Dynamic Electricity Generation for Addressing Daily Air Quality Exceedances in the US

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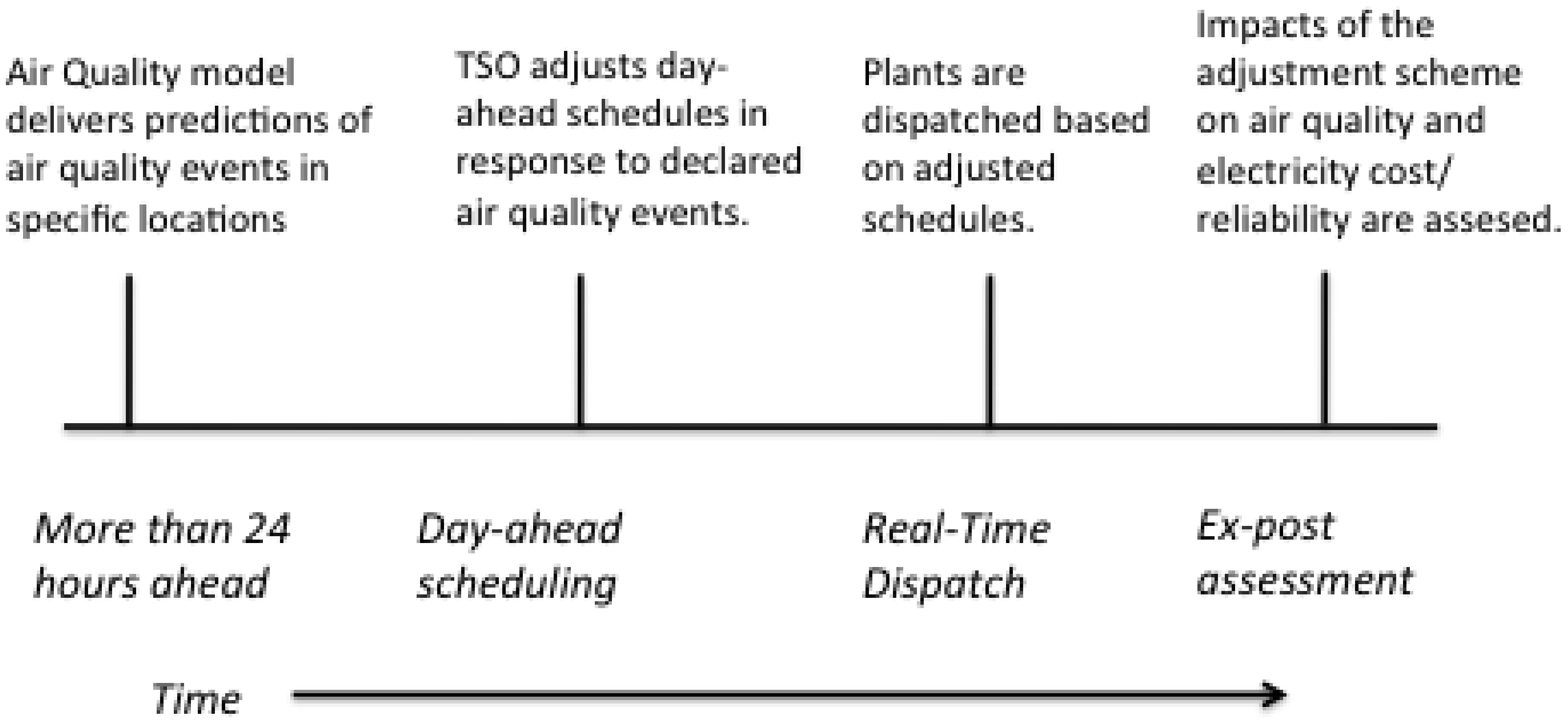
Motivation

1) Air quality is forecast daily in the US.
    - Forecasts are used to alert the public, but not generally to change polluting activities.
2) Many urban areas violate the 8-hr. daily maximum ozone standard.
    - Violations of the standard are damaging to public health and the environment.
    - Meeting the standard is costly and challenging.
3) Electric power plants contribute significantly to air pollution:
    - 18% of total US anthropogenic NO_x and 66% of SO_2 in 2008.
4) Electric power plants are managed daily to meet electrical grid demands at least cost.

A dynamic electricity system to avoid daily ozone exceedances



Air Quality model delivers predictions of air quality events in specific locations

TSO adjusts day-ahead schedules in response to declared air quality events.

Plants are dispatched based on adjusted schedules.

Impacts of the adjustment scheme on air quality and electricity cost/ reliability are assesed.

More than 24 hours ahead

Day-ahead scheduling

Real-Time Dispatch

Ex-post assessment

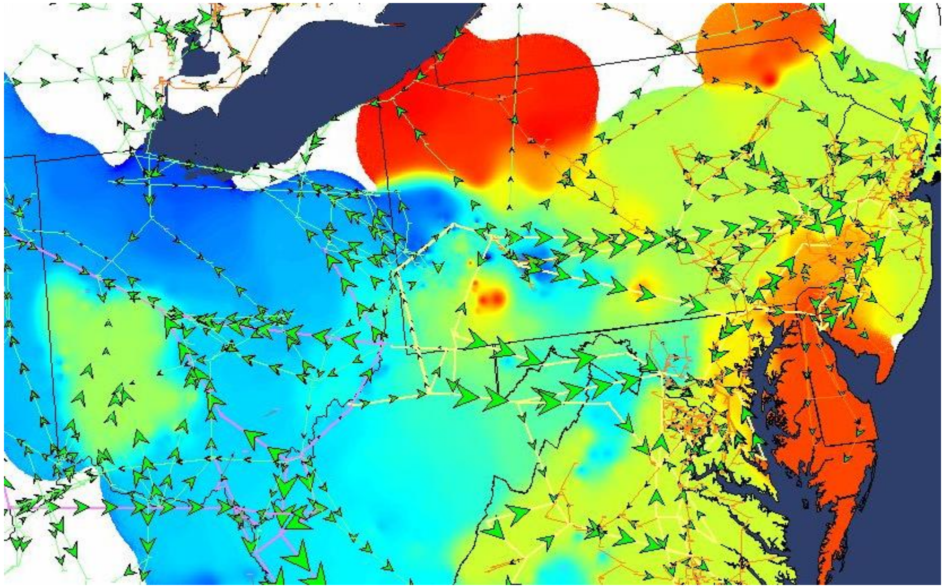
Time

Objectives

1) Design a dynamic electricity management system that incorporates air quality forecasts, with a goal of avoiding daily ozone exceedances in the eastern US

2) Demonstrate this dynamic electric system for selected episodes from the recent past, evaluating operation & decision rule choices.

Approach

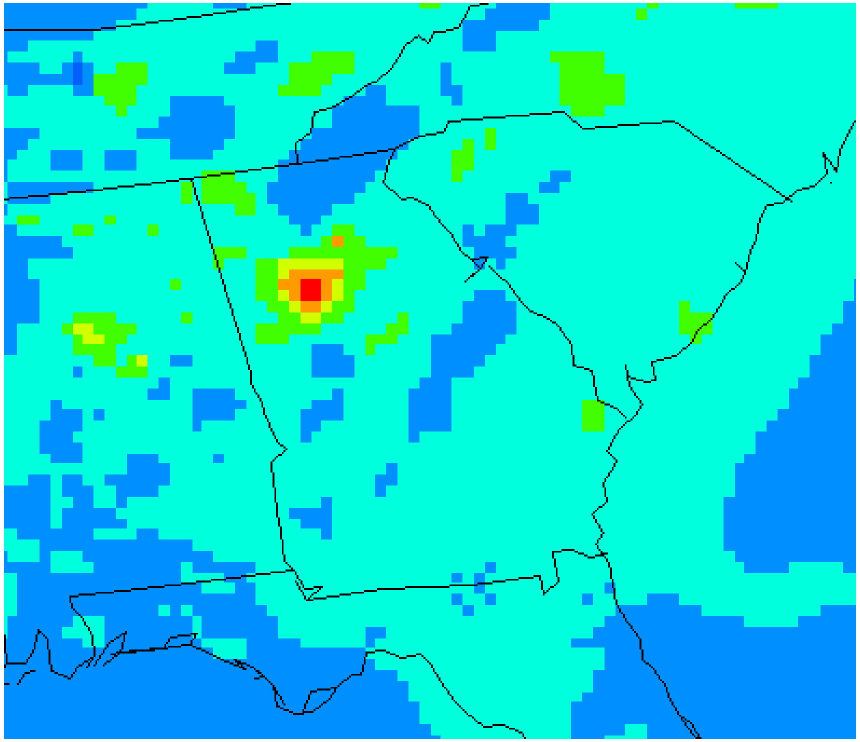


Electrical grid model

least-cost plant dispatch to meet grid demand

CAMx air quality model

emissions → concentrations



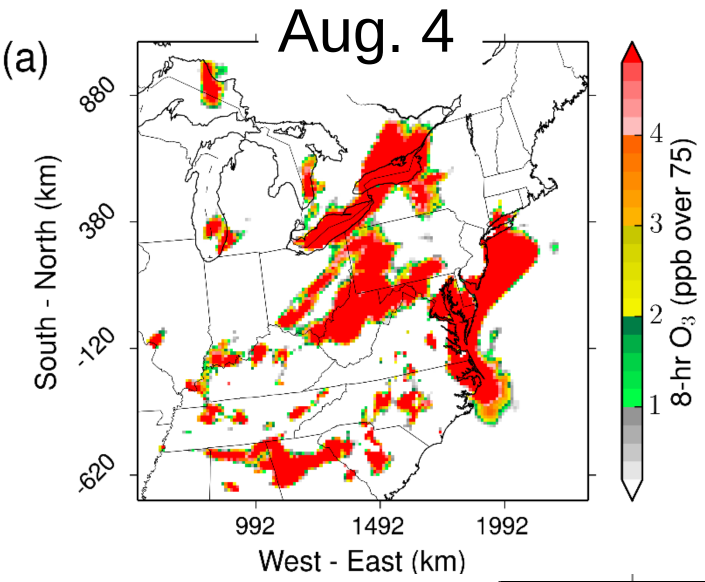
Use of air quality online sensitivity

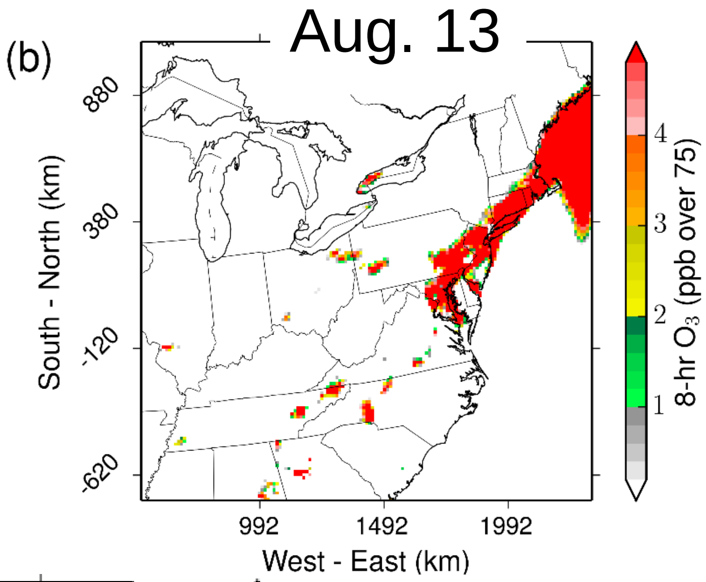
- We use and online sensitivity tool (DDM in CAMx) to estimate the sensitivity of peak ozone to NO_x from individual power plants.

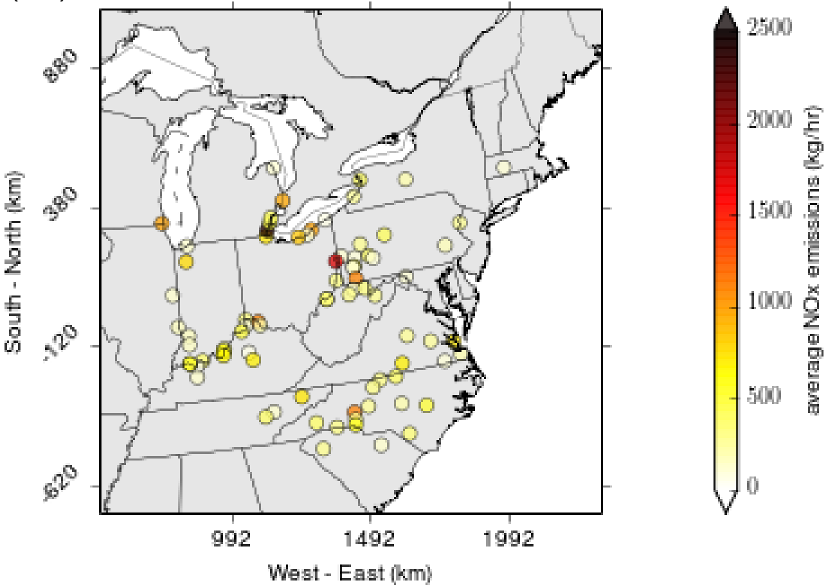
- DDM in CAMx – we have run DDM to track the sensitivity of ozone to NO_x from 80 power plants, running in parallel on multiple processors.

- If dynamic management seems like a good idea, we will recommend that online sensitivity tools be used in air quality forecast models.
  - We will investigate options to make online sensitivity practical.

Example Episode:
Pittsburgh, Aug. 4 & 13, 2005

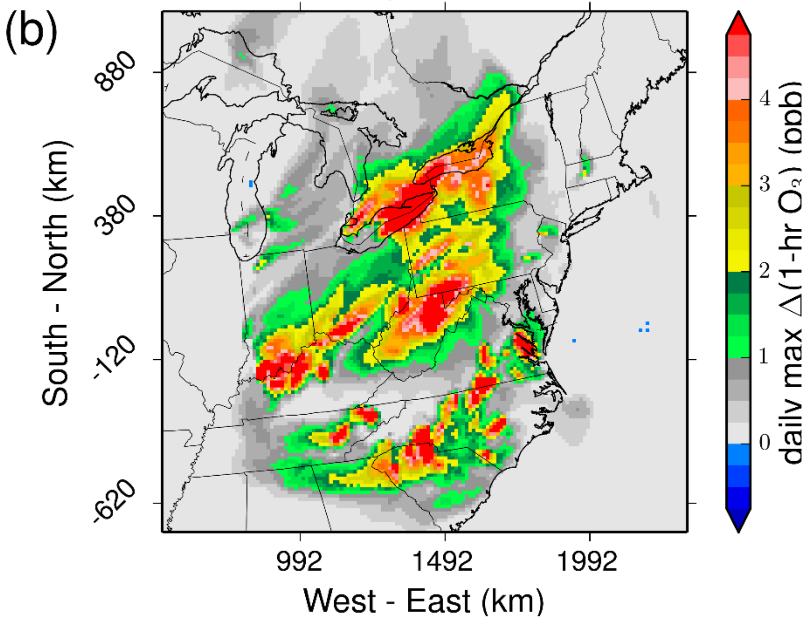




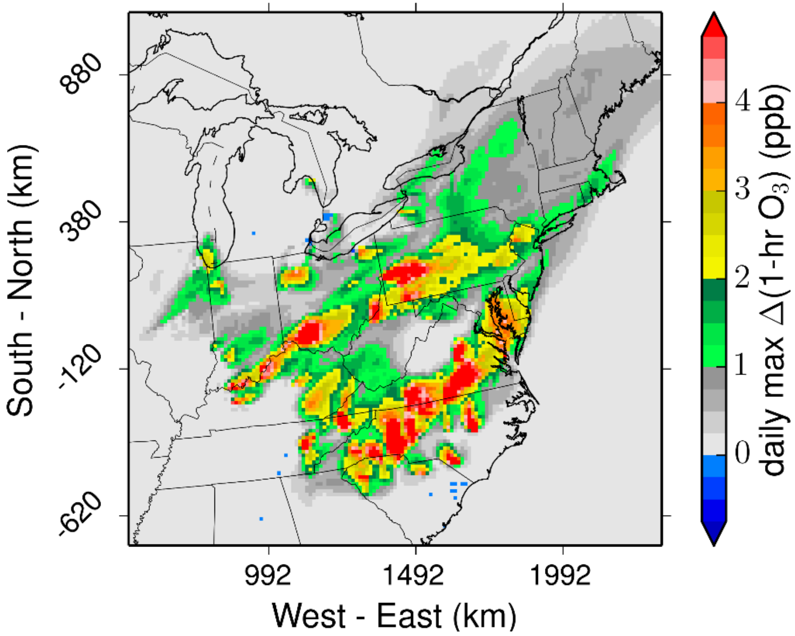


How Much do Power Plants Contribute to High Ozone?

Aug. 4

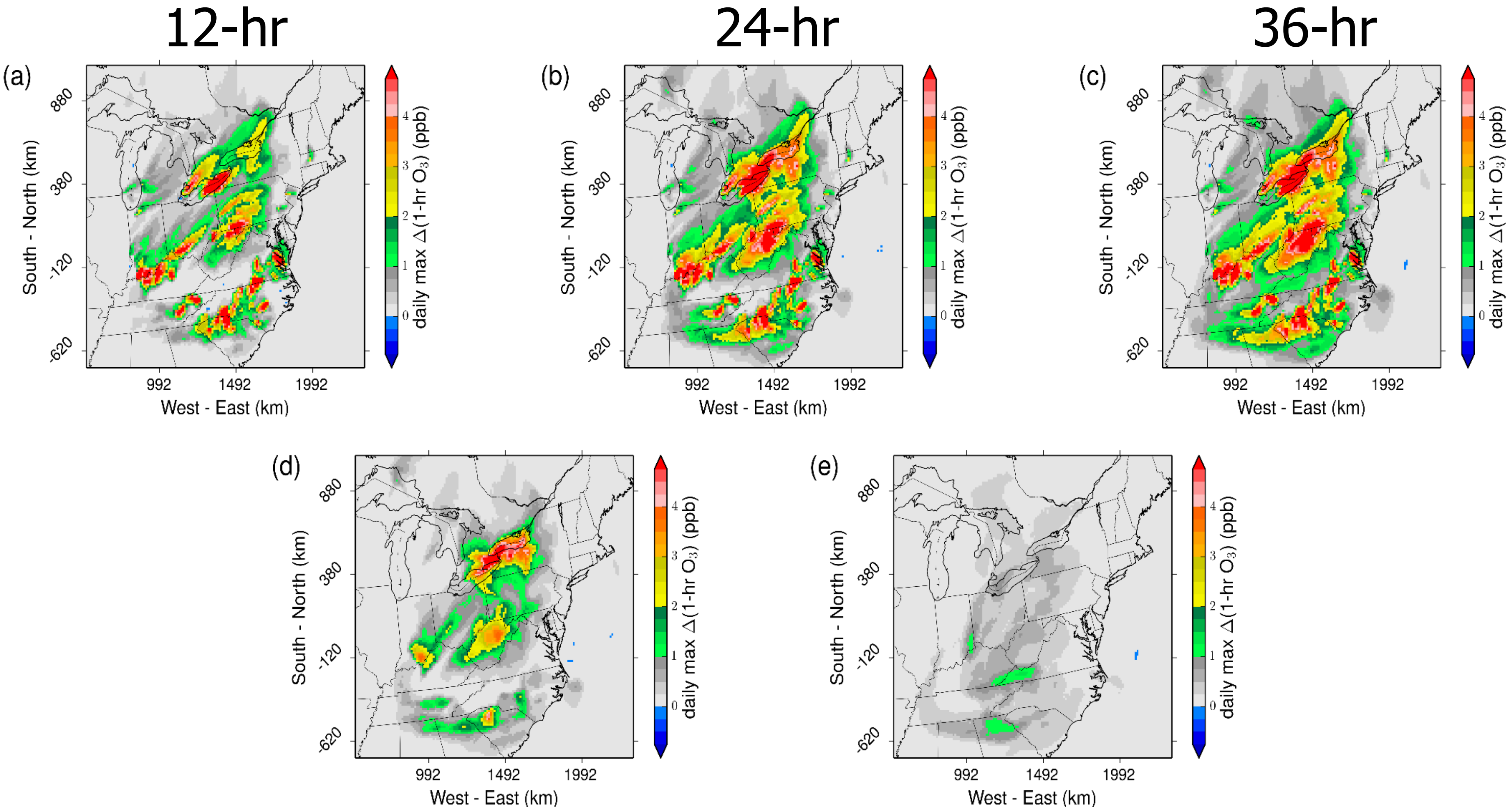


Aug. 13



Brute force sensitivities, removing emissions from 80 EGUs 24 hrs. ahead of the day analyzed.

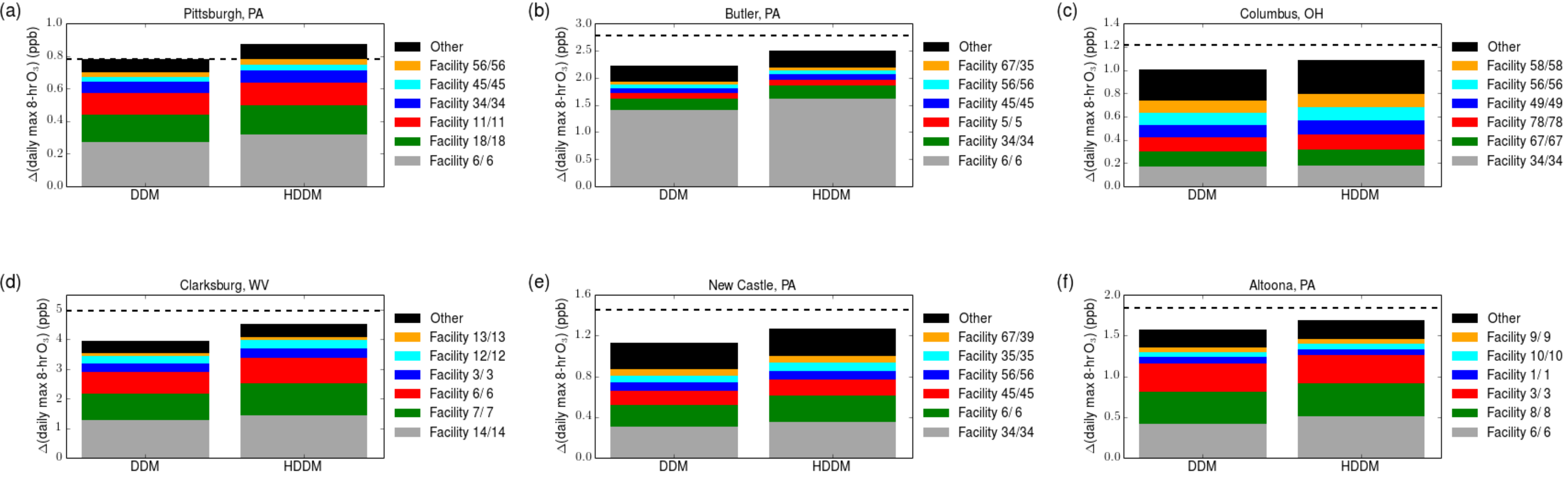
How Long Should Power Plants Reduce Output to Avoid Ozone Emergency?



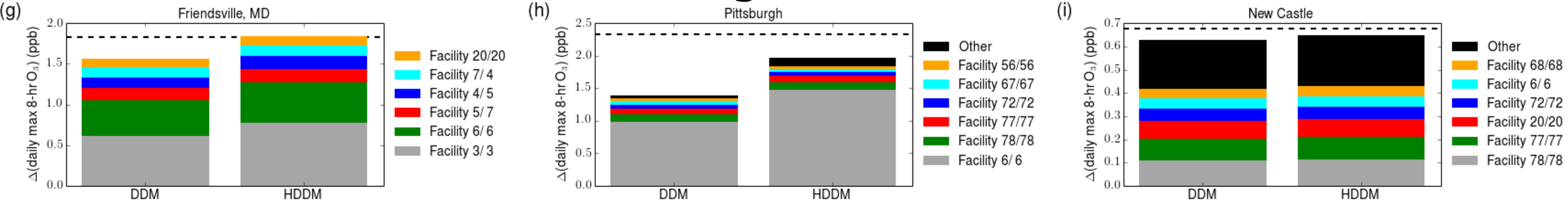
Aug. 4, brute force sensitivities, removing emissions from 80 EGUs.

How Many EGUs Need to Reduce Output?

Aug. 4



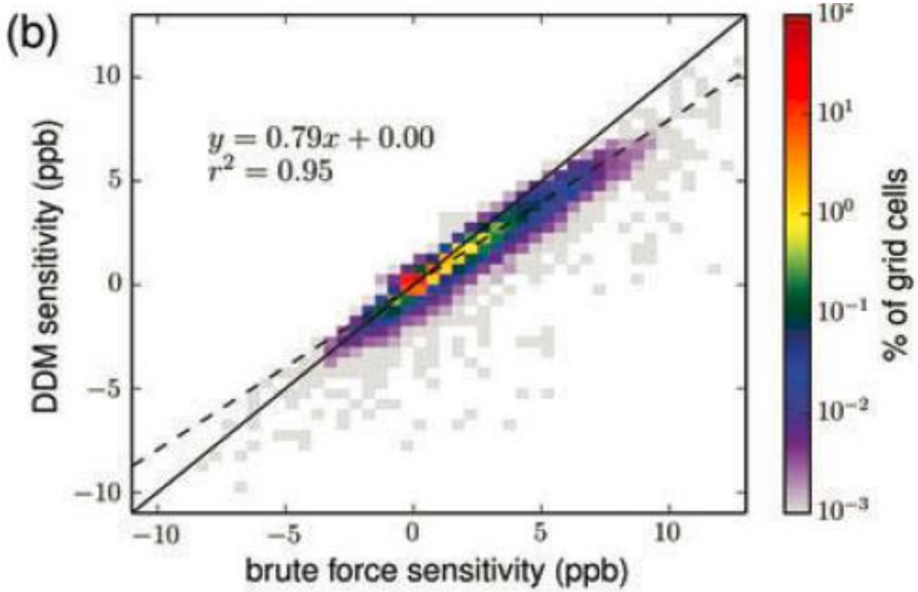
Aug. 13



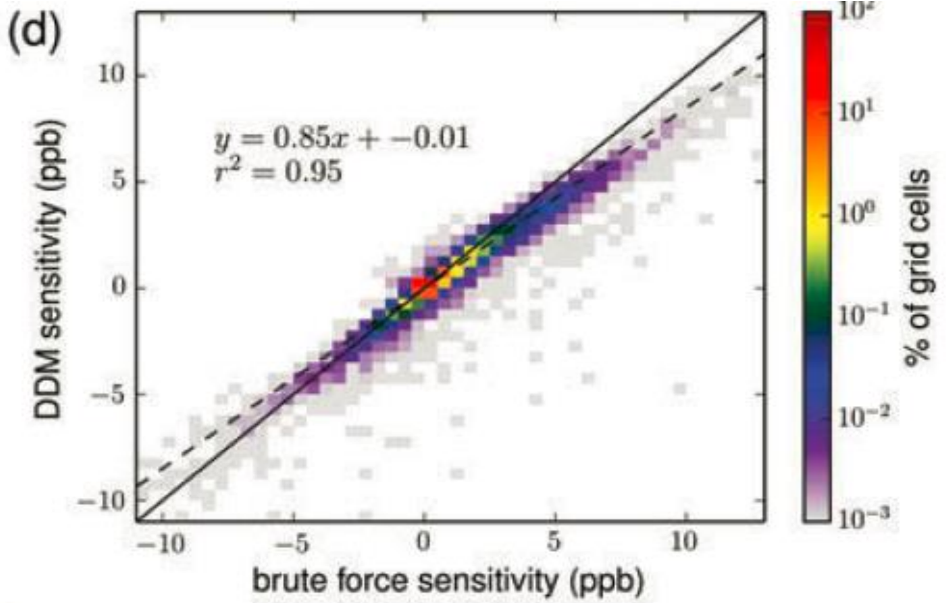
Sensitivities from DDM.

How Well Does DDM and HDDM Perform Relative to Brute Force?

Aug. 4



Aug. 13



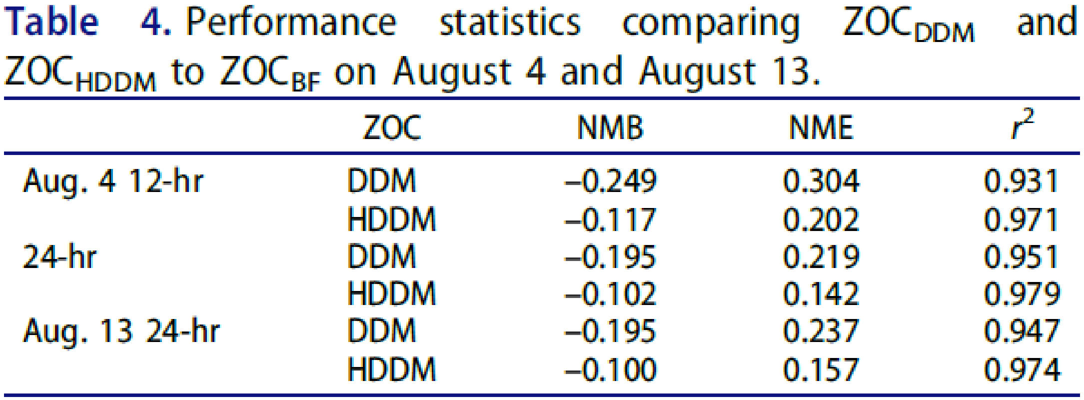


Table 4. Performance statistics comparing ZOC_{DDM} and ZOC_{HDDM} to ZOC_{BF} on August 4 and August 13.

	ZOC	NMB	NME	r^2
Aug. 4 12-hr	DDM	−0.249	0.304	0.931
	HDDM	−0.117	0.202	0.971
24-hr	DDM	−0.195	0.219	0.951
	HDDM	−0.102	0.142	0.979
Aug. 13 24-hr	DDM	−0.195	0.237	0.947
	HDDM	−0.100	0.157	0.974

Conclusions from Air Modeling

- Power plants contribute a few ppb to high ozone, enough to bring 8-hr. ozone below the standard, at least sometimes.
- To avoid high ozone, EGUs should reduce output a full day in advance, but little is additional gained from reductions further in advance.
- For high ozone in a given location, most of the total sensitivity comes from a few EGUs (<6).
- DDM and HDDM perform well, though with some biases compared to brute force. HDDM likely not worth the extra computational effort.

Couzo, E., McCann, J. B., S. Blumsack, W. Vizuete, and J. J. West (2016) Model sensitivity of ozone to electricity generation emissions in the northeastern US using three sensitivity techniques, *Journal of the Air & Waste Management Association*, online ahead of print.

Grid Modeling: Optimal Power Flow

$$\underline{\min \sum_{i=1}^{N} \sum_{t=1}^{T} C_i(P_{it} + \Delta P_{it})}$$

Choose EGU adjustments ΔP to minimize cost

$$h(x_i) = 0$$
$$g(x_i) \leq 0$$

Grid and EGU constraints

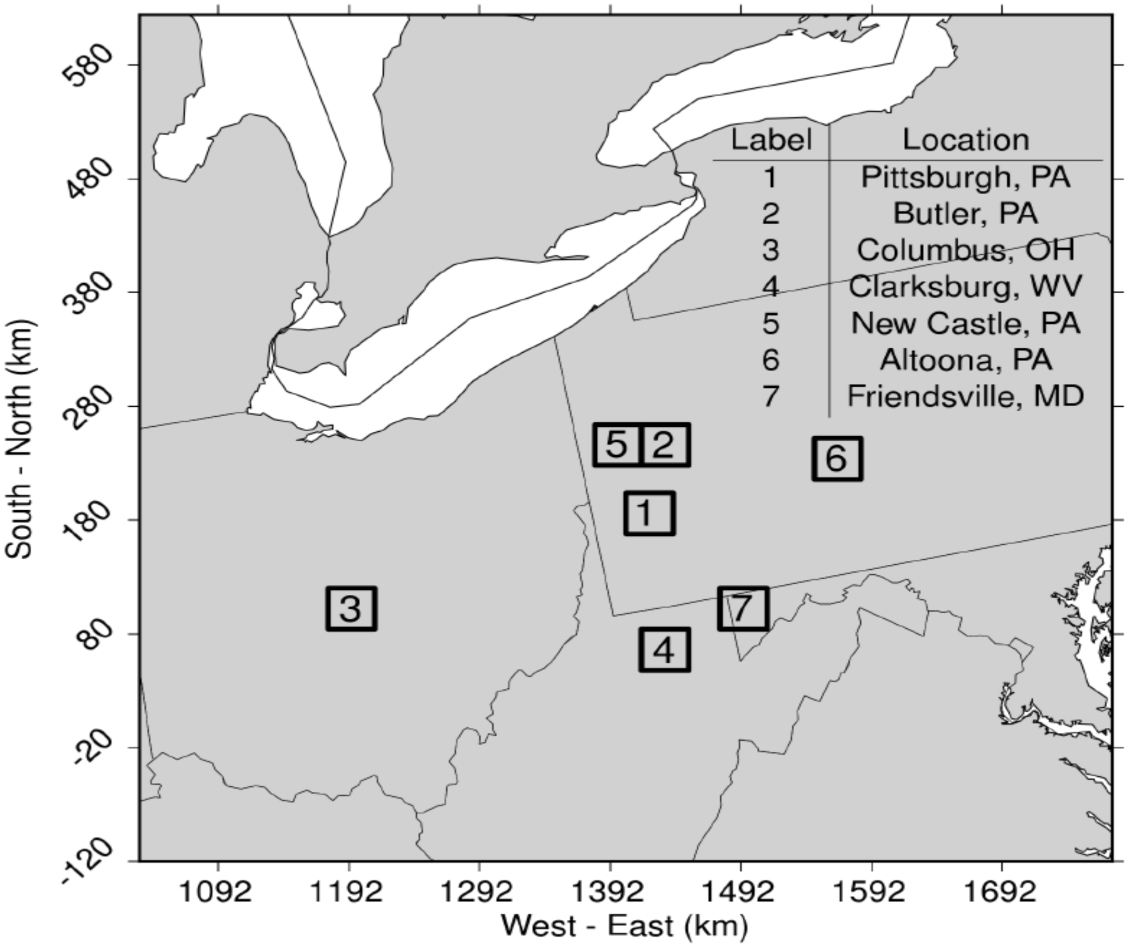
$$\sum_{i=1}^{N} P_{it} = \sum_{i=1}^{N} D_{it}$$

Supply/demand balance

$$\underline{S_{t+1} = S_t - \sum_{i=1}^{N} \sum_{k=1}^{T} a_{i,t-k}^{t+1}\, \Delta P_{t-k} \leq \bar{S} \quad \forall i, k}$$

O_3 budget constraint and transition eqn.

Example Episode: Pittsburgh, Aug. 4, 2005



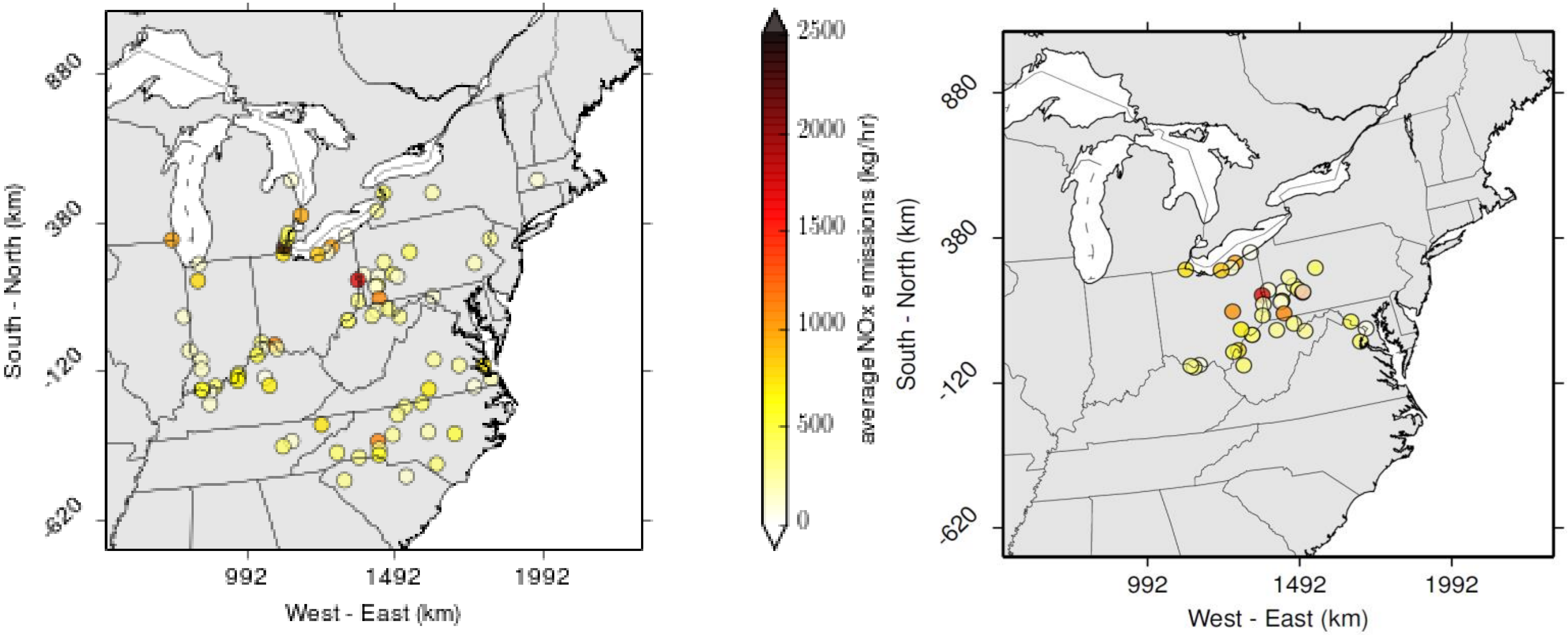
Label	Location
1	Pittsburgh, PA
2	Butler, PA
3	Columbus, OH
4	Clarksburg, WV
5	New Castle, PA
6	Altoona, PA
7	Friendsville, MD

Gridded locations where sensitivities $a_{i,t}$ are calculated

Modeling Scenarios

1) PJM. Dynamic management of EGU emissions to meet emissions budget takes place within the PJM footprint (the grid operator serving Pittsburgh). EGUs within the PJM footprint can be adjusted up or down to meet emissions budget plus reliability constraints
2) Eastern Interconnect. EGU adjustment to meet the *Pittsburgh* emissions budget covers the entire Eastern Interconnect (the power grid east of the Rocky Mountains, excluding Texas).

Coal Plant Adjustment



Eastern Interconnect Case
(80 possible EGUs)

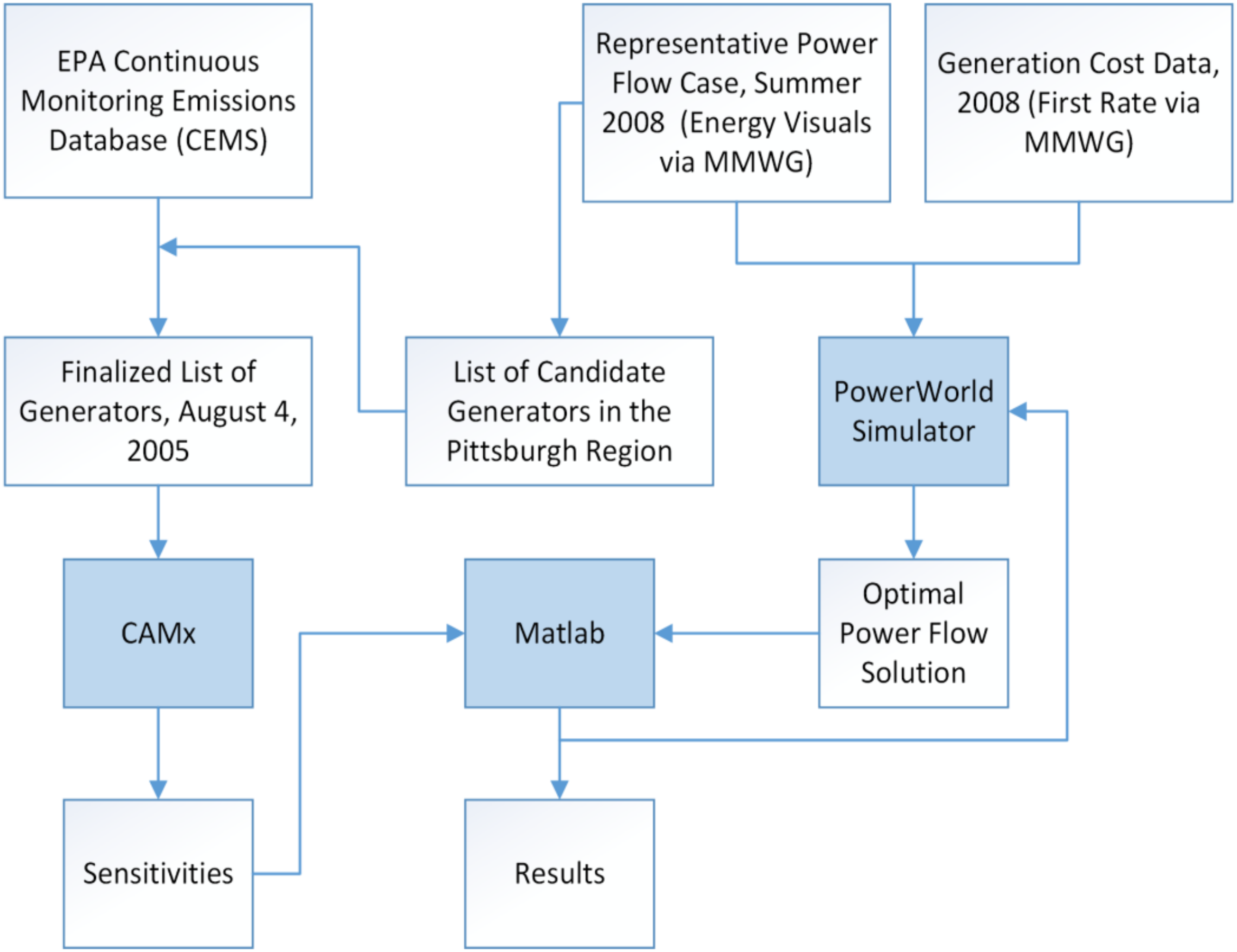
PJM Footprint Case
(40 possible EGUs)

Modeling Flow

CAMx: For each time period, creates a sensitivity for each power plant given the atmospheric variables

Matlab: Ranks generators by sensitivity and shuts them off systematically to build a cost curve; sends each scenario to Simulator.

PowerWorld Simulator: Runs the OPF and returns system cost and generator data to Matlab



EPA Continuous Monitoring Emissions Database (CEMS)

Representative Power Flow Case, Summer 2008 (Energy Visuals via MMWG)

Generation Cost Data, 2008 (First Rate via MMWG)

Finalized List of Generators, August 4, 2005

List of Candidate Generators in the Pittsburgh Region

PowerWorld Simulator

CAMx

Matlab

Optimal Power Flow Solution

Sensitivities

Results

Decision Rules for EGU Adjustment

1) **Sensitivity dispatch: EGUs are ranked according to 8-hour ozone sensitivities. EGUs with the highest sensitivities are dispatched down first.**

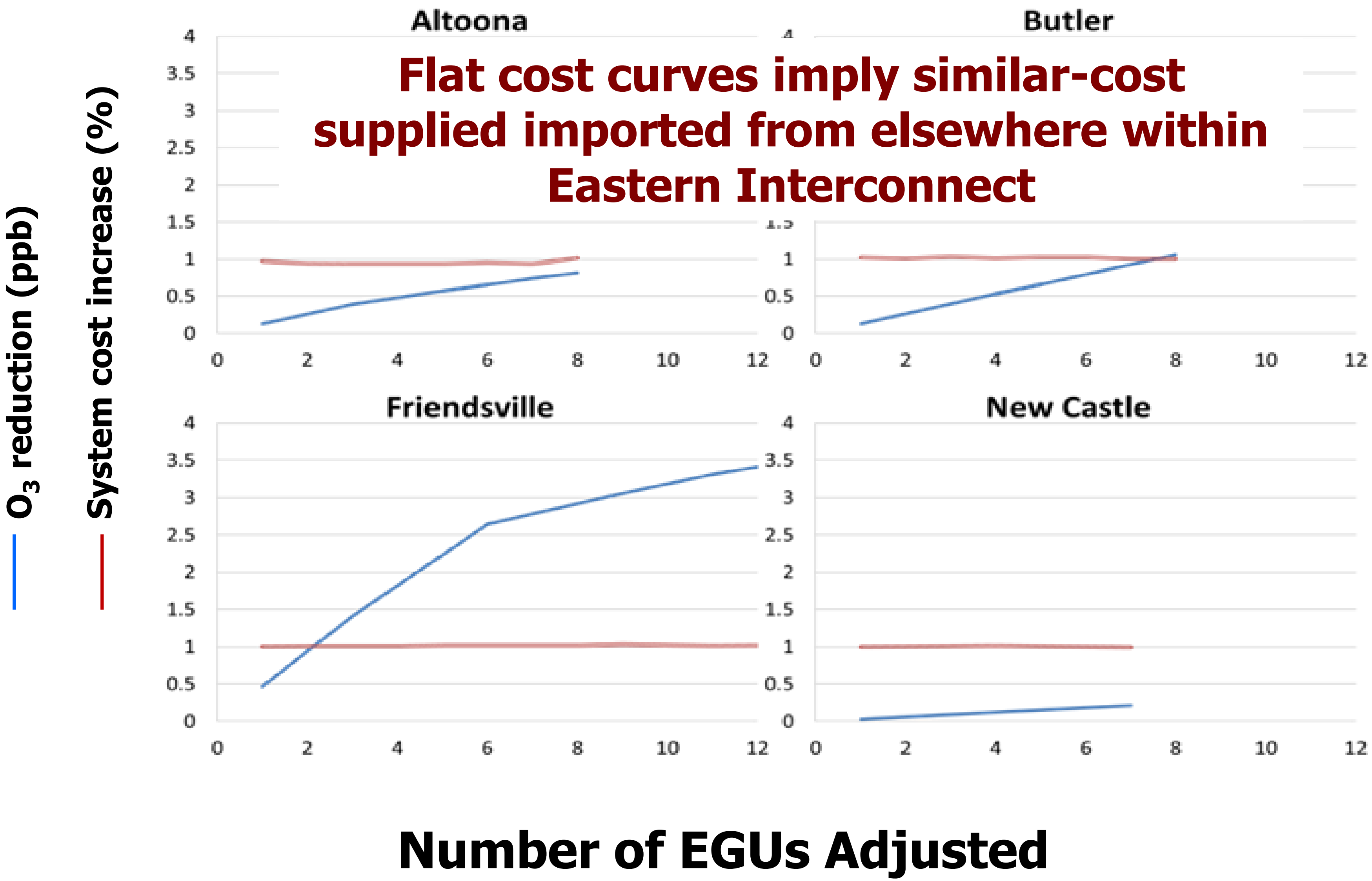
2) **Cost dispatch: EGUs are ranked according to the ratio of production cost to 8-hour sensitivity. The most cost-effective EGUs are dispatched down first. (d$/dNOx) / (dO3/dNOx) = d$/dO3**

Notes: *The cost number here is not perfect – what you really want to measure is the cost of the replacement power when an EGU is turned off. That turns out to be hard to measure offline. In the end, because of the number of EGUs needed to be within the ozone budget and because the EGUs were somewhat heterogeneous (large coal plants) there weren't a lot of differences between the two.*

Results (Sensitivity Dispatch)

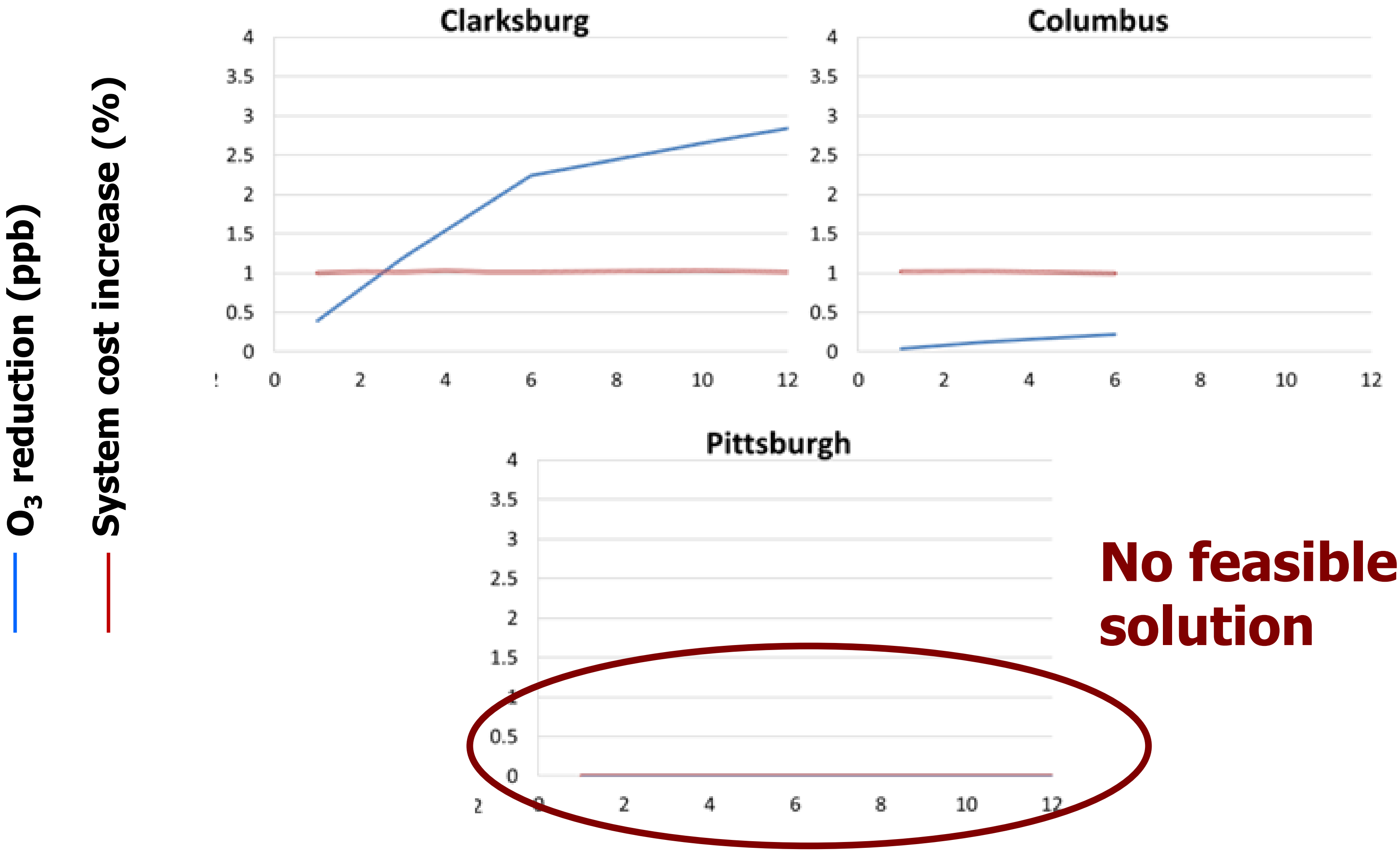
Region	Maximum Feasible Ozone Reduction (ppb)		Number of PPs with sensitivity > 1.0 ppb		Number of PPs with sensitivity > 0.1 ppb	
	EI	PJM	EI	PJM	EI	PJM
Altoona	1.58	2.24	0	0	3	6
Butler	1.73	2.38	1	1	2	4
Clarksburg	3.98	3.75	2	1	6	5
Columbus	0.97	0.13	0	0	5	0
Friendsville	4.48	1.56	2	1	5	3
New Castle	0.90	1.71	0	0	3	6
Pittsburgh	0.00	1.69	0	0	0	6

Marginal Cost of Zonal O_3 Abatement (Eastern Interconnect Case)



Flat cost curves imply similar-cost supplied imported from elsewhere within Eastern Interconnect

Marginal Cost of Zonal O_3 Abatement (Eastern Interconnect Case)



No feasible solution

Number of EGUs Adjusted

Implications

- Dispatching EGUs to meet the O_3 budget constraint is a transboundary problem.
  - Coordination required with EGUs outside of the PJM footprint.

- Even with transboundary coordination, meeting the budget constraint is not always feasible (e.g. Pittsburgh).

- Meeting the O_3 budget constraint in a specific area may be possible without substantial system cost increases.
  - Few EGUs needed to stay within the O_3 budget, and additional supplies of similar cost can be imported from other regions *assuming sufficient transboundary coordination*.

Uncertainties, Caveats

- We evaluate one high-ozone episode in 2005.
- EGU NOx emissions have decreased since 2005, but the ozone standard has also tightened.
- Costs of plant shut-down & startup are not included (and are difficult to find estimates for).

Longer term goals

- Evaluate an entire summer period with a single decision rule to see:
    - Effectiveness in avoiding air quality exceedances.
    - Changes in O_3 and $PM_{2.5}$ over the whole domain.
    - Changes in GHG emissions.
    - Changes in electrical system reliability.
    - Costs.
    - Compare costs with NO_x reductions by selective catalytic reduction (SCRs) for comparable improvement in metrics.
- Represent air quality forecast uncertainty in the electrical grid optimization.
    - Consider uncertainty in the magnitude of ozone (whether an exceedance) and in the sensitivity to power plants.
    - Consider costs of false positives and of false negatives.
- Talk with electrical power industry and stakeholders.

Table 2. Maximum 8-hr ozone concentrations for each urban region and the ZOC_{BF} during each region's maximum 8-hr ozone window on August 4, and peak 1-hr ozone concentrations and the ZOC_{BF} during the hour of maximum 1-hr ozone.

Region	max 8-hr O_3	ZOC_{BF} during max 8-hr O_3	max 1-hr O_3	ZOC_{BF} during max 1-hr O_3
Pittsburgh, PA	80.8	1.13	85.9	1.09
Butler, PA	81.5	3.01	85.5	2.04
Columbus, OH	78.9	1.43	88.7	2.36
Clarksburg, WV	87.8	5.40	94.7	7.30
New Castle, PA	78.2	1.65	82.7	1.96
Altoona, PA	72.8	2.23	78.9	2.56
Friendsville, MD	91.5	2.08	94.5	2.72

Note. ZOC_{BF} are from the 36-hr case. All values are in ppb.

Questions for system design and evaluation

1) What decision rules should grid operators use to try to avoid ozone exceedances? Hard constraints vs. cost functions? How stringent?
2) How sensitive is peak ozone to NO_x emissions from power plants? How effective would controls on local plants be? What time and spatial scales of controls would be best?
3) How can air quality forecast models use online sensitivity techniques to best forecast sensitivities to power plant NO_x?
4) How would the costs of a dynamic system compare with the costs of selective catalytic reduction units, for comparable improvements in ozone metrics?
5) How would ozone and $PM_{2.5}$ change over the whole eastern US, and would there be effects on system-wide GHG emissions and reliability?