# *Methodology for Assessing Effects of Technological & Economic Changes on the Location, Timing and Ambient Air Quality Impacts of Power Sector Emissions*

**Investigators**

**Hugh Ellis, Ben Hobbs (Johns Hopkins University),**

**Dallas Burtraw, Karen Palmer (Resources for the Future)**

This research is funded by

U.S. EPA - Science To Achieve Results (STAR) Program

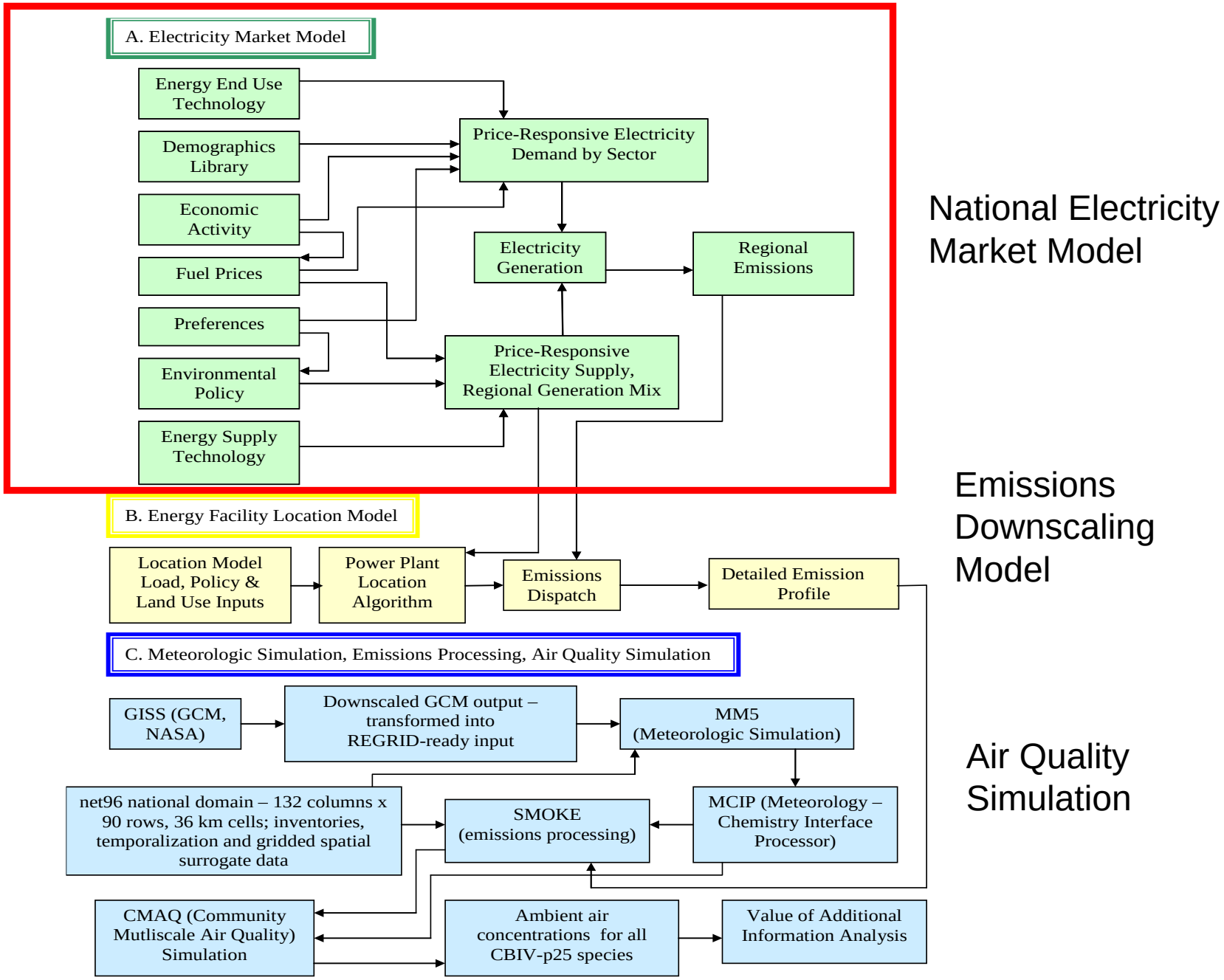
Grant # R831836

- ***Purpose:*** **Method to geographically & temporally disaggregate emissions scenarios for the electric power sector on a multi-decadal time scale**

- ***Question:*** **What might be the impacts of climate change on power sector emissions and resulting air quality?**

# *Energy Modeling*

**Dallas Burtraw, Karen Palmer, Anthony Paul**
**(Resources for the Future)**


A. Electricity Market Model
Energy End Use Technology
Demographics Library
Economic Activity
Fuel Prices
Preferences
Environmental Policy
Energy Supply Technology
Price-Responsive Electricity Demand by Sector
Electricity Generation
Regional Emissions
Price-Responsive Electricity Supply, Regional Generation Mix
National Electricity Market Model
B. Energy Facility Location Model
Location Model Load, Policy & Land Use Inputs
Power Plant Location Algorithm
Emissions Dispatch
Detailed Emission Profile
Emissions Downscaling Model
C. Meteorologic Simulation, Emissions Processing, Air Quality Simulation
GISS (GCM, NASA)
Downscaled GCM output – transformed into REGRID-ready input
MM5 (Meteorologic Simulation)
net96 national domain – 132 columns x 90 rows, 36 km cells; inventories, temporalization and gridded spatial surrogate data
SMOKE (emissions processing)
MCIP (Meteorology – Chemistry Interface Processor)
CMAQ (Community Mutliscale Air Quality) Simulation
Ambient air concentrations for all CBIV-p25 species
Value of Additional Information Analysis
Air Quality Simulation

# Information Flow in the Haiku Electricity Market Model

## User Inputs

- air pollution policies
- electricity market institutions
- technology assumptions
- macroeconomic assumptions

## Haiku

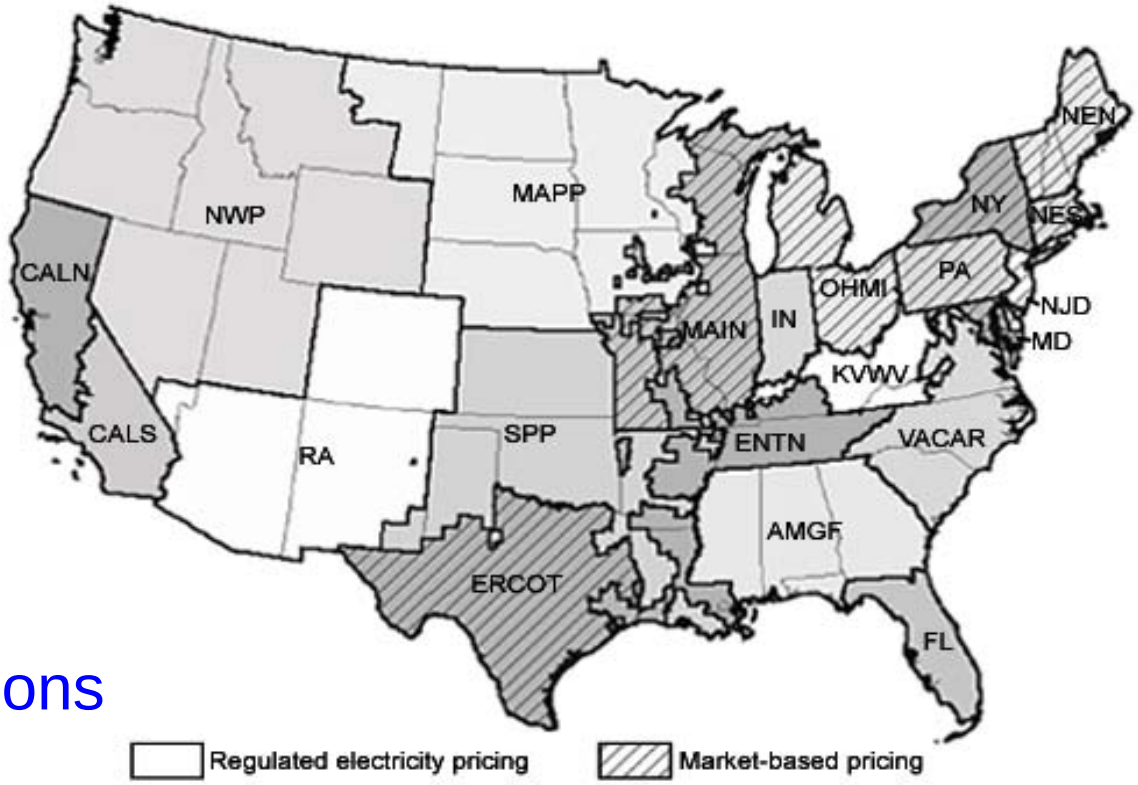
## Data

- existing generators
- fuel and resource supply
- pollution controls
- transmission grid
- electricity consumption

## Model Outputs

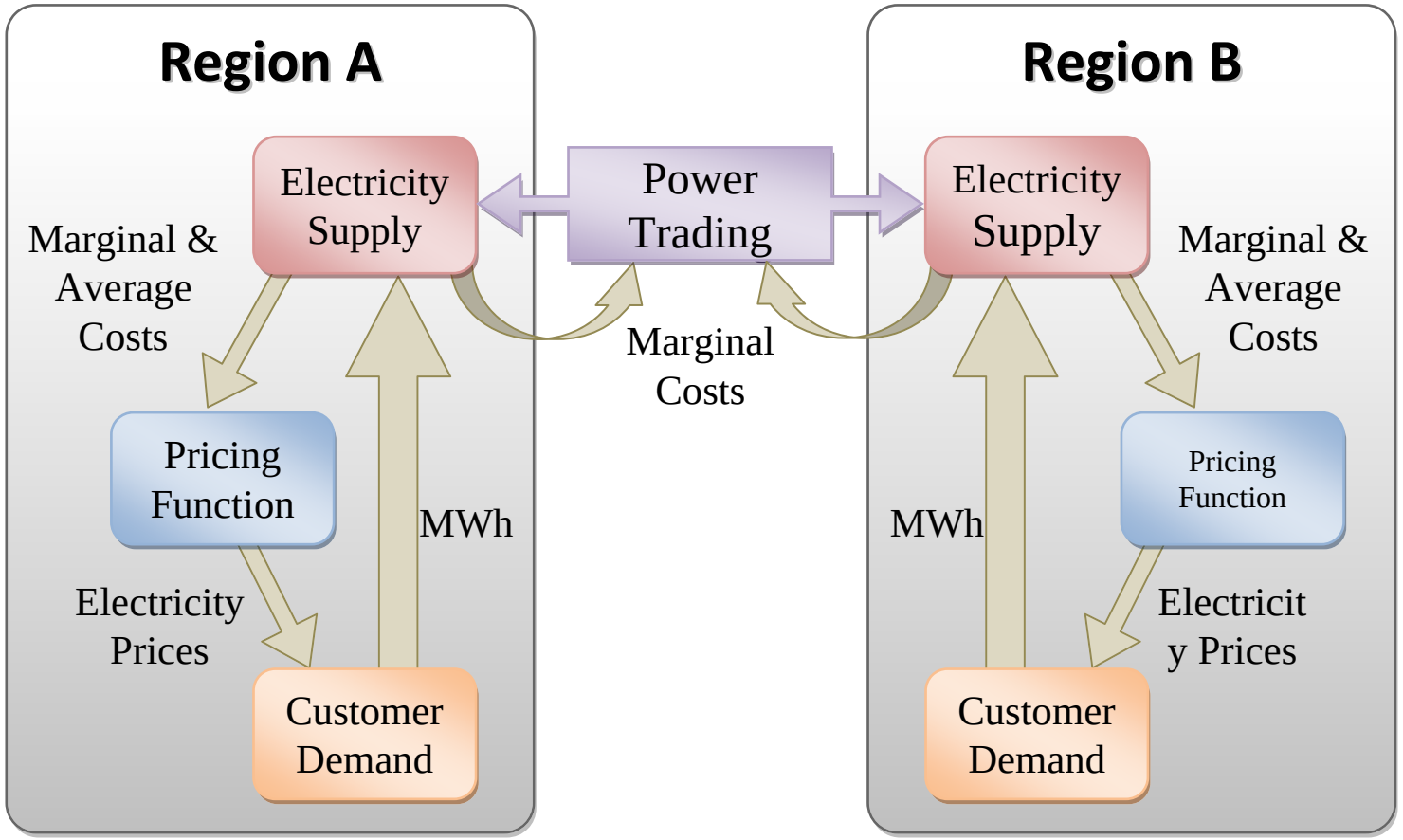
- electricity prices and demand
- electricity generation and reserve
- interregional electricity trade
- generation capacity
- pollution controls capacity
- emissions ($NO_x$, $SO_2$, $CO_2$, mercury)
- emissions allowance prices
- economic surplus

# Haiku

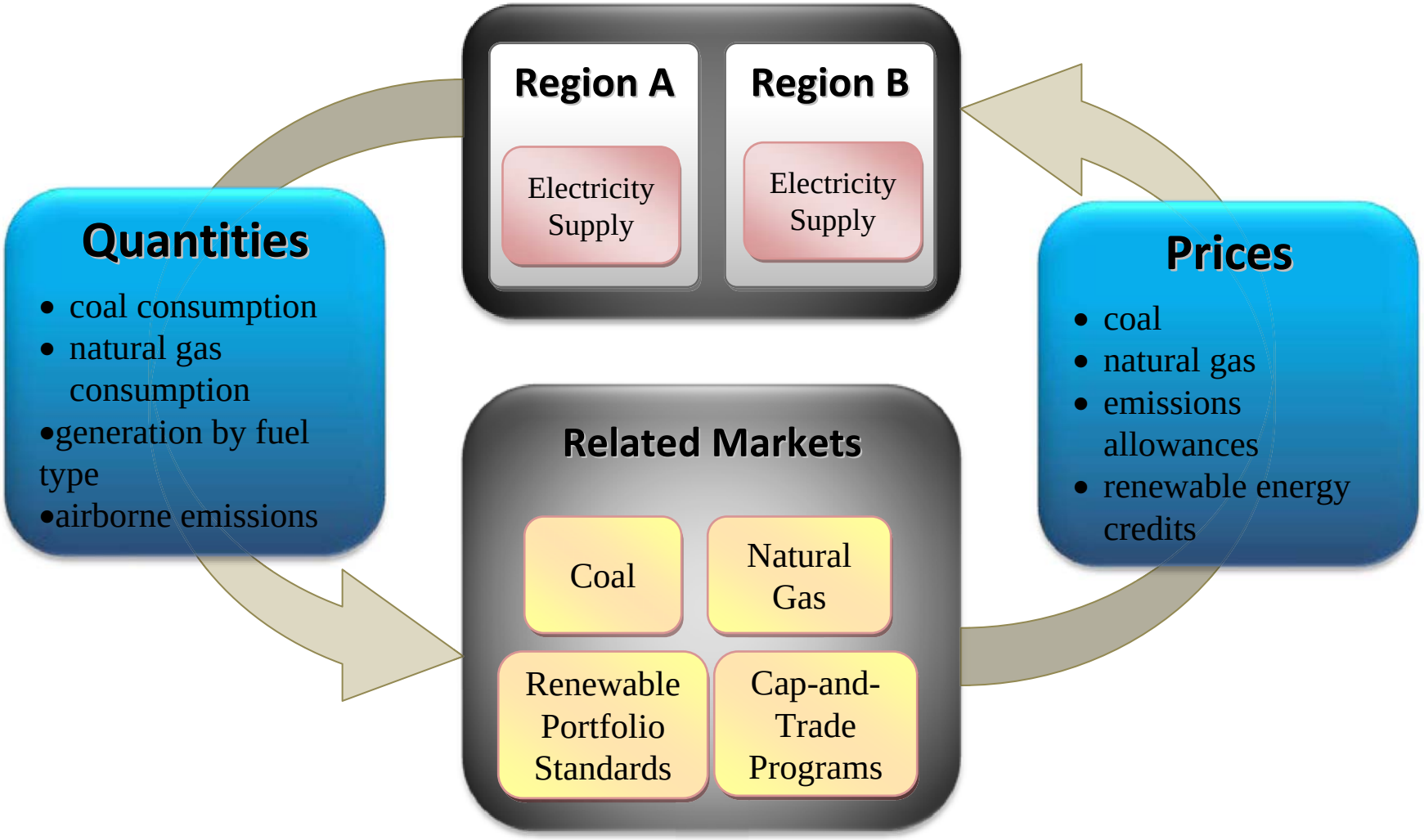



- 21 Haiku Market Regions
  - transmission grid
  - cost-of-service and wholesale competition
- Time
  - simulation years out to 2030
  - 3 seasons, 4 times of day
- Model Plants
  - groups of generators sharing fuel, technology
  - existing generators, planned & endogenous new construction

# Equilibria in Electricity Markets



# Linked Equilibria in Related Markets



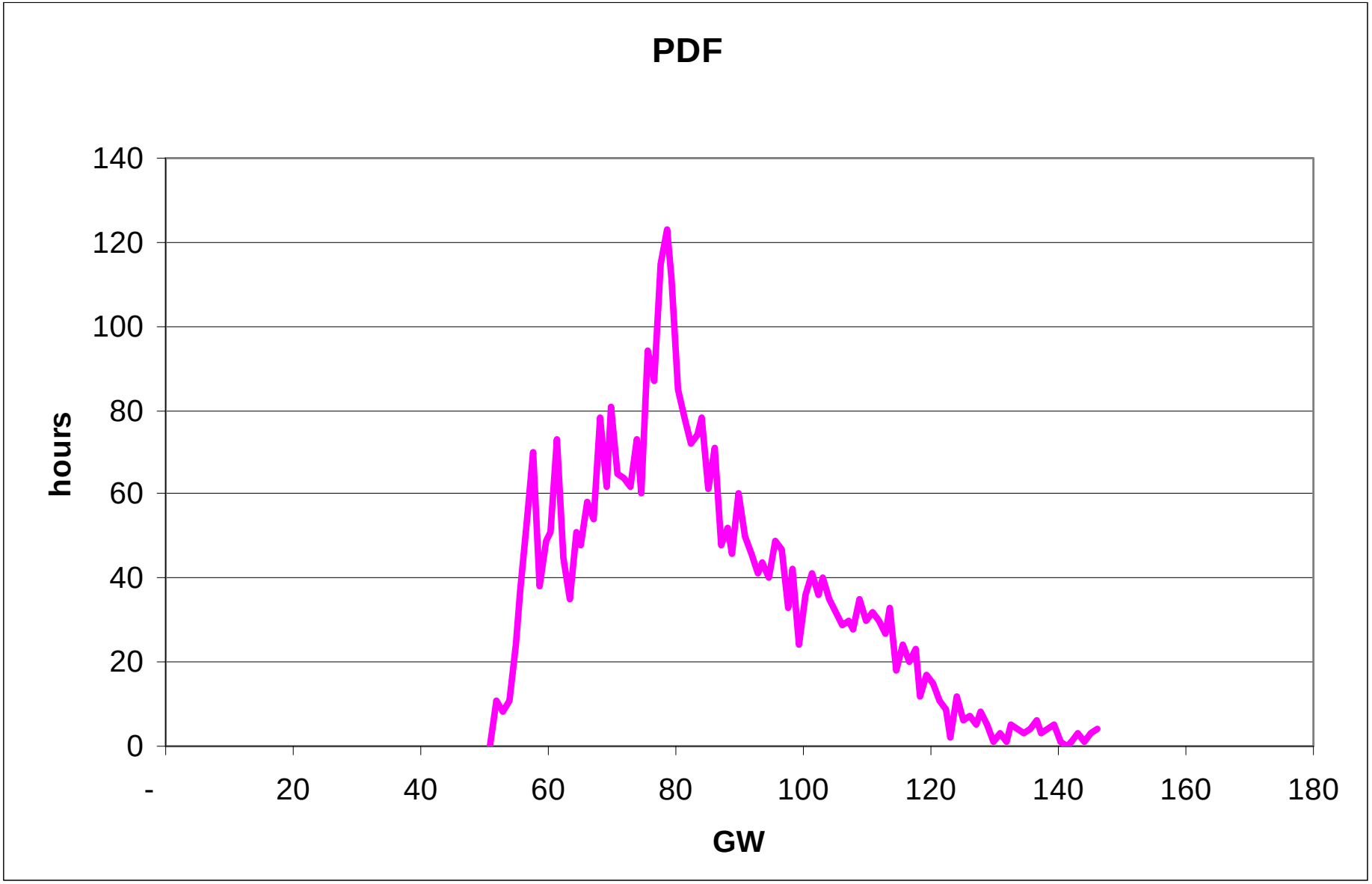
# Electricity Supply

- System Operation
  - minimize short-run generation cost
  - reserve services
- Generation Capacity Retirement/Investment
  - sequential and irreversible to minimize long-run total cost
- Air Pollution Abatement Technologies
  - SCR, FGD (wet & dry), ACI
- Other Functions
  - hydro capacity partially dispatchable
  - scheduled outages allocated by season
  - forced outages reduce capacity in all time blocks
  - limited biomass cofiring at coal boilers

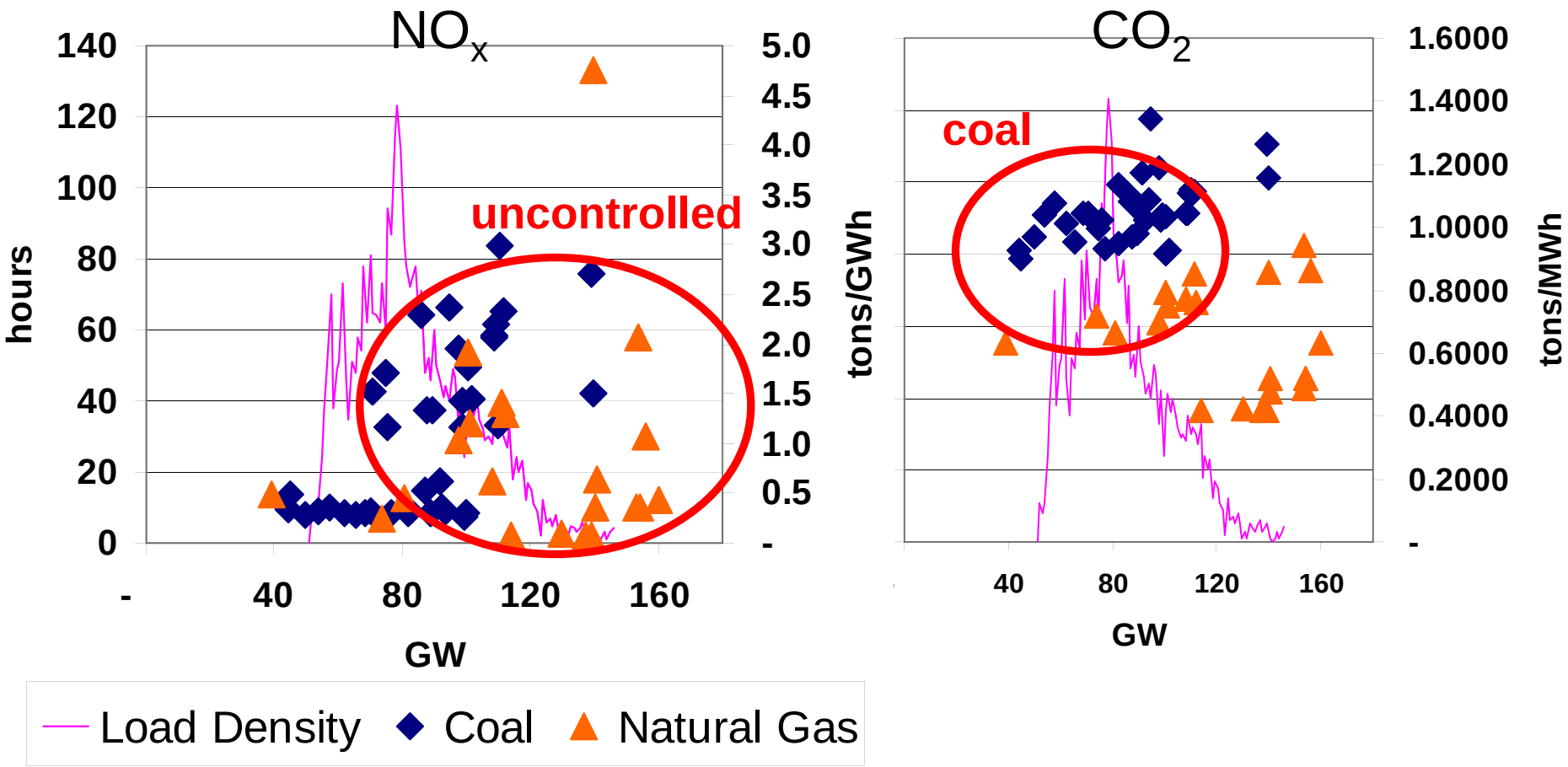
# Electricity Demand

- 3 customer classes: residential, commercial, industrial
- 2 stage demand system
  - seasonal demand depends on habit specification
  - time block allocation depends on CES function
- Habit Formation
  - simplified version takes the form: $Q_t = AQ_{t-1}^{\theta} P_t^{\varepsilon} X_t^{\beta}$
  - parameters are econometrically derived
    - $\theta$ is habit coefficient, $\varepsilon$ is short-run price elasticity
    - $X$ are covariates including weather, daylight, population, income
    - $A$ is a benchmarking constant derived using EIA projections
  - dynamics proxy for end-use capital efficiency investment

# 2006 Ozone Season Electricity Demand / PJM



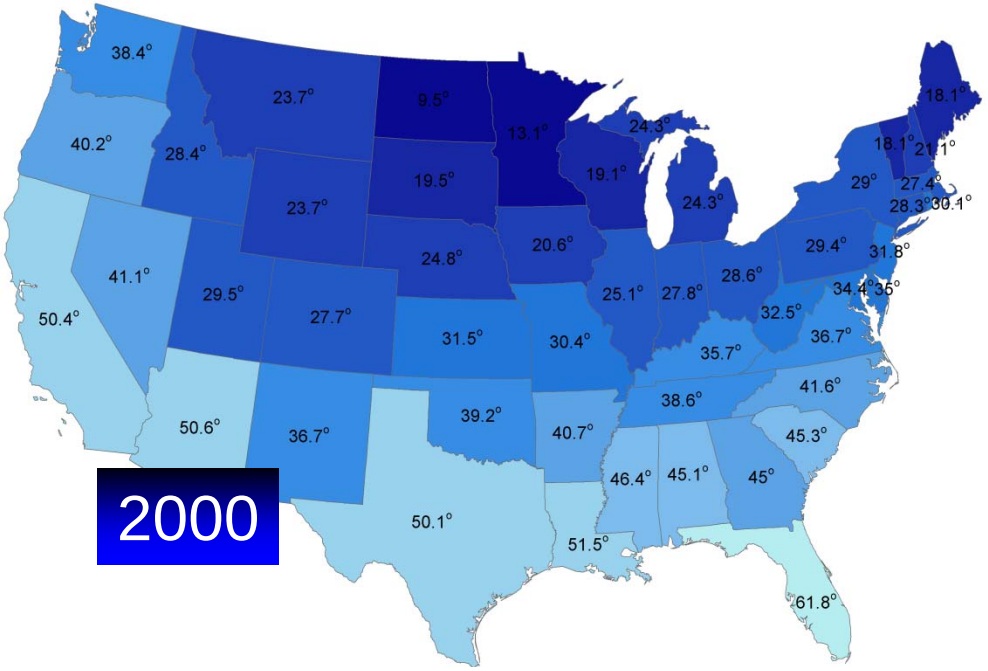
# Environmental Performance Varies with Load

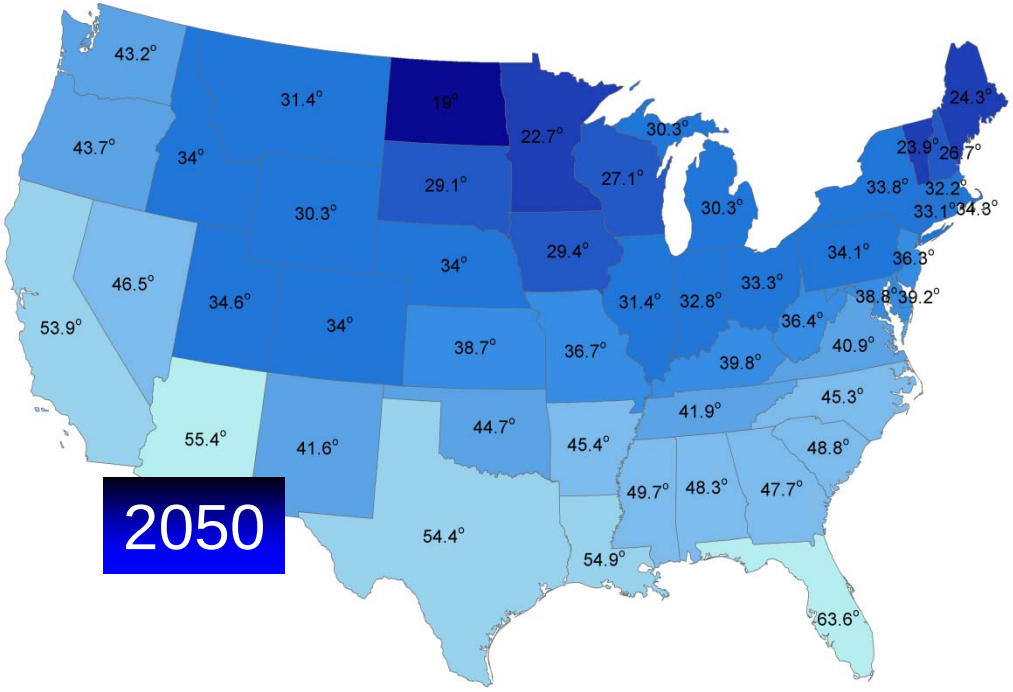



2006 Load Density and Emission Rates / PJM

# Changing wintertime temperatures

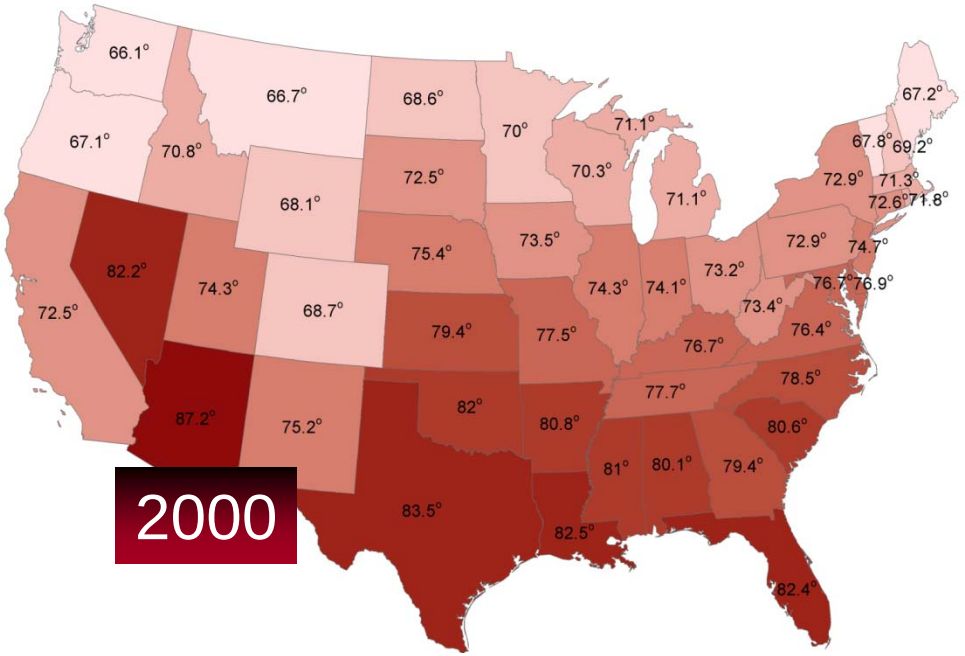
Lighter shades blue move to warmer wintertime temperatures, small reduction in electricity consumption

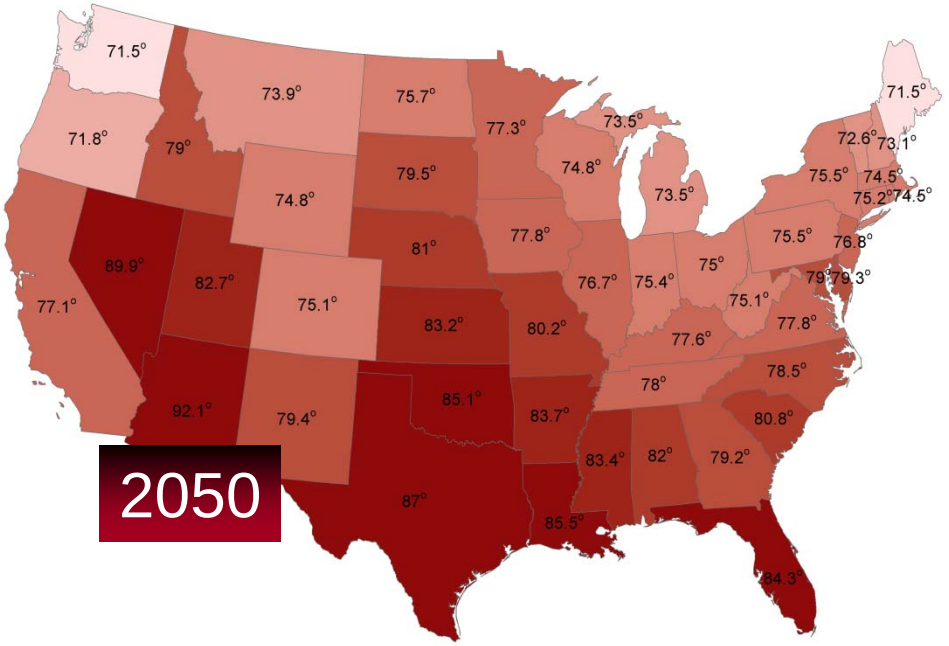


# Changing summertime temperatures

Lighter shades red move to warmer summertime temperatures, relatively large increase in electricity consumption



# Haiku Simulations

**Market equilibrium in 2030 under two climate scenarios**

1. Temperatures *circa* 2000

   (EIA reference case for 2030)

2. Temperatures *circa* 2050

   (Accelerated climate change)

Equilibrium adjustments in capacity and operation of electricity system

(Maintained assumptions: RGGI, CAIR)

# Changing climate affects demand, market equilibrium, how electricity generators operate

Temperature

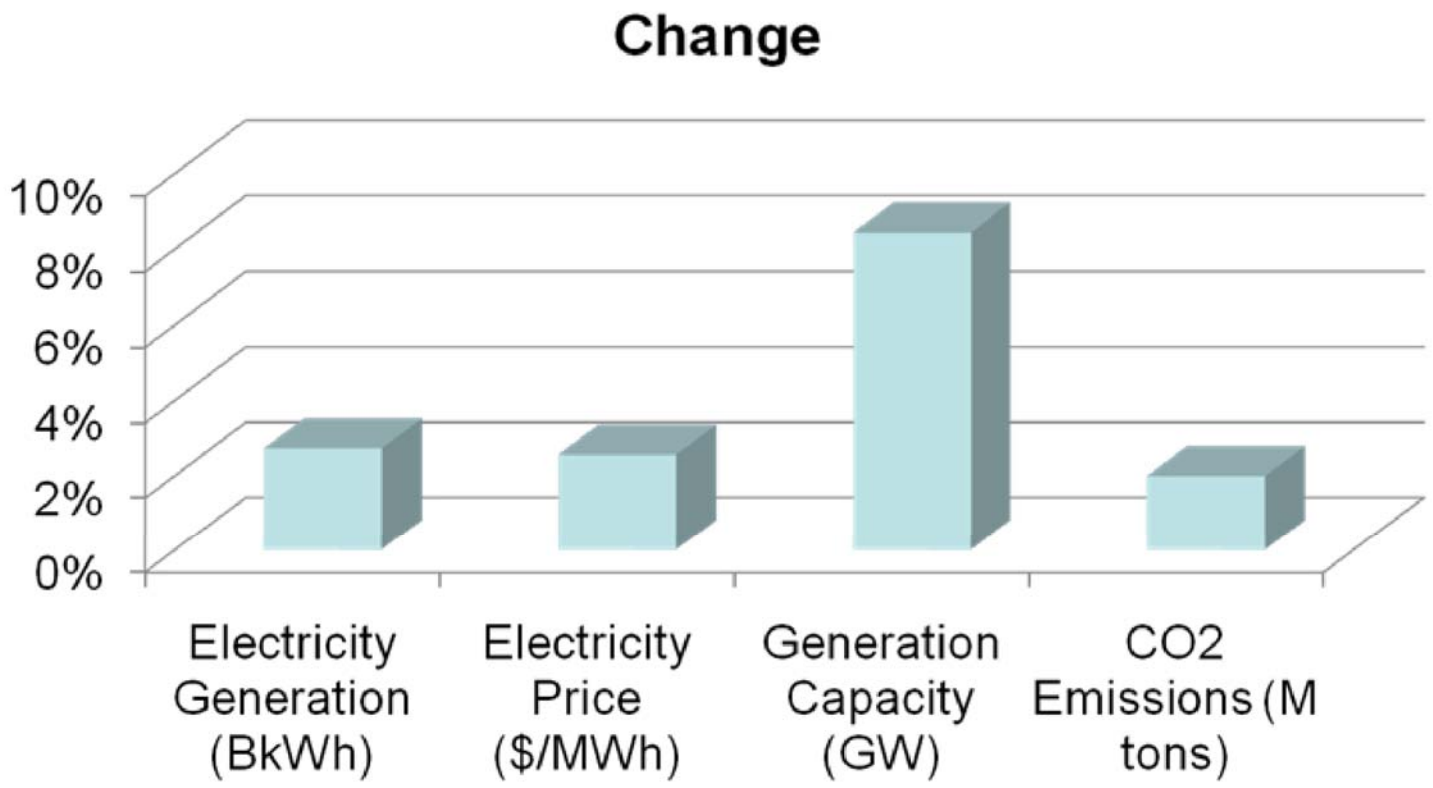
Consumption

Electricity Price

Generation Capacity

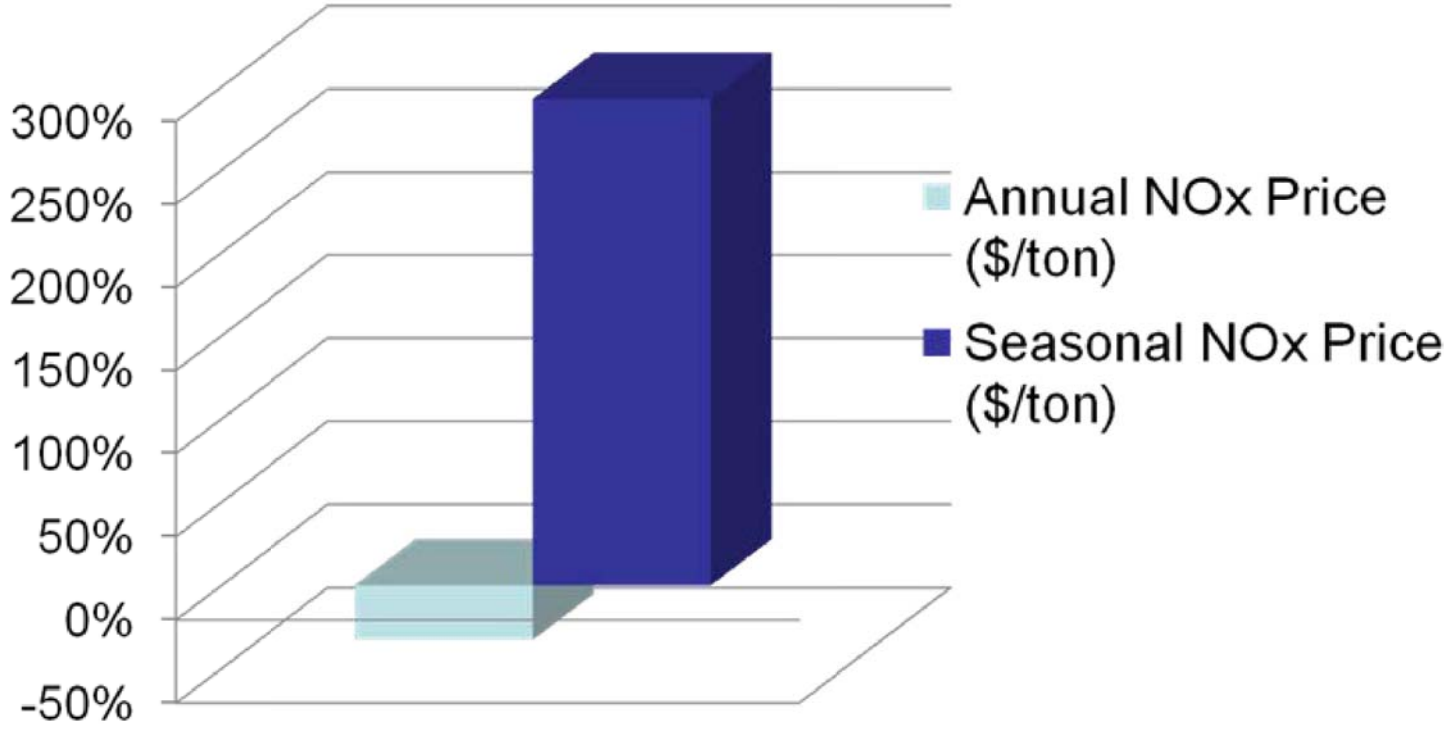
Seasonal shift in demand for emissions from winter to summer raising cost of compliance

# Changing climate affects demand, market equilibrium, how electricity generators operate




*Accelerated Climate Scenario in 2030:*
2050 climate versus 2000 climate

# Changing climate affects emissions markets (emissions are capped, but prices change reflecting ozone season demand for allowances)

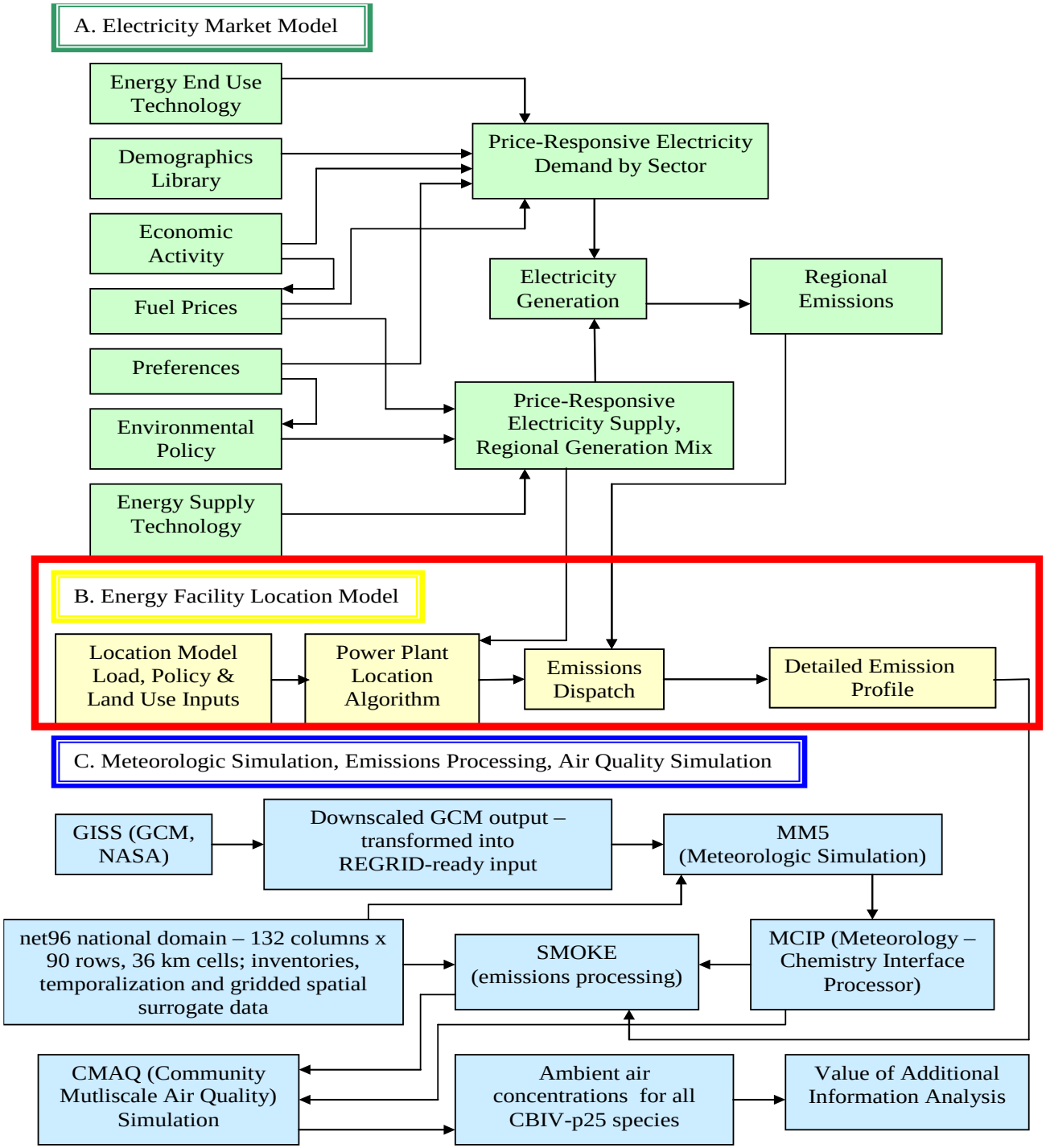



*Accelerated Climate Scenario in 2030:*
2050 climate versus 2000 climate

# *Emissions Downscaling*

**Benjamin F. Hobbs, Ming-Che Hu**
***The Johns Hopkins University***

**Yihsu Chen**
***University of California, Merced***

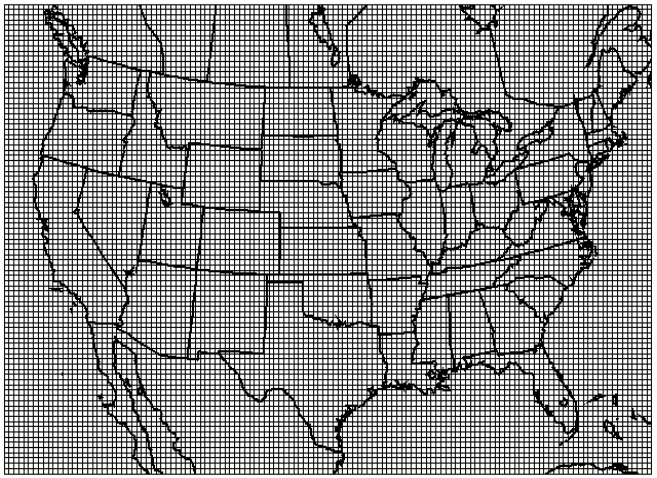



National Electricity Market Model

**Emissions Downscaling Model**

Air Quality Simulation

# The Downscaling Problem

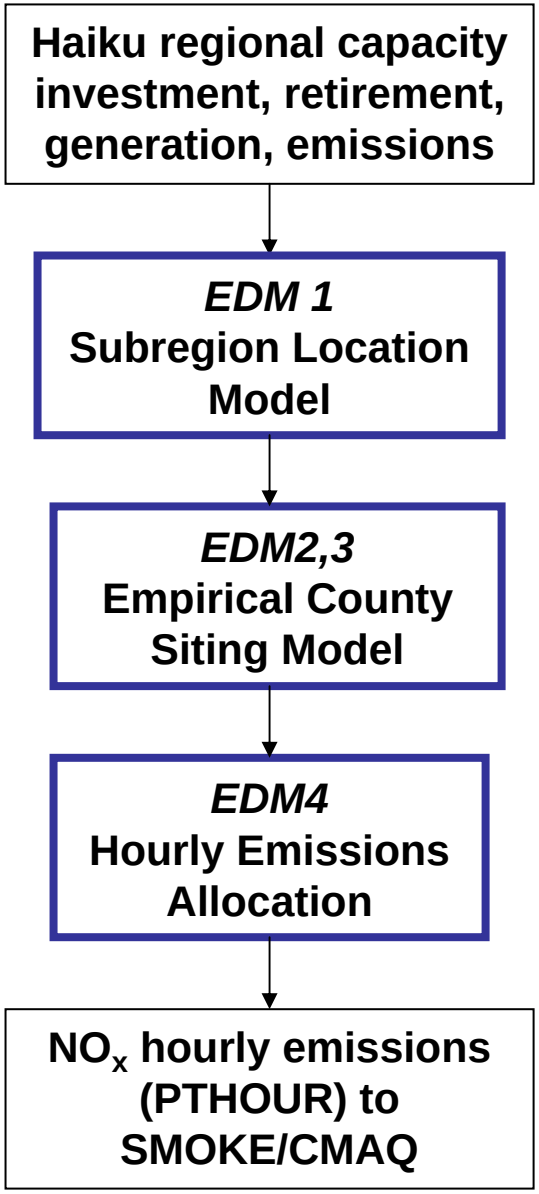


- **National electric sector models are aggregate in space and time. RFF *Haiku*:**
  - **21 market regions**
  - **12 time blocks per year**
  - **Based on average seasonal climate conditions**

- **The challenges:**
  - **CMAQ requires hourly emissions by point source**
  - **CMAQ results sensitive to interactions of location, meteorology and timing**
  - **There is significant interannual variation in weather and, thus, emissions and their impacts**

# Spatial & Temporal Disaggregation Approach

- ***EDM1***:
  - Optimization
  - Allocates Haiku regional capacity to subregions
  - Operates capacity on a detailed temporal basis for average year
  - Considers transmission grid, demand locations, fuel price differences, locations of existing facilities
- ***EDM2***:
  - Empirical (regression) siting models (one per generation technology)
  - Probability of siting new facilities in a county = f(population, non-attainment status, other characteristics)
- ***EDM3***:
  - Optimization
  - Assigns new capacity to counties consistent with EDM2
- ***EDM4***:
  - Translates EDM1 emissions to source-specific hourly emissions for particular meteorological year
  - Average over years consistent with Haiku regional emissions and energy results



# Two Climate Scenarios: Year 2030 Loads, Generation, Emissions under 1990s Climate vs. 2050s climate

- **Two scenarios of Year 2030 results from Haiku**
  - **newBL: Current 1990s climate:**
    - **all Haiku years (2010-2030) assume CDDs and HDDs typical of 1990-2006. Method is roughly consistent with EIA.**
  - **ACC: Accelerated Climate Change 2050s climate:**
    - **CDDs and HDDs change linearly from present climate (1990-2006 average climate ) from 2006 to ACC level by 2030.**

# EDM1 Downscaling Approach: Subregional Siting and Dispatch (PJM Example)

## *2030 new plant location in 1990s and 2050s climates*

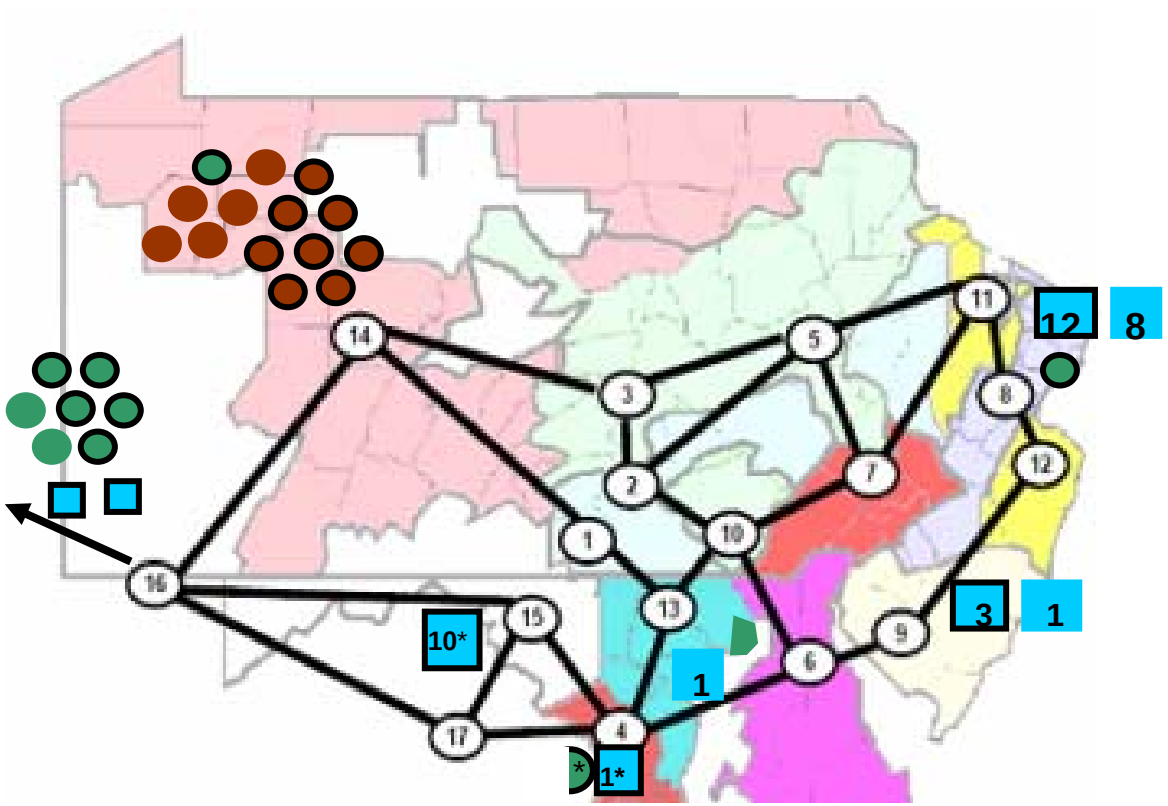
**Key:**

Integrated Gasification/Combined Cycle (1990s climate; 2050s climate increment)

Coal Steam (1990s climate; 2050s climate increment)

12 8 Gas Combined Cycle (# units) (1990s climate; 2050s climate increment)

*Note:* Asterisk indicates plant not sited there in 2050s scenario



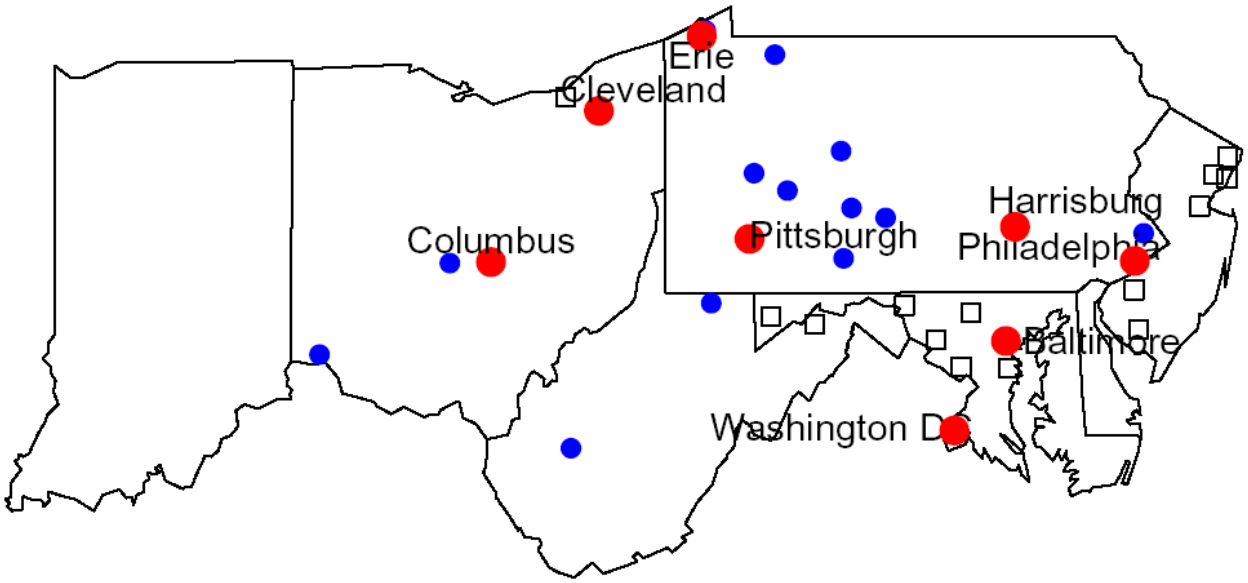
# Location:
# Effects of Fuel Costs, Effects upon Health

- **If coal in western PA is than in eastern PA**
  - **All of Haiku model plant 258 is sited in the west (4800 MW (1990s climate) and 7800 MW (2050s climate)). Power then shipped east**
- **Wouldn't occur if instead fuel prices are the same in both regions**
- **Change in emissions locations could have public health implications**
  - **Total emissions unchanged**

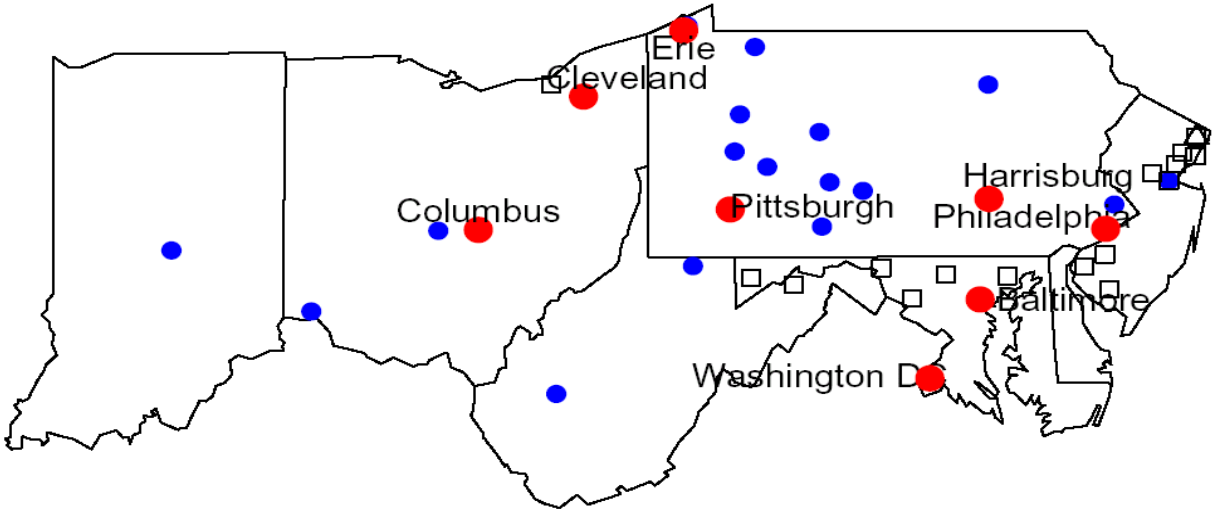
# EDM2 & EDM3 Spatial Disaggregation to Counties: New Emissions Sources in 2030, "PJM-ECAR" Region

**1990's climate**

- Baseload fossil
- Combined cycle
- Peaking
- City



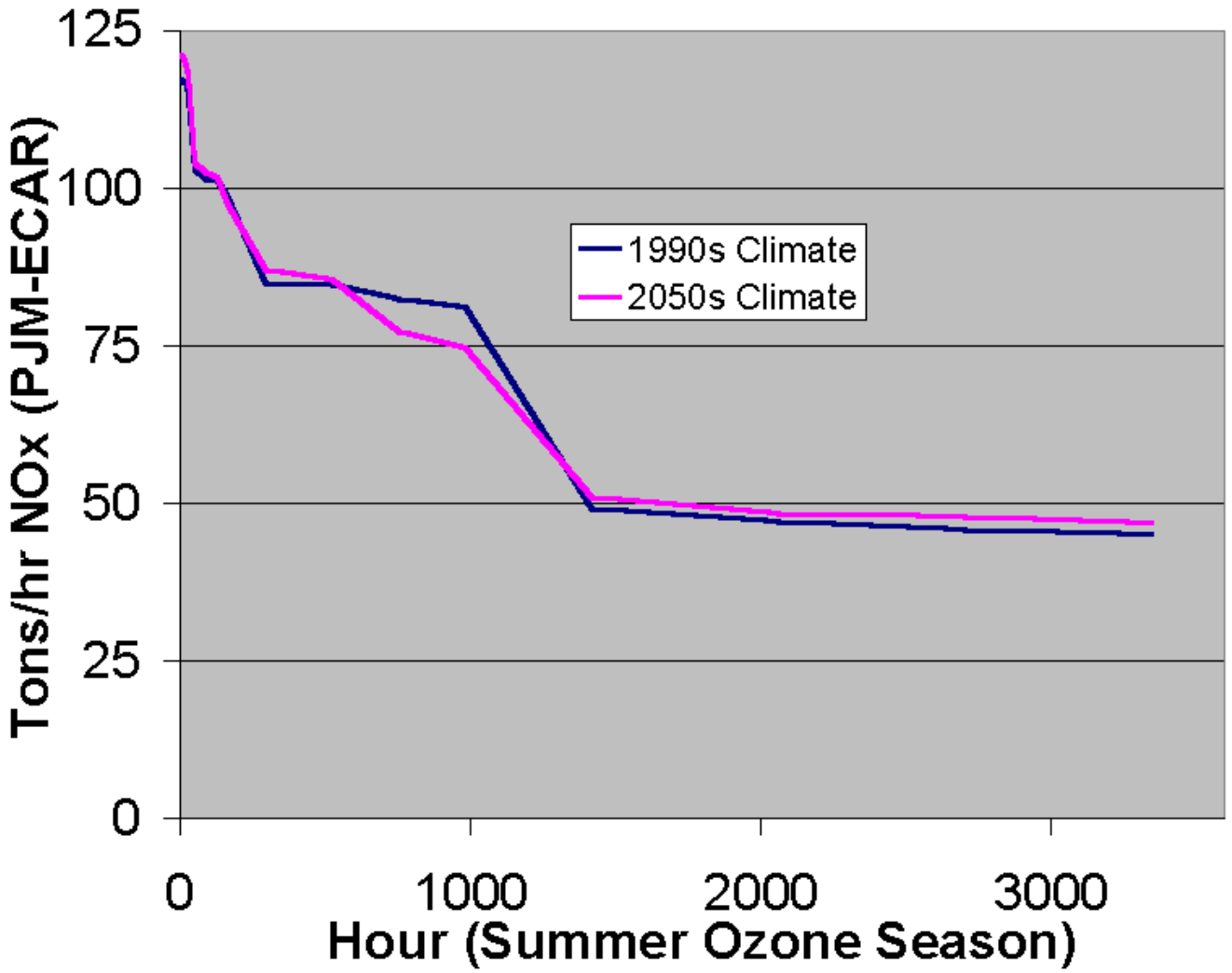

**2050's Climate (*More plants*)**



# EDM1: From Four Periods to Sixteen

## *Average Summer Emissions Duration Curve*

- **Total emissions the same (capped)**
- **2050s climate increases peak emissions by 3% (broadly consistent with our previous work)**
- **May understate peak differences (Haiku does not increase relative peak, even though greater use of Air Conditioning)**



# EDM4: Temporal Disaggregation Approach Capturing Inter-year Variability

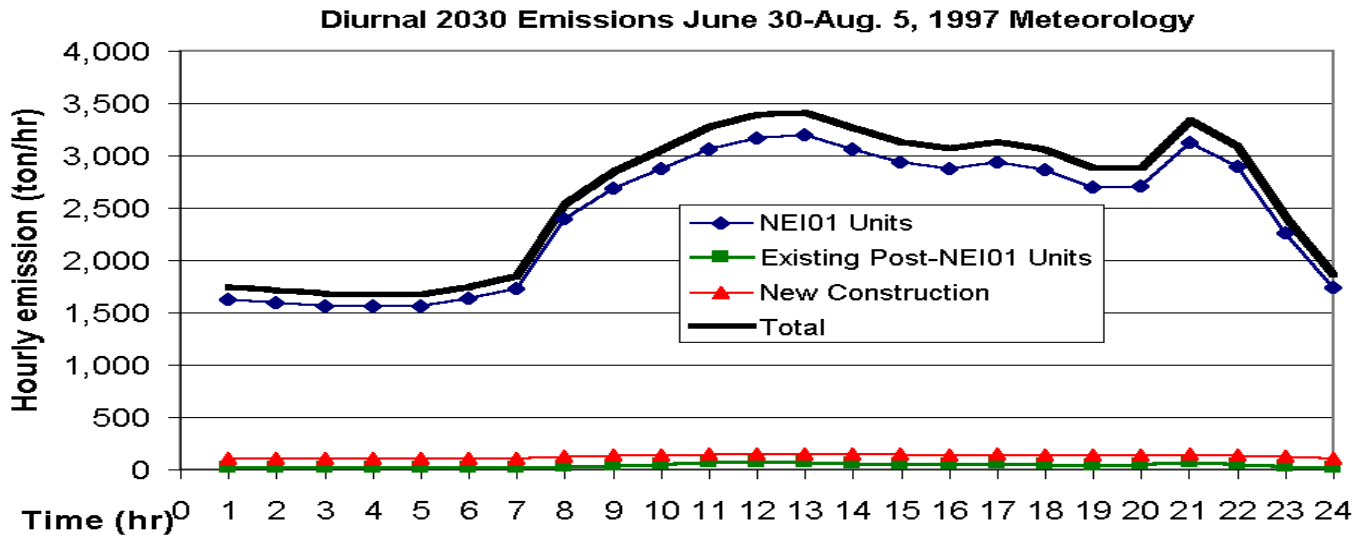
- **Inputs:**
  - **Haiku electric loads for 12 time periods under avg climate**
  - **Multiple years of simulated temperature data (from MM5)**
    - ***1990s (present climate)***
    - ***2050s (future climate)***
  - **Short-run (hourly) statistical model projects <u>short run</u> (given <u>fixed</u> capital stock) load response to temperature changes**

- **Procedure:**
  - **Project hourly normalized load response to hourly temperatures**
    - ***For each year in each decade***
  - **Converts normalized loads to hourly loads whose multiyear averages are consistent with Haiku time-averaged loads**
  - **Resulting rescaled loads vary from year-to-year based on temperature**
    - ***Emissions likewise vary annually***
    - ***Captures hourly correlation between $^{o}C$ and EGU $NO_x$ because loads/emissions chronology consistent with temperatures***

# EDM4: Example Diurnal Profiles for 2030 Emissions (1990s & 2050s climate, "PJM-ECAR" Region)

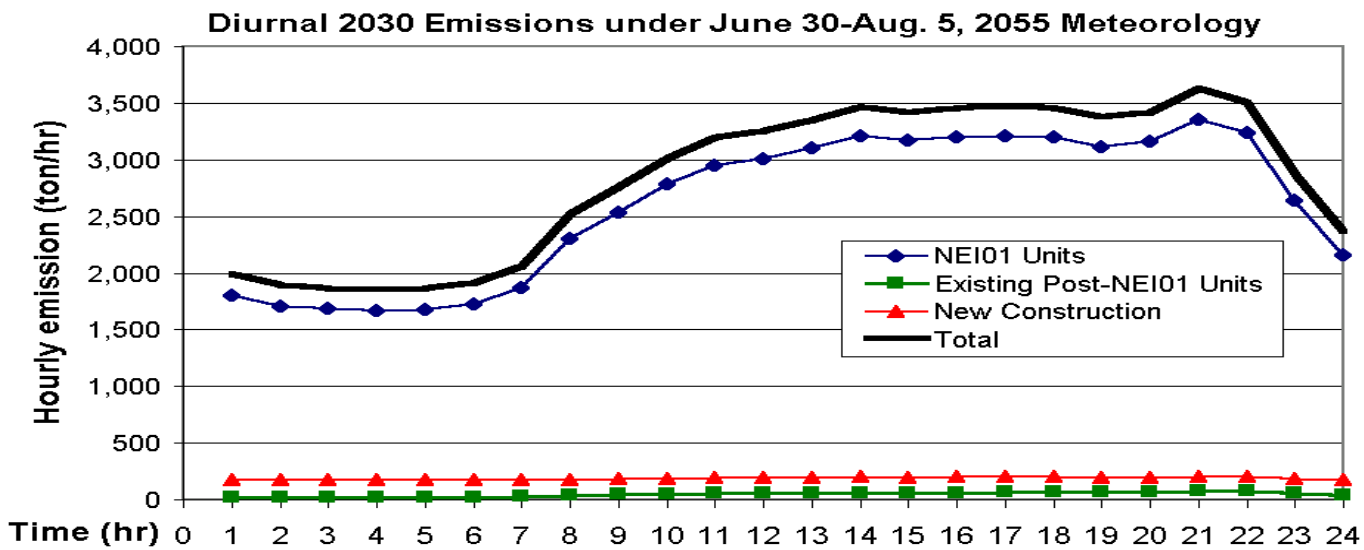
"1997":

62,800 tons




"2055":

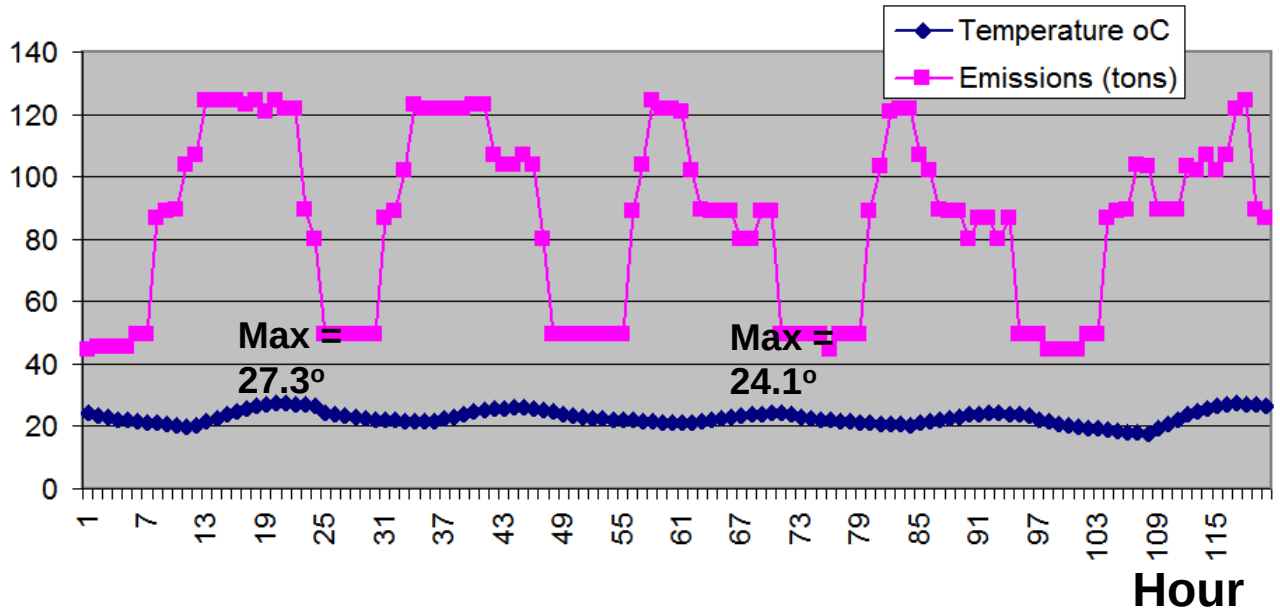
68,100 tons



# EDM4: Emissions for High Temperature Weeks

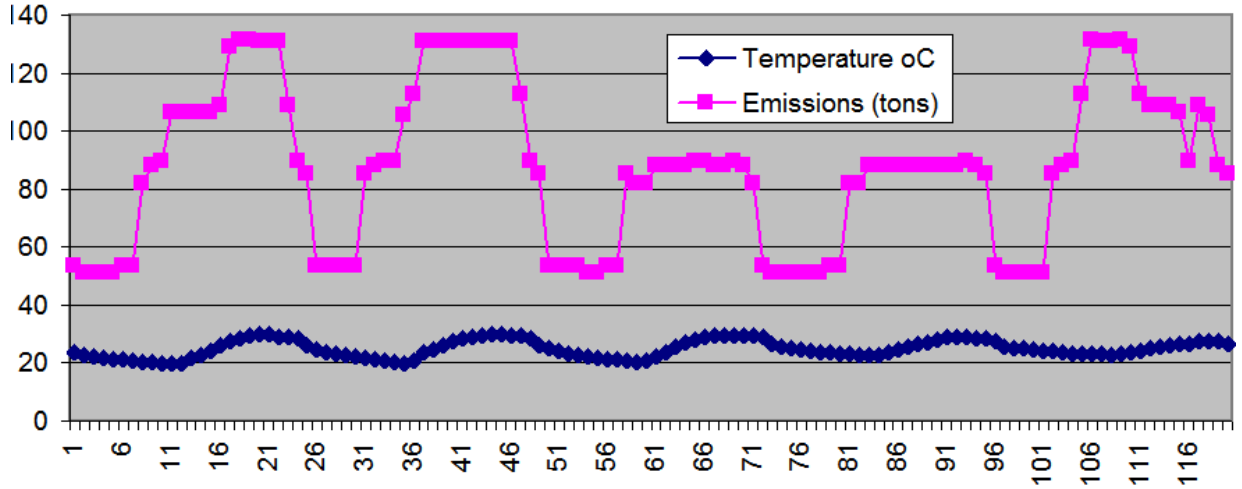
"7/28 – 8/01/1997"

*Note: Lower temperature days have lower emissions*




"7/29 – 8/02/2055"

*Note: Higher temperatures than in 1990s*



# Interannual Variability in Emission Distributions

## *There is significant year-to-year variability in temperatures →loads→emissions*

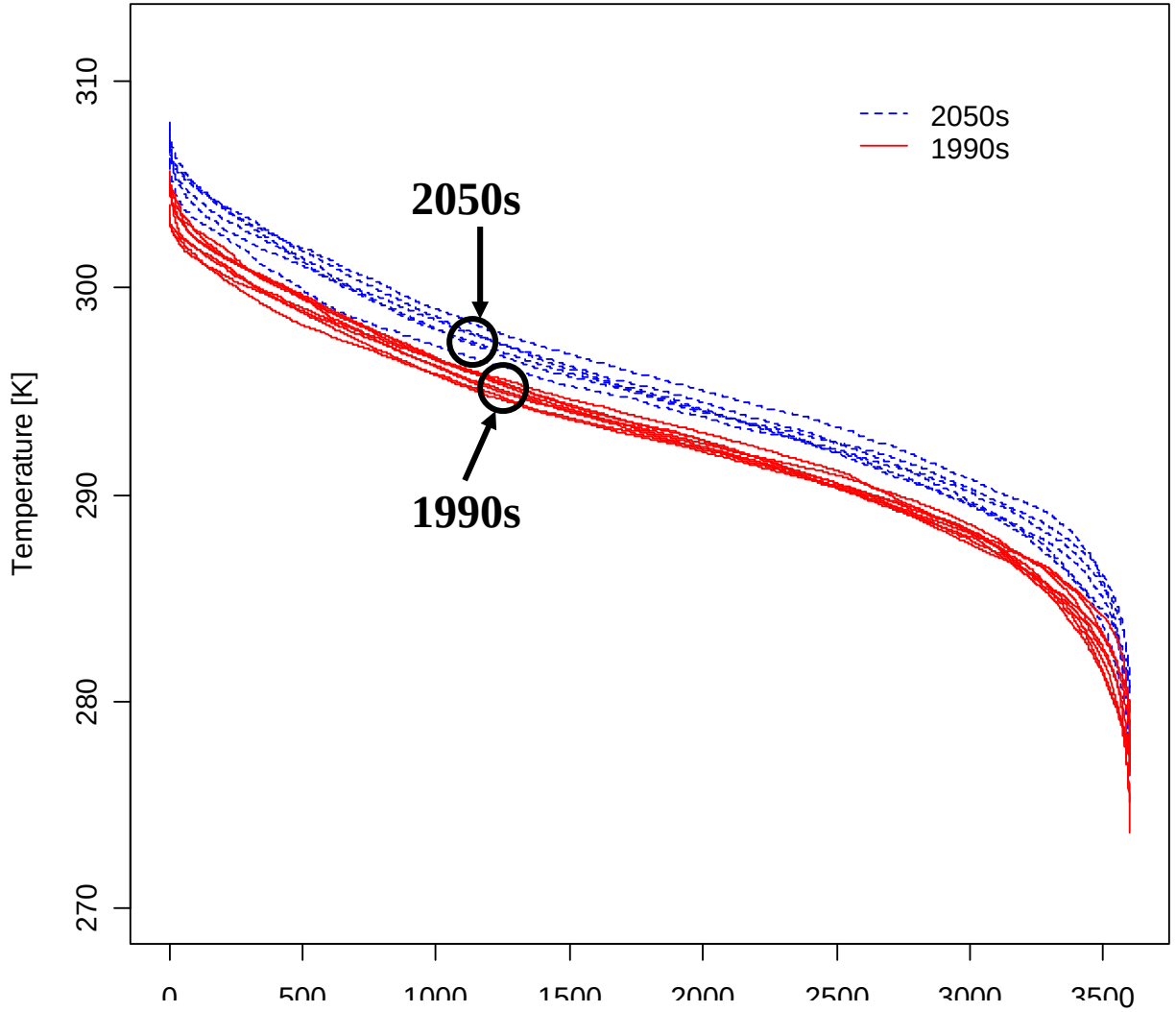
***(1) Temp. Variability***

***⇒***

***(2) Load Variability***

***⇒***

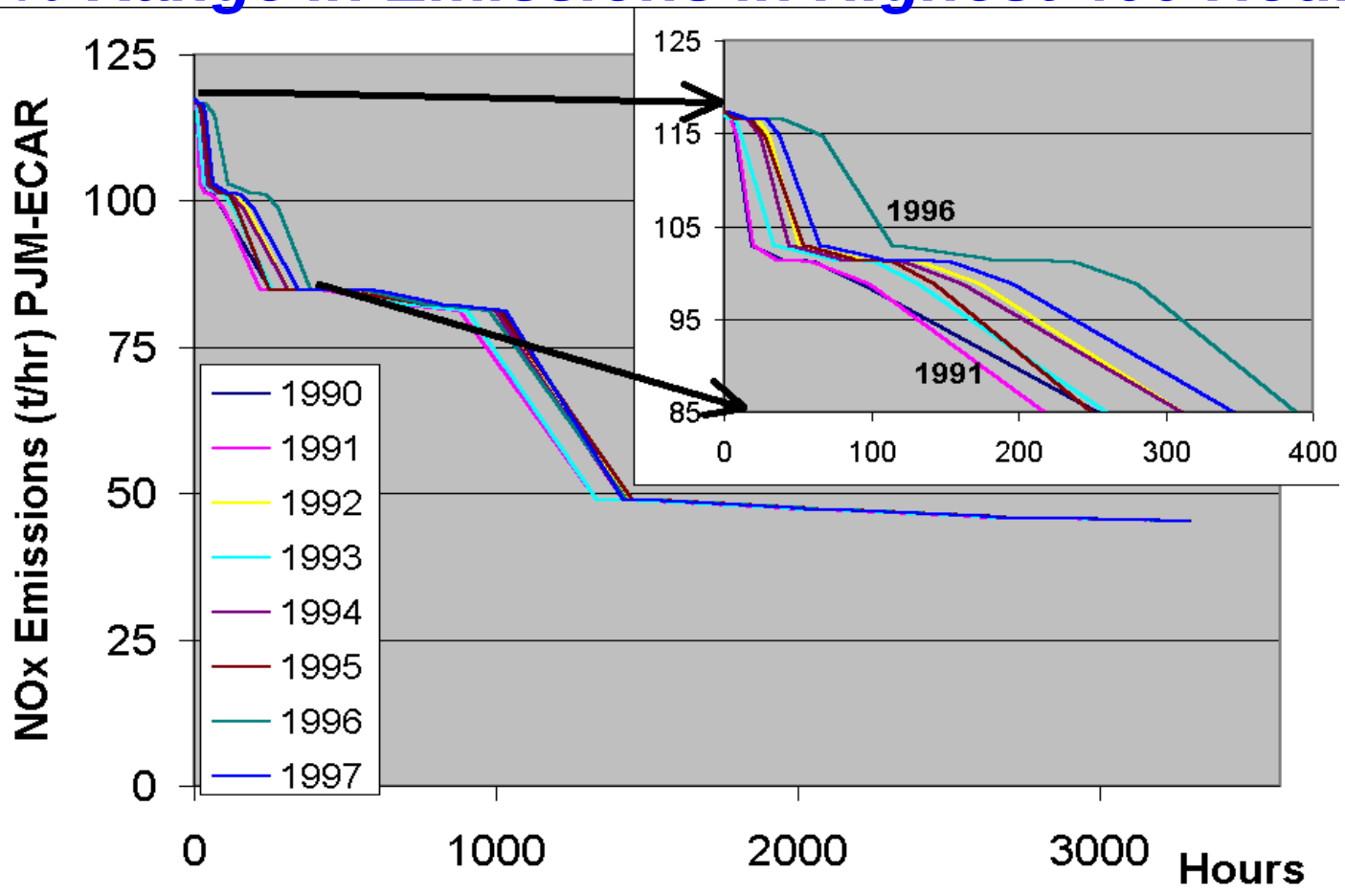
***(3) Emissions Variability***




**Right: (1) Temperature Duration Curve Showing Interannual Variability (PJM Region)**

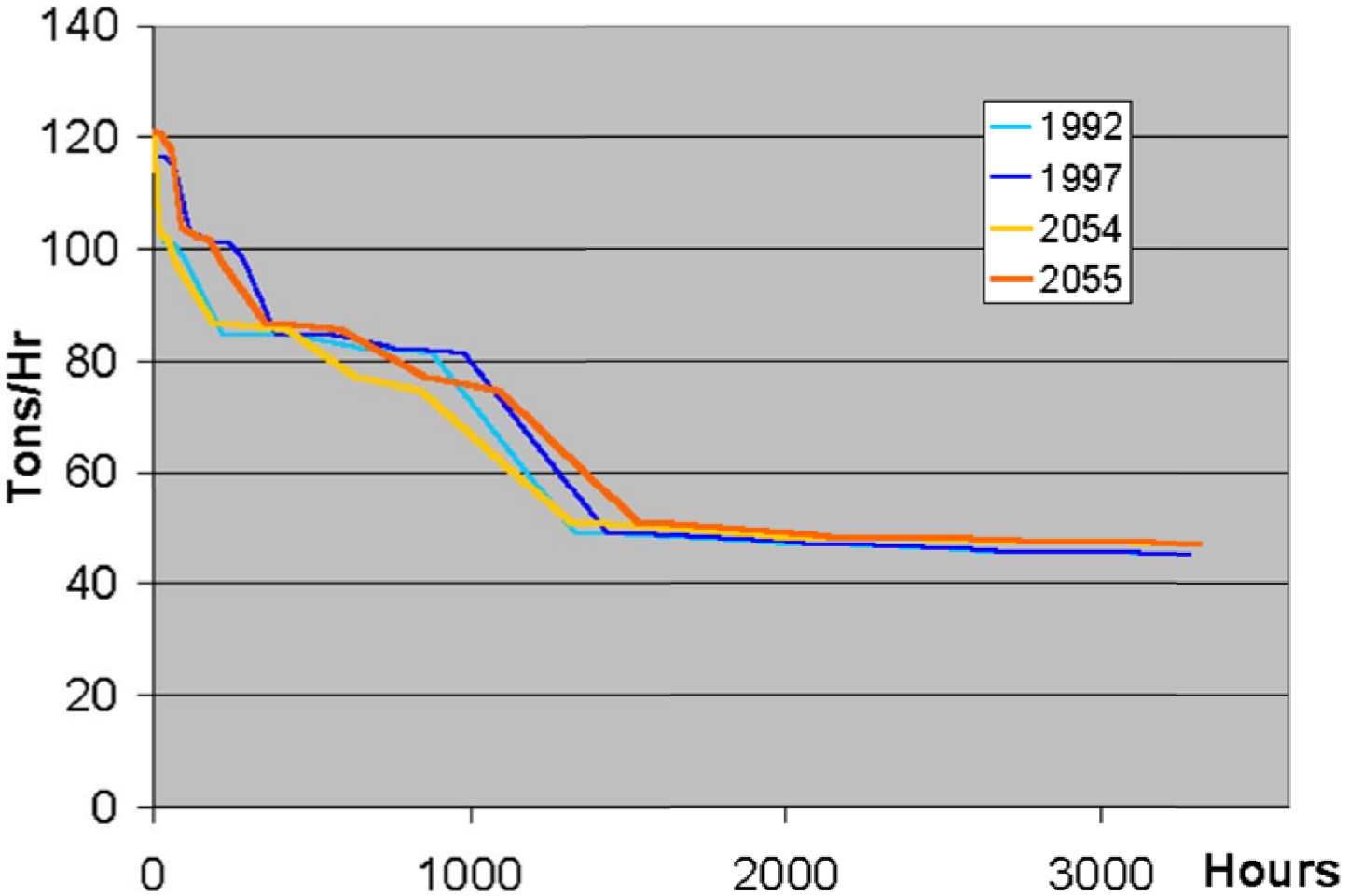
# Emissions Variability Between-Years under Given Climate

## *1990s Climate: 10% Range in Emissions in Highest 400 Hours*



# (3) PJM/ECAR Interannual variation in $NO_x$

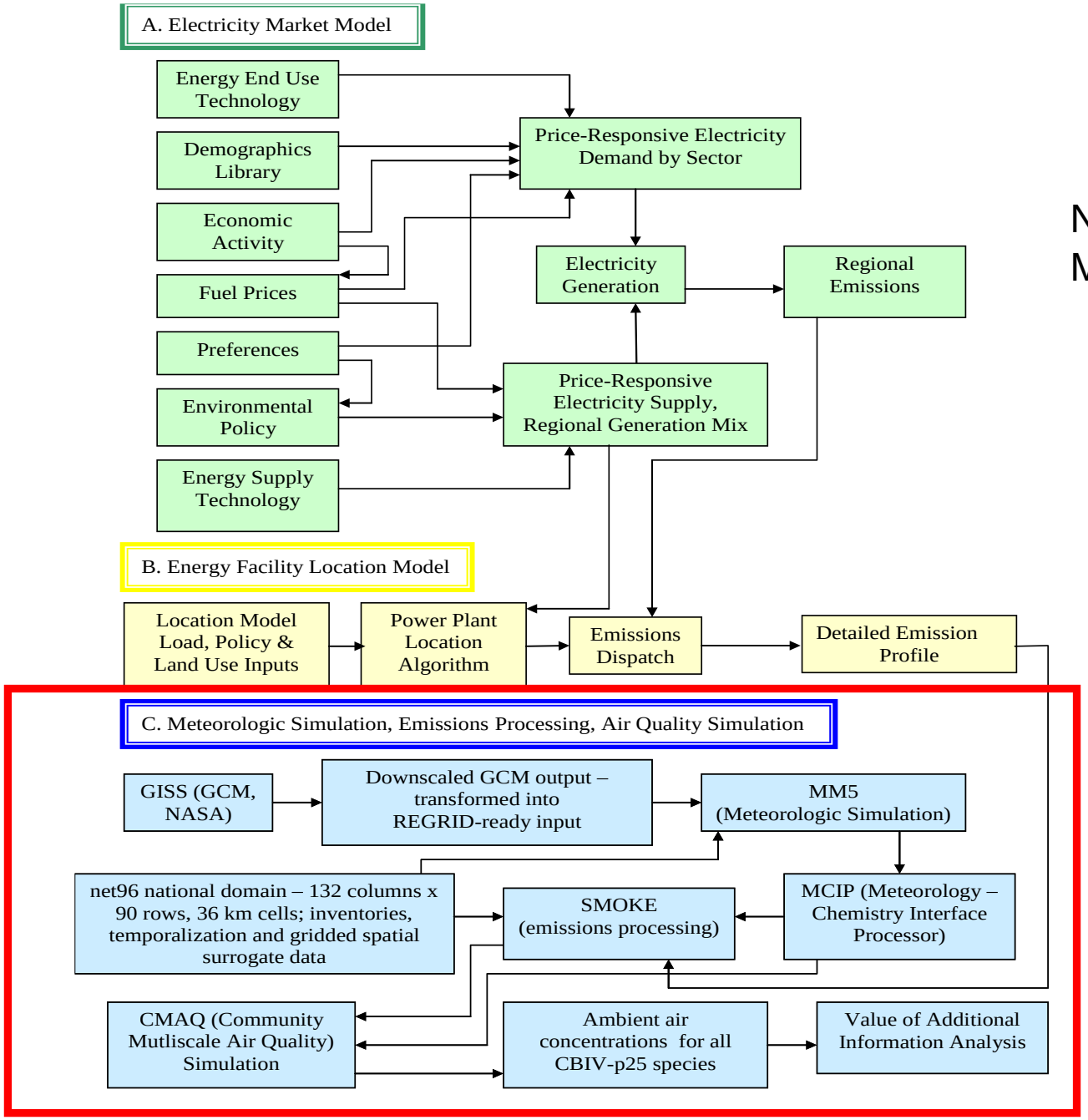
## *Between Year Variation (Within Decades) > Differences between Decades*



# *Meteorology, Emissions and Air Quality Modeling*

**Hugh Ellis**

***The Johns Hopkins University***




National Electricity Market Model

Emissions Downscaling Model

**Air Quality Simulation**

# Computing Environment

- **Linux cluster:**
- **40 dual Xeon compute nodes**
- **Mpich2**
- **Gigabit ethernet**
- **20+ Terabytes of storage**
- **environmental monitoring (liquid detection, temperature, humidity, voltage) with silent notification and automatic soft system shutdown and poweroff**

- **parallel versions of MM5 and CCTM**
- **speedup is significant**
- **network latency effects noticeable but not overly problematic**

- **Created and test a serial/parallel* implementation of SMOKE (perl and c-shell scripts invoke multiple simultaneous instances of SMOKE, one per compute node; this is helpful for SMOKE production runs involving many days and/or many days and multiple years).**

* - aka Flintstones parallelism

## Overview of Modeling Activities

- using the US 36km 132x90 national domain, the net96 emissions inventory and the cb4_ae3_aq chemical mechanism:

  - generated May through September air quality simulations (MM5-MCIP-SMOKE-CMAQ) for 1990 through 1999 driven by GISS first guess fields (4 degrees by 5 degrees; 26x20 grid at 12 pressure levels) transformed into MM5-ready (regridder) input

  -generated May through September air quality simulations for 2050-2059

  - analyses constrained by GISS first-guess data availability; this has changed

## Overview of Modeling Activities – Cont'd

-made operational and tested the air quality modeling system with new domains and emissions inventories, gridded surrogates and chemical mechanism:

- US36km_148X112 (national domain – nested in a 108km MM5 domain)
- US12km_160X120 (a nested subdomain covering the PJM electric grid)
- US4km_172X120 (a nested subdomain focused on MD, VA, PA)
- Different MM5 vertical resolutions: 15 and 34 layers
- Different MCIP vertical resolutions: 12, 13, 15 and 17 layers
- FDDA vs no FDDA

## Overview of Modeling Activities – Cont'd

- NEI01 emissions inventory

- EPA "new" gridded surrogates

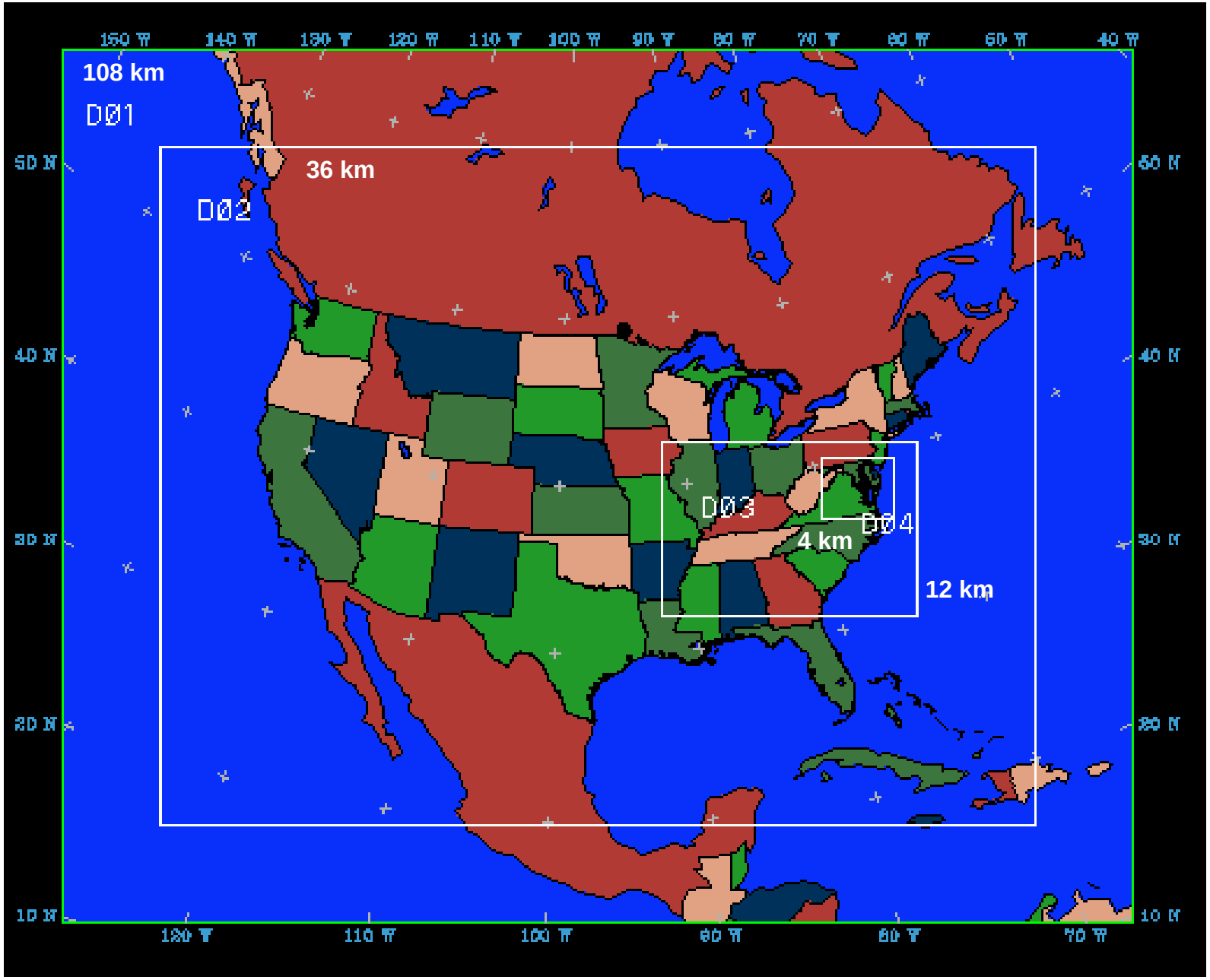
-a set of simple routines to window the new surrogates to conform to user-specified subdomains

-generation of new BELD3 inputs for user-specified subdomains using beld3smk (a component of the spatial allocator)

- cb05_ae4_aq chemical mechanism

-ping and noping selections in SMOKE V2.4 and CMAQ4.6

-different elevated source selection criteria


108 km
D01
36 km
D02
D03
4 km
D04
12 km
150 W
140 W
130 W
120 W
110 W
100 W
90 W
80 W
70 W
60 W
40 W
50 N
40 N
30 N
20 N
10 N
120 W
110 W
100 W
90 W
80 W
70 W

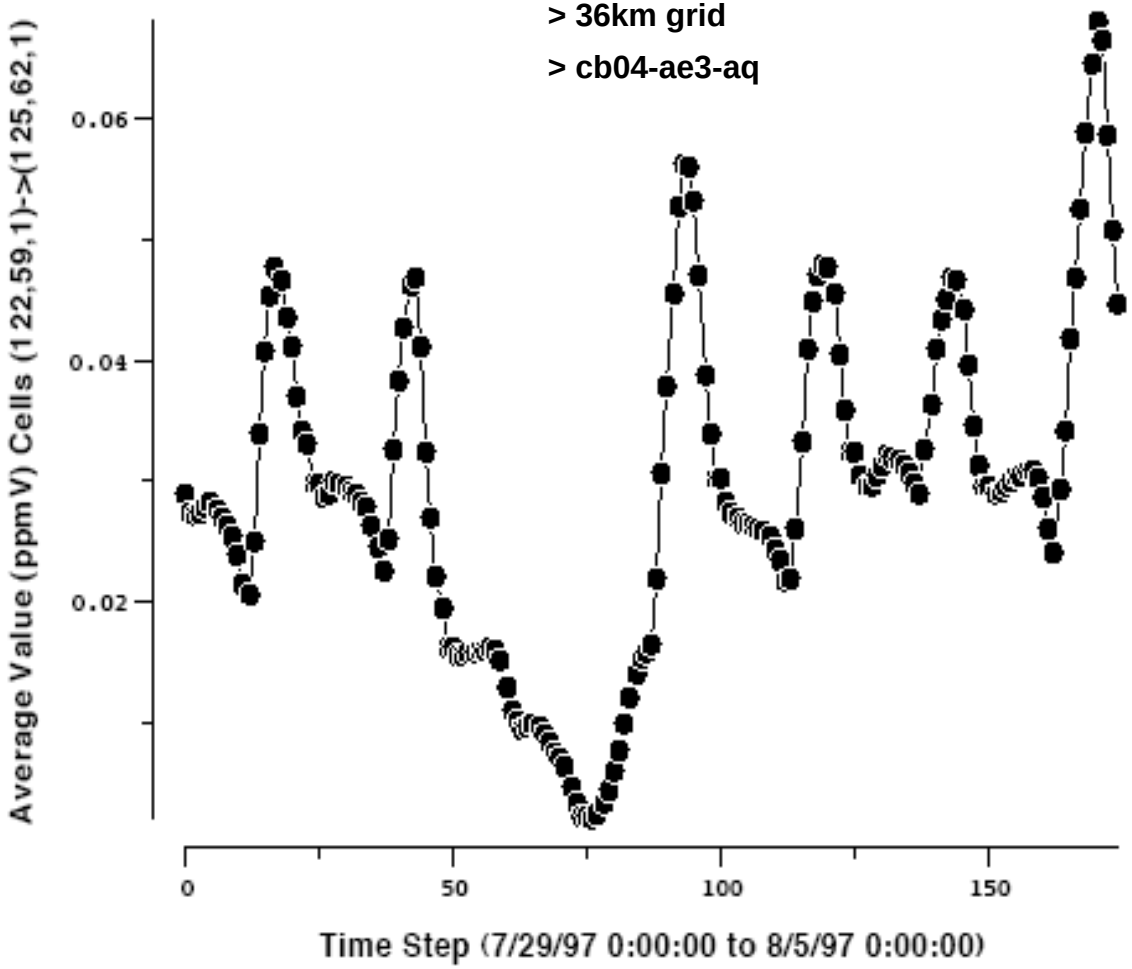
# A Sample of Air Quality Results using the NEI01 Inventory and Meteorology from late July, 1997 and 2055

**The indicated cells cover a region that includes Baltimore and DC**

**> 1997 Meteorology**

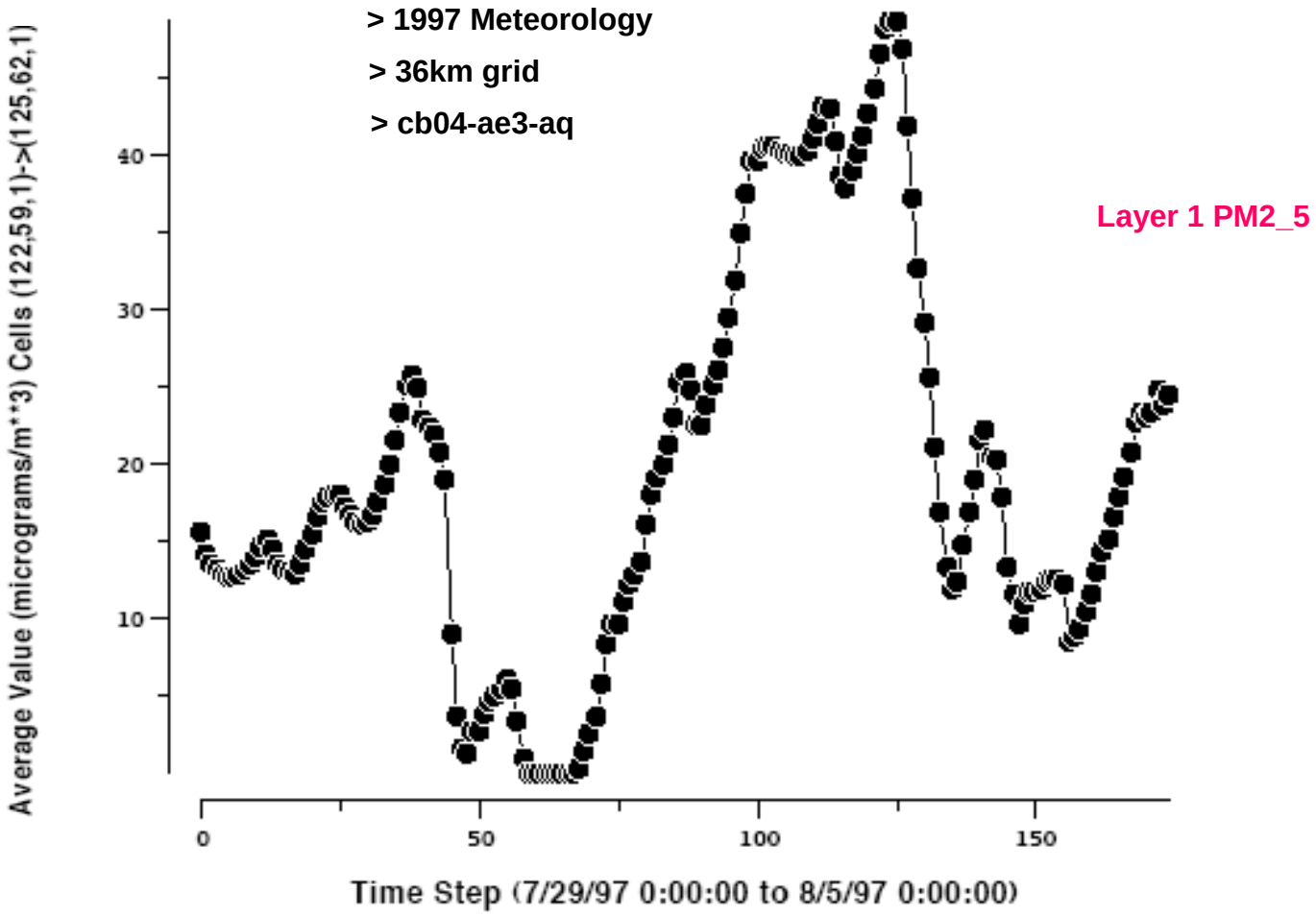
**> 36km grid**

**> cb04-ae3-aq**




**Layer 1 Ozone**

**The indicated cells cover a region that includes Baltimore and DC**

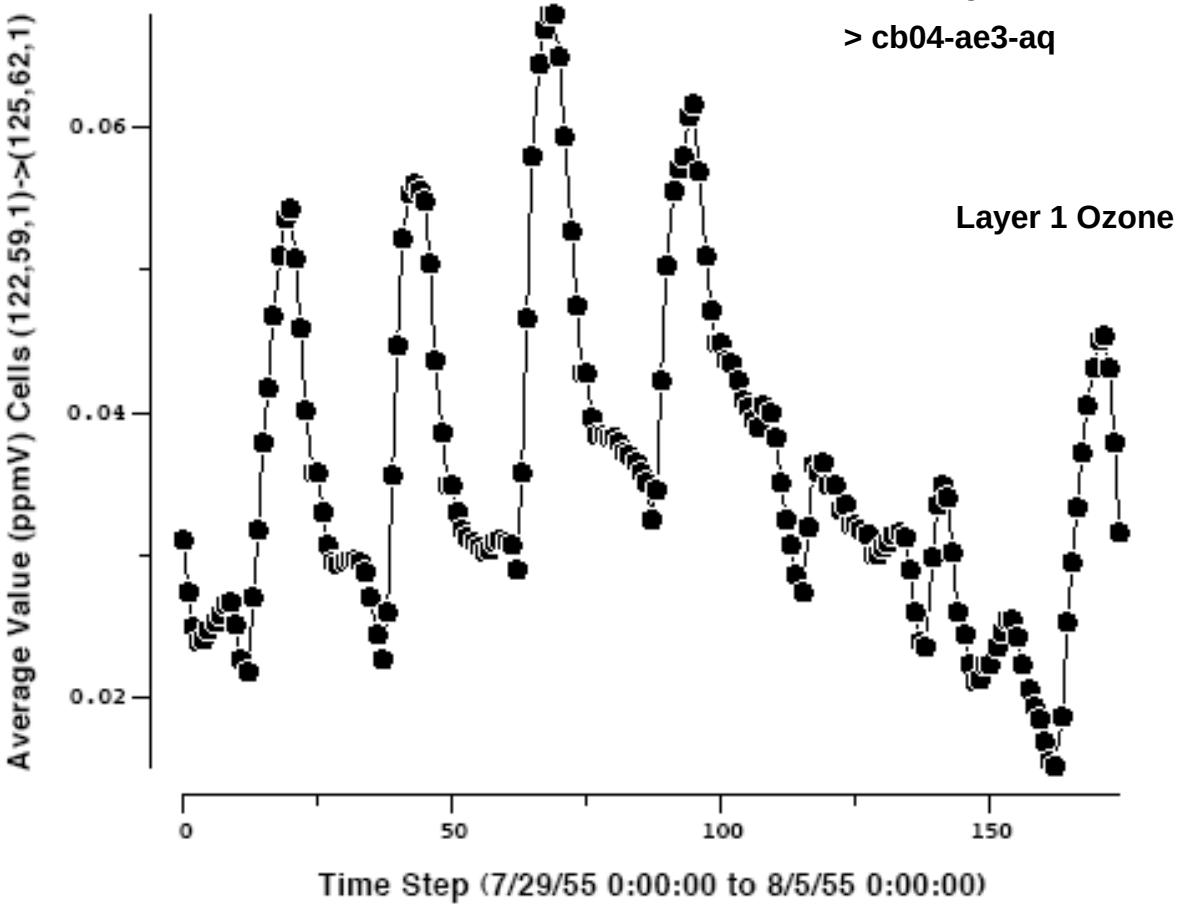


**The indicated cells cover a region that includes Baltimore and DC**

**> 2055 Meteorology**

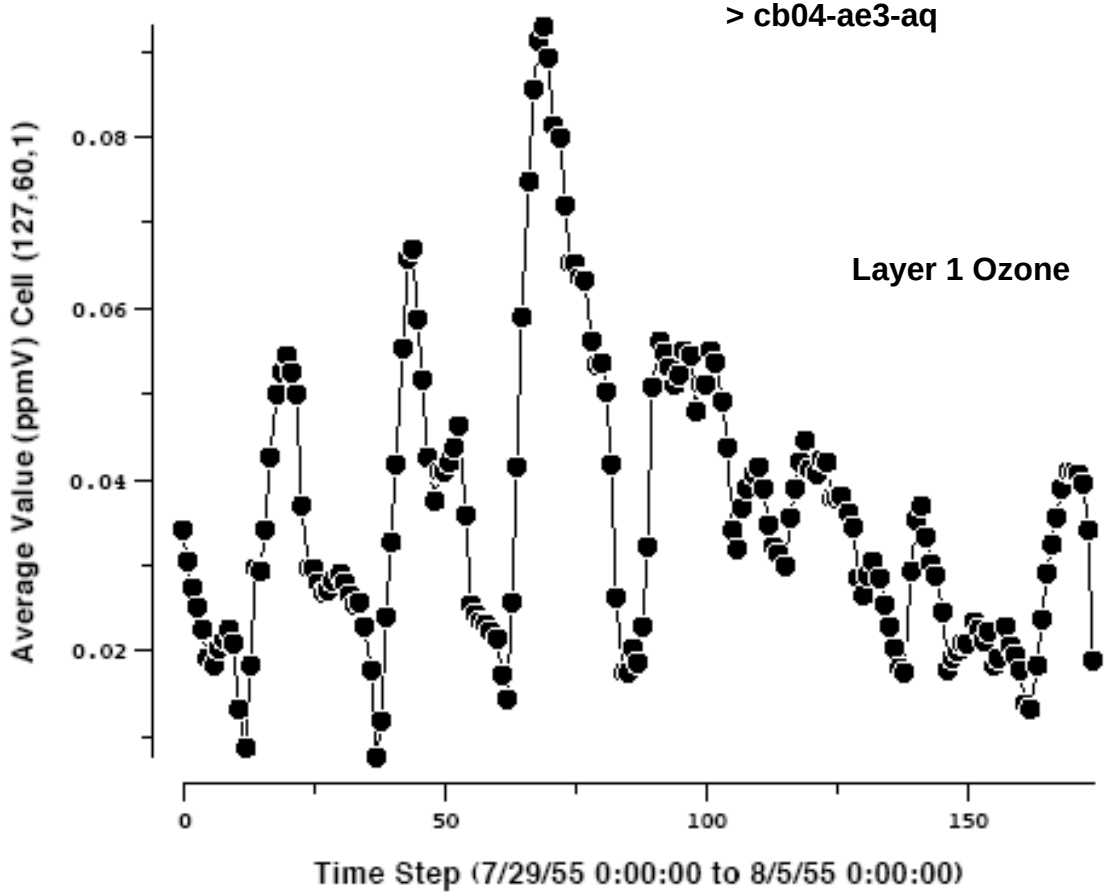
**> 36km grid**

**> cb04-ae3-aq**



Washington, D.C.

> 2055 Meteorology
> 12km grid
> cb04-ae3-aq

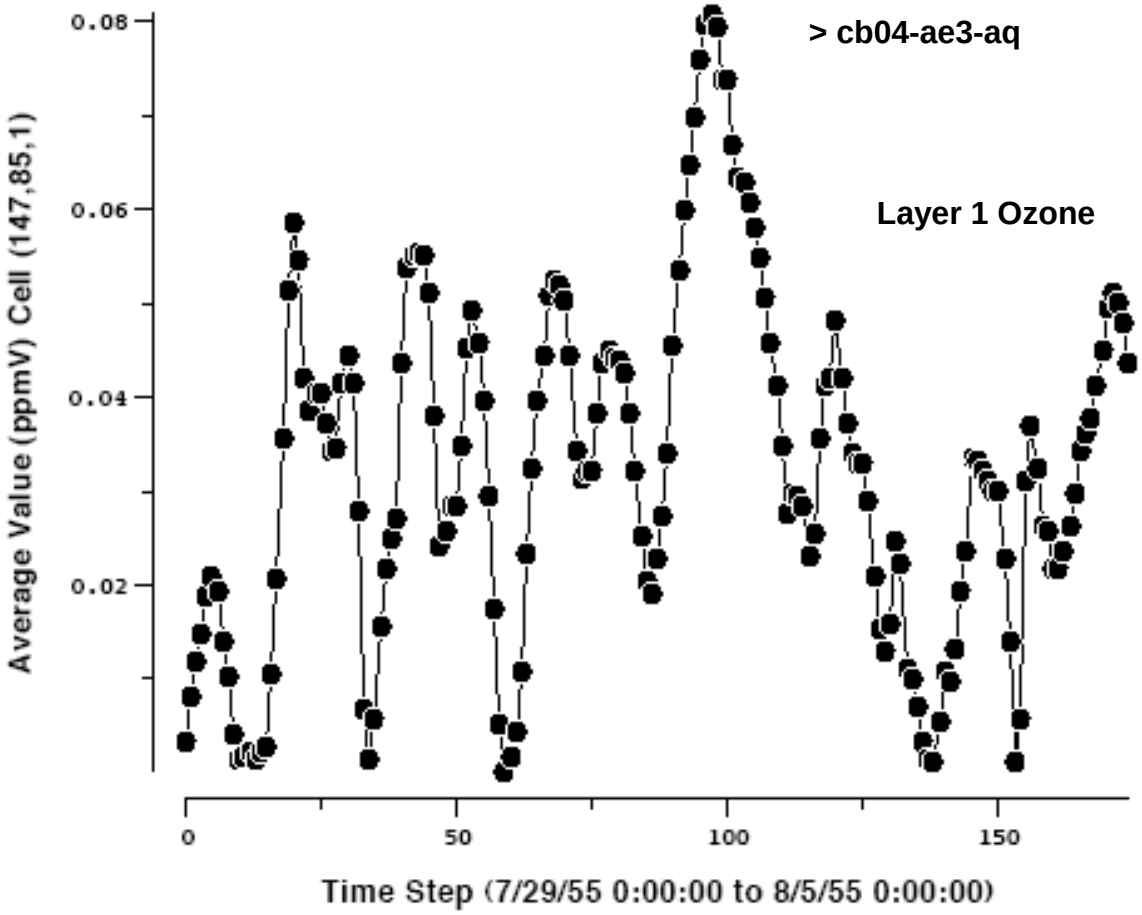


New York City

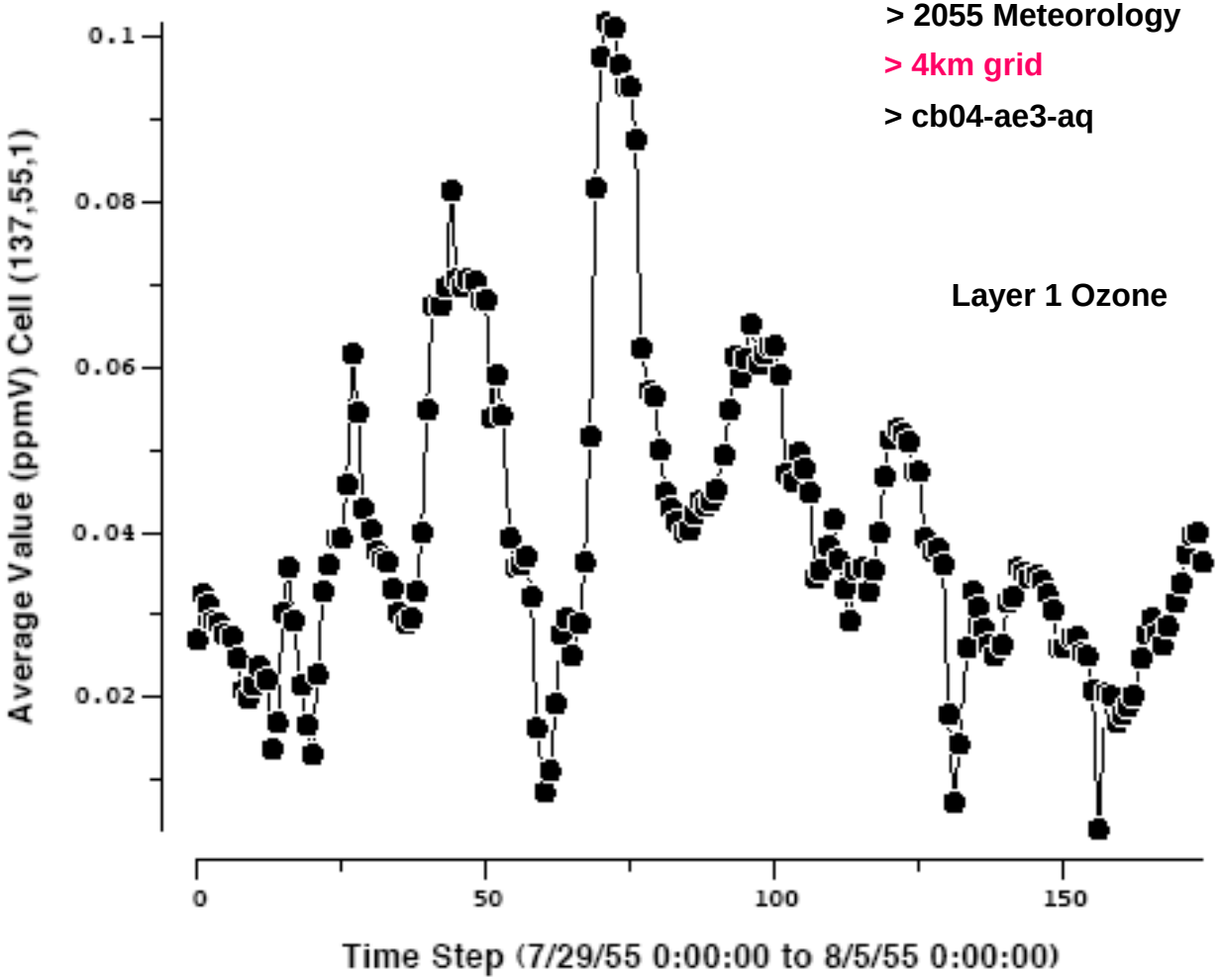
> 2055 Meteorology

> 12km grid

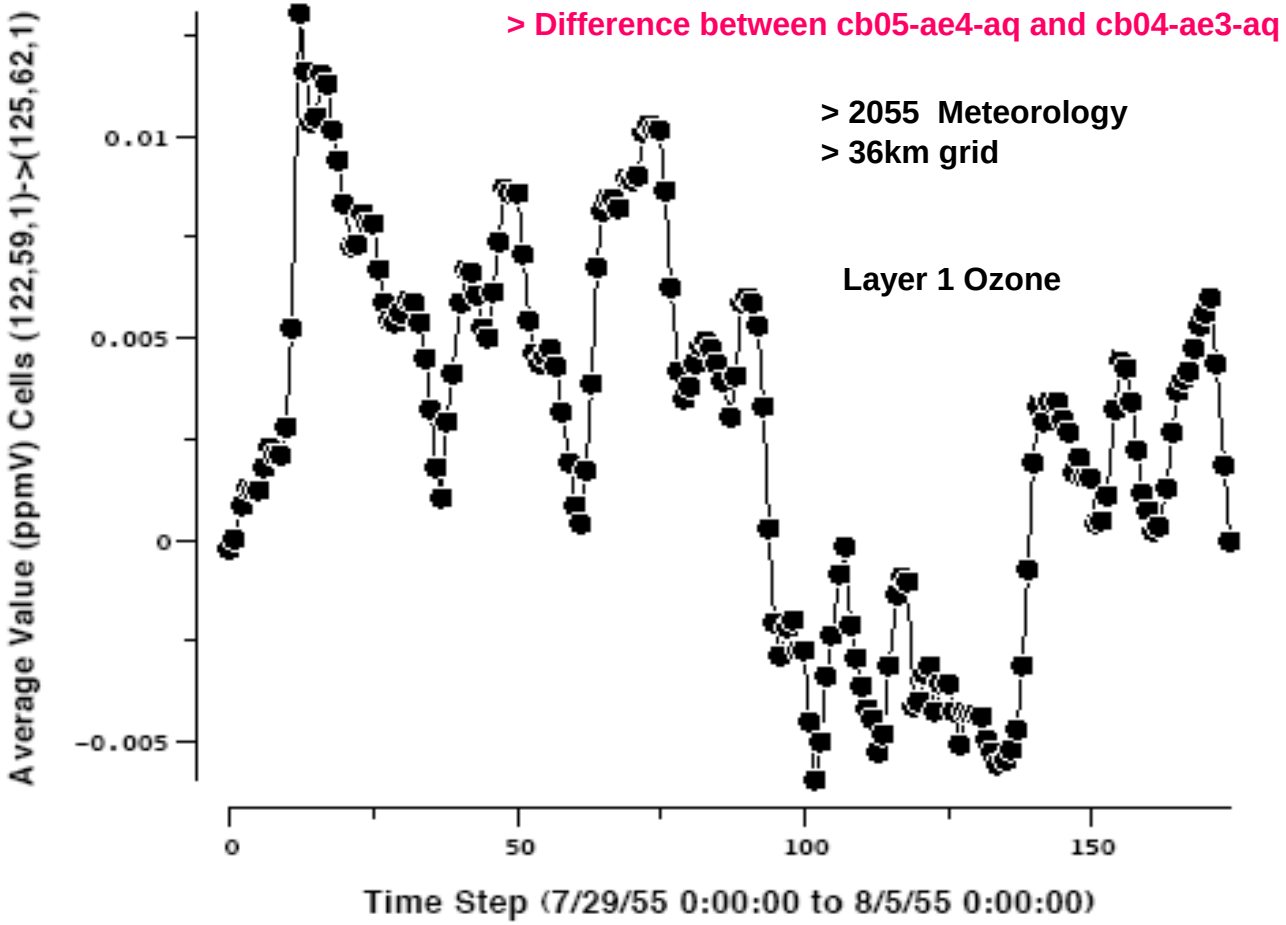
> cb04-ae3-aq



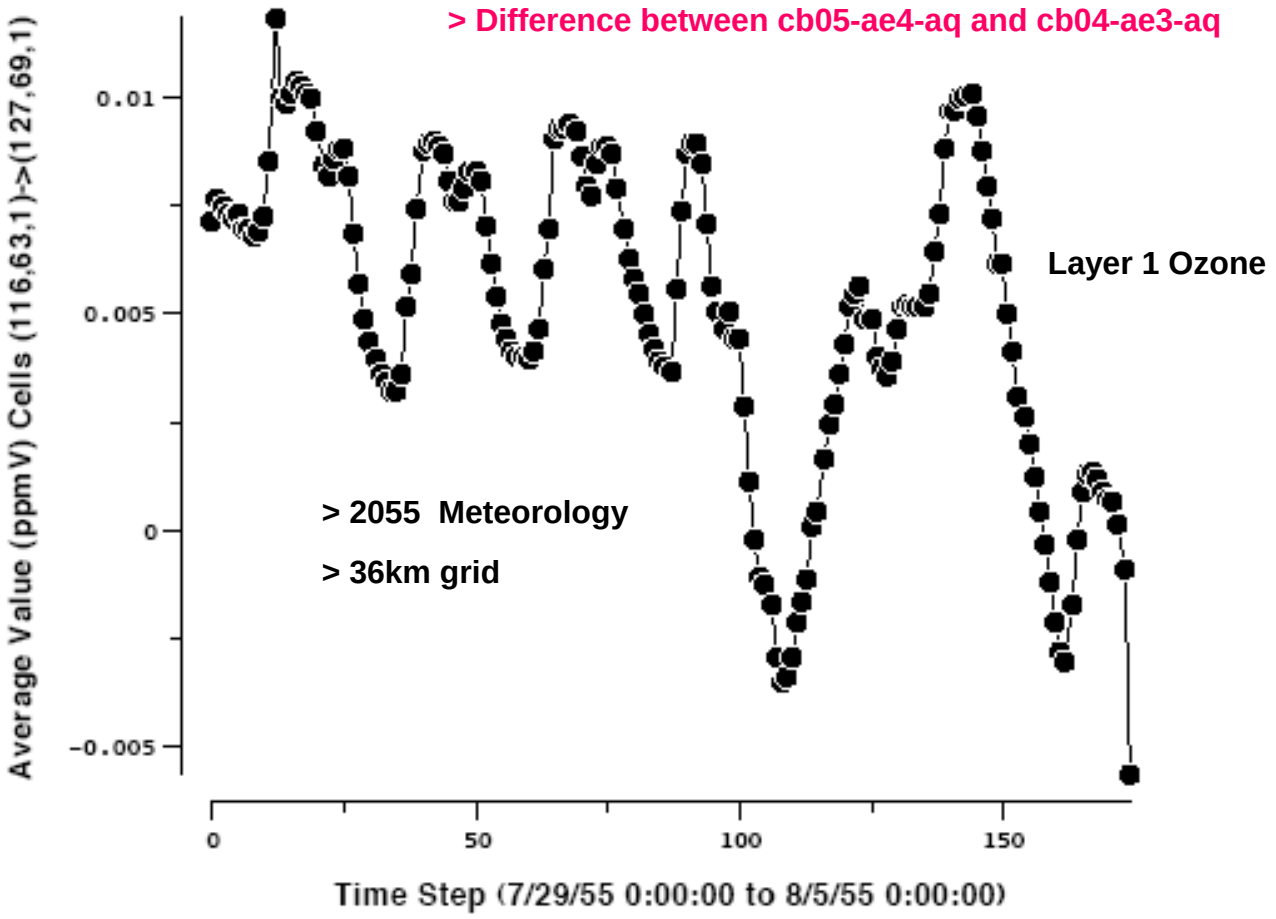
This cell is typically an
ozone hot-spot, NE of DC



**The indicated cells cover a region that includes Baltimore and DC**



**The indicated cells cover a region that includes Pennsylvania**



-To date, there exists one operational integrated emissions scenario “newBL” (i.e., new baseline)

-A second integrated emissions scenario (ACC) involving an assumption of  accelerated temperature increase was created, but is not yet operational

- Both scenarios represent supply and demand conditions for the electric power sector in 2030.  In the baseline scenario, Haiku was run with demand functions based on cooling- and heating-degree days representative of 1990s conditions for all years (i.e., every 5th year from the first year through the last, which is 2030).  The demand functions include CDD, HDD, price, and previous periods' quantity demand (lagged demand) as arguments.

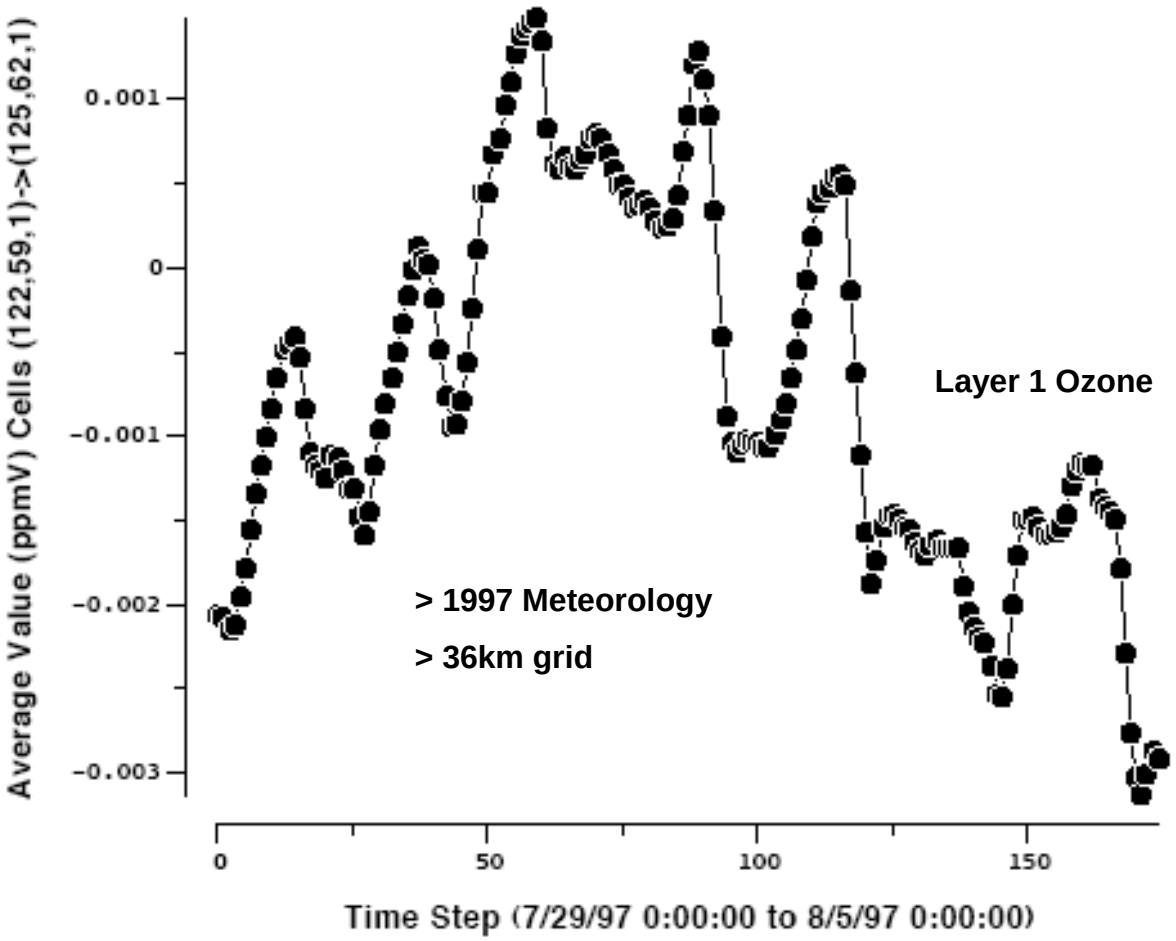
-In the ACC scenario, Haiku was instead run with demand functions with higher CDDs and lower HDDs as inputs (based on the temperature scenarios). The CDDs and HDDs were linearly interpolated between the 1990s scenario and the 2050s scenario (assumed to occur in 2030, hence "ACC"elerated run). The power system is therefore experiencing a gradually warmer climate, warming at a faster rate than GISS anticipates.

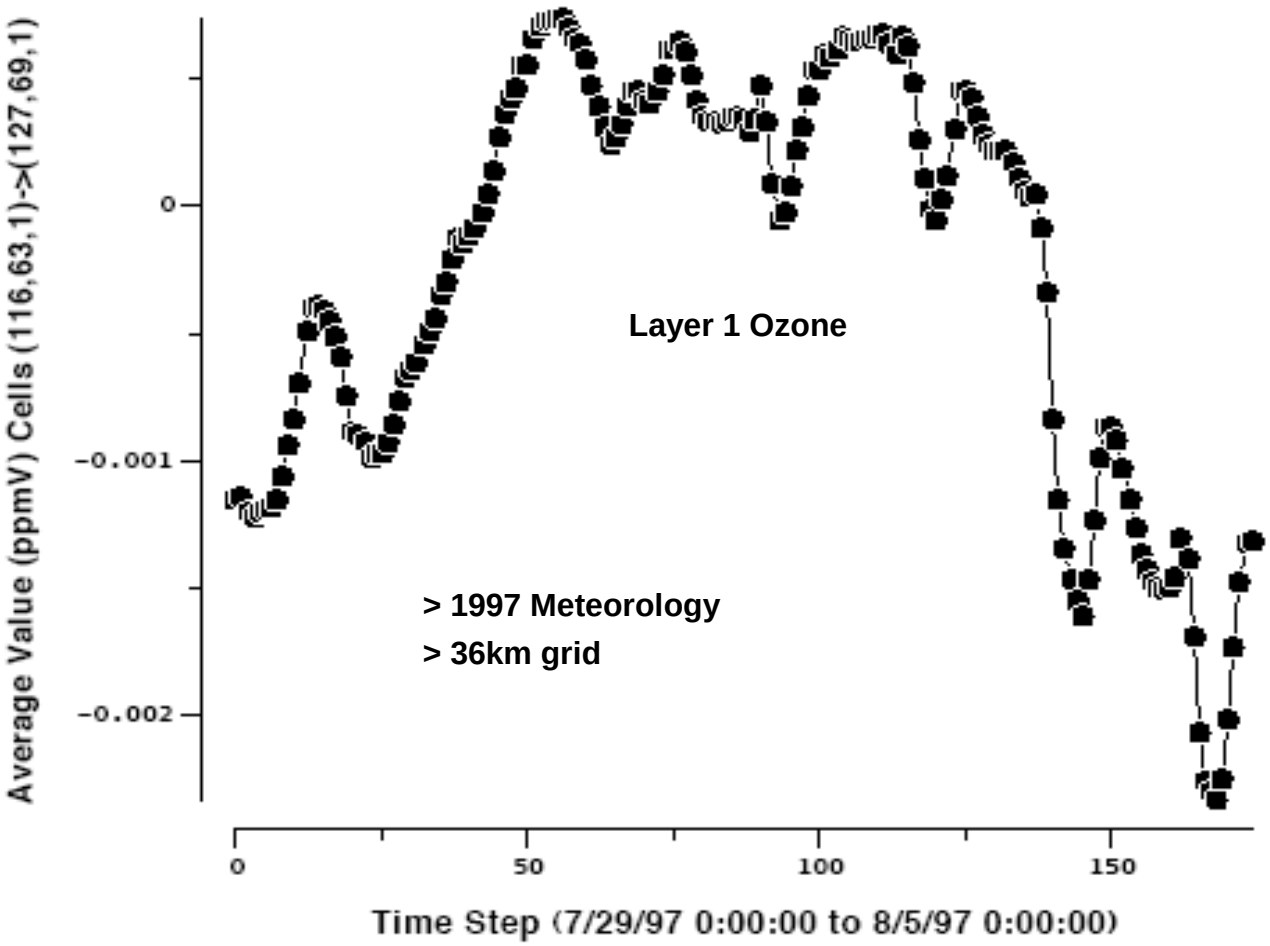
-Both cases impose NOx and SO2 caps (consistent with CAIR). Thus, total summer emissions do not change -- only their spatial and temporal distribution.

-Haiku's scenarios for 6 Haiku regions have been downscaled (NJ/DE; PA; MD; OH; KY/IN; MI) ultimately siting new plants by county and distributing emissions to hours. The distribution to hours is consistent with meteorology -- higher hourly temperatures (from the GISS scenario) mean higher loads which in turn mean higher emissions.

**The indicated cells cover a region that includes Baltimore and DC**

**> Difference between newBL and unmodified NEI01**



**The indicated cells cover a region that includes Pennsylvania**

**> Difference between newBL and unmodified NEI01**