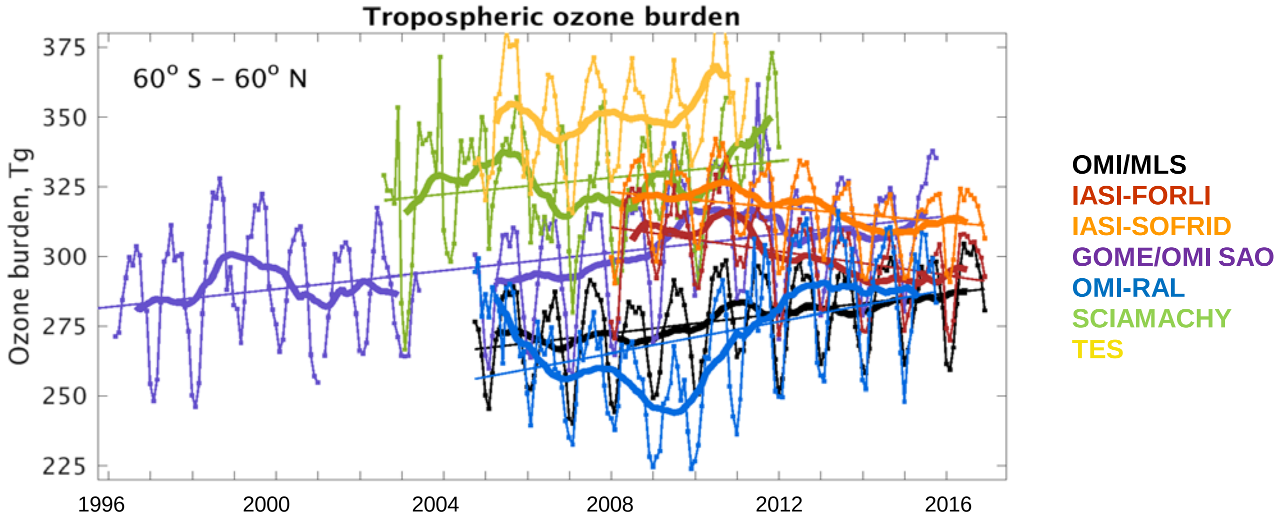
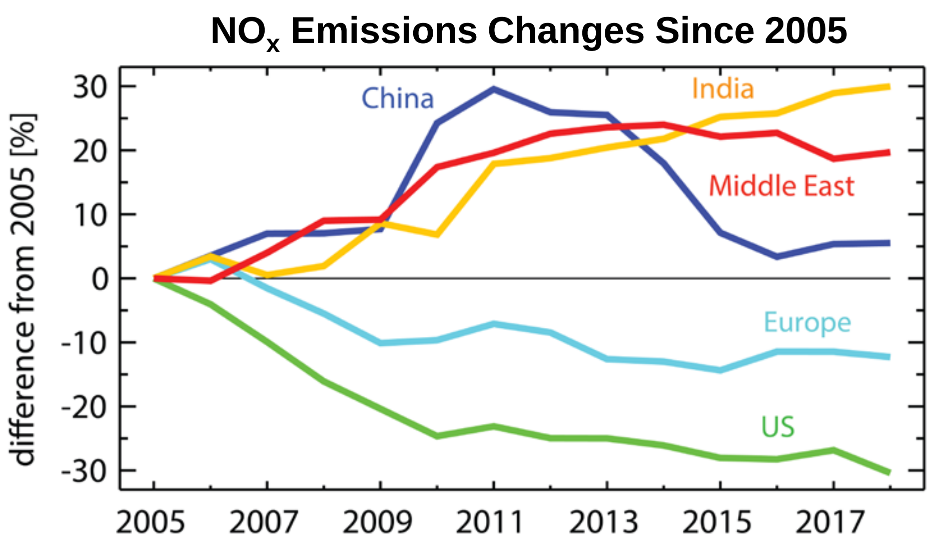
Ozone Trends Science: Building on TES's Legacy and Looking to the Future

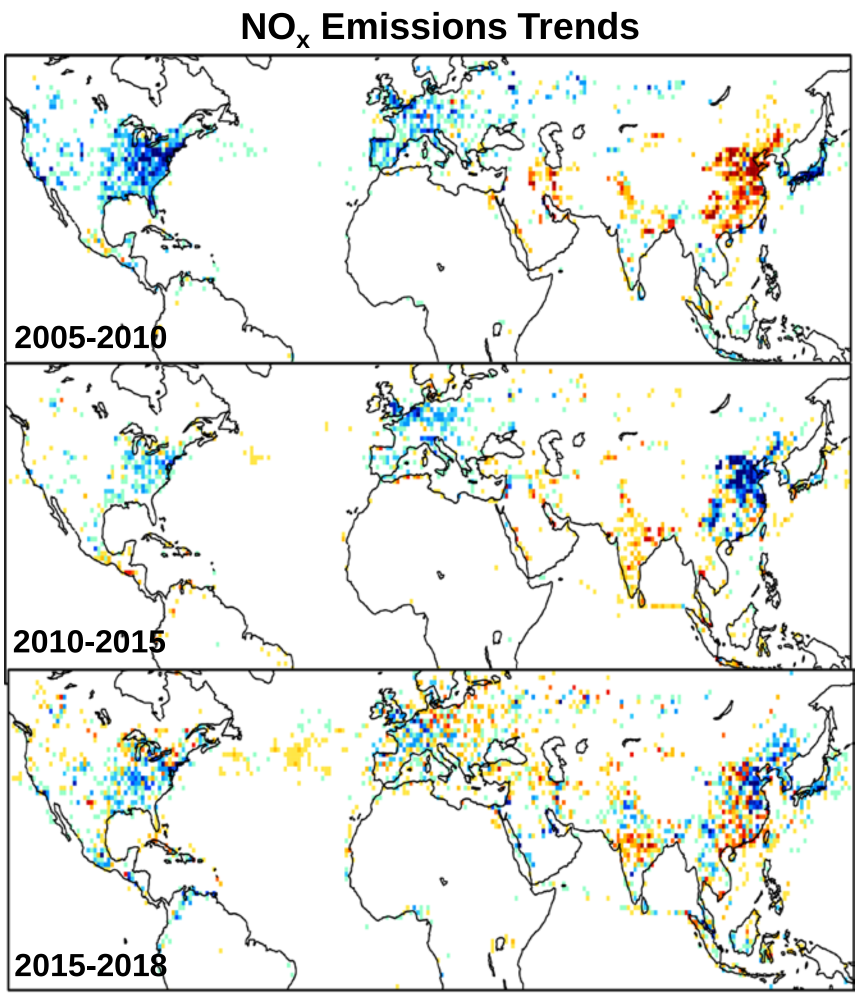
Jessica Neu[1] on behalf of the TES Science Team
[1]Jet Propulsion Laboratory, California Institute of Technology



The Dynamically Evolving Profile of Emissions



Near-constant total global emissions of 49.3 ± 2.7 TgN



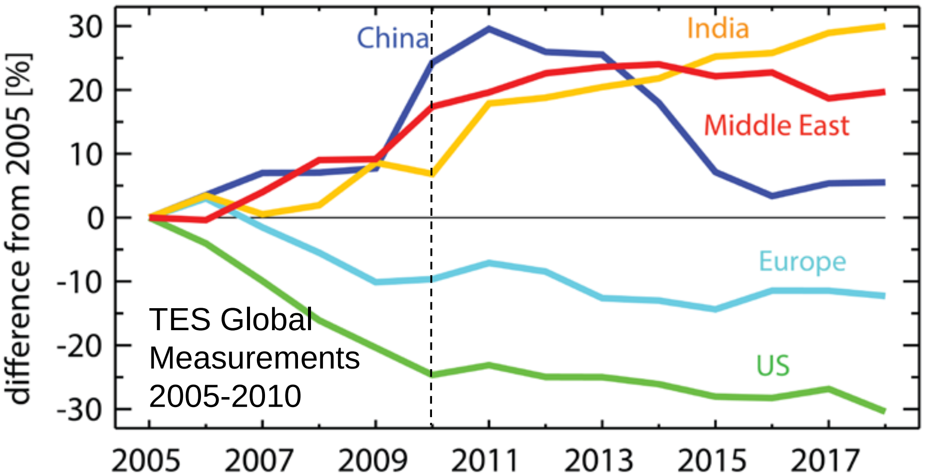
Miyazaki et al., in preparation

In the time since Aura launched, there has been a dramatic redistribution of global emissions.

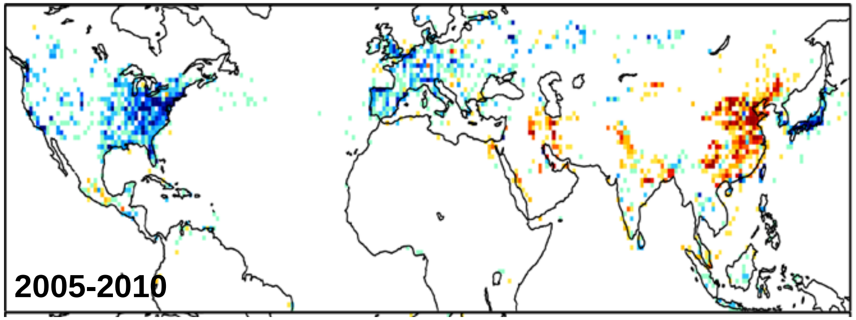
How has tropospheric ozone responded to these changes?

The TES Global Ozone Record

NO_x Emissions Changes Since 2005



NO_x Emissions Trends



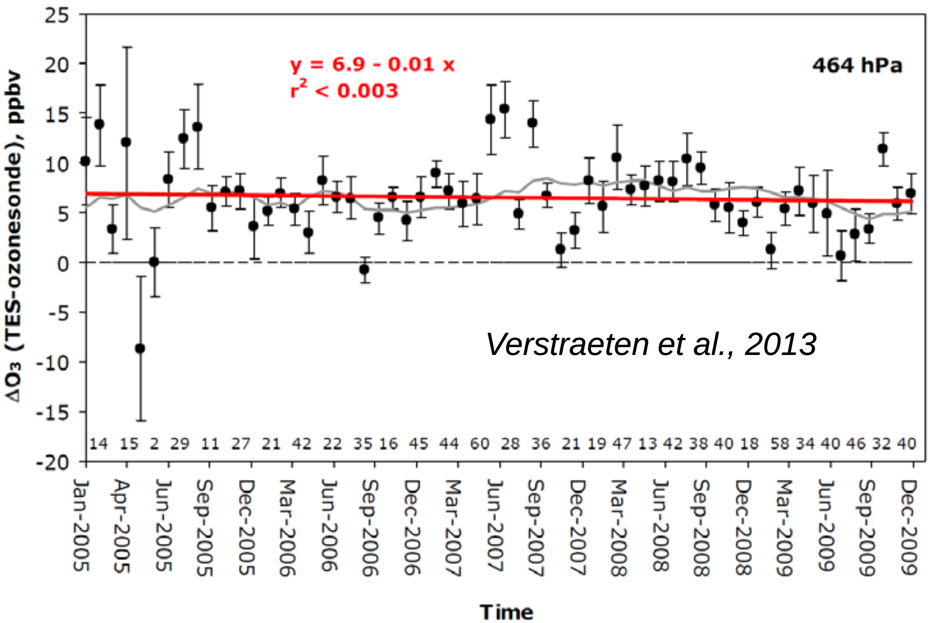
Miyazaki et al., in preparation

TES global measurements only captured the first 6 years of these emissions changes.

However, the remarkable stability of the TES ozone record with time allowed us to use these measurements to quantify and attribute the ozone changes over those 6 years.

TES Legacy #1: Setting the standard for validation of ozone trends

Stability of TES Ozone Retrievals with Time



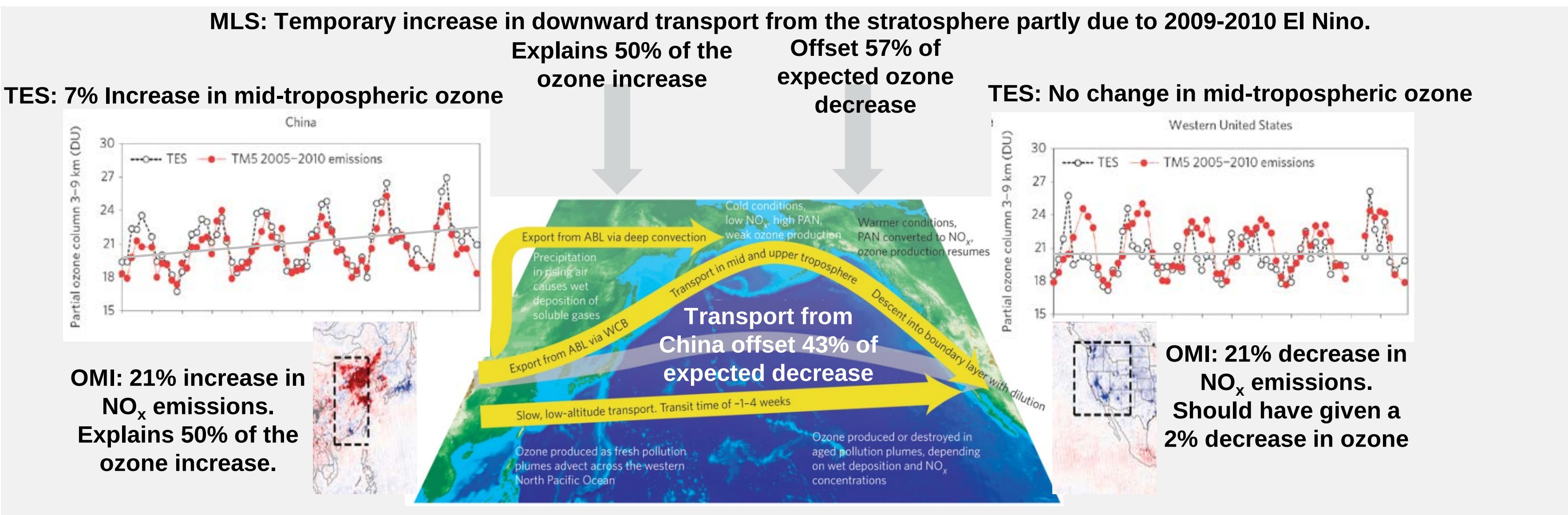
Verstraeten et al., 2013

Drivers of Regional Tropospheric Ozone Changes 2005-2010

Mid-tropospheric ozone is largely controlled by a combination of emissions, long-range transport, and downward transport from the stratosphere.

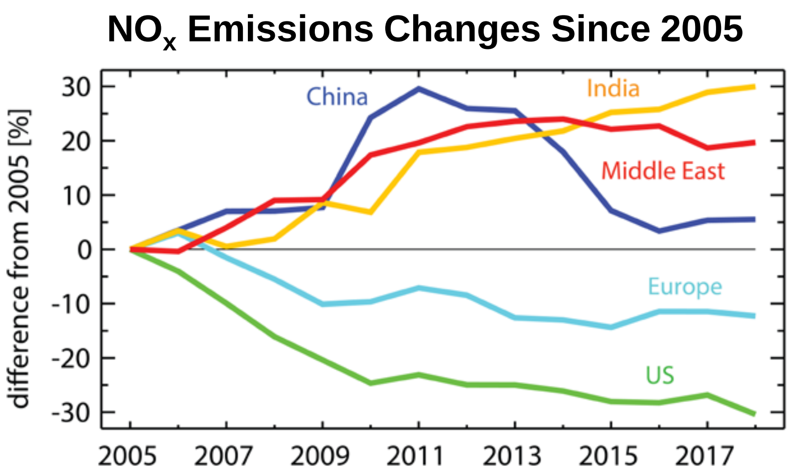
Half of the increase in mid-tropospheric ozone over Eastern China from 2005-2010 can be attributed to increasing NO_x emissions, while the other half was associated with natural variability in stratospheric transport.

Drivers of Regional Ozone Changes



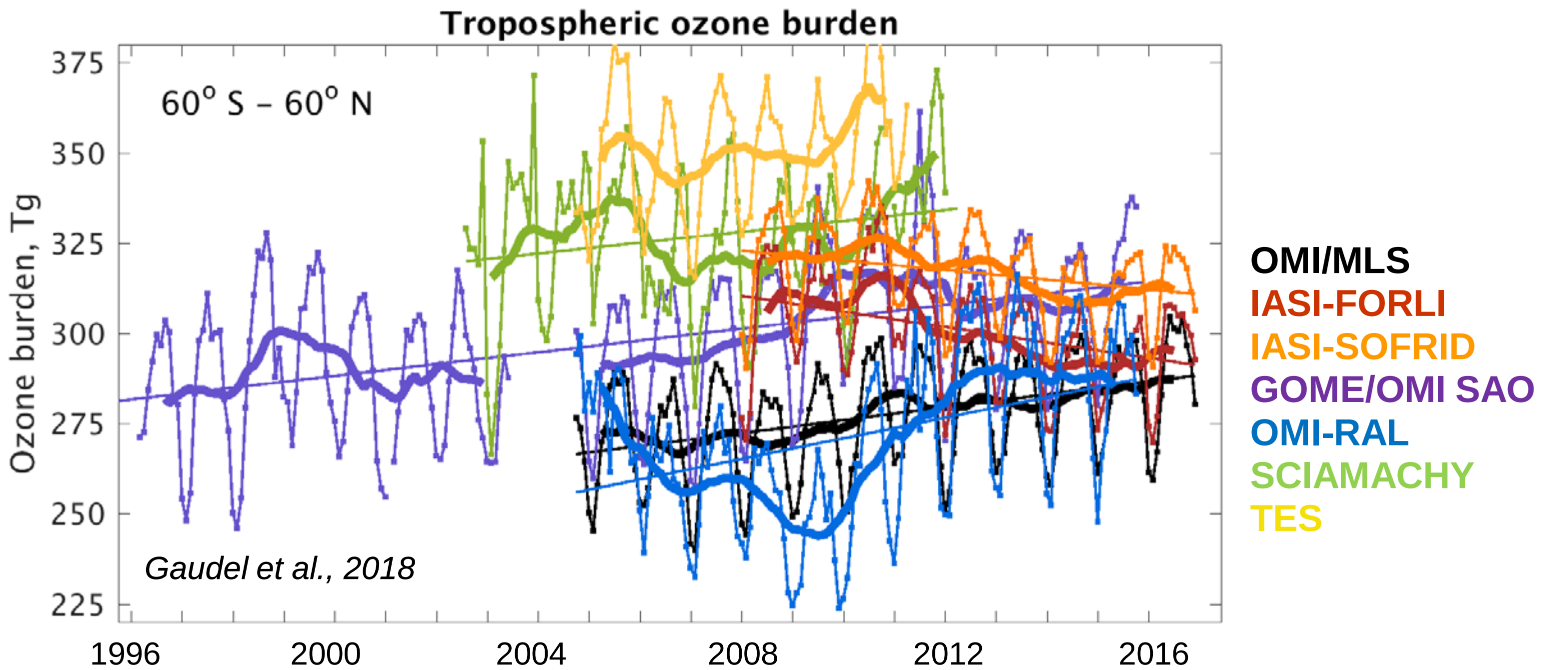
Verstraeten et al., 2015; Doherty, 2015

Intercomparing Satellite Records of Tropospheric Ozone



Over the longer record, there is poor agreement among satellite measurements of ozone with regard to both the total burden of tropospheric ozone and the change in the burden with time.

The differences are large even among different retrievals from the same instrument.



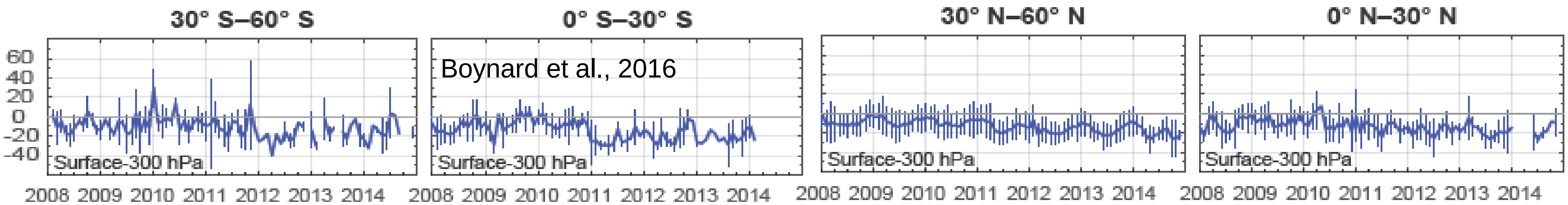
What Drives Differences in Trends?

There are 3 likely sources of trend differences:

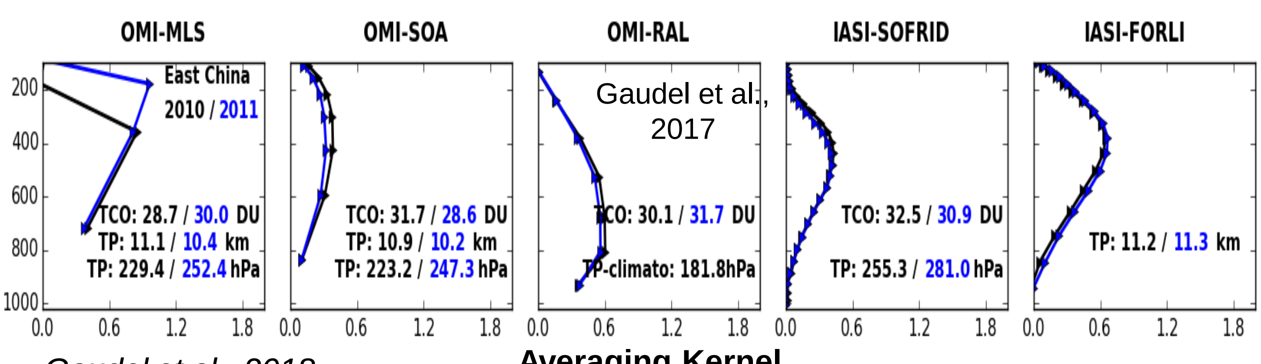
1. Changes in stability or retrieval quality with time
2. Changes in sampling with time

IASI-FORLI vs Ozonesondes

Boynard et al., 2018



IASI-FORLI differences with respect to ozonesondes increase from 2011 onward despite remarkable stability of the total ozone column. Other products include drift corrections, e.g. a -0.5 DU/decade correction was applied to OMI/MLS based on analysis showing a small row anomaly flagging error in the total ozone product.



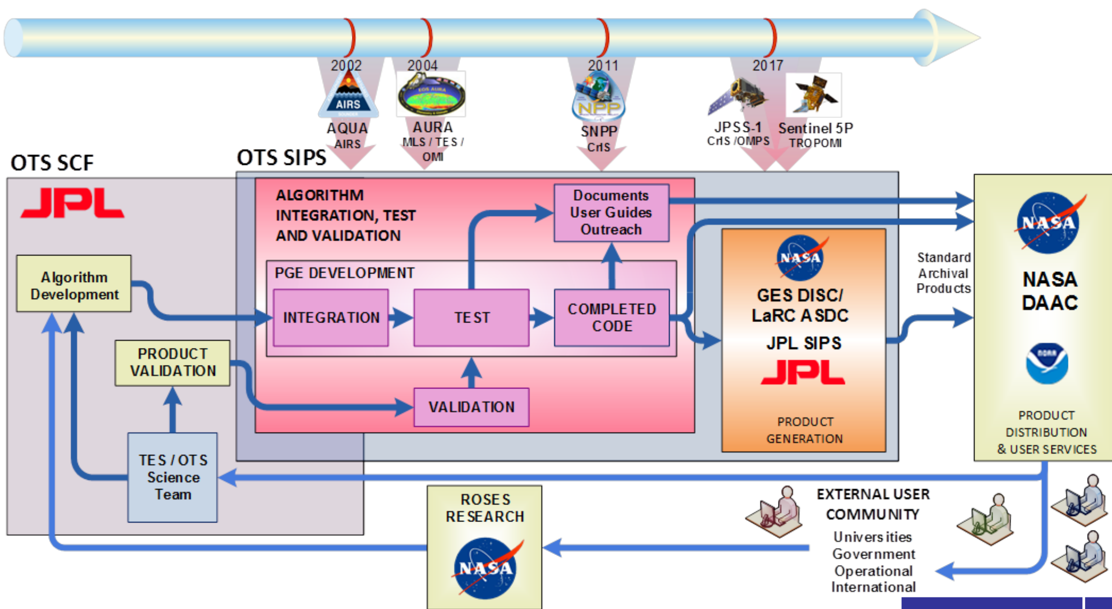
Gaudel et al., 2018

3. Differences in vertical sensitivity

The TCO products are all sensitive to different parts of the atmosphere, which may have different trends

Generating ESDRs of Ozone and Related Gases

Ozone Trend Science Computing with MUSES Processing and Development System



JPL has developed the MUlti-SpEctra, MUlti-SpEcies, MUlti-SEnsor (MUSES) system based on the TES optimal estimation algorithm to enable single footprint, OE composition retrievals from current IR sounders and combinations of these sounders with UV / NIR instruments.

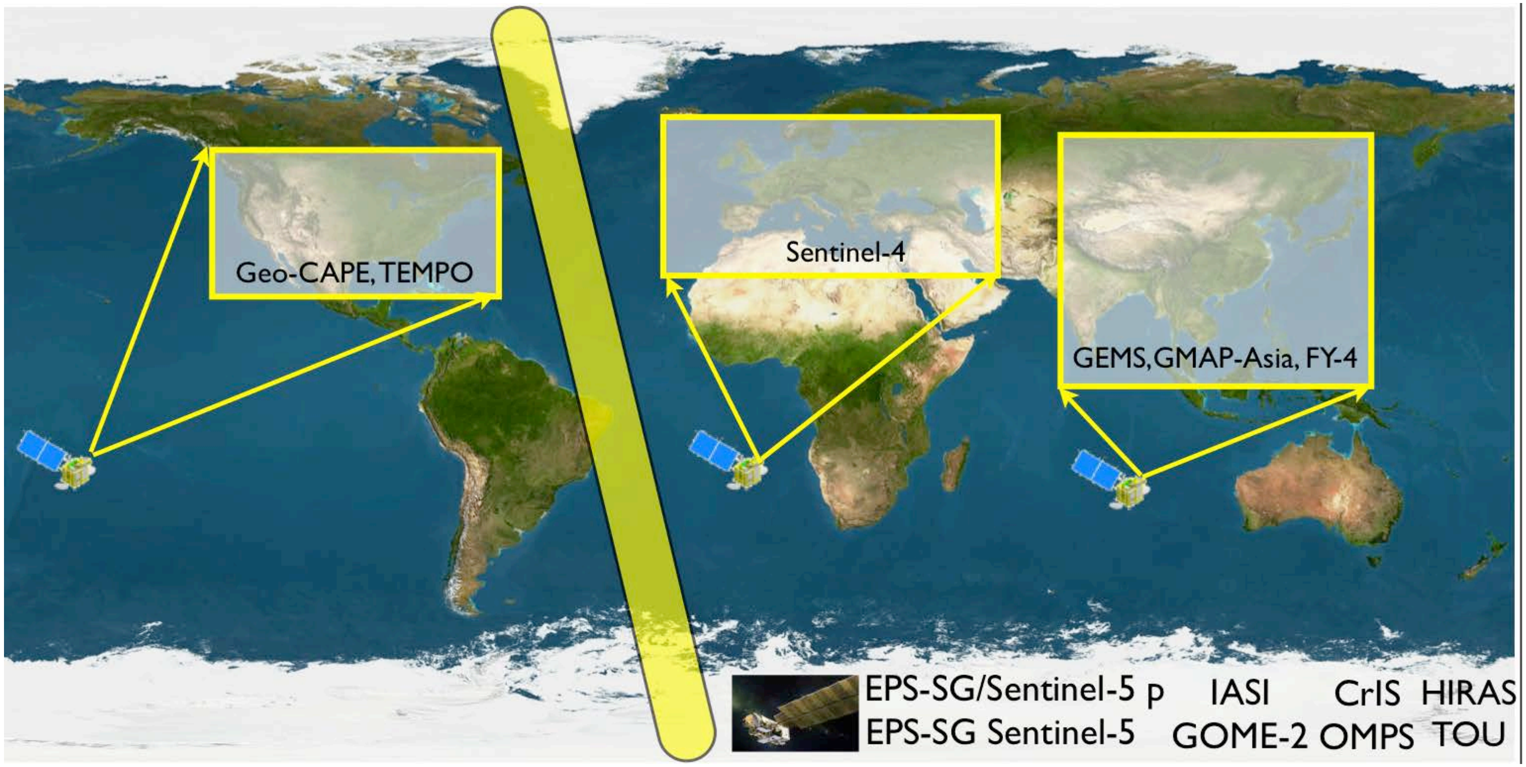
Under Ozone Trends Science funding, we will generate long-term Earth Science Data Records of tropospheric ozone that use the same algorithm, are validated against independent measurements, and have well-quantified uncertainties. Additional species relevant to the ozone budget will aid in the understanding and attribution of trends.

TES Global Survey~3000 obs/day
AIRS single pixel~3 million obs/day

	AIRS (IR)	CrIS (IR)	OMI (UV-NIR)	TropOMI (UV-NIR)
O_3	✓	✓	✓	✓
O_3 IRKs	✓	✓		
CO	✓	✓		✓
CH_4	✓	✓		✓
H_2O/HDO	✓	✓		✓
CH_3OH		✓		
NH_3		✓		
PAN		✓		
Isoprene		✓		

Algorithm developed under ROSES funding
Future research product

The Backbone of the Atmospheric Composition Observing System



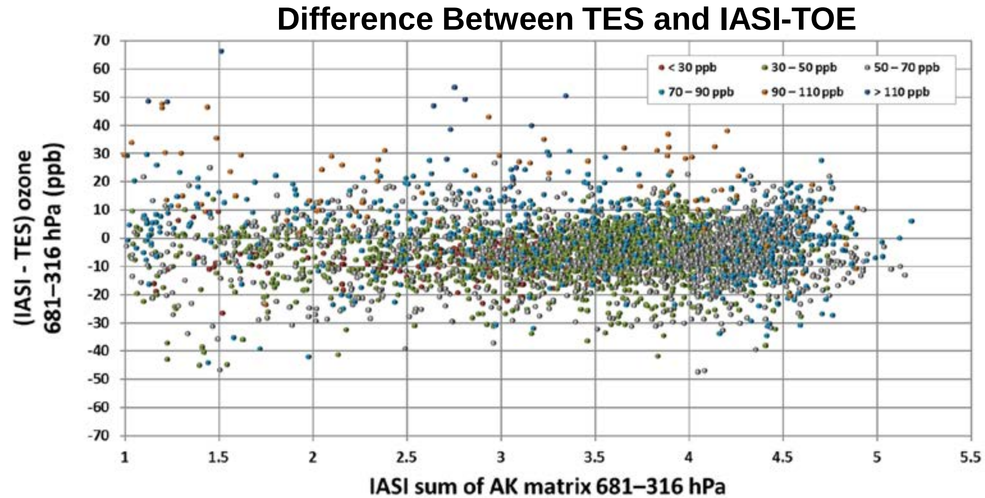
Bowman, 2013

The LEO instruments form the backbone of the upcoming atmospheric composition constellation, helping to tie together geostationary observations

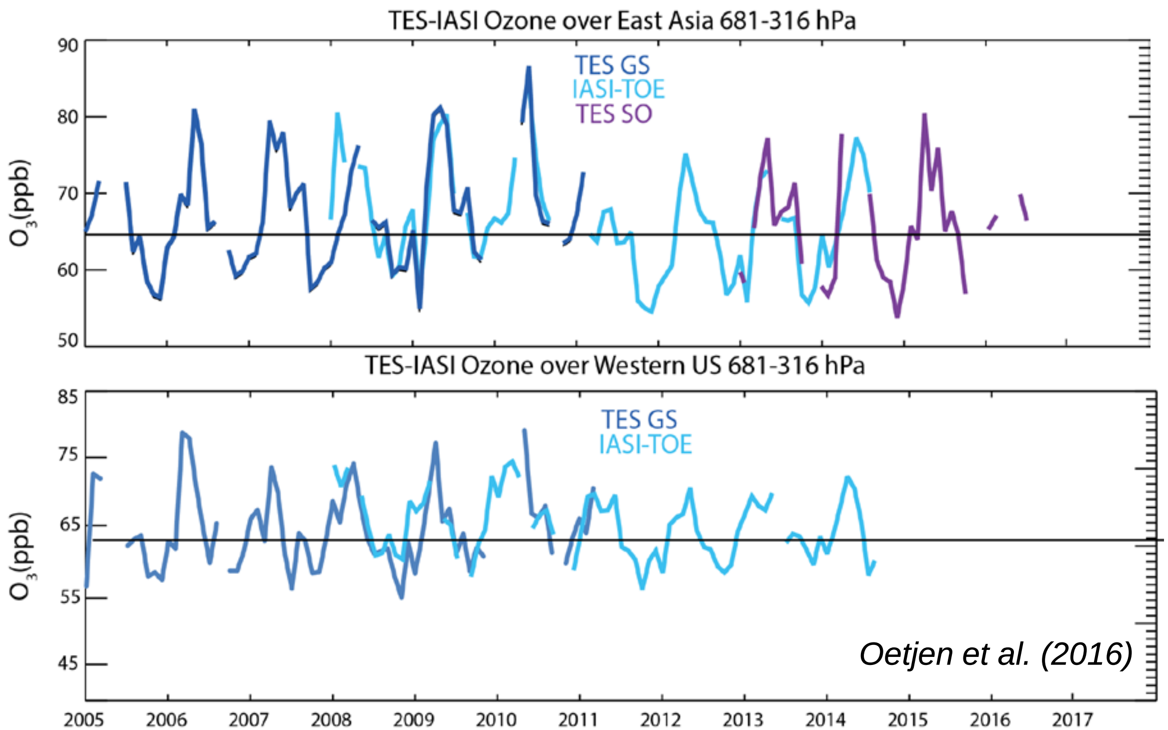
A Merged Long-Term Ozone Dataset – TES+IASI-TOE

TES Legacy #2: Developing methodology for creating merged records of tropospheric ozone with error budgets

Oetjen et al. (2014) generated retrievals of ozone from IASI using the TES OE algorithm over 3 regions (East Asia, Western US, Europe) and characterized the error budget of those retrievals.



Oetjen et al. (2016)

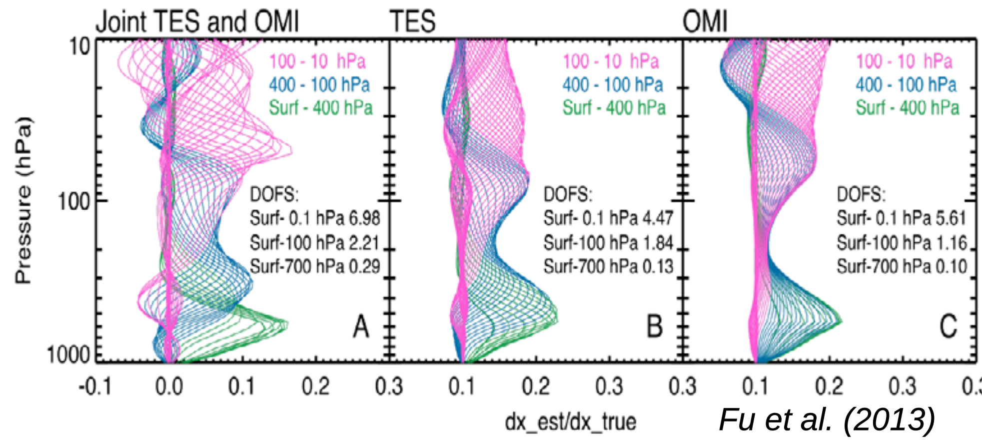


Oetjen et al. (2016) then created a merged record of TES and IASI-TOE ozone over those regions by subsampling the IASI measurements to provide coverage consistent with TES and correcting a constant offset after establishing that it did not depend on DOFs or ozone abundance.

Multi-Spectral Observations Provide Improved Vertical Resolution

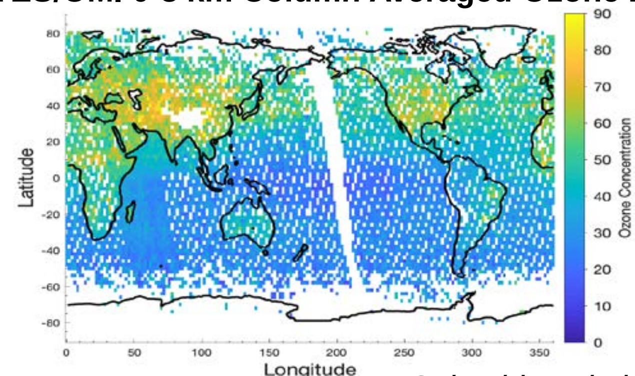
TES Legacy #3: Pioneering the development of multispectral retrievals of ozone

Fu et al. (2013) generated the first UV-TIR multispectral retrievals of ozone by combining radiances from TES and OMI. The retrievals have better vertical resolution and more sensitivity to the lowest 3 km of the atmosphere than those from either instrument alone.

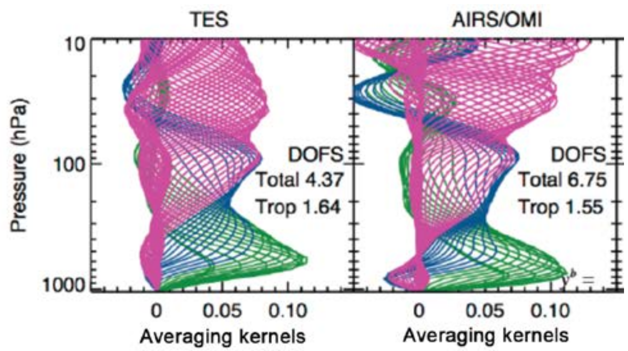


Fu et al. (2013)

TES/OMI 0-3 km Column Averaged Ozone 2007

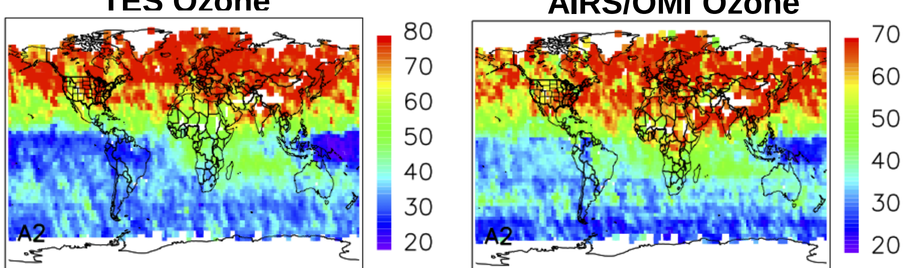


Colombi et al., in preparation



510 hPa May 2006

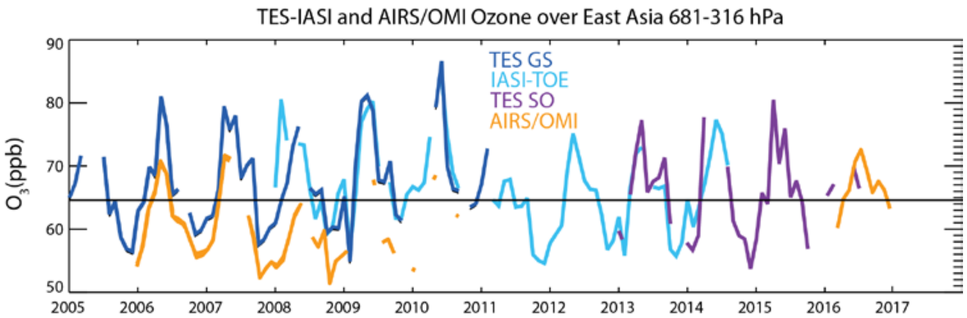
TES Ozone **AIRS/OMI Ozone**

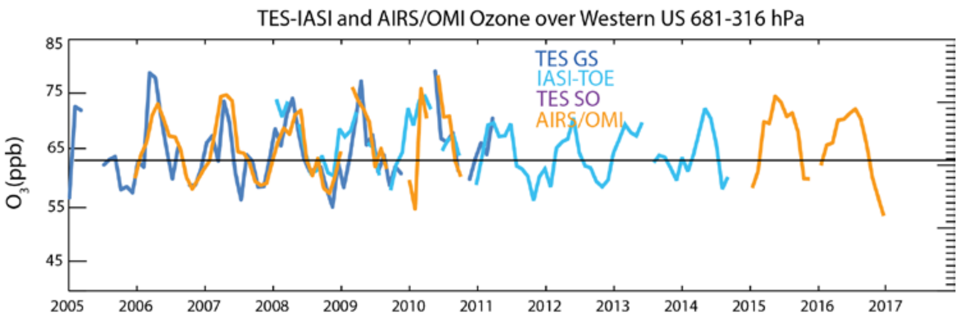


Fu et al. (2018)

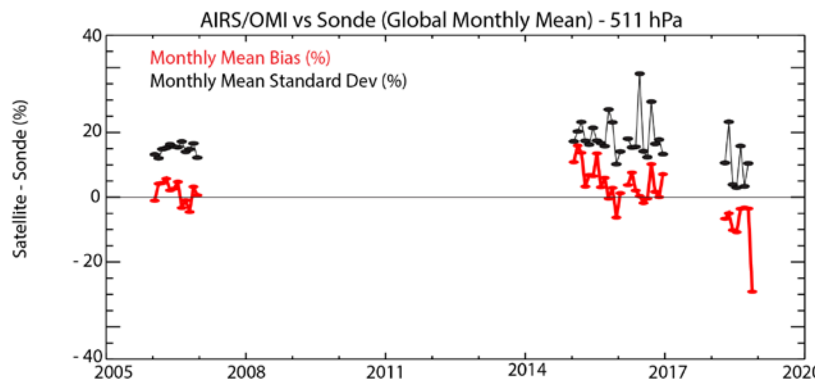
Fu et al. (2018) then showed that combing AIRS, which has coarser vertical resolution than TES, with OMI provides profiles with tropospheric DOFs similar to those from TES.

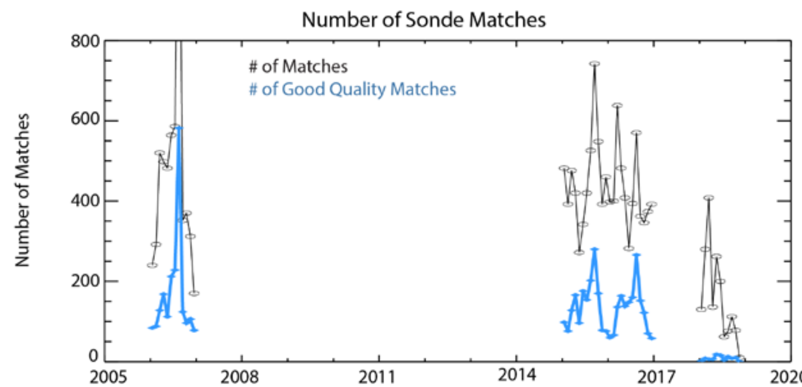
Building and Comparing Multiple Records of Tropospheric Ozone





AIRS/OMI ozone is highly consistent with the TES+IASI-TOE record over the Western US but appears to be biased low with respect to TES+IASI-TOE over East Asia. There is no indication of a positive trend in FT ozone over East Asia, Western US, or Europe in any of the records.





Preliminary evaluation of AIRS/OMI against ozonesondes suggests that biases for 2015-2016 are consistent with those from early in the record. The throughput of good quality retrievals is currently too low in 2018 to obtain reasonable statistics.

The entire time series will evaluated over multiple latitude bands.

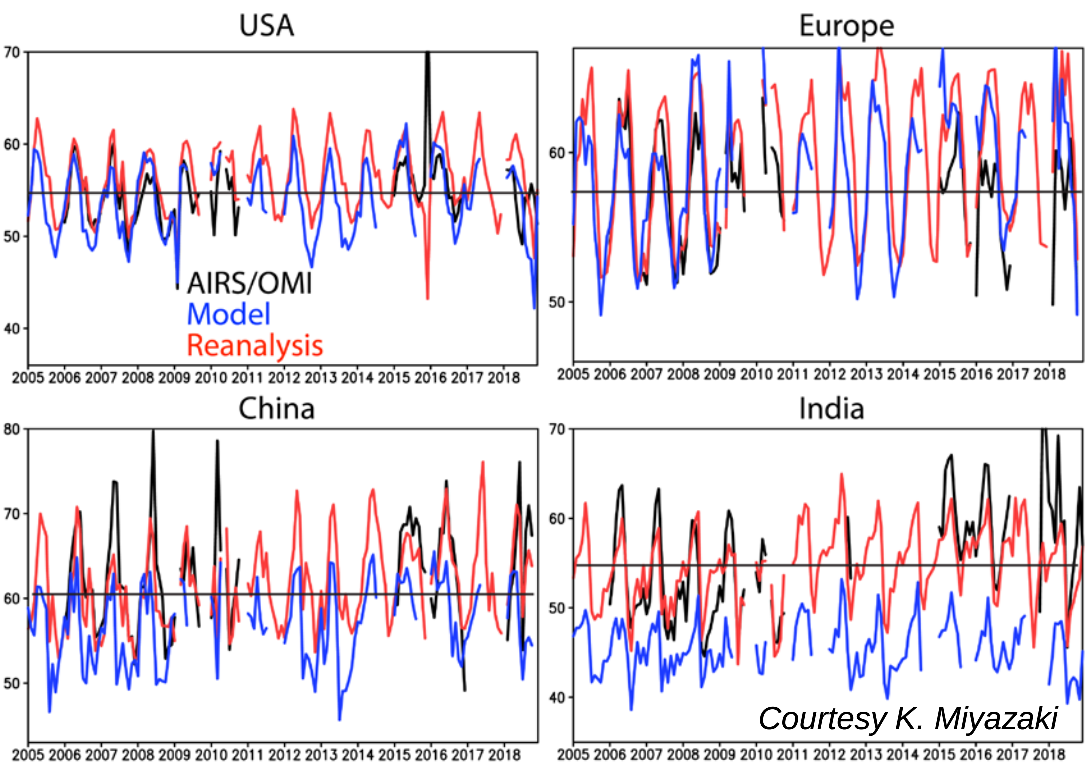
Courtesy G. Osterman

Using Chemistry Reanalyses to Evaluate and Understand Ozone Records

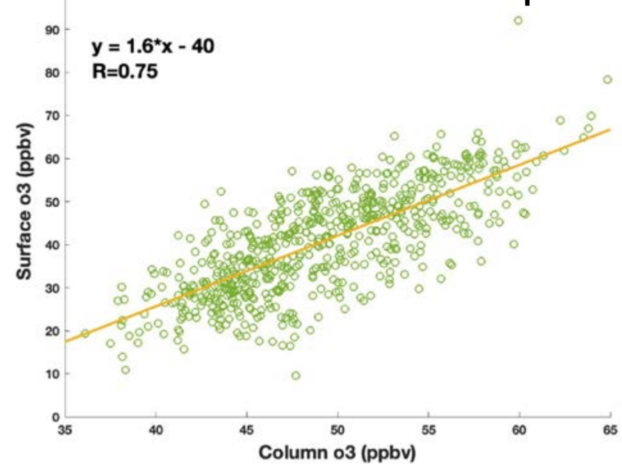
TES Legacy #4: Exploring synergistic applications of data assimilation and measurements

Ground-based and ozonesonde networks are sparse, particularly in developing regions. Tropospheric chemistry reanalyses can help bridge the spatio-temporal gap between those measurements and satellite data.

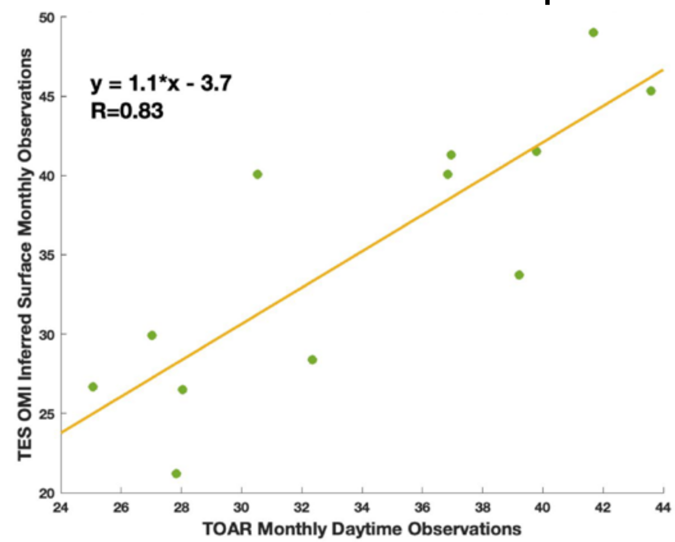
700-500 hPa ozone [ppbv]



Relationship Between 0-3 km and Surface Ozone Over Europe



Inferred TES/OMI Surface Ozone vs TOAR Surface Sites in Europe



Colombi et al., in preparation

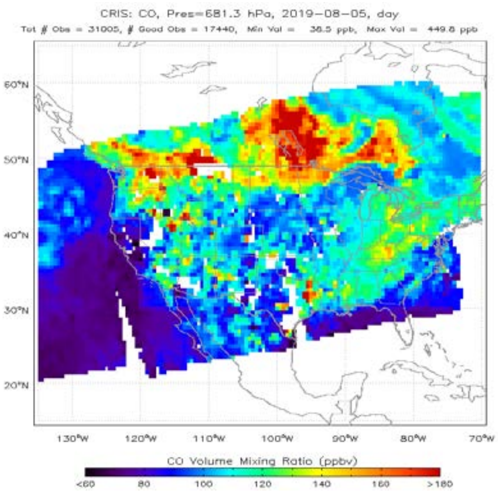
Nitrogen and VOC Species Help Us Attribute Ozone Changes

TES Legacy #4: Exploiting the richness of IR spectra

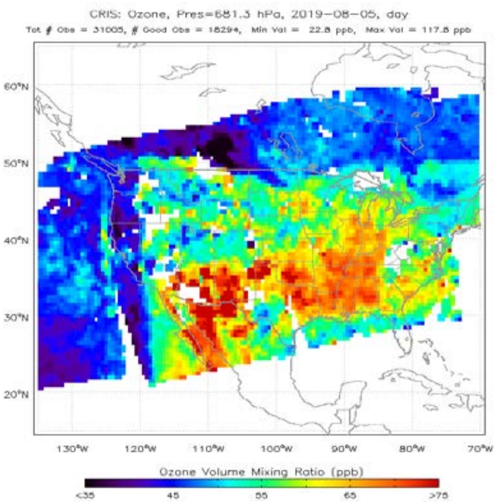
	AIRS (IR)	CrIS (IR)	TropOMI (UV-NIR)
CO	✓	✓	✓
CH_4	✓	✓	✓
CH_3OH		✓	
Isoprene		✓	
NH_3		✓	
PAN		✓	

August 5 2019, Daytime

CrIS CO

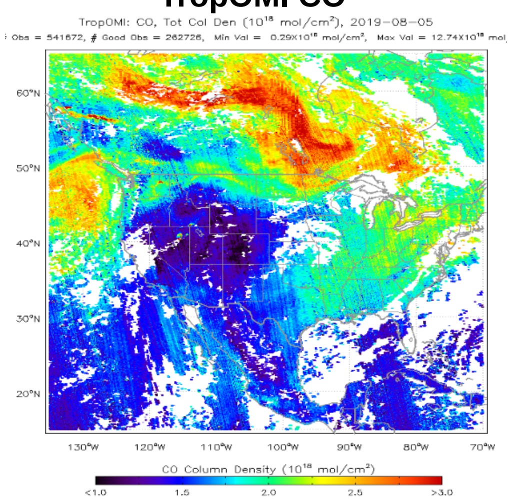


CrIS Ozone

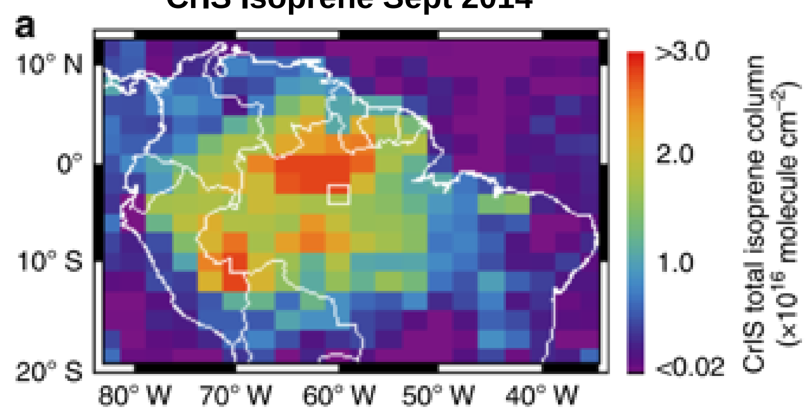


Courtesy M. Luo

TropOMI CO



CrIS Isoprene Sept 2014

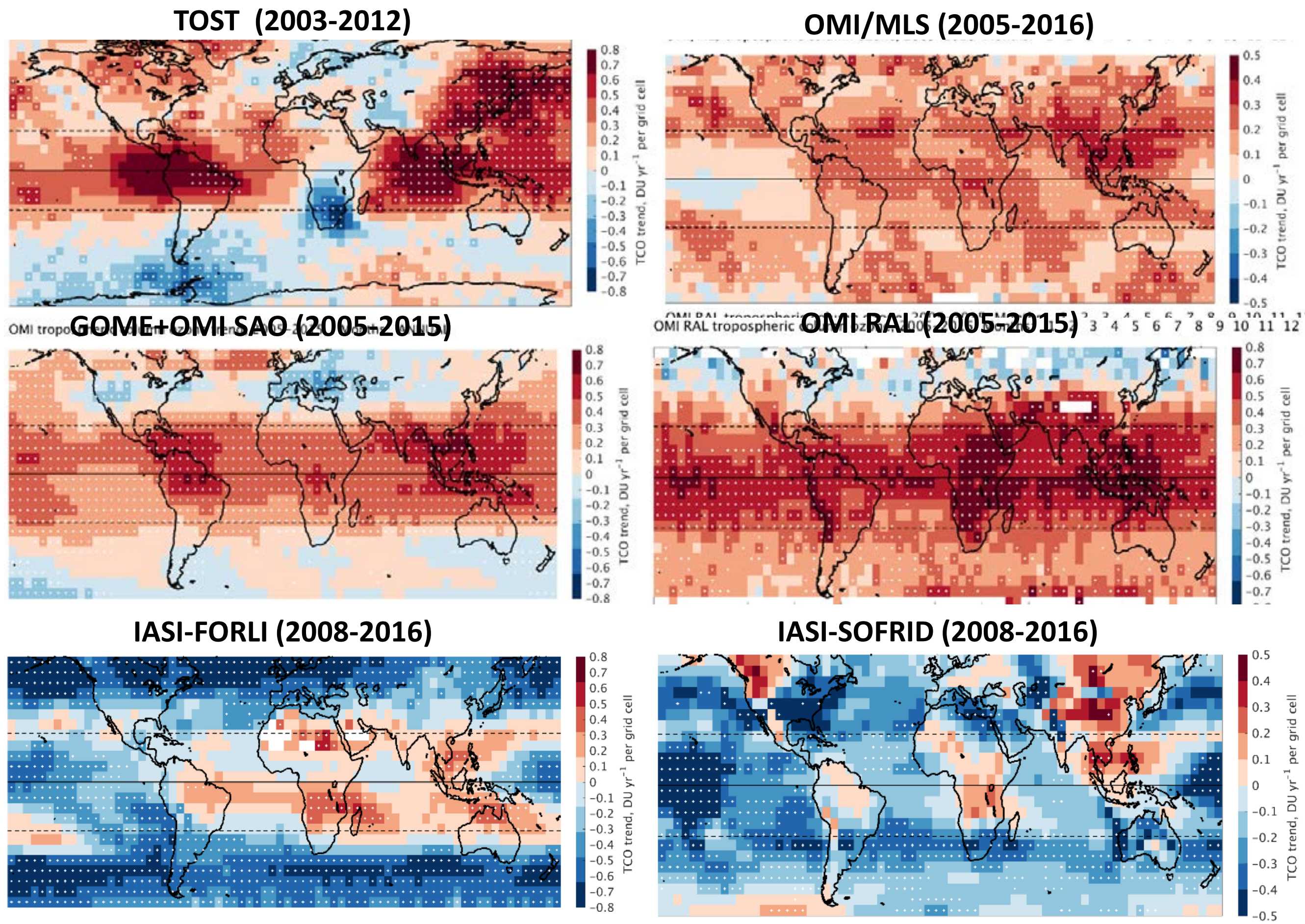


Fu et al., 2019

There is tremendous potential for an entire suite of ozone-related trace gases from IR and multispectral retrievals, with daily or better global coverage given enough computing power.

Summary

- TES's mission may be over, but we can exploit many of the approaches pioneered by the TES team to quantify and understand changes in tropospheric ozone based on the Program of Record
- Because the current IR sounders have lower spectral resolution than TES, achieving TES-like vertical resolution requires multispectral retrieval techniques applied to combinations of IR and UV instruments
- The lower noise levels and daily global coverage of the current IR sounders, however, present exciting opportunities for retrieval of minor species such as PAN, NH_3, and isoprene.
- Recent advances in tropospheric chemistry reanalyses mean that these products provide a plentiful resource for understanding differences in ozone trends from different satellites.
- TES was an Earth System sounder, and its legacy will echo through not just composition, but also the science of the water, carbon, and nitrogen cycles.



TOST (2003-2012)
OMI/MLS (2005-2016)
GOME+OMI SAO (2005-2015)
OMI RAL (2005-2015)
IASI-FORLI (2008-2016)
IASI-SOFRID (2008-2016)
TCO trend, DU yr⁻¹ per grid cell

Project	Period	Species	Instruments	Volume
HAQAST-2016 (J. Neu)	FY17-19	O3	AIRS+OMI	TES GS-like 2008, 2012, 2015 (for boundary conditions)
Aura-2013 (D. Fu)/SR15/SR17	FY14-19	O3	AIRS+OMI	Following TES GS
NASA-IDS-2016 (J. Worden)	FY18-20	CH4, (HDO)	TES+SCIAMACHY, AIRS+GOSAT	5K obs/day, 12 years
NOAA FIREX (K. Bowman)	FY18-21	O3, CO	CrIS+OMPS	7-8/15 Western US, 2-months during FIREX campaign
Suomi-NPP-2017 (H. Worden)	FY18-20	CO	CrIS+TROPOMI	four months, (one month per season), day/land only
Suomi-NPP (V. Payne)	FY18-20	PAN	CrIS	8/15,8/18 NA, Aircraft campaigns, e.g., FRAPPE, AToM
AIST (J. McDuffie):	FY18-19	O3	CrIS+OMPS	1 month, regional
ACMAP-2016 (D. Millet)	FY18-20	Isoprene	CrIS	4 months over 2 years, aircraft campaigns, e.g., KORUS-AQ