Joint AIRS+OMI Ozone Profile data for KORUS-AQ:

Updates on Validation and Science Applications

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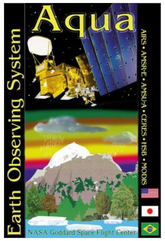
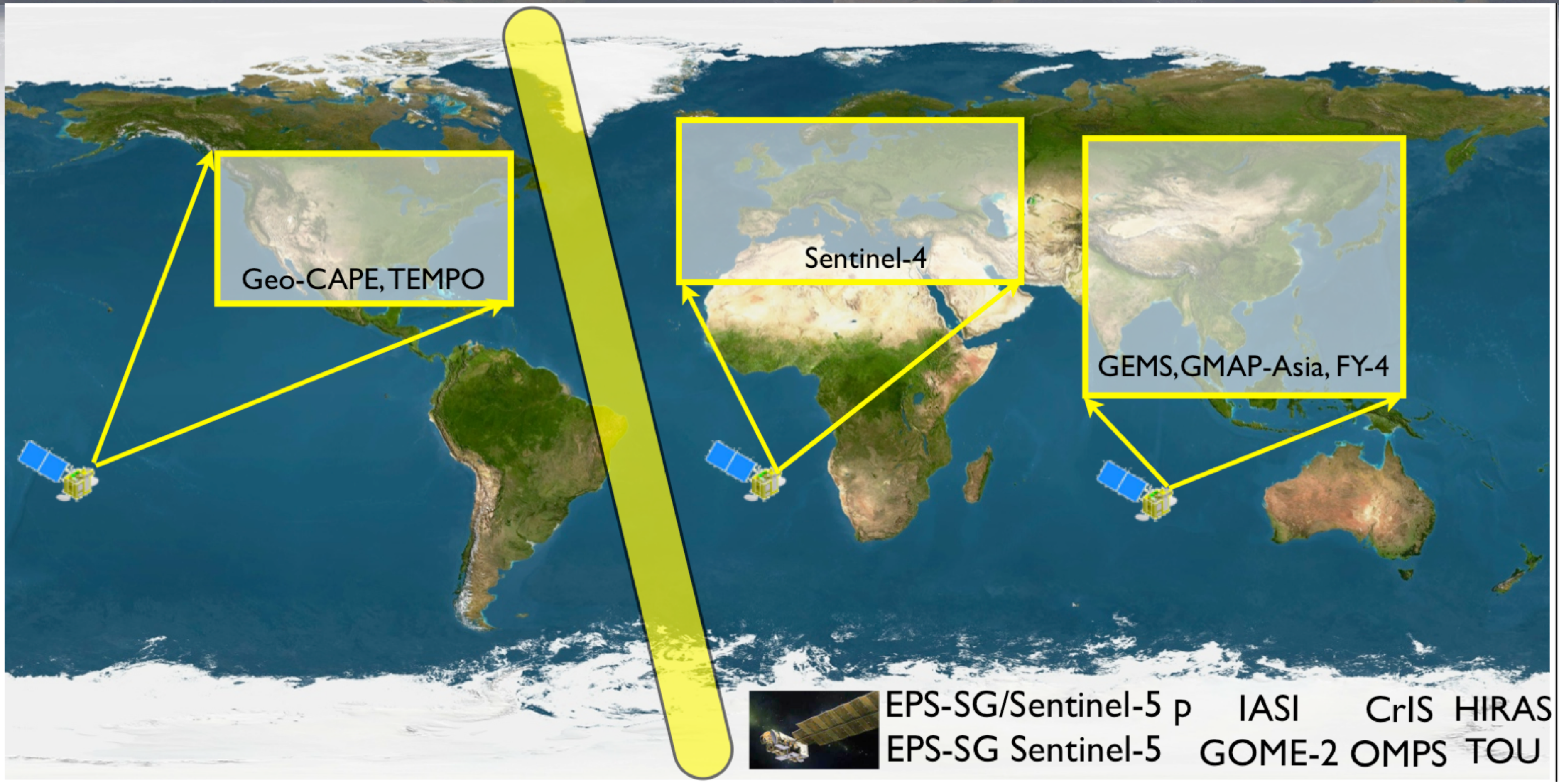


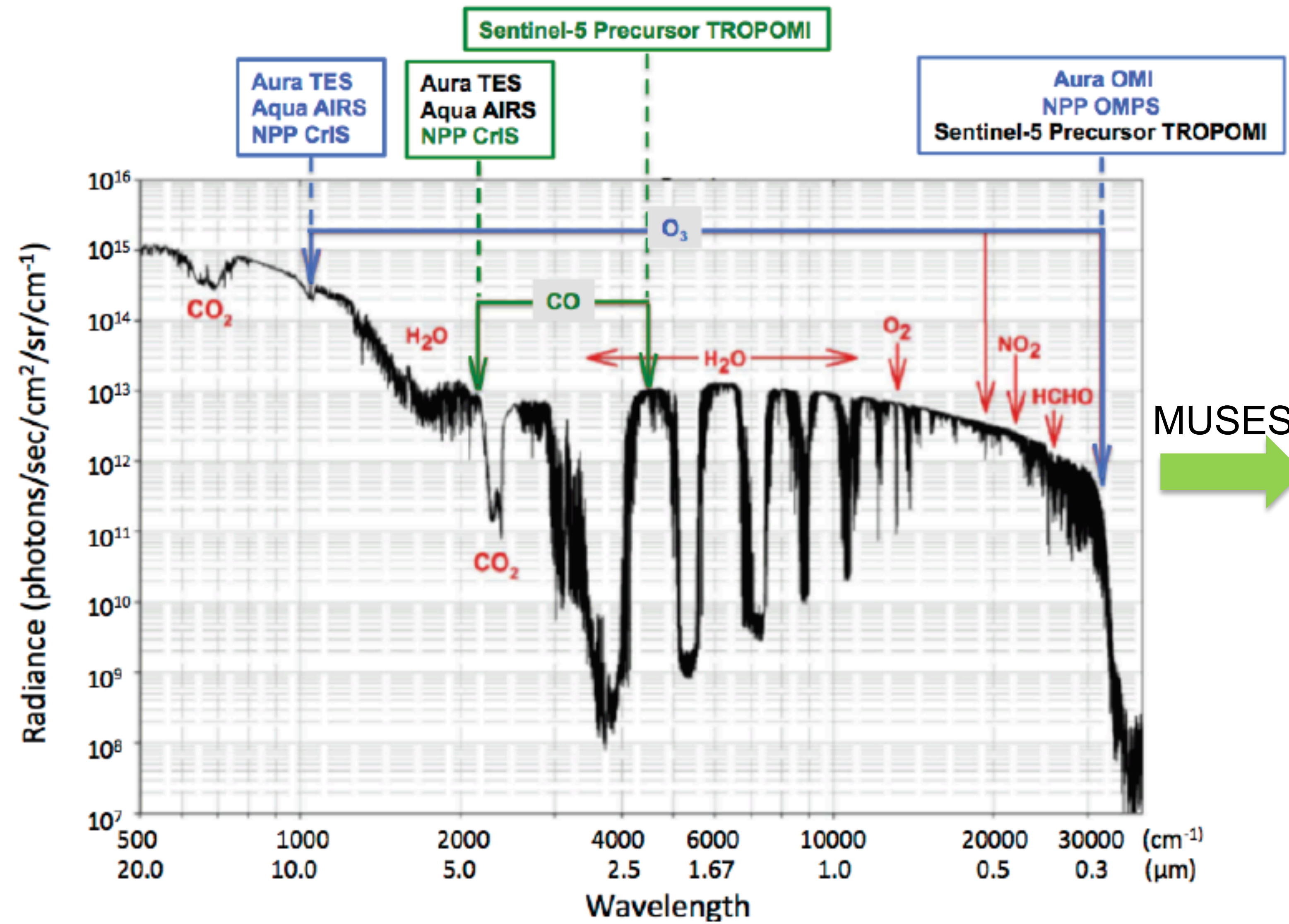
Towards an Air Quality Constellation

Bowman, *Atm. Env.* 2013

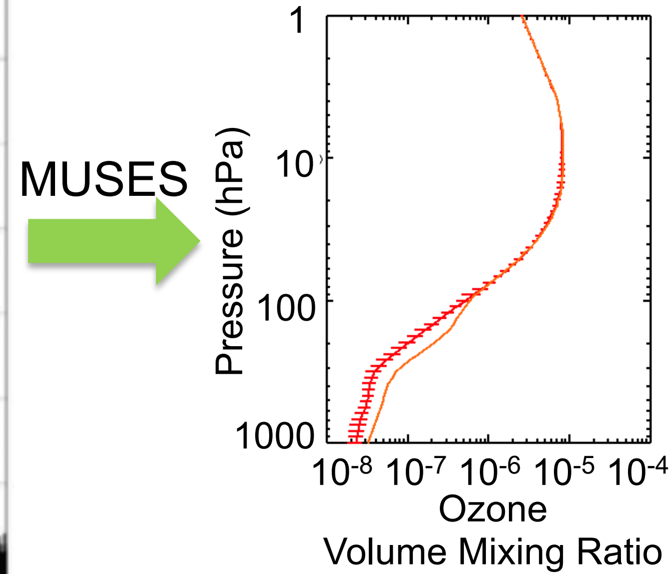


- A new generation of geostationary and low-earth orbiting (LEO) sounders will form a new composition-climate constellation.
  - Geostationary sounders including GEO-CAPE, TEMPO, Sentinel-4, GEMS will provide an unprecedented number of composition observations at high spatial resolution.
  - LEO sounders including IASI, CrIS, S5p provide the global picture and thread the geostationary observations together.
- How does the constellation improve knowledge of global air quality?

The Pan-spectral approach

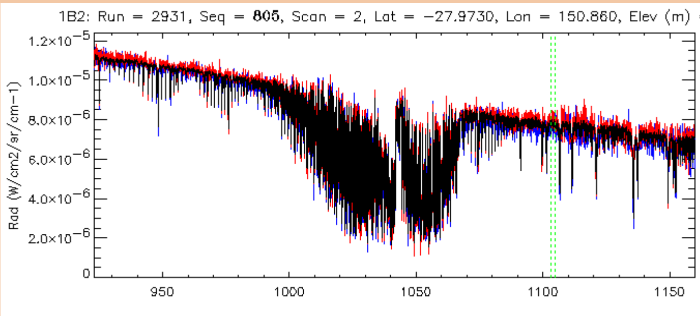


MUlti-SpEctra, MUlti-SpEcies, MUlti-SEnsors (MUSES)

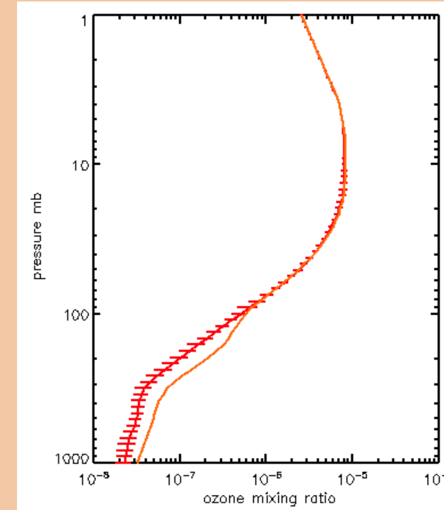


Measurements from TIR (LW) are sensitive to the free-tropospheric trace gases.
Measurements from UV-Vis-NIR (SW) are sensitive to the column abundances of trace gases.
Joint LW/SW or ultra-high spectral resolution measurements can distinguish upper/lower troposphere.

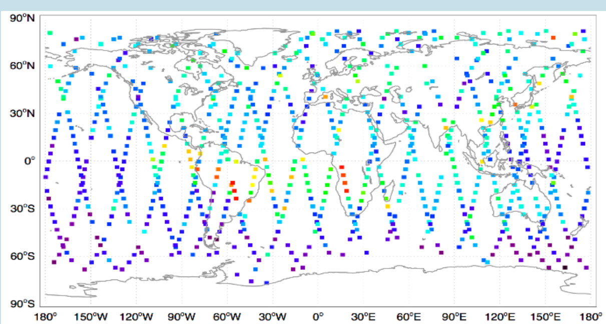
Connecting remote sensing to assimilation



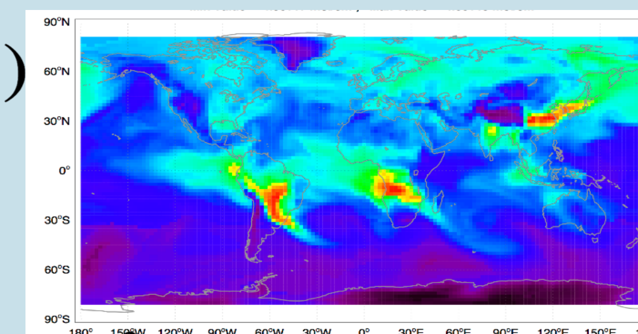
$$\|\mathbf{y}-\mathbf{F}(\mathbf{x}_a)\|^2_{\mathbf{S}_n^{-1}} + \|\mathbf{x}-\mathbf{x}_a\|^2_{\mathbf{S}_a^{-1}}$$



$$\hat{\mathbf{x}} = \mathbf{x}_a + \mathbf{A}(\mathbf{x}-\mathbf{x}_a) + \mathbf{Gn}$$



$$\mathbf{H}_i(\bullet) = \mathbf{x}_a + \mathbf{A}_i(\bullet - \mathbf{x}_a)$$

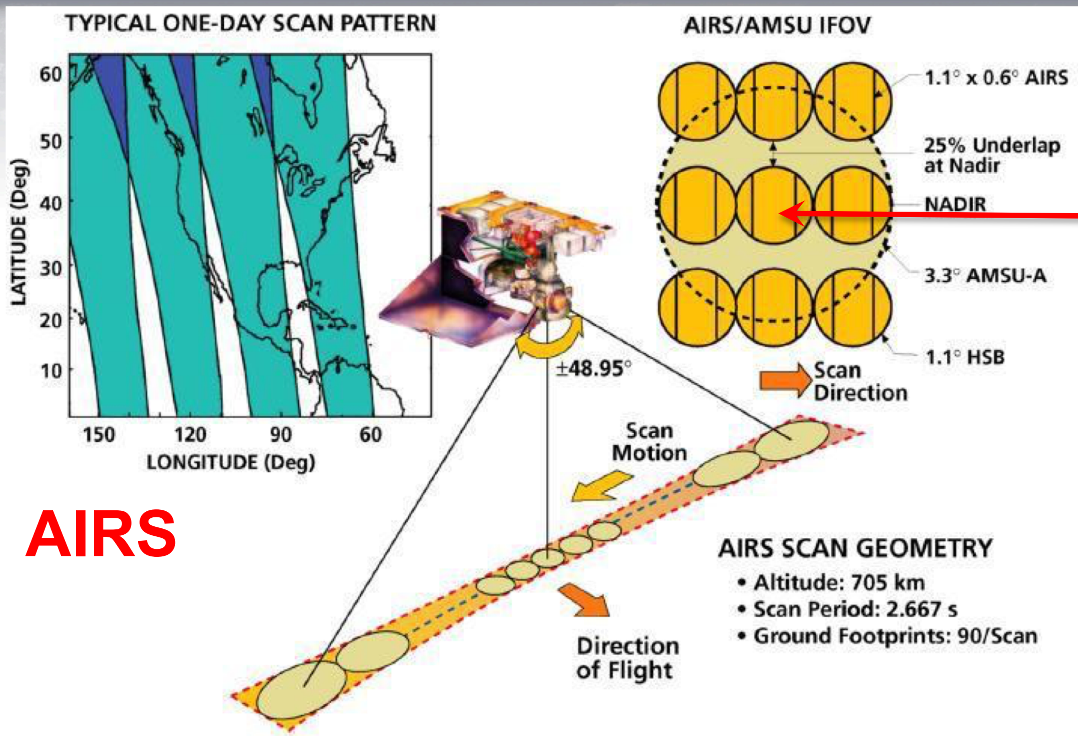


$$\sum_i \|\hat{\mathbf{x}}_i - \mathbf{H}_i(\mathbf{x})\|^2_{(\mathbf{G}_i\mathbf{S}_n^i\mathbf{G}_i^T)^{-1}} + \|\mathbf{x}_0 - \mathbf{x}_B\|^2_{\mathbf{B}^{-1}}$$

Optimal estimation (OE) techniques and error diagnostics (e.g., Bowman et al, 2002, 2006; Worden et al, 2004; Kulawik et al, 2006, 2008) for remote sensing along with the development of instrument operators for evaluation against models and assimilation are critical (Jones et al, 2003, Miyazaki et al, 2015).

The science community has come to expect these tools for rigorous science and assimilation of remote sensing data, e.g., Alvarado et al, 2015

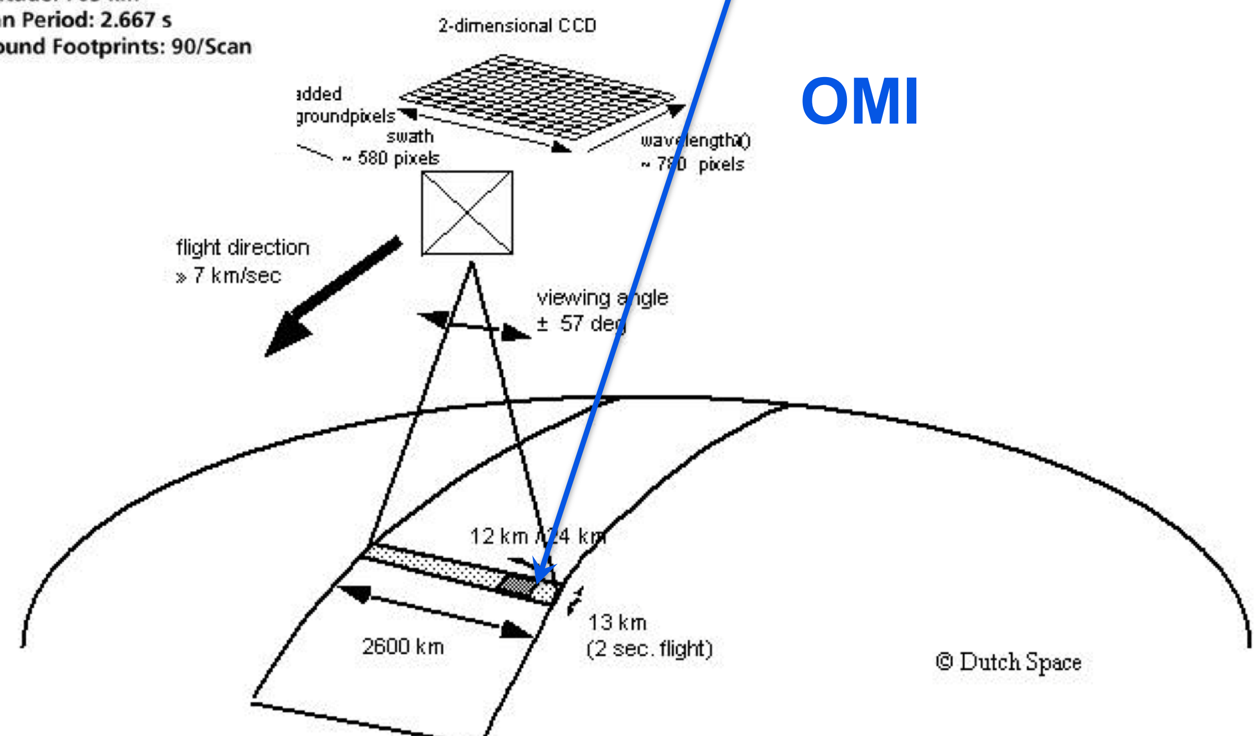
Combined AIRS single footprint to OMI measurements



AIRS

This work combines **AIRS single footprint L1B radiances** to **OMI measured radiances** for retrieving O_3 profiles.

OMI



AIRS/OMI O_3 Compare well with TES Global Survey Mode

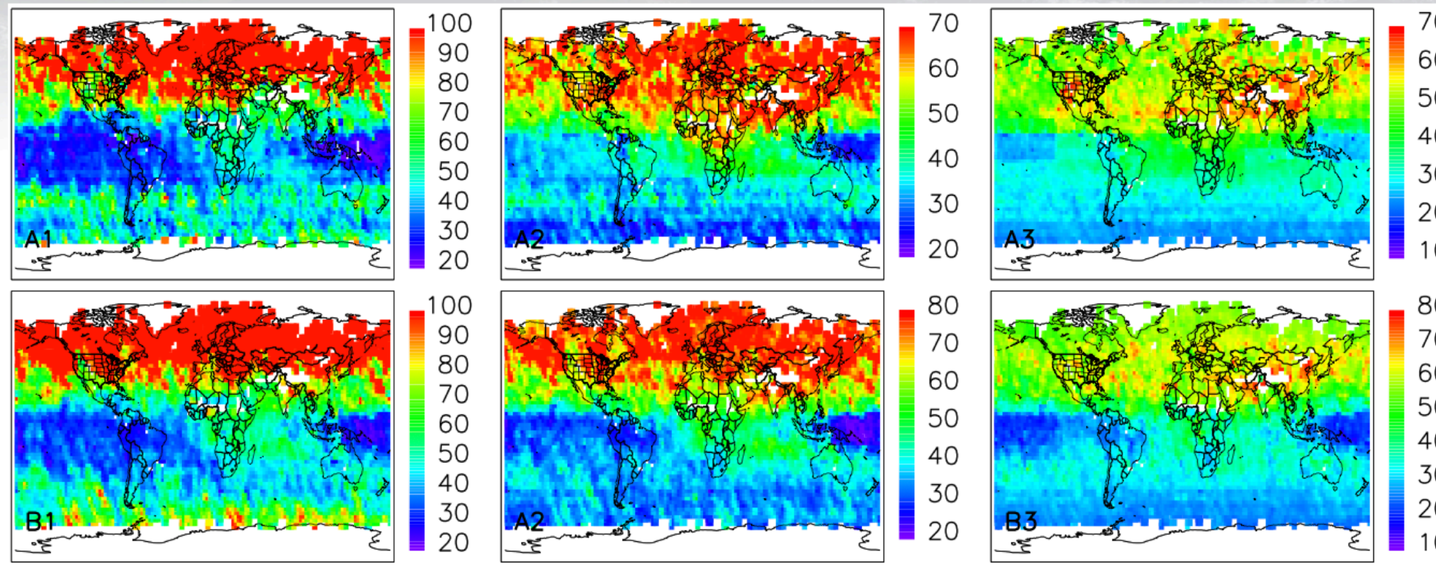
Fu et al., Submit to AMT 2018.

316 hPa | 510 hPa | 750 hPa

Joint AIRS+OMI

May 2006

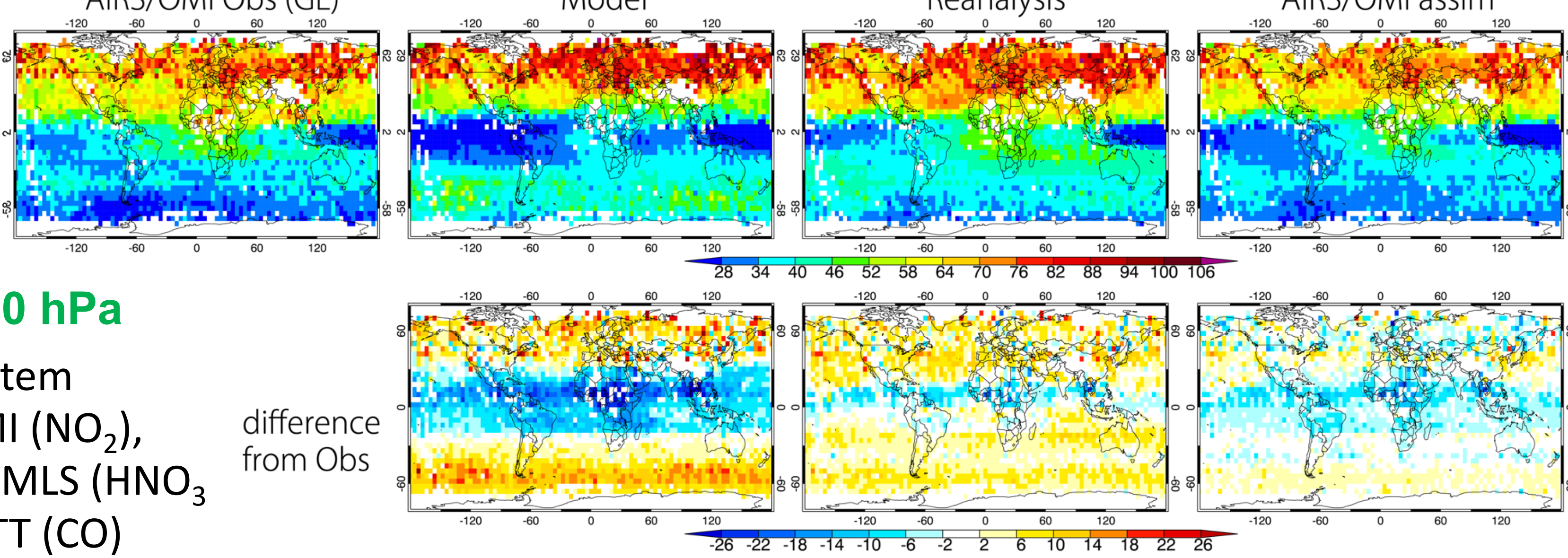
TES v6



Miyazaki et al., Submit to JGR 2018

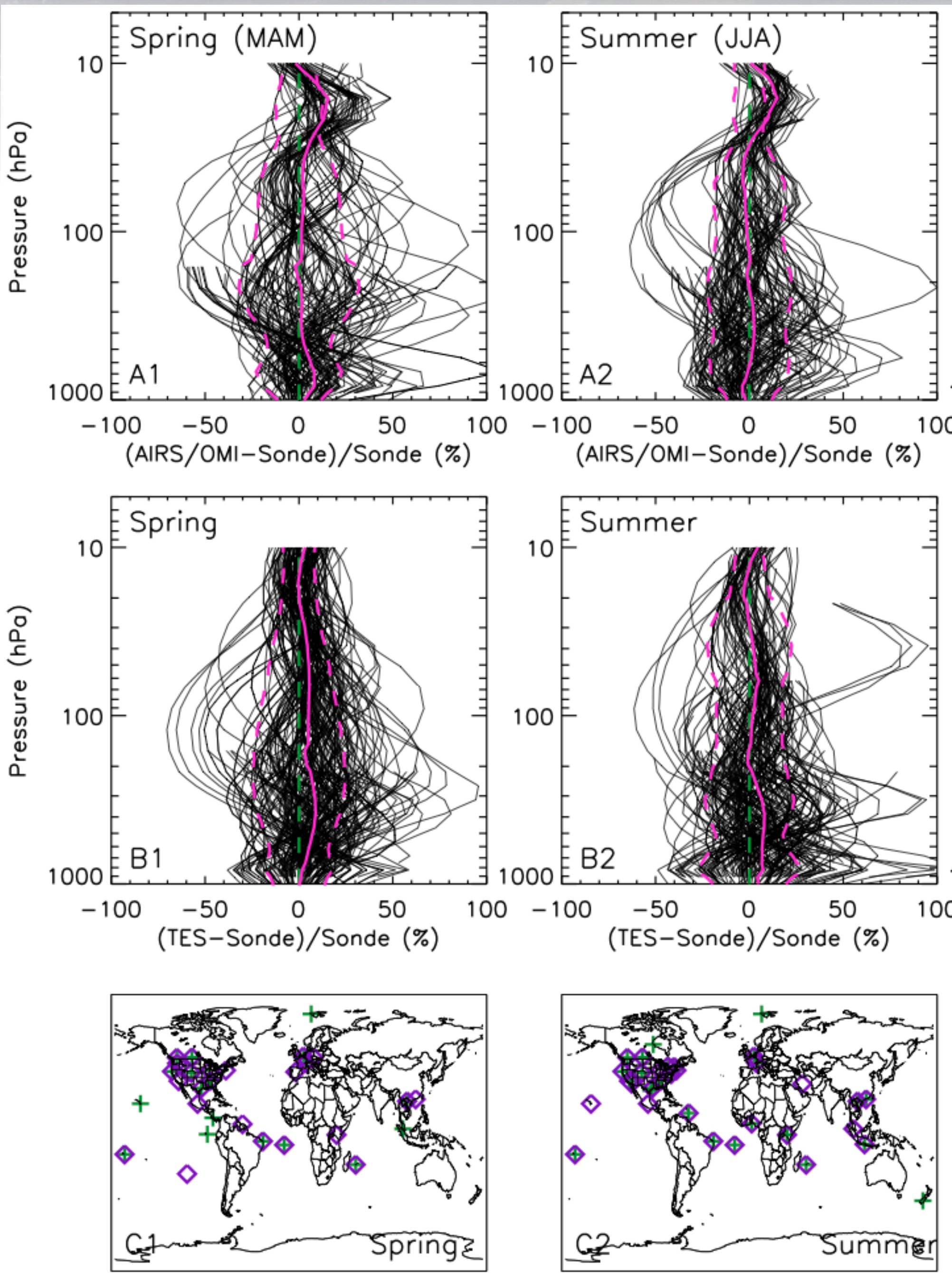
AIRS/OMI Obs (GL) | Model | Reanalysis | AIRS/OMI assim

difference from Obs



- **May 2016; 510 hPa**
- CHASER-DA system assimilated OMI (NO_2), GOME-2 (NO_2) MLS (HNO_3 and O_3), MOPITT (CO)

Comparisons to WOUDC Ozonesondes



Differences (Satellite – WOUC Sonde with Satellite Observation Operator Applied)

316 hPa	Spring		Summer	
	AIRS+OMI	TES	AIRS+OMI	TES
Mean (ppb)	2.8	6.1	0.7	4.2
Mean (%)	1.3	8.6	2.2	6.6
RMS (ppb)	17.1	19.2	13.4	17.0
RMS (%)	25.6	23.7	20.4	23.8
510 hPa	**Spring**		**Summer**	
	AIRS+OMI	TES	AIRS+OMI	TES
Mean (ppb)	1.3	3.6	-0.8	3.5
Mean (%)	3.8	7.0	1.6	7.3
RMS (ppb)	7.6	9.2	10.9	10.6
RMS (%)	17.2	17.4	20.4	17.9
750 hPa	**Spring**		**Summer**	
	AIRS+OMI	TES	AIRS+OMI	TES
Mean (ppb)	2.4	1.7	-2.2	2.6
Mean (%)	8.0	3.4	-2.0	6.6
RMS (ppb)	7.6	6.9	8.6	12.5
RMS (%)	21.1	16.2	18.8	25.3
Number of WOUDC Sonde Sites	20	25	27	30
Number of Satellite/Sonde Coincident	131	197	134	171

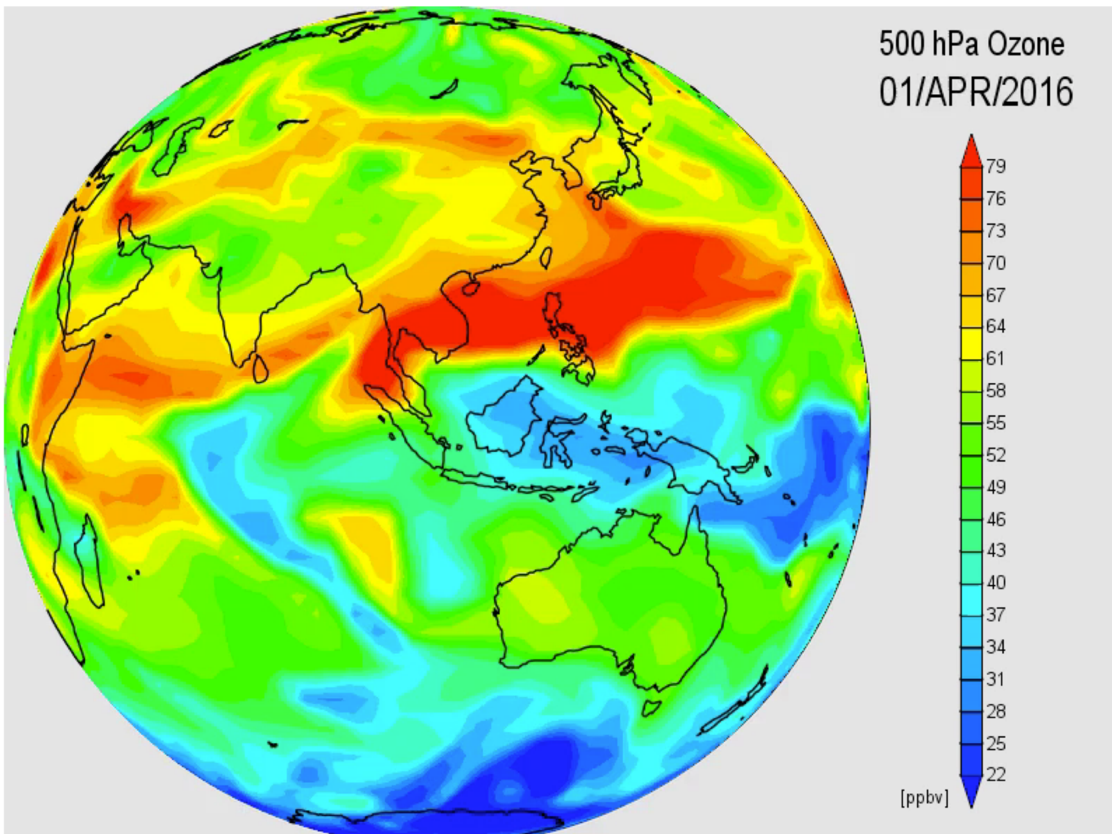
Coincident criteria

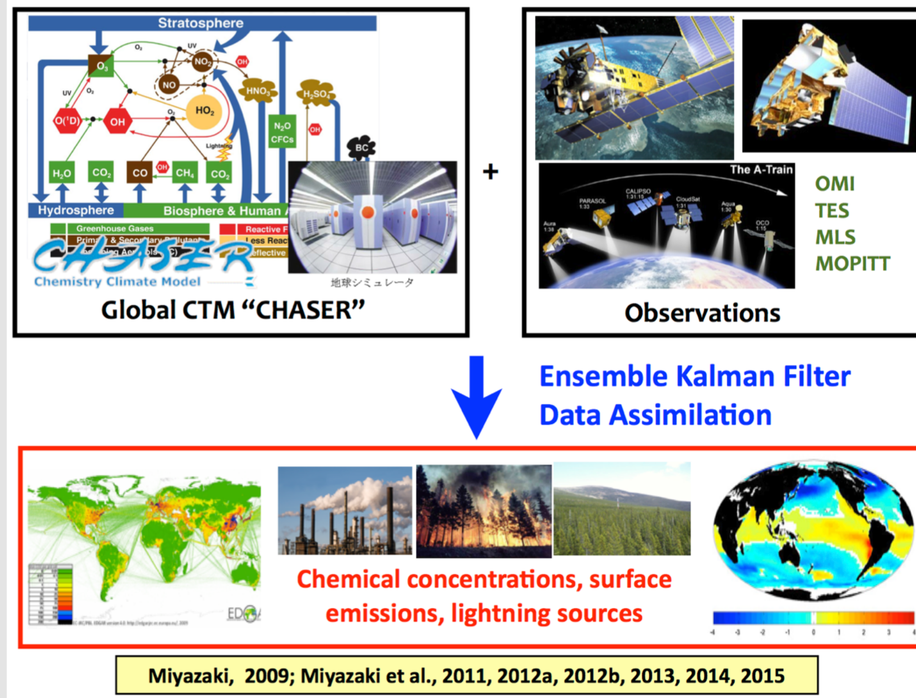
- Passed retrieval quality check
- Distance within 300 km
- Time diff. within 4 hours
- Day Time; March, April, May (MAM) 2006
- Day Time; June, July, August (JJA) 2006

Fu et al., Submit to AMT 2018.

Assimilated Global Ozone Fields

- Joint AIRS/OMI ozone profiles have been assimilated into CHASER system.
- CHASER system assimilated the OMI (NO_2), GOME-2 (NO_2) MLS (HNO_3 and O_3), MOPITT (CO) for KORUS-AQ ,recently assimilated AIRS/OMI ozone profile data



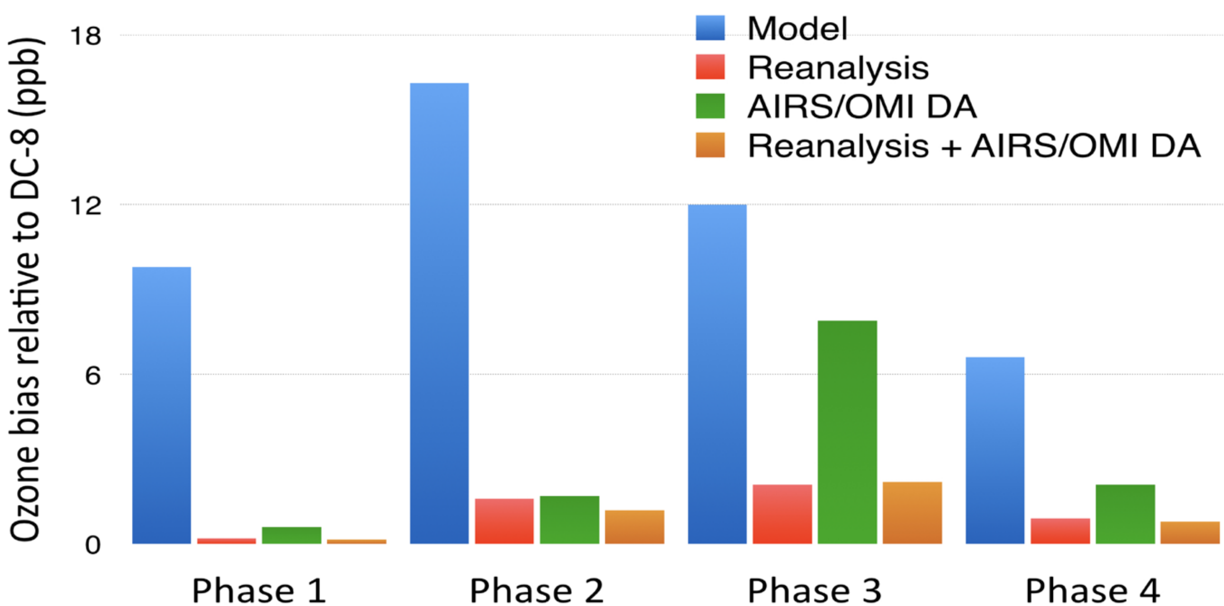


Comparisons of O_3 Profile Data among Data Sets

Miyazaki et al., Submitted to JGR 2018

Differences in comparison to AIRS+OMI Obs. (ppb)		GL SH: 55°-15°S		GL TR: 15°S-15°N		GL NH: 15°-55°S		RE	
		Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE
510 HPa	Model	4.0	8.3	-12.2	14.4	-1.3	12.0	-5.2	14.5
	Reanalysis	4.5	6.0	-1.8	6.5	4.2	9.2	0.9	10.5
	AIRS/OMI assim	-0.2	3.7	-5.3	7.1	-0.4	7.2	0.1	8.3

Phase 1: May 1-16
Phase 2: May 17-22
Phase 3: May 25-31 (OMI instrument issue)
Phase 4: June 1-6 (OMI instrument issue)



Joint AIRS/OMI O_3 Retrievals

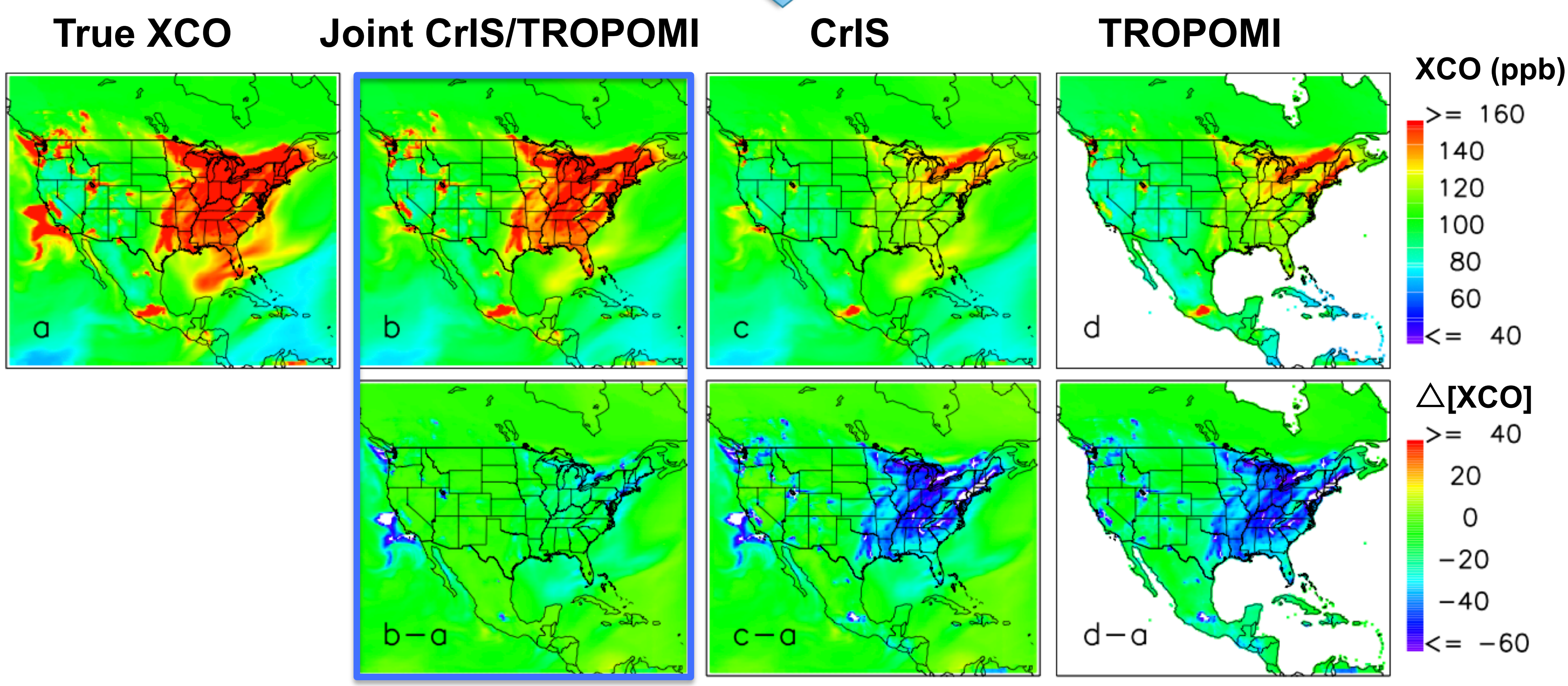
The AIRS/OMI O_3 retrievals have been configured in two modes.

- Global survey (GS) mode
  - Provides profile data with a spatial sampling similar to TES global survey
    - 28-month data have been processed including
      - **2006 Jan – Dec**
      - **2016 Mar – Jun**
      - 2007 Jan – Dec
  - **Year 2006** and **Mar-June 2016** GS data are available via the link (AIRS-OMI combined products) at https://tes.jpl.nasa.gov/data/
- Regional mapping (RE) mode
  - Processes all available measurements for flight campaigns including
    - **KORUS-AQ, Apr – Jun 2016**
    - ORACLES, Aug, Sept 2016
    - POSIDON, Sept, Oct 2016
  - **KORUS-AQ (Apr-June 2016) RE** data are available via the link (AIRS-OMI combined products) at https://tes.jpl.nasa.gov/data/

Data products have been saved in Hierarchical Data Format, a common format used in the NASA Earth Observation System level 2 products

High Resolution Near Surface CO Data via Combining CrIS/TROPOMI Measurements

- In October 13, 2017, ESA Sentinel 5 Precursor (S5P) launched successfully, forming a satellite constellation with Suomi-NPP satellite.
- It provides an unique opportunity to extend and improve the MOPITT joint TIR/NIR CO data, via combining CrIS/TROPOMI measurements [Fu *et al.*, AMT, 2016]
- **XCO maps:** near surface partial column averaged VMR [surface to ~750 hPa]



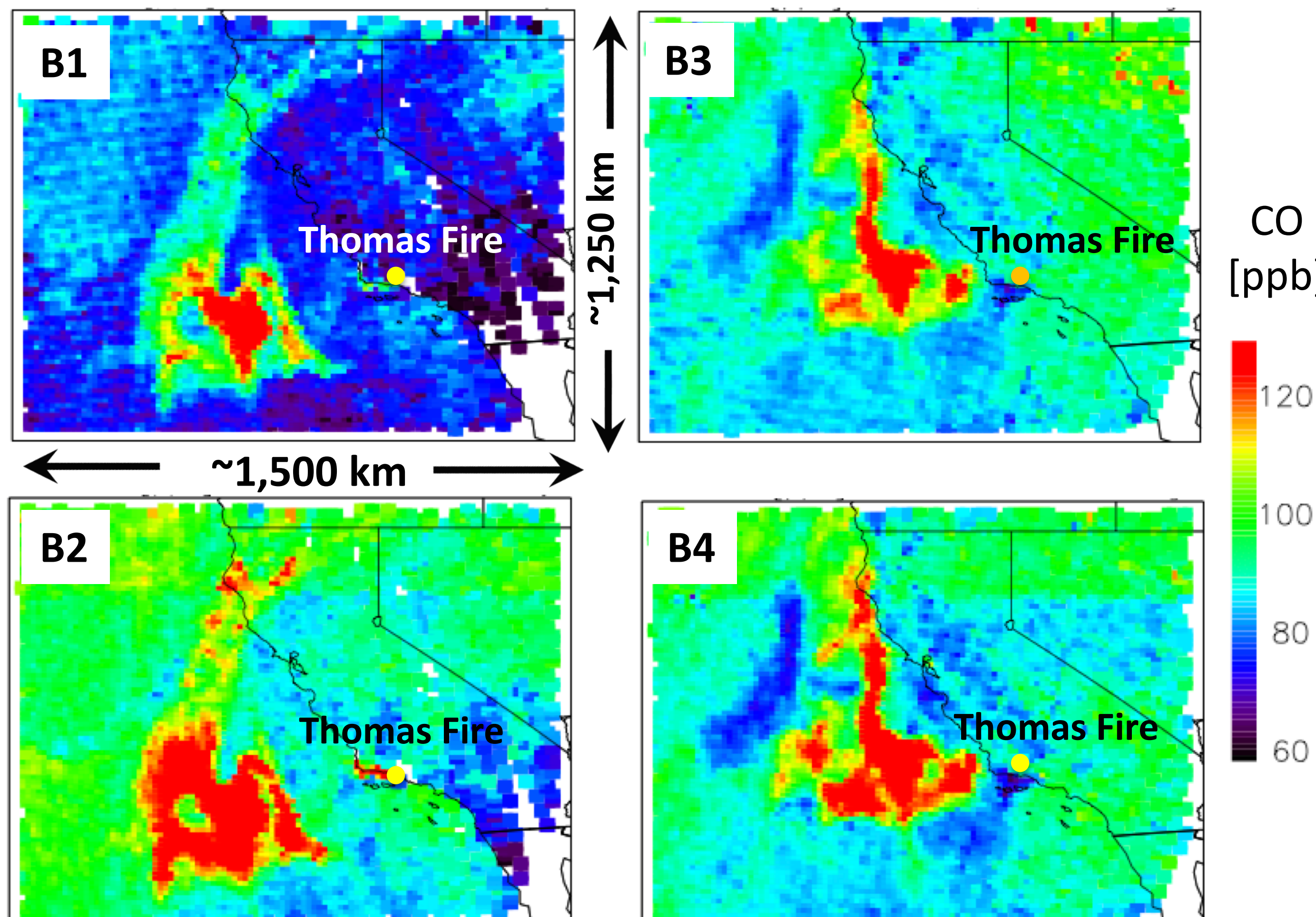
CrIS Carbon Monoxide Observations for Thomas Fire

Email Contact: dejian.fu@jpl.nasa.gov

Hazard of Thomas Fire

Location: near Los Angels, California, USA
Date: Dec 4, 2017 - Jan 12, 2018
Burn Area: 281,893 acres; ~1,140 km^2
Buildings Destroyed: 1,063
Fatalities: 1 firefighter, 1 civilian (20 indirectly)

- CO volume mixing ratio profiles (VMR) retrieved using JPL multi-spectra, multi-Species, multi-sensors (MUSES) [Fu et al, 2013, 2016]
- Provides retrieved profiles and observation operators
- 9X finer spatial resolution than the operational AIRS/CrIS products
- Algorithm heritage of TES, OMI, OCO-2, have been applied to TES, AIRS, CrIS, TROPOMI, OMI, OMPS, OCO2 for a suite of species including CO, O3, CH4, H2O, HDO, CH3OH, PAN, NH3, CO2



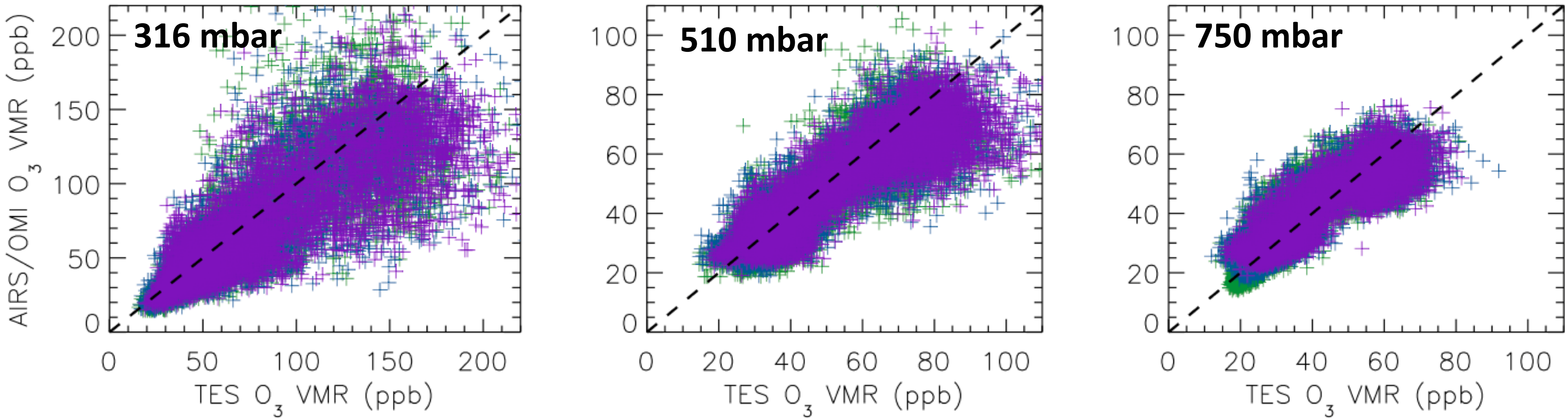
SNPP Synergic Observations
December 12, 2017

[A] VIIRS image of fire plume
[B1-4] CrIS Carbon monoxide VMR
[B1] Day time; 316 hPa
[B2] Day time; 510 hPa
[B3] Night time; 316 hPa
[B4] Night time; 510 hPa

Summary

- MUSES retrieval algorithm can combine radiances measured from long wavelength (TES, AIRS, CrIS) and short wavelength (OMI, OMPS, TROPOMI) space sensors to retrieve the vertical concentration profiles of primary gaseous pollutants including O_3 and CO.
  - Joint AIRS/OMI and CrIS/OMPS retrieved O_3 profiles can distinguish the abundances in the upper troposphere from the lower troposphere.
  - Joint CrIS/TROPOMI would help in extending the MOPITT CO profile data.
- The observation operators of joint AIRS/OMI data products enable data assimilation, e.g., "CHASER-DA", demonstrating the significant impacts on ozone distributions.
- The O_3 and CO data products from MUSES algorithm could help in the quantitative attribution of anthropogenic emissions and natural influences of pollutants for NASA KORUS-AQ and NOAA FIREX.

Joint AIRS/OMI vs. TES Global Survey O_3 March to June 2006



- The differences are within the estimated uncertainty.

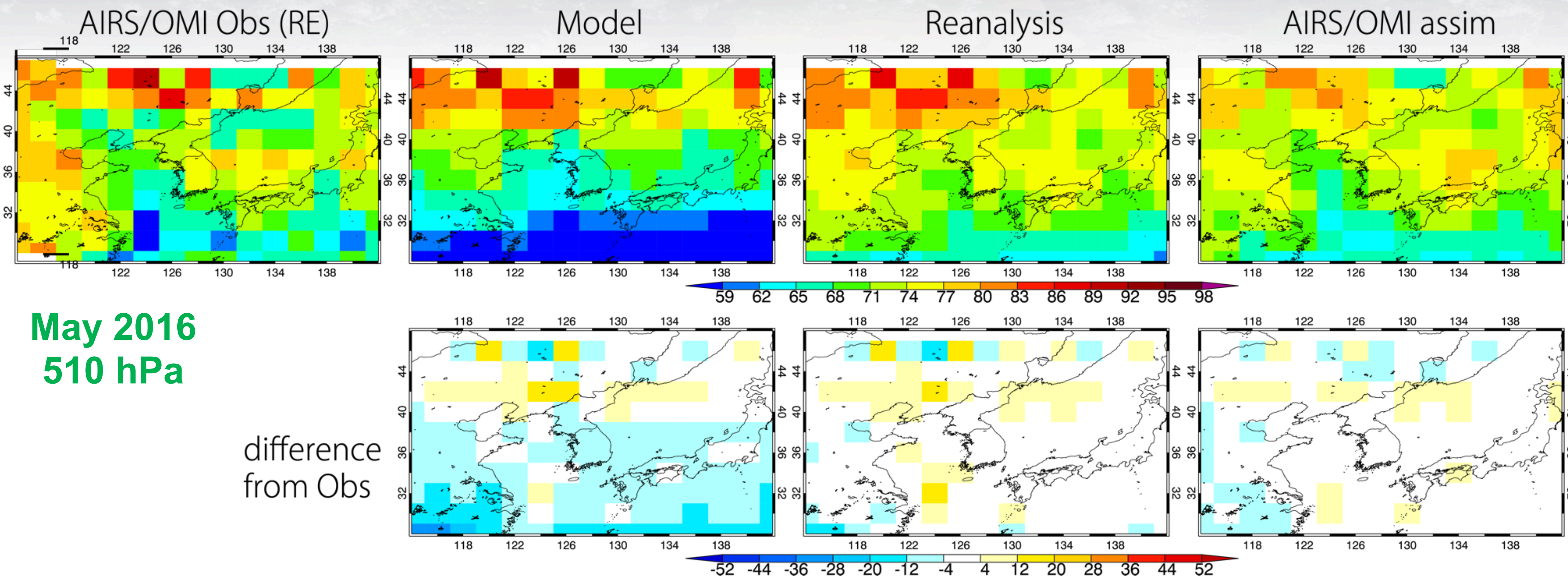
		316 hPa Mar	316 hPa Apr	316 hPa May	316 hPa Jun	510 hPa Mar	510 hPa Apr	510 hPa May	510 hPa Jun	750 hPa Mar	750 hPa Apr	750 hPa May	750 hPa Jun
Pearson Correlation Coefficient		0.85	0.84	0.84	0.84	0.87	0.88	0.89	0.86	0.90	0.90	0.90	0.83
Differences (AIRS+OMI – TES)	Mean (ppb)	-7.3	-6.9	-8.1	-6.0	-2.9	-3.3	-3.6	-4.1	-0.4	-1.2	-1.6	-2.2
	RMS (ppb)	21.5	21.6	22.6	19.8	8.6	8.9	9.2	9.5	6.7	7.0	6.4	7.1
	Mean (%)	9.8	7.3	7.3	-5.0	4.9	4.2	4.2	-4.5	-0.6	0.3	1.3	-2.3
	RMS (%)	24.2	25.7	24.7	23.8	17.3	18.2	16.4	17.0	19.3	19.8	15.9	17.4
Total Uncertainty	AIRS+OMI O_3 (%)	28.6	28.9	28.5	28.0	22.5	22.8	23.0	22.8	22.4	22.9	24.1	24.7
	TES V6 O_3 (%)	22.5	23.0	22.9	22.1	20.1	20.1	20.1	19.5	23.1	23.3	24.0	24.0

Fu et al., Submit to AMT 2018.

Number of Global Survey	AIRS+OMI	14	15	16	15
	TES	16	14	15	15

AIRS/OMI O_3 Profile Data from Regional Mapping Mode

Miyazaki et al., Submit to JGR 2018



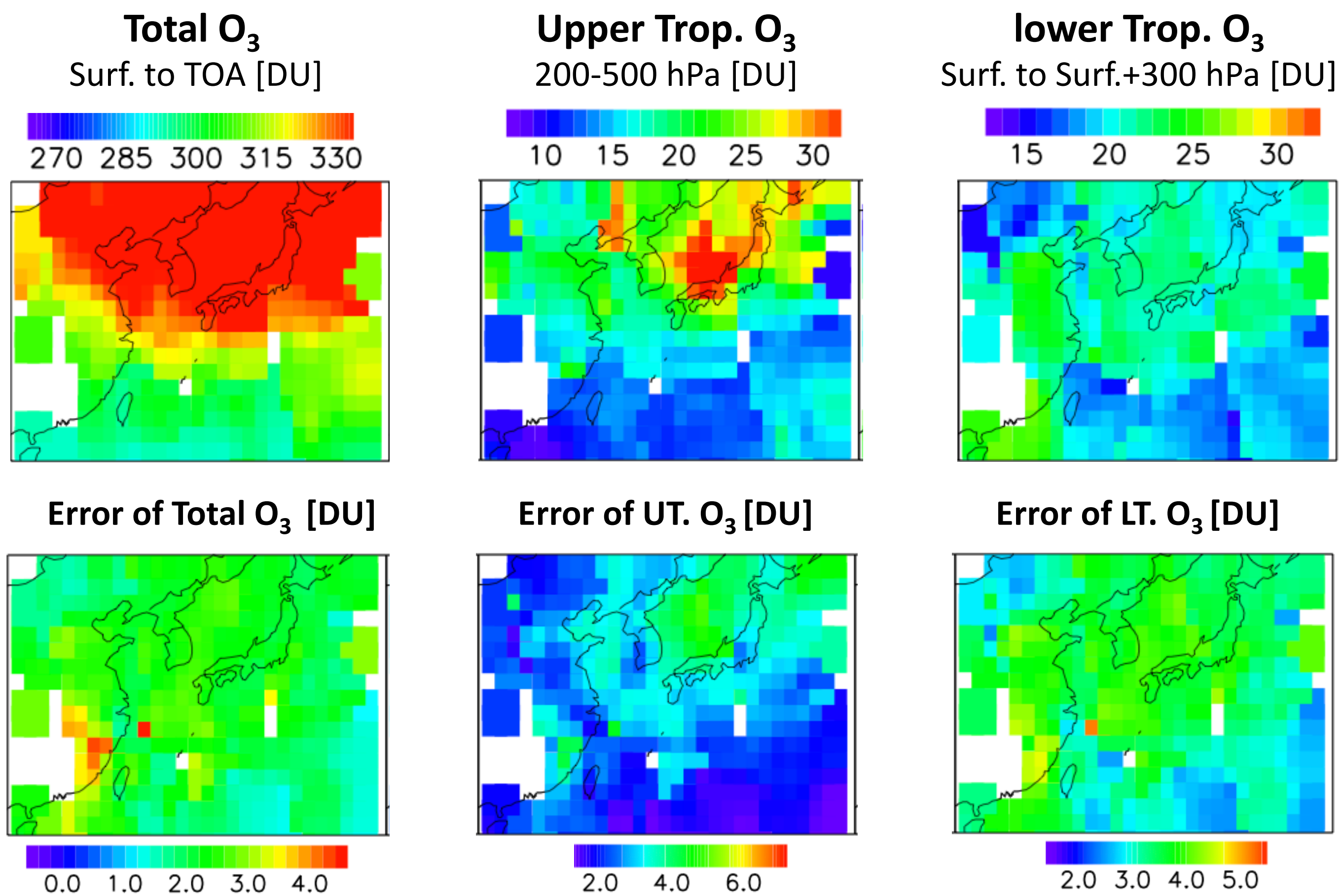
Performances of GS and RE mode joint AIRS/OMI data

- Diff. (Reanalysis without Joint AIRS+OMI – Joint AIRS+OMI Obs.) **<** (Model - Joint AIRS+OMI Obs.)
- Reanalysis without Joint AIRS+OMI closely agree to joint AIRS+OMI ozone with a mean bias of
  - 0.9 ppbv for RE mode
  - 4.2 ppbv in the northern extratropics
  - -1.8 ppbv in the tropics
  - 4.5 ppbv in the southern hemisphere

Joint AIRS/OMI O_3 Maps for KORUS-AQ Campaign

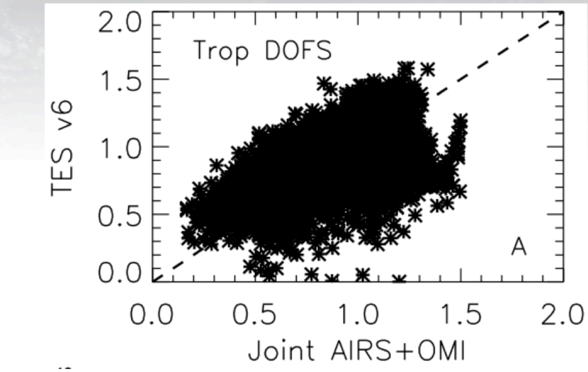
- Korea-US Air Quality study (KORUS-AQ) - International Cooperative Air Quality Field Study
- Joint AIRS/OMI O_3 profile data
  - Total ozone shows strong latitudinal dependence, dominated by stratospheric ozone.
  - The pattern of enhancement (Upper tropospheric > Lower tropospheric) over Korean peninsula <-> Japan suggests either lofting and transport of pollution from the surface or the influence of stratosphere-troposphere exchange.

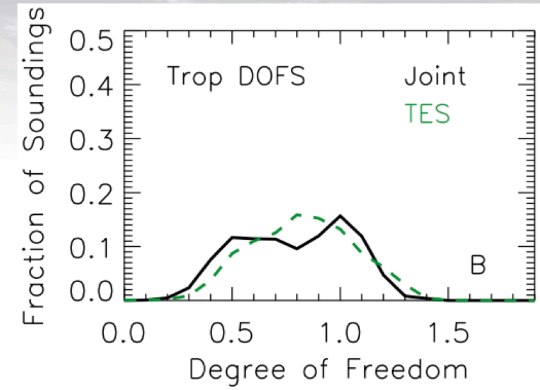
Three-day averaged May 18-20, 2016.



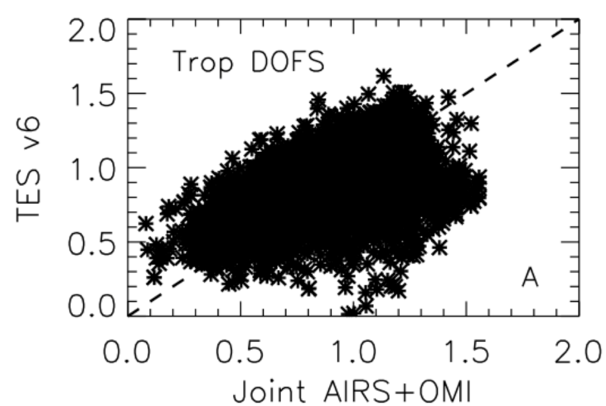
AIRS/OMI vs. TES v6 GS Trop DOFS

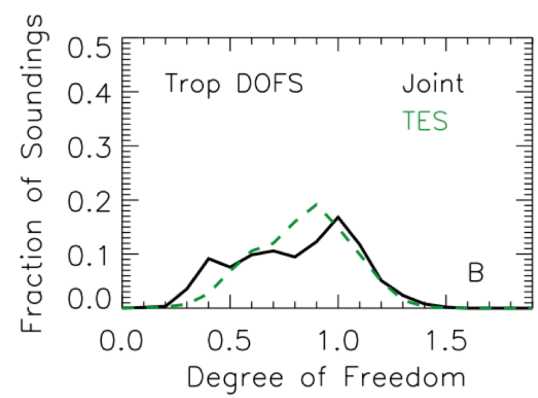
April 2006
Corr. R = 0.65;
Mean(TES/Joint) = 1.10
Mean(TES-Joint) = 0.04



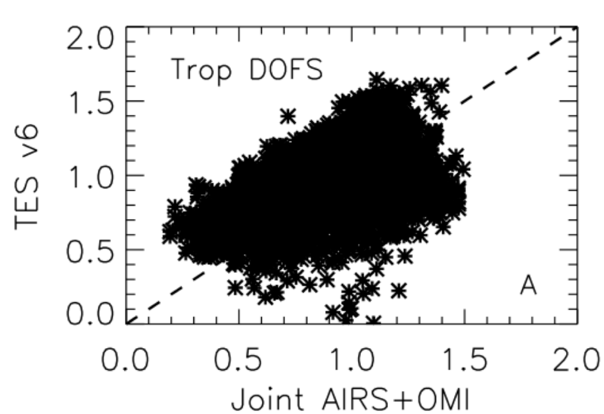


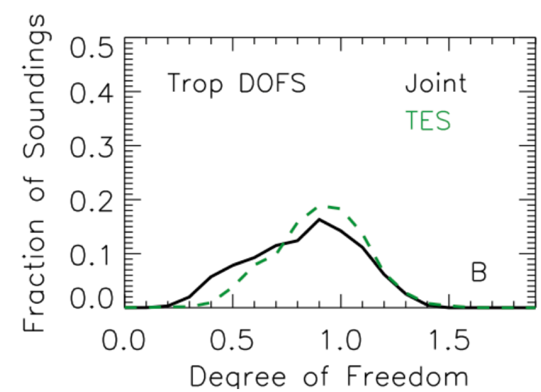
May 2006
Corr. R = 0.58;
Mean(TES/Joint) = 1.10
Mean(TES-Joint) = 0.03





June 2006
Corr. R = 0.51;
Mean(TES/Joint) = 1.14
Mean(TES-Joint) = 0.07





Fu et al., Submit to AMT 2018.

JPL/UW-Madison Team for NOAA FIREX

Fire Influence on Regional and Global Environments Experiment (FIREX) is to study the impact of biomass burning of western north America fires on climate and air quality.

JPL/UW-Madison team will combine high vertical/spatial resolution O_3 and CO data with chemical data assimilation to provide a critical synoptic context for quantifying the role of fires on atmospheric composition and air quality.

JPL MUSES algorithm will provide

- CrIS CO profile data
  - nine times higher spatial resolution vs. the CrIS operational data products
- Joint CrIS/OMPS O_3 profile data
  - could distinguish upper/lower troposphere, similar to AIRS/OMI $O_{3,}$ but 3X spatial coverage
- Both CO and O_3 profile data products provide full observation operators readily for data assimilation/model evaluation

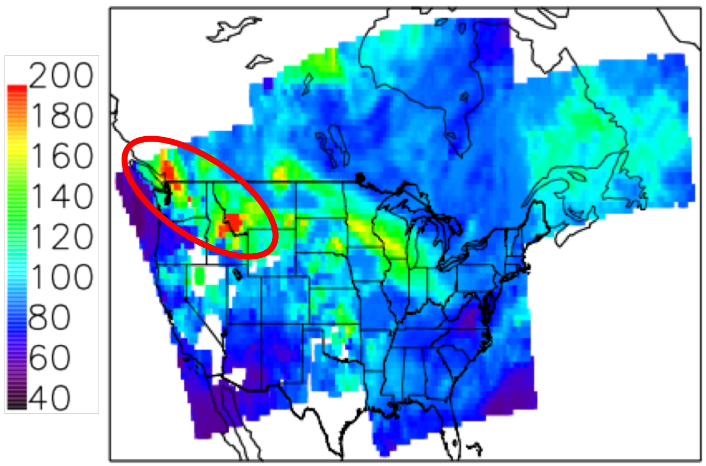
UW-Madison Real time Air Quality Modeling System (RAQMS) will provide

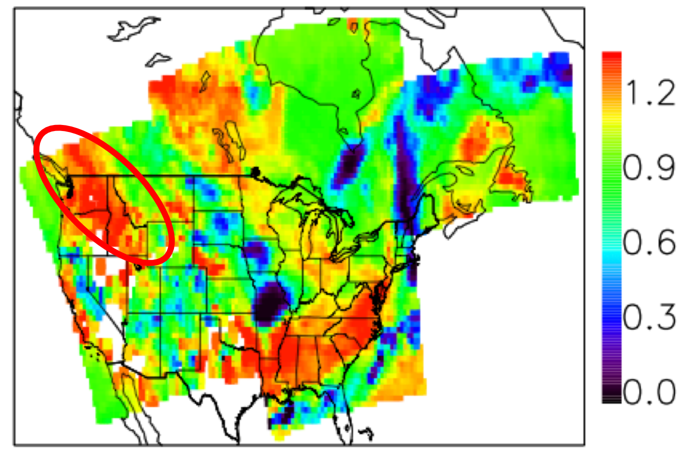
- Real-time assimilation
  - Aura-MLS stratospheric ozone profiles (>50mb)
  - Aura-OMI total ozone column (cloud cleared)
  - MODIS aerosol optical depth
- Real-time fire detection via MODIS data
- Will assimilate JPL CrIS CO and joint CrIS/OMPS O_3 profile data

MUSES-CrIS CO Maps for NOAA FIREX

- Plume of biomass burning observed on August 5, 2017
- CrIS CO profiles were retrieved using single footprint CrIS full spectral resolution data.
- MUSES algorithm retrieves trace gases profiles, cloud optical depths, surface properties and temperature profiles.

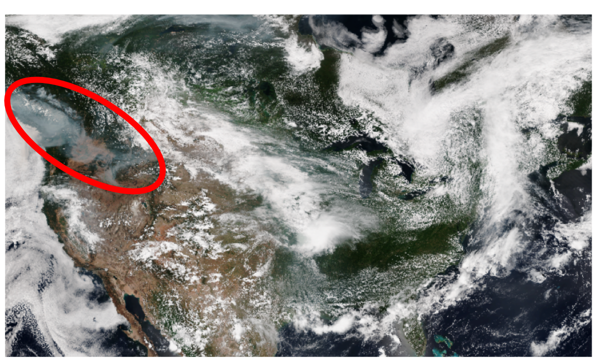
CO VMR @510 mbar ppb

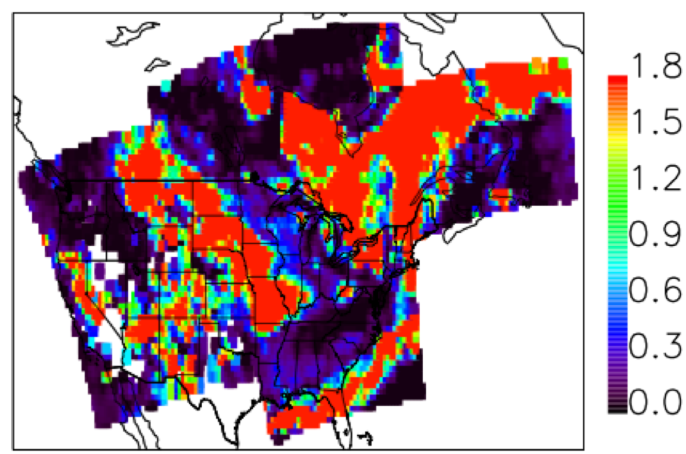




CrIS Trop. CO DOFS

MODIS Image

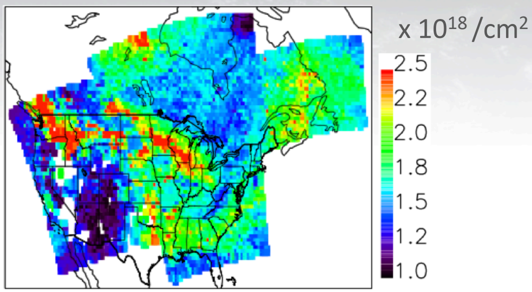




CrIS Cloud OD

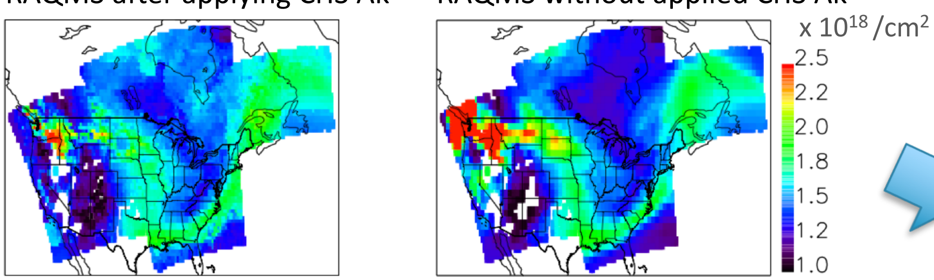
Comparisons of MUSES-CrIS and RAQMS CO Data

CrIS CO Tropospheric Column

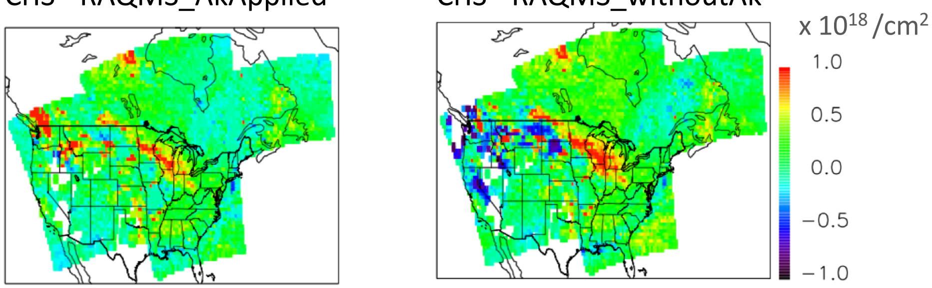


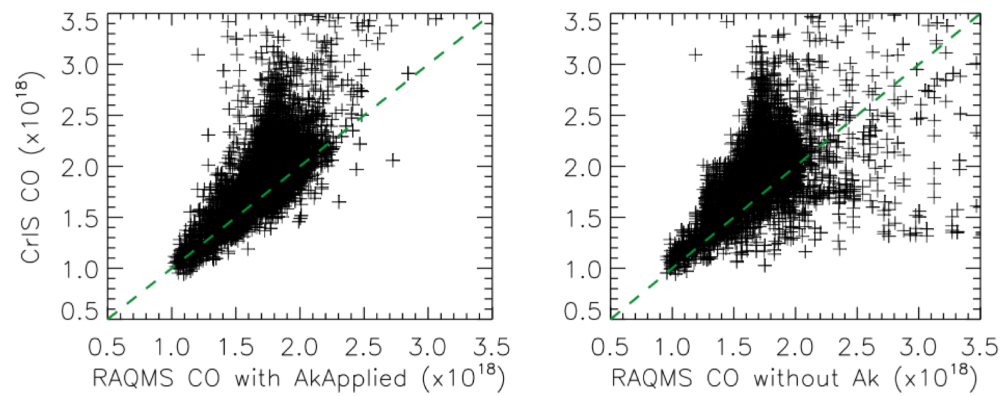
- Used CrIS single footprint full spectral resolution L1B radiances in the retrievals
- MUSES CrIS CO data show agreement to the RAQMS model fields that were applied the observation operators of CrIS CO.
- Collaborating with Dr. Pierce at UW-Madison for assimilating CrIS CO data into the RAQMS model

RAQMS after applying CrIS Ak | RAQMS without applied CrIS Ak



CrIS - RAQMS_AkApplied | CrIS - RAQMS_withoutAk





Applying MUSES CrIS CO Observation Operator to RAQMS Predicted CO Fields	Correlation Coefficient	Mean Diff		RMS	
		$x10^{18}$	%	$x10^{18}$	%
With	0.68	-0.15	6.9	0.27	11.1
Without	0.40	-0.15	6.6	0.45	25.7

Characteristics and Diagnostics of O_3 data

JPL MUSES algorithm delivers both retrieved trace gas concentration profiles and observation operators needed for trend analysis, climate model evaluation, and data assimilation.

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

$$\mathbf{y}^s = \mathbf{H}(\mathbf{x}) = \mathbf{x}_a + \mathbf{A}(\mathbf{x}_{model} - \mathbf{x}_a)$$

$\mathbf{y}^s$ is the model profiles; $\mathbf{x}_a$ 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 ($\mathbf{y}^o$- $\mathbf{y}^s$) is not biased by the *a priori* used in the retrievals.

$$\Delta\mathbf{y} = \mathbf{y}^o - \mathbf{y}^s = \mathbf{A}(\mathbf{x}_{true} - \mathbf{x}_{model}) + \varepsilon$$