Explore Information Content Efficiently from Current and Future Hyperspectral Satellite Missions using a Spectral Fingerprinting Method

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Key challenges in exploring information content of hyperspectral satellite remote sensing data

- Challenge No. 1: computation speed of Radiative Transfer Model (RTM)
  - Line-by-line: millions of monochromatic radiative transfer (RT) calculations
  - Channel-based RTMs: thousands of polychromatic RT calculations
  - Principal Component (PC)-based RTMs: hundreds of monochromatic RT calculations
- Challenge No. 2: need effective methods to deal with clouds
  - 90% of sounder FOVs contain clouds – need accurate and fast cloudy RTMs
  - Current NASA & NOAA operational L2 algorithms used cloud-clearing (CC) to remove clouds
  - Only 5-20% of channels due to RTMs speed and cloud RT accuracy limitations
  - Fitting CC-radiances does not satisfy radiometric closure requirement for physical retrievals
- Principal Component-based RTM (PCRTM) addresses these challenges
  - Fit cloudy radiance directly
    - Avoids scene homogeneity assumption needed by cloud clearing algorithm
    - Provides higher spatial resolution and more retrieval products
    - Provide radiometric closure needed for climate products
  - Include all spectral channels due to faster speed
    - All geophysical parameters retrieved simultaneously including cloud parameters

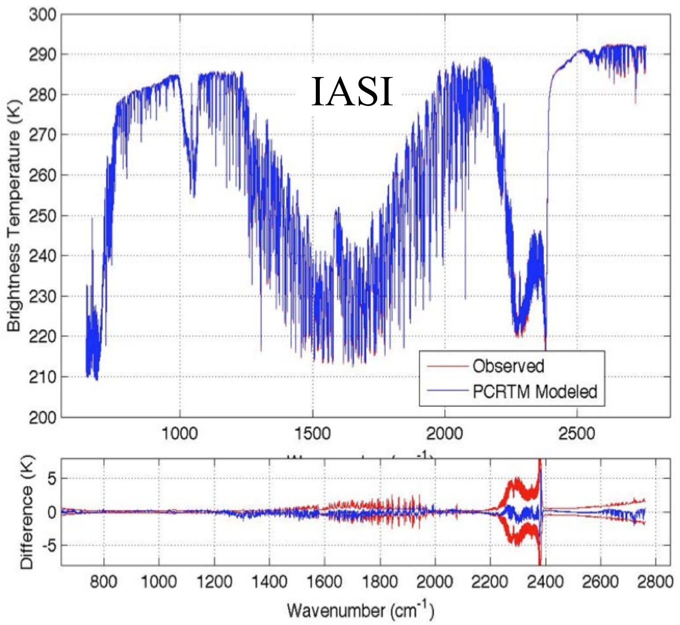
Introduction to a Principal Component-based Transfer Model (PCRTM)

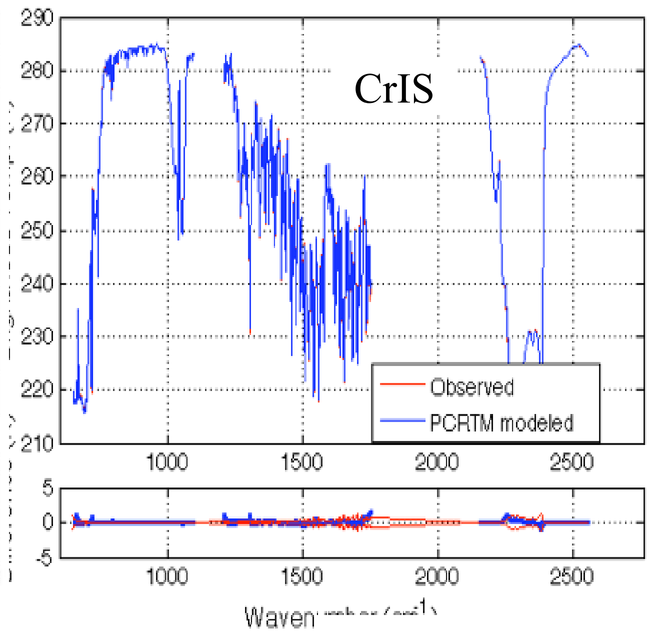
- PCRTM was first developed in 2004 and has been extensively used by many projects
  - Compress spectra into Principal Component (PC) domain
  - Performs minimum number of monochromatic calculations
  - Covers spectral range from far infrared, IR, mid-IR, Near-IR, Visible, UV-Vis spectral regions
- Calculates channel radiances (or transmittances) by linearly combining a set of PCs:

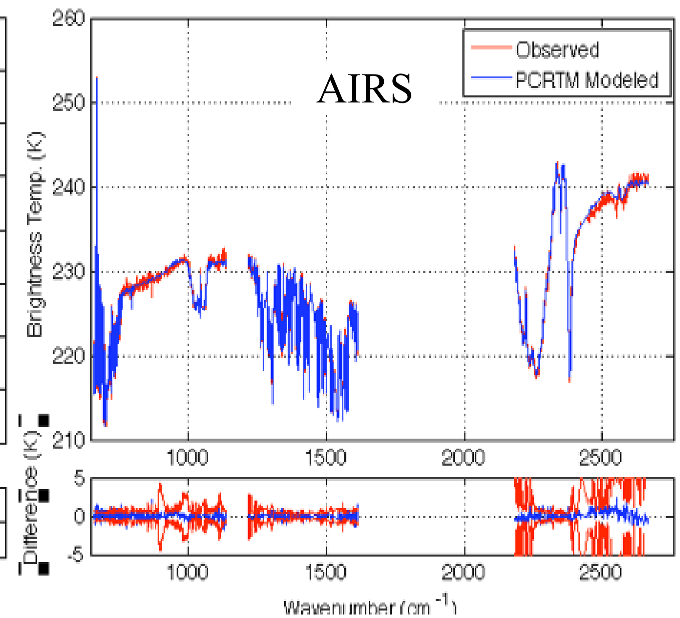
$$\vec{R}^{ch} = \sum_{i=1}^{N_{EOF}} c_i \vec{U}_i + \vec{\varepsilon} = \sum_{i=1}^{N_{EOF}} \left(\sum_{j=1}^{N_{mono}} a_j R_j^{mono} \right) \vec{U}_i + \vec{\varepsilon}$$

- Channel radiance/reflectance/flux can be obtained by a linear combination of PC-scores (*c*) and corresponding PCs (*U*)
- PCRTM is fast (5-15 milliseconds for 2200-8500 spectral channels)
- PCRTM is accurate (0.03 K Brightness Temperature RMS errors relative to line-by-line
- PCRTM handles multiple scattering clouds
- 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. 20 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...

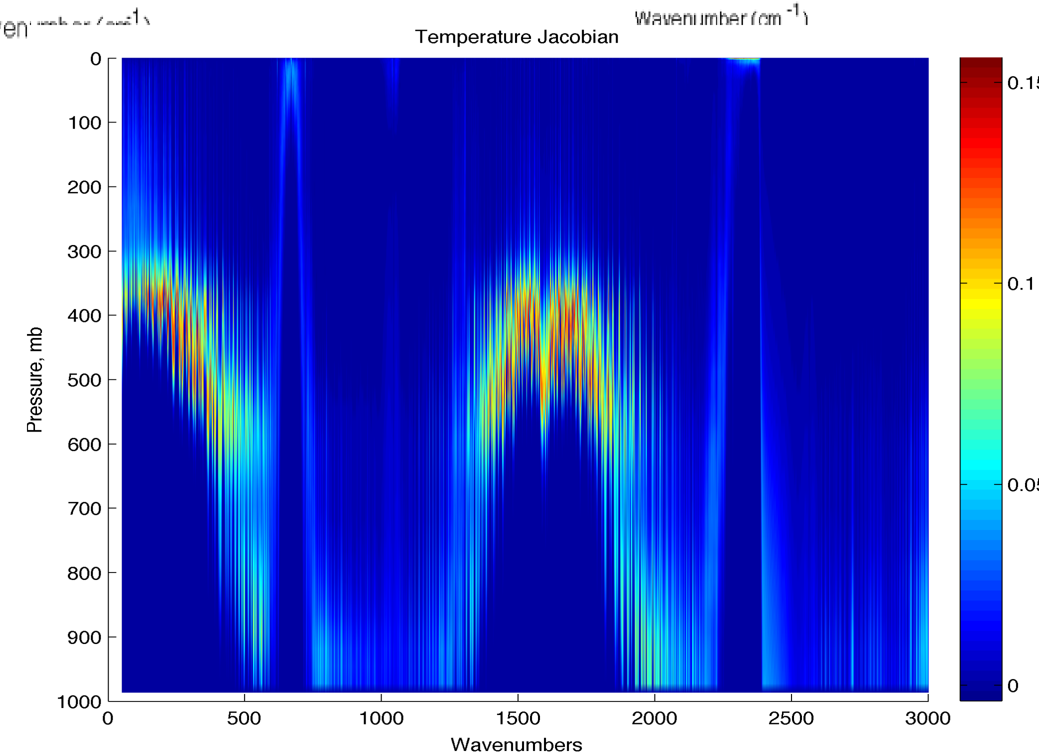
Demonstration of Speed and Accuracy of PCRTM for IR sounders



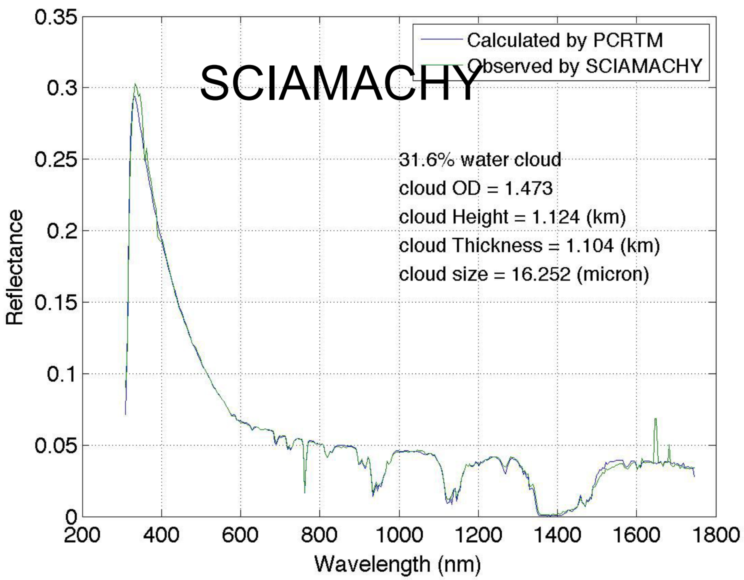


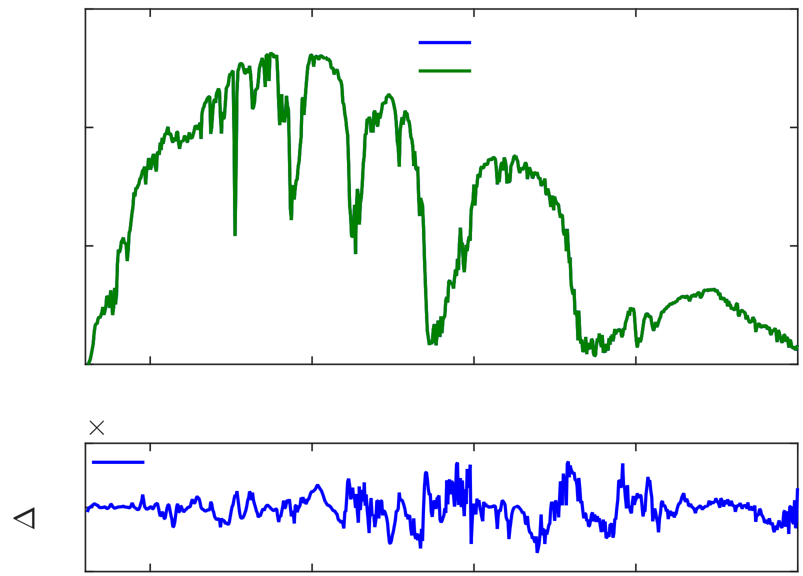


Sensor	Channel Number	PC score (seconds)
CLARREO, 0.1 cm^{-1}	19901	0.014 s
CLARREO, 0.5 cm^{-1}	5421	0.011 s
CLARREO, 1.0 cm^{-1}	2711	0.0096 s
IASI, 0.25 cm^{-1}	8461	0.011 s
AIRS, 0.5-2.5 cm^{-1}	2378	0.0060 s
CrIS,0.625-2.5 cm^{-1}	1317	0.0050 s
NAST-I, 0.25 cm^{-1}	8632	0.010 s
S-HIS, 0.5 cm^{-1}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



PCRTM Reduces RT Calculations by 3-4 Oders of Magnitude Relative to Correlated- Method for CPF-type Spectrometer





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

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

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

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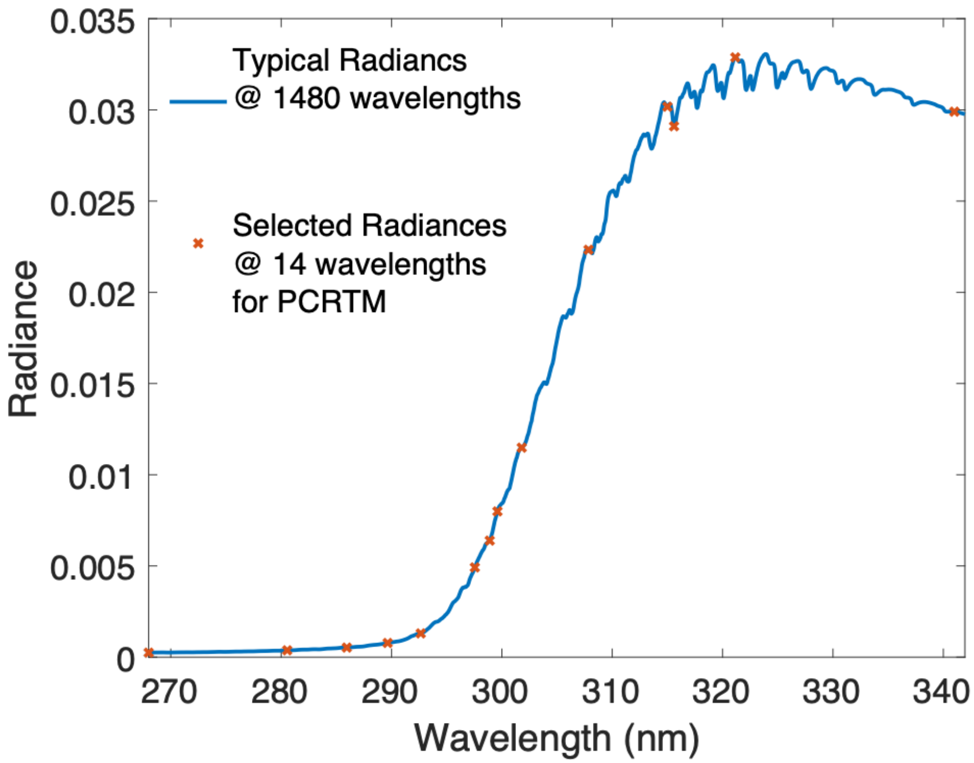
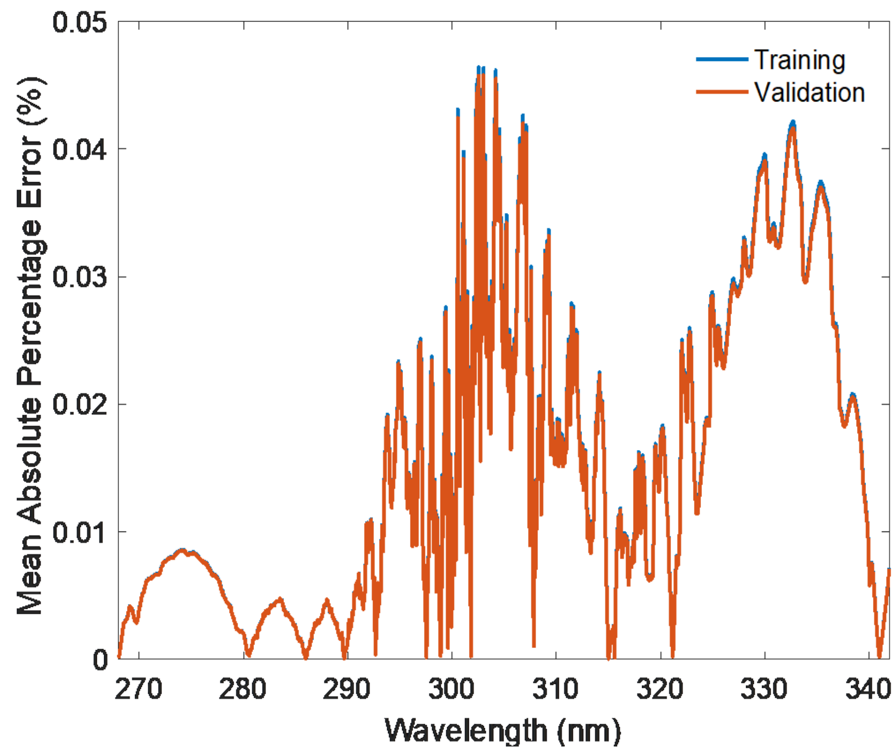
Example of Selected Wavelength Locations and RMS Errors for TEMPO/OMI Ozone Spectral Regions

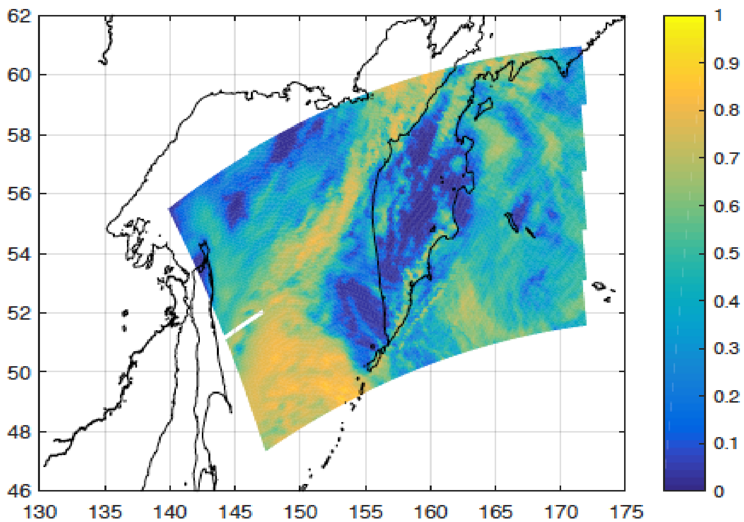
- 2 Orders of magnitude speed up in the OMI Ozone spectral region for a high-spectral resolution (0.05 nm) PCRTM
- Redundant RT calculations are avoided in PCRTM approach
- Can further reduce the number RT calculations at TEMPO or OMI spectral resolutions



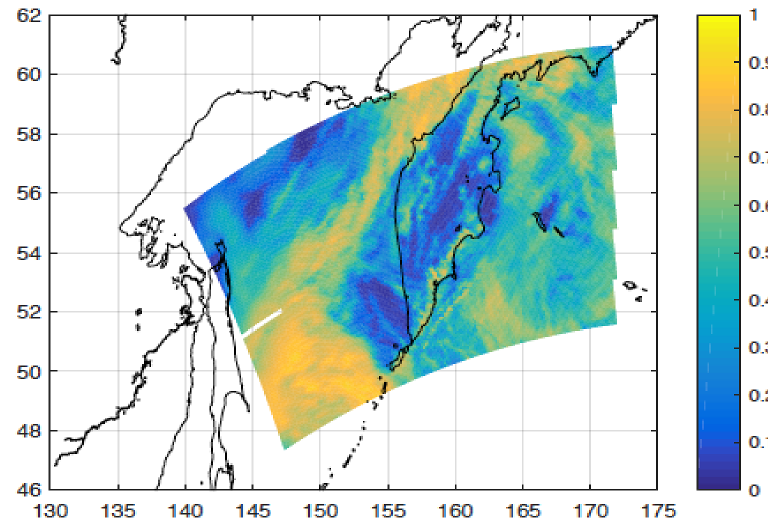


Examples of PCRTM as Fifidely Simulator

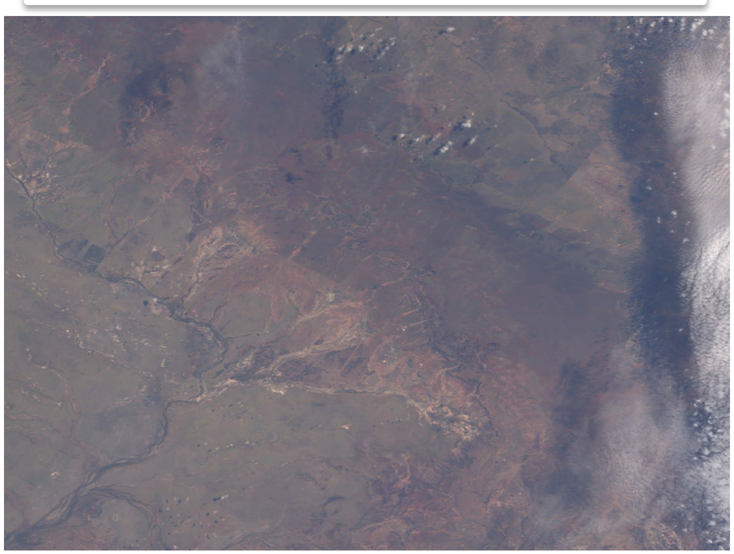
PCRTM Simulated Reflectance @646 nm using MODIS L2 data



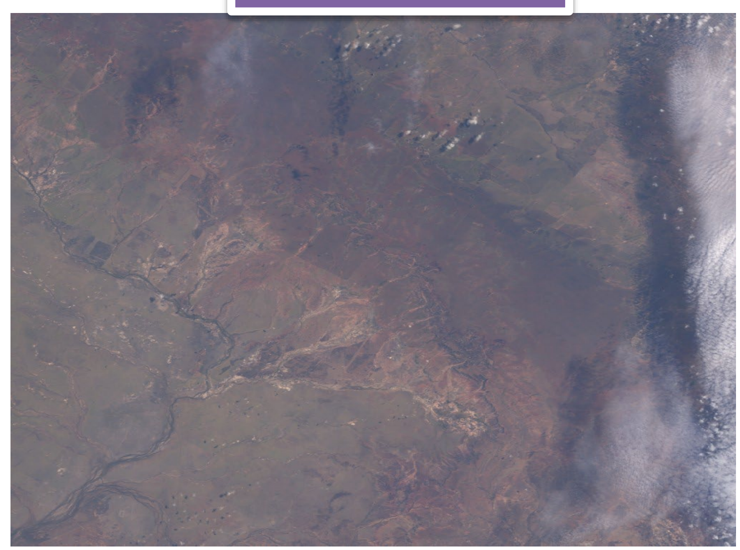
MODIS L1 Observed Reflectance @646 nm



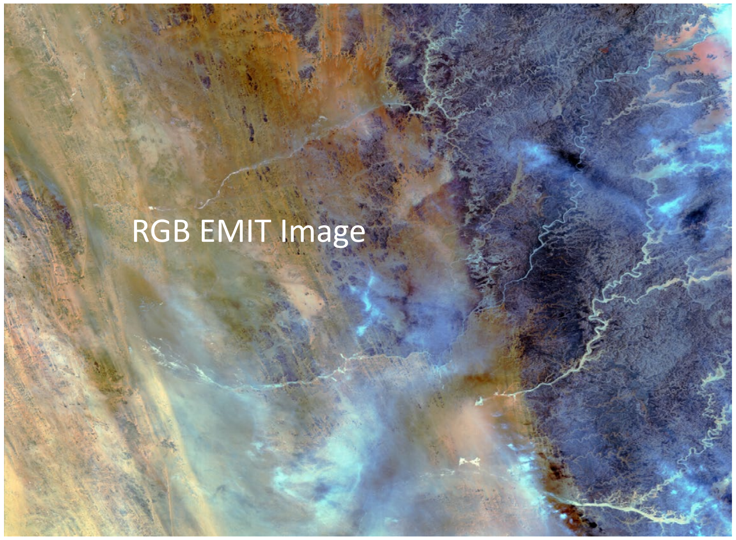
PCRTM Calculated EMIT RBG Image

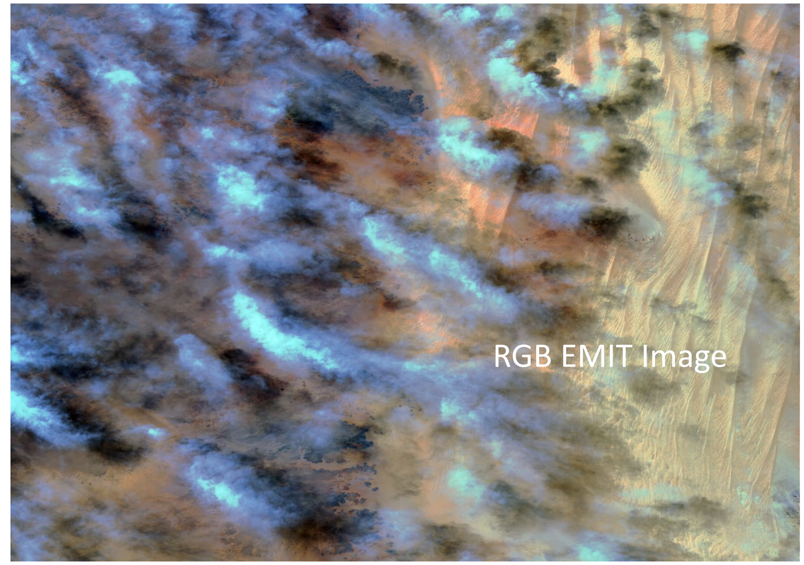


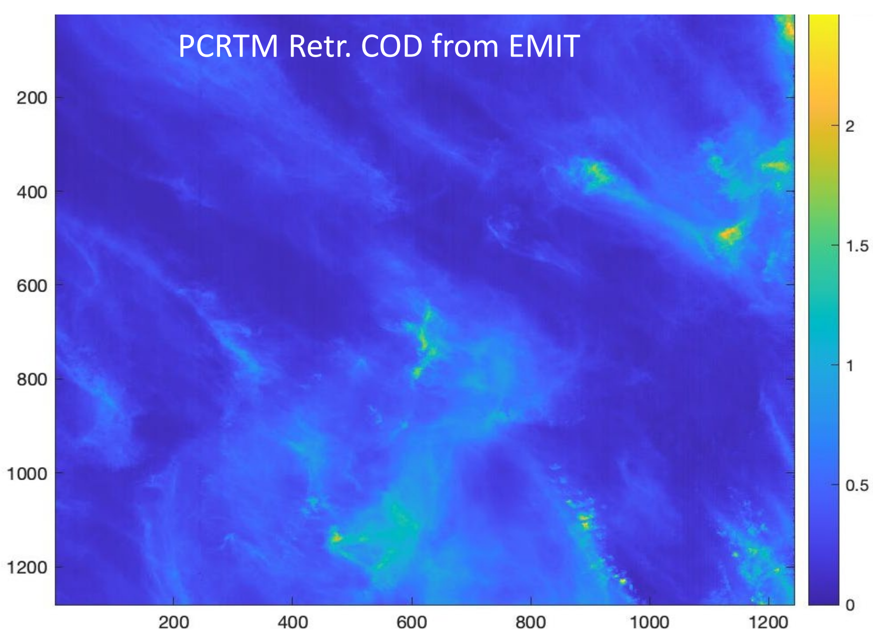
EMIT RBG Image

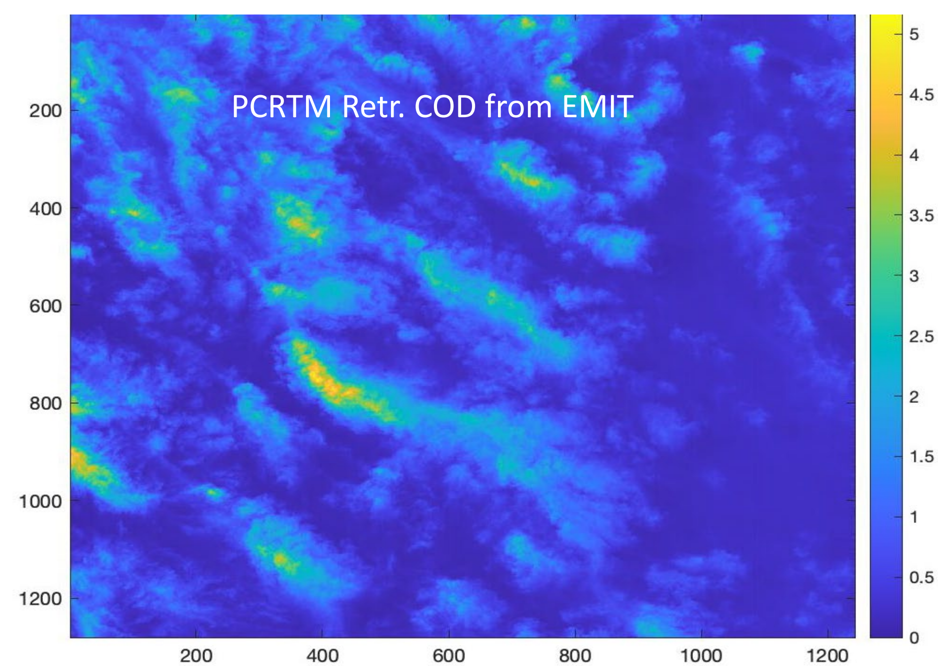


PCRTM trained AI Cloud Retrieval algorithm for EMIT





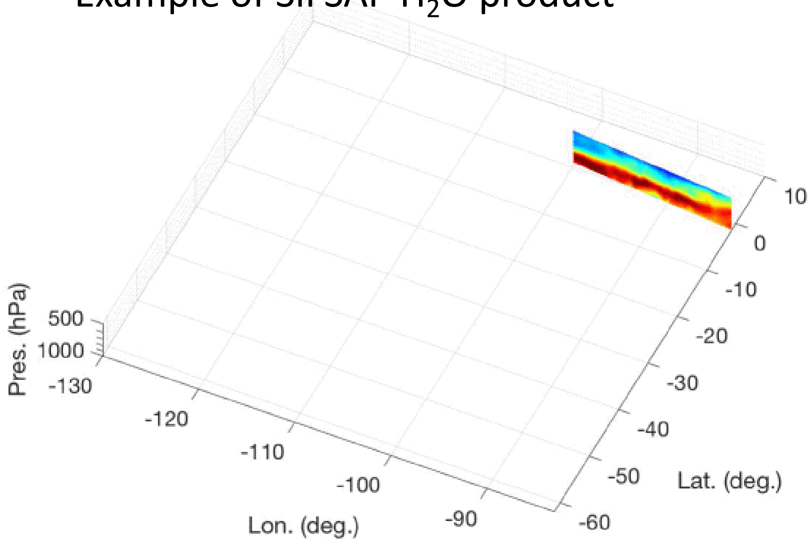




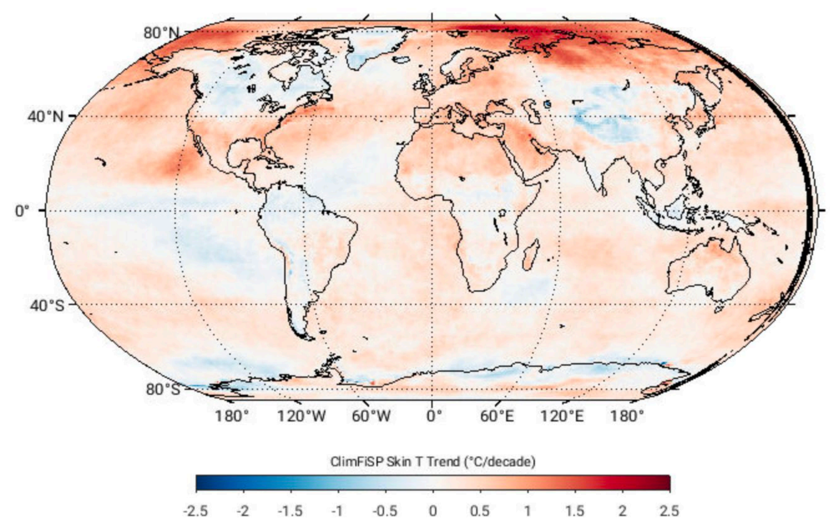
Efficient Hyperspectral Retrieval Algorithm Using Spectral Fingerprinting

- A PCRTM-based Optimal Estimtion L2 algorithm Single Field-of-view Sounder Atmospheric Product (SiFSAP) was developed at LaRC and delivered to NASA GES DISC for operational product generation from CrIS
  - 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
- Spectral fingerprinting method is much efficient: Climate Fingerprinting Sounder Products (ClimFiSP)
  - Works on spatiotemporally averaged radiance spectra
  - 3-4 orders of magnitude faster with similar accuracy
  - Ideal for multi-satellite multi-instrument data analysis
    - Use consistent radiative kernels for all satellite sensors
    - Ensure radiometric closures by fitting measured radiance spectra

Example of SiFSAP H_2O product

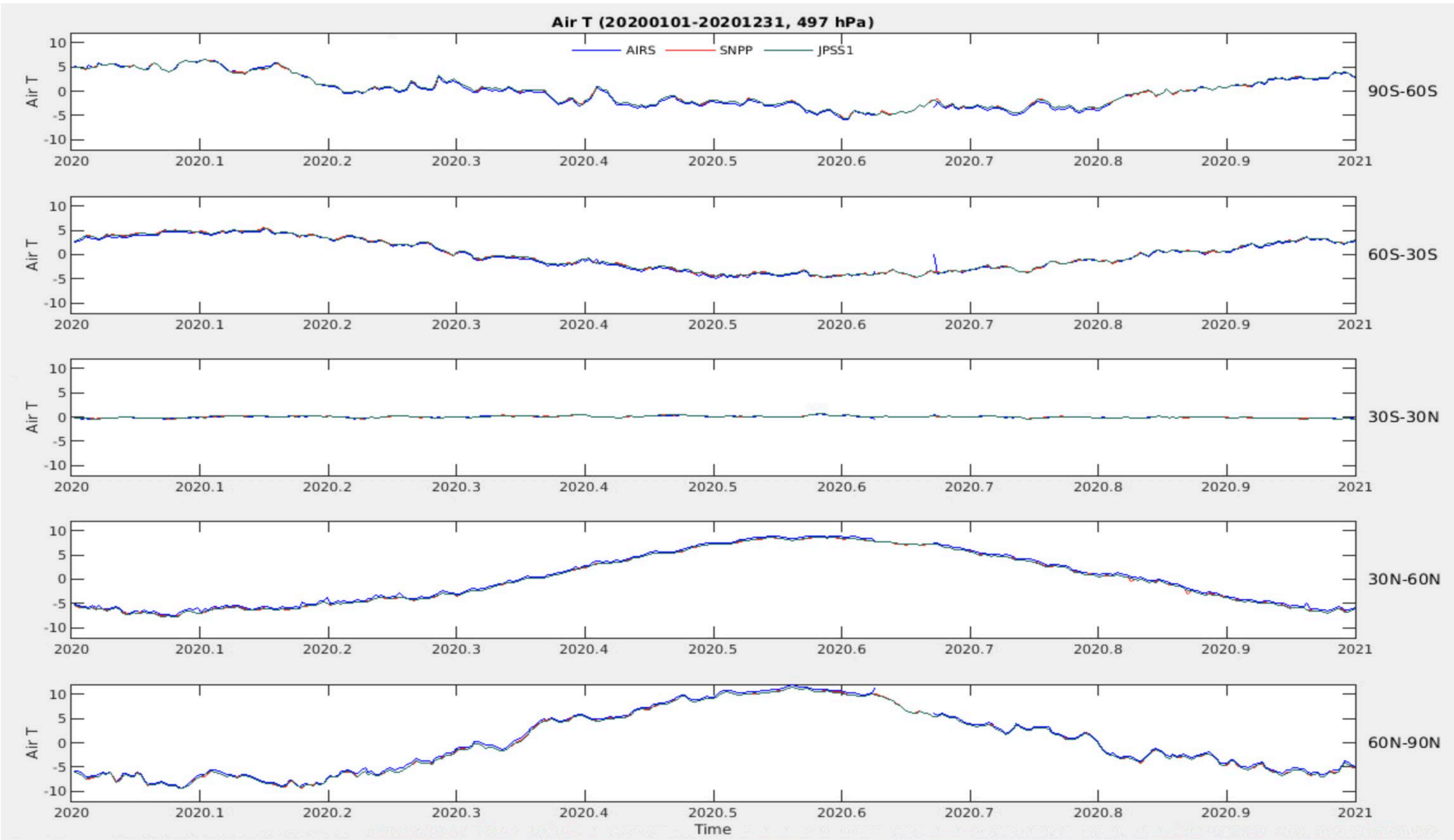


Example of ClimFiSP derived global surface temperature trend from Aqua/AIRS, SNPP and NOAA20 CrIS



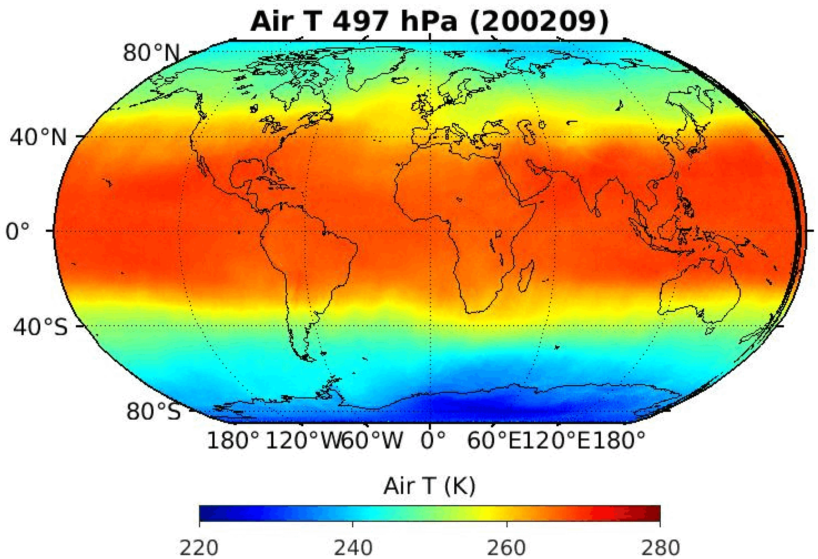
Consistent ClimFiSP Products from 3 Satellites Aqua/AIRS, SNPP/CrIS, and NOAA20/CrIS (2020)

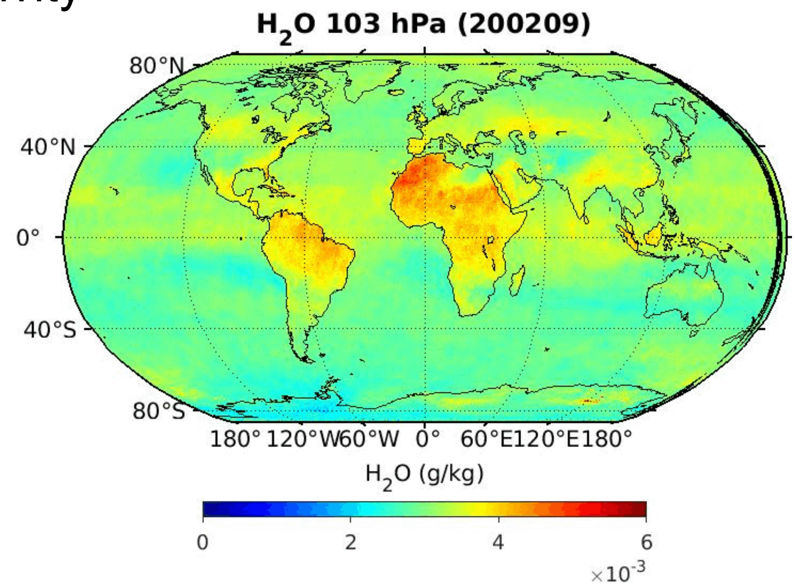
500 hPa Temperature from Aqua/AIRS (Blue) SNPP/CrIS (Red), and NOAA20/CrIS (Green)

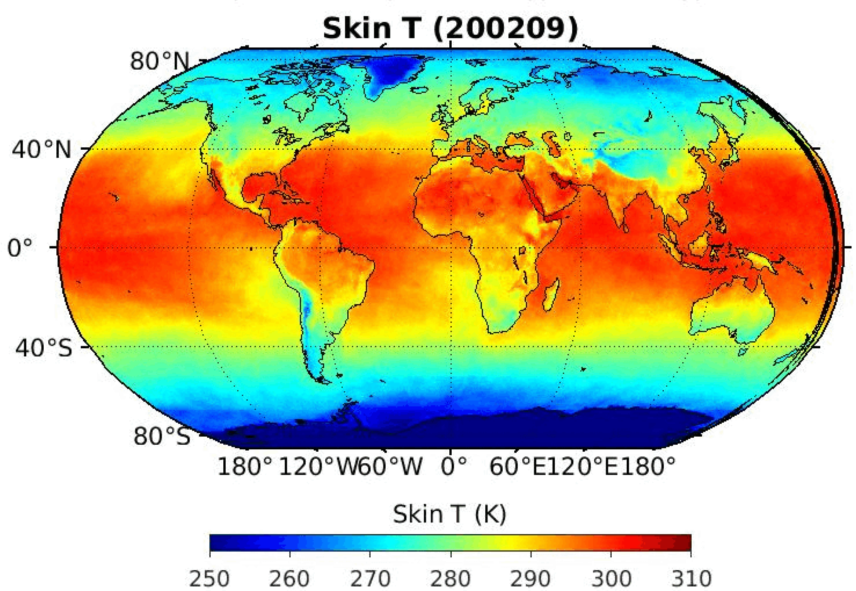


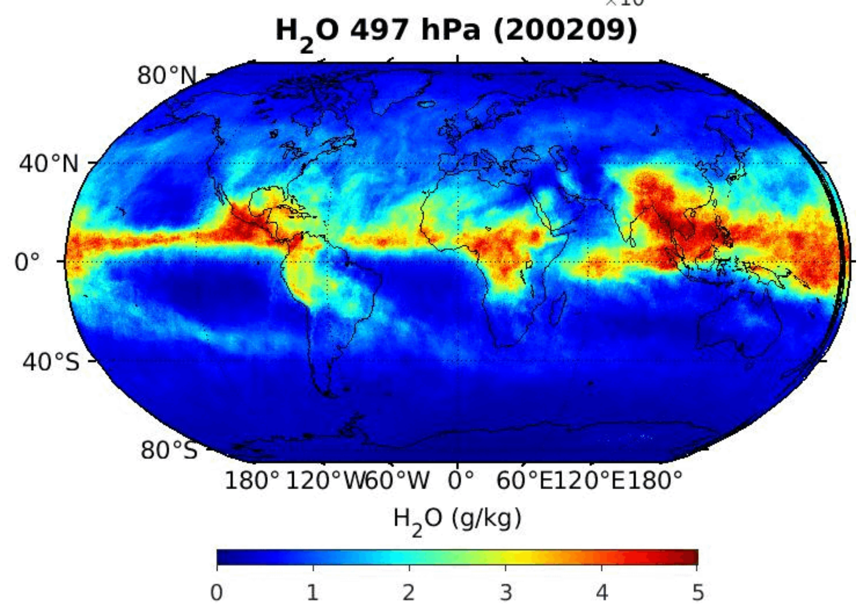
Hundres of CDRs (Daily, Time Series, and Trends) from ClimFiSP

- 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



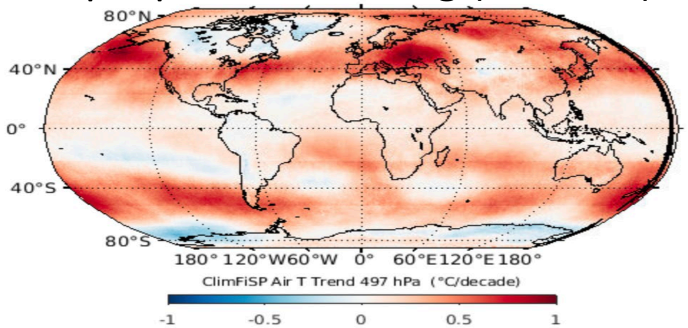




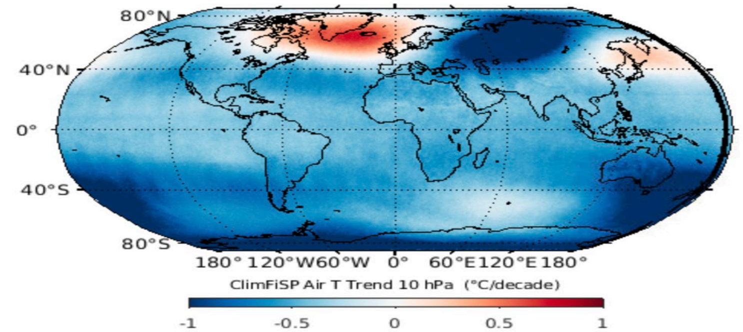


Examples of 20-year Climate Trends from ClimFiSP

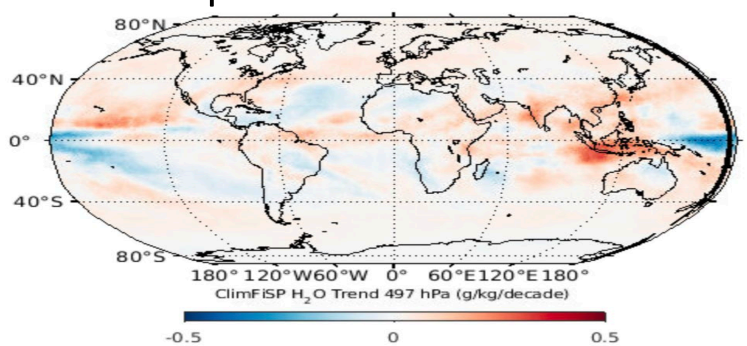
Tropospheric warming (500 hPa)



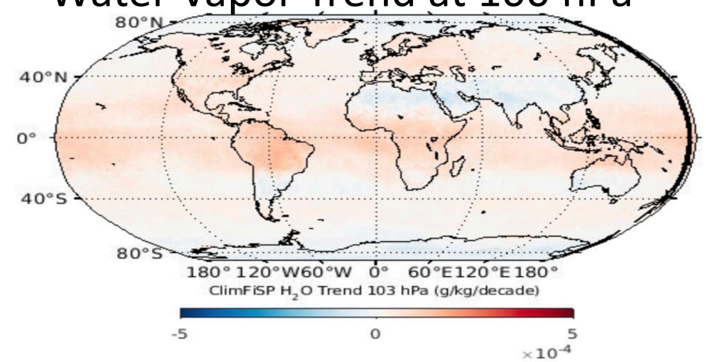
Stratospheric cooling (10 hPa)



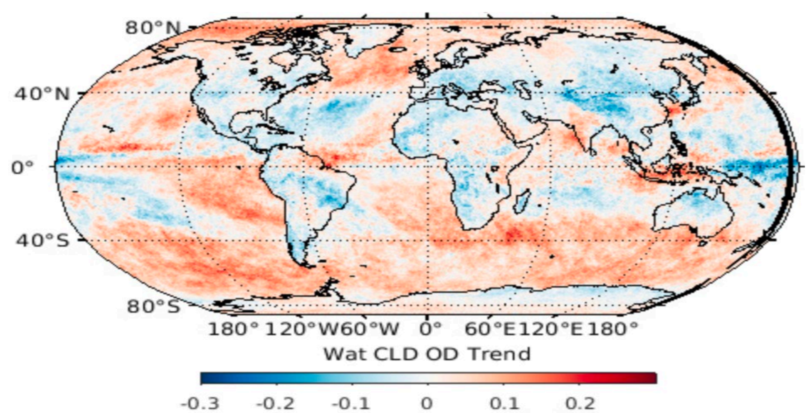
Water Vapor Trend at 500 hPa



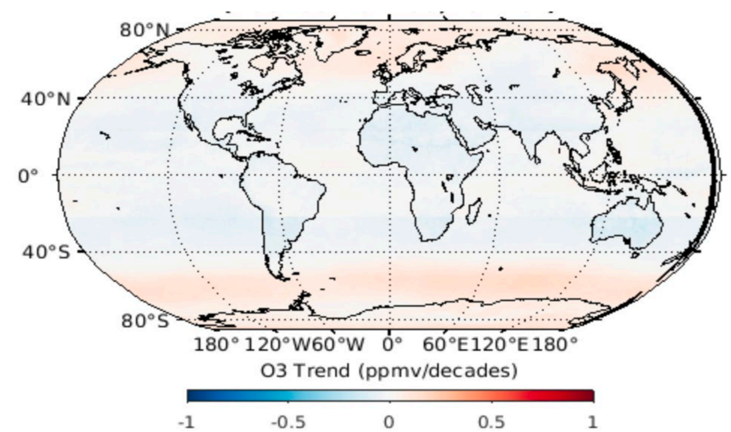
Water Vapor Trend at 100 hPa



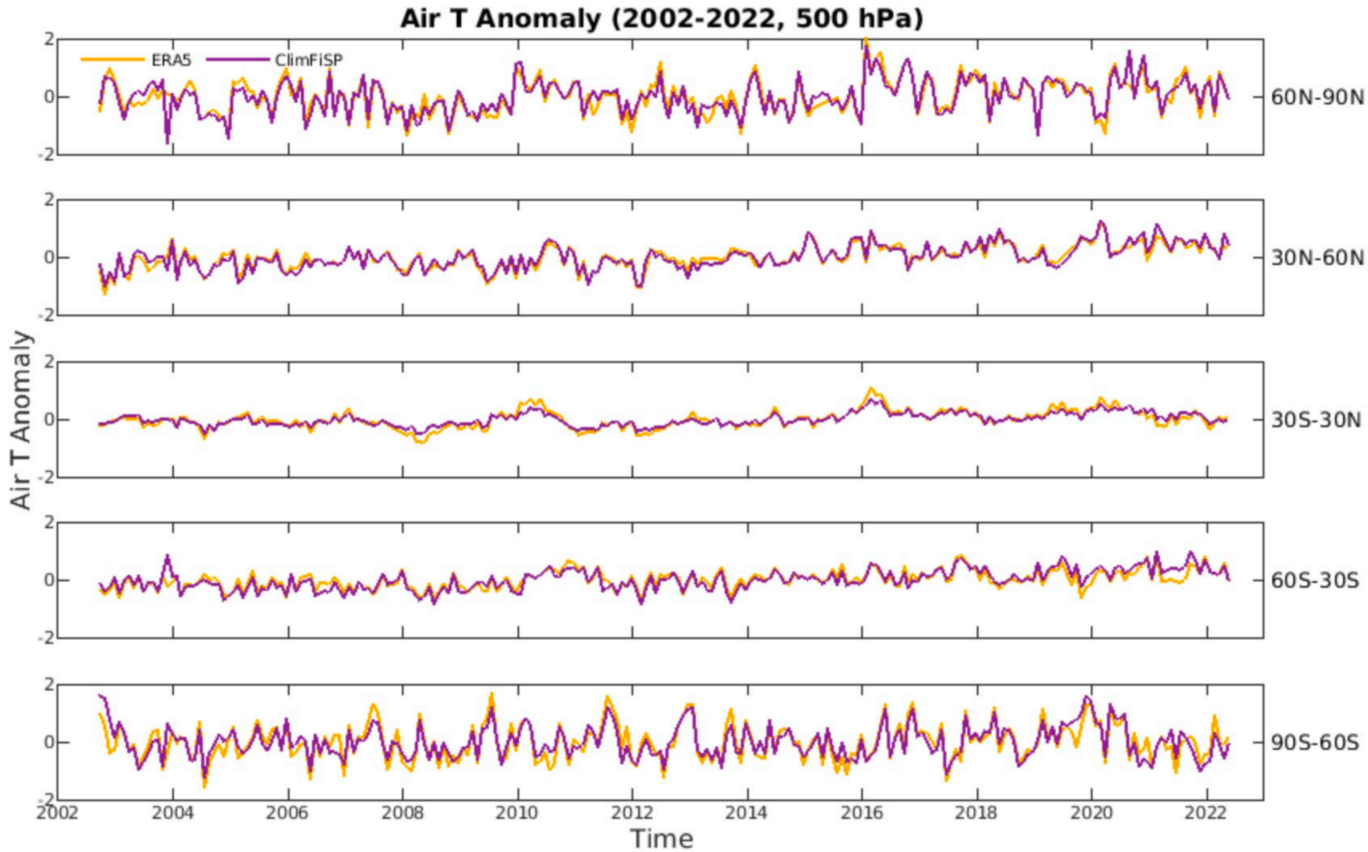
ClimFiSP Water Cloud Optical Depth Trend

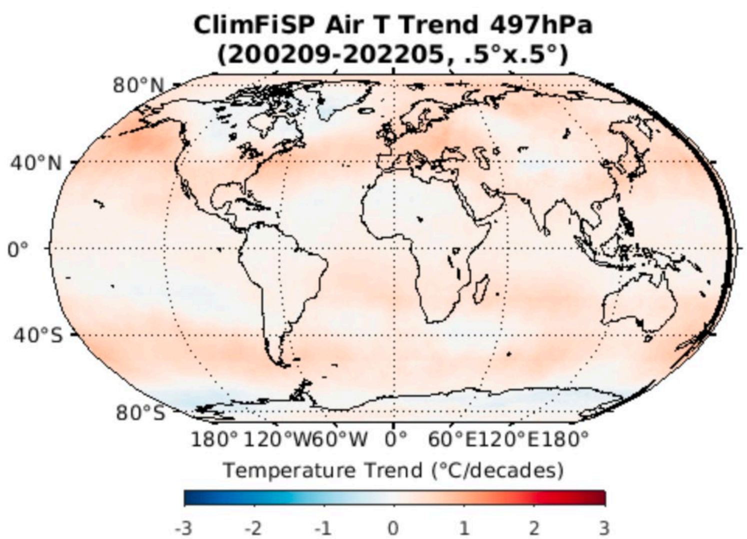


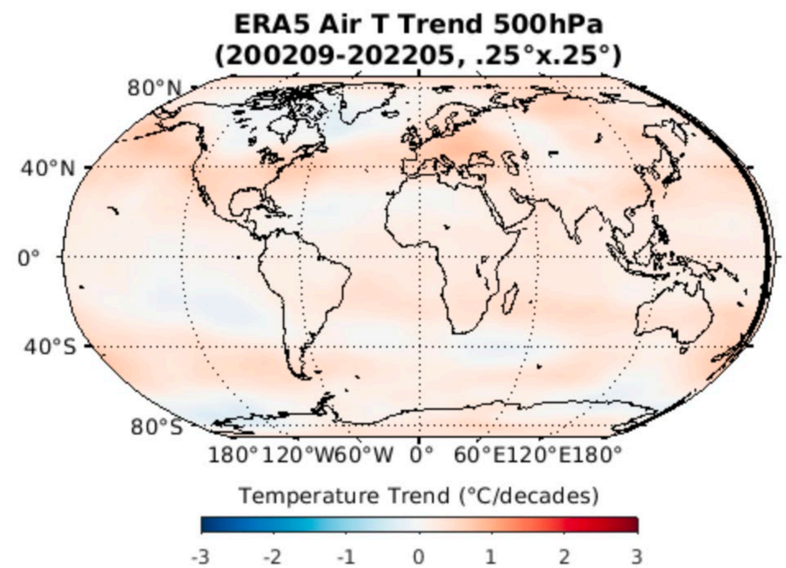
ClimFiSP Ozone Trend (10 hPa)



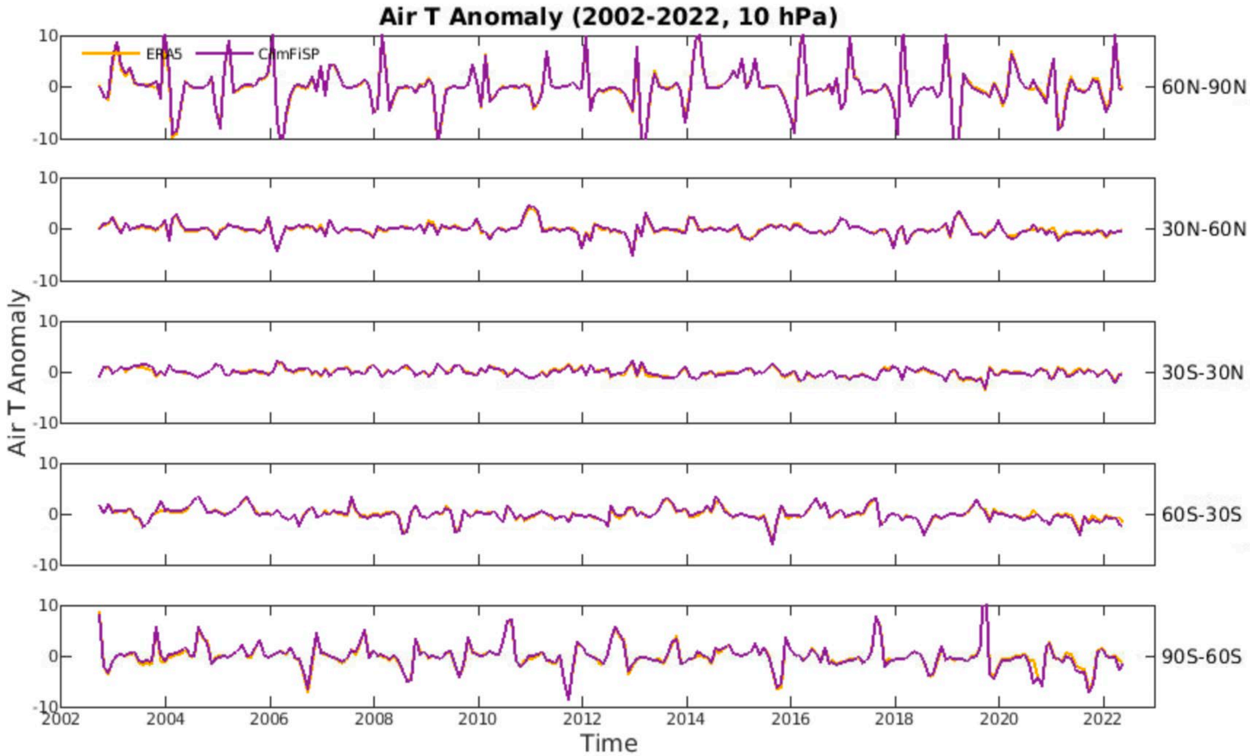
Consistent Result from ClimFiSP and ERA5 (500 hPa)

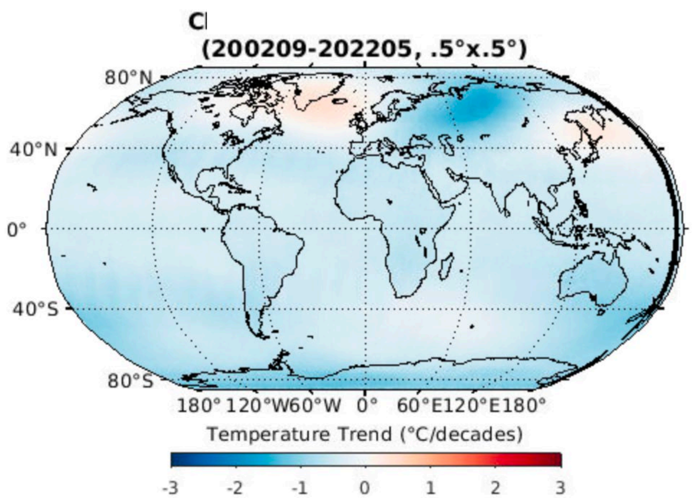


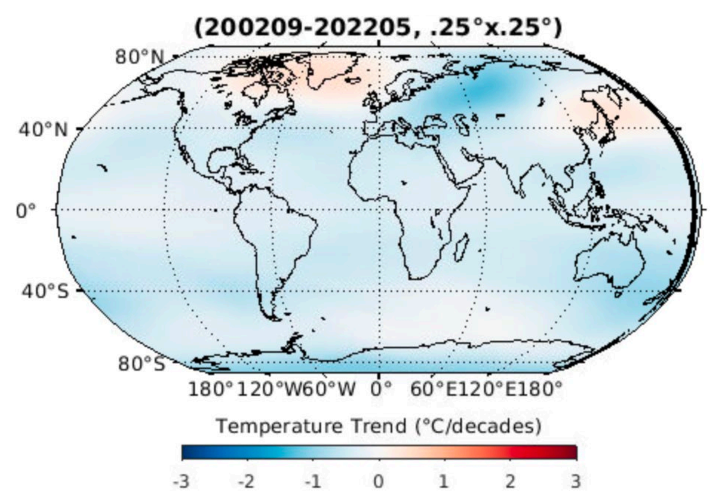




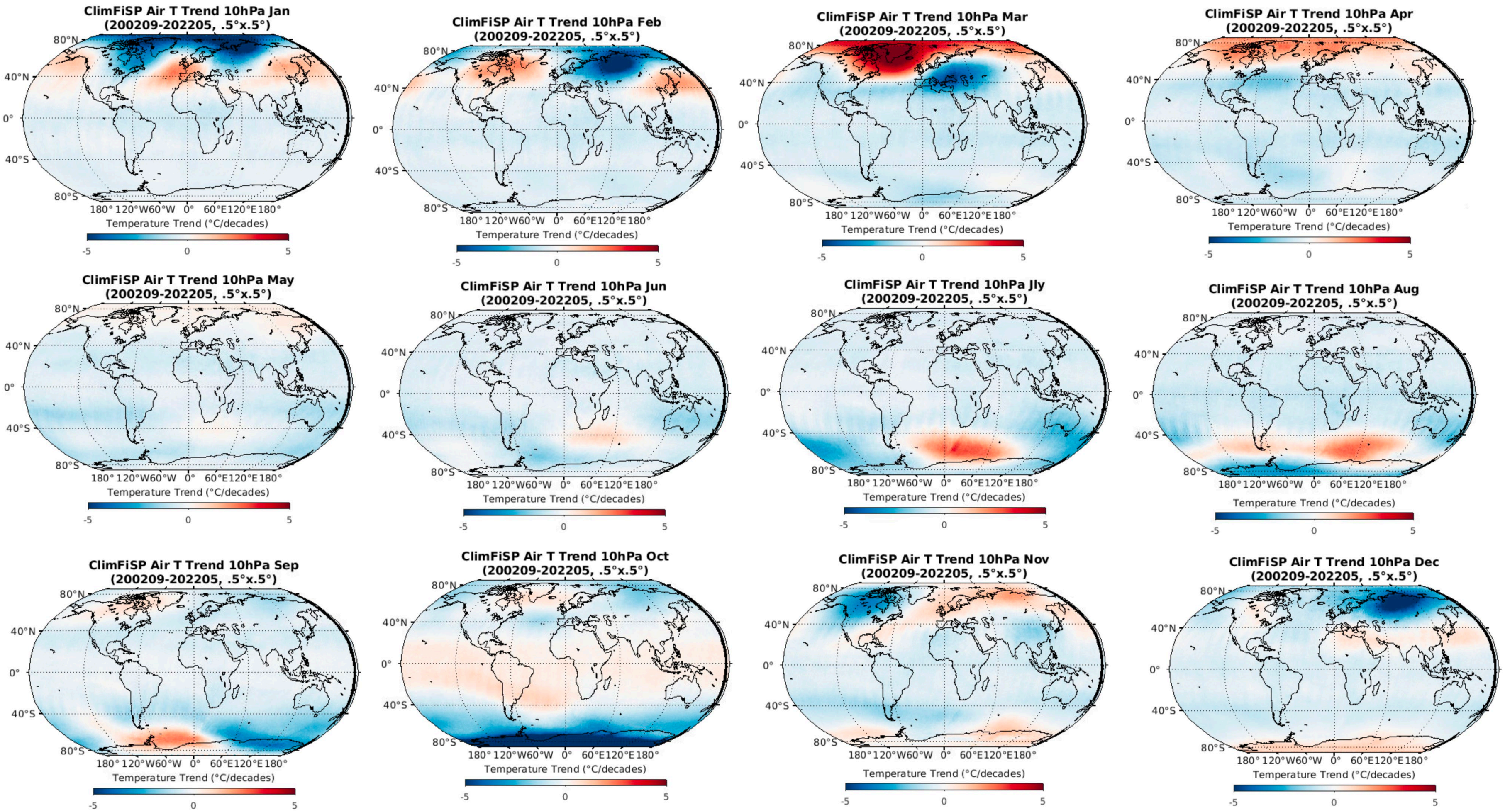
Consistent Result from ClimFiSP and ERA5 (10 hPa)







Seasonal Variation of 10 hPa Temperature Trends from ClimFiSP



Summary and Conclusions

- PCRTM can efficiently analyze hyperspectral satellite remote sensing data
  - Been developed for numerous remote sensing instruments with different spectral range and measurement types
  - Orders of magnitude faster than LBL RTMs
- PCRTM has a wide range of applications such as high fidelity satellite sensor simulator, forward model for atmospheric correction and inversion algorithm
  - CLARREO, CPF, IASI, AIRS, CrIS …
- PCRTM-based L2 and L3 algorithm are currently generating daily products from hyperspectral IR remote sensors
  - Temperature, water vapor, O_3, CO, CH_4, N_2O, CO_2 atmospheric profiles
  - Cloud temperature, pressure, optical depth, phase, and effective size
  - Surface skin temperature and surface emissivity spectra
  - SiFSAP (L2) is available at NASA GES DISC
  - ClimFiSP (L3) will be available at NASA GES DICS soon
  - 20 years of Climate Data Records from Aqua/AIRS, SNPP/CrIS, and NOAA20/CrIS has been generated
- Combination of PCRTM and spectral fingerprinting method will enable us to efficiently use all spectral information from both IR and solar remote sensors