Impact of Global Climate Change and Future Emission Changes on Regional Ozone and Fine PM Levels

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Harvard University

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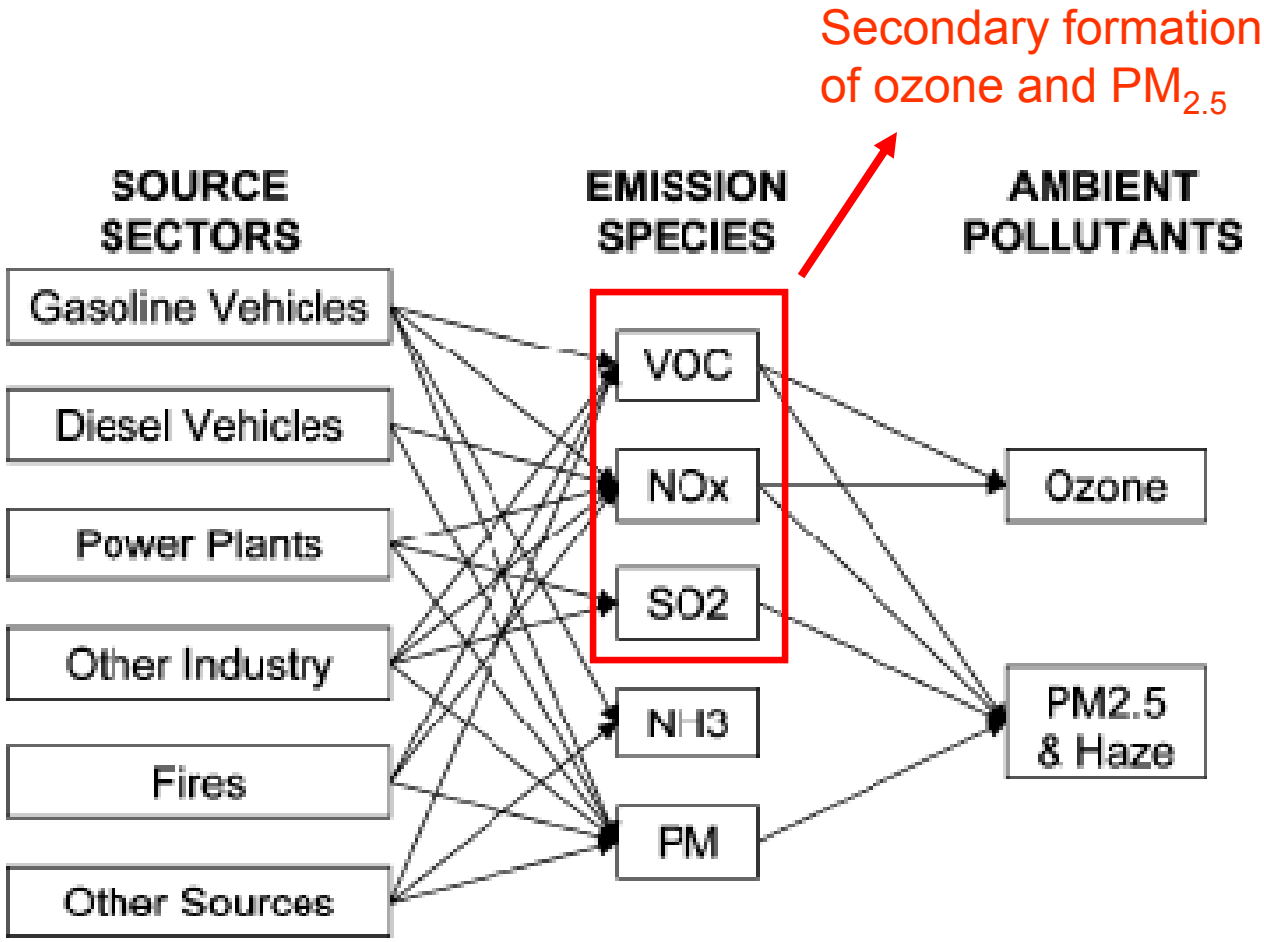
Interrelated Origins of Ozone and $PM_{2.5}$



Cohan et al., *Env. Management*, 2007

(Meng et al., *Science*, 1997; Lamarque et al.,*GRL*, 2005; Unger, *PNAS*, 2006)

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

I. *Introduction: Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet §; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.

† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).

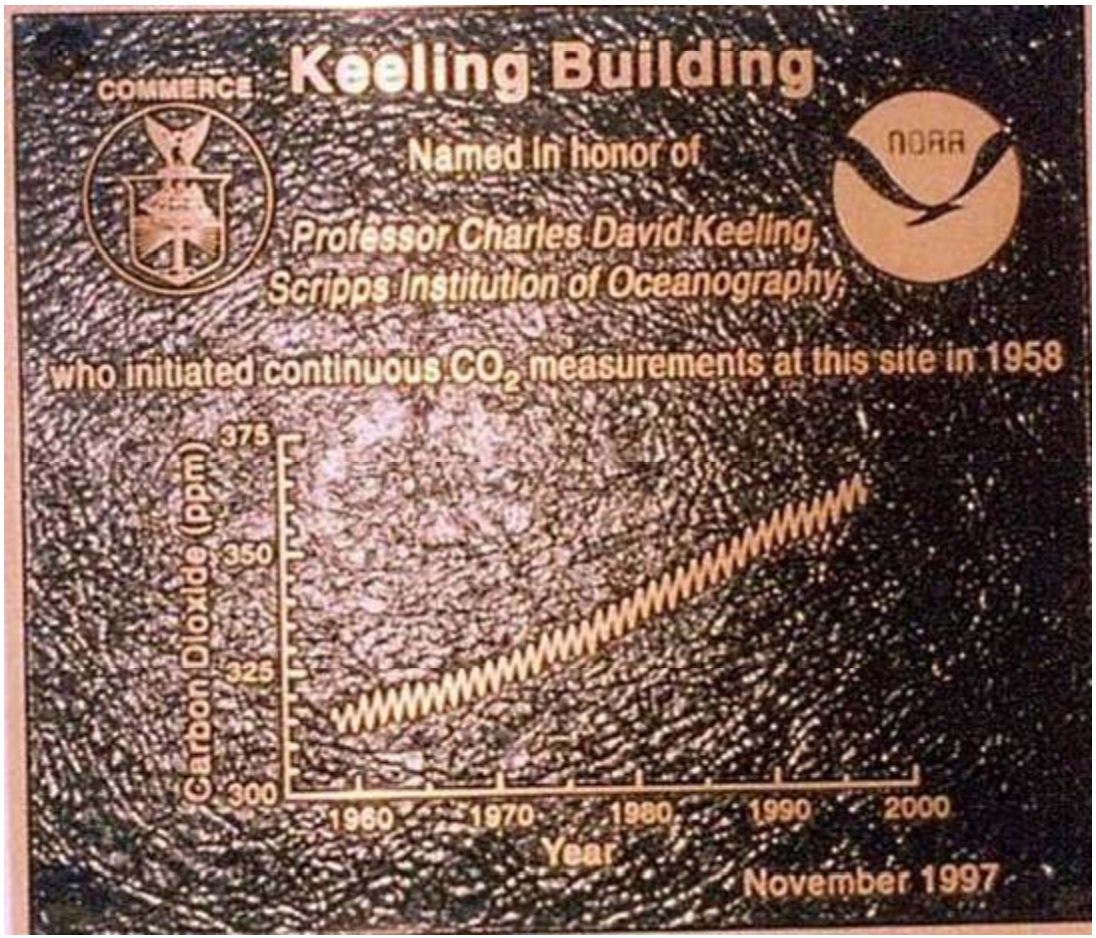
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.

§ *Comptes rendus*, t. vii. p. 41 (1838).

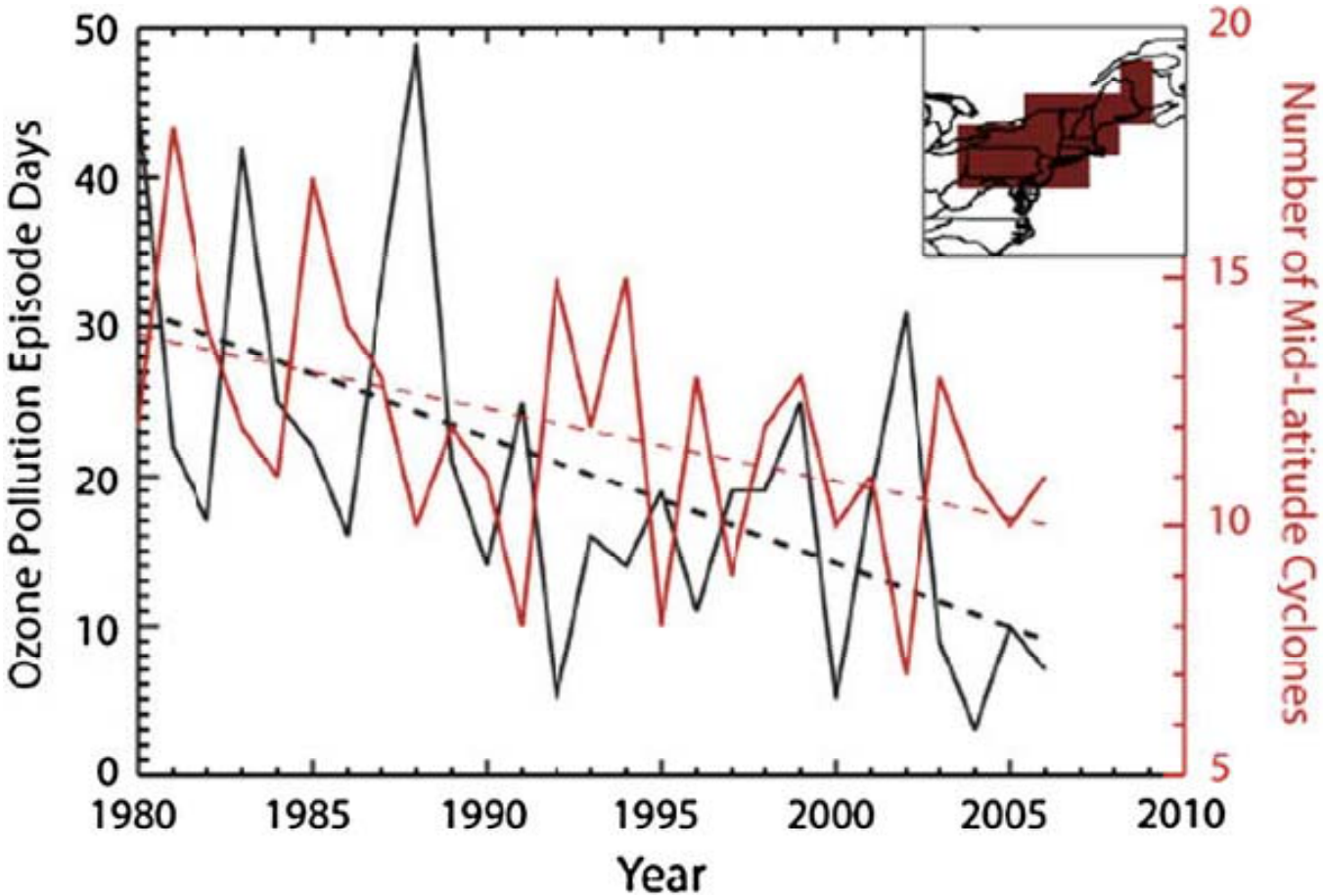
Keeling Curve (11,000 feet, Mauna Loa, Hawaii):

Very Predictable CO_2 Levels under Business-as-Usual Practices: 316 ppm in 1959, 379 ppm in 2005, 500 ppm expected in mid-century (exceeds by far the natural range over the last 650,000 years

(180 to 300 ppm)

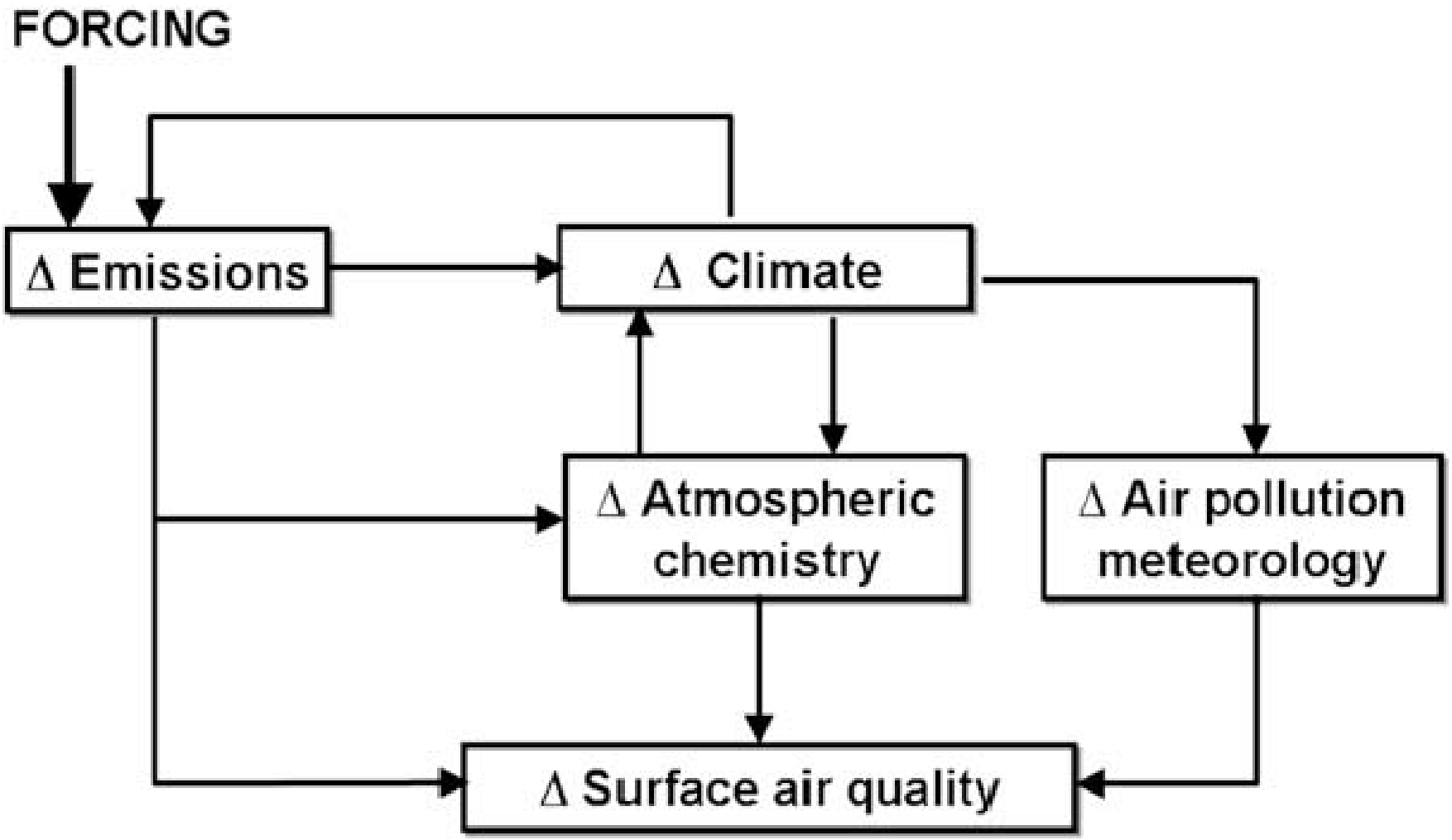


Trend in Ozone Episodes and Mid-Latitude Cyclones (1980-2006)



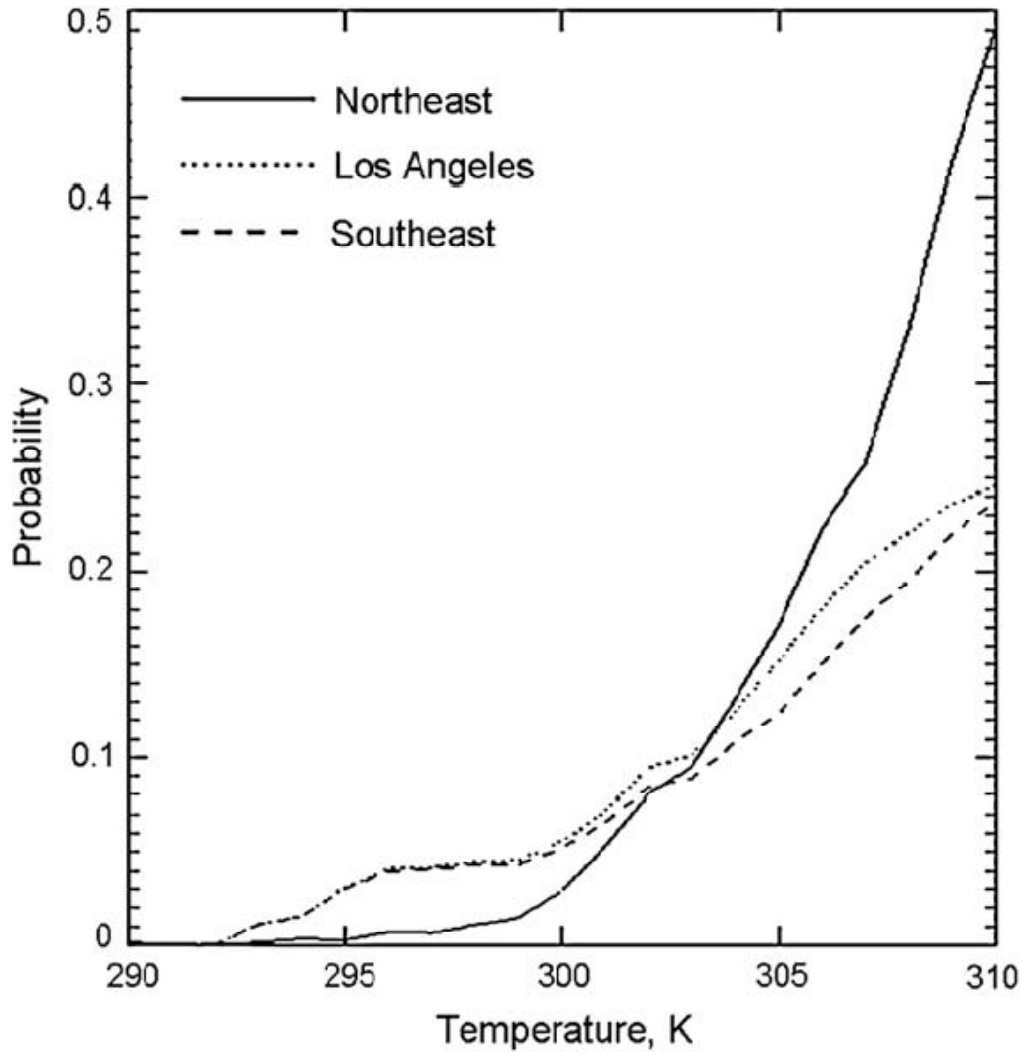
Jacob and Winner (Atmospheric Environment, 2008)

Emissions-Chemistry-Climate Interactions



Jacob and Winner (Atmospheric Environment, 2008)

Probability of Ozone > 80 ppb as a Function of Daily Max Temp (1980-1998)



Jacob and Winner (Atmospheric Environment, 2008)

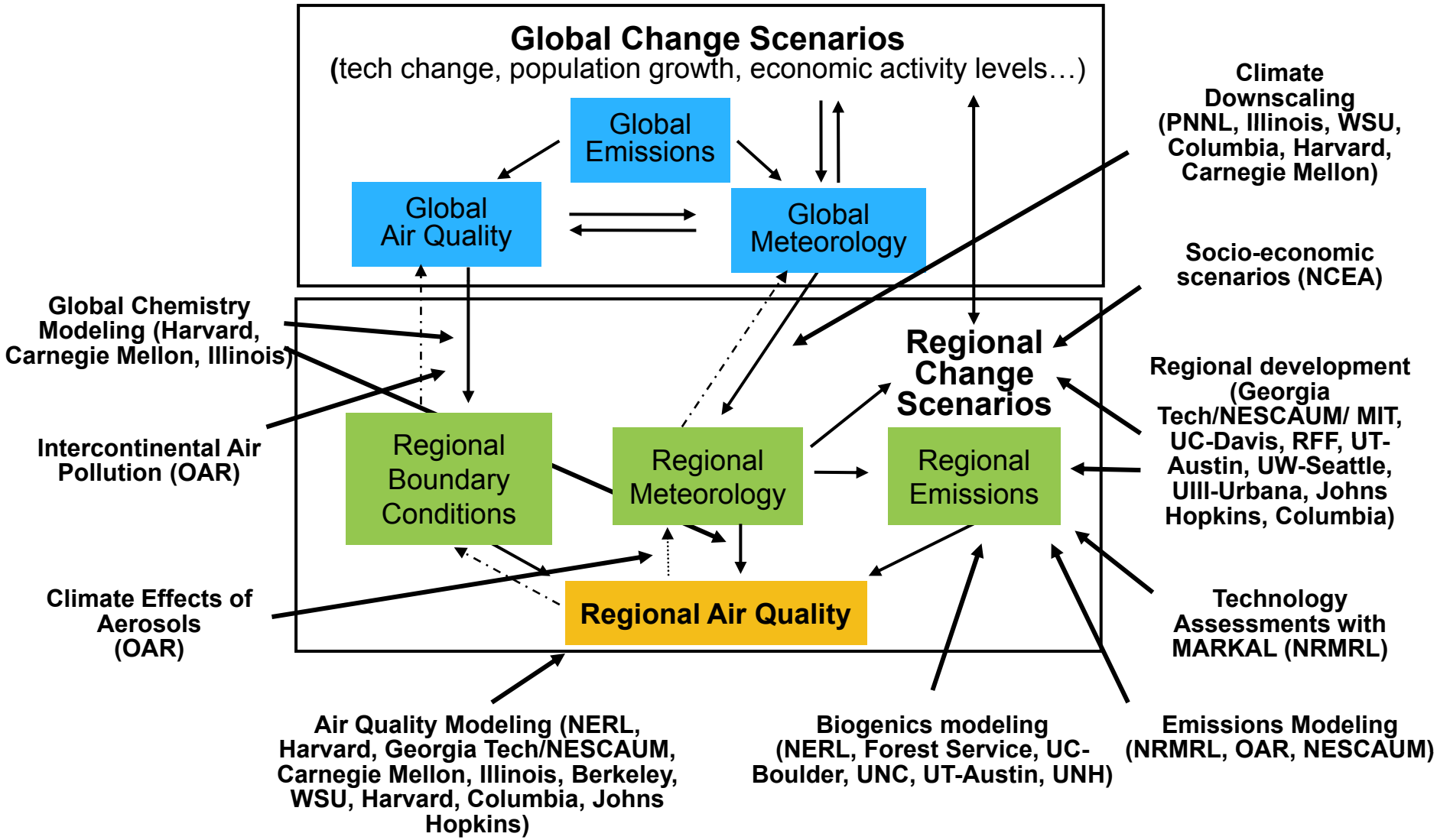
Background – What is the issue?
(Courtesy : Dr. Anne Grambsch, US EPA ORD NCEA)

- 2007 IPCC Fourth Assessment Report
  - Climate change would modify a number of chemical and physical processes that control air quality and the net effects are *likely* to vary from one region to another.
  - Climate change can affect air quality by modifying the rates at which pollutants are dispersed, the rate at which particles and soluble species are removed from the atmosphere, the general chemical environment for pollutant generation and the strength of emissions from the biosphere, fires and dust.
  - Overall, the net effect of climate change on air quality is complex.

Background – Why is this important? (Courtesy : Dr. Anne Grambsch, US EPA ORD NCEA)

- 2004 NRC Report: *Air Quality Management in the US*
  - Identified *"adapting the air quality management system to a changing (and most likely warmer) climate"* as key challenge in coming decade
- Climate change expected to impact air pollution in ways that have not been explicitly considered in AQ program planning
  - *Chemical reaction rates and atmospheric transport processes*
  - *Biogenic (and anthropogenic) emissions rates*
- Potential to affect attainment of clean air objectives?
- Critical assessment of emerging science needed to assist in making significant, long-term decisions

Air Quality Assessment – Collaborations (Courtesy : Dr. Anne Grambsch, EPA ORD NCEA)

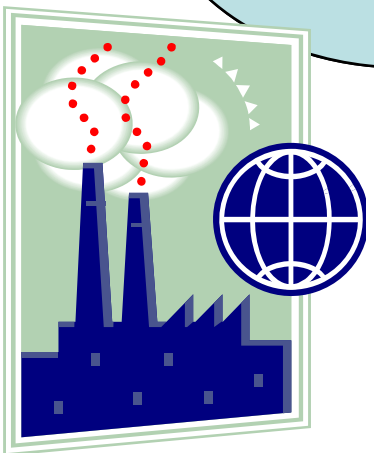


Introduction

- Climate Change is forecast to affect air temperature, humidity, precipitation amounts and frequency, etc.
- Increases in ground-level ozone concentrations are expected in the future due to higher temperatures and more frequent (and longer?) stagnation events ("climate change penalty"); effect on $PM_{2.5}$ levels more complex.
- Accurate projections of emissions of ozone and $PM_{2.5}$ precursors to distant future (year 2050) are key to evaluate the relative impacts of climate change and current control strategies/policies on ambient levels of ozone and $PM_{2.5}$
- The effects (direct and indirect) of ground-level air pollution on climate (regional and global) are <u>not</u> investigated here.

Issues

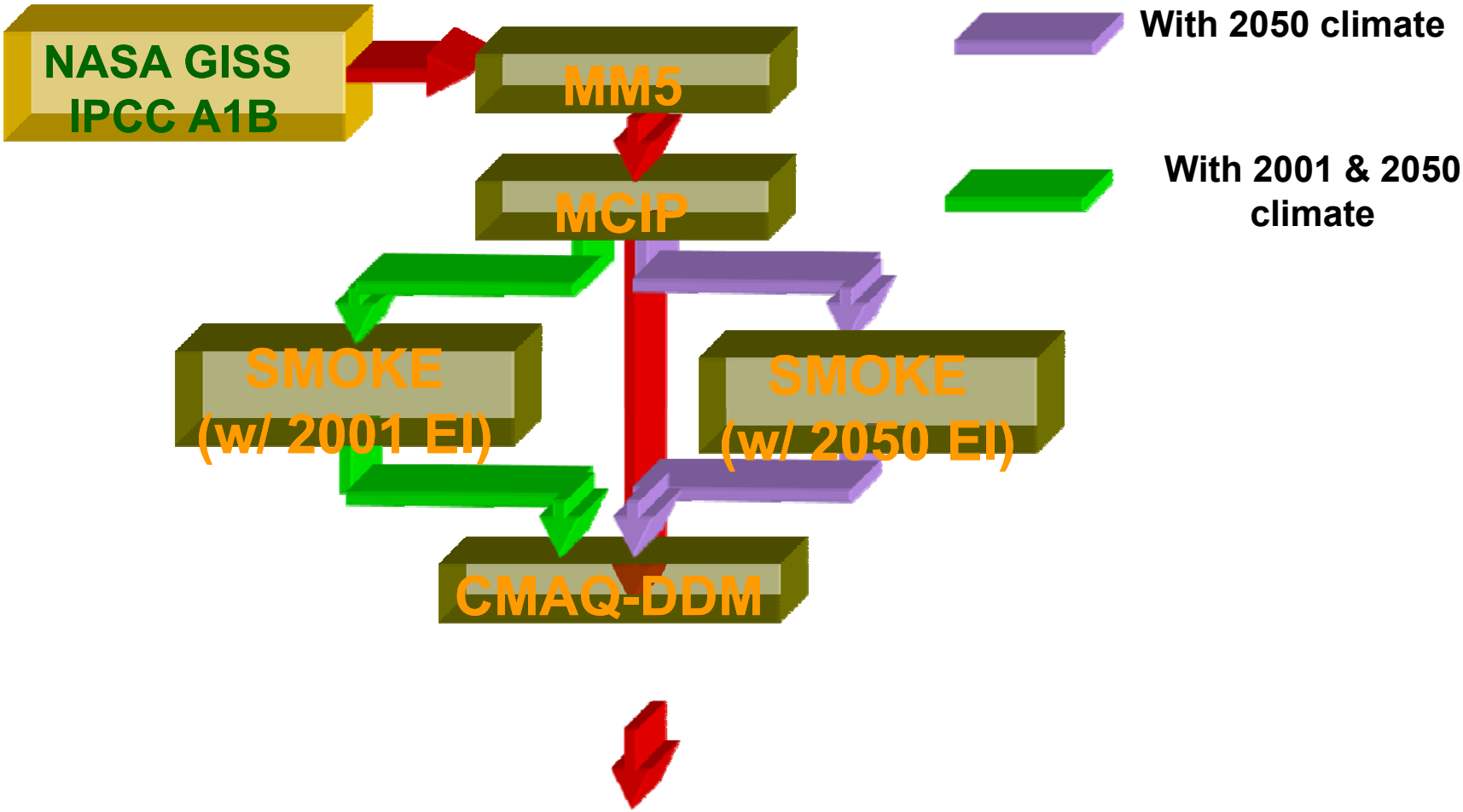
- How does the "climate change penalty" compare to benefits of planned emission reductions?
- **How well will currently planned control strategies work as changes in climate occur?**
- **How robust are the results?**



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, biogenic and anthropogenic VOCs and SO2) and associated uncertainties.

Modeling Procedure

Leung and Gustafson (2005)



*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
- 5 U.S. sub-regions
  2 Canadian sub-regions
  Northern Mexico

Emission Inventory Projection

- Accurate and consistent projection of emissions is key to comparing relative impacts on future air quality and for evaluating control strategy effectiveness
  - Academic and Policy/Government: Cooperative Effort

Woo et. al, 2006

Projecting emissions

- US -

- **Step #1: Obtain national projection data available for the near future**
  - Use EPA CAIR Modeling EI
    (Point/Area/Nonroad, from Y2001 to Y2020)
  - Use RPO SIP Modeling EI
    (Mobile, from Y2002 to Y2018)

- **Step #2: Obtain growth data for the distant future and develop cross-reference**
  - Use IMAGE model (IPCC SRES, A1B)
  - From Y2020 (Y2018 for mobile activity) to Y2050
  - X-Ref : Sectors/Fuels combination to SCCs

- **Step #3: Apply growth factors using cross-reference**
  - Use IMAGE model (IPCC SRES, A1B)
  - From Y2020(Y2018 for mobile activity) to Y2050

Projecting emissions

- CANADA/MEXICO -

- **Step #1: Obtain national projection data available for the near future or update base year inventory**
  - Use Y2020 Environmental Canada Future EI (Area/Mobile)
  - Use Y2002 Point source inventory (NYS DEC) scaled with Y2000 by-state point source summary from Environment Canada
  - Update base year Mexico inventory using Mexico NEI for 6 US-Mexico Border states

- **Step #2: Obtain simple growth data for the distant future**
  - Use IMAGE model (IPCC SRES, A1B)
  - From Y2020 to Y2050 (CAN, Area/Mobile)
  - From Y2002 to Y2050 (CAN, Point)
  - From Y1999 to Y2050 (MEX, All)

Comparison of existing "future-EI" development approaches

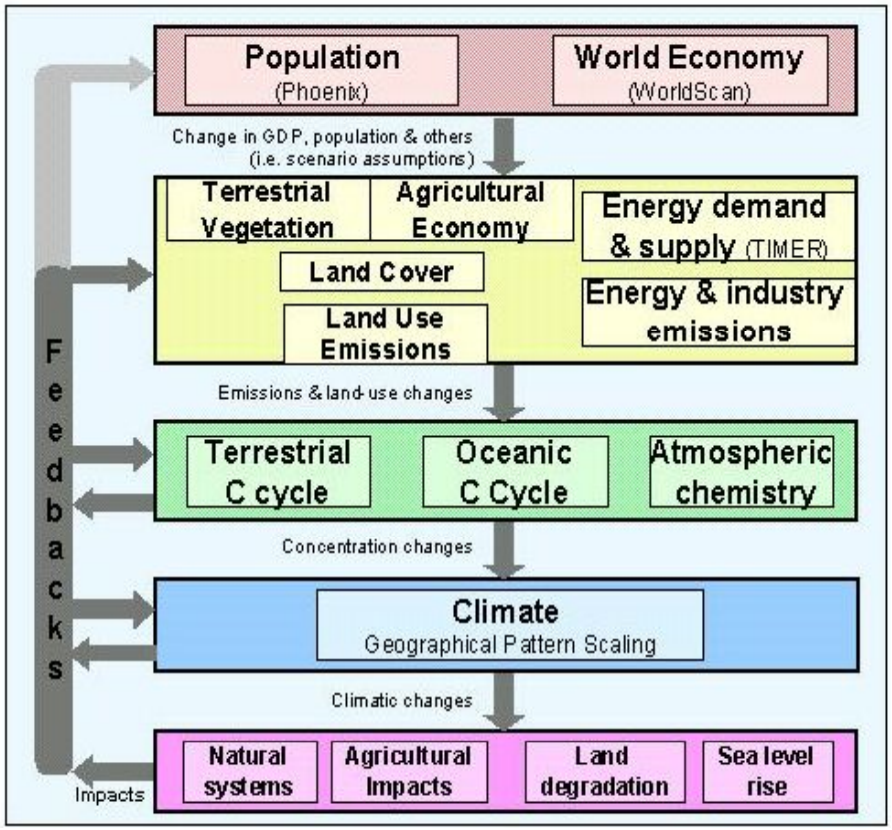
Name	Base Year	Future Years	Geographical Domain	Scenario	Source sectors	Chemical species	Model	Availability
EPA CAIR	2001	2010 /2015 /2020	Continental US	EPA BASE /CAIR	EGUs, non-EGUs	NOx, VOCs, CO, NH3, SO2, PM	IPM /EGAS/NMIM	Yes
EPA CSI	1996	2010 /2020	Continental US	EPA BASE /CSI	EGUs, Non-EGUs	NOx, VOCs, CO, NH3, SO2, PM	IPM /EGAS	Yes
RPOs	2002	2009 /2018	Continental US	OTB/OTW	EGUs & non-EGUs	NOx, VOCs, CO, NH3, SO2, PM	IPM /EGAS	Partly
SAMI	1990	2040 (/10yrs)	38 States + DC	OTB/OTW/BWC/BB	EGUs & non-EGUs	NOx, VOCs, CO, NH3, SO2, PM	SAMI	No
RIVM*	1995	~2100 (/yr)	World (17 regions)	IPCC SRES(A1, B1, A2, B2)	Energy sector/fuel combination	CO2, CH4, N2O, CO, NOx, SO2, NMVOC	IMAGE	Yes
NESCAUM /EPA	1999	~2029+ (/3yrs)	Units(EGUs), States(NE), Country	BAU, RGGI	Energy sector/fuel combination	NOx, VOCs, CO, NH3, SO2, PM	MARKAL	2007

Pros Cons Both

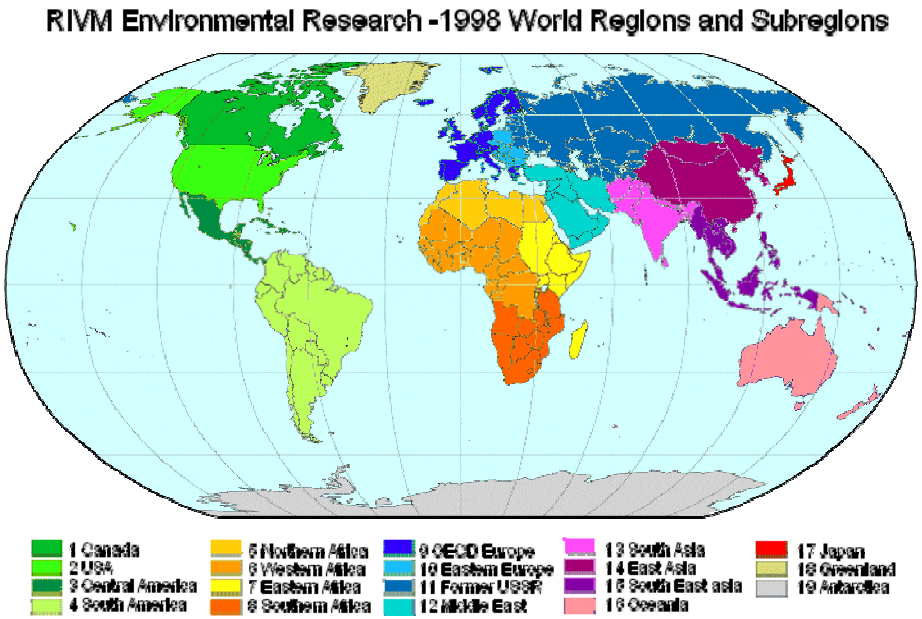
- RIVM : Netherlands's National Institute for Public Health and the Environment
- IMAGE : Integrated Model to Assess the Global Environment

RIVM IMAGE

IMAGE: A dynamic integrated assessment modeling framework for global change

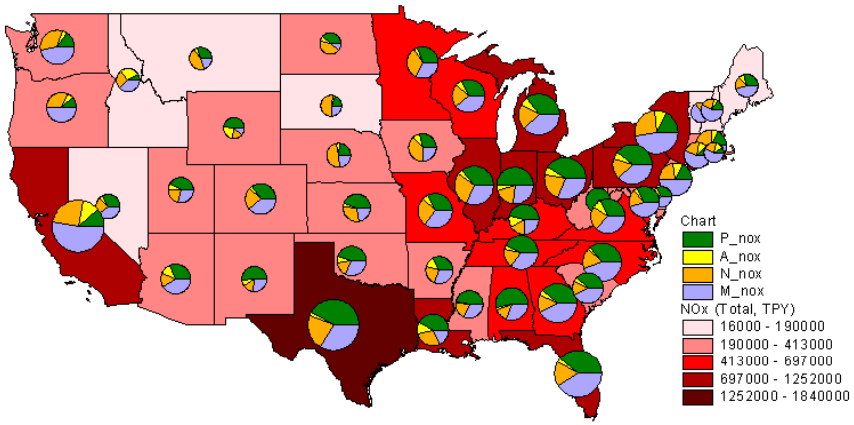


WorldScan (economy model), and PHOENIX (population model) feed the basic information on economic and demographic developments for 17 world regions into three linked subsystems (EIS, TES, and AOS*)

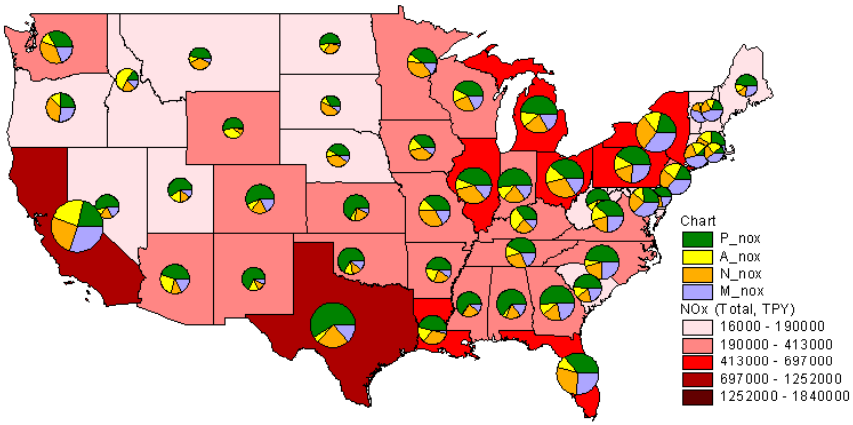


*EIS(Energy-Industry System), TES(Terrestrial Environment System), AOS (Atmospheric Ocean System)

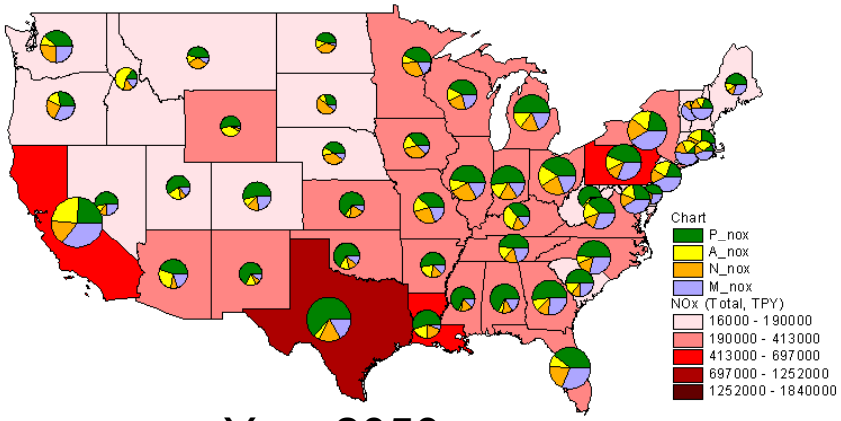
Regional Emissions: Projections



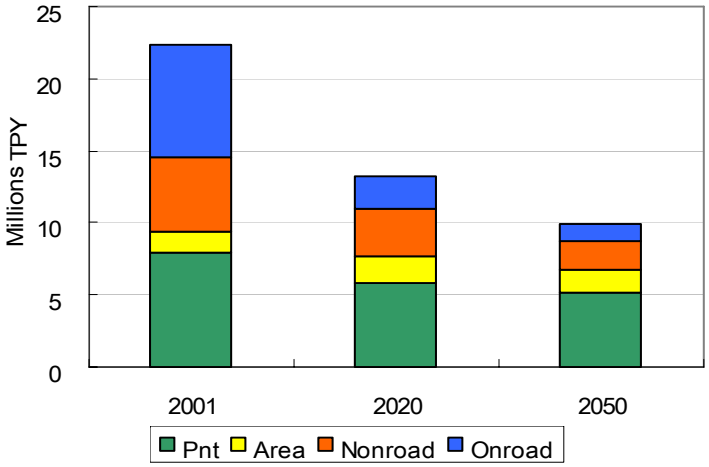
Year 2001



Year 2020

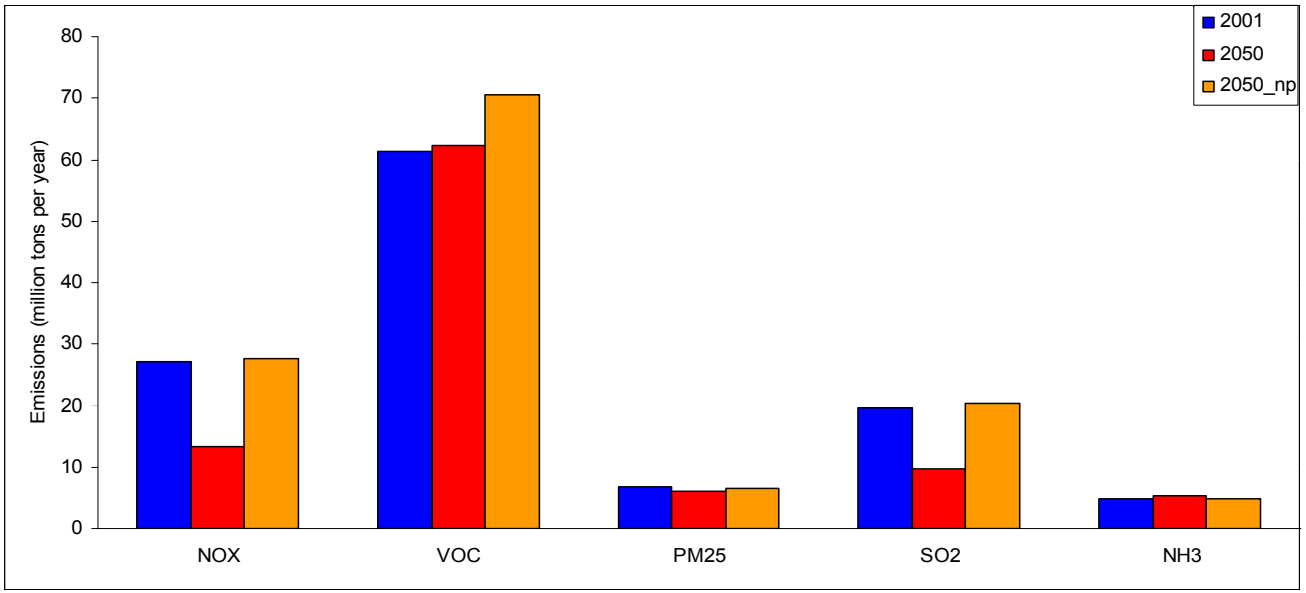


Year 2050



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

Emissions Projections (Three Countries)



2050 – 2001:

NOx: -50% VOC's: +2% $PM_{2.5}$: -10% SO_2: -50% NH_3: +7%

2050np – 2001: VOC's: +15%

np (non-projected): Emission Inventory 2001, Climate 2050

Summary of Air Quality Simulations

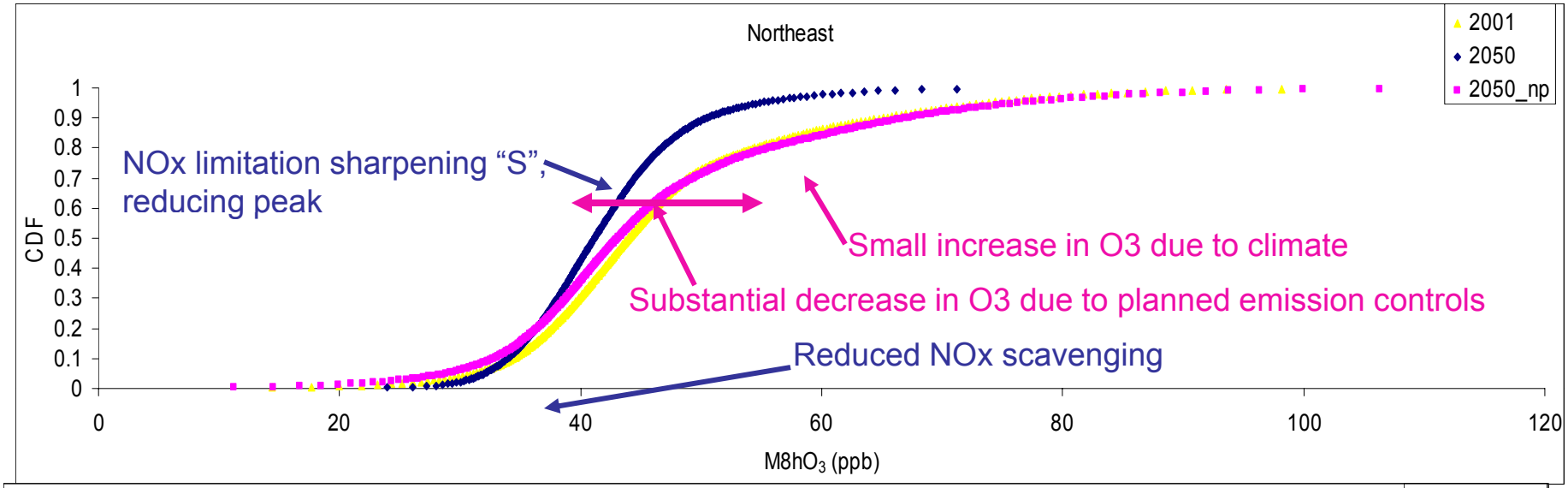
Scenario	Emission Inventory (E.I.)	Climate Conditions	Future Air Quality Impacting Factors
2001	Historic (2001)	Historic (2001 whole year)	N.A.
2000-2002 summers	Historic (2000-2002)	Historic (2000-2002 summers)	N.A.
2050_**np** (non-projected emissions, but meteorologically influenced for consistency)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

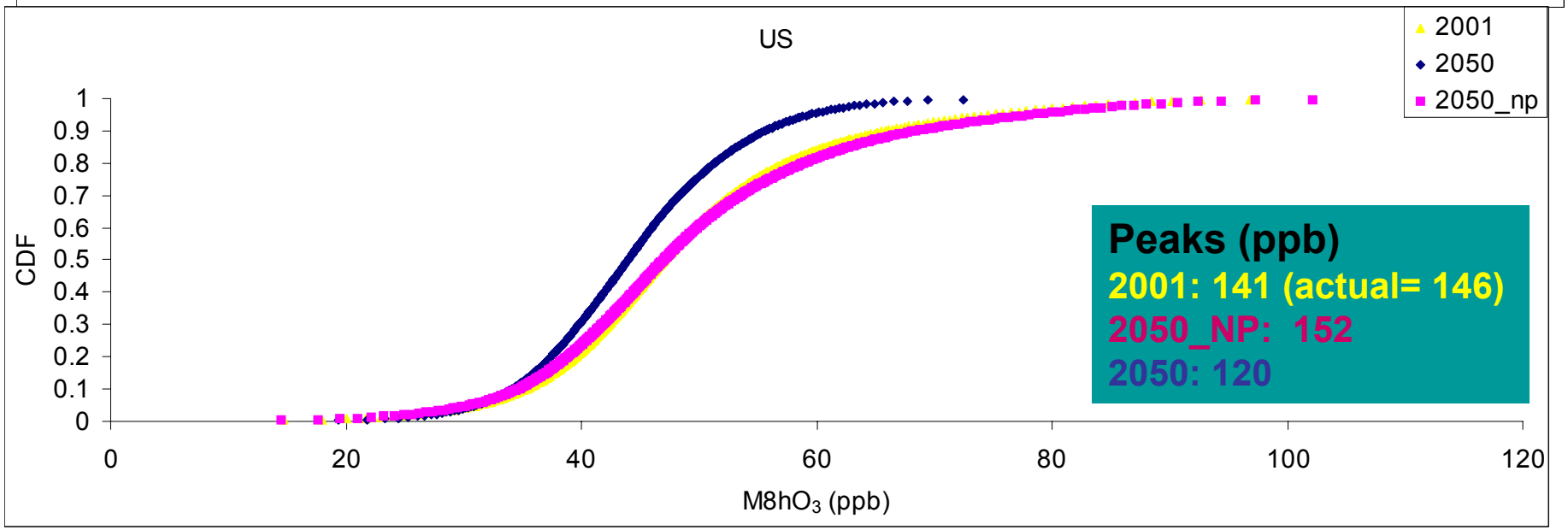
Assessment: Part I

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

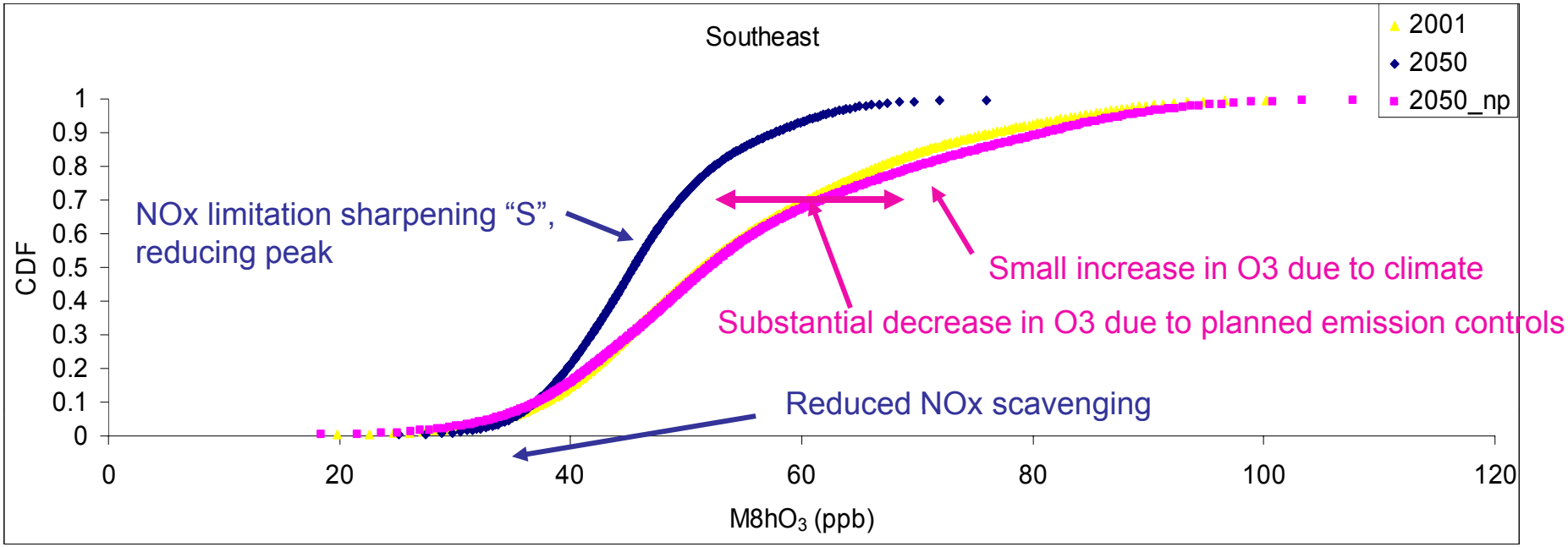
Important and interesting for comparison with the case with emission controls

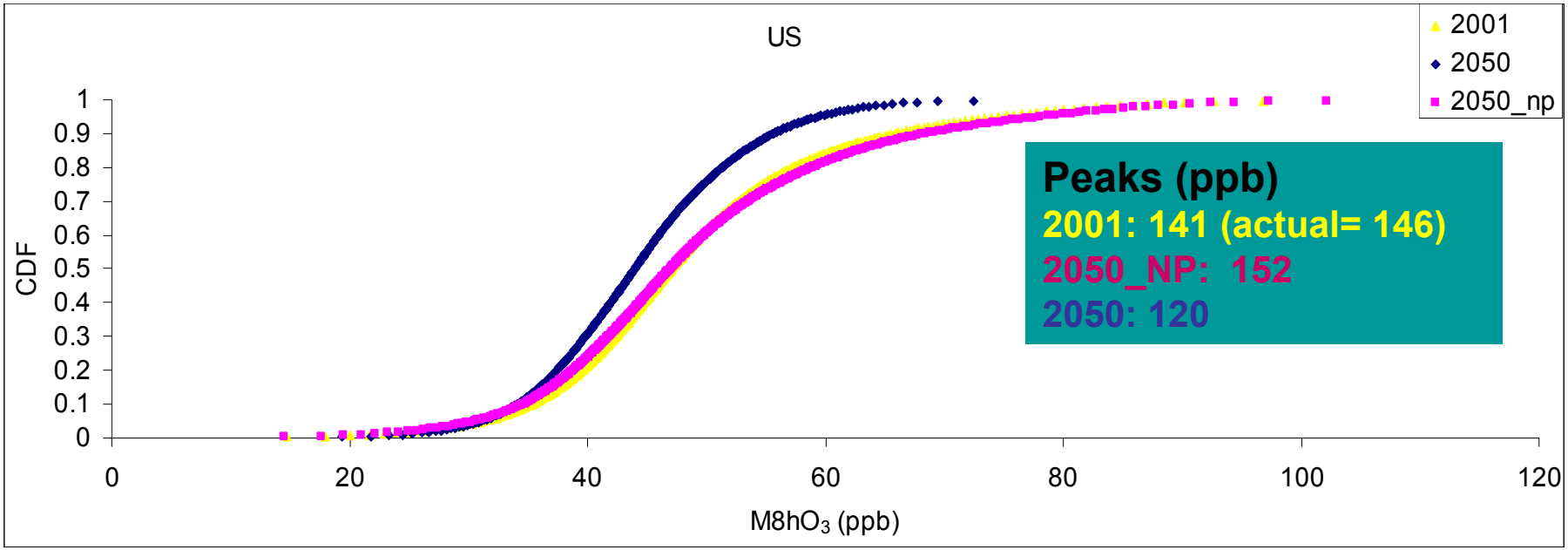
Daily maximum 8 hour ozone concentration CDF plots in 2001, 2050 and 2050_np





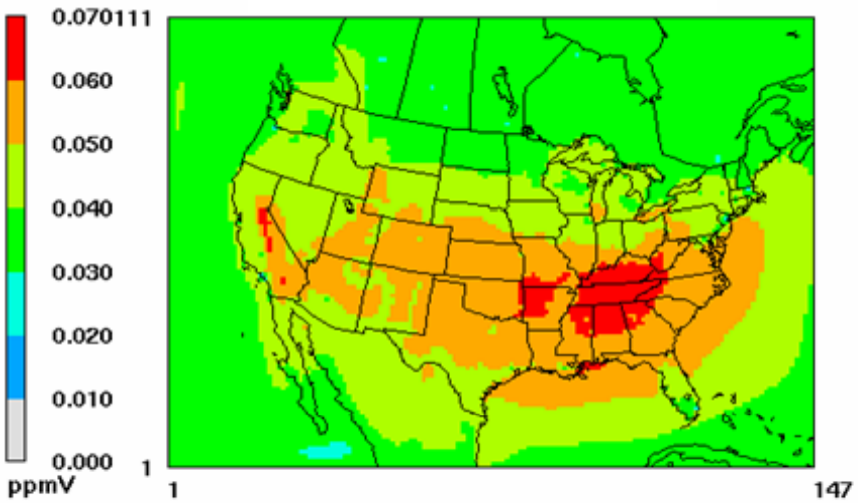
Daily maximum 8 hour ozone concentration CDF plots in 2001, 2050 and 2050_np



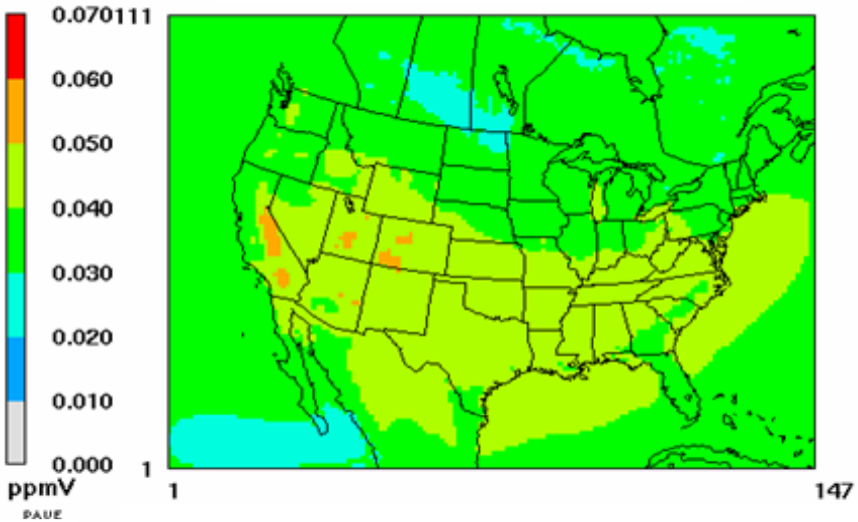


Summer Average Max 8hr O_3

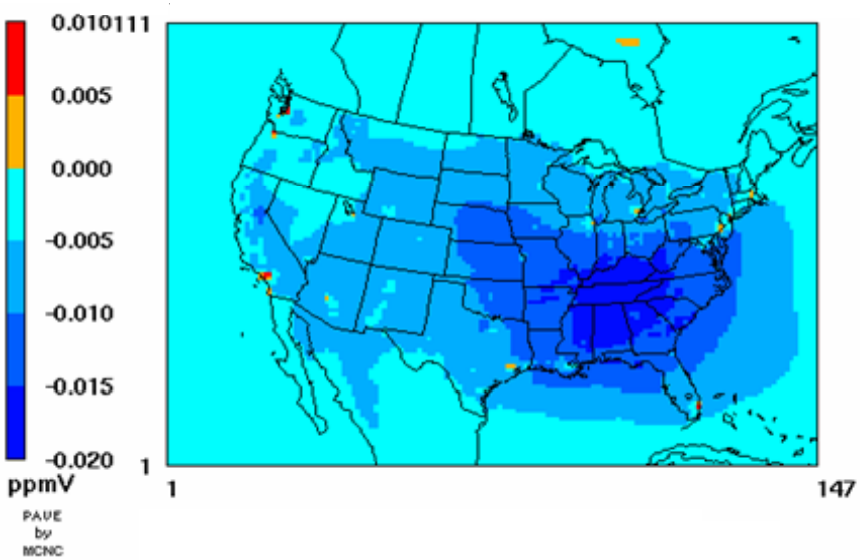
O3_2000-2002summers



O3_2049-2051summers

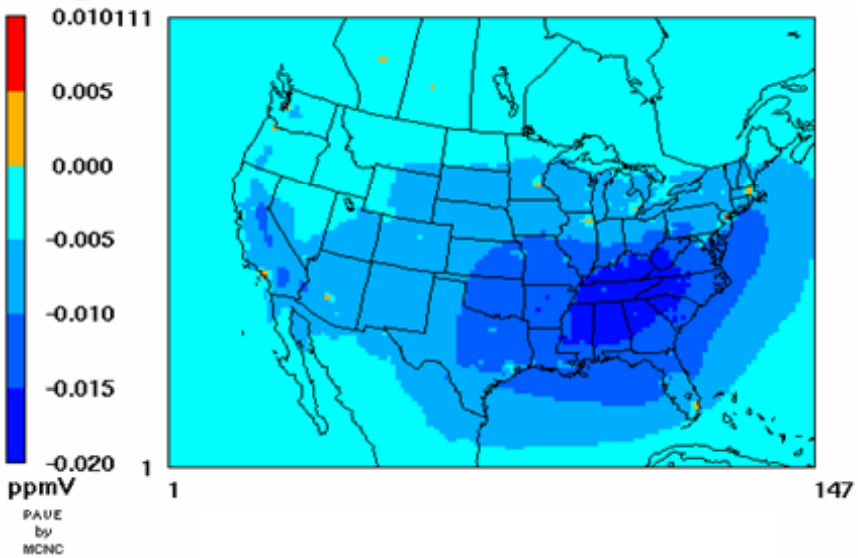


O3_FutureSummers - O3_HistoricSummers



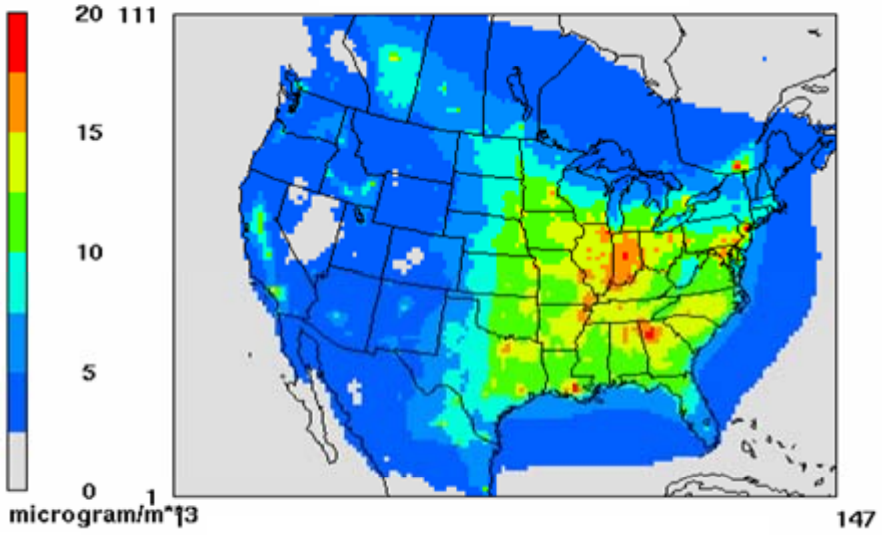
O3_FutureSummers - O3_FutureSummers_np

np: Emission Inventory 2001, Climate 2050

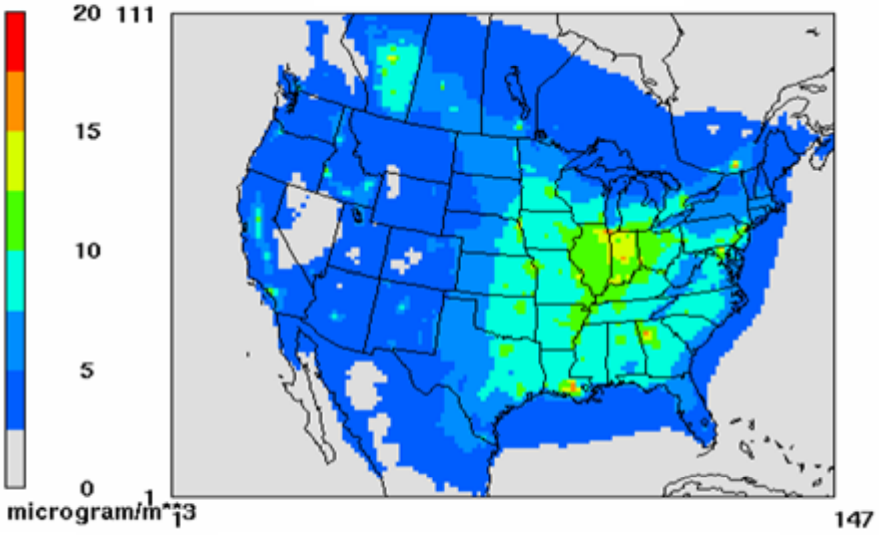


Annual $PM_{2.5}$

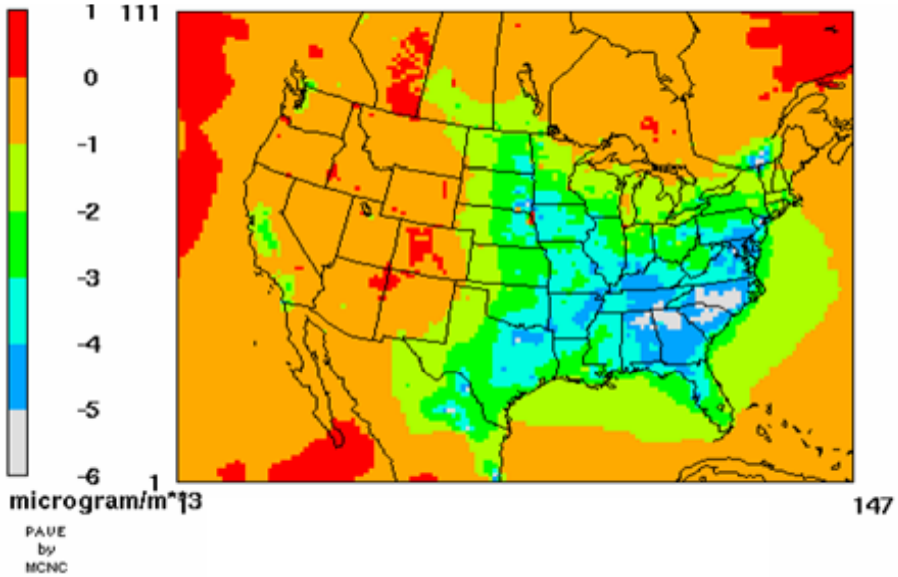
$PM_{2.5}$_2001



$PM_{2.5}$_2050

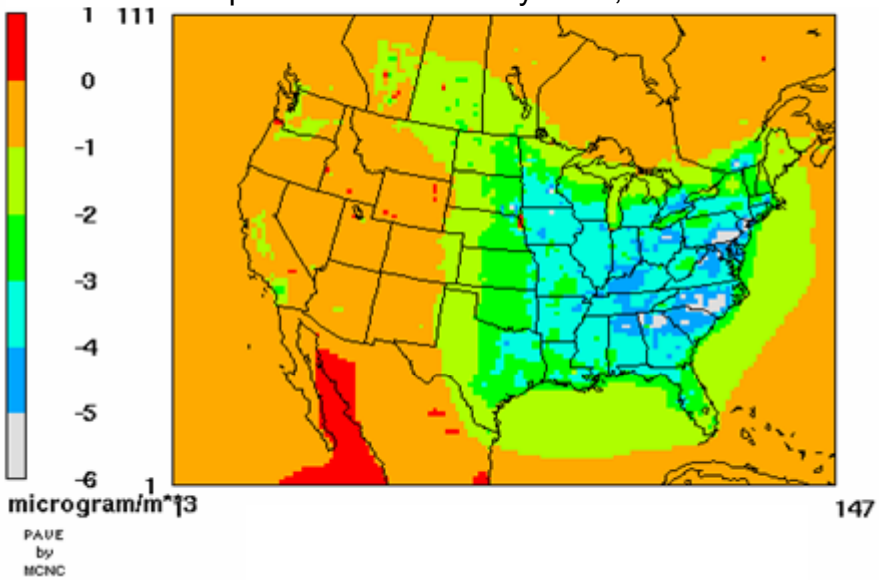


$PM_{2.5}$_2050 - $PM_{2.5}$_2001



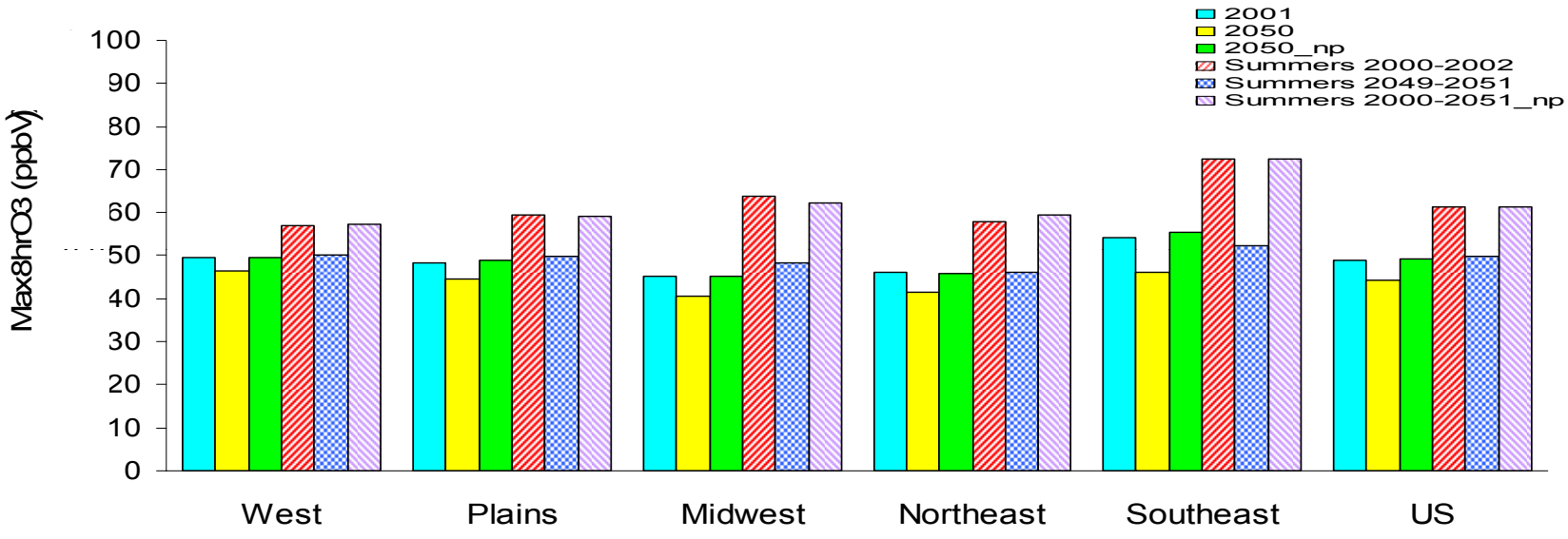
$PM_{2.5}$_2050 - $PM_{2.5}$_2050np

np: Emission Inventory 2001, Climate 2050



Impact of Potential Climate Change and Planned Controls on Average Max8hrO3

All grid averages (not just monitor locations)

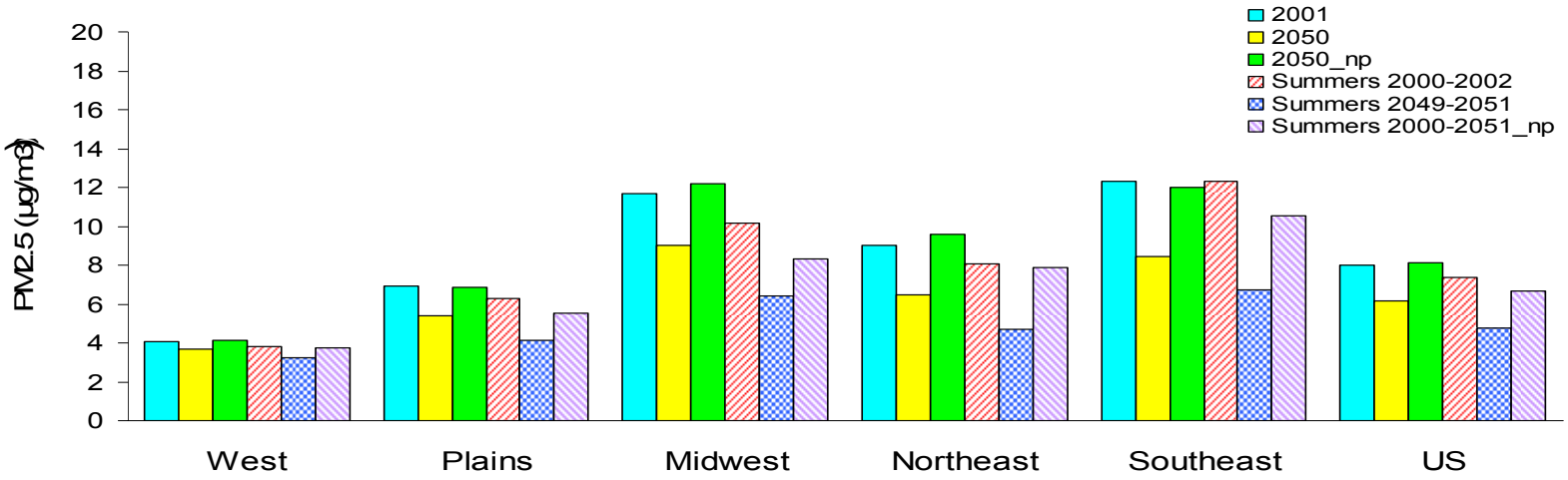


- **3-8 ppbV lower in 2050 (6-15%)**

-**About +/- 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/m^3 lower in 2050

- maximum 0.6 µg/m^3 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

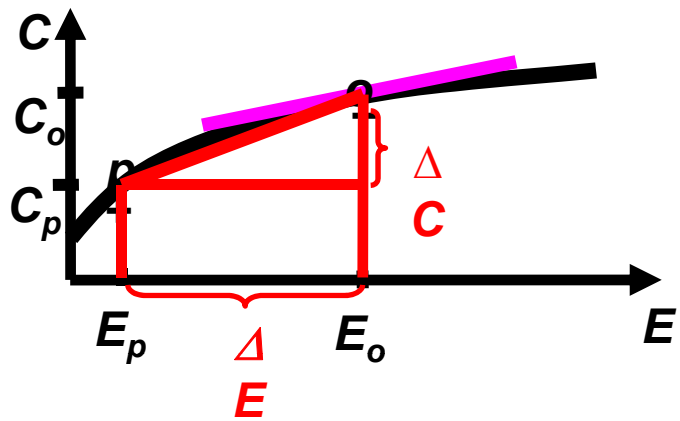
Assessment: Part II

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

➔ Now this is more of our focus (an issue of primary importance to policymakers: how well current policies based on current climate would respond to changed climate?)

Semi normalized First-order Sensitivity Calculated using DDM-3D

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



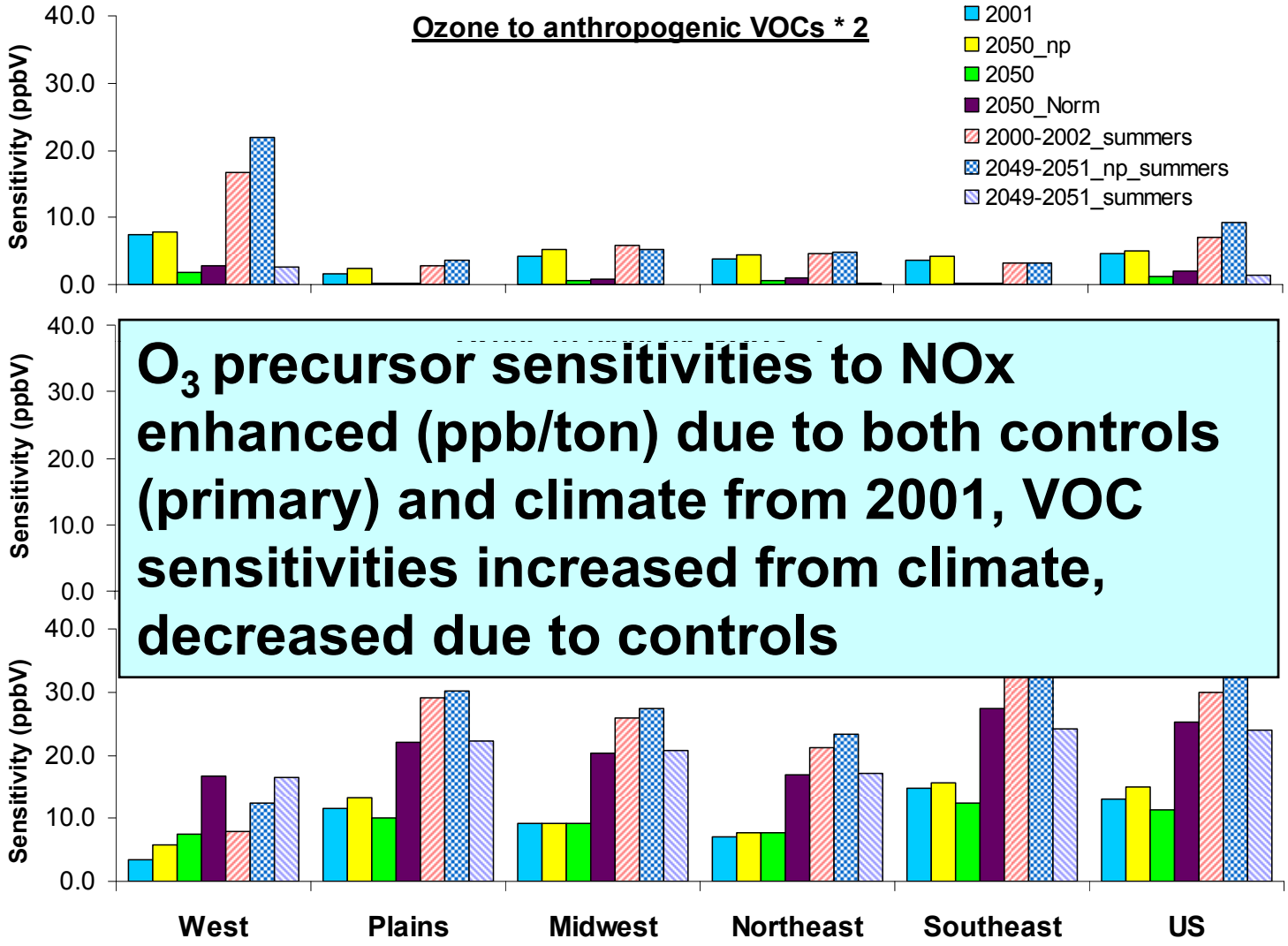
$S_{i,j}$: sensitivity

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

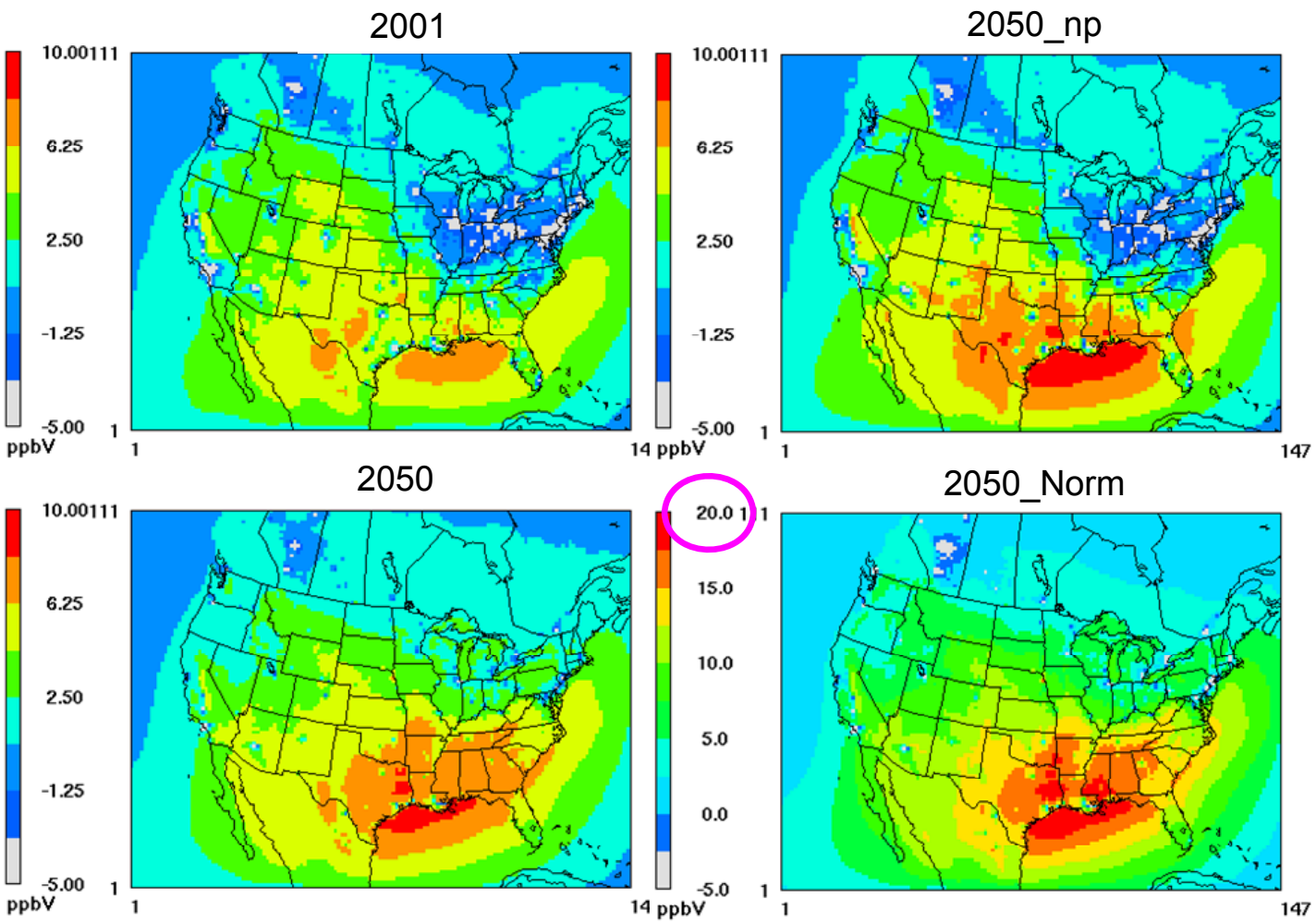
Sensitivities of Daily 4th Highest 8-hr Ozone



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

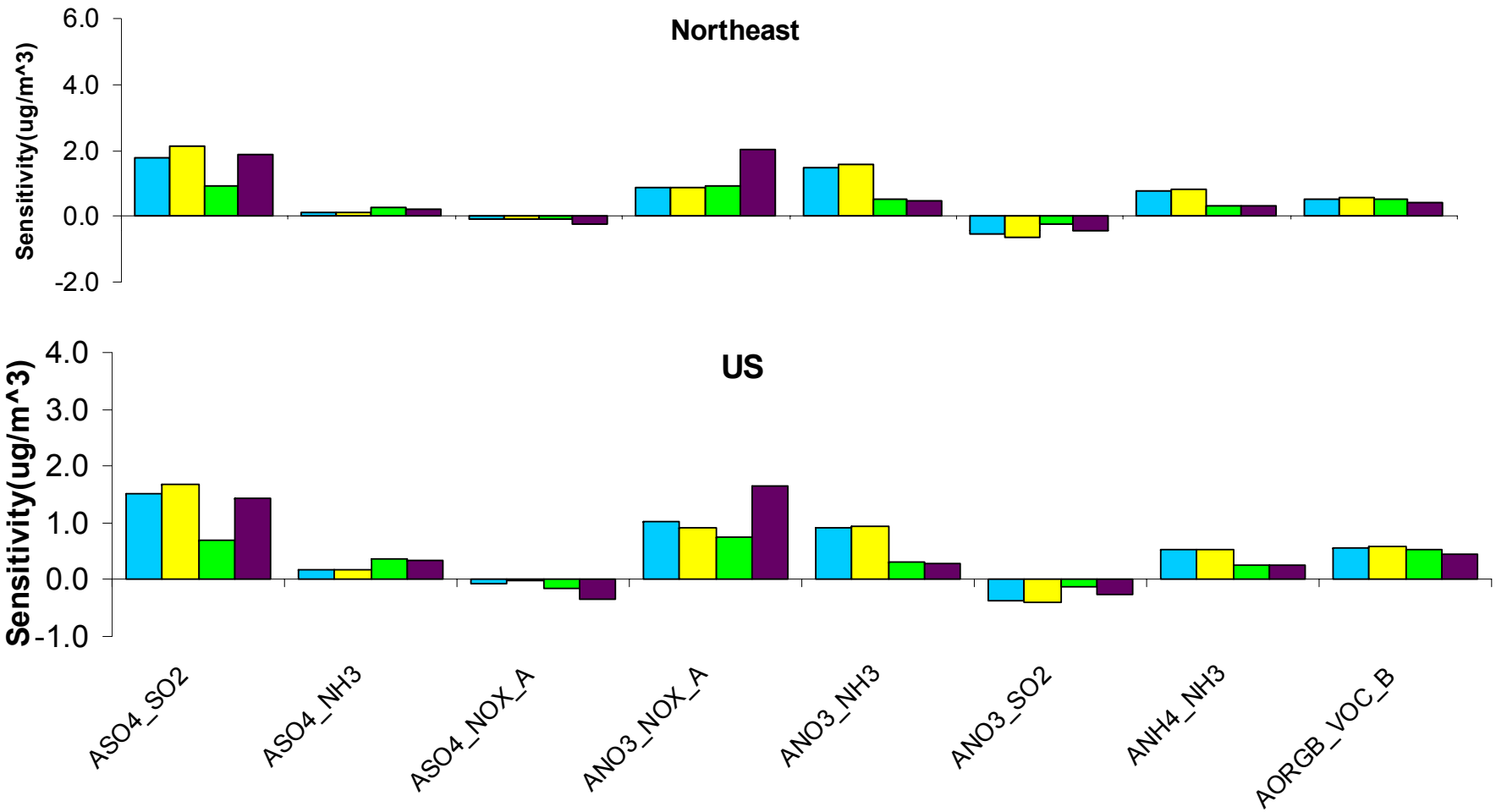
Norm: Adjusted for emissions change

Spatial Distribution of Sensitivities of Annual Ozone to Anthropogenic NO_x Emissions

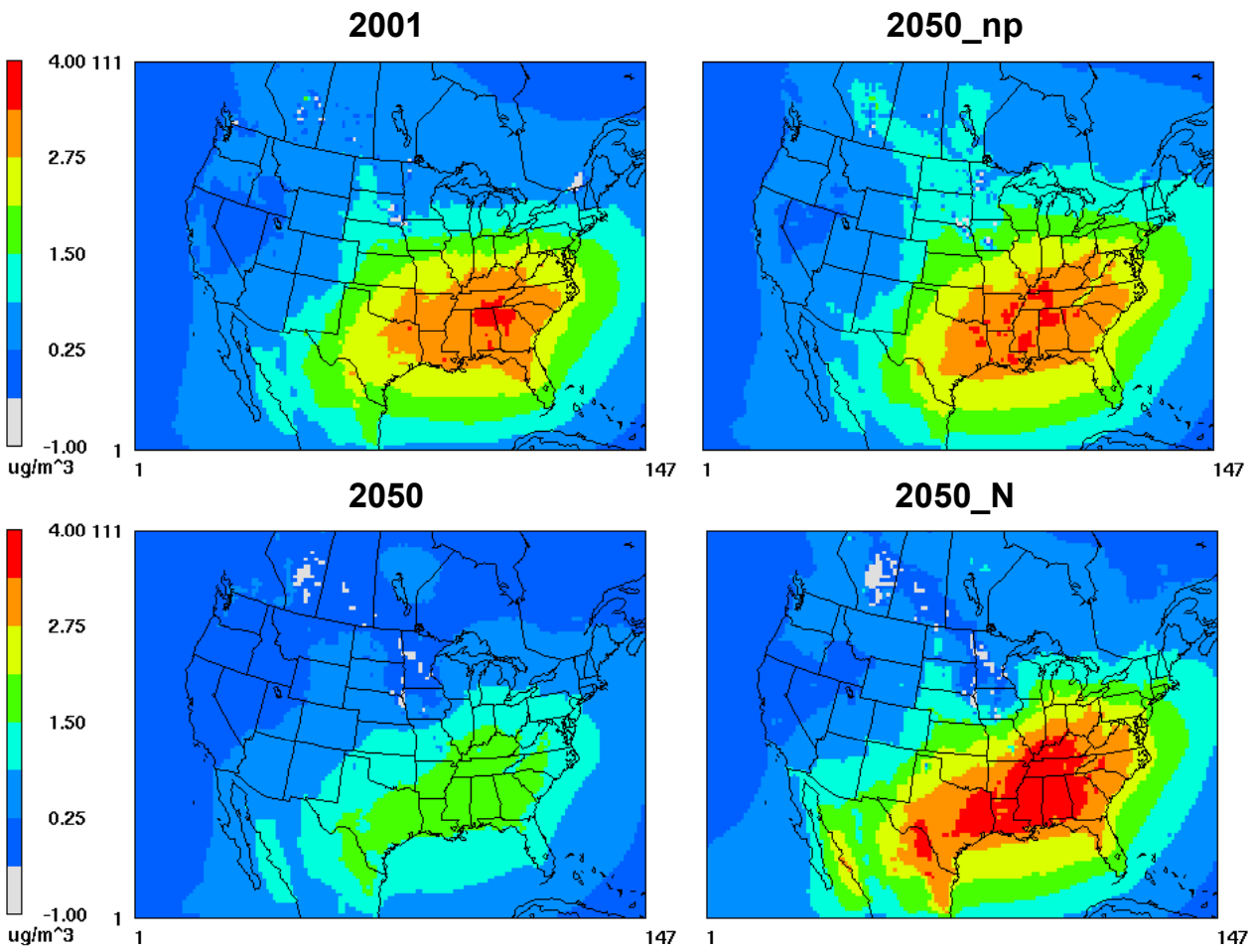


Sensitivities of Speciated $PM_{2.5}$ Formation

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



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



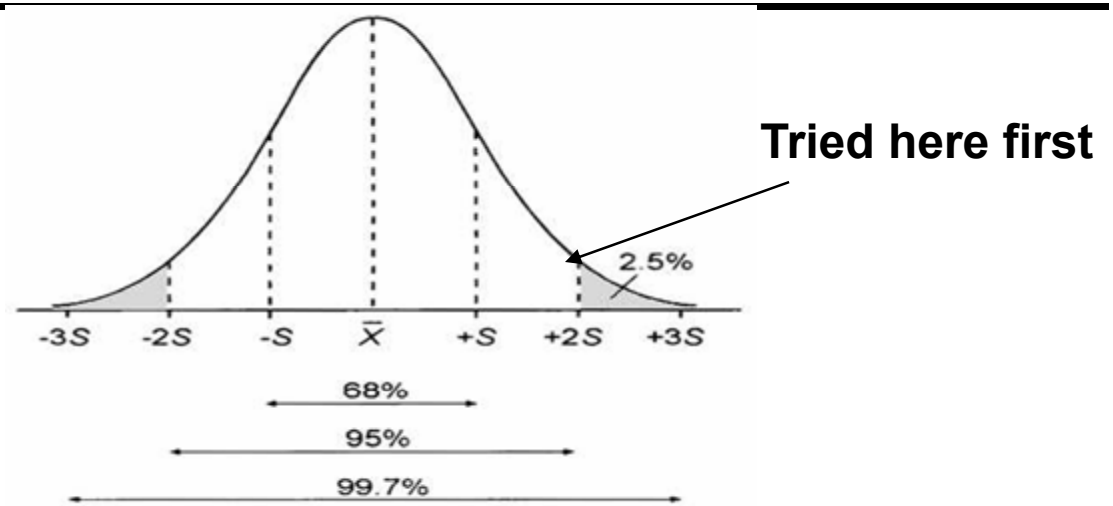
Assessment: Part III

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

➔ A second central question

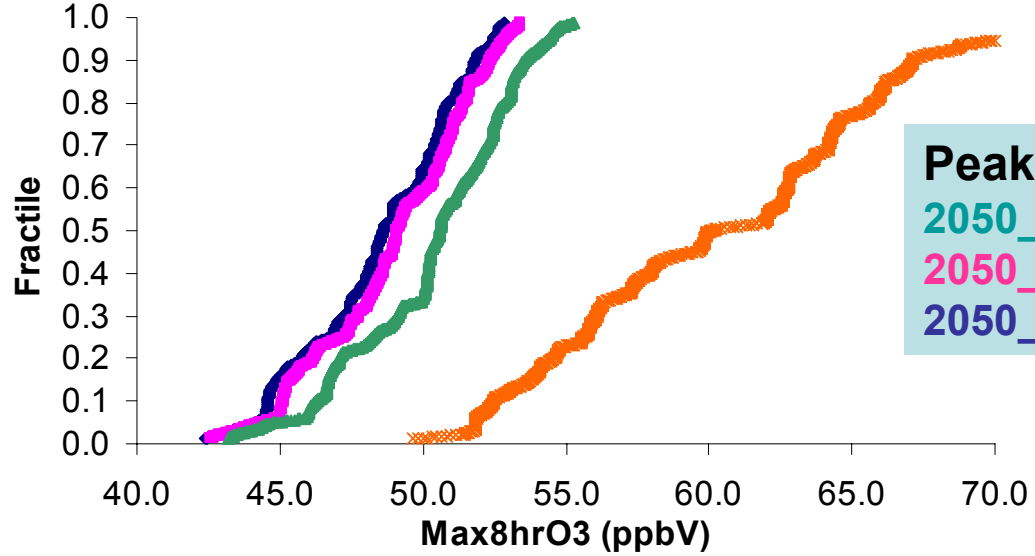
Summary of Uncertainty Simulations

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

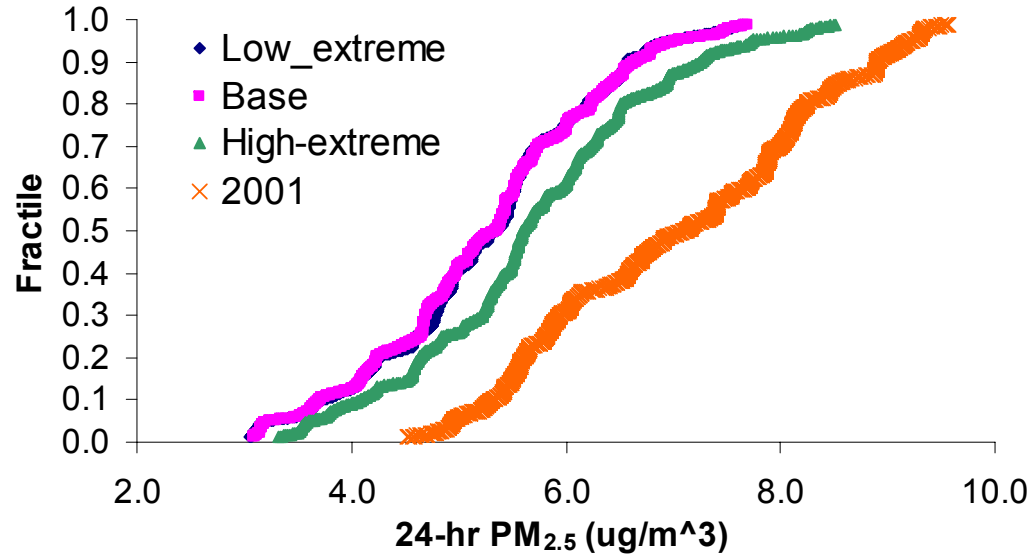


CDFs of Max8hrO3 and 24-hr $PM_{2.5}$ in Summer of 2050

2001 shown for comparison



Peaks (ppb)
2050_99.5: 142
2050_50: 131
2050_0.5: 126



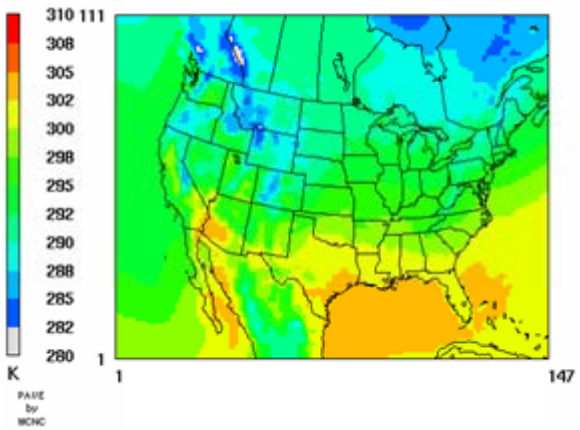
No. of Days M8hrO3 > 80ppbV in Summer of 2050

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

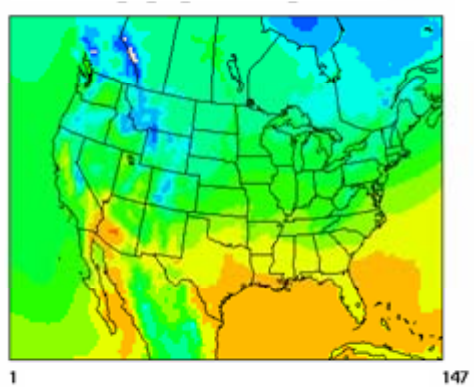
Uncertainties in Temperature

Temperature

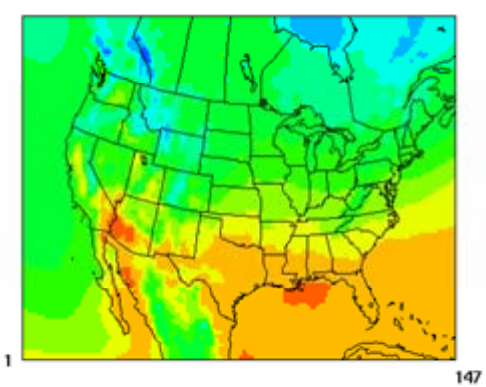
low



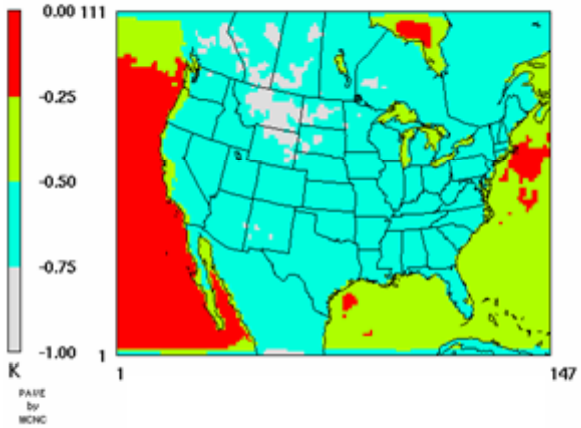
base



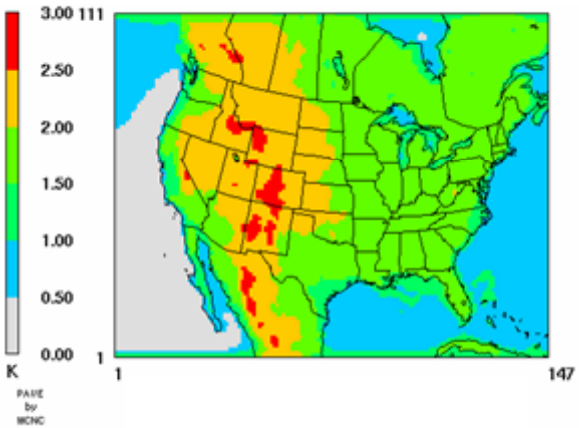
high



low - base

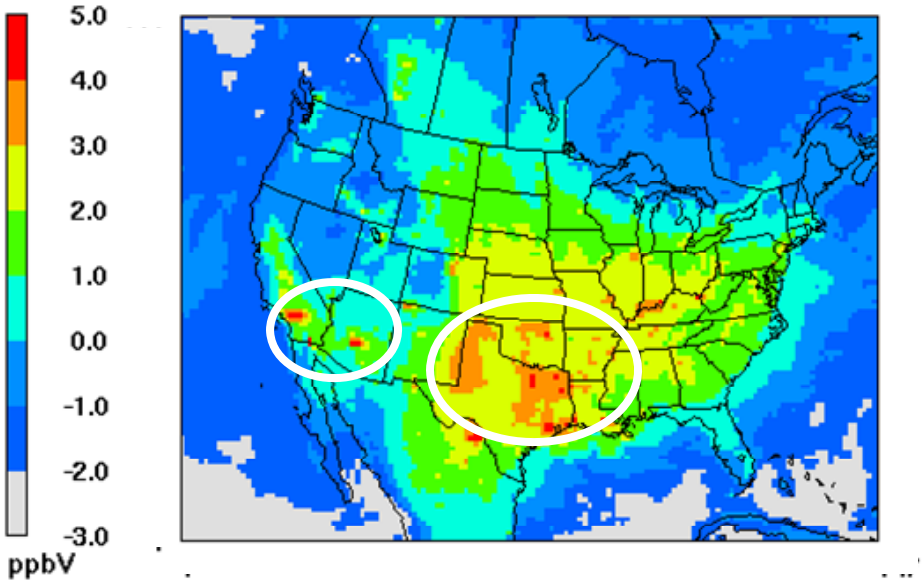


high - base

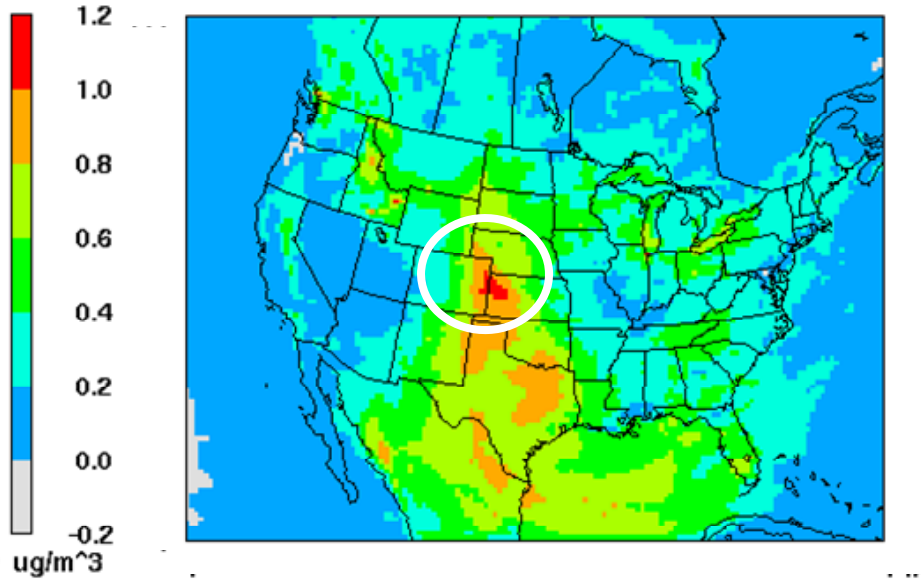


Uncertainties in Summertime Max8hrO3 and $PM_{2.5}$

Max8hrO3



$PM_{2.5}$



(High-extreme scenario) – (Base scenario)

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 about the impact of uncertainty of future climate change.

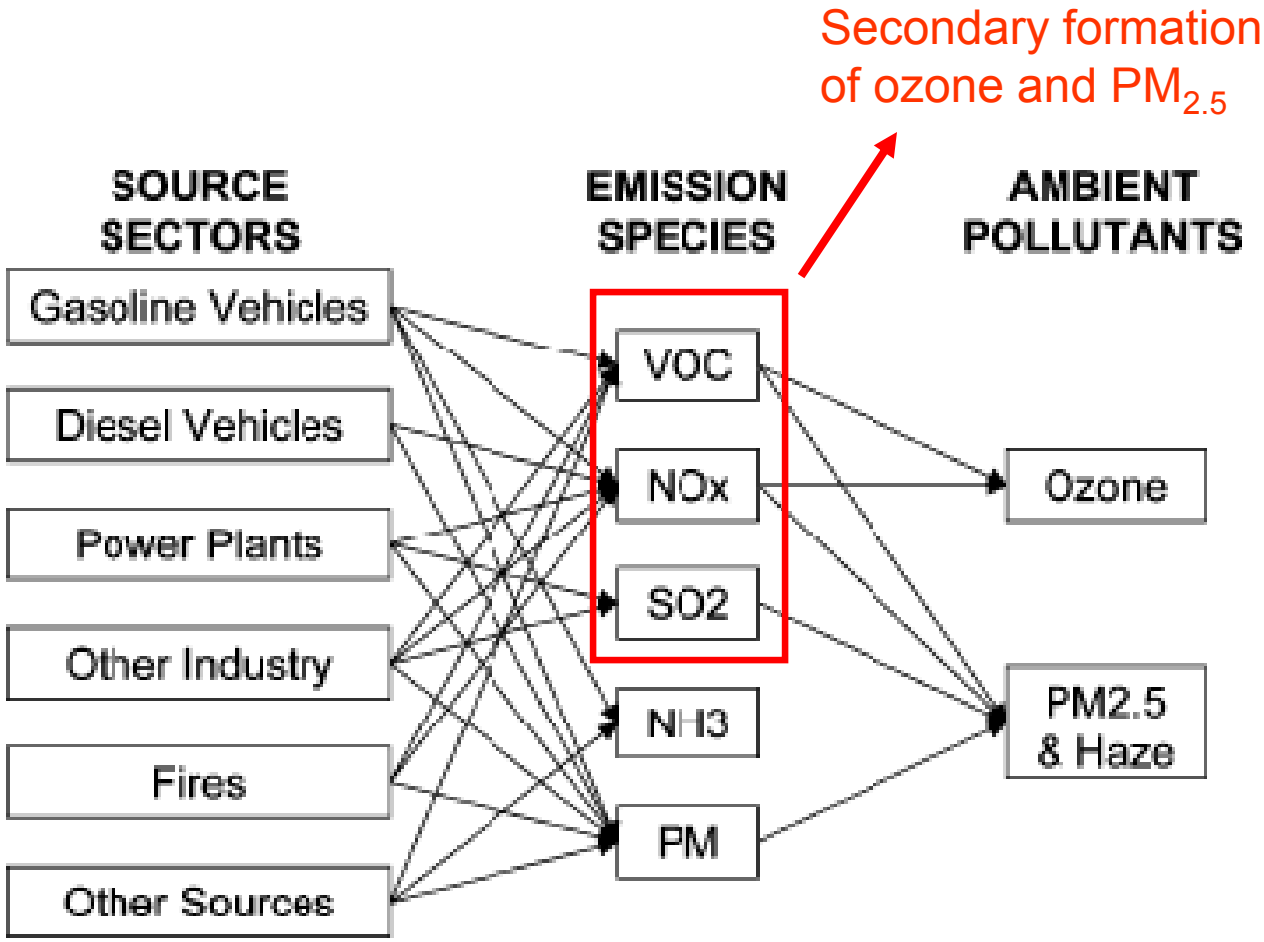
Assessment: Part IV

Cross-Sensitivities (or Linked Responses of Ozone and fine PM to Emission Controls)

Multi-Pollutant Control Strategies (multi, n= 2, only two pollutants)

➔ Now and in the Future

Interrelated Origins of Ozone and $PM_{2.5}$



Cohan et al., *Env. Management*, 2007

(Meng et al., *Science*, 1997; Lamarque et al.,*GRL*, 2005; Unger, *PNAS*, 2006)

Five Cities in the Continental US

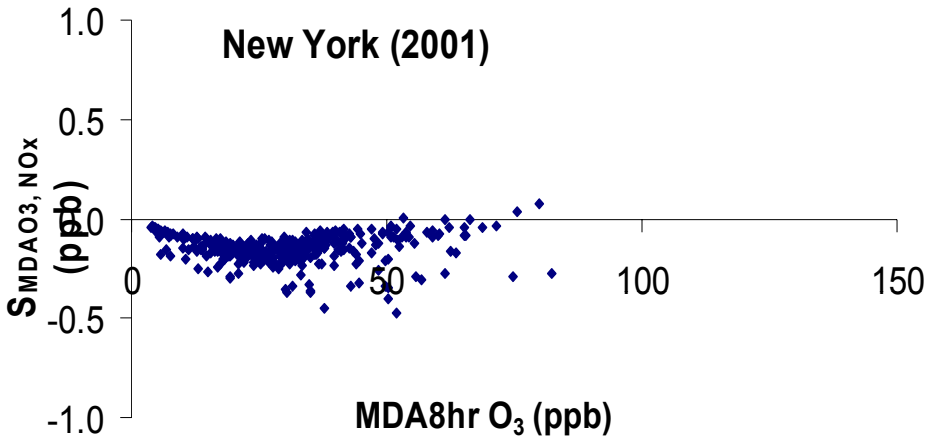
Five cities - Nonattainment areas for **MDA8hr O_3** and **24-hr $PM_{2.5}$** levels

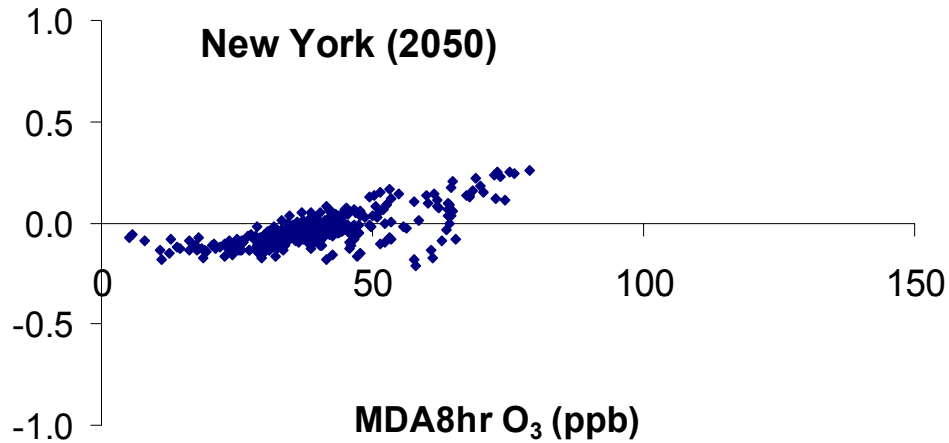
MDA8hr O_3 – city center and regional maximum

$PM_{2.5}$ – city center

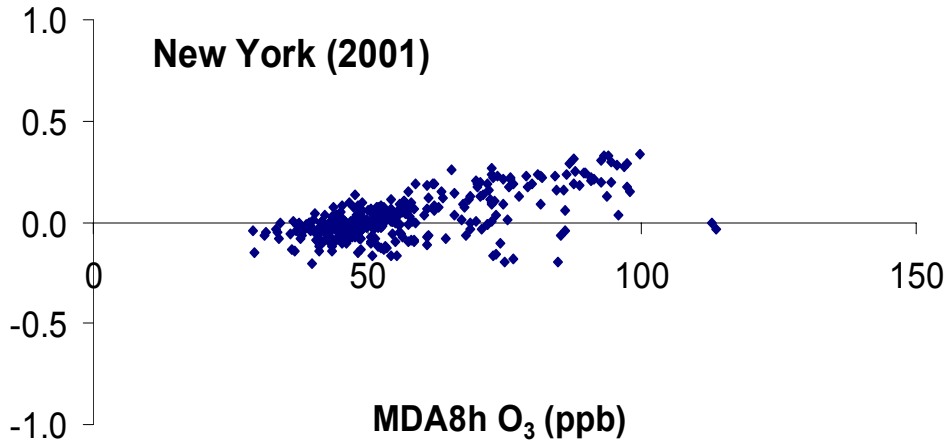
Daily Max. 8-hr Ozone Concentration and Sensitivity – New York City

City center





Regional max.



Sensitivities of MDA8h O_3 to anthropogenic NO_x (Y-axis)

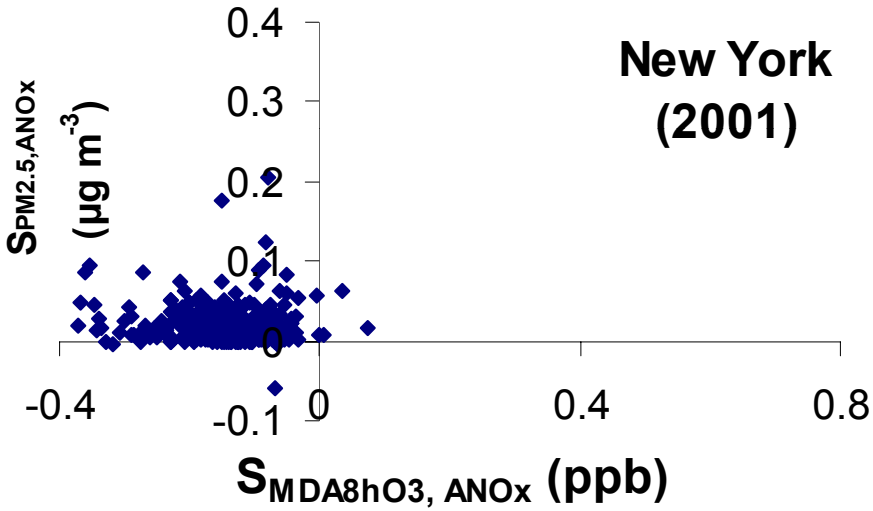
versus

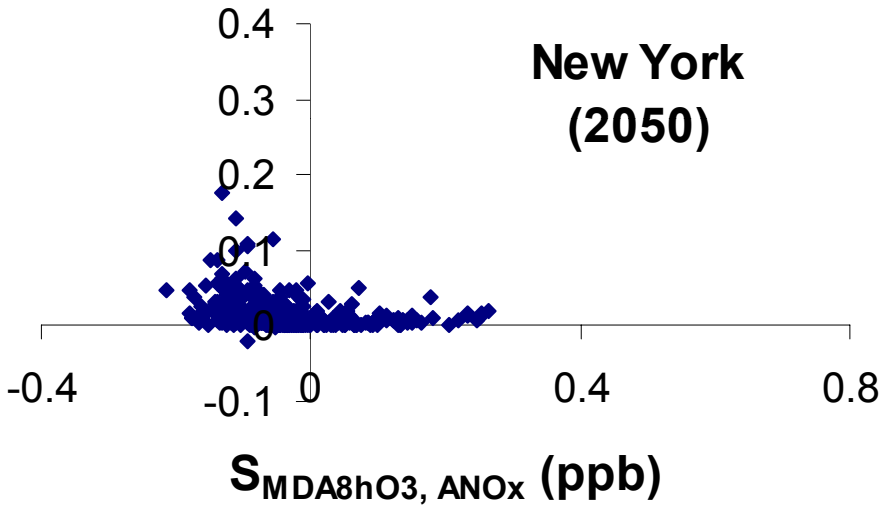
MDA8h O_3 concentrations (X-axis)

Sensitivities of Daily Max. 8-hr O_3 and 24-hr $PM_{2.5}$ to Anthropogenic NO_x Emissions – New York City

City center

(1% changes in emissions)





Y-axis: Sensitivities of 24-hr $PM_{2.5}$ to anthropogenic NO*x* emissions

X-axis: Sensitivity of daily max. 8-hr ozone to anthropogenic NOx emissions

Liao, et al., 2008

Number of Days with Positive and Negative Ozone Sensitivities to NOx

	2001 (+ / -)	2050 (+ / -)
Atlanta	144 / 215	276 / 83
Chicago	31 / 328	131 / 218
Houston	117 / 242	294 / 65
Los Angeles	87 / 272	285 / 74
New York	3 / 356	79 / 280

Note: The first seven days of each year are excluded to minimize the impacts of initial concentrations, leaving 359 days for analysis

Liao et. al, 2008

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 (“climate change penalty”), PM mixed
- “Statistics of Extremes” are quite different than “Statistics of Averages”
- The impact of precursor emission changes from planned controls on ozone and $PM_{2.5}$ levels is higher than due to climate-induced effects
  - Carefully forecasting emissions is critical to relevancy of results
- 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, and a bit due to climate change
  - Sensitivities of $PM_{2.5}$ to precursors similar on per ton basis
    - Lower NOx and higher NH_3 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
- Contributions of biogenic VOC emissions to PM formation more important in the future (higher temp, higher biogenic emissions, lower SOx and NOx emissions)
- 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 suggests that control choices are robust