A Spectral Fingerprinting Method for Deriving Consistent Climate Data Records from Multiple Satellite IR Sounders

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Outline

- Why choose climate spectral fingerprinting method for process multiple satellite data?

- Key Components of the spectral fingerprinting method
  - PCRTM (Principal Component-based Radiative Transfer Model)
  - SiFSAP (Single Field-of-view Sounder Atmospheric Product) algorithm
  - ClimFiSP (Climate Fingerprinting Sounding Product) algorithm

- Summary Conclusions

Overview of different retrieval algorithms for inverting hyperspectral IR sounder data (1)

- Iterative physical retrieval algorithms based on fitting "cloud-cleared" radiance
  - Only clear sky radiative transfer model (RTM) needed
  - Uses Cloud-Clearing (CC) method to remove the cloud spectral features from the radiance spectra
    - Needs good a priori
    - Scarifies spatial resolution
    - Radiometric closure with CC radiance
  - Examples of CC algorithms
    - NUCAPS (NOAA Unique Combined Atmospheric Processing System)
    - CLIMCAPS (Community Long-Term Infrared Microwave Combined Atmospheric Product System)
    - AIRS V7 (AIRS V7 Level-2 algorithm)
- Iterative physical retrieval algorithm based on fitting all-sky radiance
  - All-sky RTM needed
  - 9-times higher area spatial resolution relative to CC method
  - Radiometric closure with all-sky observed radiances
  - Examples of cloudy algorithms
    - SiFSAP ((Single Field-of-view Sounder Atmospheric Product): fit all spectral channels
    - JOSFRA (Joint Single Footprint Retrieval Algorithm): fit selected channels

Overview of different retrieval algorithms for inverting hyperspectral IR sounder data (2)

- Statistical based retrieval algorithm based on all-sky radiances
  - ➢ Much faster than iterative physical retrieval algorithms
  - ➢ Using stratification/classification/AI to reduce non-linearity
  - ➢ PCA is used for dimension reduction
  - ➢ Performance highly depends on the quality of training data
  - ➢ No radiometric closure to the observed radiances
  - ➢ Trained based on RTM simulated radiance
    - o Bill Smith and UW dual-regression algorithm with PCRTM-based de-aliasing
  - ➢ Trained using collocated ECMWF T/Q/O3:
    - o IASI operational Level-2 retrieval algorithm: PWLR (Piece-Wise Linear Regression)
    - o MIT Lincoln Laboratory Stochastic Cloud Clearing/Neural Network algorithm (SCCNN)
- Spectral fingerprinting method based physical retrieval algorithm (*new!*)
  - ➢ As fast as statistical retrieval algorithm
  - ➢ Accurate retrieval with performance equivalent to a physical algorithm
  - ➢ Radiometric closure with the observed all-sky radiance
  - ➢ ClimFiSP (Climate Fingerprinting Sounder Product)
    - o Machine-learning linear inversion based on SiFSAP physical retrievals
    - o Consistent radiative kernels used for different satellite sensors
    - o Can generate products using single-FOV or spatial-temporally averaged radiances
    - o Suitable for real-time and long-term climate applications

Key Components of the Spectral Fingerprinting Method: PCRTM

- PCRTM radiative transfer model
  - ➢ Compress thousands of channels into hundreds of Principal Components (PCs)
  - ➢ *Super fast*: 4 orders of magnitude faster than LBL RTMs (5-14 millisecond in IR)
  - ➢ *Very accurate*: 0.03 K RMS error in IR, 0.05% in solar
  - ➢ *Physical-based RTM:* RT calculations done monochromatic and rigorously
  - ➢ Performs multiple scattering calculations of clouds and aerosols
  - ➢ Developed for numerous airborne and satellite remote sensors (NAST-I, AIRS, CrIS, IASI, SHIS, CLARREO, PREFIRE, FORUM, CPF, HYSICS, SCHIAMCHY, OMI/TEMPO, EMIT, SBG …)

Radiometric Closure for SiFSAP and ClimFISP

SiFSAP PCRTM modeled and observed spectra of three major hyperspectral sounders
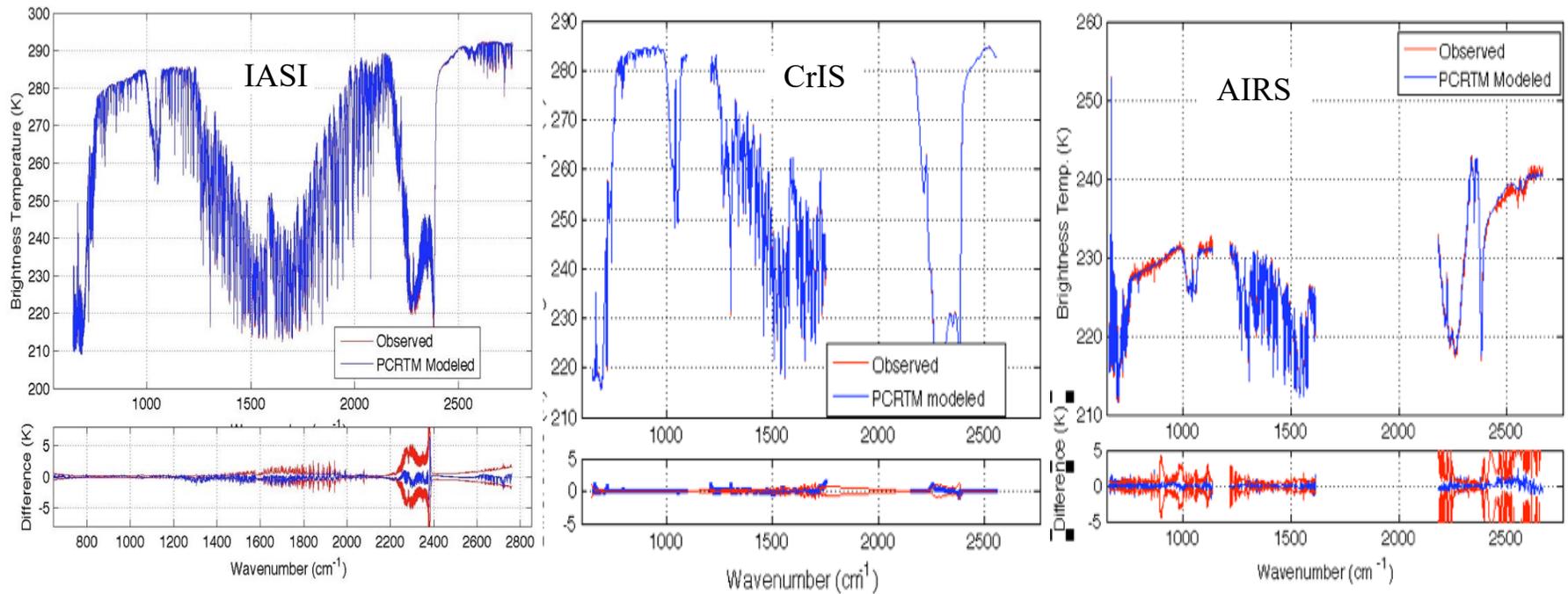
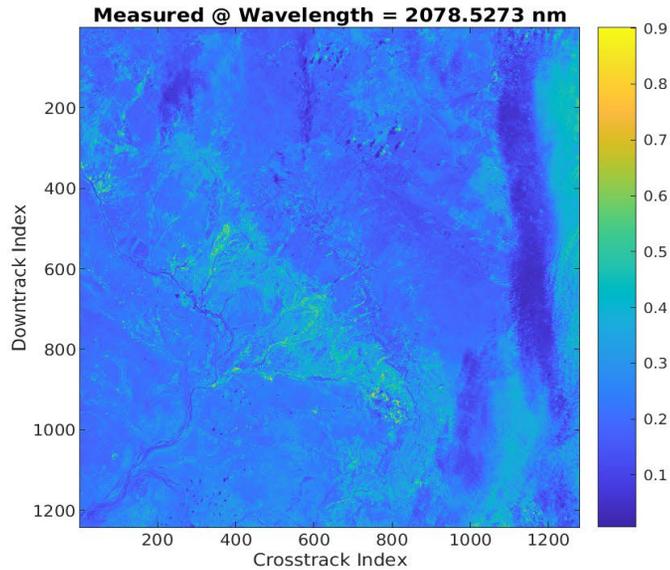Examples of CrIS Spectral Anomaly (2016-2017)
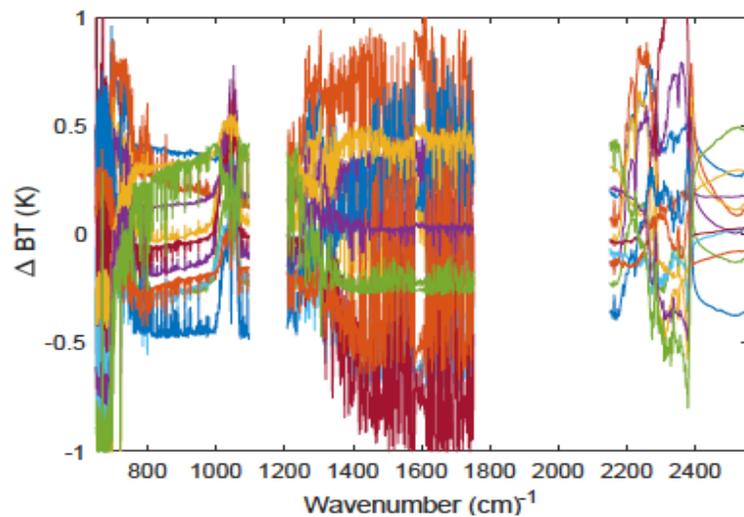
ClimFISP fiited CrIS residual spectra
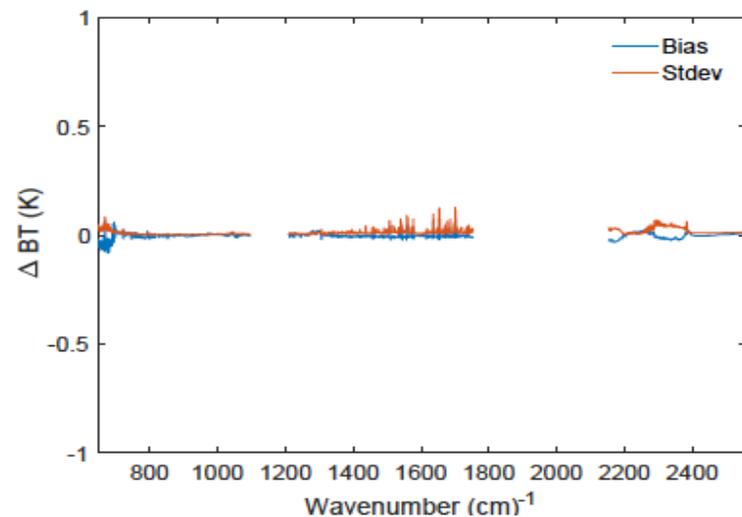
PCRTM simulated spectra agree all well with EMIT observation with 1.6 million pixels in solar spectral region
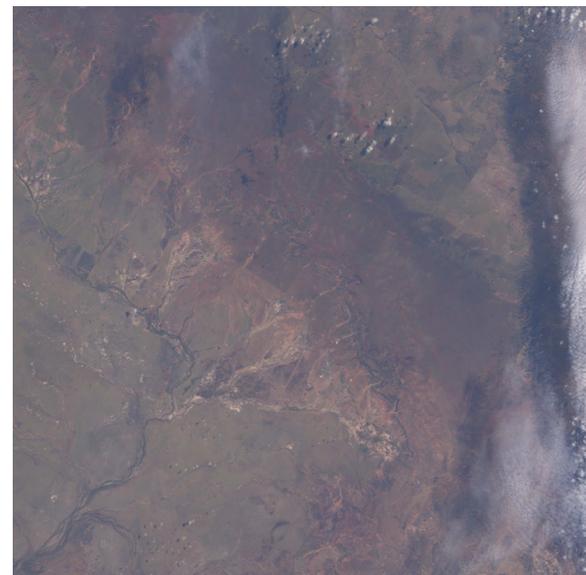
EMIT observed radiance at 2078.5 nm
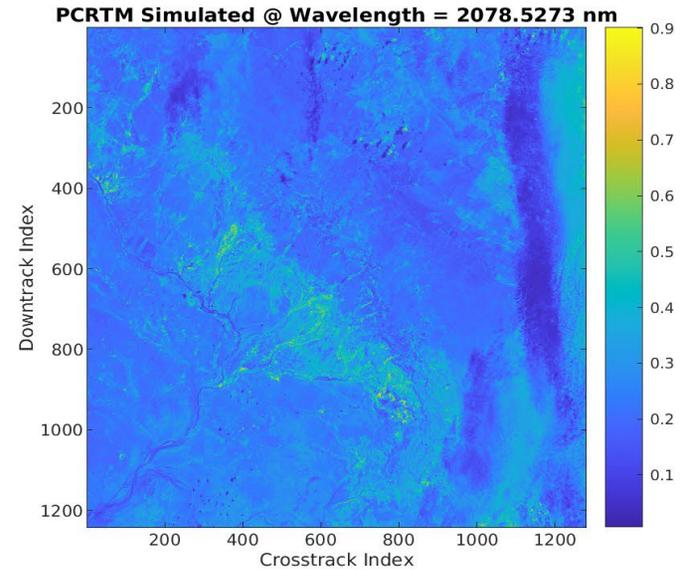
PCRTM simulated radiance at 2078.5 nm using EM L2 product as input

EMIT observed RGB image

PCRTM simulated RGB image

Key Components of the Spectral Fingerprinting Method: SiFSAP

- Key features of the SiFSAP optimal estimation algorithm
  - Combined IR/MW retrieval algorithm
  - Fast and accurate PCRTM forward model
  - Uses climatology without the need of NWP as a priori
  - All spectral channels used
  - Fits all-sky clear and cloudy radiance directly
  - All parameters that affect the TOA radiance spectrum are retrieved simultaneously
- List of SiFSAP (hundreds of atmospheric products)
  - T, H_2O, O_3, CO, and other trace gas vertical profiles at 98 pressure levels
  - Cloud phase, size, optical depth, effective emissivity, cloud fraction, height/temperature
  - Surface emissivity spectrum for each FOV at a few hundres wavelengths
  - Surface air and skin temperature for both ocean and land
  - Averaging kernels, DOF, retrieval errors from the OE retrievals
  - Derived quantities such as PBL height, tropopause height etc.
- SiFSAP is supported by the NASA NNH17ZDA001N-TASNPP, NNH20ZDA001N-SNPPSP, and NNH22ZDA001N-MEASURES
  - Science Code and algorithm have been ported to NASA Sounder SIPS
  - SNPP ATMS/CrIS product available at NASA GES DISC since 2023
  - https://sounder.gesdisc.eosdis.nasa.gov/data/SiFSAP/SNDRSNIML2SFSPSUP.2/
- References Liu et al. 2006, 2009, Wan et al. 2020, 2023, Xiong et al. 2022, 2023

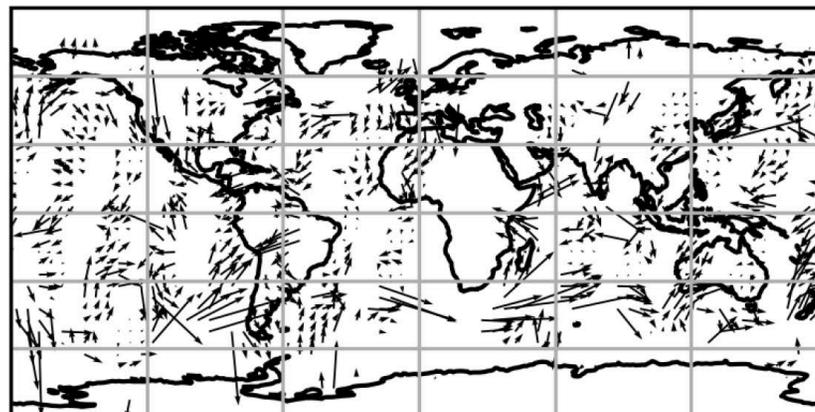# Higher Spatial Resolution SiFSAP (from SNPP and NOAA20) Products Help 3D Wind (Univ. Arizona)

SIFSAP (July 7, 2020)

RMSVD = 6.1 m/s   850 hPa   Δs = 0.77 m/s
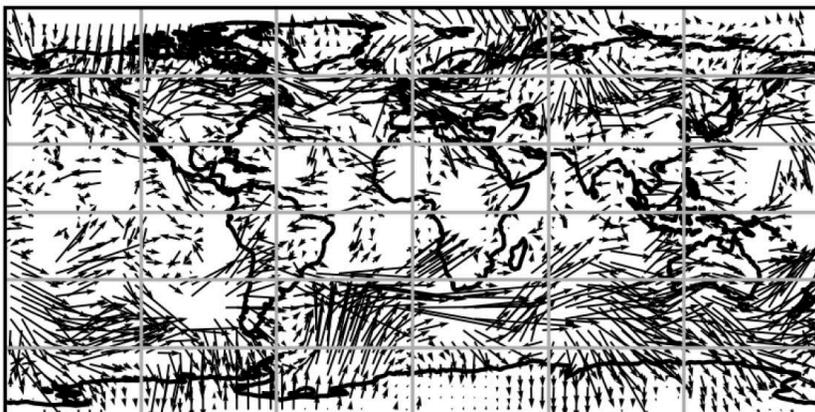
RMSVD = 5.87 m/s   500 hPa   Δs = -0.91 m/s
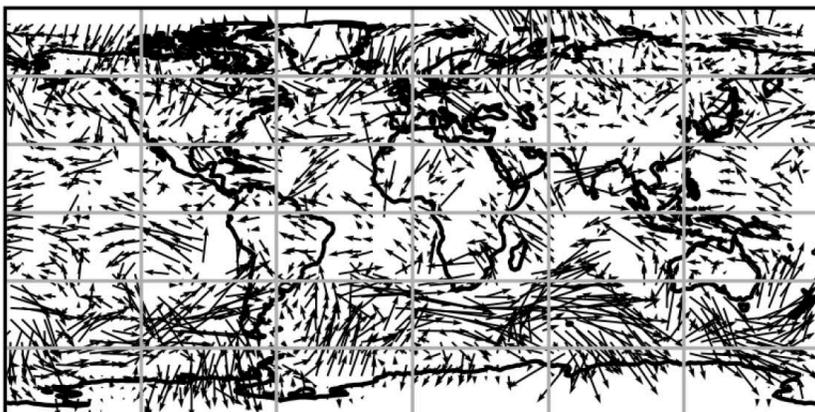
CLIMCAPS (July 7 2020)
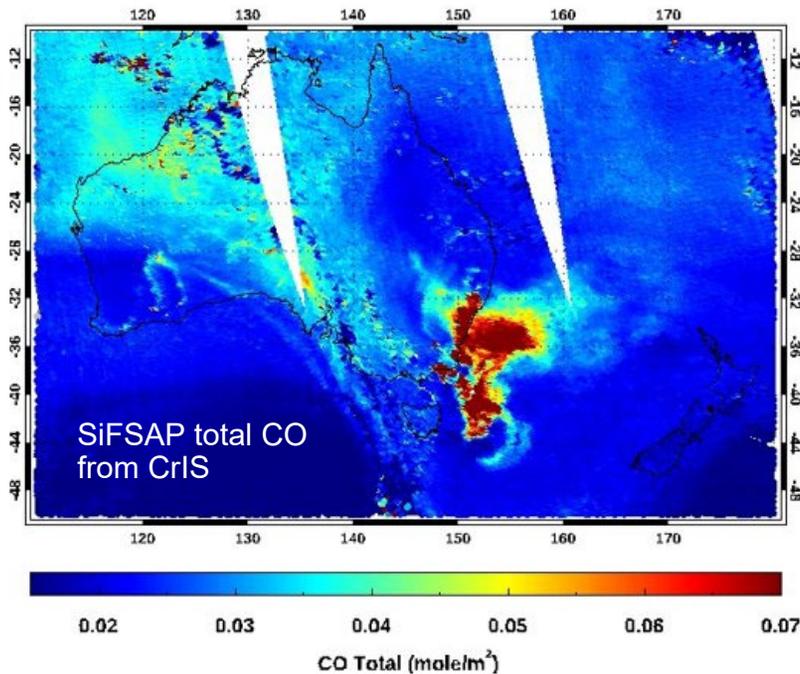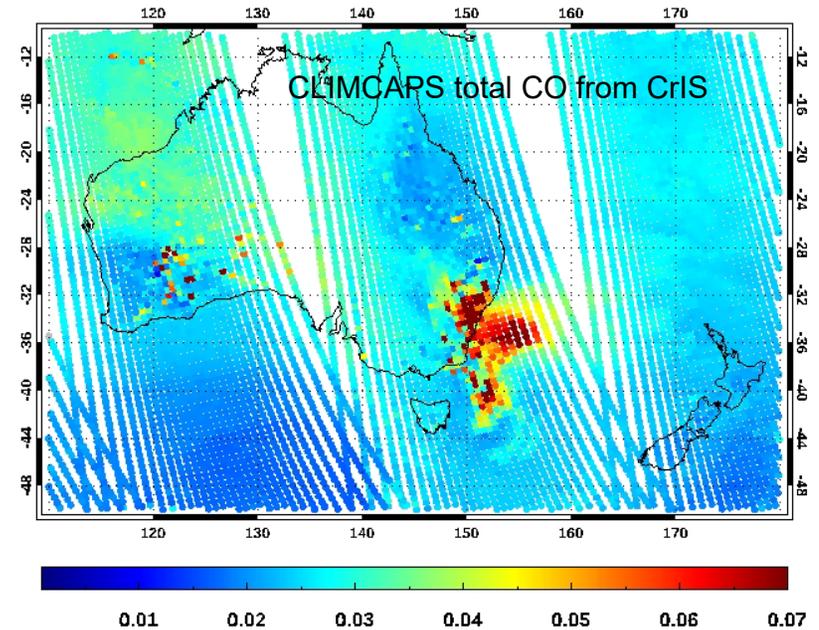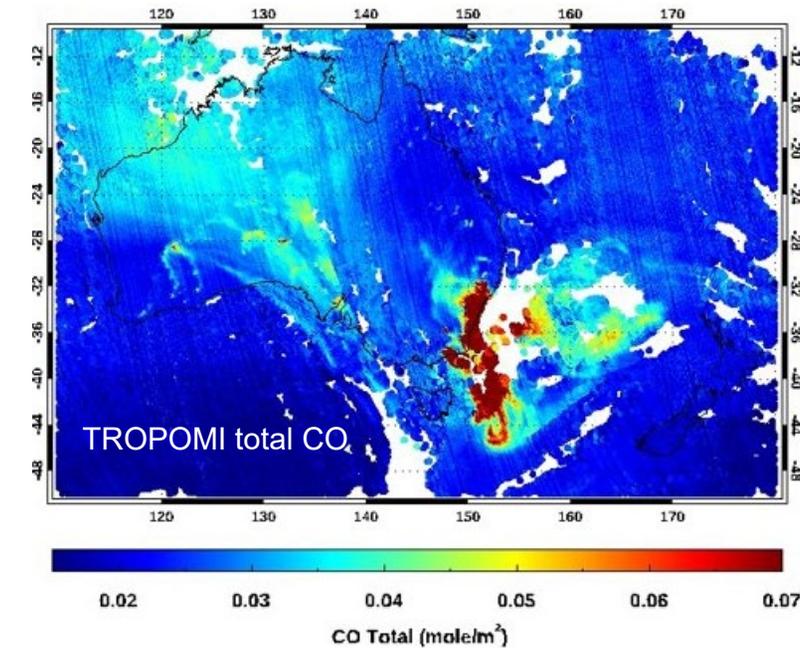
RMSVD = 5.72 m/s   850 hPa   Δs = -2.18 m/s

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

High Spatial Resolution SiFSAP CO from CrIS Captures Fine Plume Features 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

Key Components of the Spectral Fingerprinting Method: ClimFiSP

- Key Features of ClimFiSP L1/L3 algorithm
  - ➢ Performs retrievals on gridded L1 data directly
  - ➢ 3-4 orders of magnitude faster than L1-L2-L3 approach
  - ➢ Uses consistent radiative kernels for all IR sounders
  - ➢ Fits all-sky cloudy radiance spectra directly to ensure radiometric closure
  - ➢ All sounder spectral channels (thousands) are used in ClimFiSP L3 algorithm

- Retrieved atmospheric and surface properties are compressed into PC-domain
  - ➢ Reduce the ill-condition of the inversion
  - ➢ Efficiently keep error covariance and averaging kernels into smaller dimension

$$\Delta x = (\mathbf{K}^T \Sigma^{-1} \mathbf{K} + S_a^{-1})^{-1} \mathbf{K}^T \Sigma^{-1} \Delta r$$

- A machine-learning method is used to match radiance spectra to appropriate reference states with radiative kernels, reference states (r and x) and associated errors covariance matrices derived from SiFSAP
  - ➢ ClimFiSP products come with OE error estimations
  - ➢ Approaching the performance of SiFSAP with much faster speed
  - ➢ Can work on single FOV or spatiotemporally average radiance spectra

- CimFiSP supported by the NASA NNH17ZDA001N-TASNPP, NNH20ZDA001N-SNPPSP, and NNH22ZDA001N-MEASURES
  - ➢ Science Code and algorithm have been ported to NASA Sounder SIPS
  - ➢ Product should be available at NASA GES DISC before the end of 2024
  - ➢ Product list is the same as SiFSAP

- References
  - Liu et al. 2017, Wu et al 2020, 2024

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

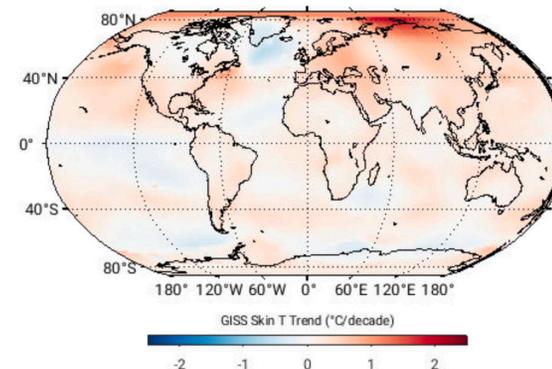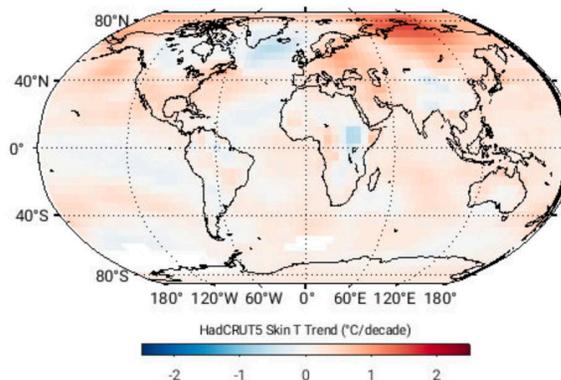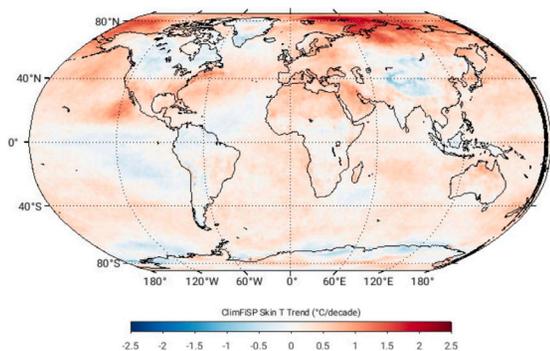500 hPa Temperature from Aqua/AIRS (Blue) SNPP/CrIS (Red), and NOAA20/CrIS (Green)
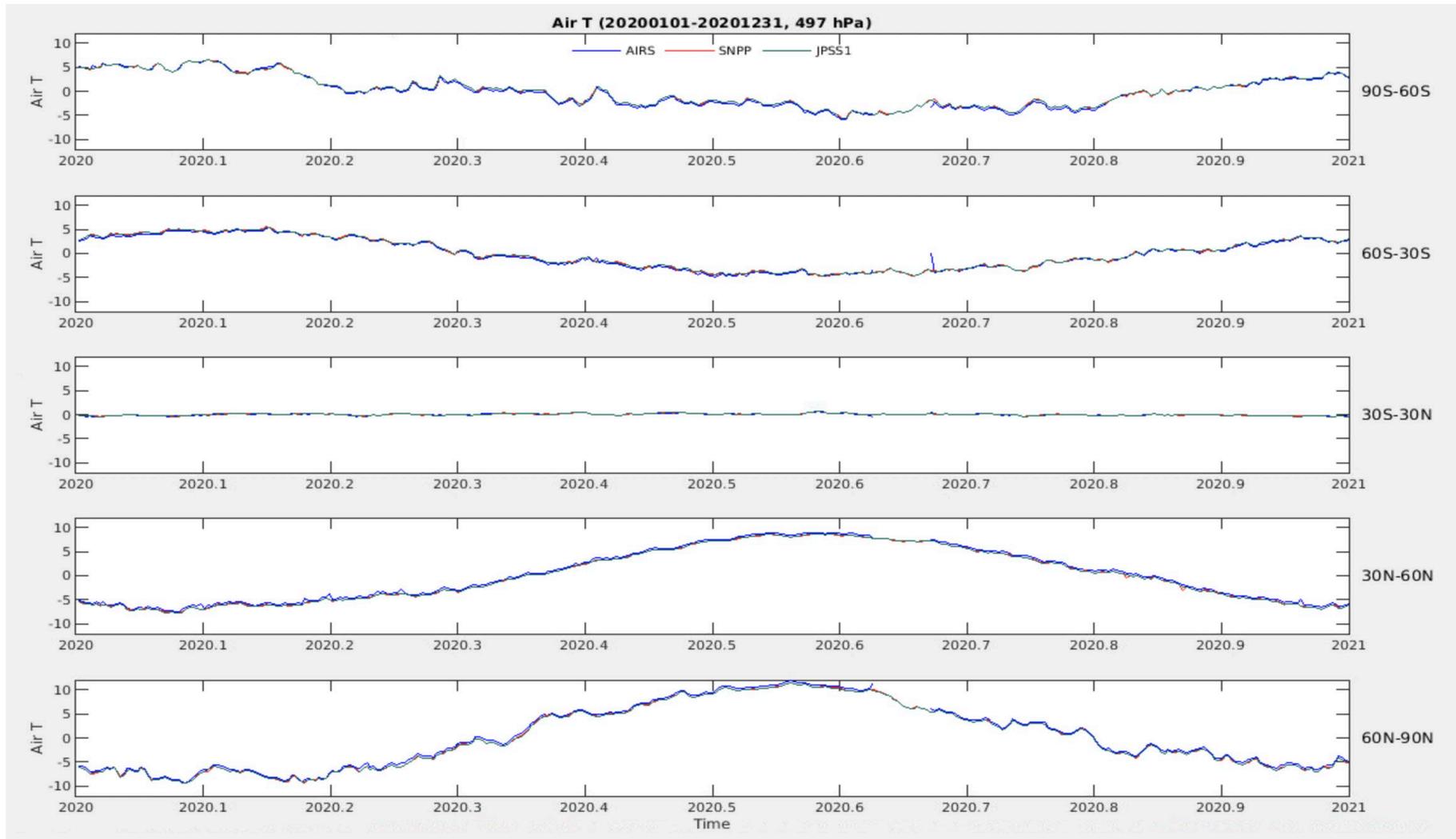
ClimFiSP surface skin temperature anomalies and trends Sep. 2002 – Jun. 2022
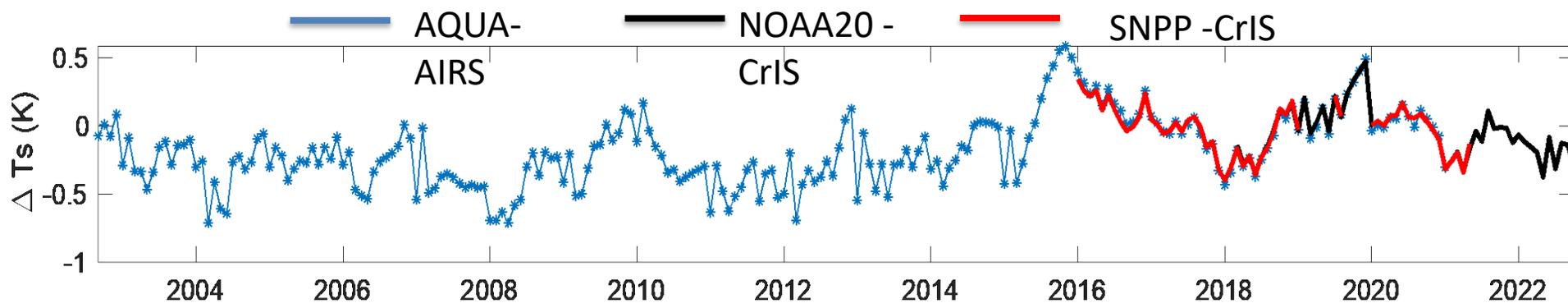
20-year Climate Trends from ClimFiSP
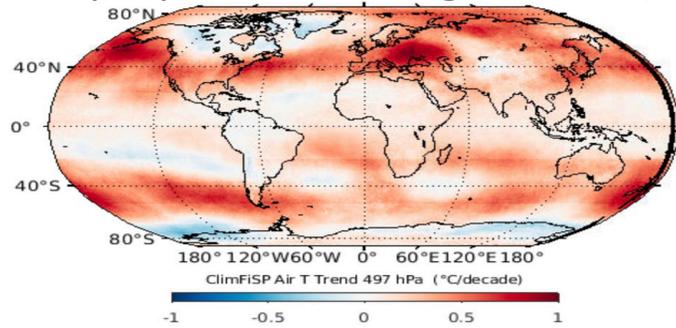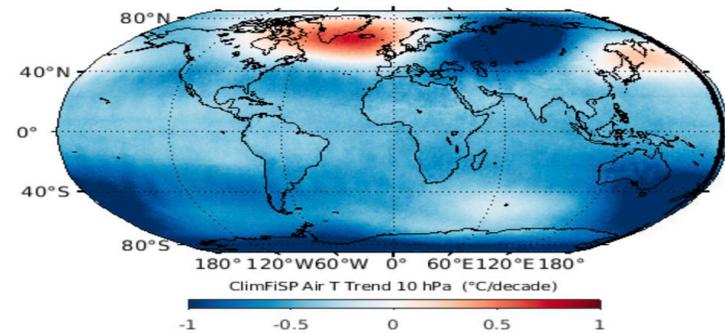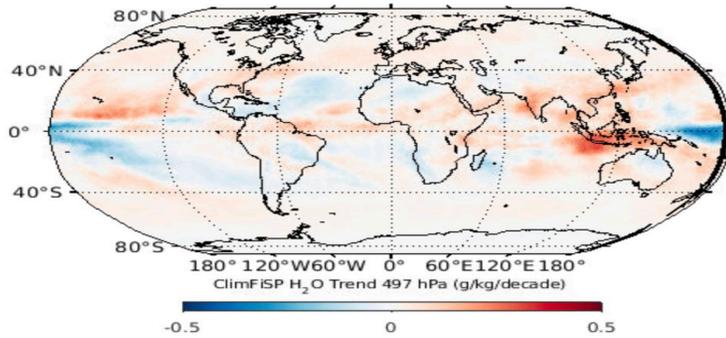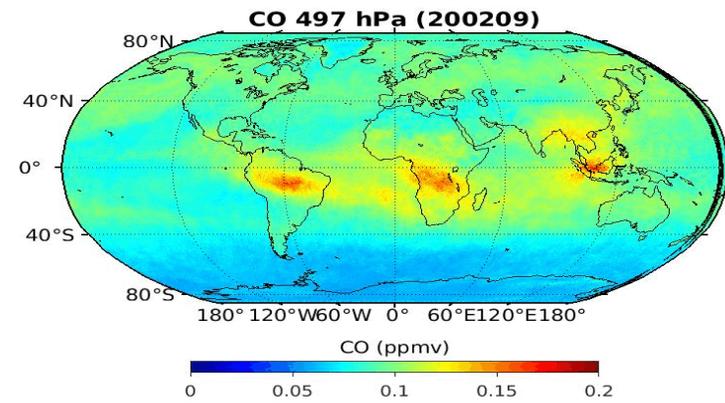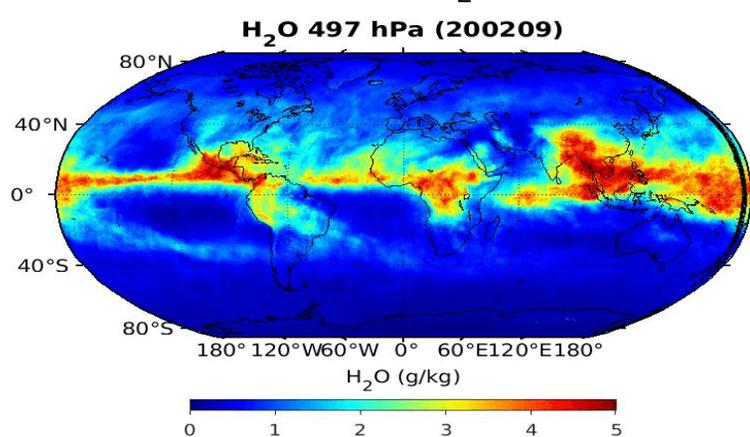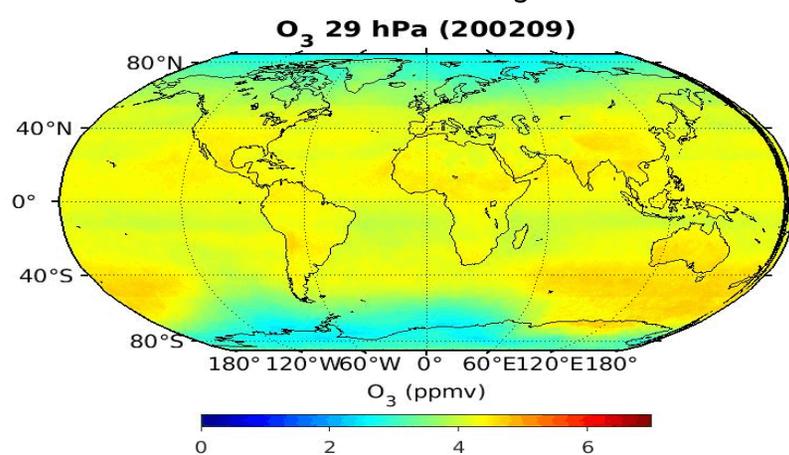
Summary Conclusions

- Both SiFSAP and ClimFiSP retrieves more than geophysical parameters simultaneously
  - ➢ Temperature, water vapor, and trace gas atmospheric profiles (98 pressure levels)
  - ➢ Cloud temperature, pressure, optical depth, phase, and effective size, fraction, emissivity
  - ➢ Surface skin temperature and surface emissivity spectra
- SiFSAP (L2) products are being produced at NASA GES DICS
  - ➢ Available to public in NASA GES DISC since 2023
  - ➢ Fit all-sky hyperspectral sounder radiance using all spectral channels
  - ➢ 9-time denser (or area spatial resolution) products compared to cloud-clearing algorithm
  - ➢ Products are radiometrically consistent with observed radiance spectra
  - ➢ Examples show advantages of higher-spatial resolution SiFSAP for various applications
- ClimFiSP product will be available at GES DISC soon
  - ➢ Aqua AIRS, SNPP and NOAA-20 ClimFiSP will be available before the end of 2024
  - ➢ Super fast with performance comparable to the SiFSAP
  - ➢ Works on single FOV or spatiotemporally average sounder radiance spectra
  - ➢ Radiometrically consistent data products with error estimations
  - ➢ Consistent methodology for multiple satellite sensors
  - ➢ Generated 20 year of climate data records from Aqua/AIRS, SNPP/CrIS, and JPSS/CrIS