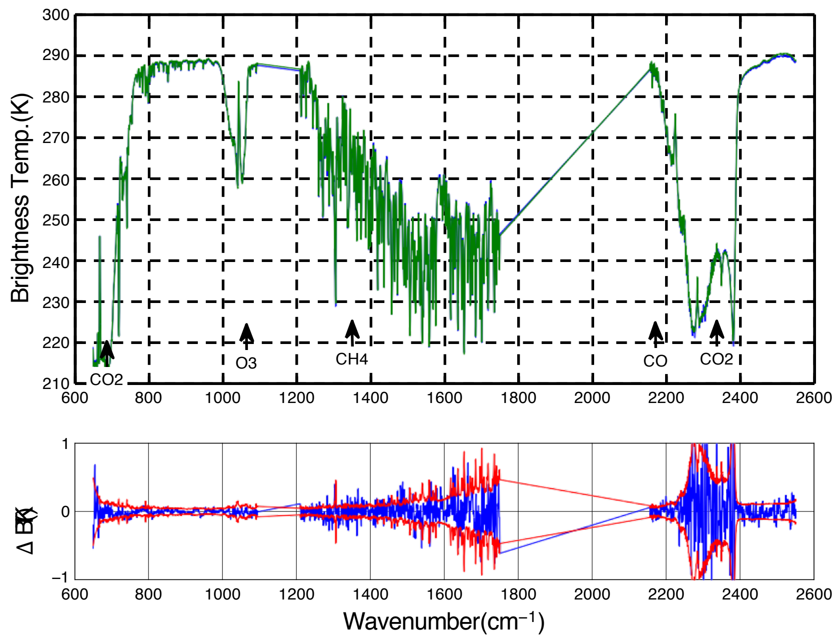


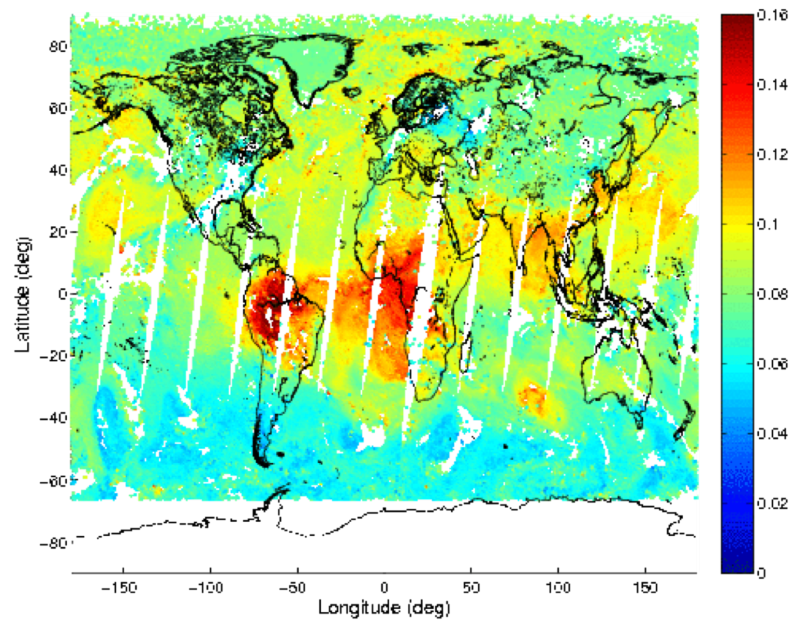
Retrieved Atmospheric Temperature from combined CrIS/ATMS PCRTM algorithm



CO plumes retrievals from high resolution CrIS data

- PCRTM can be used to retrieve
  - Atmospheric temperature, water, trace gas 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





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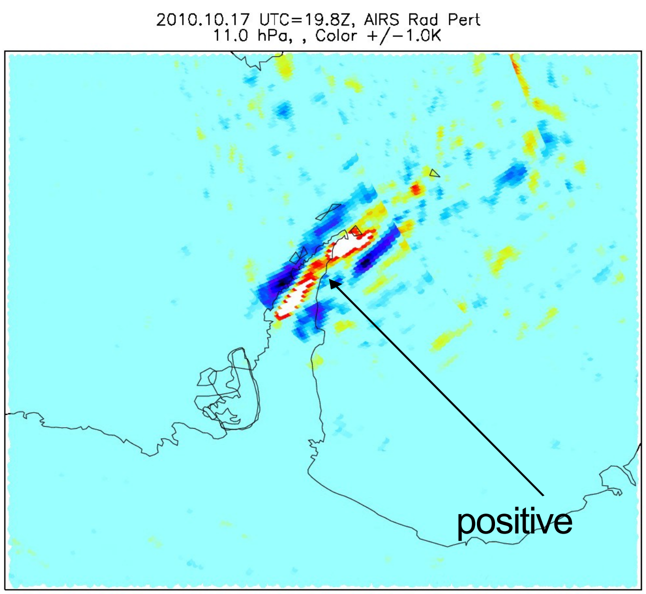
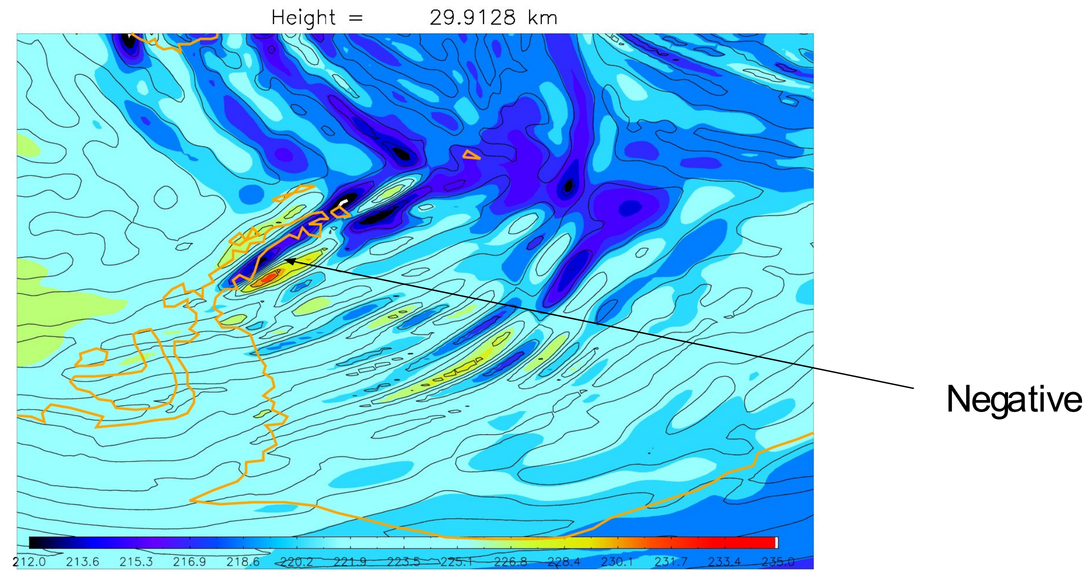
Deriving Gravity Wave from AIRS PCRTM Retrievals (with Collaboration with Jie Gong at Goddard)

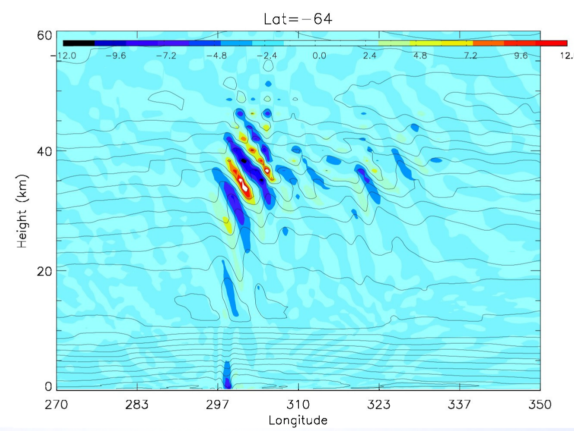
AIRS L1B Radiance Perturbation @ 11 hPa



ECMWF Analysis Resolved gravity wave (GW) @ 11 hPa
(Temperature convolved with AIRS weighting function to get “simulated radiance”

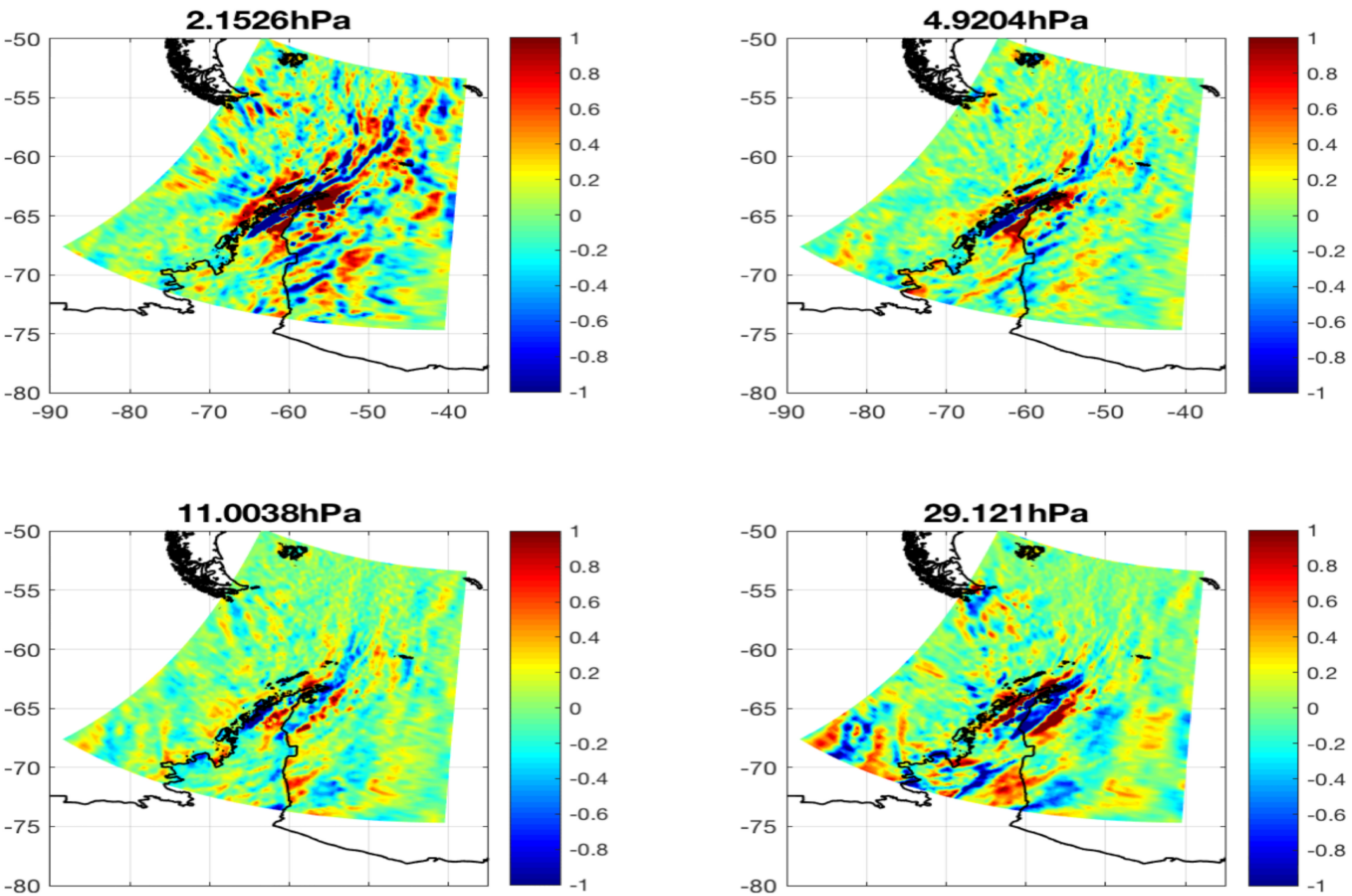


ECMWF simulated this strong topographic GW event very well in terms of magnitude and vertical structure, but the phase alignment is off by one phase line.



ECMWF Analysis
Longitude-height cross-section

PCRTM Retrieved gravity wave features from AIRS hyperspectral data



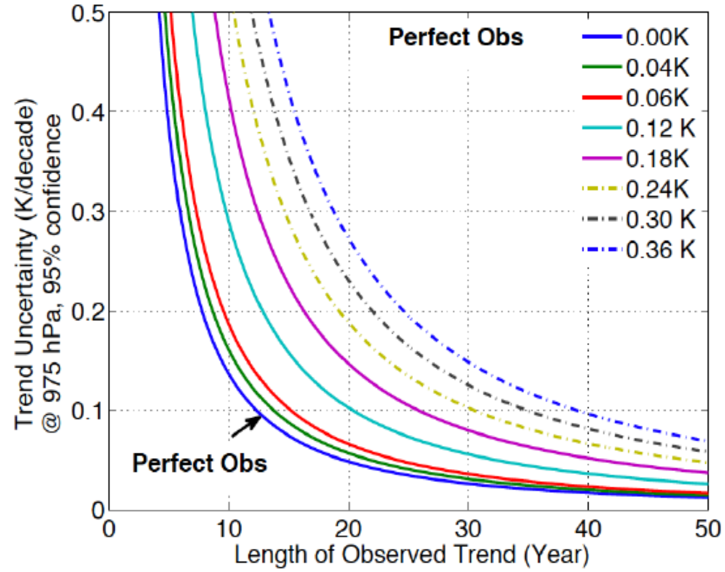
Climate fingerprinting Accuracy requirement

- Climate trend detection uncertainty is impacted by instrument calibration accuracy and natural variabilities

$$\delta\alpha_{trend} = (12 \triangle t)^{-3/2}\sqrt{\sigma_{meas}^2\tau_{meas} + \sigma_{var}^2\,\tau_{var}}$$

- σ_{meas} is the climate variable observation uncertainty due to the instrument radiometric calibration error, which determines measurement uncertainty factor f

$$f = \sqrt{\sigma_{meas}^2\ \tau_{meas}/\sigma_{var}^2\ \tau_{var}}$$



The attribution of radiance change to climate variable anomaly

$$\Delta\alpha = (S^T\Sigma^{-1}S)S^T\Sigma^{-1}\Delta R$$

ΔR - the radiance spectral fingerprints, S - radiative kernel,

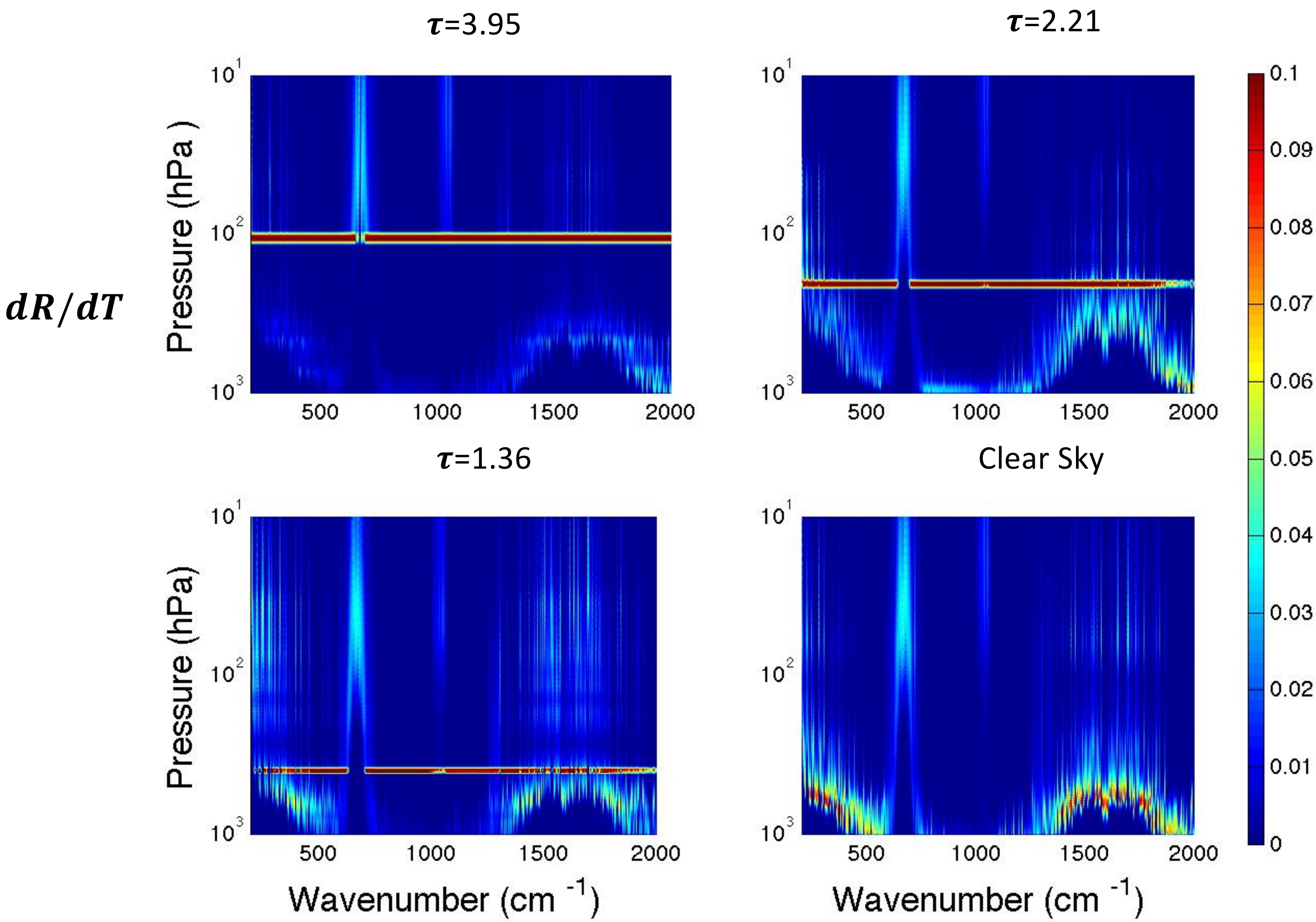
$\Delta\alpha$ - climate variable anomaly, Σ - spectral fingerprints uncertainty

$$\sigma_{meas} = (S^T\Sigma^{-1}S)S^T\Sigma^{-1}\,\delta R$$

A radiometric consistent radiative kernel is an important factor in spectral fingerprinting

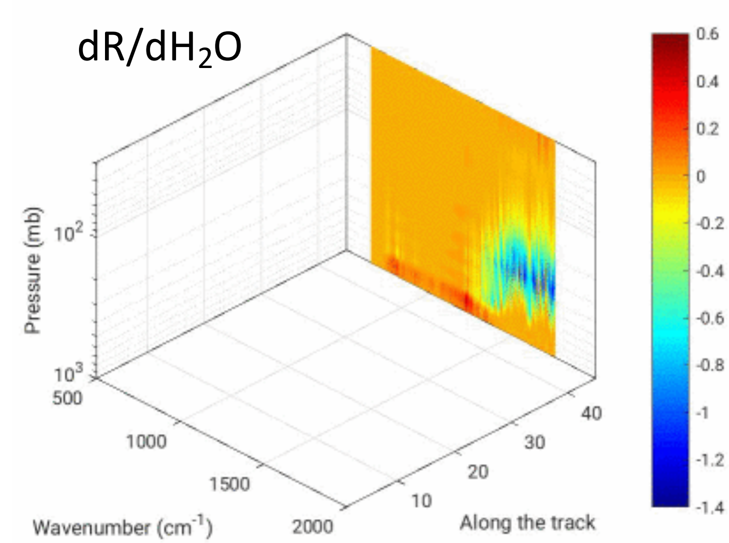
- Need consistent linearization points
- Need accurate radiative kernel in the presence of clouds
- PCRTM and PCRTM-RA is used to accurate calculate radiative kernels

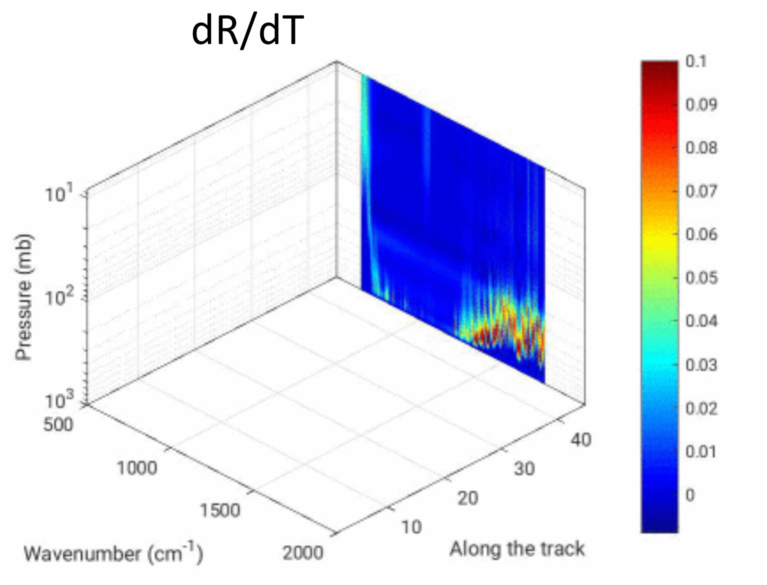
Temperature Jacobian in the presence of clouds

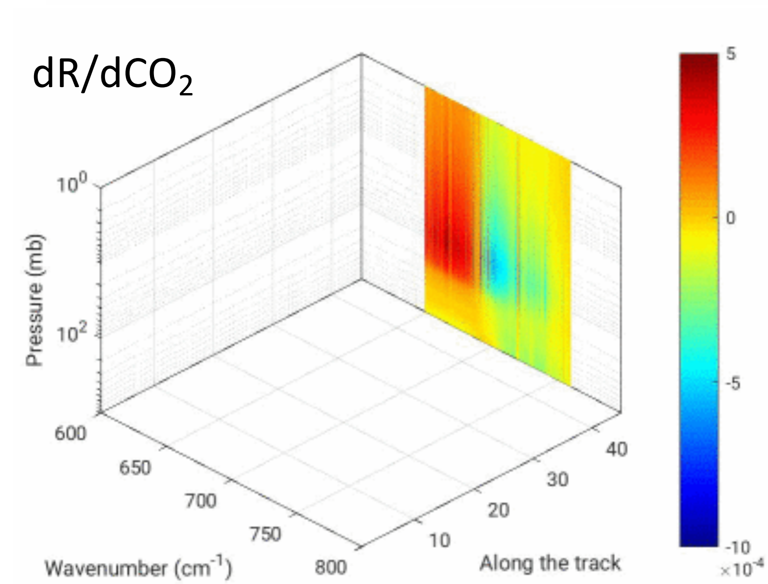


Spatial and Spectral Information of the Radiative Kernel

- Example PCRTM retrieved radiative kernel for CrIS along the scanline direction
- Retrieved parameters include
  - T, H_2O, CO_2, CO, CH_4, N_2O, O_3, cloud phase/temperature/optical depth/size, surface skin temperature and surface emissivity



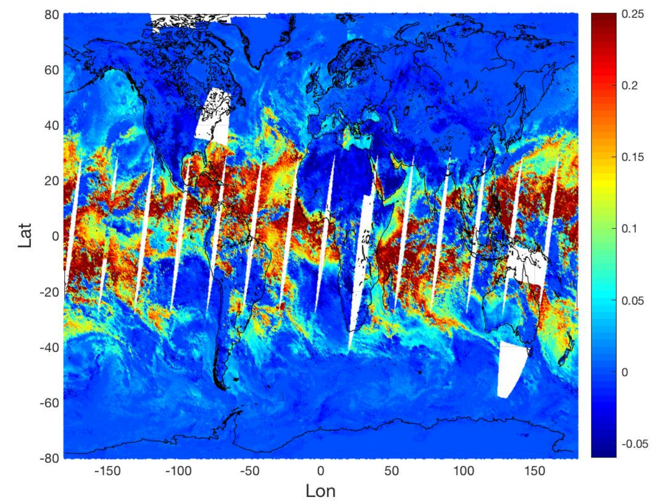




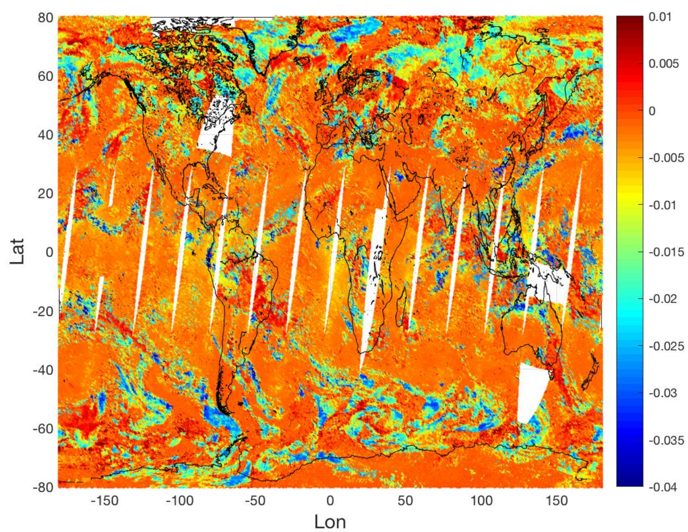
Global distribution of the Radiative Kernel

- Example PCRTM retrieved radiative kernel for CrIS at different altitudes
- Retrieved parameters include
  - T, H_2O, CO_2, CO, CH_4, N_2O, O_3, cloud phase/temperature/optical depth/size, surface skin temperature and surface emissivity

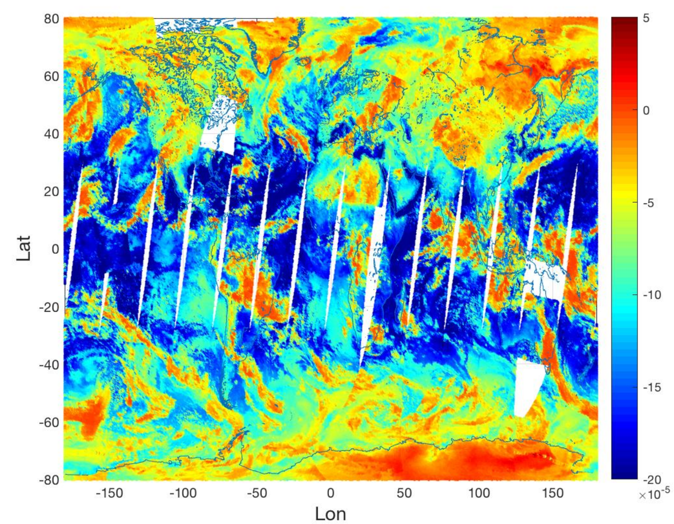
dR/dH_2O



dR/dT



dPC/dCO_2



Summary and Conclusions

- PCRTM has many applications is satellite remote sensing
  - Trained to work from far-IR to UV-Vis spectral regions
  - Updated to handle multiple scattering clouds
  - Trained for polarized RT calcuations of (I, Q, U)
  - A few ms per spectrum in IR spectral region
  - 2-4 orders of magnitude faster than MODTRAN in solar spectral region
  - Accurate relative to line-by-line models
  - Tested with AIRS, CrIS, IASI, NAST-I, CLARREO, SCIAMACHY, HYSICS, HyspIRI
  - Climate OSSE
  - Radiative kernel/Spectral fingerprinting
  - Information contents analysis
  - Instrument requirement studies
  - Geophysical parameter retrievals
- Single FOV cloud retrieval algorithm is capable of retrieving
  - Atmospheric Temperature, Water, CO2, CO, CH4, O3, and N2O profiles
  - Cloud phase, height, temperature, size, optical depth
  - Surface emissivity spectrum and skin temperature
  - In the process of extending it to solar spectral region
- PCRTM and PCRTM-RA is used for spectral fingerprinting of AIRS and CrIS data
  - Radiative kernel derived from AIRS and CrIS data
  - Consistent with radiance anomaly linearization points

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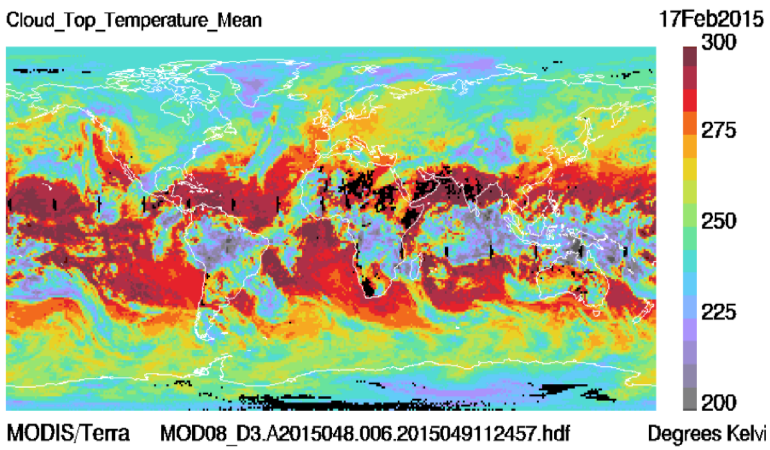

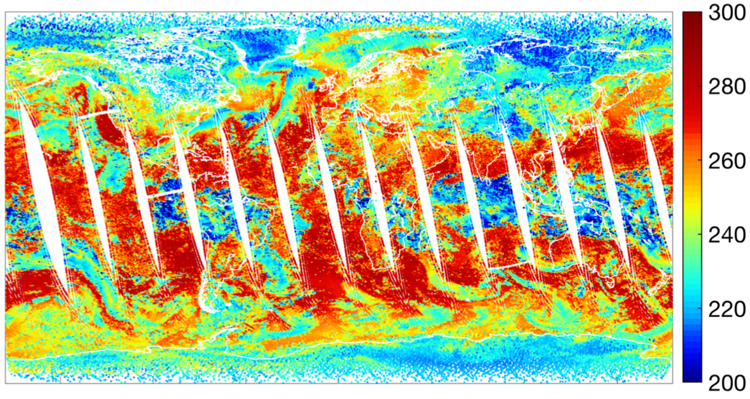

(Xu.Liu-1@nasa.gov)