MUlti-SpEctral, MUlti-SpEcies, MUlti-SatEllite (MUSES) retrieval algorithm: towards extending multi-decadal NASA EOS atmospheric composition data records

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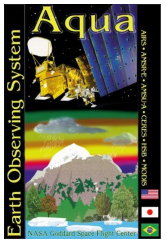
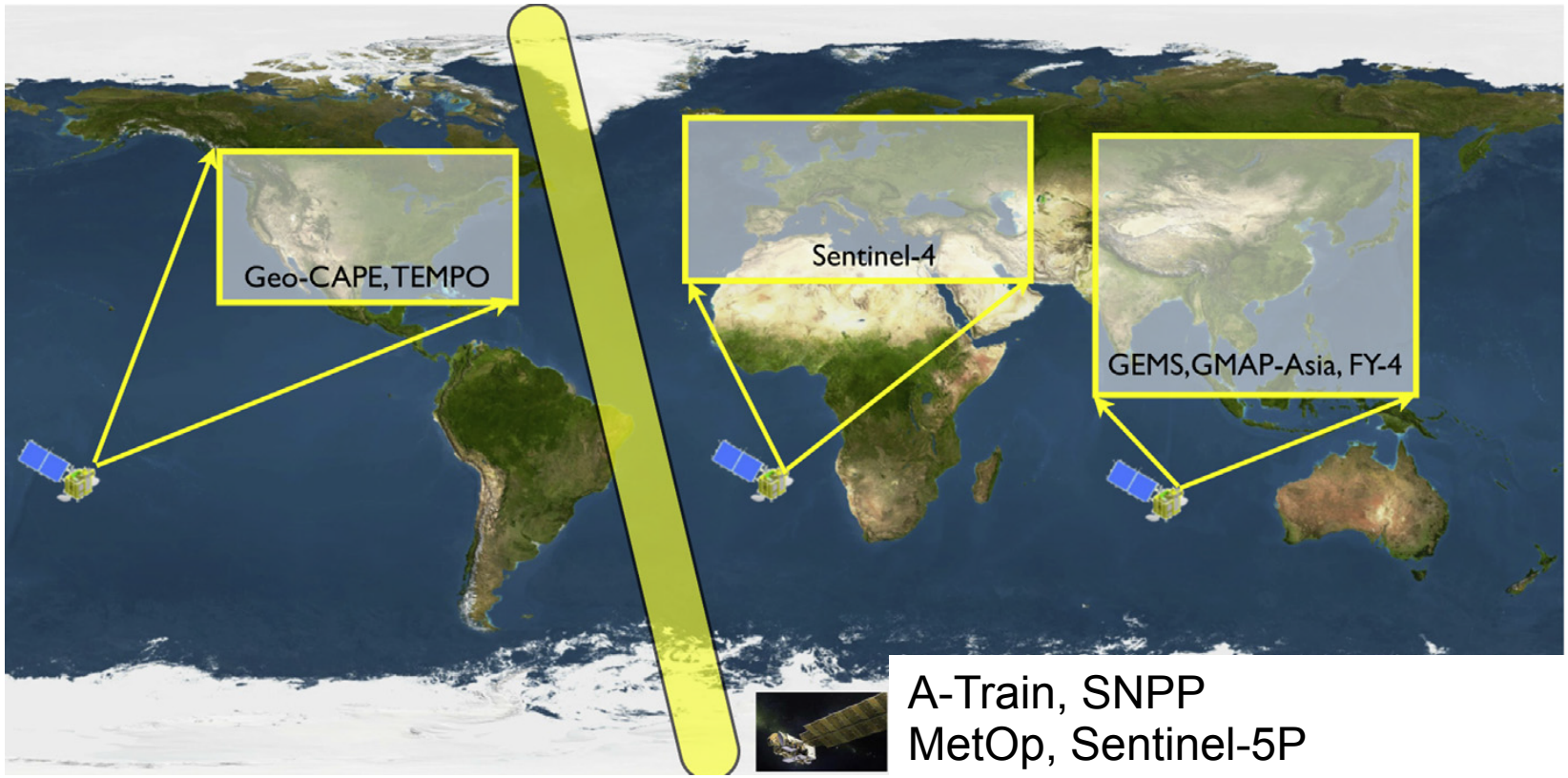


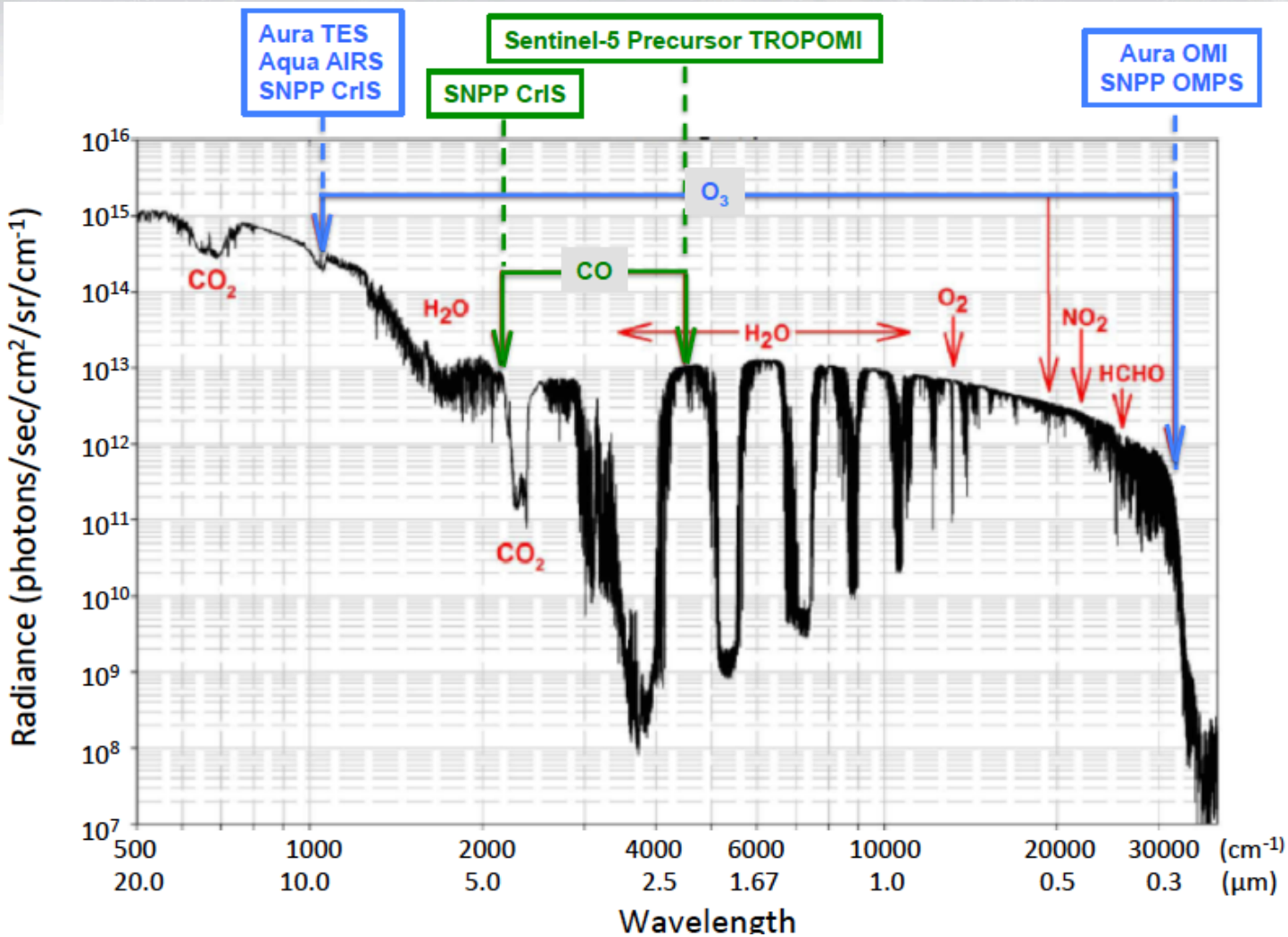
A new Atmospheric Composition Constellation to Observe Global and Regional Pollution

The rapid change in global emissions and their impact of air quality and climate requires a new observing system of GEO and LEO sounders to quantify global sources of local pollution.

- LEO A-Train AIRS/OMI and SNPP CrIS/OMPS can support this constellation by distinguishing lower and upper tropospheric O_3 signals
- LEO sounders will be a crucial link between GEO sounders over America, Europe and Asia as well as the sole satellite observations in the SH.



Spectral Regions Used in Joint Retrievals



This presentation will mainly report

- Joint AIRS/OMI ozone profile retrievals
- Joint CrIS/TROPOMI carbon monoxide profile retrievals [Fu et al., AMTD 2015]

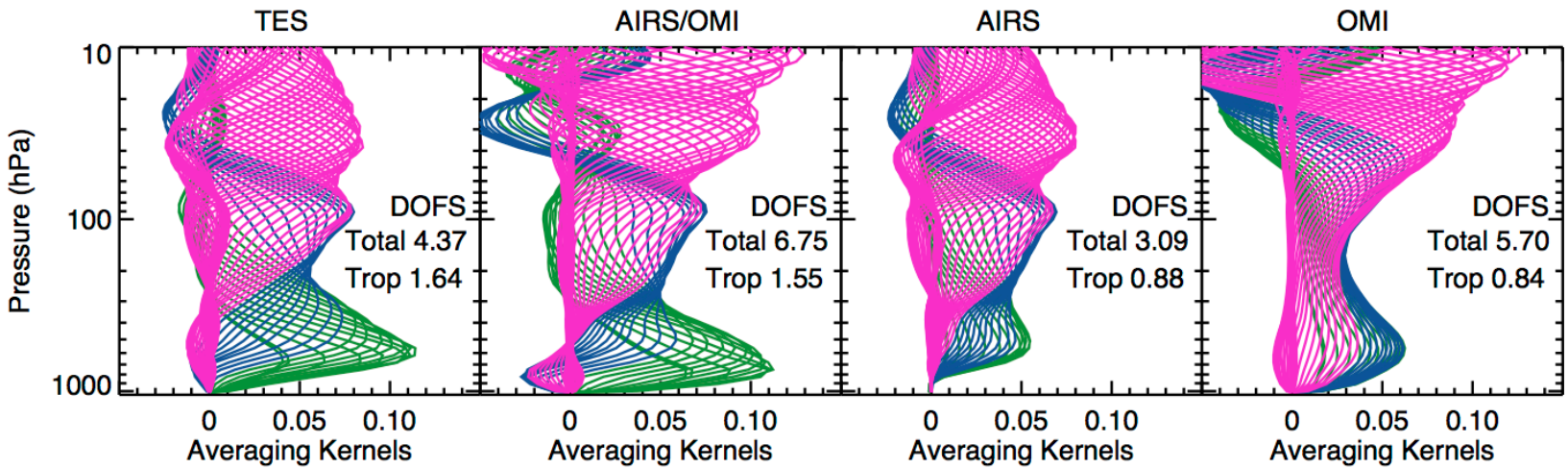
JPL MUSES Retrieval Algorithm

Multi-**S**pectra, **Mu**lti-**S**pecies, **Mu**lti-**Se**nsors (MUSES)

- Builds off of heritage from the Tropospheric Emission Spectrometer (TES) optimal estimation (OE) algorithm to combine *a priori* and satellite data; including rigorous error analysis diagnostics and observation operators needed for trend analysis, climate model evaluation, and data assimilation
- has generic design to incorporate forward model radiances from hyperspectral measurements from multiple sensors into the joint retrieval algorithm.
- We will demonstrate through prototype studies the following missions:
  - ozone profiles
    - ✓ TES/OMI -> probe the variability of [O_3] in the LMT (Fu D., *et al.*, ACP, 2013; Worden *et al.*, AMT 2013).
    - ✓ AIRS/OMI/MLS -> provide decade long global record of O_3 profiles with the highest vertical resolution and accuracy compared to any single platform on A-Train satellites
    - ✓ CrIS/OMPS -> extend EOS O_3 data records with the highest vertical resolution and accuracy compared to any single nadir sensor on SNPP satellite
  - carbon monoxide profiles
    - ✓ CrIS/TROPOMI -> extend EOS MOPITT CO data records [Fu et al., AMTD 2015]

Sample Averaging Kernels and Estimated Uncertainty

- JPL MUSES provides rigorous error analysis diagnostics and observation operators needed for trend analysis, climate model evaluation, and data assimilation
- Joint AIRS/OMI (using single footprint L1B radiances) vs. each instrument alone
  - Total DOFS of 6.8, and Tropospheric DOFS of 1.6, and smaller total error
  - When adding MLS information, tropospheric DOFS increases to 3.0



e.g., a data assimilation system applies an observation operator (H)

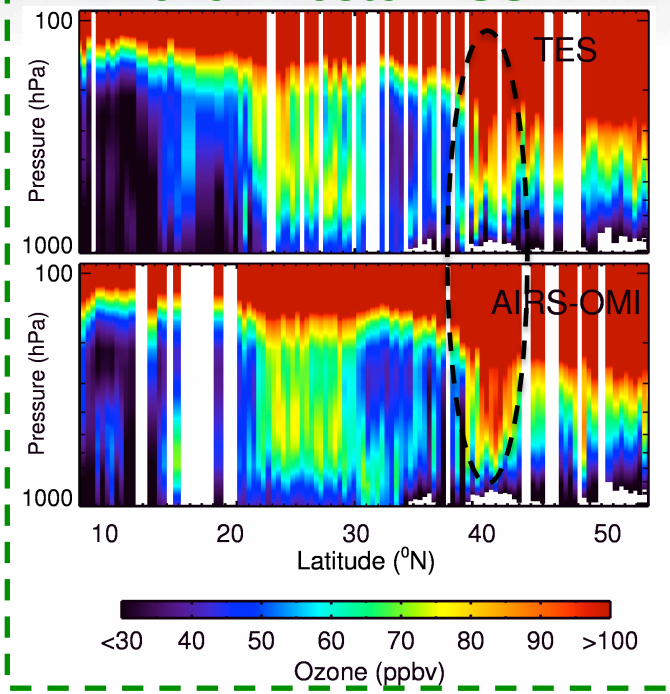
$$y^s = H(x) = x_a + \mathbf{A}(x_{model} - x_a) \quad \text{(Equation 1)}$$

where, y^s is the model profiles with vertical resolution identical to that of satellite observations, x_a is a *priori* profiles used in the retrievals, **A** is the averaging kernels of satellite observations. After applying observation operator to model profiles, the satellite-model differences (y^o - y^s) is not biased by the *a priori* used in the retrievals.

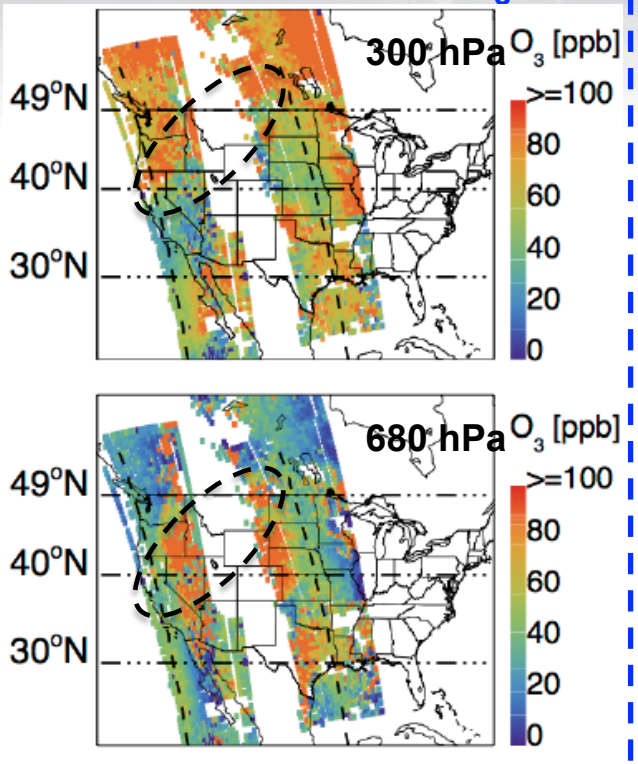
$$\Delta y = y^o - y^s = \mathbf{A}(x_{true} - x_{model}) + \varepsilon \quad \text{(Equation 2)}$$

Joint AIRS/OMI observations on August 23, 2006 during TexAQS Aircraft Flight Campaign

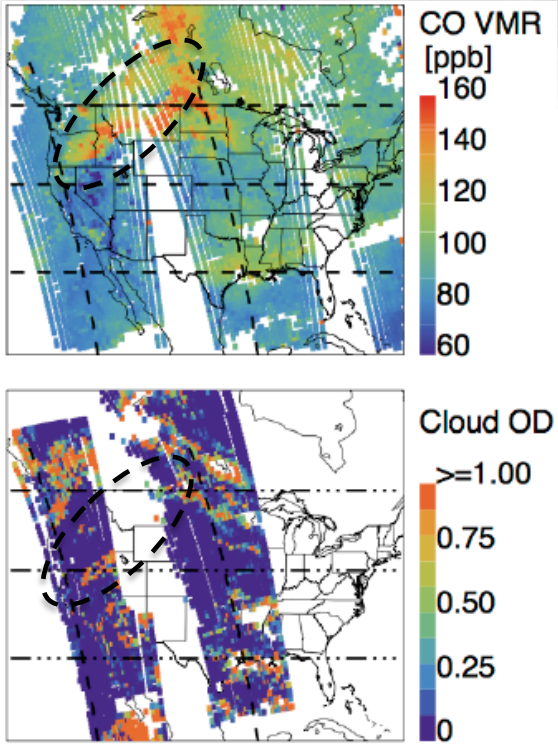
Collocated TES & Joint AIRS/OMI O_3 Measurements over Western USA



Joint AIRS/OMI O_3



AIRS CO and Cloud



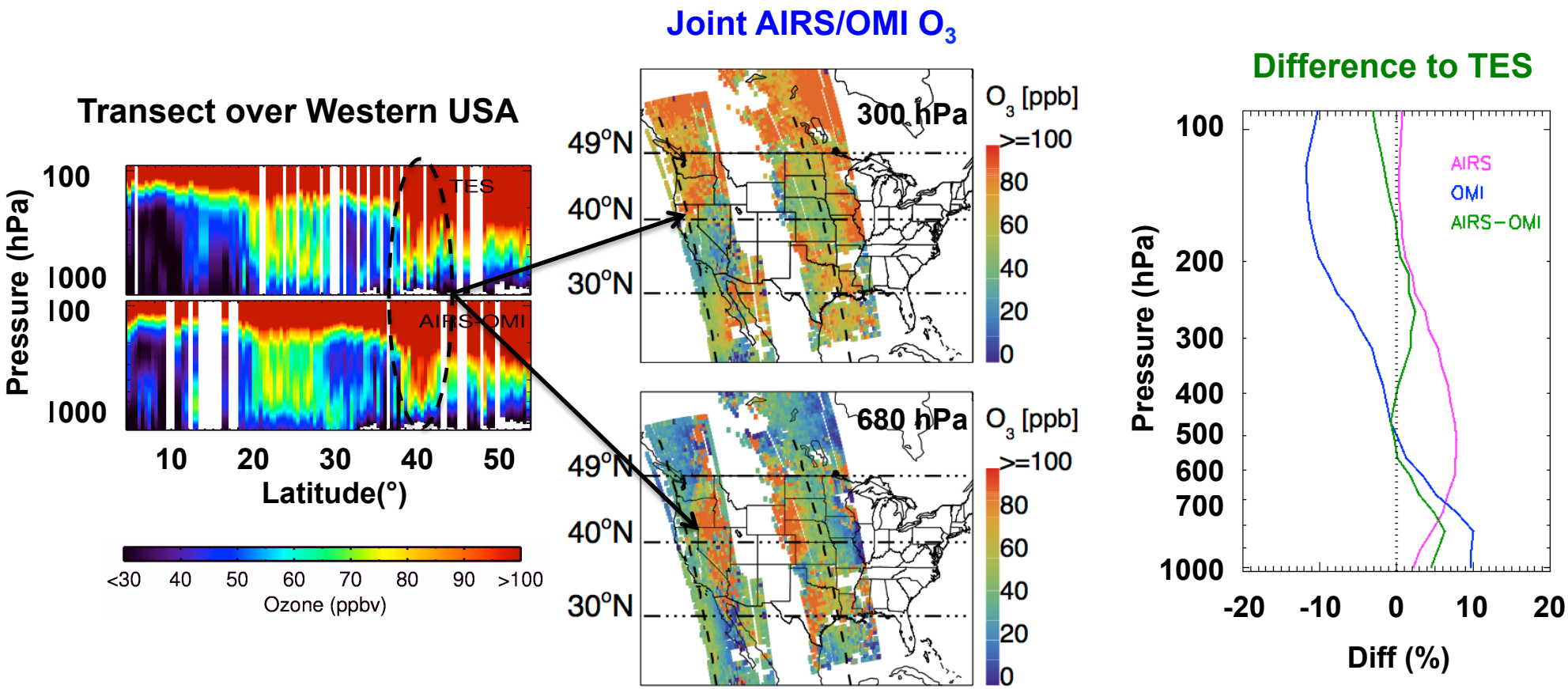
Joint AIRS/OMI observations on August 23, 2006 during TexAQS aircraft flight campaign

- MUSES is capable of providing regional scale daily maps of O_3 and its precursors (CO, NH_3, CH_3OH, HCOOH, CH_4, PAN) using measurements from multiple space sensors (TES, AIRS, CrIS, OMI, OMPS).
- Joint AIRS/OMI O_3 data product is capable of distinguishing the amount of O_3 between lower and upper trop, similar to TES, with broader spatial coverage, could help in distinguishing between local and non-local drivers of pollution.
- Joint AIRS/OMI O_3 data are being applied to quantify the impacts of fire emissions on air quality. Figure showed that enhanced ozone was detected, collocating to the enhanced CO due to the fire emissions.

Comparisons to Aura-TES Operational L2 O_3 Data Products

Joint AIRS/OMI ozone retrievals

- Differ from the *a priori* profiles
- Show best agreement to TES, in comparisons to each instrument alone

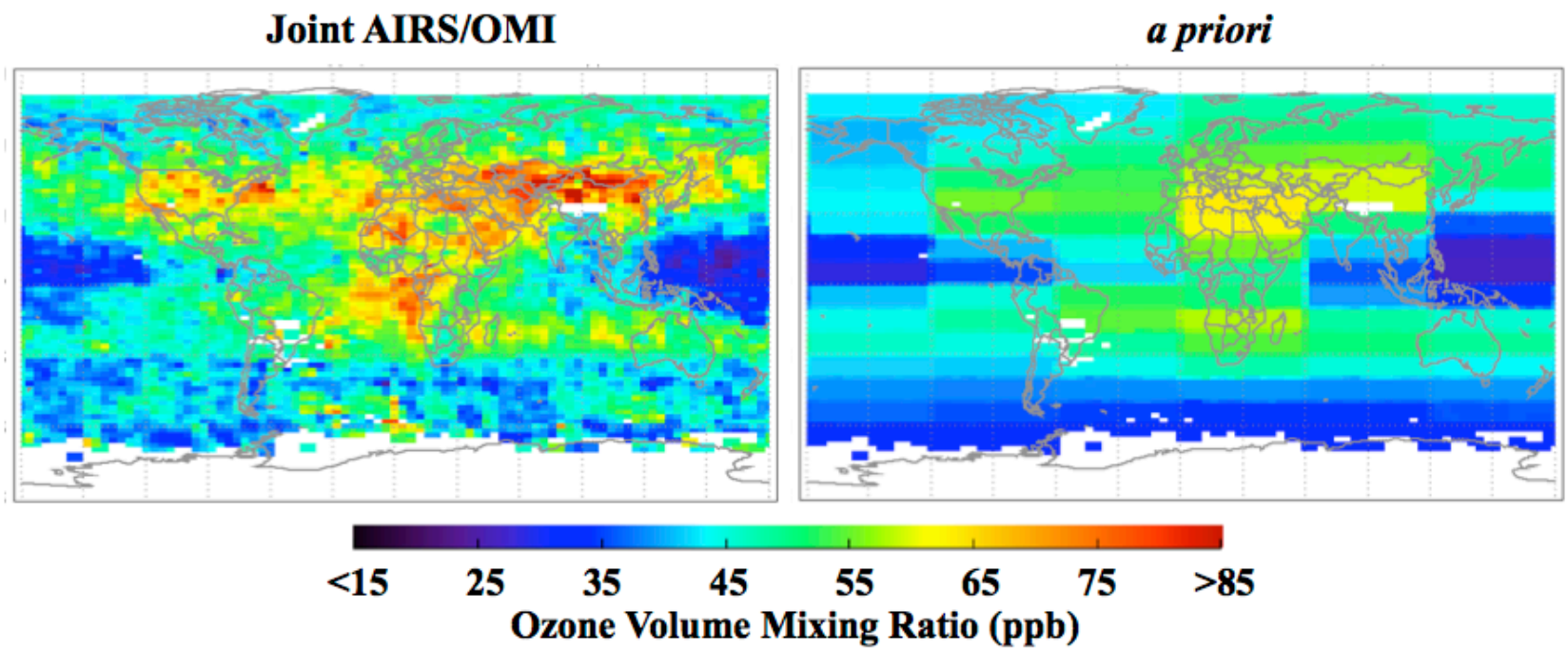


Monthly O_3 Global Maps – towards Providing Decade Long Global Ozone Profiles

The JPL MUSES has been implemented and applied to joint AIRS/OMI ozone retrievals over global scale. We are processing June to August 2006 data.

Characteristics (e.g., August 2006)

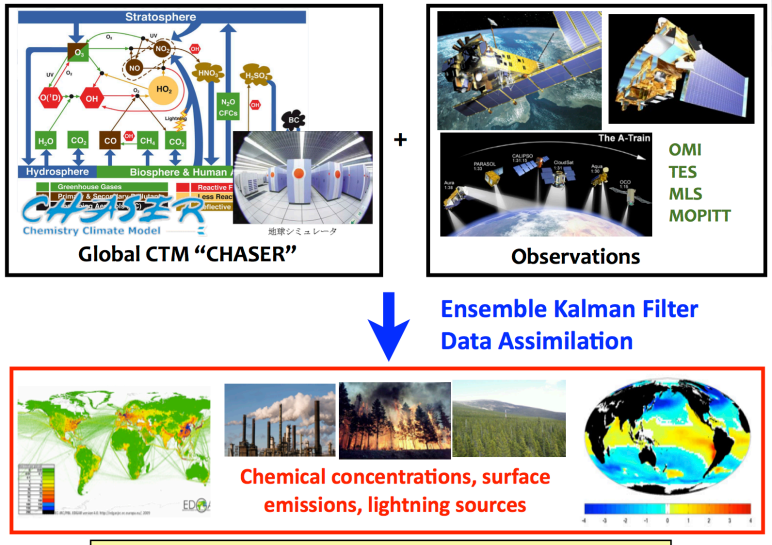
- Both TES and Joint AIRS/OMI show similar spatial patterns, e.g., capturing the enhanced ozone over the continental outflow and biomass burning active regions
- Differ from *a priori*



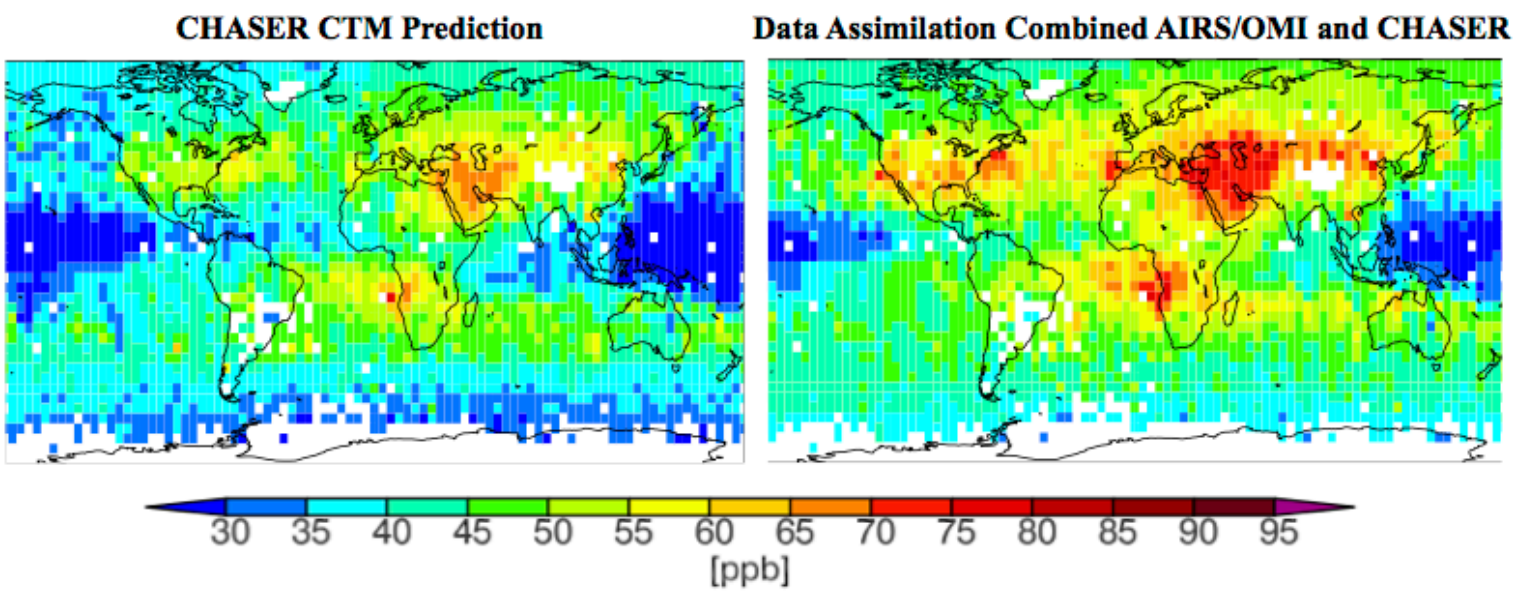
Data Assimilation System of the NASA A-Train Observations

- Dr. Kazuyuki Miyazaki, implemented the CHASER data assimilation system.

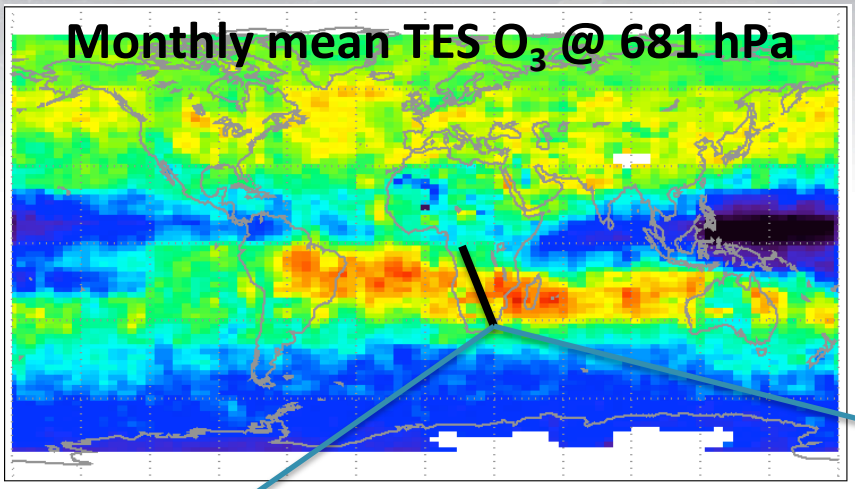
- Joint AIRS/OMI ozone data has been assimilated into the CHASER-DA, which has a proven capability to assimilate the atmospheric composition observations from multiple A-Train instruments.
- CHASER-DA leads to chemically/dynamically consistent integrated atmospheric state.

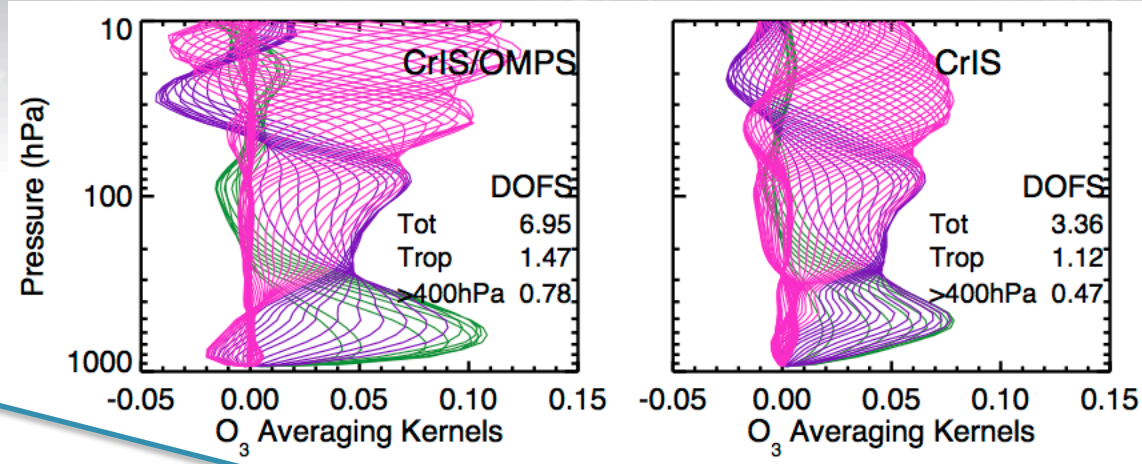


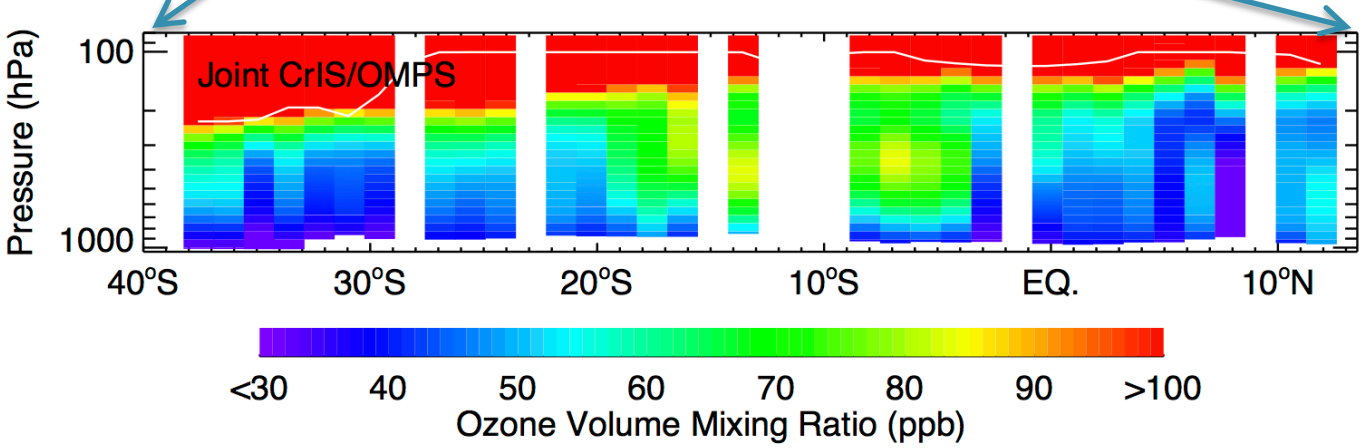
Miyazaki, 2009; Miyazaki et al., 2011, 2012a, 2012b, 2013, 2014, 2015

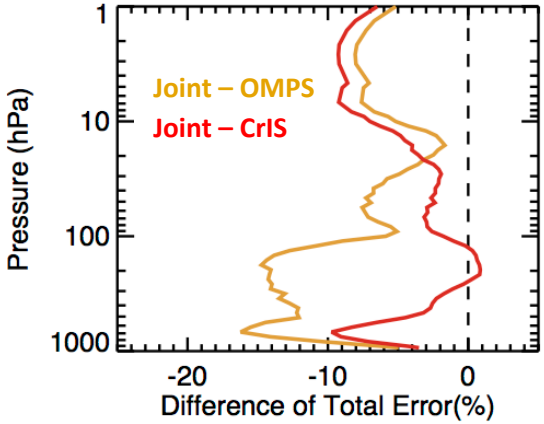


Joint CrIS/OMPS Retrievals – towards Extending EOS O_3 Data to Next Decade(s)









- CrIS/OMPS would provide measurements from 2012 – 2027.
- MUSES algorithm is capable of performing joint CrIS/OMPS ozone retrievals – vertical resolution and measurement uncertainty similar to that of AIRS/OMI measurements.
- Joint CrIS/OMPS O_3 and CrIS CO observations will support the NOAA FIREX flight campaign (Fire Influence on Regional and global Environments Experiment) – an intensive study of the impacts of western North America fires on climate and air quality.

Joint CrIS/TROPOMI Retrievals – towards Extending EOS CO Data

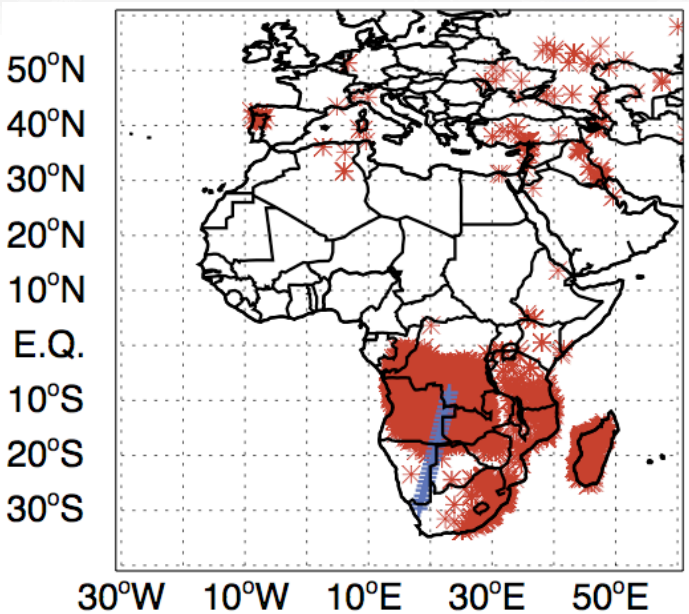
- All NASA space missions capable of measuring atmospheric CO concentration from space, have passed their nominal lifetime by years.
- MOPITT is the only satellite borne senor now that has both TIR and NIR channels.
- Joint TROPOMI/CrIS measurements are the only space sensors in the coming years (>=7 years) that could extend the MOPITT multi-spectral data record.

Mission	Nominal Life Time	Years after Its Design Life Time	Spectral Resolution		Footprint Size	Swath Width
	Start – End	Year	TIR[a] cm^{-1}	NIR[b] cm^{-1}	km^2	km
CrIS/TROPOM	**2016 – 2023**	**0**	**0.625**	**0.458**	**14×14**	**2200**
MOPITT	2000 – 2006	9	0.500	0.500	22×22	640
CrIS	2011 – 2026	0	0.625	NA	$\pi \times (14/2)^2$	2200
TES	2004 – 2010	5	0.060	NA	8×5	5
AIRS	2002 – 2008	7	~ 1.800	NA	$\pi \times (14/2)^2$	1600
TROPOMI	2016 – 2023	0	NA	~ 0.458	7×7	2600
SCIAMACHY	2002 – 2007	Terminated	NA	~ 0.485	30×60	960

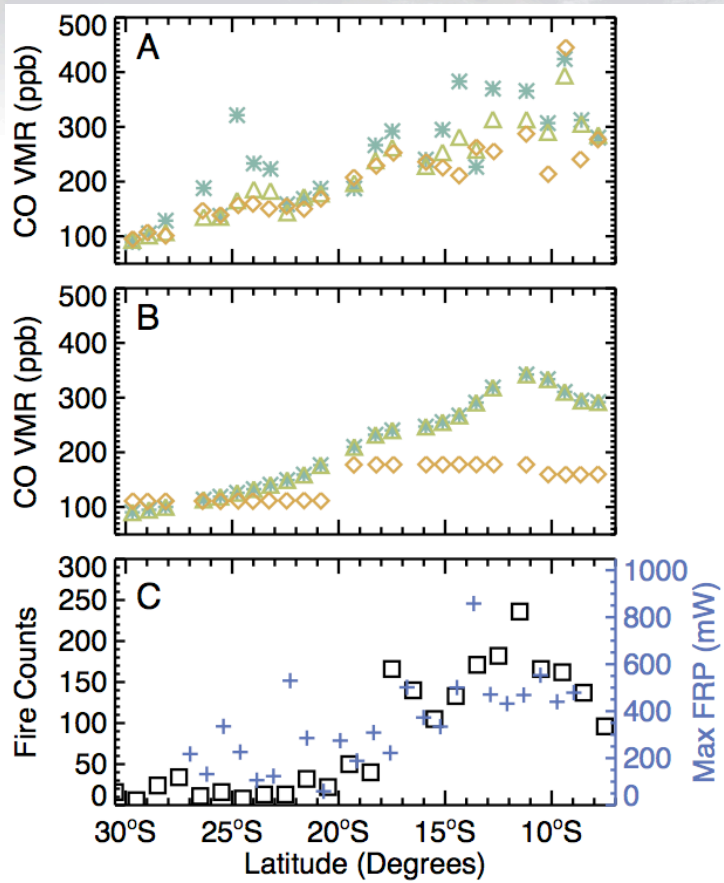
[a] First fundamental band of carbon monoxide, centered around 4.6 μm in the thermal infrared.
[b] First overtone band of carbon monoxide, centered around 2.3 μm in the near infrared.

CrIS Retrievals and Comparisons to MOPITT Operational Level 2 Data Products for August 27-28, 2013

MOPITT and CrIS pixel location
MODIS fire location



Fu *et al.*, AMTD, 2015



[A] Retrieved CO VMR
mean [surface to 700 hPa]
Joint MOPITT TIR/NIR
MOPITT TIR
CrIS

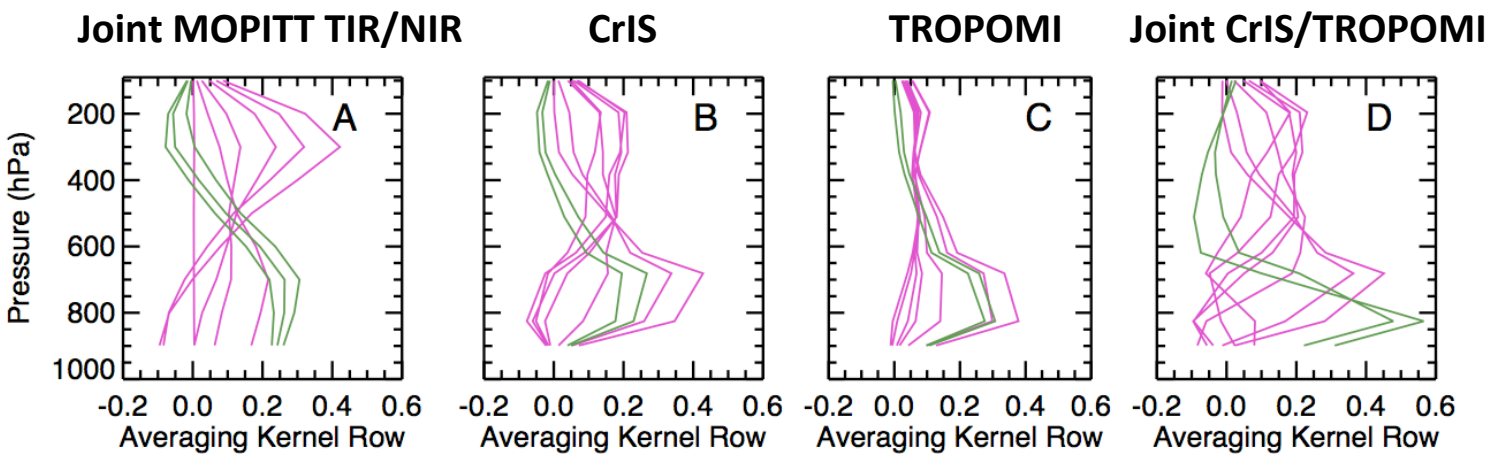
[B] A priori CO VMR
mean [surface to 700 hPa]
MOPITT
CrIS

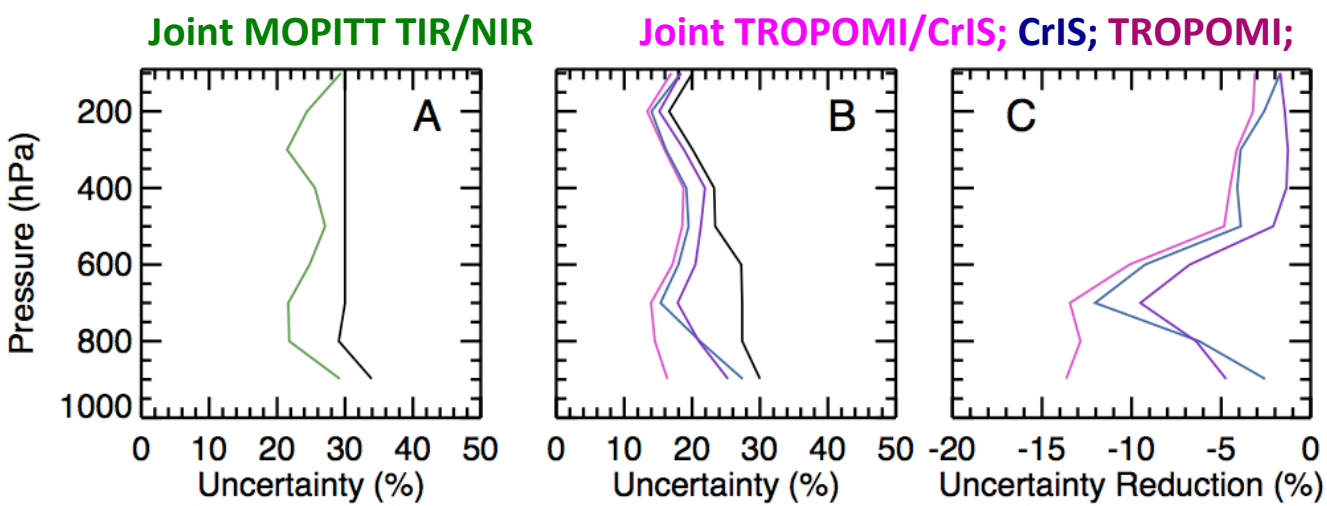
[C] MODIS
Fire Counts
Fire Radiative Power

Data Products in Comparisons	Mean ppb	RMS ppb
CrIS - MOPITT TIR	-6.9	22.8
CrIS - MOPITT Joint TIR/NIR	-22.9	38.8

Joint CrIS/TROPOMI CO Retrievals – Improving Vertical Sensitivity and Reducing Uncertainty

Altitude	Sensor	TIR	NIR	Joint TIR/NIR
Surface to TOA	MOPITT	1.4	0.5	1.9
	CrIS	1.6	-	2.2
	TROPOMI	-	1.3	





Summary

- The JPL MUSES retrieval algorithm has the capability of combining AIRS and OMI measurements to provide improved ozone data products, in compared to each instrument alone.
  - are able to distinguish the ozone abundances in the upper troposphere from the lower troposphere
  - show better agreement to the well-validated TES data products
- The JPL MUSES retrieval algorithm is able to process joint AIRS/OMI observations over global scale – leading to provide the decade long global ozone data records that fully satisfy the NASA EOS data product standards.
- The joint AIRS/OMI data products have been assimilated in global CTM "CHASER", demonstrating the potentials of this data products. Our colleagues are working on assimilating AIRS/OMI data products in GEOS-Chem model.
- The flexibility of JPL MUSES has demonstrated through the prototype retrievals for multi-satellite missions [TES/OMI (Fu et al., ACP 2013), AIRS/OMI, CrIS/OMPS, CrIS/TROPOMI (Fu et al., AMTD, 2015)].
- We are preparing manuscripts that summarize the JPL MUSES retrieval algorithm, sample retrievals and their characteristics.
- Thank you for attention. Questions?

Backup

Joint OMI/AIRS/MLS Retrievals: towards Decade Long Global Record of Ozone Profiles

- By incorporating the assimilated Aura MLS ozone profiles into the joint retrievals, the vertical resolution and error characteristics of these joint OMI/AIRS tropospheric ozone estimates can be substantially improved, compared to joint OMI/AIRS measurements.
- This increased sensitivity is critical for evaluating the radiative response of ozone to surface emissions and the role of stratospheric / tropospheric exchange, long range transport, and tropical fires (or pyro-convection) on the tropospheric ozone distribution.