A Fast and Efficient Method for Deriving 20 years of Climate Data Records from Multiple Satellite IR Sounders

Xu Liu
NASA Langley Research Center, Hampton, VA

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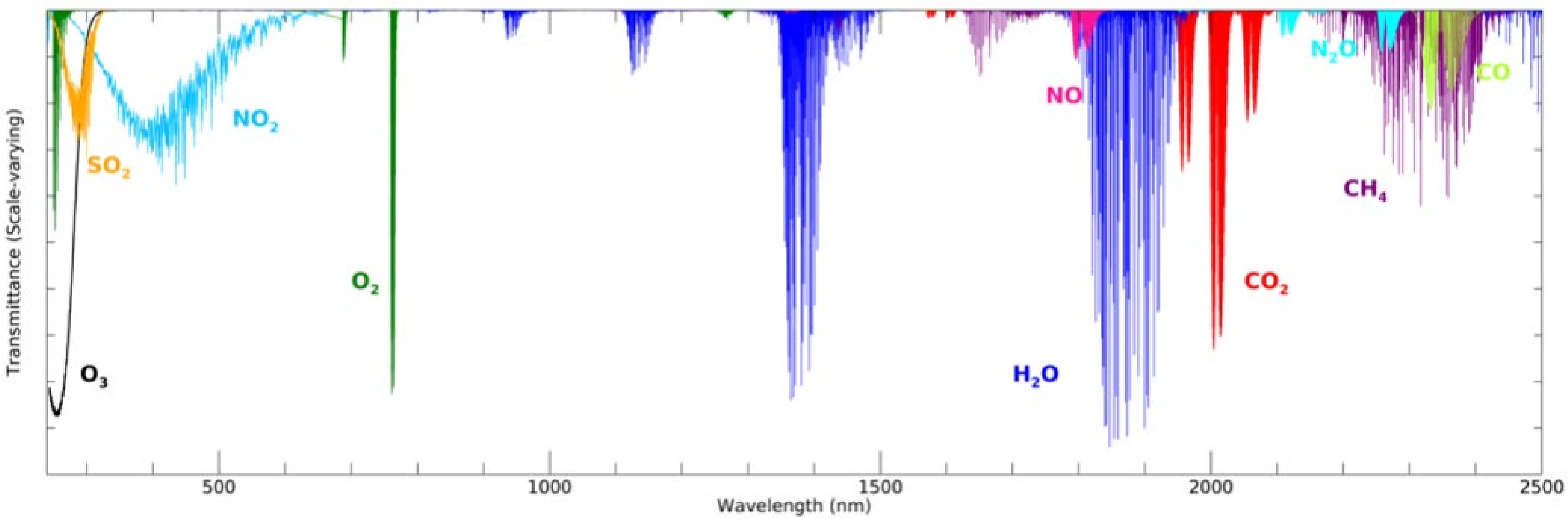
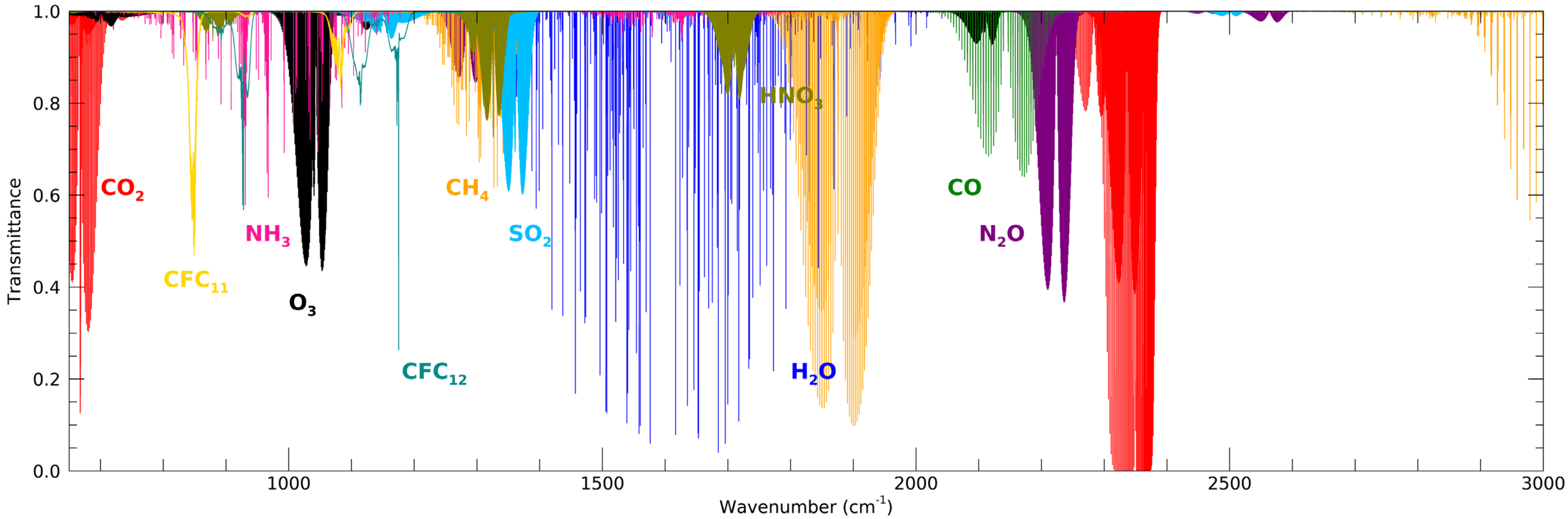
Fast and Accurate Radiative Transfer Models are Needed

Hyperspectral satellite remote sensors (e.g. AIRS, CrIS, IASI, CPF, TRUTHS) have high information content. However, radiative transfer modeling is challenging

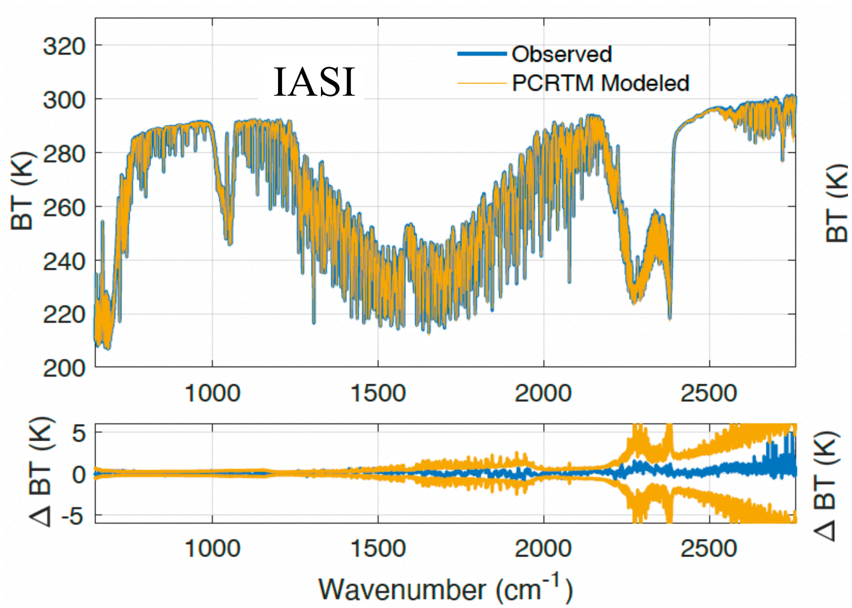


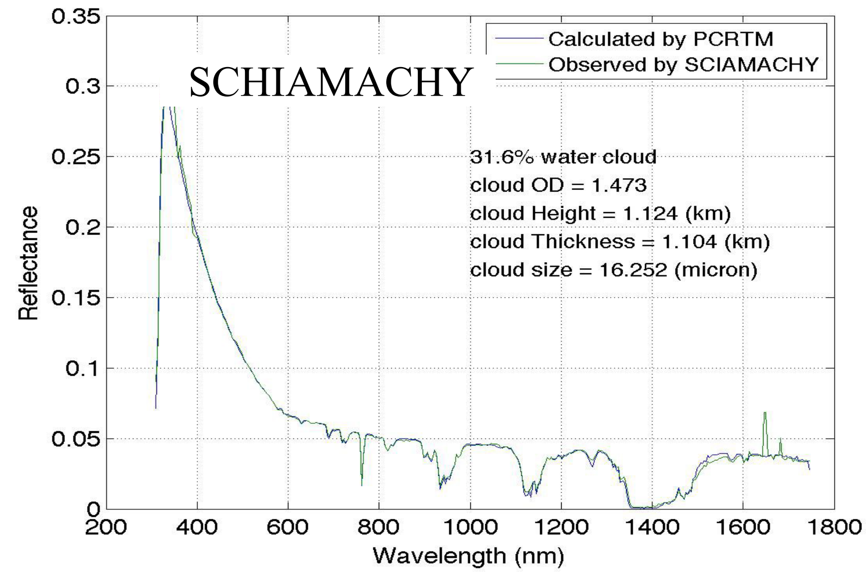


Principal Component-based Transfer Model (PCRTM) is An Ideal Fast RTM for Hyperspectral Data

- PCRTM is a physical-based RTM
  - RT is done monochromatically
- PCRTM is fast
  - Orders of magnitude faster than Line-by-Line (LBL) models (reduces RT calculations from millions to hundreds)
- PCRTM is accurate
  - 0.03 K Brightness Temperature RMS errors relative to LBL for thermal IR
  - Less than 0.05% relative to LBL in solar spectral region
- PCRTM was developed in 2004 and has been extensively used by many projects
  - AIRS, IASI, CrIS, NAST-I, S-HIS, CLARREO, CPF, EMIT, SCHIAMACHY, OMI ..
  - Covers far infrared, mid-IR, Near-IR, Visible, UV-Vis spectral regions
  - Handles cloud and aerosols
  - Handle polarization due to gas, clouds, aerosols, and surface (in solar spectral region)
- PCRTM has been used for many applications
  - Forward model for a physical retrieval algorithm
  - High fidelity satellite radiance/reflectance spectral simulator for new satellite sensors
  - Observing System Simulation Experiments (OSSEs)
  - Training data for AI algorithms
  - Spectral matching and angular matching error corrections for inter-satellite sensor calibrations
  - Instrument spectral characterization and new sensor performance studies

Demonstration of Speed and Accuracy of PCRTM for IR sounders





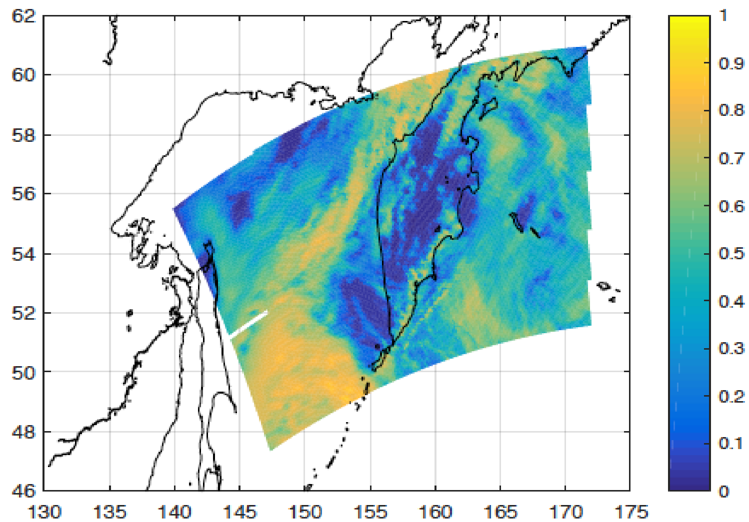
Sensor	Channel Number	PC score (seconds)
CLARREO, 0.1 cm^{-1}	19901	0.014 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s
IASI, 0.25 cm^{-1}	8461	0.011 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s
CrIS,0.625-2.5 cm^{-1}	1317	0.0050 s
NAST-I, 0.25 cm^{-1}	8632	0.010 s
S-HIS, 0.5 cm^{-1}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

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

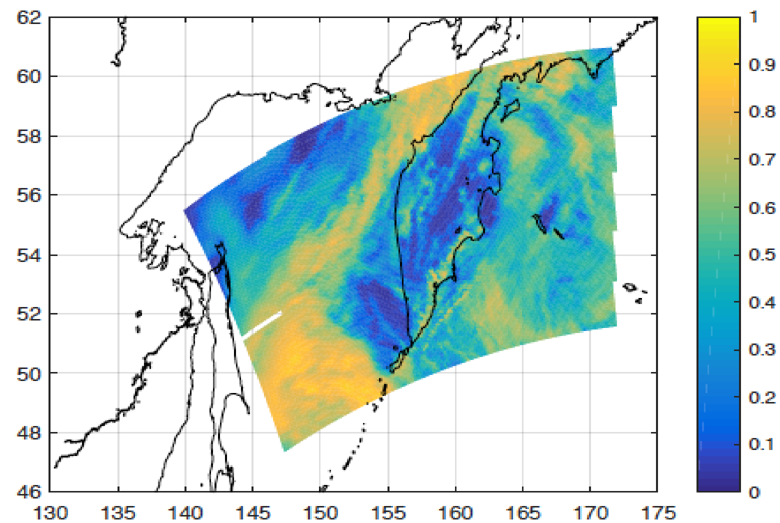
PCRTM	M1	M2	Speedup to Regular PCRTM-SOLAR	Speedup to MODTRAN
Land 8 nm	263	49	5	5286
Ocean 8 nm	241	23	10	11,262

Examples of PCRTM as Fidelity Simulator

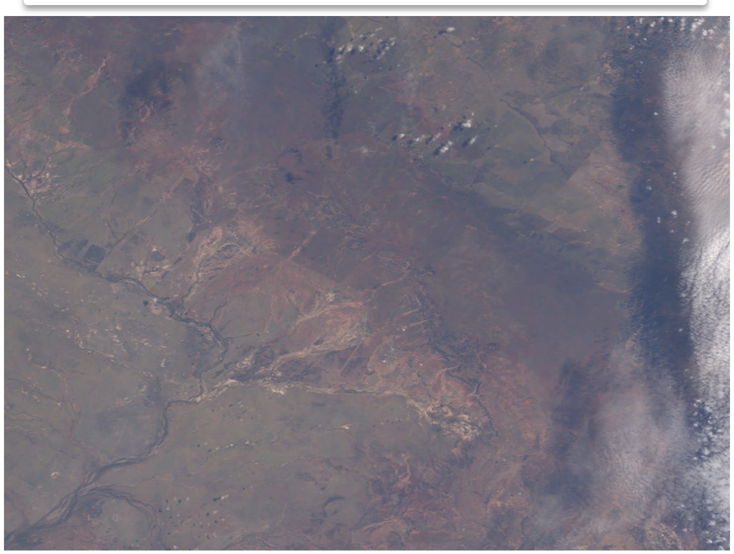
PCRTM Simulated Reflectance @646 nm using MODIS L2 data



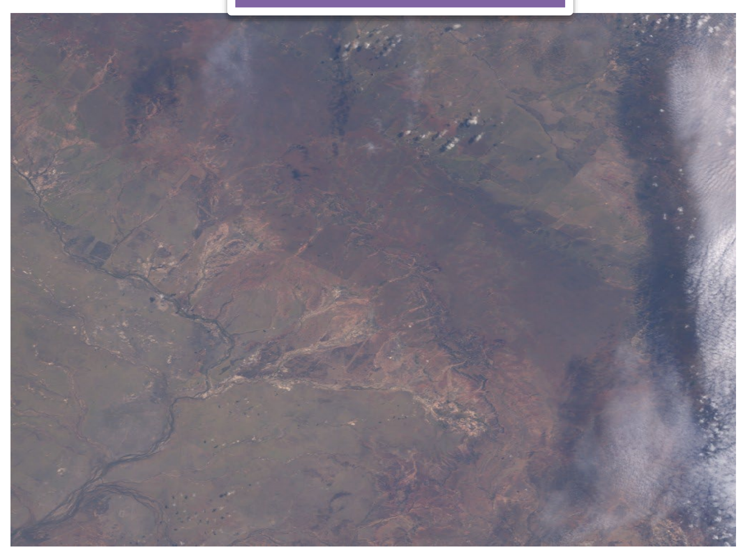
MODIS L1 Observed Reflectance @646 nm



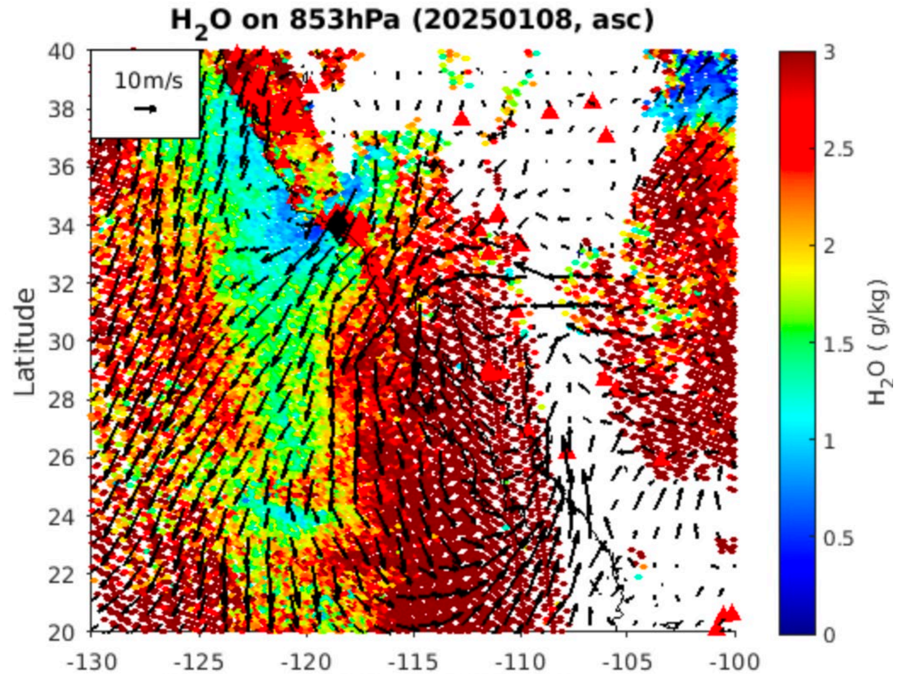
PCRTM Calculated EMIT RBG Image

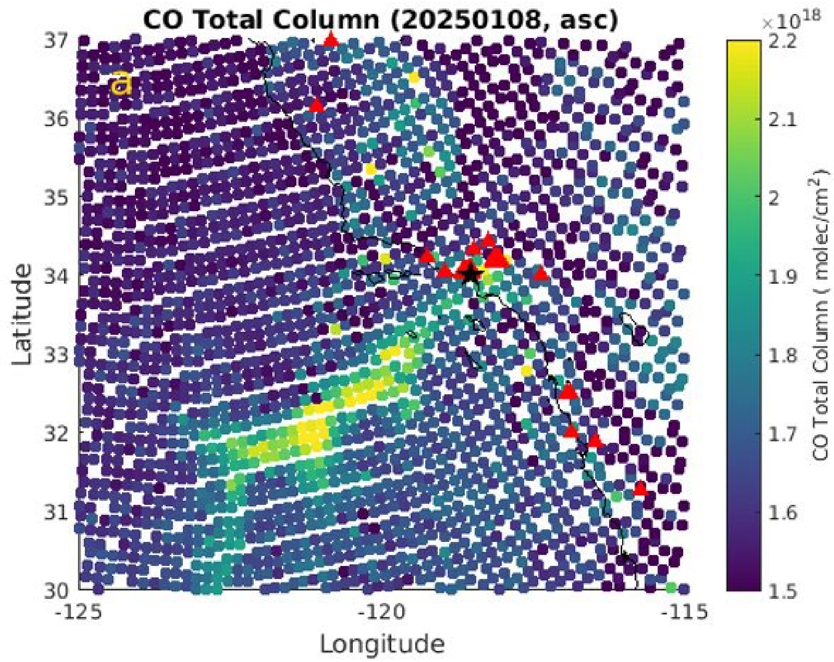


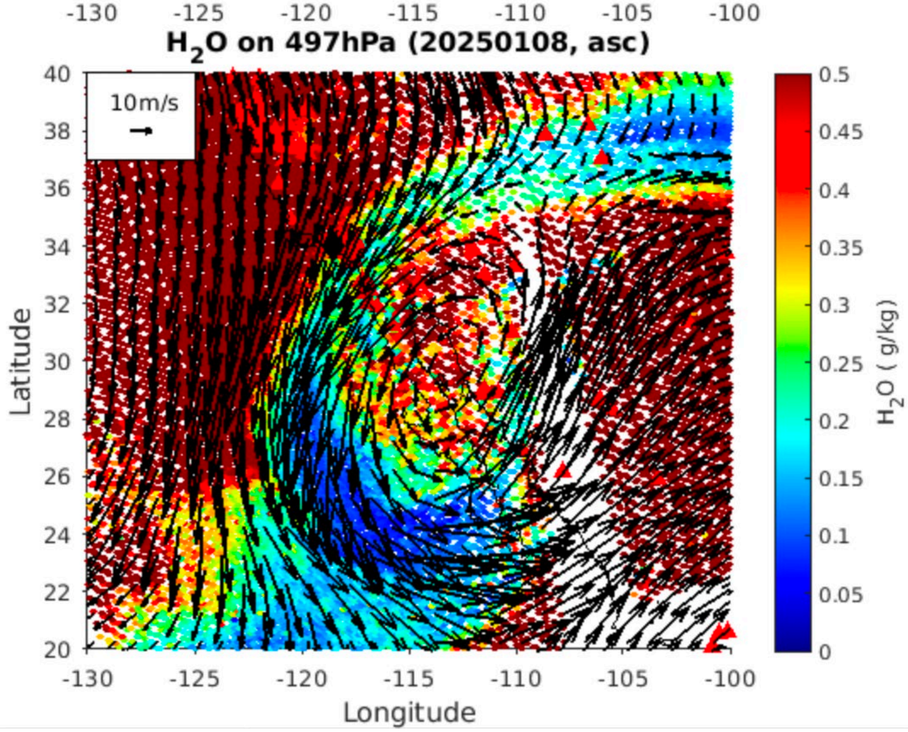
EMIT RBG Image

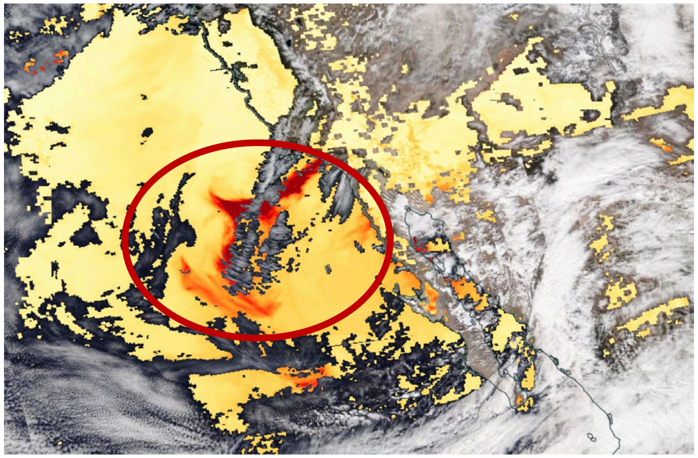


PCRTM-based Retrieval Product for January 2025 LA fires



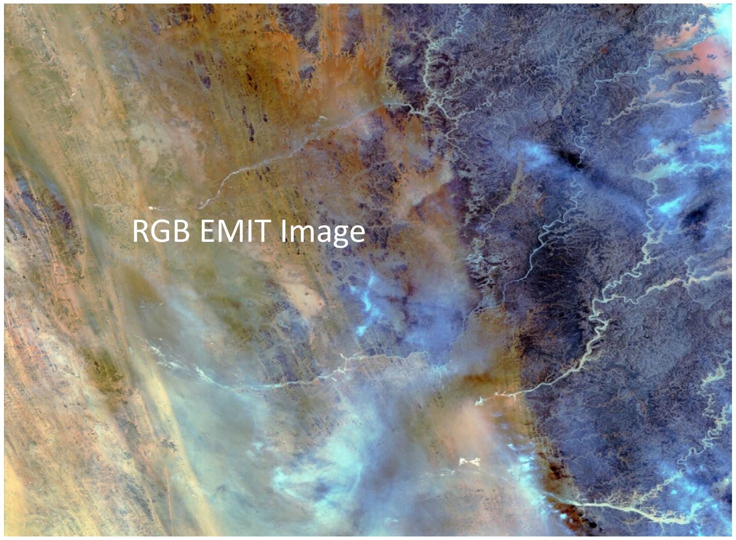


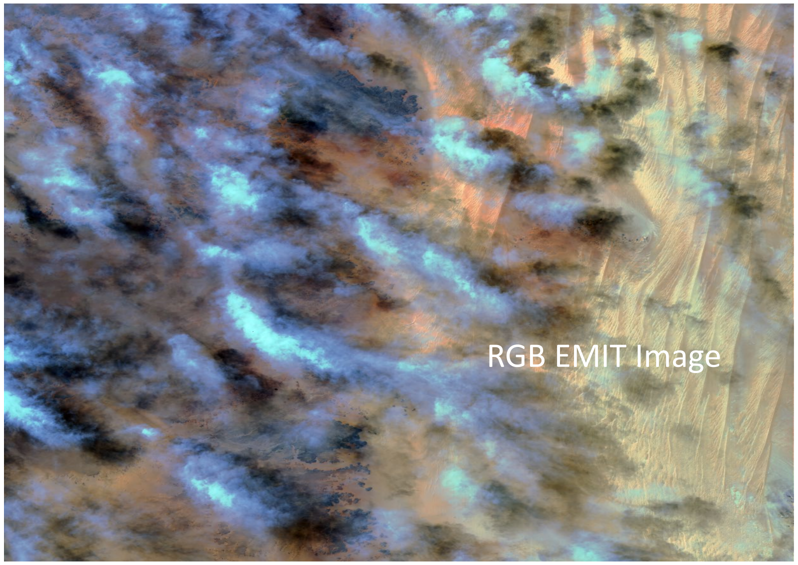


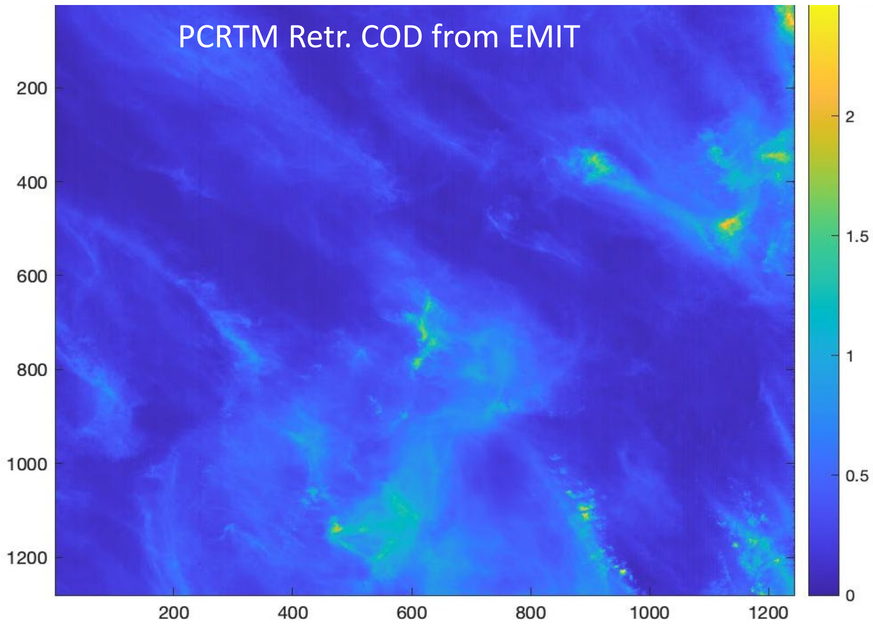


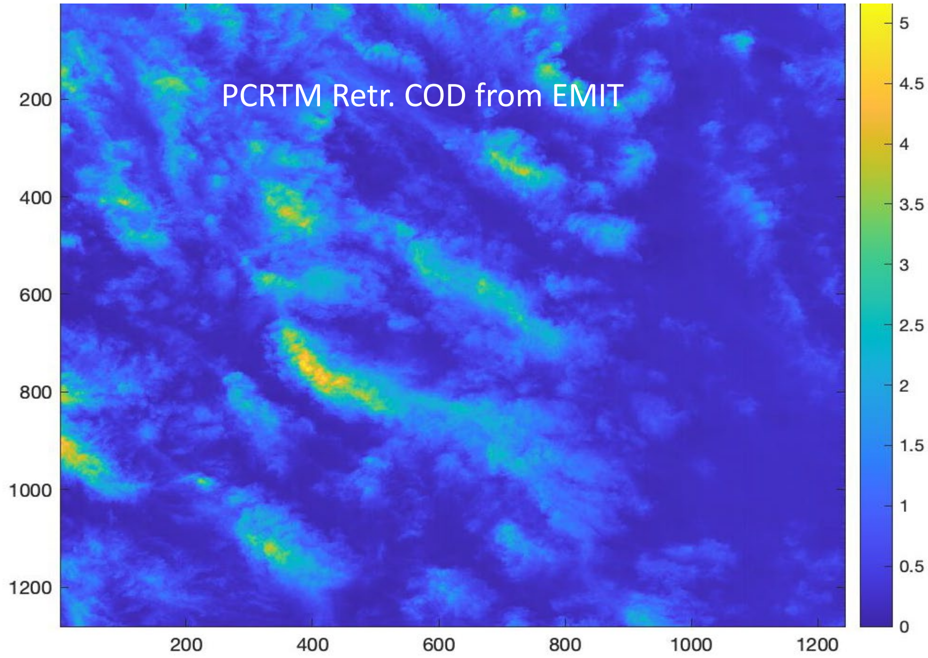
20250108 Deep blue aerosol optical thickness
NOAA-20 / VIIRS

PCRTM trained AI Cloud Retrieval algorithm for EMIT









Climate Benchmarking Using Spectral Fingerprinting Method

$$\boldsymbol{\Delta R} = \boldsymbol{S\Delta X} + \boldsymbol{\varepsilon}$$

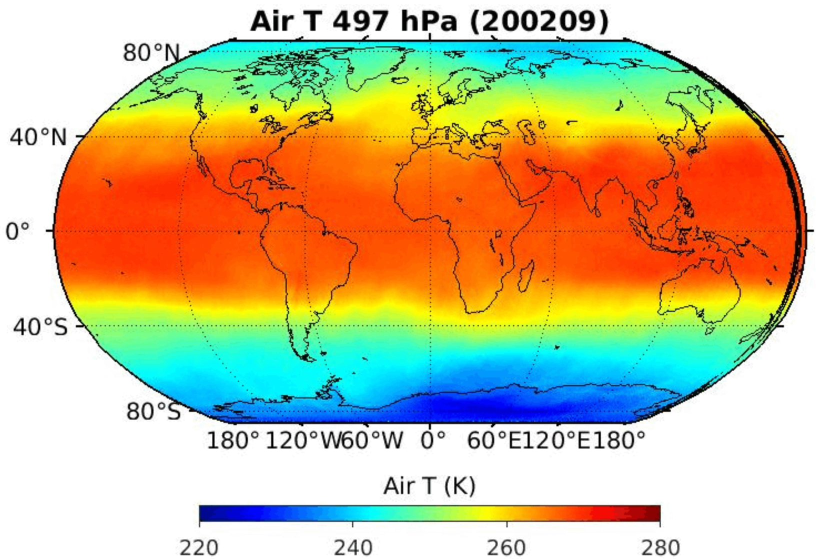
$$\Delta \boldsymbol{X} = (\boldsymbol{S}^T\boldsymbol{\Sigma}^{-1}\boldsymbol{S} + \boldsymbol{\Sigma}_a)^{-1}\ \boldsymbol{S}^T\boldsymbol{\Sigma}^{-1}\Delta\boldsymbol{R}$$

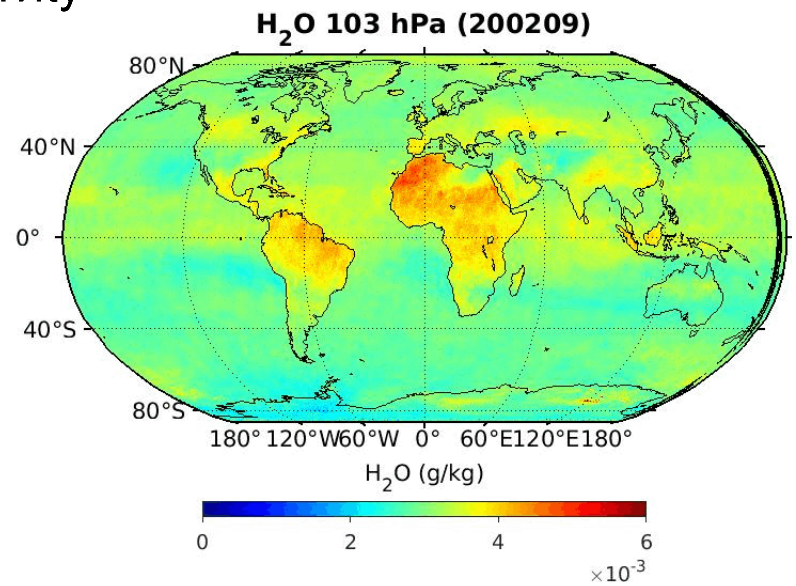
$\boldsymbol{\Delta d}$ - climate spectral radiance anomaly,
$\boldsymbol{\Delta \alpha}$ – anomaly of climate variables,
$\boldsymbol{S}$ - spectral fingerprinting kernel,
$\boldsymbol{\varepsilon}$ - fingerprinting error term

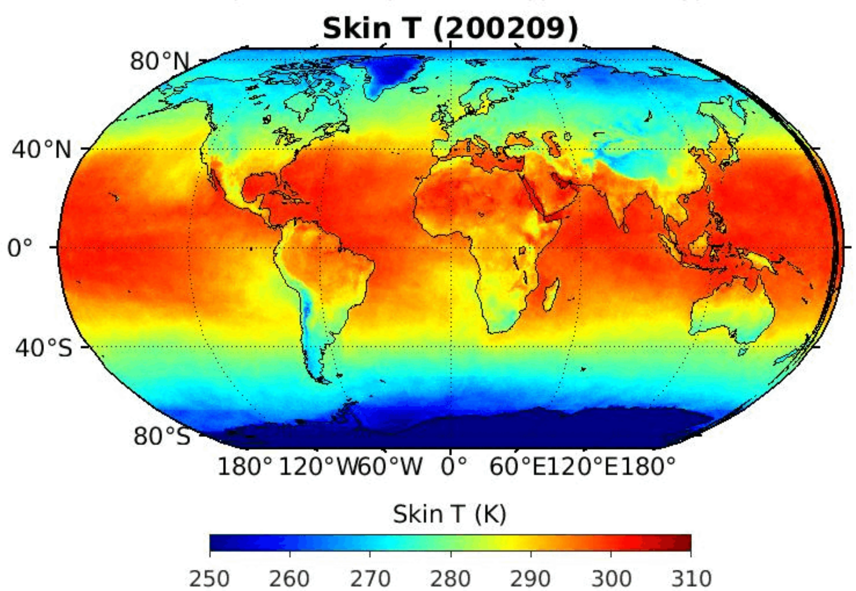
- The spectral fingerprinting kernel is derived from a PCRTM-based Single Field-of-view Sounder Atmospheric Product (SiFSAP) algorithm using real satellite observations
- SiFSAP has been operation at theNASA GES DISC since 2023
  - ➢ 9-times higher area spatial resolution relative to previous sounder products
  - ➢ Uses all spectral channel under all sky condition
  - ➢ Retrieve temperature, clouds, trace gases, and surface properties simultaneously
- A Climate Fingerprinting Sounder Products (ClimFiSP) has been delivered to GES DISC
  - ➢ Works on spatiotemporally averaged radiance spectra
  - ➢ 3-4 orders of magnitude faster with similar accuracy
  - ➢ Ideal for multi-satellite multi-instrument data analysis
    - o Use consistent radiative kernels for all satellite sensors
    - o Ensure radiometric closures by fitting measured radiance spectra

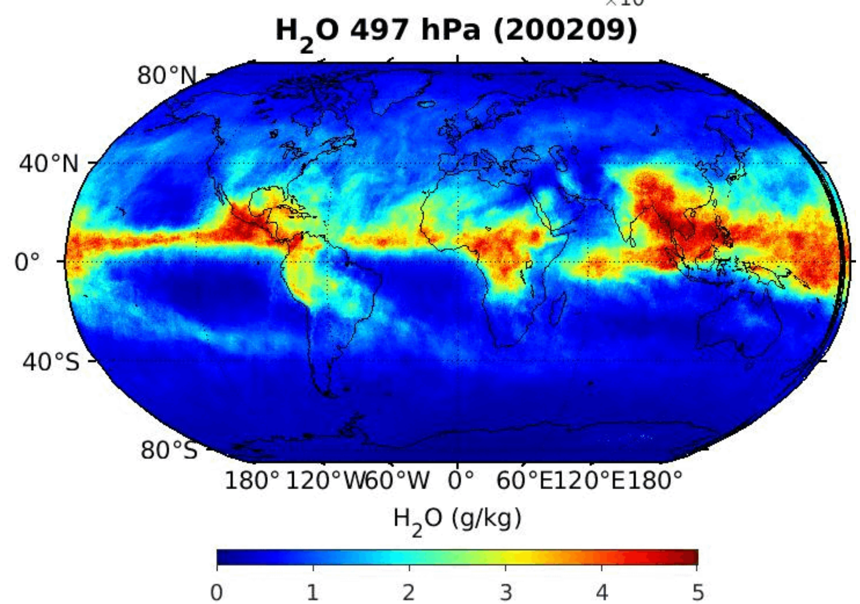
Hundres of CDRs (Daily, Time Series, and Trends) from ClimFiSP

- Atmospheric temperature, water vapor, O3, and other trace gas vertical profiles
- Cloud optical depth, cloud height, and cloud particle size
- Surface skin temperature, and surface emissivity

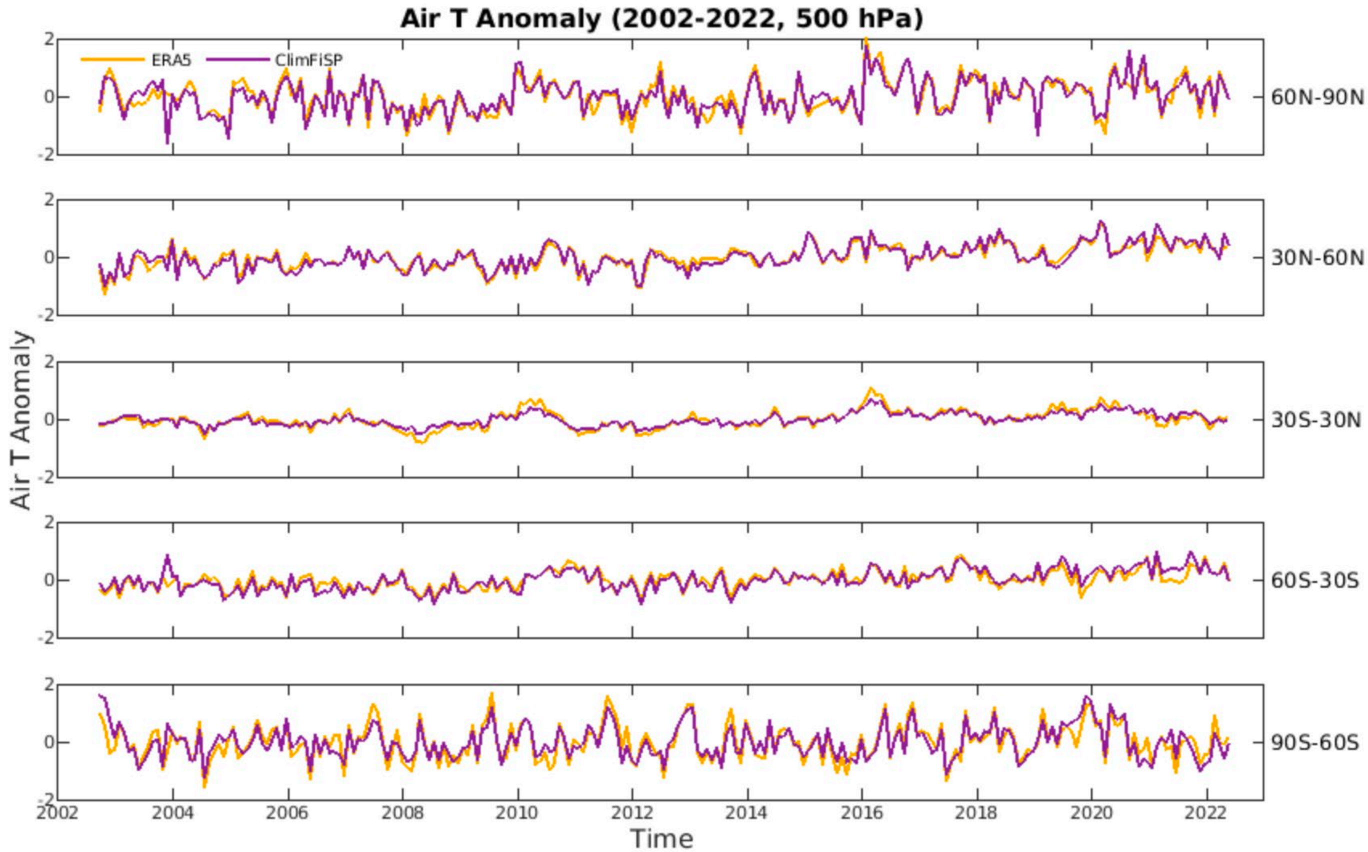


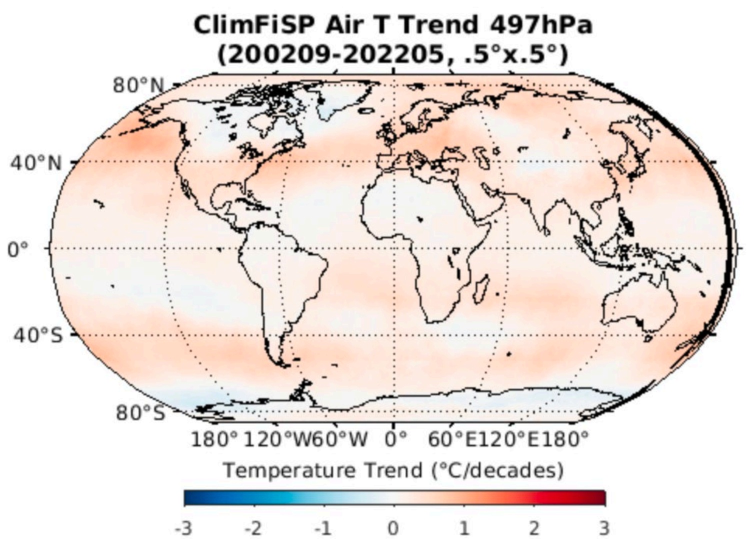


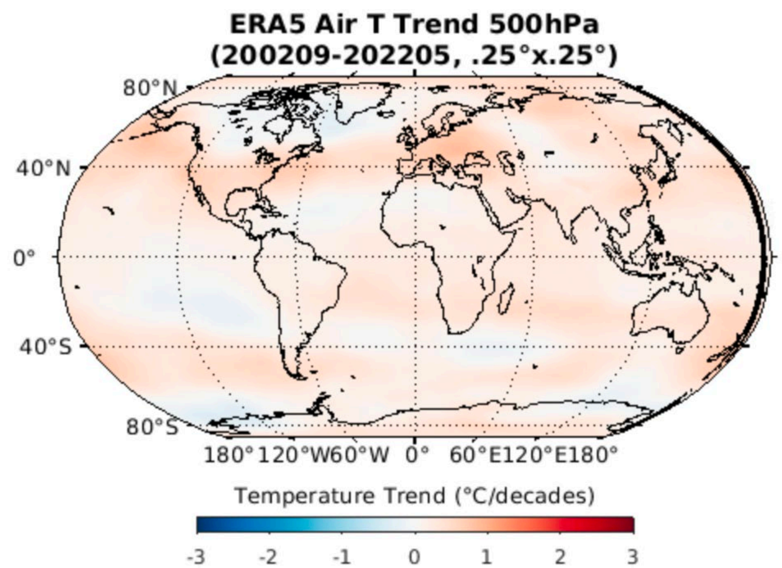




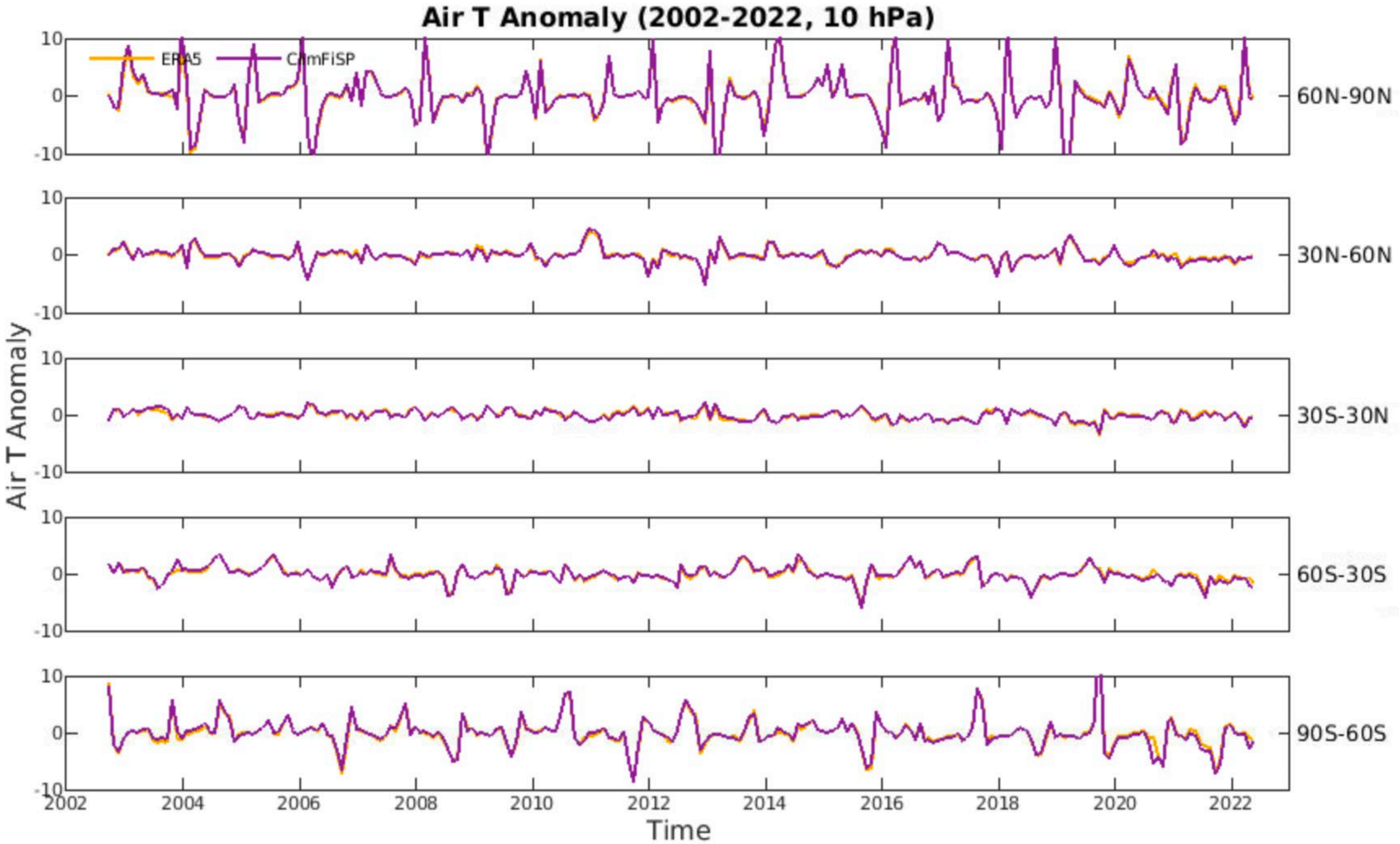
Consistent Result from ClimFiSP and ERA5 (500 hPa)

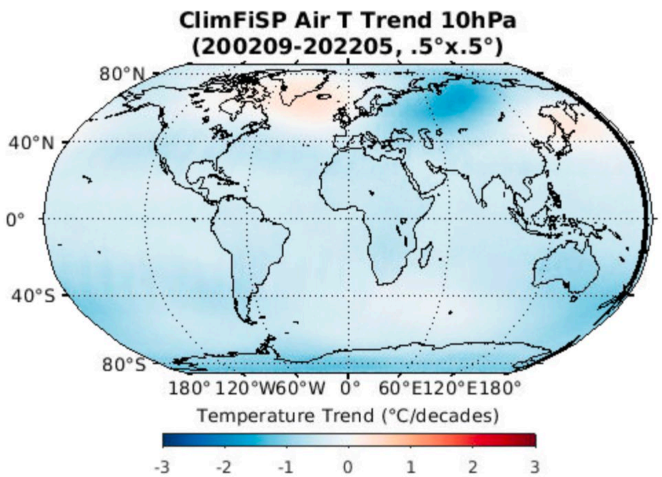


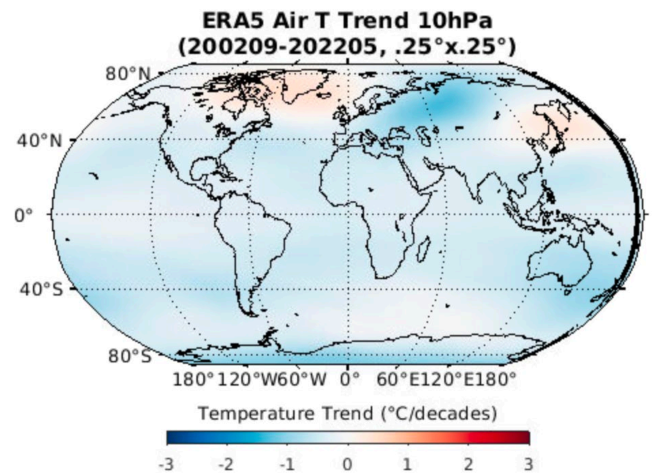




Consistent Result from ClimFiSP and ERA5 (10 hPa)

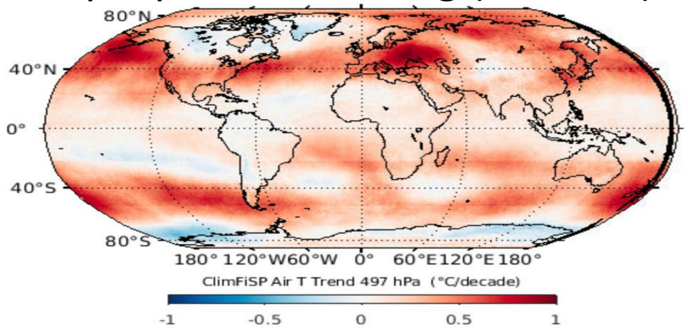




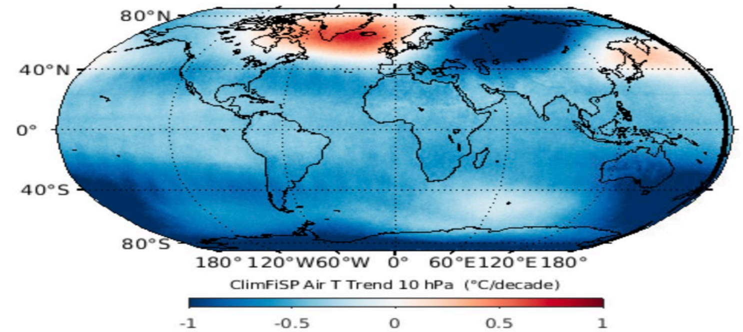


Examples of 20-year Climate Trends from ClimFiSP

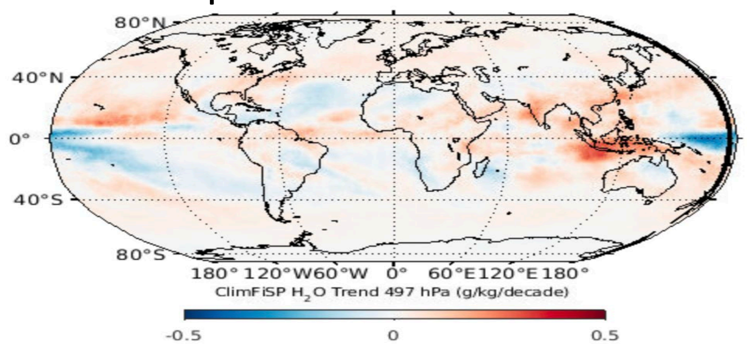
Tropospheric warming (500 hPa)



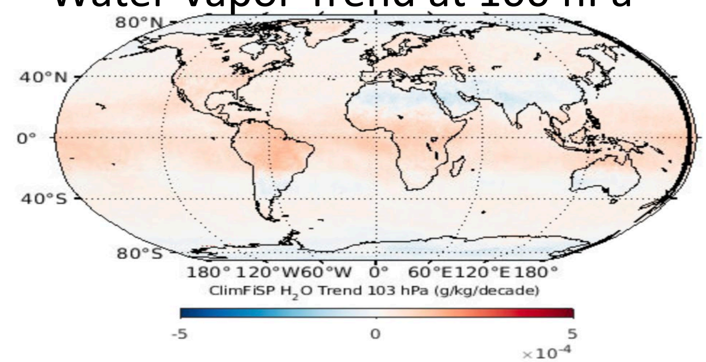
Stratospheric cooling (10 hPa)



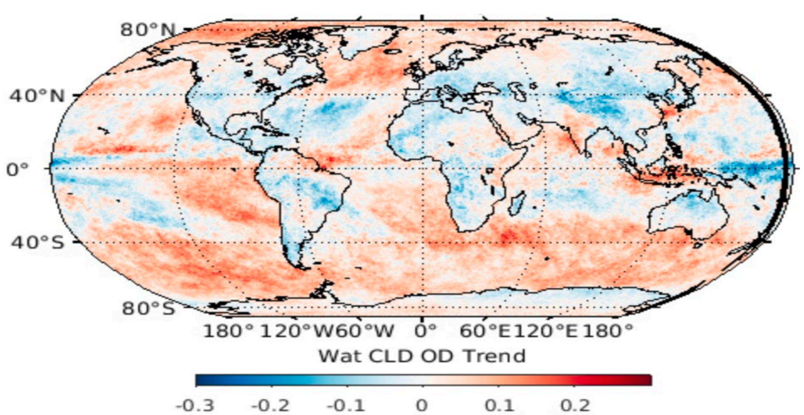
Water Vapor Trend at 500 hPa



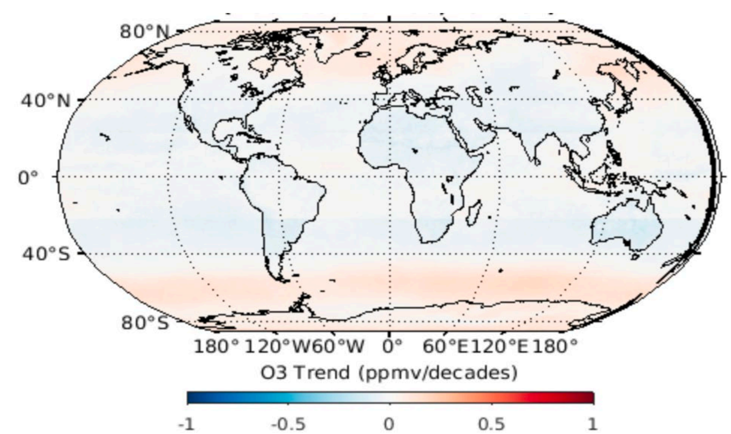
Water Vapor Trend at 100 hPa



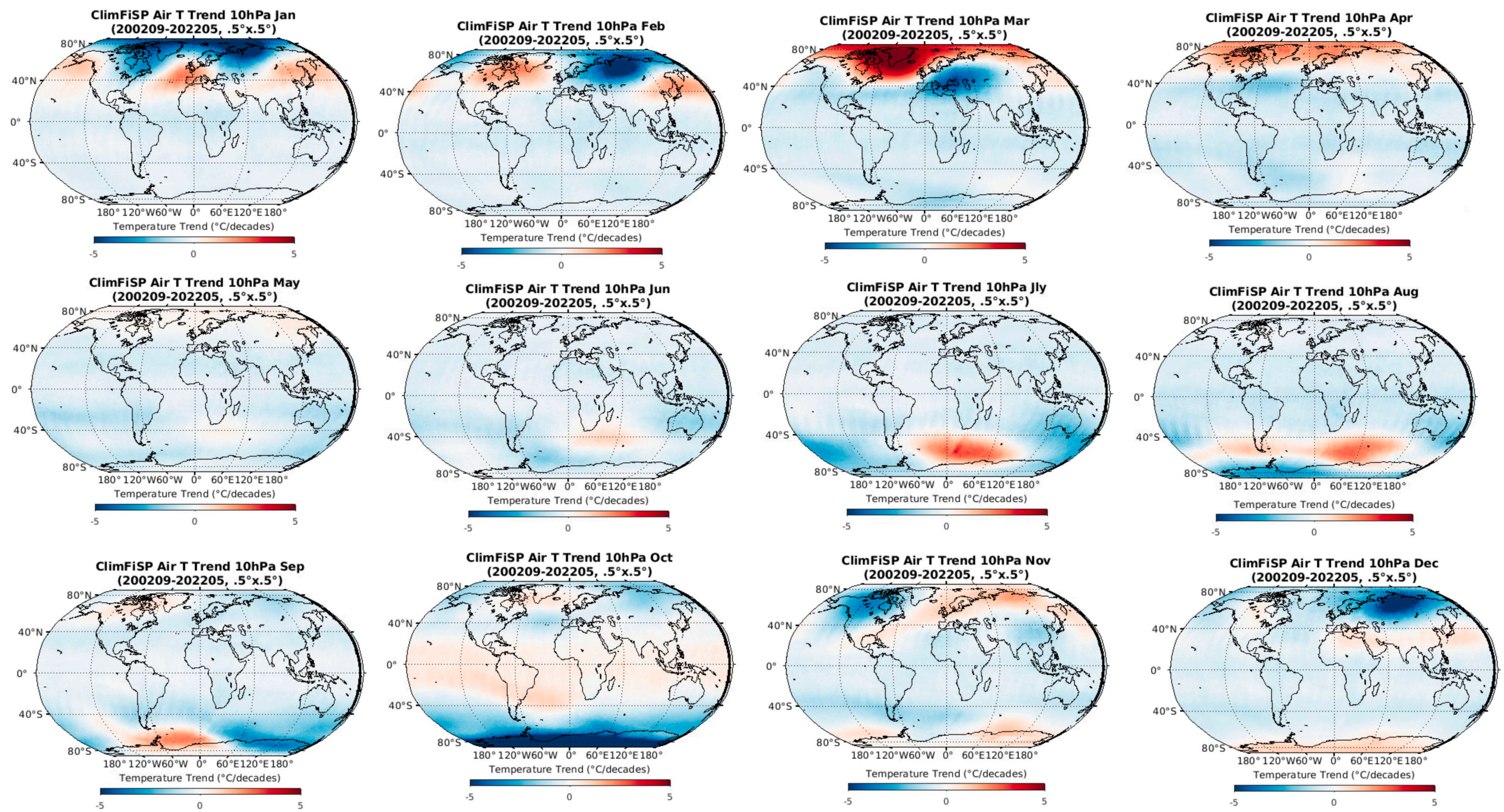
ClimFiSP Water Cloud Optical Depth Trend



ClimFiSP Ozone Trend (10 hPa)



Seasonal Variation of 10 hPa Temperature Trends from ClimFiSP



Summary and Conclusions

- Hyperspectral satellite remote sensors provide high information content
- Accurately calibrated satellite measurements are needed
- PCRTM can efficiently simulate hyperspectral satellite remote sensing data
- PCRTM has a wide range of applications such as high-fidelity satellite sensor simulator, forward model for atmospheric correction and inversion algorithm, AI training data generation….
- PCRTM-based spectral fingerprinting method is an efficient way to deal hyperspectral data from multiple remote sensors
- PCRTM enables us to efficiently use all spectral information from both IR and solar remote sensors