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

Dissertation Defense

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November 4, 2008

Where we are going…

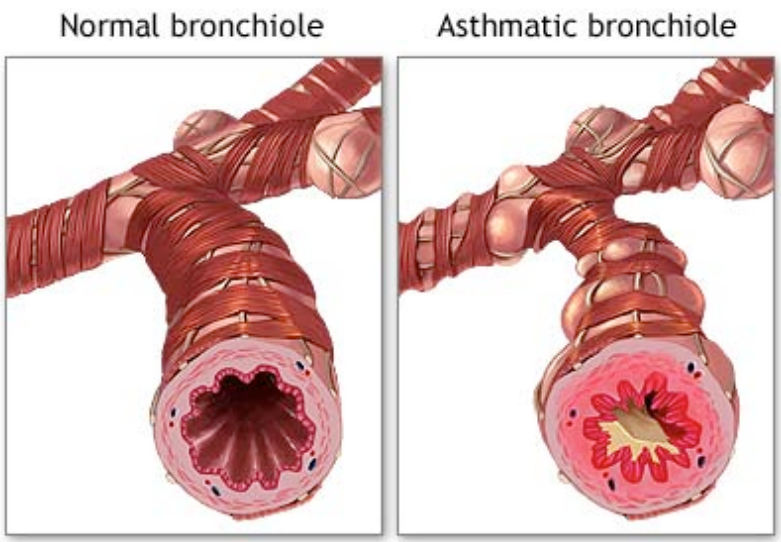
- Background:

  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_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 (O_3):

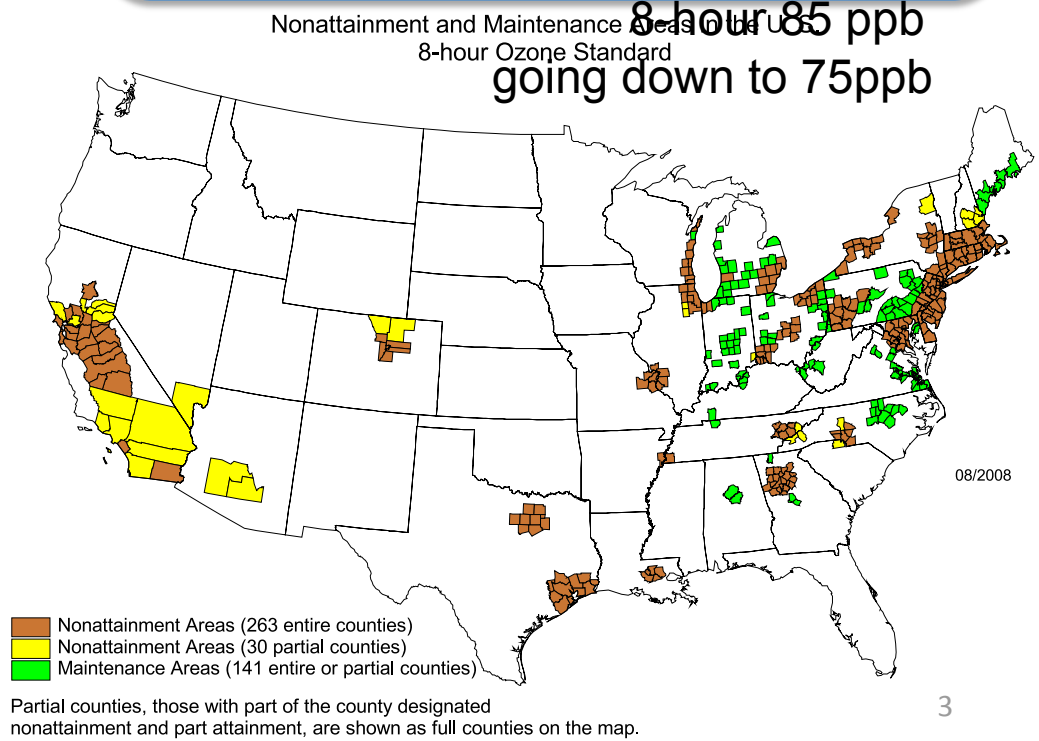
Mortality, Morbidity and the National Ambient Air Quality Standards (NAAQS)



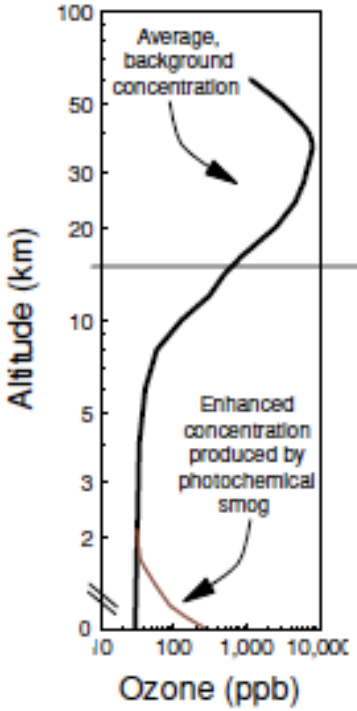
EPA responded under the Clean Air Act
Standards established for Ozone:
1-hour 125 ppb
8-hour 85 ppb
going down to 75ppb

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



Photochemical Smog:
where Weather and Chemistry combine



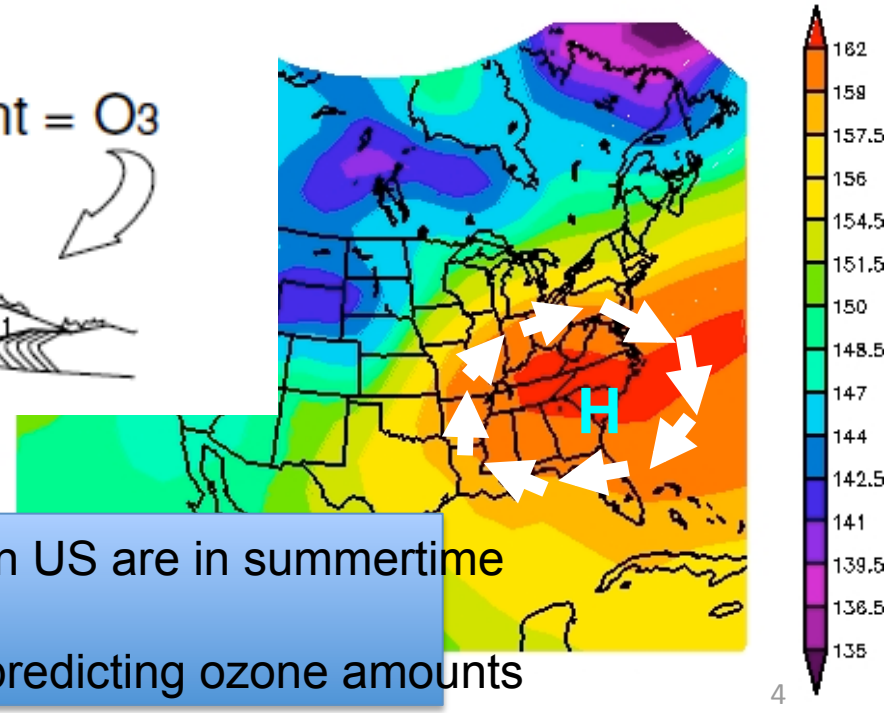
O_2 + UV Sunlight = O + O

O + O_2 = O_3

Stratosphere

Troposphere

CO, VOC } + NOx + Sunlight = O_3

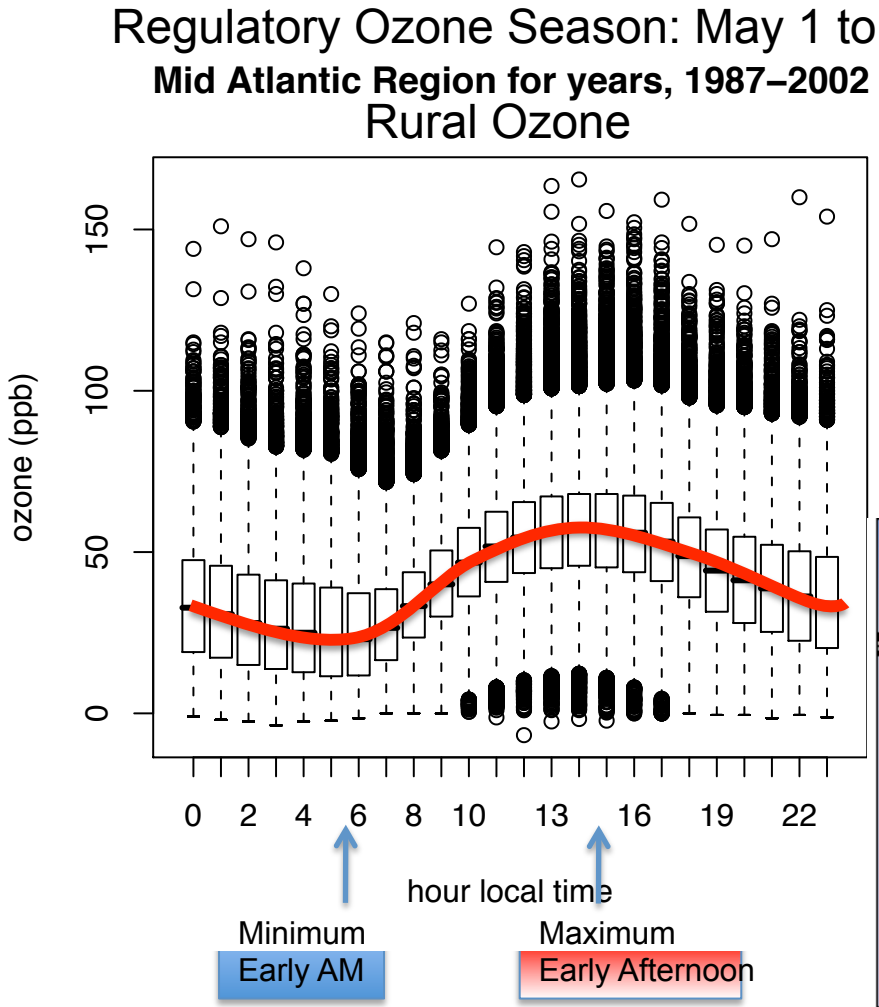


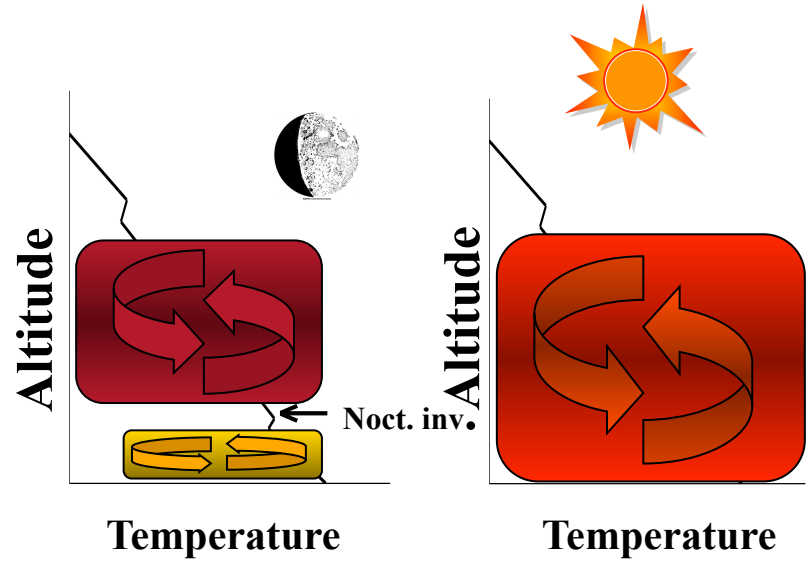
Source: http://www.narsto.org/section.src?SID=7
NARSTO O3 assessment ch. 1, 2006

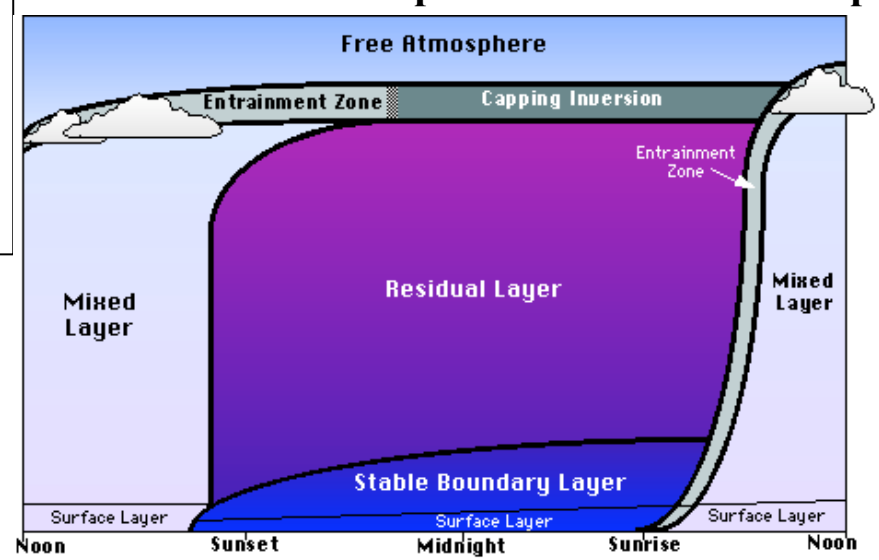
Severe O_3 air pollution episodes in the eastern US are in summertime

Temperature is the best weather variable for predicting ozone amounts

Photochemical smog:
The story of a summer day







Structure of Planetary Boundary Layer
adapted from Stull, 1988.

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?

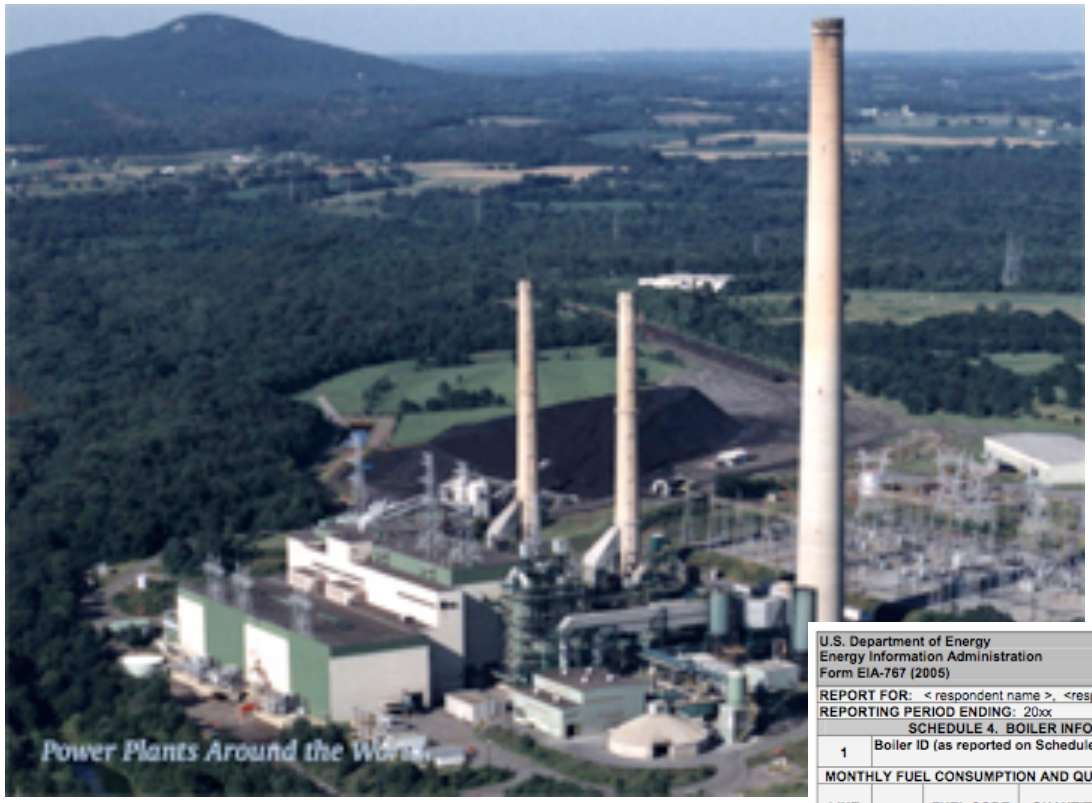
- What is the impact of NO_X emissions from power plants on tropospheric ozone in the eastern US?
  - One day changes observed and modeled from an "accidental experiment" due to a large scale electrical blackout.
  - Long term trends in photochemical smog. Response to the control program implemented 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…



Dickerson Power Plant

Historically emissions were estimated using fuel data

Note: Data reported monthly one time per year

U.S. Department of Energy
Energy Information Administration
Form EIA-767 (2005)

STEAM-ELECTRIC PLANT OPERATION AND DESIGN REPORT

Form Approved
OMB No. 1905-0129
Approval Expires: 11/30/2007

REPORT FOR: < respondent name >, <respondent id>, <plant name>, <plant code>

REPORTING PERIOD ENDING: 20xx

SCHEDULE 4. BOILER INFORMATION, PART A. FUEL CONSUMPTION AND QUALITY (COMPLETE A SEPARATE PAGE FOR EACH BOILER)

1	Boiler ID (as reported on Schedule 2)		Boiler Status (use code)		Hours Under Load During Year (nearest hour)	

MONTHLY FUEL CONSUMPTION AND QUALITY DURING YEAR

LINE NO.	MONTH	FUEL CODE (a)	QUANTITY (b)	HEAT CONTENT (c)	SULFUR CONTENT (d)	ASH CONTENT (e)	MONTH	FUEL CODE (f)	QUANTITY (g)	HEAT CONTENT (h)	SULFUR CONTENT (i)	ASH CONTENT (j)
2	Jan						Jul					
3												
4												
5												
6	Feb						Aug					
7												
8												
9												
10	Mar						Sep					
11												
12												
13												
14	Apr						Oct					
15												
16												
17												
18	May						Nov					
19												
20												
21												
22	Jun						Dec					
23												
24												
25												

TOTAL SUM OF ALL MONTHS (January to December) BY FUEL CODE (Quantity)

26	Total		
27	Total		
28	Total		
29	Total		

ANALYSIS METHOD FOR PRIMARY FUEL TYPE

30	Sampling Procedure	PM [ ] UM [ ] CD [ ] GC [ ] GB [ ] OT [ ]	
31	Method Of Analysis		
32	Laboratory Performing Analysis		

CHECK IF PAGE IS NOT APPLICABLE [ ] Page of

Example Calculation: Heat Input

$$HTI_{SCC} = FC_{SCC} * HC_{fuel} * UC$$

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

$$CO2b_{bfuel} = FC_{bfuel} * HC_{bfuel} * CCC_{bfuel} * COX_{bfuel} * (44/12) * UC$$
$$SO2_{bSCC} = FC_{bSCC} * SC_{bSCC} * UEF_{bSCC} * (1\text{-}SO2EFF_{blr}/100) * UC$$
$$NOX_{bSCC} = FC_{bSCC} * UEF_{bSCC} * (1\text{-}NOXEFF_{blr}/100) * UC$$

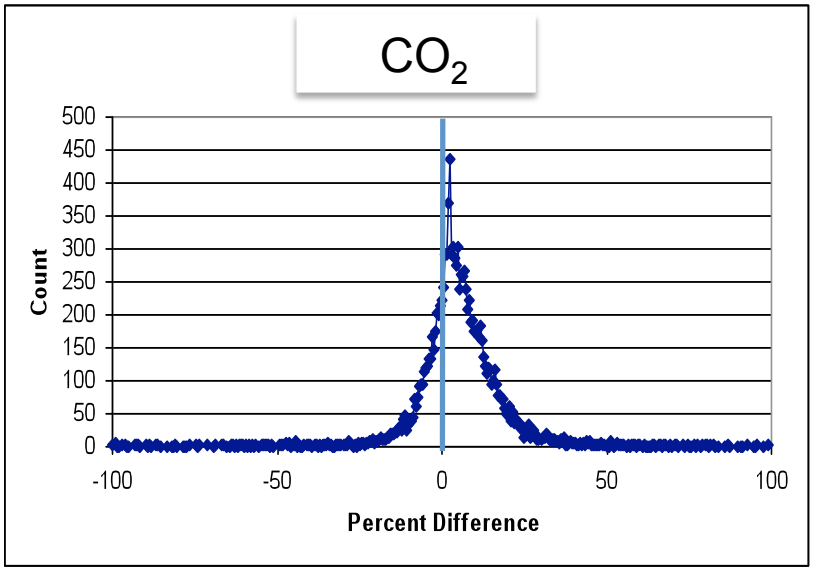
CEMS based Emission Monitoring: Observing what goes out of the stack

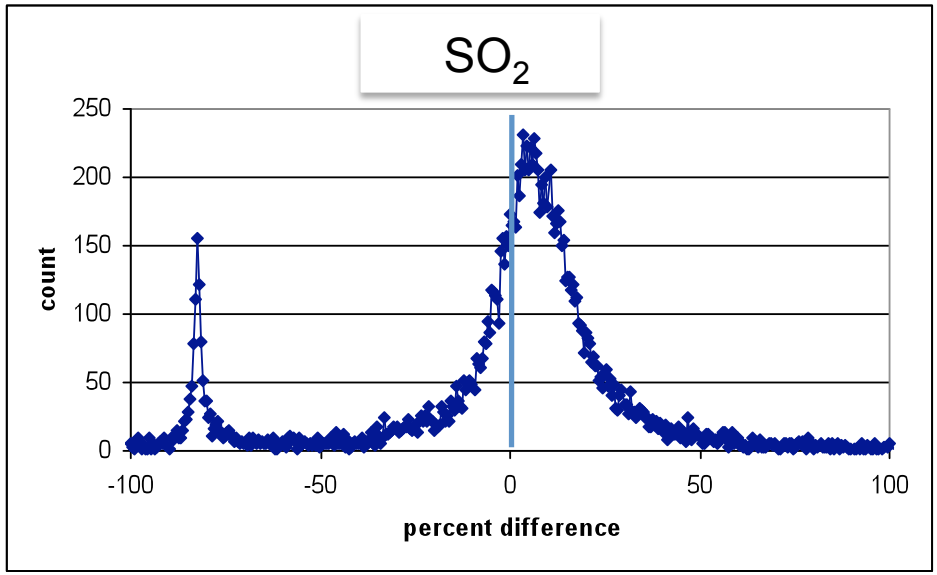
CO_2, NO_X, SO_2
Flow
Opacity

Note: Data reported
for each Hour
every calendar quarter

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

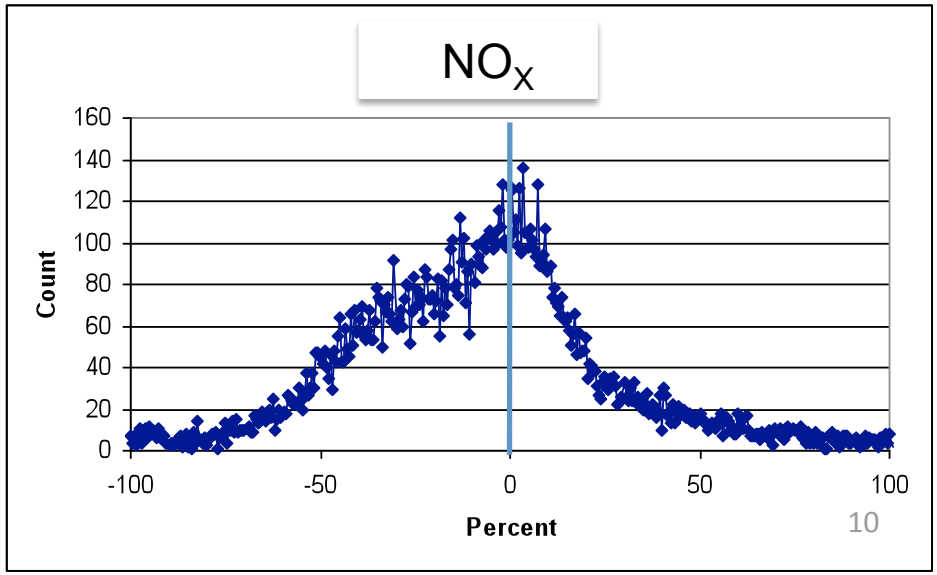
Histogram Comparing Methods





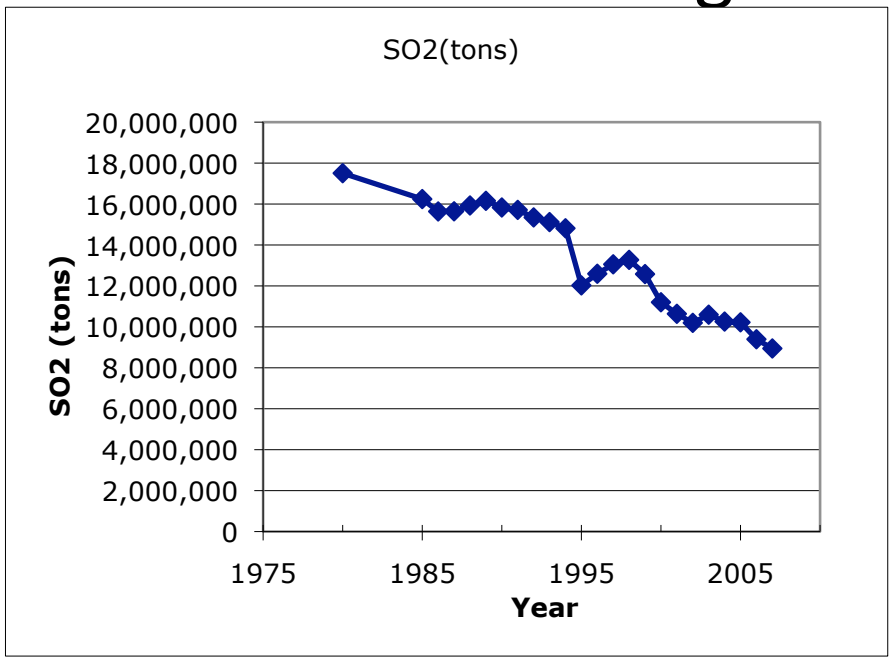
$$PD_{blr} = 100 * (CEM_{blr} - EIA_{fuel}) / EIA_{fuel}$$

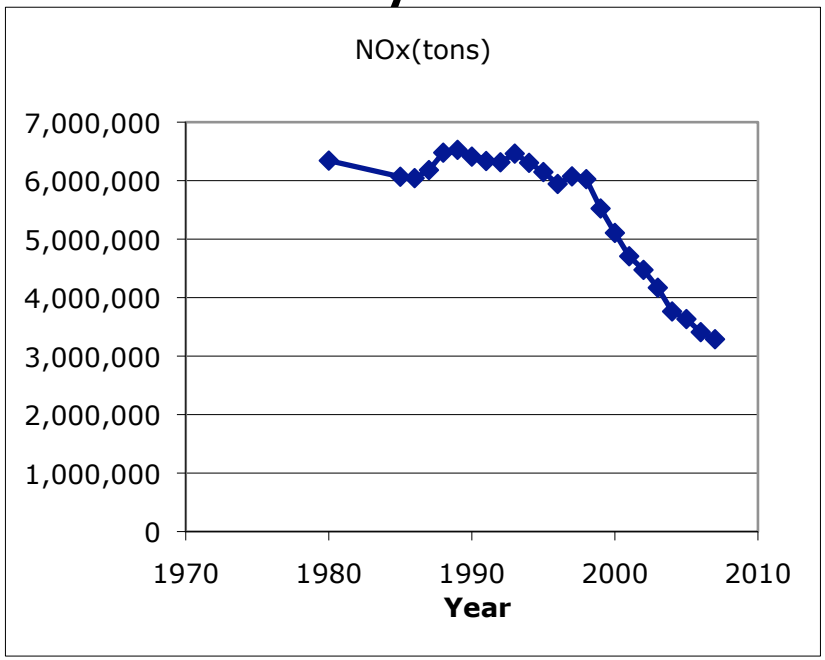
- On Average the fuel based method:
  - for CO_2 is 5% lower
  - For SO_2 is 5% lower
- Is a poor method for NO_X



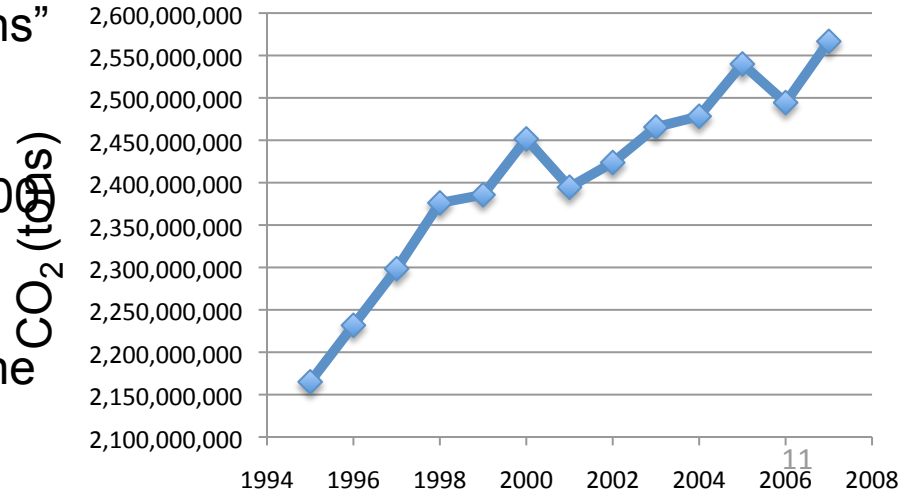
Application:

Long term commodity trends





- SO_2 difference implies the environment "wins"
- CO_2 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

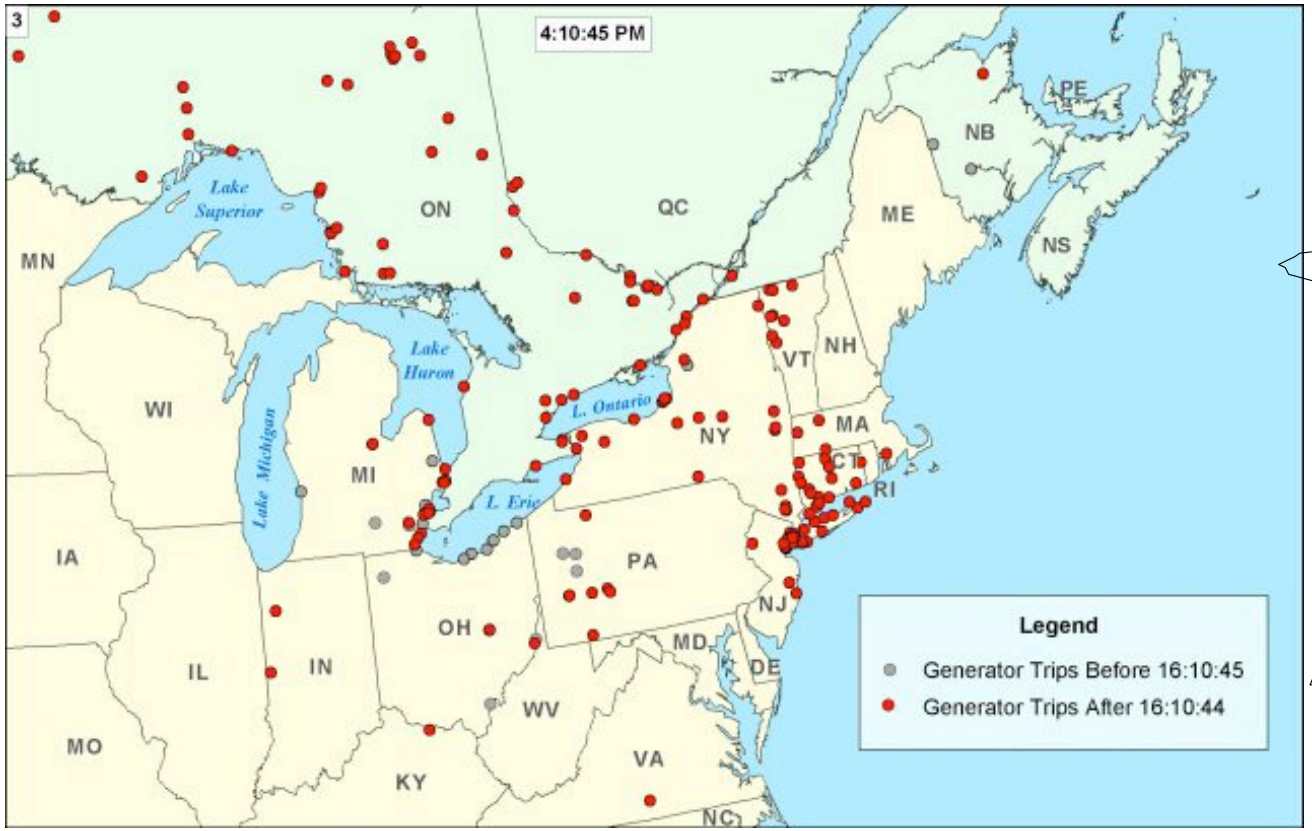
- Hourly data can be used for model input
- Hourly data can be compared to observations

- 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….

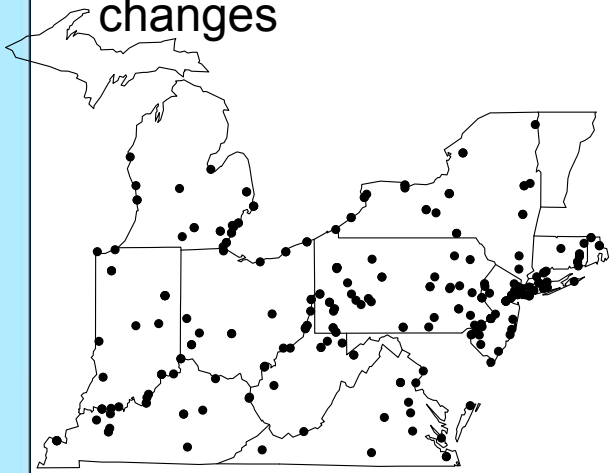
An electrical blackout starting on August 14, 2003 at 4:00pm and lasting for the next 24 hours

Marufu *et al. GRL*, (2004)



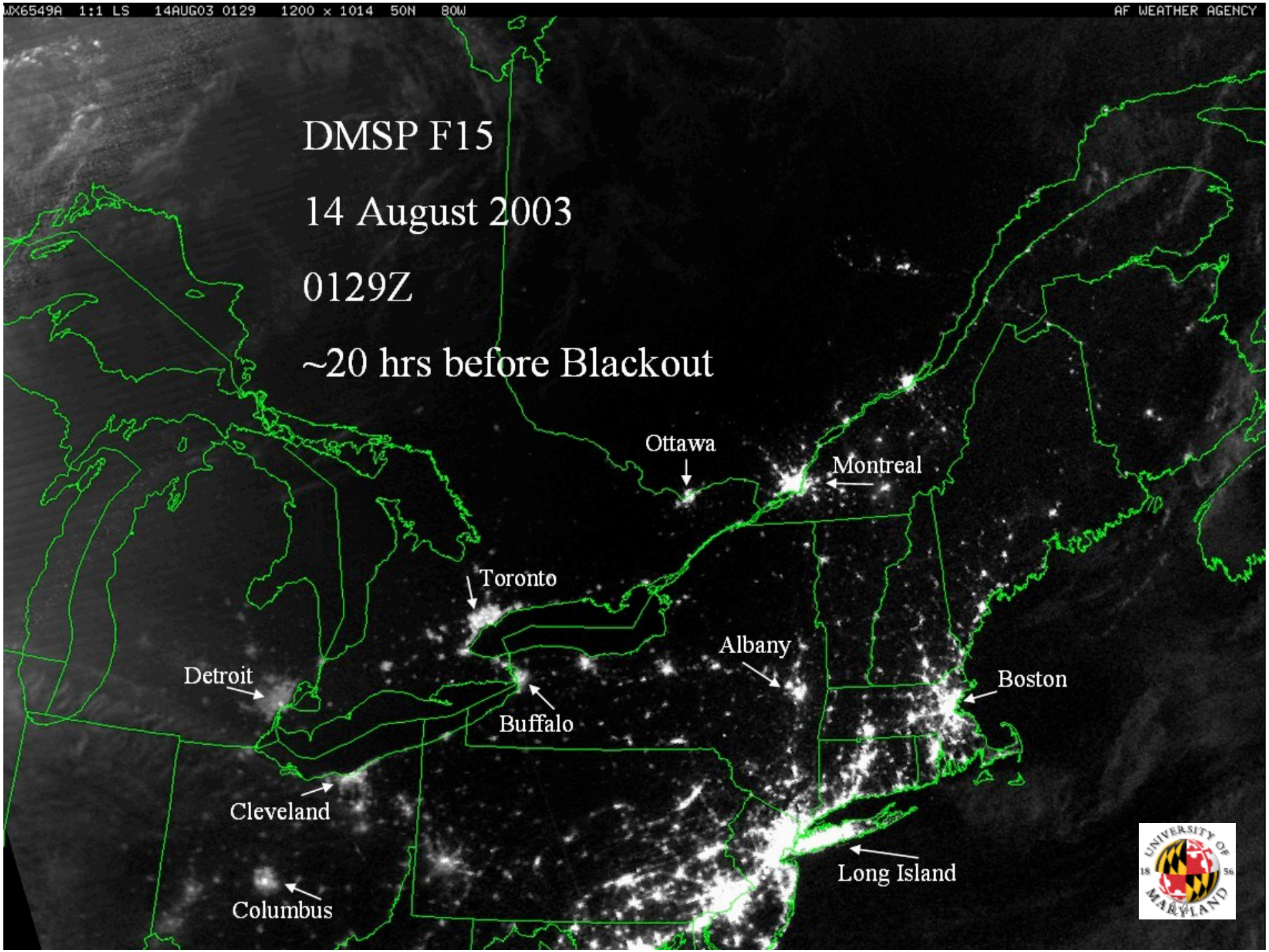
North American Electric Reliability Council Final Report, 2004

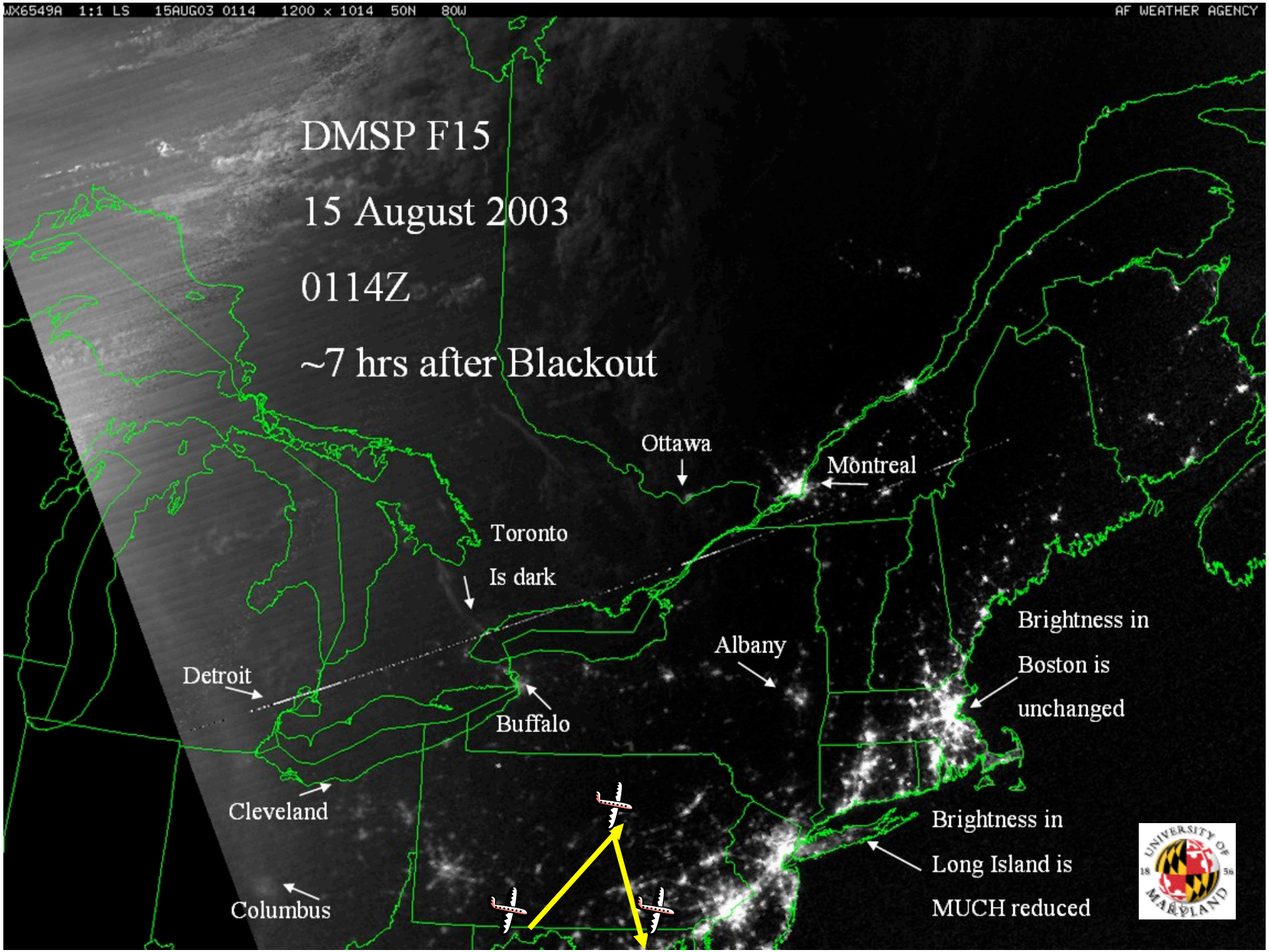
More plants are affected than the plants with Generator trips due to load changes



Plants with reduced NO_X emissions during the 24 hours of the blackout

Must look at hourly CEM data

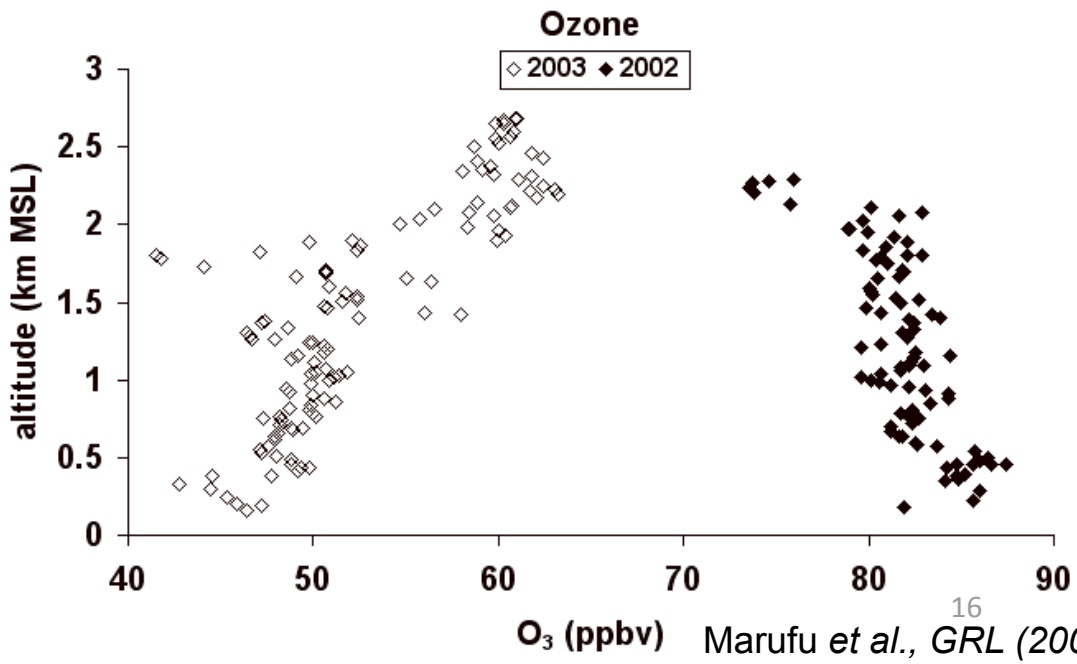

WX6549A 1:1 LS 14AUG03 0129 1200 x 1014 50N 80W
AF WEATHER AGENCY
DMSP F15
14 August 2003
0129Z
~20 hrs before Blackout
Ottawa
Montreal
Toronto
Albany
Boston
Detroit
Buffalo
Cleveland
Long Island
Columbus


WX6549A 1:1 LS 15AUG03 0114 1200 x 1014 50N 80W
AF WEATHER AGENCY
DMSP F15
15 August 2003
0114Z
~7 hrs after Blackout
Ottawa
Montreal
Toronto
Is dark
Albany
Detroit
Buffalo
Cleveland
Columbus
Brightness in
Boston is
unchanged
Brightness in
Long Island is
MUCH reduced

Aircraft Observations

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

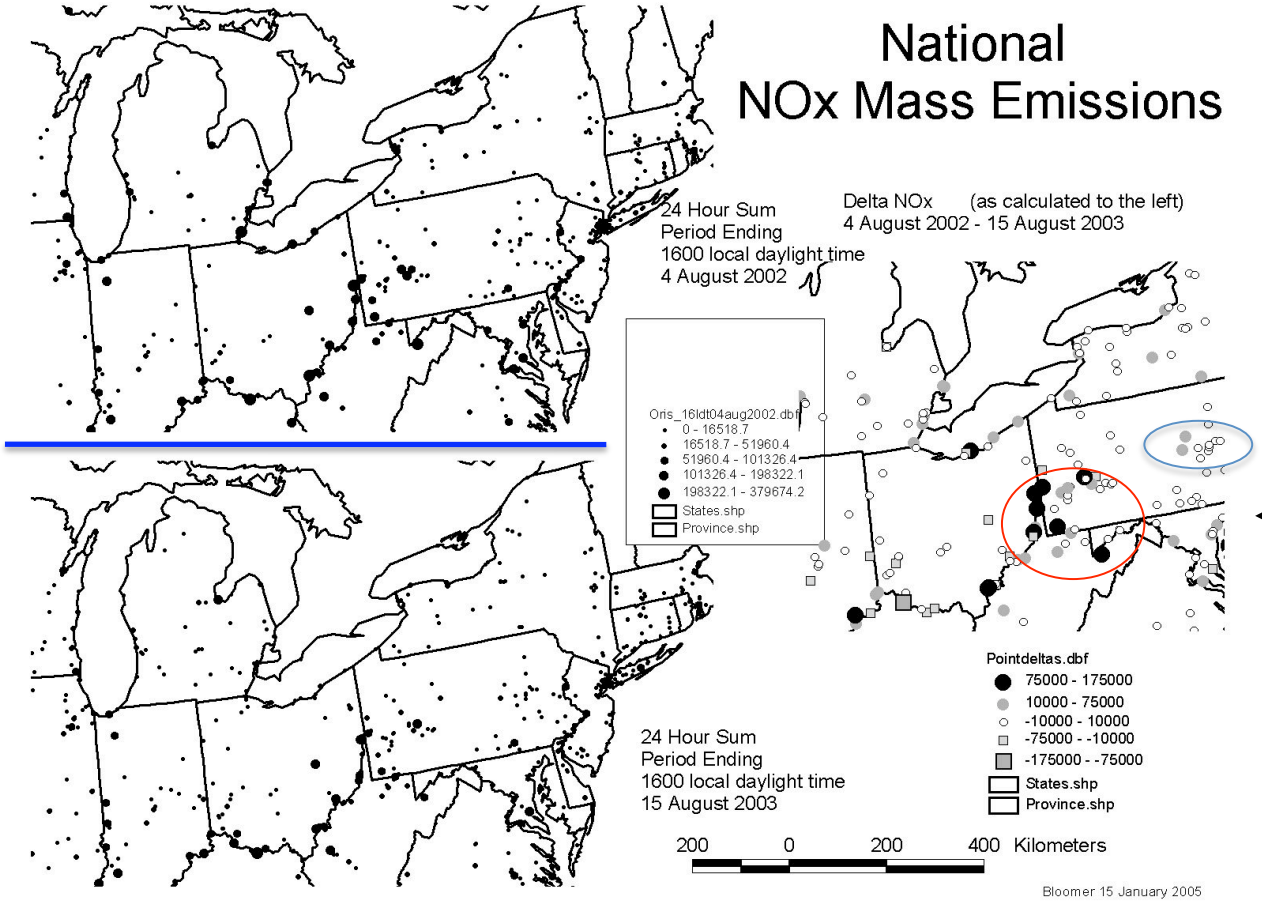
Differences below 2km of between 30 and 40 ppb



Marufu *et al., GRL (2004)*

Emissions Change from CEM Data

2002

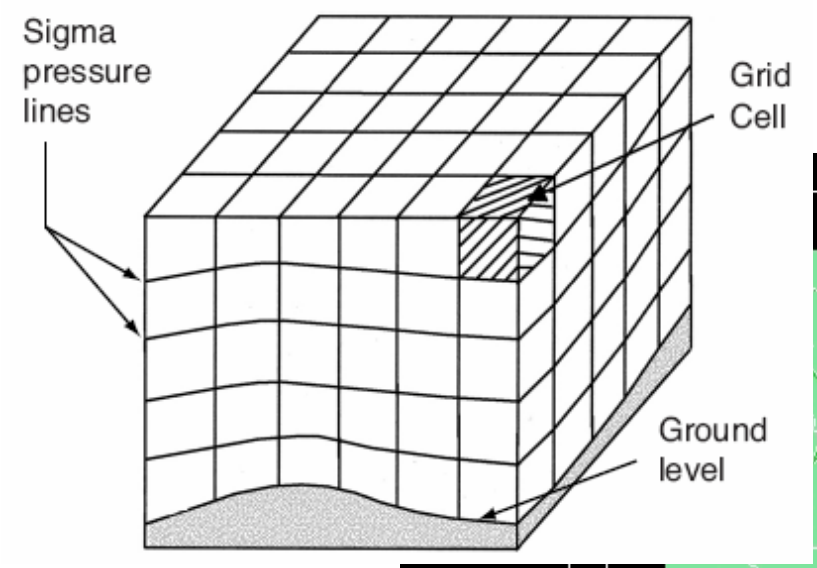


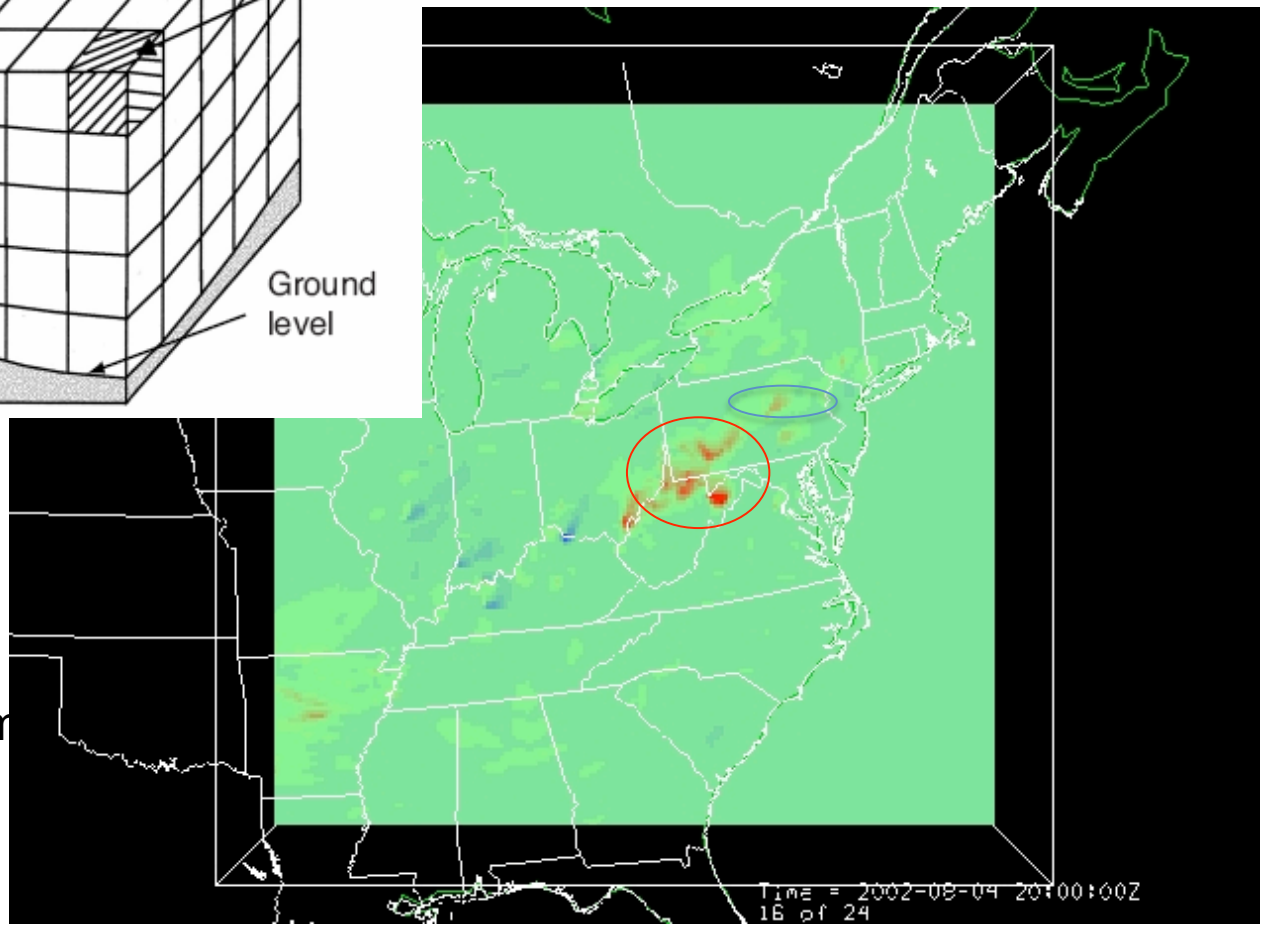
Source: US EPA Clean Air Markets Division Data and Maps facil_ss

2003

Area of largest NOx Differences corresponds To area of largest $[O_3]$ differences

CMAQ Simulation and Results

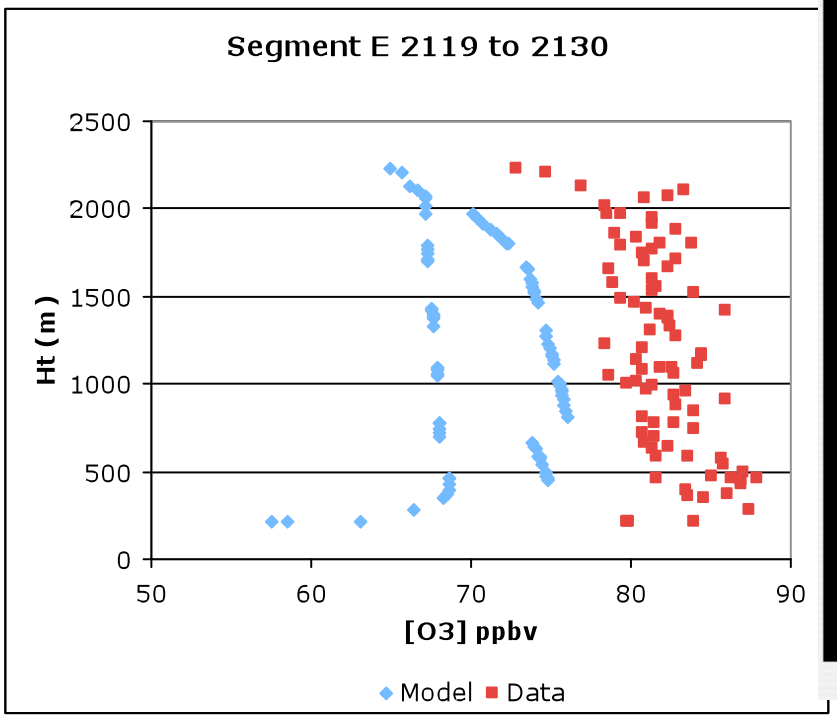


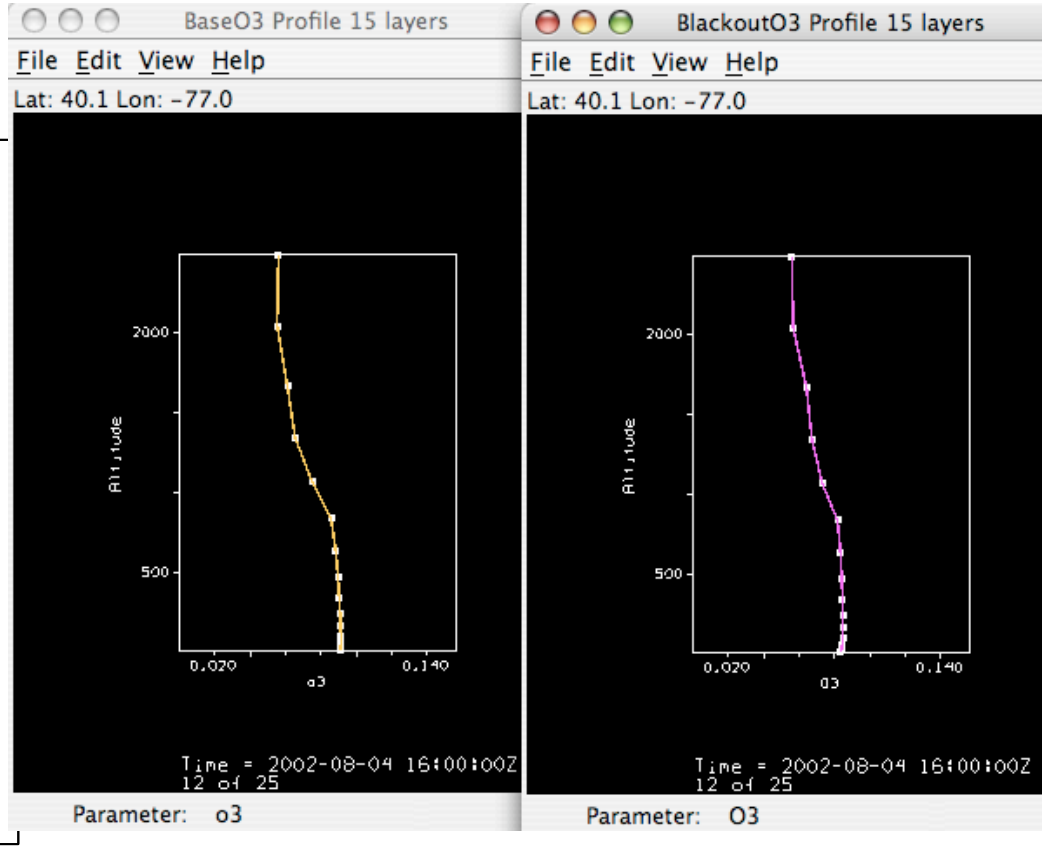


CMAQ v4.5.1
Cb_IV with mods.
ae3_aq: aerosols
and aqueous chem
MM5 meteorology
12kmX12km grid

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

Sampling the Simulation to compare with the aircraft data



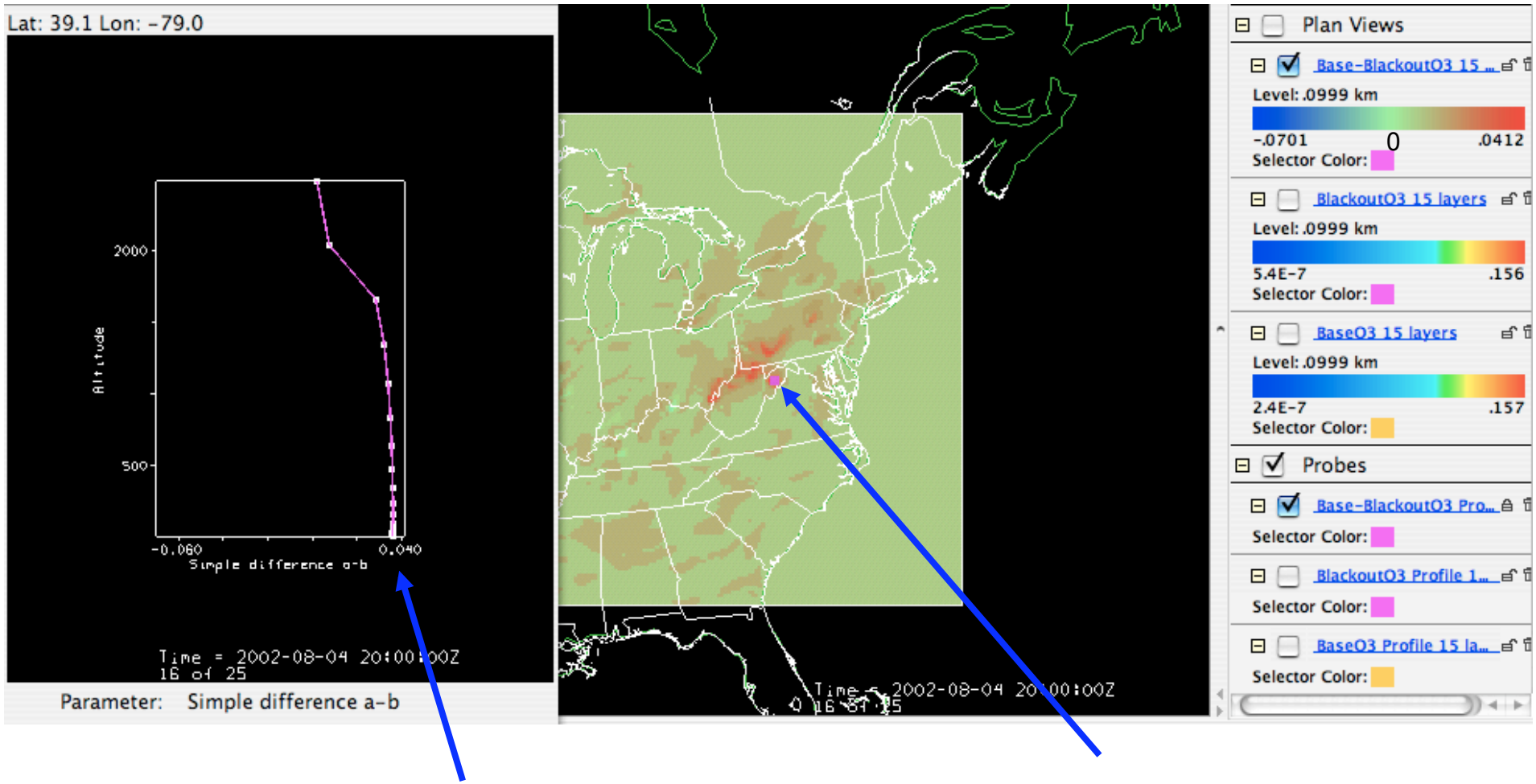


Base Simulation sampled in space/time
Pairing with aircraft observations
Crosses grid squares

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 40ppbv 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…

$$y(t,h) = Y(t,h) + y'(t,h).$$

$$Y(t,h) = A(t,h) + B(t,h)\cdot t,$$

$$A(t,h) = a_0(h) + \sum_{k=1}^{K}\left[a_k(h)\sin\left(\frac{2\pi kt}{T}\right) + b_k(h)\cos\left(\frac{2\pi kt}{T}\right)\right],$$

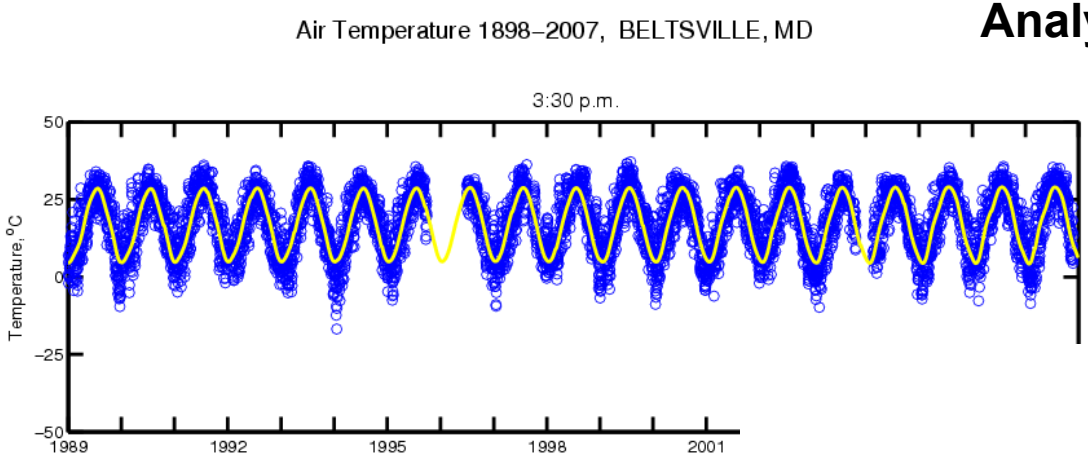
$$B(t,h) = \alpha_0(h) + \sum_{m=1}^{M}\left[\alpha_m(h)\sin\left(\frac{2\pi mt}{T}\right) + \beta_m(h)\cos\left(\frac{2\pi mt}{T}\right)\right].$$

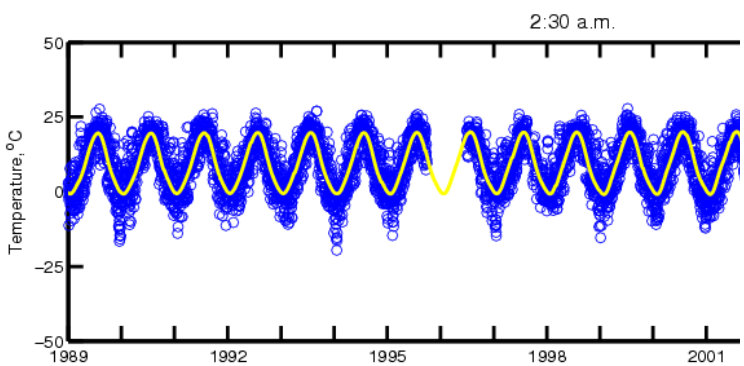
The Goal is to see if we can separate and quantify the influence of climate changes upon ozor

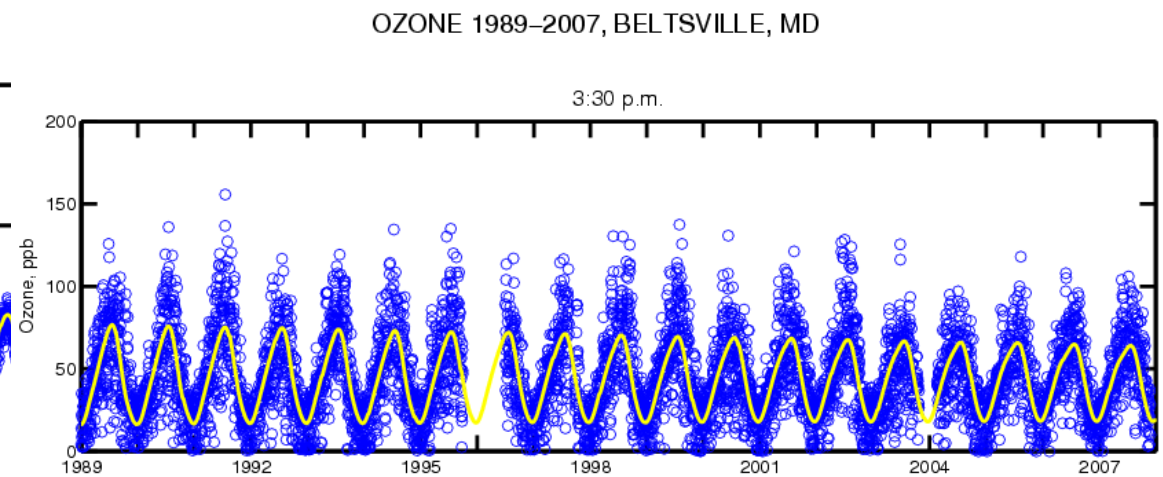
A specific example: BELTSVILLE, MD

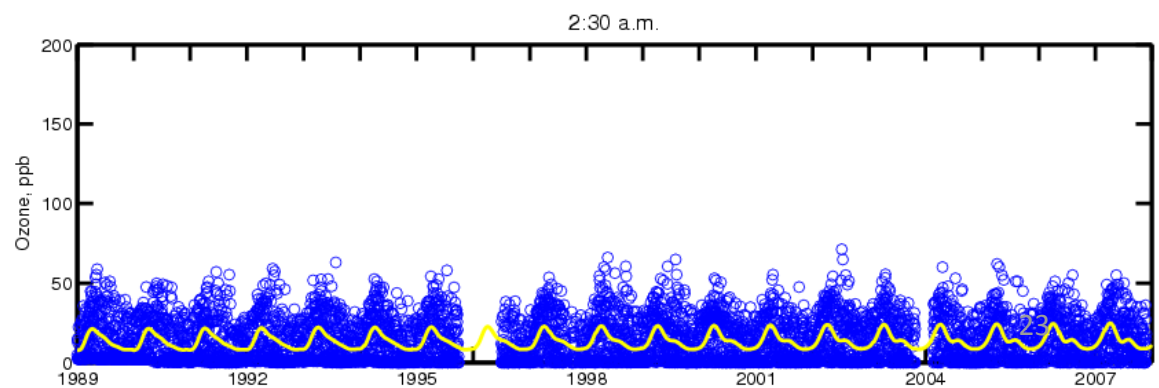
Illustrates the math:

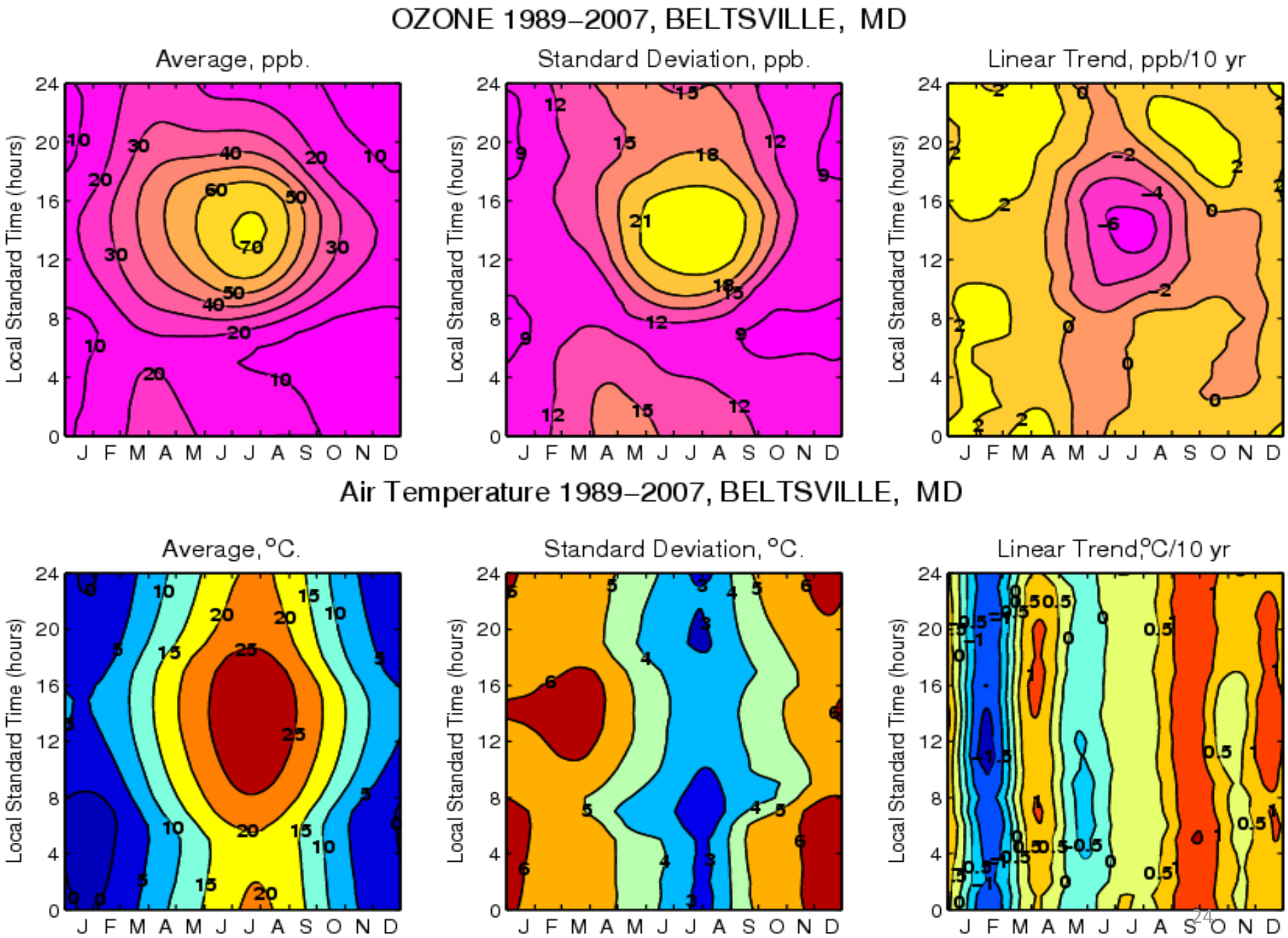
Analysis of Ozone and Air Temperature
Hourly Observation
1989-2007



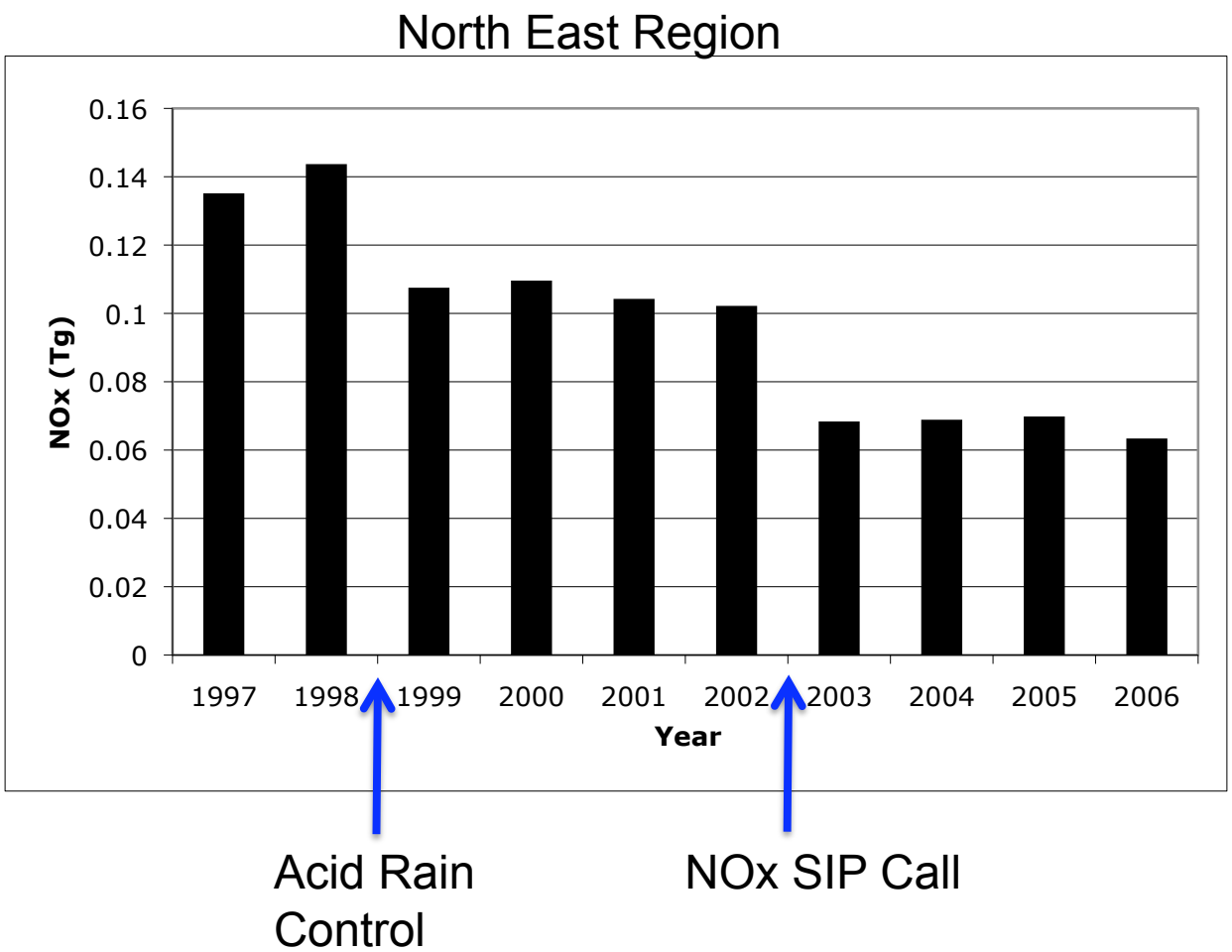




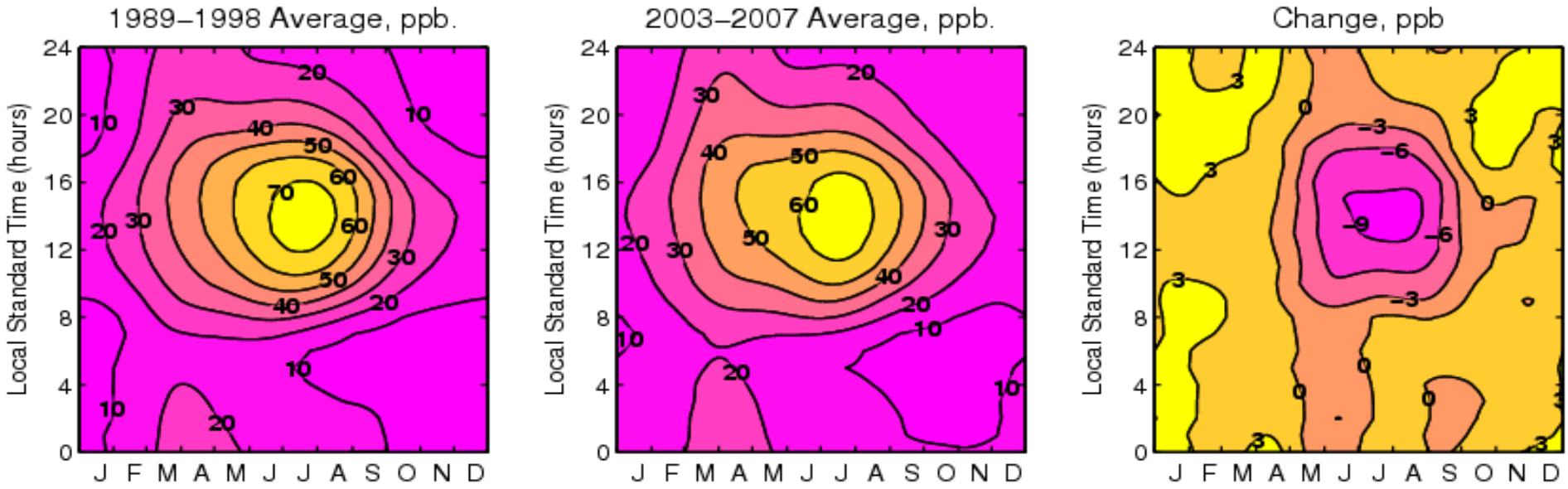



OZONE 1989–2007, BELTSVILLE, MD
Average, ppb.
Standard Deviation, ppb.
Linear Trend, ppb/10 yr
Air Temperature 1989–2007, BELTSVILLE, MD
Average, °C.
Standard Deviation, °C.
Linear Trend, °C/10 yr
Local Standard Time (hours)
J F M A M J J A S O N D

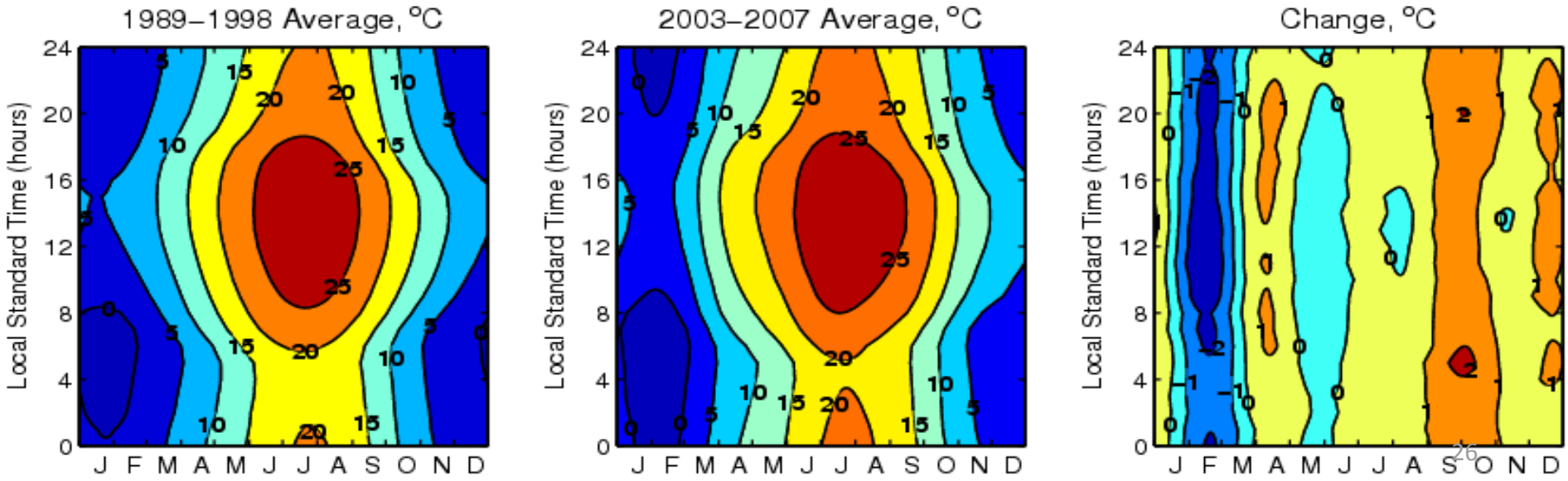
Remember:
Emissions change significantly as a result of control programs



CHANGE of OZONE AVERAGES from 1989–1998 to 2003–2007. BELTSVILLE, MD



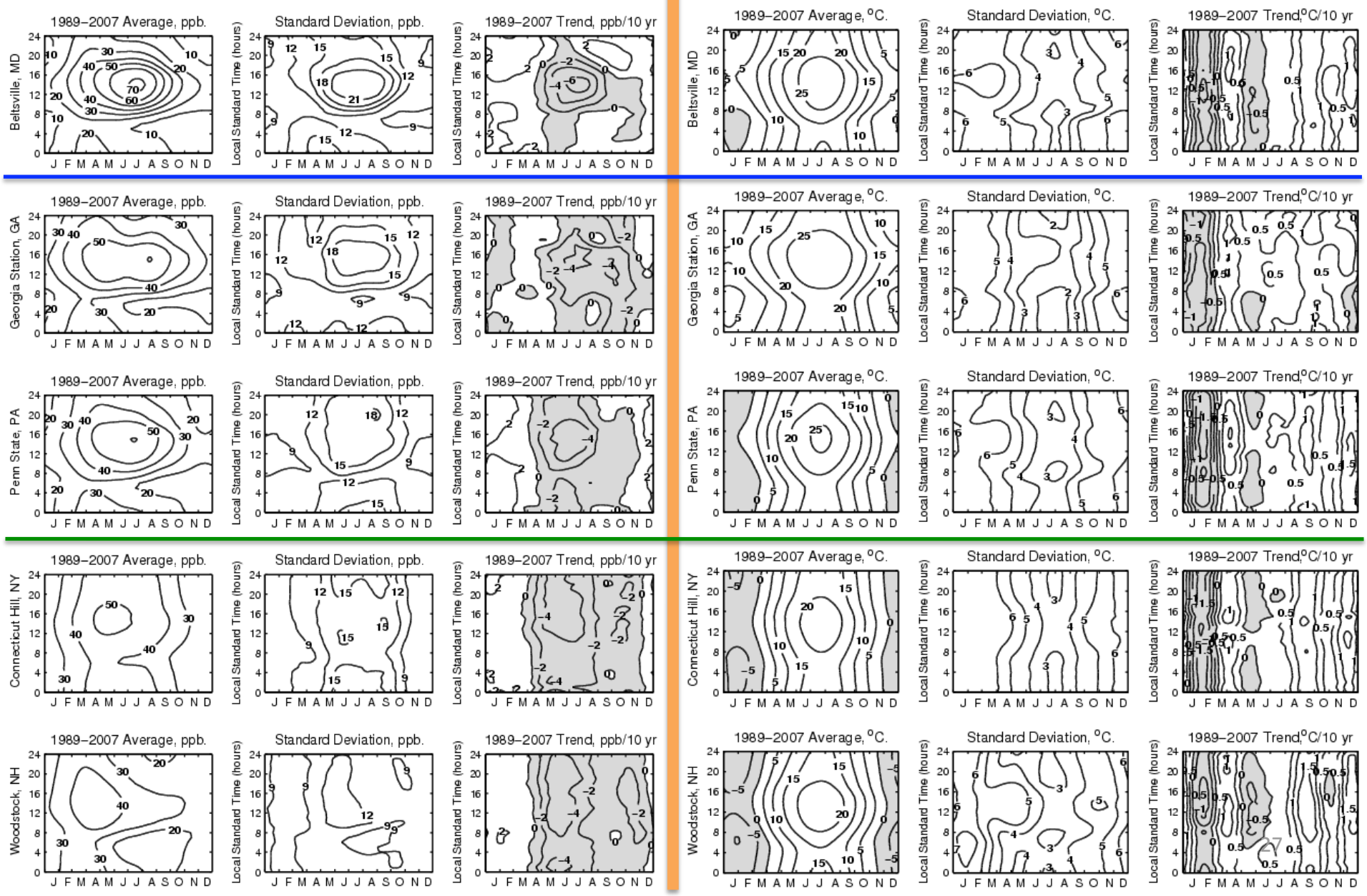
CHANGE of AIR TEMPERATURE AVERAGES from 1989–1998 to 2003–2007. BELTSVILLE, MD



Expand Consideration across eastern U.S.

OZONE MONITORING, EPA CASTNET STATIONS

AIR TEMPERATURE MONITORING, EPA CASTNET STATIONS



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

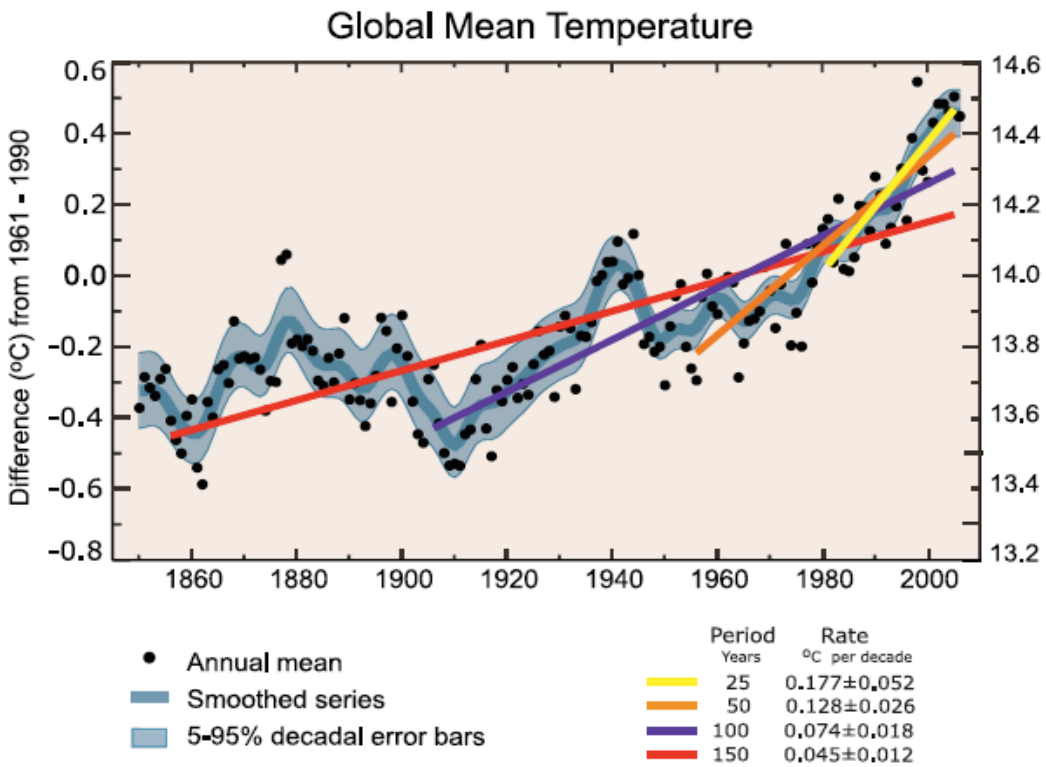
Emissions

Photochemical Smog

and Climate Change

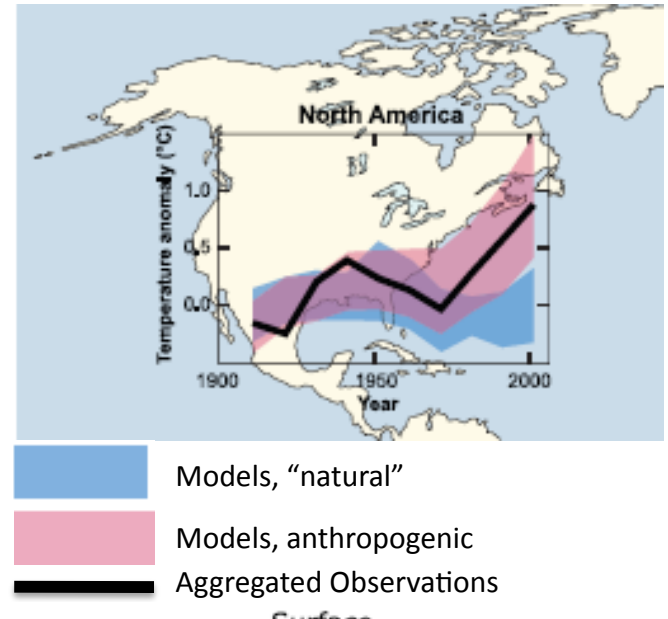
“Warming of the climate system is unequivocal.”

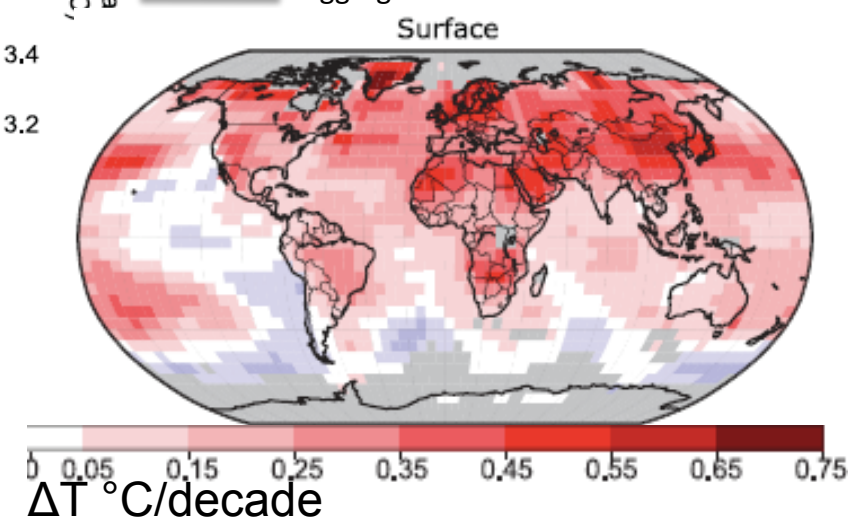
Dr. R K Pachauri Chairman IPCC Press Presentation Saturday, 17 November 2007 Valencia, Spain



IPCC, AR4, WG1, Ch. 3

Models Say…





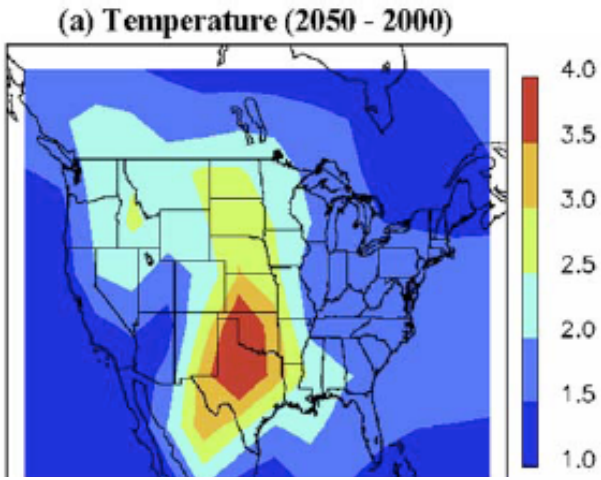
A Climate Change Penalty

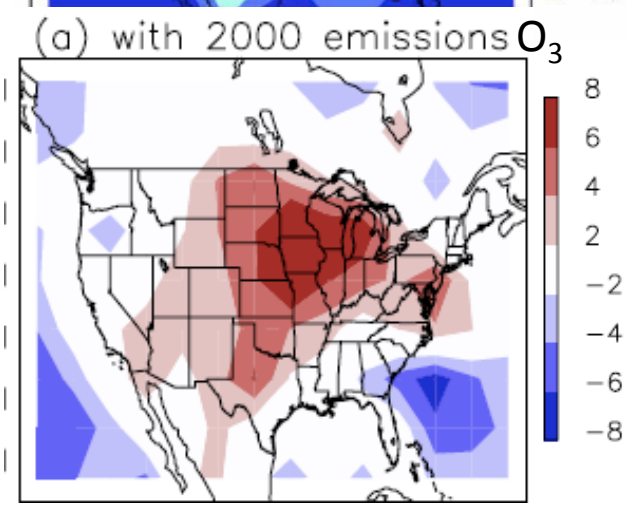
Emission Change
Weather Change
Ozone Change

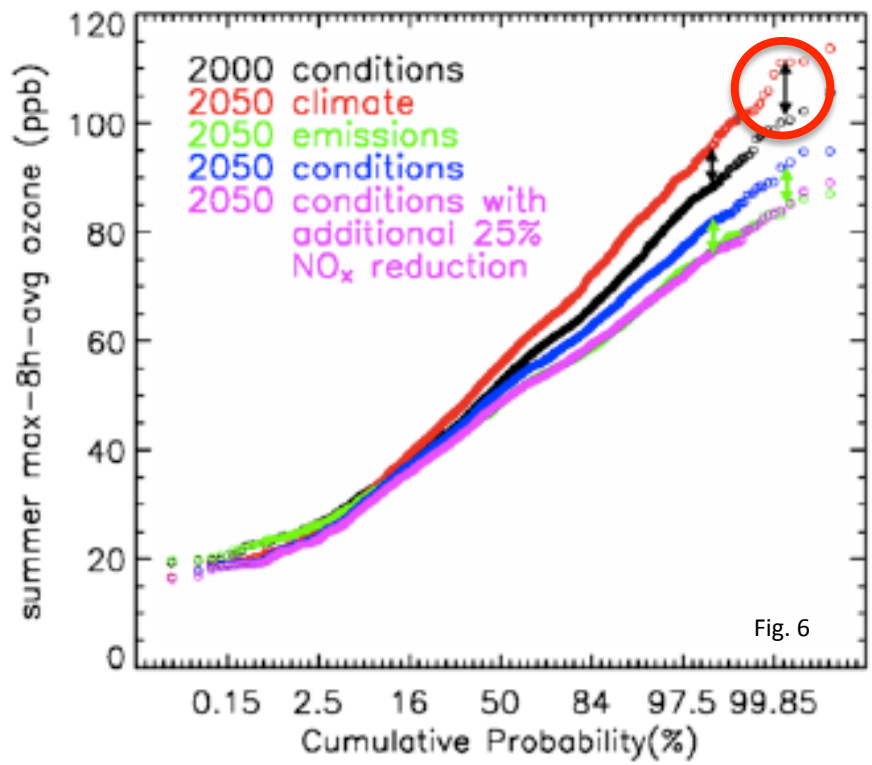
Can we separate the signals?
If so, how?
What does it mean?

Defined

Use a Model
Make some Predictions







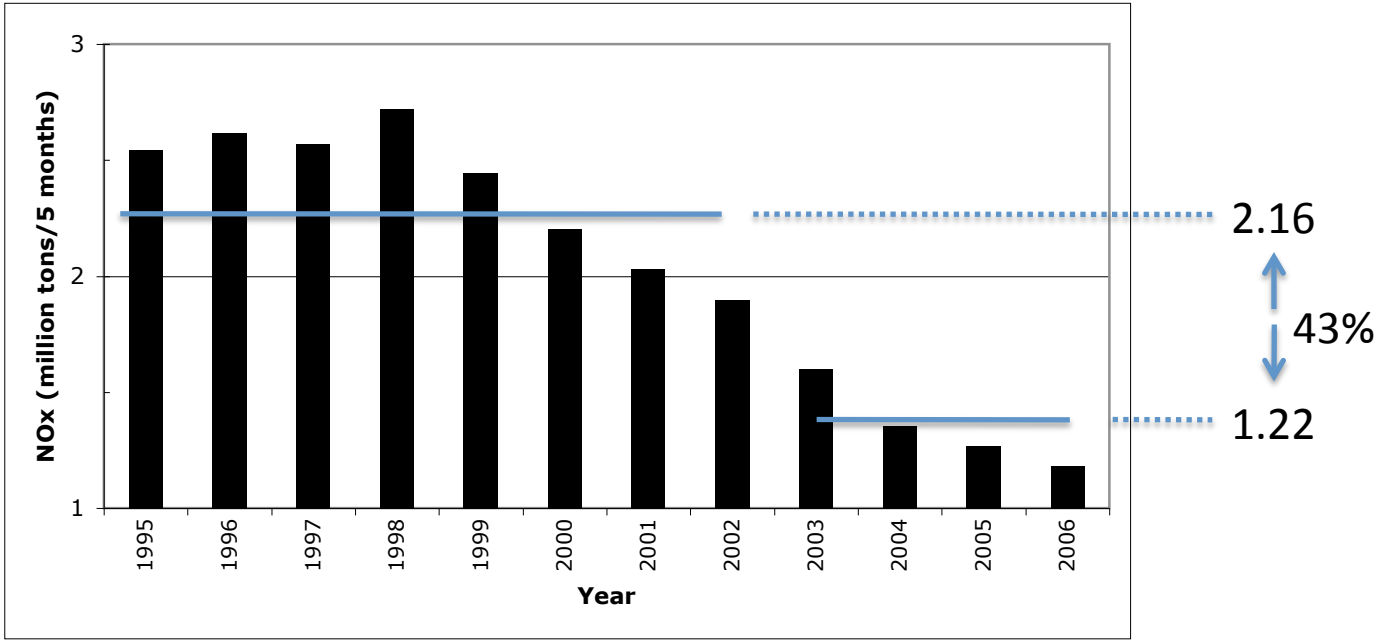
First Definition of The Climate Change Penalty

Wu, S., L. J. Mickley, E. M. Leibensperger, D. J. Jacob, D. Rind, and D. G. Streets (2008), Effects of 2000–2050 globalchange on ozone air quality in the United States, J. Geophys. Res., 113, D06302, doi:10.1029/2007JD008917.

The Reality is more complicated: Emission Reductions

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

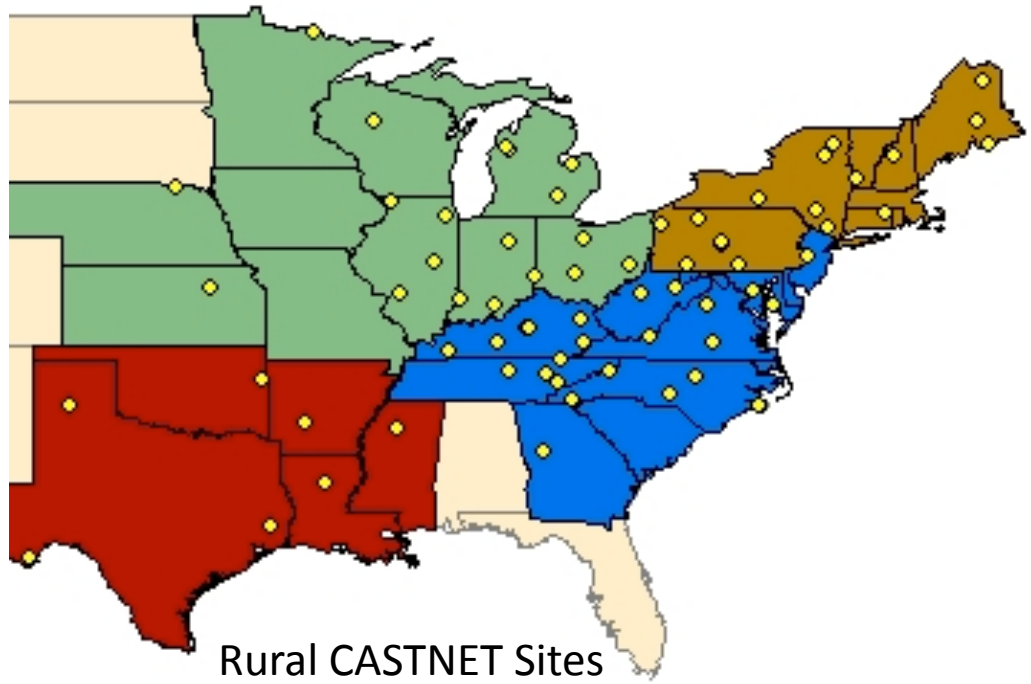
National Ozone Season NOx Emissions from Power Plants



CEM Observed Ozone Season Power Plant Emissions

So how can we tell what happened to Ozone?

J. Lehman *et al.*, *Atmos. Environ.* **38**, 4357 (2004).



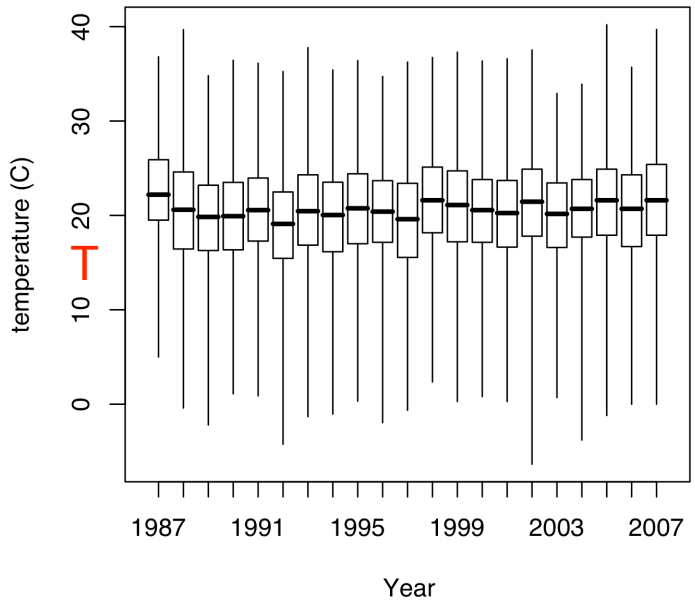
Chemically Coherent Receptor Regions
Derived from Rotated Principal Component Analysis

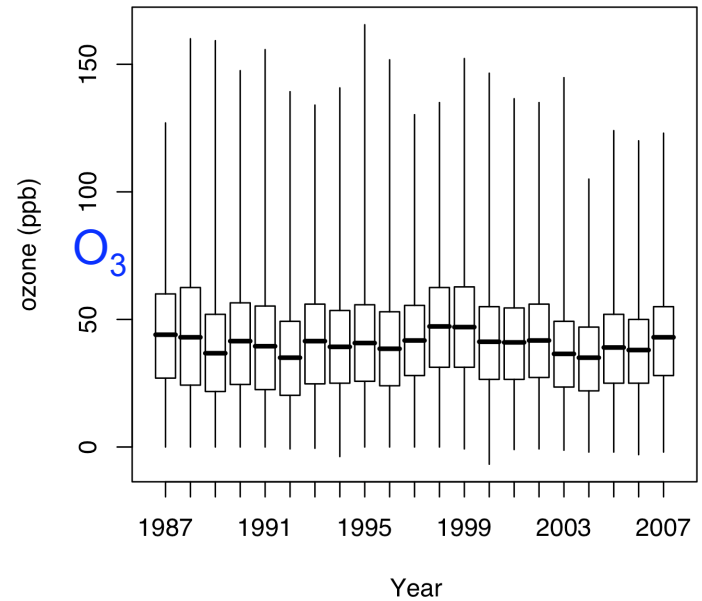
Rural, CASTNET, offers additional opportunities due to co-located meteorological observations

Observations: Mid-Atlantic Temperature and Ozone

Inter-annual Variability:

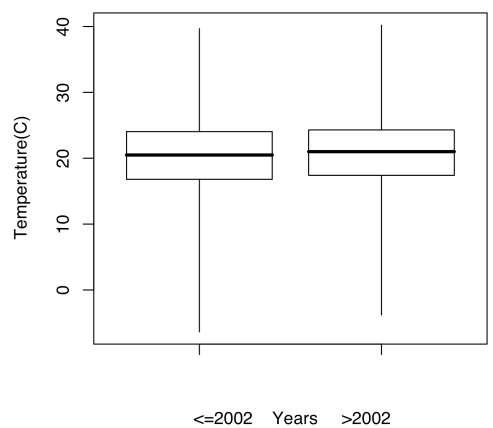
Difficult to see trends

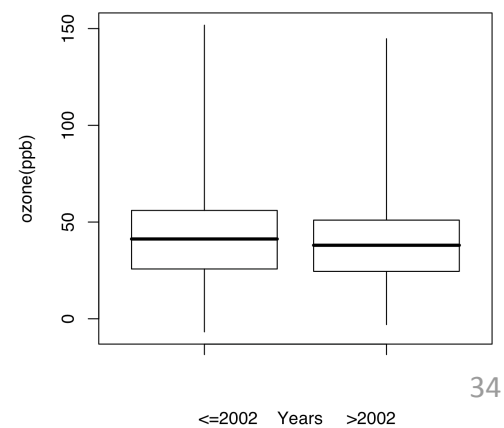




Grouping Relative to Emission Changes

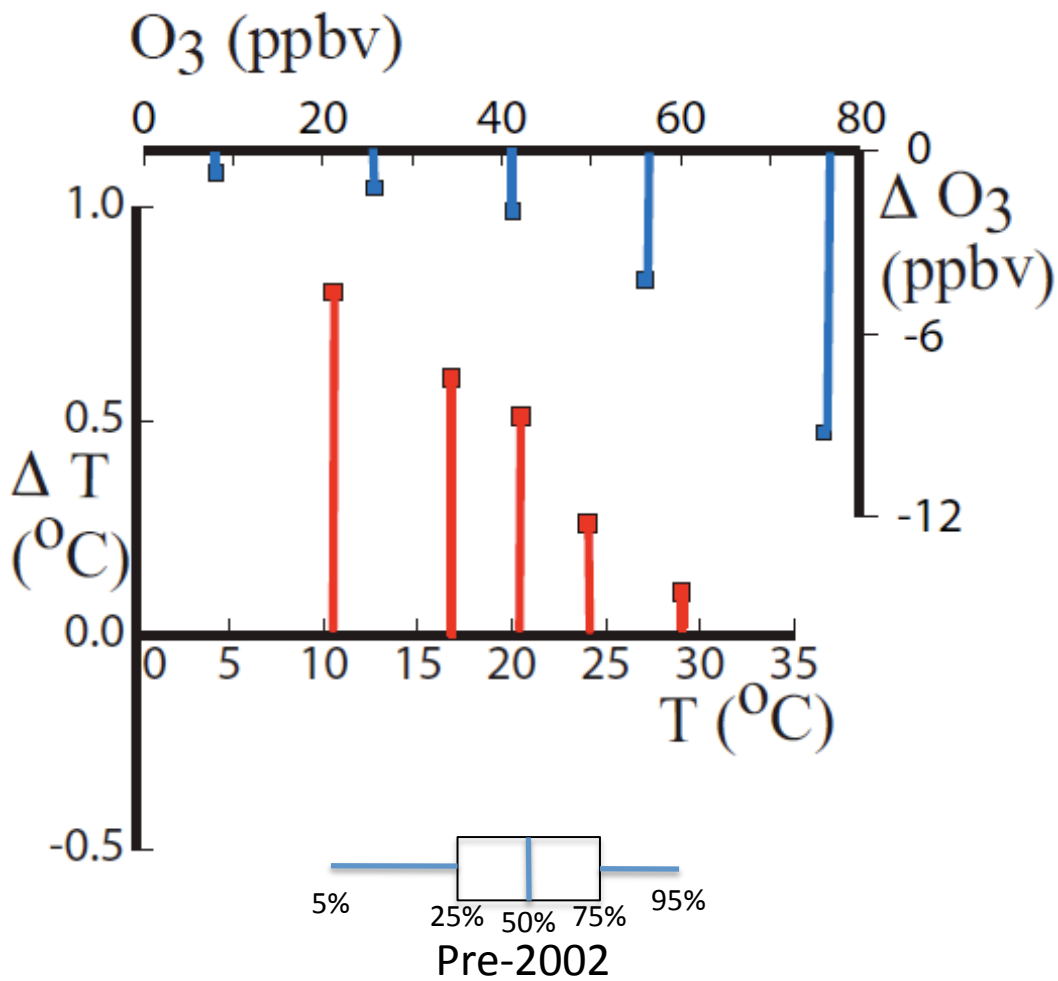
Signals start to become apparent





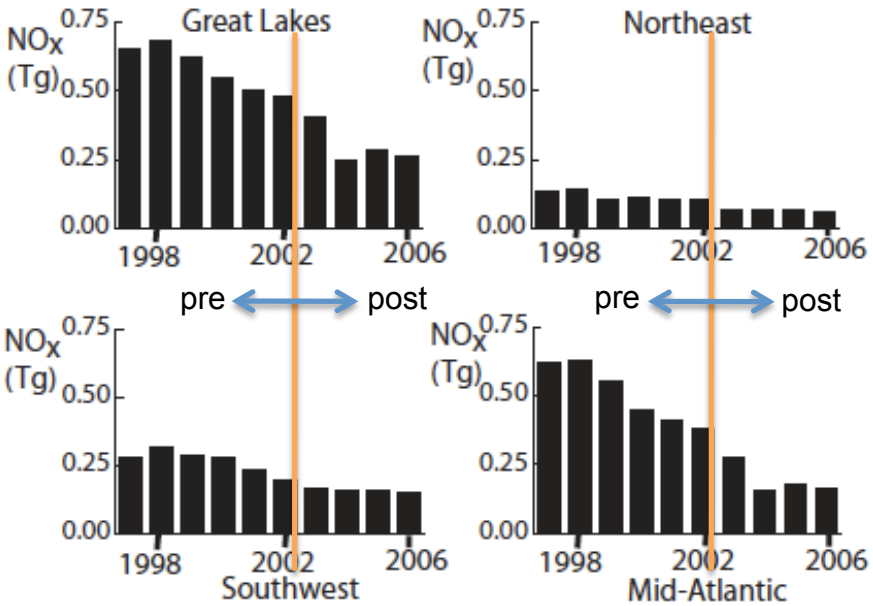
Observations: Mid-Atlantic Temperature and Ozone

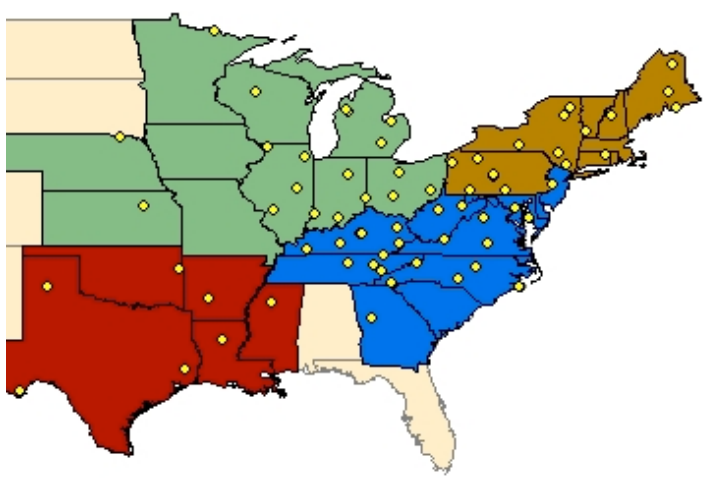
Temperature Went Up. Warming After 2002

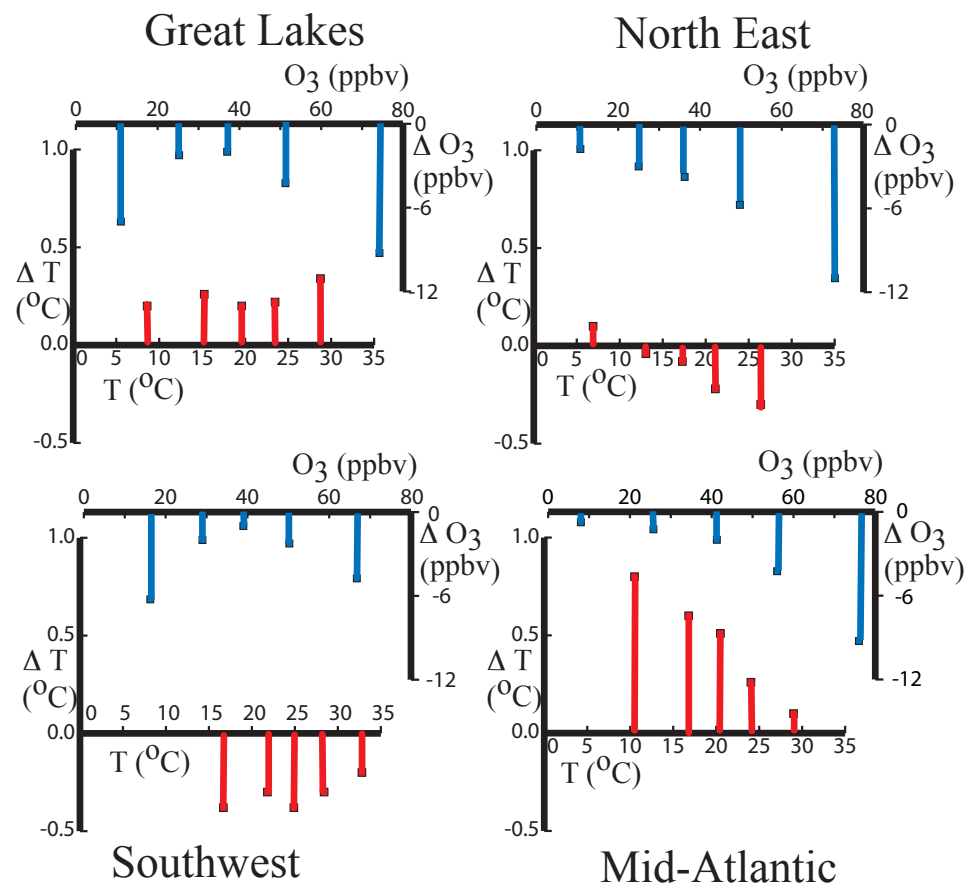


Ozone Went Down After 2002

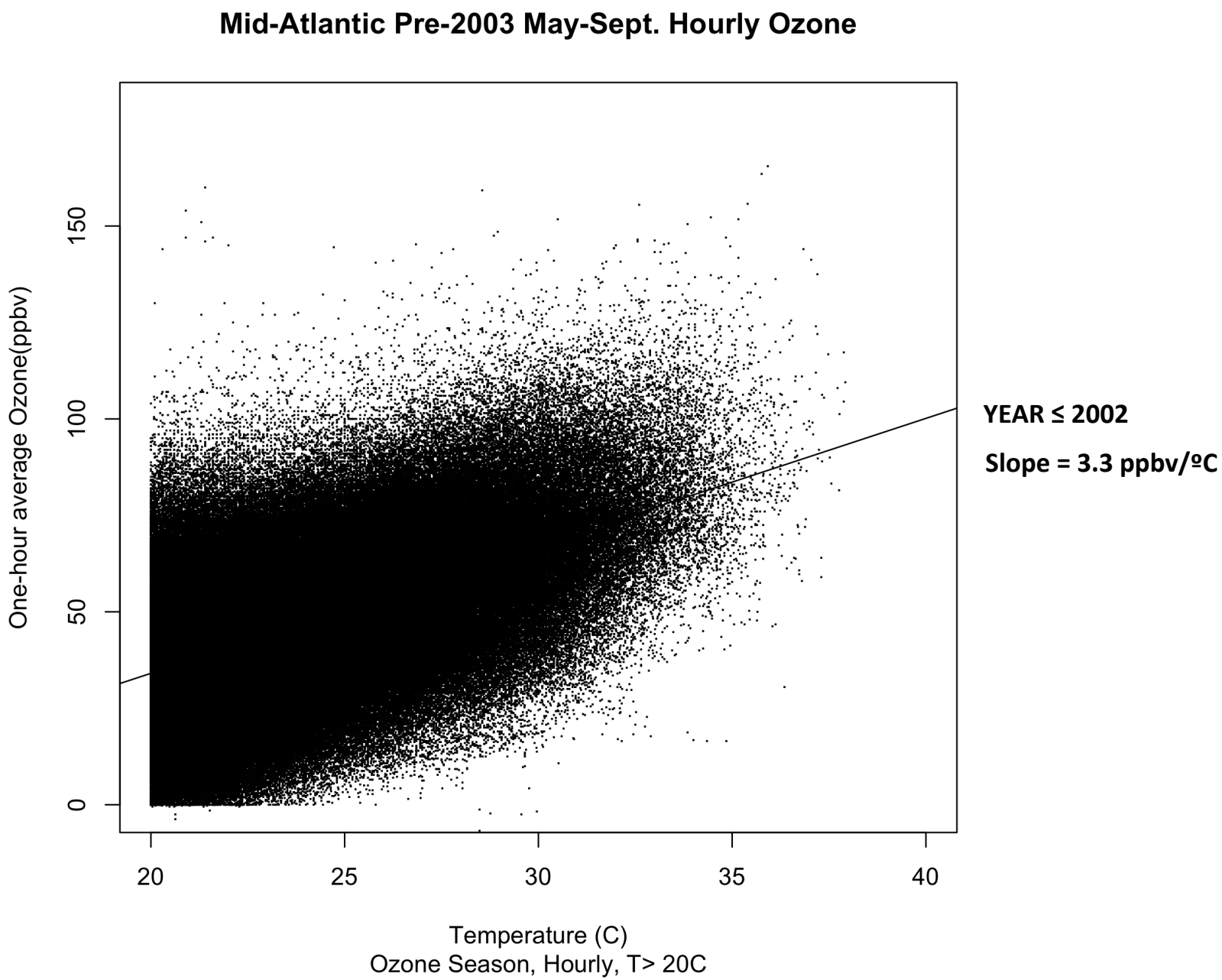
Ozone, Temperature and Emission Changes across the Eastern U.S.







Can we observe the influence of warming on air quality?



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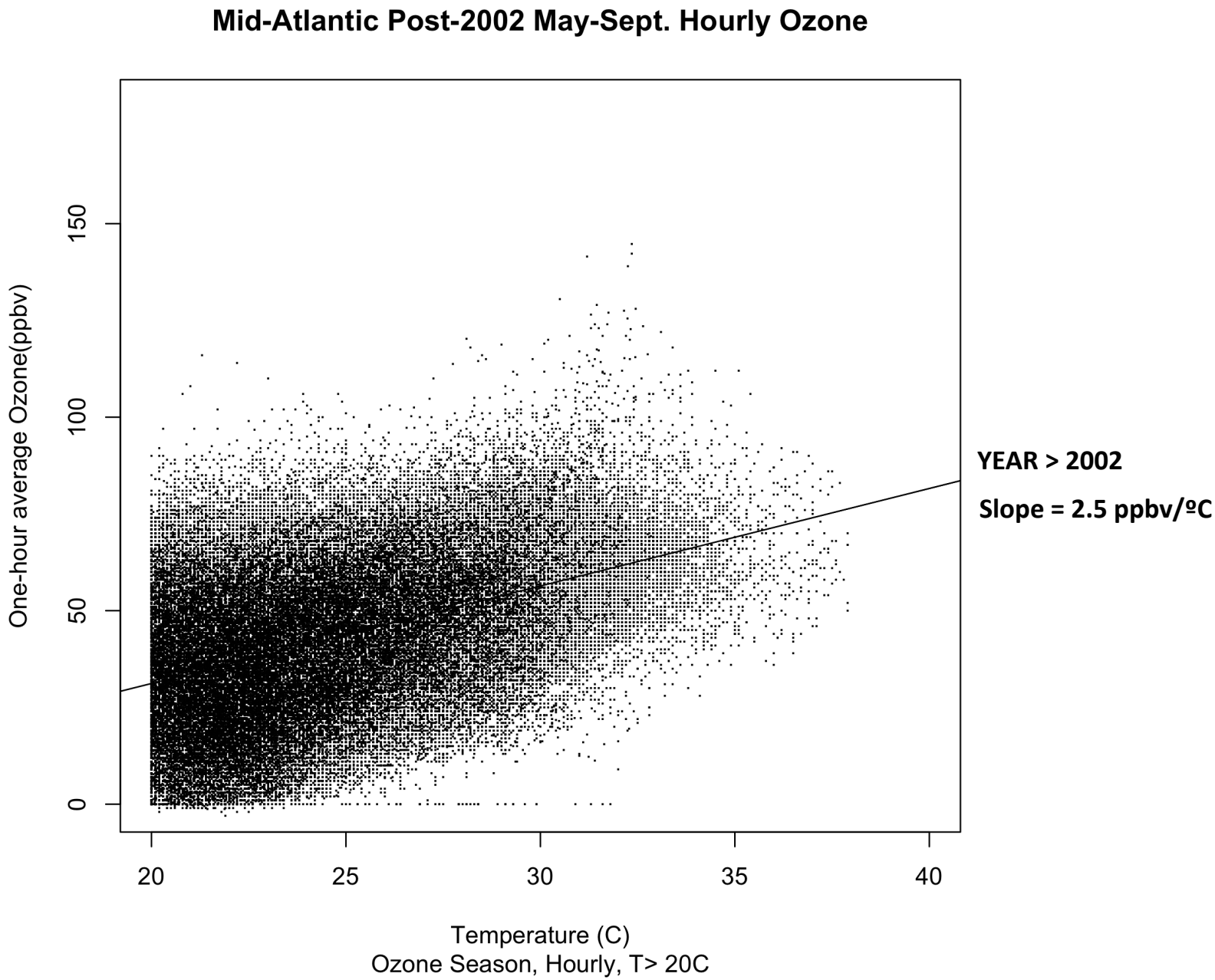

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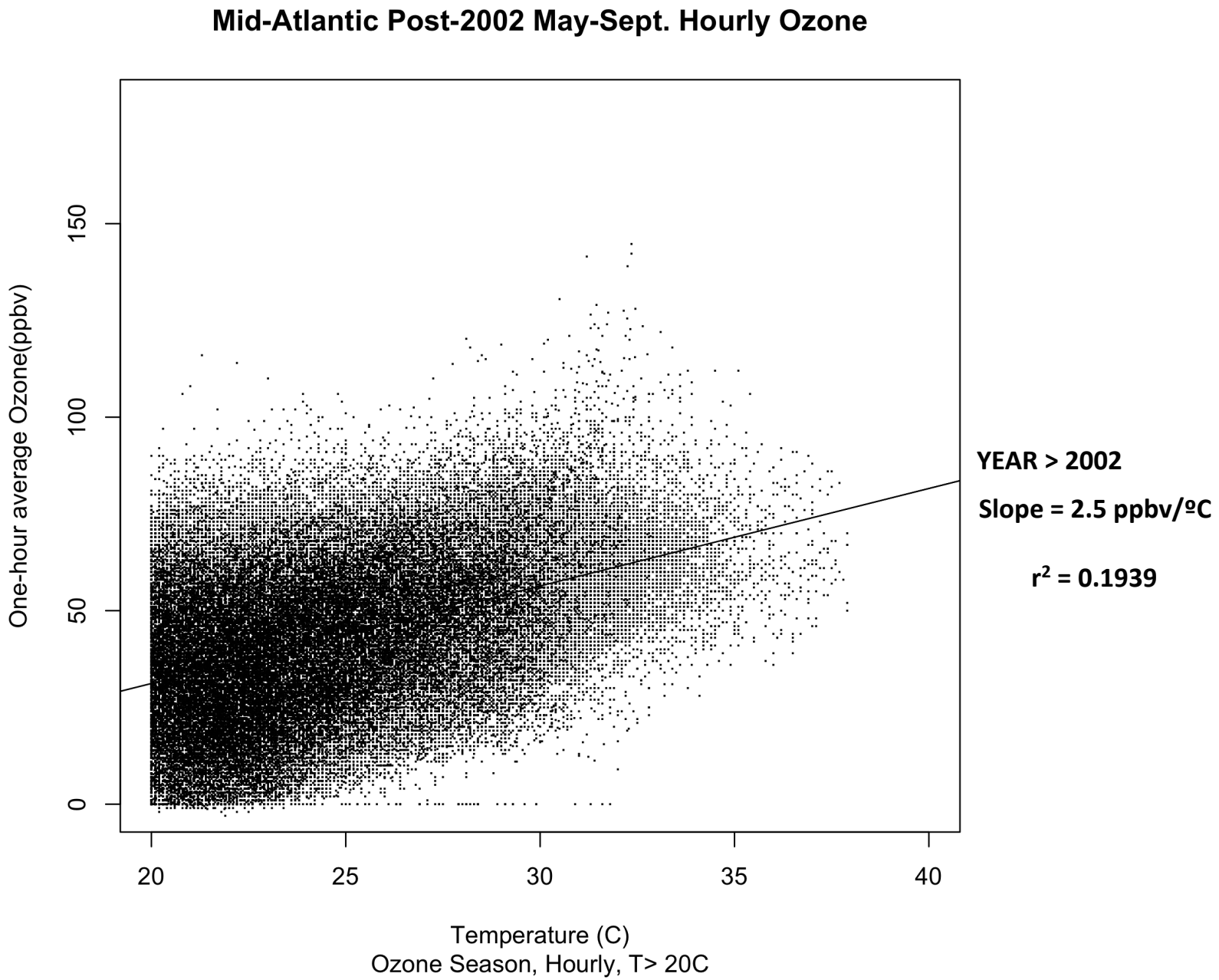
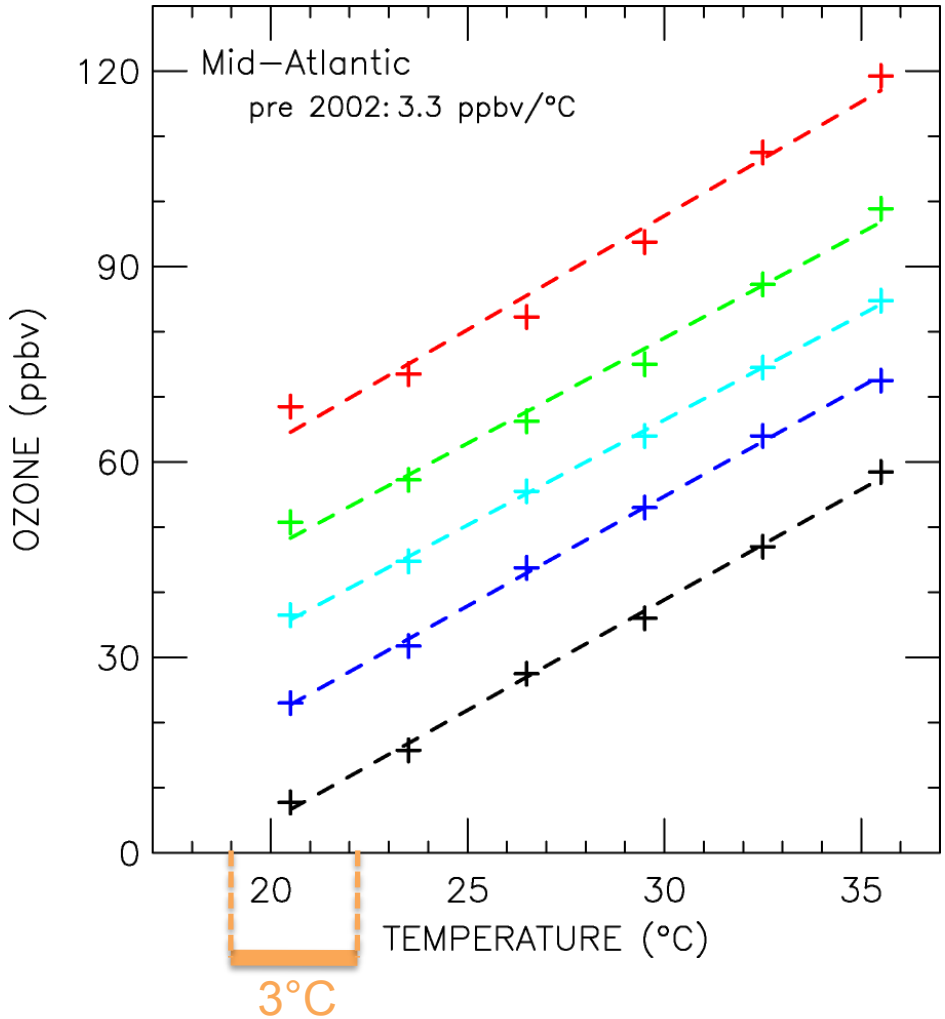
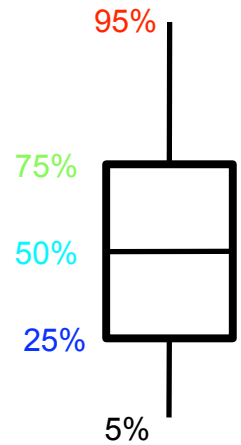


Looking deeper into the data: method

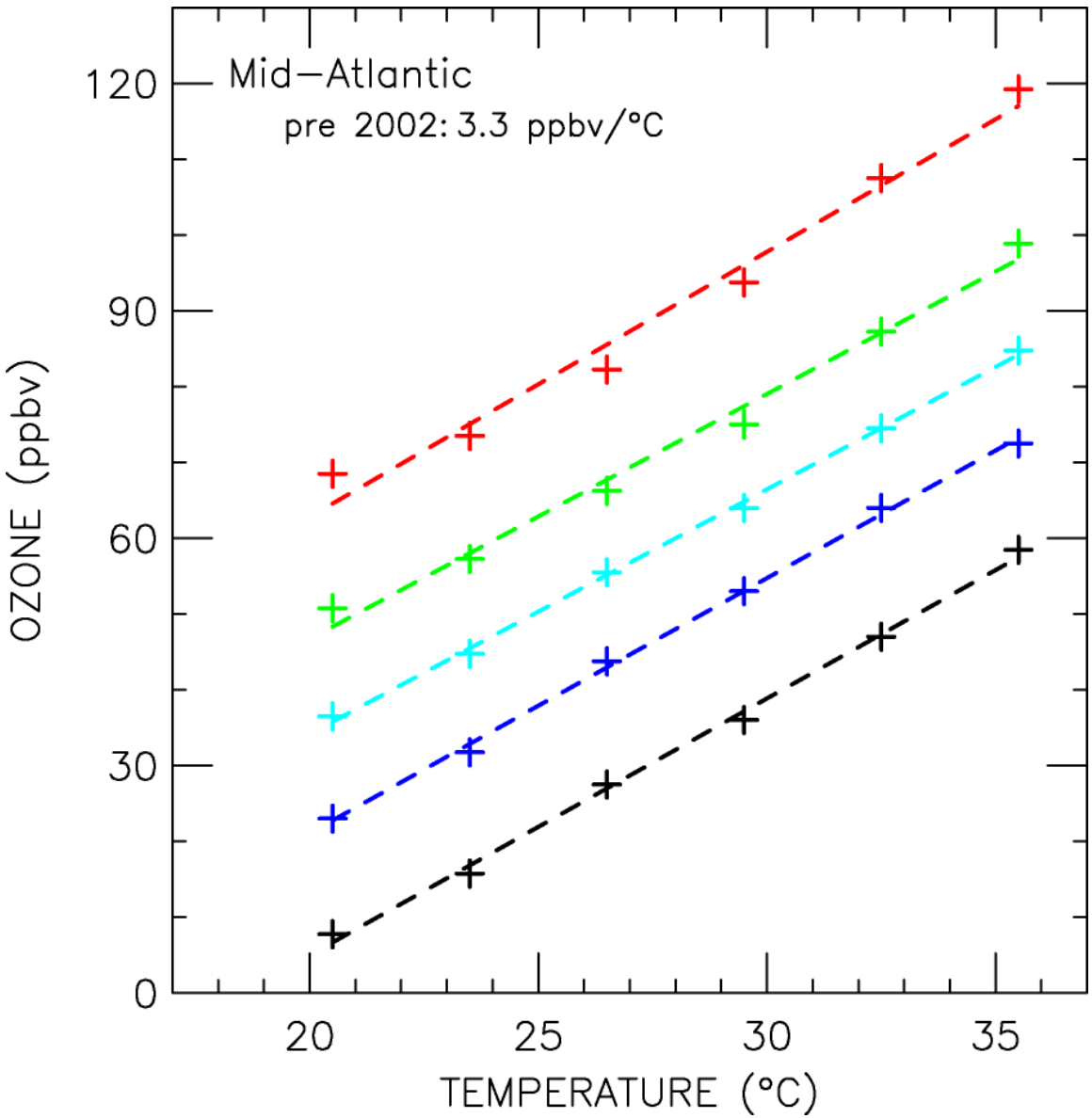


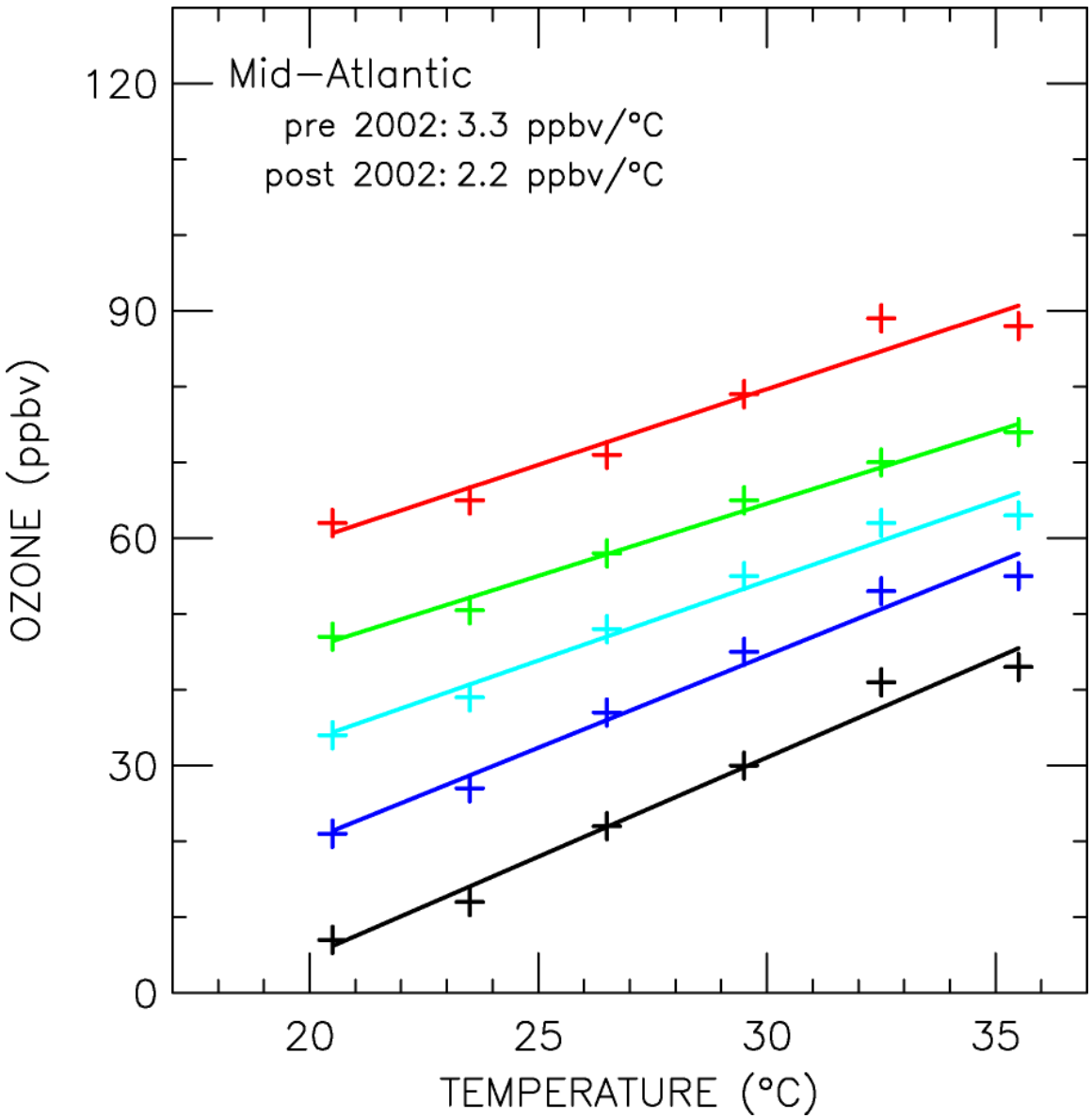
Temperature Binning

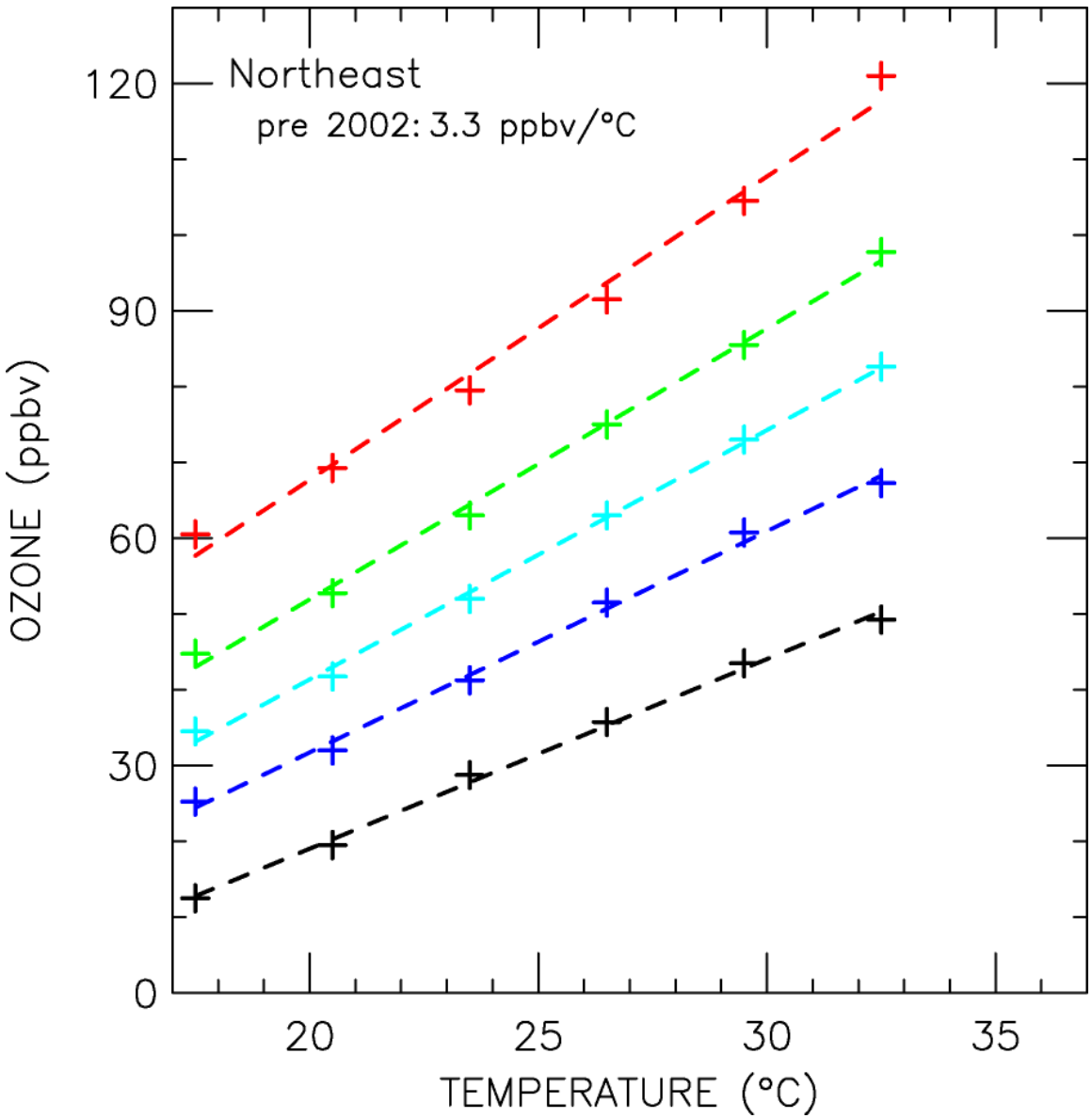


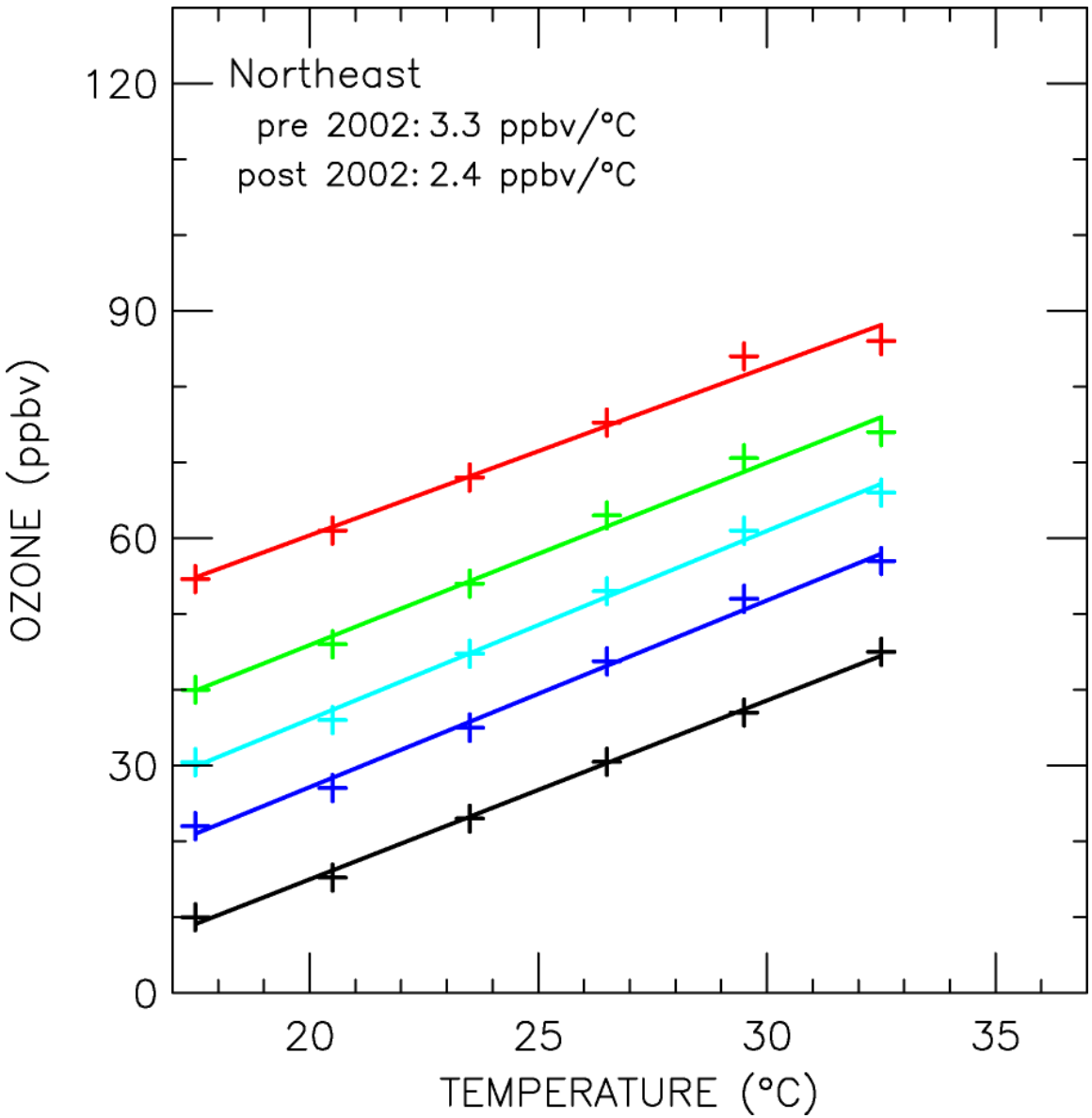
Ozone rises as temperature increases

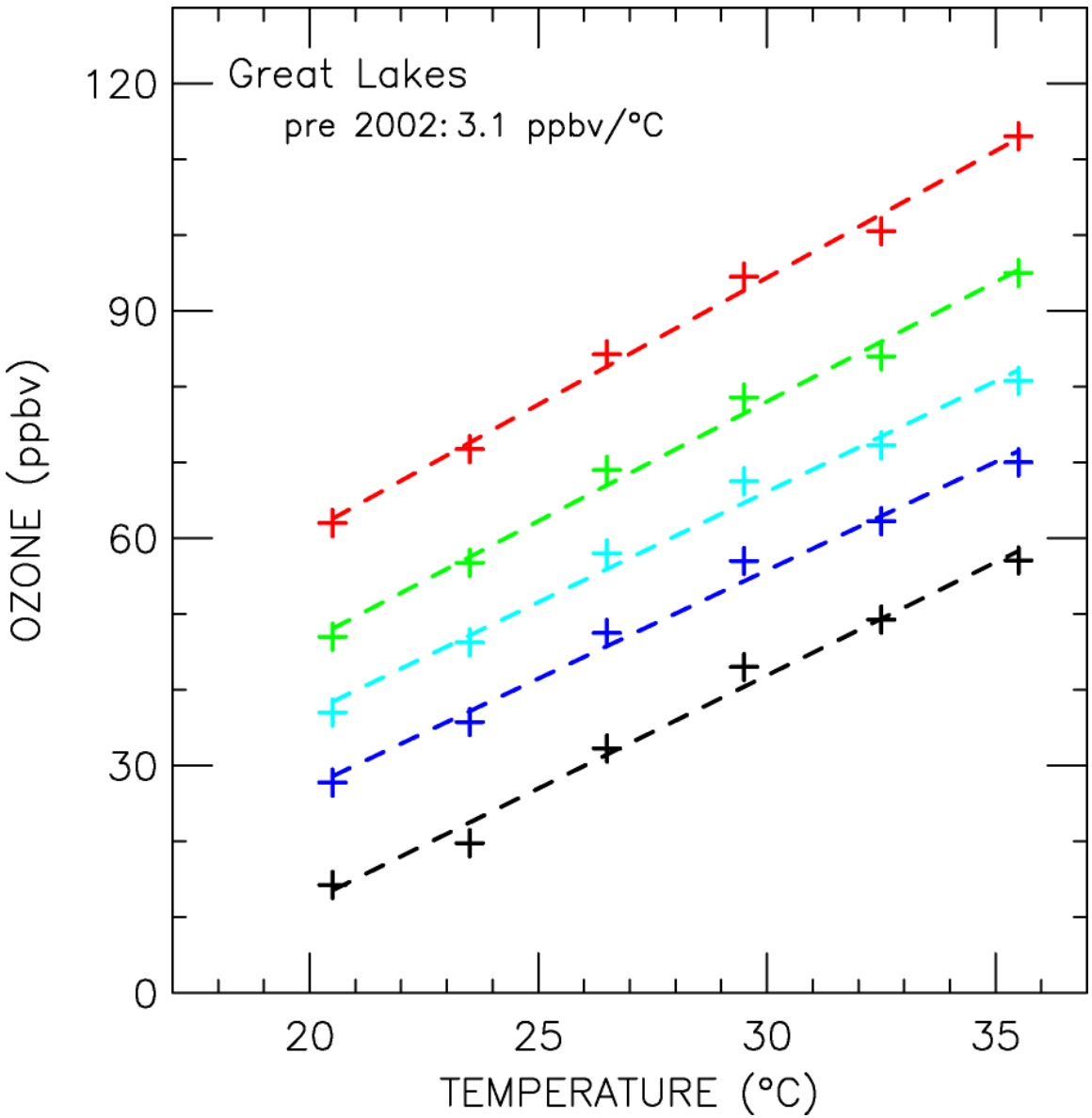
The slope is defined to be the
"climate penalty factor"

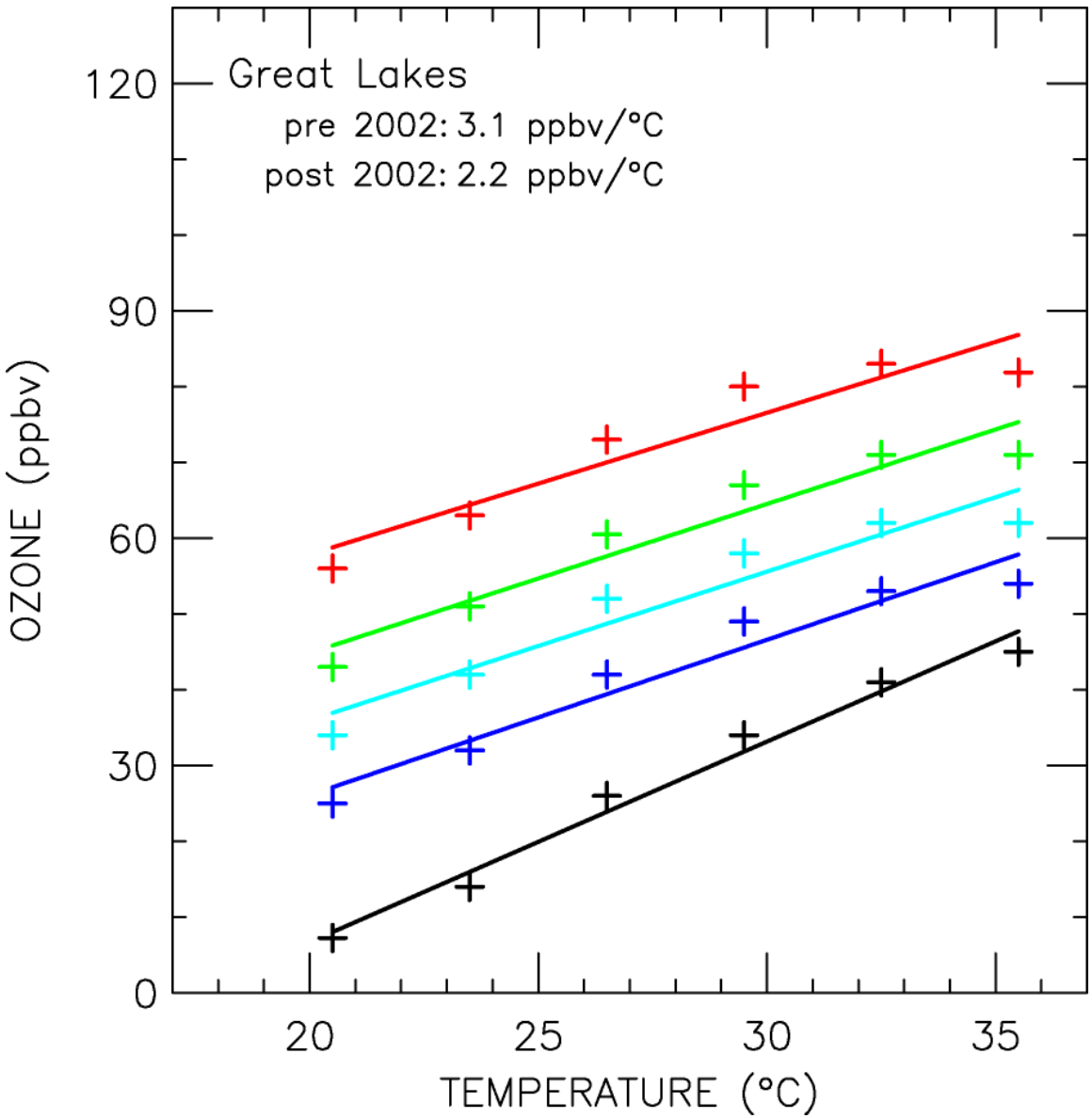

Mid−Atlantic
pre 2002: 3.3 ppbv/°C
OZONE (ppbv)
TEMPERATURE (°C)
0
30
60
90
120
20
25
30
35

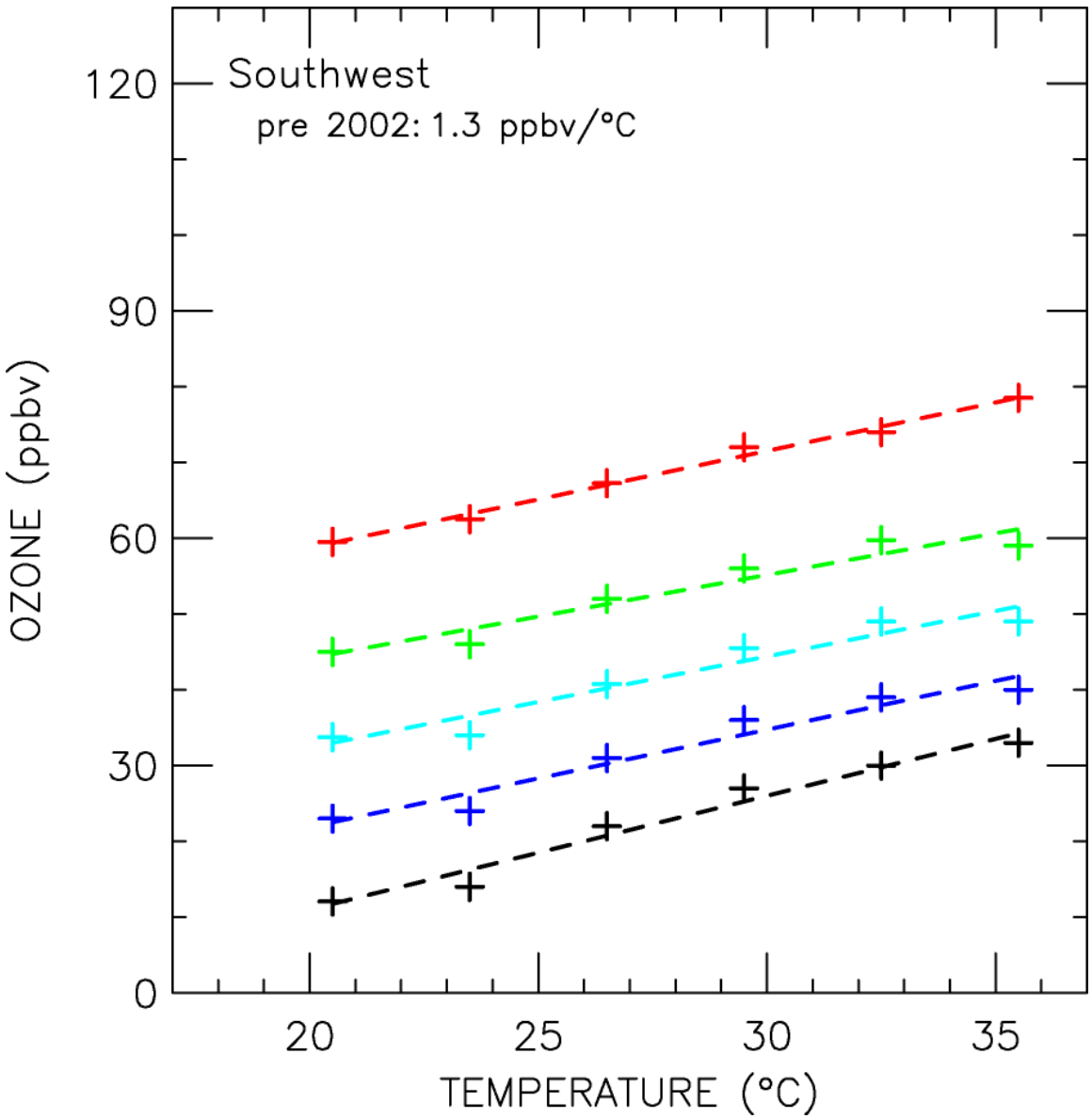

Mid−Atlantic
pre 2002: 3.3 ppbv/°C
post 2002: 2.2 ppbv/°C
OZONE (ppbv)
TEMPERATURE (°C)
0
30
60
90
120
20
25
30
35

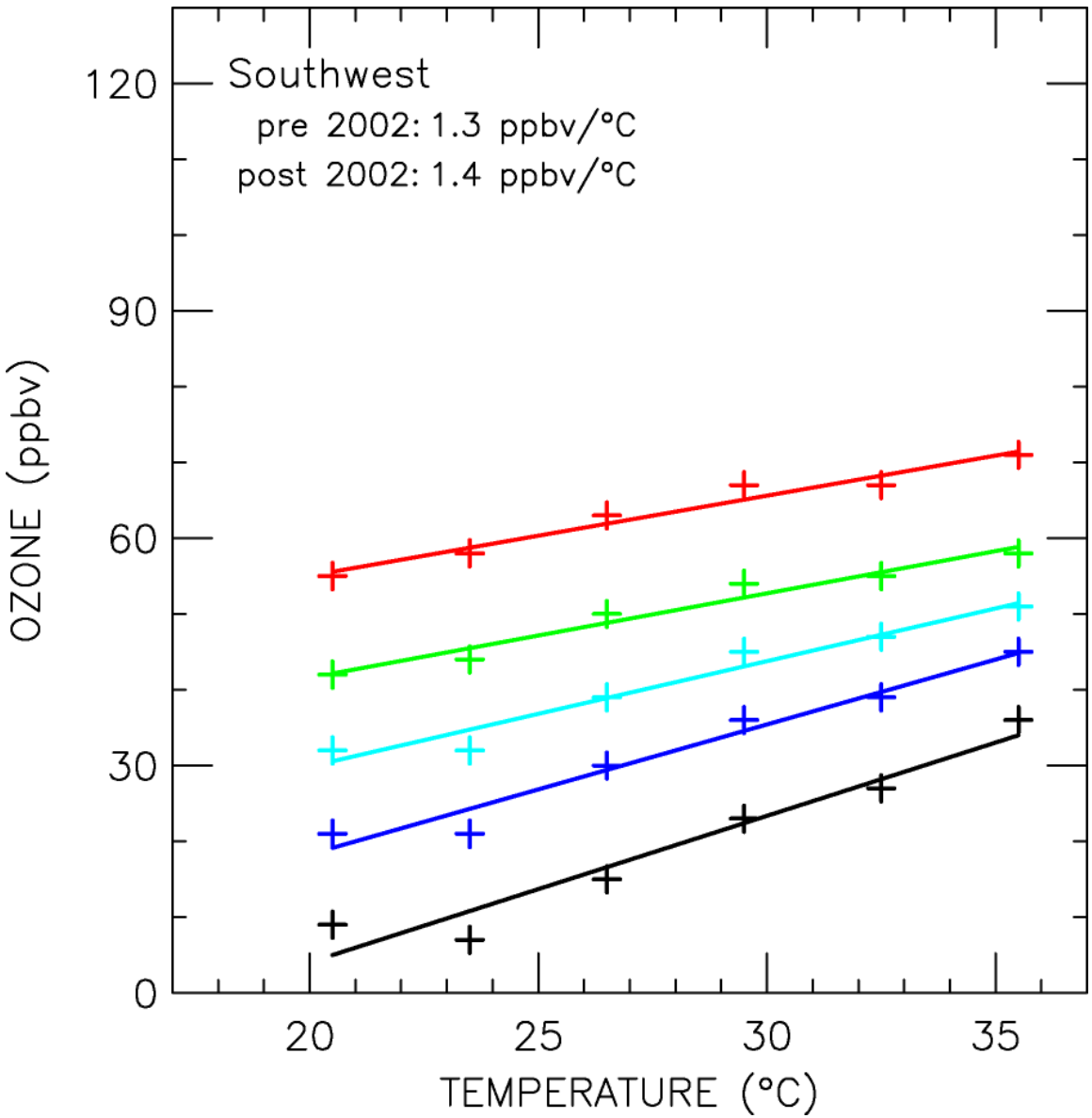

Northeast
pre 2002: 3.3 ppbv/°C
OZONE (ppbv)
TEMPERATURE (°C)
0
30
60
90
120
20
25
30
35


Northeast
pre 2002: 3.3 ppbv/°C
post 2002: 2.4 ppbv/°C
OZONE (ppbv)
0
30
60
90
120
20
25
30
35
TEMPERATURE (°C)

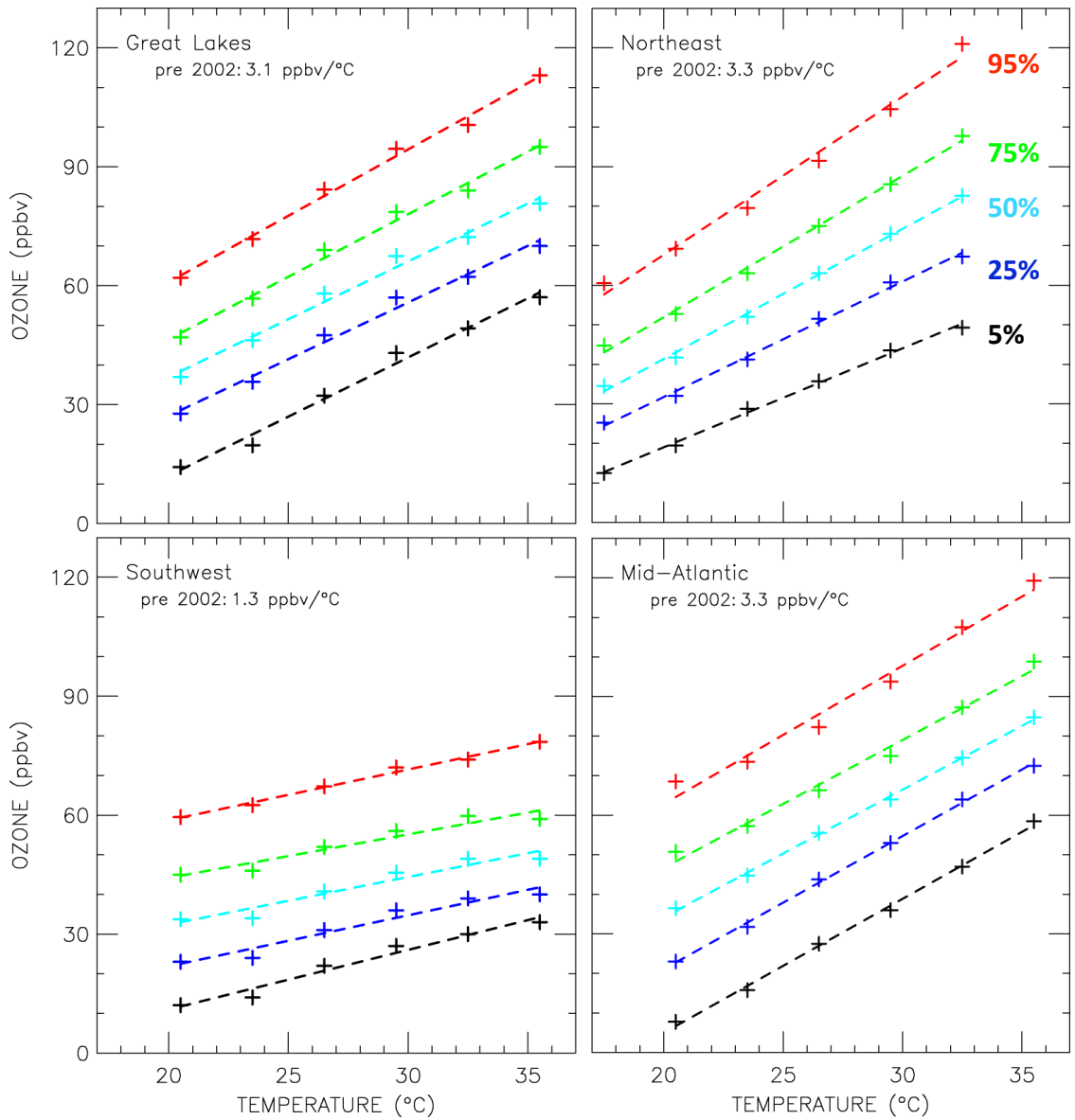

Great Lakes
pre 2002: 3.1 ppbv/°C
OZONE (ppbv)
TEMPERATURE (°C)
0
30
60
90
120
20
25
30
35


Great Lakes
pre 2002: 3.1 ppbv/°C
post 2002: 2.2 ppbv/°C
OZONE (ppbv)
TEMPERATURE (°C)
0
30
60
90
120
20
25
30
35


Southwest
pre 2002: 1.3 ppbv/°C
OZONE (ppbv)
TEMPERATURE (°C)
0
30
60
90
120
20
25
30
35


Southwest
pre 2002: 1.3 ppbv/°C
post 2002: 1.4 ppbv/°C
OZONE (ppbv)
0
30
60
90
120
20
25
30
35
TEMPERATURE (°C)

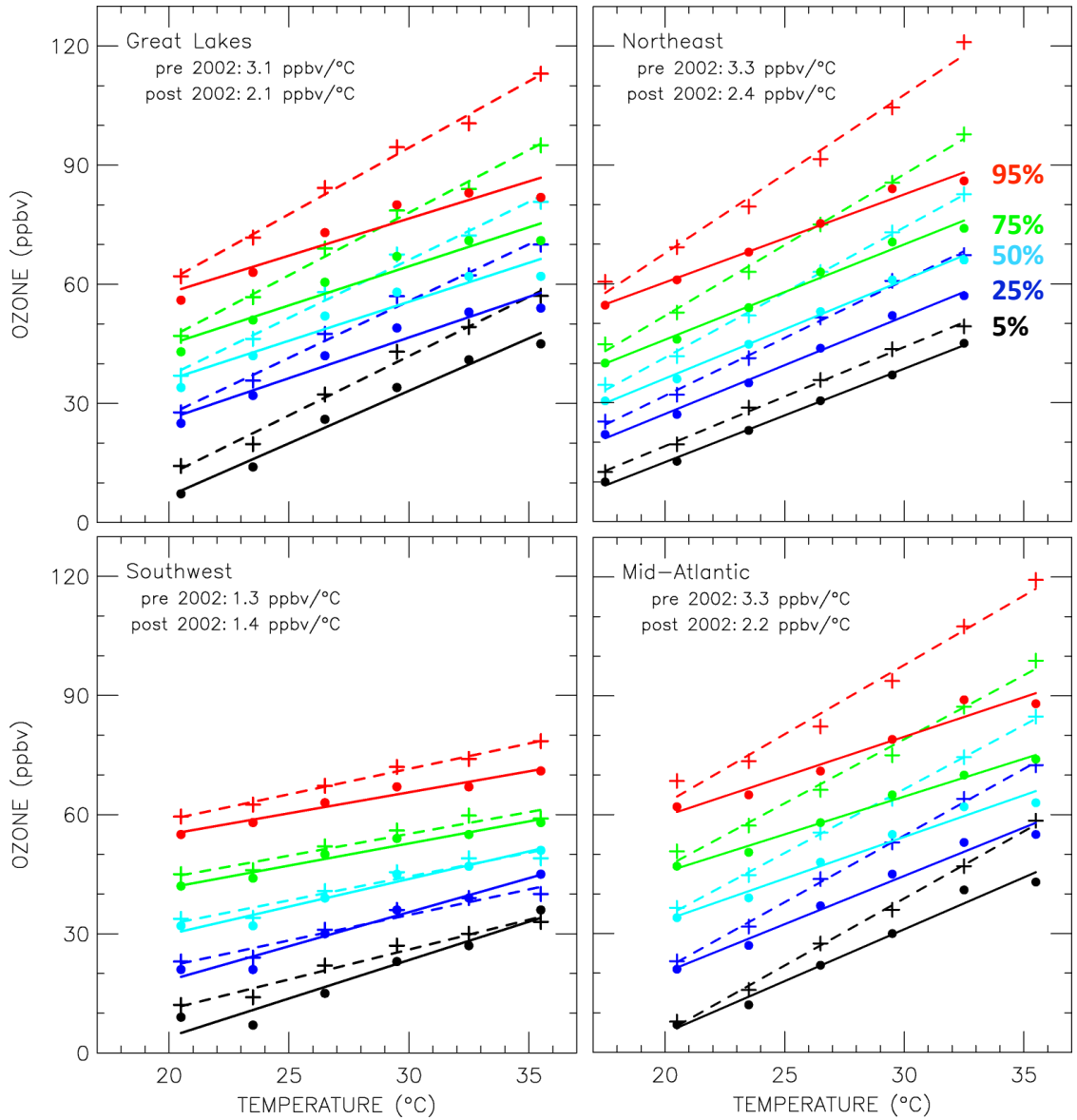
Can we observe the influence of warming on air quality?



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 NO*x* emissions Lowered Ozone over the entire distribution

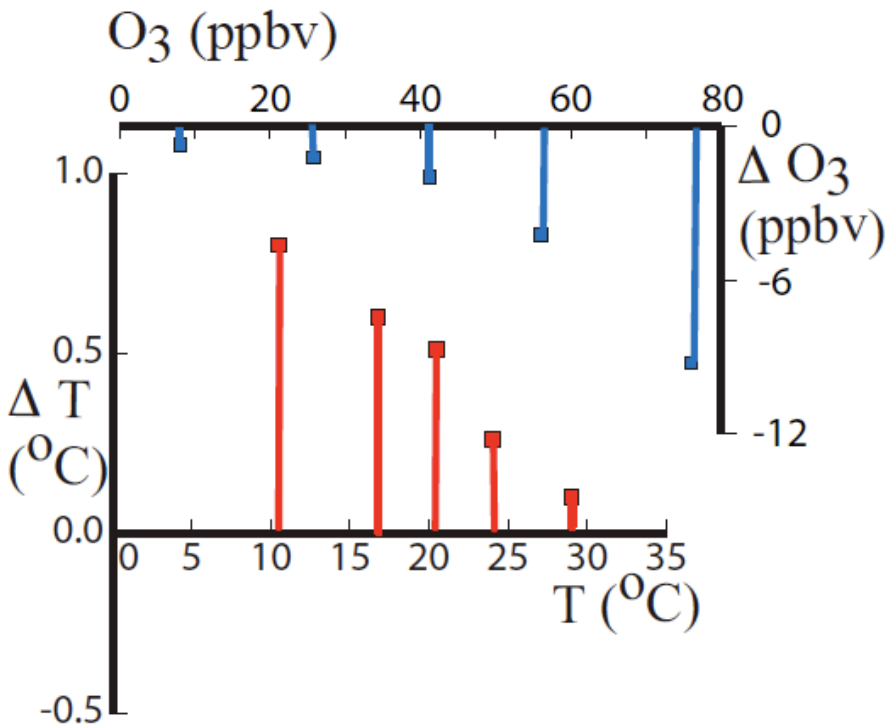
And decreases the Climate Penalty Factor

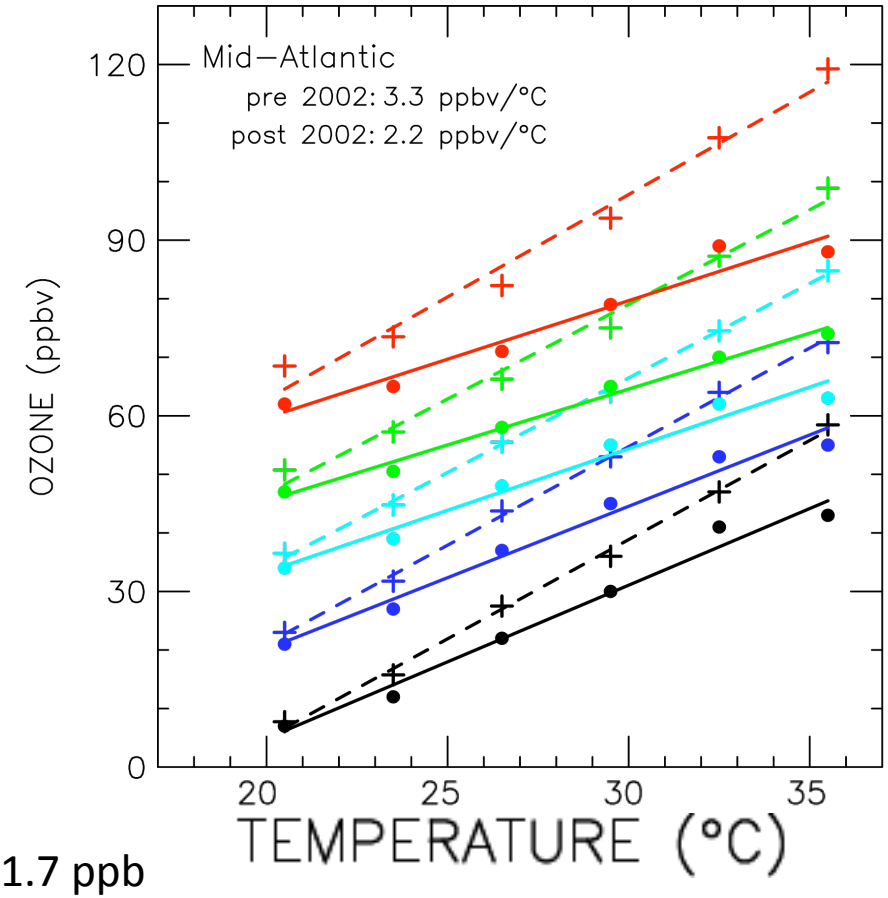
The change in the climate penalty factor is remarkably consistent across receptors dominated by power plant emissions. Ignoring SW:

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



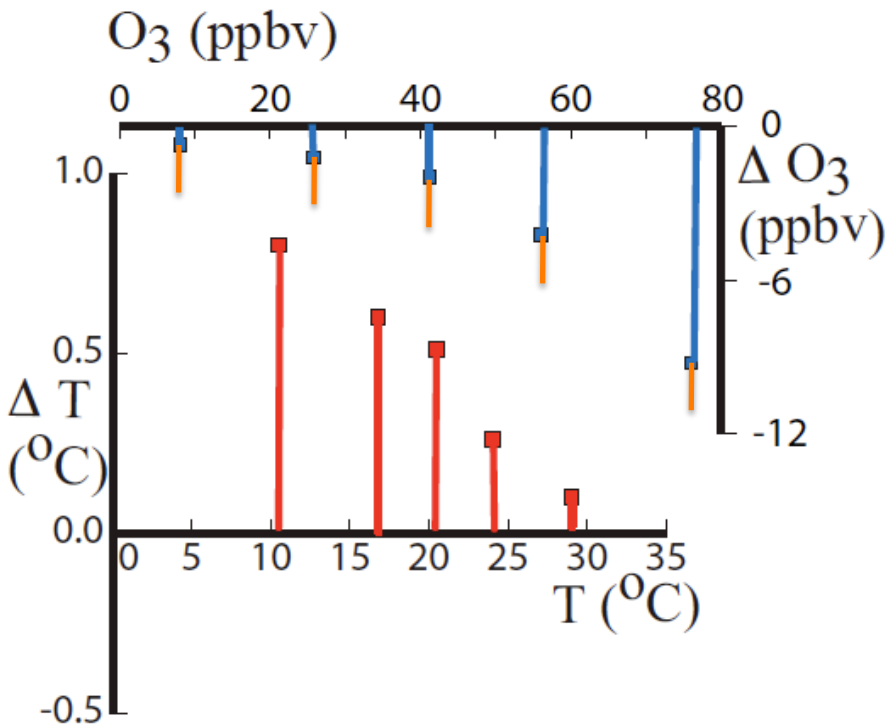


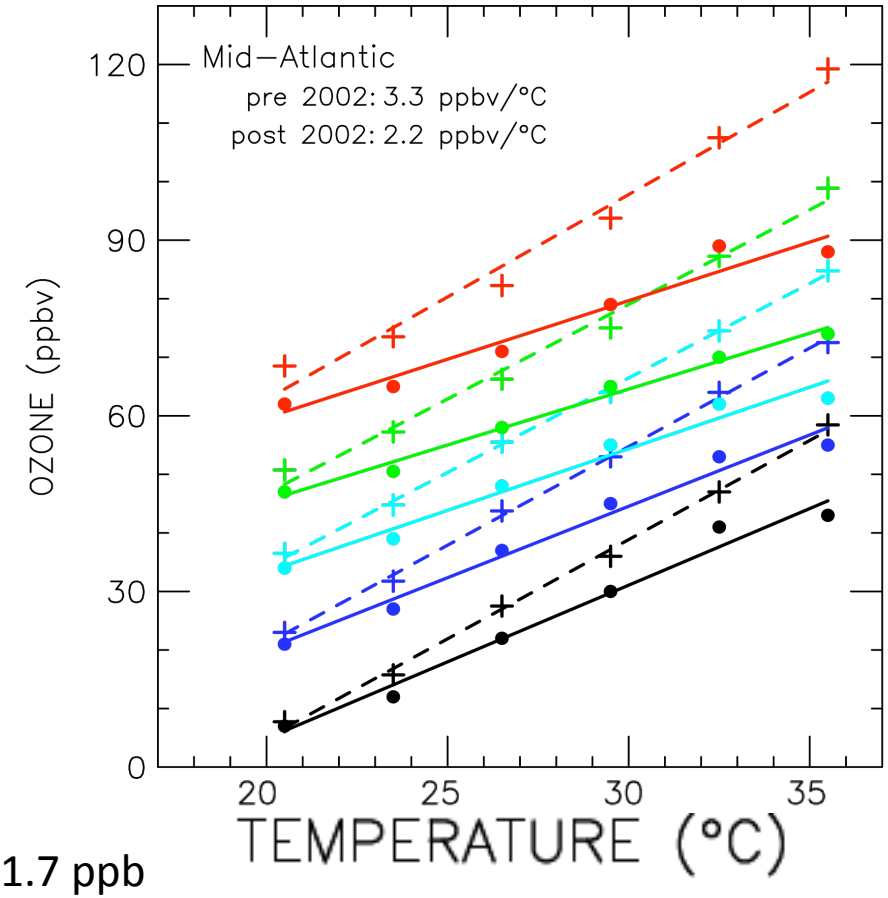
Median Temperature increases about 0.5°C
Climate Penalty Factor of 3.3 or 2.2 ppb/°C

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

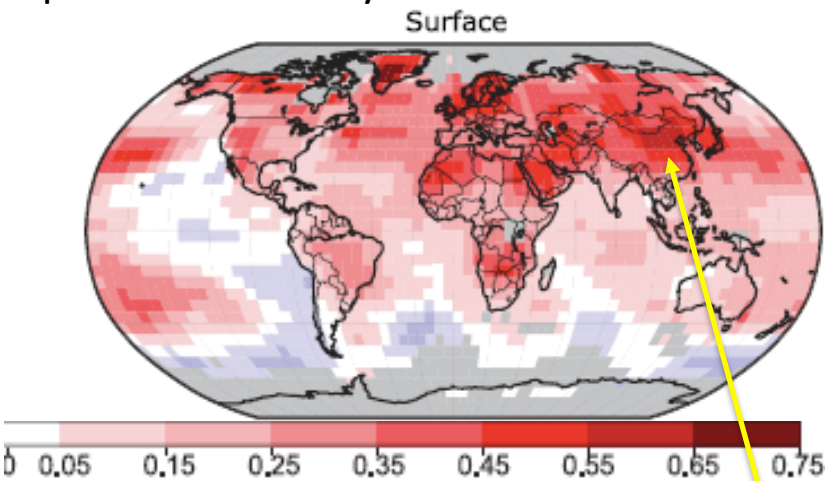
Climate Change Penalty observed for Mid-Atlantic of between 1.1 and 2.3 ppb

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.

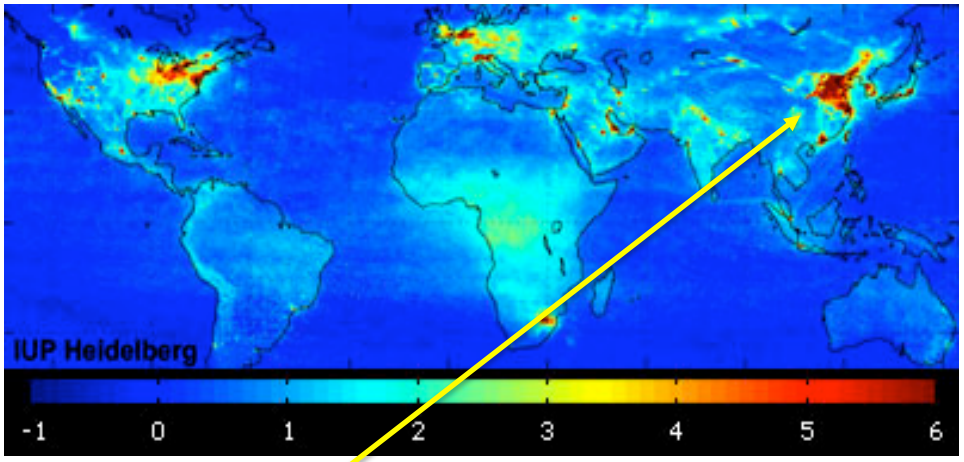
Implications for a warming world

Temperatures already observed to be warming



IPCC, AR4, WG1, Ch. 3

Global NO_2 Observed from Space



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

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

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"

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_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….