A Principal-Component-based Radiative Transfer Model (PCRTM) for Hyperspectral Shortwave and Longwave Satellite Sensors and Its Applications

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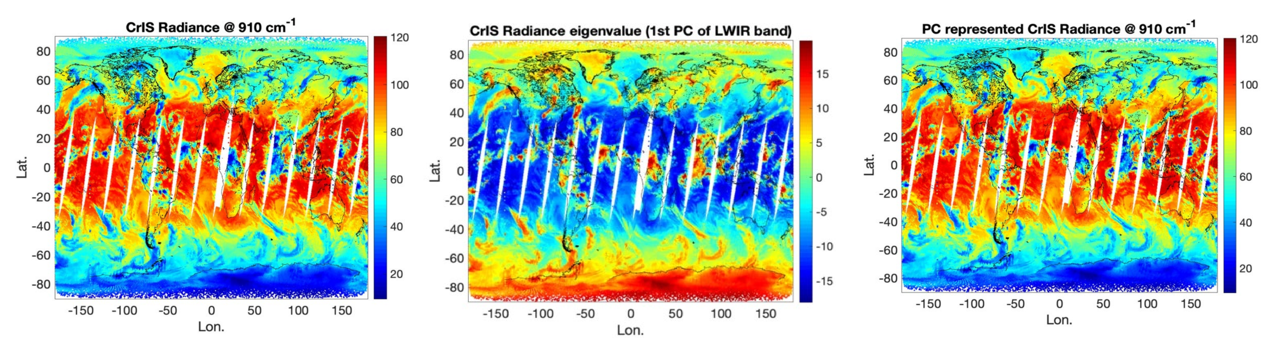
Motivation

- Fast and accurate forward models are needed to invert hyperspectral data
  - Hundreds to thousands of spectral channels with millions of observations each day
  - Line-by-line (LBL) radiative transfer model (RTM) is too slow (needs millions of LBL RT calculations to account for atmospheric gas spectral contributions)
  - Traditional channel-based forward models are also too slow (at least one RT calculations needed for each channel
- Principal Component Analysis (PCA) converts hyperspectral data into super-channels
  - Principal Components (PCs) capture the spectral correlations (remove redundant info)
  - Super channels (PC-scores) capture all original spectral information
  - Reduced data dimension (super-channel number << than the original channel numbers)
- Many future IR hyperspectral sounder data will be delivered as PC-scores
  - For efficient data transfer
  - Forward model and inversion models in PC-domains are desired



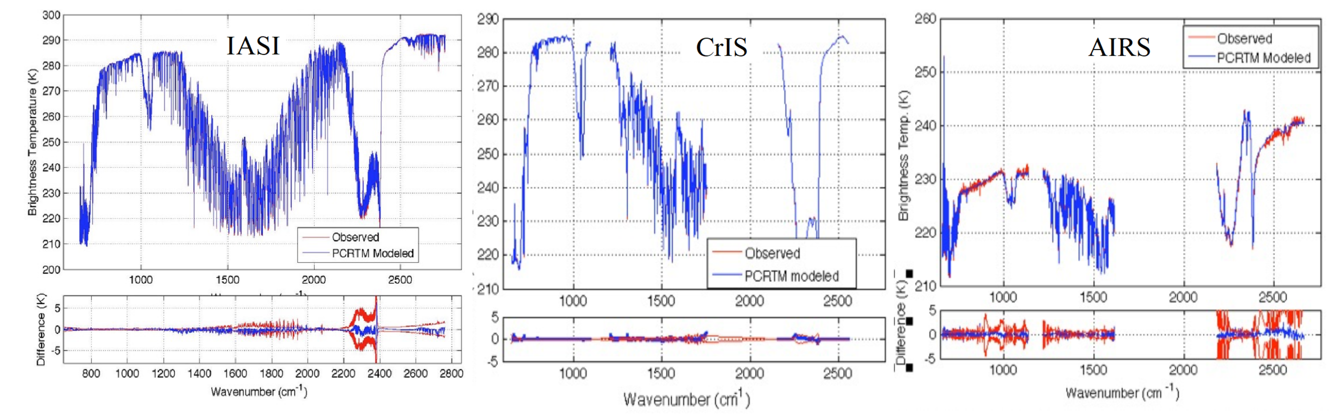
Introduction to a Principal Component-based Transfer Model (PCRTM)

- Channel-based fast radiative transfer models may be too slow
  - Not taking advantages of spectral correlations across the whole spectral regions
  - Reductant RT calculations performed
- PCRTM was first developed in 2004 and has been extensively used by many projects
  - Compress spectra into Principal Component (PC) domain
  - Performs minimum number of monochromatic calculations
  - Covers spectral range from far infrared, IR, mid-IR, Near-IR, Visible, UV-Vis spectral regions
- Calculates channel radiances (or transmittances) by linearly combining a set of PCs:

$$\vec{R}^{ch} = \sum_{i=1}^{N_{EOF}} c_i \vec{U}_i + \vec{\varepsilon} = \sum_{i=1}^{N_{EOF}} \left(\sum_{j=1}^{N_{mono}} a_j R_j^{mono} \right) \vec{U}_i + \vec{\varepsilon}$$

- Channel radiance/reflectance/flux can be obtained by a linear combination of PC-scores (c) and corresponding PCs (U)
- Selected publication related to PCRTM
  - Liu et al. 2004, 2006, 2007, 2009, 2016, 2017, 2018, Yang et al. 2016, 2023, Wu et al 2017,2020, 2022, 2023, Chen et al 2013, Pan et al 2013, Seiji et al 2011, 2014, Huang et. al. 2014. Pan et al. 2015, 2017, 2020, Feldman et al.2013, Bantges et al. 2016, Rose et al. 2013, Sergio et al AMT 2018,Aunman et al. JGR, 2018, 2023, Jang et al, 2023, Xiong et al. 2022, 2023...

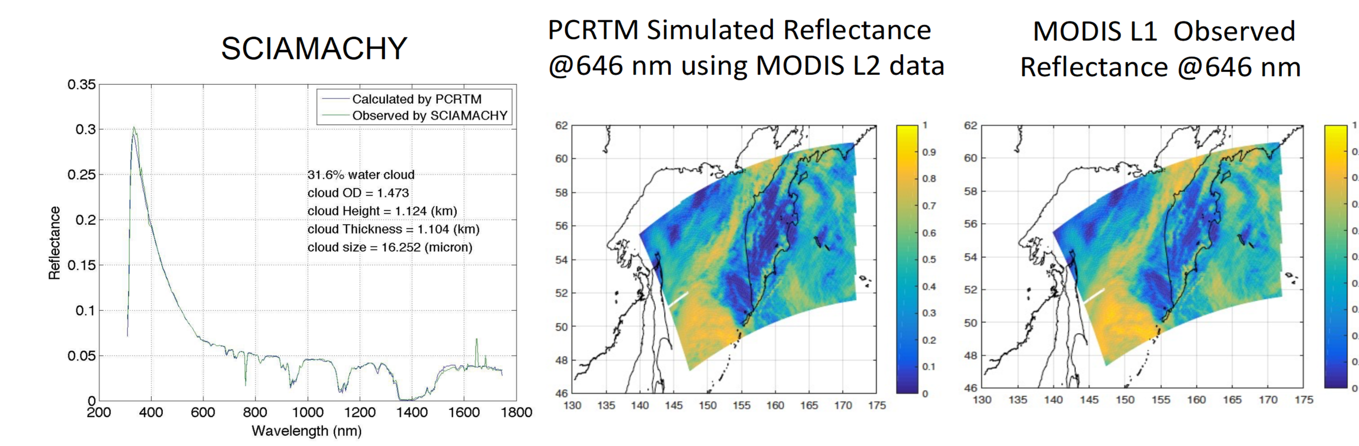
Demonstration of Speed and Accuracy of PCRTM for IR sounders



Sensor	Channel Number	PC score (seconds)
CLARREO, 0.1 cm^{-1}	19901	0.014 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s
IASI, 0.25 cm^{-1}	8461	0.011 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s
CrIS,0.625-2.5 cm^{-1}	1317	0.0050 s
NAST-I, 0.25 cm^{-1}	8632	0.010 s
S-HIS, 0.5 cm^{-1}	4316	0.008 s
CrIS, 0.625 cm^{-1}	2211	0.009 s

- PCRTM calculated TOA radiance spectra match IASI, CrIS, and AIRS observations very well for both clear and cloudy conditions
- PCRTM IR speed: Milliseconds/spectrum
- Channel-based IR RTMs: seconds or fractional seconds per spectrum

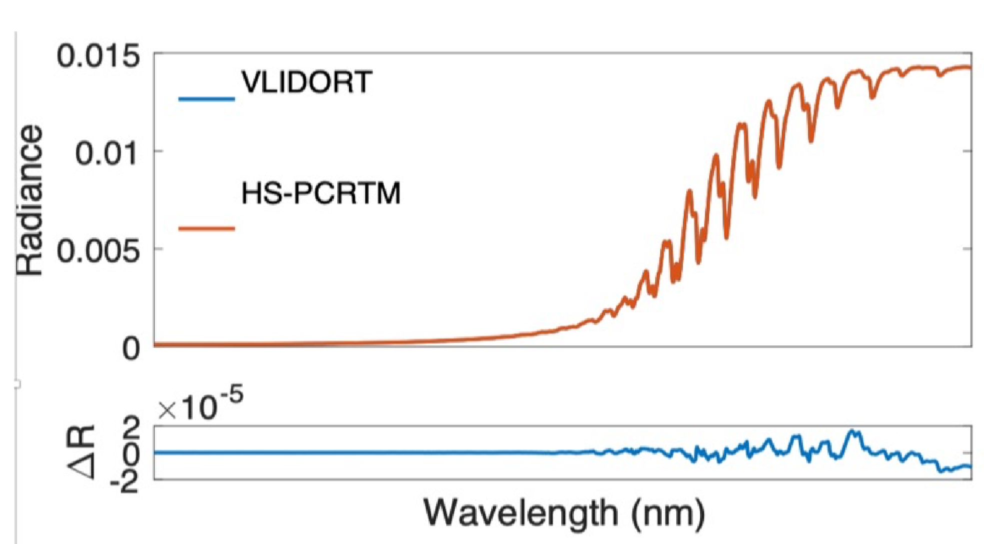
PCRTM for Reflected Solar Region



- PCRTM calculated reflectances agree well with those observed by SCHIAMACHY and MODIS
- PCRTM is 3-4 orders of magnitude faster than MODTRAN
- A Climate OSSE, which will take MODTRAN 10 years to run on one CPU, can be accomplished with PCRTM in 10-20 hours using one CPU
- MODTRAN-based PCRTM has been developed for CALRREO, CPF, EMIT, and SCHIAMACHY
- VLIDORT-based PCRTM (which accounts for polarization) has been developed for OMI/TEMPO O_3 spectral region and being developed for EMIT and SBG
- PCRTM has been extensively used by CLARREO and CPF for various studies (spectral fingerprinting, spectral band expansion, angular mismatch error correction for satellite inter-cal etc.

PCRTM for TEMPO/OMI O_3 Spectral Region

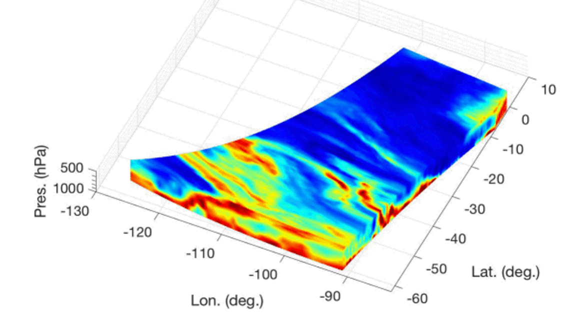
- VLIDORT-based PCRTM (HS-PCRTM) can further reduce the computational time
  - Perform 2-stream monochromatic RT calculations at original PCRTM selected frequencies
  - Perform higher streams RT calculations at even less monochromatic frequencies
  - The accuracy is not comprised (see example below)



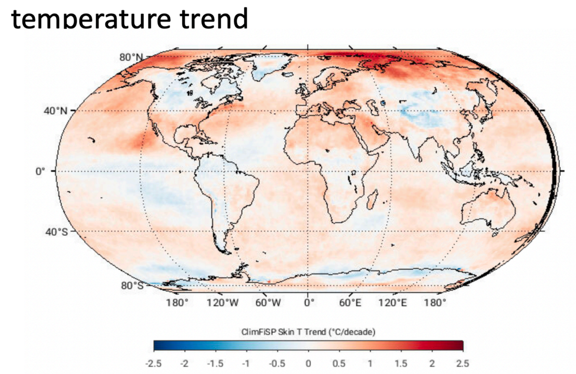
Two PCRTM-based Inversion Algorithms

- L2 products: Single Field-of-view Sounder Atmospheric Product (SiFSAP)
  - 3-times higher spatial resolution
  - Uses all spectral channel
  - All sky algorithm-retrieves cloud explicitly
  - Retrieve temperature, clouds, trace gases, and surface properties simultaneously
- L3 Products: Climate Fingerprinting Sounder Products (ClimFiSP)
  - Works on spatiotemporally averaged radiance spectra
  - High quality climate product from multiple satellite data fusion
    - Use consistent radiative kernels
    - Ensure radiometric closures
- Both products will be available at NASA GES DISC for public access
- The PCRTM based algorithm has been extended to solar spectral region

Example of SiFSAP H_2O product



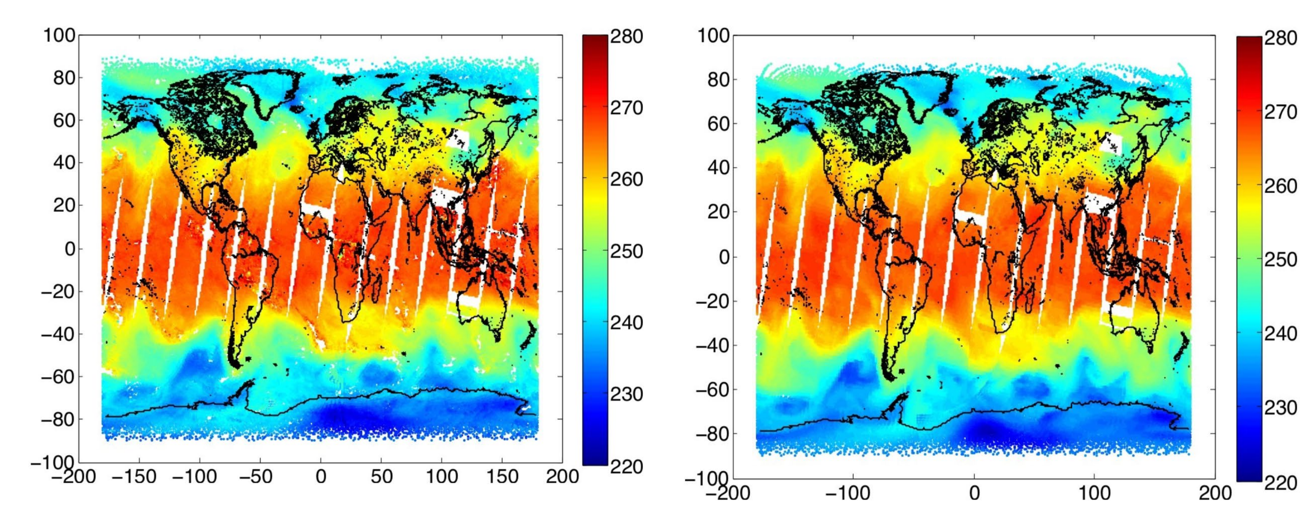
Example of ClimFiSP derived global surface temperature trend



PCRTM Retrieved Atmospheric Temperature from CrIS/ATMS

500 hPa Retrieved from ATMS/CrIS using PCRTM_RA

500 hPa Temperature from ECMWF



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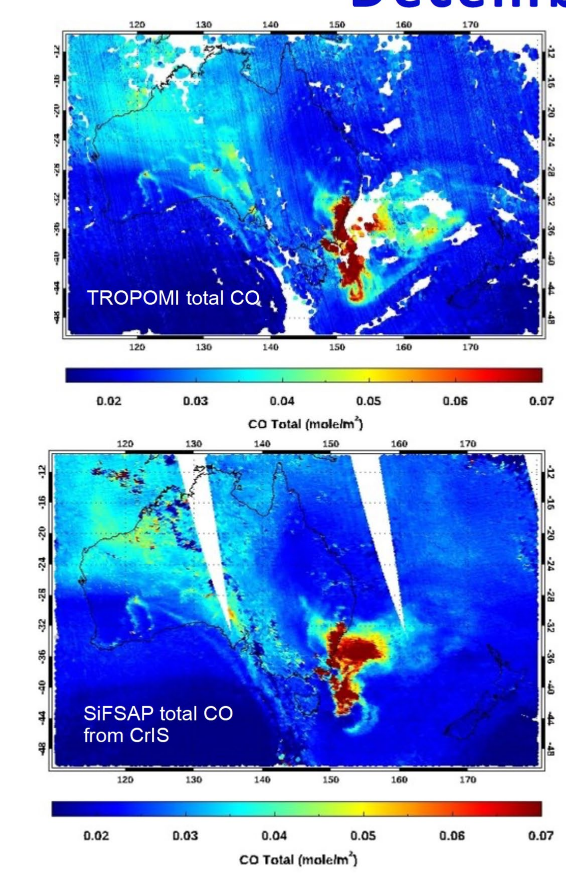
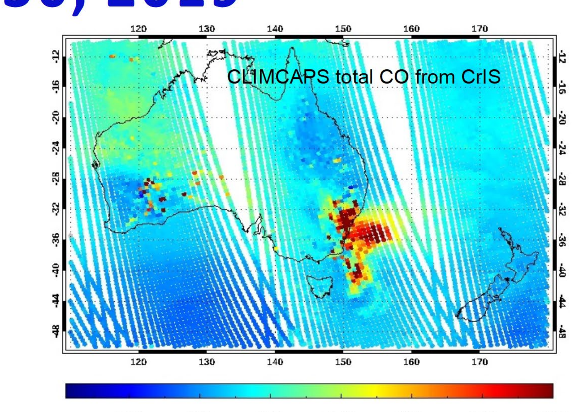
PCRTM Retrieved CO from Australia Fires on December 30, 2019





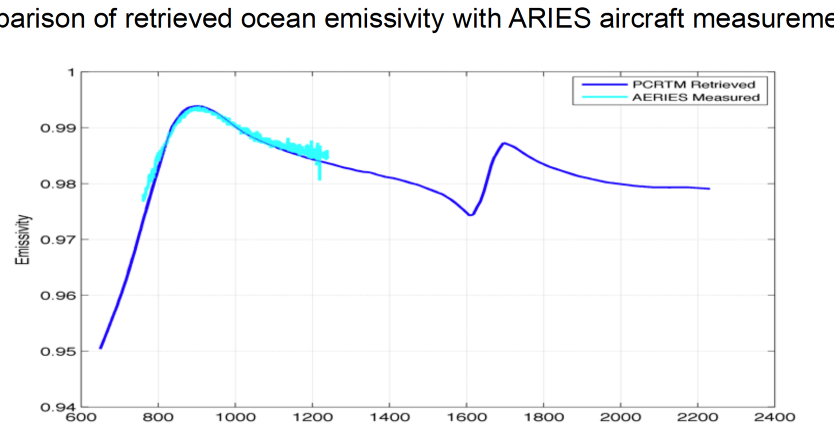
- Both TROPOMI (4 km resolution) and SiFSAP (14 km) capture fine CO plume spatial distributions
- CLIMCAPS cannot capture the fine CO features
  - ➢ Low resolution retrieval (45 km)
  - ➢ Less coherent CO due to errors in cloud clearing
- SiFSAP is less affected by the fire particular (dust) emission relative to TROPOMI
  - ➢ SiFSAP retrieves effective cloud optical depth to compensate for fire particular contributions
  - ➢ TROPOMI has many non-successful retrievals due to clouds and fire dust emissions

PCRTM Rretrieved Surface Temperature and Emissivity

Comparison of PCRTM retrieved surface skin temperature with ARIES measured Tskin

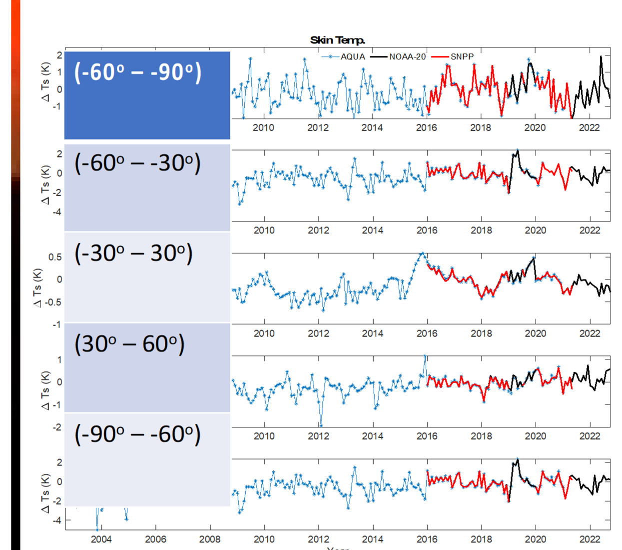
Date	Location	Surface Pressure (hPa)	ARIES Measured skin temperature (K)	IASI-retrieved surface skin temperature (K)
19 April 2007	ARM CART site	972.0	284.7	284.8
29 April 2007	Gulf of Mexico	1021.7	297.8	297.6
30 April 2007	Gulf of Mexico	1017.5	298.6	298.1
4 May 2007	Gulf of Mexico	1009.9	297.4	297.1

Comparison of retrieved ocean emissivity with ARIES aircraft measurements

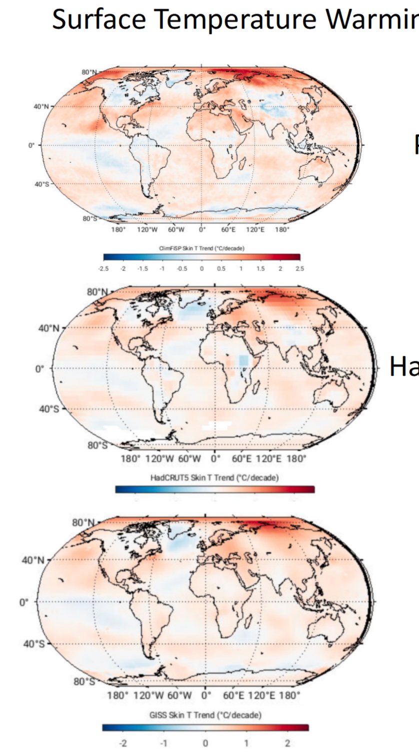


PCRTM-based Climate Products from AIRS and CrIS Sep. 2002 – June 2022

Zonally Surface Temperature Anomalies

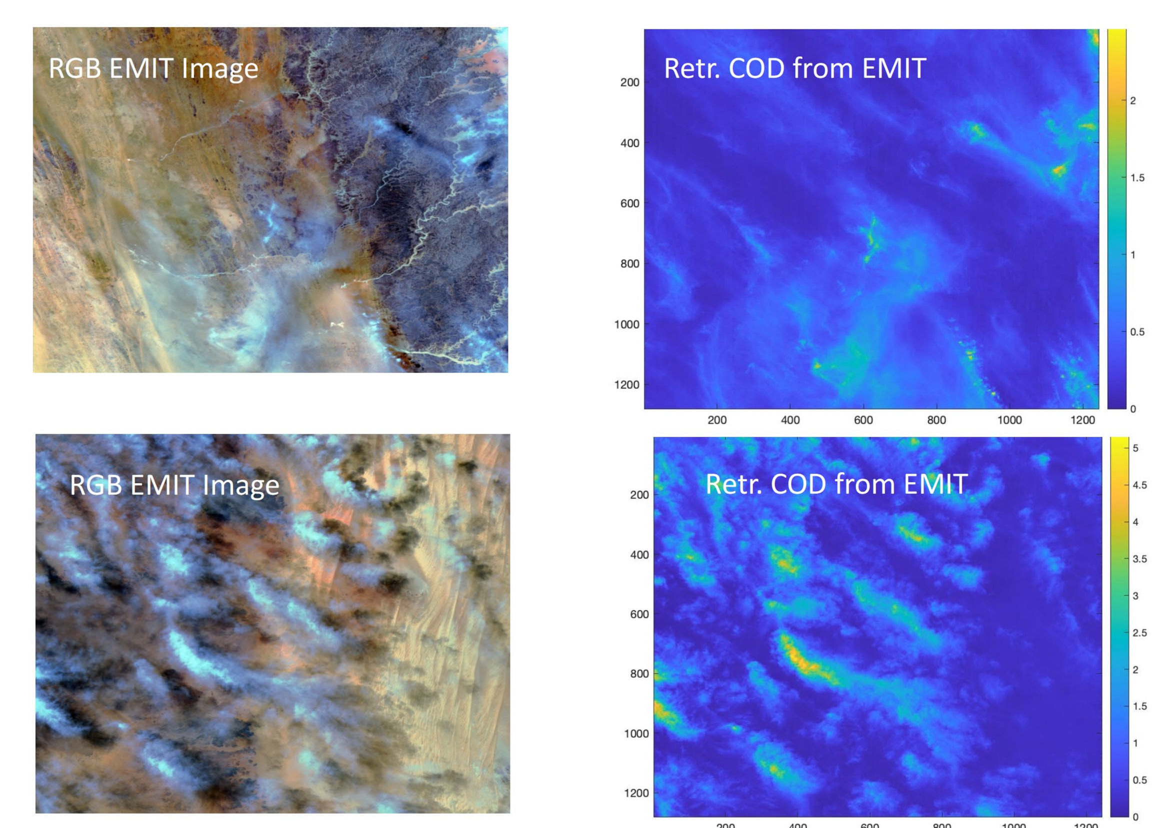


Surface Temperature Warming Trend



PCRTM-based SiFSAP and ClimFiSP sounder products will be generated at NASA GES DISC for public access

PCRTM Cloud Retrieval for EMIT Data



Summary and Conclusions

- PCA can be used to compress both the satellite observed data and the state vector in an inversion process
  - Stabilize inversion solution by reduce random noise
  - Speed up inversion process by reducing the matrix and vector dimensions
- PCRTM is a fast and accurate forward model for analyzing satellite data
  - Enable all sky retrievals due to accurate cloud calculations
  - Uses all spectral channels instead limited selected channels
  - Can be used for pre-launch sensor design and post-launch data analysis
- PCRTM-based inversion algorithms provide radiometrically consistent products
  - High-spatial resolution L2 products for weather, air quality, and atmospheric dynamic studies
  - Consistent long-term climate data records (T, Q, cloud …) from multiple satellite IR hyperspectral sounders