Evaluation of NO\textsubscript{x} Emissions in the Western US using WRF-Chem Model Simulations and Satellite Observations

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Outline
- Bottom-up assessment of NO\textsubscript{x} emissions
- Satellite and model determination of atmospheric NO\textsubscript{2} columns
- Review previous work: NO\textsubscript{x} emission controls at Eastern US power plants
- Analysis of NO\textsubscript{x} emissions from Western US power plants and urban areas
EPA assessments of NO\textsubscript{x} emission trends based on bottom-up inventories

- US NO\textsubscript{x} emissions have decreased 20% since 1999
- Largest decreases in two biggest sectors
  - Highway mobile sources: emission models
  - Electric power generation: stack measurements
- Power generation now smaller contributor

*EPA National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*
http://www.epa.gov/ttn/chief/trends/index.html
Satellite Measurements of NO$_2$ Vertical Columns

NO$_x$ emissions $\propto$ NO$_2$ columns (summer day $\Rightarrow$ short NO$_x$ lifetime)

**GOME**
*Global Ozone Monitoring Experiment*
• On ERS-2
• August 1995 - June 2003
• Horizontal resolution: 320 $\times$ 40 km$^2$
• Global coverage: 3 days
• Overpass time: 10:30 am local solar

**SCIAMACHY**
*SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY*
• On ENVISAT
• March 2002 ~
• Horizontal resolution: 60 $\times$ 30 km$^2$
• Global coverage: 6 days
• Overpass time: 10:30 am local solar

**OMI**
*Ozone Monitoring Instrument*
• On EOS-Aura
• November 2004 ~
• Horizontal resolution: 13 $\times$ 24 km$^2$
• Global coverage: 1 day
• Overpass time: 1:30 pm local solar

**Extracting NO$_2$ vertical columns**
• Measure NO$_2$ absorption: DOAS
• Remove stratospheric component
• Cloud filtering: cloud fraction < 0.15
• Convert tropospheric residual to vertical column
  ▪ vertical sensitivity: radiative transfer model
  ▪ air mass factor: chemical transport model
WRF-Chem Modeling of NO₂ Vertical Columns

**Weather Research and Forecasting - Chemistry model**
- [www.wrf-model.org/WG11](http://www.wrf-model.org/WG11)
- Simulates atmospheric chemistry online within WRF meteorological model
- Various chemical mechanisms, aerosol modules
- Variety of treatments of planetary boundary layer, microphysics, radiation, and convection

**Setup for these case studies**
- Eastern US
  - Summer 2004 simulation period
  - 27 x 27 km² horizontal resolution
- Western US
  - Summer 2005 simulation period
  - 15 x 15 km² horizontal resolution
- Emissions
  - EPA NEI1999 updated with 2004/2005 CEMS power plant data
Previous Work: NO$_x$ Controls at Eastern US Power Plants

Examine effects of NO$_x$ controls on large point sources in the Eastern US beginning in the late 1990s
• National and regional pollution control programs
• Focus on coal-burning power plants
• Improved burner technology, post-burner ammonia scrubbers

Power Plant NO\textsubscript{x} Emission Decreases Measured by CEMS

Continuous Emission Monitoring Systems (CEMS)

- Stack measurements of hourly NO\textsubscript{x}, SO\textsubscript{2}, and CO\textsubscript{2} emissions made by utility companies
- Data for 966 facilities in 1999 and 1427 facilities in 2004

**Annual trends** ➤ Substantial NO\textsubscript{x} emission reductions since late 1990’s while maintaining amount of electric power generated

\[
\Delta(\text{US}) = -36\%
\]
\[
\Delta(\text{Ohio River}) = -45\%
\]

**EPA Clean Air Markets Division Emissions Query Wizard**
http://camddataandmaps.epa.gov/gdm/index.cfm?fuseaction=emissions.wizard
Eastern US Power Plant NO$_x$ Emission Reductions Detected by Satellite

Summer 2004 Average NO$_2$ Vertical Columns

- Model reproduces satellite NO$_2$ vertical columns over urban areas
- Model NO$_2$ columns too large over power plants using 1999 emissions

Eastern US Power Plant NO$_x$ Emission Reductions Detected by Satellite

Summer 2004 Average NO$_2$ Vertical Columns

- Model with summer 2004 power plant emissions agrees much better with satellite NO$_2$ columns over power plants
- Satellite detects changes in Ohio River Valley from recent power plant NO$_x$ emission controls

Year-to-Year Trends in Eastern US Satellite NO$_2$ and Emissions

- Similar trends in satellite NO$_2$ columns and NO$_x$ emissions
  - Power plant NO$_x$ controls have decreased NO$_2$ columns
  - Mobile NO$_x$ emission changes smaller than those from power plants

Boundary Layer $O_3$ Response to NO$_x$ Emission Reductions

- O$_3$ generally decreases in response to power plant NO$_x$ emission reductions
- Small $\Delta$[O$_3$] in northern US
  - persistent cold fronts and unusually cold conditions in summer 2004
- Up to 10% [O$_3$] decreases in Ohio River Valley, VA, NC, and GA

Average of all model output between 0 & 1 km at 20 UTC (1500 EST) for all days June-August 2004

NO$_x$ Emissions from Western US Power Plants and Cities

Use discrete satellite signals in Western US to evaluate NO$_x$ emissions from individual power plants and urban areas

• Steady, well-known power plant emissions
  • “Calibrate” satellite and model algorithms
• Rapidly growing urban areas with lots of motor vehicles
  • How well are mobile source NO$_x$ emissions understood?
  • Are overall NO$_x$ emissions declining?
Isolating NO\textsubscript{x} Emissions from Different Source Sectors

SCIAMACHY, Eastern US
Summer 2004 Average

Max = 22.43 (10^{15} \text{ molec. cm}^{-2})
Isolating NO$_x$ Emissions from Different Source Sectors

SCIAMACHY, Western US

*Summer 2005 Average*

Satellite signals from Western US NO$_x$ sources more distinct than in Eastern US

➢ Isolate and assess different emission sources
Isolating NO$_x$ Emissions from Different Source Sectors

NO$_2$ Vertical Columns from OMI (Ozone Monitoring Instrument) on Aura satellite (launched July 2004)

OMI images courtesy of James Gleason (NASA)
NO$_x$ Emissions from Western US Power Plants

- Isolated plants have discrete signatures in satellite retrievals
- Power plant emissions are measured continuously at each stack
- Currently no NO$_x$ pollution controls on large coal-burning plants

“Calibration” for satellite-model comparison

 SCIAMACHY, Summer 2005
Satellite - Model NO\textsubscript{2} Column Comparison: Power Plants

Summer 2005 average NO\textsubscript{2} columns over boxes shown on previous map

Western US Power Plants

\begin{center}
\begin{tabular}{l}
\textbf{NO\textsubscript{2} Columns (molec. cm\textsuperscript{-2})} \\
\hline
FOU1 & 4.2 \\
FOU2 & 3.8 \\
MOHA & 2.7 \\
REID & 2.5 \\
NAVA & 2.3 \\
CRAI & 2.1 \\
DAVE & 2.0 \\
HUNT & 1.8 \\
INTE & 1.6 \\
CHOL & 1.4 \\
JIMB & 1.2 \\
BONA & 1.0 \\
COLS & 0.8 \\
NORT & 0.6 \\
\end{tabular}
\end{center}
Satellite - Model NO₂ Column Comparison: Power Plants

*Summer 2005 average NO₂ columns over boxes shown on previous map*

Western US Power Plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>NO₂ Columns (molec. cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOU1</td>
<td>6 × 10¹⁵</td>
</tr>
<tr>
<td>FOU2</td>
<td>2 × 10¹⁵</td>
</tr>
<tr>
<td>MOHA</td>
<td>2 × 10¹⁵</td>
</tr>
<tr>
<td>REID</td>
<td>2 × 10¹⁵</td>
</tr>
<tr>
<td>NAVA</td>
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</table>

OMI (NASA) / WRF-Chem
Satellite - Model NO$_2$ Column Comparison: Power Plants

Summer 2005 average NO$_2$ columns over boxes shown on previous map

[Graph showing NO$_2$ columns for various Western US Power Plants]

- OMI (Bremen)
- WRF-Chem
Satellite - Model NO₂ Column Comparison: Power Plants

Good agreement between satellite and model NO₂ columns over Western US power plants
- Optimize satellite column retrievals and model parameterizations
- Model enables comparison of different satellite retrieval approaches
- Consistency for different retrievals gives confidence in conclusions about emissions
NO\textsubscript{x} Emissions from Western US Urban Areas

Build on satellite-model comparisons for power plants

- Evaluate urban area emission inventories and monitor changes

SCIAMACHY, Summer 2005
Satellite - Model NO$_2$ Column Comparison: Urban Areas

Summer 2005 average NO$_2$ columns over boxes shown on previous map

Western US Cities

NO$_2$ Columns (molec. cm$^{-2}$)

12x10$^{15}$

SCIAMACHY

WRF-Chem
Satellite - Model NO$_2$ Column Comparison: Urban Areas

Summer 2005 average NO$_2$ columns over boxes shown on previous map

Western US Cities:
- LOSA
- SANF
- SACR
- FRES
- BAKE
- LASV
- RENO
- SALT
- DENV
- PHOE
- TUCS
- ELPA
- ALBU
- BOIS

NO$_2$ Columns (molec. cm$^{-2}$)
- OMI (NASA)
- WRF-Chem
Satellite - Model NO$_2$ Column Comparison: Urban Areas

Summer 2005 average NO$_2$ columns over boxes shown on previous map

Western US Cities

NO$_2$ Columns (molec. cm$^{-2}$)

- LOSA
- SANF
- SACR
- FRES
- BAKE
- LASV
- RENO
- SALT
- DENV
- PHOE
- TUCS
- ELPA
- ALBU
- BOIS

OMI (BREMEN)
WRF-Chem
Large differences between satellite and model NO$_2$ columns over many Western US cities

- Urban emissions not well represented by 1999 inventory
- Trends in NO$_x$ emissions since 1999?
- Are emission changes mostly due to motor vehicles?
OMI shows weekend decline in urban NO$_2$ columns
• Reduced traffic, particularly heavy-duty diesel vehicles
• Lower mobile source NO$_x$ emissions on weekends

Day of week changes in satellite NO$_2$ columns first reported by:
S. Beirle et al. (2003), Weekly cycle of NO$_2$ by GOME measurements: a signature of anthropogenic sources, Atmos. Chem. Phys., 3, 2225-2232
Year-to-Year Trends in Satellite NO$_2$ Columns over Urban Areas

Satellites demonstrate decline in NO$_2$ columns over many Western US cities in recent years

- Urban NO$_x$ emissions appear to be decreasing
- Increasing population and motor vehicle fuel use
  - Effect of cleaner engines, especially light-duty gasoline vehicles
Conclusions

• Combination of space-based instruments and regional air quality model
  ➢ Useful evaluation of NO$_x$ emission inventories and trends
• Effects of major NO$_x$ emission reductions at Eastern US power plants
  ➢ Point source pollution control strategies have resulted in widespread, measurable changes to atmospheric pollutant levels
• Relative contributions from Western US NO$_x$ sources and their long-term trends
  ➢ Power plants serve as calibration for NO$_2$ vertical columns
  ➢ Impact of cleaner motor vehicles on urban to regional scale appears to be measurable by space-based instruments