Time and Locational Differentiated NO_X Control in Competitive Electricity Markets

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Motivation

Ground-level Ozone Problem

1. **Episodic and Complex relationship with NO_X emissions ($NO_X = NO + NO_2$)**

   Conditions for ozone formation vary hourly and by location: depend on NO_X, VOCs, temperature, wind, etc.

2. **Persistent in Northeastern U.S.**

   Non-attainment of air quality standards despite regulations including summertime NO_X cap-and-trade since 1999

3. **Literature: time- and location-differentiated regulation needed**

   Ozone-related NO_X damages vary by location and time

   e.g. Tong, Daniel Q, Nicholas Z. Muller, Denise L. Mauzerall, and Robert O. Mendelsohn (2006). "Integrated Assessment of the Spatial Variability of Ozone Impacts from Emissions of Nitrogen Oxides" *Environmental Science & Technology* **40** (5): 1395-1400.

4. **Electricity production is the primary stationary source of NOx emissions in the Northeastern US**

Overview

Hypothesis: time- and location-differentiated cap-and-trade for NO_X from power plants might achieve ground level ozone standards more efficiently through combination of

Weather forecasting

Atmospheric chemistry modeling

} **Air Quality Forecasting**

Liberalized wholesale electricity markets

- day-ahead and real-time markets with bid-based, security constrained economic dispatch
- ISO announces redemption rates based on weather forecasting regularities leading to extreme ozone concentrations

<u>WORK IN PROGRESS</u>

GROUND LEVEL OZONE

Ground-level Ozone (Smog) - is formed when NOx and volatile organic compounds (VOCs) react in the presence of sunlight. Children, people with lung diseases such as asthma, and people who work or exercise outside are susceptible to adverse effects such as damage to lung tissue and reduction in lung function. Ozone can be transported by wind currents and cause health impacts far from original sources. Millions of Americans live in areas that do not meet the health standards for ozone. Other impacts from ozone include damaged vegetation and reduced crop yields

Source: U.S. EPA

OZONE CHEMISTRY

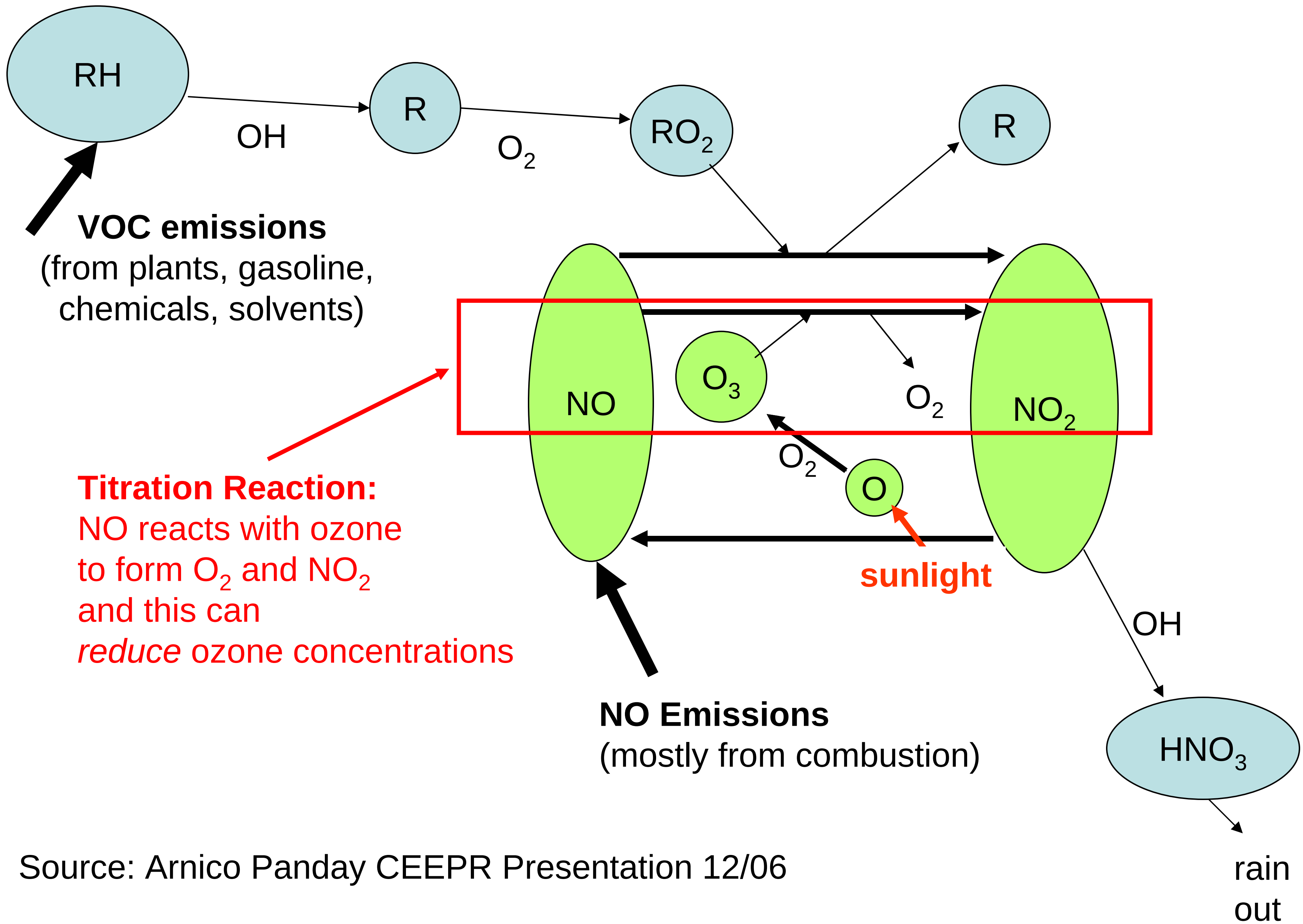
VOC emissions come from both natural sources like oak trees and transportation and industrial sources like cars, dry cleaners, paints and solvents

- NO_X emissions in rural areas interacting with natural VOC sources and can create more ozone which moves downwind to urban areas
- NO_x emissions from stationary sources can also move downwind to urban areas with significant VOC and NOx emissions from local stationary and mobile sources increasing ozone downwind
- It takes time for a "plume" to move downwind

Sunlight drives the reactions that create ozone and this leads to a diurnal ozone pattern

NO reacts with O_3 to form O_2 and NO_2 and this can <u>reduce</u> ozone (titration reaction)

Ozone (O_3) chemistry



Source: Arnico Panday CEEPR Presentation 12/06

Biogenic VOC Emissions

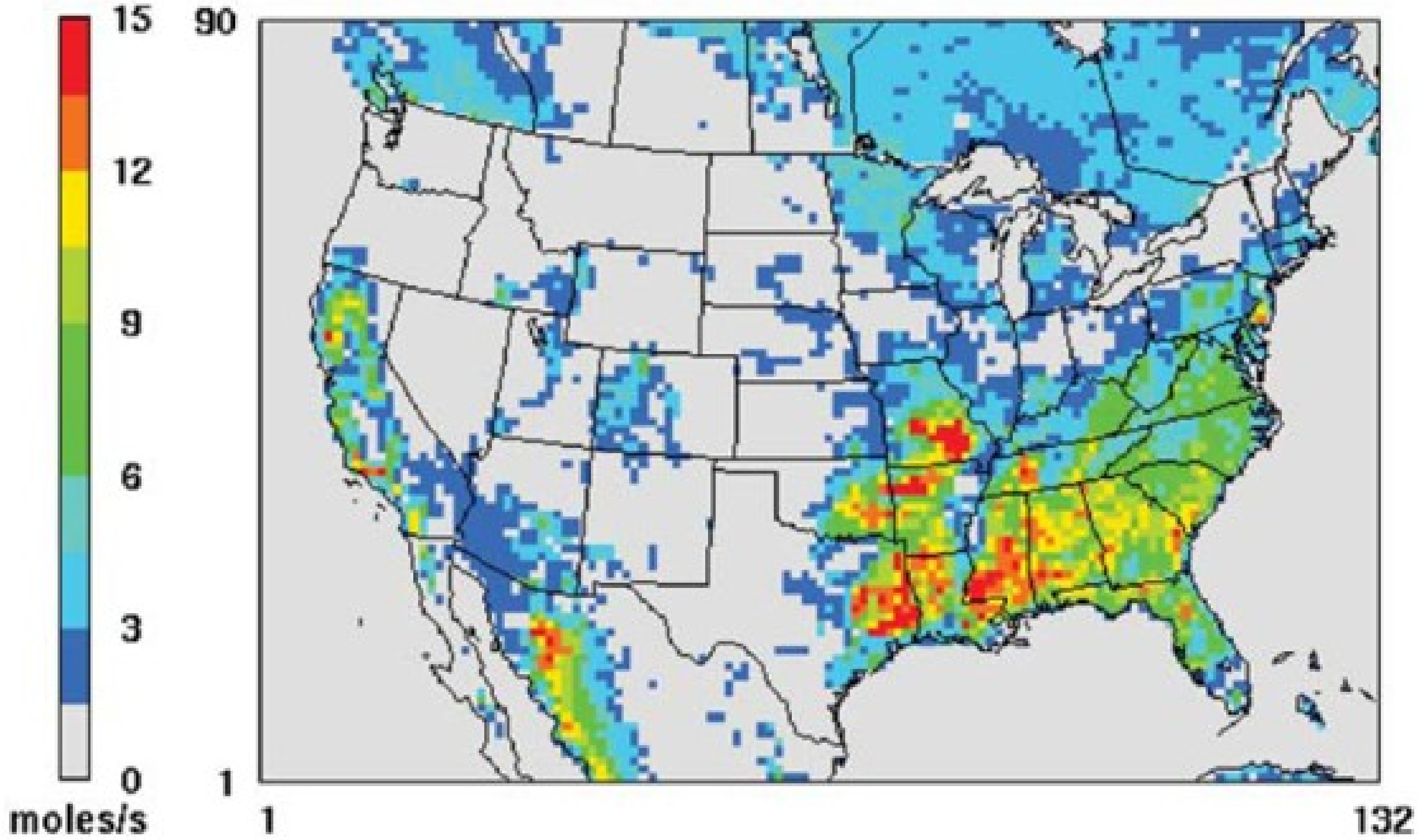
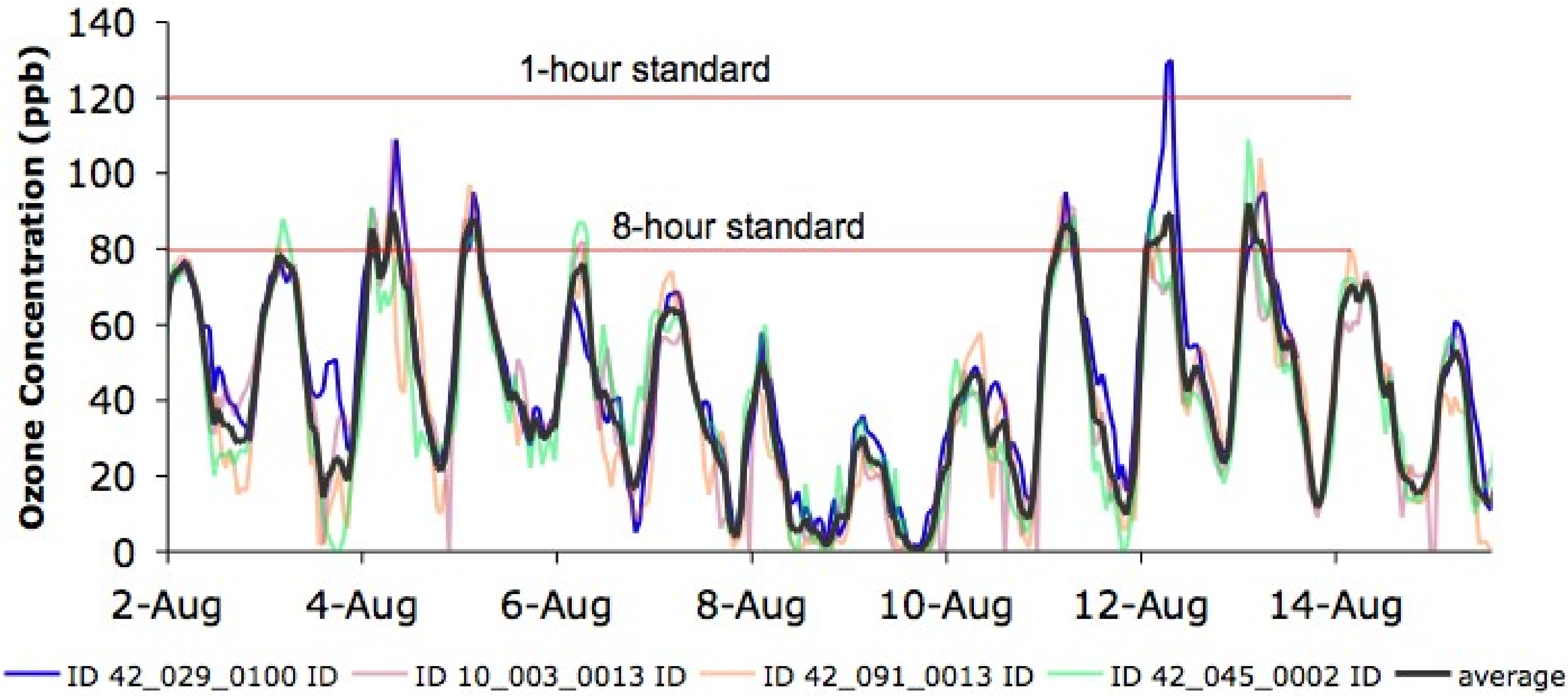


Fig. 4. July emissions of isoprene in the United States (monthly mean of 24-h daily averages) from the biogenic emission inventory system version 3 (BEIS3).

Mauzerall et al., 2005 and Arnico Panday CEEPR 12/06

Diurnal Ozone Patterns

Ozone concentrations from monitors near the Delaware - Pennsylvania border



Examples from the literature:

- In Bangkok, Thailand: low ozone concentrations within the city, higher concentration downwind (Zhang, 2002).
- In Taiwan: <u>increases</u> in observed ozone attributed to <u>reductions</u> in NO emissions (Chou, 2006).
- Weekend effect in Los Angeles: higher ozone on weekends when there is less automobile traffic and therefore less NO_X.

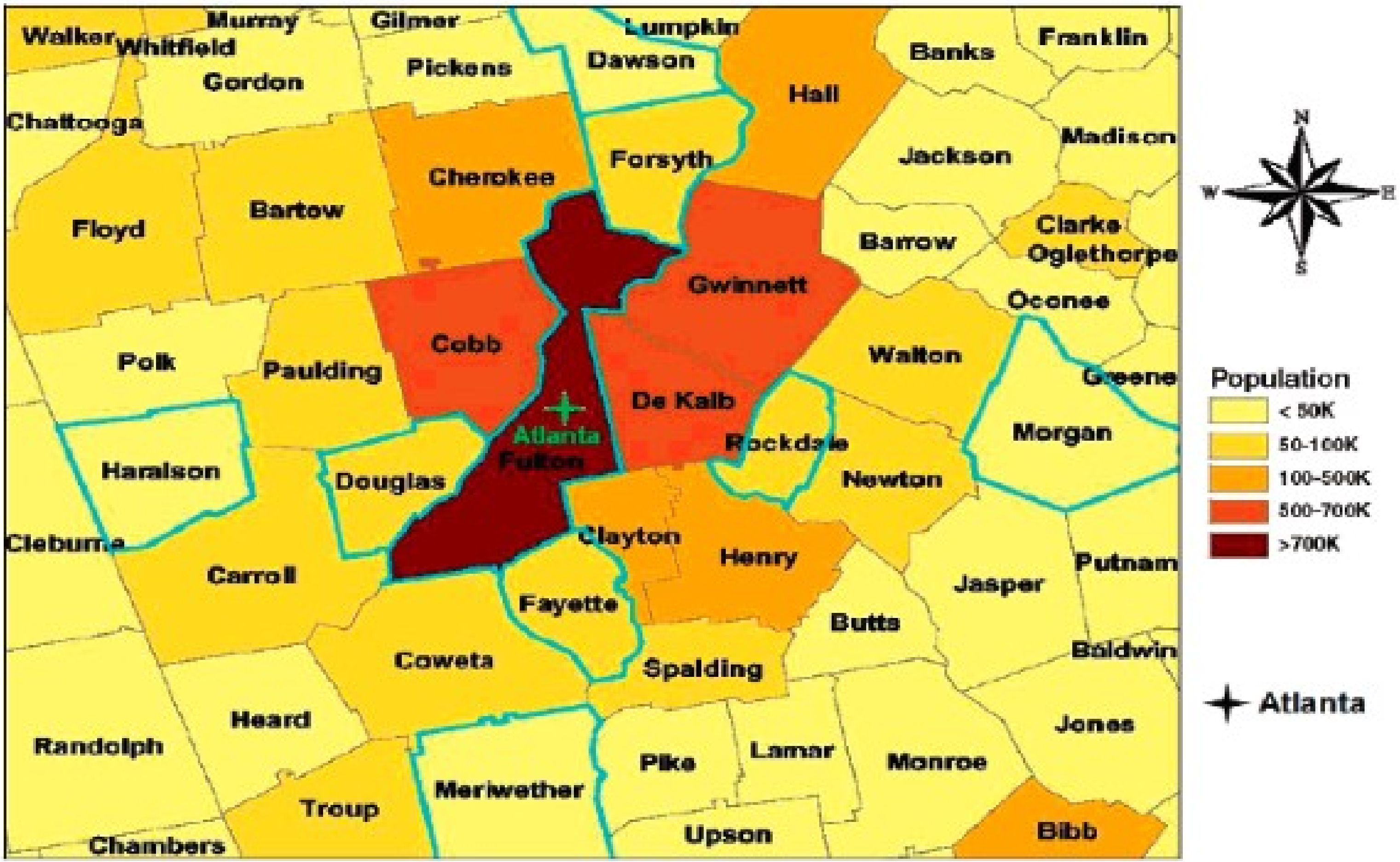


FIGURE 1. Map of Atlanta metropolis and the surrounding area. Selected counties (with blue boundaries) designate locations where additional NO_x emissions are added.

Source: Tong et. al.

SCENARIO:
increase NO_X emissions in a county upwind of Atlanta:

Ozone decreases Upwind, but increases Within Atlanta and Downwind of Atlanta.

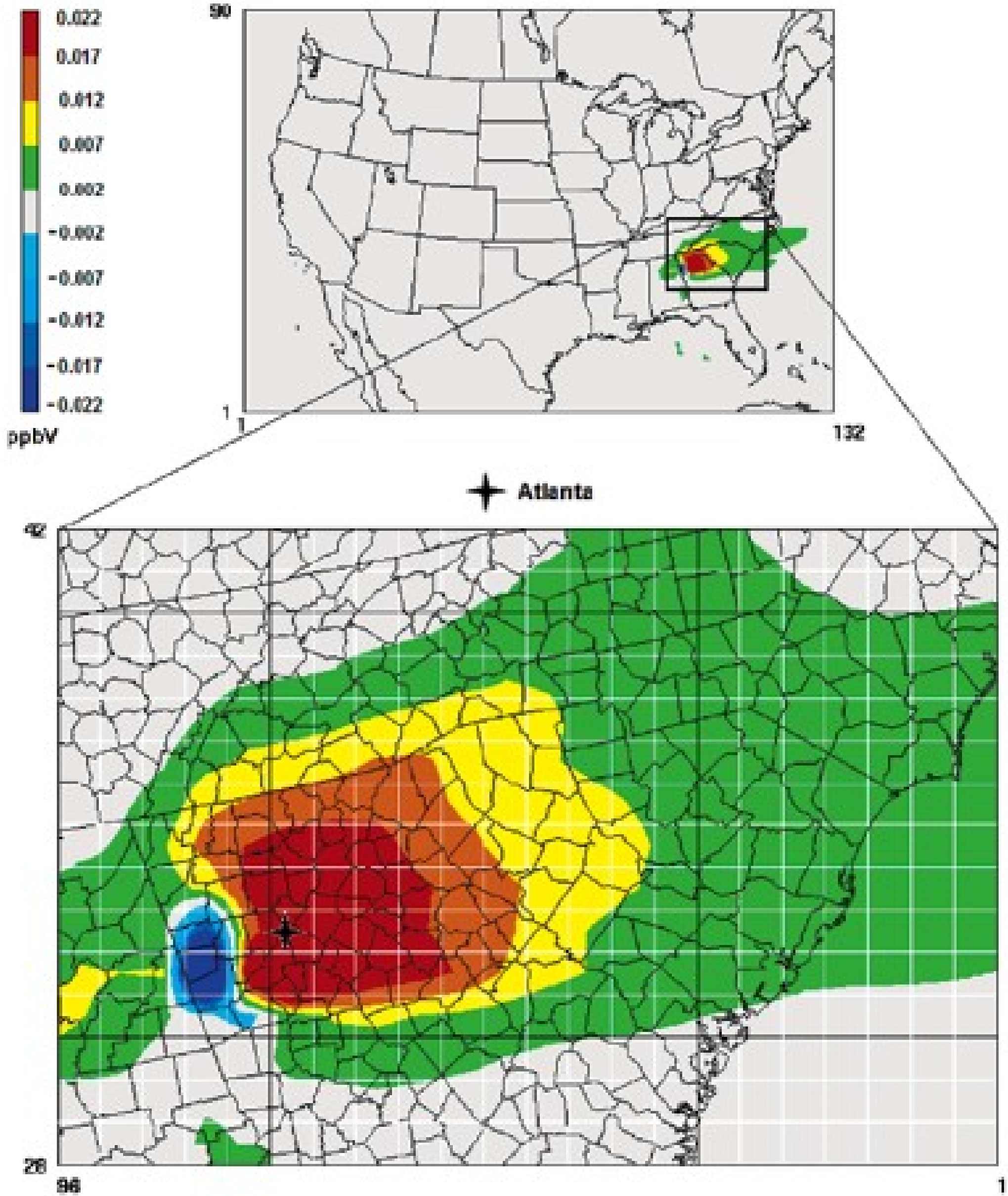


FIGURE 2. Change in monthly average concentrations of surface O_3 (ppbv) due to added emissions of 0.5 mol/sec NO_x in Haralson County, Georgia.

Tong et al., 2006

SCENARIO:
increase NO_X
emissions in
Atlanta:

Ozone decreases
Within Atlanta, but
increases
downwind of
Atlanta.

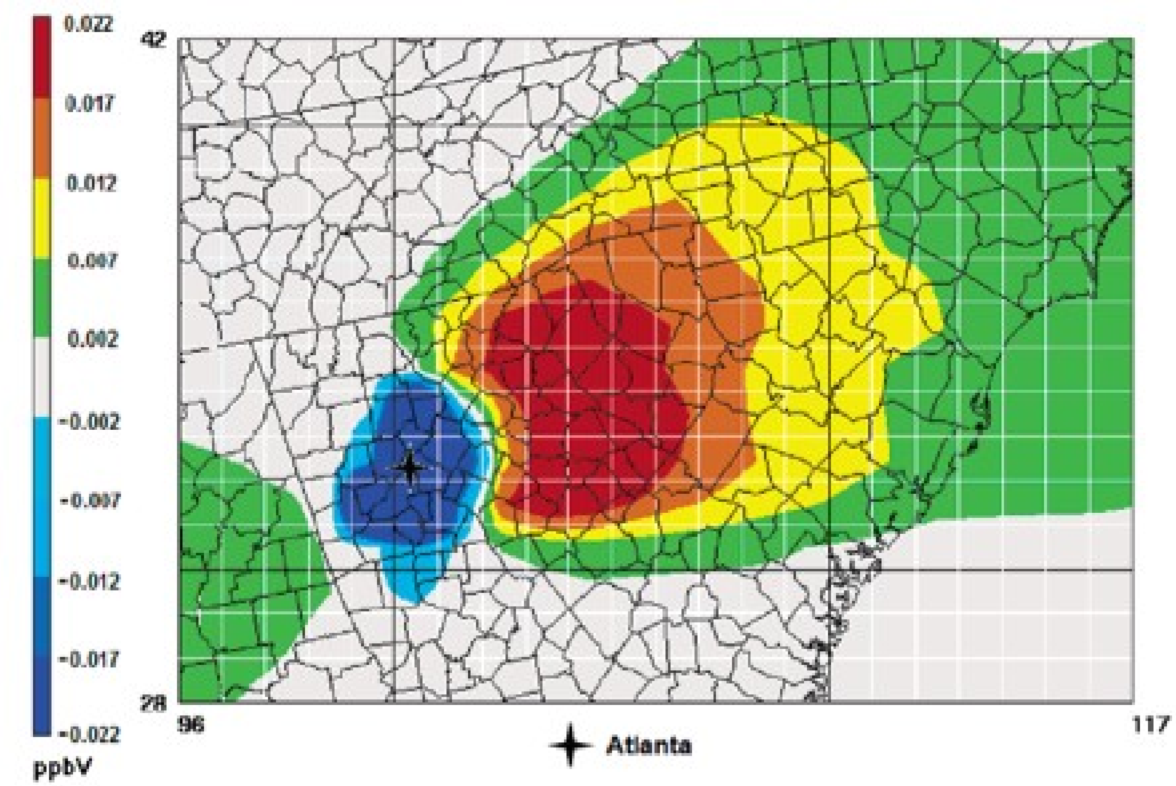
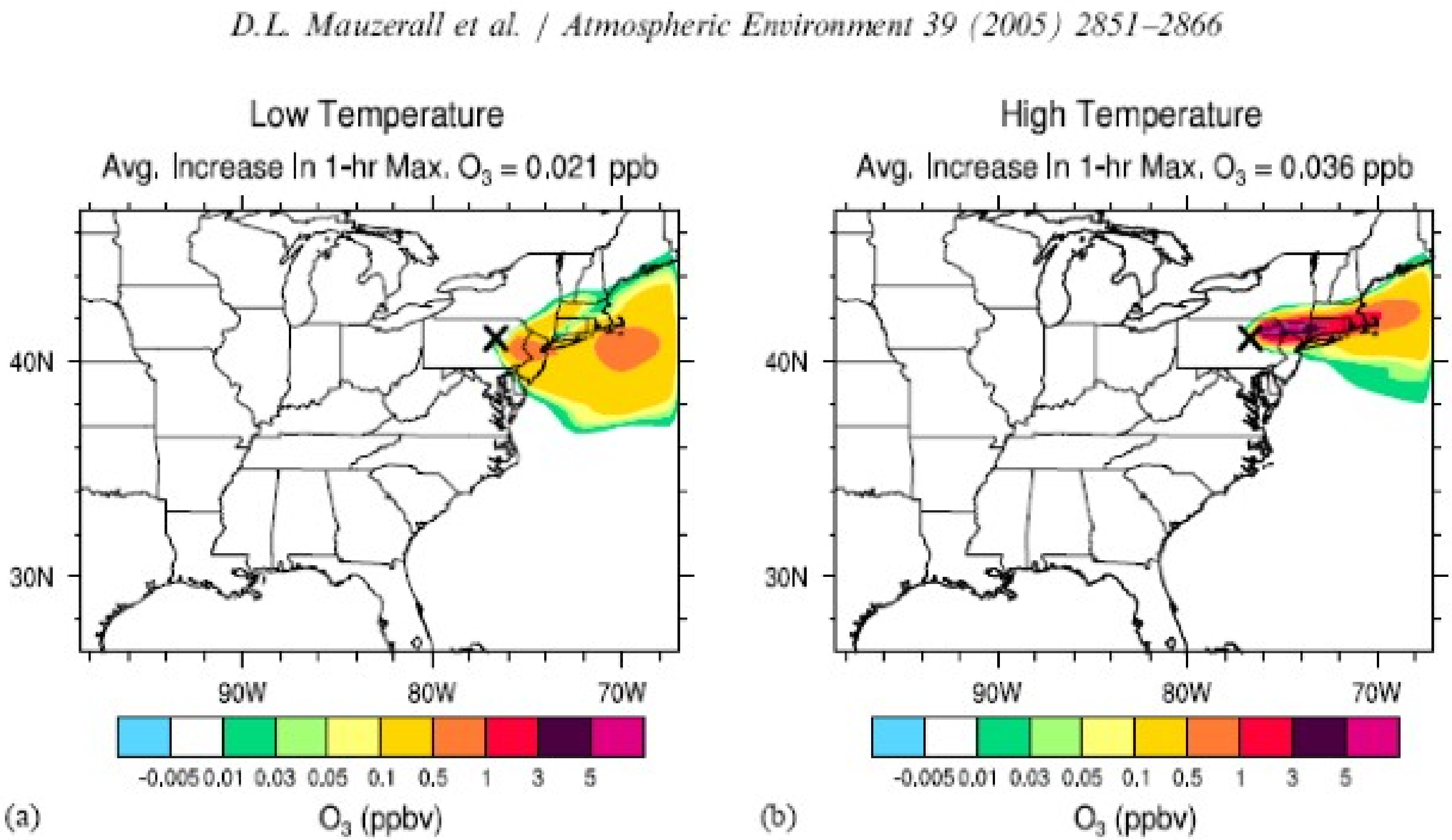
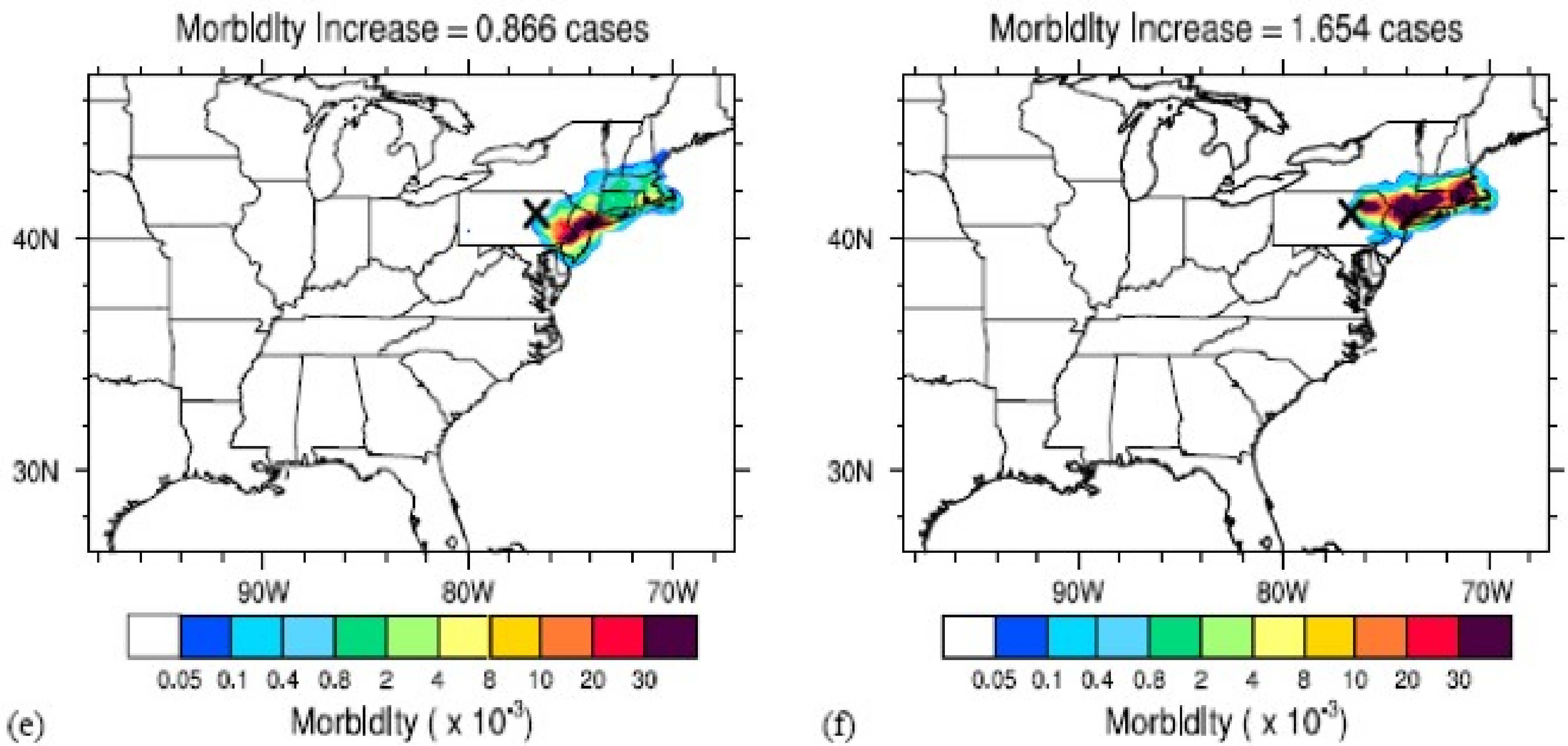


FIGURE 4. Change in monthly average concentrations of surface O_3 (ppbv) due to added emissions of 0.5 mol/sec NO_x in Fulton County, Georgia.

Tong et al., 2006



Source: Mauzerall et. al.



Source: Mauzerall et. al.

Current NO_X Emissions Regulatory Framework For Stationary Sources

Seasonal cap and trade systems in Eastern United States

- emissions permits allocated to states and by states to large stationary sources
- 1999-2003: 11 states + DC
- 2004-present: 21 states + DC
- Applies during *"summer ozone season"* – May through September
- Limited banking from one year to the next

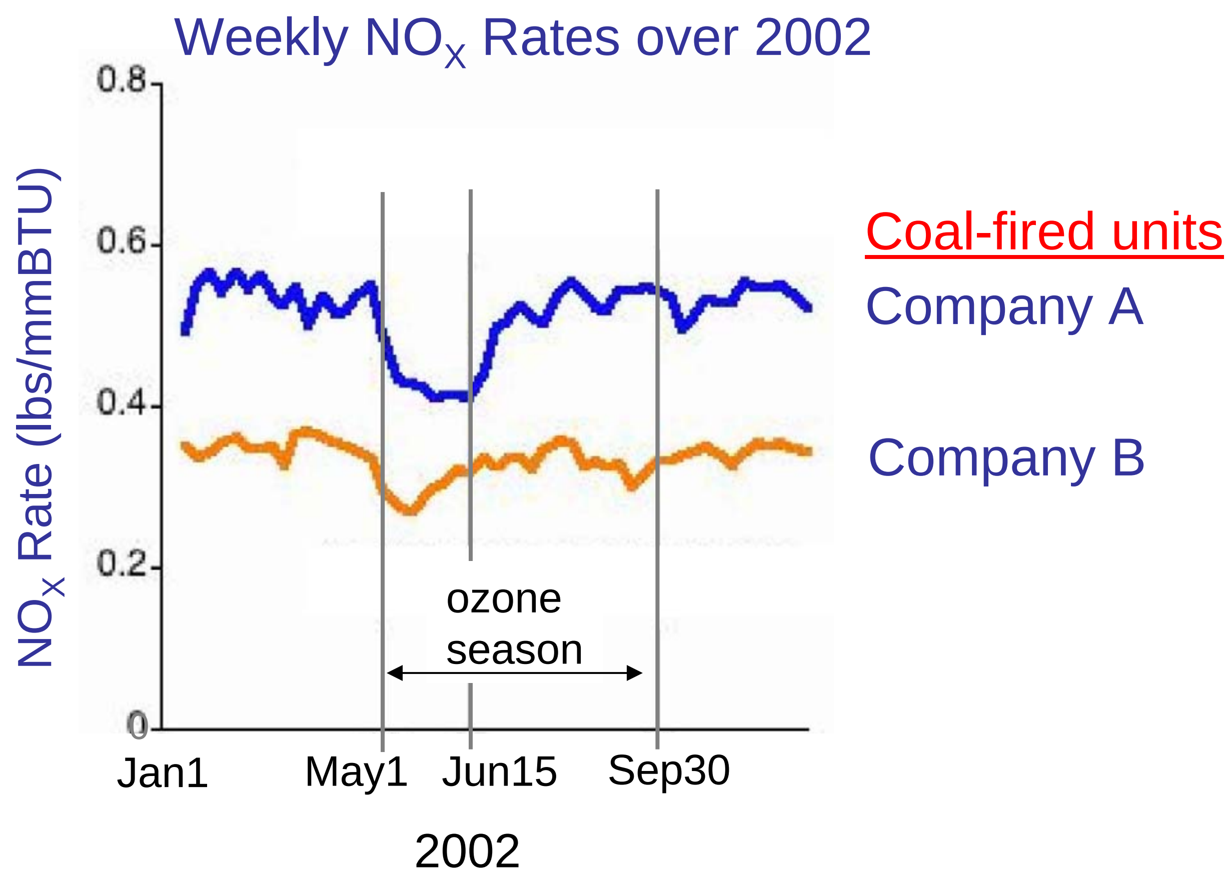
Regulators seeking to tighten emissions constraints because standards are not being met during a small number of hours

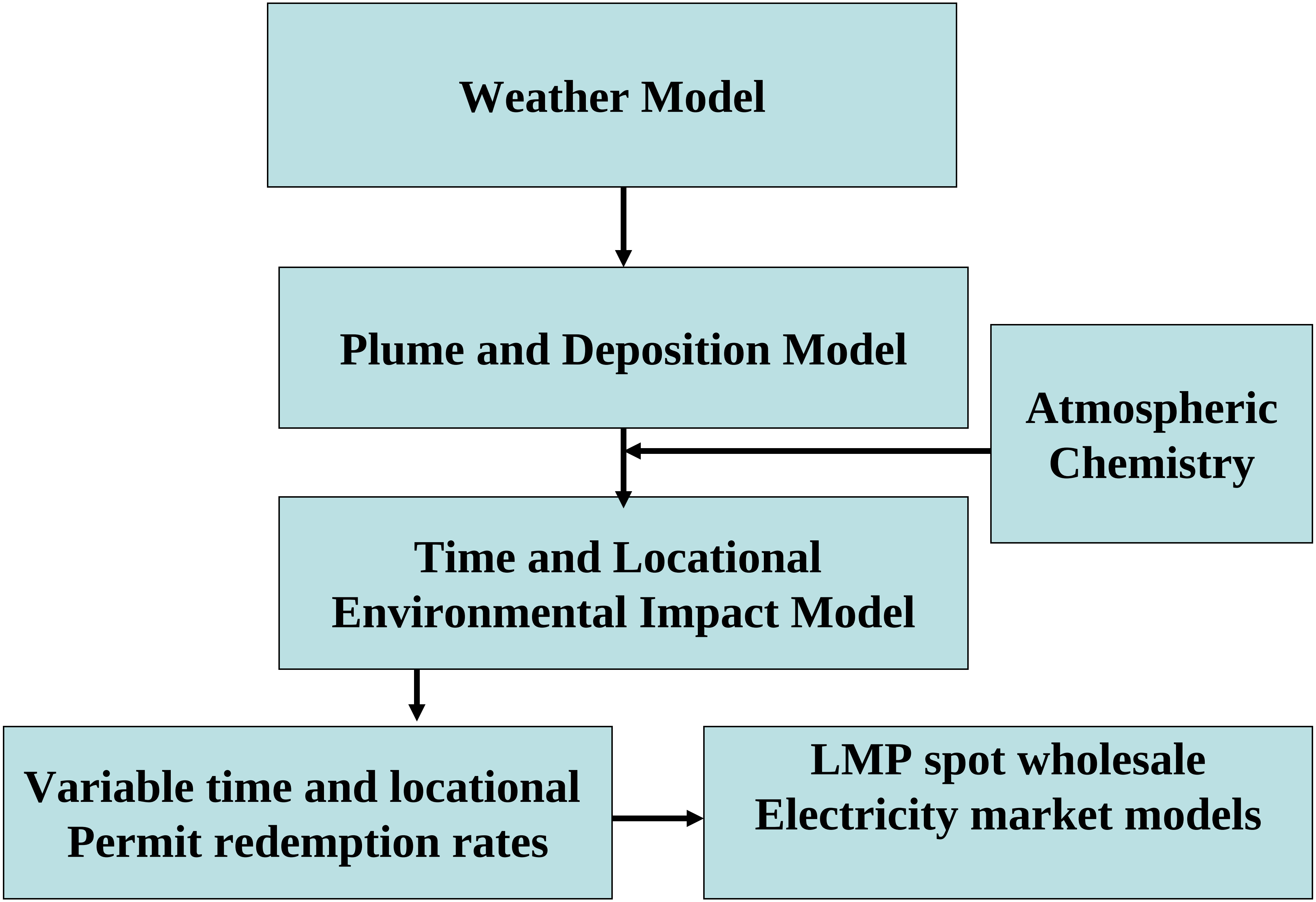
- Mobile sources handled differently. Focus is on stationary sources primarily electric power plants.
- Regulators focusing on tightening stationary source caps or technology requirements to meet ozone ambient standards

Is there a better way to use cap and trade mechanisms to reduce the impact of emissions during extreme ozone conditions?

Abatement Incentives

Seasonal cap-and-trade lacks incentives to encourage well-timed abatement




Weather Model
Plume and Deposition Model
Atmospheric Chemistry
Time and Locational Environmental Impact Model
Variable time and locational Permit redemption rates
LMP spot wholesale Electricity market models

Overview

Research Program

1. **Predict ozone episodes**
   sufficient lead time and accuracy to influence electricity markets

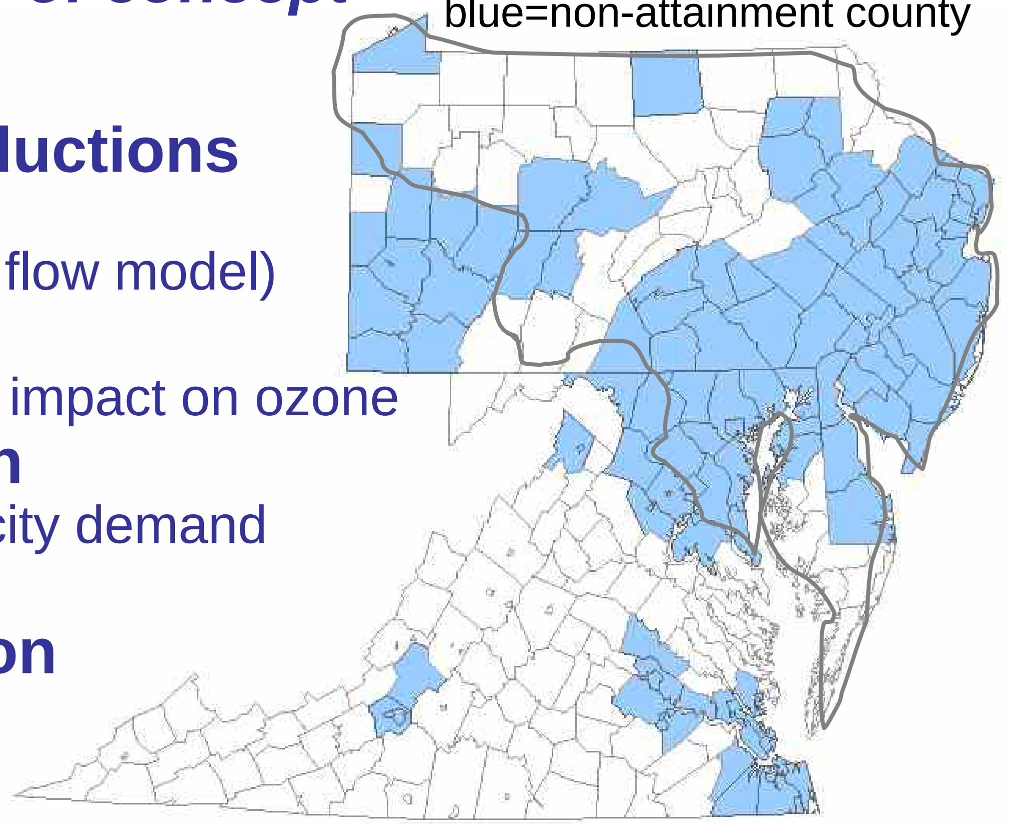
2. **Identify locations and times in which NO_X reductions most important** to reduce likelihood of episodes

3. **Estimate possible NO_X reductions from power plants**
   - while continuing to balance supply and demand
   - especially studying hot summer days when network is constrained

4. **NO_X price-induced redispatch incentives through LMP wholesale electricity market (simple preliminary analysis)**
   - sufficient magnitude, right times, right locations
   - NO_X permit prices, incentives to redispatch, effects on
   - locational wholesale electricity prices, and demand response

Potential NO_X Reductions

Analysis of NO_X reductions from redispatch in "Classic" PJM --- "proof of concept"



Source: EPA Office of Air and Radiation, AQS Database
Friday, July 21, 2006

Estimate potential NO_X reductions

– two methods
  (zonal and optimal power flow model)

– results in terms important for impact on ozone

  a. **Temporal variation**
    – variation with electricity demand

  b. **Locational variation**
    – reductions by county

Methods

Two complimentary methods

1. Zonal Model

- most detailed representation of unit-level NO_X
- characteristics

2. Optimal Power Flow Model (PowerWorld)

- most detailed network representation

Shared characteristics:

- hold total demand (and generation) constant and balance supply and demand
- model at least most frequent transmission constraints
- generating units “turn down” to 20% capacity reflect unit commitment and reflect forced outage rates
- use unit-level NO_X emission rate data

Overview of Classic PJM

Hourly Data, 2005		**Ozone-Season**	**Off-Season**	**Annual**	
PJM Demand^	avg	74	68	71	*(GW)*
	max	116	97	116	
Classic PJM Demand	avg	36	32	33	*(GW)*
	max	59	46	59	
Classic PJM Fossil	avg	19	16	18	*(GW)*
	max*	36	26	35	
Classic PJM NOx Emissions	avg	19.6	30.0	25.7	*(Tons)*
	max*	44.7	46.2	46.2	

^Does not include the DUQ control area that joined PJM May 1, 2005
*Max from the highest demand hour in Classic PJM in 2005 in the ozone season (7/27/05 16:00) and non-ozone season (1/18/05 19:00) respectively

Publicly available data from PJM, EPA CEMS, EIA. EPA data on 95% of PJM fossil capacity matched to network.

Fossil Fuel Capacity and Generation by Fuel-Type in Classic PJM during the 2005 Ozone Season

Hourly Data, Season 2005	*Ozone*	**Coal**	**Natural Gas**	**Oil**	**TOTAL**	
Capacity	rated	21	15	10	46	*(GW)*
	unforced^	19	14	9	42	
Generation	avg	15	3.0	1.6	19	*(GW)*
	max*	18	10	8.2	36	
NOx Emissions	avg	15.8	1.2	2.6	19.6	*(Tons)*
	max*	20.2	6.9	17.6	44.7	
NOx Emission Rates	avg	2.15	0.78	3.19	2.02	*(lbs/ MWh)*
	max*	2.24	1.37	4.29	2.46	

Fuel Category Designations from the EPA's Clean Air Markets Database
*Max from the highest demand hour in Classic PJM in 2005 in the ozone season (7/27/05 16:00)
^Derated by the equivalent demand forced outage rate for PJM in 2005 (7.3%) (PJM 2006)

Nuclear (13 GW Capacity) and **Hydro** (3 GW Capacity) held constant in simulations.

Zonal Method

1. ***create abstract "graph" of transmission system***

2. ***empirically identify "zones" based on frequent transmission congestion and identify generating units within each zone***

    - groups cannot contain a line that was congested for more than 100 hours in 2005 (PJM 2005 State of the Market Report)
    - LMP standard deviation <$10/MWh in at least 90% of sample of ozone season hours

3. ***'re-dispatch' generating units to minimize NO_X emissions constrained by transmission congestion***

    - within-zone exchange is possible
    - between-zone exchange possible when no congestion present
    - exchange generation in high-LMP zone for that in low-LMP zone creates counter-flow and is allowed
    - exchange of generation in low-LMP zone for that in high-LMP zone worsens congestion and is not allowed

Optimal Power Flow Model

PowerWorld

PJM Financial Transmission Right (FTR) Model

- basic information on network (e.g. line impedances)

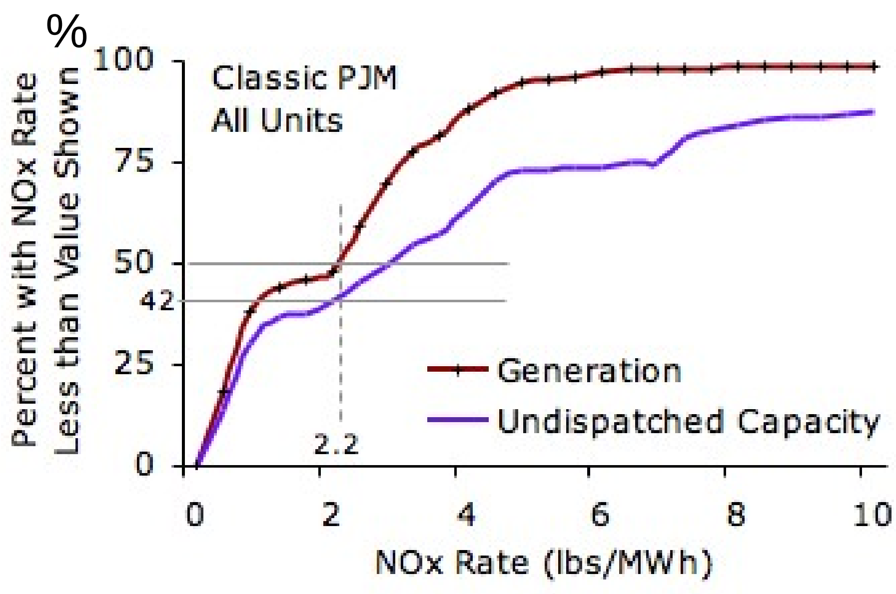
Compare base-case flows to NO_X minimizing case

- scale load and generation data to match high-demand hours
- calculate total NO_X emissions from "base case"
- alter generation to minimize NO_X for "NO_X-minimizing case"
- alter NO_X-minimizing case such that base-case power flows…
  1. on lines loaded at >100% capacity do not increase
  2. on lines loaded above 90% do not increase by more than 3%
  3. on lines loaded above 80% do not increase by more than 13%
  4. no new lines have power flow over capacity
     – calculate NO_X emissions from "Transmission Constraints Case"

Undispatched Low-NO_X Capacity

(August 4, 2005 at 2PM)

All Units in Classic PJM



Coal Units in Classic PJM

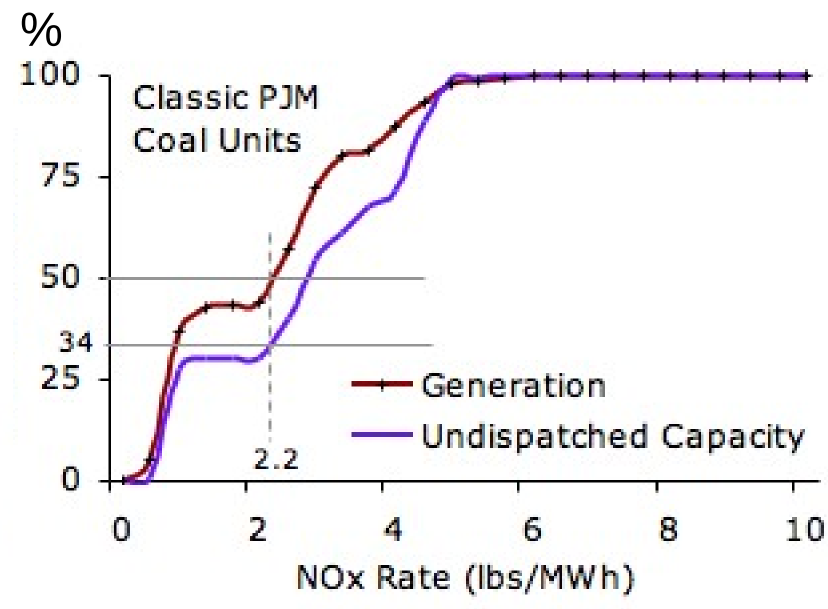


Figure 2 Cumulative Distributions of Generation and Undispatched Capacity by NO_X Emission Rate in Classic PJM on August 4th, 2005 at 2pm.
Graph on the left is for all fossil fuel-fired generating units in Classic PJM and the graph on the right is for coal-fired units only.

Results of Simulation of Potential Reductions in NO_X Emissions from Redispatch in Classic PJM using both Zonal and PowerWorld Models

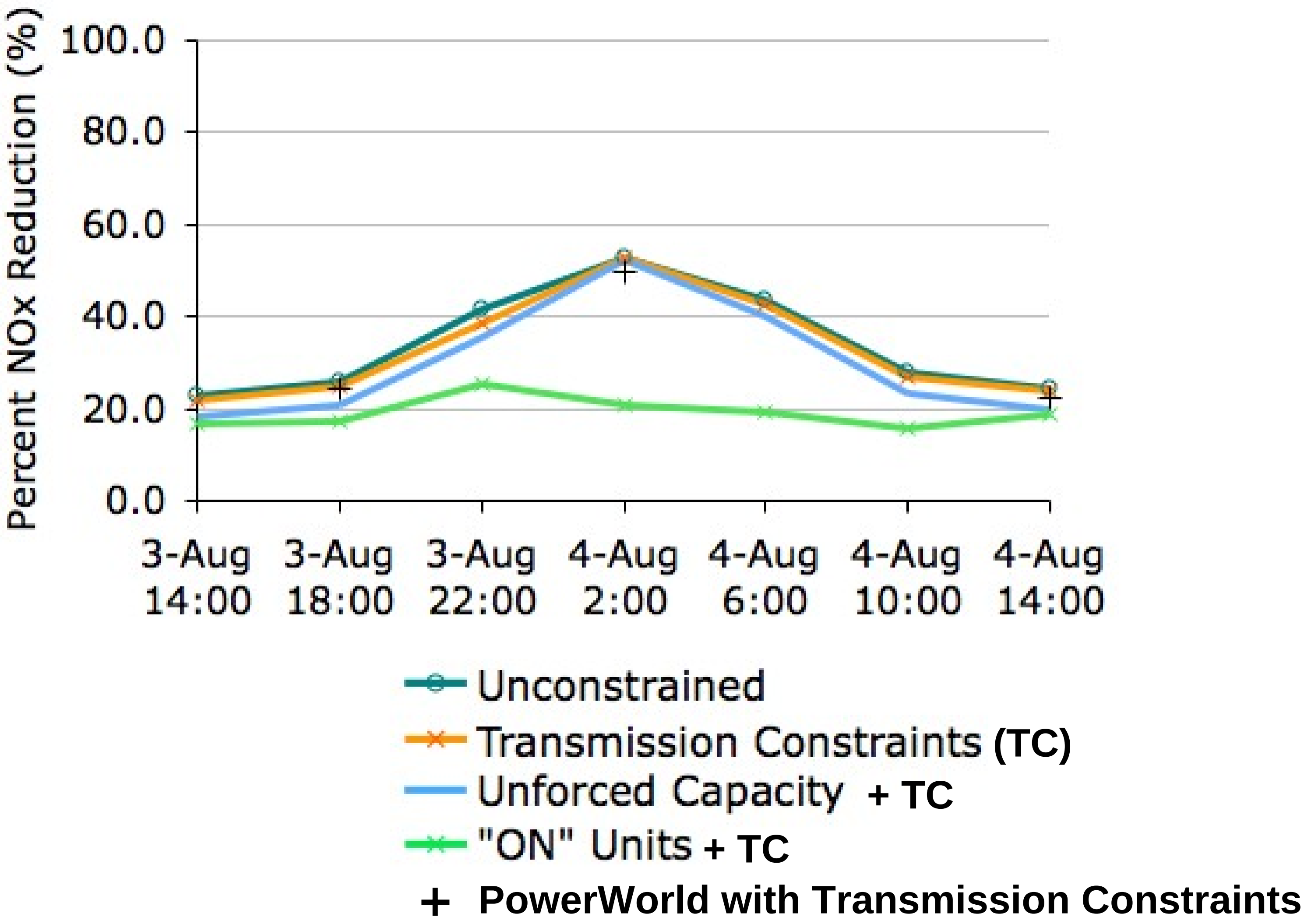
	Base Case		Unconstrained Case		Transmission Constraints Case		Unforced Capacity^ with Trans. Const.*		Only "ON" Units with Trans. Const.*	
Date	**Generation**	**NOx**	**NOx Reduction**	**%**	**NOx Reduction**	**%**	**NOx Reduction**	**%**	**NOx Reduction**	**%**
Zonal Results										
8/3/05 14:00	33	35	8.1	23	7.7	22	6.5	18	6.0	17
8/3/05 16:00	34	38	9.5	25	9.1	24	--	-	--	-
8/3/05 18:00	33	35	9.2	26	8.8	25	7.4	21	6.1	17
8/3/05 20:00	30	29	8.2	29	7.6	26	--	-	--	-
8/3/05 22:00	26	26	10.8	42	10.0	39	9.2	36	6.5	25
8/4/05 0:00	21	21	10.8	52	10.7	52	--	-	--	-
8/4/05 2:00	19	19	9.9	53	9.9	53	9.8	52	3.9	21
8/4/05 4:00	20	20	10.5	52	8.5	42	--	-	--	-
8/4/05 6:00	23	23	10.1	44	9.9	43	9.3	40	4.5	19
8/4/05 8:00	27	26	9.6	37	9.0	35	--	-	--	-
8/4/05 10:00	31	28	7.9	28	7.6	27	6.7	24	4.5	16
8/4/05 12:00	33	33	7.3	22	6.8	21	--	-	--	-
8/4/05 14:00	35	38	9.2	24	9.1	24	7.5	20	7.1	19
PowerWorld Results*										
8/3/05 18:00	32	34	8.6	25	8.3	24	--	-	--	-
8/4/05 2:00	18	17	9.5	56	8.5	50	--	-	--	-
8/4/05 8:00	26	24	8.5	35	8.1	34	--	-	--	-
8/4/05 14:00	33	37	8.6	23	8.3	22	--	-	--	-
	(GW)	*(Tons)*	*(Tons)*	*(%)*	*(Tons)*	*(%)*	*(Tons)*	*(%)*	*(Tons)*	*(%)*

* These simulations were only performed for every four hours and have not been completed in PowerWorld.

** The emissions data were not completely matched to the PowerWorld data. The simulations of NOx reductions were therefore performed with fewer units. The lower initial levels of generation and NOx in the base case compared to the zonal simulations for the same hours reflect this.

^ Capacities were derated by the 2005 demand equivalent forced outage rate for PJM of 7.3% (PJM 2006).

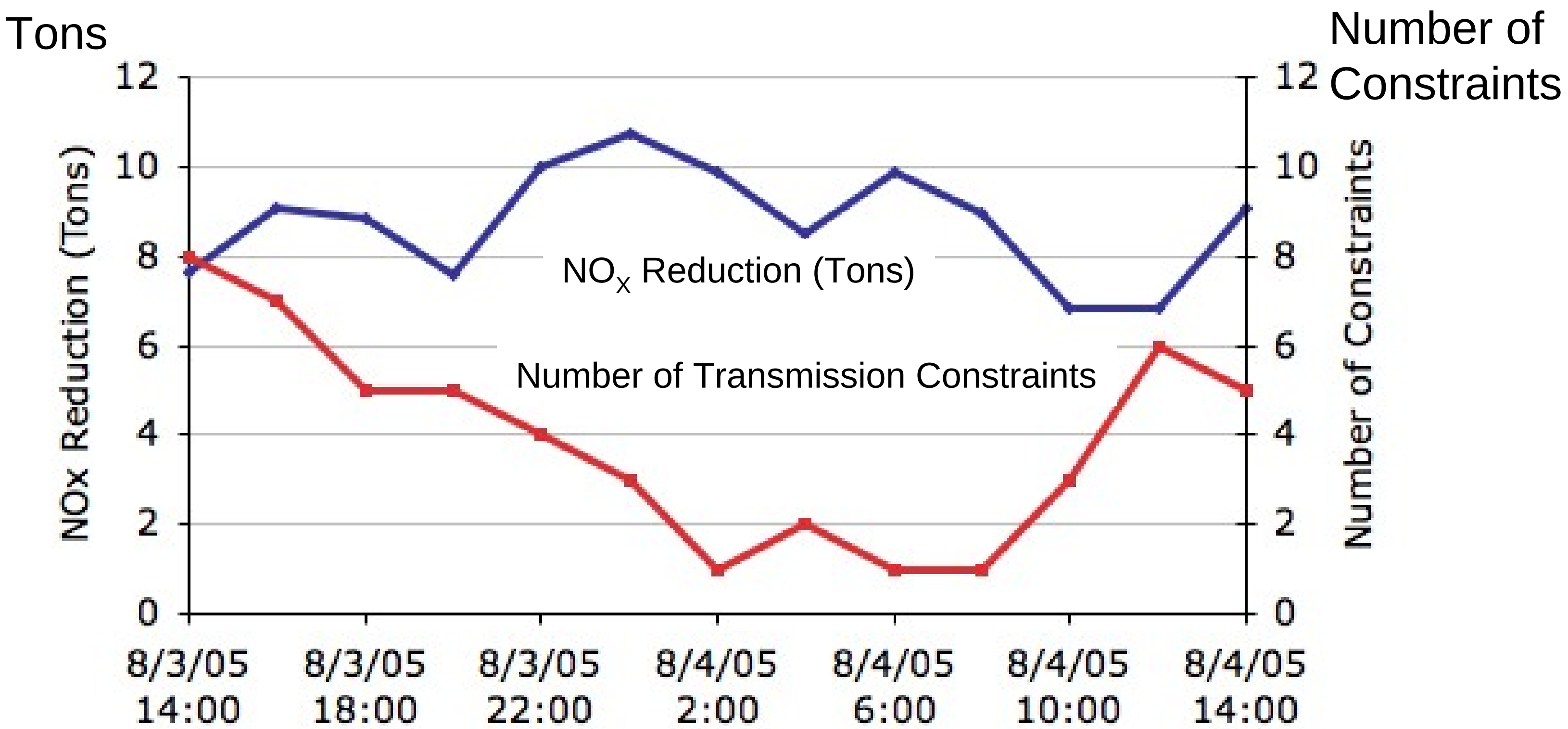
Percent Reductions (Zonal)



Hourly Reductions (Zonal)

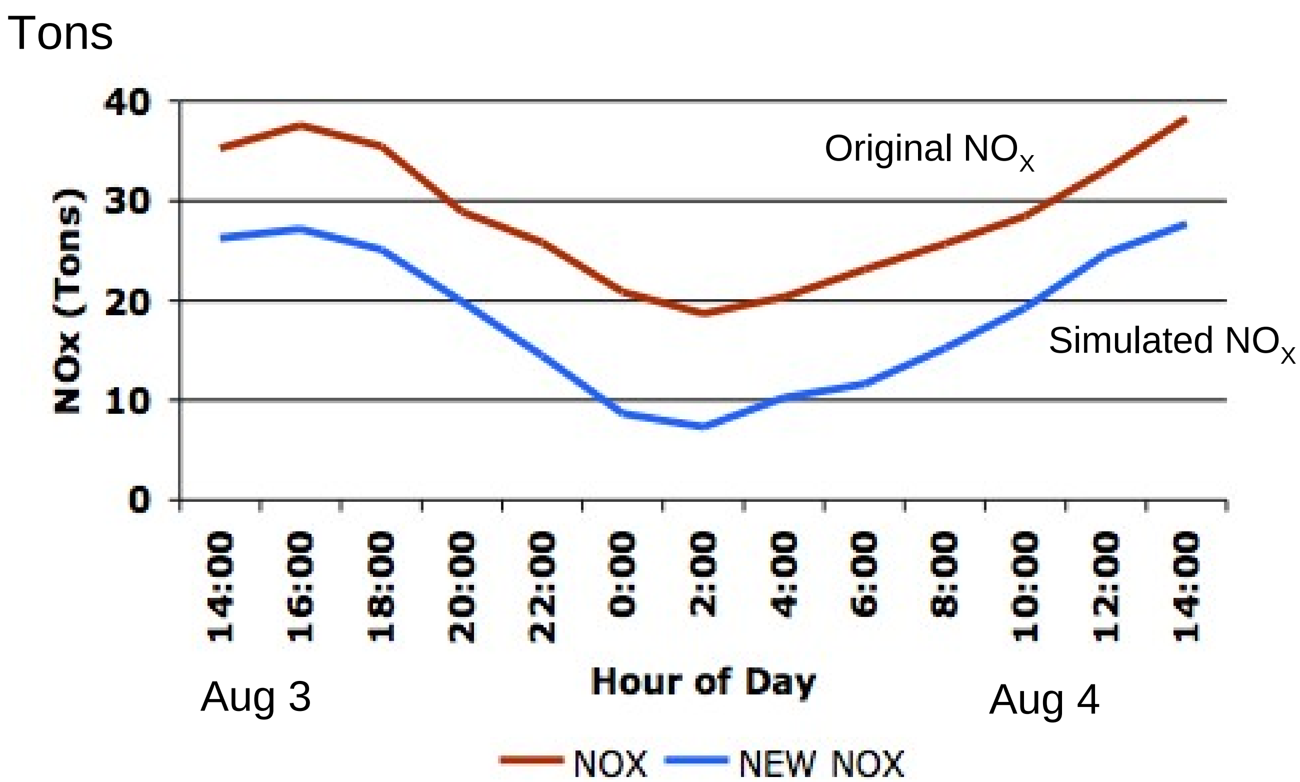
NO_X Reduction and Initial Number of Transmission Constraints

– Classic PJM, August 3 and 4, 2005



Hourly Reductions
(NO_X reduction in tons)

Original and Simulated NO_X with Transmission Constraints
– August 3 and 4, 2005

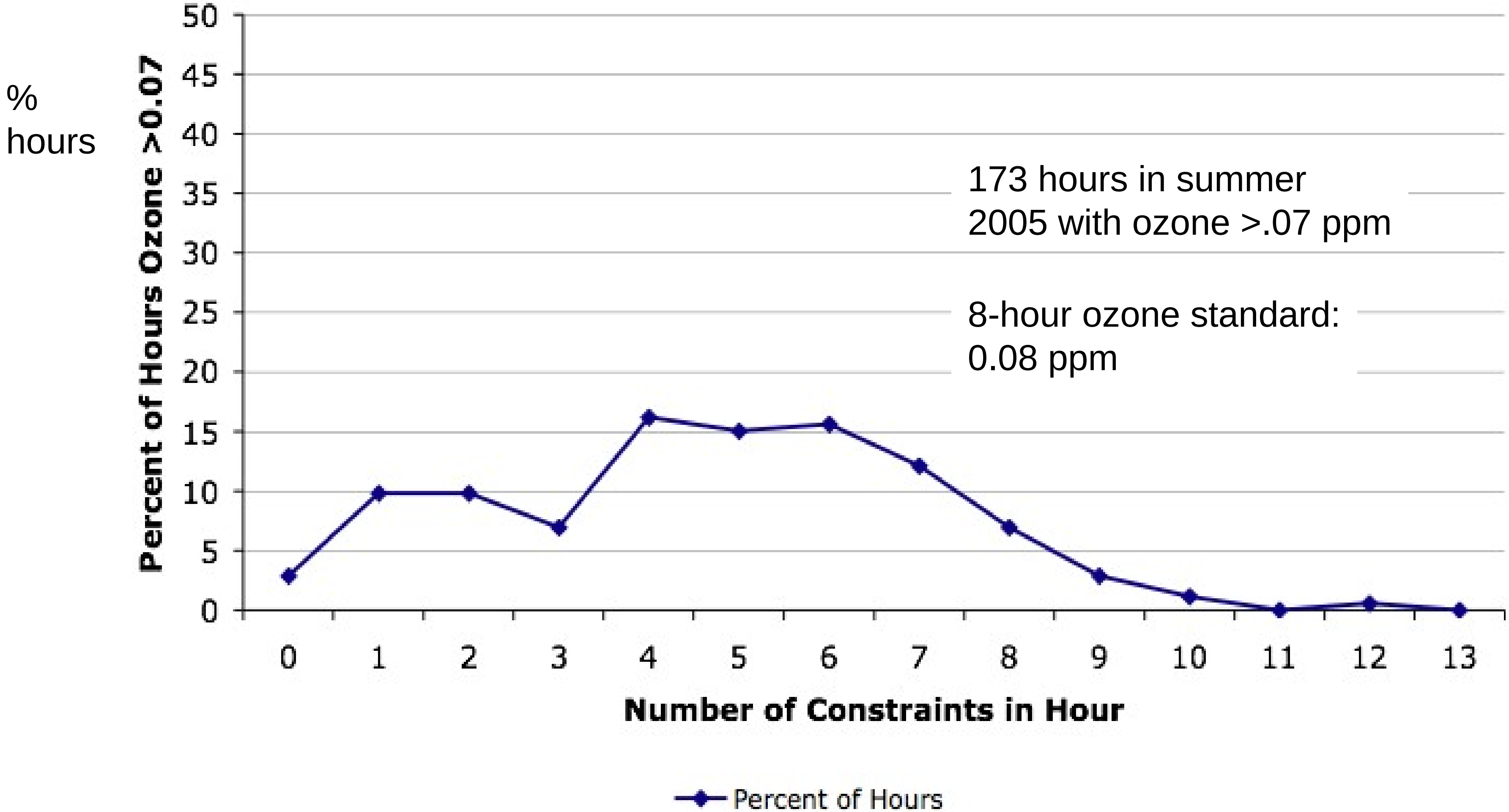


Reasons low-NO_X generation not already dispatched:

1. Higher costs
2. Participation in ancillary-service markets
3. Start-up, shut-down costs
4. Network constraints
5. NO_X-rate versus efficiency tradeoff

Ozone and Transmission Congestion
(% of hours)

To what extent does transmission congestion coincide with high ozone concentrations?



Impact of Transmission Constraints

Why small impact?

Only small changes in generation from NO_X minimizing case needed to meet transmission constraints

e.g. 8/4/05 14:00

to minimize NO_X total of 9000 MW "redispatched" (26%)

then 1230 MW changed again to meet constraints

⇨ many exchanges not limited by transmission constraints

⇨ small NO_X penalty from meeting transmission constraints

Low-NO_X capacity often located on high-LMP side of transmission constraints

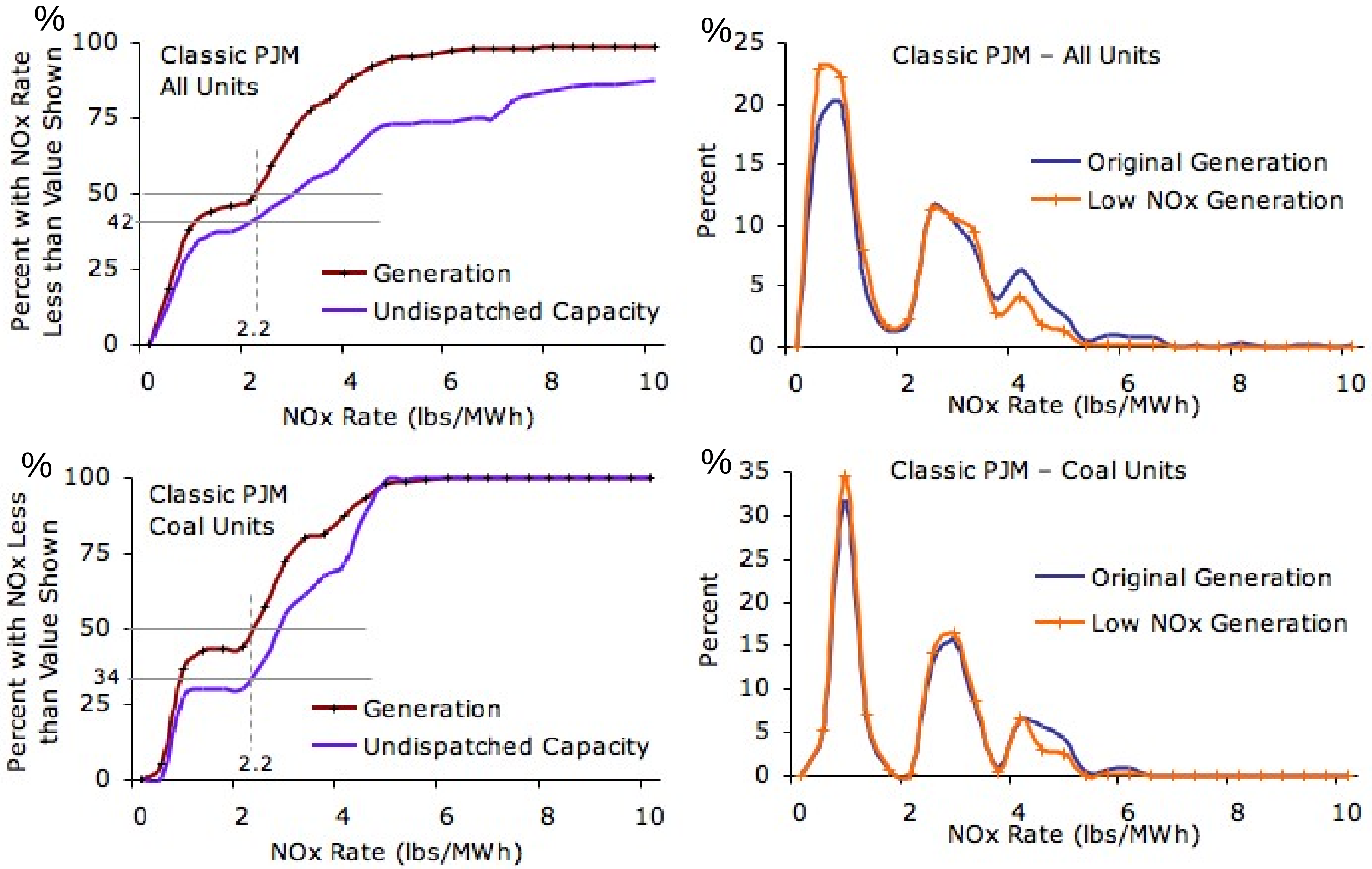
e.g. 8/4/05 14:00

capacity on high-LMP side of 10THST-OST: 1.8 lbs/MWh

low-LMP side : 3.1 lbs/MWh

Considerable within-zone variation in NO_X rates

Heterogeneity in NO_X Rates

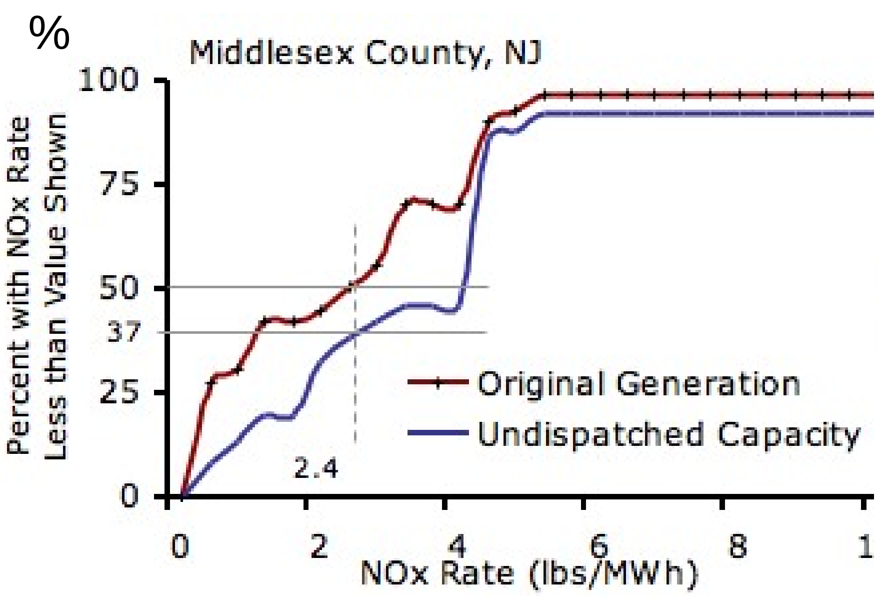


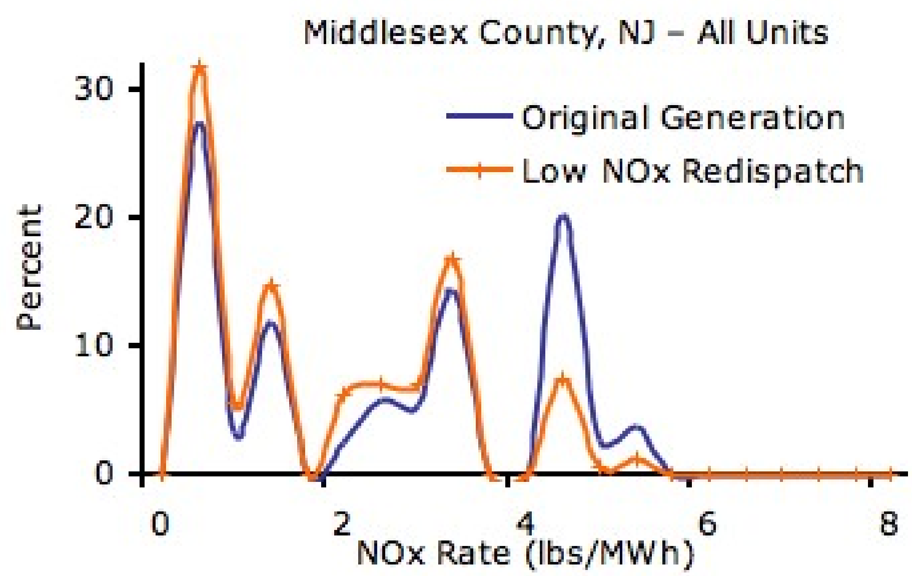
Heterogeneity in NO_X Rates: County Level Example

Locational NO_X Rate Heterogeneity

e.g. Middlesex County, NJ

8/4/05 14:00





Results: by location

Hourly Results

August 4, 2005 2 pm

STATE	COUNTY	NOx	Delta NOx	Generation	Delta Gen
NJ	Hudson	4581	-3153	906	-457
NJ	Middlesex	4651	-1716	1721	-56
PA	Northampton*	6481	-1716 (-692)	2769	-281
NJ	Burlington	2553	-1557	152	64
MD	Baltimore	2605	-1451	462	-191
DE	New Castle	3650	-1159	1369	-30
NJ	Cape May	1752	-1134	431	-217
PA	Clearfield	1464	-967	348	-229
MD	Charles	5240	-886	1395	-144
MD	Harford	1146	-749	267	39
MD	Prince George'	5283	-715	2097	120
⋮					⋮
NJ	Mercer	733	22	628	20
PA	Montour	508	23	1474	64
PA	Wyoming	85	26	43	13
PA	Philadelphia	546	32	273	34
NJ	Union	247	49	1530	307
PA	Berks	592	77	215	28
NJ	Ocean	409	80	557	95
PA	Lebanon	0	88	0	475
PA	Venango	81	213	0	258
PA	Delaware	3141	257	1360	111
DC	DC*	613	1011 (9)	271	279
		(lbs)	*(lbs)*	*(MW)*	*(MW)*

* Exchanging the 279 extra generation in DC for generation in Northampton County yields the results in parentheses (to remedy the large increase in NOx in DC if needed).

NO_X Price Induced Redispatch

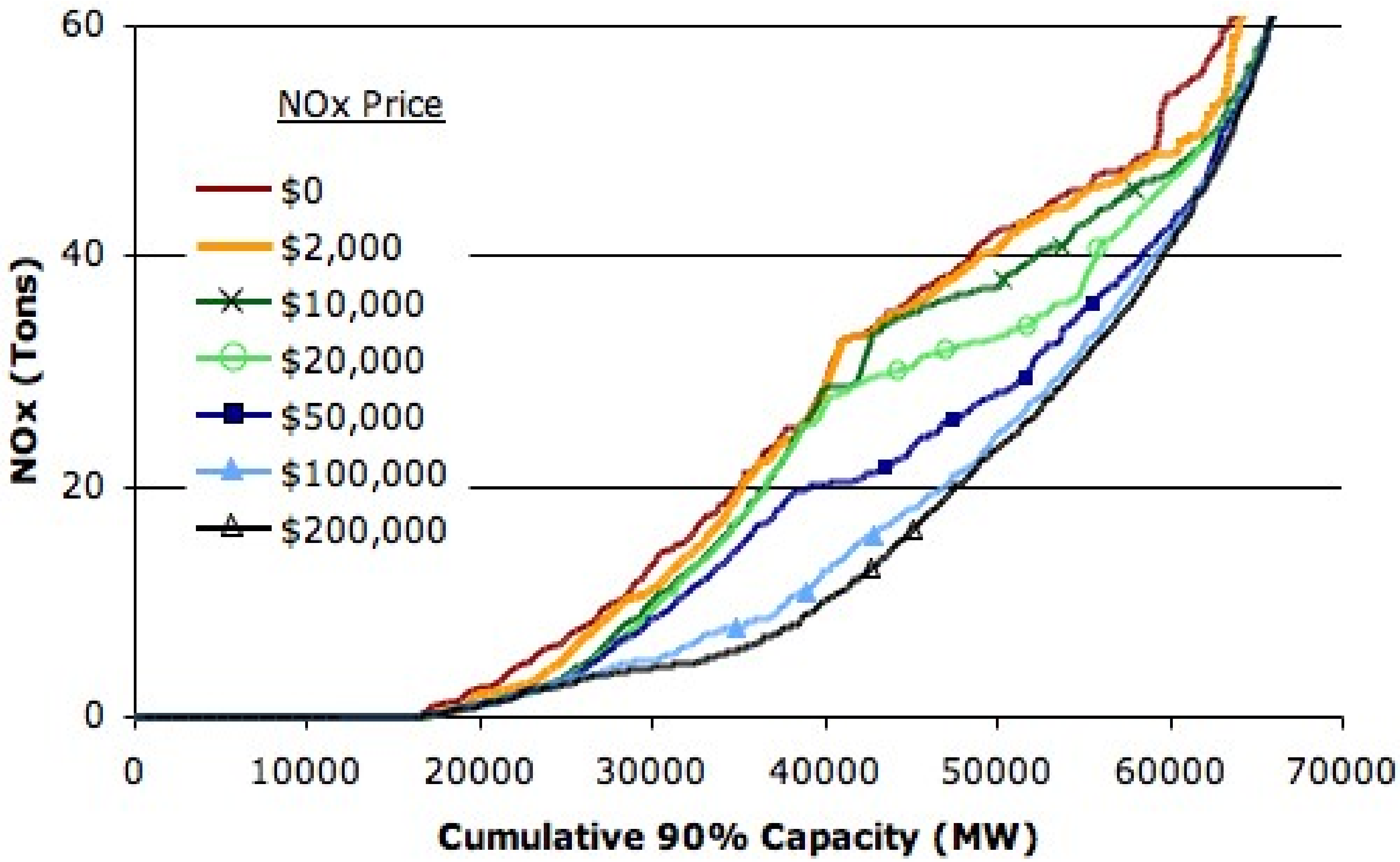
- Preliminary analysis of the effects of NO_X prices on redispatch in the wholesale electricity market assuming perfect competition
- Unconstrained case only examined so far
- Vary NO_X price from $zero to $200,000/ton (but remember that the system has already adapted to historical <u>seasonal</u> NO_X prices in the range of $1,000 to $5,000/ton)
- Examine resulting redispatch and changes in NO_X emissions

Results

2005 Classic PJM	NOx Permit Price	August 3rd Redutions	August 4th Reductions
	Base Emissions	843	868
Daily NOx Reductions (Tons)	**$10,000/Ton**	53	46
	%	*6*	*5*
	$20,000/Ton	121	119
	%	*14*	*14*
	$50,000/Ton	216	215
	%	*26*	*25*
	$100,000/Ton	326	328
	%	*39*	*38*
	$200,000/Ton	367	365
	%	*44*	*42*

Total NO_X reductions over two 24-hour periods in 2005 in Classic PJM for a range of NO_X permit prices applied uniformly to all generating units in Classic PJM.
The percent reductions from the base case (observed emission rates and dispatch given historical NO_X permit and fuel prices) are also presented.

Results



NOx Price
$0
$2,000
$10,000
$20,000
$50,000
$100,000
$200,000
NOx (Tons)
0
20
40
60
0
10000
20000
30000
40000
50000
60000
70000
Cumulative 90% Capacity (MW)

Conclusions

Major conclusion:
Short-term abatement flexibility is available

- NO_X-rate heterogeneity important
- Redispatch to reduce NO_X often relieves transmission constraints
- High NO_X prices needed during ozone episodes to induce significant market redispatch
- Investment in NO_X controls for some peaking units may be economical
- Potential implications for integrating stationary and mobile source regulations

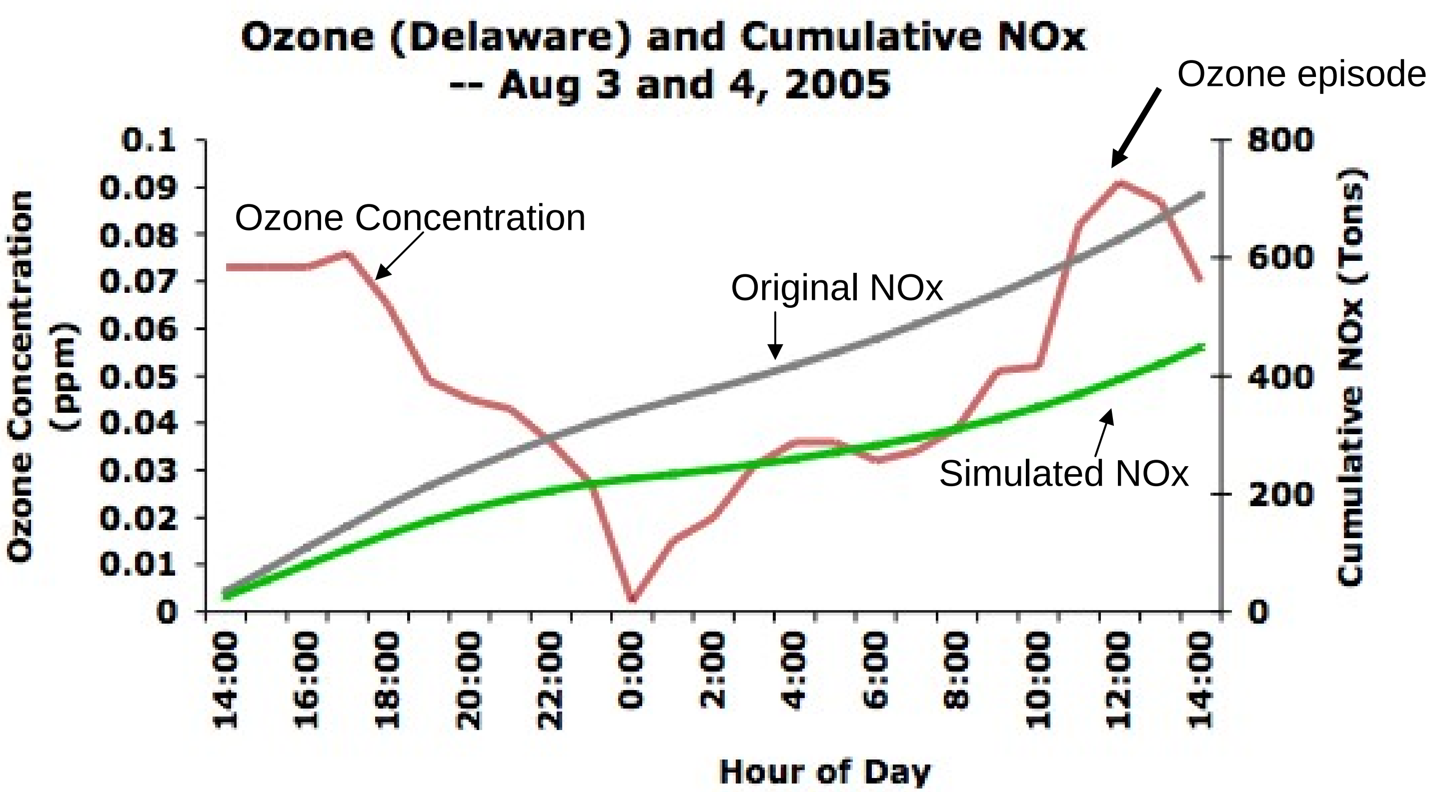
FUTURE WORK

- More work on NO_X allowance exchange-ratios needed to provide incentives for redispatch
- Variable use of control technologies and control-efficiency tradeoff
- Combine with atmospheric chemistry modeling

BACKUP

Cumulative Reduction and Ozone

Cumulative reduction: 258 tons in 24 hours or 37%



Ozone and Transmission Congestion

To what extent does transmission congestion coincide with high ozone concentrations?