Implications of Climate Change for Regional Air Pollution, Health Effects and Energy Consumption Behavior

Principal Investigator

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Faculty Participants

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Graduate Students

Michelle Bell (JHU), Yihsu Chen (JHU), Christian Crowley (GWU)

The project involves four modeling efforts:

- **Hourly Electricity Load Modeling and Forecasting**
- **Electricity Generation and Dispatch Modeling**
- **Regional Air Pollution Modeling**
- **Health Effects Characterization**

Findings:

Electricity Generation and Dispatch Modeling

•Hourly electricity load model developed

•Preliminary examinations of the effects of temperature and climate variability

•Forecast model performance: The greatest average hourly over-prediction is for 9pm of 377Mwh. The mean absolute percent error (mape) is 1.6%.

•The greatest average hourly under-prediction is at 12pm of 150Mwh. The mape is 1.2%.

•Nineteen of twenty four hours have an mape less than 1%

Findings:

Hourly Electricity Load Modeling and Forecasting

- Examined impact of 4.5 ^{o}F warming upon 7 state mid-Atlantic/midwest region

Findings:

Regional Air Pollution Modeling

- Models3 framework successfully installed and functioning
- Good agreement with measured ozone concentrations for 1990 and 1995 episodes
- Good/OK agreement with measured PM10 concentrations for a 1995 episode

Next Steps:

Electricity Load Modeling and Forecasting

- Model the PJM load control areas using local temperatures. (Note – we have the hourly data sets put there are missing data issues we need to address. About 5% of the observations are missing.)

- Compare local effects to the general model.

- Provide load sensitivities to supply dispatch and generation models.

- Develop longer term sectoral electricity demand models.

- Permit price, income, and technological effects in addition to climate change and variability.

Next Steps:

Electricity Generation and Dispatch Modeling

- Interface emissions model with demand models for 7 state region, and Models3
  - From emissions model to Models3: temperature, velocity, flow, and emissions (particulate, NO_x, SO_2) for each electric generator stack
  - Significant effort required to ensure consistency of power sector and Models3 stacks because of capacity additions/retirements
- Adjust short run results to account for emissions caps and transmission limits
  - Caps now disregarded so emissions impacts may be overstated
- Scenario development for energy technology availability and economics
- Long run market model for capacity mix to simulate response to demand / generator characteristic changes

Next Steps:

Regional Air Pollution Modeling

- Installation of Models3 Version 4
- Emissions interface development with the electricity generation and dispatch models (now using SMOKE in Models-3)
- Incorporation of synthetic met observations into MM5 (within Models-3)
- Execute climate change-driven scenarios

Hourly Electricity Load Modeling and Forecasting

Christian Crowley and Fred Joutz

Department of Economics

The George Washington University

Objectives

- Develop hourly electricity load models
- Test for the effect of temperature and climate variability
- Link the temperature driven load sensitivities to the electricity dispatch and generation models

Scope of Study

- Electricity Loads in the PJM ISO (Pennsylvania-New Jersey-Maryland Interconnect)
- Hourly Data by 10 Load Control Areas, roughly utilities
- January 1st, 1998 through April 30th , 2001

PJM Interconnection

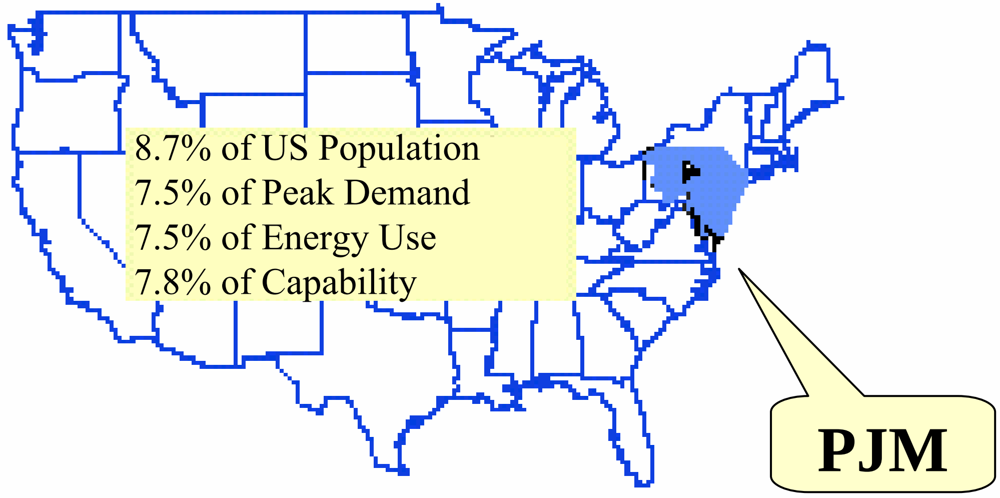
PJM is the Independent System Operator (ISO) that serves Pennsylvania, New Jersey and Maryland, in addition to Delaware, DC and part of Northern Virginia.

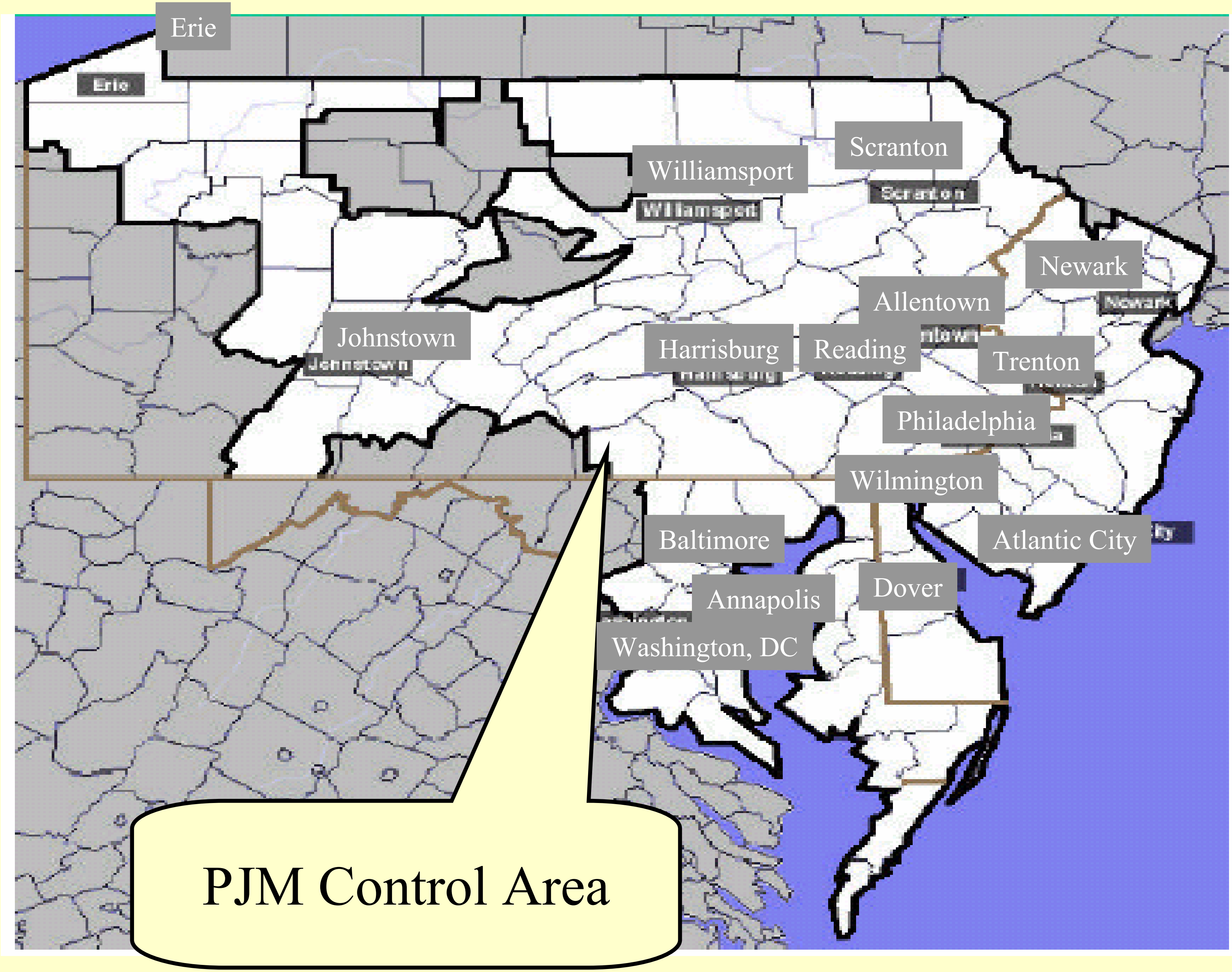
ISOs are groups of utility companies that control the long distance, high voltage power lines that deliver electricity from generation facilities to customers.

PJM Interconnection

PJM is the largest wholesale electricity market in the world, providing power to commercial and residential customers generated from coal, oil, gas, nuclear and hydroelectric resources.

PJM is the largest centrally dispatched control area in North America




Erie
Williamsport
Scranton
Newark
Allentown
Johnstown
Harrisburg
Reading
Trenton
Philadelphia
Wilmington
Baltimore
Atlantic City
Dover
Annapolis
Washington, DC
PJM Control Area

Preliminary Modeling Efforts

- Specification
- Data
- Software
- Elasticity Estimates

Reason for "preliminary" status is difficulty in obtaining complete and comprehensive weather data.

Hourly Model Specification

- Employ simple standard “seasonal” time series modeling approach (Diebold, 2001 and Abraham and Ledolter, 1983)
- $H_{it} = \beta_0 + \beta_1 H_{i-1,t} + \beta_2 H_{i,t-1} + \beta_3 HDD_t + \beta_4 HDD_t^2 + \beta_5 CDD_t + \beta_6 CDD_t^2 + \beta_7 Weekend_t + \beta_8 Holiday_t + \beta_9 Summer_t + \beta_{10} Winter_t + e_t$
- Where the last term is a white noise disturbance

Hourly Model Specification

- The terms HDD and CDD refer to Heating Degree Day and Cooling Degree Day terms.

- HDD = hourly temperature – 72F

  = 0, if hourly temperature below 72F
- CDD = 65F – hourly temperature

  = 0, if hourly temperature above 65F

Hourly Model Specification

Dummy variables are used to capture seasonal effects:

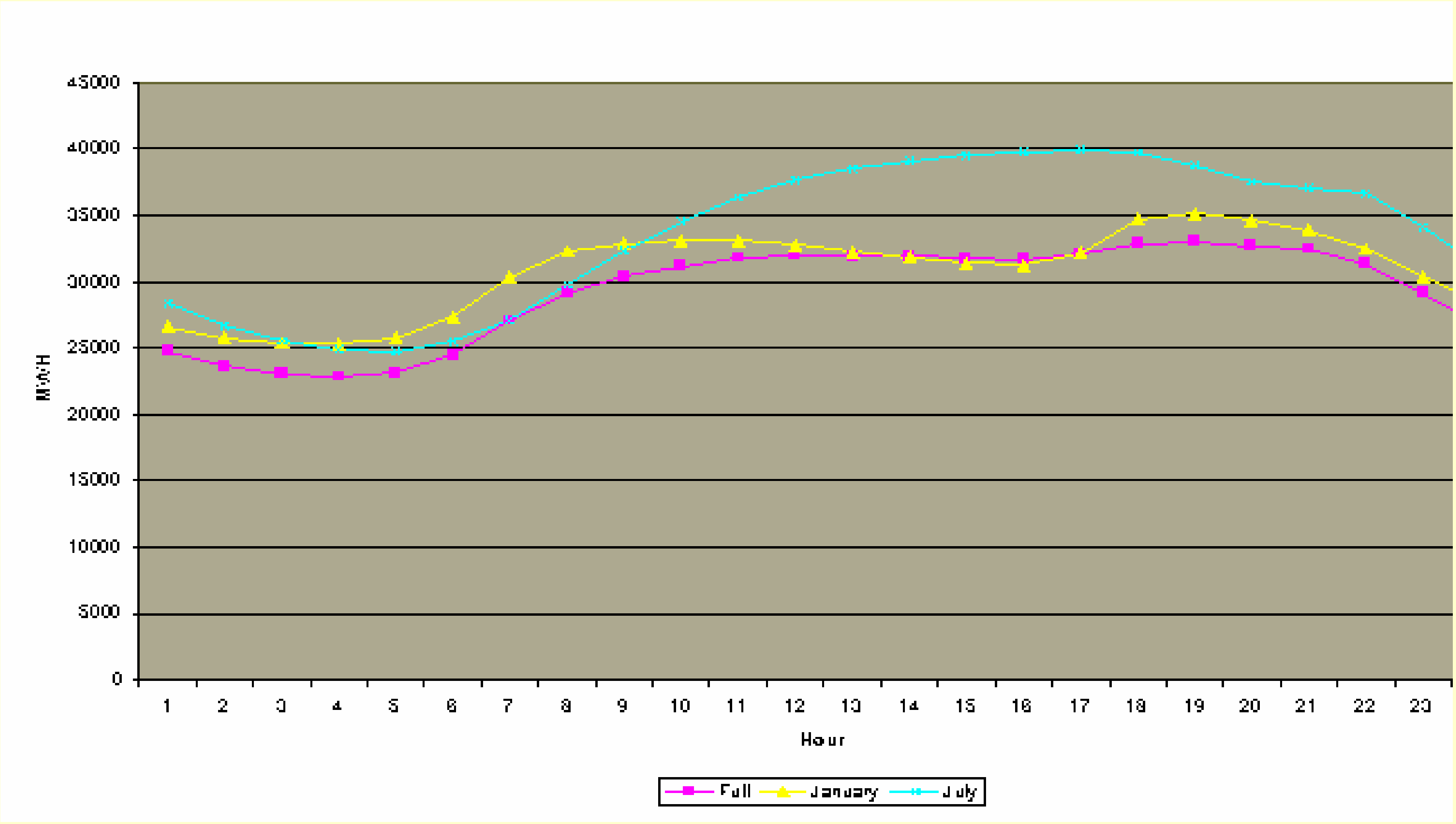
- Weekend – for day of week
- Holiday – for federal and major religious holidays
- Summer – months of June, July, and August
- Winter – months of December, January, and February

Data

- Sample period is hourly from January 1st, 1998 through April 30th, 2001.
- Load for the entire PJM region.
- Weather data for the entire sample was obtained for the Philadelphia International Airport National Weather Station. However, we had access only to daily maximum and minimum temperatures.

Load Curve – Hourly Average

January 1st, 1998 – April 30th, 2001

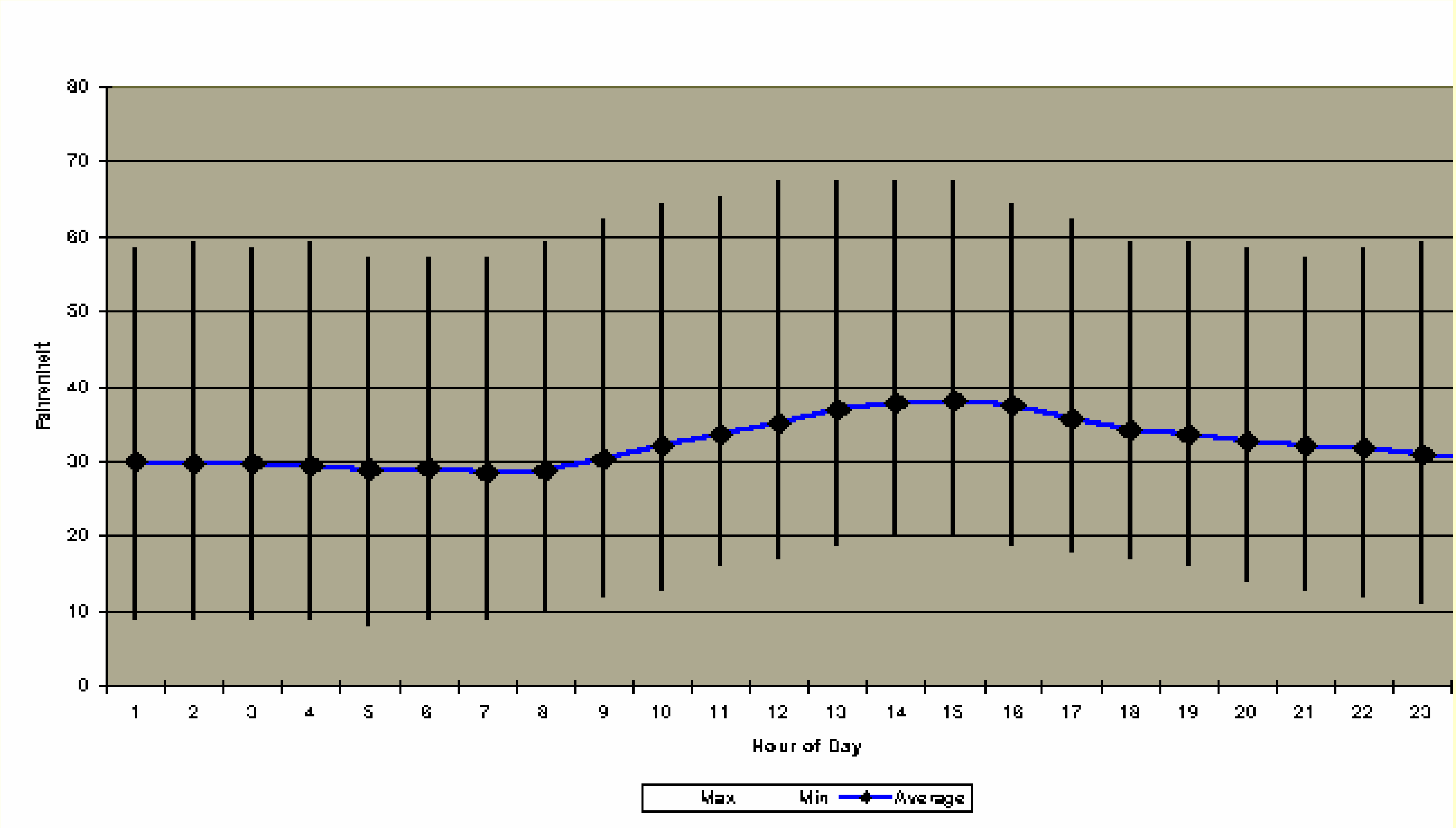


Load Curve – Hourly Maximum

January 1st, 1998 – April 30th, 2001

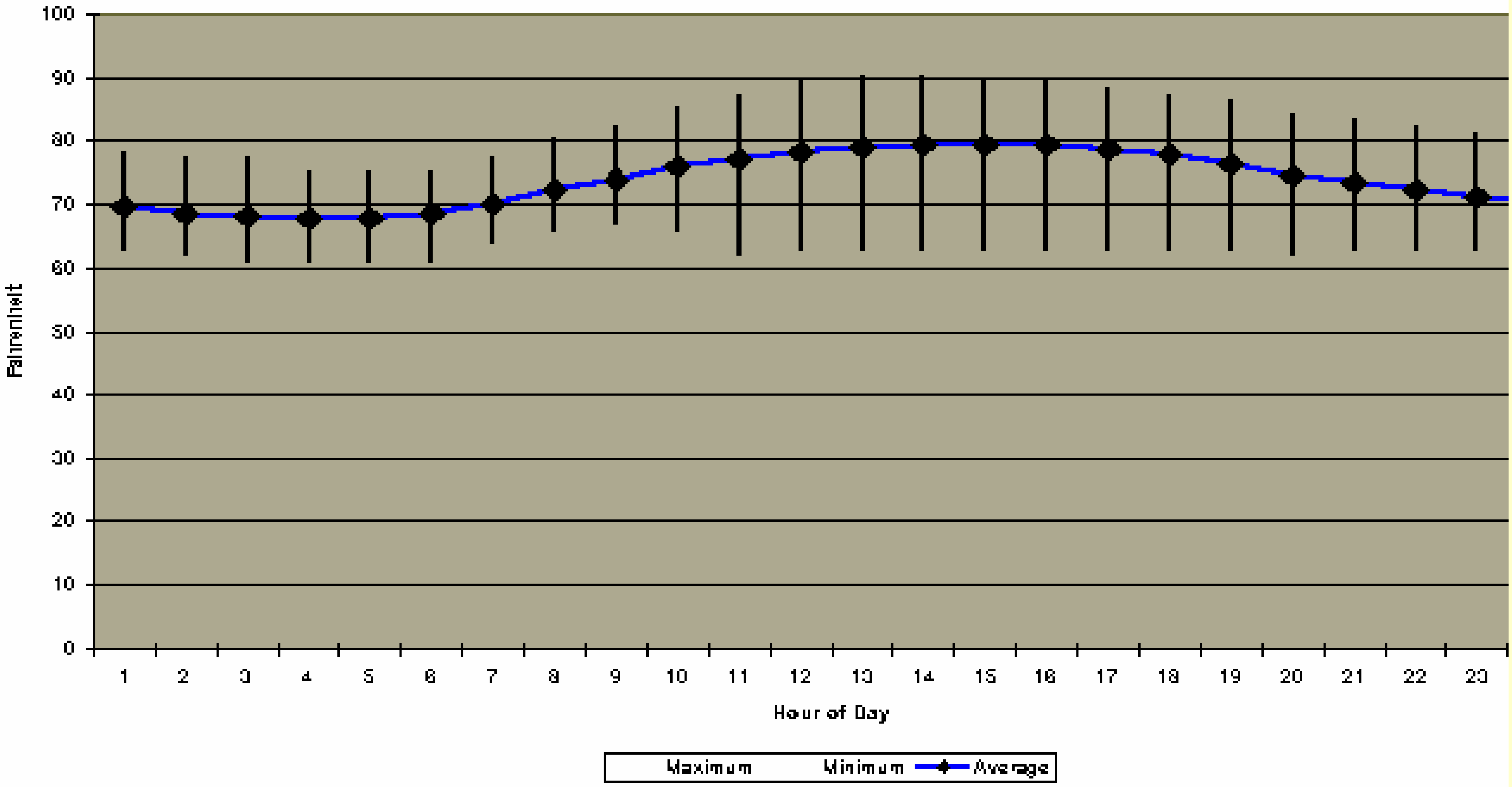
Hourly Temperature Averages and Ranges: Winter

Philadelphia International Airport: January 2000



Hourly Temperature Averages and Ranges: Summer

Philadelphia International Airport: July 2000



Software

- MetrixND (2001) – standard modeling and forecasting software used in the electric utility industry
- Eviews version 4 – popular econometric software package

Temperature Elasticities

- The elasticities measure the sensitivity of electricity loads to cooling and heating degree changes.
- We attempt to capture the impact of 1F change in the maximum or minimum temperature on the load for a particular hour.

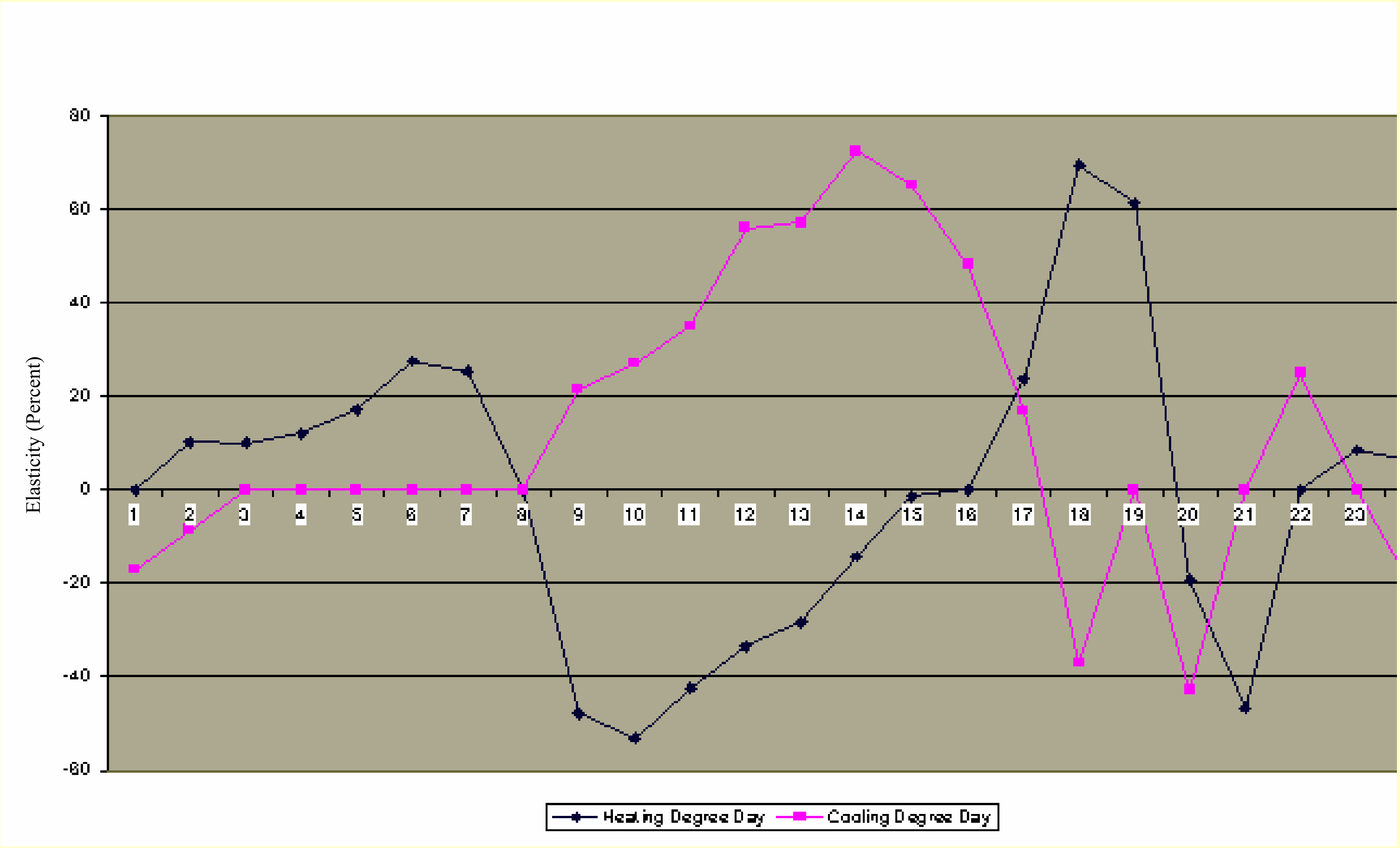
Temperature Elasticities

The elasticities for the ith hour are defined as:

- $\eta_{iHDD} = (\beta_3 + \beta_4 * 2 * MHDD) * MHDD / MHi$ and
- $\eta_{iCDD} = (\beta_5 + \beta_6 * 2 * MCDD) * MCDD / MHi$

The M in front of HDD, CDD, and MHi terms means that they are evaluated at their mean values.

Elasticity Estimates for HDDs and CDDs



Temperature Elasticities

It is easy to see that heating degree day effects have two peaks,

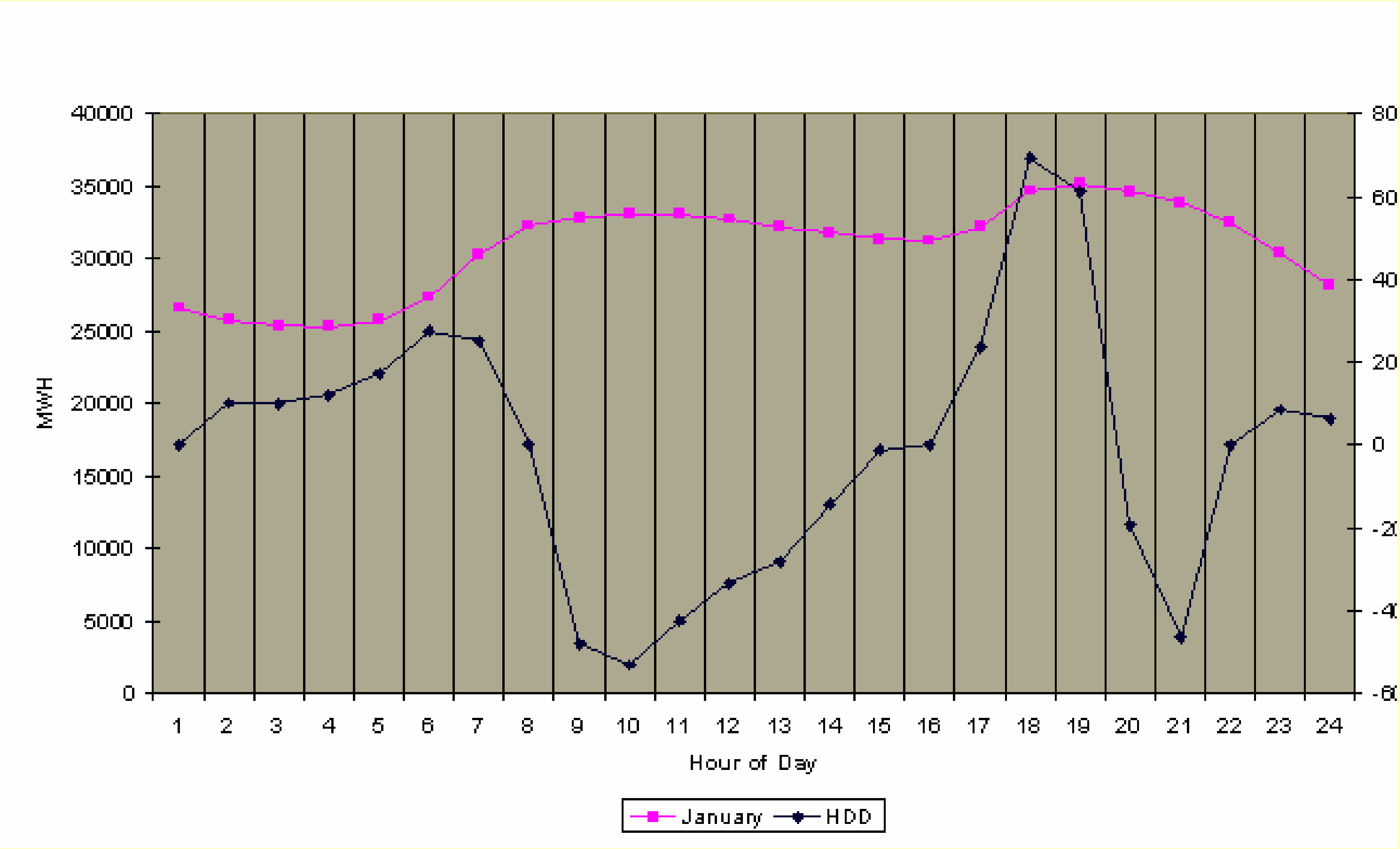
- First, when people go home in the evening and
- Second, during the night,
- There is a sink in the evening between 8pm and 10pm; this can be the result of cooking and other appliance use before going to bed. These activities produce heat and moderate the need for electric load for heating needs.

Temperature Elasticities

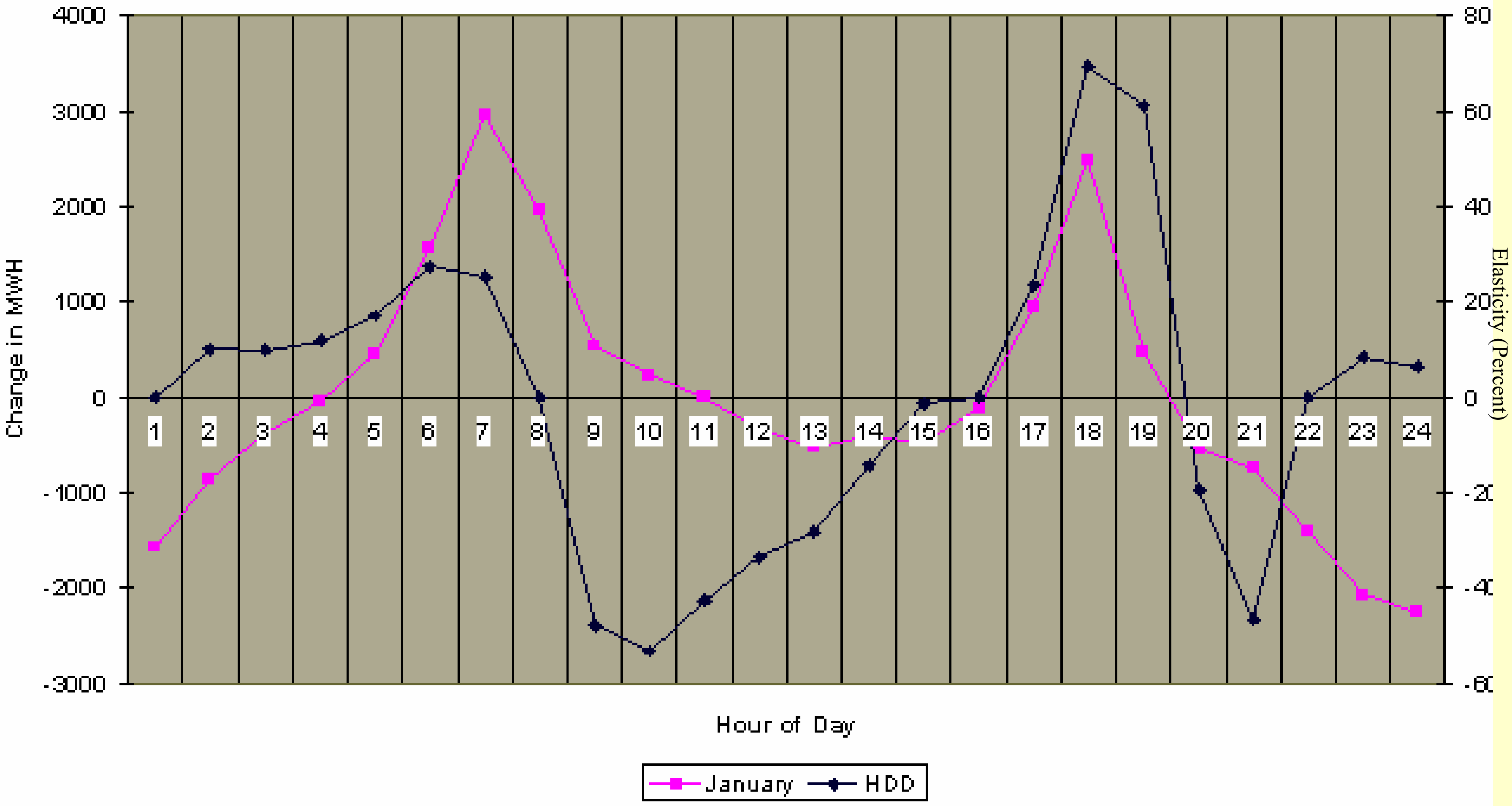
Cooling degree day effects are the opposite, they are positive during the day and peak in the afternoon between 1pm and 3pm.

- The seasonal effect is important
- July loads rise relatively quickly starting at 6am, however the cooling degree elasticity effect is not apparent until later, peaking during the warmest part of the day in the afternoon

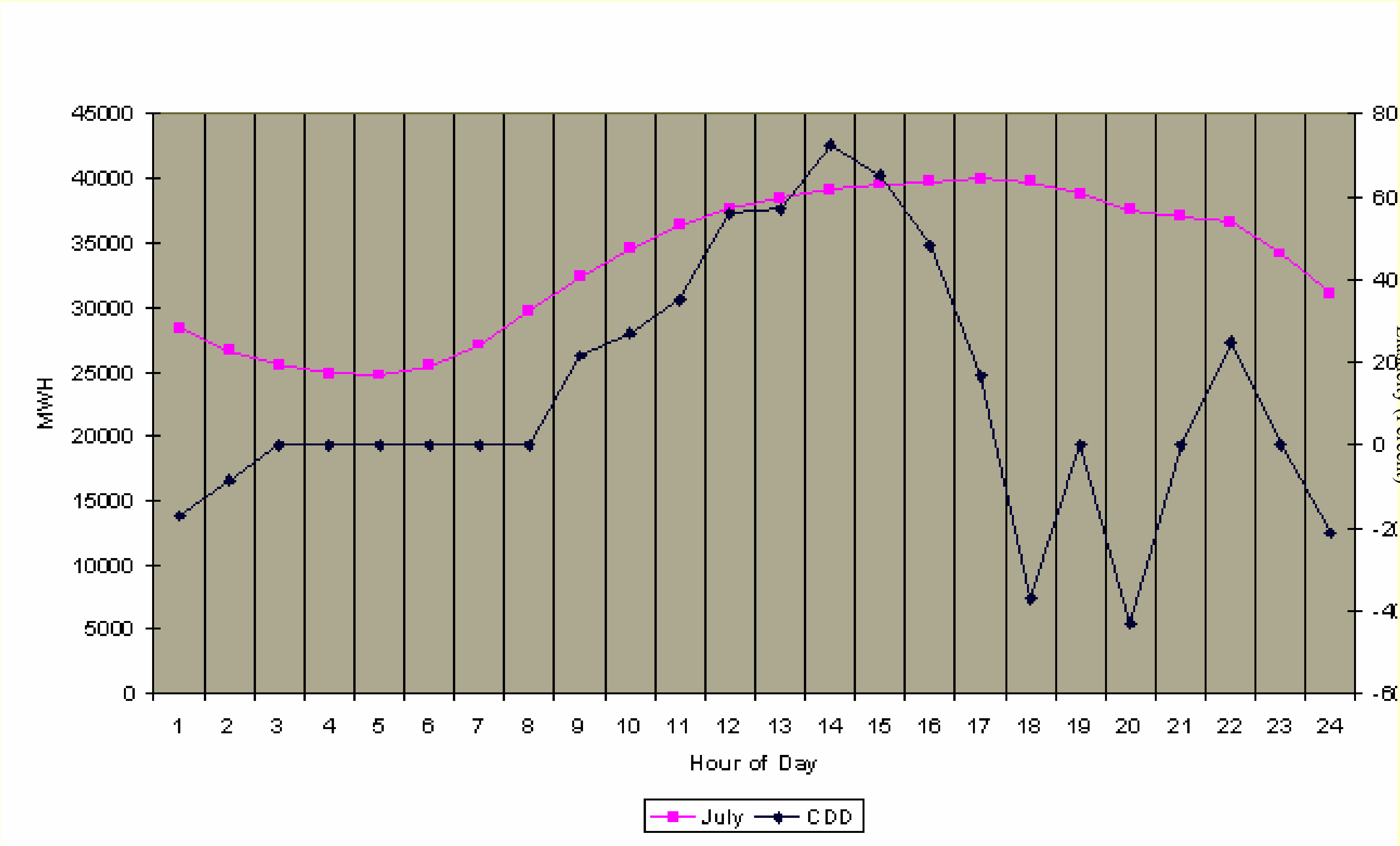
January's Hourly Load and Heating Degree Elasticity



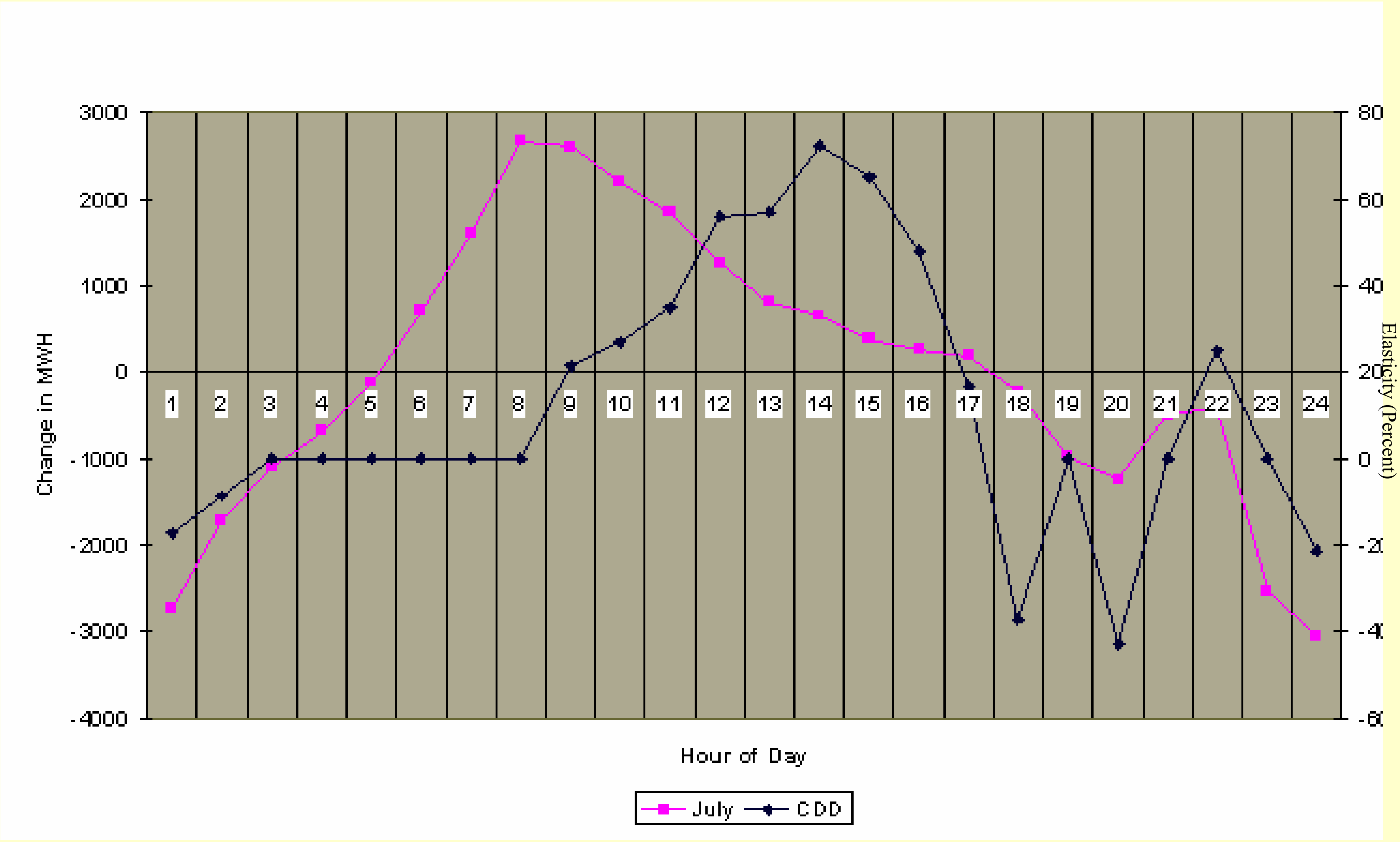
Change in January's Hourly Load and Heating Degree Elasticity



July's Hourly Load and Cooling Degree Elasticity



Change in July's Hourly Load and Cooling Degree Elasticity



Forecast Evaluation

- The hourly models are grouped into a system of equations to make use of the dynamic or recursive structure.
- The hourly models are first estimated through June 30th, 2001.
- Forecasts are made for each hour in July and August, 2000; there is a total of 62 forecasts for each hour.

Forecast Evaluation

- The grouped hourly predictions are based on their own lags and the predetermined hourly forecasts.
- Forecasts are calculated based on the updated values of the two types of variables beyond the estimation sample

Forecasts Error Summary Statistics from Group Forecast Approach

for July and August 2000

	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12
average	82.5	59.7	31.1	26.2	47.5	91.5	-133.3	-149.7	140.1	156.6	151.4	152.6
rmse	287.4	163.8	165.1	143.5	150.1	250.0	388.0	350.4	433.4	327.3	296.1	269.8
mae	218.5	127.3	130.6	103.1	110.4	203.0	331.4	288.2	359.7	259.7	236.9	220.0
mape	0.8	0.5	0.5	0.4	0.5	0.8	1.2	1.0	1.2	0.8	0.7	0.6

	H13	H14	H15	H16	H17	H18	H19	H20	H21	H22	H23	H24
average	92.9	26.3	-24.3	-11.5	-11.7	-11.4	111.5	94.6	377.4	-186.4	44.6	121.9
rmse	275.7	211.7	230.3	259.9	257.9	303.0	318.2	372.2	704.5	493.2	258.8	261.1
mae	227.2	176.6	190.9	214.4	207.1	241.1	273.0	279.9	584.6	393.9	196.2	196.5
mape	0.6	0.5	0.5	0.6	0.6	0.7	0.8	0.8	1.6	1.2	0.6	0.7

Forecast Evaluation

- The greatest average hourly over-prediction is for 9pm of 377Mwh. The mean absolute percent error (mape) is 1.6%.
- The greatest average hourly under-prediction is at 12pm of 150Mwh. The mape is 1.2%.
- Nineteen of twenty four hours have an mape less than 1%

High Ozone Simulations

- Two simulations were performed for high ozone periods in July and August 2000.
- July 30th – August 2nd and
- August 7th - August 9th

High Ozone Simulations

- The models are fit up to each date using the full sample.
- Forecasts are made under the assumption that the daily high would be 2F greater than observed.
- The simulated values are plotted relative to what was predicted using the actual values.

High Ozone Simulations

- The predicted effects appear to be rather minor.
- In the first period loads are about 0.4% higher.
- In the second period loads are about 0.55% higher.

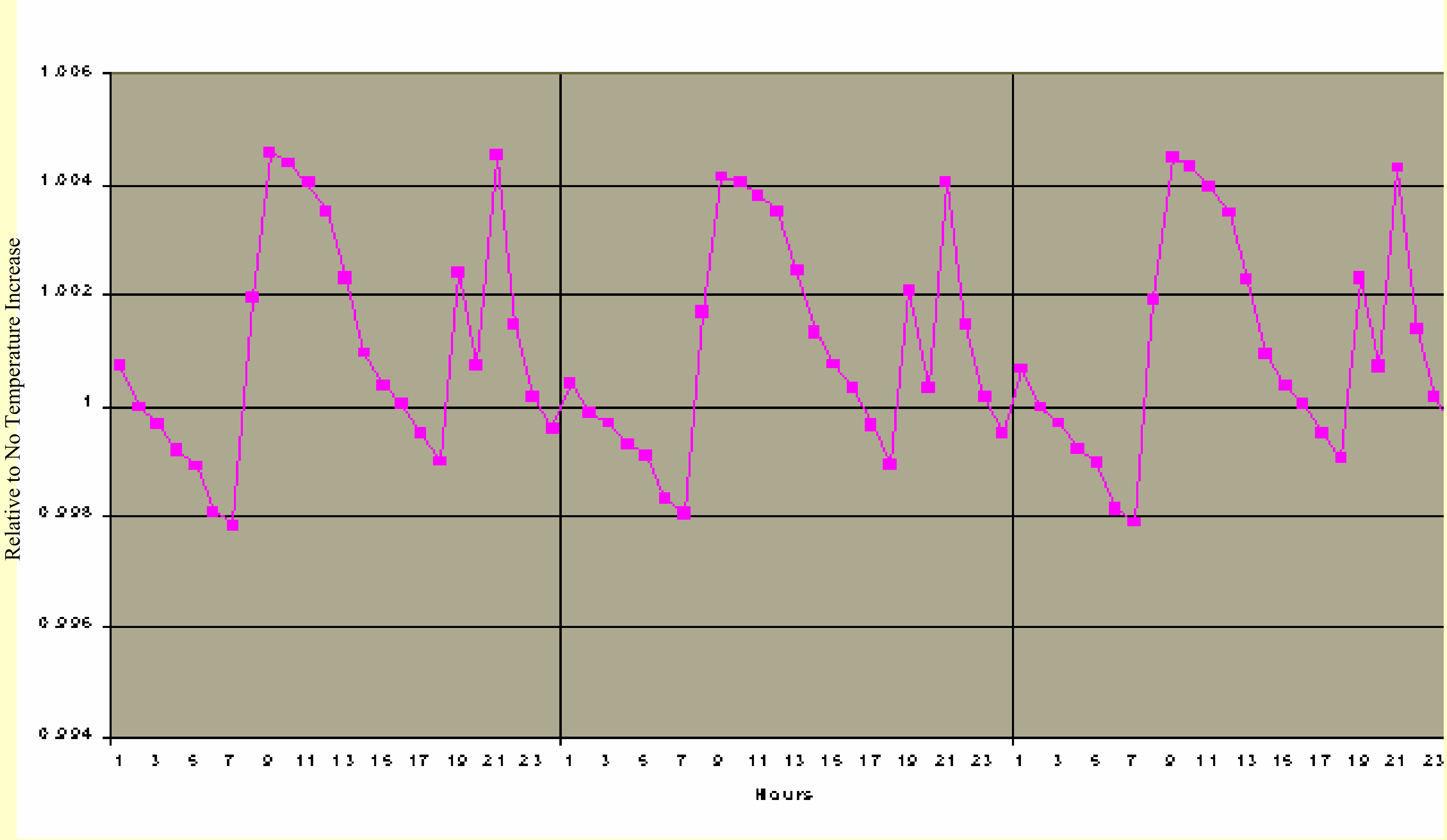
High Ozone Simulations

- There is no impact from midnight to 6pm.
- There does not appear to be an impact during peak hours from 3pm-7pm.
- The greatest effects are in the late morning and at sundown from 7pm to 9pm.

Simulation Effect on PJM Load

Scenario: 2°F Rise in Temperature

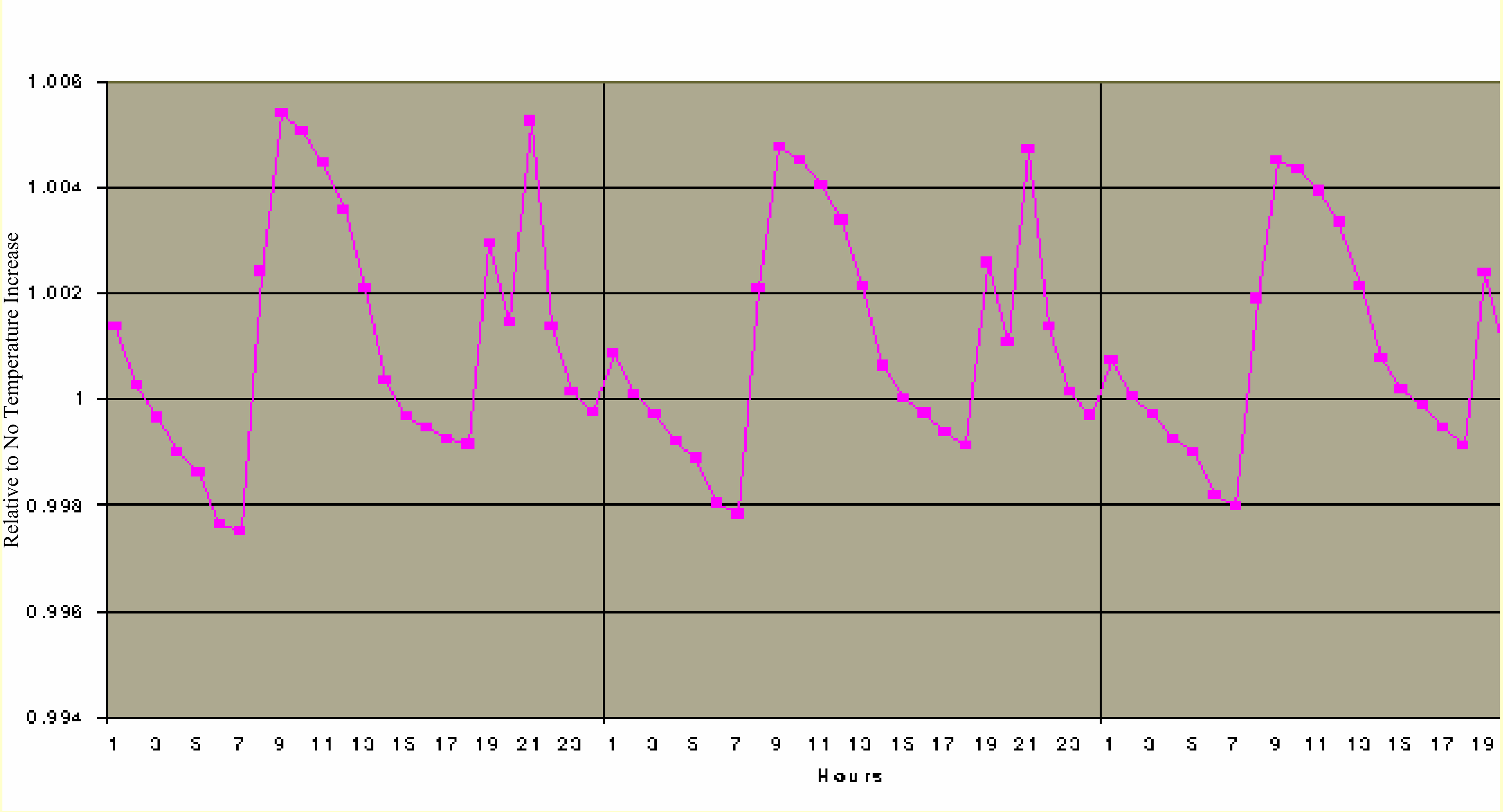
High Ozone Episode: July 31st – August 2nd, 2001



Simulation Effect on PJM Load

Scenario: 2°F Rise in Temperature

High Ozone Episode: August 7th – 9th, 2001



Next Steps

- Model the PJM load control areas using local temperatures. (Note – we have the hourly data sets put there are missing data issues we need to address. About 5% of the observations are missing.)
- Compare local effects to the general model.
- Provide load sensitivities to supply dispatch and generation models.

Next Steps

- Develop longer term sectoral electricity demand models.
- Permit price, income, and technological effects in addition to climate change and variability.

Electricity Generation and Dispatch Modeling

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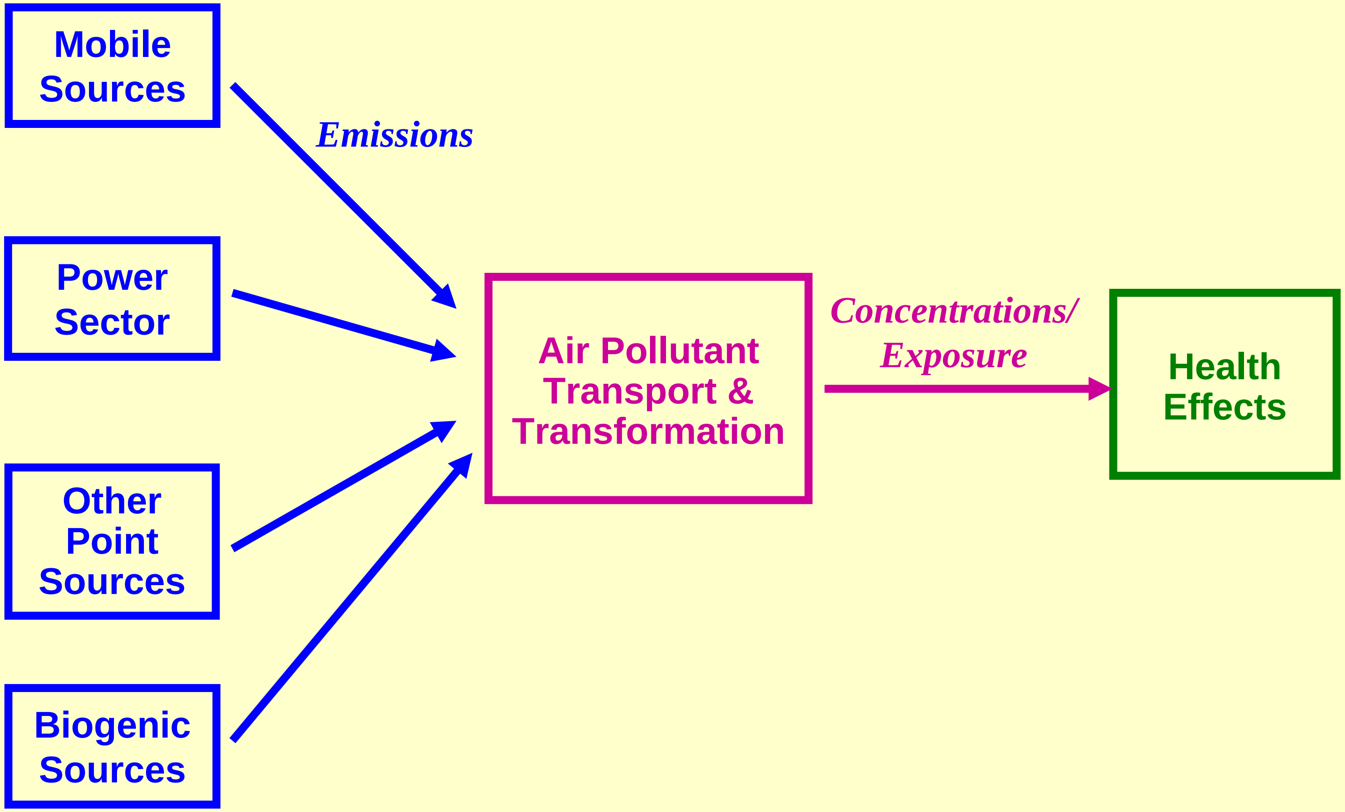
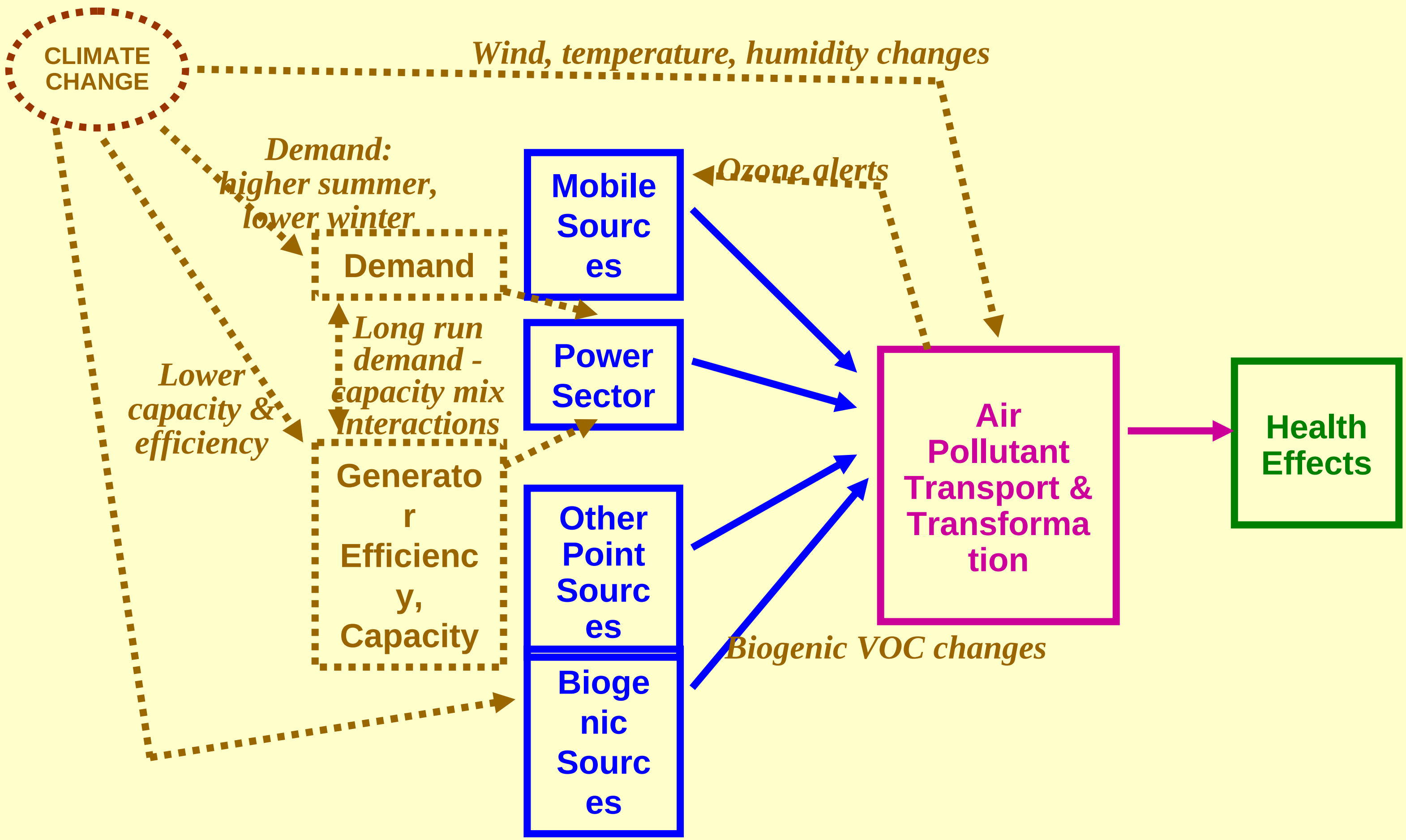
Tropospheric Ozone Production Process



Climate Change Effects Analyzed



Effects of Climate Change on Components of Power System

	Short Run Effects	**Long Run Adaptations**
Power Demands:	**ΔUse of equipment** *(e.g., air conditioner hours)*	**ΔMix of equipment** *(e.g., #, size of air conditioners)*
Generator Characteristics:	**ΔThermal capacity & efficiency** *(e.g., Carnot)*; **ΔWater supply**	**ΔMix of generators** *(fuel sources, peak vs. baseload)*

Year 1 Power Sector Analysis: Climate Change Adaptations and Emission Responses

- Examine impact of 4.5 ^{o}F warming upon 7 state mid-Atlantic/midwest region
  - 1681 generating units (from EPA, DOE data bases)
  - 3 day period (July 31 - Aug. 2, 2000): 97,000 MW peak
- Assumptions:
  - Based on utility analyses of short-run demand sensitivities, assume summer load increases 1% for each 1^{o} F increase.
    - However, our PJM analysis indicates sensitivity may be less in Mid-Atlantic
  - Thermal plant efficiency from literature and Carnot calculations; no hydro. E.g.,
    - Gas turbine heat rate increases 0.07% / 1^{o} F increase
    - Steam plants heat rate increases 0.06% / 1^{o} F increase
  - Capacity using reported winter and summer capacities.
    - Average 0.23% decreases / 1^{o} F increase
  - No transmission constraints

Demand & Generator Performance Effects of a 4.5 ^{o}F Increase, 3 MidSummer Days

Base Case

Tons NO_x	Tons SO_x
9,000	31,000

Generator Performance Impact Alone

Tons NO_x	Tons SO_x
0.5%	0.4%

Demand Impact Alone

Tons NO_x	Tons SO_x
+6.25%	+5.63%

(Note: Superlinear effect,
as exceeds +4.5% load change)

Joint Generator & Demand Impact

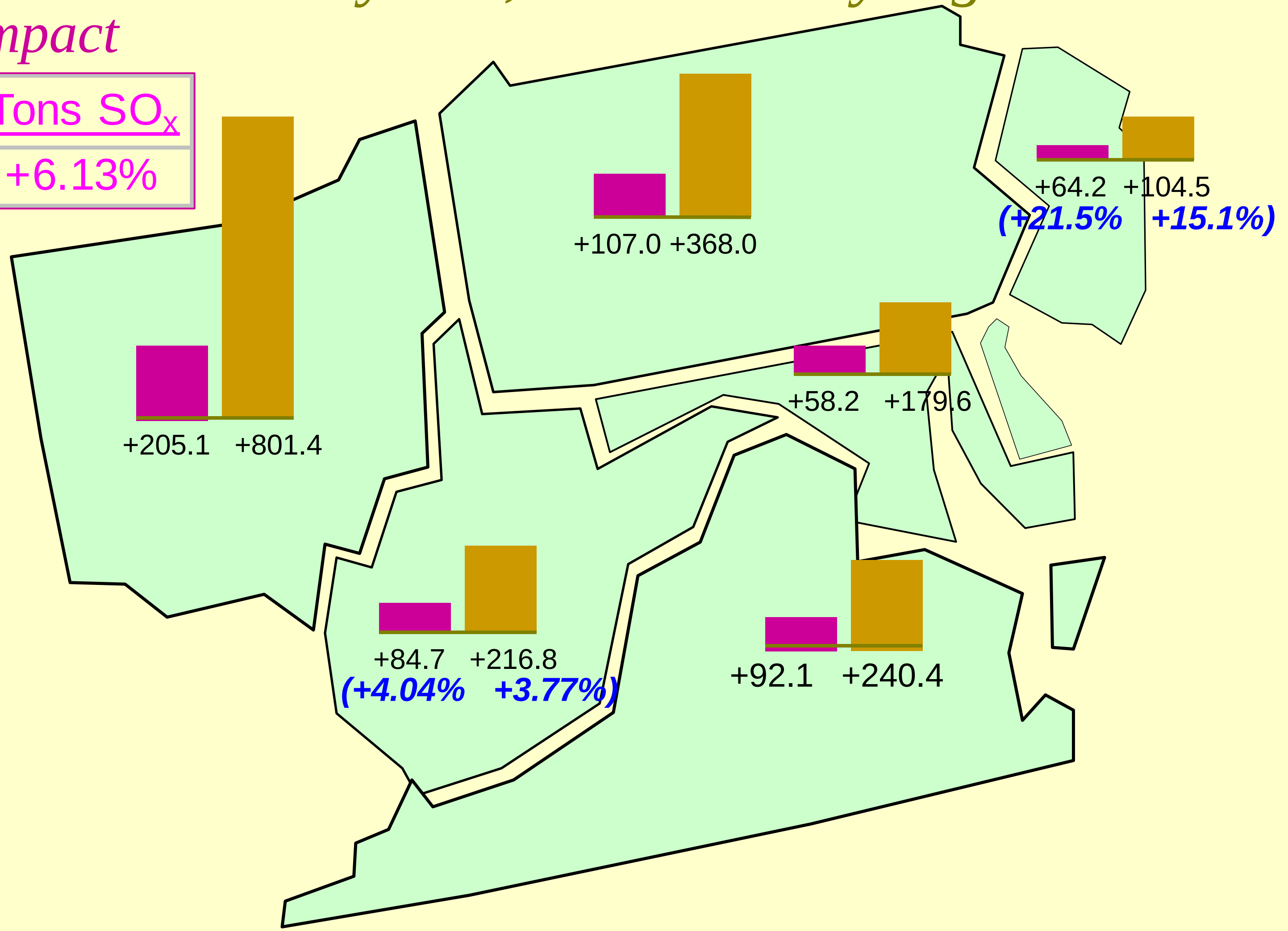
Tons NO_x	Tons SO_x
+6.83%	+6.13%

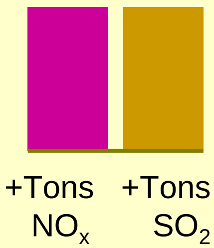
Location matters:
Emissions do not increase by same % everywhere

WV *relatively low; NJ relatively high*

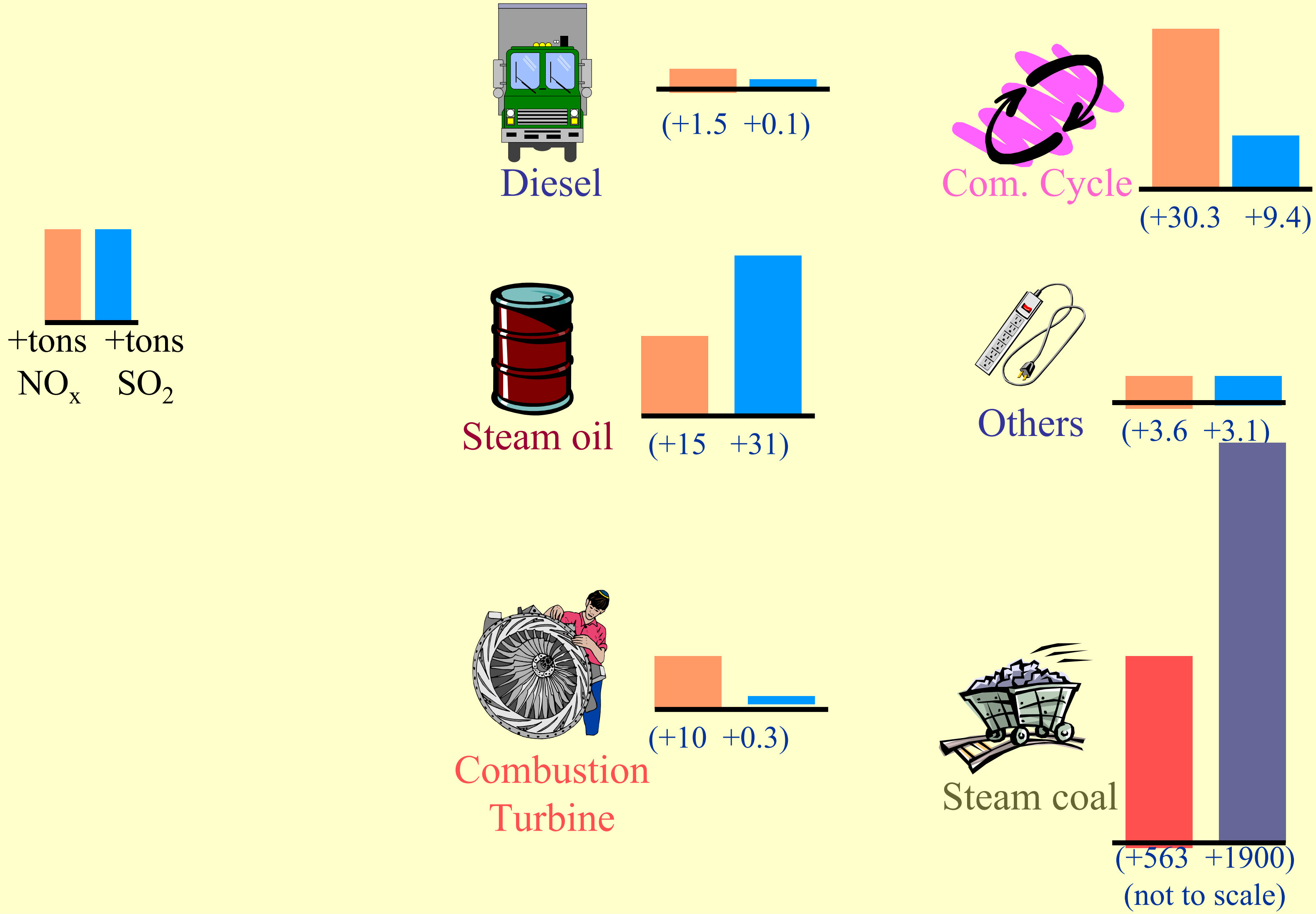
Total Impact

Tons NO_x	Tons SO_x
+6.83%	+6.13%





Plant Emission Profile (total impact)



Upcoming Power Sector Emissions Tasks

- Interface emissions model with demand models for 7 state region, and Models3
  - From emissions model to Models3: temperature, velocity, flow, and emissions (particulate, NO_x, SO_2) for each electric generator stack
  - Significant effort required to ensure consistency of power sector and Models3 stacks because of capacity additions/retirements
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Regional Air Pollution Modeling

Michelle Bell and Hugh Ellis

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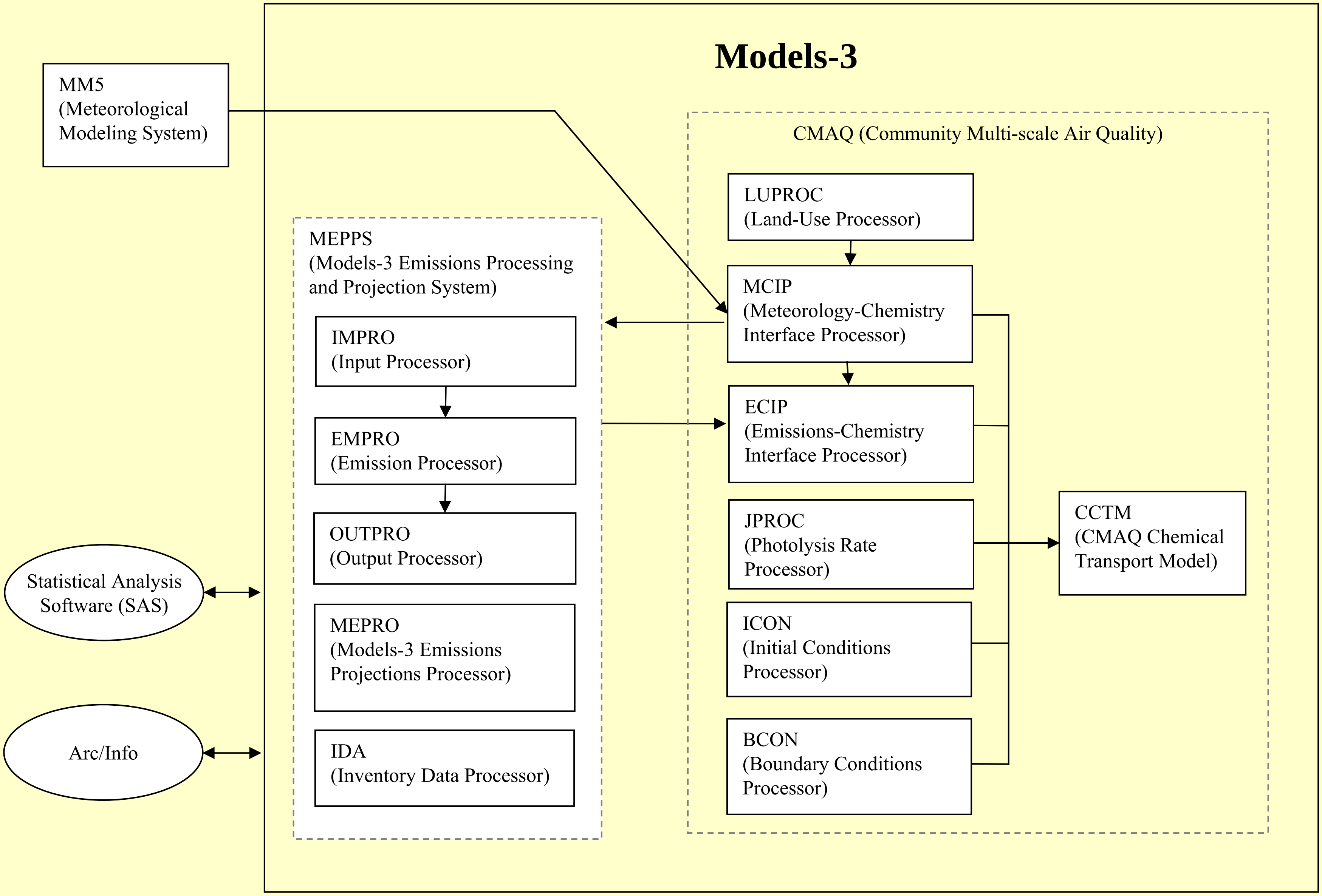
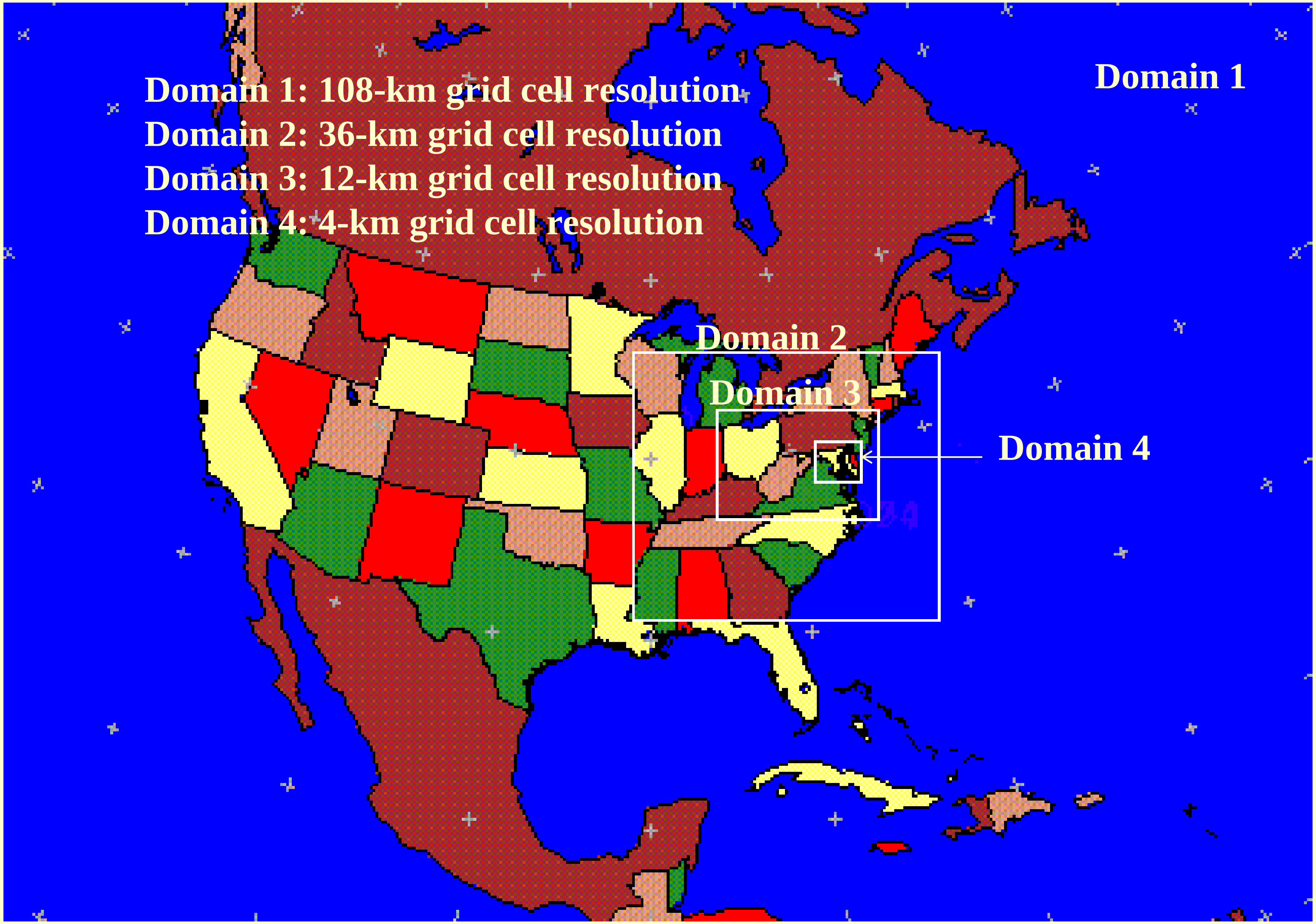


Models-3 Framework



Spatial Domains Used In Meteorological Modeling

Data sources for meteorological modeling (MM5)

Static data input to MM5 describe the simulation domain and include topography, vegetation, and land-use information from the PSU/NCAR, the Geophysical Data Center, and the USGS (United States Geological Survey).

MM5 uses gridded meteorological background fields to calculate "first guess" initial and boundary conditions. Meteorological observations (*e.g.*, temperature, relative humidity, wind direction and speed) are used to improve the first-guess fields. The following NCAR datasets were used as input to MM5:

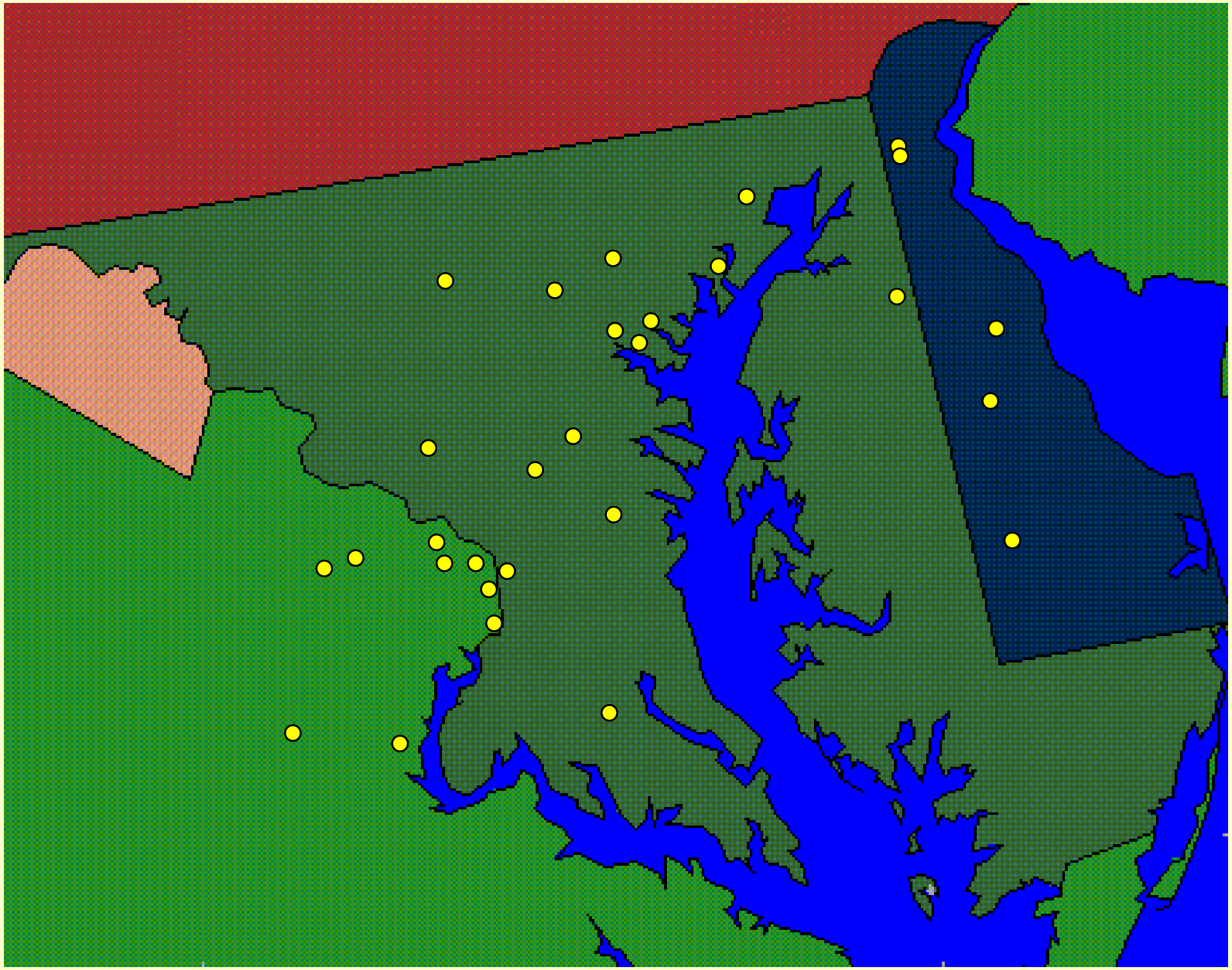
- **First guess fields: NCAR dataset 082.0, National Centers for Environmental Prediction (NCEP) Global Tropospheric Analyses**

- **Surface observations: NCAR dataset 464.0, Lists A, NCEP ADP Global Surface Observations, land-based 6-hr measurements**

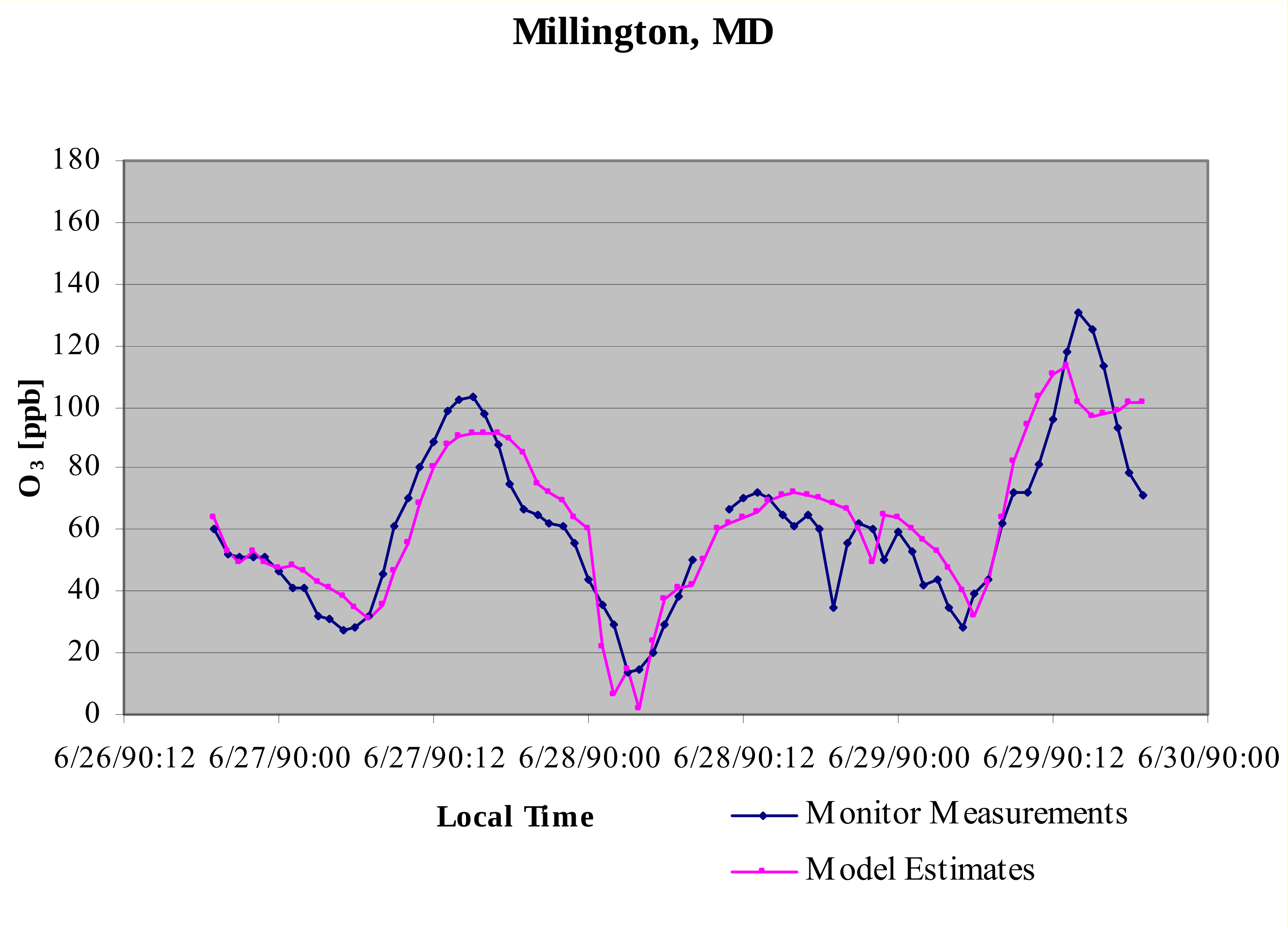
- **Surface observations: NCAR dataset 464.0, Lists B, NCEP ADP Global Surface Observations, land- and ship-based 3-hr measurements**

- **Upper air observations: NCAR dataset 353.4, List A, NCEP ADP Global Upper Air Observation Subsets, raobs**

Four-dimensional data assimilation (Observation Nudging) was used for the 108, 36, and 12-km domains



Air Pollution Monitoring Network



Millington, MD
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O3 [ppb]
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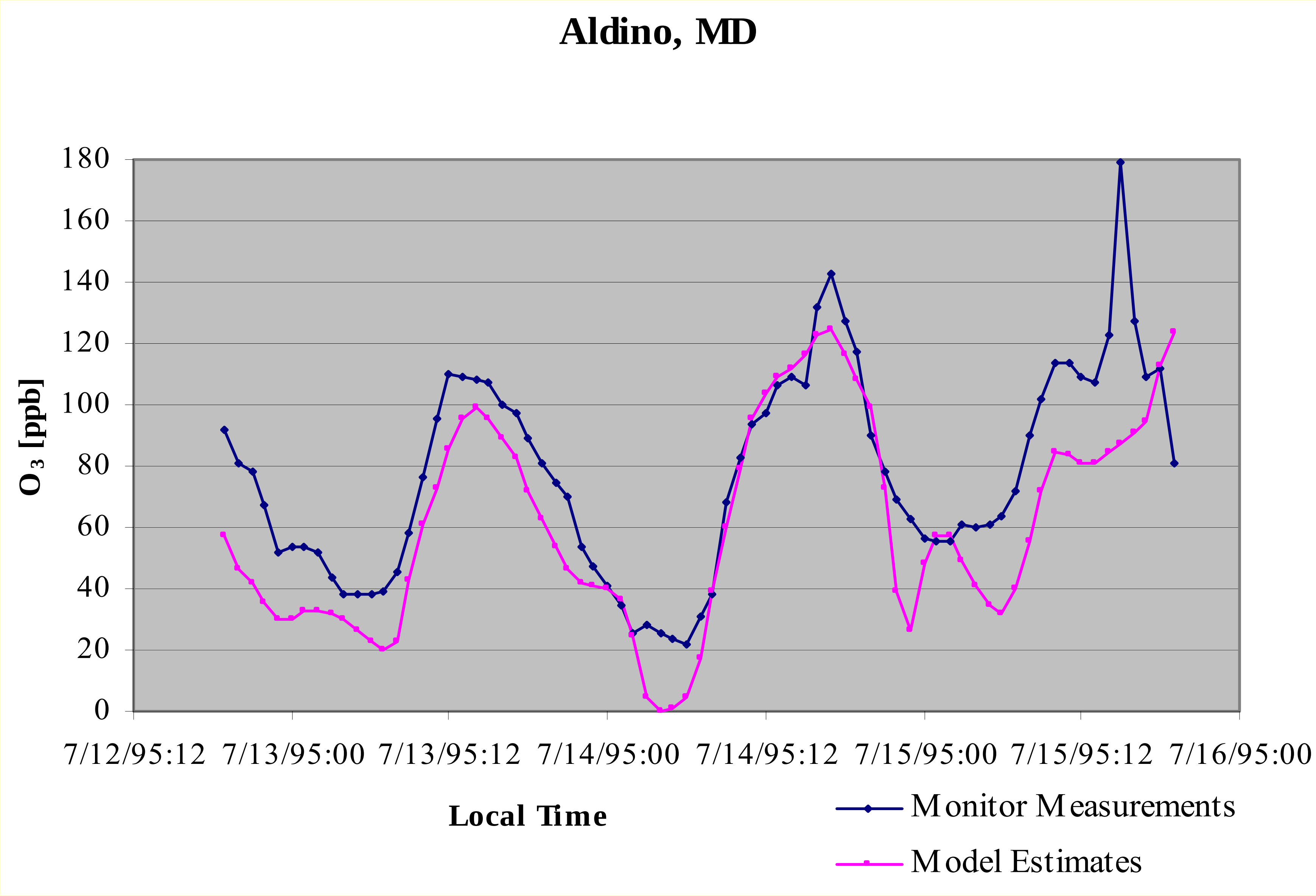
Local Time
Monitor Measurements
Model Estimates



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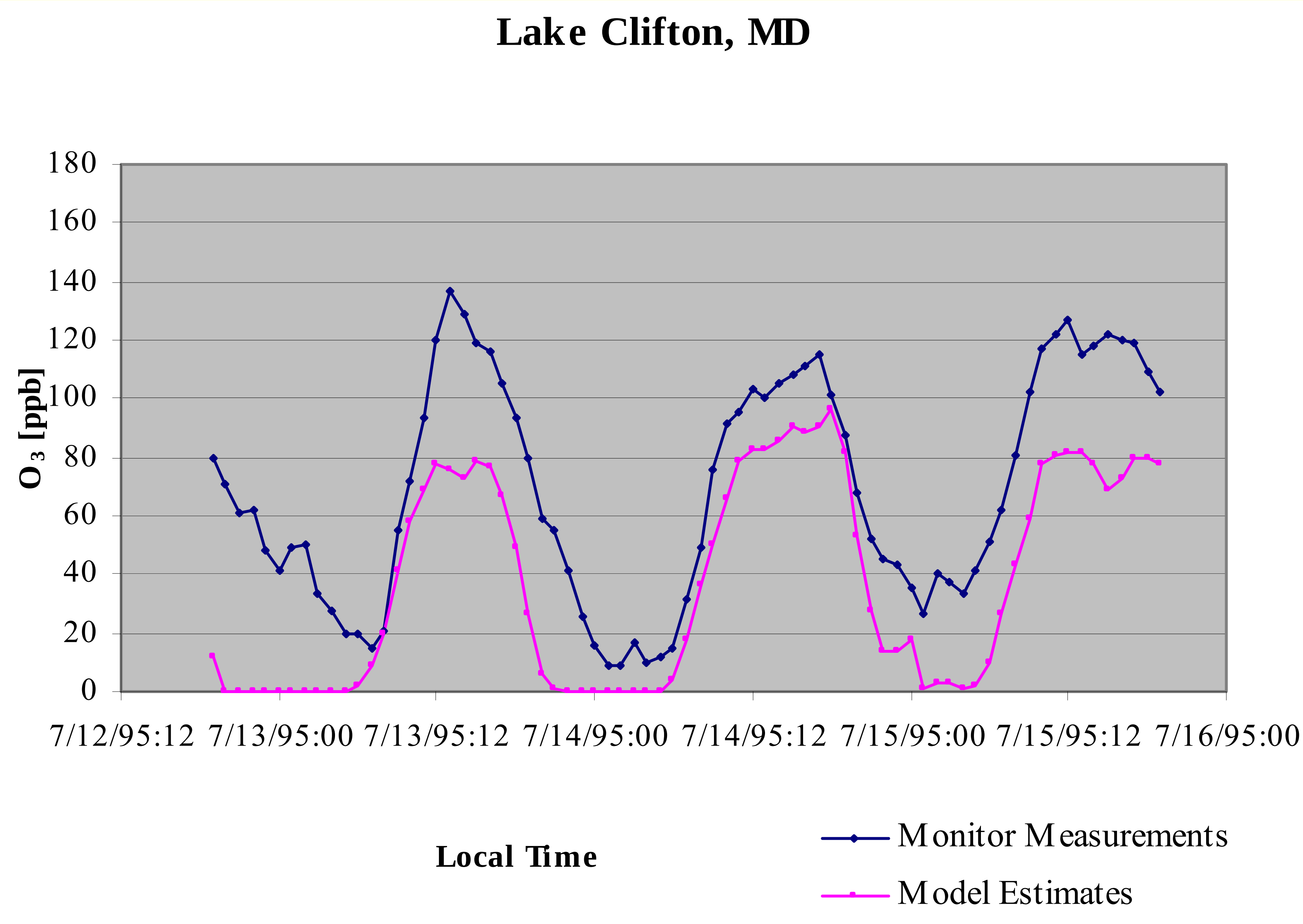
Local Time
Monitor Measurements
Model Estimates


Lake Clifton, MD
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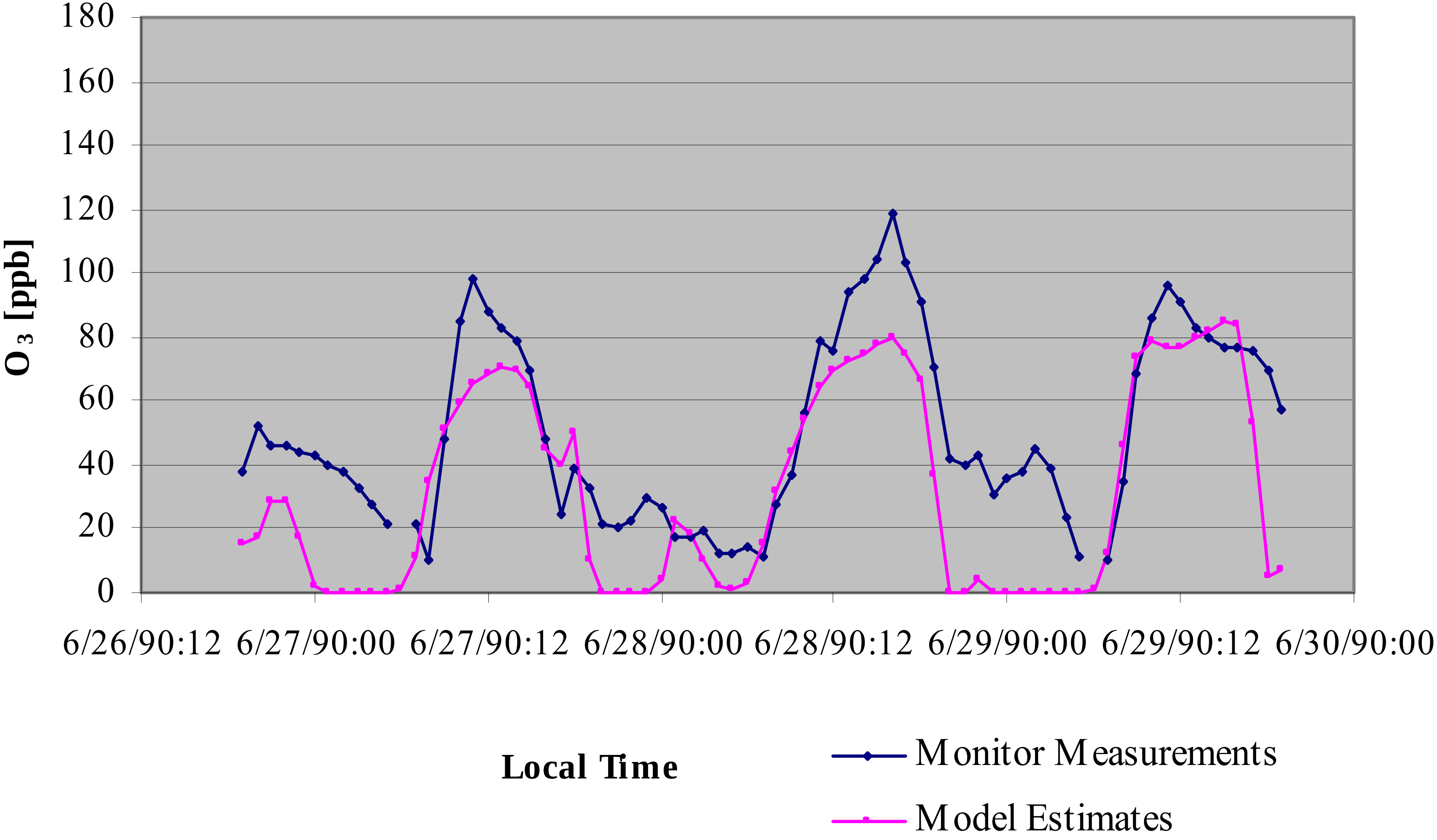
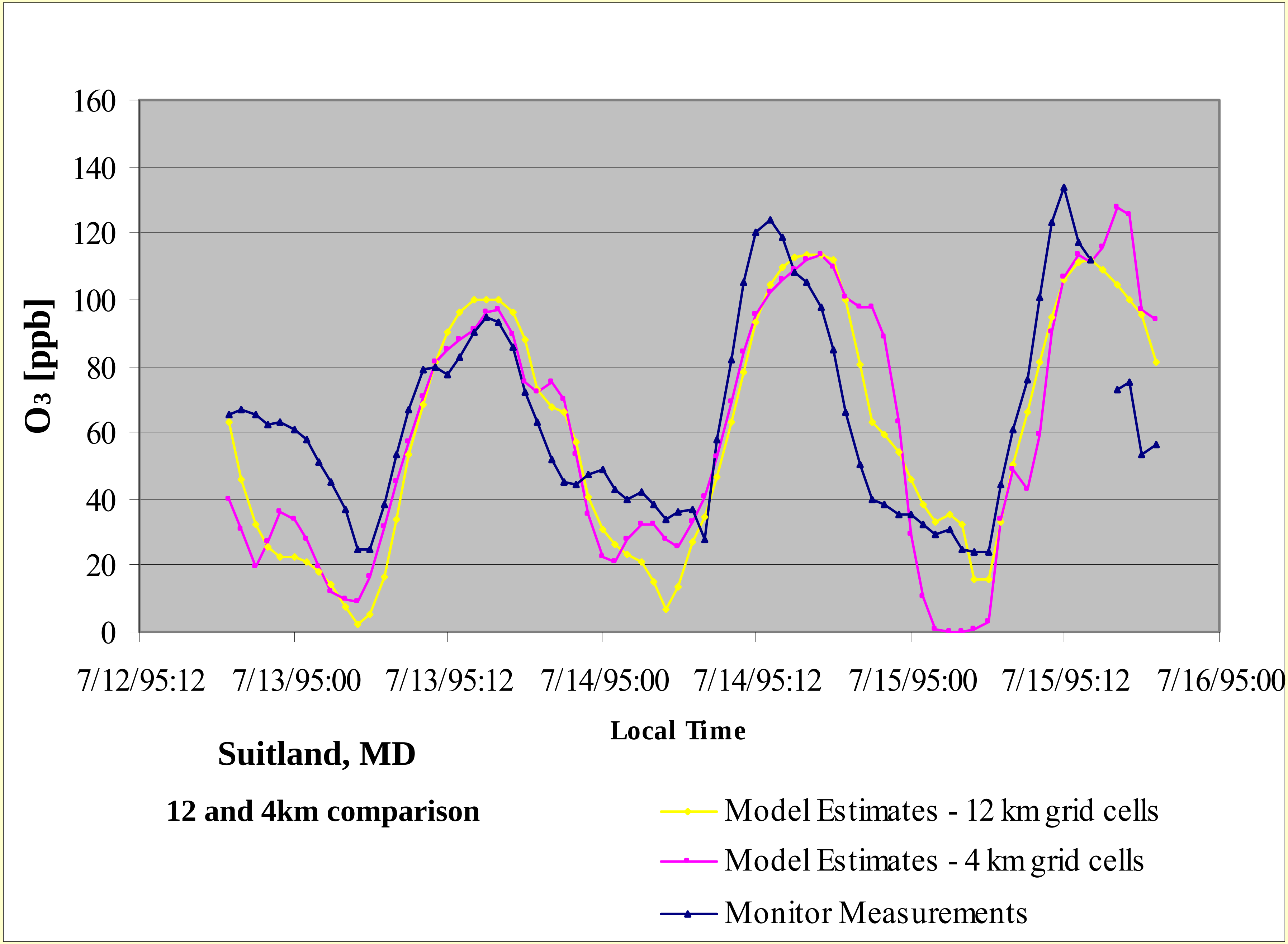
7/16/95:00
Local Time
Monitor Measurements
Model Estimates

S. 18th and Hayes St., VA

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O3 [ppb]
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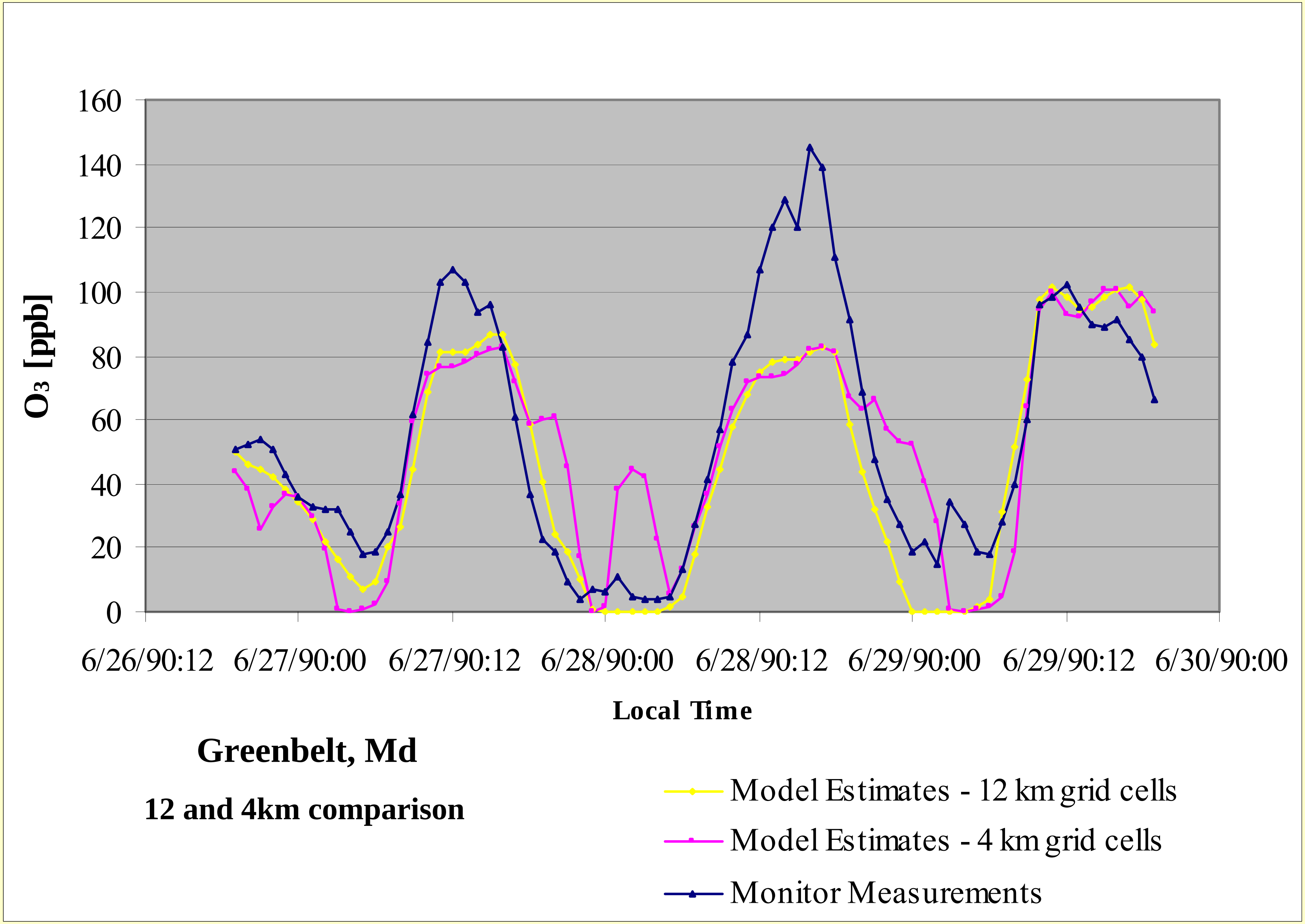
7/14/95:12
7/15/95:00
7/15/95:12
7/16/95:00
Local Time
Suitland, MD
12 and 4km comparison
Model Estimates - 12 km grid cells
Model Estimates - 4 km grid cells
Monitor Measurements



160
140
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80
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20
0
O3 [ppb]
6/26/90:12
6/27/90:00
6/27/90:12
6/28/90:00
6/28/90:12
6/29/90:00
6/29/90:12
6/30/90:00
Local Time
Greenbelt, Md
12 and 4km comparison
Model Estimates - 12 km grid cells
Model Estimates - 4 km grid cells
Monitor Measurements

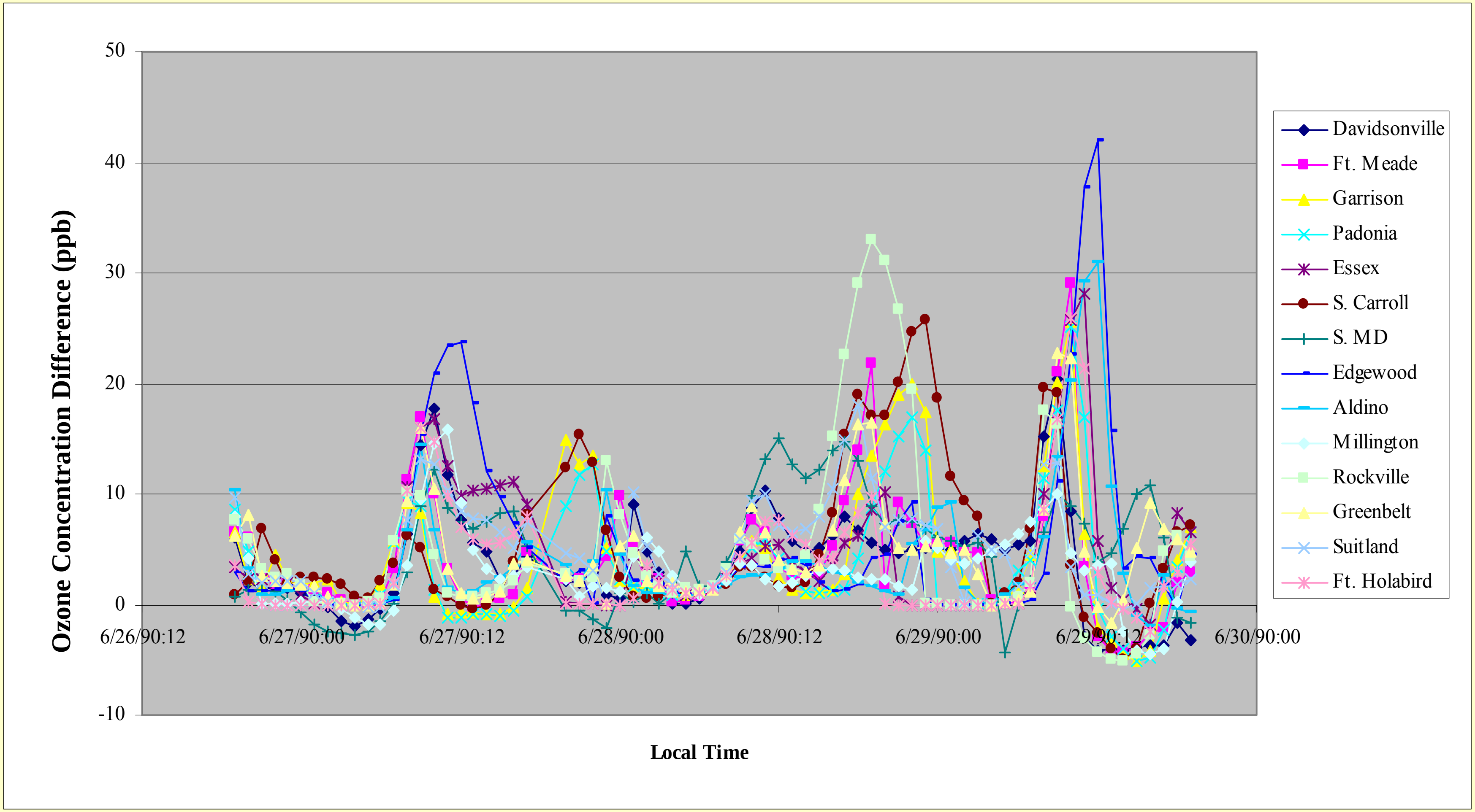
Modified Emissions Scenarios

1) baseline: unadjusted emissions using the 1990 NET emissions inventory;

2) biogenic emissions increased by 100% for isoprene, terpene, and "other" VOCs; and

3) biogenic emissions increased as in (2) and mobile source emissions of VOCs and NO_x increased by 100%.

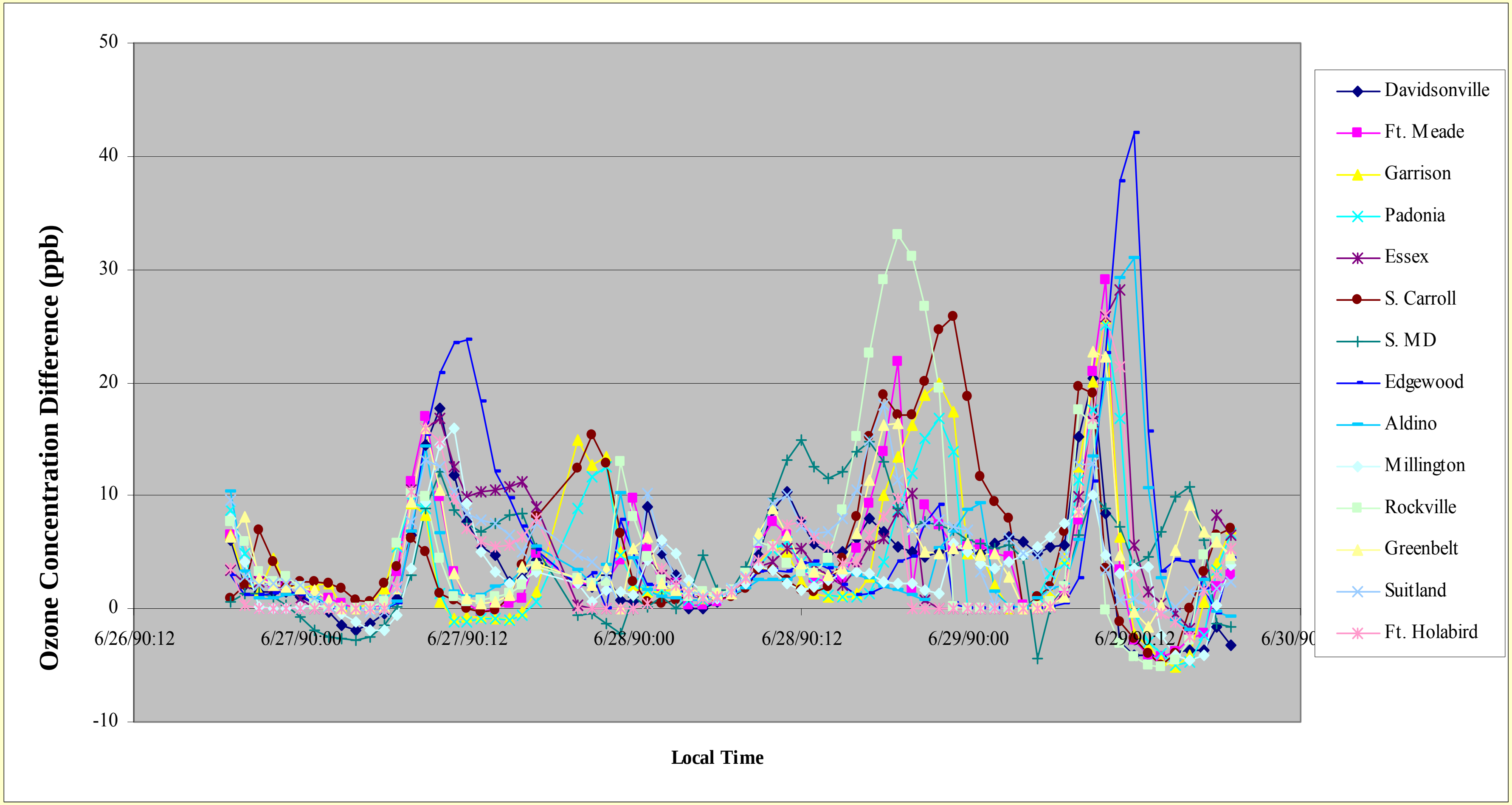
Concentration Differences: Scenarios 1 and 2



Scenario 1 – Baseline

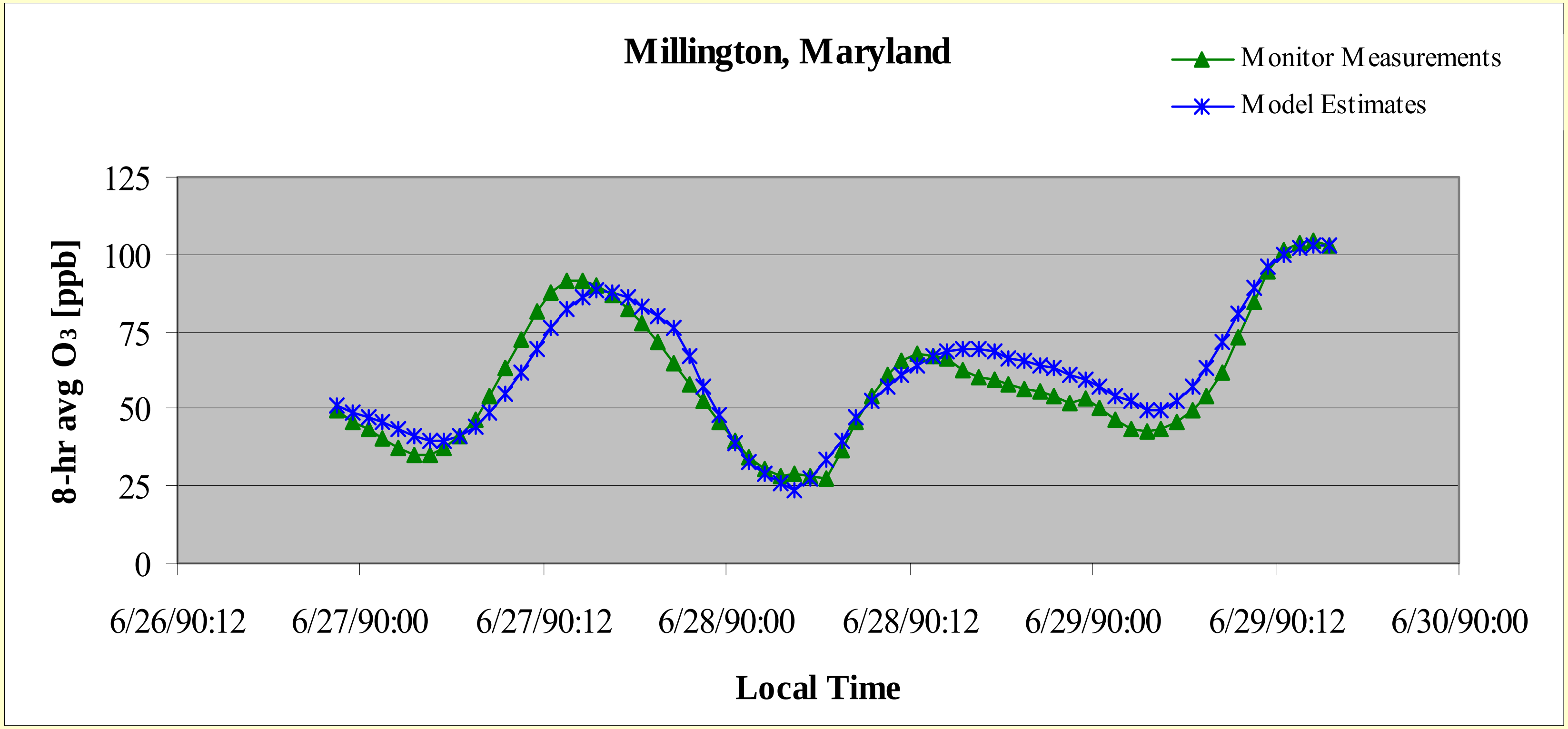
Scenario 2 – Doubled Biogenic VOC

Concentration Differences: Scenarios 1 and 3



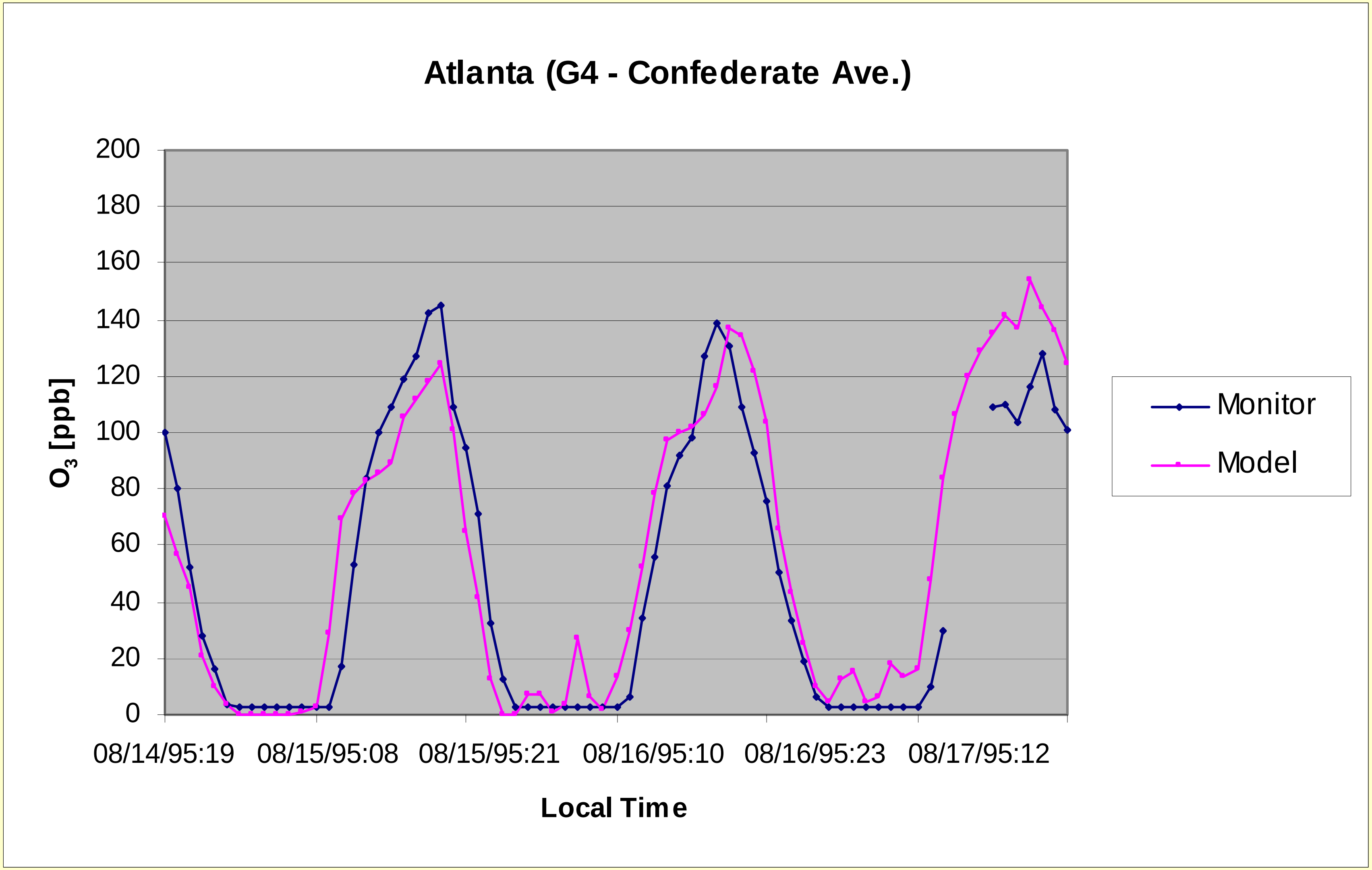
Scenario 1 – Baseline

Scenario 3 – Doubled Biogenic VOC and Doubled Mobile VOC, NOx

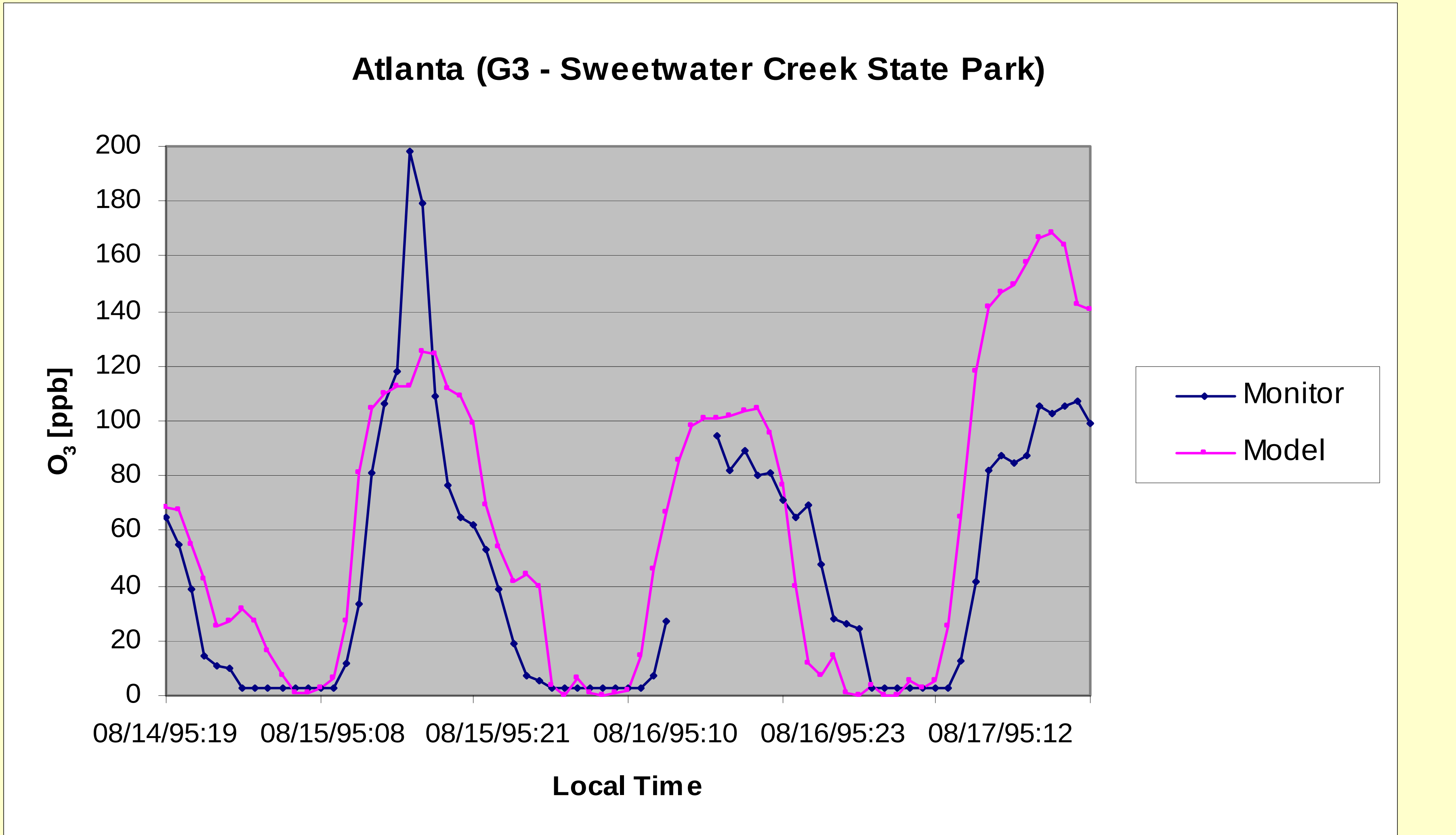


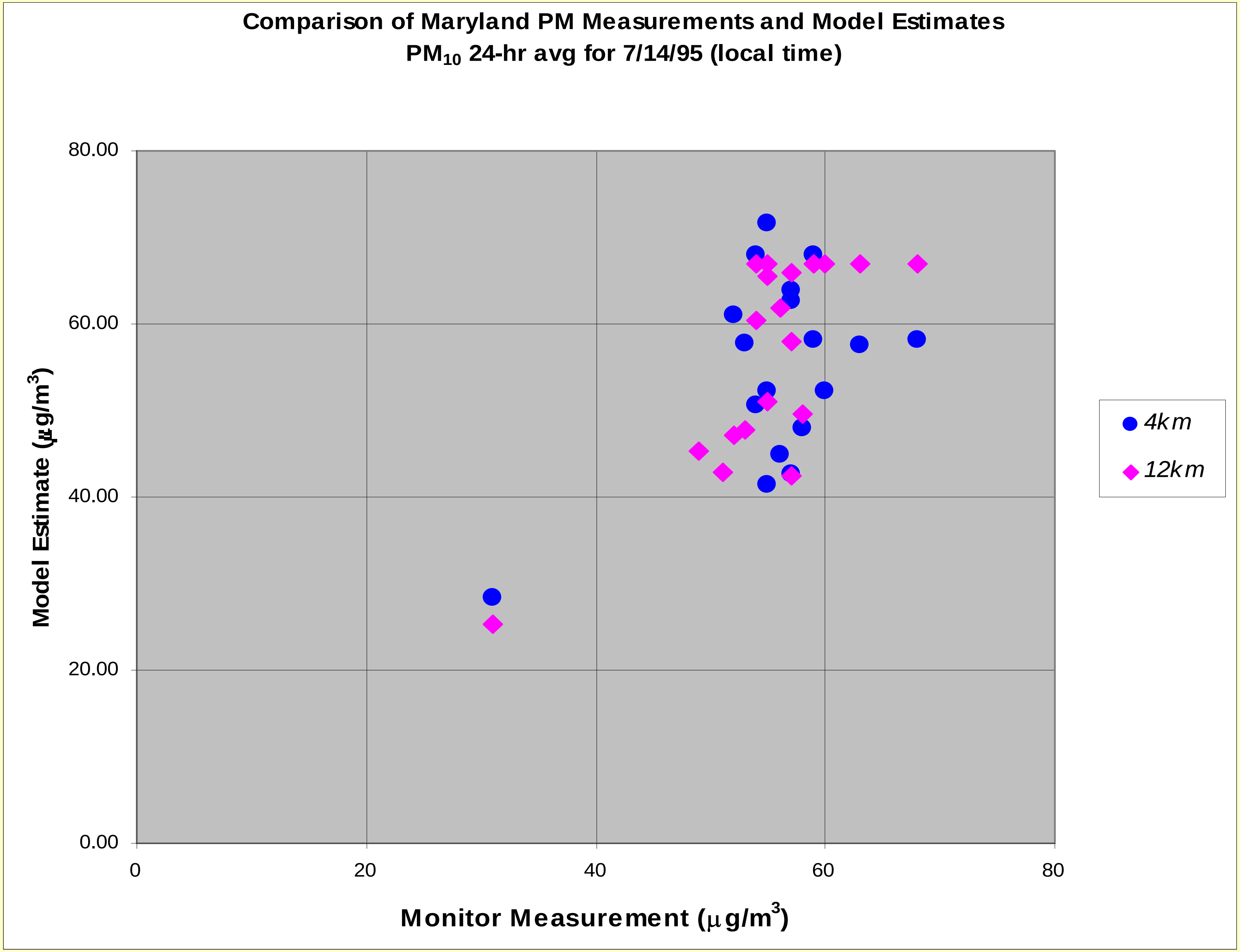
Millington, Maryland
Monitor Measurements
Model Estimates
8-hr avg O3 [ppb]
125
100
75
50
25
0
6/26/90:12
6/27/90:00
6/27/90:12
6/28/90:00
6/28/90:12
6/29/90:00
6/29/90:12
6/30/90:00
Local Time

	1990 Episode			*1995 Episode*		
	Maryland	Virginia	Delaware	Maryland	Virginia	Delaware
# of monitors in 4-km resolution domain	14	6	3	13	8	3
1-hr O_3 > 120 ppb						
% of monitors with measured exceedences	43	33	33	92	25	67
% of monitor locations with model-estimated exceedences	7	0	0	77	12	33
8-hr avg O_3 > 80 ppb						
% of monitors with measured exceedences	93	83	100	100	100	100
% of monitor locations with model-estimated exceedences	100	100	100	100	100	100



Atlanta (G4 - Confederate Ave.)
O3 [ppb]
200
180
160
140
120
100
80
60
40
20
0
08/14/95:19
08/15/95:08
08/15/95:21
08/16/95:10
08/16/95:23
08/17/95:12
Local Time
Monitor
Model


Atlanta (G3 - Sweetwater Creek State Park)
O_3 [ppb]
200
180
160
140
120
100
80
60
40
20
0
08/14/95:19
08/15/95:08
08/15/95:21
08/16/95:10
08/16/95:23
08/17/95:12
Local Time
Monitor
Model


Comparison of Maryland PM Measurements and Model Estimates
PM10 24-hr avg for 7/14/95 (local time)
Model Estimate (µg/m3)
80.00
60.00
40.00
20.00
0.00
0
20
40
60
80
Monitor Measurement (µg/m3)
4km
12km