Deriving Weather and Climate Products from IR Sounders using Single FOV Retrieval and Spectral Fingerprinting Methods

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Acknowledgements
P. Yang, S. DeSouza-Machado, J. Gong, C. Barnet, B. Baum, Sounder SIPS, NOAA NUCAPS Team, NASA NAS and NCCS, NASA DACC, NOAA CLASS, NASA Science of Terra, Aqua, and Suomi NPP Program, NASA NAST-I Program …..

Outline

- Introductions
  - Why do we need Single FOV Retrieval method for IR hyperspectral Sounders
  - What are advantages of using spectral fingerprinting method for climate studies
  - What is the relationships between the two methods
- Description of PCRTM Single FOV all-sky retrieval algorithm
  - PCRTM forward model
  - Optimal estimation inversion
  - Weather and composition products:
    - Atmospheric Temperature, Water, CO_2, CO, CH_4, O_3, and N_2O profiles
    - Cloud phase, height, temperature, size, optical depth
    - Surface emissivity spectrum and skin temperature
- Fusion of long-term AIRS and CrIS Sounder Data for Climate Products
  - Basic methodology
  - Atmospheric temperature and water vapor anomalies from AIRS and CrIS
  - Results compare well with single FOV PCRTM retrievals
- Summary and Conclusions

Introduction

- Why do we need Single FOV Retrieval method for IR hyperspectral Sounders
  - There are three methods for handling clouds: Hole hunting, Cloud-clearing (CC), and Cloud retrievals
- Hole hunting is more suitable for imaging high spatial resolution remote sensors
  - Fit radiance spectral directly but very low yield
  - Sounder SFOV is contaminated with clouds ~90% of time
- CC depends on validity of the cloud-clearing assumption
  - All the geophysical parameters within one FOR are homogeneous except for clouds
  - Fits cloud-cleared radiance spectra instead of original observed radiances
  - Cloud-clearing (CC) heavily depends on the quality of the first guess
- SFOV Retrieval Algorithm (SFOV-RA) fits observed radiance spectra directly
  - Provides radiometric closure
  - Provides higher spatial resolution EDRs than CC method (good for gravity wave studies, nowcasting, CAPE calculations, atmospheric trace gas species)
  - Provides cloud products simultaneously during the inversion process
  - Provides error covariance matrix and averaging kernels
- What are advantages of using spectral fingerprinting method for climate studies
  - Works on spatiotemporally averaged data
  - Very fast (skips time-consuming L2 data products)
  - Fits radiance anomaly spectra directly (radiometric closure)
- Relationships between the SFOV-RA and spectral fingerprinting
  - Radiance closure requires handling cloud explicitly together with all other parameters
  - PCRTM model is the key to both SFOV-RA and spectral fingerprinting
  - SFOV-RA provides radiometric consistent radiative kernels needed for the fingerprinting
  - Data fusion using consistent forward model and inversion for all IR sounders

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Description of SFOV-RA (PCRTM and PCRTM-RA)

- Two key components for a SFOV-RA
  - A Principal Component-based Radiative Transfer Model (PCRTM)
    - Explore correlations by compressing hyperspectral data into Principal Component (PC) domain
    - Properly handles absorption, emission, and scattering of atmospheric molecules and clouds
    - Physical-based RT model by performing radiative transfer at only critically important frequencies
    - Consistent spectroscopy and training data for all IR sounders
  - Simultaneous PCRTM Retrieval Algorithm (PCRTM-RA)
    - Uses 120-200 PCs- equivalent to use all spectral channels
    - Uses all available spectral information to separate contributions from atmospheric trace gases, cloud and surfaces
    - Uses PCA to reduce random measurement noises
    - No need to account for errors due to non-retrieved parameters (such as those in a sequential inversion algorithm)
- Leverage more than a decade of PCRTM-RA development at NASA LaRC
  - Validated using AIRS, IASI, CrIS, and NAST-I sounder data
  - Processed 2.4 years of CrIS/ATMS data recently
  - Foundation for spectral fingerprinting method for AIRS and CrIS (can be used for IASI, and IASI-NG)
- PCRTM-RA SFOV-RA products include
  - Atmospheric Temperature, Water, CO_2, CO, CH_4, O_3, and N_2O profiles
  - Cloud phase, height, temperature, size, optical depth
  - Surface emissivity spectrum and skin temperature

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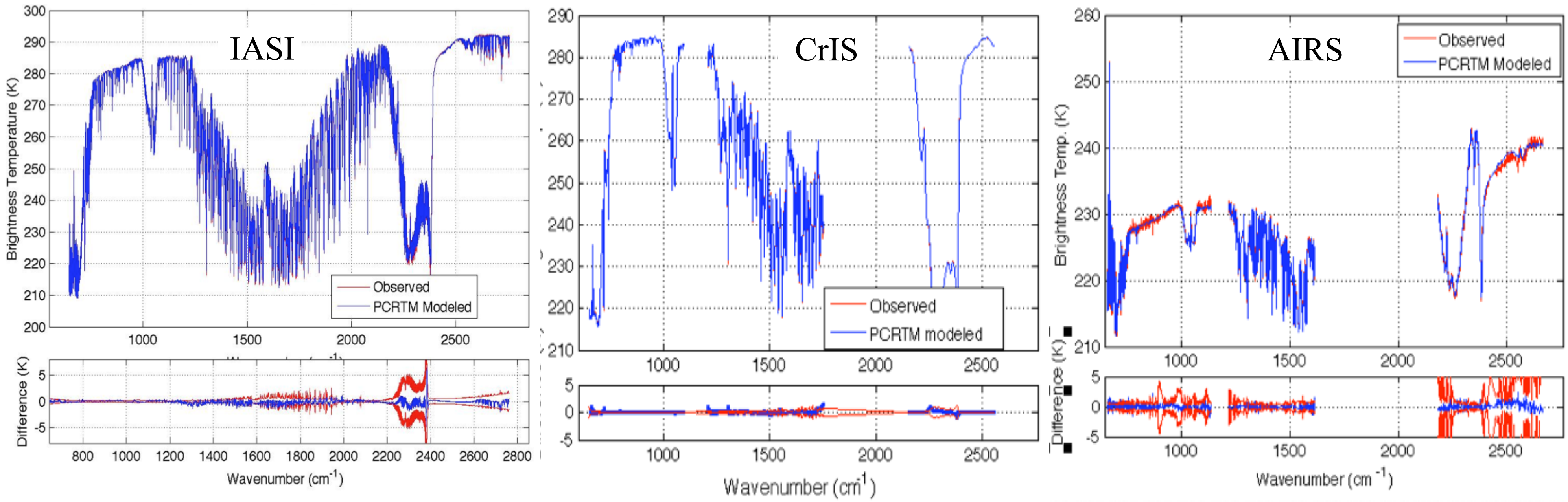
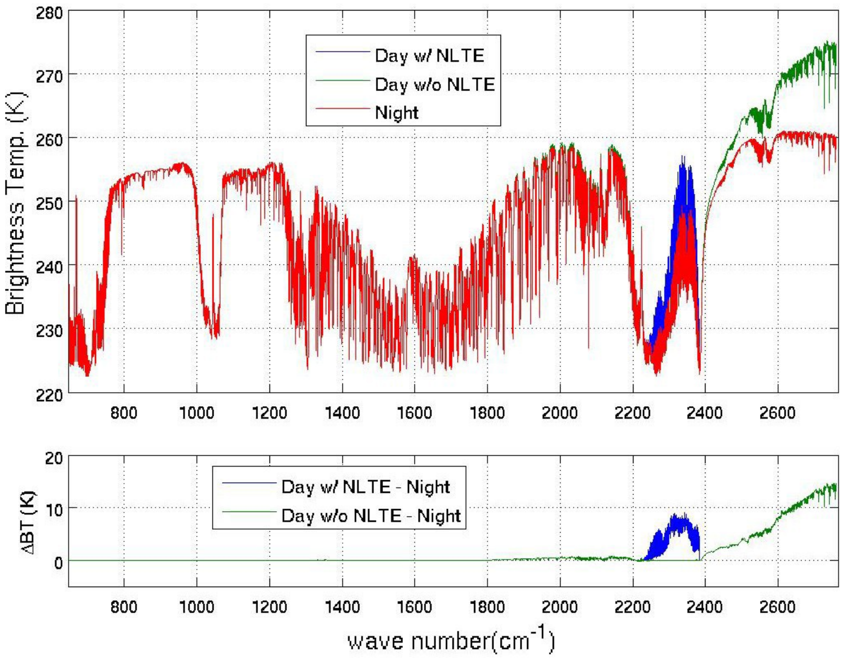
PCRTM Forward Model is Accurate and Fast

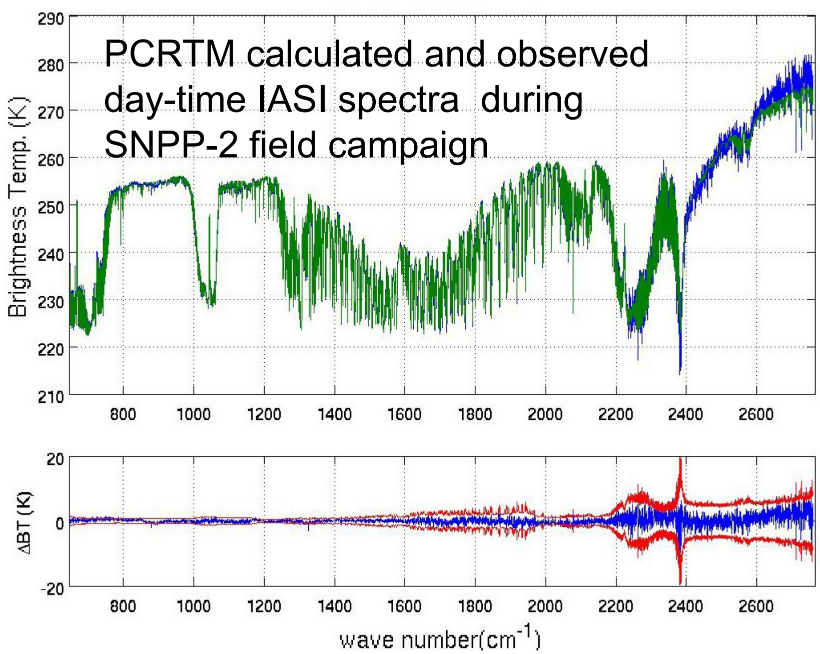


Sensor	Channel Number	PC score (seconds)	PC score + radiance	PC score + PC Jacobian
CLARREO, 0.1 cm^{-1}	19901	0.014 s	0.022 s	0.052 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s	0.013 s	0.039 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s	0.012 s	0.036 s
IASI, 0.25 cm^{-1}	8461	0.011 s	0.012 s	0.044 s
AIRS, 0.5-2.5 cm^{-1}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

- Spectral coverage (50-3000 cm^{-1})
- Multilayer, multiple scattering clouds included
- 15 variable trace gases
- Output analytical Jacobians
- Very accurate relative to Line-by-Line RT
  - Bias error < 0.002 K
  - RMS error < 0.03K
- 4 orders of magnitude faster than LBLRTM

PCRTM handles NLTE and solar scattering properly





Inter-comparison of 6 RT models simulating AIRS cloudy spectra in the using ECMWF cloud fields (Aumann et al, 2017 JGR)
http://dx.doi.org/10.1029/2017JD028063

bt2616 (AIRS observed –calculated)	day PDF correlation	day bias ± stddev [K] 1437 cases
SARTA_pM1	0.8744	+5.00±14.79
SARTA_p999	0.8779	+7.05±15.57
PCRTM_ERO	0.9855	+1.55±15.90
PCRTM_MRO	0.9846	+0.73±15.84
PCRTM_ERO2	0.9804	+2.52±16.79
PCRTM_MRO4	0.9766	+0.91±16.22
HT_CMO	0.6669	+15.04±20.11
HT_CRO	0.6492	+15.97±19.76
HT_CMRO	0.6653	+15.13±20.10
HT_SMO	0.9215	+3.69±15.86
HT_SRO	0.9628	+3.87±15.83
HT_SMRO	0.9245	+3.65±15.88
RTTOV_MRO	0.8948	+4.81±15.86
RTTOV_CMSS	0.8803	+8.07±15.26
σ-IASI_as	0.4809	+20.94±18.94*
CRTM2_tcc	0.3991	+20.55±17.60
CRTM_mro	0.6680	+13.90±18.74
CRTM_2col	0.6410	+15.33±18.59

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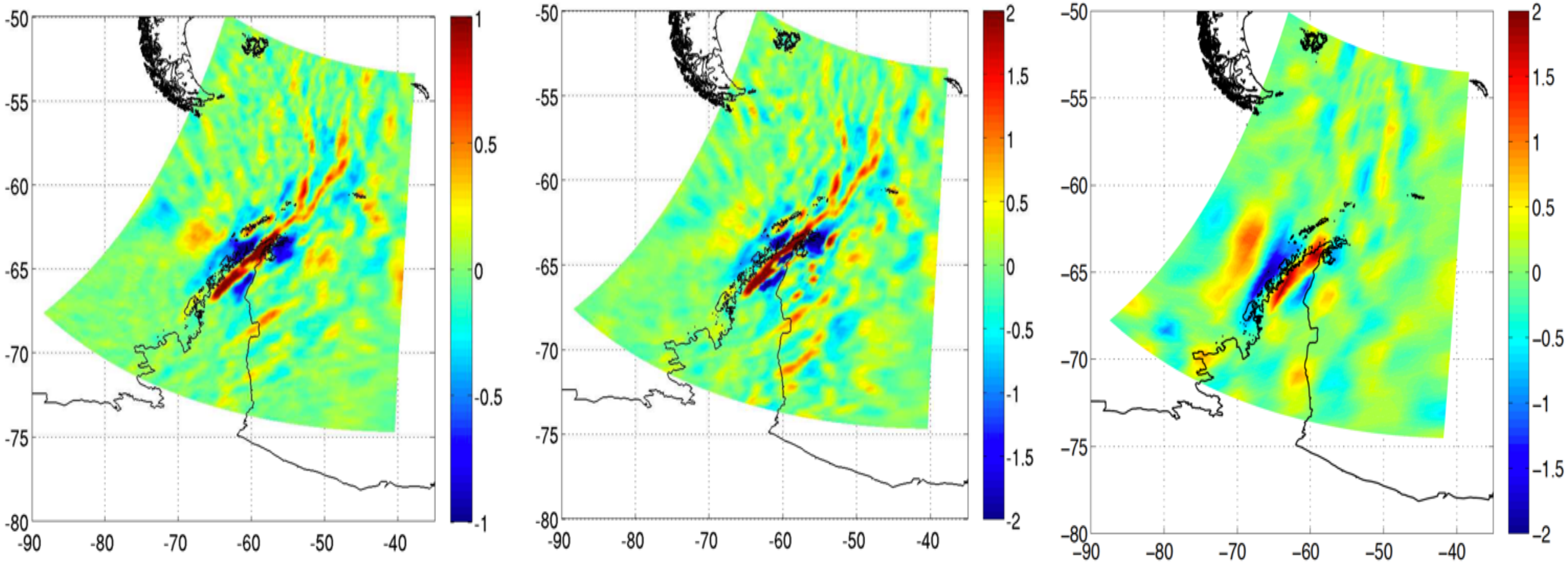
Example of Resolving Gravity Wave using SFOV PCRTM-RA on AIRS Data



Gravity wave detected by AIRS on Oct. 17th, 2010 near South Shetland Islands of Antarctic.

Perturbations (in Brightness temperature) from the AIRS channel radiance @ 2356.4 cm^{-1}

Perturbations in the stratospheric temperature @2.7 hPa from the PCRTM retrieval

Perturbations in the stratospheric temperature @ 2.7 hPa from the AIRS level 2 products

We wish to thank J. Gong and D. Wu from NASA for their collaborations on this work

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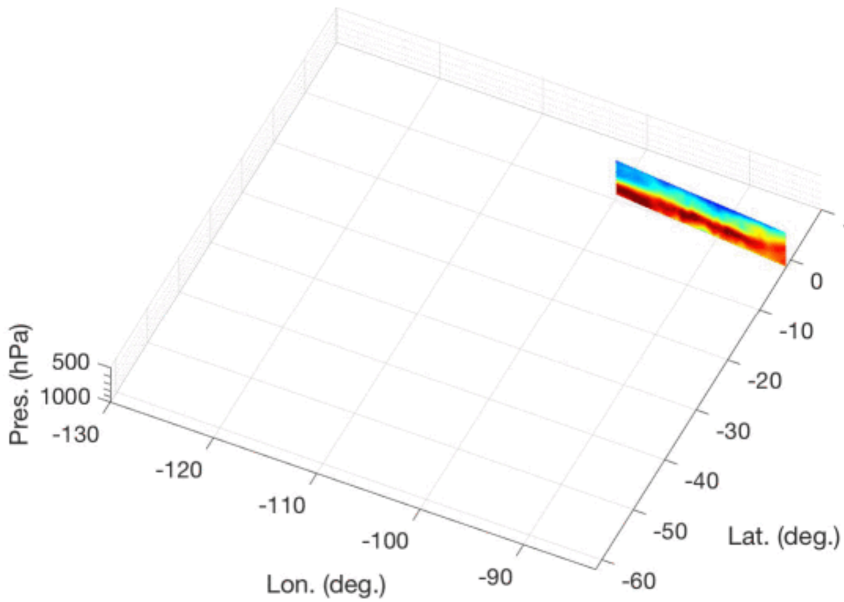
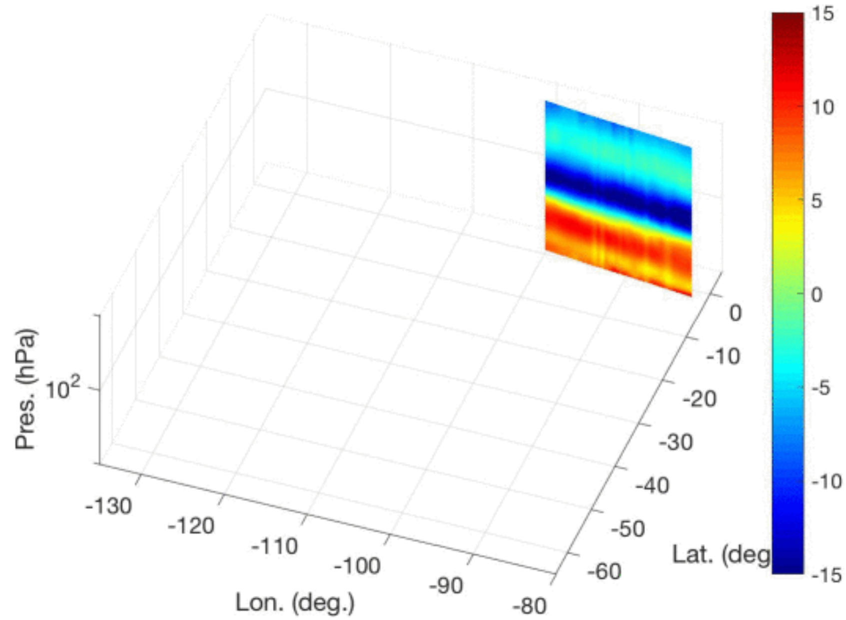
PCRTM Retrieval Algorithm can capture detailed 3-D atmospheric temperature and humidity features

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



Retrieved Atmospheric Temperature from combined CrIS/ATMS PCRTM algorithm



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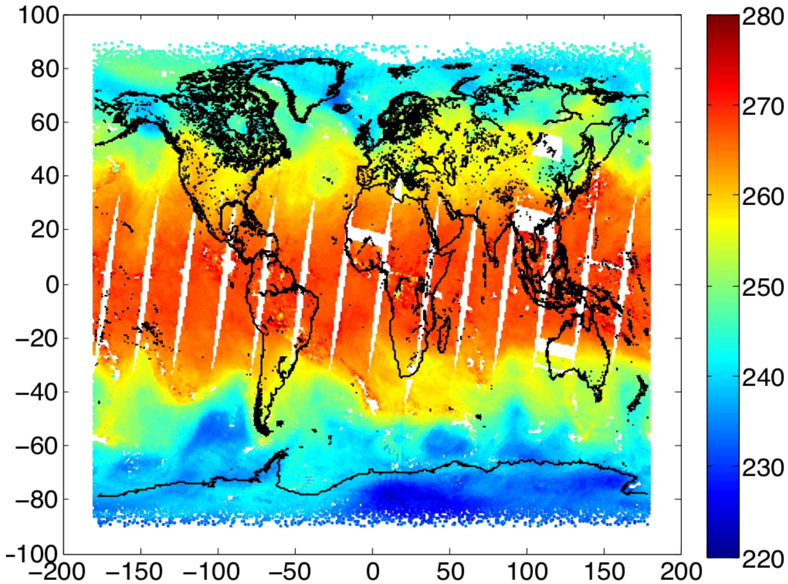
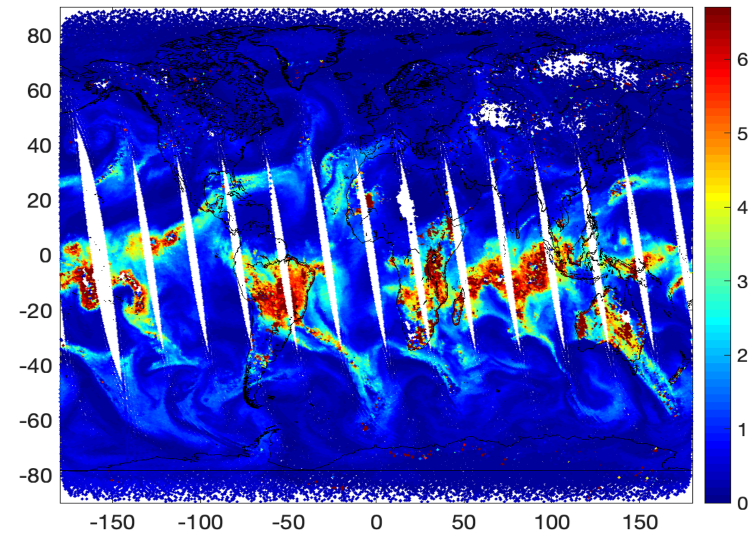
Examples of PCRTM-RA Retrieved and ECMWF Atmospheric Water Vapor from CrIS

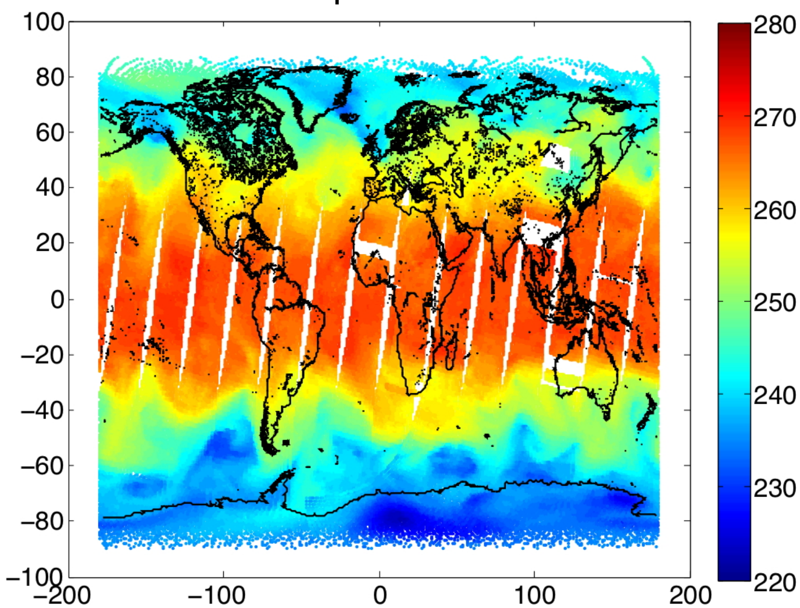
PCRTM-RA Retrieved Temperature at 500 hPa



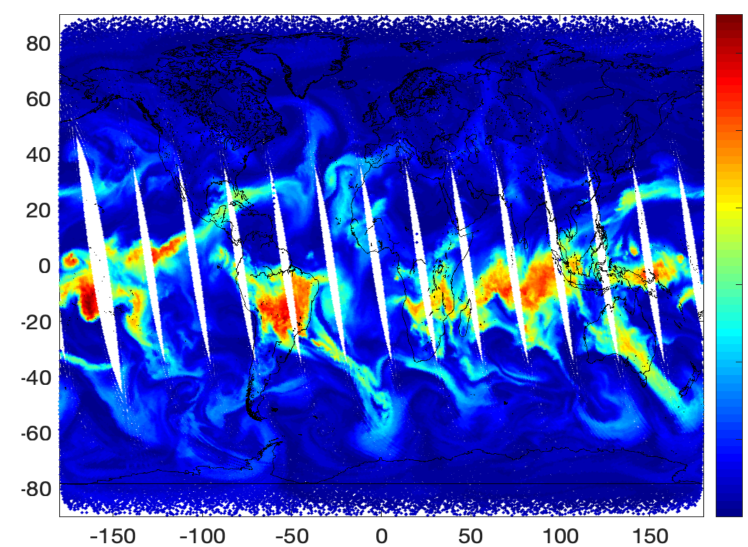
PCRTM-RA Retrieved H_2O at 500 hPa



500 hPa Temperature from ECMWF



H_2O at 500 hPa from ECMWF



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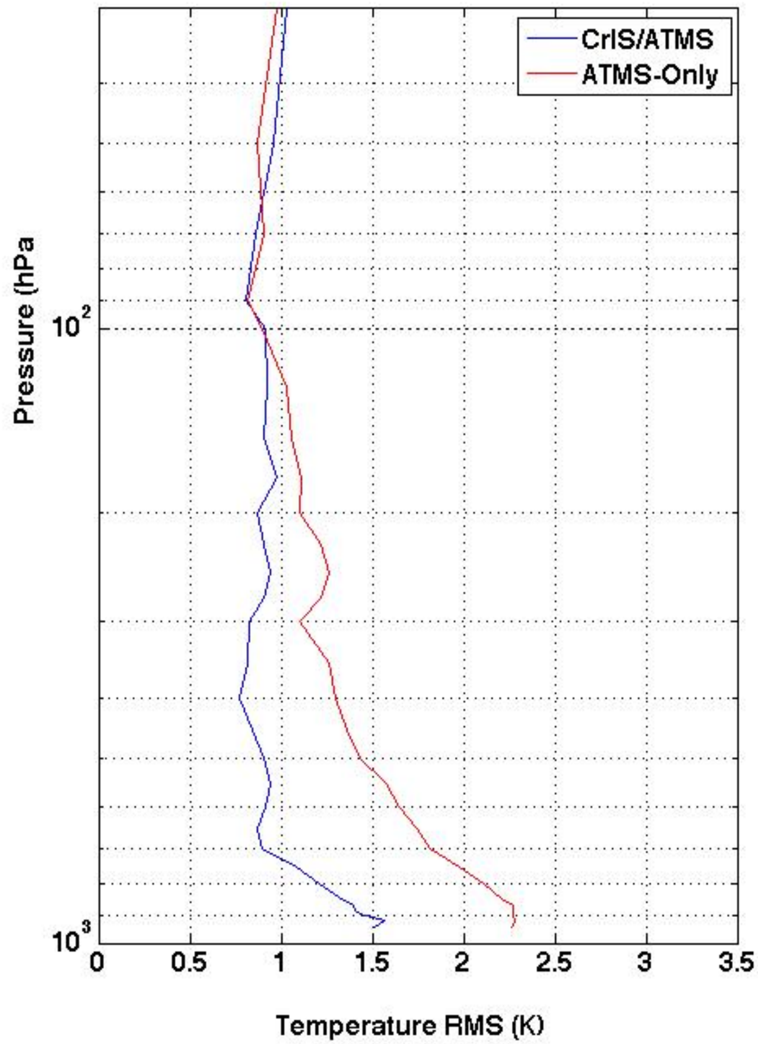
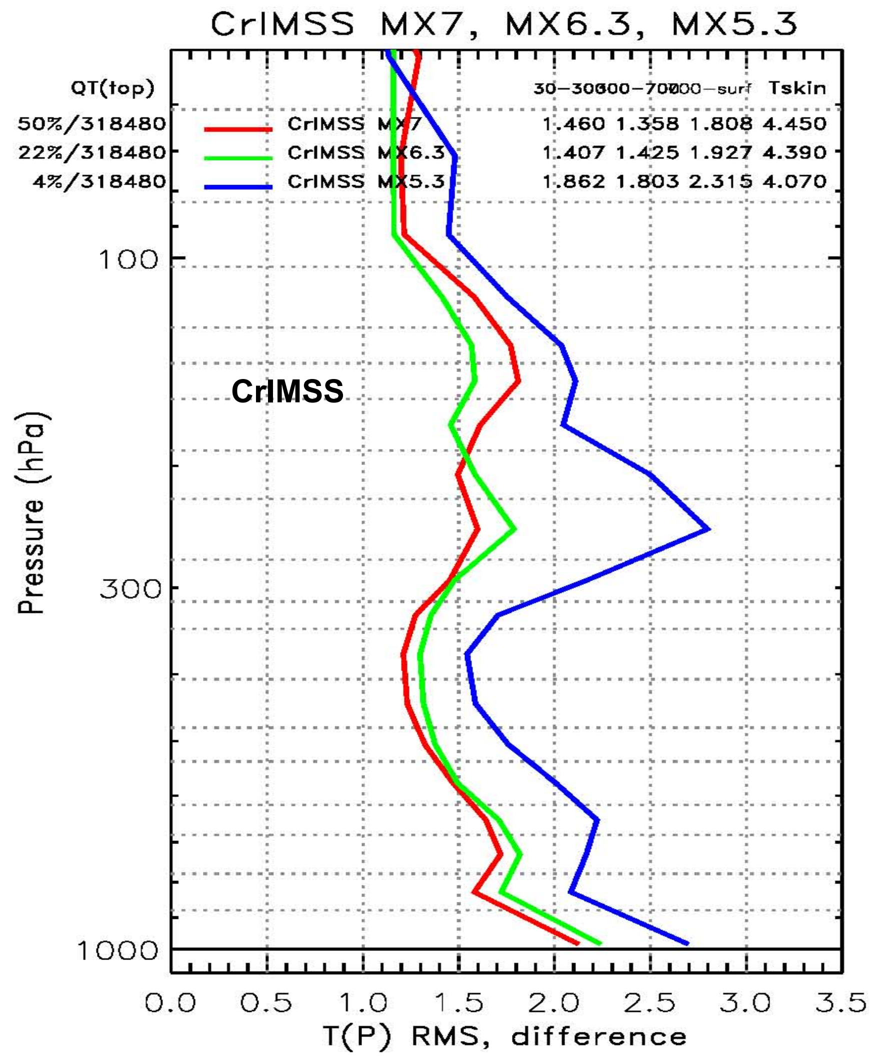
Atmospheric temperature profile retrieval with and without multiple spectral regions





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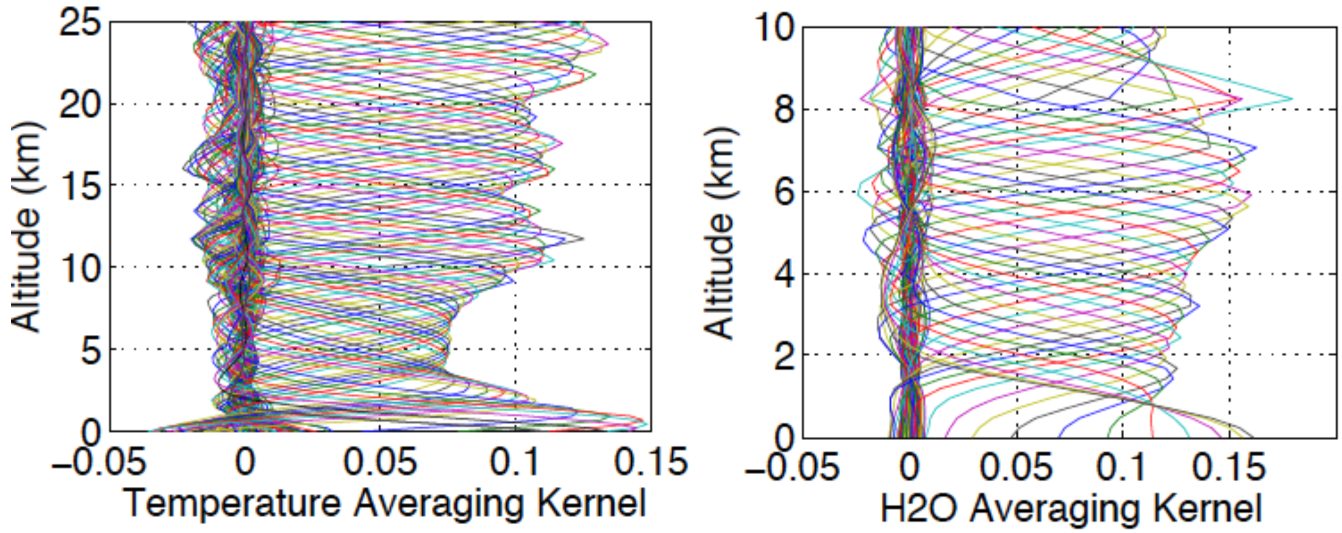
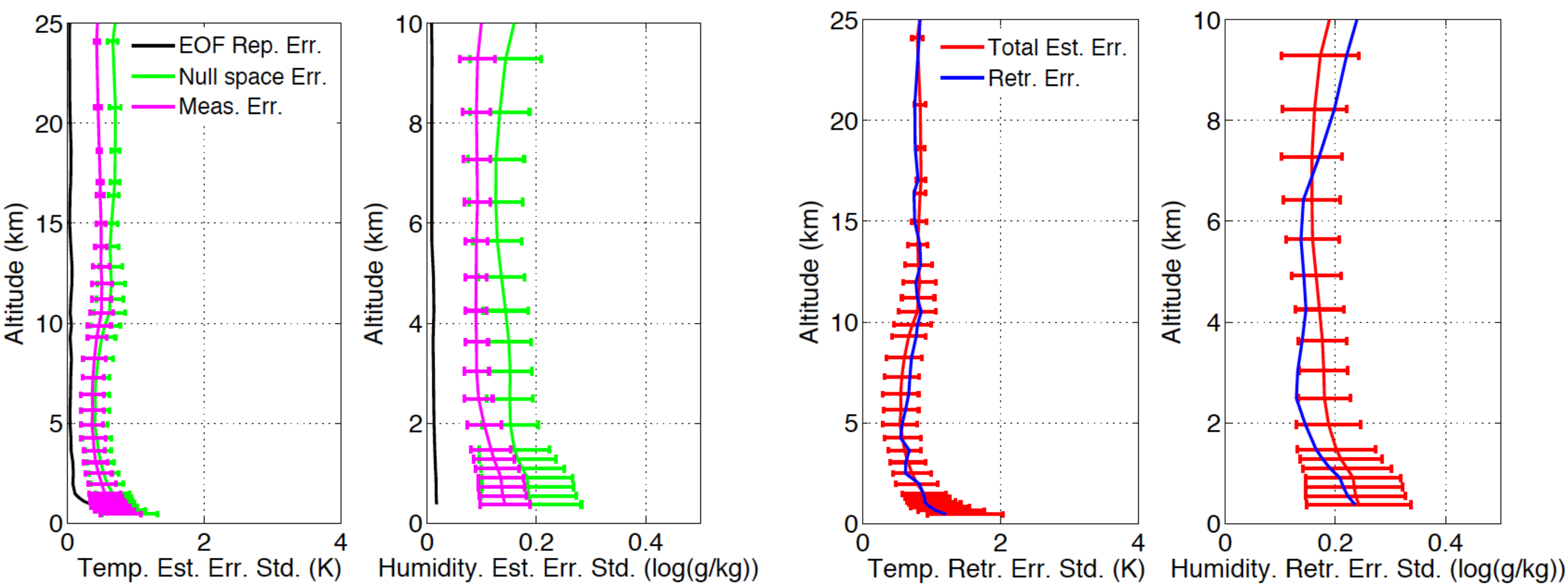
Averaging Kernel and Error Covariance Matrix Provided by PRCTM-RA

- Averaging kernel (A) provide information degree of freedom [trace(A)] and vertical resolution
- Error Estimated by the error covariance matrix is consistent with simulated retrieval known truth





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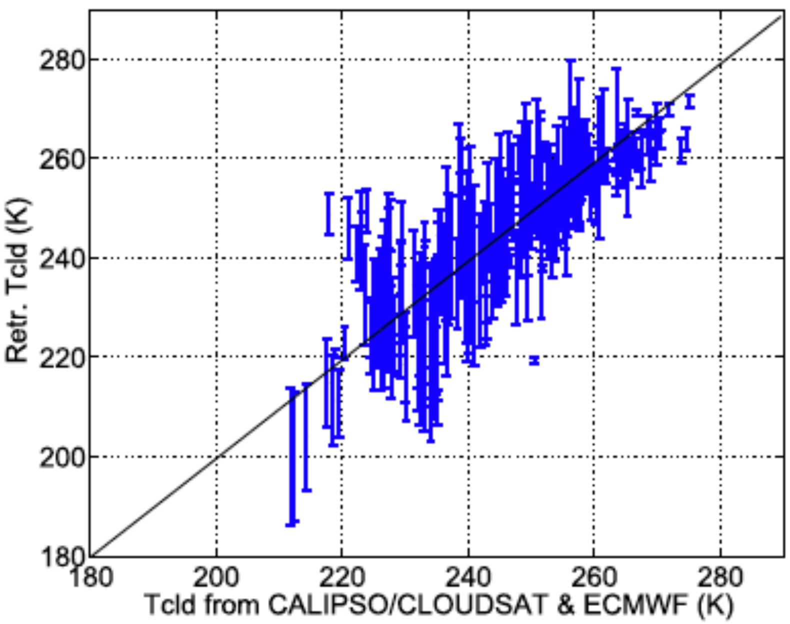
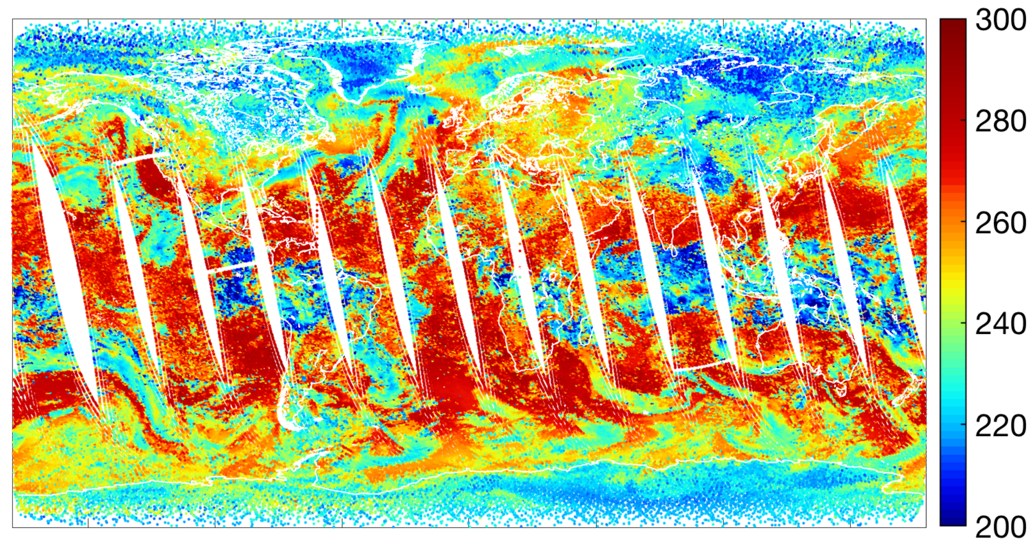
Cloud top Temp., particle size, optical depth

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

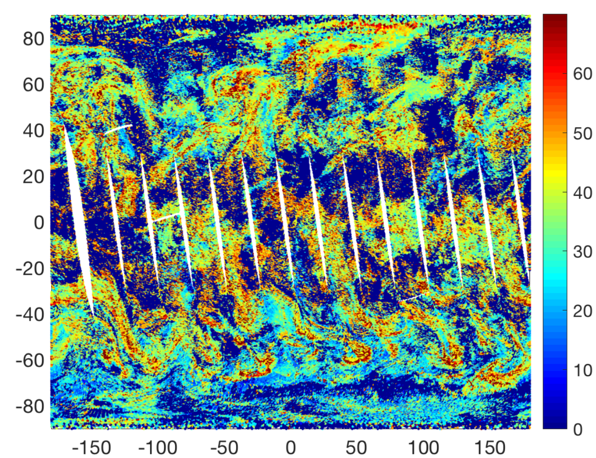


Retrieval results from CrIS/ATMS observations

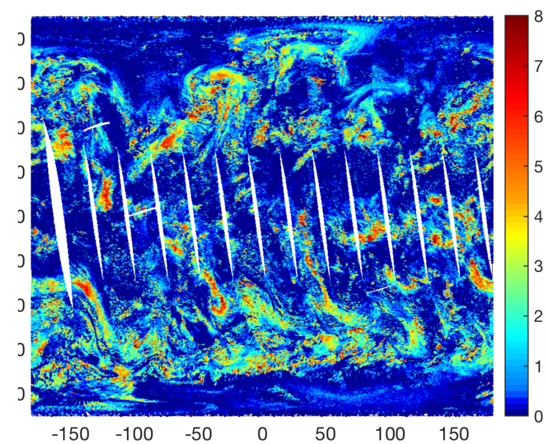
$Cloud\ Temp.(K)$



De (diameter µm)



$\boldsymbol{\tau}$ @550nm



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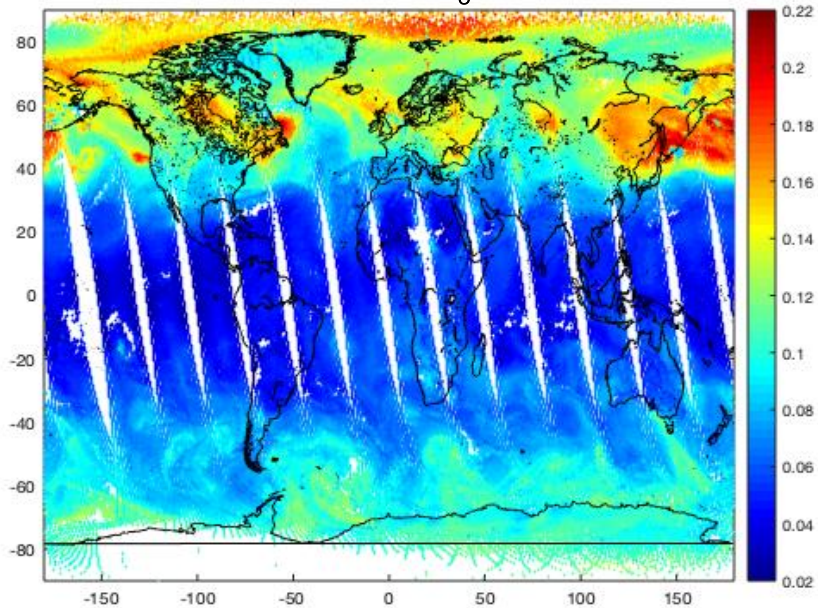
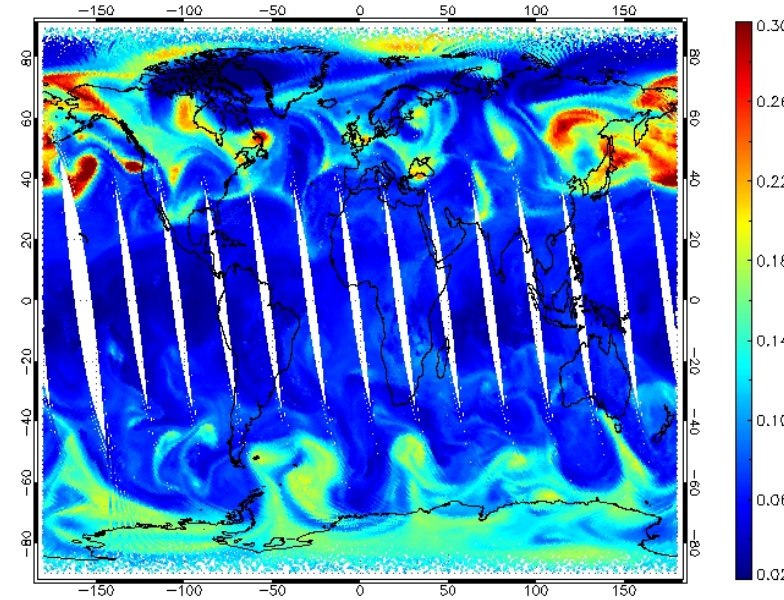
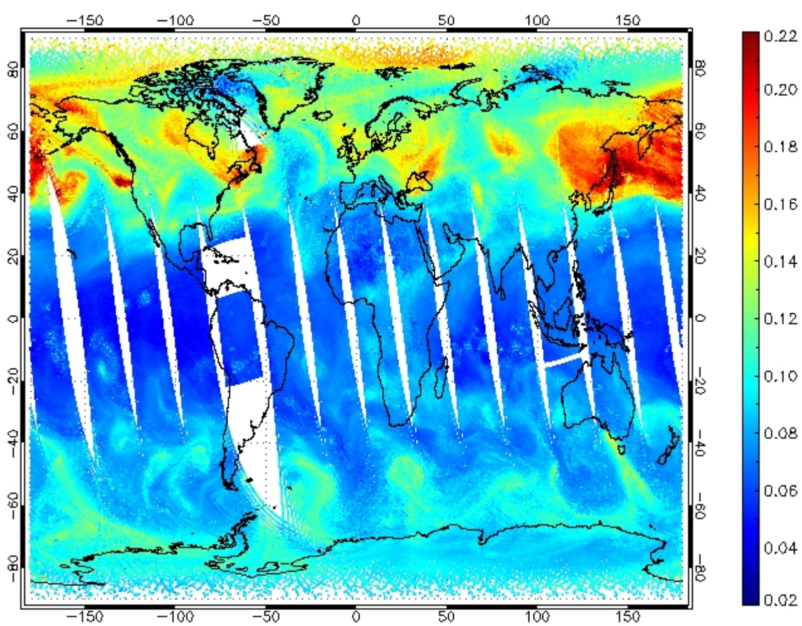
Comparisons of PCRTM-RA, NUCAPS, and CLIMCAPS Retrieved O_3 from CrIS data on January 14, 2016

PCRTM-RA Retrieved O_3 at 300 hPa

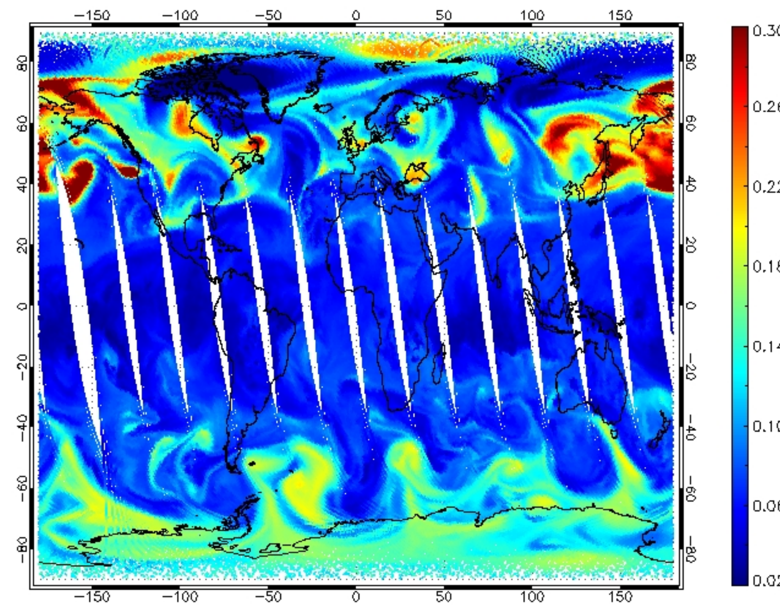


CLIMCAPS Retrieved O_3 at 300 hPa





NUCAPS Retrieved O_3 at 300 hPa



MERRA2 O_3 used as CLIMCAPS Prior

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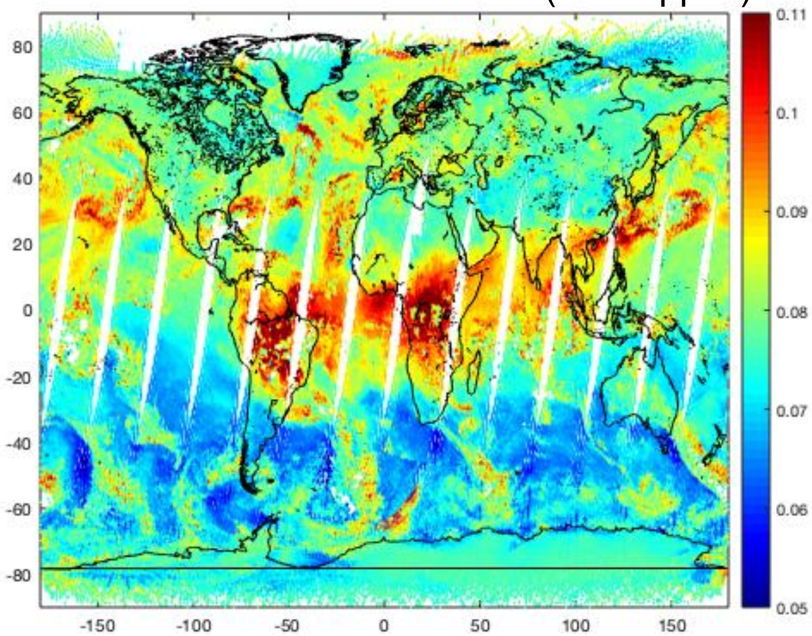
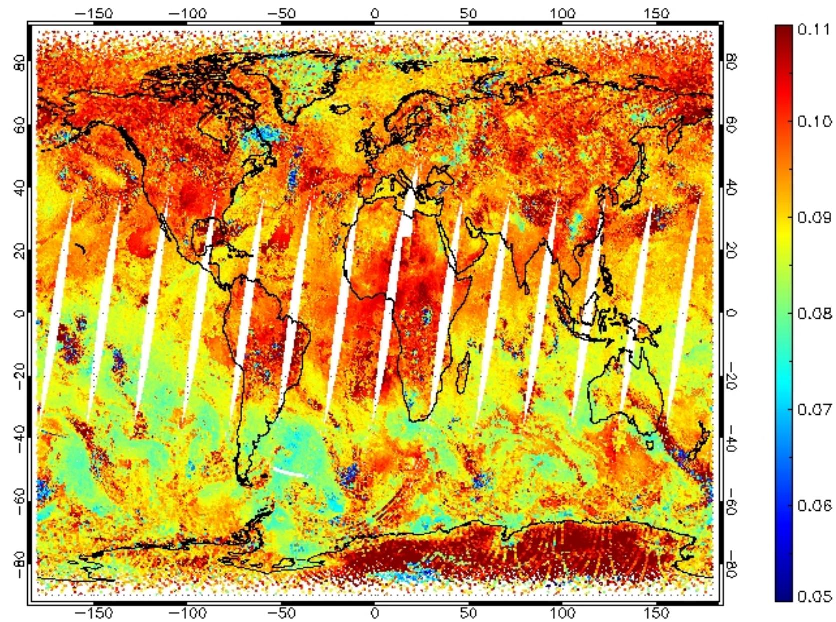
Comparisons of PCRTM-RA, NUCAPS, and CLIMCAPS Retrieved CO at 300 hPa from CrIS data on January 14, 2016

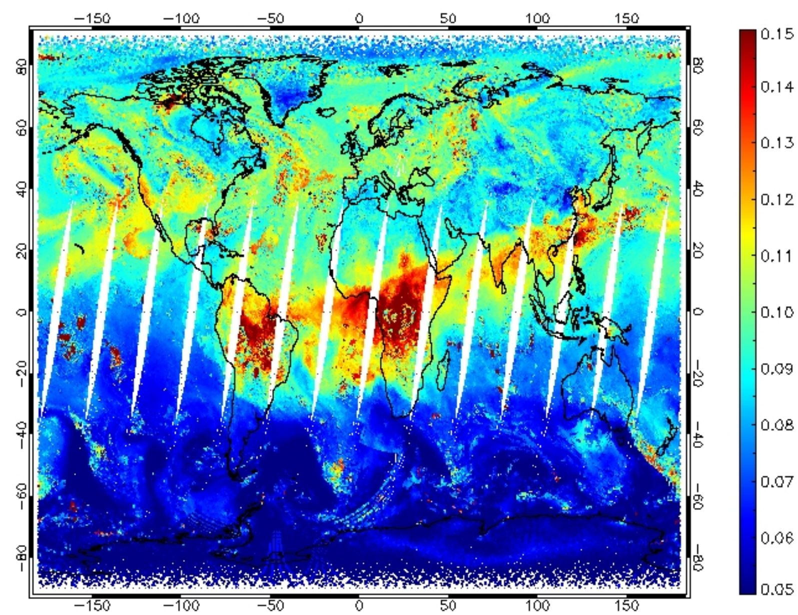
PCRTM-RA Retrieved CO (5-110 ppbv)





NUCAPS Retrieved CO (5-110 ppbv)

CLIMCAPS Retrieved CO (5-150 ppbv)



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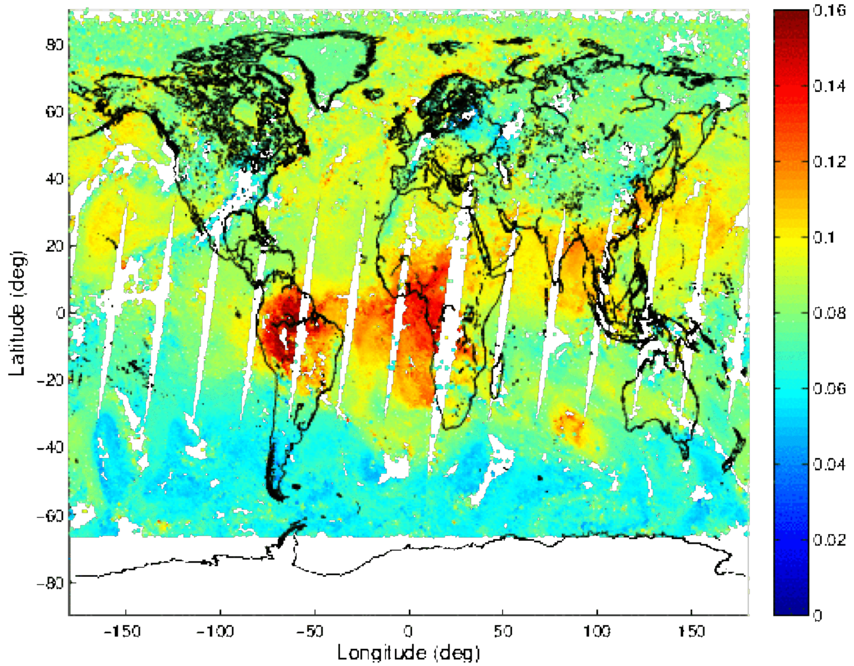
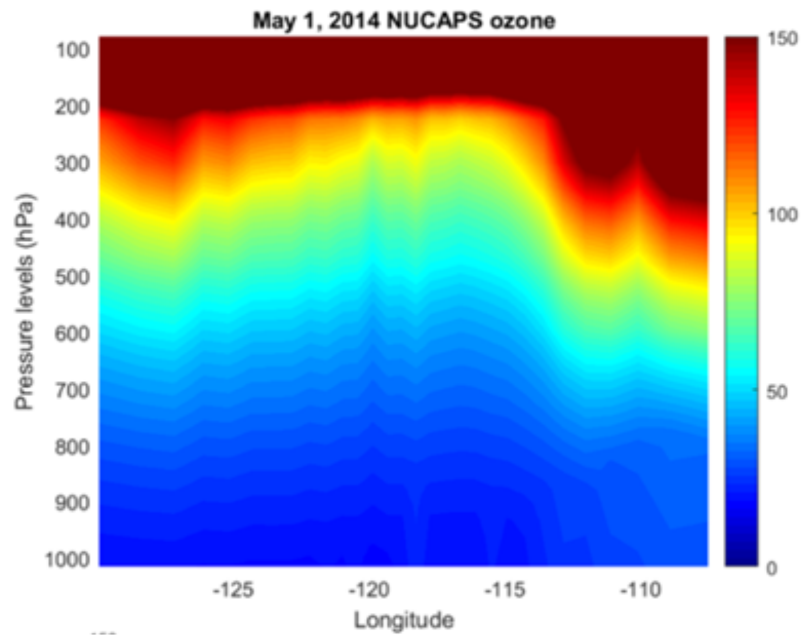
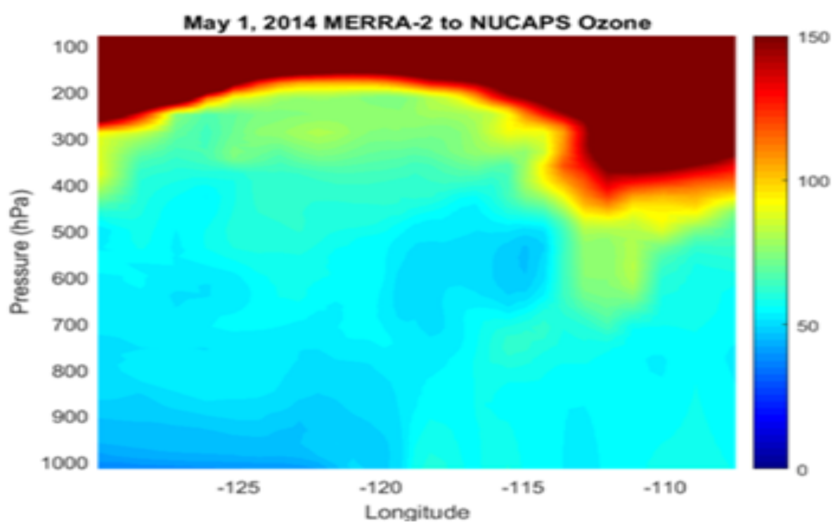
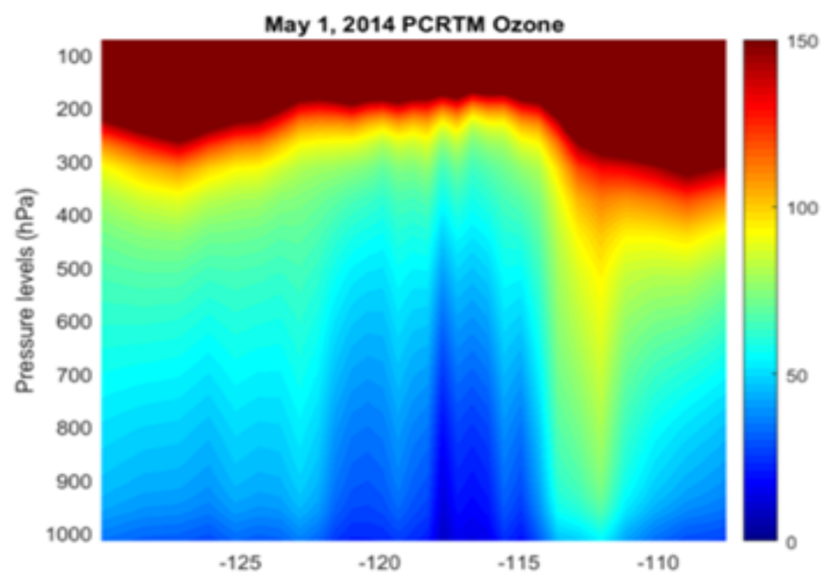
More Examples Trace Gases Retrieval using PCRTM-RA (CO plume movement and O_3 Stratospheric Intrusion

12/21/2015 ~ 12/27/2015 CO @300mb









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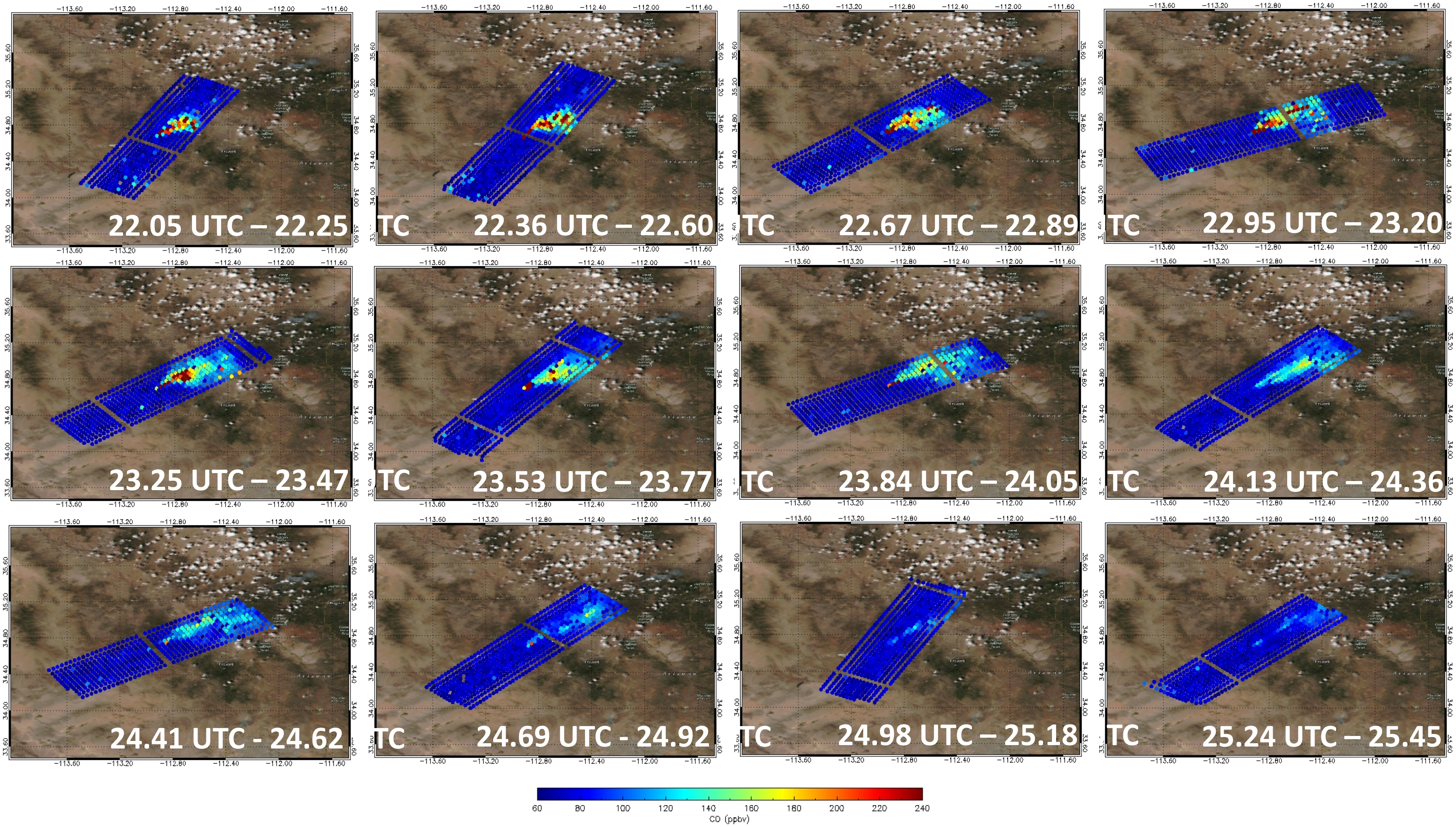
Trace Gas Retrievals and results from recent FIREX-AQ NAST-I field campaign data



- Retrieved global CO at 300 mb from NAST-I during FIREX-AQ on August 16, 2019

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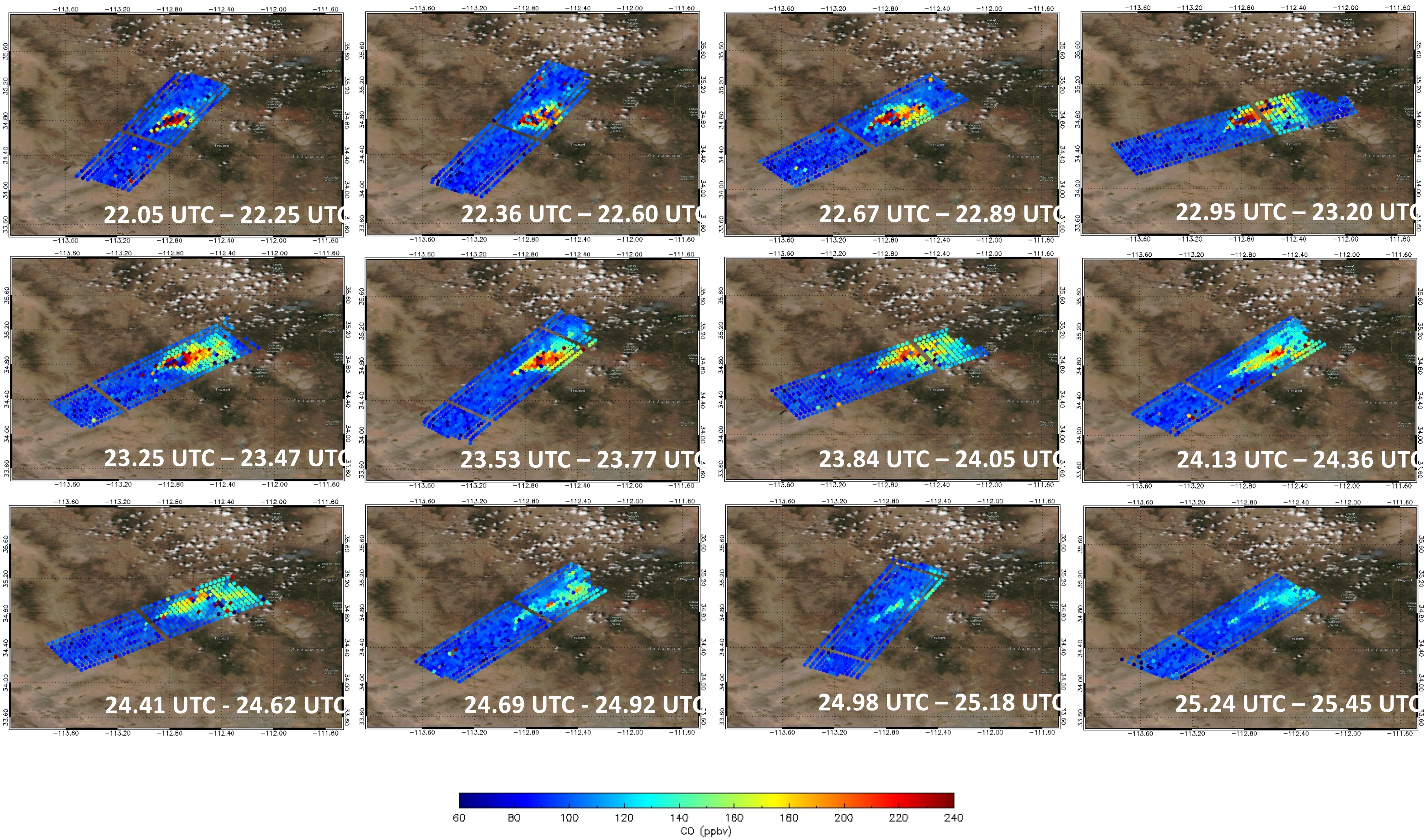
Trace Gas Retrievals and Preliminary results from recent FIREX-AQ field campaign data



- Retrieved global CO at 800 mb from NAST-I during FIREX-AQ on August 16, 2019

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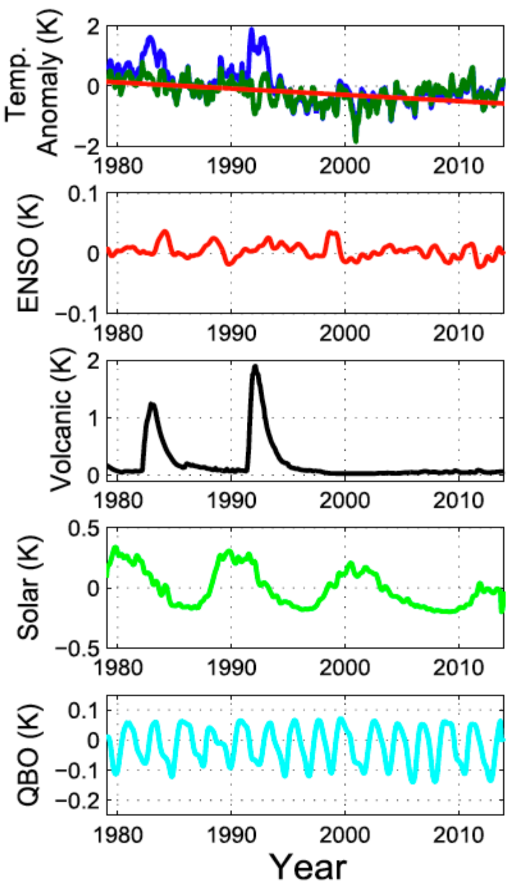
Spectral fingerprinting methodology



- Assumes a linear relationship between the change in climate variables and the introduced change in TOA spectral radiance within specified spatiotemporal scale

$$\Delta\mathbb{R} = S\Delta\alpha + \varepsilon$$

$\Delta\mathbb{R}$ - the radiance spectral fingerprints, S - radiative kernel,
$\Delta\alpha$ - the change in climate variable, ε – nonlinearity residual.

- Attributes TOA spectral radiance change to the change in climate variable

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

Σ - spectral fingerprints uncertainty, covariance of ε

Spectral fingerprinting challenges

- Requires complicated radiative kernels S to account for contributions from major climate variables including temperature, water vapor, surface properties, trace gases, and clouds

- Needs to ensure the 'radiance closure'

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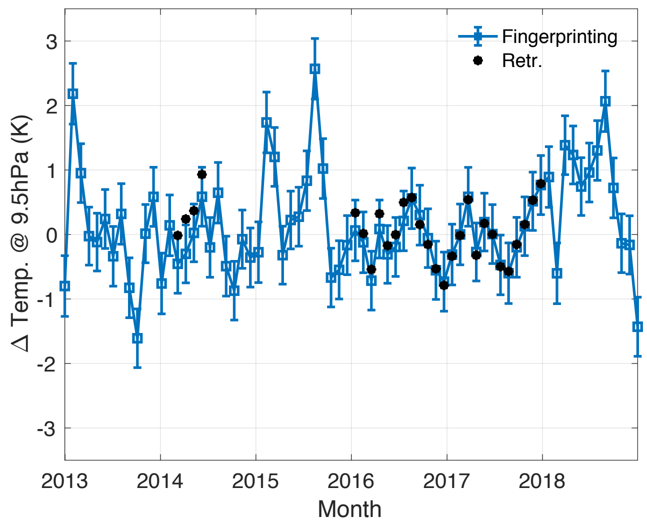
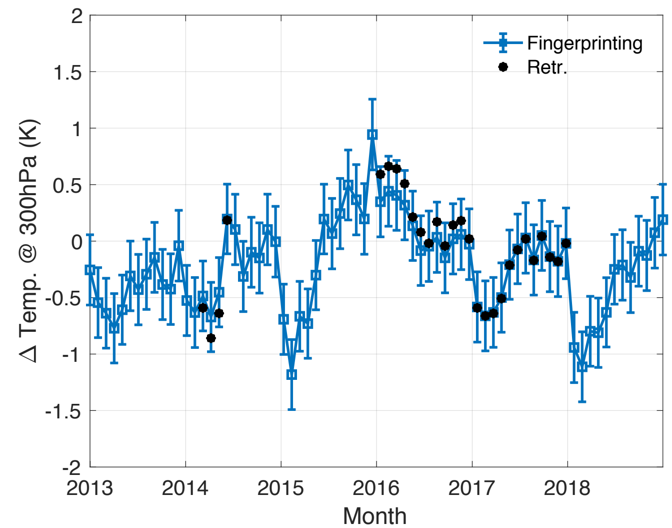
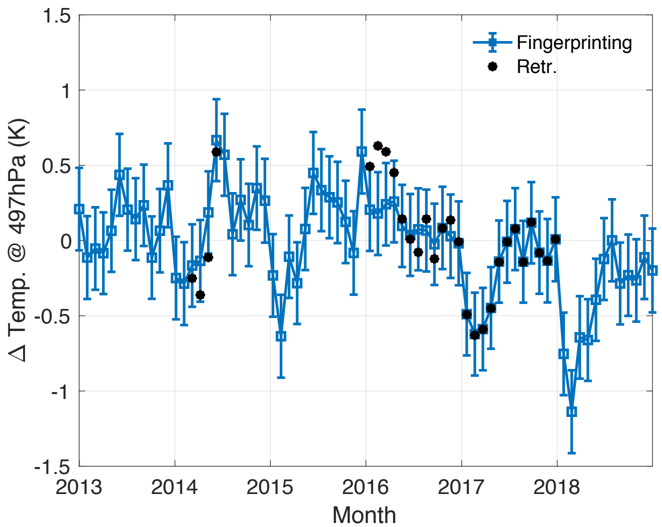
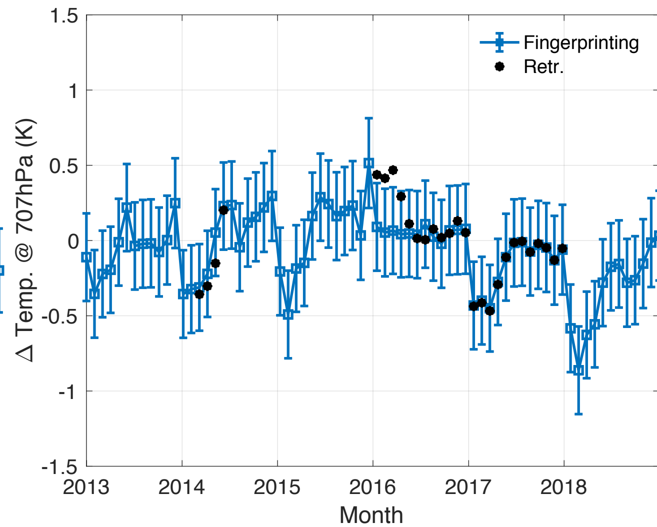
Comparison of SFOV PCRTM-RA Results and Spectral Fingerprinting Results for CrIS

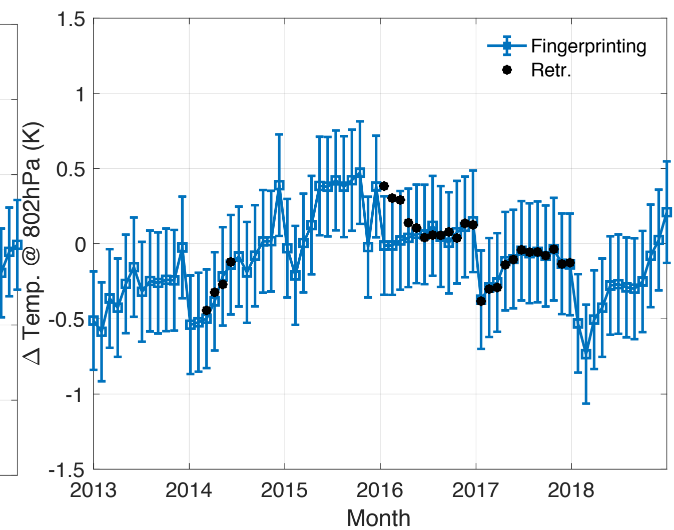
Monthly mean tropical ocean Temp. anomalies from CrIS Descending Observations











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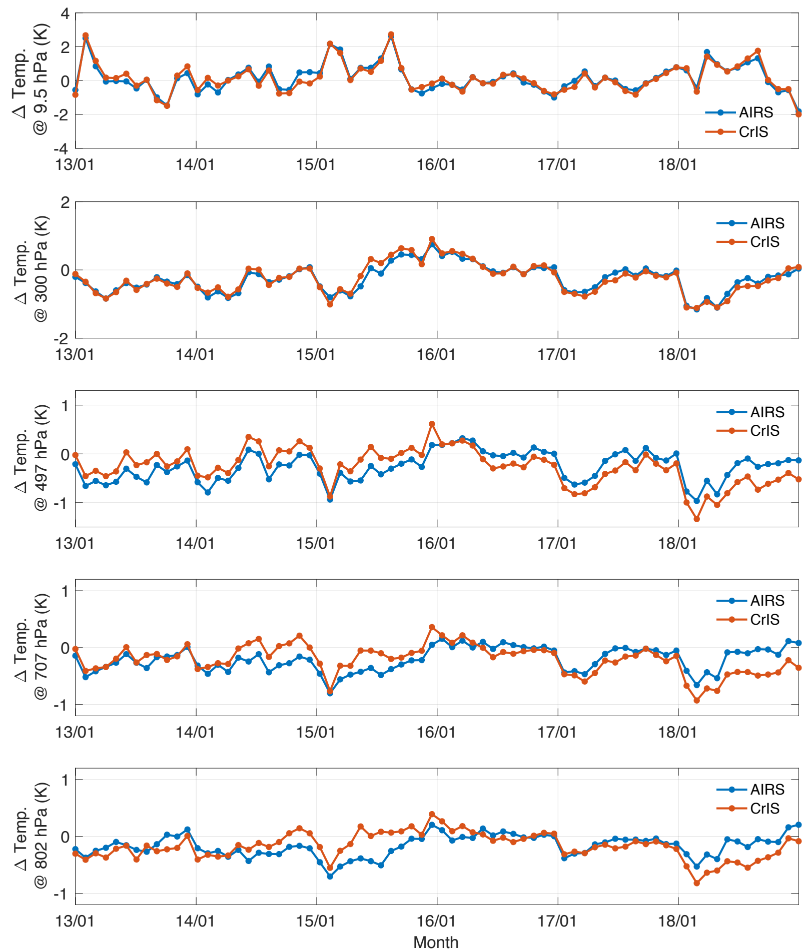
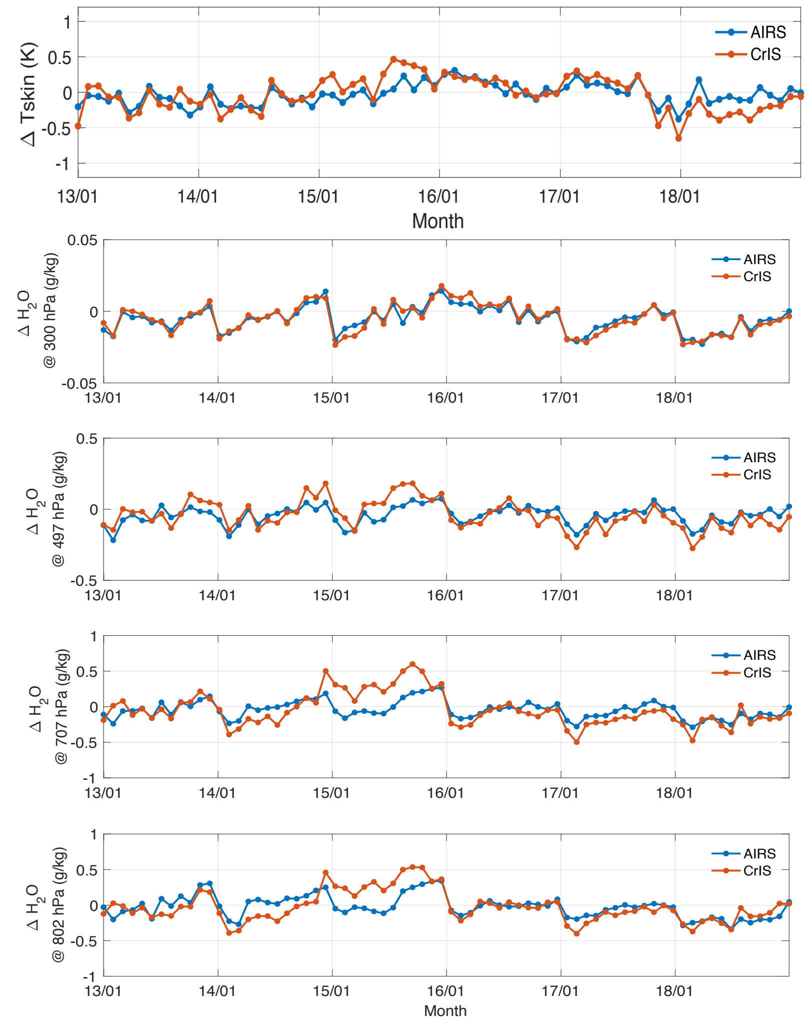
PCRTM Spectral Fingerprinting Results on AIRS and CrIS Data

- Comparison between the temperature anomalies at different altitudes derived from the monthly mean AIRS spectral anomalies observed over tropical ocean regions from January, 2013 to December, 2018 and the corresponding values from the CrIS monthly mean spectral anomalies.





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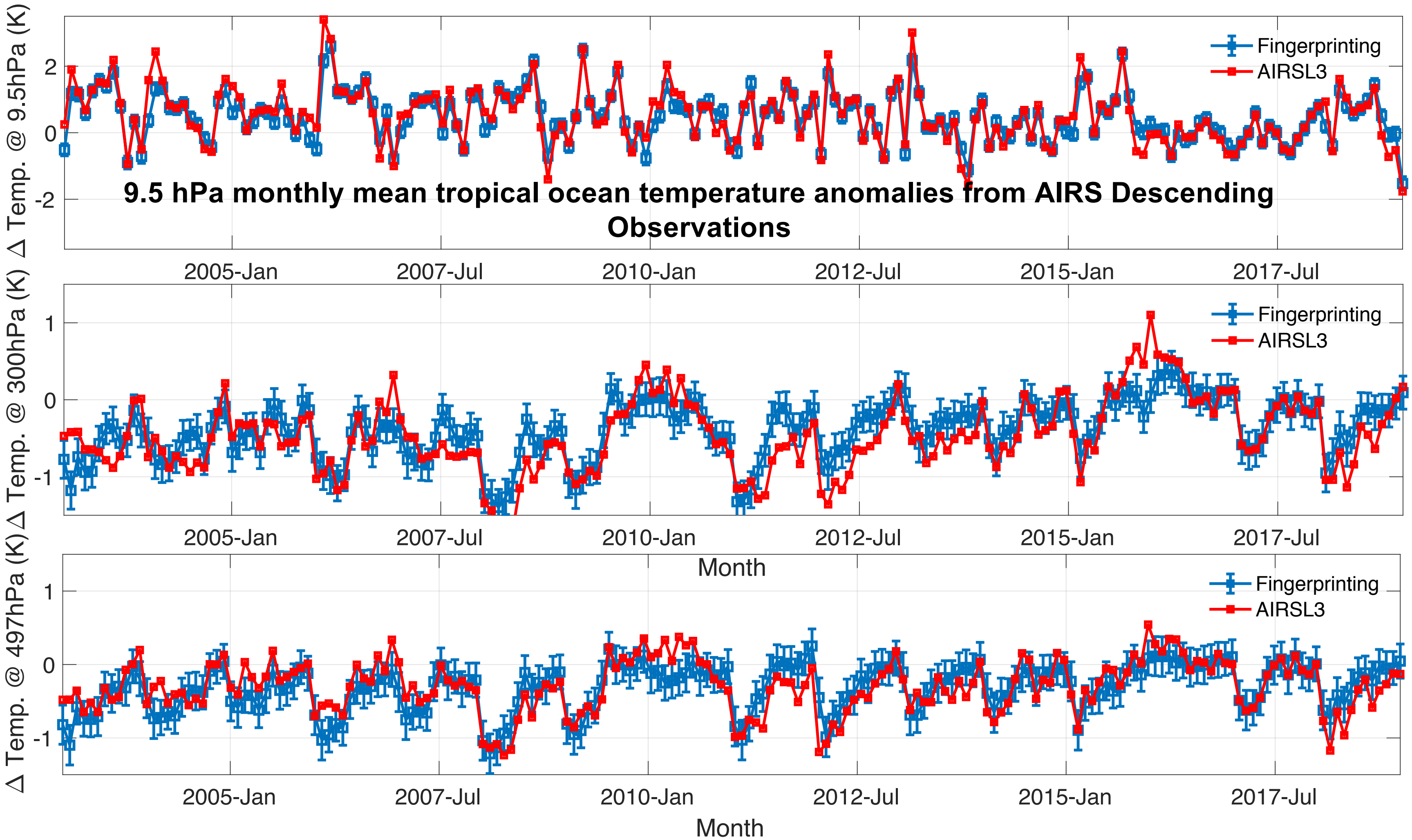
Comparison of AIRS L3 Product with PCRTM Spectral Fingerprinting for Long-term AIRS Data



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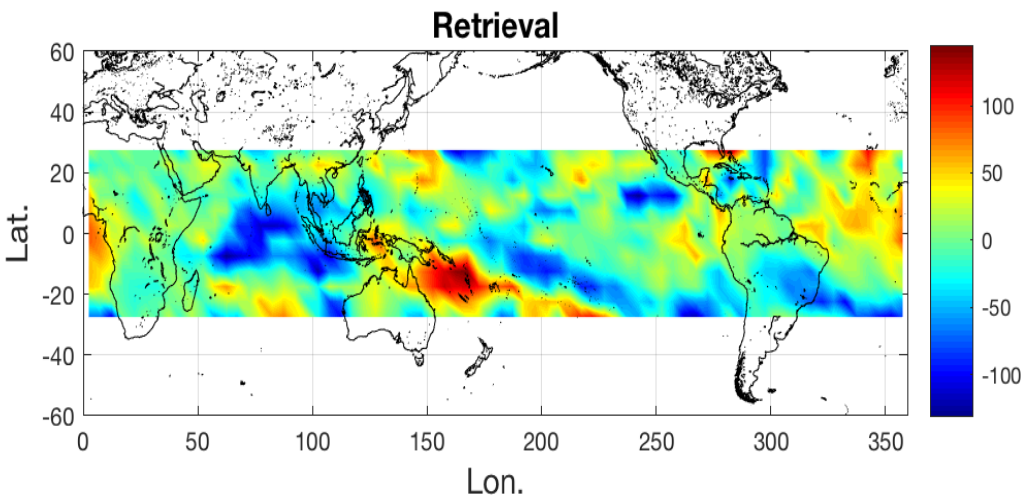
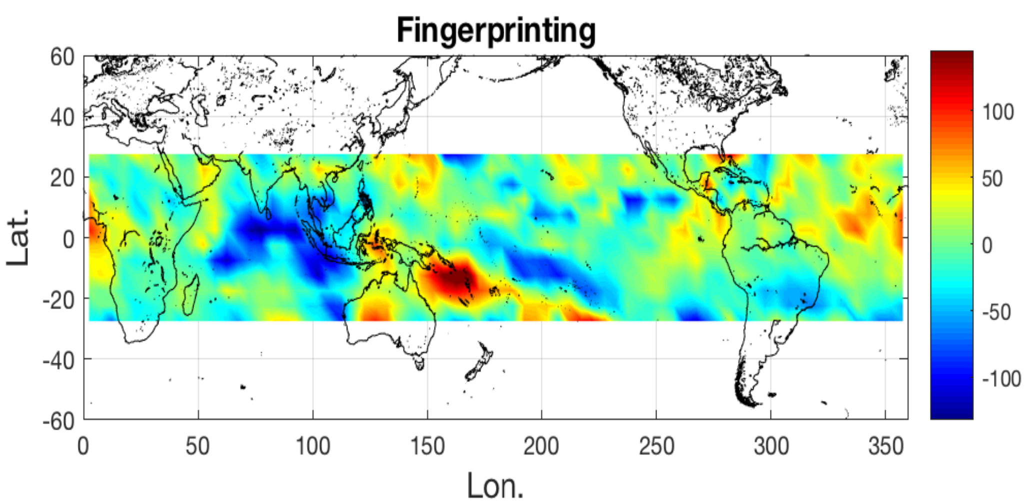
Summary and conclusions

- PCRTM-RA has been validated over the past decade with numerous IR sounders
  - AIRS, CrIS, IASI, and NAST-I
  - Provides radiometric closure
  - High spatial resolution
  - Provides cloud products simultaneously during the inversion process
  - Provides error covariance matrix and averaging kernels
- Single FOV PCRTM-RA provide high spatial resolution products for weather and composition studies
  - Atmospheric Temperature, Water, CO_2, CO, CH_4, O_3, and N_2O profiles
  - Cloud phase, height, temperature, size, optical depth
  - Surface emissivity spectrum and skin temperature
  - In the process of extending it to solar spectral region
- Spectral fingerprinting using PCRTM is a great tool for climate change studies
  - Works on gridded average radiances
  - PCRTM produces realistic radiative kernels
  - Results compare well with single FOV PCRTM retrievals

5x5 Degree Gridded Cloud Optical Changes (2016 minus 2017) using PCRTM Retrieval and Spectral Fingerprinting

Cloud Height Difference (2016-2017) for the month of June derived from CrIS/ATMS data





Cloud Optical Depth Difference (2016-2017) for the month of June derived from CrIS/ATMS data