Development of Radiative Transfer Models and Retrieval Algorithms for Satellite Remote Sensors

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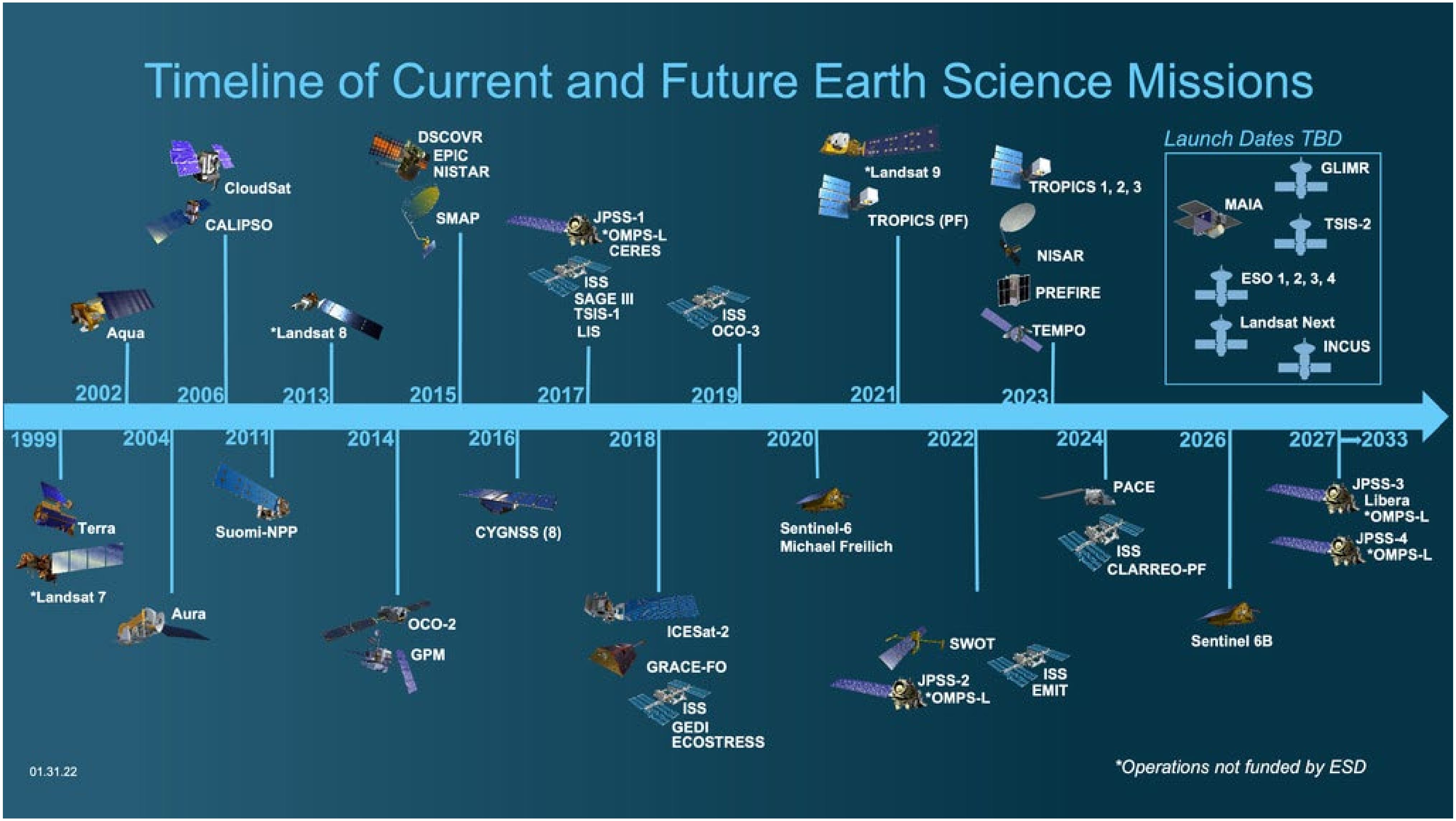
Outline of the Presentation

1. Principal Component-based Radiative Transfer Model (PCRTM)—A way to deal with challenges facing hyperspectral IR sounding

2. Two algorithms for deriving atmospheric and surface properties from IR sounders
   - New NASA L2 products: Single Field-of-view Sounder Atmospheric Product (SiFSAP)
   - New NASA L3 products: Climate Fingerprinting Sounder Product (ClimFiSP)

1. Other examples of using PCRTM applications

2. Conclusion and ways forward



Timeline of Current and Future Earth Science Missions
Launch Dates TBD
GLIMR
MAIA
TSIS-2
ESO 1, 2, 3, 4
Landsat Next
INCUS
1999
Terra
*Landsat 7
2002
Aqua
2004
Aura
2006
CloudSat
CALIPSO
2011
Suomi-NPP
2013
*Landsat 8
2014
OCO-2
GPM
2015
DSCOVR
EPIC
NISTAR
SMAP
2016
CYGNSS (8)
2017
JPSS-1
*OMPS-L
CERES
ISS
SAGE III
TSIS-1
LIS
2018
ICESat-2
GRACE-FO
ISS
GEDI
ECOSTRESS
2019
ISS
OCO-3
2020
Sentinel-6
Michael Freilich
2021
*Landsat 9
TROPICS (PF)
2022
SWOT
JPSS-2
*OMPS-L
ISS
EMIT
2023
TROPICS 1, 2, 3
NISAR
PREFIRE
TEMPO
2024
PACE
ISS
CLARREO-PF
2026
Sentinel 6B
2027→2033
JPSS-3
Libera
*OMPS-L
JPSS-4
*OMPS-L
01.31.22
*Operations not funded by ESD

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:

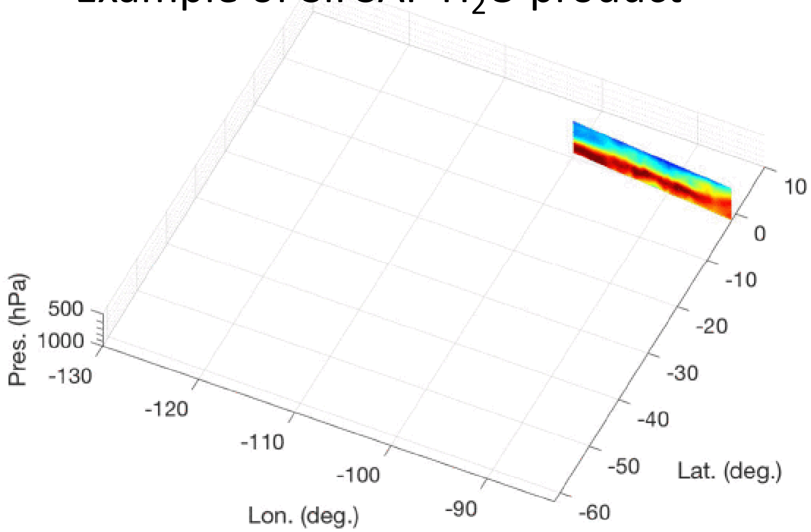
$$\vec{R}^{ch} = \sum_{i=1}^{N_{EOF}} c_i \vec{U}_i + \vec{\varepsilon} = \sum_{i=1}^{N_{EOF}} \left(\sum_{j=1}^{N_{mono}} a_j R_j^{mono} \right) \vec{U}_i + \vec{\varepsilon}$$

- 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...

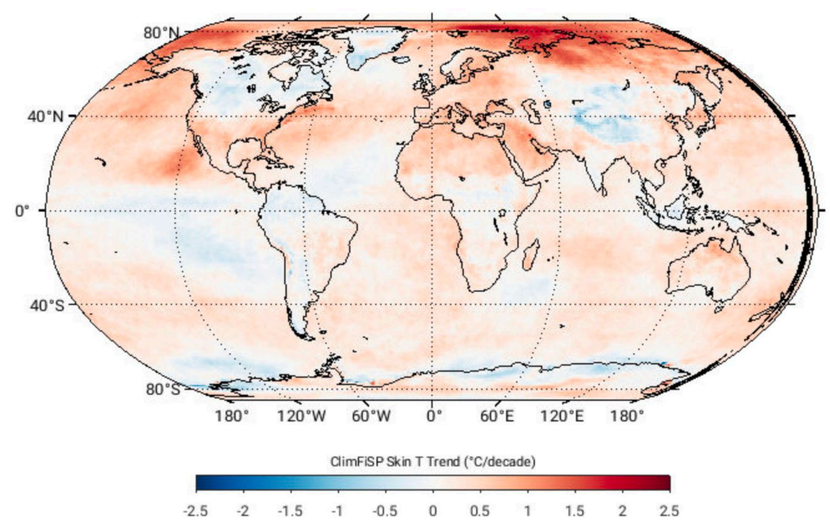
Two PCRTM-based Inversion Algorithms

- 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
  - Generates high-quality climate product from multiple satellite data (20 years AIRS, SNPP CrIS, and NOAA20 CrIS)
    - Use consistent radiative kernels for all three satellite sensors
    - 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

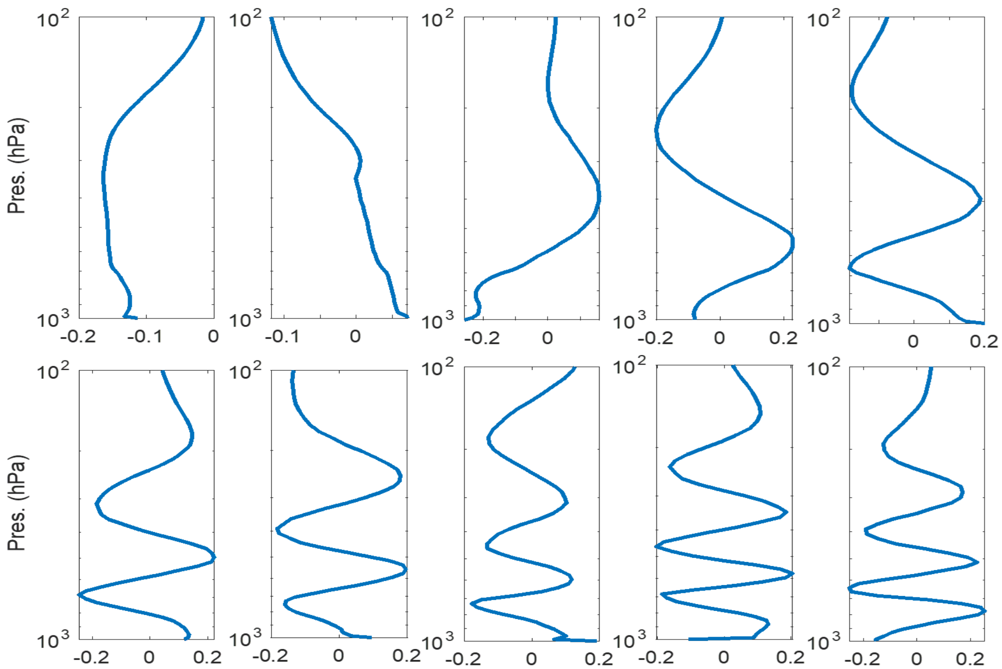


Example of ClimFiSP derived global surface temperature trend



Compression of both Hyperspectral Observations and Retrieved Parameters

Example of PCs representing H2O vertical profiles



Reducing AIRS, CrIS, and IASI dimensions

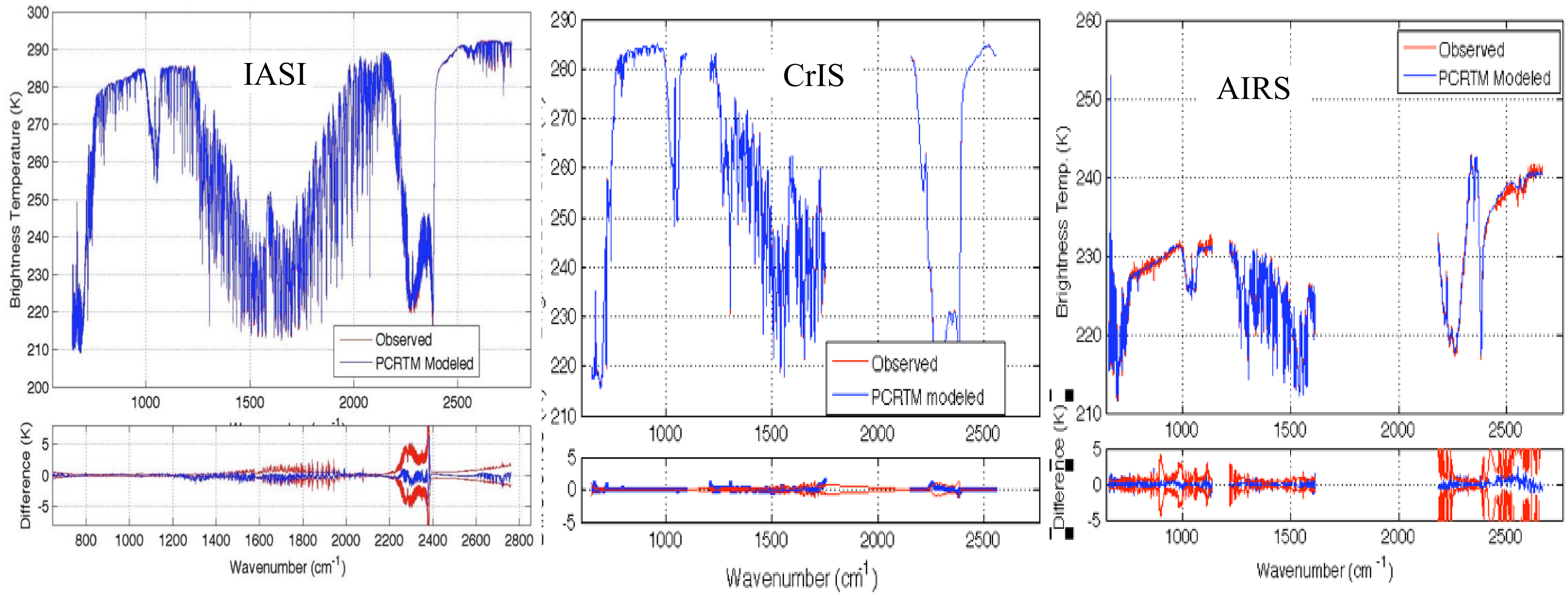
Satellite Sensors	Original Dim	PC-compressed Dim
CrIS	2211	124
AIRS	2378	120
IASI	8461	190

Reducing atmospheric temperature, water vapor, and trace gas profile dimensions and surface emissivity dimensions using PCA

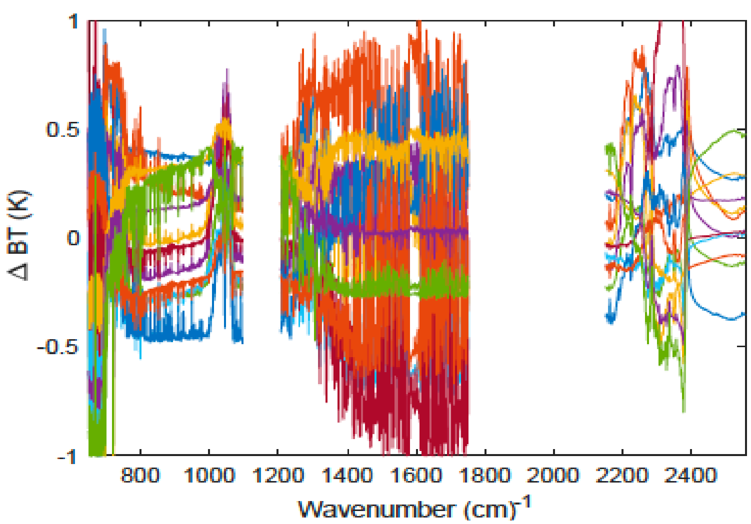
Geophysical Parameters	Original Dimension	PC-compressed Dimension
Temperature	101	20
H2O	101	15
CO2	101	1
O3	101	10
CO	101	4
CH4	101	2
N2O	101	2
IR Surface Emissivity	Hundreds - thousands	8
MW Surface Emissivity	15-22	5

Radiometric Closure for SiFSAP and ClimFISP

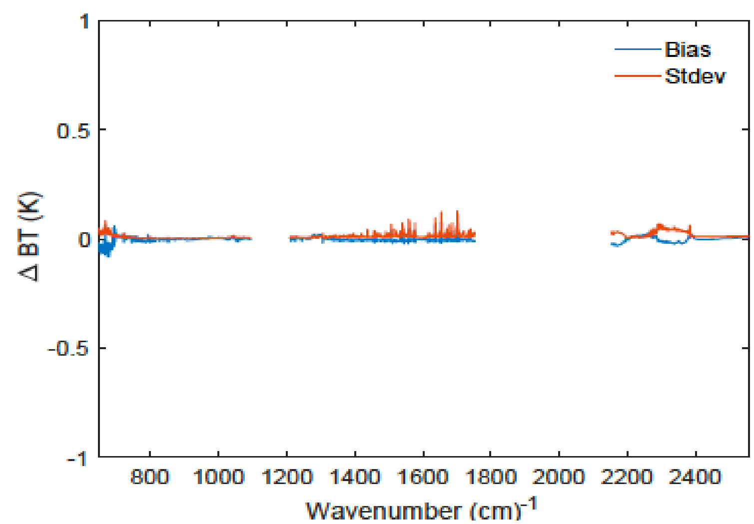
SiFSAP PCRTM modeled and observed spectra of three major hyperspectral sounders



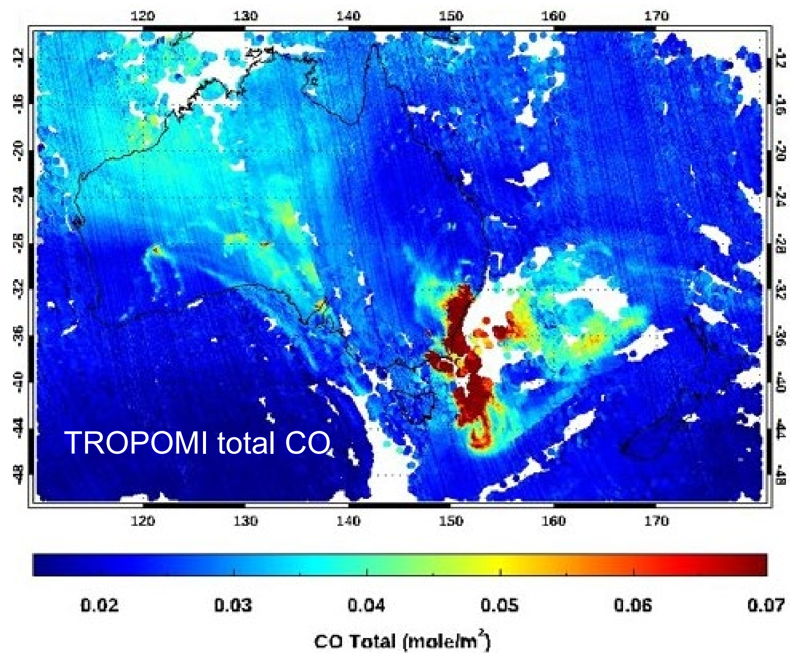
Examples of CrIS Spectral Anomaly (2016-2017)

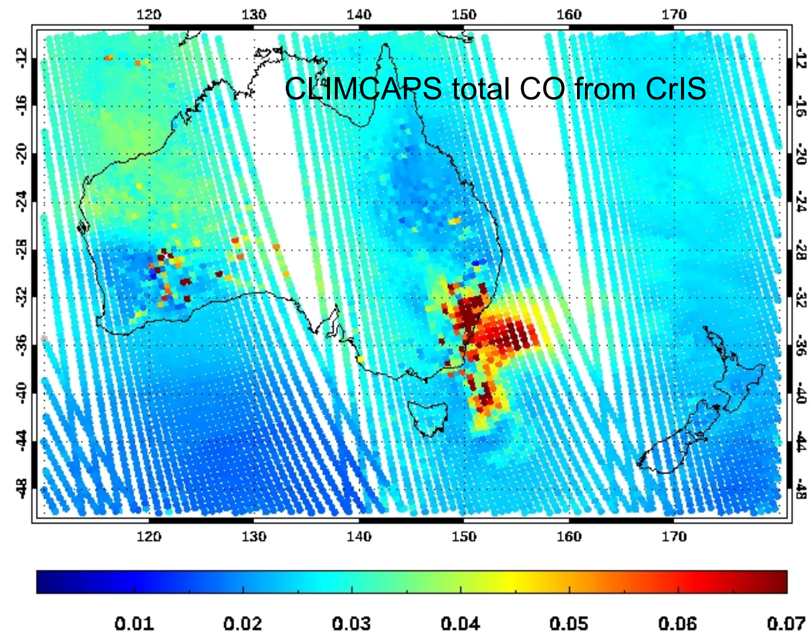


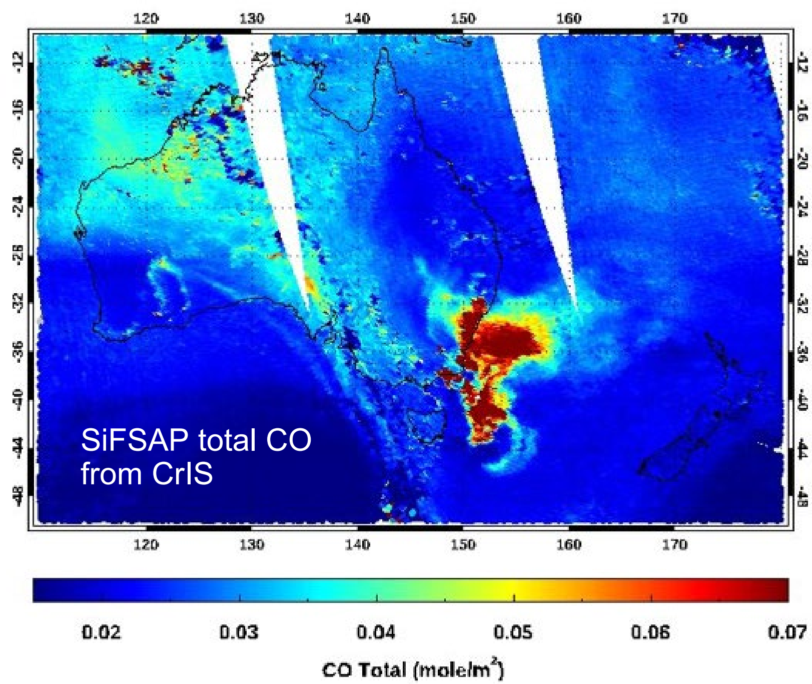
ClimFISP fiited CrIS residual spectra



High Spatial Resolution SiFSAP CO from CrIS and comparison with TROPOMI for 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

Example of 3-D Atmospheric Wind Vectors Derived from SNPP/CrIS and NOAA20/CrIS SiFSAP (Univ. Arizona)

SIFSAP (July 7, 2020)

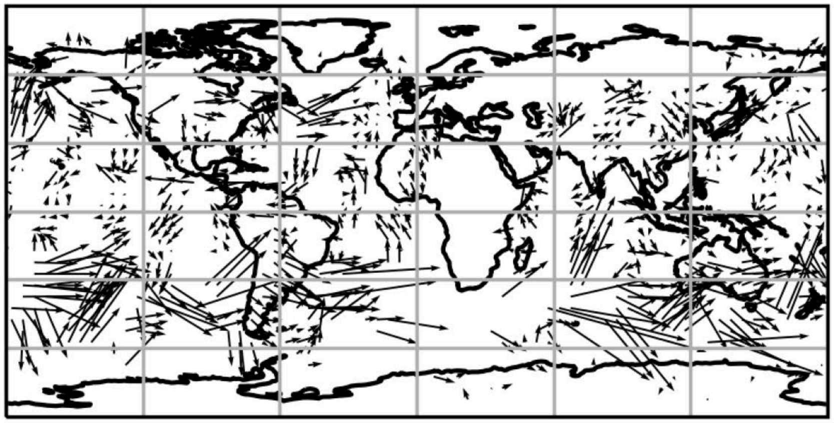
CLIMCAPS (July 7 2020)

RMSVD = 6.1 m/s 850 hPa Δs = 0.77 m/s

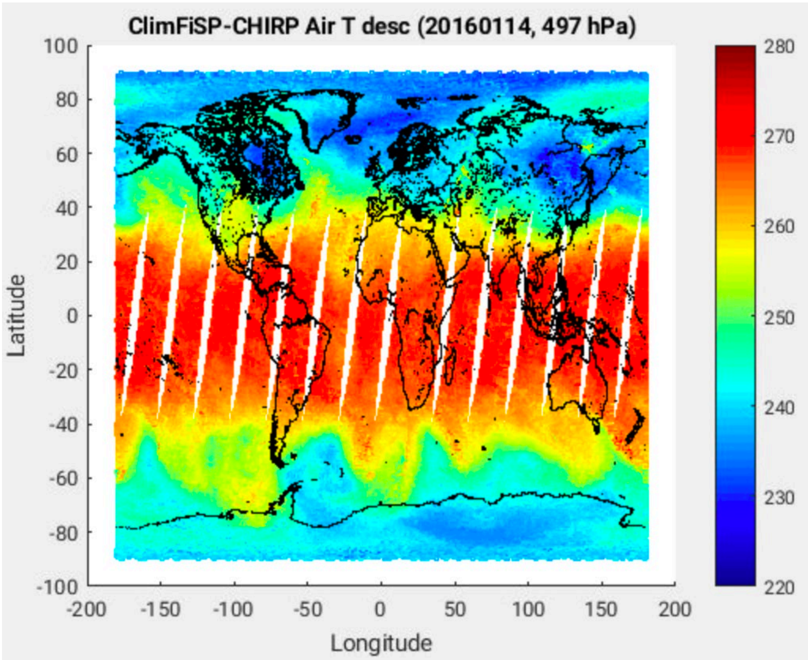
RMSVD = 5.72 m/s 850 hPa Δs = -2.18 m/s

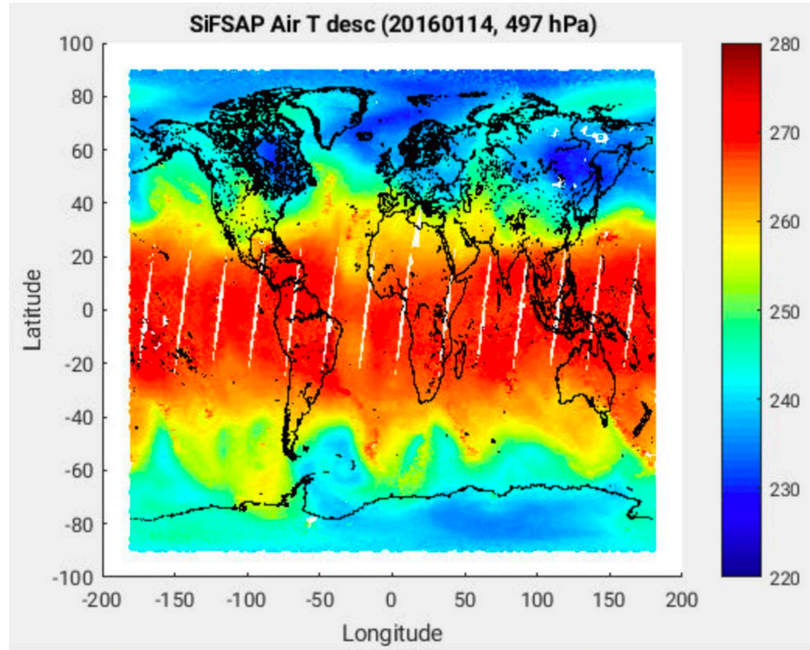
RMSVD = 5.87 m/s 500 hPa Δs = -0.91 m/s

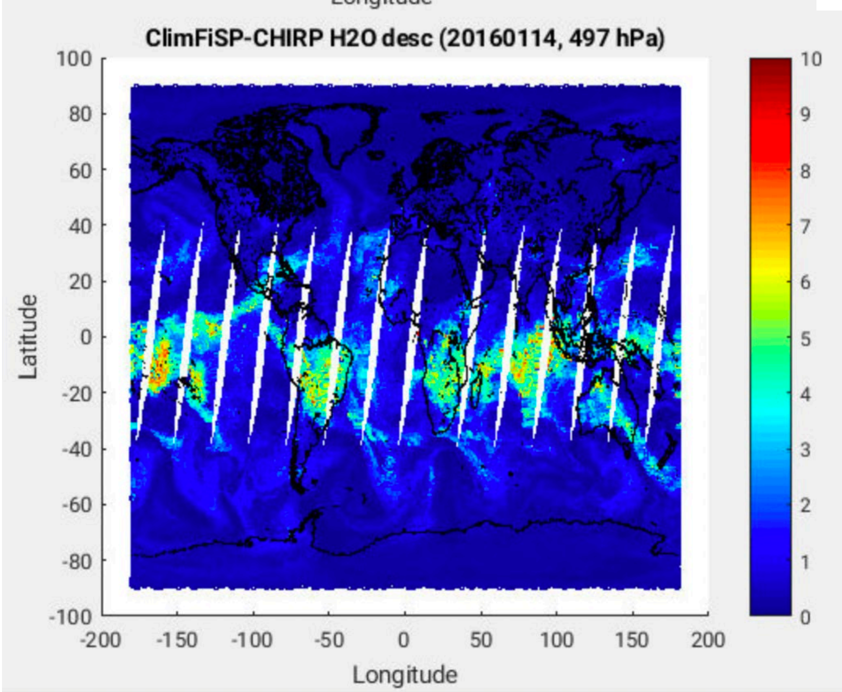
RMSVD = 5.99 m/s 500 hPa Δs = -2.09 m/s

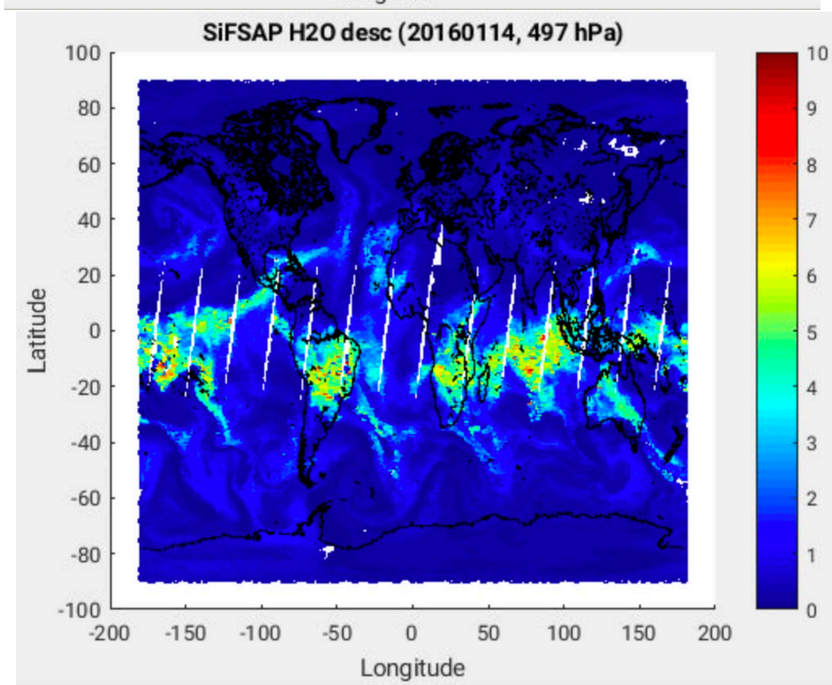


Consistent Daily Products from both SiFSAP and ClimFiSP



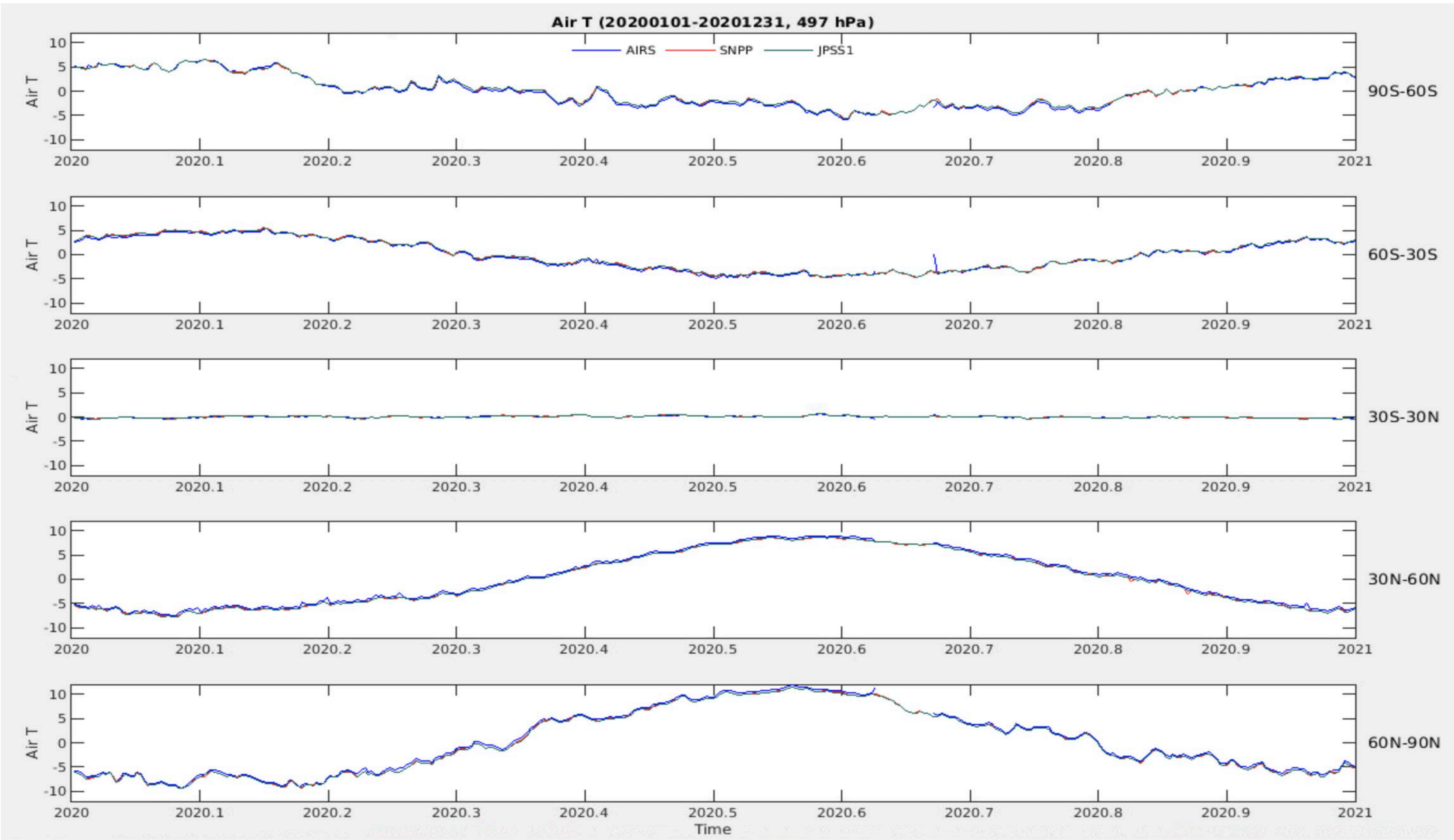






Consistent ClimFiSP Products from Aqua/AIRS, SNPP/CrIS, and NOAA20 CrIS (2020)

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

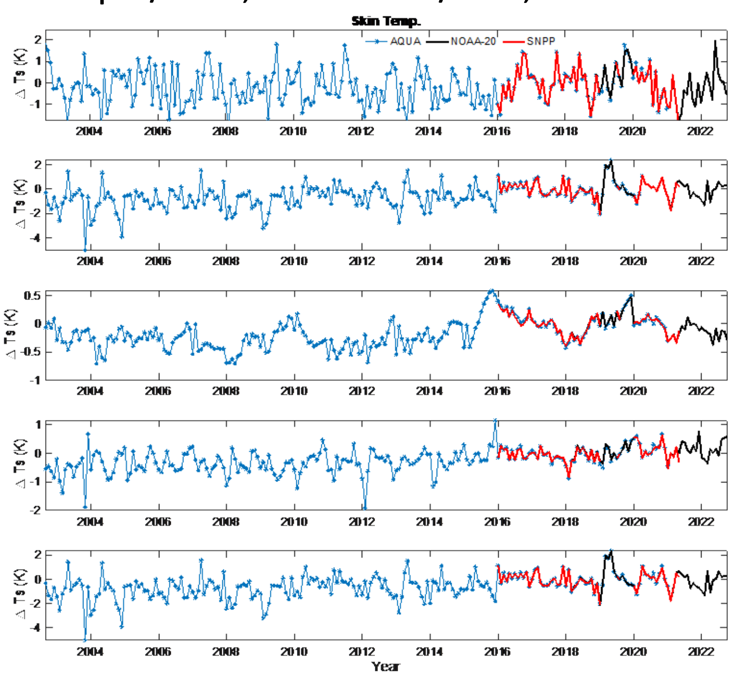


Applying the ClimFiSP Algorithm to CHIRP

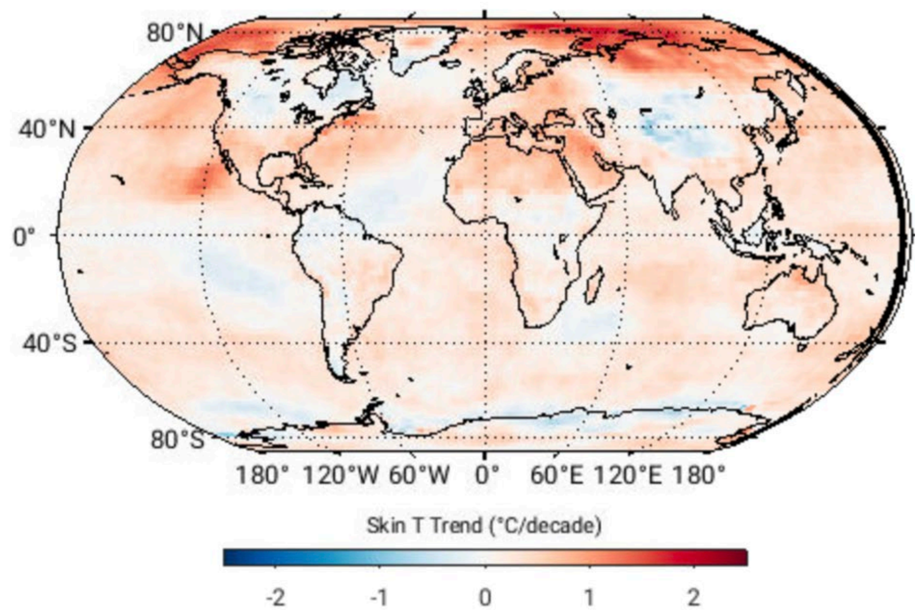
- CHIRP - Climate Hyperspectral Infrared Radiance Product
  - Bias-corrected radiance (L1) time series for Aqua/AIRS, SNPP/CrIS, and NOAA20/CrIS
  - Generated by Larrabee Strow et al (2021)
  - Available at NASA Sounder SIPS and DACC

- We have applied the ClimFiSP algorithm to CHIRP data from 2003-2022
  - Obtained climate time series for:
    - 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

Example of ClimFiSP derived global surface temperature time series for different latitude bins
Blue:Aqua/AIRS, Red: SNPP/CrIS, Black: NOAA20/CrIS

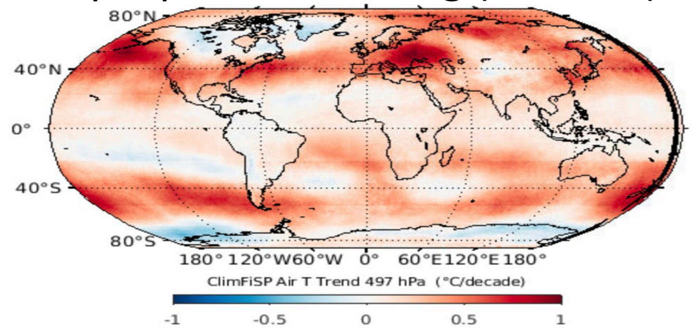


Example of ClimFiSP derived global surface temperature trend from 20 years of sounder data

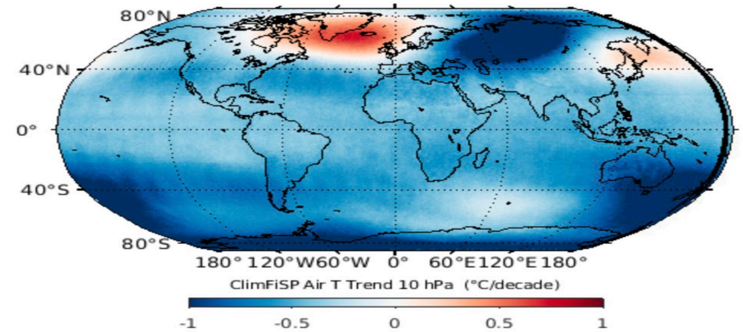


20-year Climate Trends from ClimFiSP

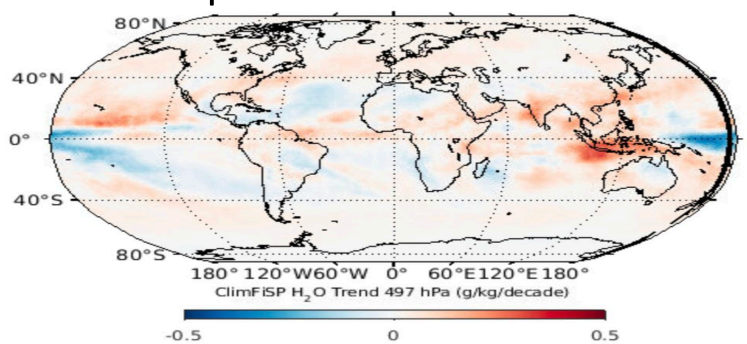
Tropospheric warming (500 hPa)



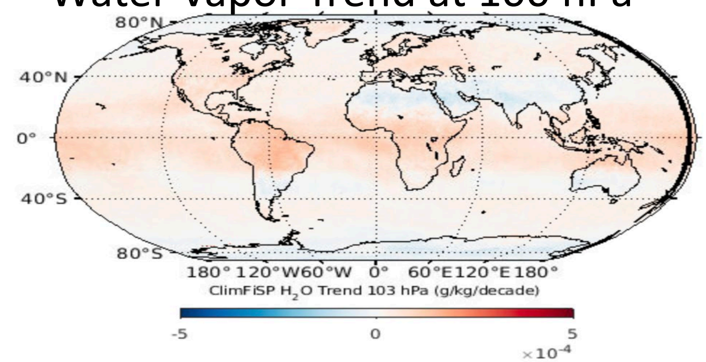
Stratospheric cooling (10 hPa)



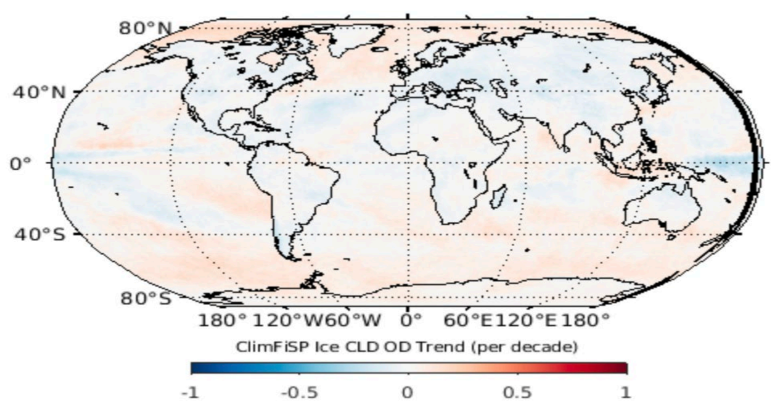
Water Vapor Trend at 500 hPa



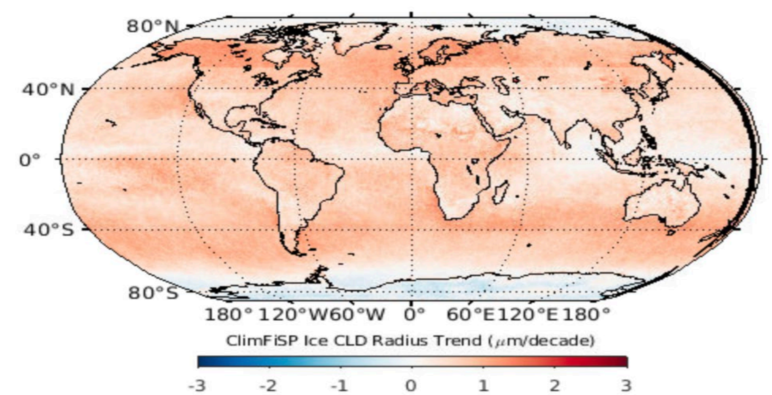
Water Vapor Trend at 100 hPa

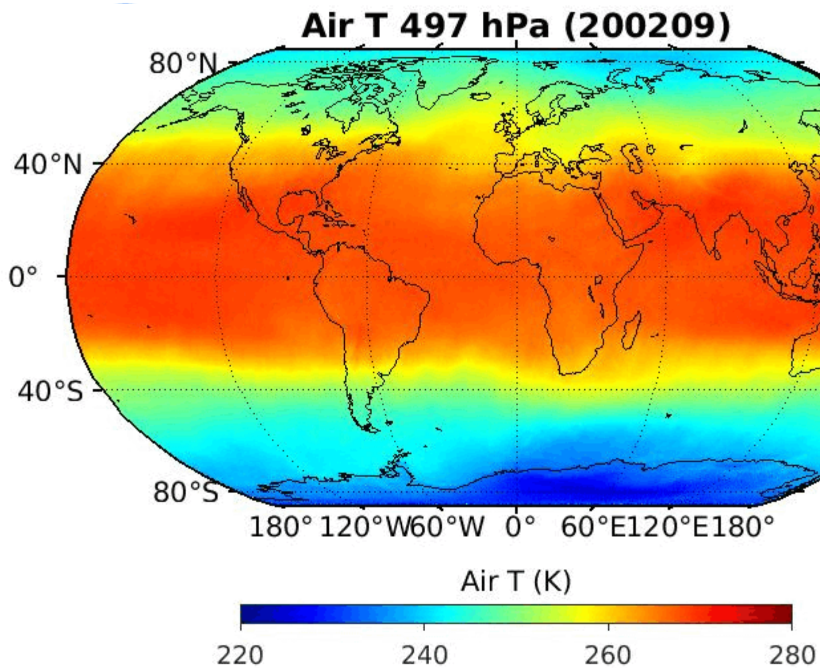


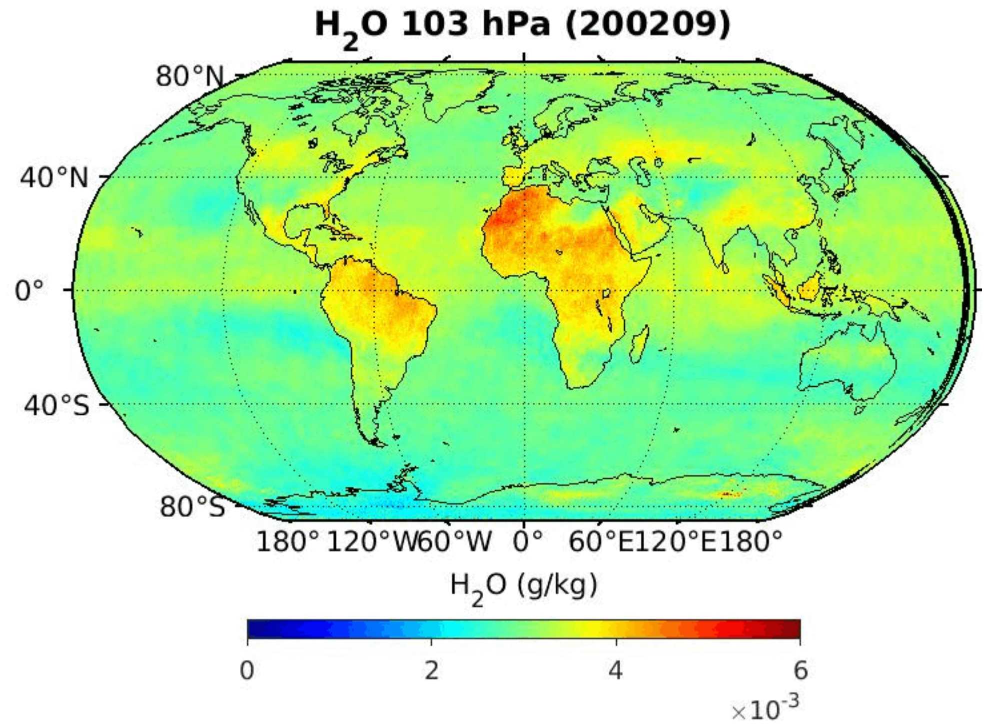
ClimFiSP Ice Cloud Optical Depth Trend

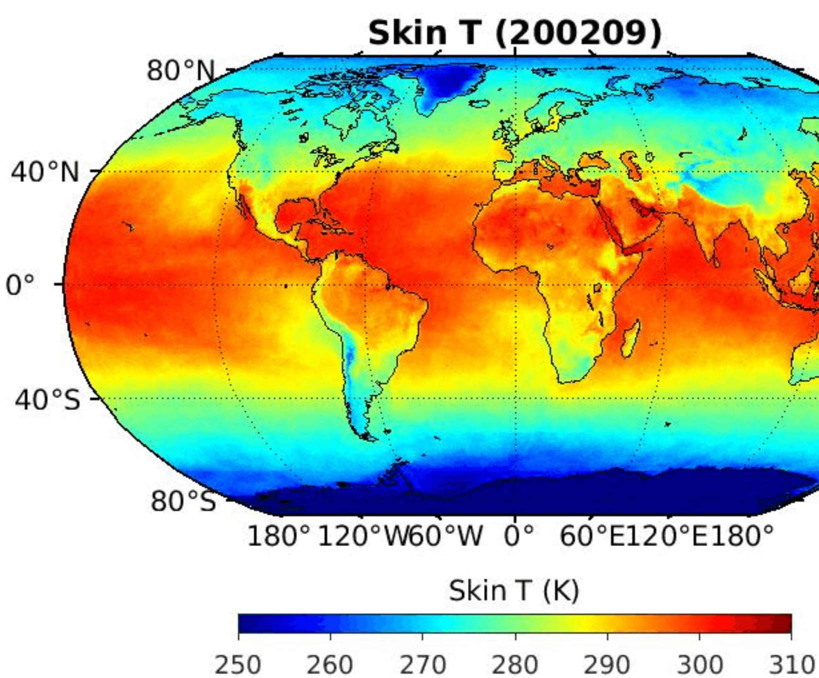


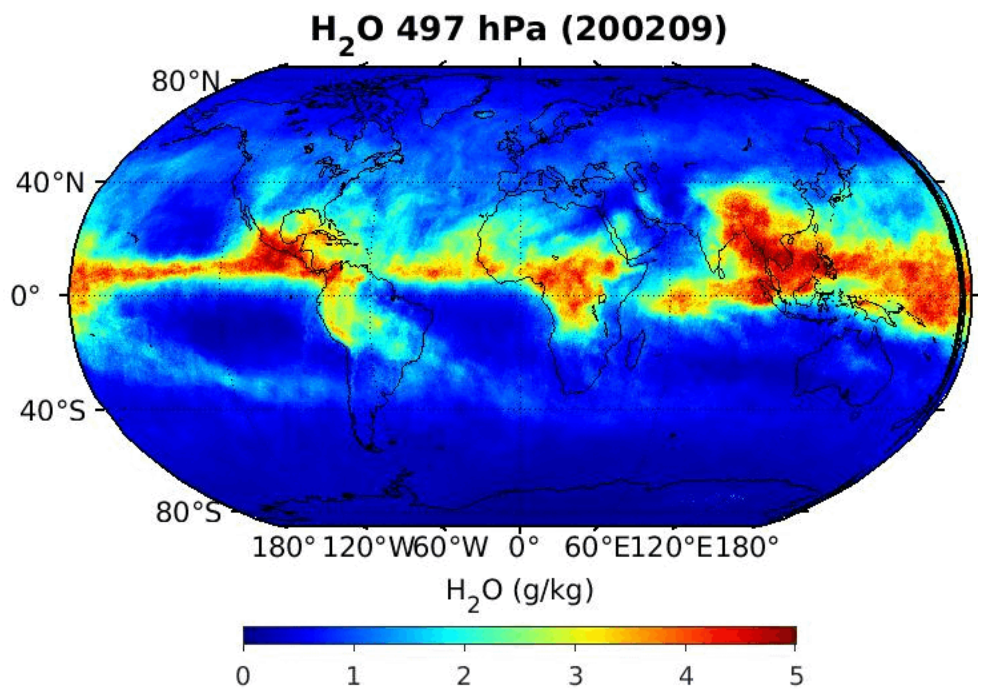
ClimFiSP Ice Cloud Effective Radius



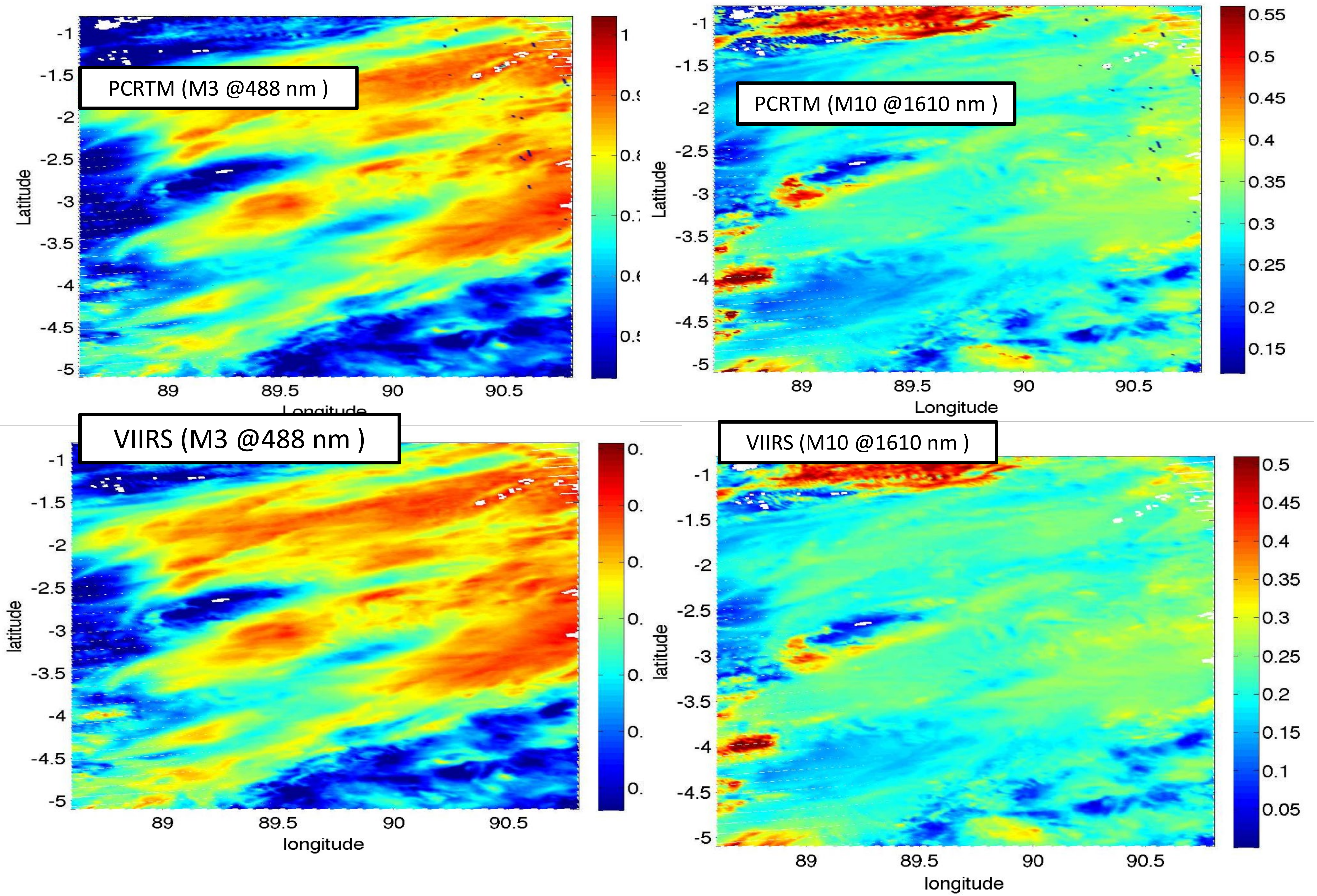

Air T 497 hPa (200209)
80°N
40°N
0°
40°S
80°S
180° 120°W60°W 0° 60°E120°E180°
Air T (K)
220
240
260
280


H_2O 103 hPa (200209)
80°N
40°N
0°
40°S
80°S
180° 120°W60°W 0° 60°E120°E180°
H_2O (g/kg)
0
2
4
6
$\times 10^{-3}$

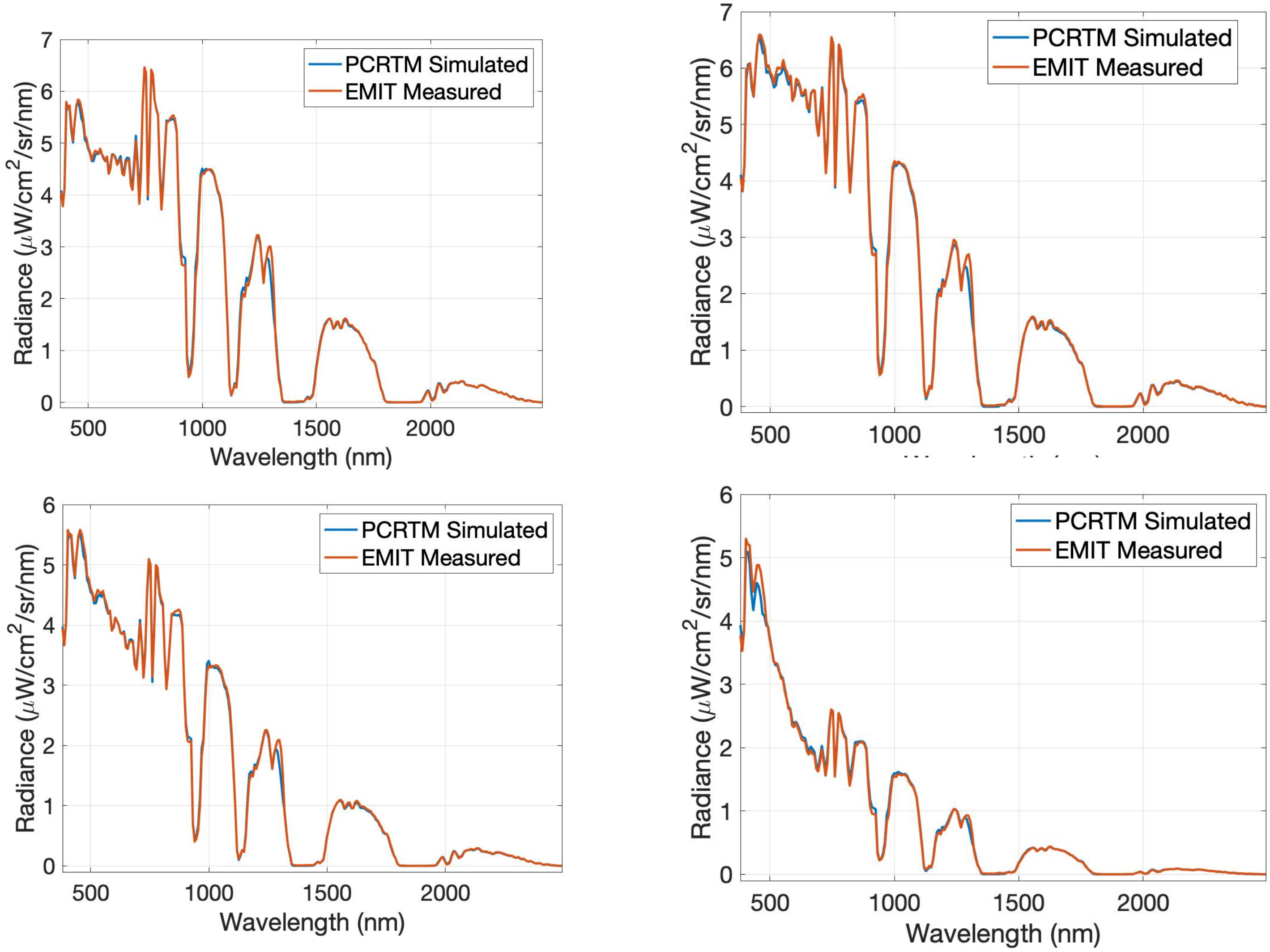

Skin T (200209)
80°N
40°N
0°
40°S
80°S
180° 120°W60°W 0° 60°E120°E180°
Skin T (K)
250
260
270
280
290
300
310


H_2O 497 hPa (200209)
80°N
40°N
0°
40°S
80°S
180° 120°W60°W 0° 60°E120°E180°
H_2O (g/kg)
0
1
2
3
4
5

High Fidelity CPF Simulator Validated Using VIIRS Observations

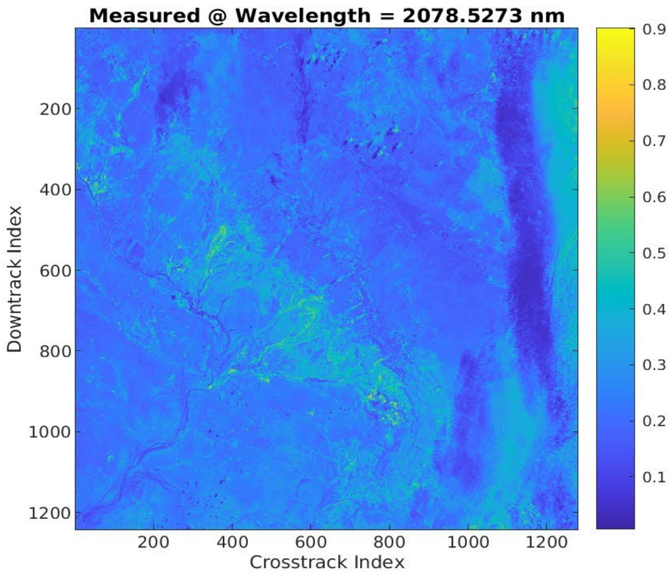


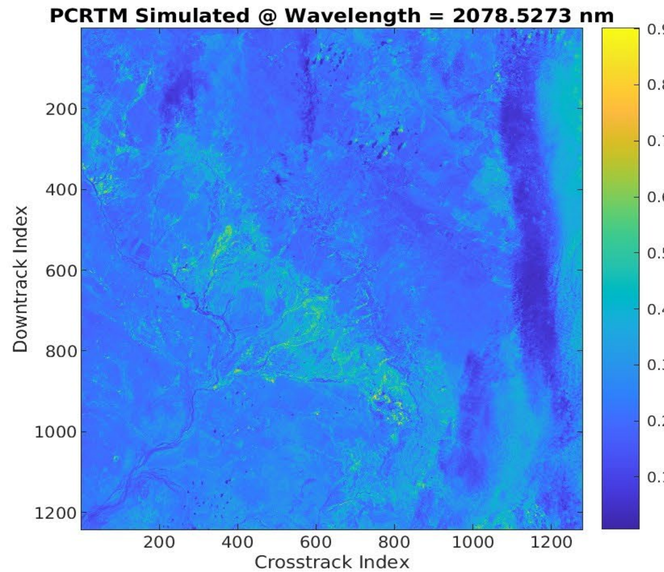
Examples of PCRTM simulated and EMIT observed spectra



PCRTM simulated spectra agree all well with EMIT observation at different wavelengths and 1.6 million pixels

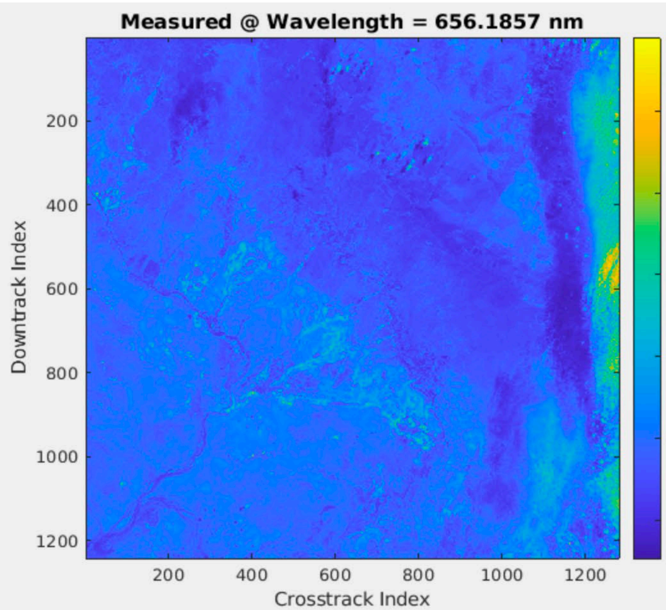
EMIT observed radiance at 2078.5 nm

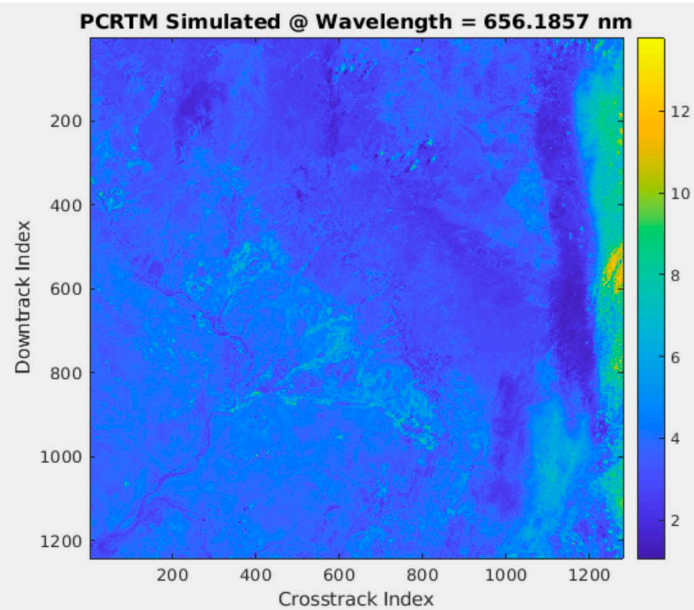




PCRTM simulated radiance at 2078.5 nm using EM L2 product as input

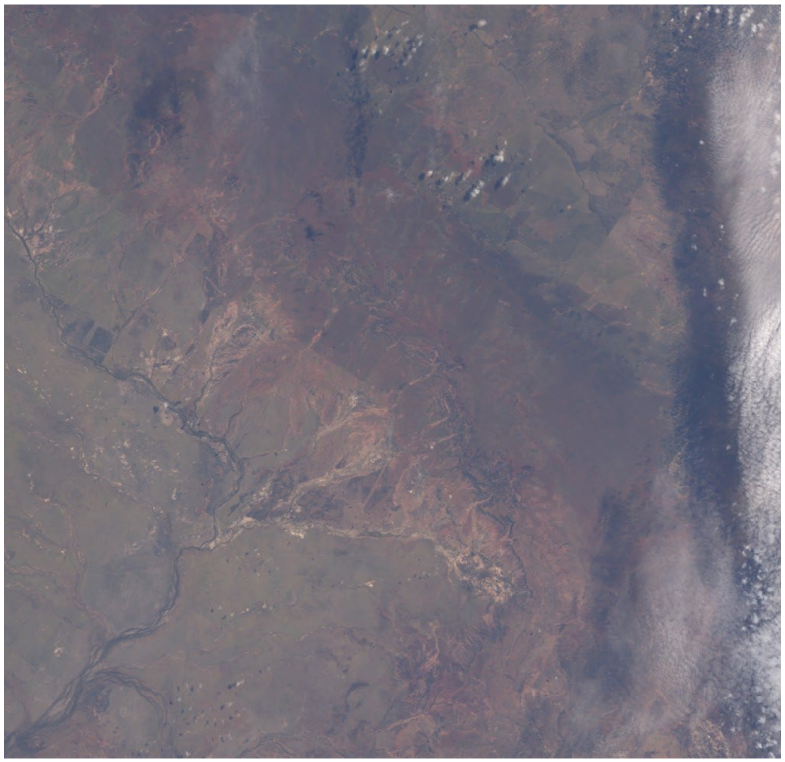
EMIT observed radiance at 656.2 nm



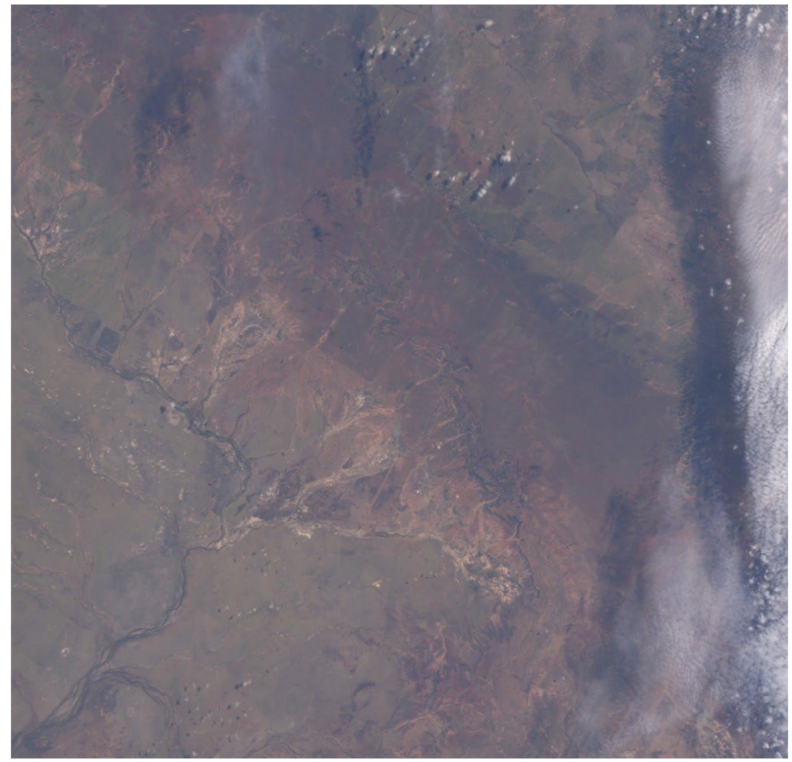


PCRTM simulated radiance at 656.2 nm using EM L2 product as input

PCRTM Simulated RGB image and spectra agree well with EMIT L1 observations (indicating high EMIT L2 product quality)

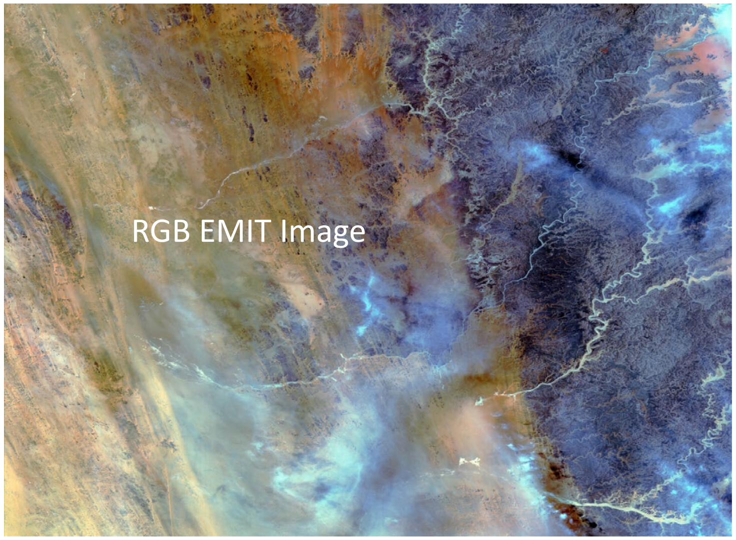


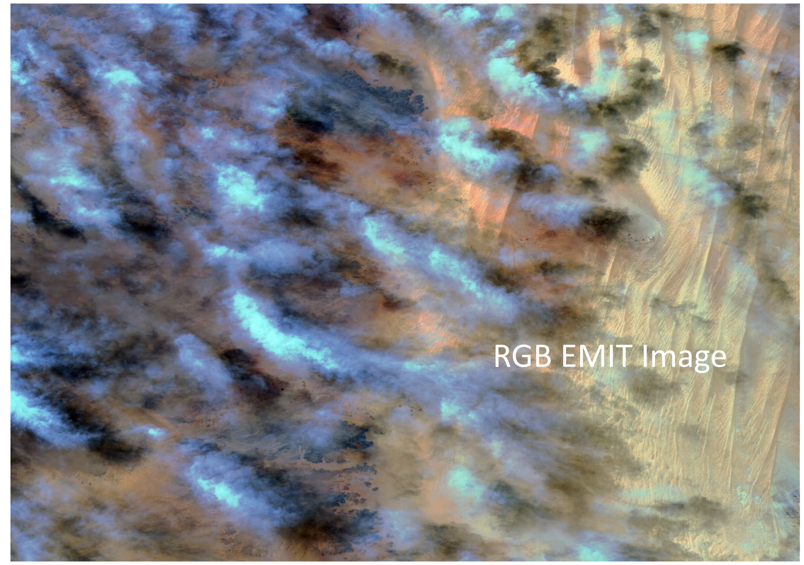
EMIT RBG Image

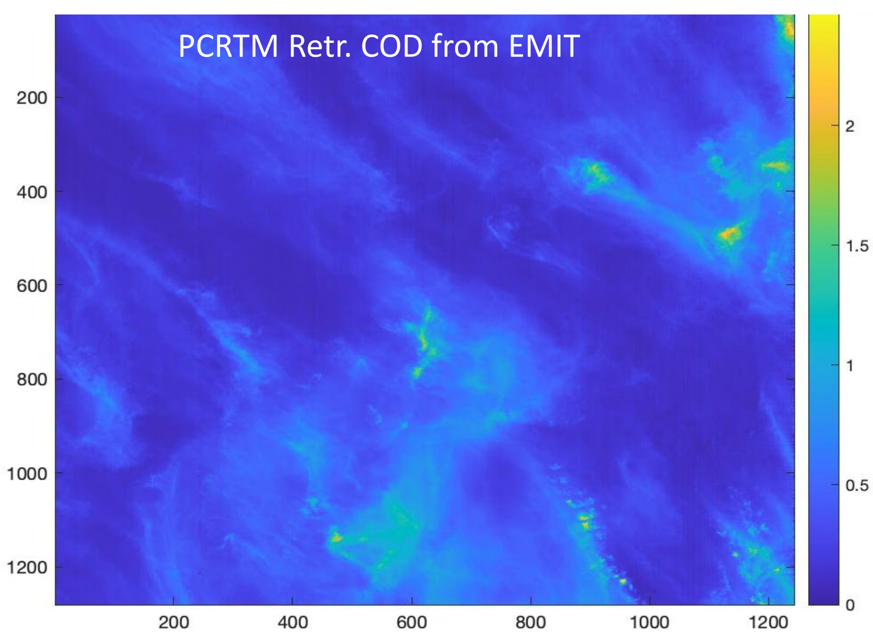


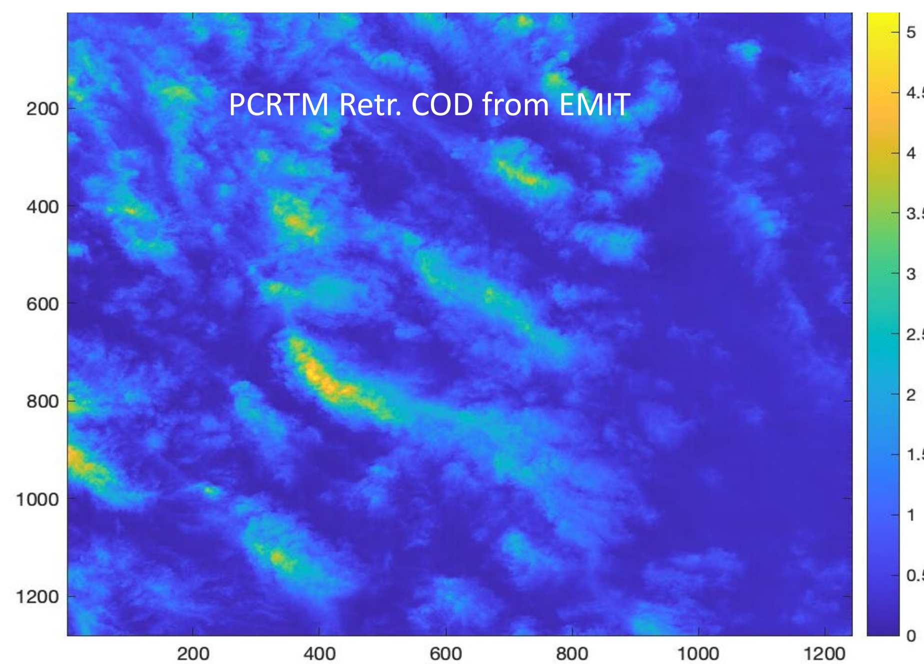
PCRTM Calculated EMIT RBG Image

PCRTM generated data are used to train an AI Cloud Retrieval algorithm for EMIT and applied successfully using EMIT data









Summary and Conclusions

- PCRTM is ideal for dealing with hyperspectral satellite remote sensors
- Both SiFSAP and ClimFiSP produce 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
  - 9-times area spatial resolution relative to current cloud-clearing products
  - Radiometric closure condition met
- ClimFiSP (L3) is in the process of being transitioned to NASA GES DICS
  - 20 years of Climate Data Records from Aqua/AIRS, SNPP/CrIS, and NOAA20/CrIS
- WPCRTM has a wide range of applications such as high fidelity satellite sensor simulator, forward model for atmospheric correction, AI-based algorithm etc.