FUSION OF HYPERSPECTRAL SOUNDER PRODUCTS VIA SPECTRAL FINGERPRINTING METHODOLOGY

Wan Wu[1], Xu Liu[1], Liqiao Lei[2], Xiaozhen Xiong[1], Qiguang Yang[2], Qing Yue[3], Daniel K. Zhou[1], Allen M. Larar[1]

[1] NASA Langley Research Center, Hampton, VA
[2] Science Systems and Applications, Inc. Hampton, VA
[3] Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

Satellite based measurements of top-of-atmosphere (TOA) spectral radiances in the infrared (IR) region have been in existence for almost two decades and are expected to be continued in the following decades. The data from multiple hyper-spectral IR sounders can therefore be combined to build a long-term data record to further global scale climate trend research. Challenges associated with the fusion of data from different sensors come from the stability and consistency requirement on the climate record. The direct radiance observations from different sounders need to be homogenized by reconciling the differences in calibration, spectral response function (SRF), and spatial-temporal sampling. When geophysical variables derived from radiances measured by different sounders are combined to form long-term climate records, the impacts of any inconsistencies between overlapping measurements on the retrieval must be carefully assessed in order to estimate the uncertainty of the corresponding climate anomalies/trends derived. This paper presents a novel climate fingerprinting methodology and establishes a rigorously-defined inverse relationship that allows us to efficiently evaluate the change in essential climate variables from the change in spectral radiances measured in prescribed spatial and temporal averaging scales. The inverse spectral fingerprinting relationship is constructed based on a unified spectral kernel scheme, providing a direct means for quantifying the potential discontinuity in the derived climate anomalies due to inconsistencies between overlapping measurements. We show in this paper a sample application of using the spectral fingerprinting scheme to derive long-term, global-scale surface temperatures from the Climate Hyperspectral Infrared Radiance Product (CHIRP) and quantify the inter-satellite biases.

***Index Terms*—** Climate, spectral fingerprinting, hyper-spectral sounder, trend, anomaly

1. INTRODUCTION

There is a growing need in the climate community to explore the application of hyper-spectral IR sounder data for long-term climate trend studies. The Atmospheric Infrared Sounder (AIRS) aboard the Aqua satellite has been in low-Earth orbit since 2002. The Cross-track Infrared Sounder (CrIS) aboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite was launched in 2011. S-NPP CrIS was followed by the NOAA/NASA Joint Polar Satellite System (JPSS) JPSS-1 CrIS launched in 2018. The launch of three more JPSS CrIS sensors has been planned. These hyperspectral sensors together will be able to provide a multiple decades long, continuous measurement record that is invaluable for long-term climate trend studies. Although operational data products for different IR sounders have been developed, geophysical property data from those products are susceptible to errors from two sources: 1) error in the measured radiances and 2) error introduced by the data production algorithm. The absolute radiometric accuracy of current sounders has not reached the desired 'climate benchmark' level [1]. The retrieval of geophysical variables from hyper-spectral radiances is generally a complex inversion process and most algorithms lack a rigorously-defined scheme to ensure the solution is radiometrically consistent with the measured TOA radiances. Therefore, the use of hyper-spectral sounder data for climate studies requires us to explore a new methodology which focuses on the measurement stability and algorithm consistency to meet the accuracy requirements. A climate signal can be viewed as the difference between two climate states. Therefore, it is the stability of the sounder measurements, not necessarily the absolute accuracy of the instrument, that determines the accuracy of the climate signal detection. Similarly, the impact on climate trend accuracies will be minimized if algorithm-introduced errors are consistently imposed on all data samples. AIRS and CrIS have been shown to be very stable [2]. Therefore, data records of essential climate variables like temperature and water vapor derived from these hyperspectral measurements using a consistent scheme can be invaluable for climate trend analysis. However, calibration offsets between different hyper-spectral sensors are expected. Intrinsic instrument differences between AIRS and CrIS, and potential orbital sampling differences among Aqua, S-NPP, and JPSS series will also introduce inconsistencies in long-term radiance record of multiple sounders. The inter-satellite radiometric biases need to be characterized and the error introduced in the derived climate anomaly needs to be eliminated. This paper introduces work addressing the difference between overlapping measurements of AQUA AIRS and SNPP CrIS to build a long-term surface temperature record using the spectral fingerprinting methodology.

2. SPECTRAL FINGERPRINTING METHODOLOGY

The spectral fingerprinting methodology is based on the linear relationship between the change in climate variables $\Delta\boldsymbol{\alpha}$ at a specified spatiotemporal scale and the introduced change in top-of-atmosphere (TOA) spectral radiance $\Delta\boldsymbol{d}$, i.e., the climate fingerprints.

$$\Delta\boldsymbol{d} = \boldsymbol{S}\Delta\boldsymbol{\alpha} + \boldsymbol{\varepsilon}, \tag{1}$$

where $\Delta\boldsymbol{d}$ is the climate spectral fingerprints, $\Delta\boldsymbol{\alpha}$ represents the corresponding anomaly of climate variables, $\boldsymbol{S}$ is the spectral kernel that characterizes the linear relationship, and $\boldsymbol{\varepsilon}$ is the fingerprinting residual term. $\Delta\boldsymbol{\alpha}$ is derived from $\Delta\boldsymbol{d}$ following an inverse relationship

$$\Delta\boldsymbol{\alpha} = (\boldsymbol{S}^T\boldsymbol{\Sigma}^{-1}\boldsymbol{S} + \boldsymbol{\Sigma}_a)^{-1}\boldsymbol{S}^T\boldsymbol{\Sigma}^{-1}\Delta\boldsymbol{d}. \tag{2}$$

where $\boldsymbol{\Sigma}$ is the covariance of the residual term $\boldsymbol{\varepsilon}$ and $\boldsymbol{\Sigma}_a$ is a priori used to constrain the variation $\Delta\boldsymbol{\alpha}$. $\boldsymbol{S}$, $\boldsymbol{\Sigma}$, and $\boldsymbol{\Sigma}_a$ are constructed using sample data from the Single Field-of-view Atmospheric Sounder Products (SiFSAP) for full spectral resolution (FSR) S-NPP CrIS [3-4]. More details about the spectral fingerprinting methodology can be found in [5].

It is noted here that the spectral fingerprinting method focuses on obtaining the change of climate variables while SiFSAP are instantaneous retrieval results. SiFSAP are produced for each FOV of hyper-spectral sounder measurements via a computationally intensive iterative retrieval process. Although the same radiative transfer model and *a priori* are used to produce SiFSAP of different sounders, tuning for the SiFSAP algorithm in terms of bias correction and the accommodation for measurement-based retrieval uncertainties is differentially optimized. SiFSAP fits spectral radiances of different sounders on their native SRFs and channels centers, respectively. Such a subtle but fundamental difference in the SiFSAP algorithm prevents a clearly defined evaluation for the inconsistency between CrIS SiFSAP and AIRS SiFSAP purely due to the instrument related differences between overlapping measurements, which are critical for the radiometric consistency check in climate trend analysis. As a comparison, the spectral fingerprinting methodology is based on a one-step, linear inversion relationship that reduces computational cost by orders of magnitude. Most importantly, the spectral fingerprinting scheme is designed to use a consistent algorithm for different sounders, provided that the measurements from different sensors can be reconciled to a common spectral grid.

The spectral fingerprinting scheme gives the change in geophysical variables $\Delta\boldsymbol{\alpha}$ for a given change in spectral radiance $\Delta\boldsymbol{d}$. Based on the space-time averaged $\boldsymbol{\alpha}$ that is derived by adding $\Delta\boldsymbol{\alpha}$ to the corresponding reference state $\overline{\boldsymbol{\alpha}}$ ($\overline{\boldsymbol{\alpha}}$ is obtained from the selected sample data of SiFSAP), we can construct Climate Fingerprinting Sounder Products (ClimFiSP). We have constructed the global spectral fingerprinting scheme on a $1/2^{\circ} \times 1/2^{\circ}$ daily grid. $\boldsymbol{\alpha}$ for a larger space-time scale can be constructed by averaging the $1/2^{\circ} \times 1/2^{\circ}$ daily mean data within the prescribed grid accordingly. ClimFiSP are first validated using the S-NPP SiFSAP. Fig. 1 illustrates the side-by-side comparison between the daily mean surface skin temperatures of ClimFiSP and SiFSAP. The excellent agreement shown between these two sets of results confirms the efficacy of using the spectral fingerprinting method to derive geophysical properties of a specified climate state.

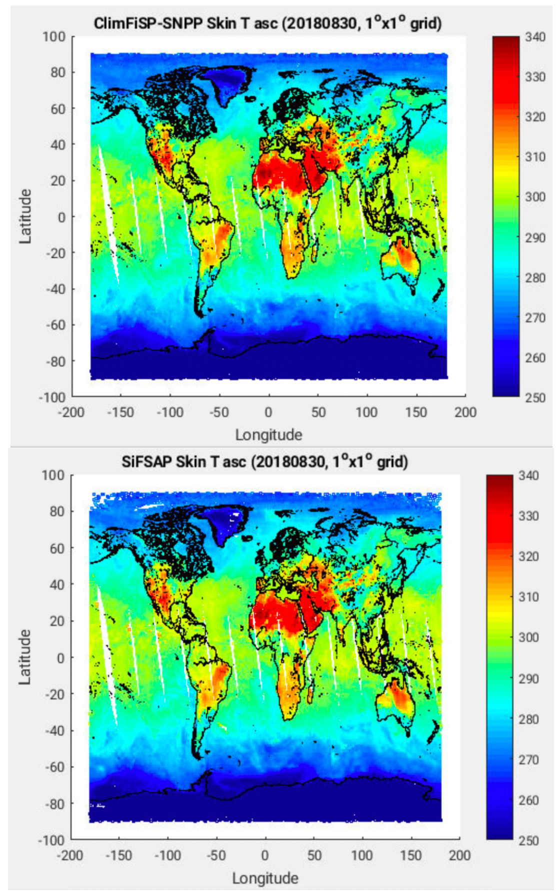

Figure 1 Day time surface skin temperature averaged over a $\mathbf{1^{o}} \times \mathbf{1^{o}}$ spatial grid for August 30, 2018. Top panel: data from ClimFiSP; Lower panel: data from SiFSAP.

3. CONSTRUCTING LONG TERM CLIMATE RECORD USING CHIRP DATA

CHIRP has been developed to facilitate the characterization and removal of the inter-satellite radiometric biases in combined AIRS-CrIS spectral radiance data records [2]. CHIRP converts the radiances of both AIRS and CrIS to a common Spectral Response Function (SRF) and a common wavenumber grid. The CHIRP record starts with AQUA AIRS data from September 1st, 2002, switches to S-NPP CrIS data from September 1st, 2016, and then to JPSS-1 CrIS from September 1st, 2018 [6].

S and **Σ** (Eq. 2) are built from S-NPP CrIS SiFSAP and converted from CrIS FSR mode to CHIRP mode, following the same a double Fourier transform scheme used to build S-NPP CHIRP [2]. We want to characterize the potential radiance shift due to the switch of sensors in CHIRP and illustrate the corresponding discontinuity introduced in long-term climate anomaly records via the spectral fingerprinting method. We have processed 16 years of CHIRP data from 2002 to 2018. Fig 2. highlights the difference between monthly mean spectral radiance anomaly (in Brightness Temperature) over the tropical region (S 20º to N 20º latitudinal zone) derived from CHIRP AIRS and that from CHIRP CrIS from September 1, 2016 to December 31, 2017.

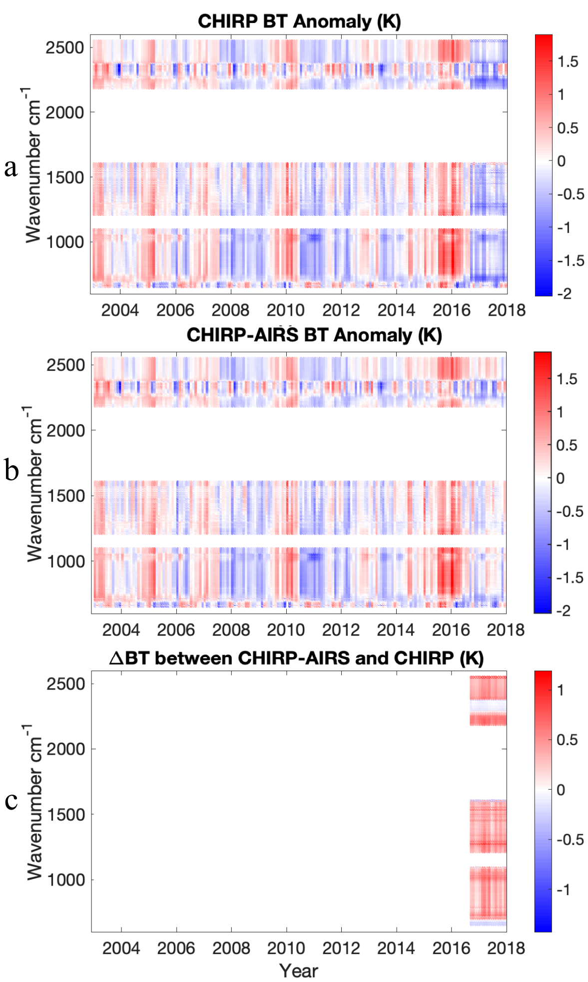

Figure 2 Nighttime tropical region monthly mean spectral radiance anomaly in Brightness Temperature (BT) from a) CHIRP and b) CHIRP AIRS. The difference due to the switch of sounder data from AIRS to CrIS starting from September, 2016 is illustrated in c).

Fig. 3 compares the surface skin temperature anomaly derived from years of CHIRP (AIRS + CrIS) with that from the AIRS only CHIRP using a consistent fingerprinting scheme.

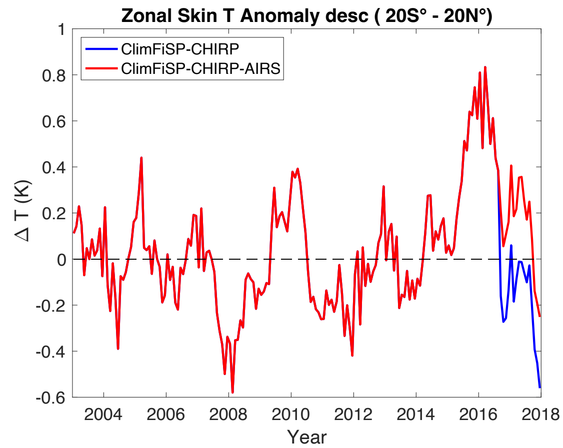

Figure 3 Nighttime tropical region monthly mean surface skin temperature anomaly derived from CHIRP and CHIRP-AIRS.

3. CONCLUSION

We have established a spectral fingerprinting methodology to derive long-term climate anomalies from a synthesized data record that combines measurements from different hyper-spectral IR sounders. We characterize the inter-satellite bias between overlapping measurements of AIRS and CrIS using CHIRP and further evaluate its impact on the surface skin temperature anomalies derived. Addressing the potential discontinuity in a climate data record is critical to ensure a high level of trust in climate trend analysis. The framework established here can be extended to construct long-term records of other essential climate variables.

5. REFERNECES

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