Improving Knowledge of Emissions using Satellite and Aircraft Observations and Regional Models

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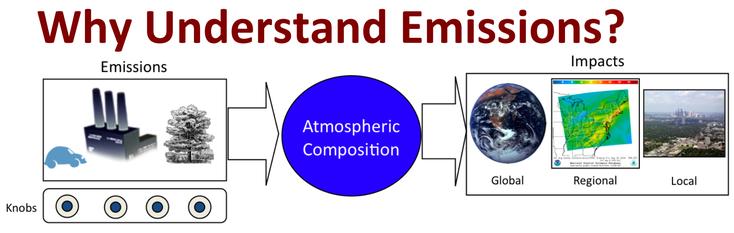
Why Understand Emissions?



Actions about the atmosphere focus on emissions.

Our efforts to understand emissions are motivated by the fact that effective actions aimed at changing the atmosphere must focus on emissions. Emissions are the key drivers to changes in atmospheric composition, and in turn, to air quality and climate. Accurate, timely, and complete information on emissions is therefore critical to environmental science and policy. In this *Century of Accountability*, stakeholders are increasingly asking scientists to provide quantitative information about emissions and their impacts.

G. J. Frost, et al. (2013), *Atmos. Environ.*, **81**, 710-712

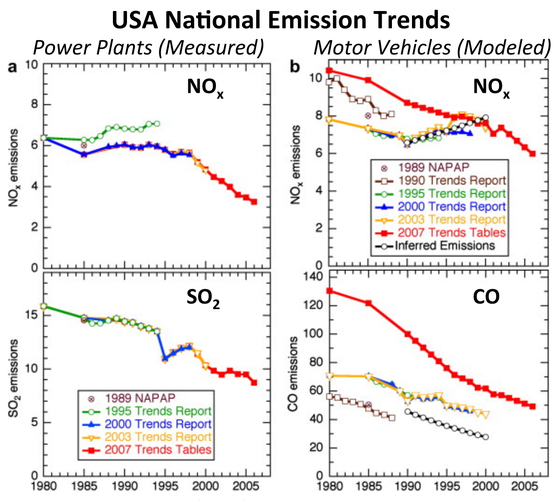
Inventories: Important but Uncertain

Bottom-up emissions inventories are the primary tool used by scientists and decision-makers to quantify emissions and make predictions about the future.

Inventories are complex aggregated calculations combined with some representative measurements. This complexity leads to long periods for developing inventories, inconsistencies between different inventory data sets, lack of transparency about inventory development methods, and incomplete access to inventory data. Most importantly, these issues result in difficulty establishing uncertainties on inventories.

Even inventories for the USA, developed over many years at substantial cost, have significant issues with consistency and uncertainties. Most USA sectors derive their emissions estimates from models that can be very uncertain. One exception is electrical power generation plants, with their routine measurements by in-stack continuous emission monitoring systems (CEMS).

USA National Emission Trends



P. S. Monks et al. (2009) *Atmos. Environ.*, **43**, 5268-5350

Methods

Top-down approach to understanding emissions

Our top-down approach uses different sampling platforms to measure the abundance and variability of atmospheric constituents. It also employs atmospheric models of varying complexity as transfer standards between a constituent's abundance and its emissions. This approach quantifies the total emissions from a region, the temporal variability and spatial distribution of emissions, and partitions the emissions contributions from different source sectors. We provide objective evaluations of inventories, allowing us to understand and reconcile differences between bottom-up and top-down methods. By quantifying uncertainties in our estimates and using different methods to arrive at the same answer, we increase confidence in our conclusions.

Aircraft Measurements

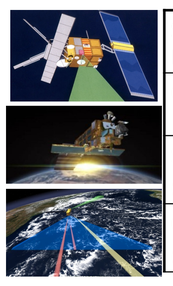
We use instrumented research aircraft to measure multiple chemical species upwind and downwind of emissions sources. These flights generally take place during daytime under well mixed conditions. From such measurements, we can map out the spatial distribution of sources and look at temporal variability. Under the right conditions, we can also estimate source emissions using the mass balance approach.

Satellite Retrievals

In the examples shown here, we use satellite measurements of tropospheric NO_2 columns to understand and improve NO_x emissions. In this work we take advantage of the short lifetime of NO_x in the daytime in summer, so that satellite-measured NO_2 columns are directly proportional to NO_x emissions at regional scales.

These methods rely on chemical-transport models to simulate NO_2 columns which are in turn compared to the satellite measurements, providing information on the accuracy and trends of NO_x emissions.

For power plants, CEMS data provide input for modeling NO_2 columns and a check on satellite measured NO_2 columns. Satellite NO_2 columns confirmed in this way can then be used to evaluate inventories for other NO_x sources that are more uncertain, such as cities.



Satellite NO_2 Instrument	Period	Overpass time	Global coverage	Pixel size
GOME (ERS-2)	1995-2003	10:30 LT	3 days	340 x 40 km^2
SCIAMACHY (ENVISAT)	2002-2012	10:00 LT	6 days	60 x 30 km^2
OMI (AURA)	2004-present	13:30 LT	1 day	27 x 13 km^2 (nominal)

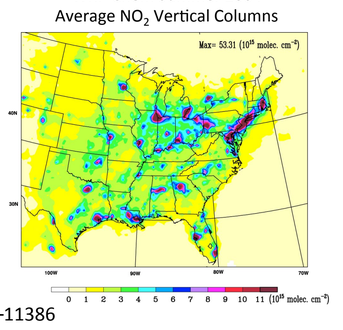
Modeling

Regional Chemical-Transport Model

The WRF-Chem (Weather Research and Forecasting - Chemistry) model simulates atmospheric chemistry online within the WRF meteorological model. Emissions inputs consist of the US EPA National Emission Inventory (NEI) and CEMS data.

S.-W. Kim et al. (2006), *Geophys. Res. Lett.*, *33*, L22812
S.-W. Kim et al. (2009), *J. Geophys. Res.*, *114*, D11301
S.-W. Kim et al. (2011), *Atmos. Chem. Phys.*, *11*, 11361–11386

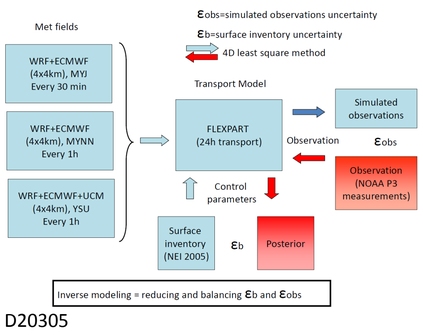
WRF-Chem Summer 2004 Average NO_2 Vertical Columns



Mesoscale Inverse Model

The inverse model is based on the FLEXPART Lagrangian particle dispersion model, driven by an ensemble of 3 meteorological simulations (WRF). Research aircraft observations are assimilated by the inverse model. Emissions prior is the US NEI.

J. Brioude et al. (2011), *J. Geophys. Res.*, *116*, D20305



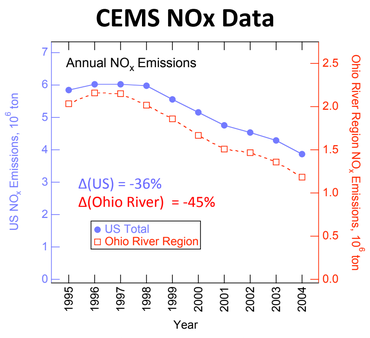
Quantifying Power Plant Emission Decreases with Satellites and Models

S.-W. Kim et al. (2006), *Geophys. Res. Lett.*, *33*, L22812, doi:10.1029/2006GL02774

Significant NO_x controls were installed on large point sources, particularly electrical power generation plants, across the Eastern USA beginning in the late 1990s.

We demonstrate that satellites can quantitatively detect the impact of these power plant NOx emissions controls by measuring their impact on atmospheric NO_2 levels.

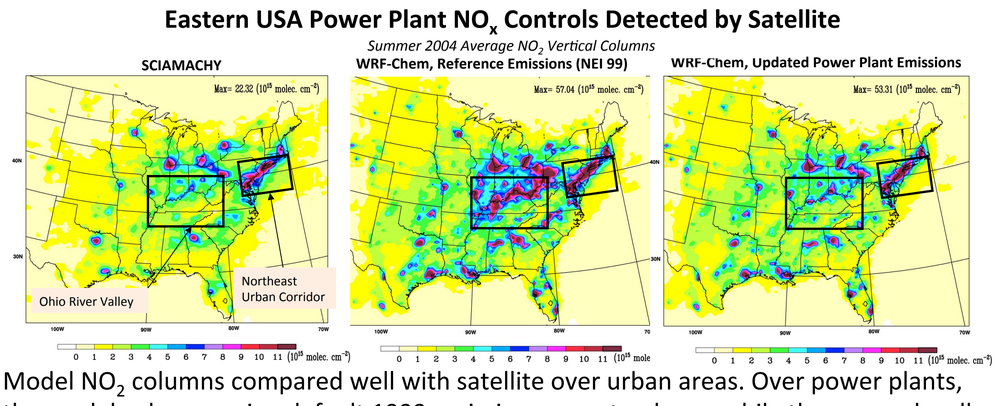
CEMS NOx Data



Power plant in-stack NO_x monitors (CEMS) show substantial NO_x emission reductions since late 1990's.

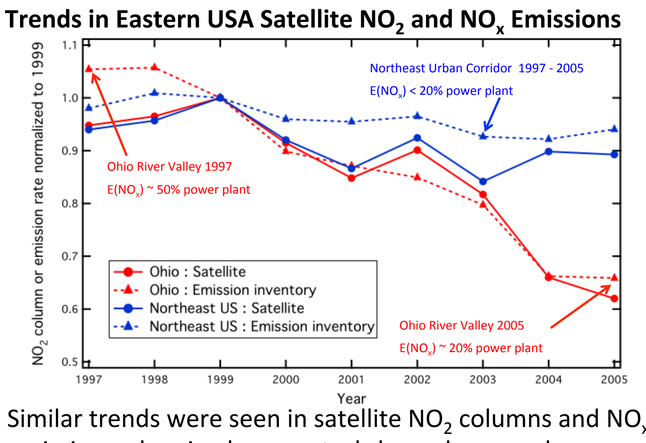
Eastern USA Power Plant NO_x Controls Detected by Satellite

Summer 2004 Average NO_2 Vertical Columns



Model NO_2 columns compared well with satellite over urban areas. Over power plants, the model columns using default 1999 emissions were too large, while they agreed well using 2004 CEMS data for the plants. These model-satellite comparisons show that the satellite detects the atmospheric NO_2 changes due to power plant NO_x emission controls.

Trends in Eastern USA Satellite NO_2 and NO_x Emissions



Similar trends were seen in satellite NO_2 columns and NO_x emissions, showing how controls have decreased power plant emissions while urban emissions did not change as much.

Using Satellites and Models to Understand Power Plant and Urban Emissions

S.-W. Kim et al. (2009), *J. Geophys. Res.*, *114*, D11301, doi:10.1029/2008JD011343

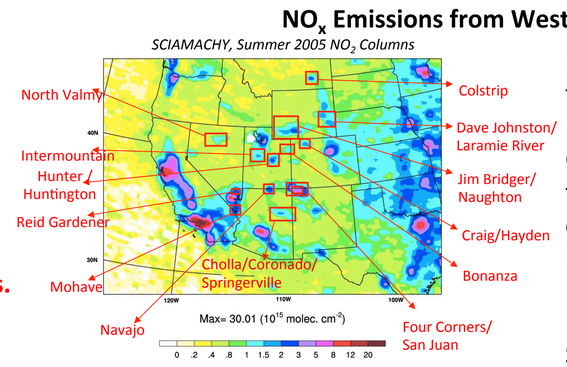
In the Western USA, well separated NO_2 satellite signals allow us to evaluate NO_x emissions from individual power plants and from urban areas.

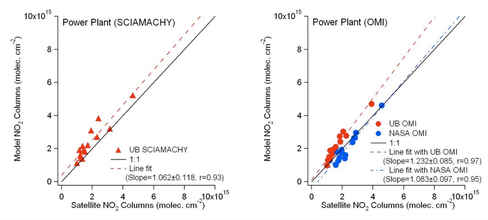
Power plant emissions, monitored in-stack, are used to "calibrate" satellites and models.

Emissions in rapidly growing urban areas with lots of motor vehicles are less well understood. Satellites provide a check on emissions for urban areas and other less well quantified source regions.

NO_x Emissions from Western USA Power Plants

SCIAMACHY, Summer 2005 NO_2 Columns



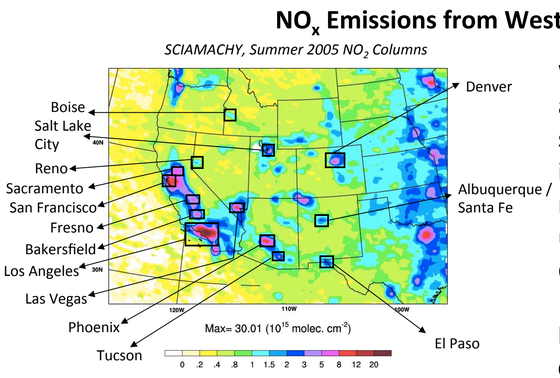


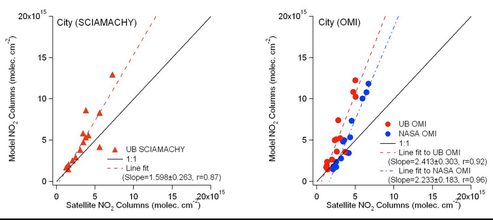
Isolated plants have discrete signatures in the satellite retrievals. Plant emissions are measured continuously at each stack. Currently many large coal-burning plants in the Western USA do not have NO_x pollution controls. So these plants, with their large NO_2 columns, help us check the satellite and model data.

Satellite and model columns are basically the same over these power plants. This allows us to optimize satellite column retrievals and model parameterizations, and to compare different satellite retrieval approaches. Consistency for different retrievals gives us confidence in conclusions about emissions.

NO_x Emissions from Western USA Urban Areas

SCIAMACHY, Summer 2005 NO_2 Columns





We use our evaluated satellite retrievals and model simulations to examine sources that have more uncertain inventories, such as urban areas, and to monitor changes in these regions. In USA urban areas, NO_x emissions are dominated by motor vehicles.

Large satellite - model NO_2 column differences were seen over many Western US cities. This result indicates that urban emissions in 2005 were not well represented by the 1999 inventory. This result is not surprising, since USA motor vehicle NO_x emissions were known to have decreased between 1999 and 2005.

Emissions Quantification by Combining Aircraft and Satellite Data with Models

Eastern Texas has many large emissions sources, including power plants, urban areas, industrial facilities, and ports. These sources are located in close proximity to one another in the Houston area.

Satellite data help verify inventories at the scale of the Dallas and Houston urban areas.

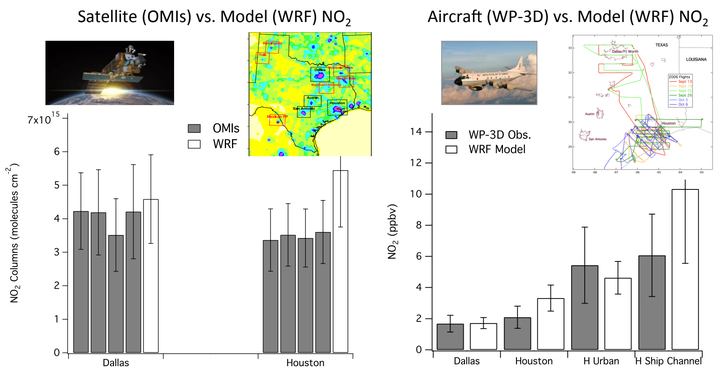
Research aircraft deployed during field campaigns in the region study individual sources.

When combined with forward and inverse models, aircraft data allow us to identify the sources leading to the emissions biases detected by satellites.

Observed and WRF-Chem NOx in Houston

S.-W. Kim et al. (2011), *Atmos. Chem. Phys.*, *11*, 11361–11386

Satellite (OMIs) vs. Model (WRF) NO_2 | Aircraft (WP-3D) vs. Model (WRF) NO_2

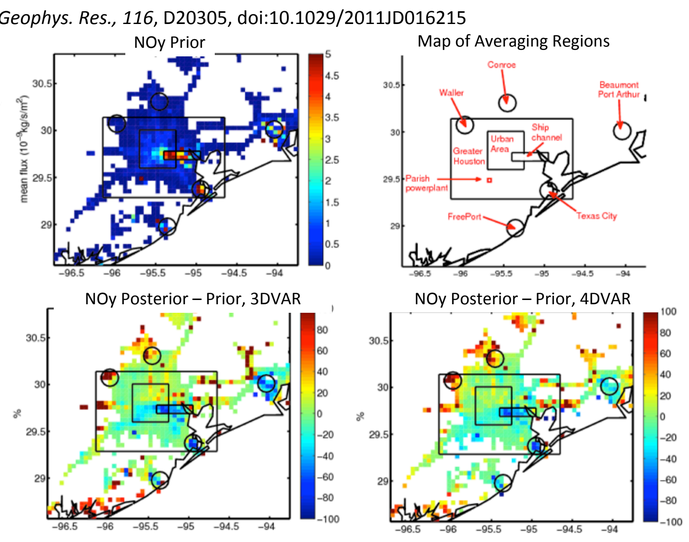


There is consistency between the satellite and aircraft observational comparisons with the WRF-Chem model. NO_x observations and the model agree in Dallas and the Houston urban core. Biases over the industrial and port regions of Houston show the NO_x inventory for these sectors is in error.

Inverse Modeling of Houston NOx Emissions

J. Brioude et al. (2011), *J. Geophys. Res.*, *116*, D20305, doi:10.1029/2011JD016215

Inverse modeling of NO_x using the research aircraft data is quantitatively consistent with WRF-Chem model comparisons to satellite and aircraft data. Posterior NO_x emissions in the Houston urban core remain relatively unchanged from the prior inventory. However, in the industrial portion of Houston, posterior NO_x emissions are significantly lower than the prior. Consistency between the WRF-Chem and inverse model results gives us confidence in our assessment of the NO_x inventory.



GEIA Connects Emissions Science to its Global Stakeholders

Founded in 1990

http://www.geiacenter.org

GEIA, the Global Emissions Initiative, aims to improve the scientific basis of emissions information worldwide.

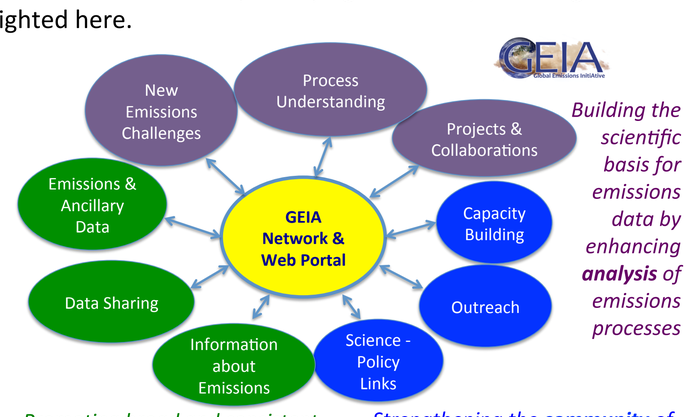
GEIA is a 25-year-old community activity of the International Geosphere-Biosphere Programme. GEIA distributes harmonized emissions datasets, oversees expert working groups on emissions from different world regions and sectors, organizes conferences, and supports a network of over 1500 emissions experts and users worldwide. GEIA provides a forum for exploring new methods aimed at quantifying emissions, including the studies highlighted here.

GEIA Leadership Team

Co-Chairs: Gregory Frost, Leonor Tarrasón
Database Manager: Claire Granier
Network Manager: Paulette Middleton

GEIA Scientific Steering Committee

Alexander Baklanov, Beatriz Cardenas, Hugo Denier van der Gon, Gregory Frost, Claire Granier, Alex Guenther, Greet Janssens-Maenhout, Johannes Kaiser, Terry Keating, Zbigniew Klimont, Catherine Liousse, Paulette Middleton, Toshimasa Ohara, Ute Skiba, Leonor Tarrasón, Yuxuan Wang

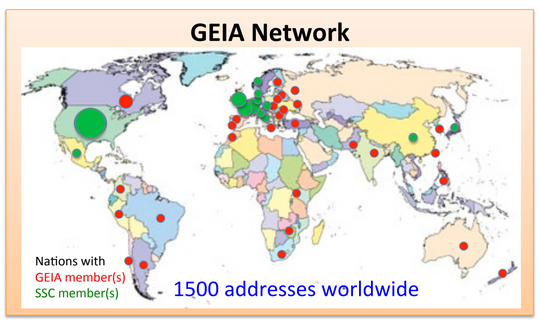


*Building the scientific basis for emissions data by enhancing **analysis** of emissions processes*

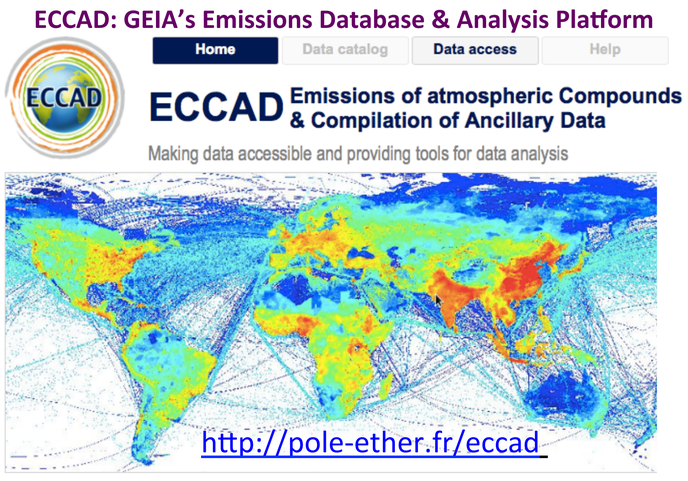
*Promoting broad and consistent **access** to emissions information*

*Strengthening the **community** of emissions stakeholder groups*

GEIA Network



GEIA Working Groups

China Emissions
Latin America/Caribbean Emissions
VOC Emissions Speciation
Historic Emissions
Urban Emissions

ECCAD: GEIA's Emissions Database & Analysis Platform