All-sky Retrieval of Atmospheric Temperature, Water Vapor, Clouds, Trace Gases, and Surface Properties from Operational Hyperspectral IR Sounders

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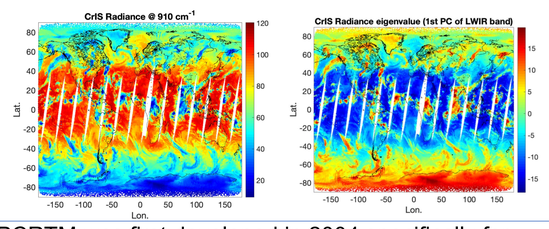
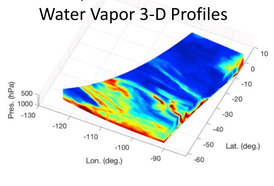
Ways to Efficiently Deal With Hyperspectral IR sounder Remote Sensing Data

- Modern hyperspectral satellite remote sensors provide wealth of information on
  - Atmospheric properties such as temperature, water vapor and trace gas vertical profiles
  - Cloud and aerosol properties
  - Surface properties (temperature, emissivity, reflectivity …)
- 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 radiative transfer model is too slow (needs millions mono 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 capture the information content of the original channel spectrum
  - Super-channel number << than the original channel numbers



Example of SiFSAP Retrieved Water Vapor 3-D Profiles

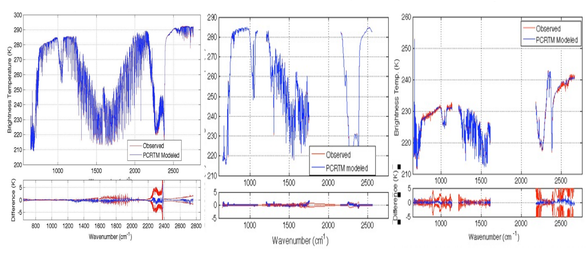


- PCRTM was first developed in 2004 specifically for hyperspectral remote sensors
  - Number of RT calculations are << number of spectral channels
    - Orders of magnitude faster than LBL RTMs
  - RT calculations done monochromatically
    - Physical-based RTM and accurate relative to LBL RTMs

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

  - Provides analytical Jacobian needed for satellite data inversions

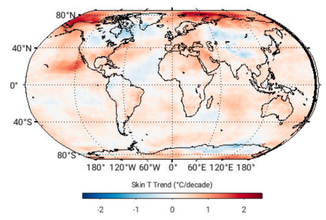
PCRTM simulated and observed AIRS, CrIS, and IASI spectra



Two Retrieval Algorithms Based on PCRTM for Generating Sounder Products

- 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

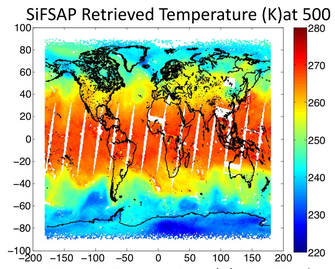
Example of ClimFiSP Global Tskin Trend from AIRS



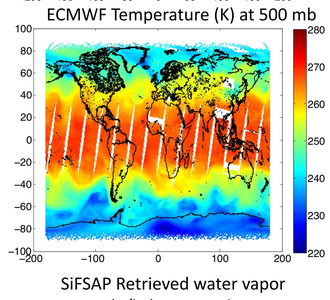
Description of SiFSAP Algorithm and Examples of SiFSAP Products

- Supported by NASA NNH17ZDA001N-TASNPP and NNH20ZDA001N-SNPPSP
  - ➢ Being prepared at Sounder SIPS for transitioning to NASA GES DISC for routine product generation
- Key Components:
  - ➢ Performs retrieval for each FOV with the presence of clouds
  - ➢ RTM cloudy forward model
  - ➢ non-linear optimal estimation physical retrieval algorithm
  - ➢ 9 times high spatial resolution than operational CrIS and AIRS algorithm
  - ➢ Uses all spectral information instead of selecting only a few hundred channels
  - ➢ Fitting observed radiance spectra directly instead of cloud-cleared radiances
- SiFSAP Products:
  - ➢ Vertical Profiles of T, H_2O, and trace gases (CO_2, O_3, CO, CH_4, N_2O)
  - ➢ Cloud (phase, height, cloud top pressure, particle size, optical depth)
  - ➢ Surface temperature and emissivity
  - ➢ Averaging kernels and radiative kernels

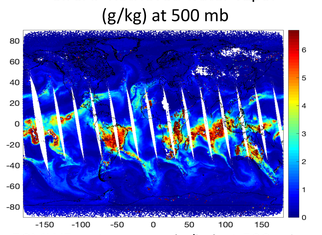
SiFSAP Retrieved Temperature (K)at 500 mb



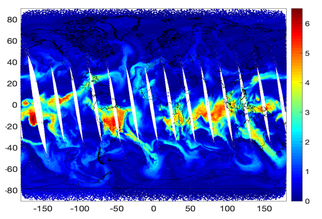
ECMWF Temperature (K) at 500 mb

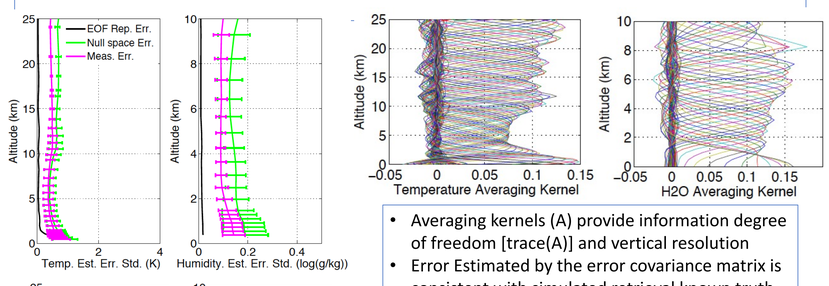


SiFSAP Retrieved water vapor (g/kg) at 500 mb



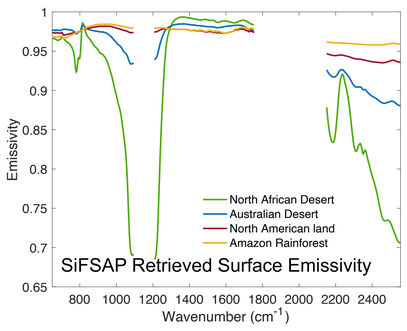
ECMWF water vapor (g/kg) at 500 mb





- Averaging kernels (A) provide information degree of freedom [trace(A)] and vertical resolution
- Error Estimated by the error covariance matrix is consistent with simulated retrieval known truth

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

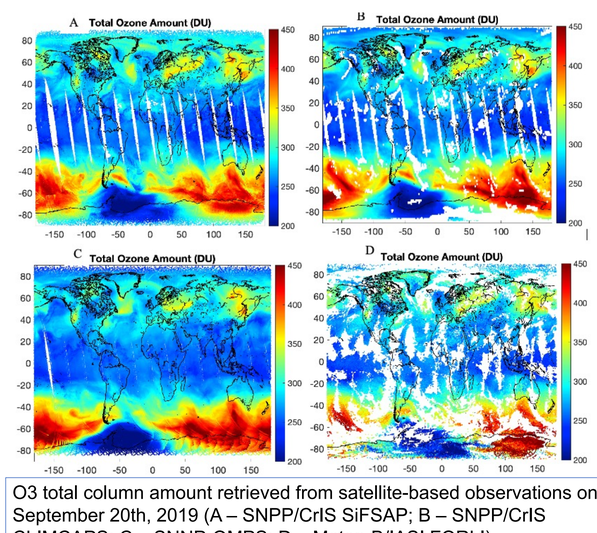


SiFSAP Retrieved Surface Emissivity

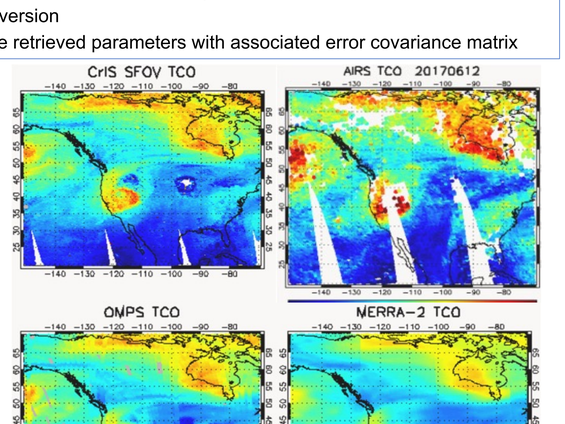
- Iterative Optimal Estimation Inversion:

$$X_{n+1} - X_n = (K^T S_\epsilon^{-1} K + S_a^{-1})^{-1} \left(K^T S_\epsilon^{-1} (R - R_n) - S_a^{-1} (X - X_a) \right)$$

- PCRTM compresses ***R***, ***Se***, and ***K*** into smaller dimensions
- Applying PCA to ***X*** will further reduce the dimension of ***X, K*** and ***Sa***
- Advantages of using PCA
  - ➢ reduces the ill-condition of the inversion process
  - ➢ Speed up the inversion
  - ➢ Easy to store the retrieved parameters with associated error covariance matrix

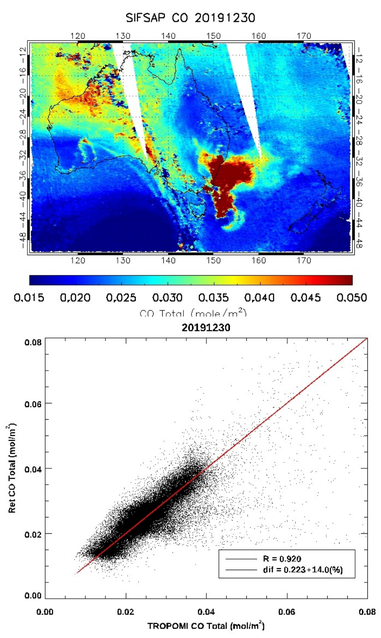


O3 total column amount retrieved from satellite-based observations on September 20th, 2019 (A – SNPP/CrIS SiFSAP; B – SNPP/CrIS CLIMCAPS; C – SNNP-OMPS; D – Metop-B/IASI FORLI).

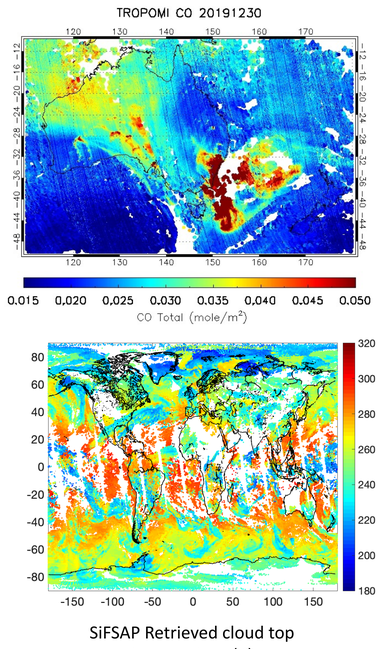


Top left: SIFSAP Total Column Ozone (TCO), Top right: AIRS operational L2 CO, Bottom left: OMPS total CO, Bottom right: MERRA-2 total CO

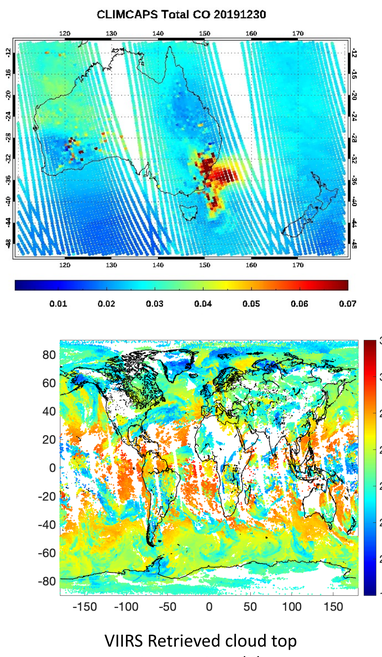
Examples of SiFSAP Products (continued from previous column)



Scatter plot of SiFSAP CO column vs TROPOMI CO column



SiFSAP Retrieved cloud top temperature (K)



VIIRS Retrieved cloud top temperature (K)

Description of the ClimFiSP Algorithm and Examples of ClimFiSP Products

- Issues with traditional L1-L2-L3 climate products
  - ➢ L2 algorithm inconsistency for different satellite sensors
  - ➢ Lack of radiance closure (e.g cloud-clearing method)
  - ➢ L1-L2-L3 algorithm is computational demanding
- ClimFiSP is designed to address the above-mentioned deficiencies
  - ➢ Works on gridded L1 products directly using consistent radiative kernels
  - ➢ All parameters including clouds retrieved simultaneously
  - ➢ More than 5 orders of magnitude faster than traditional L1-L2-L3 method
  - ➢ Quick re-generation of climate products when instrument is re-calibrated or L1 algorithm is improved
- Provide radiative kernels needed for climate studies
  - ➢ Climate model validations using satellite data
  - ➢ Climate model diagnosis/improvements
- Supported by NASA NNH17ZDA001N-TASNPP and NNH20ZDA001N-SNPPSP
  - ➢ Consistent climate products from AIRS, SNPP CrIS, and JPSS CrIS
  - ➢ Harvest decades of hyperspectral sounder measurements for climate studies
  - ➢ Provides products attractive to wide range of users

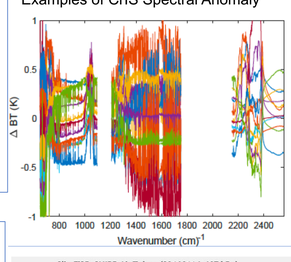
- Gridded AIRS and CrIS spectral anomaly derived from L1 directly
  - ➢ No assumptions when generating the anomaly spectra
  - ➢ All radiometrically significant geophysical variables are included in the radiative kernels
  - ➢ ClimFiSP include all geophysical variables including clouds
- Spectral fingerprinting errors are characterized

$$\boldsymbol{\Sigma_x} = (\boldsymbol{S^T \Sigma^{-1} S + \Sigma_a})^{-1}$$

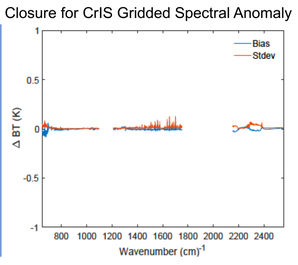
- Information content for each retrieved variable can be determined (diagonal elements of the averaging kernel)

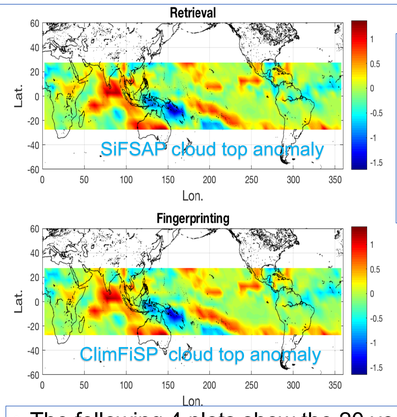
$$\boldsymbol{A_x} = (\boldsymbol{S^T \Sigma^{-1} S + \Sigma_a})^{-1} \boldsymbol{S^T \Sigma^{-1}\ S}$$

Examples of CrIS Spectral Anomaly

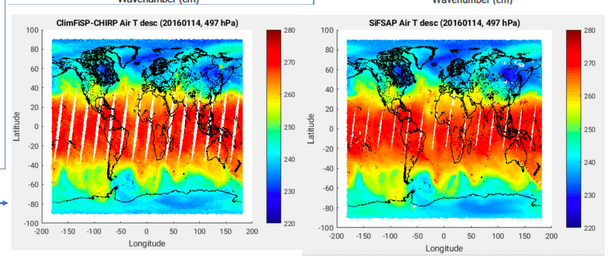


Closure for CrIS Gridded Spectral Anomaly



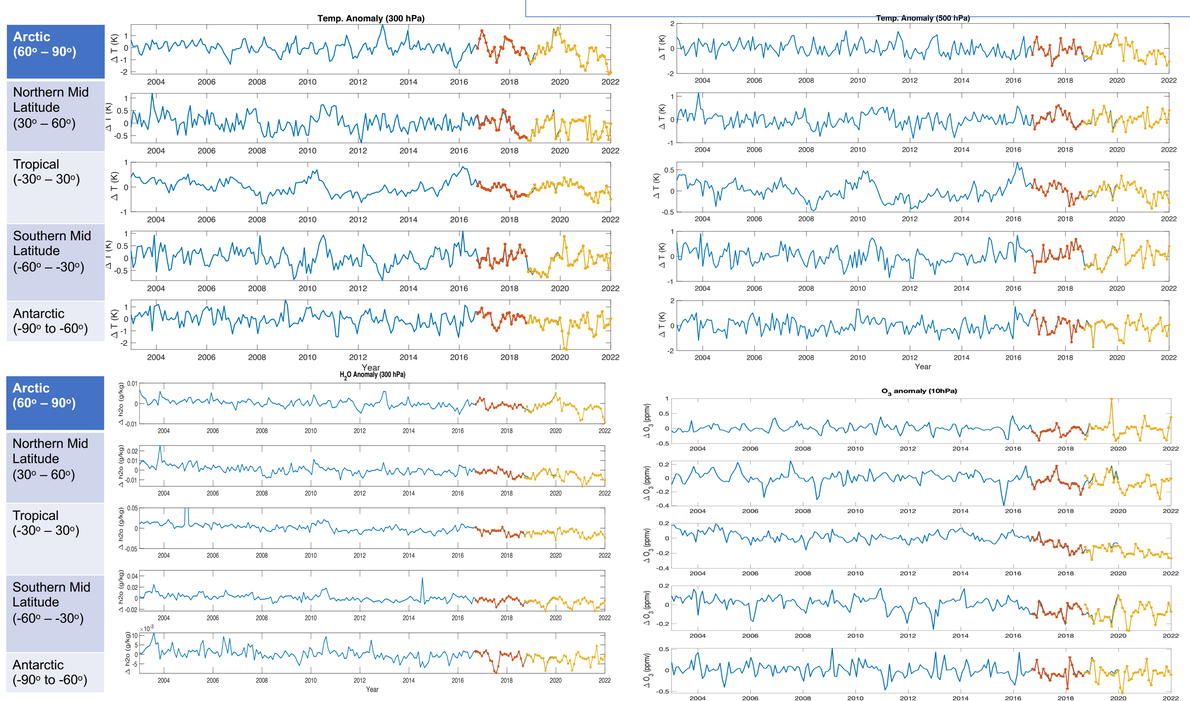


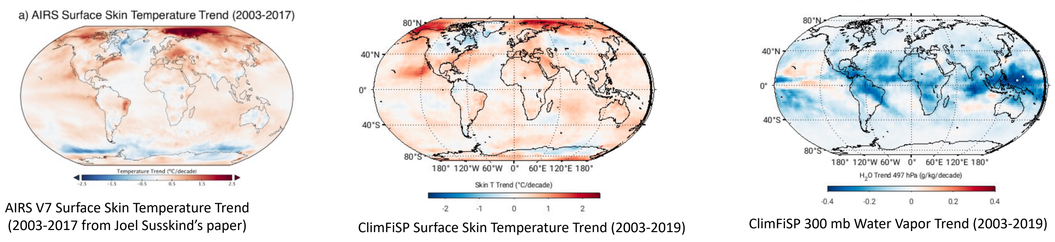
Comparison of 500 mb Temperature from SiFSAP and ClimFiSP (the figure to the right of this text box)
- ➢ SiFSAP (right plot)
- ➢ ClimFiSP (left plot)



- The following 4 plots show the 20 years anomaly plots of surface temperature, 500 mb temperature, 300 mb water vapor, and 10 mb ozone for different latitude zones
  - ➢ Blue color lines are derived from CHIRP AIRS
  - ➢ Red color lines are derived from CHIRP SNPP CrIS
  - ➢ Orange color lines are derived from CHIRP J1 CrIS

- 20 years of CLimate Data Record has been generated using the ClimFiSP
- 3 satellite IR hyperspectral sounder data were used
  - ➢ AIRS on Aqua
  - ➢ CrIS on SNPP
  - ➢ CrIS on NOAA 20
- Climate Hyperspectral Infrared Radiance Product (CHIRP)
  - ➢ Generated by Larrabee Strow
  - ➢ Available on NASA Sounder SIPS and DAAC
- The ClimFISP products has spatial resolution of 0.5 x 0.5 degree





AIRS V7 Surface Skin Temperature Trend (2003-2017 from Joel Susskind's paper)

ClimFiSP Surface Skin Temperature Trend (2003-2019)

ClimFiSP 300 mb Water Vapor Trend (2003-2019)

Summary and More information on PCRTM

- PCRTM is the key component in analyzing hyperspectral IR sounder data under all sky conditions
  - ➢ 50 wavenumber (far IR) to 30000 wavenumber (UV) for many sensors: AIRS, CrIS, IASI, S-HIS, NAST-I, CPF, OMI, SCIAMACHY…
  - ➢ Multiple scattering clouds/aerosols, non-LTE, surface BRDF included
  - ➢ 0.05 K accuracy in IR and 0.02% accuracy in UV-VIS (relative to LBL)
  - ➢ 3-4 orders of magnitude faster than LBLRTM and MODTRAN
- 2 PCRTM-based retrieval algorithms SiFSAP and ClimFiSP have been developed
  - ➢ Will be available at NASA DAAC soon
  - ➢ SiFSAP has generated excellent results from AIRS, CrIS, IASI with higher spatial resolution than cloud-clearing algorithm
  - ➢ ClimFiSP has generated 20 years of high-quality climate data records with consistent fingerprinting method from IR sounders

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