Sensitivity and Uncertainty Assessment of Global Climate Change Impacts on Regional Ozone and $PM_{2.5}$

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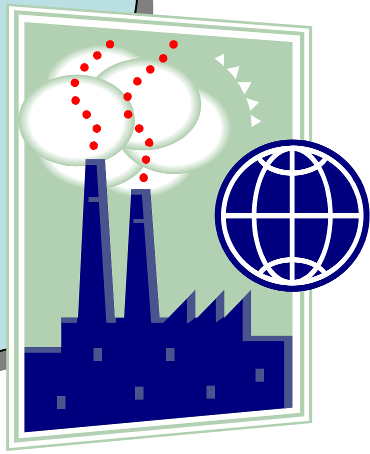
Issues

➢ How does the climate change penalty compare to benefits of planned emission reductions?

➢ **How well will currently planned control strategies work as changes in climate occur?**

➢ **How robust are the results?**



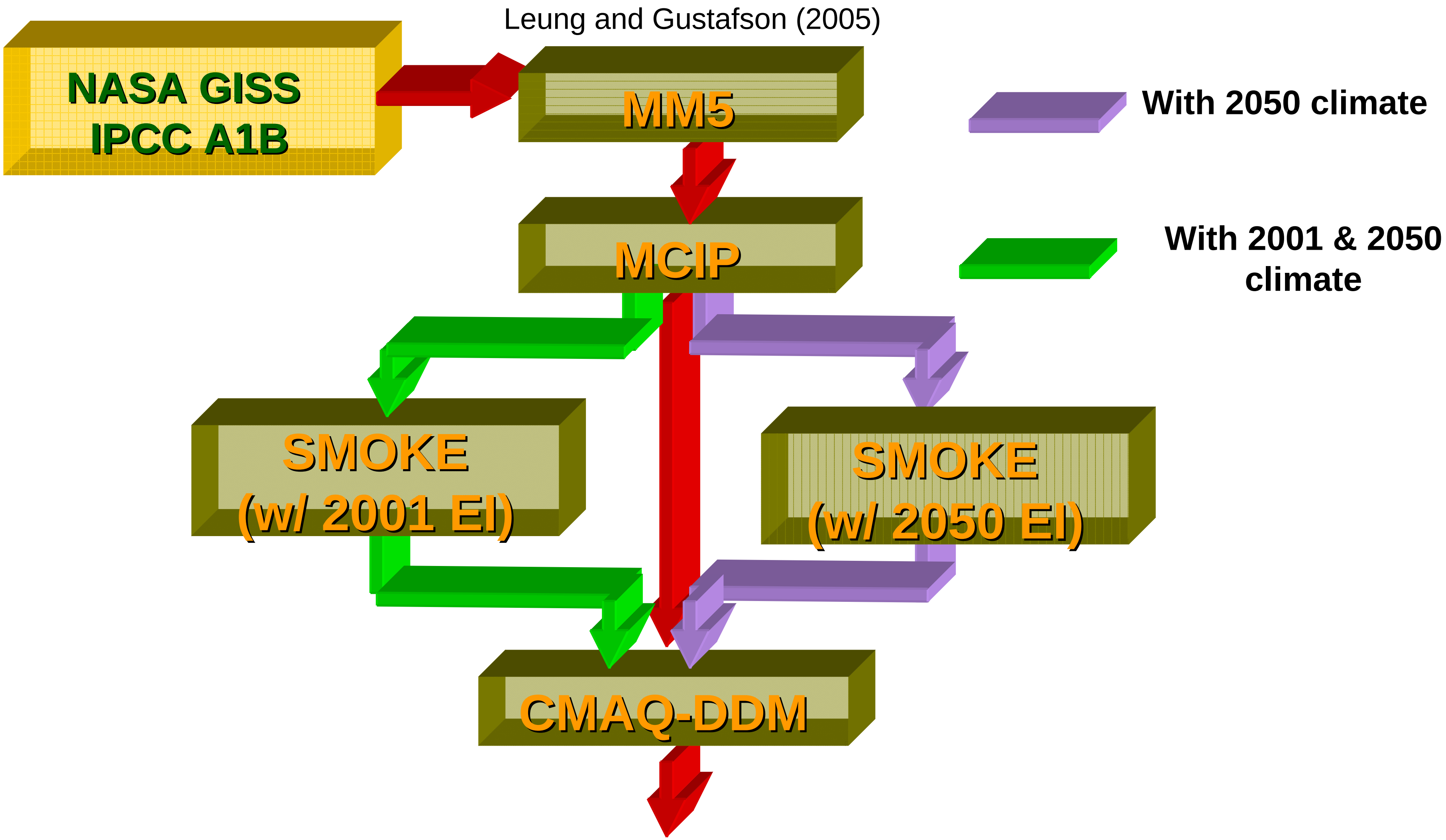
Above questions can be answered by **quantifying sensitivities** of air pollutants (e.g., ozone and PM2.5) to their precursor emissions (e.g., NO*x*, NH3, VOCs and SO2) and **associated uncertainties.**

To cut out a lot of repetitive stuff…

- Similarities with some others
  - Downscaled GISS using MM5 for input in to CMAQ
  - Base years around 2000 (we use 2000-2002), future around 2050 (we concentrate on 2049-2051)
- Differences
  - Focus:
    - Sensitivities and uncertainties in responses to emission changes
    - Analyze by regions
  - Emissions (really important)
  - Averaging interval (ours is shorter)
  - Science-policy interface and capacity building via NESCAUM
    - Briefing with regional, state policy makers (CA, NE, GA)

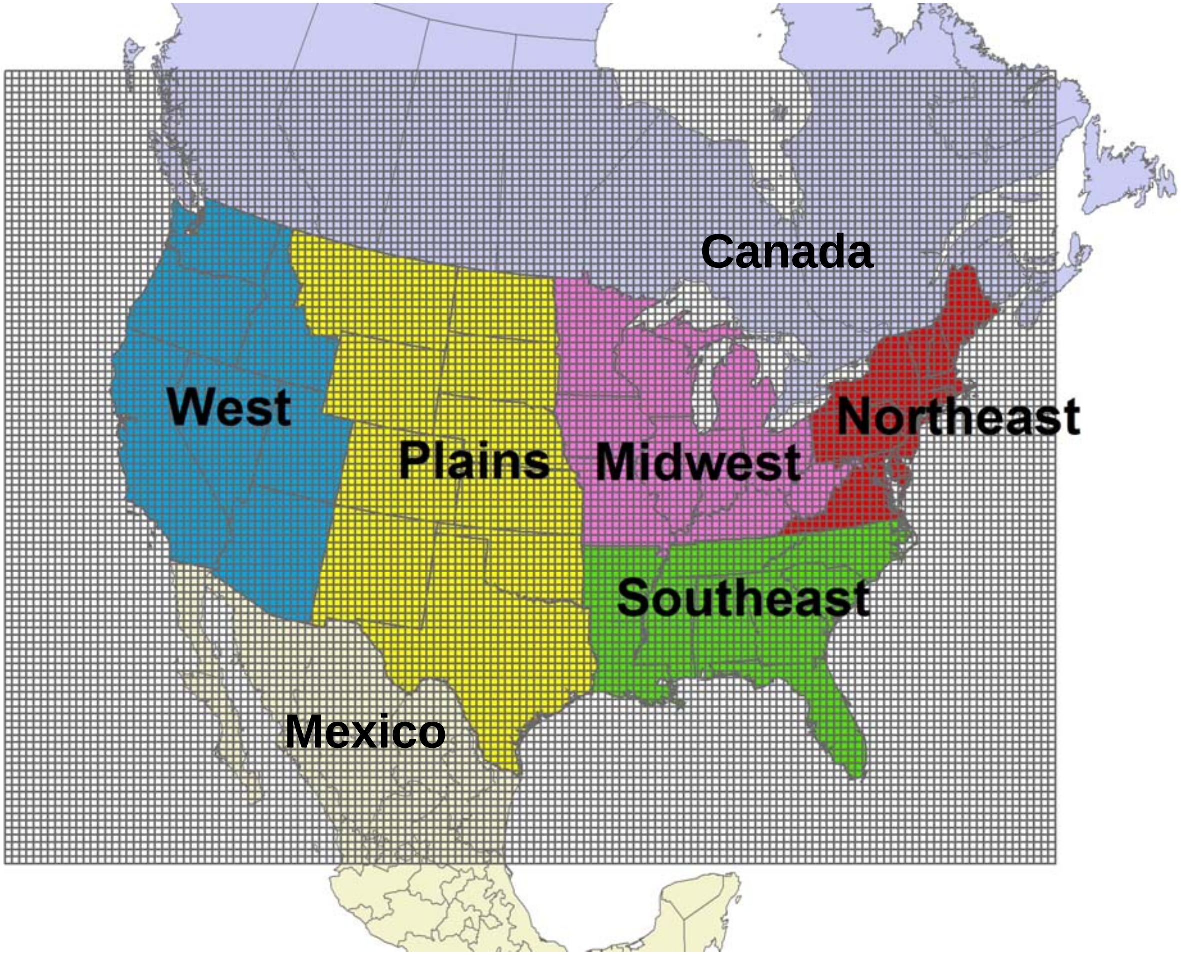
Woo et. al, 2006

Modeling Procedure



*Leung and Gustafson (2005), *Geophys. Res. Lett.*, *32*, L16711

Air Quality Simulation Domain



- 147 x 111 grid cells
- 36-km by 36-km grid size
- 9 vertical layers
- U.S. regions:
  - West (ws)
  - Plains (pl)
  - Midwest (mw)
  - Northeast (ne)
  - Southeast (se)

•Also investigating Mexico and Canada

Emission Inventory Projection

- **Accurate projection of emissions key to comparing relative impacts on future air quality and control strategy effectiveness**
  - **Working with NESCAUM vital**

Step 1. Use latest projection data available for the near future

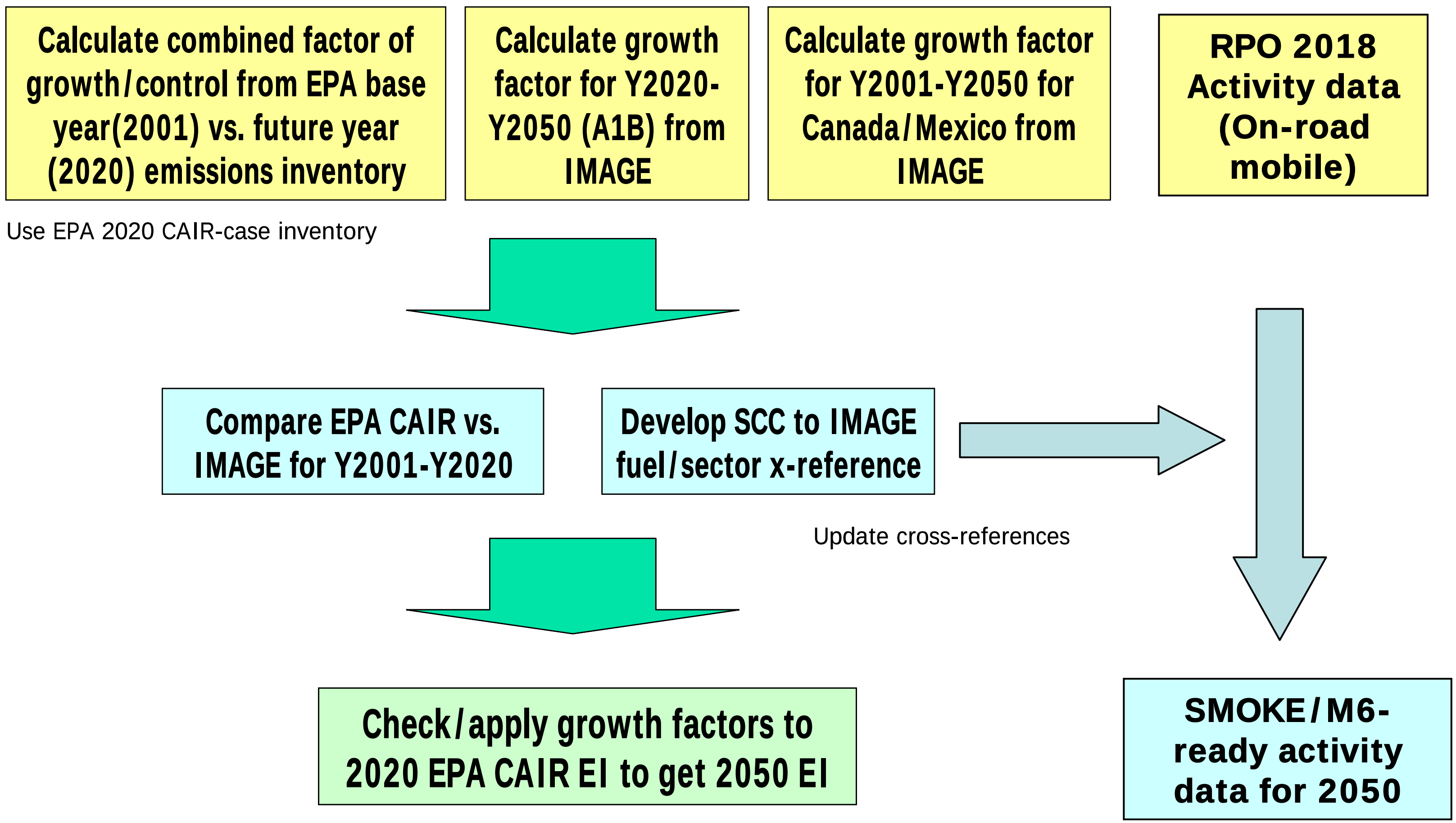
- Use EPA CAIR Modeling EI (Point/Area/Nonroad, from 2001 to 2020)
- Use RPO SIP Modeling EI (Mobile, from 2002 to 2018)

Step 2. Get growth data for the distant future

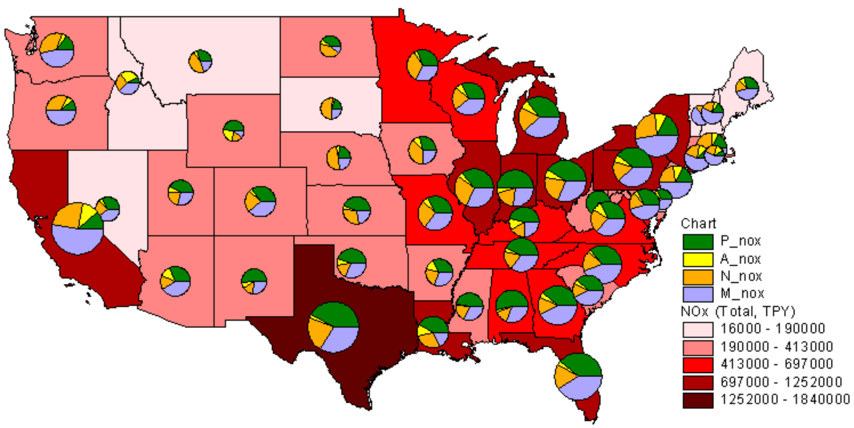
- Use IMAGE model (IPCC SRES, A1B)
- From 2020 (2018 for mobile activity) to 2050
- Use SMOKE/Mobile6 for Mobile source control

Woo et. al, 2006

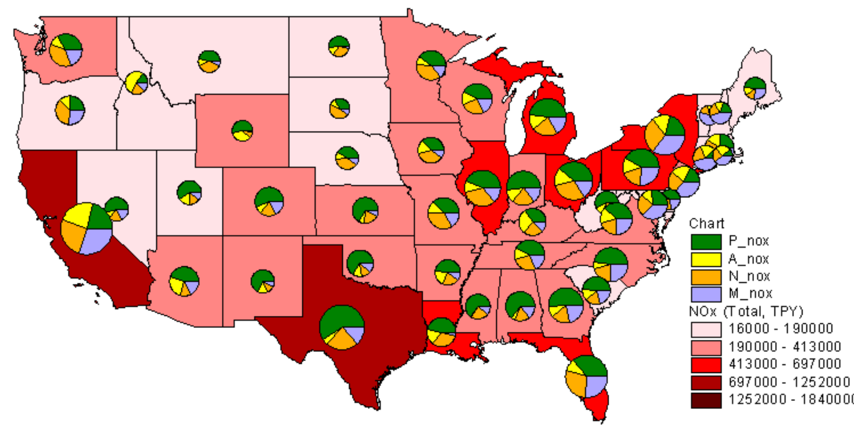
Emission Inventory Projection



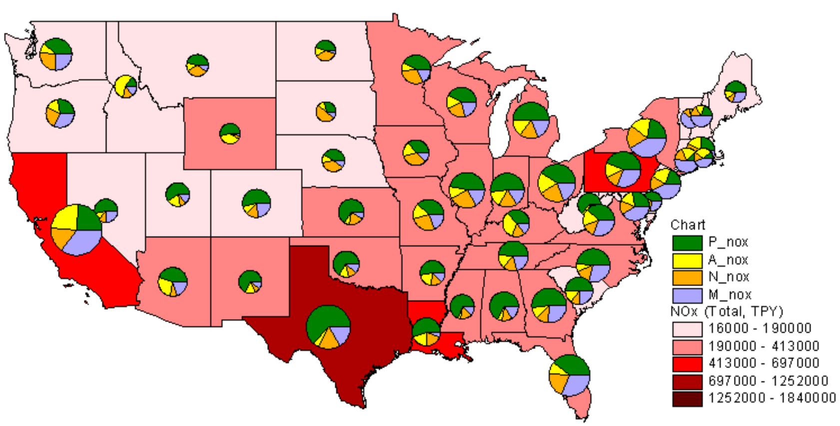
Regional Emissions



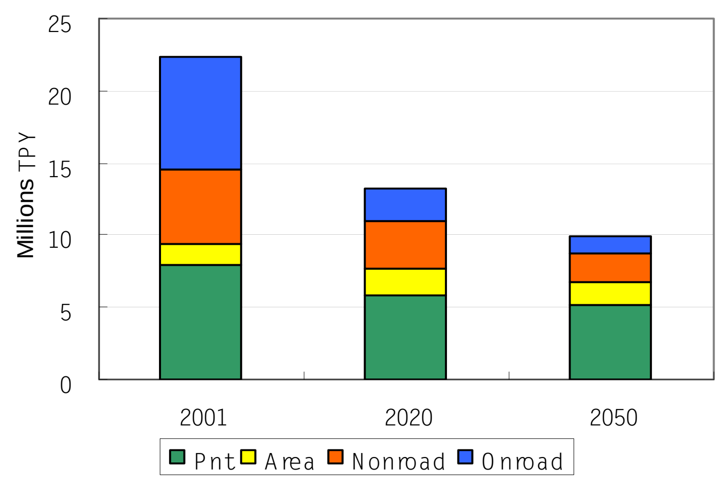
Year 2001



Year 2020

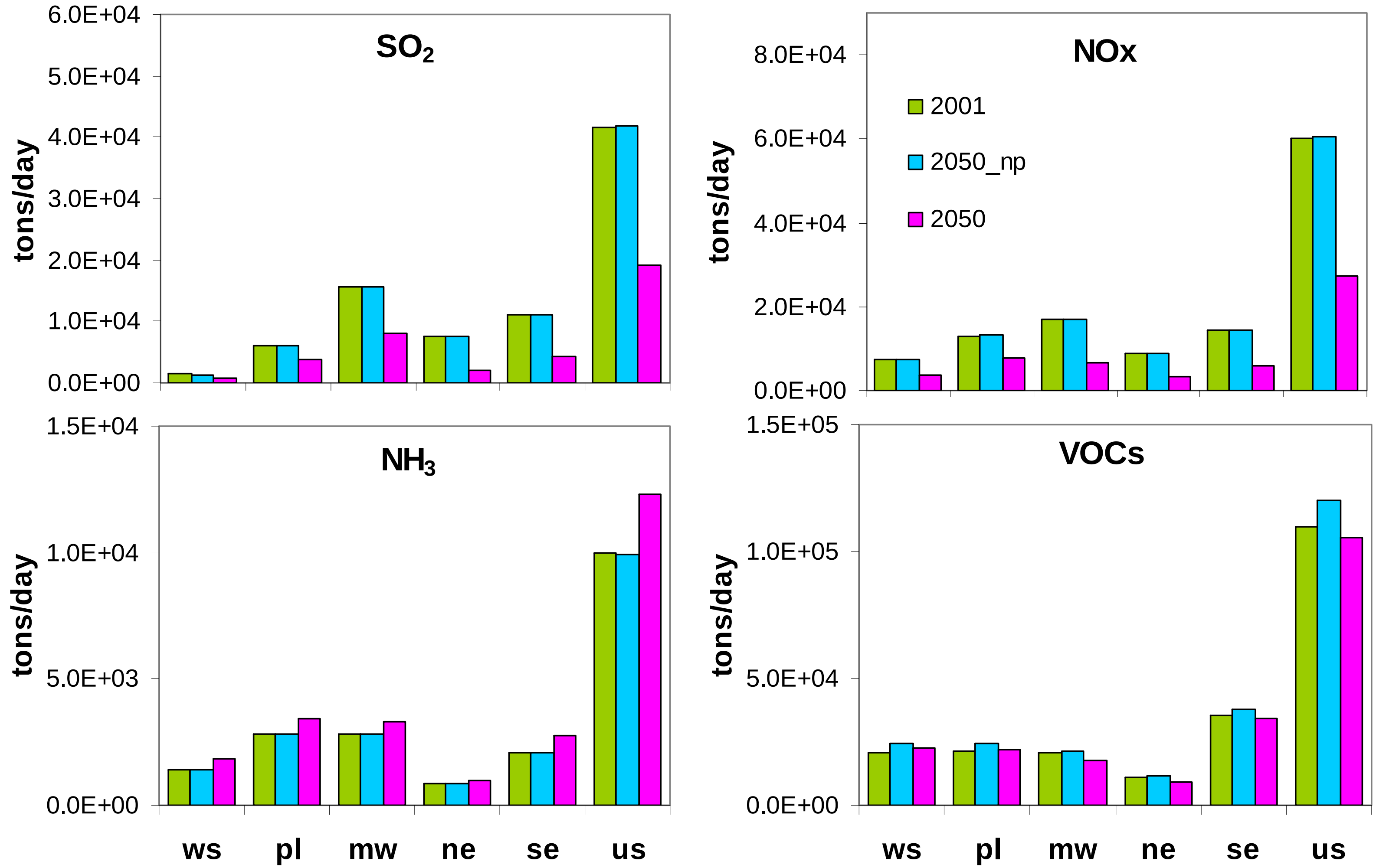


Year 2050



Present and future years NOx emissions by state and by source types

Emission Changes



Summary of Air Quality Simulations

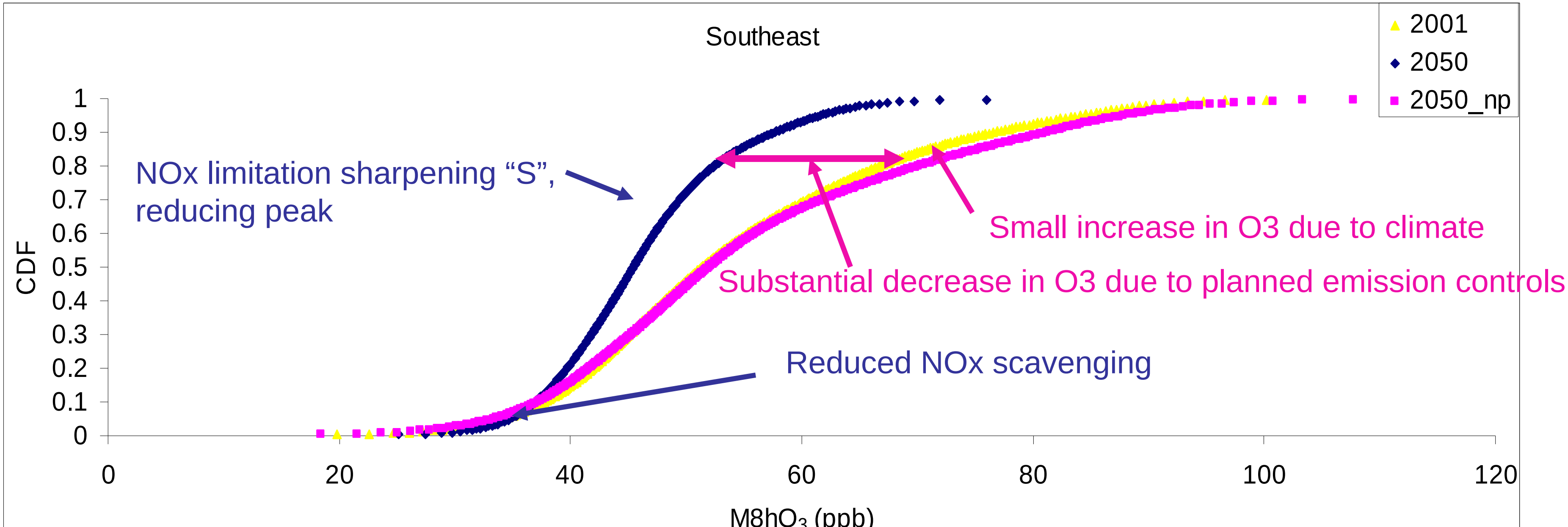
Scenario	Emission Inventory (E.I.)	Climate Conditions	Future Air Quality Impacting Factors
2001	Historic (2001)	Historic (2001 whole year)	N.A.
2000-2002 summers	Historic (2000-2002)	Historic (2000-2002 summers)	N.A.
2050_**np** (non-projected emissions, but meteorologically influenced for consistency)	Historic (2001)	Future (2050 whole year)	Potential future climate changes
2049-2051_np summers	Historic (2000-2002)	Future (2049-2051 summers)	Potential future climate changes
2050	Future (2050)	Future (2050 whole year)	Potential future climate changes & projected E.I.
2049-2051 summers	Future (2049-2051)	Future (2049-2051 summers)	Potential future climate changes & projected E.I.

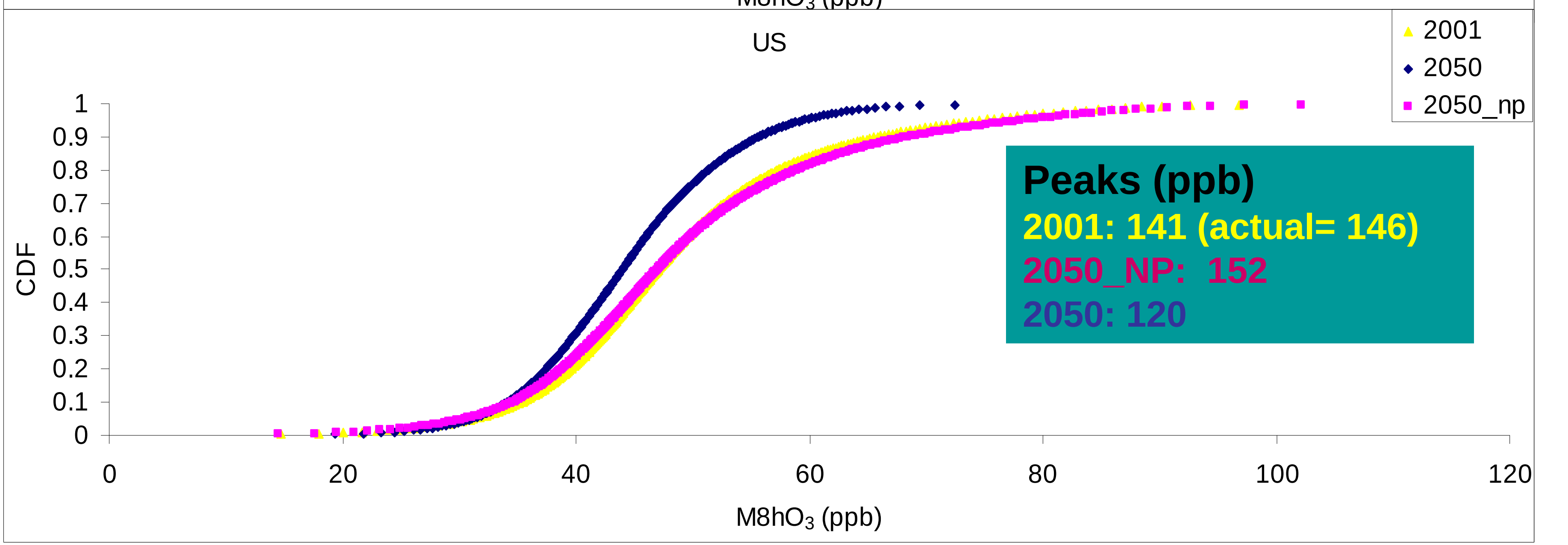
Approach I

Impact of Future Climate Change on Ground-level Ozone and $PM_{2.5}$ Concentrations

- Not the central focus of this research, but important and interesting for comparison

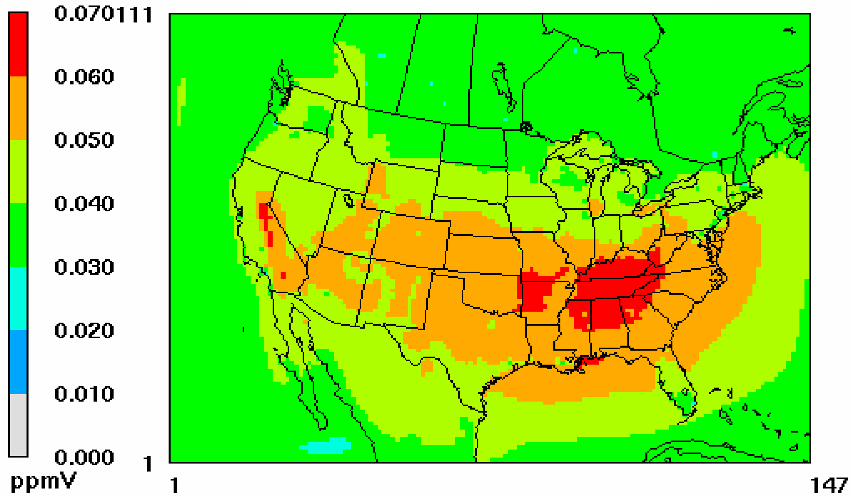
Daily maximum 8 hour ozone concentration CDF plots in 2001, 2050 and 2050_np



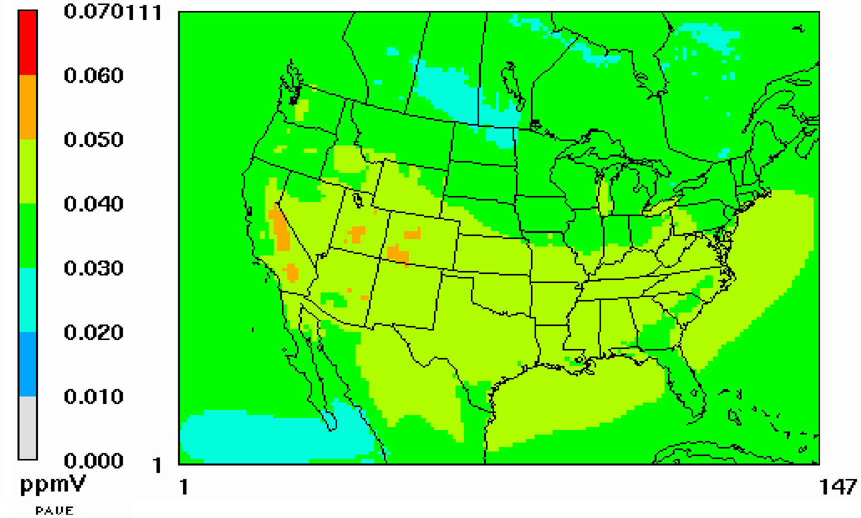


Summer Average Max 8hr O_3

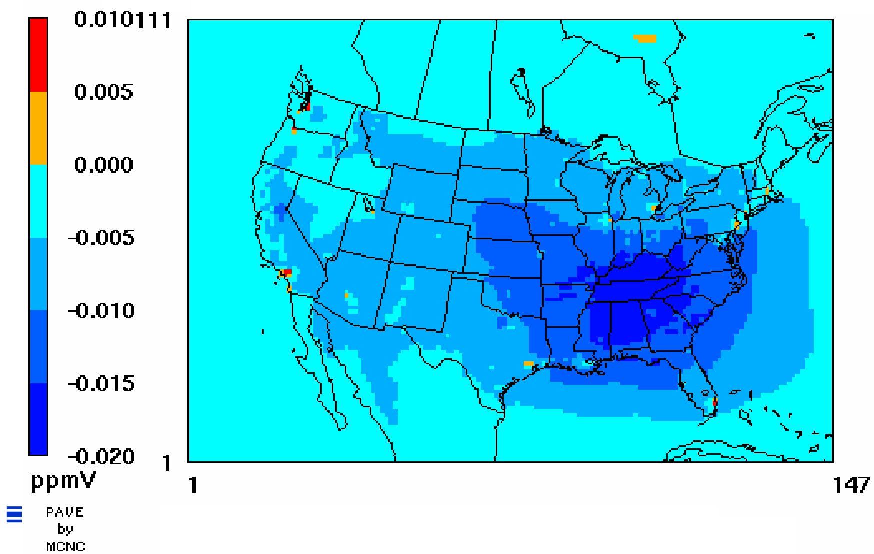
O_3_2000-2002summers



O_3_2049-2051summers

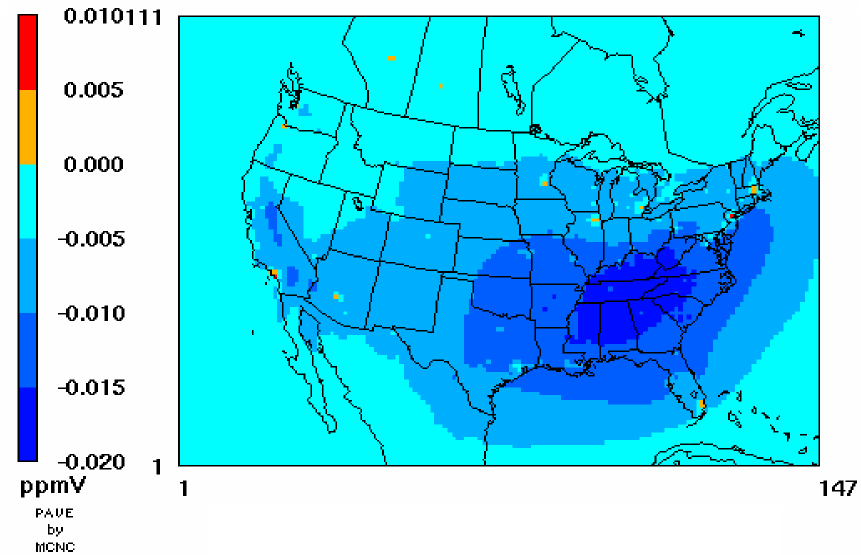


O_3_FutureSummers - O_3_HistoricSummers



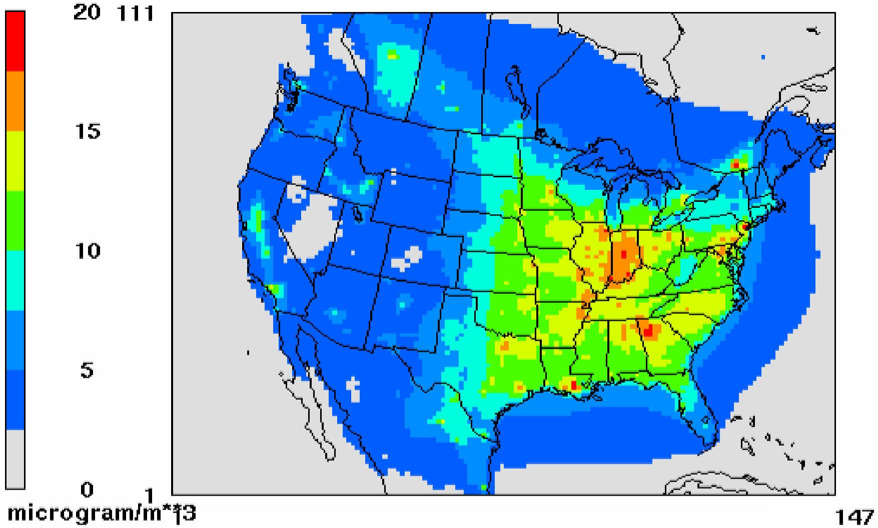
O_3_FutureSummers - O_3_FutureSummers_np

np: Emission Inventory 2001, Climate 2050

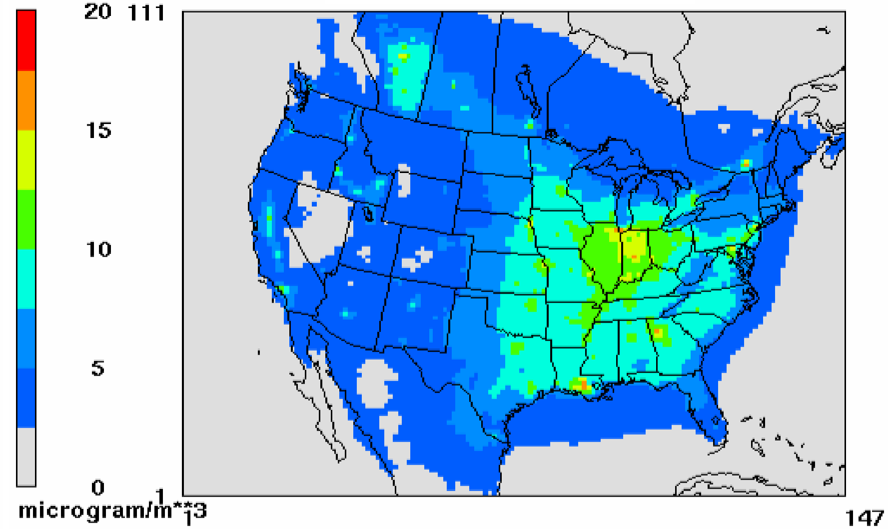


Annual $PM_{2.5}$

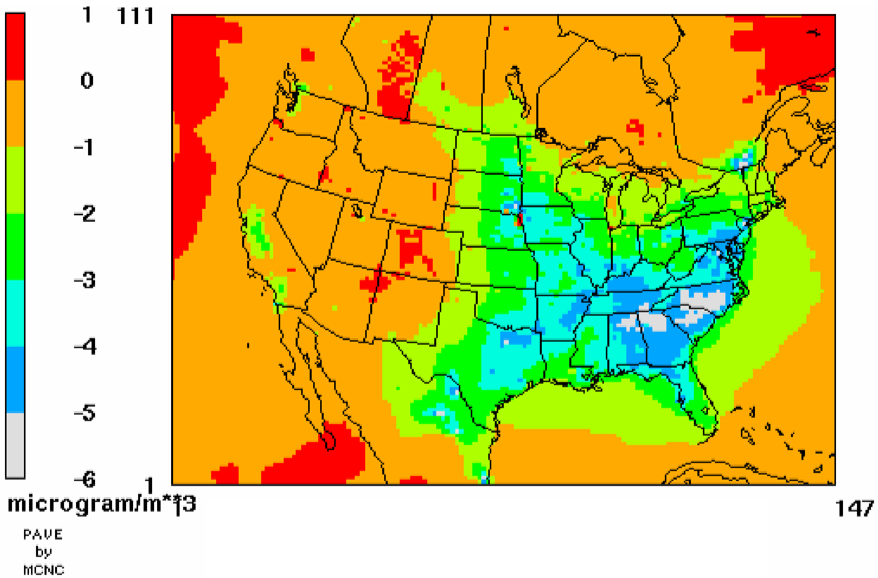
$PM_{2.5}$_2001



$PM_{2.5}$_2050

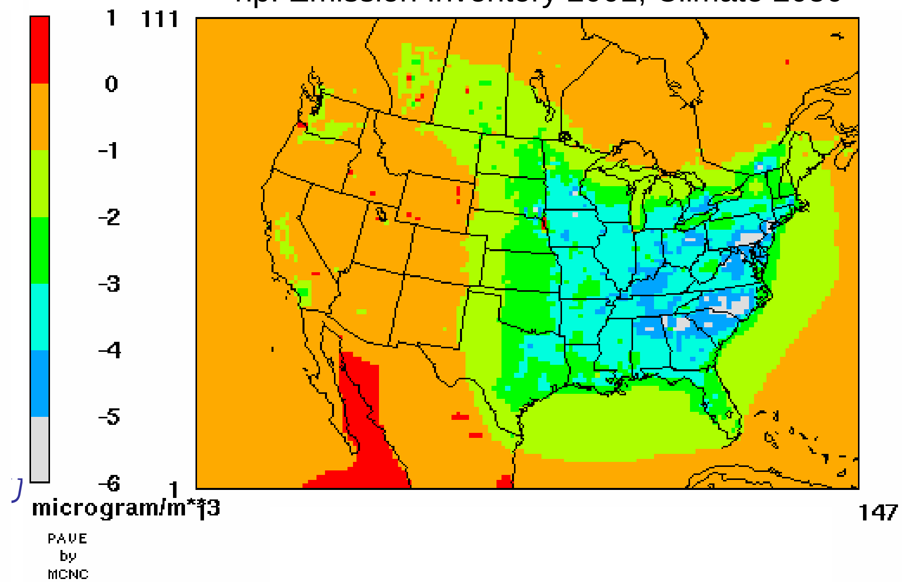


$PM_{2.5}$_2050 - $PM_{2.5}$_2001

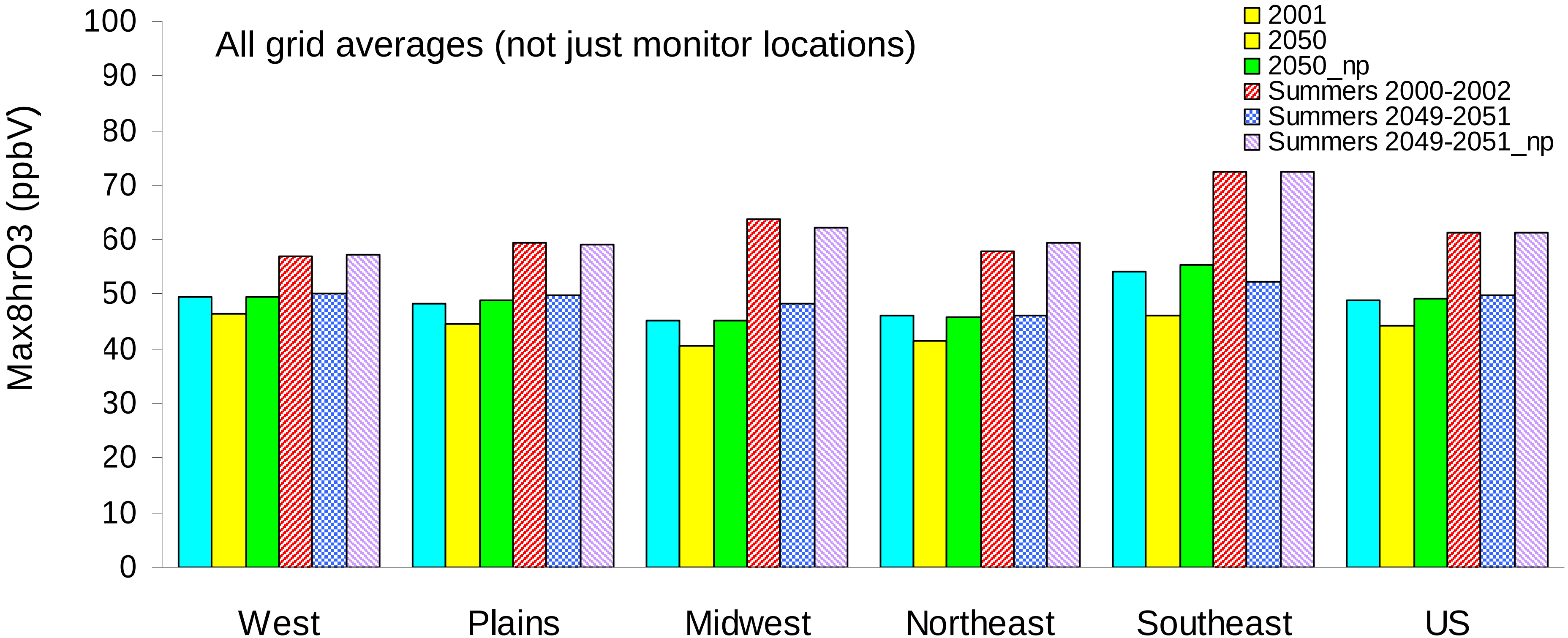


$PM_{2.5}$_2050 - $PM_{2.5}$_2050np

np: Emission Inventory 2001, Climate 2050

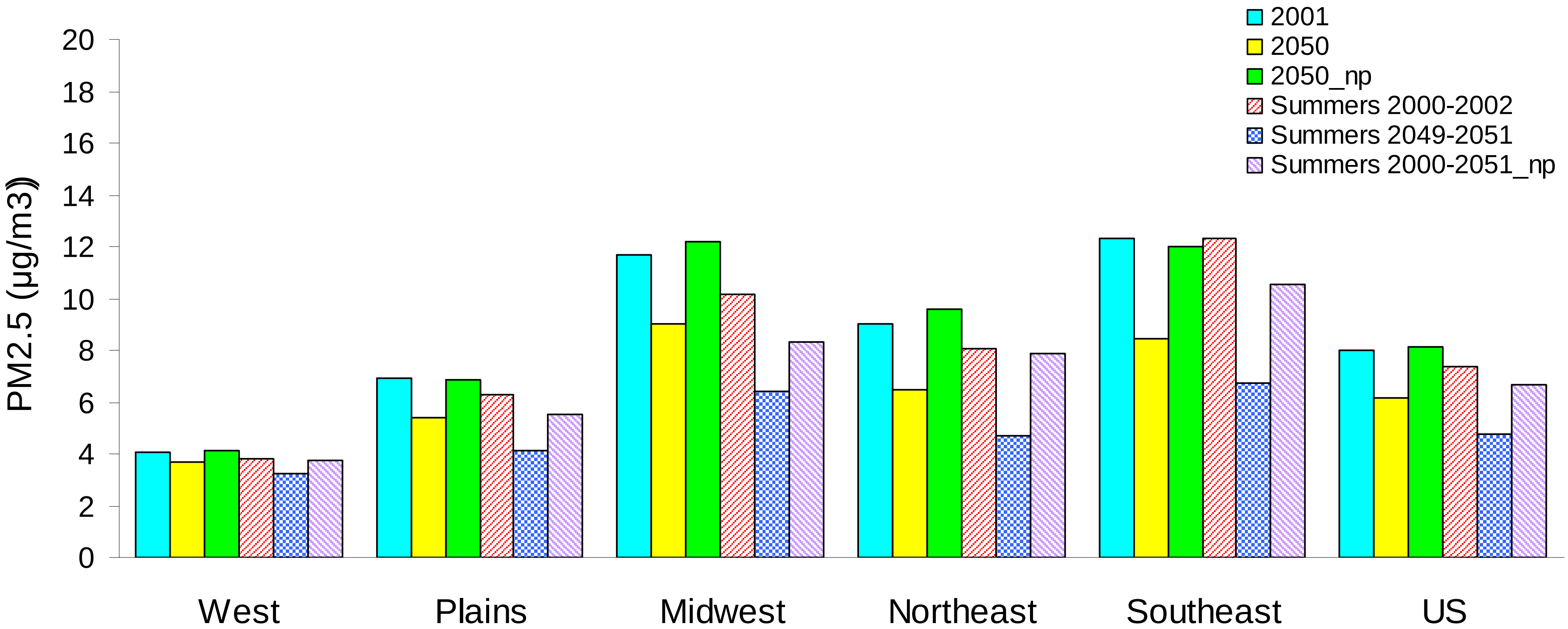


Impact of Potential Climate Change and Planned Controls on Average Max8hrO3



- **3-8 ppbV lower in 2050 (6-15%)**
- **Only +/- 1ppbV difference without considering future emission controls (2050_np) (-2 to + 3%)**
- **More significant reductions in summers. (12-28%)**

Impact of Potential Climate Change on $PM_{2.5}$



- about 0.3-3.8 µg/m³ lower in 2050

- maximum 0.6 µg/m³ difference without considering future emission controls (2050_np)

-Usually np is lower in summer, though can be higher on average

Annual Averaged Changes from 2001 in Averaged Max8hrO3 & $PM_{2.5}$

	Max8hrO3 (%)		$PM_{2.5}$ (%)	
	2050	2050np	2050	2050np
West	-6.5	0.2	-9.2	2.9
Plains	-7.9	1.4	-22.0	-0.8
Midwest	-10.5	-0.2	-22.7	4.2
Northeast	-10.0	-0.5	-28.5	6.5
Southeast	-14.8	2.3	-31.4	-2.4
US	-9.2	0.9	-23.4	1.1

Regional Predicted Max8hrO3 Characteristics

Unit of 99.5% and peak: ppbV

	2000-2002 summers			2049-2051 summers			2049-2051_np summers		
	# of days over 80 ppb	# of days over 85 ppb (sim/act)	Peak	# of days over 80 ppb	# of days over 85 ppb	Peak	# of days over 80 ppb	# of days over 85 ppb	Peak
West / Los Angeles	149	95/85	119	31	6	97	221	186	146
Plains / Houston	127	107/87	127	29	10	94	165	146	143
Midwest / Chicago	78	66/32	138	19	12	106	59	44	152
Northeast / New York	51	38/46	112	1	0	81	82	60	121
Southeast / Atlanta	199	182/54*	124/ 139	0	0	78	195	177	131

Significant improvement

Stagnation events Increase in some areas

* 1998-2000: 137

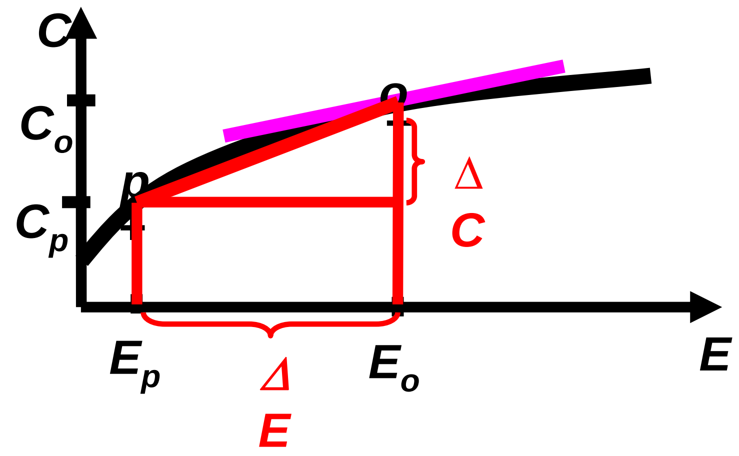
Assessment II

Sensitivity Analysis of Ground-level Ozone and $PM_{2.5}$

➔ Now this is more of our focus

Seminormalized First-order Sensitivity Calculated using DDM-3D

$$S_{i,j} = E_j \frac{\partial C_i}{\partial E_j}$$



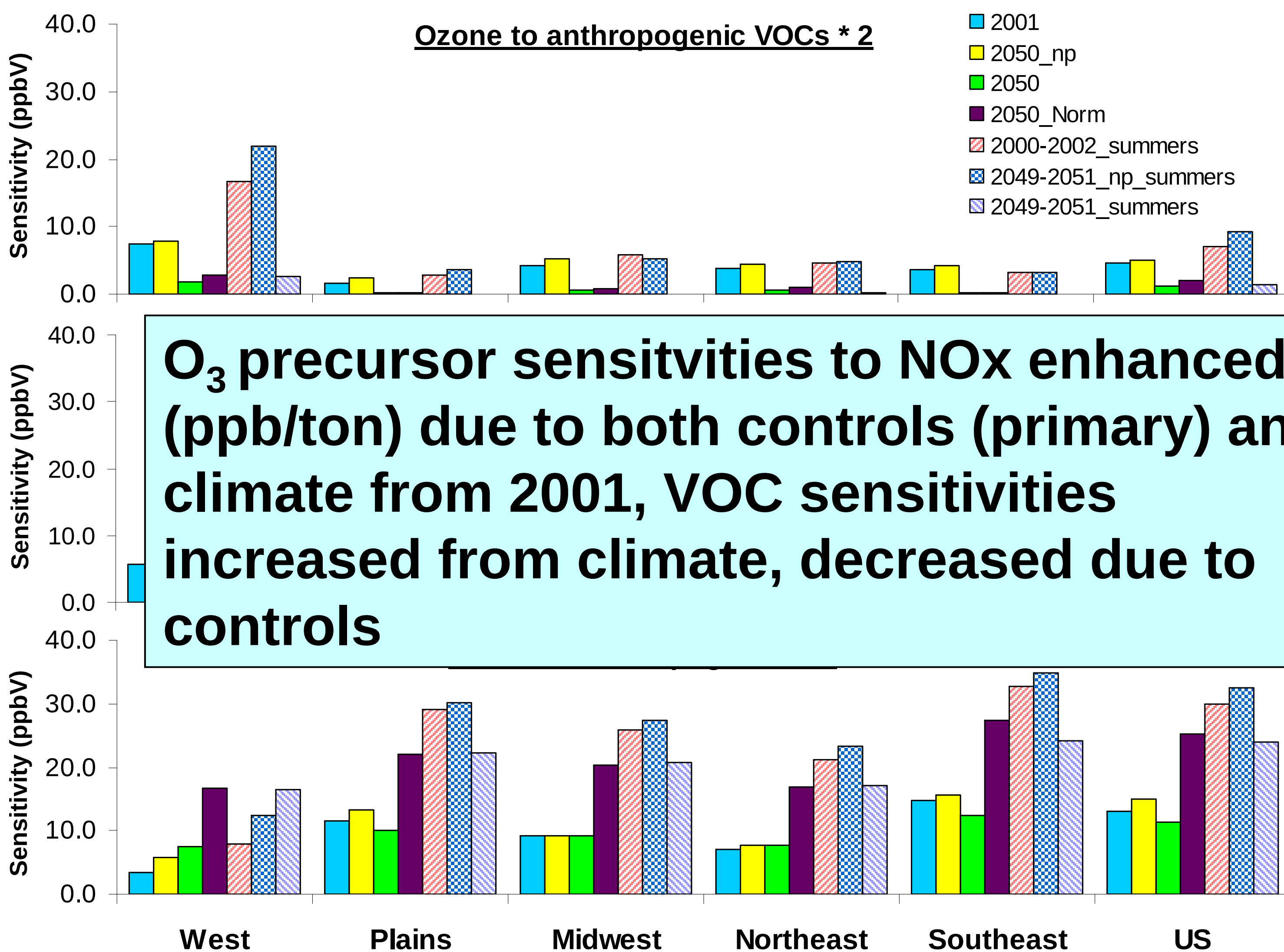
$S_{i,j}$: sensitivity

Ci : concentration of pollutant *i*

Ej : emission of precursor *j*

- Sensitivities are calculated mathematically (about 12 per run) and have the same units as concentration of the air pollutants.
- Local sensitivity
  - Relative response to an incremental change in emissions
  - Read results as the linearized response to a 100% change

Sensitivities of Daily 4th Highest 8-hr Ozone



O_3 precursor sensitvities to NOx enhanced (ppb/ton) due to both controls (primary) and climate from 2001, VOC sensitivities increased from climate, decreased due to controls

GIT, NESCAUM and MIT

Norm: Adjusted for emissions change

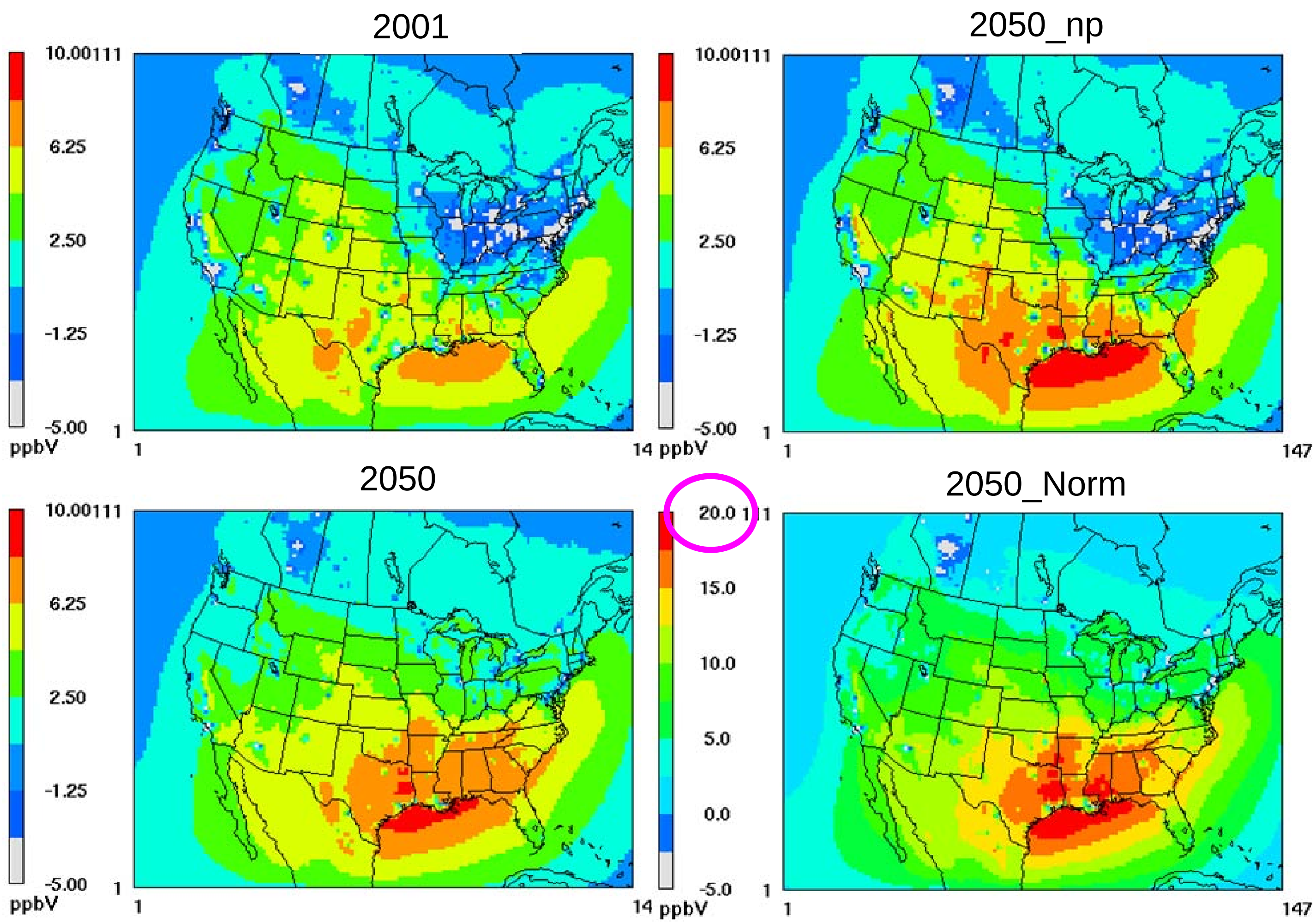
Summertime Ozone Sensitivities to Anthropogenic NO_x Emissions

Unit: ppbV

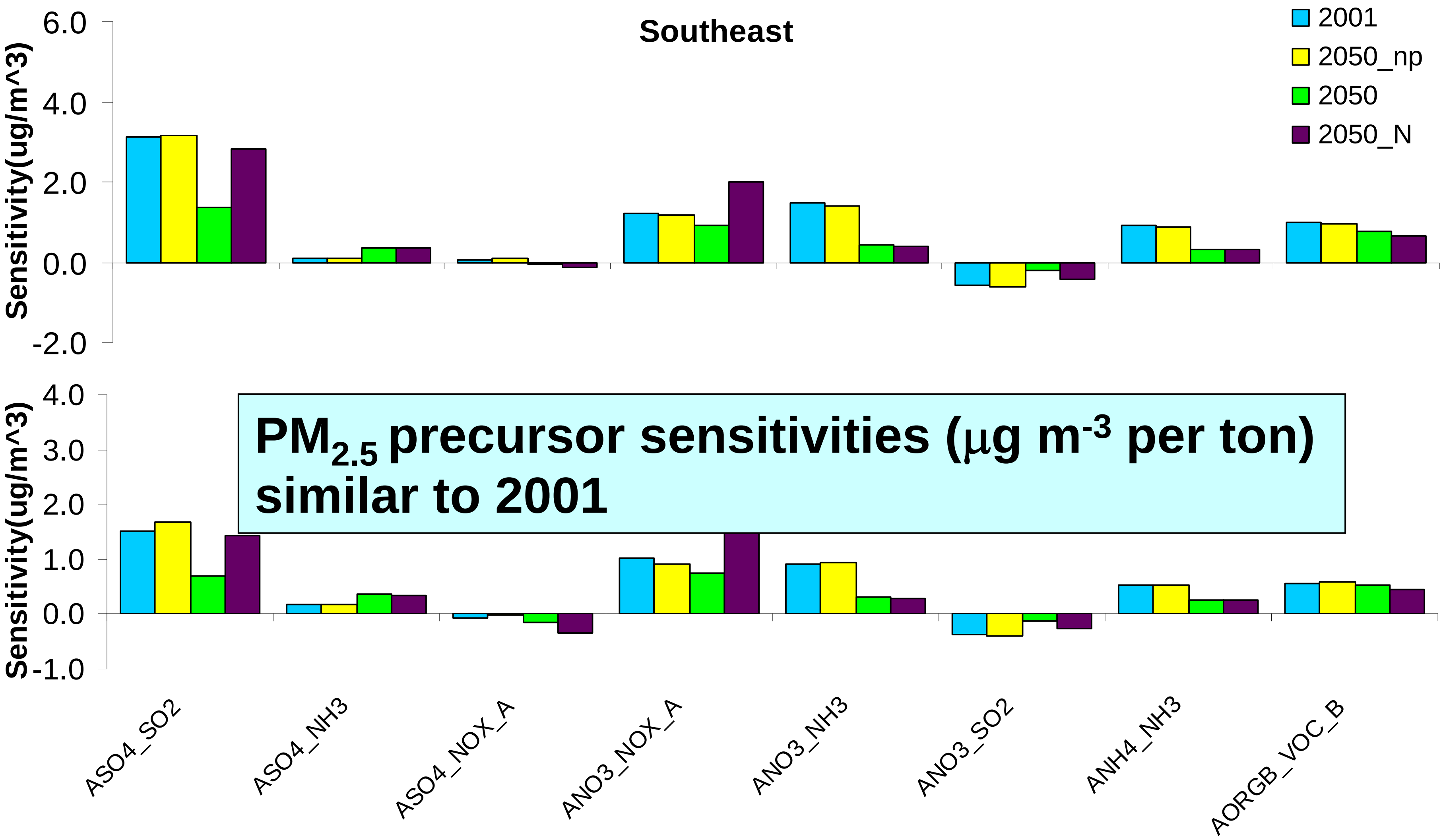
		2000	2001	2002	2049_np	2050_np	2051_np	2049	2050	2051
Southeast	1st	38.8	35.0	37.6	38.8	37.4	43.4	27.7	29.7	30.3
	2nd	36.3	33.6	34.5	36.8	36.2	40.5	25.7	26.7	28.2
	3rd	34.9	32.6	34.8	36.5	35.1	39.3	24.5	25.5	26.3
	4th	33.5	31.1	33.3	34.9	33.3	36.6	24.0	23.7	24.9
US	1st	31.7	29.3	33.6	28.0	32.5	30.9	26.0	29.3	29.7
	2nd	31.3	29.7	33.6	27.7	33.2	33.4	24.0	27.9	28.7
	3rd	32.0	29.8	32.0	29.8	34.2	34.4	23.5	26.5	27.1
	4th	30.8	27.9	31.2	29.4	32.9	35.3	21.7	24.5	25.6

- Slight increase in future sensitivities using “non-projected” emissions
    - NOx emissions about the same: similar sensitivity per ton
- Decreased sensitivity to projected emissions due to decrease in NOx emissions
    - Per ton sensitivities increase

Spatial Distribution of Sensitivities of Annual Ozone to Anthropogenic NO_x Emissions



Sensitivities of Speciated $PM_{2.5}$ Formation



$PM_{2.5}$ precursor sensitivities ($\mu g\ m^{-3}$ per ton) similar to 2001

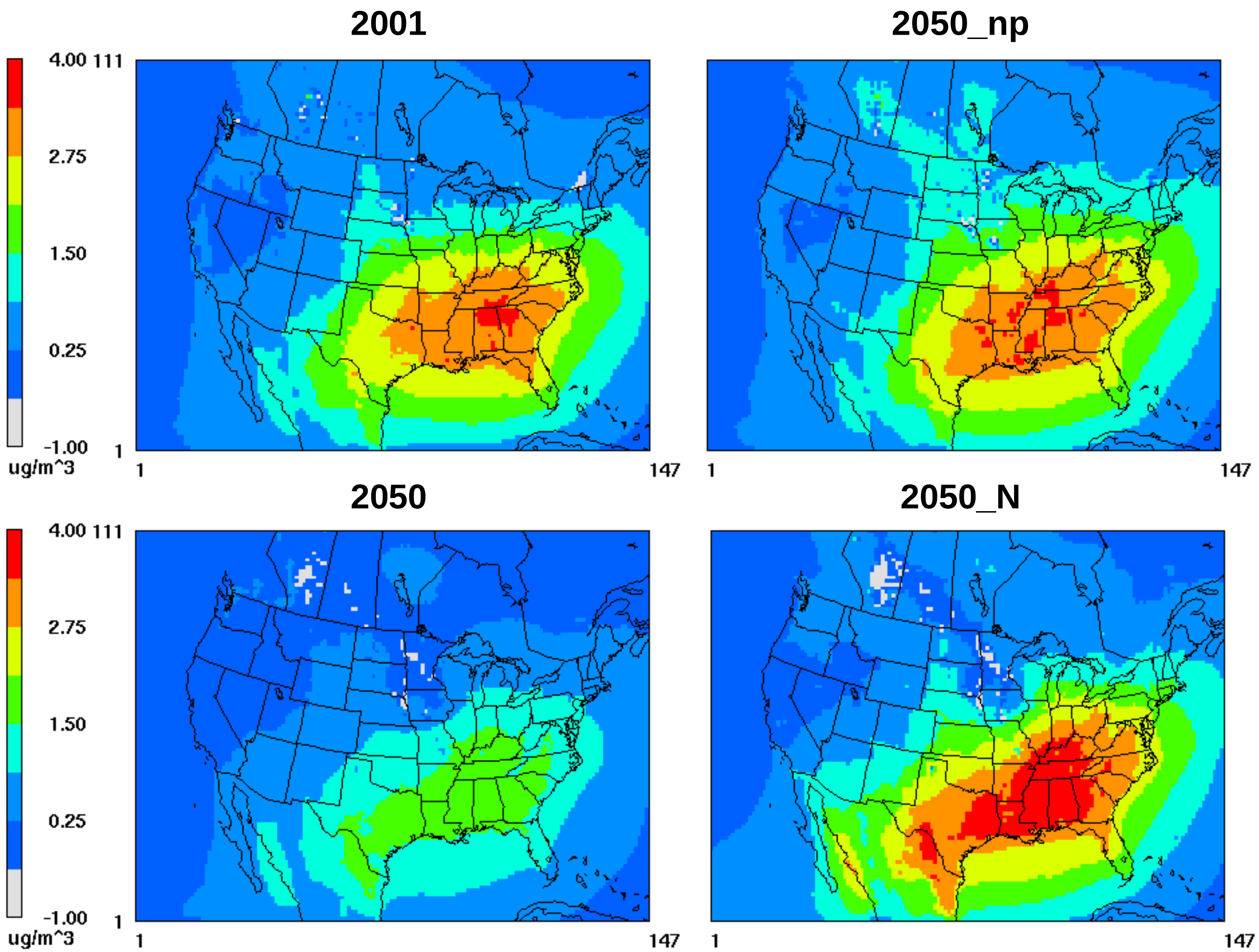
Summertime Sensitivities of Sulfate Aerosol to SO_2 Emissions

Unit: ug/m^3

	2000	2001	2002	2049_np	2050_np	2051_np	2049	2050	2051
West	0.498	0.463	0.435	0.413	0.460	0.457	0.189	0.222	0.213
Plains	2.461	2.574	2.849	1.982	2.503	1.937	1.010	1.283	1.019
Midwest	3.353	3.215	4.598	2.596	3.605	3.216	1.222	1.651	1.495
Northeast	2.511	2.332	3.265	2.258	3.196	2.577	0.922	1.229	1.025
Southeast	5.180	4.730	5.785	4.016	5.012	3.856	1.689	2.093	1.653
US	2.558	2.488	3.045	2.039	2.632	2.138	0.947	1.212	1.005

- **Year-to-year sensitivities similar. (Similar with sens. of ozone to NO_x)**
- **Decrease in sensitivities in 2049-2051 due to lower emissions**

Spatial Distribution of Sensitivities of $PM_{2.5}$ Formation to SO_2 Emissions

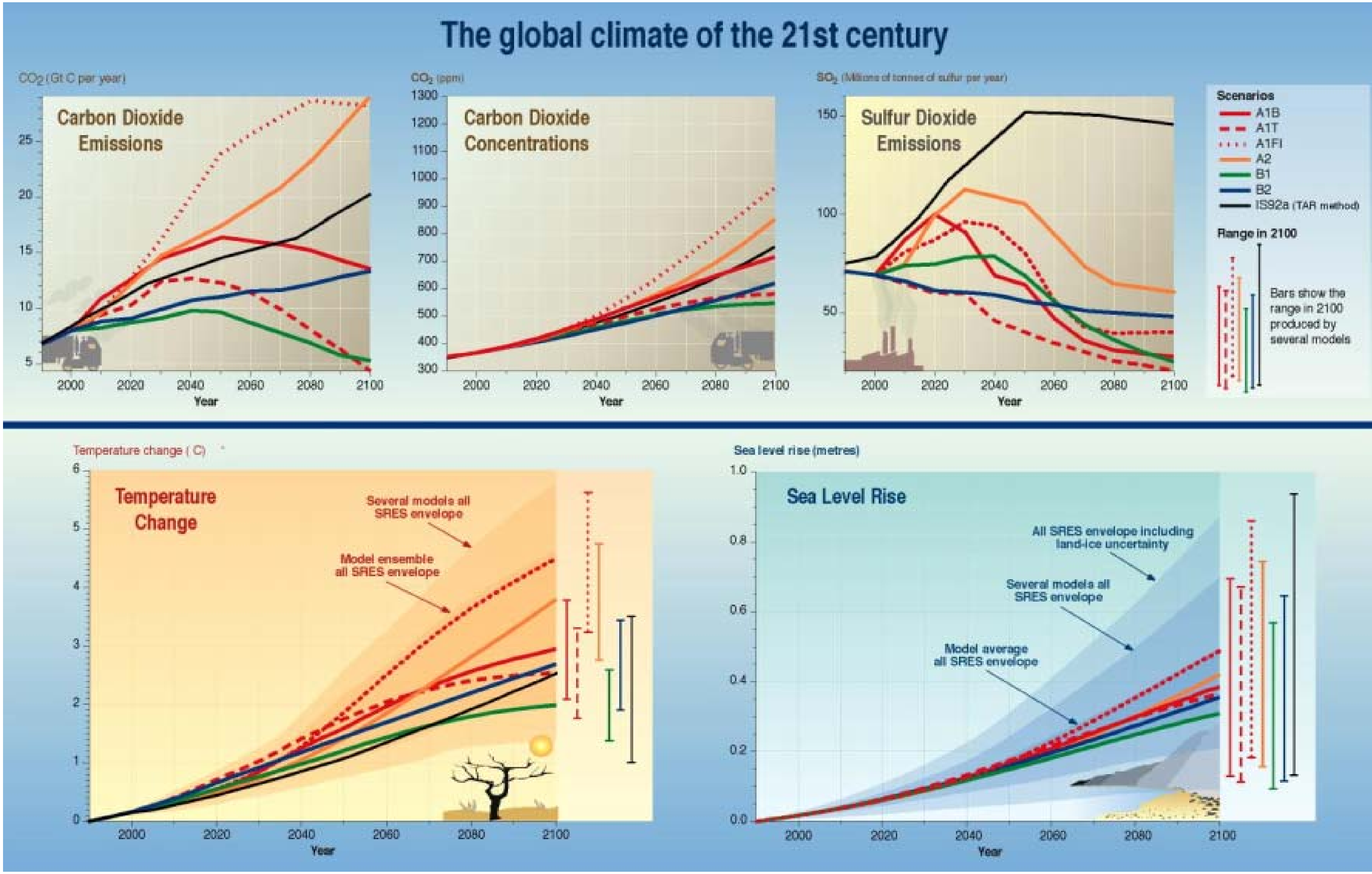


Assessment III

Uncertainty Analysis of Impact of Climate Change Forecasts on Regional Air Quality and Emission Control Responses

➔ A second central question

21st-Century Climate (IPCC)



GIT, NESCAUM and MIT

Source: IPCC (2001), Climate Change 2001: The Scientific Basis

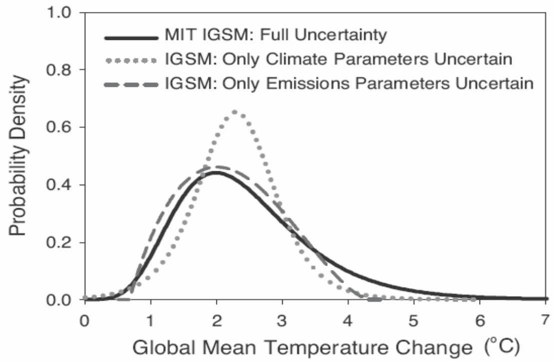
Uncertainties are Considered for: (MIT's IGSM)

- Anthropogenic emissions of greenhouse gases
- Anthropogenic emissions of short-lived climate-relevant air pollutants
- Oceanic heat uptake
- Specific aerosol forcing

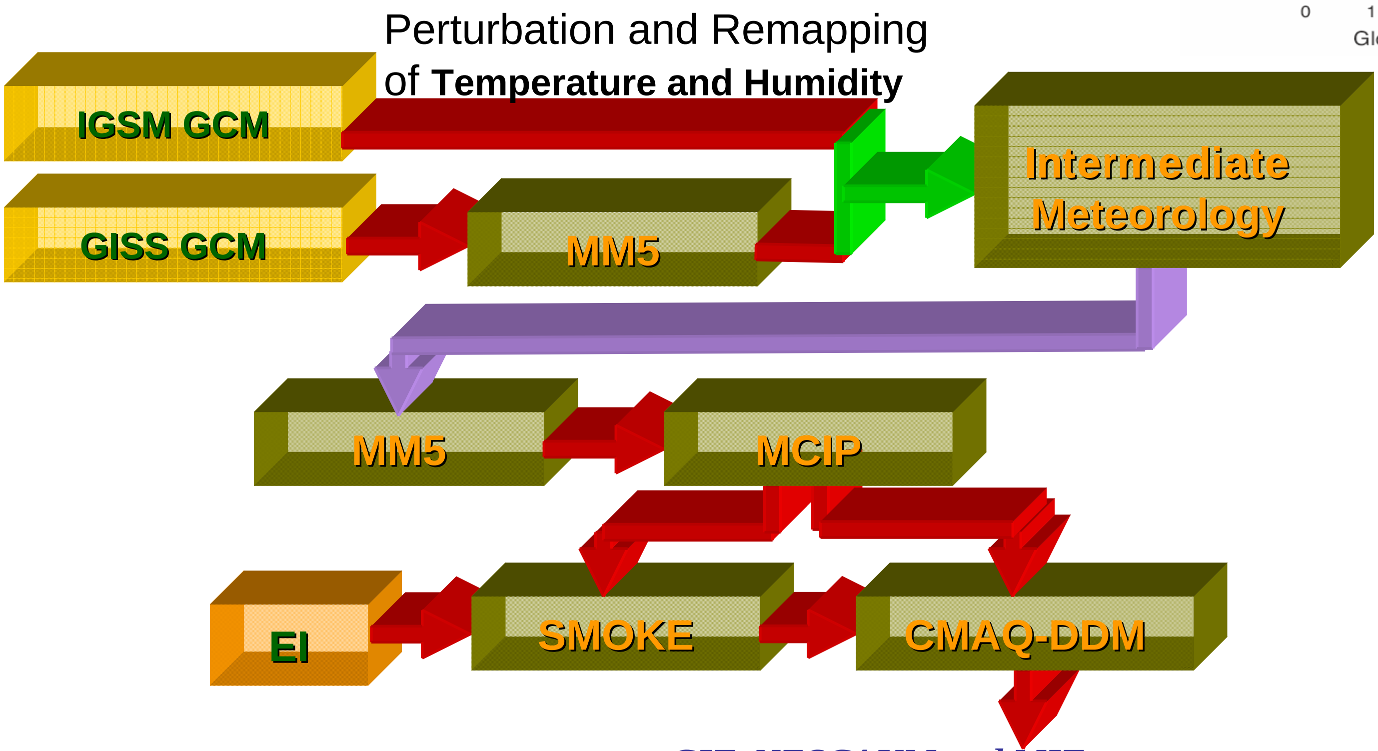
Source: Webster *et al.,* 2003, 2002

Uncertainty

Modeling approach



Meteorological data derived based on climatic change runs using MIT's Integrated Global System Model (IGSM) for future years



Uncertainty Simulations

- Our studies suggested that T and Abs. Hum. had major impacts
- Perturbations:

-- 3-dimensional temperature

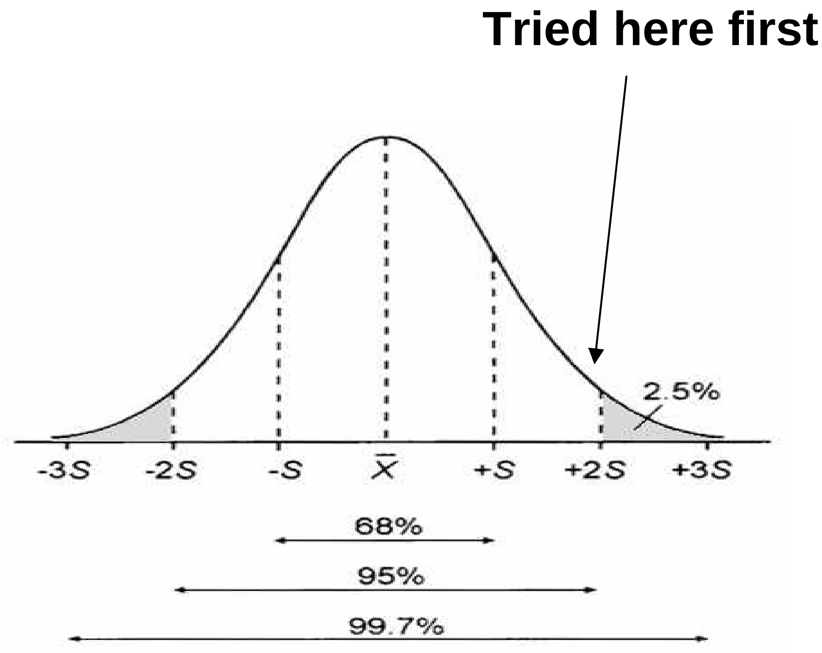
-- 3-dimensional absolute humidity

- Levels of perturbation:

-- 99.5th percentile (High-extreme)

-- 50th percentile (Base: "rerun"*)

-- 0.5th percentile (Low-extreme)



*For consistency, the 50th percentile is rerun as the fields are changed since the IGSM monthly average distribution is not identical to the GISS-MM5

Expansion of IGSM into the 3rd Dimension

Write a 3D time-dependent variable "a" using Reynolds Decomposition (m = monthly mean specifically):

$$a(y,x,z,t) = \overline{a(y,z,m)} + a^{'}(y,x,z,t)$$

y: latitude, z: altitude, x: longitude
m: monthly (averaged) values
t: MM5 temporal resolution of every 6-hr

where $\overline{a(y,z,m)}$ denotes the longitude-averaged term of a (also called the steady component), and $a^{'}(y,x,z,t)$ is the fluctuating term

and $\sum_t a^{'}(y,x,z,t) = 0$

Expansion into the 3rd Dimension (cont'd)

Steps:

- Using MM5 proxy data to derive a' and ā for given months; build index relations between them;
- Replace ā with IGSM result;
- Convert the new ā back to a using a' to derive needed 3D field.
- Use to re-run MM5

Note that in order to derive ā of IGSM results:

-The discrepancies in monthly and zonal means between MM5 and IGSM were defined and then minimized in conversion

- Spatial resolution was corrected using interpolation of IGSM data

- Latitudinal distribution of ā was based on MM5-weighted IGSM

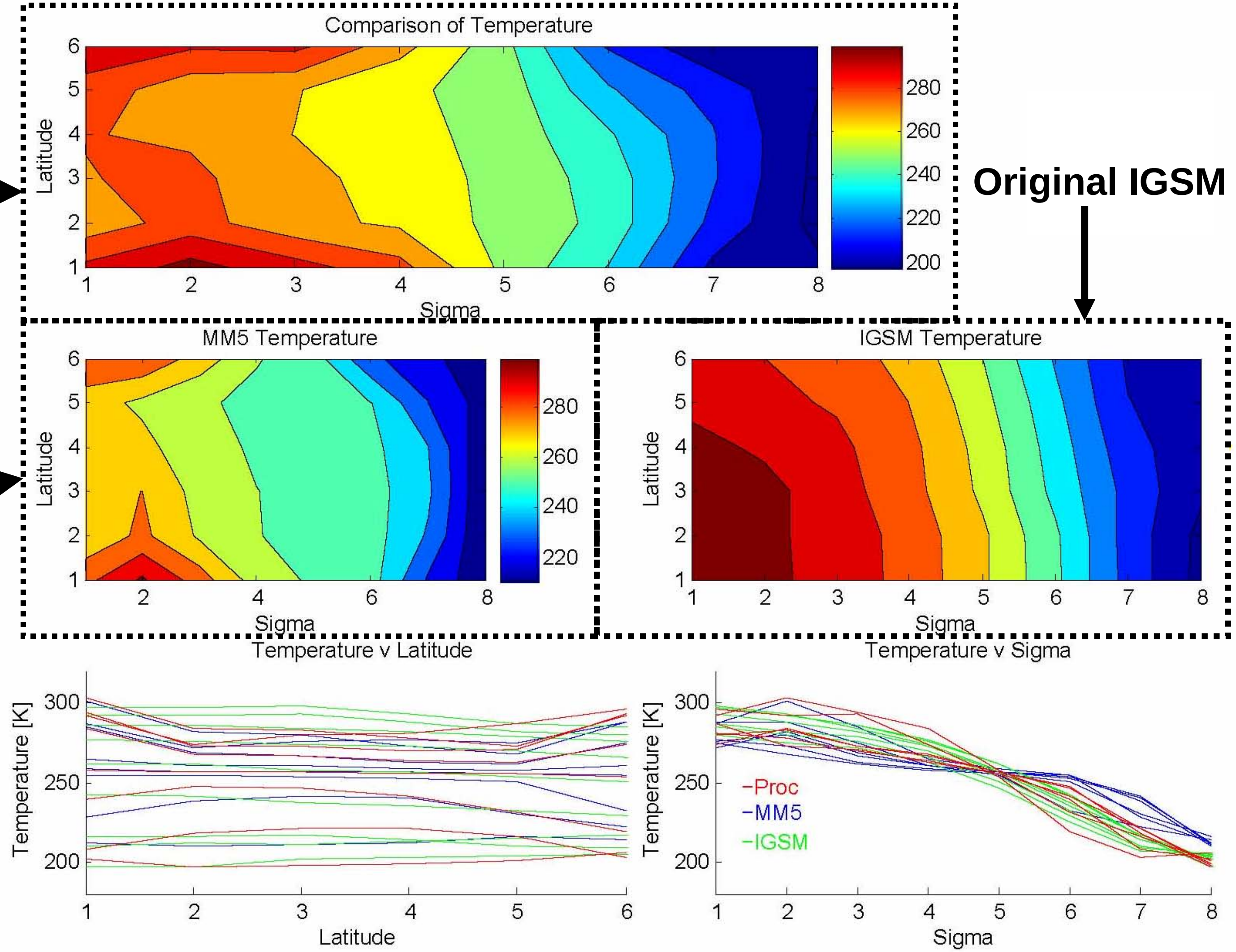
http://www.nature.com/news/2004/040913/images/climate.jpg

Improved Conversion of Temperature Based on a Remapping of Coordinate Index

New Temperature: combined new monthly (from IGSM) & fluctuating term (MM5)

Original IGSM

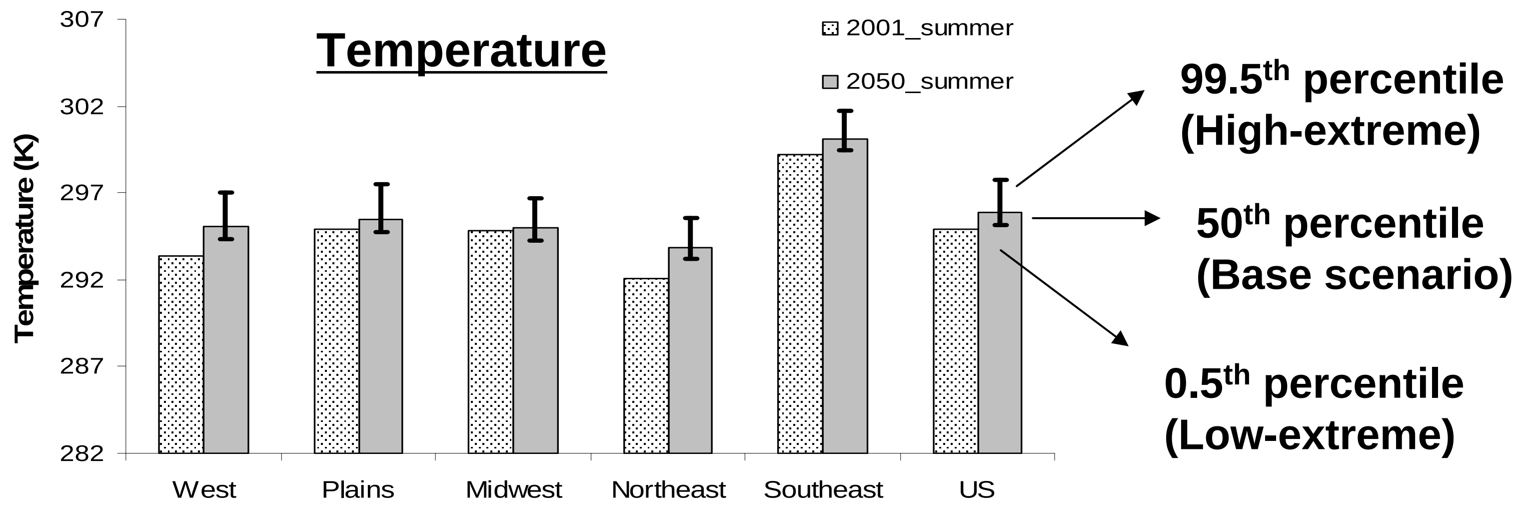
Original MM5 = steady + fluctuating terms

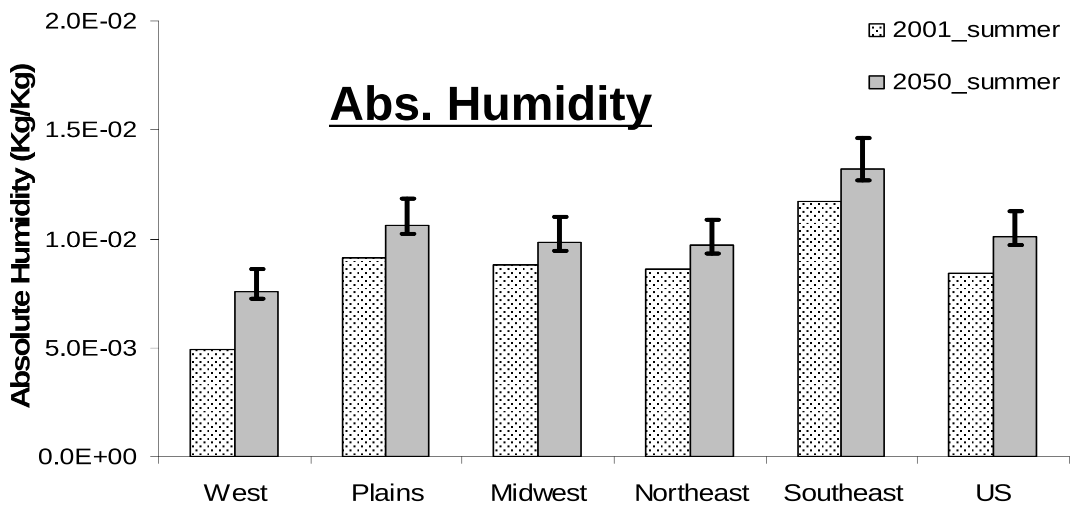


Summary of Uncertainty Simulations

Scenario	Perturbations	Sources
High-Extreme Scenario	99.5 % percentile of 3-D temperature and absolute humidity	IGSM and GISS
Base Scenario	50.0 % percentile of 3-D temperature and absolute humidity	IGSM ~IPCC A1B scenario
Low-Extreme Scenario	0.5 % percentile of 3-D temperature and absolute humidity	IGSM and GISS

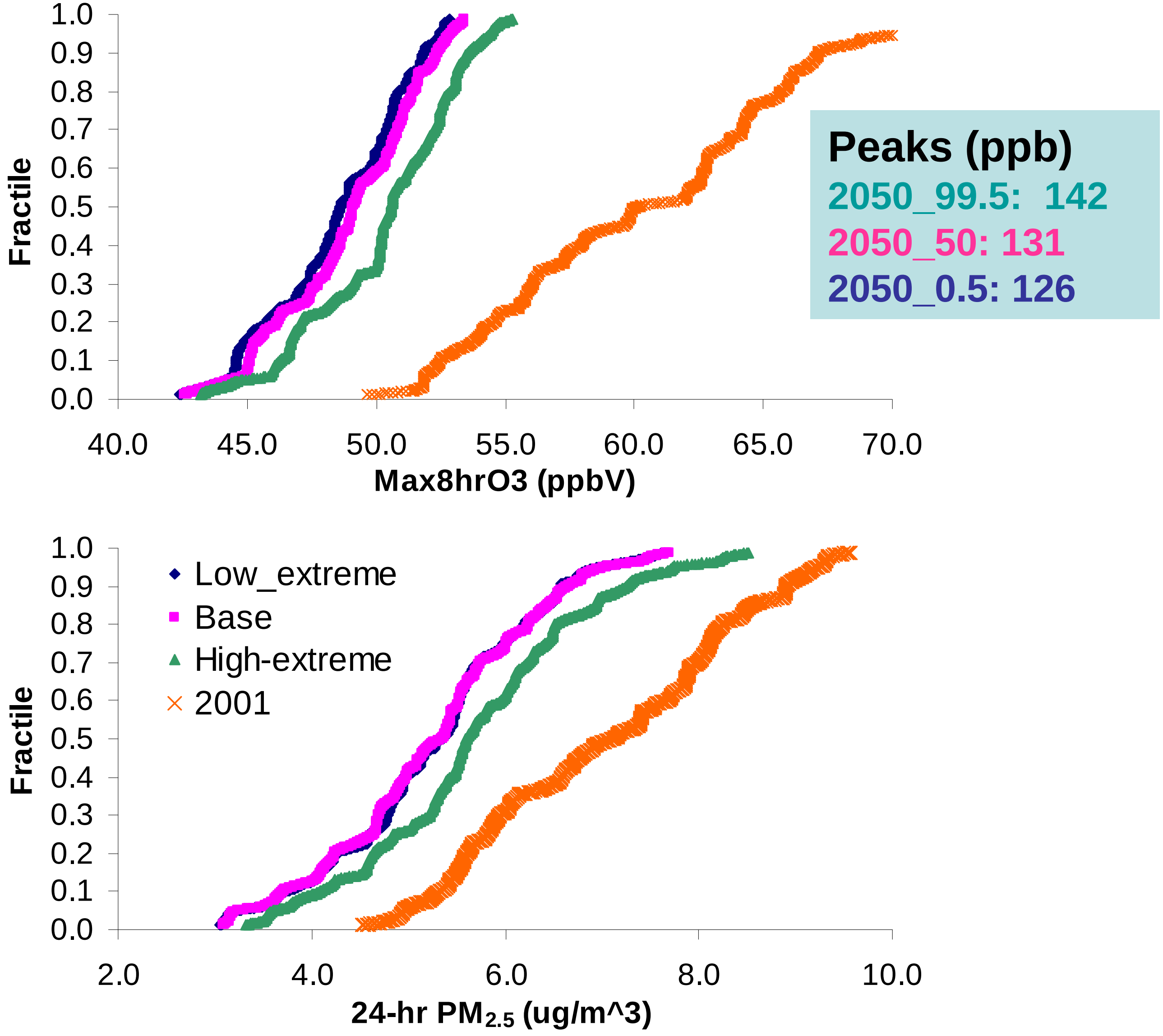
Uncertainties in Meteorology





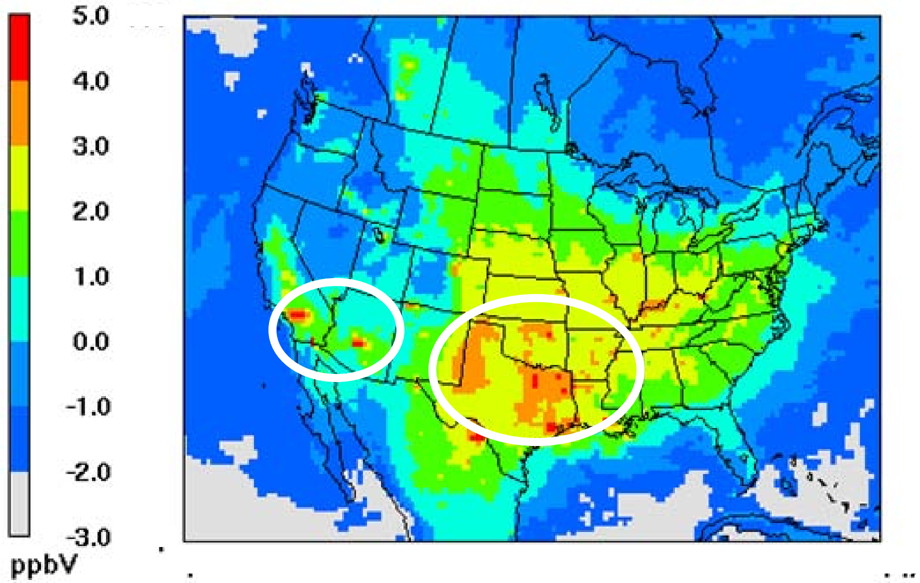
CDFs of Max8hrO3 and 24-hr $PM_{2.5}$ in Summer of 2050

2001 shown for comparison

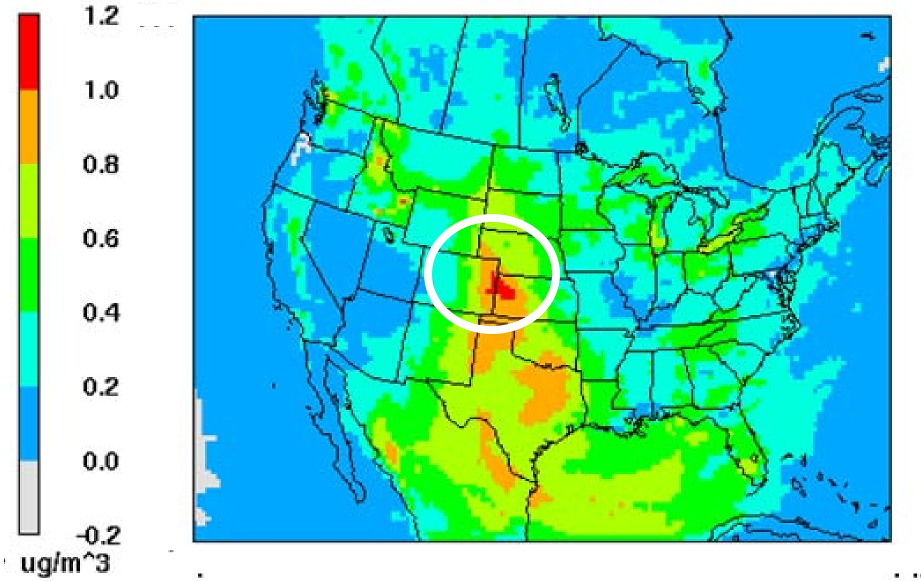


Uncertainties in Summertime Max8hrO3 and $PM_{2.5}$

Max8hrO3



$PM_{2.5}$

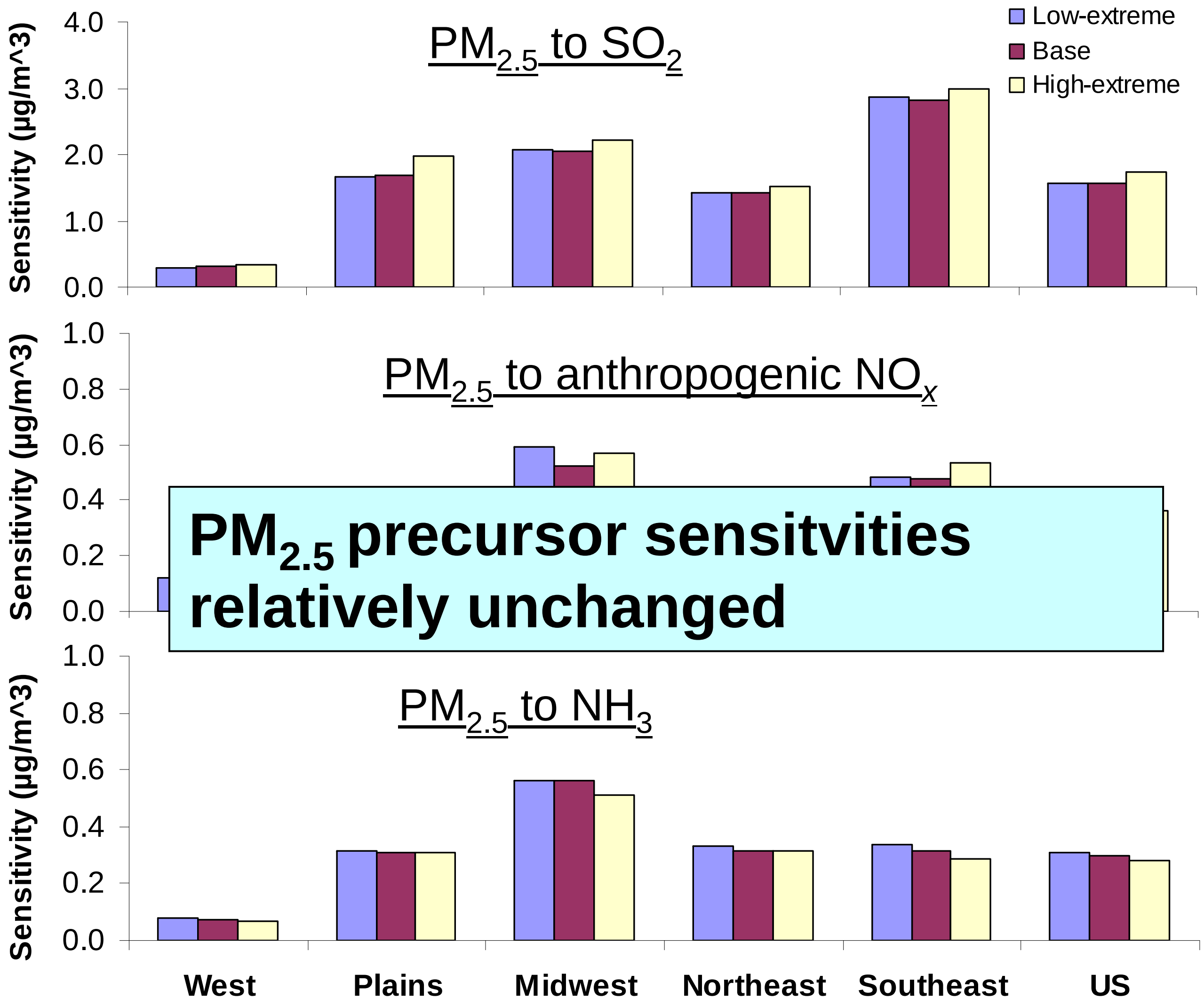


(High-extreme scenario) – (Base scenario)

No. of Days M8hrO3 > 80ppbV in Summer of 2050

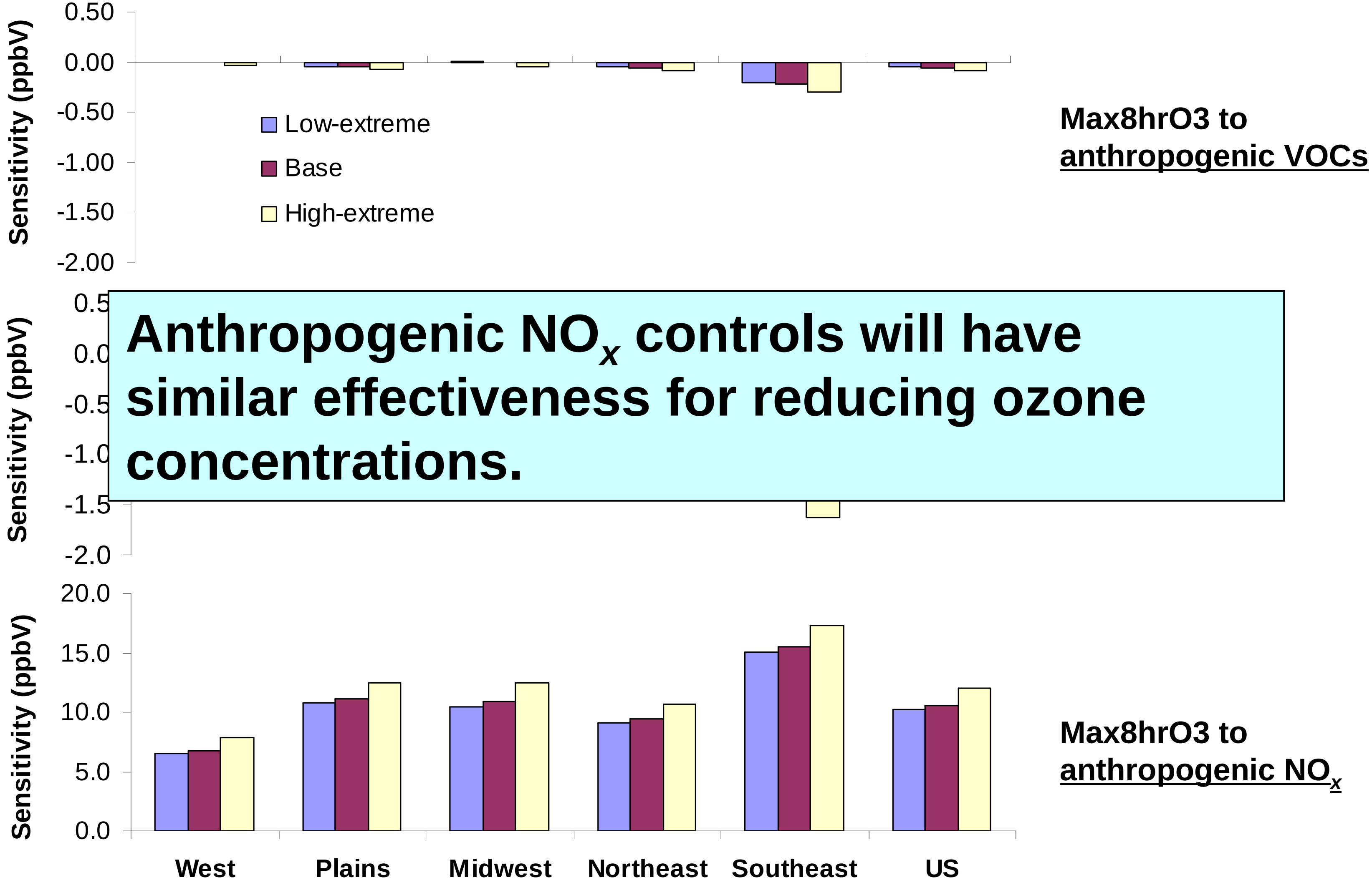
Region / City	Low-extreme (0.5%)	Base (50%)	High-extreme (99.5%)
West / Los Angeles	2 Days	6 Days	7 Days
Plains / Houston	5 Days	**10 Days**	**24 Days**
Midwest / Chicago	3 Days	4 Days	6 Days
Northeast / New York	0	0	0
Southeast / Atlanta	0	0	2 Days

Uncertainty in $PM_{2.5}$ Sensitivity



$PM_{2.5}$ precursor sensitvities relatively unchanged

Uncertainty in Max8hrO3 Sensitivity



Anthropogenic NO_x controls will have similar effectiveness for reducing ozone concentrations.

How do uncertainties in climate change, impact the ozone and $PM_{2.5}$ concentrations and sensitivities?

Results suggest that modeled control strategy effectiveness is not affected significantly, however, areas at or near the NAAQS in the future should be concerned more about the uncertainty of future climate change.

Conclusions

- Climate change, alone, with no emissions growth or controls has mixed effects on the ozone and $PM_{2.5}$ levels as well as on their sensitivities to precursor emissions.
  - Ozone generally up some, PM mixed
- The impact of changes in precursor emissions due to planned controls and anticipated changes in activity levels is higher than the impact of climate change on ozone and $PM_{2.5}$ levels.
  - Carefully forecasting emissions is critical to result relevancy
- Spatial distribution and annual variations in the contribution of precursors to ozone and $PM_{2.5}$ formation remain quite similar.
  - Sensitivities of ozone to NOx increase on a per ton basis mostly due to reduced NOx levels, a bit due to climate
  - Sensitivities of PM2.5 to precursors similar on per ton basis
    - Lower NOx and higher NH3 emissions increase sensitivity of NO3 to NOx in 2050 projected emissions case

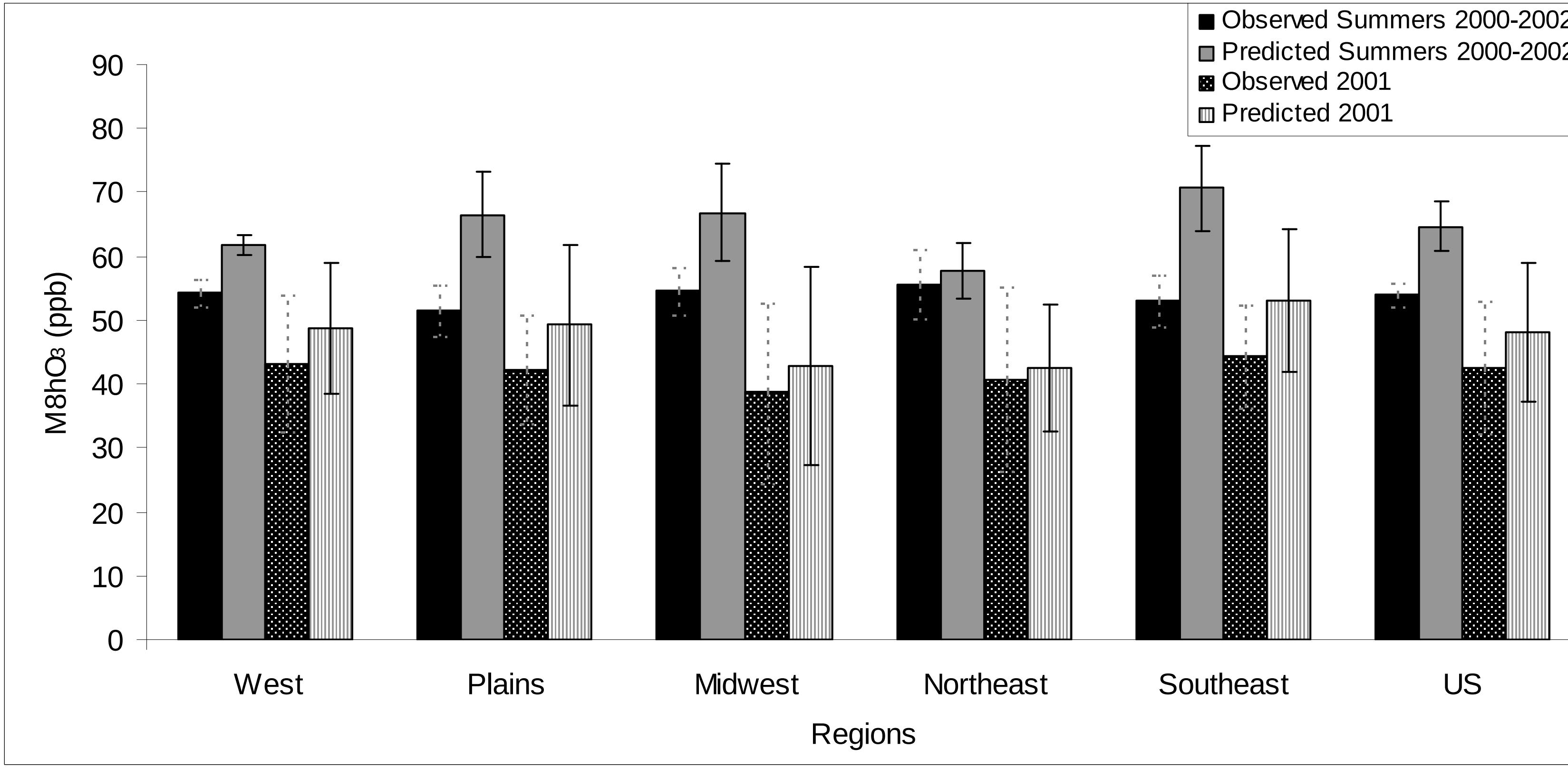
Conclusions (cont'd)

- Controls of NO_x and SO_2 emissions will continue to be effective for improving air quality under impact of potential future climate changes.
- The uncertainties in future climate change have a relatively modest impact on simulated future ozone and $PM_{2.5}$
  - Extremes simulated to get significant changes
    - High-extreme (99.5th percentile) led to increases in ozone and PM.
- Addressing uncertainties suggest that control choices are robust
- University-NESCAUM partnership very effective
  - NESCAUM expertise in emissions: key to most policy meaningful results
  - Quicker dissemination of results of policy relevancy
  - Built capacity at NESCAUM
- Results being used in health study (using BENMAP)
  - Used TS-expansion to provide ozone and PM fields in 2030 and 2080
    - Grid-by-grid analysis

Acknowledgements

- US EPA for funding under STAR grant No. R830960
- L-Y Leung for providing MM5 results and discussions

Evaluation of Max8hrO3 Concentrations



Simulation results matched to monitors

Are the climate change impacts significant?

- Testing of the significance of climate change between historic (2001) and future (2050) years in terms of annual-average temperature difference
- 1000 samples are randomly chosen from 16317 (111*147 grids) data points
- T-test Two-Sample:

	2001	*2050*
Mean	285.4259	287.1715
Variance	74.71309	64.44908
Observations	1000	1000
df	1998	
P(T<=t) one-tail	1.54E-06	
P(T<=t) two-tail	3.07E-06	

→ Small p-value

➔ Temperature increase is significant between 2001 and 2050 with >95 % C.I.

Difference in Climate Change among 2000-2002 & 2049-2051

- Testing of the significance of climate change in terms of temperature difference in 2000-2002 and 2049-2051
- 1000 samples are randomly chosen from 16317 data
- One-Factor ANOVA with 3 levels:

2000 - 2002

factor	df	SS	MS
year	2	13.46	6.73
residual	2997	292709.78	97.67
total	2999		

F-value = 0.069

2049 - 2051

factor	df	SS	MSE
year	2.00	13.67	6.84
residual	2997.00	19818.47	6.61
total	2999.00		

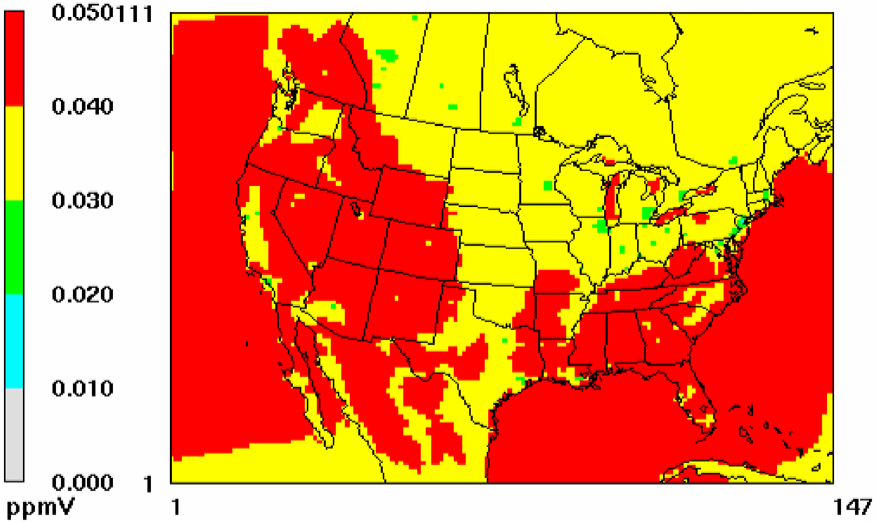
F-value = 1.03

Critical value of $F_{2, 2999, 0.025} \sim 3.0$

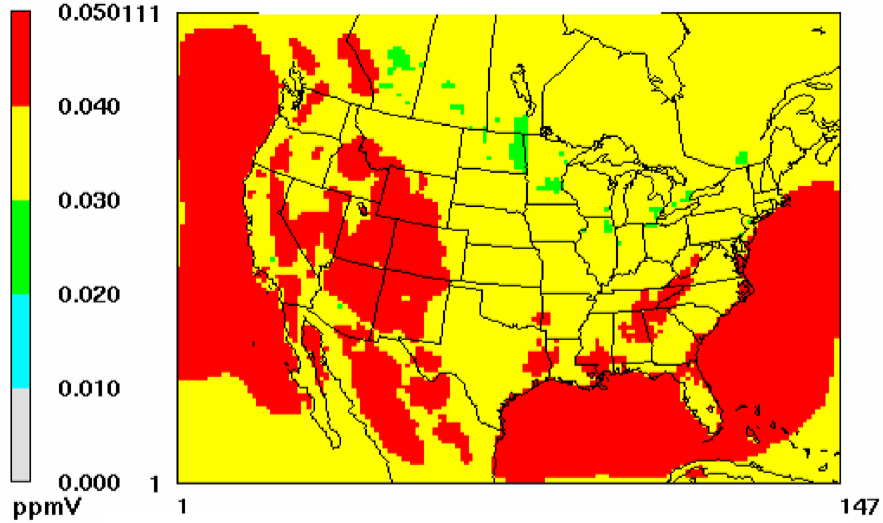
➔ No significant temperature difference between 2000-2002 as well as 2049-2050 with >95 % C.I.

Annual O_3

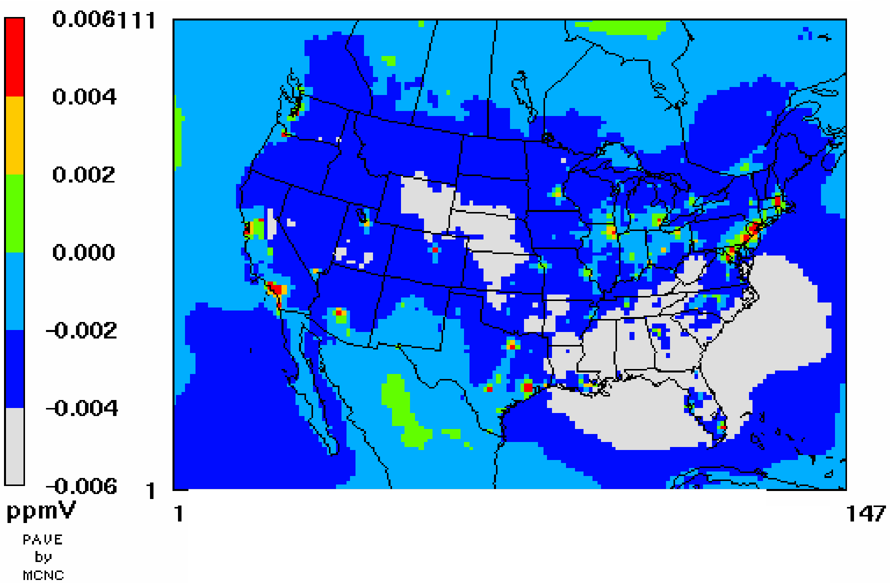
O_3_2001



O_3_2050

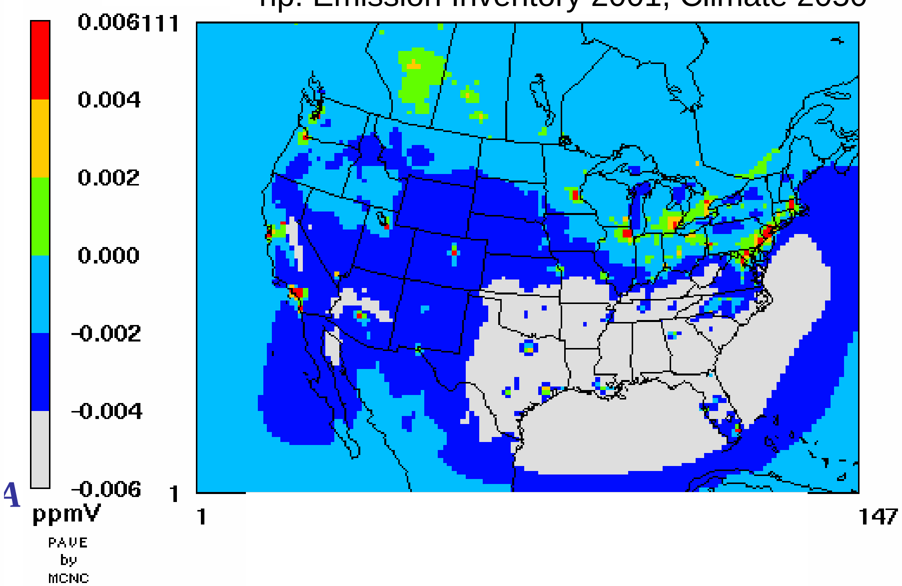


O_3_2050 - O_3_2001

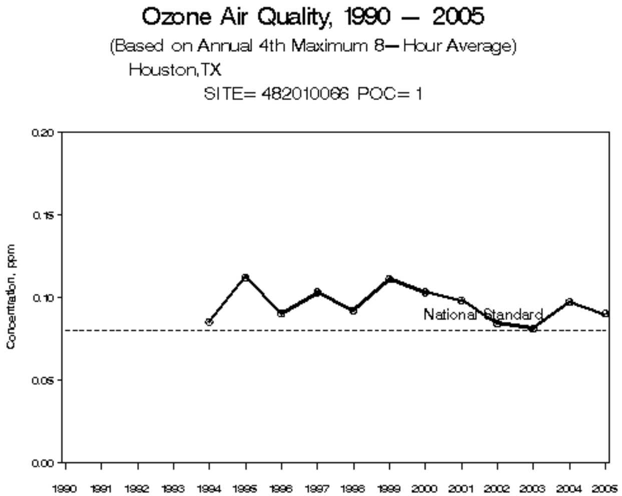


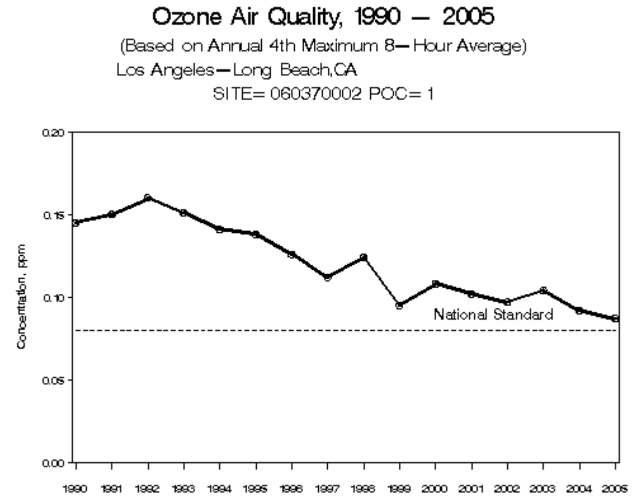
O_3_2050 - O_3_2050np

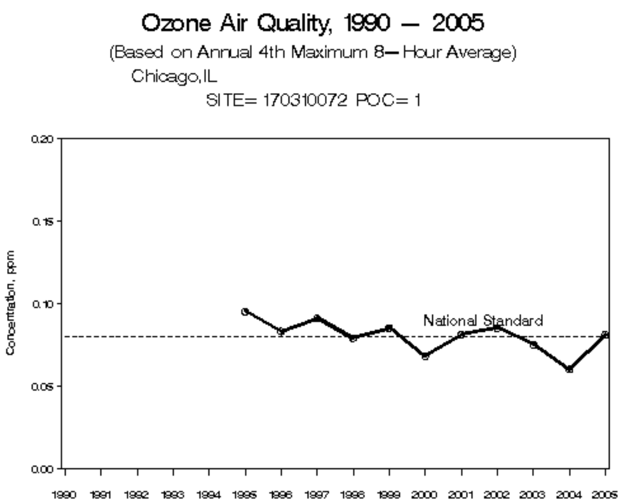
np: Emission Inventory 2001, Climate 2050

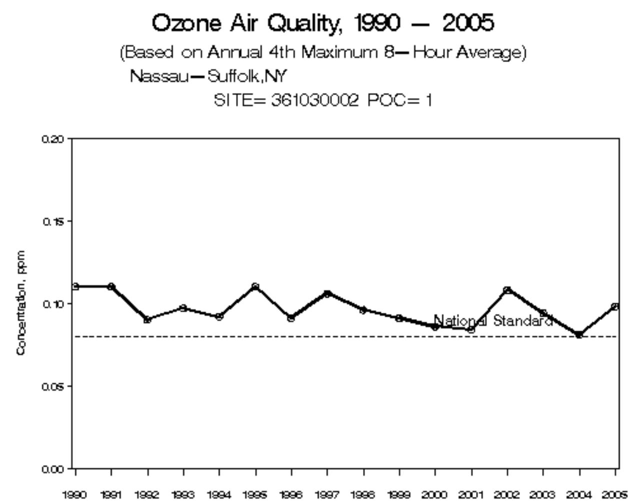


Ozone Trends



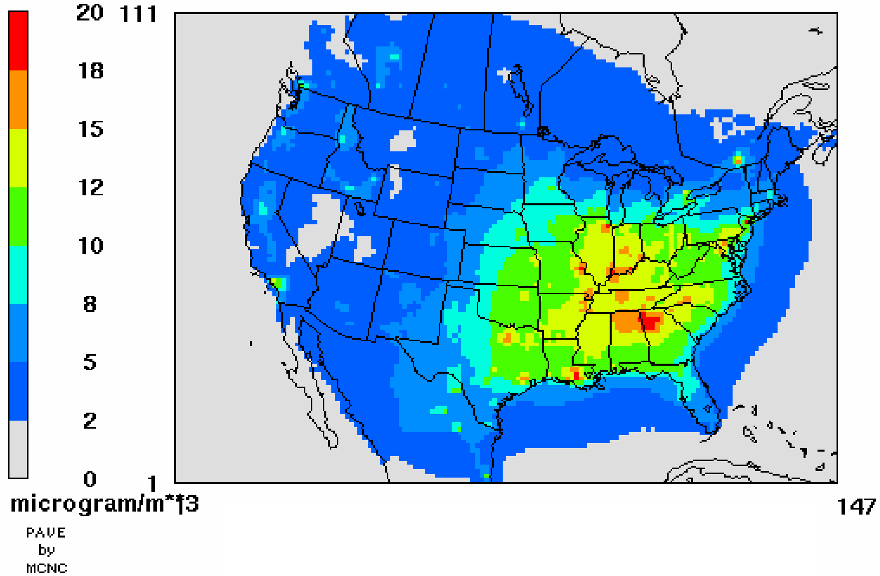




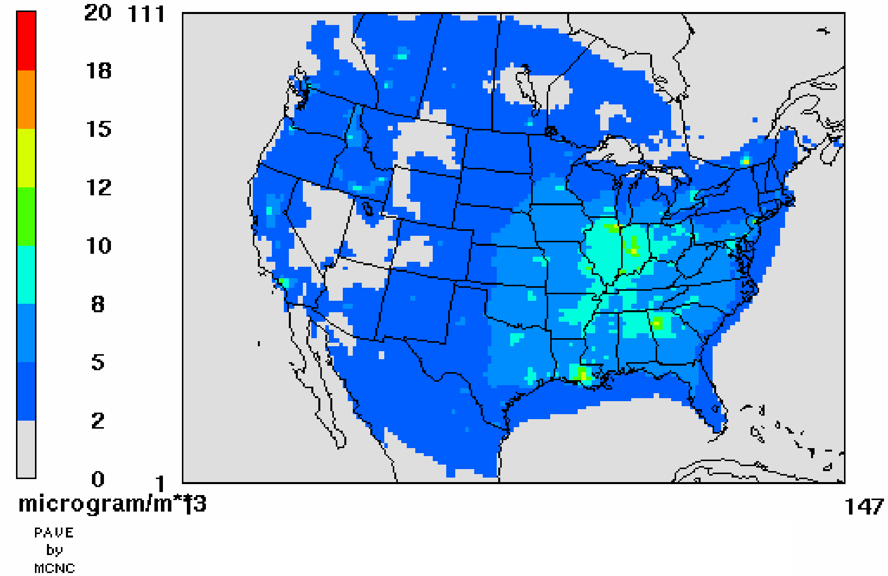


SUMMER $PM_{2.5}$

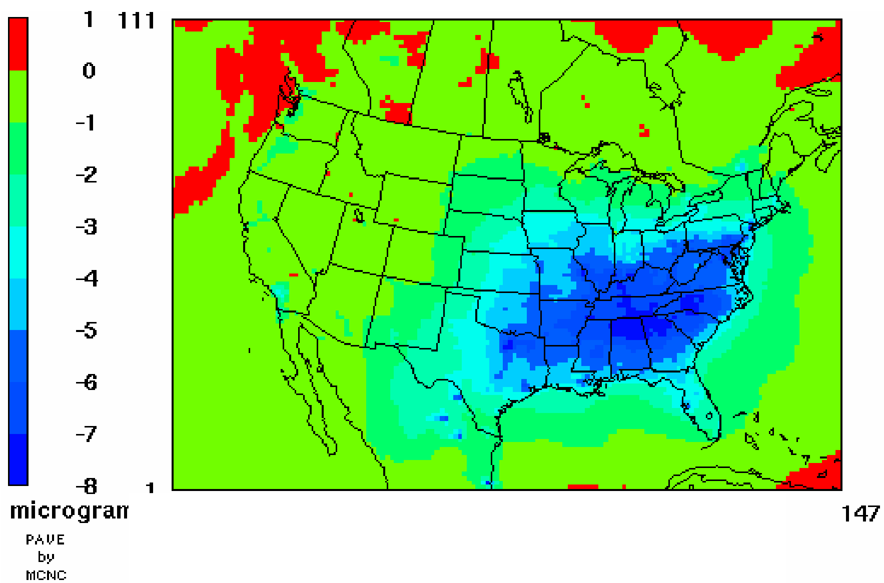
$PM_{2.5}$_2000-2002summers



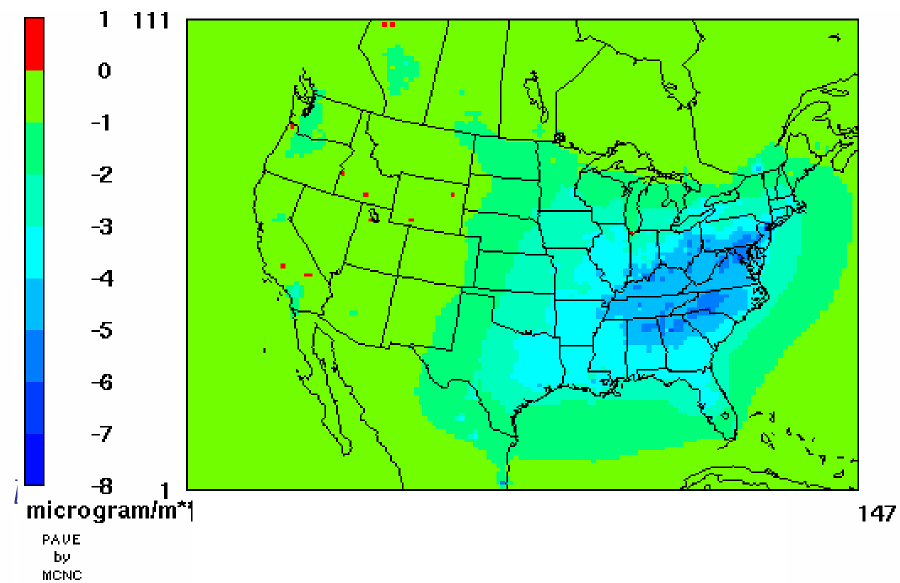
$PM_{2.5}$_2049-2051summers



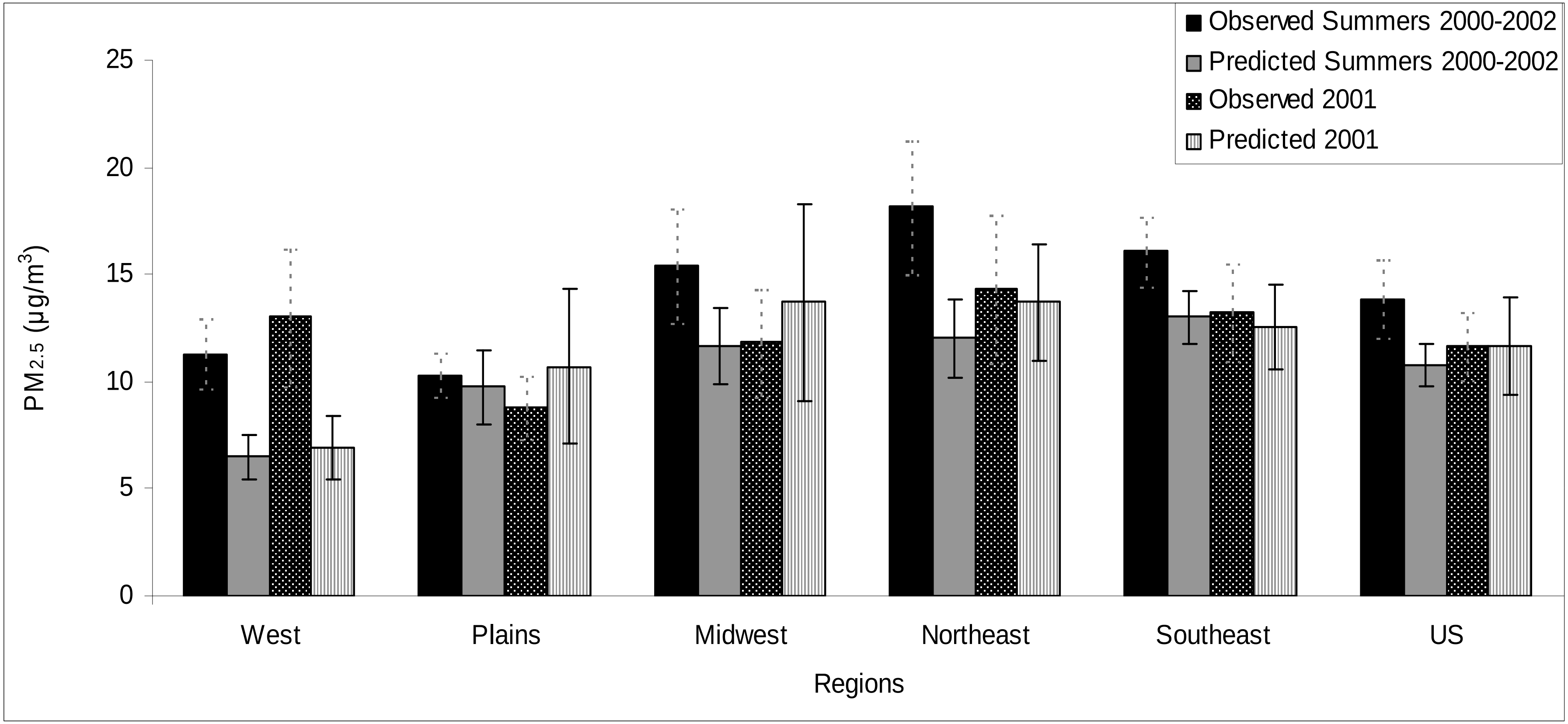
$PM_{2.5}$_FutureSummers – $PM_{2.5}$_HistoricSummers



$PM_{2.5}$_FutureSummers – $PM_{2.5}$_FutureSummers_np



Evaluation of $PM_{2.5}$ Concentrations

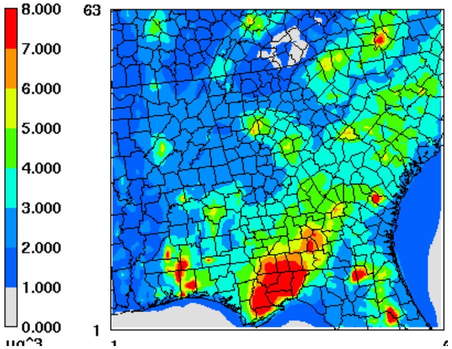


Simulation results matched to monitors
Low bias due to organic aerosol

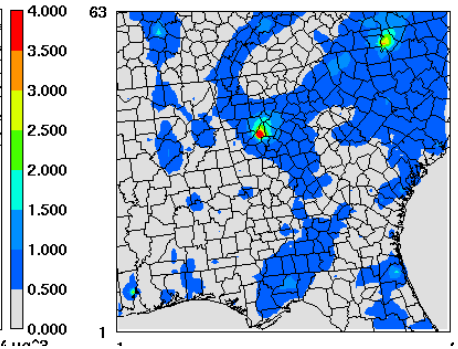
Source Contributions: Speciated $PM_{2.5}$ (Jan. 2002)

Speciated $PM_{2.5}$

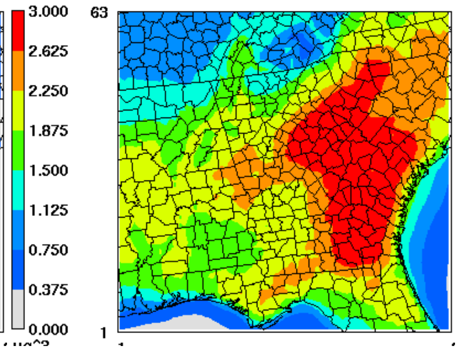
Primary OM: 3.0 μg/m^3



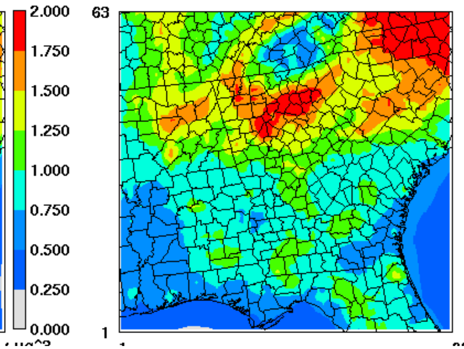
EC: 0.5 μg/m^3



SOA: 1.8 μg/m^3

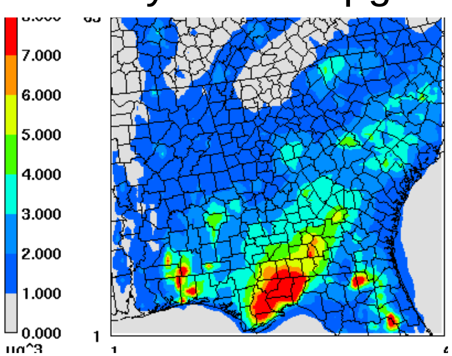


Ammonium: 1.0 μg/m^3

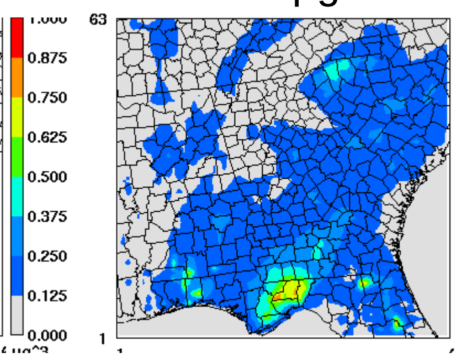


Speciated $PM_{2.5}$ from biomass burning

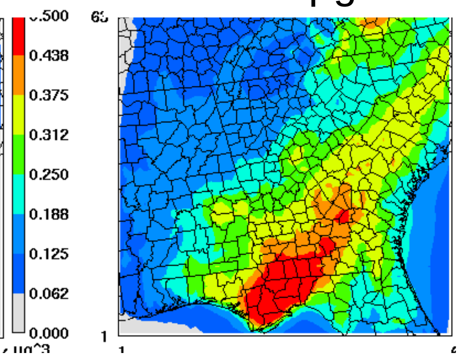
Primary OM: 2.0 μg/m^3



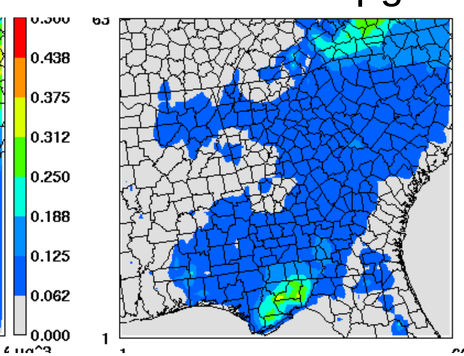
EC: 0.2 μg/m^3



SOA: 0.3 μg/m^3



Ammonium: 0.1 μg/m^3

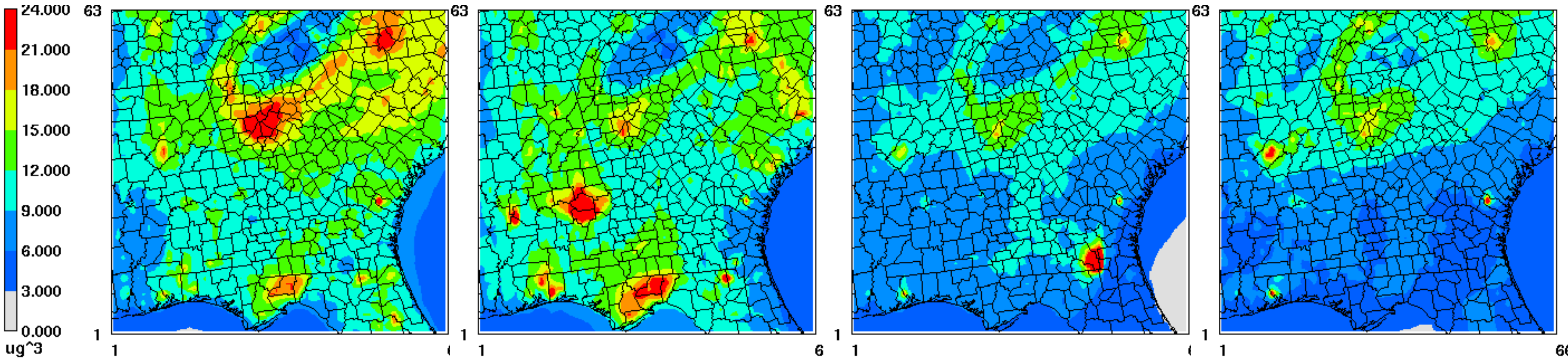


* Monthly average, domain-wide average values

Burning Season: $PM_{2.5}$

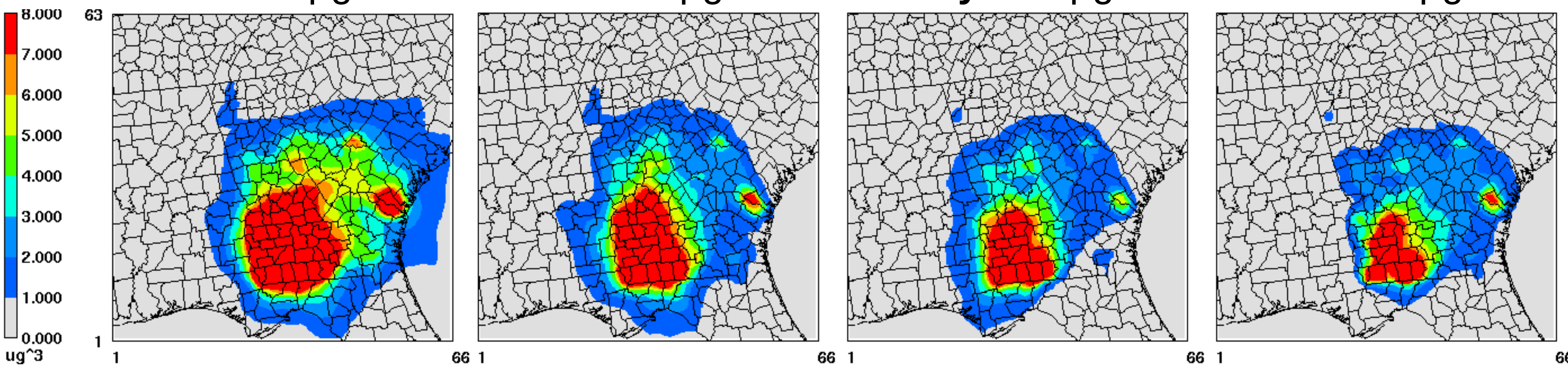
$PM_{2.5}$ concentrations without forest fires in Georgia

Jan: 13.0 µg/m^3 | **Mar: 11.2** µg/m^3 | **May: 10.1** µg/m^3 | **Jul: 8.3** µg/m^3



$PM_{2.5}$ caused by forest fires in Georgia

Jan: 7.3 µg/m^3 | **Mar: 4.8** µg/m^3 | **May: 3.4** µg/m^3 | **Jul: 3.0** µg/m^3

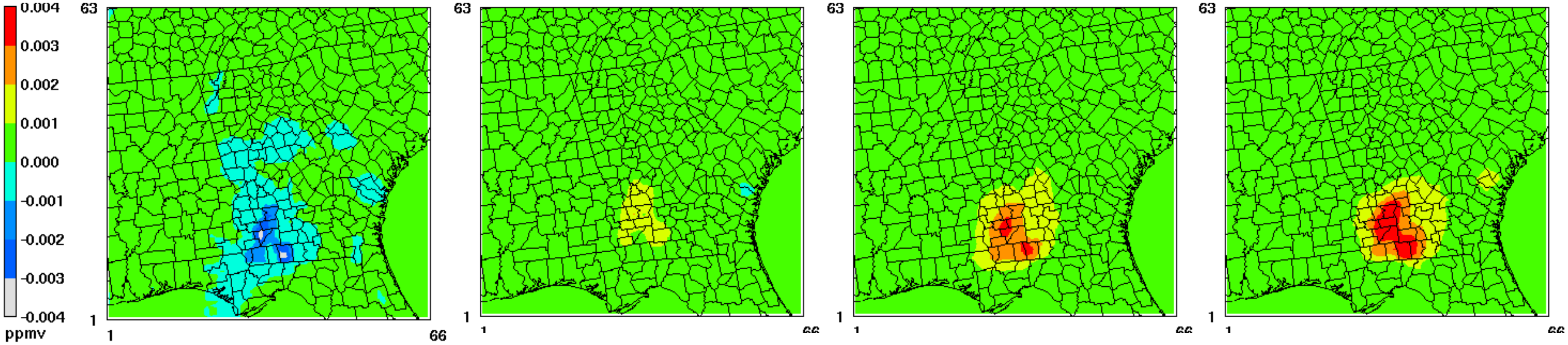


* Monthly average, average for Georgia

Burning Season: Ozone

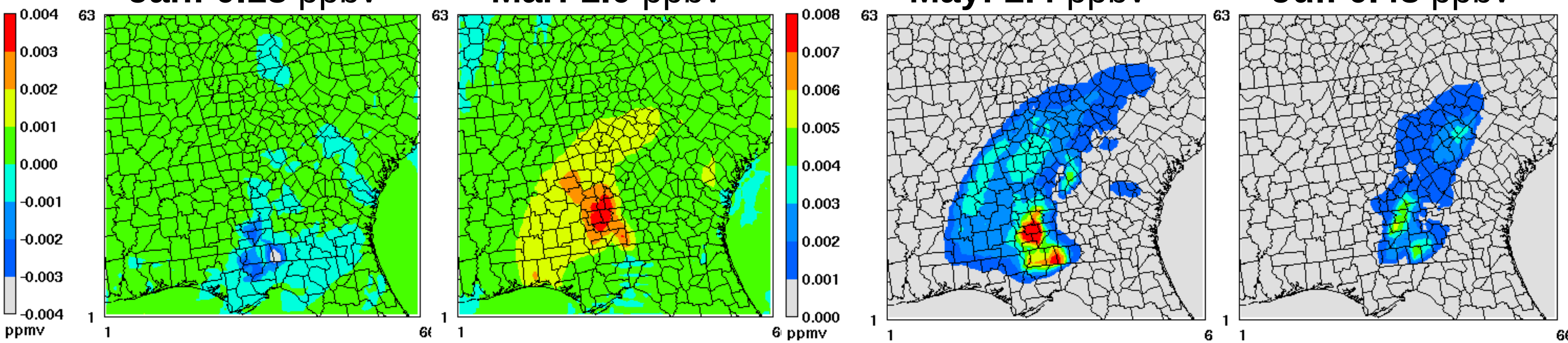
Monthly average of daily maximum 8-hr ozone source contributions

Jan: 0 ppbv **Mar: 0.30** ppbv **May: 0.40** ppbv **Jul: 0.27** ppbv



Peaks of daily maximum 8-hr ozone source contributions

Jan: 0.18 ppbv **Mar: 1.0** ppbv **May: 2.4** ppbv **Jul: 0.48** ppbv



*Values are averages for Atlanta metropolitan area.

No. of Days M8hrO3 > 85ppbV & Peak Values in Summer of 2050

Region / City	Low-extreme (0.5%)	Base (50%)	High-extreme (99.5%)
West / Los Angeles	0 Days / 81.7 ppbV	0 Days / 84.0 ppbV	6 Days / 90.7 ppbV
Plains / Houston	2 Days / 87.3 ppbV	**3 Days / 90.5 ppbV**	**12 Days / 98.6 ppbV**
Midwest / Chicago	1 Days / 86.8 ppbV	1 Days / 89.0 ppbV	4 Days / 97.2 ppbV
Northeast / New York	0 Days / 47.8 ppbV	0 Days / 48.4 ppbV	0 Days / 50.1 ppbV
Southeast / Atlanta	0 Days / 75.1 ppbV	0 Days / 77.8 ppbV	1Days / 85.3 ppbV

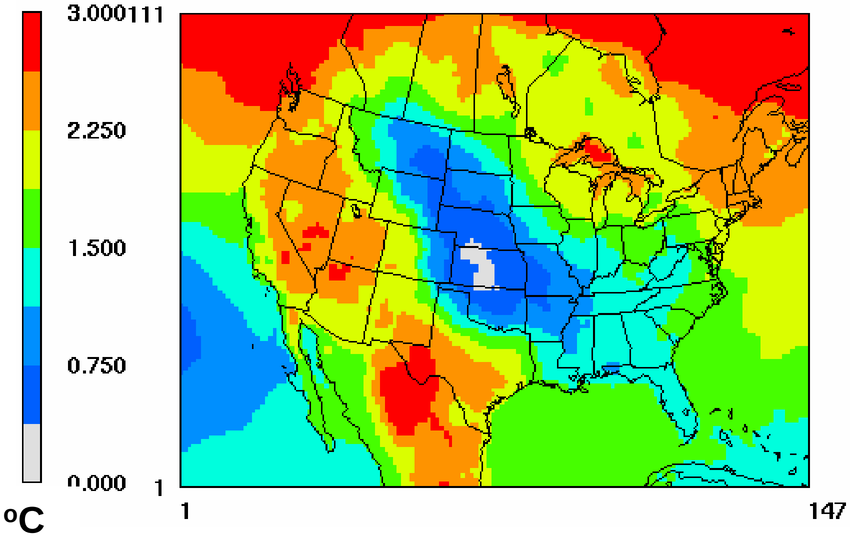
Introduction

- Climate change is forecast to affect air temperature, absolute humidity, precipitation frequency, etc.
- Increases in ground-level ozone concentrations are expected in the future due to higher temperatures and more frequent stagnation events.
- Ozone-related health effects are also anticipated to be more significant.
- Both ozone and $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 micron meters) are also found to impact climate via direct and indirect effects on radiative forcing.

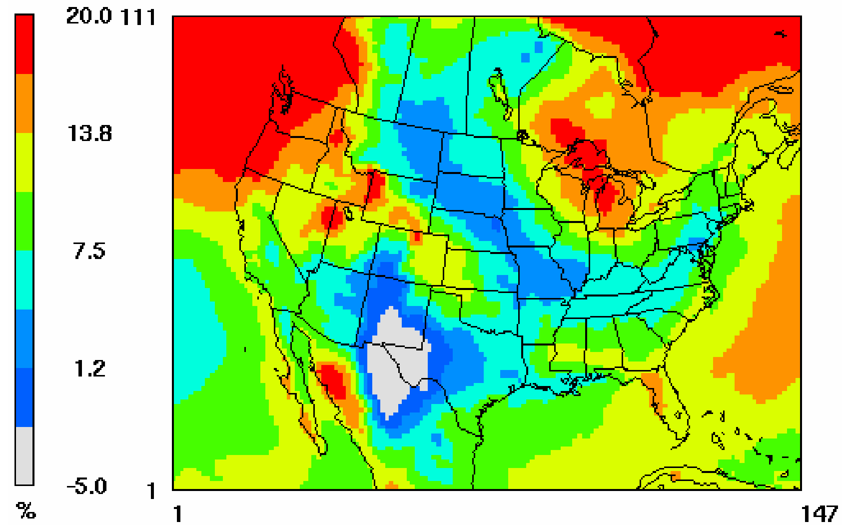
http://www.nature.com/news/2004/040913/images/climate.jpg

Potential Climate Changes in 2050

Temperature (°C)

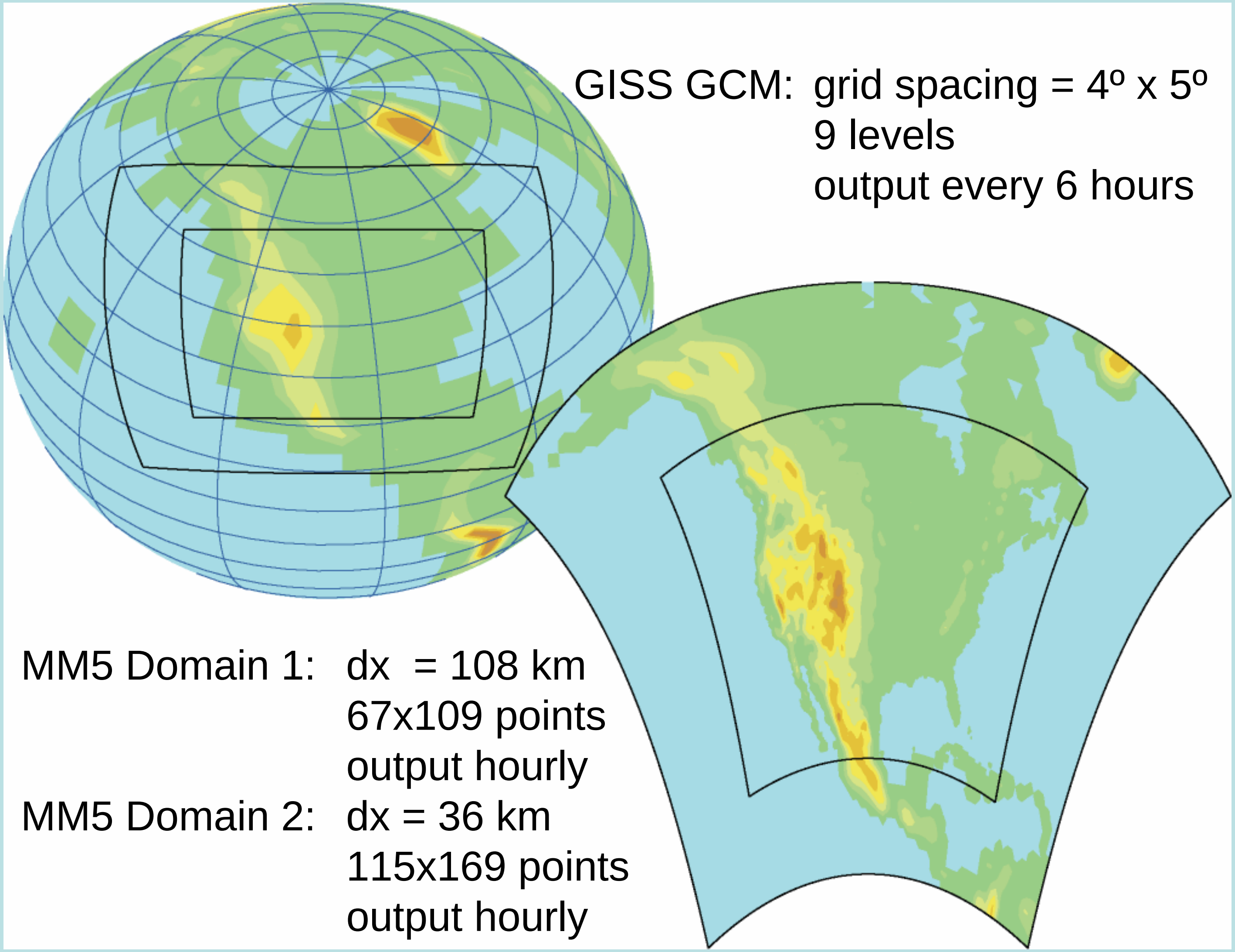


Absolute Humidity (%)



- According to IPCC SRES, A1B scenario

Global and Regional Climate Models*



*Leung and Gustafson (2005), *Geophys. Res. Lett.*, *32*, L16711