Pushing the Application Limit of Hyperspectral IR Sounder Remote Sensing for Frontiers of Weather and Climate Studies

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Introduction

- The application scope and challenges associated with the hyper-spectral IR sounder application for weather and climate studies

- The solution we can offer to address those challenges

- Solutions we have developed:
  - **S**ingle **F**ield-of-view **S**ounder **A**tmospheric **P**roduct (**SiFSAP**)
  - **Clim**ate **Fi**ngerprinting **S**ounder **P**roduct (**CimFiSP**)

The use of hyper-spectral IR sounder measurements for weather and environmental monitoring applications

❖Hyper-spectral IR sounder retrieval products have been used for NWS and environmental monitoring

- The satellite observations of T and Q provides information (e.g. potential instability) that the numerical models did not simulate. Including those data in NWS system Improves forecaster confidence.
- Trace gases data have been used for fire detection, pollution monitoring, atmospheric chemistry and transport study, etc.

❖Demanding needs:

- Low latency delivery of more satellite sounding results
- Higher spatial resolution (single field-of-view) results
  - ✓ The spatial resolution of the retrieval products based on the cloud-clearing approach is much **lower** than the native spatial resolution of the observations offered by the IR sounders.
- Retrieval under cloudy sky conditions.
- Well defined error estimation scheme
- …

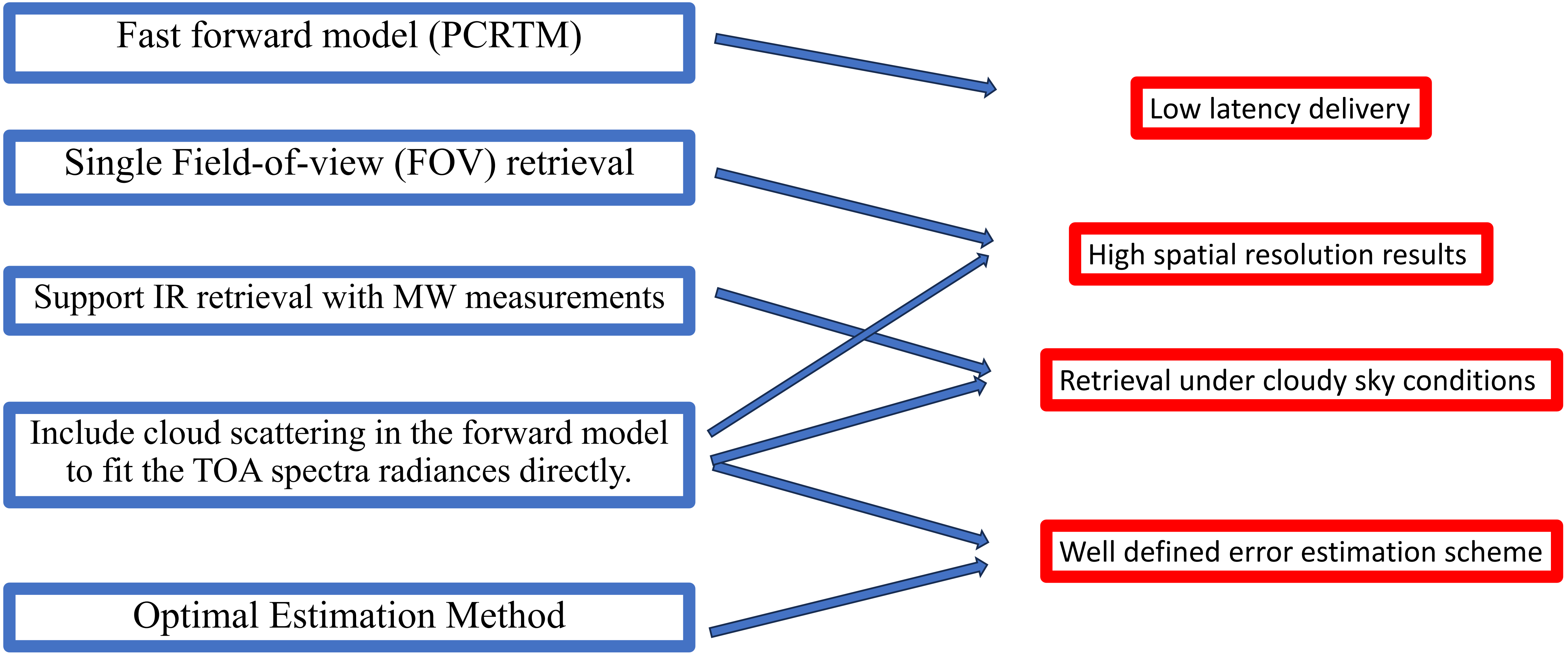
The use of hyper-spectral IR sounder measurements for climate studies

- ❖ There is a growing interest in using more than two-decade long IR sounder data record (AIRS, IASI, and CrIS) for climate anomaly/trend analysis.

- ❖ Challenges:

- Ensure the consistency between multiple satellite data records when they are merged to form a continuous data record.
  - ✓ Radiometric consistency between the radiance data records of different sensors.
    - ❑ Efforts in L1 calibration improvement
    - ❑ Reconciliation in space, time, angular, spectral sampling between different sensor measurements
    - ❑ Absolute consistency in the data processing algorithm.
- Construct a well-defined error estimation scheme to trace error/uncertainty in the trend/anomaly of critical climate variables back to the error/uncertainty in the TOA spectral radiance data record.
- Satisfy the need for a fast algorithm to provide the low latency data processing capability, aiming at reprocessing the complete satellite data record quickly following each major updates in L1 radiance data product.

Technical approaches to address the needs for weather applications

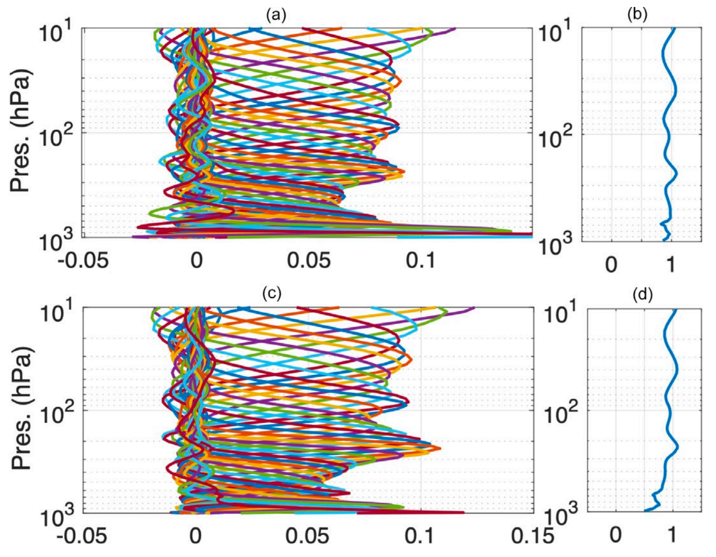


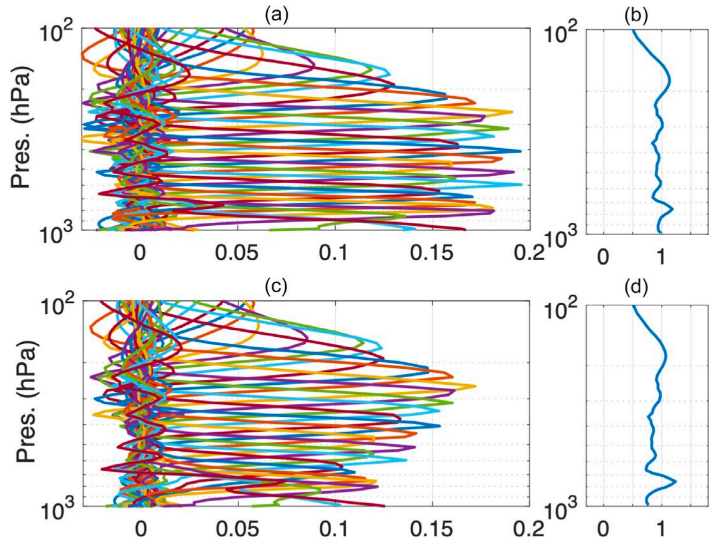
Spectral fingerprinting approach to address the needs for climate applications

- Use the same algorithm to process data of different IR sounders
- Use IR sounder data products merged into the same spectral domain (CHIRP)
- Instead of fitting the TOA spectral radiances directly, fit the change in spectral radiances (anomalies)
- Use the fingerprint methodology that combines the machine-learning based scene classification technique with the optimal estimation method based radiative kernel technique
- Process global scale spatial-temporally averaged data under all-sky conditions

- Radiometrically consistent data fusion
- Well defined error estimation scheme
- Low latency data procession
- Mitigate the sampling difference

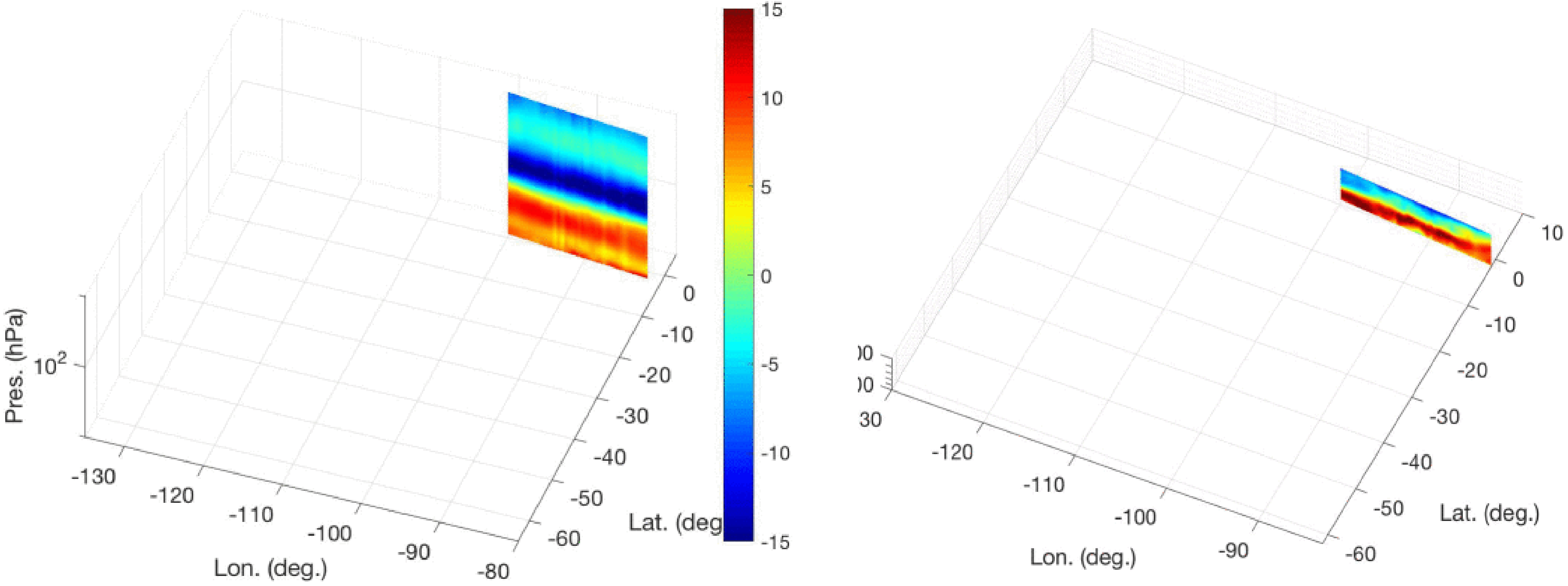
SiFSAP T and Q retrieved under all sky conditions





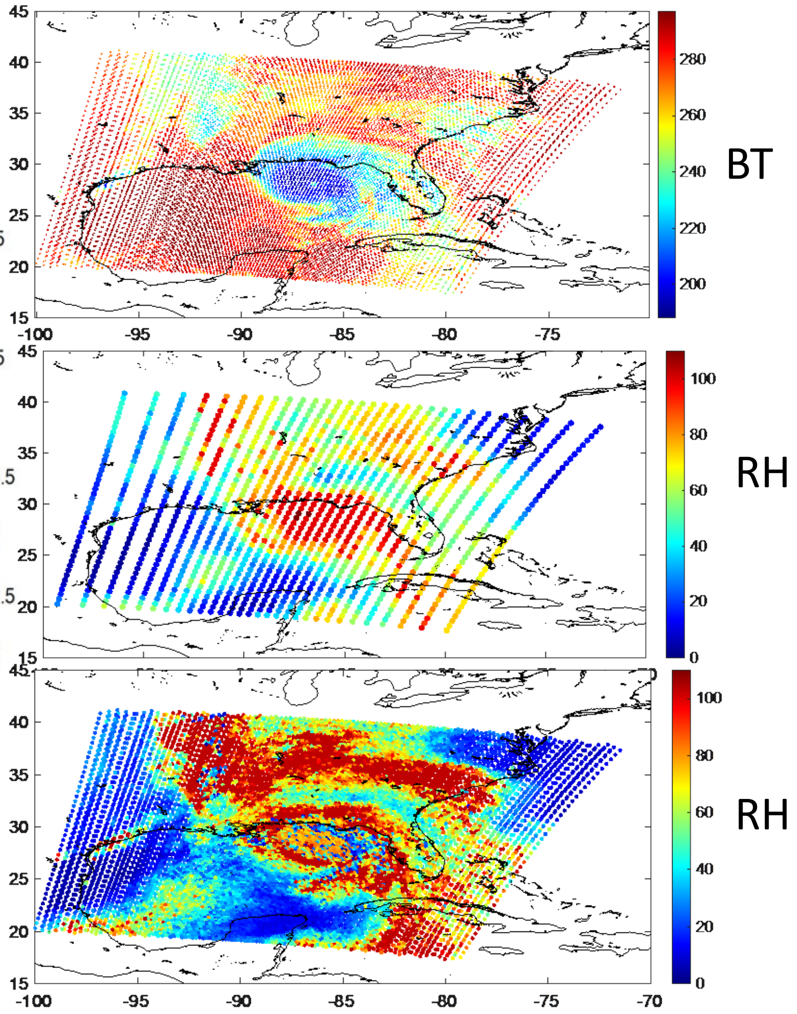
3-D atmospheric features revealed by SiFSAP

Temp. H_2O

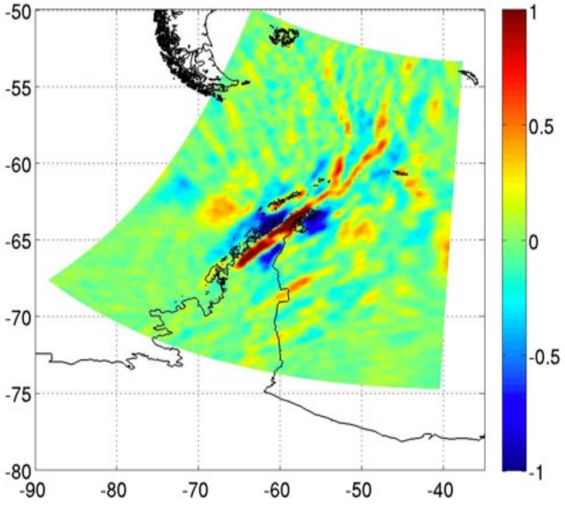


Using SiFSAP for meteorological or climate Study at small horizontal gradient scale

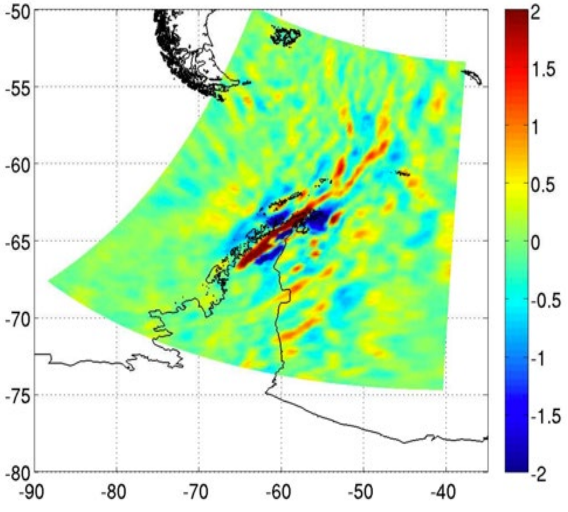
Hurricane Michael 2018



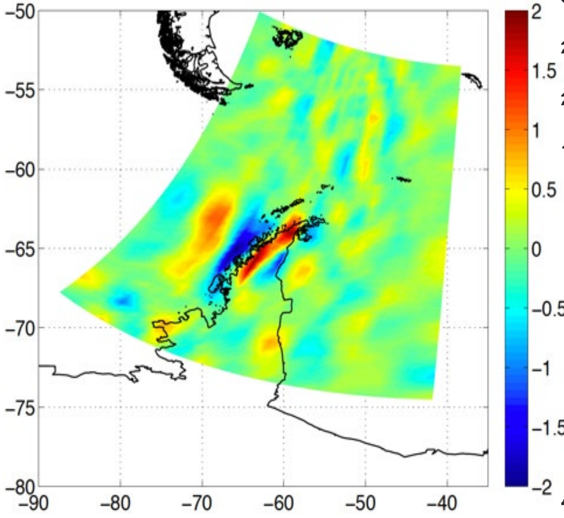
Gravity wave detected by AIRS on Oct. 17th, 2010 near South Shetland Islands



From AIRS Level1B



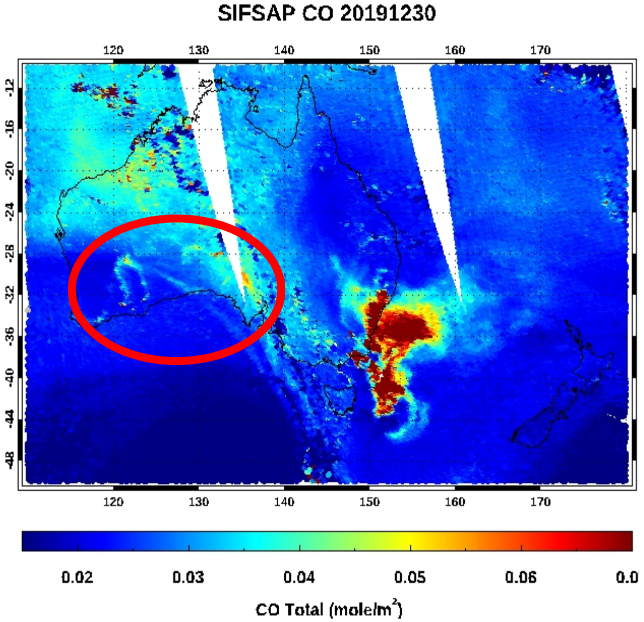
From SiFSAP AIRS Temp. @ 2.7hPa

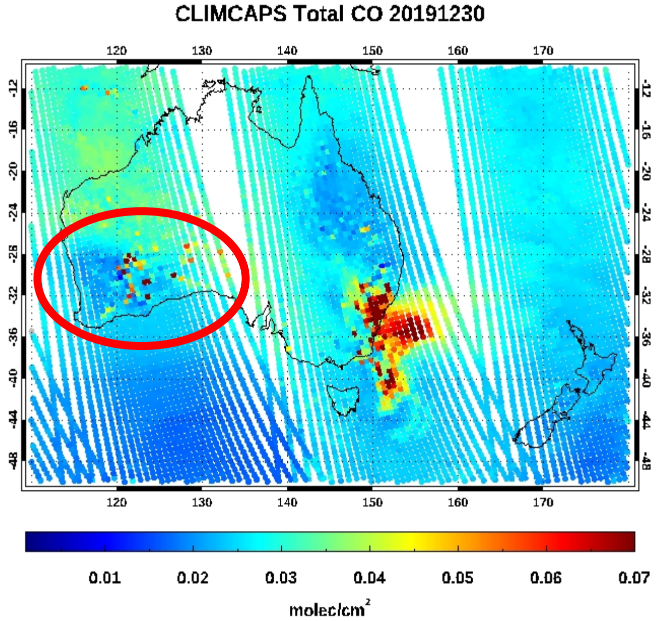


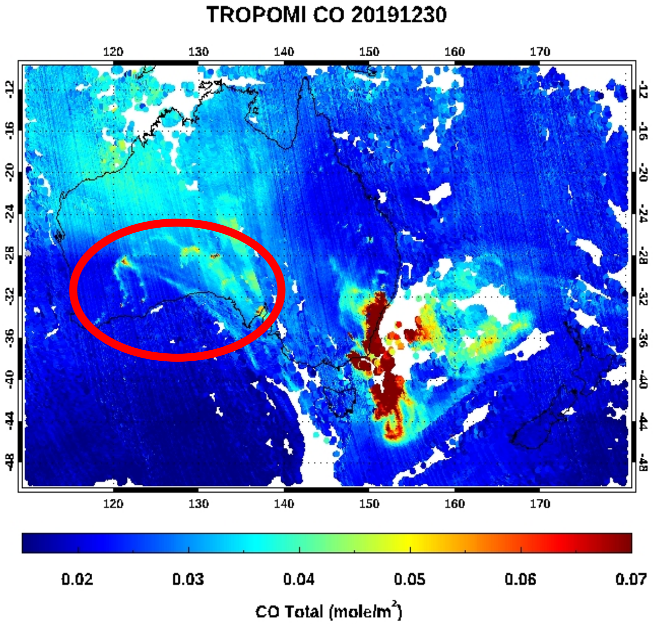
From AIRS v7 Temp. @ 2.7hPa

Using SiFSAP for meteorological or climate Study at small horizontal gradient scale

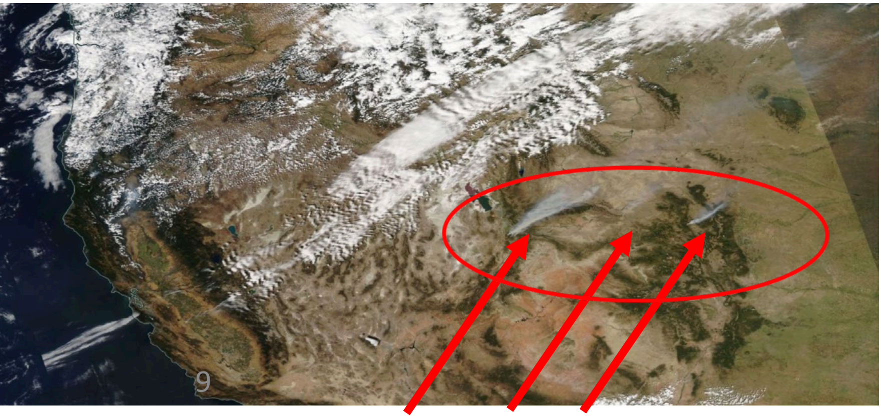
Australia Fire



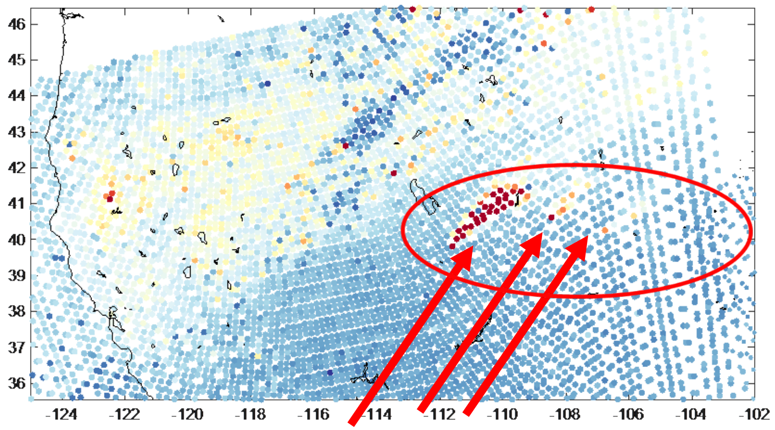




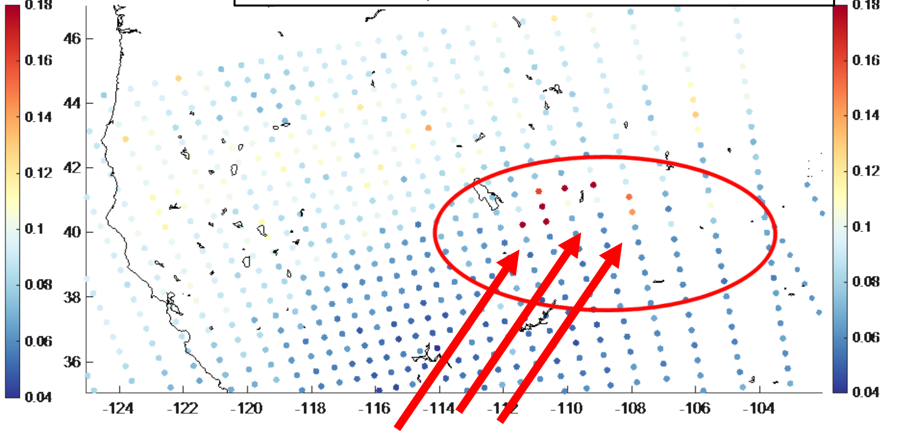
Western US, 13th September 2018 MODIS image



Western US, SNPP SiFSAP CO



Western US, SNPP CLIMCAPS CO



Low latency Data procession scheme of ClimFiSP

Standard L1-L2-L3 retrieval scheme

Level 1 spectral radiances ***R***

↓

L2 retrieval process for all individual observations

Time consuming iterative process

↓

Level 2 geophysical variables ***X***

↓

Level 3 space time gridded variables $\overline{\boldsymbol{X}}$

Fingerprinting scheme

Level 1 spectral radiances ***R***

↓

Level 3 space time gridded radiances $\overline{\boldsymbol{R}}$

↓

Fingerprinting for space time gridded observations

↓

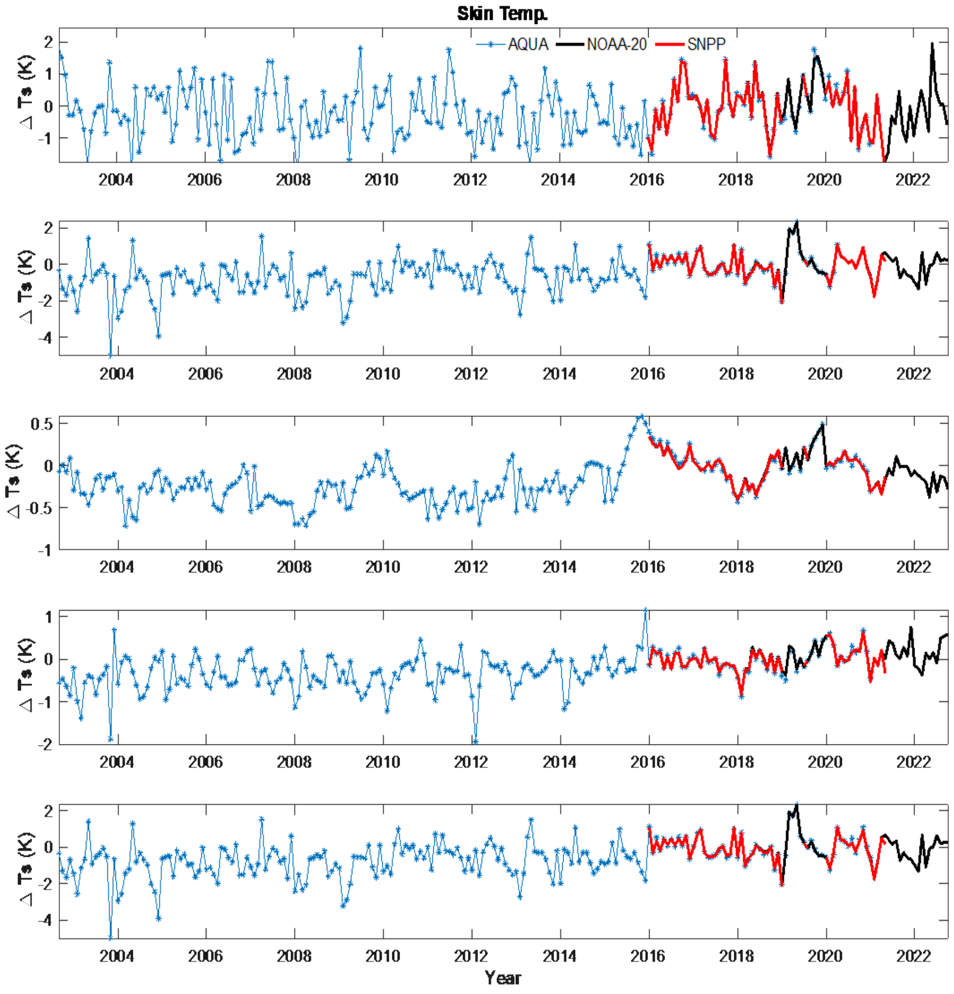
Level 3 space time gridded variables $\overline{\boldsymbol{X}}$

The computational cost of spectral fingerprinting is at least two orders of magnitude less than a standard L1-L2-L3 scheme.

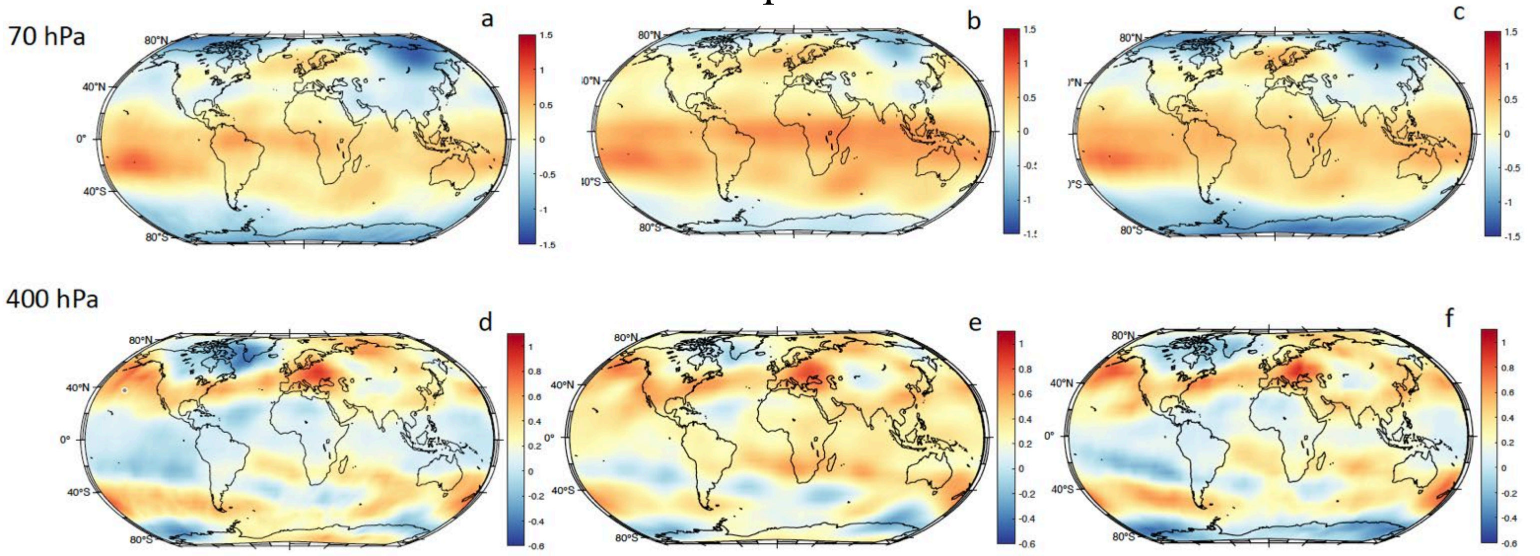
Note: ***R*** = F(***X***) F – radiative transfer relationship; However, $\overline{\boldsymbol{R}}$ ‡ F($\overline{\boldsymbol{X}}$).

ClimFiSP anomalies and trends

Tskin anomaly

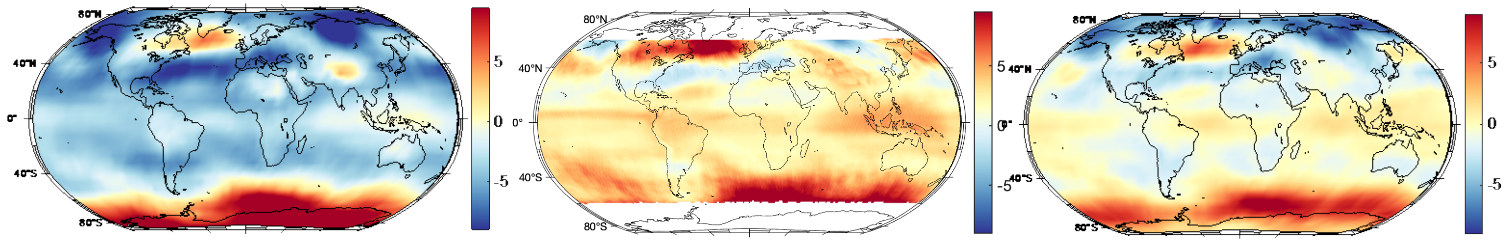


Air Temp. Trends



CLIMCAPS ERA5 ClimFiSP

Total Column O_3 Trends

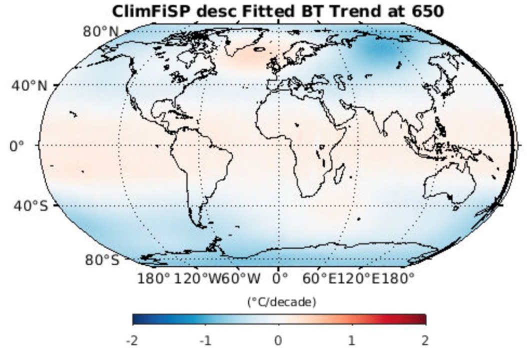


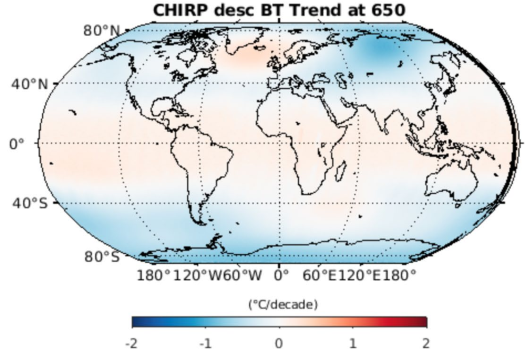
CLIMCAPS OMI ClimFiSP

Radiometric Consistency - ClimFiSP vs observations

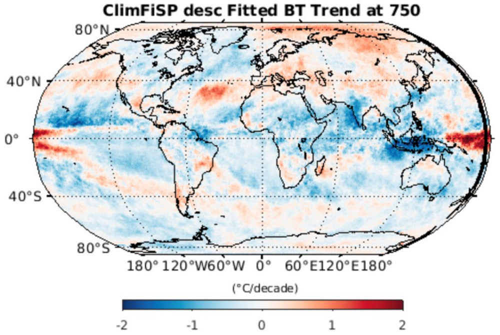
Bright Temp. Trends at different wavelengths (wavenumbers cm^{-1}) based on 20 years of ClimFiSP and CHIRP-AIRS

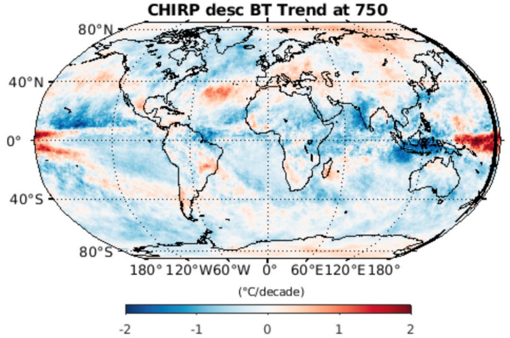
BT Trend (desc, 650)



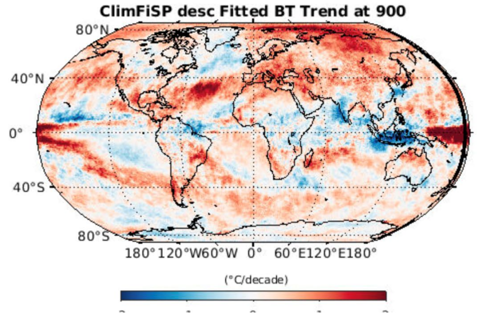


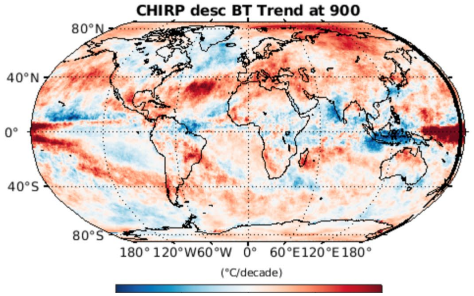
BT Trend (desc, 750)



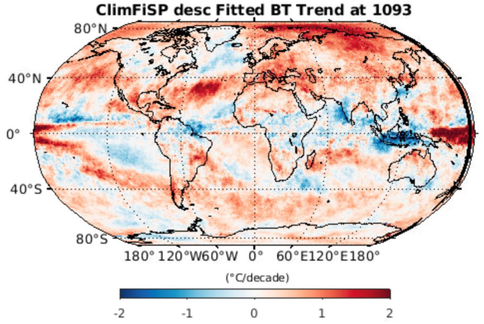


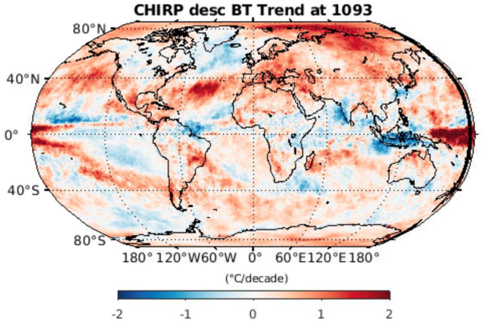
BT Trend (desc, 900)



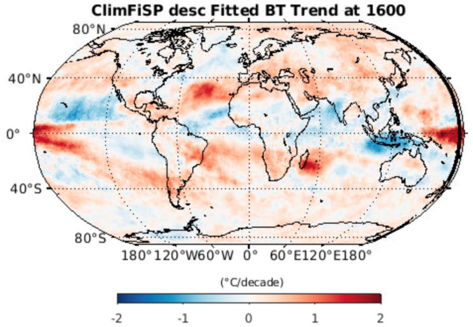


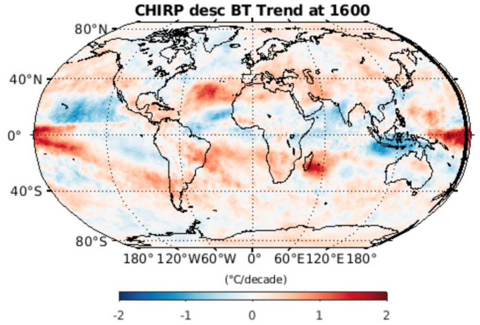
BT Trend (desc, 1093)





BT Trend (desc, 1600)





Summary

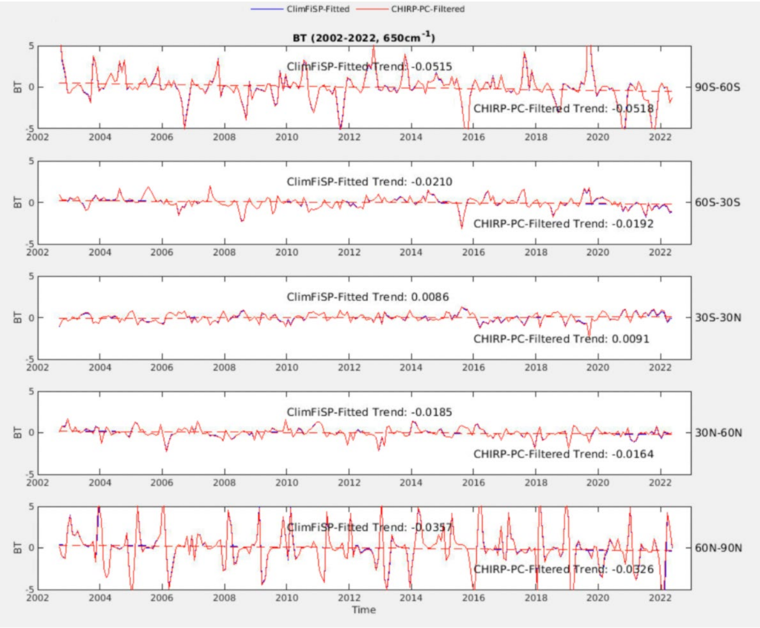
- SiFSAP has been developed with support via the NASA ROSES grants. The production algorithm has been validated at JPL SIPS and delivered to NASA GES DISC. The official data product will be released soon at NASA GES DISC

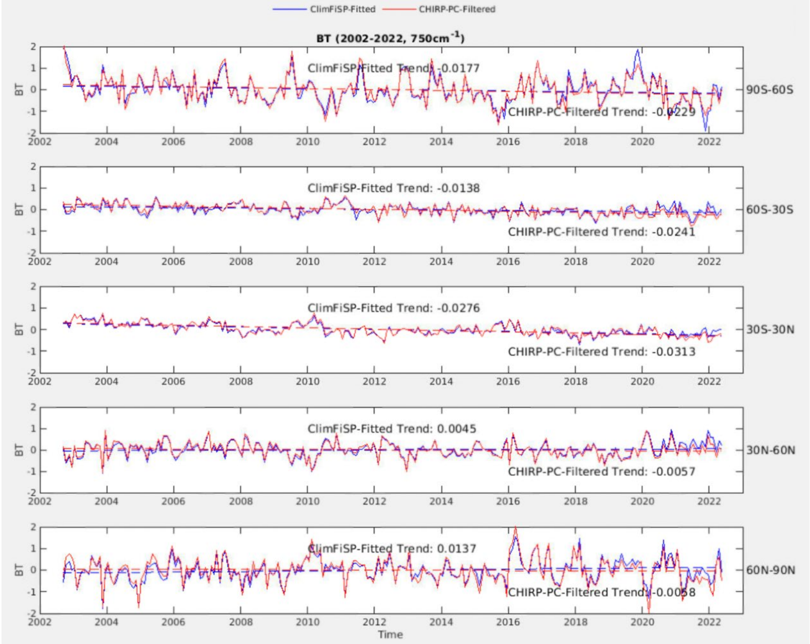
- SiFSAP complements other sounder level-2 data products by providing higher spatial resolution data to facilitate meteorological or climate study at small horizontal gradient scale, and a complete set of geophysical variables that allow a variety of applications such as the derivation of spectrally resolved TOA and surface flux under all-sky conditions.

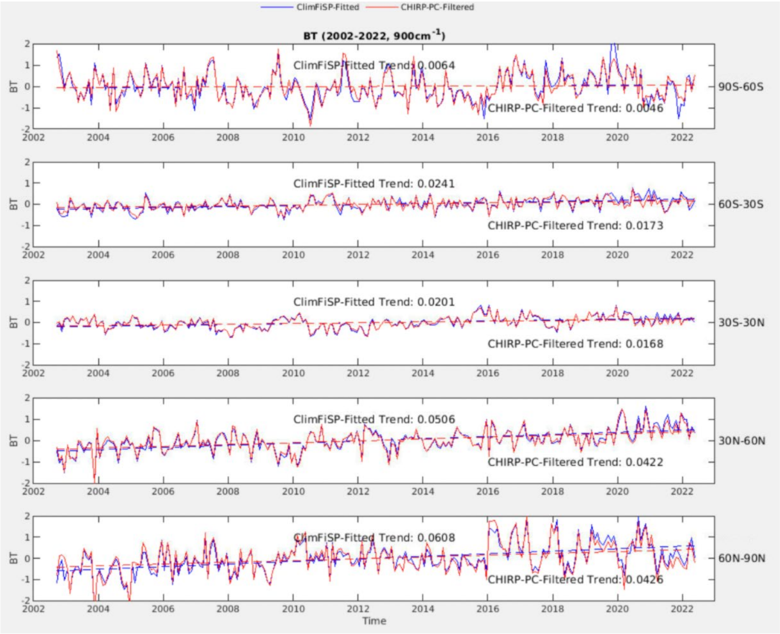
- The fingerprinting scheme reduces the computational cost by at least two orders of magnitude as compared with the standard L1-L2-L3 scheme, allowing an ultra-low latency delivery of product updates. ClimFiSP includes error estimation, facilitate the trend uncertainty analysis.

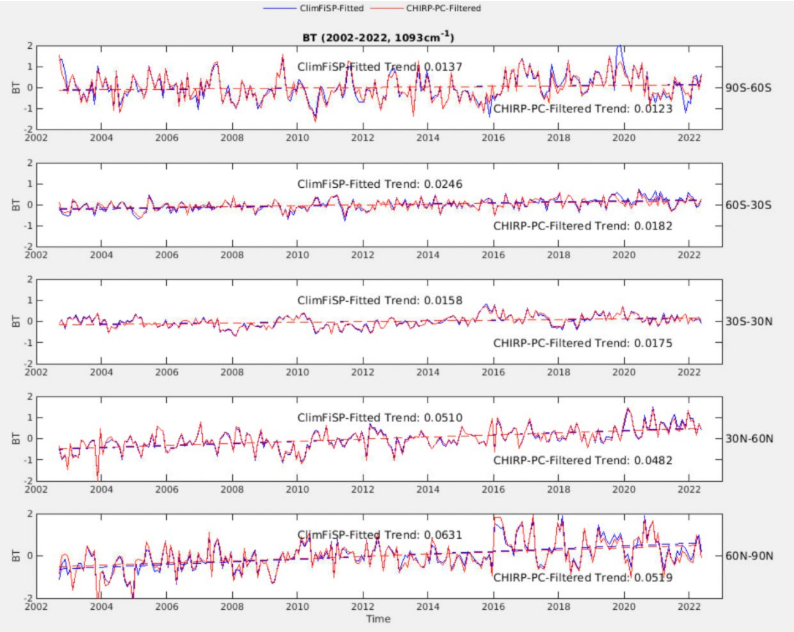
- SiFSAP and ClimFiSP will be used to support research activities to explore PBL information using sounder measurements and build polar region CDR funded by other ROSES grants.

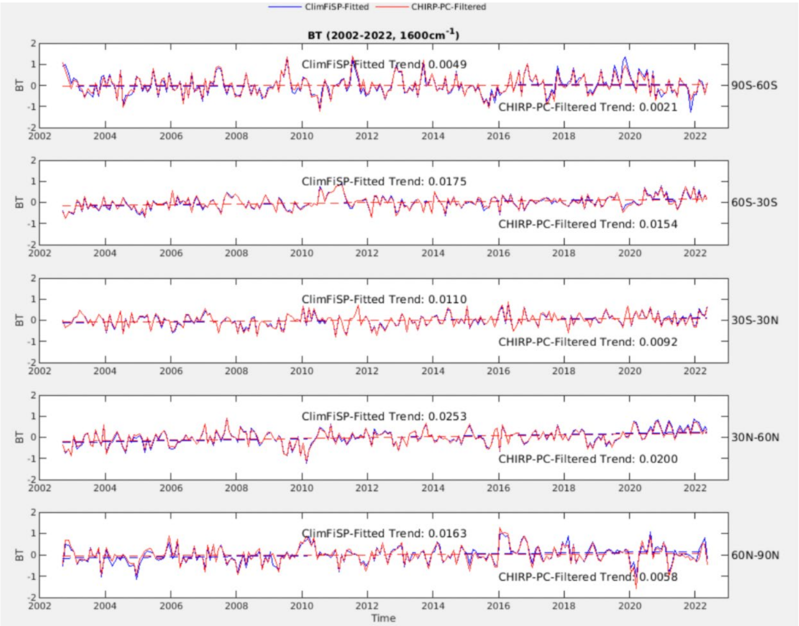
ClimFiSP Spectral Fitting











From SiFSAP to ClimFiSP

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

$\Delta X = (S^T\Sigma^{-1}S + \Sigma_a)^{-1}\, S^T\Sigma^{-1}\Delta R.$

$\boldsymbol{\Delta R}$ - climate spectral radiance anomaly,

$\boldsymbol{\Delta X}$– anomaly of climate variables,

$\boldsymbol{S}$ - spectral fingerprinting kernel,

$\boldsymbol{\varepsilon}$ - fingerprinting nonlinearity error term

Error Estimation

$\Sigma_X = (S^T\Sigma_R^{-1}S + \Sigma_a^{-1})^{-1}$

Σ_R and Σ_a are error covariance terms for $\boldsymbol{\Delta \bar{R}}$ and $\boldsymbol{\Delta \bar{X}}$

$\boldsymbol{\Delta R} = \boldsymbol{\bar{R}} - \boldsymbol{\bar{R}}_{\mathrm{ref}}$ $\quad \boldsymbol{\Delta X} = \boldsymbol{\bar{X}} - \boldsymbol{\bar{X}}_{\mathrm{ref}}$

$\boldsymbol{\bar{R}}_{\mathrm{ref}}$, $\boldsymbol{\bar{X}}_{\mathrm{ref}}$ preconstructed spectral radiance observations and corresponding climate variables of representative states at specified space-time grid (e.g. daily average, 0.5 × 0.5 lon. × lat.).

Note: $\boldsymbol{R}$ = F($\boldsymbol{X}$) F – radiative transfer relationship; However, $\boldsymbol{\bar{R}}$ ‡ F($\boldsymbol{\bar{X}}$).

	Spectral Fingerprinting	Individual Retrieval	
Spectral Anomaly (Trend) / Indiv. Radiance	$\boldsymbol{\Delta R}$	$\boldsymbol{R}$	$\boldsymbol{\Delta R} = \boldsymbol{\bar{R}} - \boldsymbol{\bar{R}}_{\mathrm{ref}}$
Radiative Kernel / Jacobian	$\boldsymbol{S}$	$\boldsymbol{K}$	$\boldsymbol{S} = \overline{\boldsymbol{K}}$
Climate Anomaly (Trend) / geophysical Variable	$\boldsymbol{\Delta X}$	$\boldsymbol{X}$	$\boldsymbol{\Delta X} = \boldsymbol{\bar{X}} - \boldsymbol{\bar{X}}_{\mathrm{ref}}$