Air Pollution Response to Changing Emissions at Power Plants in the Eastern U.S.

Dissertation Defense
Bryan Bloomer
November 4, 2008
Where we are going...

• Background:
  How photochemical smog forms in the eastern U.S.

• Answer three main questions:
  – How accurate are emission inventories from power plants?
  – What is the impact of NO\textsubscript{X} emissions from power plants on tropospheric ozone in the eastern US?
    • One day changes
    • Long term changes and trends
  – Can the impact of warming be discerned in the air pollution record?

• Bring it all together:
  – Photochemical Smog and Climate Change:
    A Climate Penalty and Control Policy
Tropospheric Ozone ($\text{O}_3$): Mortality, Morbidity and the National Ambient Air Quality Standards (NAAQS)

Morbidity = people sick
- lost work days
- Hospital admissions
- 1ppb increase = thousands more cases per city

Mortality = death
- cardio vascular (heart attack, stroke from Bell et al. Meta Analysis: 1 to 1.5% increase in deaths per 10ppb)
- symptoms: anxiety, sweating, pressure, shortness of breath

EPA responded under the Clean Air Act
Standards established for Ozone:
- 1-hour 125 ppb
- 8-hour 85 ppb going down to 75ppb

Nonattainment and Maintenance Areas (263 entire counties)
Nonattainment Areas (30 partial counties)
Maintenance Areas (141 entire or partial counties)

Partial counties, those with part of the county designated nonattainment and part attainment, are shown as full counties on the map.
Photochemical Smog: where Weather and Chemistry combine

Severe $O_3$ air pollution episodes in the eastern US are in summertime.

Temperature is the best weather variable for predicting ozone amounts.

Source: [http://www.narsto.org/section.src?SID=7](http://www.narsto.org/section.src?SID=7)
NARSTO O3 assessment ch. 1, 2006
Photochemical smog: The story of a summer day

Regulatory Ozone Season: May 1 to Sept 30
Mid Atlantic Region for years, 1987–2002
Rural Ozone
What is new in this talk?

• How accurate are emission inventories from power plants?
  – How does changing measurement technology affect emissions estimates and what are the implications for air pollution control policy?
  – How have emissions actually changed over time?

• What is the impact of NO$_X$ emissions from power plants on tropospheric ozone in the eastern US?
  – One day changes observed and modeled from an “accidental experiment” due to a large scale electrical blackout.
  – Long term trends in photochemical smog. Response to the control program implemented via the NOx SIP call.

• Can the impact of climactic changes and global warming be discerned in the air pollution record?
  – Two techniques developed, and applied, to this problem.
Starting with Emissions

- Fuel Based estimates used historically
- The modern state of the art: CEMS

- Implications include:
  - Considering a trading program for climate change implies a $2.5 billion decision and suggests options for a control program design so as to include other economies...
Historically emissions were estimated using fuel data.

Dickerson Power Plant

Example Calculation: Heat Input

\[ HTI_{SCC} = FC_{SCC} \times HC_{fuel} \times UC \]

- **HTI** = heat input (MMBtu)
- **FC** = annual reported fuel consumption (unit/year)
- **HC** = annual weighted average heat content (Btu/unit)
- **UC** = units conversion factor

\[ CO2_{bfuel} = FC_{bfuel} \times HC_{bfuel} \times CCC_{bfuel} \times COX_{bfuel} \times (44/12) \times UC \]

\[ SO2_{bSCC} = FC_{bSCC} \times SC_{bSCC} \times UEF_{bSCC} \times (1-SO2EFF_{blr} \times 100) \times UC \]

\[ NOX_{bSCC} = FC_{bSCC} \times UEF_{bSCC} \times (1-NOXEFF_{blr} \times 100) \times UC \]

Note: Data reported monthly one time per year.
CEMS based Emission Monitoring: Observing what goes out of the stack

The method for emissions since 1995
For All Fossil Fueled Power Plants > 25 MW
(with a few exceptions granted by Congress)

Note: Data reported for each Hour every calendar quarter

$CO_2$, $NO_x$, $SO_2$
Flow
Opacity
Histogram Comparing Methods

\[ PD_{blr} = 100 \times \frac{CEM_{blr} - EIA_{fuel}}{EIA_{fuel}} \]

- On Average the fuel based method:
  - for CO\(_2\) is 5% lower
  - For SO\(_2\) is 5% lower
  - Is a poor method for NO\(_X\)
Application:

Long term commodity trends

- SO₂ difference implies the environment “wins”
- CO₂ has a bigger story associated with it
  - 5% implies 122,000,000 tons (circa 2000)
  - At a recent market price of $20 per ton that is a $2.45 billion difference due to measurement method alone

CEMS are the method of choice.
CEMS provide a unique, new tool for evaluating air quality impacts of emissions

- Hourly data can be used for model input
- Hourly data can be compared to observations

- The Blackout of 2003
  - Unique experiment
  - Hourly, to one day emission reductions
  - Modeling to diagnose the model and assign cause

- Learn about short term response of air quality system and how well our model represents it.
  - If it represents the system well, we can use it to diagnose and forecast a response to emission and climate changes....
An electrical blackout starting on August 14, 2003 at 4:00pm and lasting for the next 24 hours


More plants are affected than the plants with Generator trips due to load changes

Plants with reduced NO\textsubscript{X} emissions during the 24 hours of the blackout

Must look at hourly CEM data
DMSP F15
14 August 2003
0129Z
~20 hrs before Blackout
Aircraft Observations

- Flight on August 15, 2003, about 24 hours into the blackout in central Pennsylvania
- Flight on August 4, 2002 for comparison

Differences below 2km of between 30 and 40 ppb

Marufu et al., GRL (2004)
Emissions Change from CEM Data

2002

National NOx Mass Emissions

2003

Area of largest NOx Differences corresponds To area of largest \([O_3]\) differences
CMAQ Simulation and Results

Difference between 2002 actual and Blackout Zero-out Simulation
(red corresponds to decreases in [O3] starting about 15 ppbv and extending to about 40 ppbv)
Sampling the Simulation to compare with the aircraft data

Base Simulation sampled in space/time
Pairing with aircraft observations
Crosses grid squares

Simulation sampled for a single time on a single column

Big differences between adjacent grid squares and time steps
Largest modeled difference on the order of the difference observed by aircraft.

Difference of up to almost 40 ppbv located directly downwind of Mt. Storm Power plant. But only for one hour, in one grid.
Can we rely on a model to answer our questions?

• Overall the blackout shows
  – The model does reproduce a decrease in ozone of almost 40 ppb, but
    • The model is not as responsive as the real world seems to be to emission changes
    • Reductions don’t last as long in the model
    • The spatial extent for a response is smaller
    • The amount of response, overall, appears to be less

• Gilliland *et al.* (2008) have published that the model does not reproduce well lower free tropospheric ozone, consistent with our results

• Model needs improvements in mixing and/or NOx chemistry (future work).

• Let’s look at measurements some more.
Question#3. Application of a Climatological Analysis Method to Air Pollution Observations

• Konstantin Vinnikov, Alan Robock and others developed this method and applied it to a wide variety of climatological data, including temperatures, ice extent in the arctic, drought indices and other data in early 2000’s...

\[ y(t,h) = Y(t,h) + y'(t,h). \]
\[ Y(t,h) = A(t,h) + B(t,h) \cdot t, \]
\[ A(t,h) = a_0(h) + \sum_{k=1}^{K} \left[ a_k(h) \sin \left( \frac{2\pi kt}{T} \right) + b_k(h) \cos \left( \frac{2\pi kt}{T} \right) \right], \]
\[ B(t,h) = \alpha_0(h) + \sum_{m=1}^{M} \left[ \alpha_m(h) \sin \left( \frac{2\pi mt}{T} \right) + \beta_m(h) \cos \left( \frac{2\pi mt}{T} \right) \right]. \]

The Goal is to see if we can separate and quantify the influence of climate changes upon ozone...
A specific example: BELTSVILLE, MD

Analysis of Ozone and Air Temperature
Hourly Observation
1989-2007

Illustrates the math:
Remember:
Emissions change significantly as a result of control programs

North East Region

Year

NOx (Tg)


Acid Rain Control

NOx SIP Call

Expand Consideration across eastern U.S.
Application of a Climatological Analysis Method to Air Pollution Data, **Conclusions:**

• **Method is applicable:**
  – Significant change in Ozone concentration trend is observed (much of the trend is apparently due to a reduction after NOx SIP Call.)
  – Change in climatic regime of air temperature (warming) occurs simultaneously with observed change in Ozone concentration.
    • The observed change in air temperature exceeds the global warming signal and is due to other factors such as decreasing PM$_{2.5}$

• **Method’s results provide indications for reconsidering length of the ozone season and the form of the ambient air quality standard**
Putting it all together: Meteorology Emissions Photochemical Smog and Climate Change
“Warming of the climate system is unequivocal.”

Dr. R K Pachauri Chairman IPCC Press Presentation Saturday, 17 November 2007 Valencia, Spain

Models Say...

IPCC, AR4, WG1, Ch. 3
A Climate Change Penalty

Emission Change
Weather Change
Ozone Change

Can we separate the signals?
If so, how?
What does it mean?

Use a Model
Make some Predictions

The Reality is more complicated:

Emission Reductions

Remember: IPCC reports temperatures went up in Eastern US
We see a warming trend in the data…

National Ozone Season NOx Emissions from Power Plants

CEM Observed Ozone Season Power Plant Emissions
So how can we tell what happened to Ozone?

Chemically Coherent Receptor Regions
Derived from Rotated Principal Component Analysis

Rural, CASTNET, offers additional opportunities due to co-located meteorological observations
Observations: Mid-Atlantic Temperature and Ozone

Inter-annual Variability:
Difficult to see trends

Grouping Relative to Emission Changes
Signals start to become apparent
Observations: Mid-Atlantic Temperature and Ozone

Temperature Went Up. Warming After 2002

Ozone Went Down After 2002
Ozone, Temperature and Emission Changes across the Eastern U.S.
Can we observe the influence of warming on air quality?

Mid-Atlantic Pre-2003 May-Sept. Hourly Ozone

YEAR ≤ 2002
Slope = 3.3 ppbv/°C
Can we observe the influence of warming on air quality?

Mid-Atlantic Post-2002 May-Sept. Hourly Ozone

YEAR > 2002
Slope = 2.5 ppbv/°C
Can we observe the influence of warming on air quality?

Mid-Atlantic Post-2002 May-Sept. Hourly Ozone

YEAR > 2002
Slope = 2.5 ppbv/°C
$r^2 = 0.1939$
Looking deeper into the data:

The slope is defined to be the "climate penalty factor"

Ozone rises as temperature increases

Temperature Binning
Mid-Atlantic
pre 2002: 3.3 ppbv/°C
Mid-Atlantic

pre 2002: 3.3 ppbv/°C
post 2002: 2.2 ppbv/°C
Northeast

pre 2002: 3.3 ppbv/°C
post 2002: 2.4 ppbv/°C
Great Lakes
pre 2002: 3.1 ppbv/°C
Great Lakes
pre 2002: 3.1 ppbv/°C
post 2002: 2.2 ppbv/°C
Southwest
pre 2002: 1.3 ppbv/°C
Southwest

pre 2002: 1.3 ppbv/°C
post 2002: 1.4 ppbv/°C
Can we observe the influence of warming on air quality?

Climate Penalty Factors

Consistent across the distribution AND across the power plant dominated receptor regions
Can we observe the influence of warming on air quality?

Reducing NOx emissions
Lowered Ozone over the entire distribution
And decreases the Climate Penalty Factor

The change in the climate penalty factor is remarkably consistent across receptors dominated by power plant emissions. Ignoring SW:

The average of 3.3 ppb/°C pre-2002 Drops to 2.2 ppb/°C after 2002

Bloomer et al., Science, 2008
In Review
An observed Climate Change Penalty

Median Temperature increases about 0.5°C
Climate Penalty Factor of 3.3 or 2.2 ppb/°C

Leads to a Climate Change Penalty of 1.1 to 1.7 ppb

Temperatures warmed 0.68°C since pre-1999 implying a penalty of 1.5 to 2.3 ppb
An observed Climate Change Penalty

Median Temperature increases about 0.5°C
Climate Penalty Factor of 3.3 or 2.2 ppb/°C

Leads to a Climate Change Penalty of 1.1 to 1.7 ppb

Temperatures warmed 0.68°C since pre-1999 implying a penalty of 1.5 to 2.3 ppb

Climate Change Penalty observed for Mid-Atlantic of between 1.1 and 2.3 ppb
Implications of the Climate Change Penalty in Ozone Air Pollution

• A 2 ppb higher ozone is
  – About the same amount as the air quality improvement modeled for many non-attainment areas justifying the entire NO$_x$ SIP call
  – NO$_x$ SIP call annualized capital costs modeled to be about $2.1 billion per year (1997$)

• 2 ppb increase, across the population of the Eastern US, is from 8,000 to 16,000 additional premature deaths per year due to local climate change.
Implications for a warming world

Temperatures already observed to be warming

Ozone is predicted to increase in areas warming and especially where emissions are growing

Warming with growing precursor emissions
Large populations at risk of increased mortality and morbidity

Climate Penalty Factors
Imply Amplified smog formation
Use them to build in “adequate margin of safety”

Burrows et al., 2004.
http://www.esa.int/esaEO/SEM340NKPZD_index_0.html

IPCC, AR4, WG1, Ch. 3
Answers in this talk.

• How accurate are emission inventories from power plants?
  – How have emissions changed over time?
  – How does changing measurement technology affect emissions and air pollution control policy?

➢ This research evaluated two method of emissions estimates, established the accuracy of CEM for long term data, and provided new policy options for regional to global control strategies.

• What is the impact of NO\textsubscript{x} emissions from power plants on tropospheric ozone in the eastern US?
  – One day changes observed and modeled from an “accidental experiment” due to a large scale electrical blackout.
  – Long term trends in photochemical smog. Response to the control program implemented via the NOx SIP call.

➢ NOx control at power plants is effective for reducing short term and long term, regional scale photochemical smog, more so than models predict.

• Can the impact of climactic changes and global warming be discerned in the air pollution record?
  – Two techniques developed, and applied, to this problem.

➢ Yes. Application of climatological analysis offers new, policy relevant insights. Climate Penalty Factors provide a powerful tool for evaluating climate related air quality trends and policies regionally and globally.
Pause, for the end....