Relationships and Trends among Satellite NO_2 Columns and NO_x Emissions

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… with the support of NASA AQAST and acknowledgment of the contributions of AQAST colleagues working on emissions:

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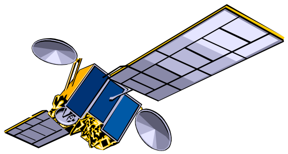
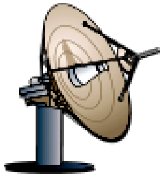
Daniel Jacob, Harvard University, AQAST team leader
John Haynes, NASA program manager

NASA Air Quality Applied Sciences Team (AQAST)

The AQAST goal is to transfer Earth Science knowledge to serve the needs of U.S. air quality management with focus on the use of NASA satellites, suborbital platforms, and models



satellites



suborbital platforms

models

AQAST

Air Quality Management Needs

- **Pollution monitoring**
- **Exposure assessment**
- **AQ forecasting**
- **Source attribution of events**
- **Quantifying and monitoring emissions**
- **Assessment of natural and international influences**
- **Understanding of transport, chemistry, aerosol processes**
- **Understanding of climate-AQ interactions**

(http://aqast.org)

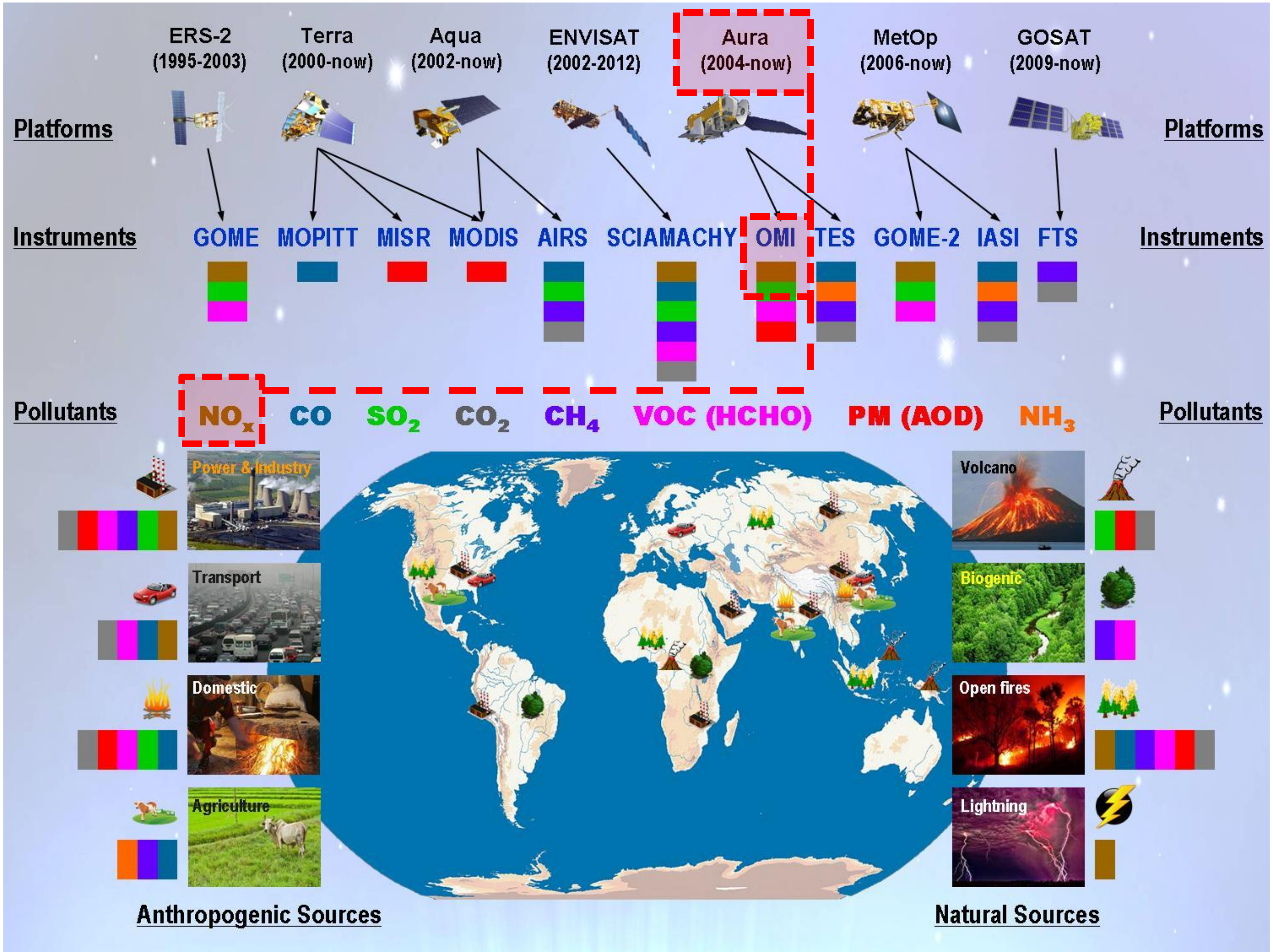
Objective of the emissions component: Assessment of the applicability of current worldwide studies of satellite retrievals and emissions estimation to U.S. air quality management

Issue: How can U.S. air quality managers make use of satellite retrievals to improve emission estimates, and what developments are needed to improve the usefulness of those retrievals?

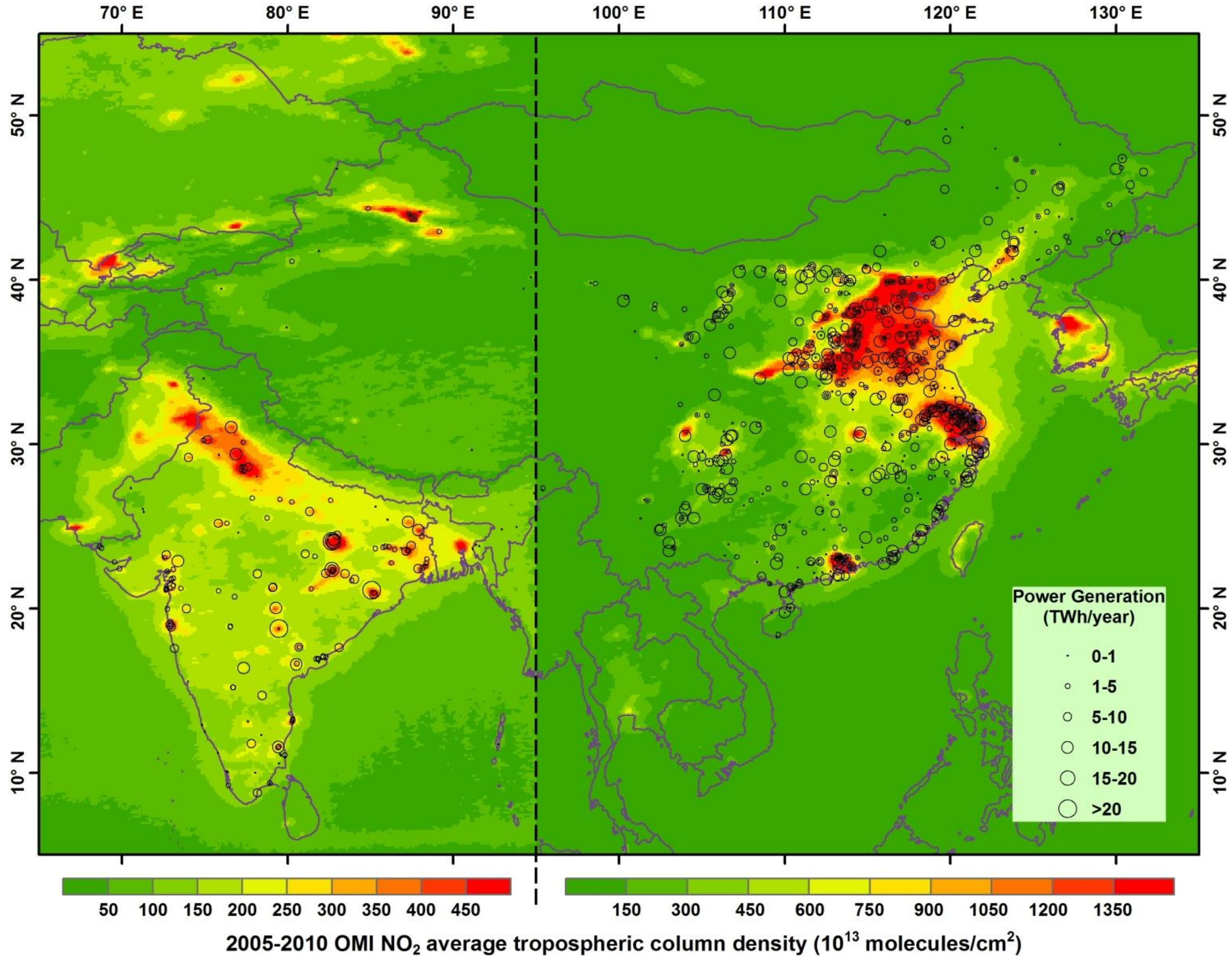
Some potential applications in the U.S. (not exhaustive):

problematic industrial sources and industrial complexes, uncertain area sources (including biogenic), oil/gas extraction, verification of regional emission reductions and trends, quantification of atmospheric lifetimes, quantification of uncertain Mexican and Canadian emissions, etc., etc.

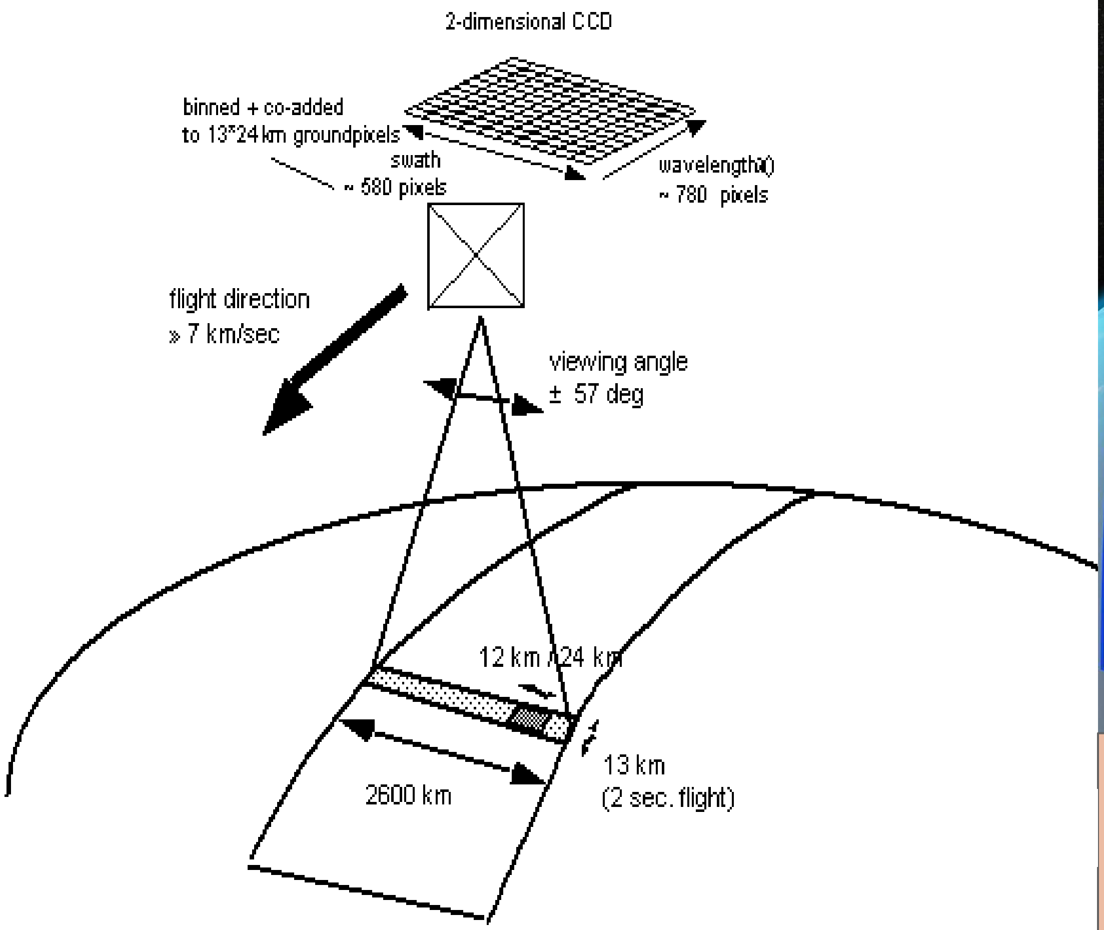
The complexity of satellite platforms, instruments, pollutants, sources, and world regions. How to process the information?

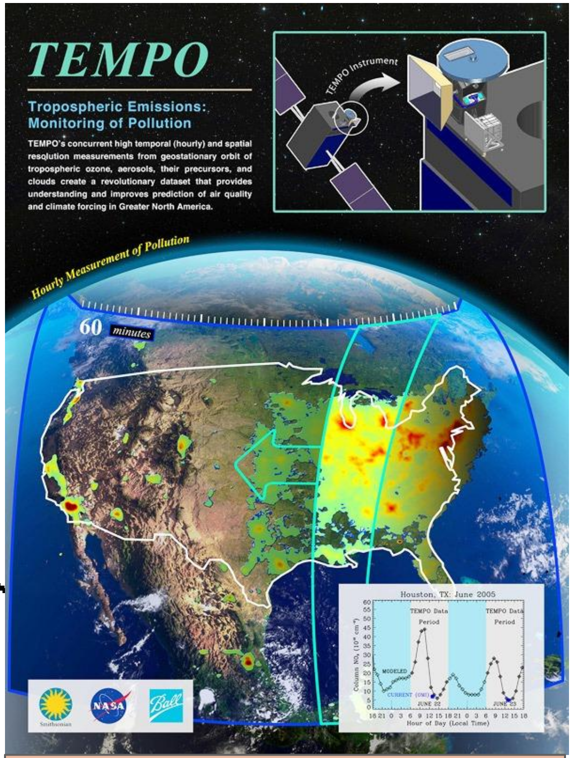


Initial studies of high-NO_x source regions in Asia were promising



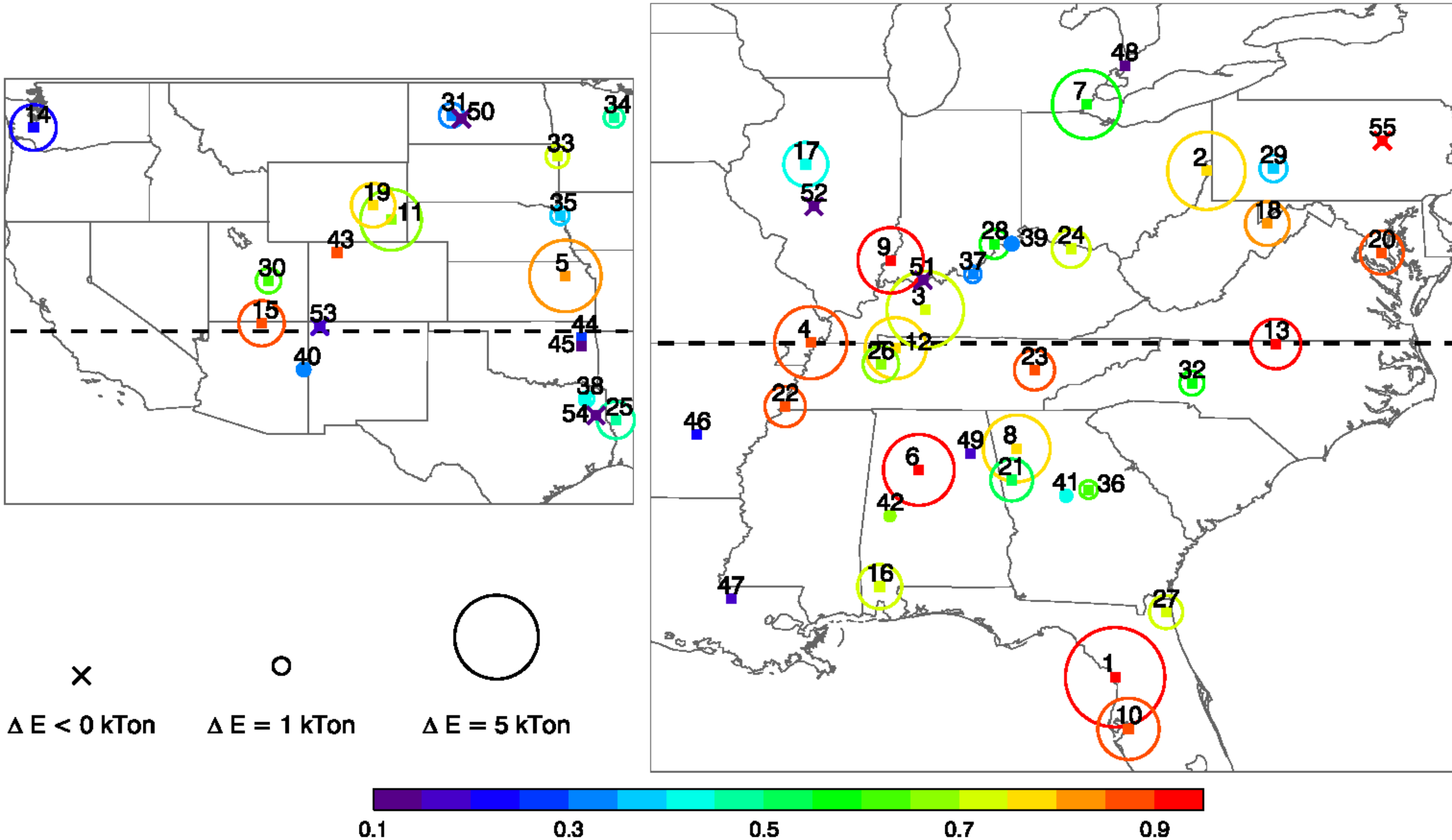
There is the potential to quantify point sources of NO_x, SO_2, etc., from OMI, if pollutant transport and chemical conversion cooperate





Coming in ~2019: TEMPO, in geosynchronous orbit over North America at 2 × 4.5 km, 1-hour resolution!

NO_x emissions from U.S. power plants [*Duncan et al.*, 2013]

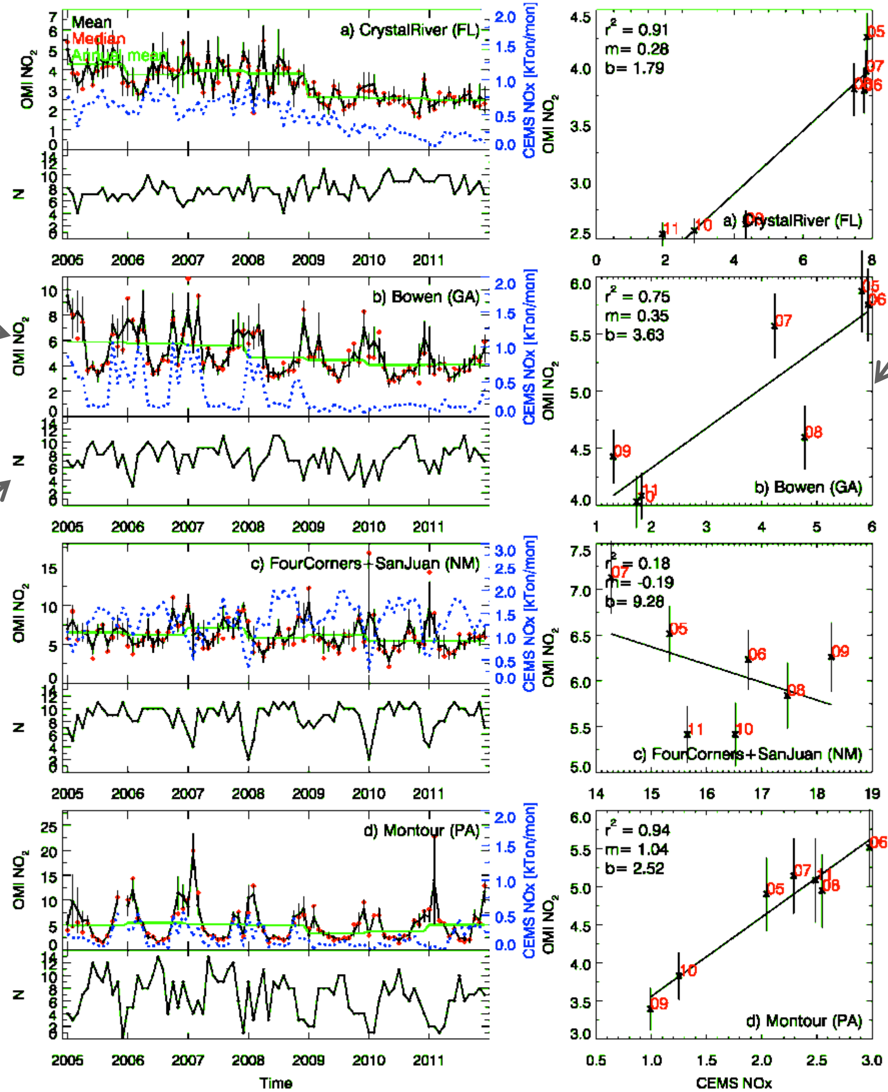


(size of circle represents change in emissions between 2005 and 2011; color of circle represents r^2 correlation between annual-average OMI and CEMS data)

Sample measurement data sets for four power plants in FL, GA, NM, and PA over a seven-year period, 2005-2011 [*Duncan et al.*, 2013]

monthly OMI NO_2
daily CEMS NO_x
annual mean NO_2

sample size (days per month)



$r^2 = 0.91$

Annual mean OMI NO_2 vs annual CEMS NO_x

$r^2 = 0.75$

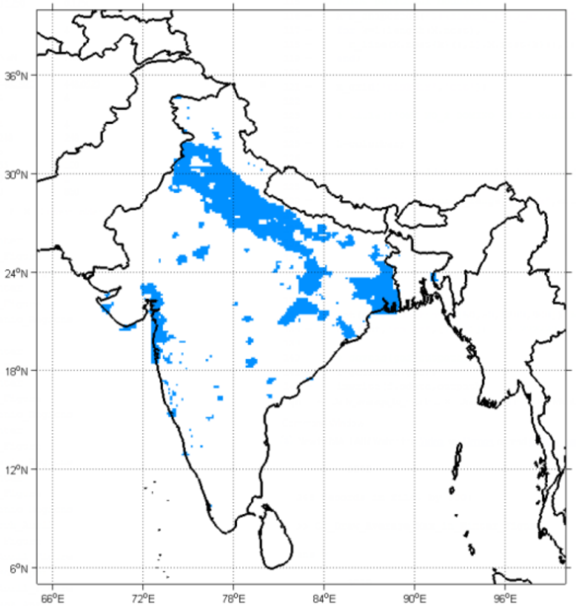
$r^2 = 0.18$

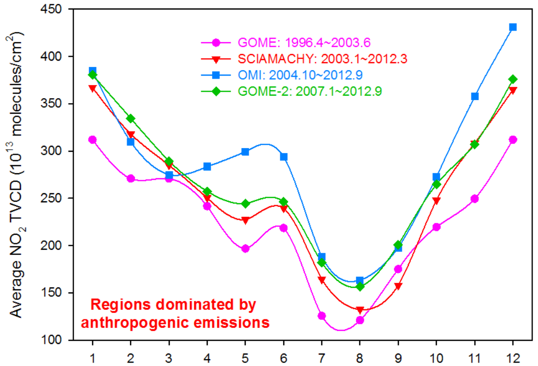
$r^2 = 0.94$

Identification of NO_x source regions using seasonality [*Lu et al.*, 2013]

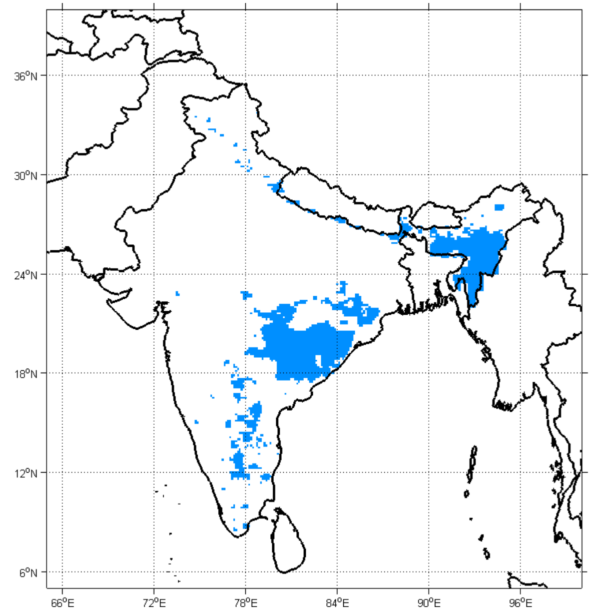
Example: OMI NO_2 (2005-2011)

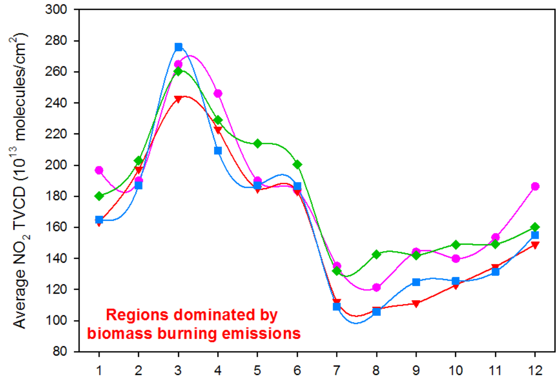
Anthropogenic emissions dominant (Dec/Jan peak)



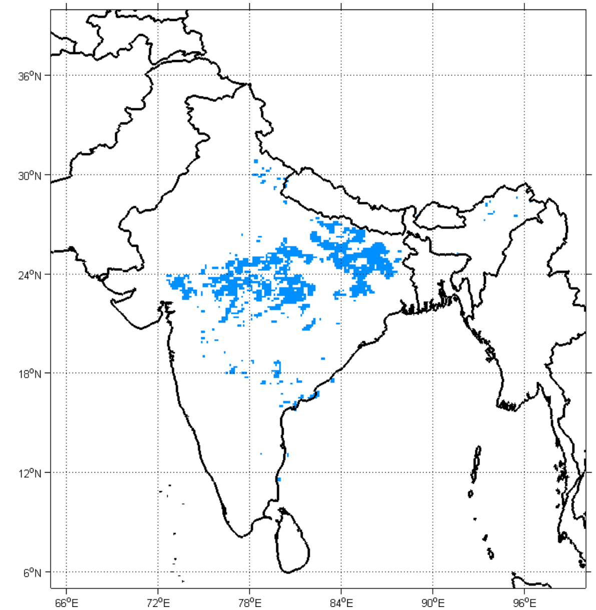


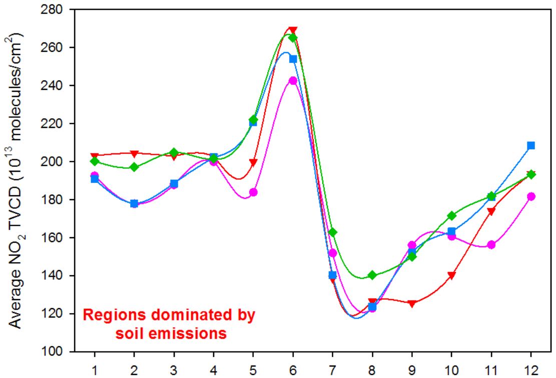
Biomass burning emissions dominant (Mar/Apr peak)





Soil emissions dominant (Jun peak)





Application of satellite observations for timely updates to NO_x emission inventories (Randall Martin group)

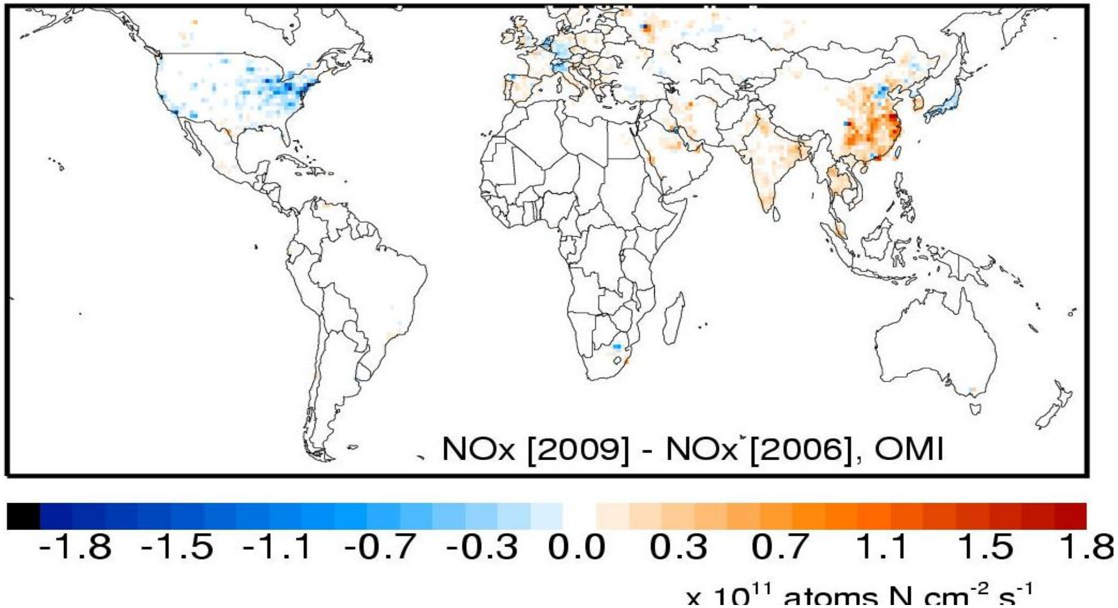
Use CTM to calculate local sensitivity of changes in trace-gas column to changes in emissions

Fractional Change in Emissions

$$\Delta E = \beta \times \Delta \Omega$$

Fractional Change in Trace-Gas Column

Local Sensitivity of Column Changes to Emission Changes

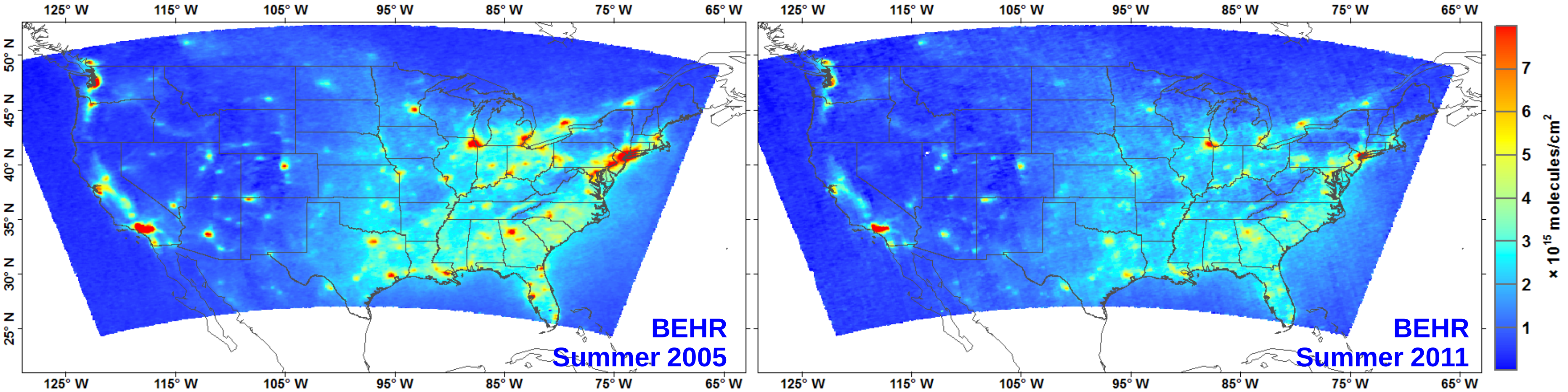


Forecast global inventory for 2009, based on bottom-up inventory for 2006 and monthly OMI NO_2 for 2006-2009

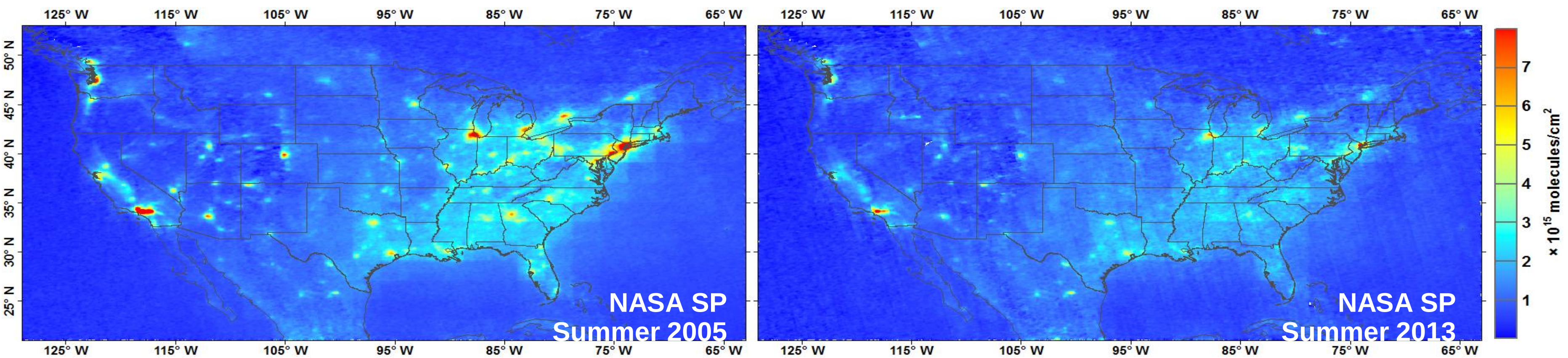
Lamsal et al., 2011

General decrease of OMI NO_2 over U.S. since 2005

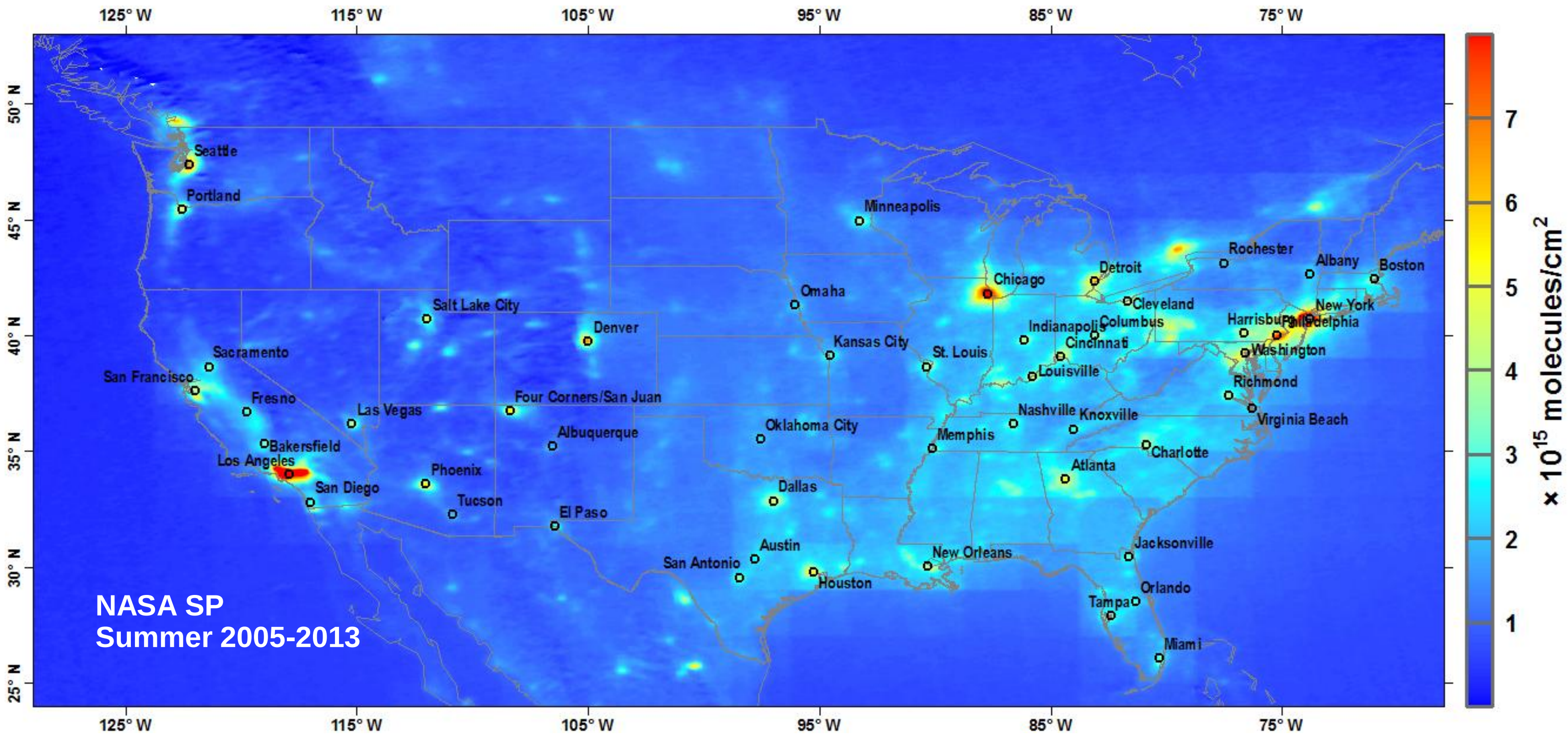
Summertime BEHR OMI NO_2 (2005 vs. 2011)



Summertime NASA SP OMI NO_2 (2005 vs. 2013)



New examination of urban NO_x emissions using OMI

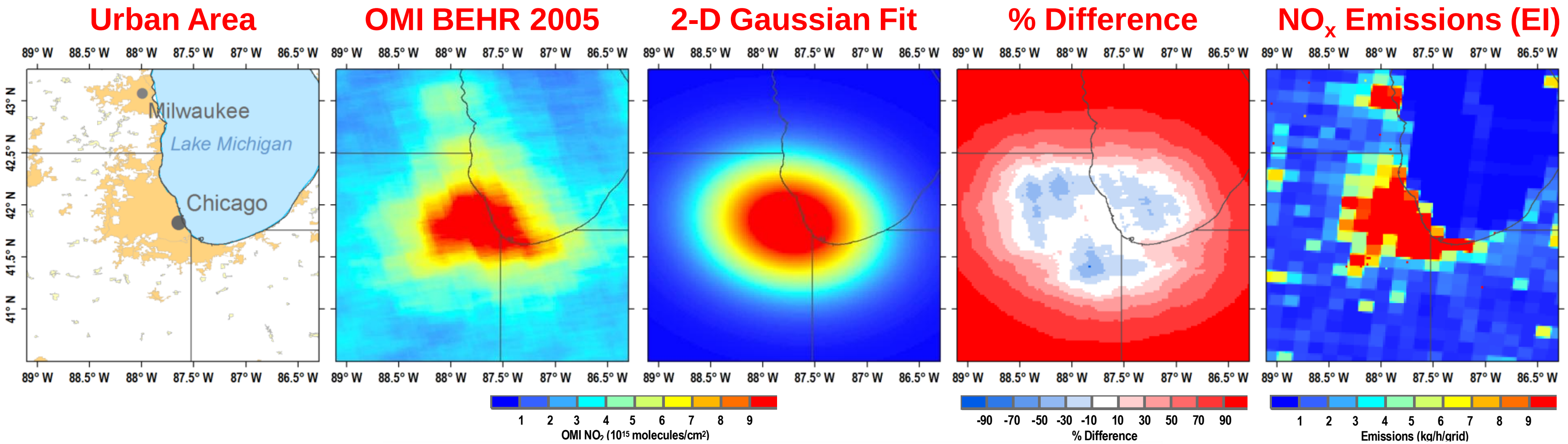


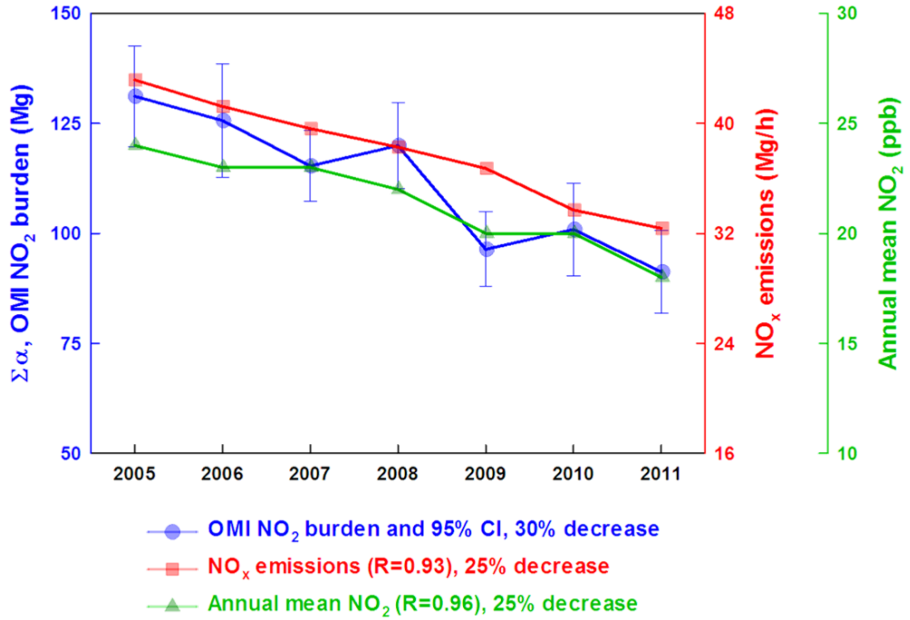
- Examined the top 80 urban areas on the basis of population
- Combined adjacent urban areas that share the same NO_2 hotspot
- Excluded some urban areas, the NO_2 signals of which are not isolated

51 urban areas selected for further examination

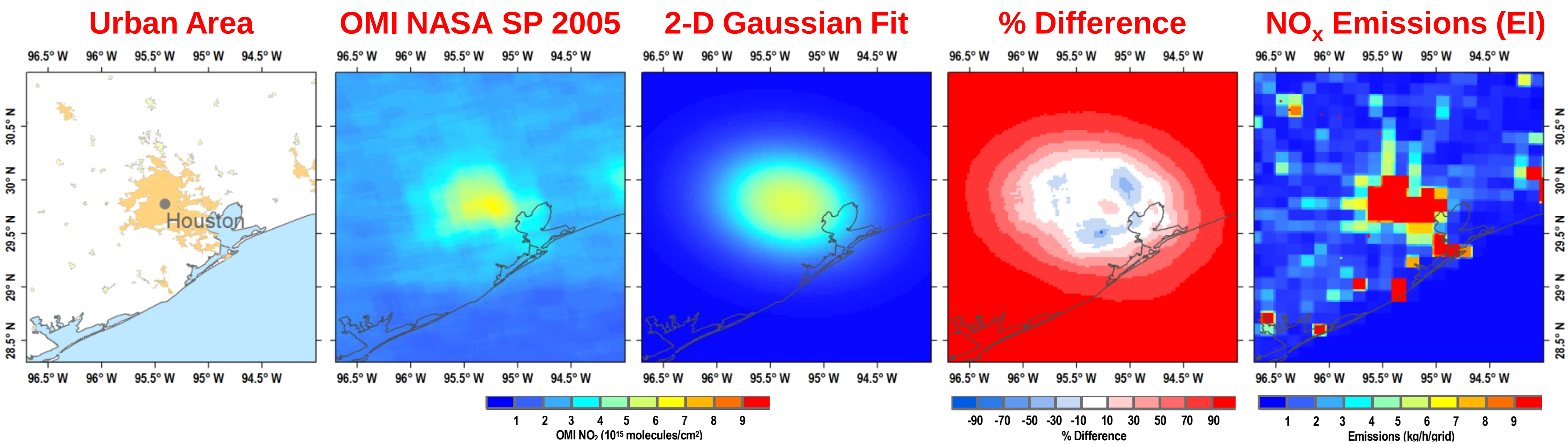
- Represent about 40% of total NO_x emissions in the U.S.

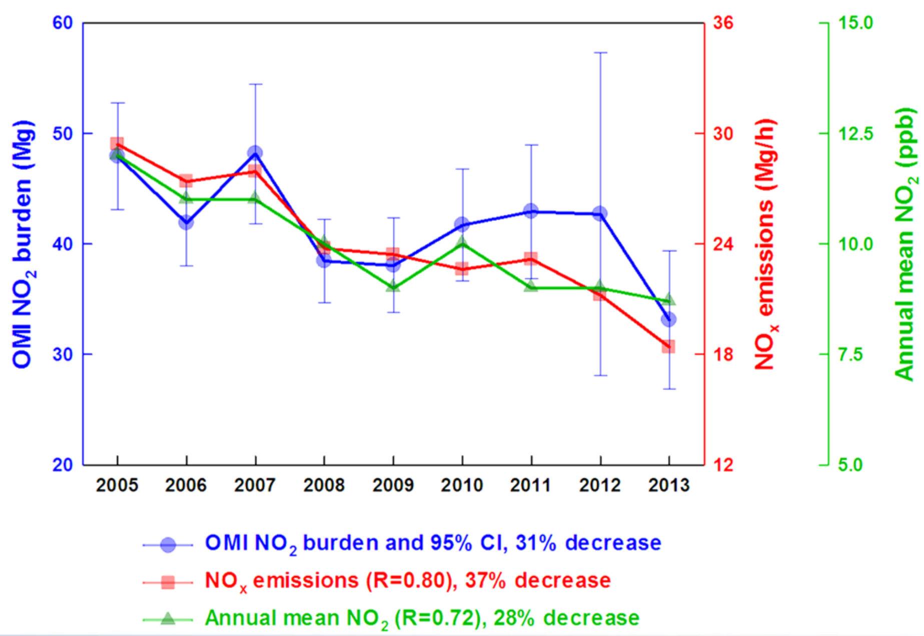
Example: Chicago



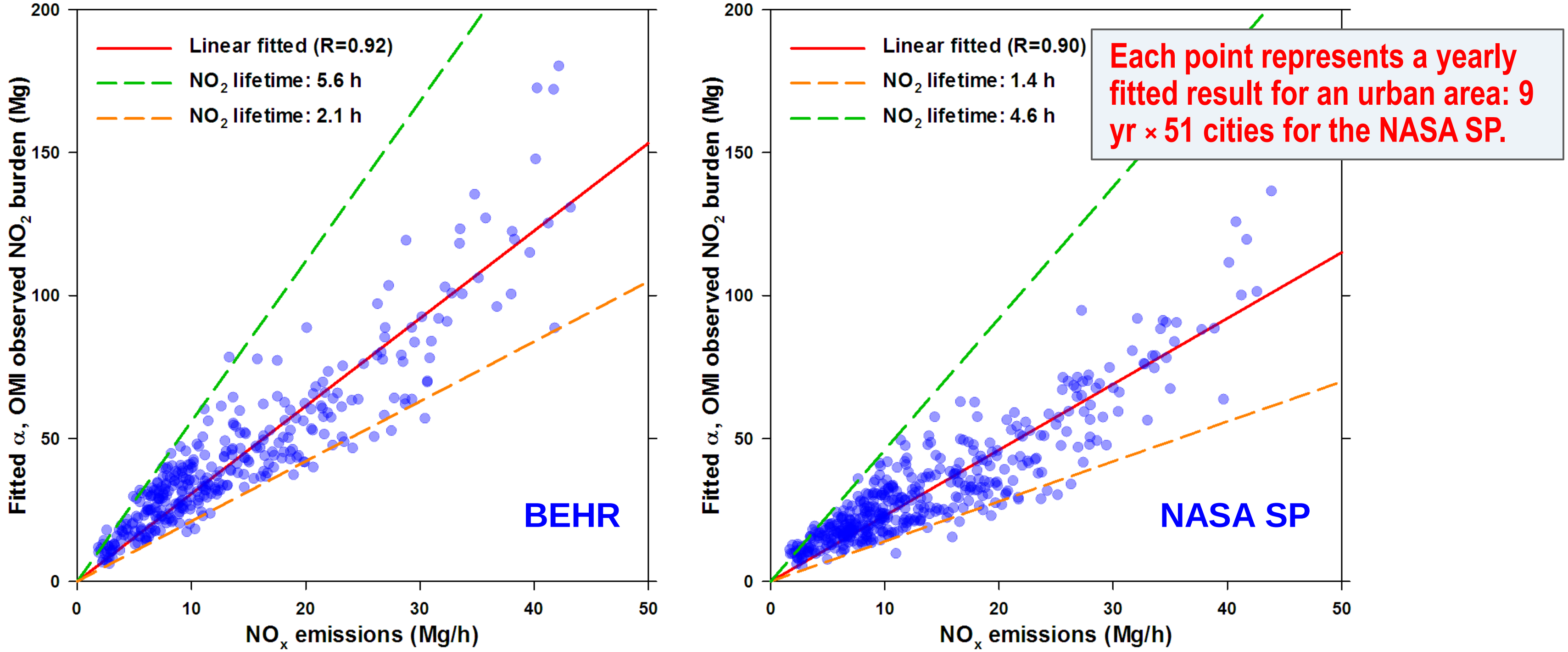


Example: Houston





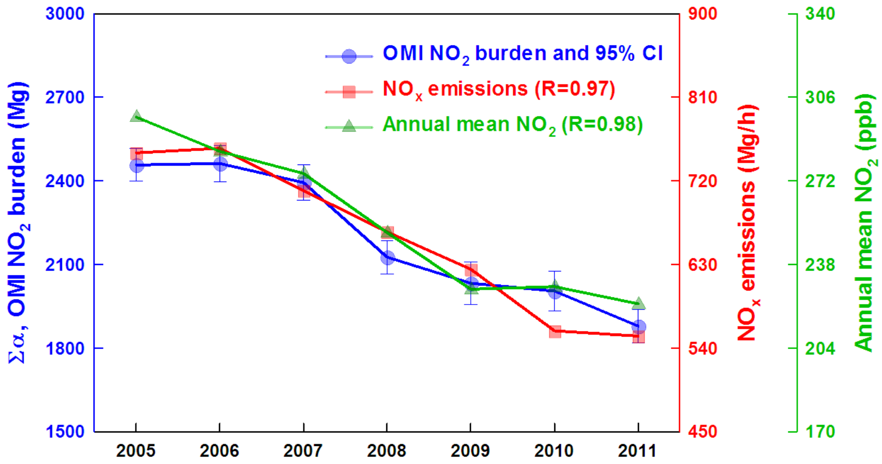
NO_x emissions vs OMI NO_2 burden



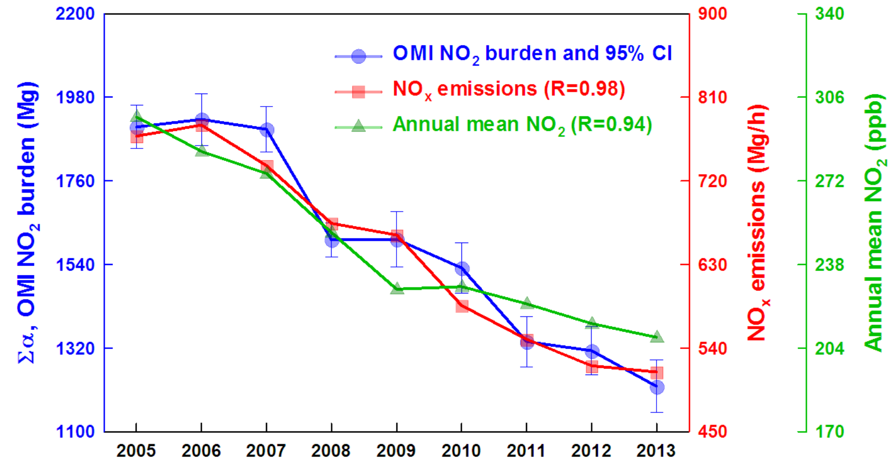
- Good agreement between NO_x emissions and OMI NO_2 observations
- The 95% CI of the summertime NO_2 dispersion lifetime in U.S. urban areas
  - **Berkeley retrievals** 2.1~5.6 h **NASA retrievals** 1.4~4.6 h
- Uncertainties of urban NO_x emissions estimated from OMI NO_2 observations
  - **Berkeley retrievals** ±45% **NASA retrievals** ±57%

Trend of the OMI NO_2 burden summed over all selected urban areas

BEHR



NASA SP



From 2005 to 2011 ***From 2005 to 2013***

Total amount of NO_2 observed by the OMI over selected urban areas

24% decrease ***36% decrease***

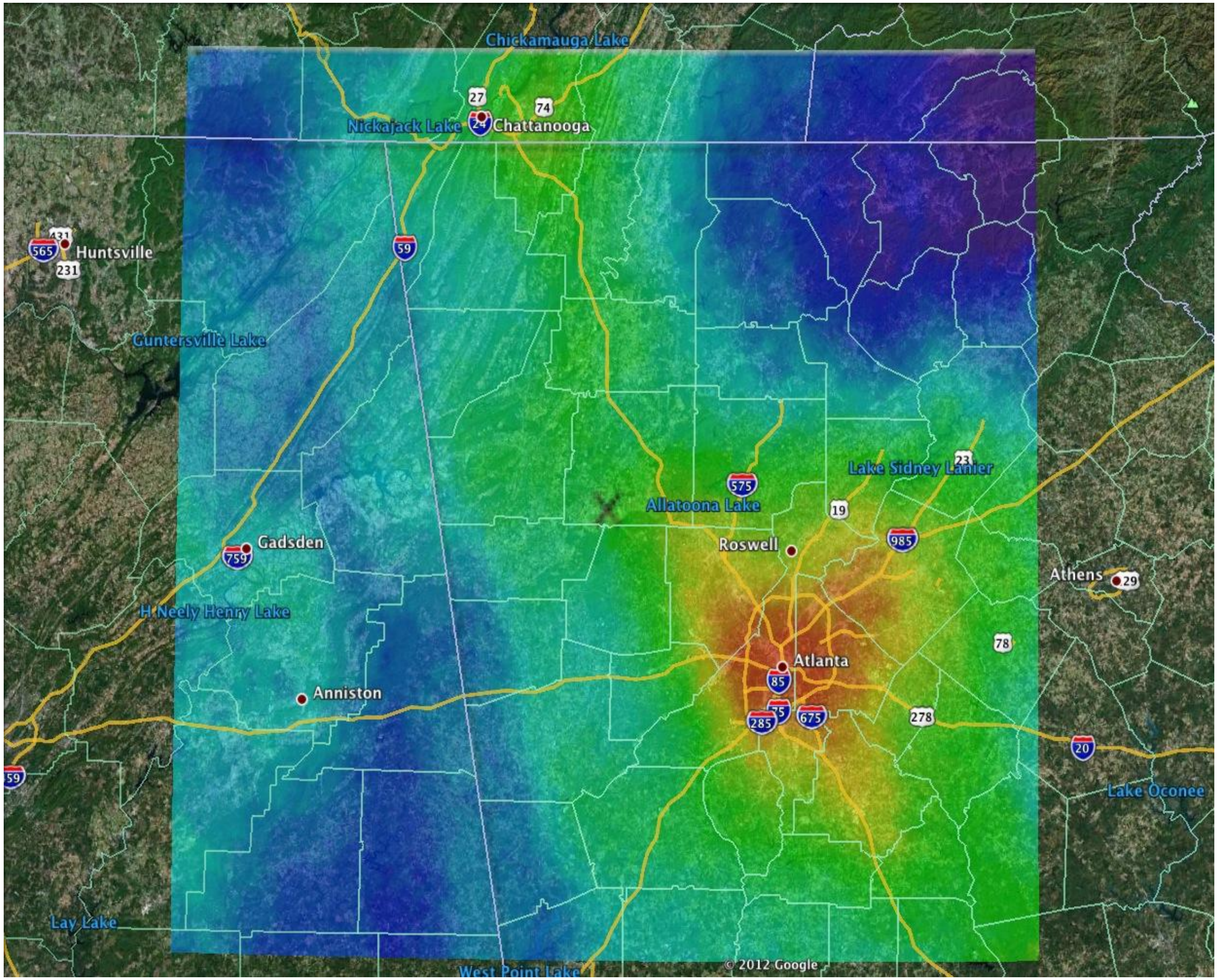
Total NO_x emissions from selected urban areas

26% decrease ***33% decrease***

Averages of annual mean NO_2 concentrations in selected urban areas

25% decrease ***30% decrease***

OMI NO_2 around Atlanta using oversampling—a transportation signal?



Bryan Duncan, unpublished, 2012

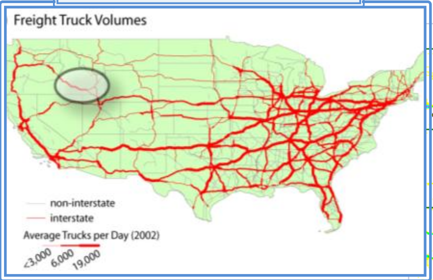
Relationships and trends among satellite NO_2 columns, NO_x emissions, and air quality in North America

David Streets (PI), Greg Carmichael, Dan Cohan, Ben de Foy, Bryan Duncan, Arlene Fiore, and Tracey Holloway

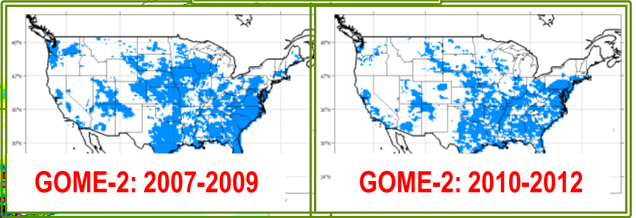
Carmichael, Fiore: Modeled NO_2 columns

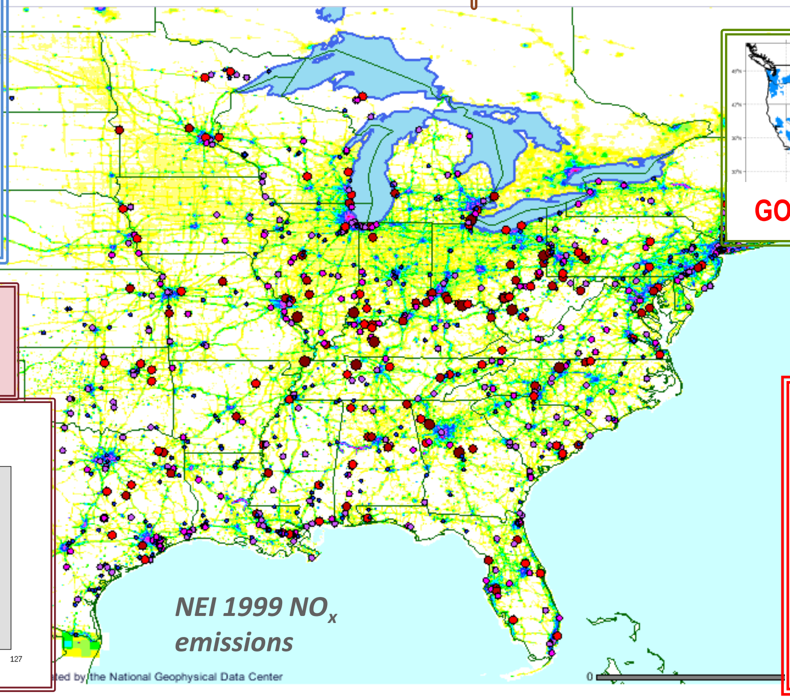
de Foy: oversampling, surface monitoring

Holloway: mobile sources

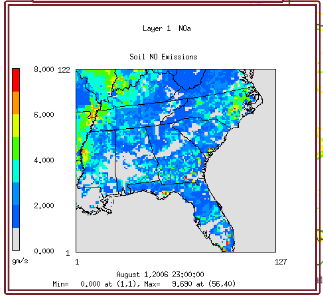


Streets: urban areas

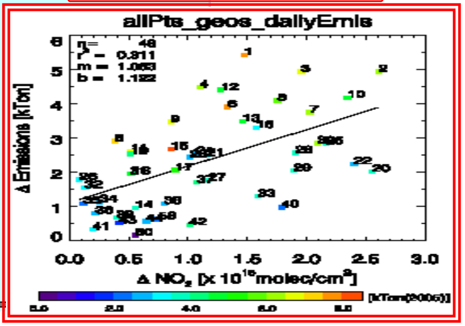




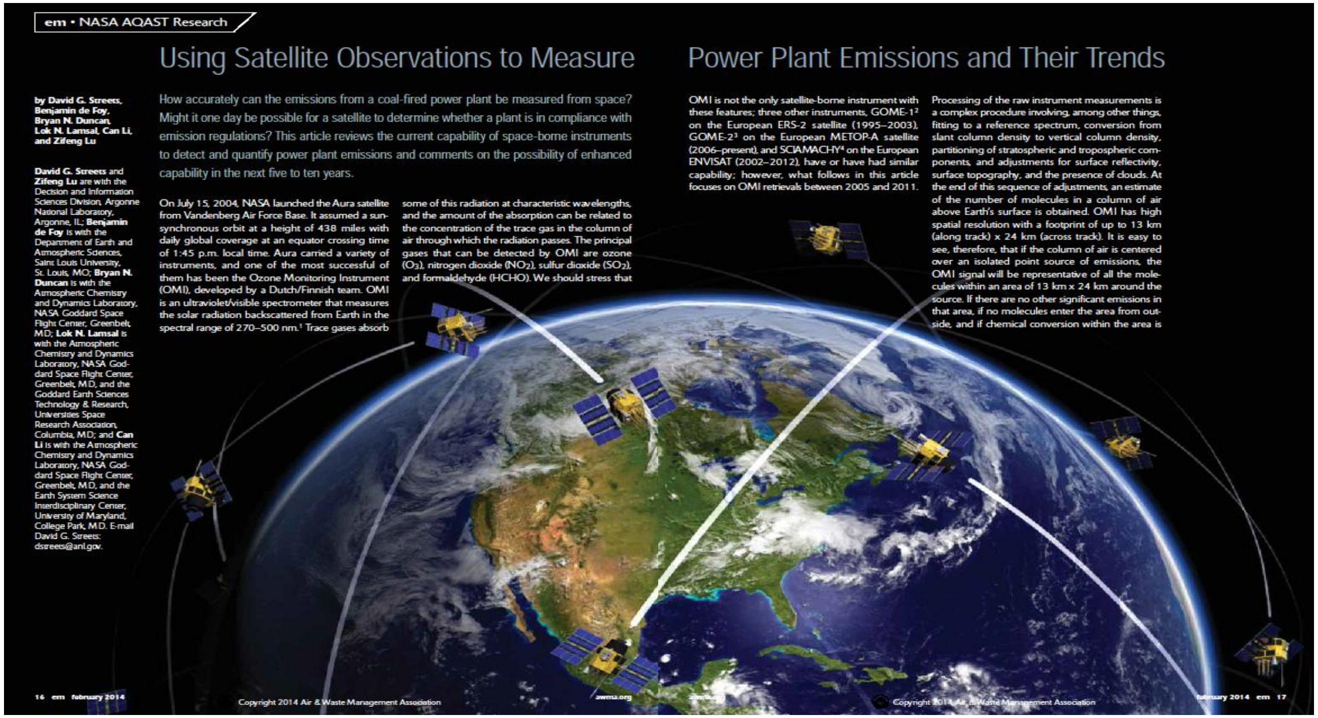
Cohan: soil NO_x



Duncan: power plants



AQAST publications on emissions



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Using Satellite Observations to Measure Power Plant Emissions and Their Trends

by David G. Streets, Benjamin de Foy, Bryan N. Duncan, Lok N. Lamsal, Can Li, and Zifeng Lu

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How accurately can the emissions from a coal-fired power plant be measured from space? Might it one day be possible for a satellite to determine whether a plant is in compliance with emission regulations? This article reviews the current capability of space-borne instruments to detect and quantify power plant emissions and comments on the possibility of enhanced capability in the next five to ten years.

On July 15, 2004, NASA launched the Aura satellite from Vandenberg Air Force Base. It assumed a sun-synchronous orbit at a height of 438 miles with daily global coverage at an equator crossing time of 1:45 p.m. local time. Aura carried a variety of instruments, and one of the most successful of them has been the Ozone Monitoring Instrument (OMI), developed by a Dutch/Finnish team. OMI is an ultraviolet/visible spectrometer that measures the solar radiation backscattered from Earth in the spectral range of 270–500 nm.[1] Trace gases absorb some of this radiation at characteristic wavelengths, and the amount of the absorption can be related to the concentration of the trace gas in the column of air through which the radiation passes. The principal gases that can be detected by OMI are ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and formaldehyde (HCHO). We should stress that OMI is not the only satellite-borne instrument with these features; three other instruments, GOME-1[2] on the European ERS-2 satellite (1995–2003), GOME-2[3] on the European METOP-A satellite (2006–present), and SCIAMACHY[4] on the European ENVISAT (2002–2012), have or have had similar capability; however, what follows in this article focuses on OMI retrievals between 2005 and 2011.

Processing of the raw instrument measurements is a complex procedure involving, among other things, fitting to a reference spectrum, conversion from slant column density to vertical column density, partitioning of stratospheric and tropospheric components, and adjustments for surface reflectivity, surface topography, and the presence of clouds. At the end of this sequence of adjustments, an estimate of the number of molecules in a column of air above Earth's surface is obtained. OMI has high spatial resolution with a footprint of up to 13 km (along track) x 24 km (across track). It is easy to see, therefore, that if the column of air is centered over an isolated point source of emissions, the OMI signal will be representative of all the molecules within an area of 13 km x 24 km around the source. If there are no other significant emissions in that area, if no molecules enter the area from outside, and if chemical conversion within the area is

- Duncan, B.N., et al., *Satellite Data for U.S. Air Quality Applications: Examples of Applications, Summary of Data End-User Resources, Answers to FAQs, and Common Mistakes to Avoid*, Atmospheric Environment, submitted (2014).
- Streets, D.G., et al., *Using Satellite Observations to Measure Power Plant Emissions and Their Trends*, EM Magazine, 16-21 (Feb 2014).
- Lu, Z., et al., *Ozone Monitoring Instrument Observations of Interannual Increases in SO_2 Emissions from Indian Coal-Fired Power Plants during 2005-2012*, Environmental Science & Technology, *47*, 13,993-14,000 (2013).
- Duncan, B.N., et al., *The Observed Response of Ozone Monitoring Instrument (OMI) NO_2 Columns to NO_x Emission Controls on Power Plants in the United States: 2005-2011*, Atmospheric Environment, *81*, 102-111 (2013).
- Streets, D.G., et al., *Emissions Estimation from Satellite Retrievals: A Review of Current Capability*, Atmospheric Environment, *77*, 1011-1042 (2013).
- Lu, Z., and D.G. Streets, *Increase in NO_x Emissions from Indian Thermal Power Plants during 1996-2010: Unit-Based Inventories and Multi-Satellite Observations*, Environmental Science & Technology, *46,* 7463-7470 (2012).