



Impact of Potential Future Climate Change on Regional Ozone and Fine Particulate Matter Levels in the USA

**(A Joint Research Project of
Georgia Tech, NESCAUM, and MIT)**

Chair's Air Pollution Seminar
California Air Resources Board
Sacramento, CA, January 10, 2007

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Acknowledgements

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Northeast States for Coordinated Air Use Management
(NESCAUM)

C. Wang

Massachusetts Institute of Technology

and L.-Y. Leung

Pacific Northwest National Laboratory (PNNL)

Who we are

- NESCAUM (Northeast States for Coordinated Air Use Management)
- The Clean Air Association of the Northeast States
- A nonprofit organization founded in 1967 to assist the New England states in developing air pollution policy, technical, and management programs.

Who we are (cont.)

- **Our Members include:**
 - **ME, NH, VT, MA, RI, CT, NY and NJ**



The Clean Air Association of the Northeast States

101 Merrimac Street, 10th Floor Boston, MA 02114
Phone 617-259-2000 Fax 617-742-9162
Arthur N. Marin, Executive Director

NESCAUM Mission

- **The five elements:**

- Provide technical assistance to the member States
- Provide policy guidance and strategic advice to the States
- Represent States in various national forums
- Identify and explore emerging issues and programs that will be important to the States in the coming years
- Provide a forum for the States to work together to resolve regional problems

An Example of NESCAUM's Role: Climate Change Programs with Regional and National Scope

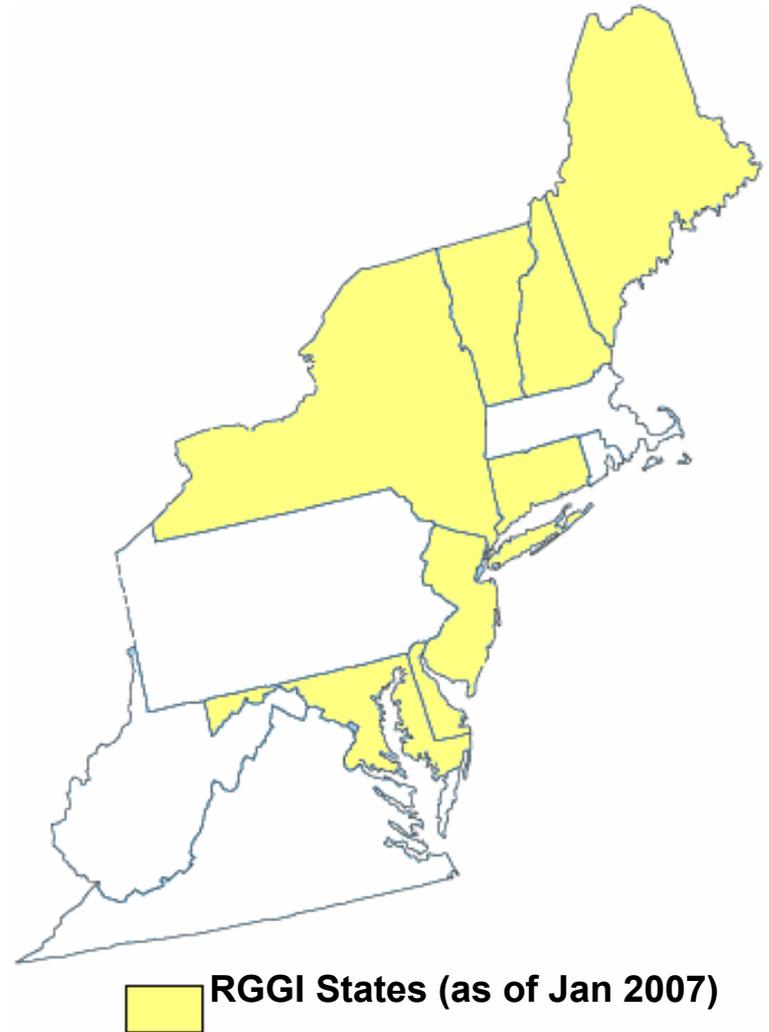
Multi-State Climate Registry

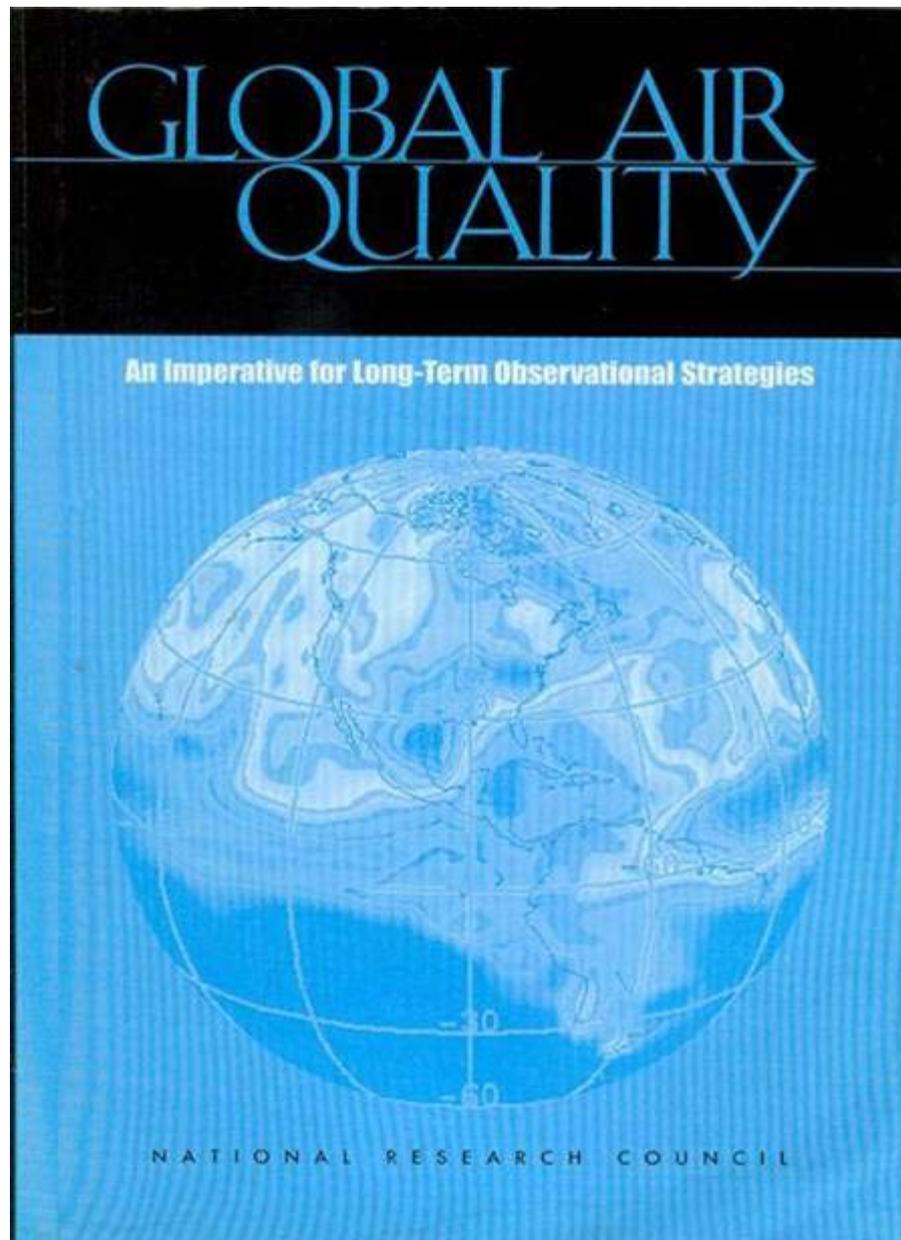
- NESCAUM is helping to coordinate efforts to develop high-quality GHG emissions data and information systems:
 - **Mission:** Provide companies and organizations with opportunity to document early action, demonstrate environmental leadership, and identify GHG risks and opportunities
 - **Benefits:** Program will support multiple state/regional climate policy goals (mandatory and voluntary), leverage state resources, facilitate linkages between programs, and promote transparency and accountability
 - **Goals:** Registry will ensure consistency between reporting programs, help establish common currency, and establish high level of environmental integrity in emissions accounting and reporting
 - **Participating States:** More than 30 eastern, midwestern, and western states engaged in registry development process

Contact: Heather Kaplan, Climate Policy Analyst, hkaplan@nescaum.org

Regional GHG Initiative (RGGI)

- NESCAUM served as Resource Panelist to RGGI State Working Group
- Supported analysis on potential economic impacts of RGGI in the northeast (REMI)
- Supported states through the RGGI model rule public comment process
- Currently providing analytical and other support to individual states in implementing RGGI





Published 2001

== *Georgia Institute of Technology* ==



The 2001 NRC Report Notes:

- **Our ability to understand observed changes in global air quality and to accurately predict future changes will depend strongly on answering two important questions:**
 - **How can global air quality change affect, and in turn be affected by, global climate change?**
 - **How is global air quality affected by the international and intercontinental transport of air pollutants?**

“Scientific” Scales of Air Pollution

- **Air Pollution is a “Mixture” of Scales**
 - **Local** (CO, ozone, SO₂, PM, mercury);
 - **Regional** (ozone, PM, NO_x, mercury, acid deposition, regional haze)
 - **Global** (CFCs, CO₂, mercury, methane, “background” ozone)
- CO₂ is global, but has local and regional impacts

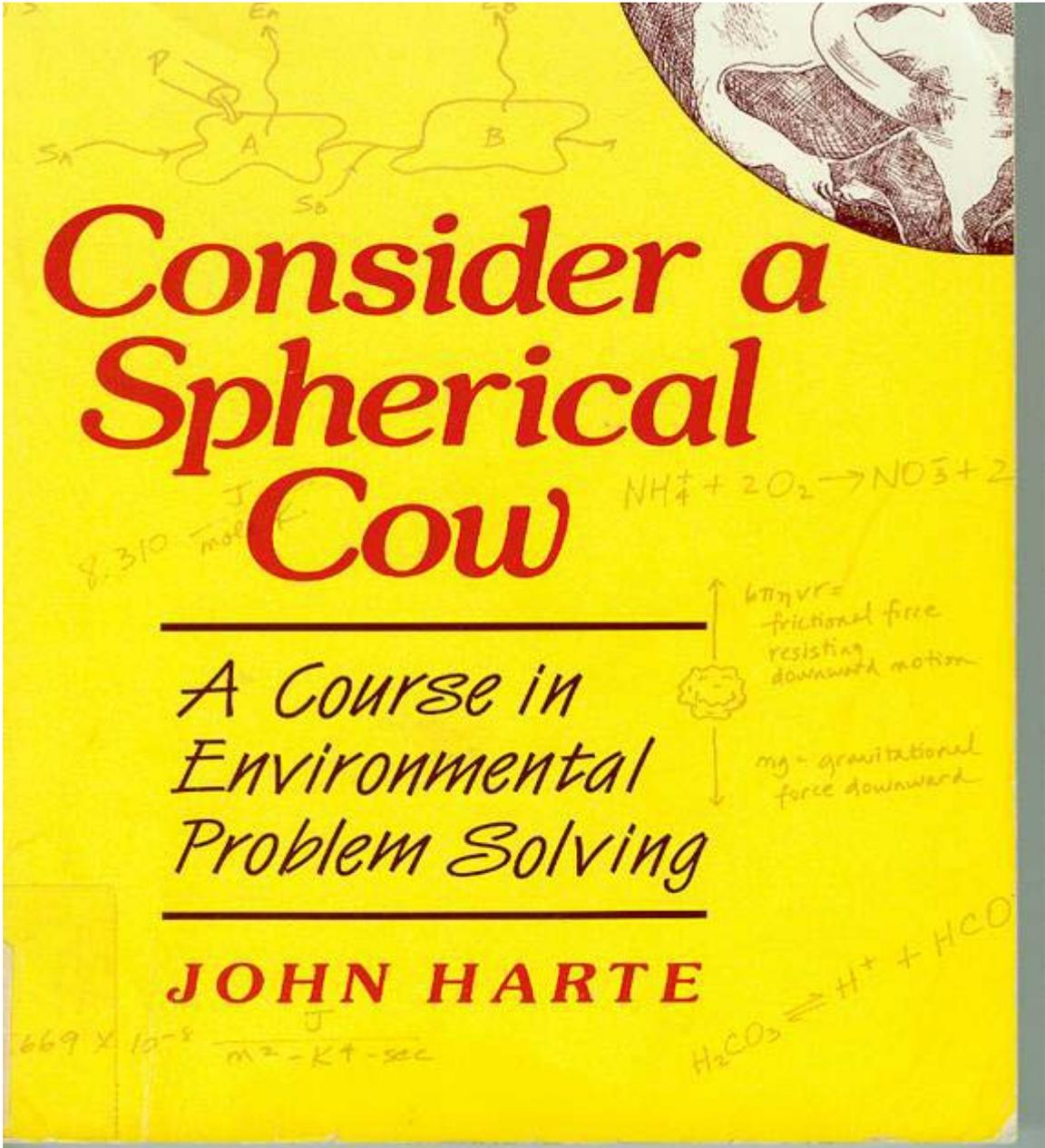
Recent Events

- **November 29, 2006: In the US Supreme Court (Oral Arguments): Massachusetts, et al., v. EPA, et al.**
- The key questions: Is CO₂ a pollutant under the Clean Air Act and does EPA have the authority to regulate it? Does the State of Massachusetts have “standing”?
- Justice Scalia: I thought that the standing requires imminent harm. If you have not been harmed already, you have to show the harm is imminent. Is this harm imminent?
- Mr. Milkey (attorney for Mass.): It is, Your Honor. We have shown that the sea levels are already occurring (“rising”) from the current amounts of greenhouse gases in the air, and that it means it is only going to get worse as the ---
- Justice Scalia: When? I mean when is the predicted cataclysm?
- Mr. Milkey: Your Honor, it is not so much a cataclysm as ongoing harm. The harm does not suddenly spring up in the Year 2100, it plays out continuously over time. And even to the extent you focus on harms that occur in the future, there is nothing conjectural about that. Once these gases are emitted into the air, and they stay a long time, the laws of physics take over.

Recent Events (Cont.)

- Later on, Mr. Milkey: Your Honor, first of all, I do think we have special standing. For example, here it is uncontested that greenhouse gases are going to make [the] **ozone** problem worse, which makes it harder for us to comply with our existing Clean Air Act responsibilities.
- A Point to Note: The word “Uncertainty” appears twenty three times in the oral arguments. As in: “the studies that are being developed to reduce the uncertainty,” in the area of global warming (Chief Justice Roberts); “there will always be scientific uncertainty,” (Mr. Milkey); “those are two very different levels of uncertainty,” (Chief Justice Roberts), referring to lead emissions from vehicles and impact of CO₂ on global warming; “..now is not the time [for EPA to] to exercise such authority, in light of the substantial scientific uncertainty surrounding global climate change and the ongoing studies designed to address those uncertainties,” (Mr. Garre, U.S. Department of Justice), and so on.

It is the mark of an instructed mind to rest satisfied with the degree of precision which the nature of the subject permits and not to seek an exactness where only an approximation of the truth is possible -- Aristotle



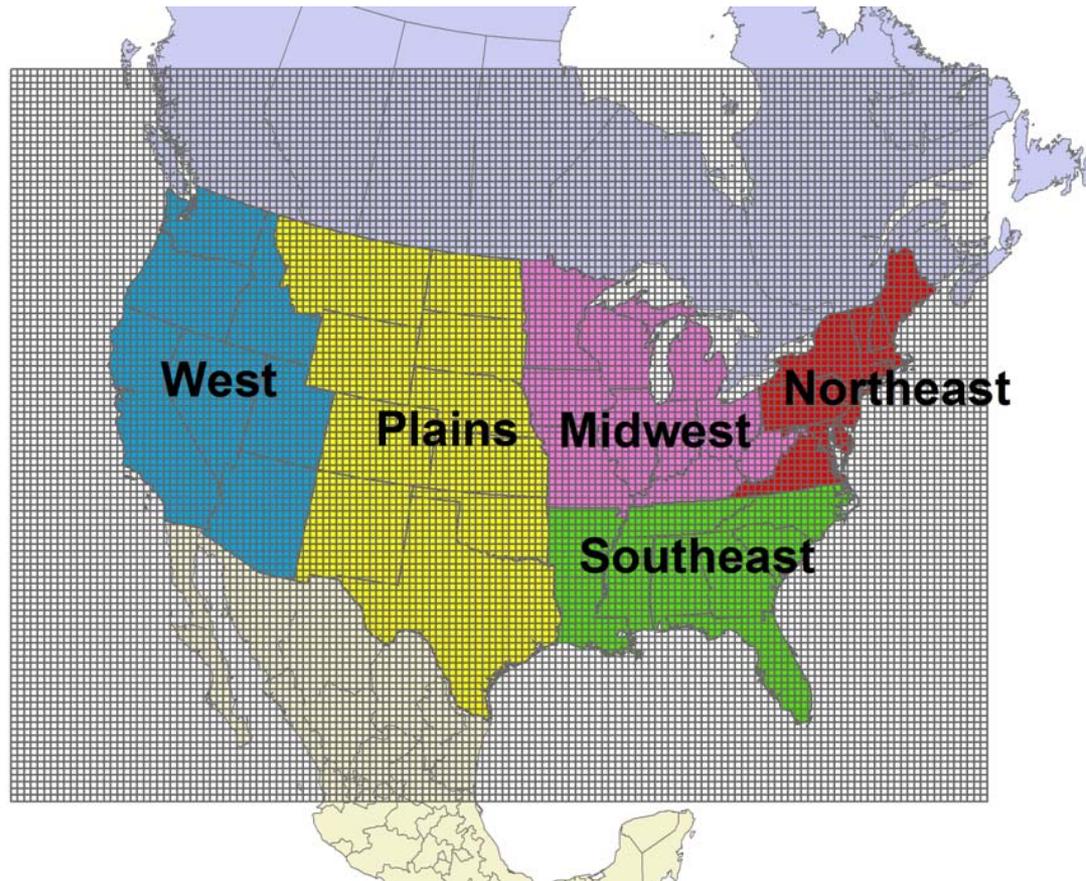
The background is a yellow sticky note with various handwritten annotations. At the top left, there are diagrams of a cow's head and neck with labels 'A', 'B', 'P', 'Ea', 'Sa', and 'So'. To the right is a circular inset showing a cow's face. In the center, the title 'Consider a Spherical Cow' is written in large red letters. Below the title, there is a chemical equation $NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H_2O$. To the left of the title, there is a calculation $8.310 \frac{J}{mol \cdot K}$. Below the title, there is a diagram of a cow's head with two arrows: one pointing up labeled $6\pi\eta vr$ and 'frictional force resisting downward motion', and one pointing down labeled mg and 'gravitational force downward'. At the bottom left, there is a calculation $669 \times 10^{-8} \frac{J}{m^2 \cdot K \cdot sec}$. At the bottom right, there is a chemical equation $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$.

Consider a Spherical Cow

*A Course in
Environmental
Problem Solving*

JOHN HARTE

Regional future O₃ and PM_{2.5} levels & components over US

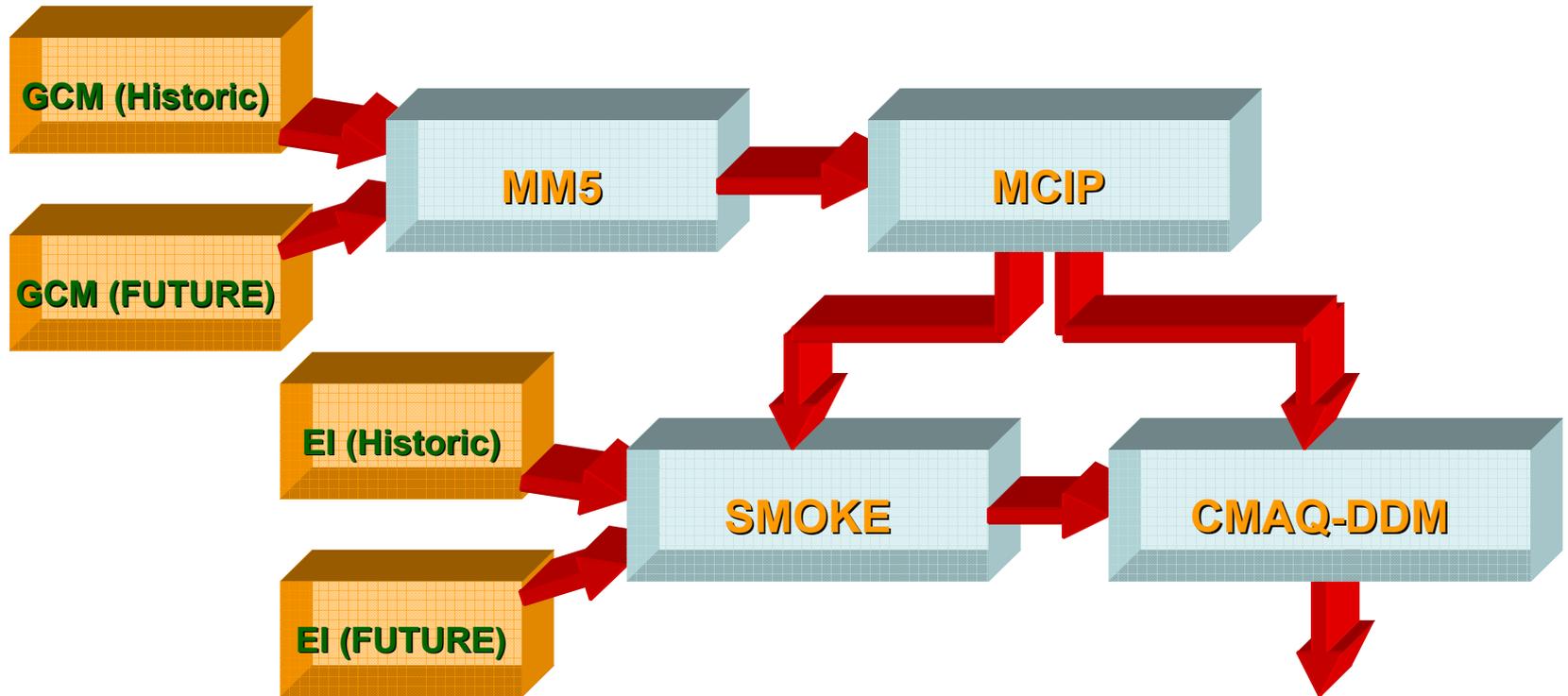


grids: 147 x 111
resolution: 36 x 36 km

Historic period: summer 2000, 2001 (full year), summer 2002

Future climate: summer 2049, 2050 (full year), summer 2051

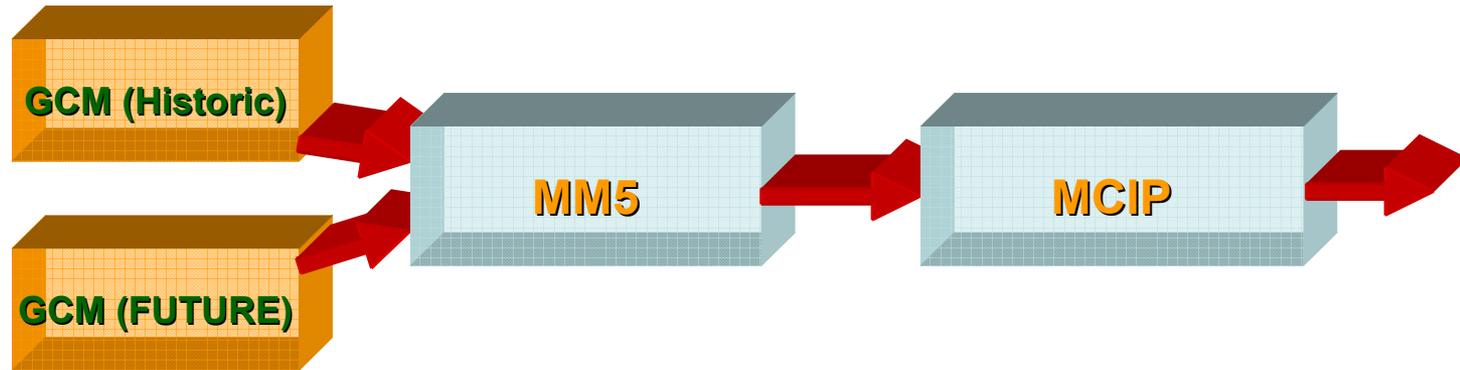
Modeling approach



GCM: Global Climate Model

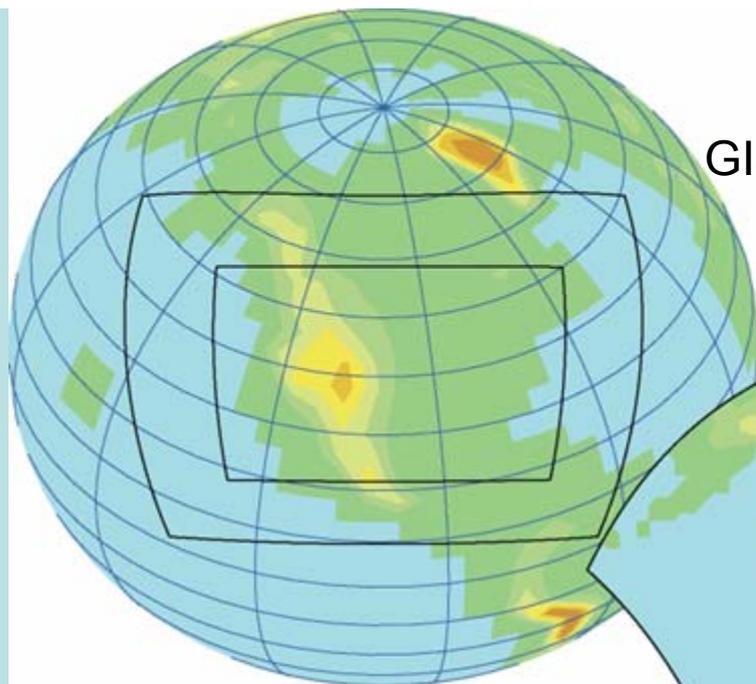
EI: Emission Inventory

Meteorology

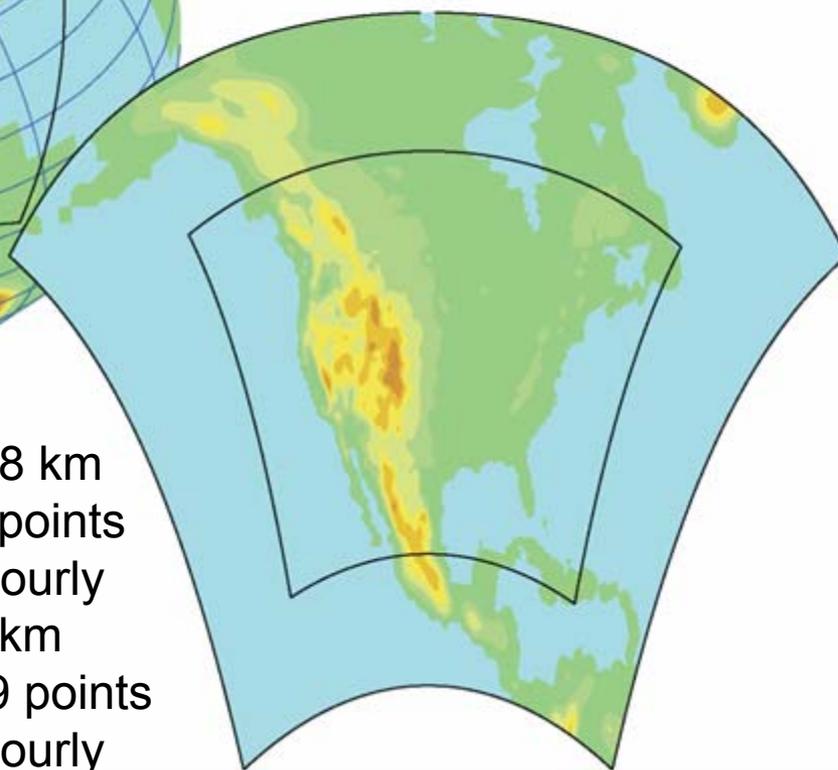


Downscaling meteorology (GISS-GCM) using MM5

Global and Regional Climate Models*



GISS GCM: grid spacing = $4^\circ \times 5^\circ$
9 levels
output every 6 hours



MM5 Domain 1: $dx = 108 \text{ km}$
67x109 points
output hourly

MM5 Domain 2: $dx = 36 \text{ km}$
115x169 points
output hourly

Numerical Experiments

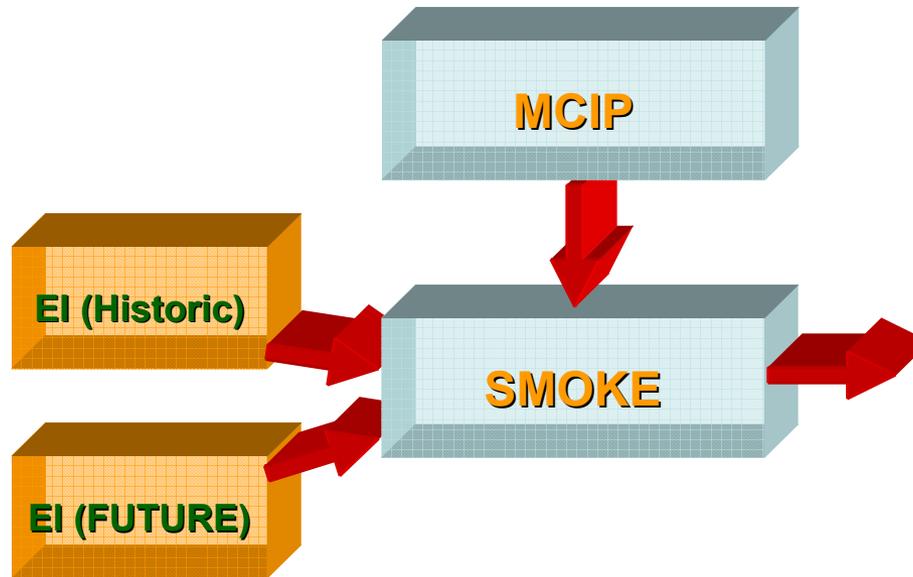
- **Global climate simulations**

- GISS includes CO and BC tracers and a “qflux ocean” boundary condition
- A transient simulation was performed for 1950 - 2052
- The A1B SRES scenario for greenhouse gases was assumed for the future (2000 – 2052) and observed greenhouse gas concentrations were used for 1950-2000

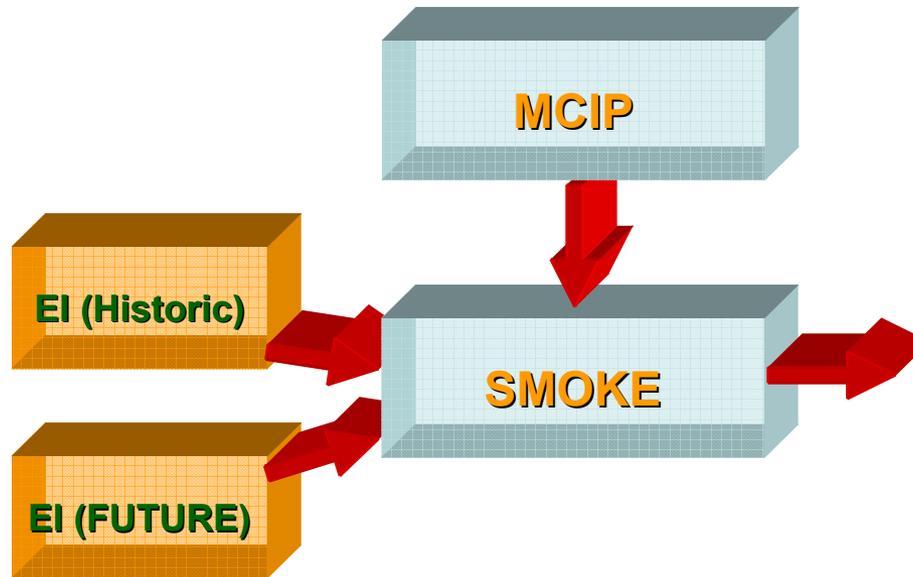
- **Regional climate simulations**

- One simulation driven by NCEP/NCAR reanalysis for 1990-2000 for model evaluation
- The base case driven by GISS: 1995-2005 (includes 2000-02)
- A future case driven by GISS: 2045-2055 (includes 2049-51)

Emissions



Emissions



Emissions inventories:

2001: U.S.: Clean Air Interstate Rule (CAIR) 2001
Canada: Environment Canada 2000
Mexico: U.S. EPA's 1999 BRAVO

2050: IPCC-A1B emissions scenario and CAIR 2020

Projection of Future Emissions

* **Develop 2050 Emission Inventory**

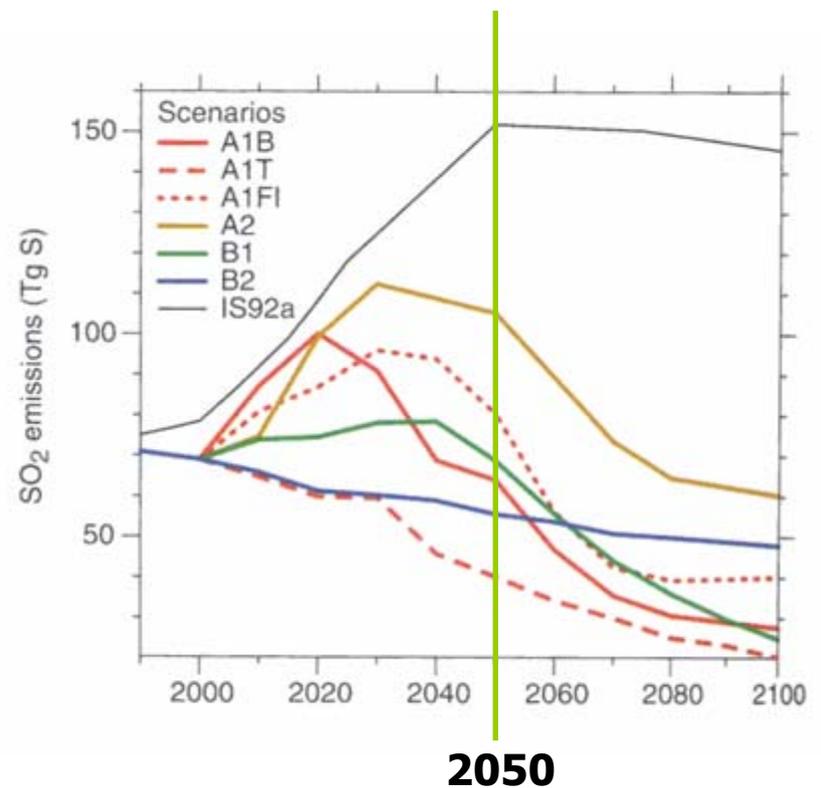
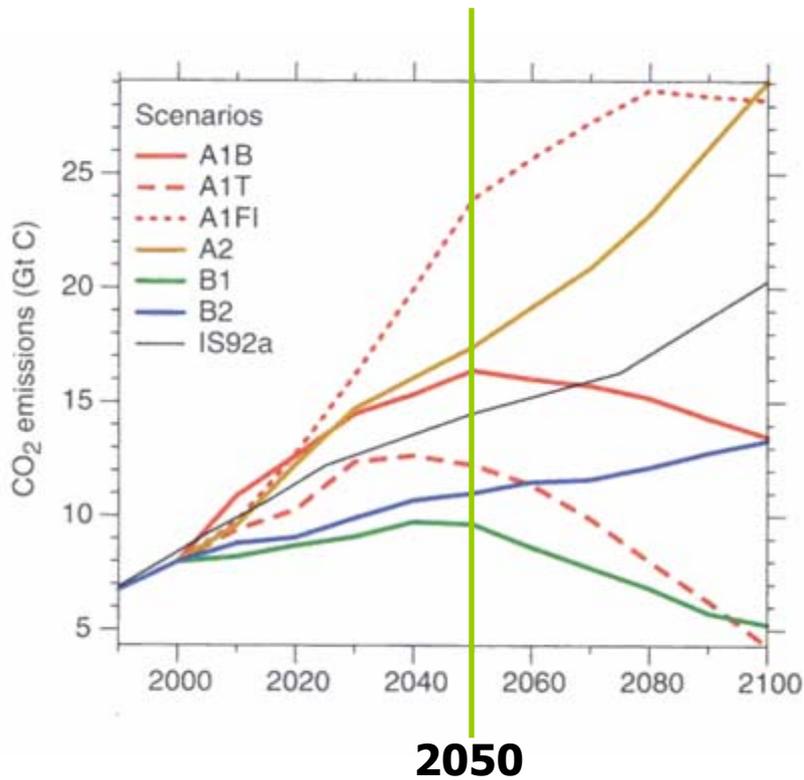
- Target year: Year 2050, Annual
- Format: SMOKE-ready
- Sector: Anthropogenic only
- Geographical domain: US/CAN/MX
- Projection approach:

Two-stage approach when national projections are available

* **In support of modeling**

- Did not create new future energy/emissions scenarios

IPCC SRES Scenarios (Global CO₂ & SO₂)



Basic Strategy

Future-year EI development

- Obtain the best available future EI data possible
- Fill-up gaps from near/certain future to distant/uncertain future

Example : Use EPA projection until 2020 and use IPCC scenario from 2020-2050

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	NO _x , VOCs, CO, NH ₃ , SO ₂ , PM	IPM /EGAS/NMIM	Yes
EPA CSI	1996	2010 /2020	Continental US	EPA BASE /CSI	EGUs, Non-EGUs	NO _x , VOCs, CO, NH ₃ , SO ₂ , PM	IPM /EGAS	Yes
RPOs	2002	2009 /2018	Continental US	OTB/OTW	EGUs & non-EGUs	NO _x , VOCs, CO, NH ₃ , SO ₂ , PM	IPM /EGAS	Partly
SAMI	1990	2040 (/10yrs)	38 States + DC	OTB/OTW/B WC/BB	EGUs & non-EGUs	NO _x , VOCs, CO, NH ₃ , SO ₂ , PM	SAMI	No
RIVM*	1995	~2100 (/yr)	World (17 regions)	IPCC SRES(A1, B1, A2, B2)	Energy sector/fuel combination	CO ₂ , CH ₄ , N ₂ O, CO, NO _x , SO ₂ , NMVOC	IMAGE	Yes
NESCAUM /EPA	1999	~2029+ (/3yrs)	Units(EGUs), States(NE), Country	BAU, RGGI	Energy sector/fuel combination	NO _x , VOCs, CO, NH ₃ , SO ₂ , PM	MARKAL	2007

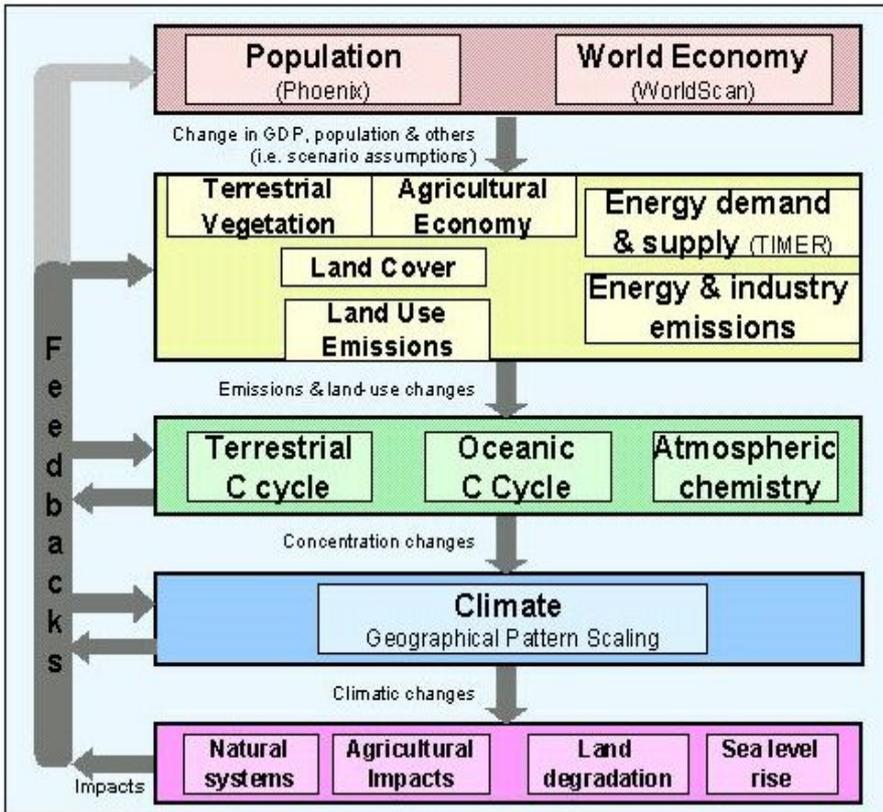
Pros
 Cons
 Both

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

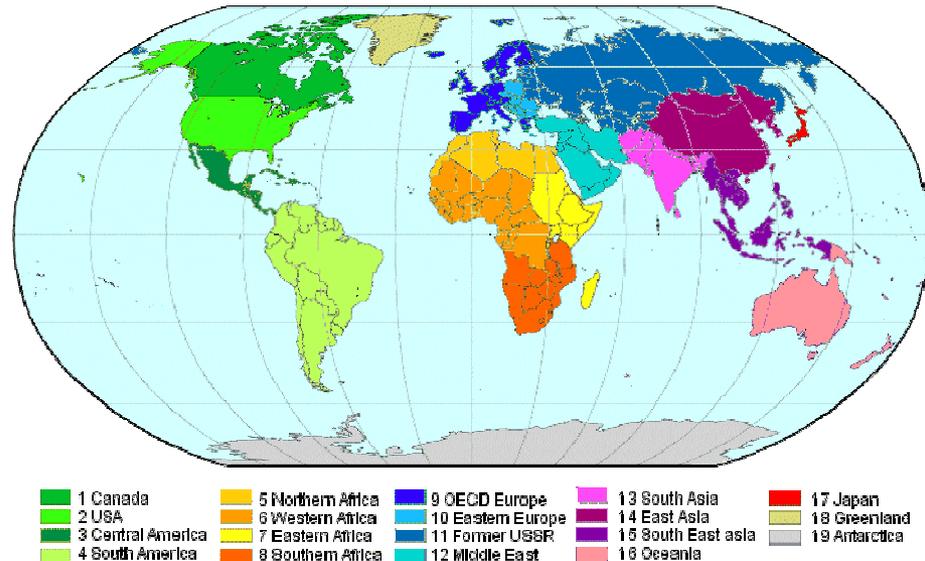
RIVM IMAGE

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*)

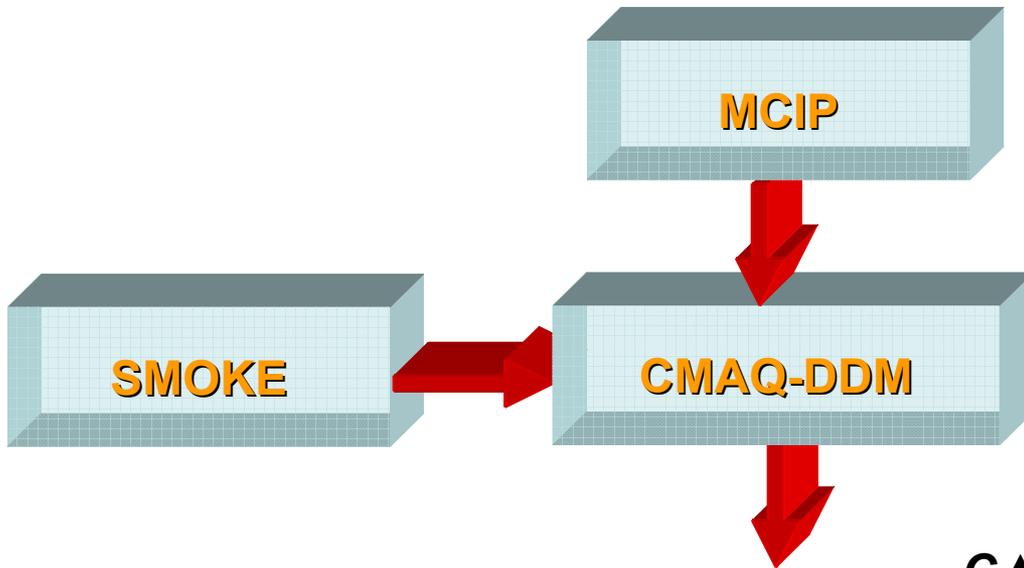


RIVM Environmental Research -1998 World Regions and Subregions



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

Air Quality

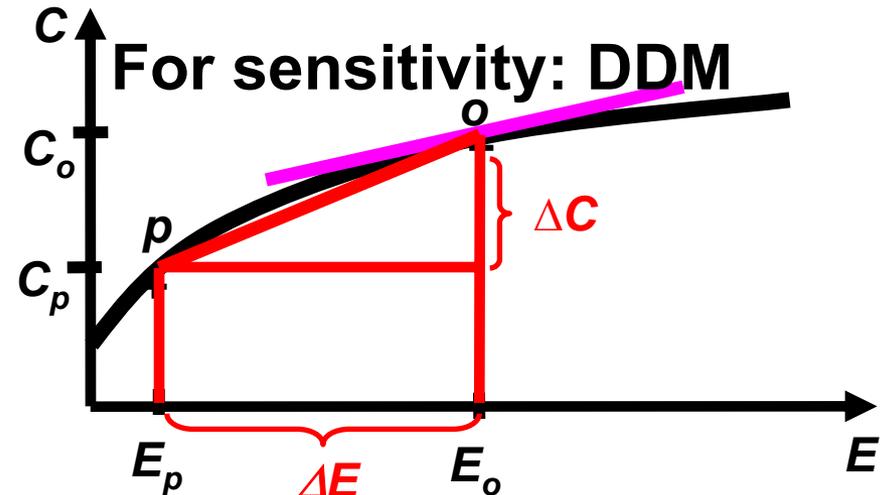


Brute Force (BF):

$$S = \Delta C / \Delta E$$

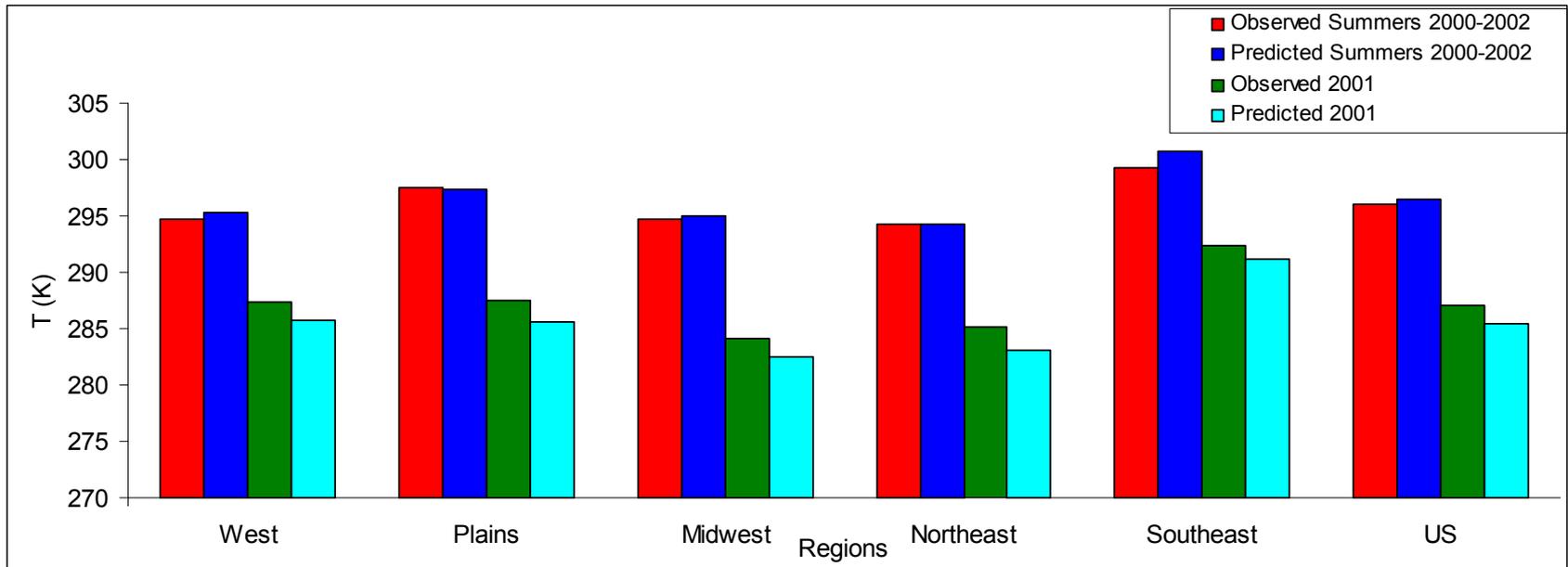
Decoupled Direct Method (DDM):

$$S = \partial C / \partial E$$



Baseline Evaluation

Temperature

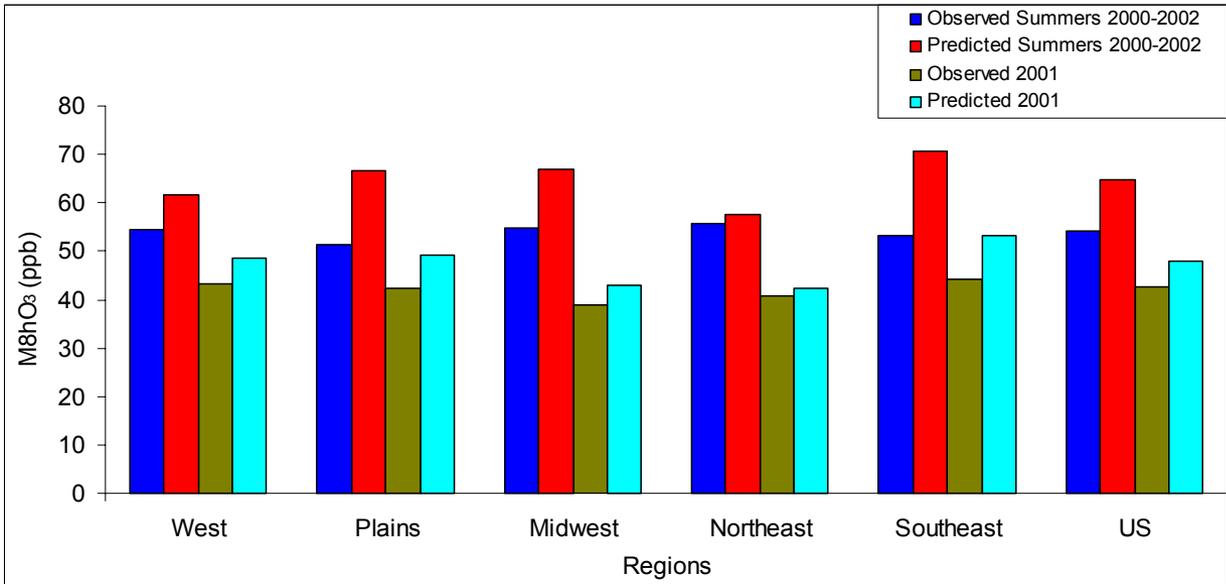


A general under prediction in temperatures

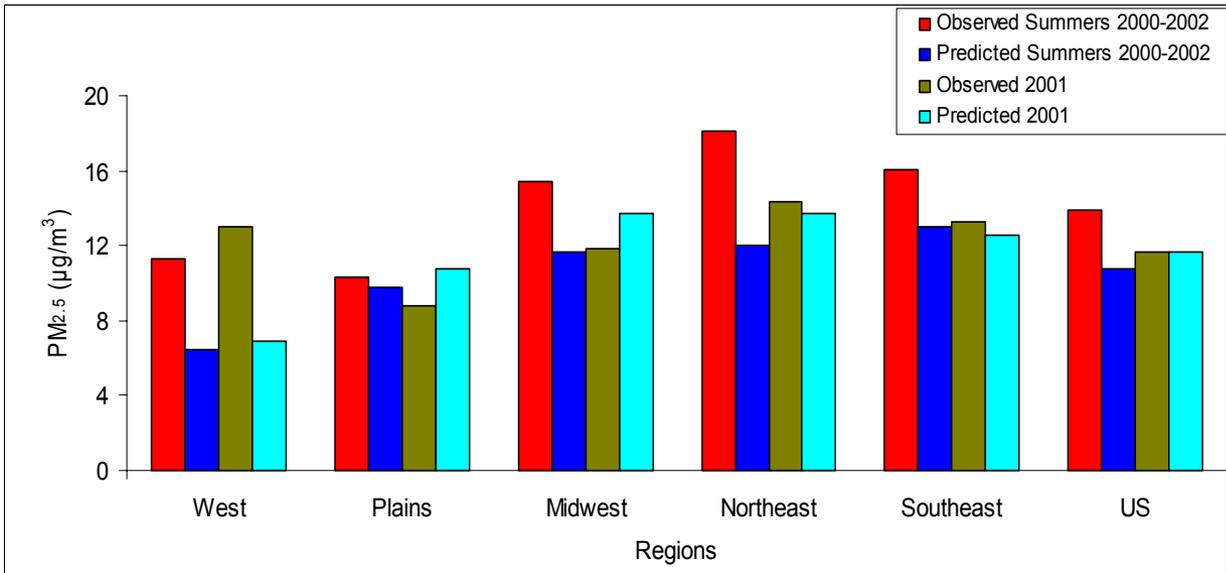
Better performance during summer months and worst during fall, caused by the high mesoscale variability during seasonal transition.

Baseline Evaluation

O₃



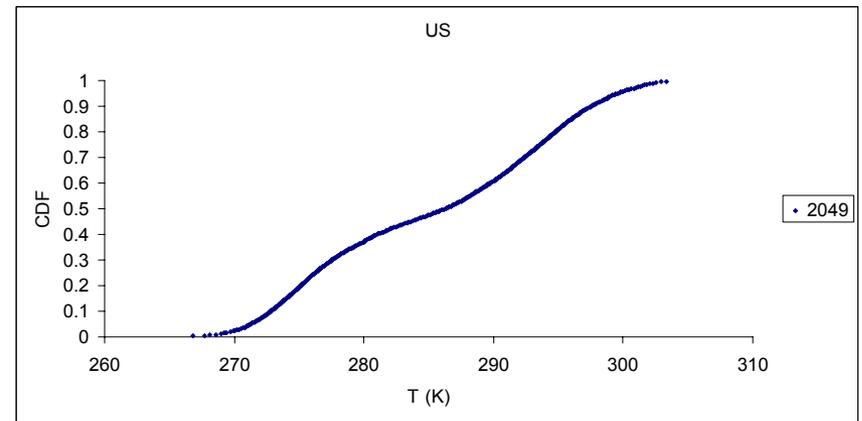
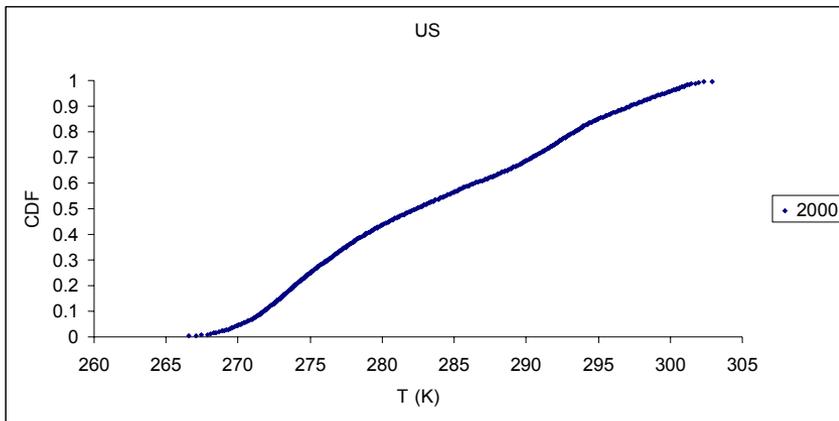
PM_{2.5}



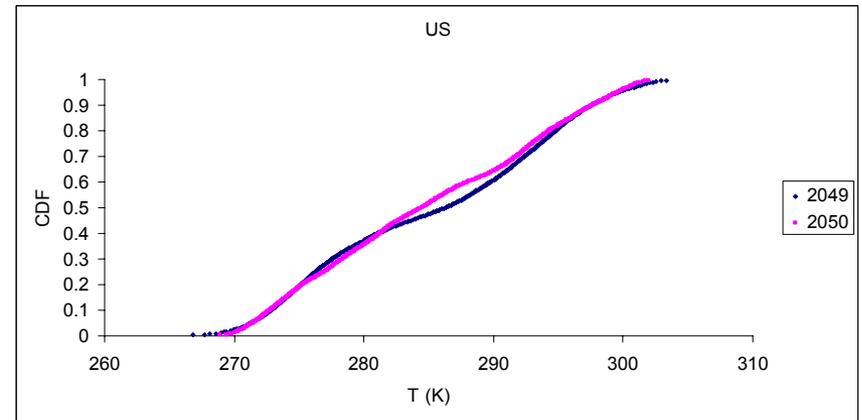
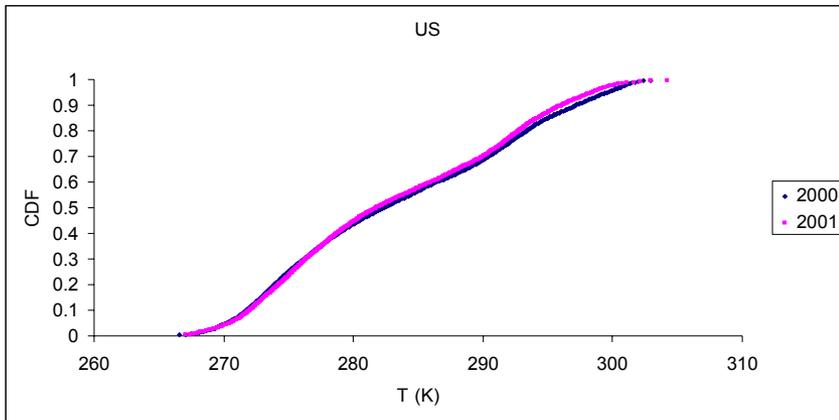
METEOROLOGY

Are historic and future years representative?

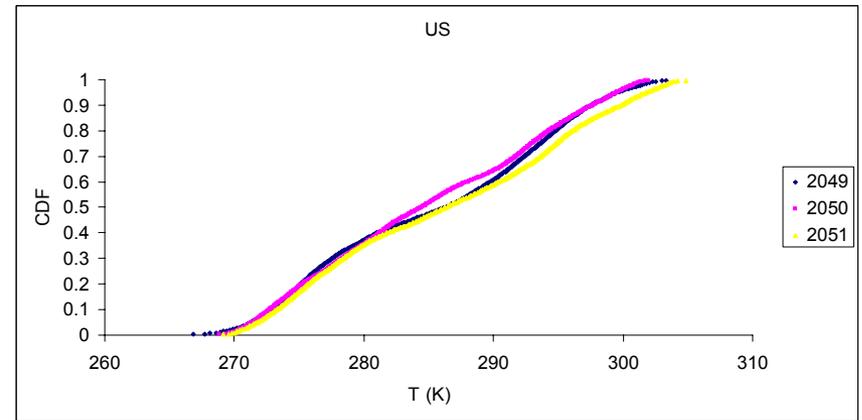
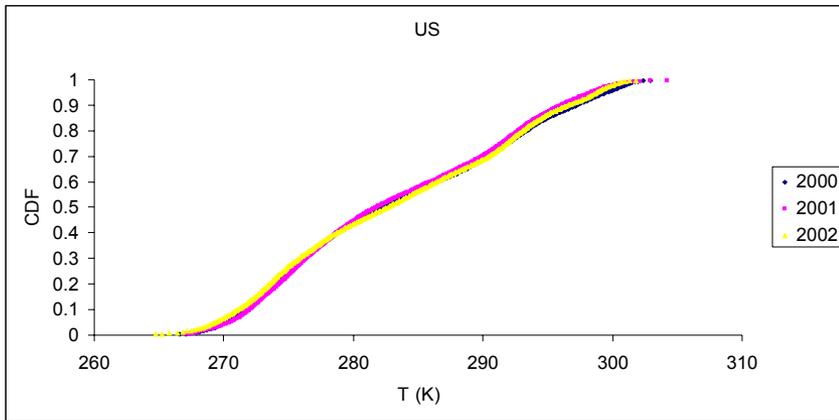
Surface Temperature Distribution



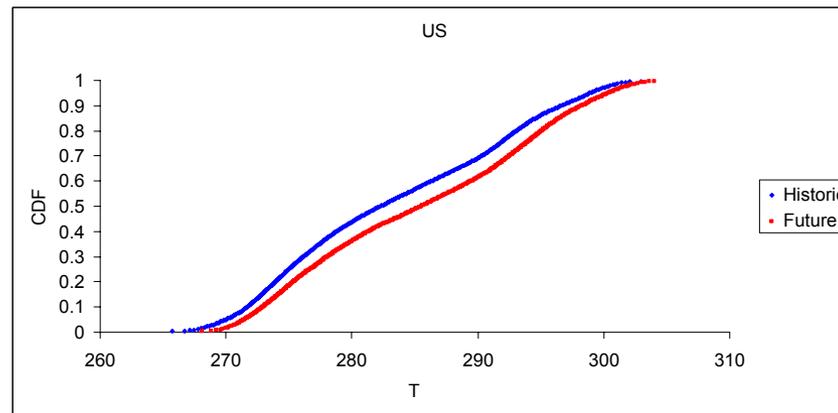
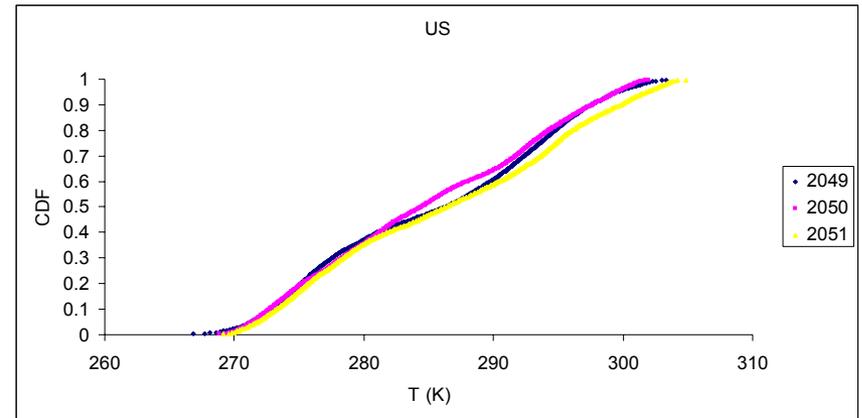
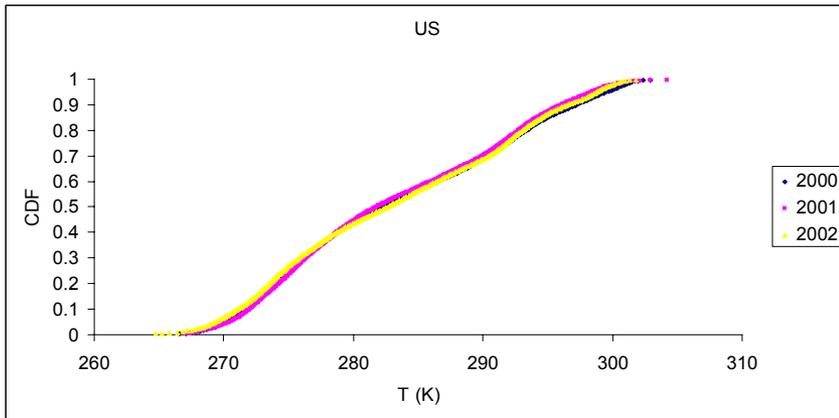
Surface Temperature Distribution



Surface Temperature Distribution



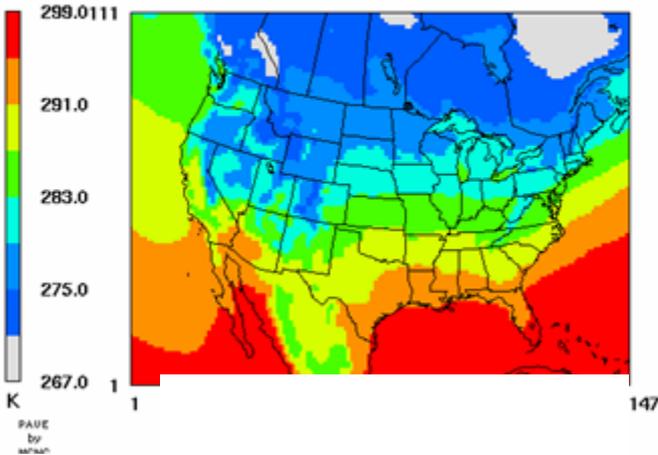
Combined Temperature Distribution



Temperature (Spatial Distribution)

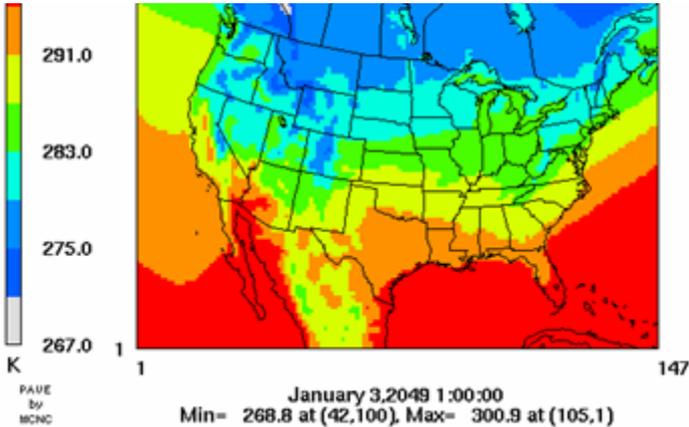
2000

d-out_conc_2000TAQV.ncf



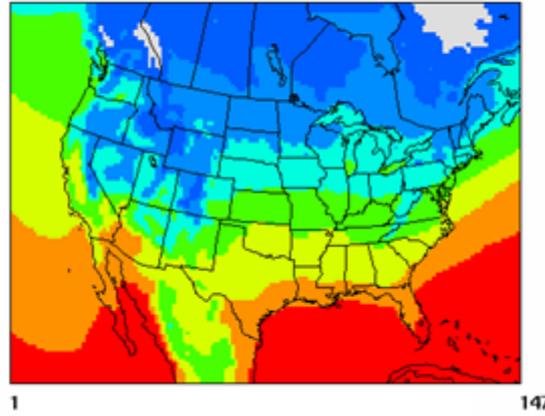
Layer 1 TAJ

2049



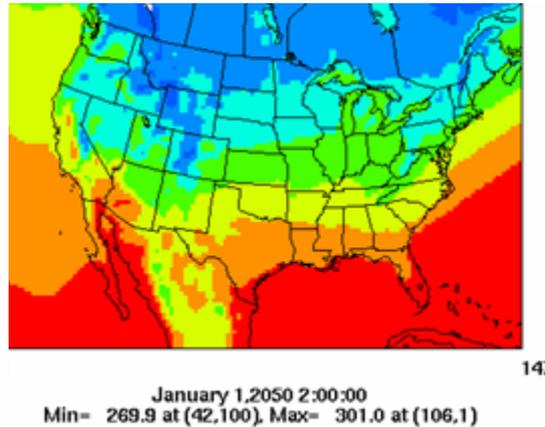
2001

e-out_conc_2001TAQV.ncf



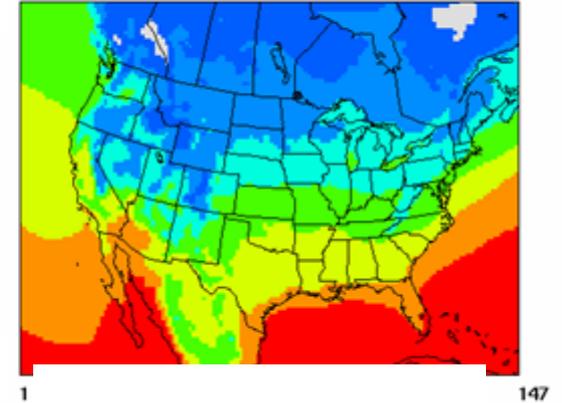
Layer 1 TAK

2050



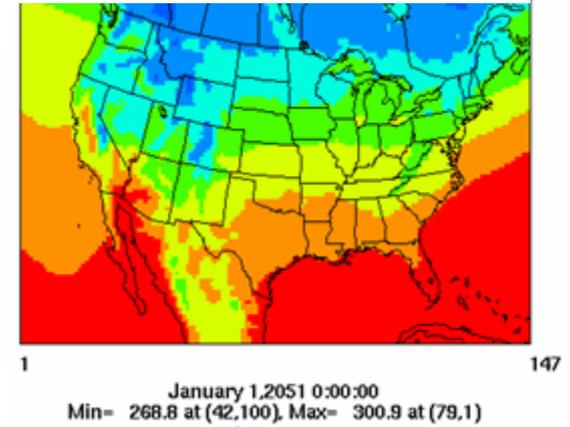
2002

f-out_conc_2002TAQV.ncf



Layer 1 TAI

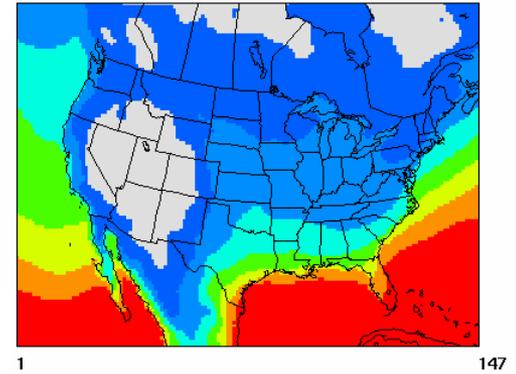
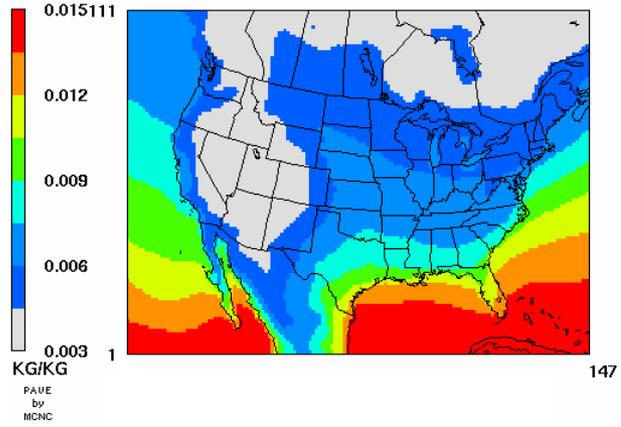
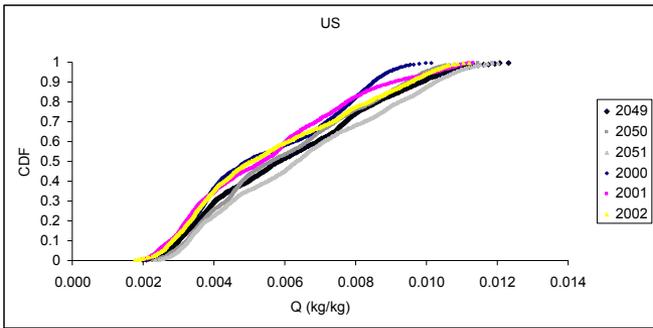
2051



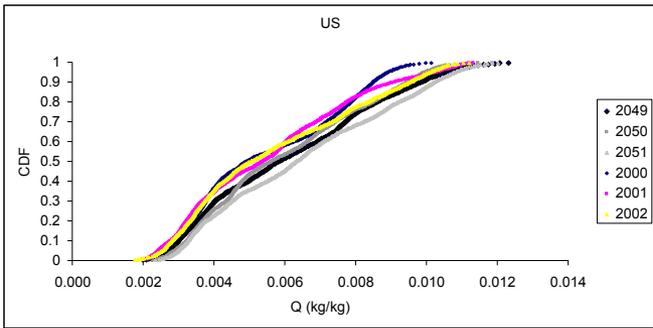
Humidity

2001

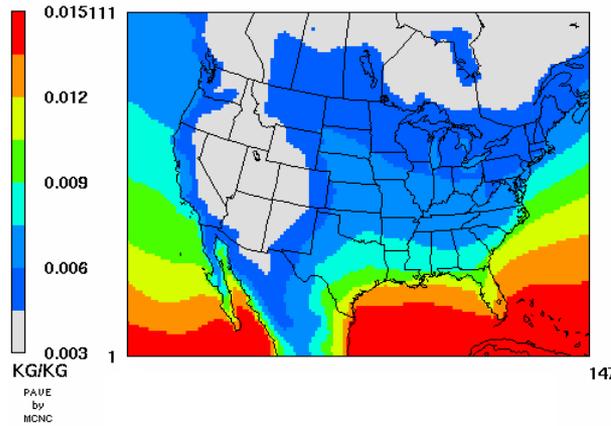
2050



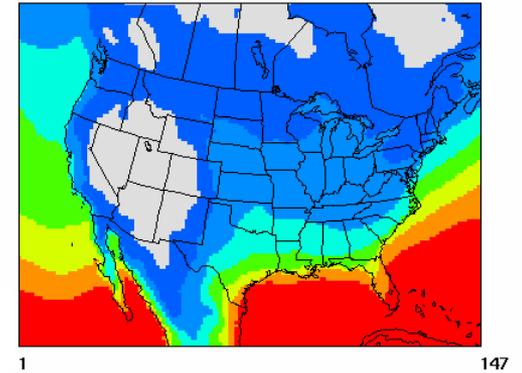
Humidity



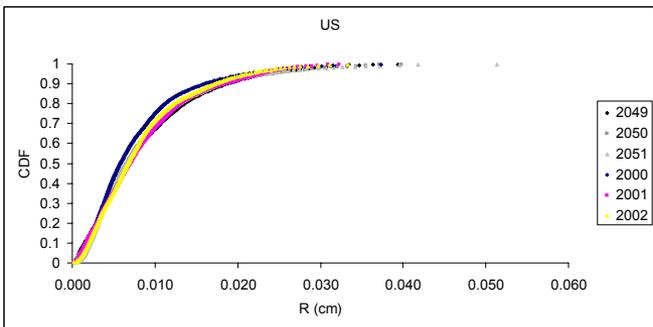
2001



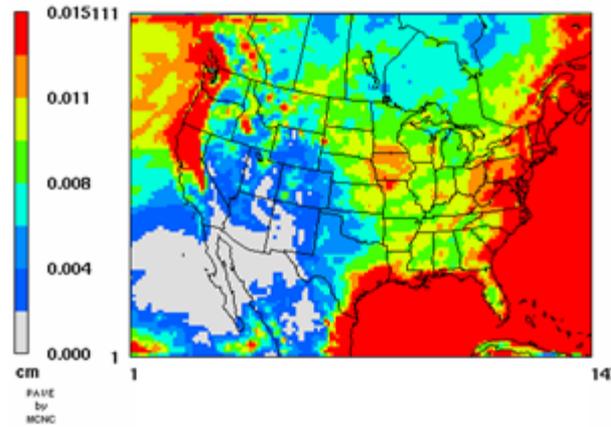
2050



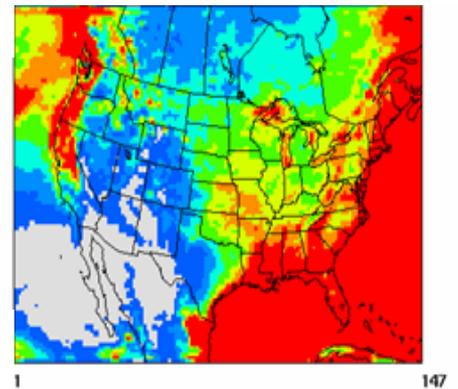
Rain



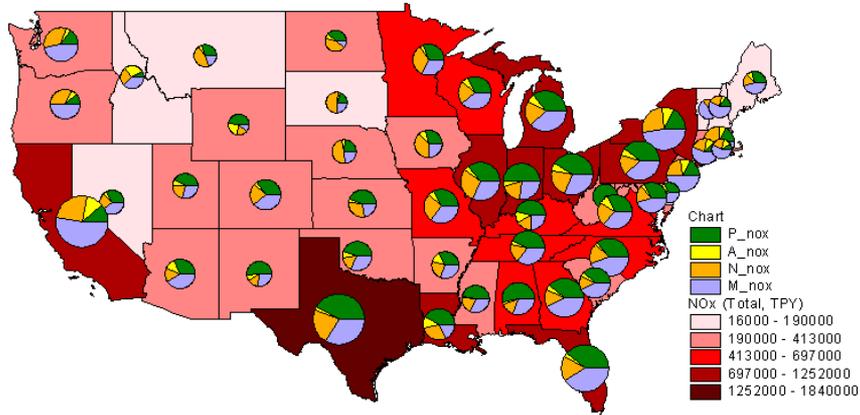
2001



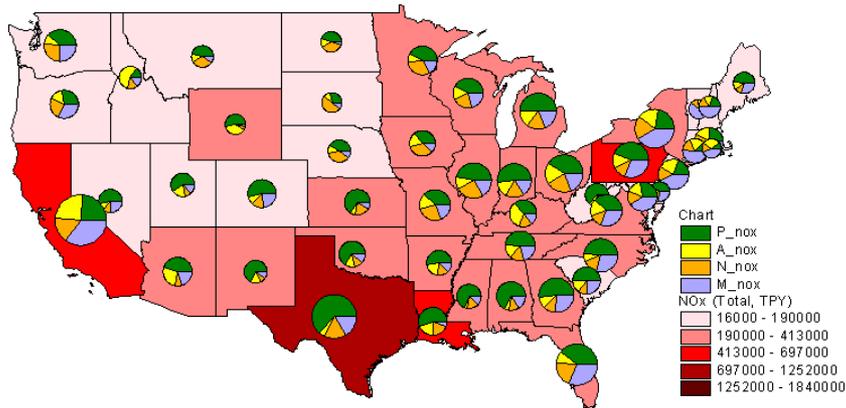
2050



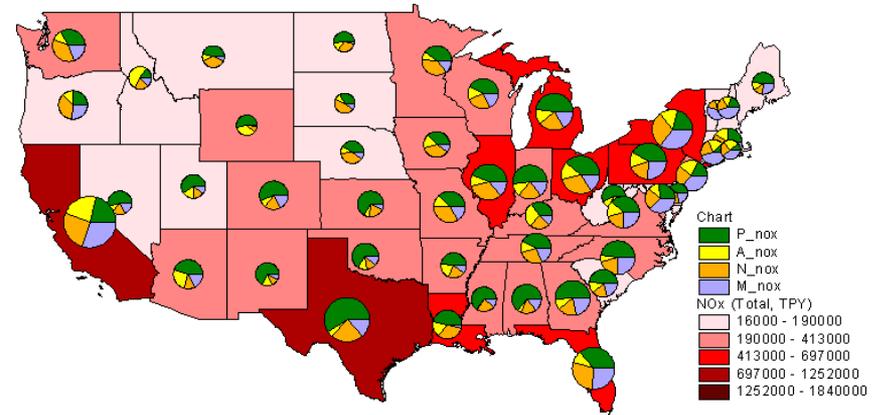
Regional Emissions: Projections



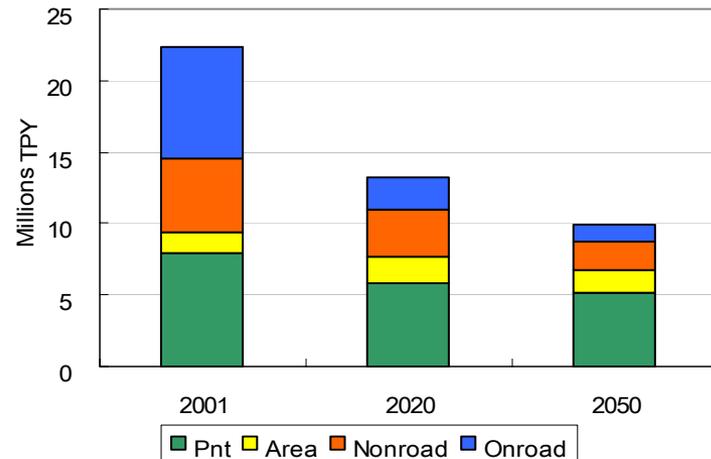
Year 2001



Year 2050

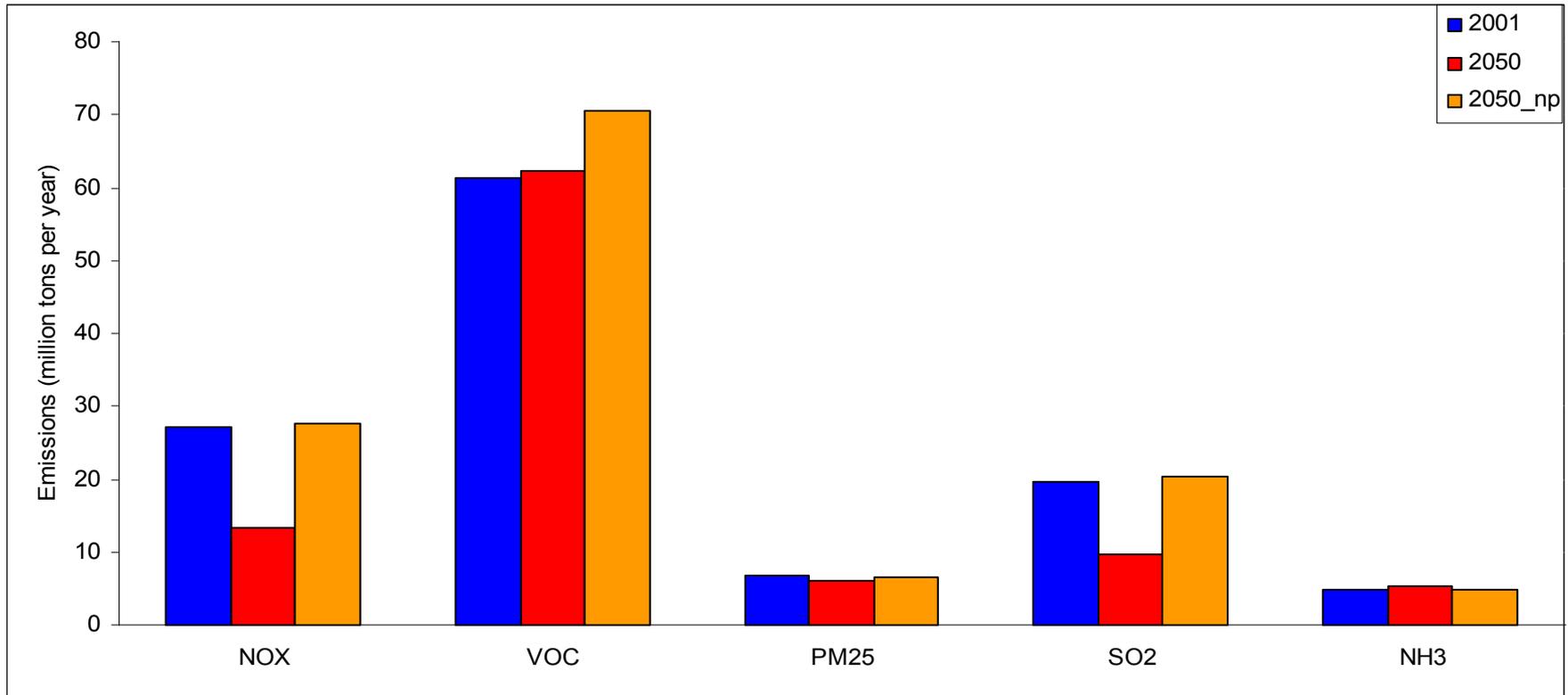


Year 2020



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

Emissions Projections



2050 – 2001:

NOx: -50%

VOC's: +2%

PM_{2.5}: -10%

SO₂: -50%

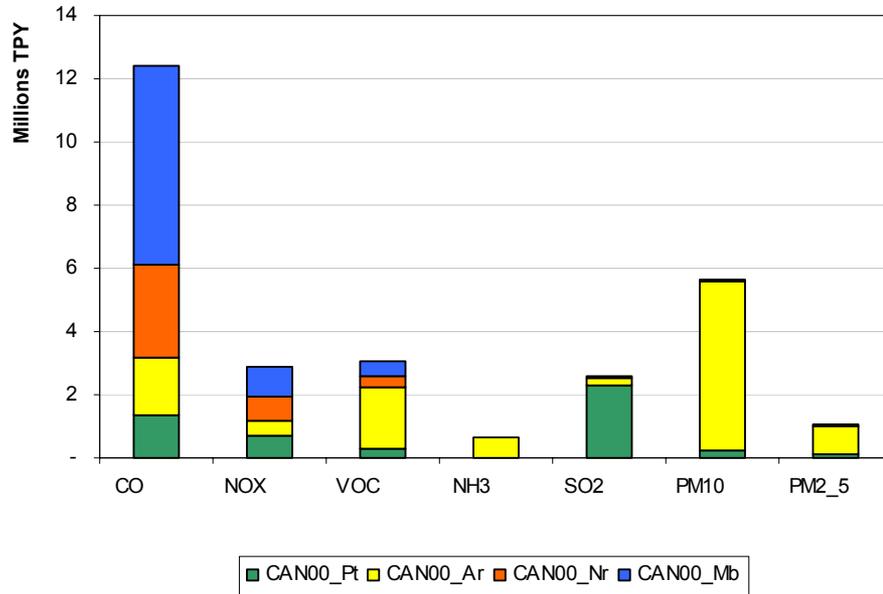
NH₃: +7%

2050np – 2001:

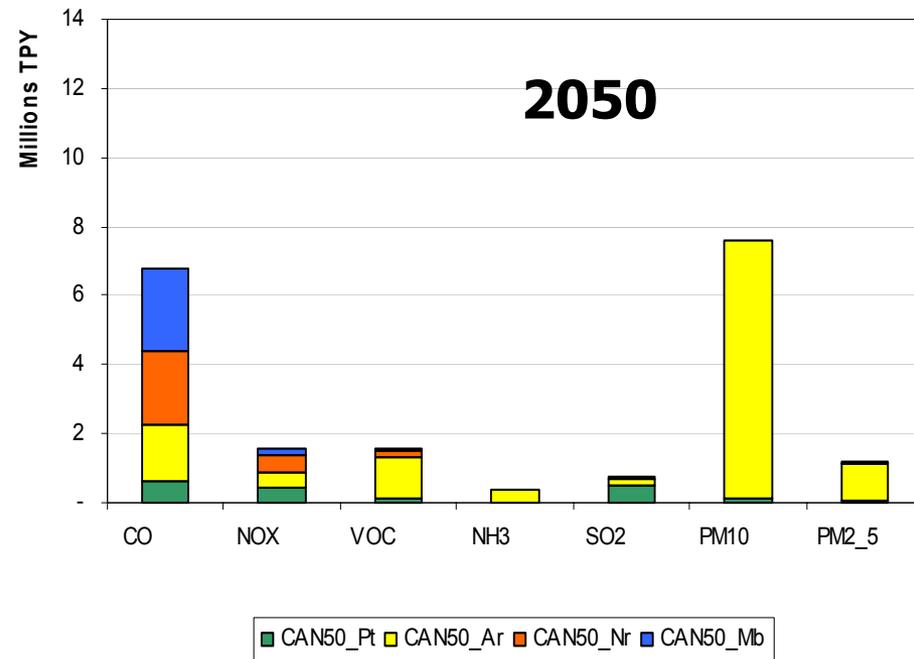
VOC's: +15%

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

Future Emissions (CANADA)

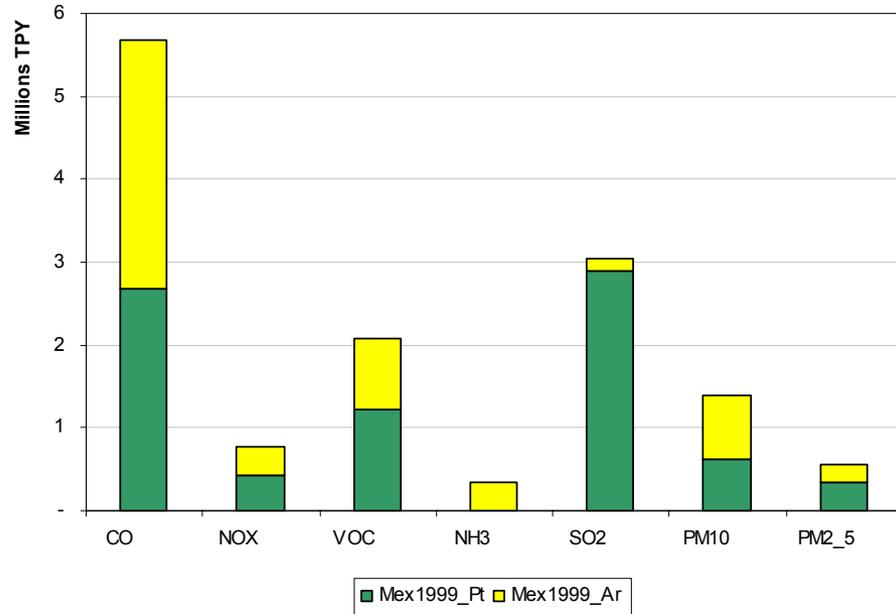


2000

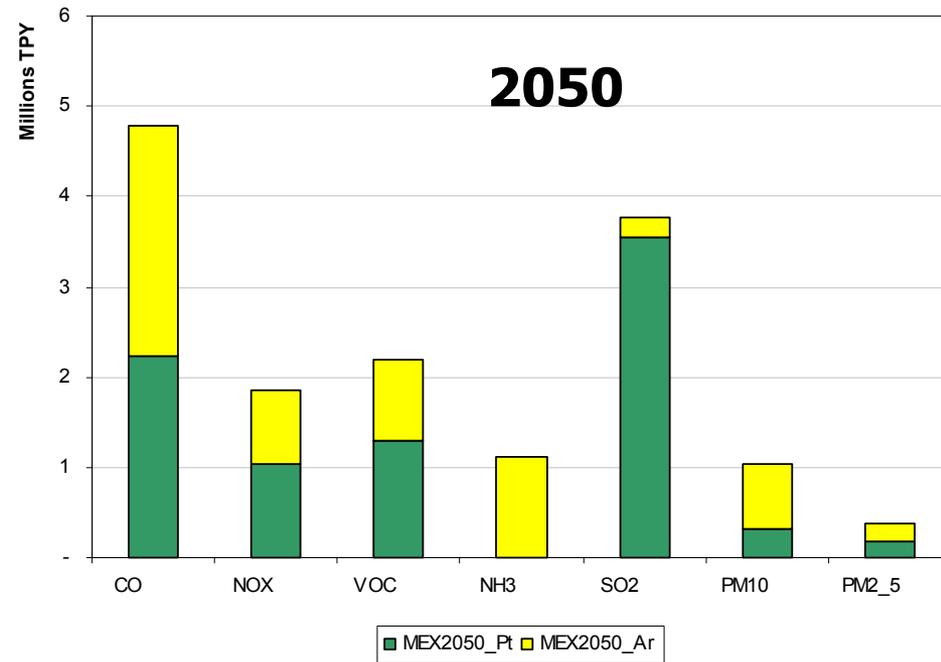


2050

Future Emissions (Mexico)



1999



Changes (in percent) in pollutants concentrations for future compared to historic values

	M8hO ₃ (%)		PM _{2.5} (%)		SO ₄ (%)		NO ₃ (%)		NH ₄ (%)		OC (%)	
	Summers	Summers _np	Summers	Summers _np	Summers	Summers _np	Summers	Summers _np	Summers	Summers _np	Summers	Summers _np
Summer												
West	-11.6	0.9	-15.7	-2.0	-32.2	-3.7	-72.8	-42.8	-33.0	-6.9	-6.7	0.7
Plains	-15.8	-0.1	-34.3	-12.1	-48.7	-16.4	-46.4	-15.2	-41.8	-14.1	-16.2	-7.7
Midwest	-24.4	-2.5	-37.1	-18.4	-52.6	-22.4	-68.5	-24.1	-45.7	-21.9	-19.1	-11.7
Northeast	-20.2	2.8	-41.2	-1.7	-56.7	-2.2	-79.3	-28.8	-44.5	-0.8	-25.2	-0.4
Southeast	-27.9	0.3	-45.2	-14.3	-60.5	-16.5	-77.1	-37.1	-47.9	-13.3	-27.5	-14.8
US	-18.9	0.0	-35.9	-9.9	-52.6	-13.9	-65.6	-22.6	-43.9	-12.2	-17.2	-5.5
Annual	2050	2050np	2050	2050np	2050	2050np	2050	2050np	2050	2050np	2050	2050np
West	-6.5	0.2	-9.2	2.9	-20.2	4.8	-41.4	-17.6	-24.9	-3.4	4.0	8.9
Plains	-7.9	1.4	-22.0	-0.8	-29.2	5.5	-45.3	-17.9	-31.7	-3.2	-3.4	4.7
Midwest	-10.5	-0.2	-22.7	4.2	-22.2	12.6	-48.5	-7.7	-28.7	4.2	-9.3	6.6
Northeast	-10.0	-0.5	-28.5	6.5	-37.4	10.3	-45.6	-4.3	-32.6	5.9	-13.0	10.7
Southeast	-14.8	2.3	-31.4	-2.4	-41.5	0.5	-54.9	-12.4	-37.0	-1.7	-14.9	-3.6
US	-9.2	0.9	-23.4	1.1	-30.8	6.2	-47.8	-12.4	-31.6	-0.2	-6.4	4.4

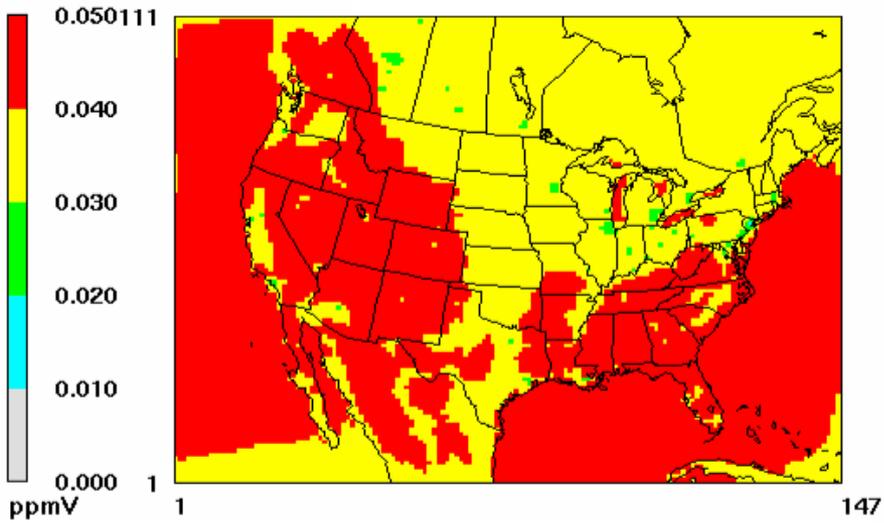
np: Emission Inventory 2001, Climate 2050

Regional and local (cities) predicted maximum eight-hour O₃ (M8hO₃) concentration characteristics

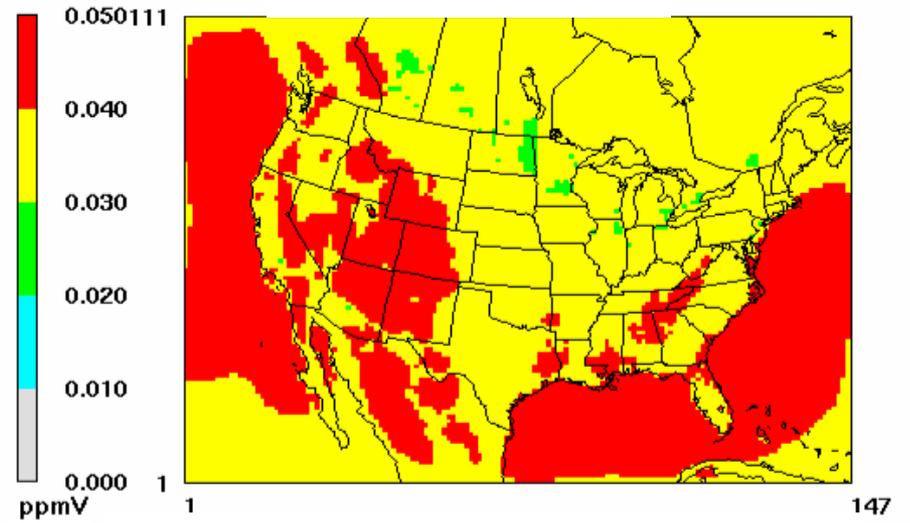
Region / City	M8hO ₃ (ppb)								
	summers 2000-2002			summers 2049-2051			summers 2049-2051_np		
	Region	City		Region	City		Region	City	
	99.5%	# of days over 80 ppb	Peak value	99.5%	# of days over 80 ppb	Peak value	99.5%	# of days over 80 ppb	Peak value
West / Los Angeles	65	149	119	55	31	97	67	221	146
Plains / Houston	72	127	127	59	29	94	73	165	143
Midwest / Chicago	89	78	138	73	19	106	101	59	152
NorthEast / New York	84	51	112	65	1	81	91	82	121
SouthEast / Atlanta	94	199	124	64	0	78	94	195	131

np: Emission Inventory 2001, Climate 2050

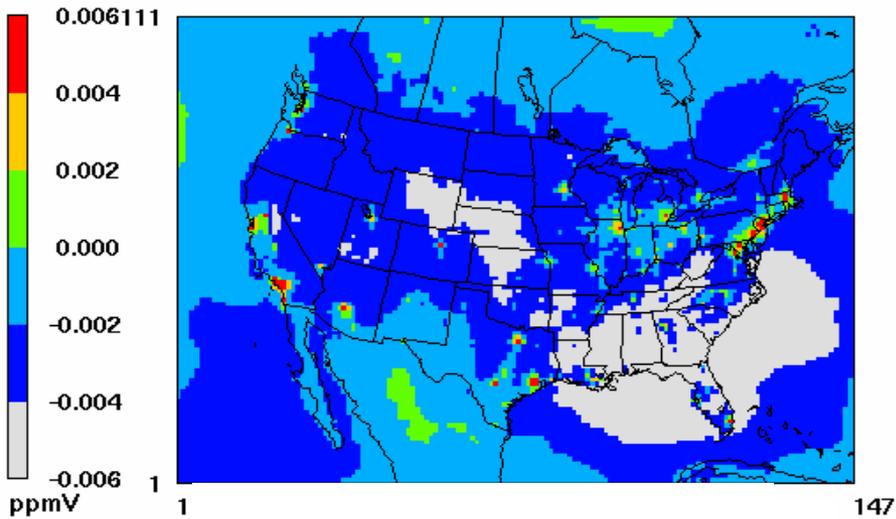
O₃_2001



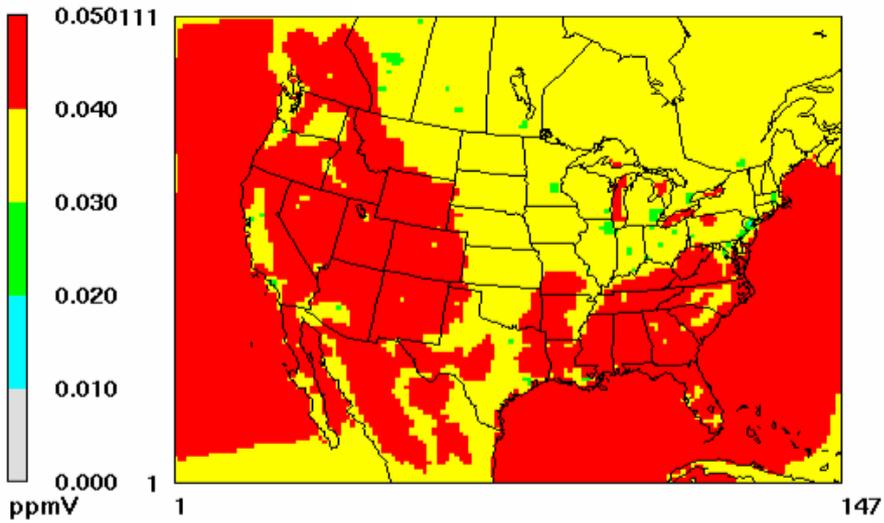
O₃_2050



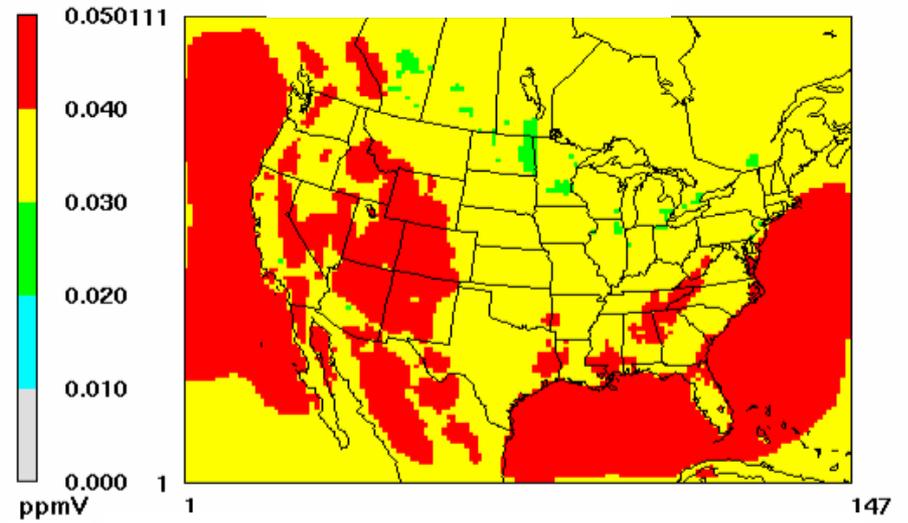
O₃_2050 - O₃_2001



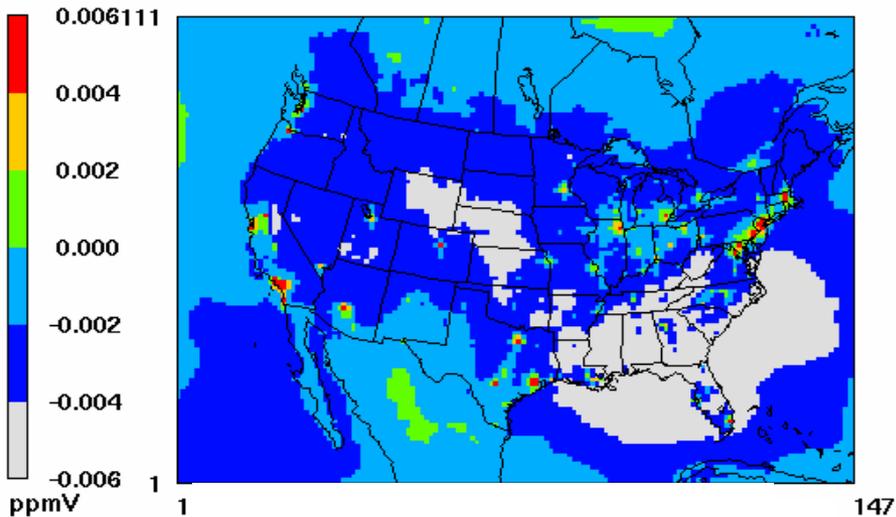
O₃_2001



O₃_2050

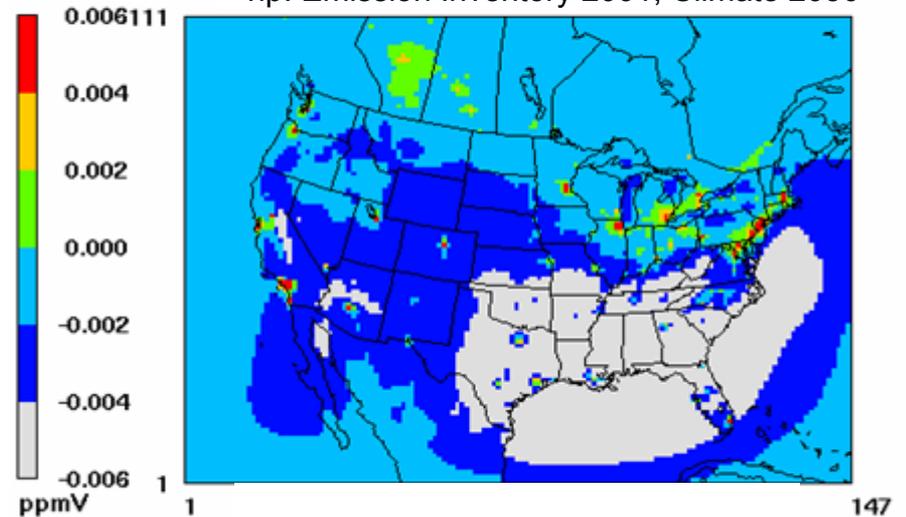


O₃_2050 - O₃_2001

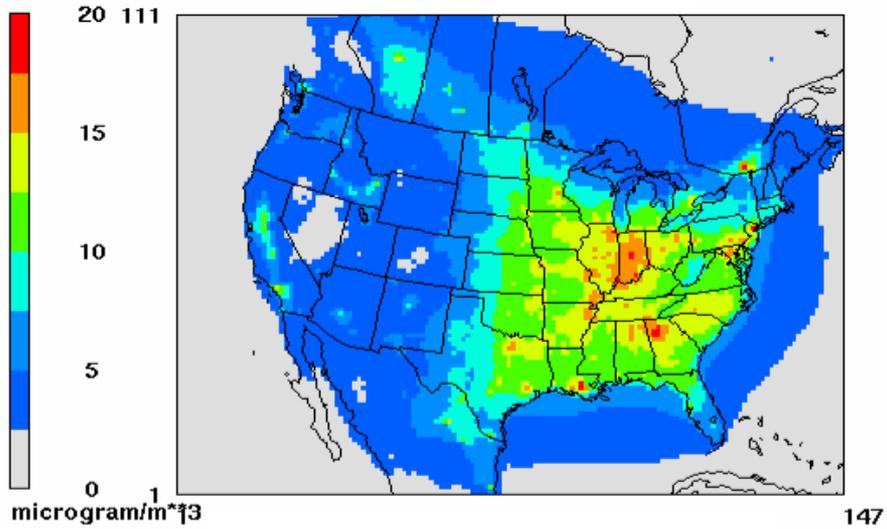


O₃_2050 - O₃_2050np

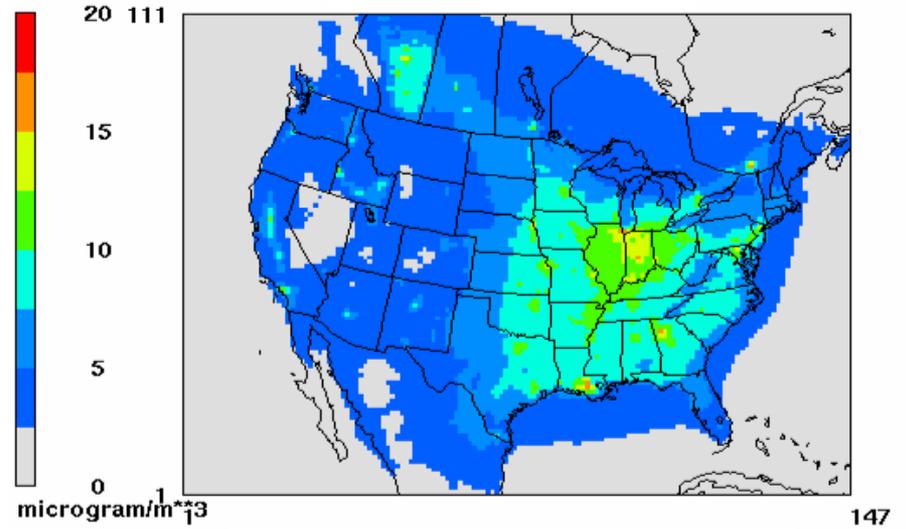
np: Emission Inventory 2001, Climate 2050



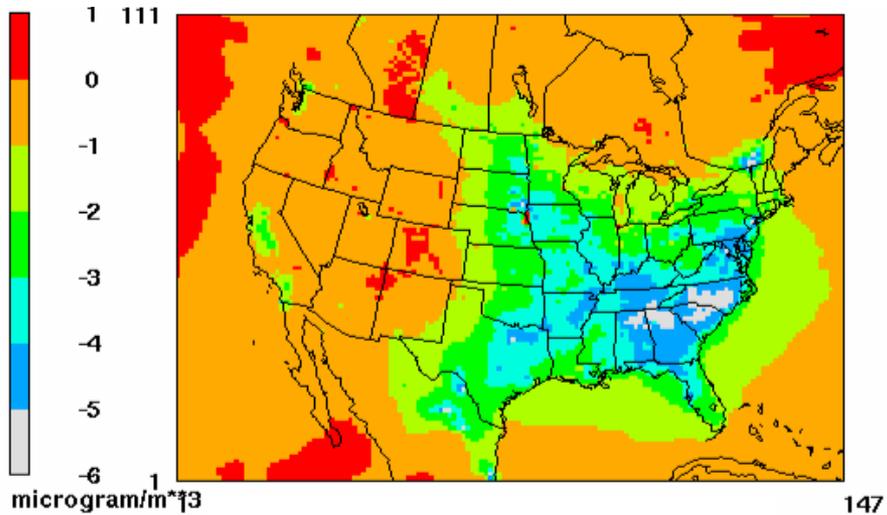
PM_{2.5}_2001



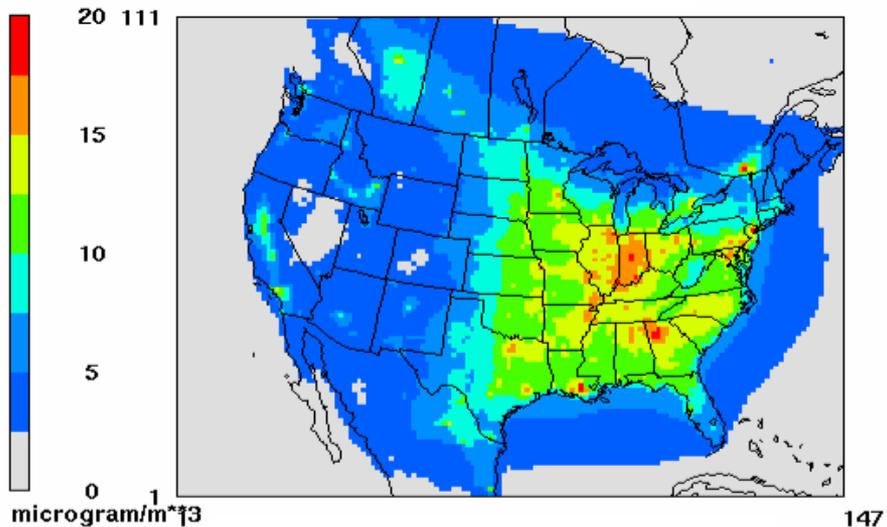
PM_{2.5}_2050



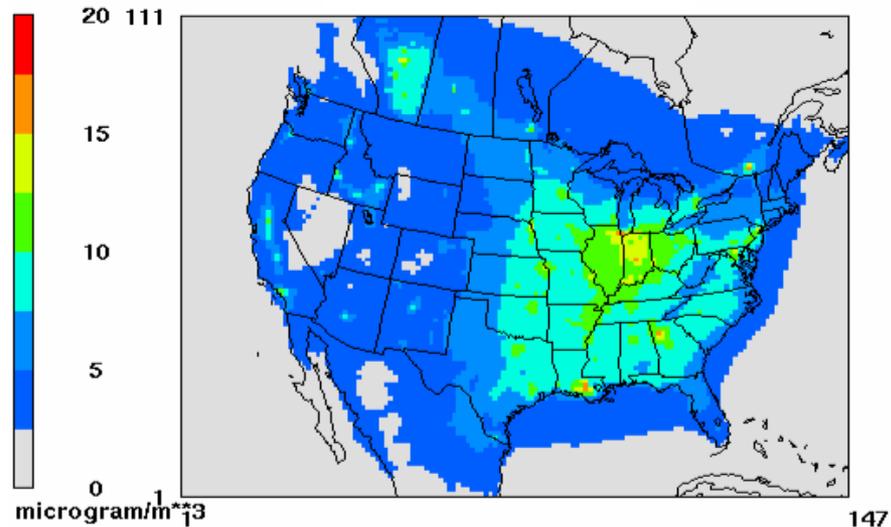
PM_{2.5}_2050 - PM_{2.5}_2001



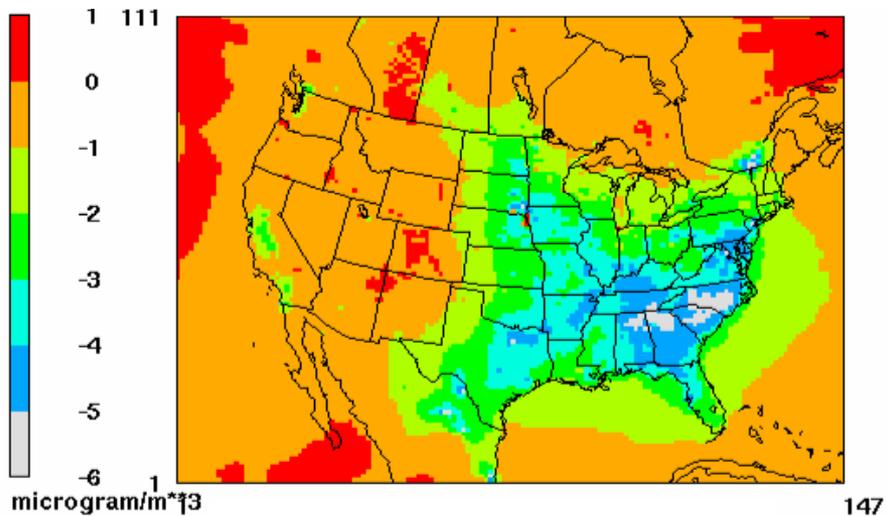
PM_{2.5}_2001



PM_{2.5}_2050

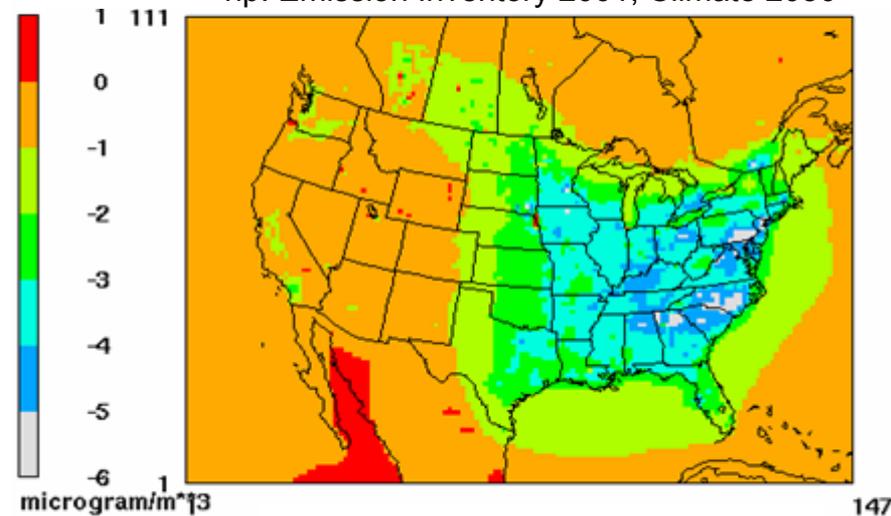


PM_{2.5}_2050 - PM_{2.5}_2001



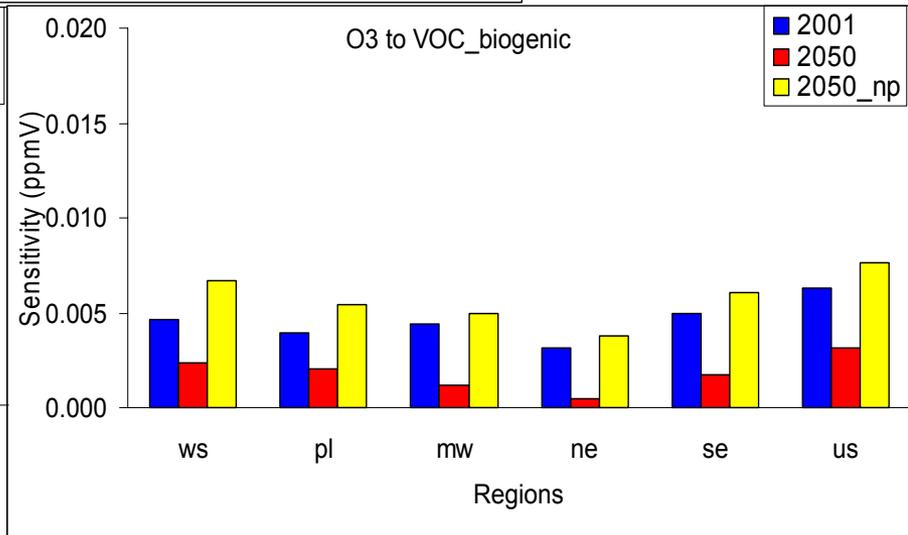
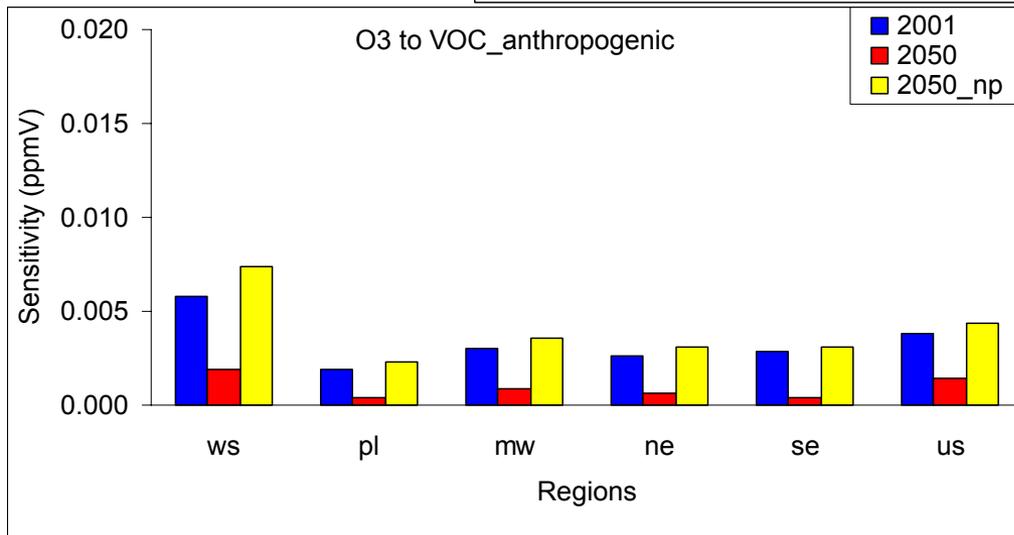
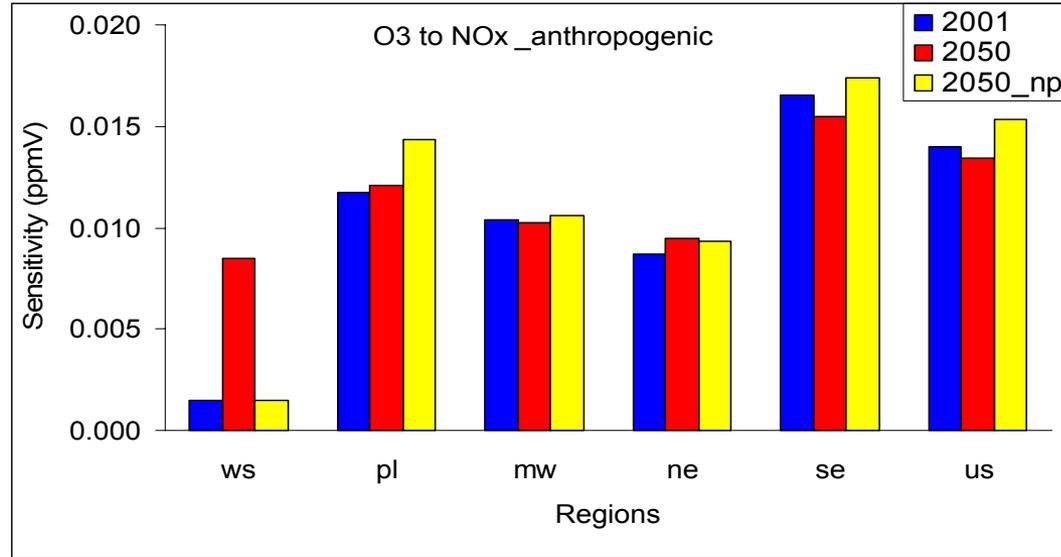
PM_{2.5}_2050 - PM_{2.5}_2050np

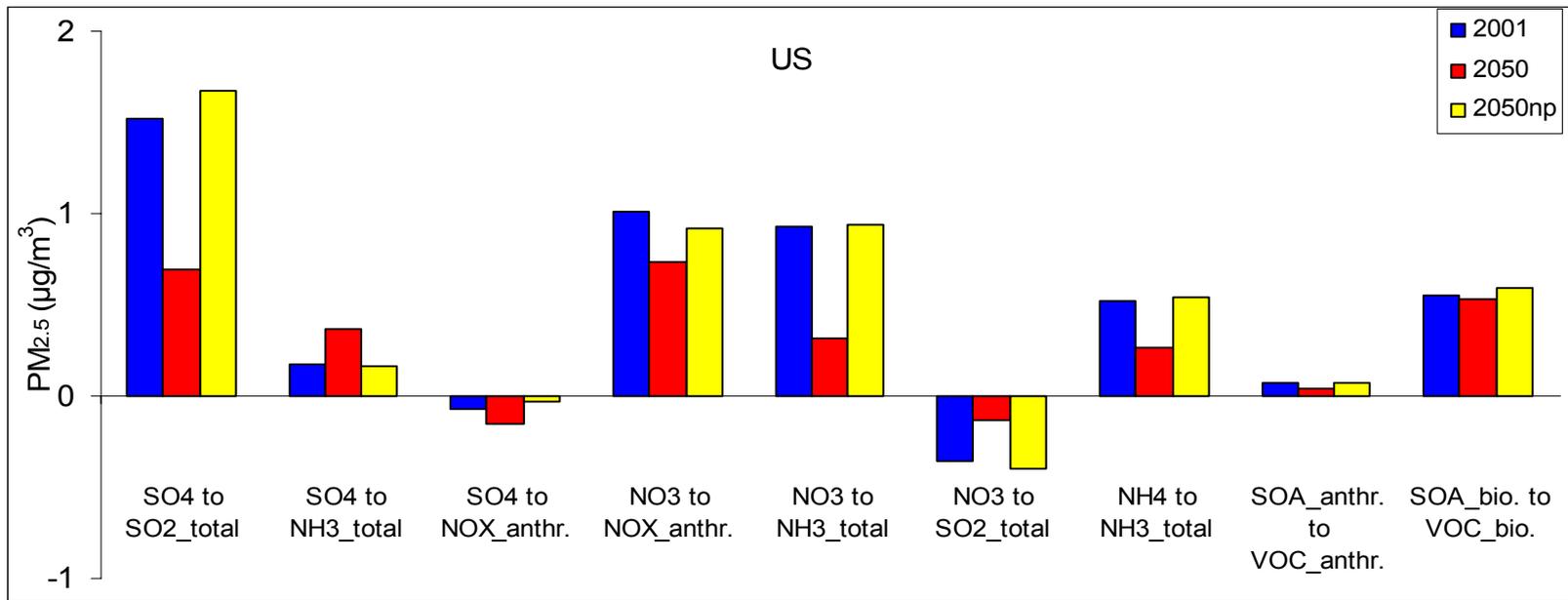
np: Emission Inventory 2001, Climate 2050



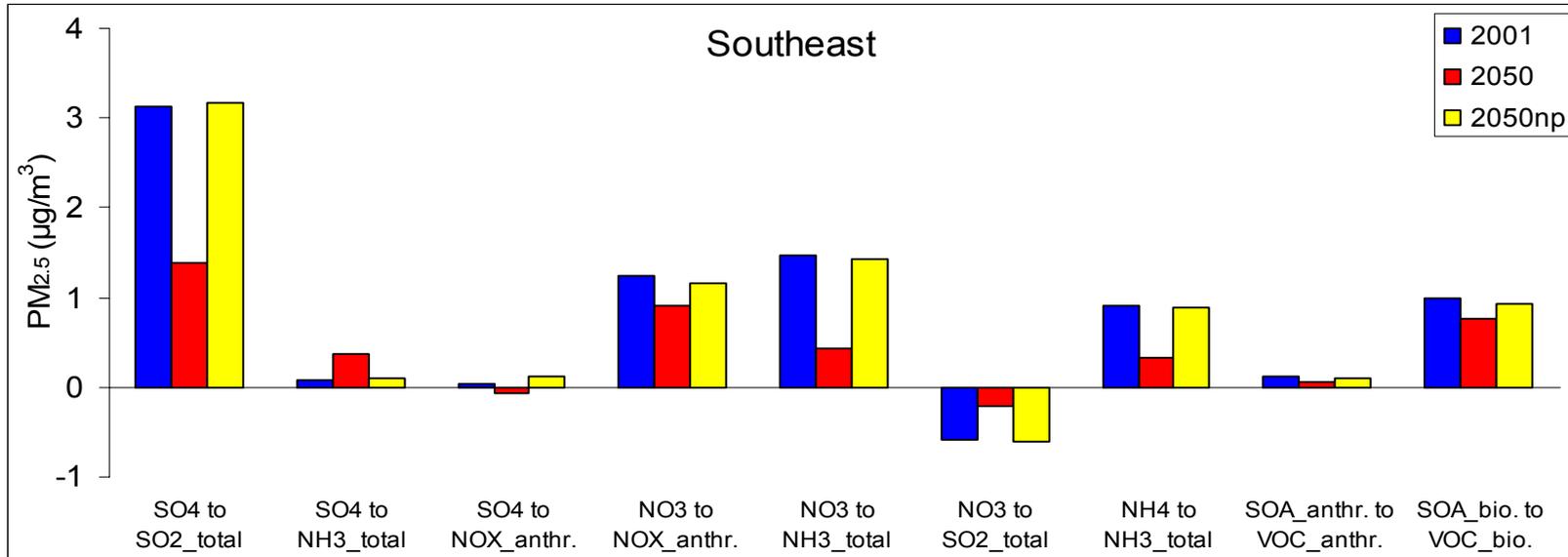
Sensitivity of Ozone to Climate and Emission Controls

O₃





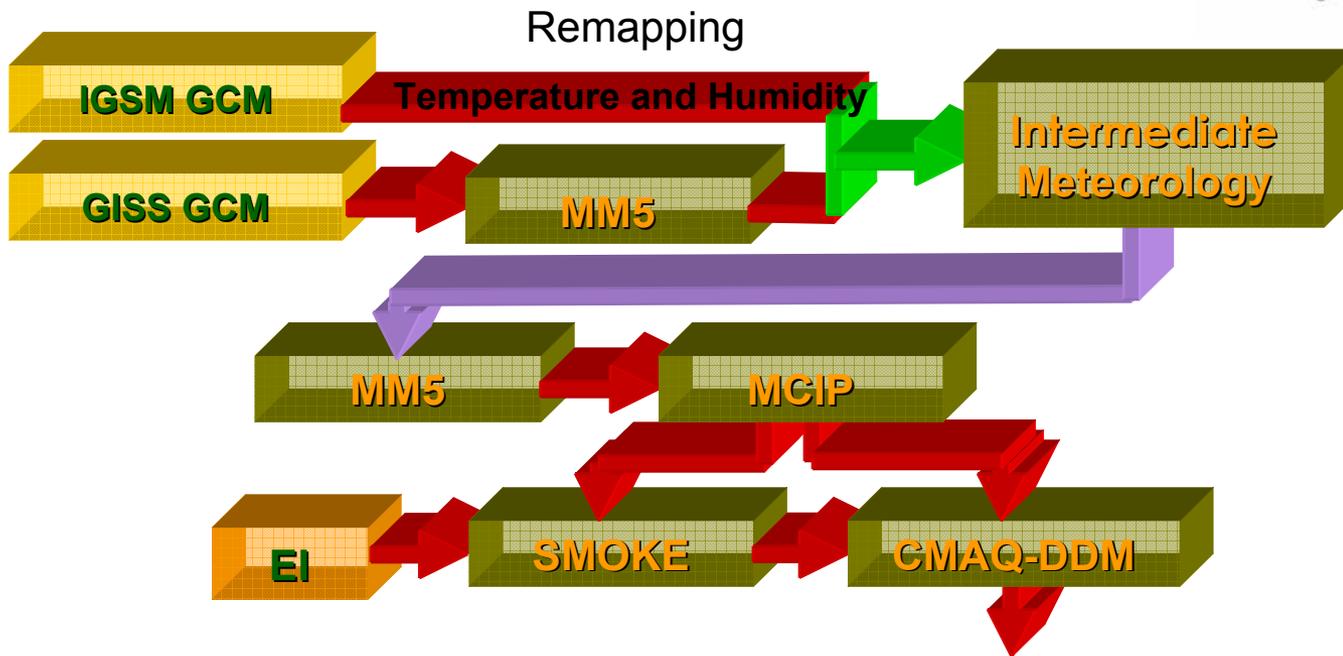
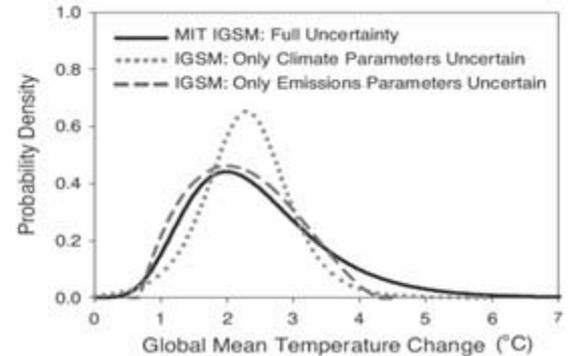
PM_{2.5}



Uncertainty Analysis of Results

Modeling approach

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

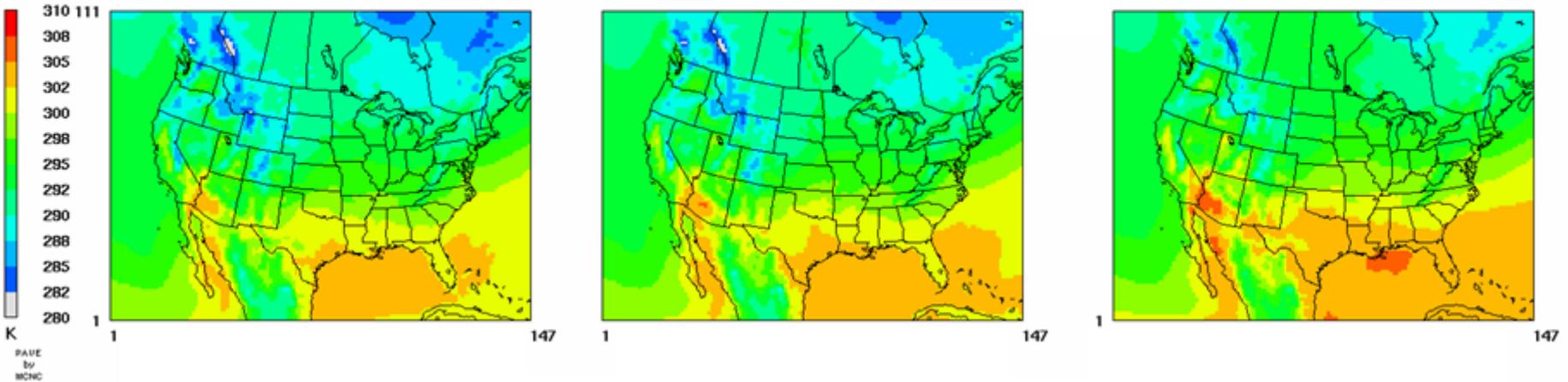


Summer 2050 average temperature

lower

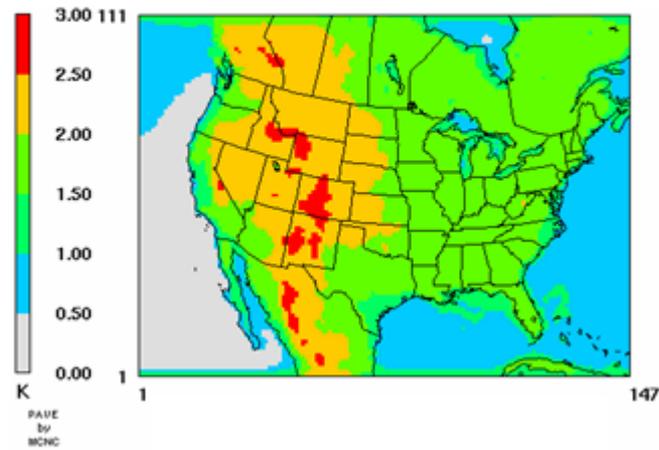
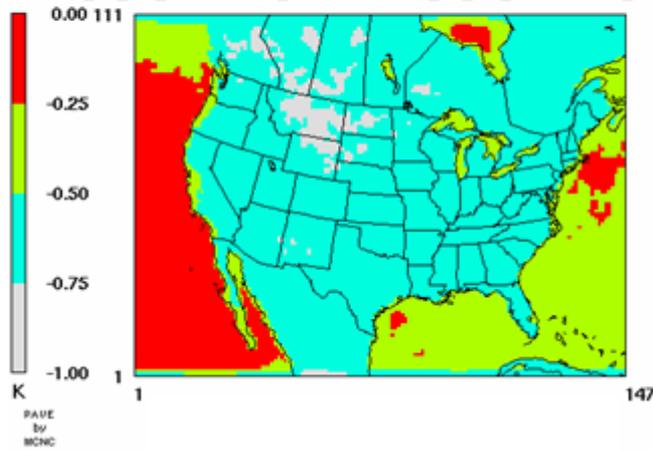
middle

upper



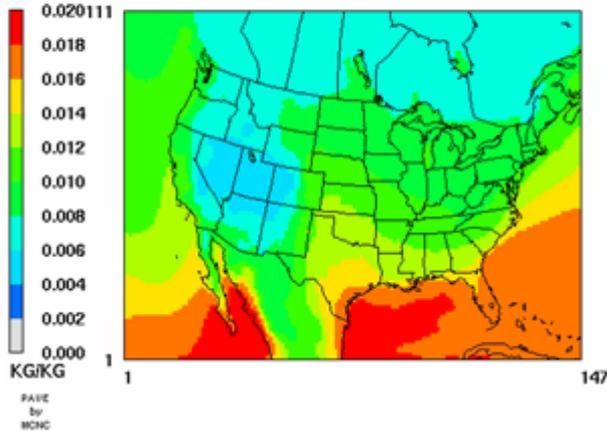
lower - middle

upper - middle

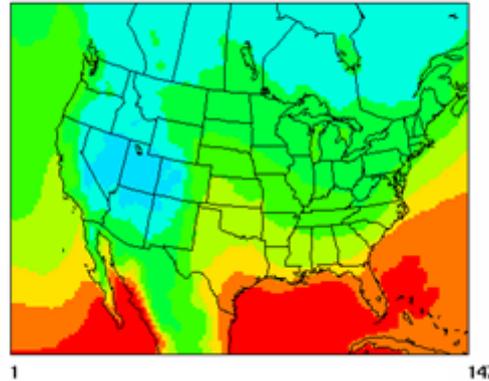


Summer 2050 average humidity

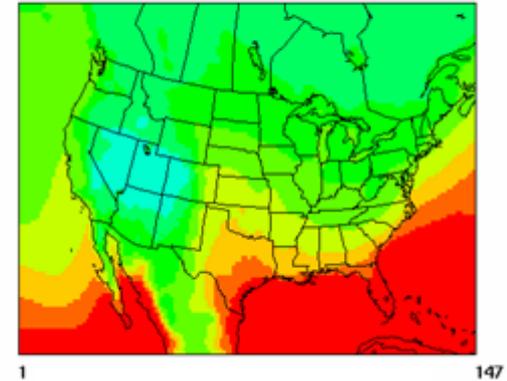
lower



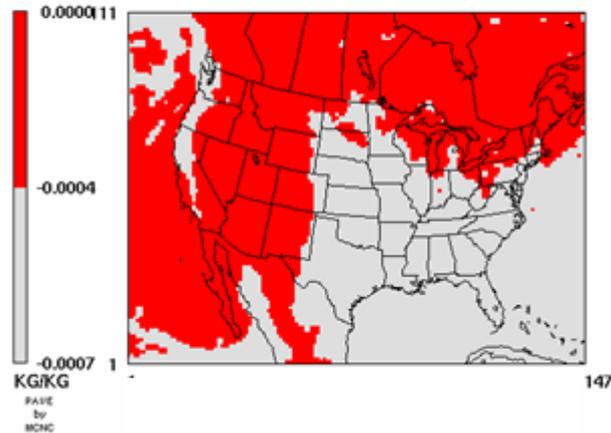
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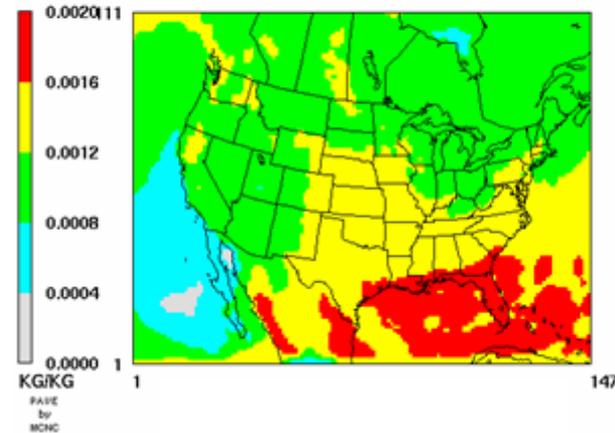
upper



lower - middle

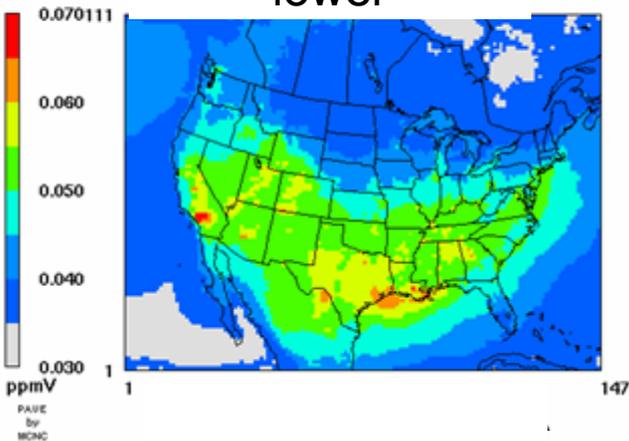


upper- middle

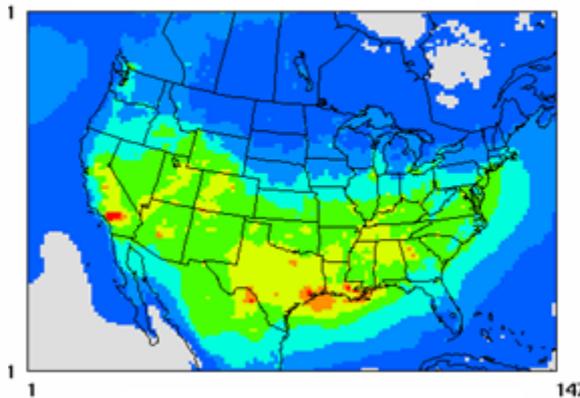


Summer 2050 average max8hrO₃

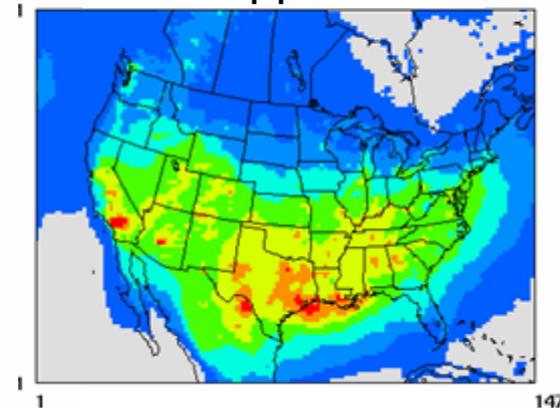
lower



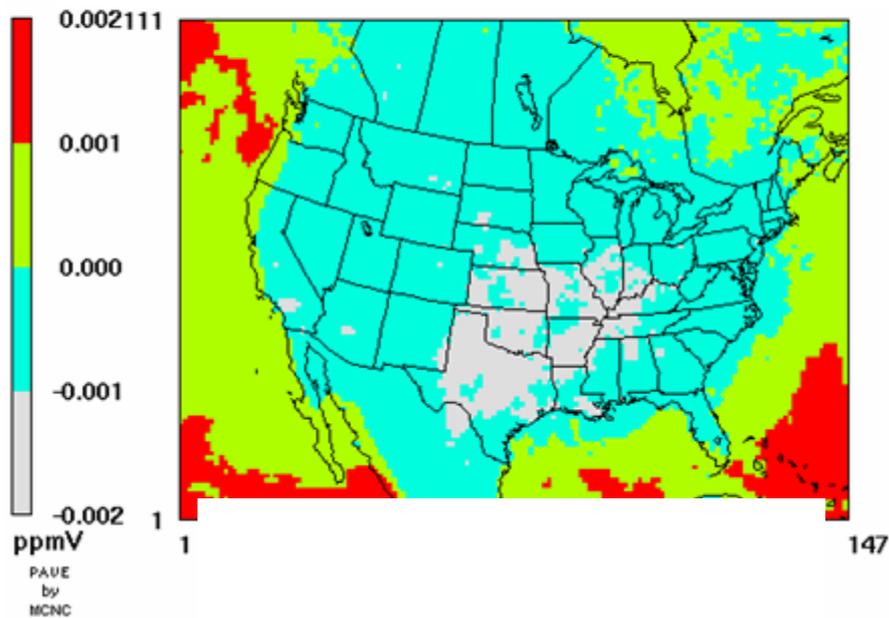
middle



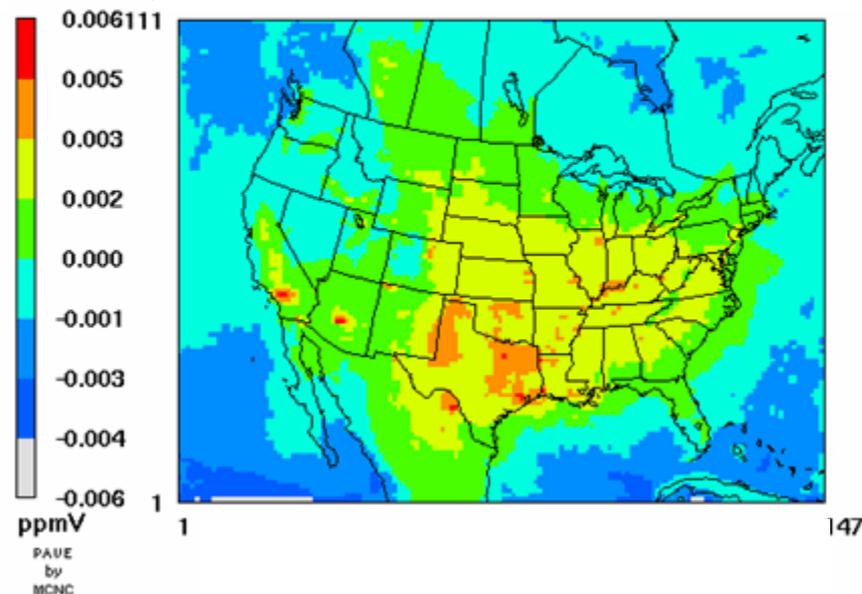
upper



lower – middle

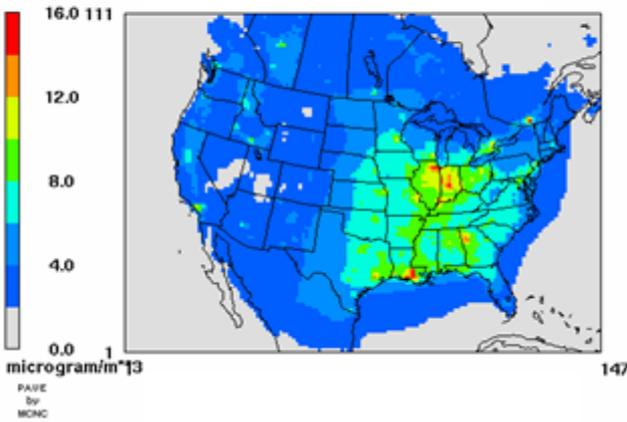


upper – middle

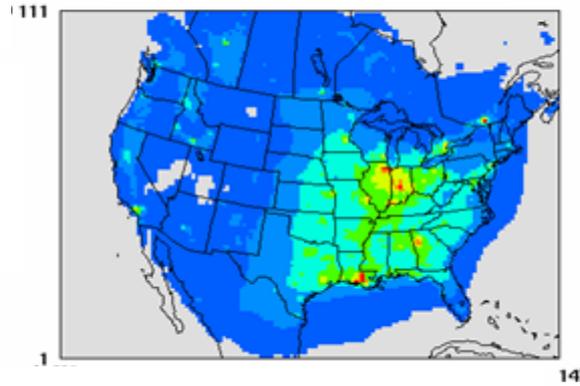


Summer 2050 average PM_{2.5}

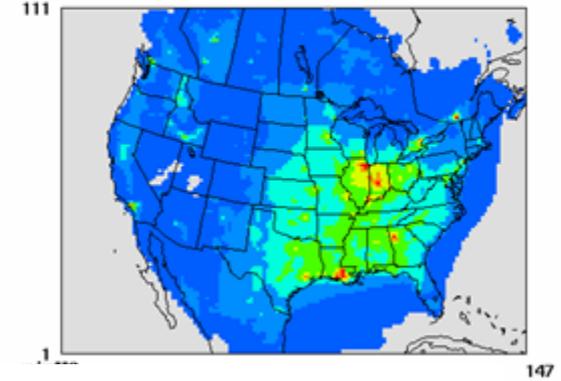
lower



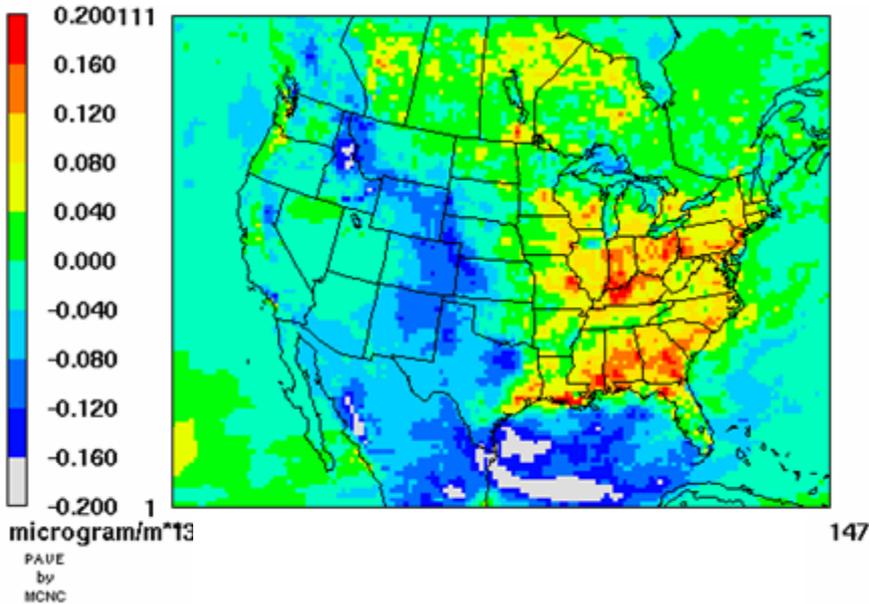
middle



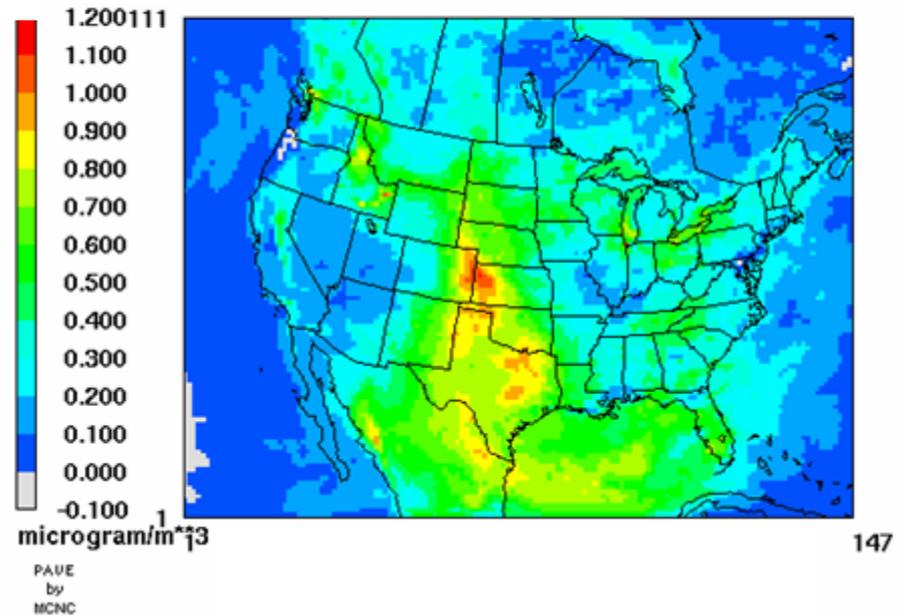
upper



lower – middle



upper – middle



What is the uncertainty in some mega-cities?

M8hO ₃ (ppb)									
Summer 2050 low				Summer 2050 middle			Summer 2050 up		
Region / City	Region	City		Region	City		Region	City	
	99.5%	# of days over 80 ppb	Peak value	99.5%	# of days over 80 ppb	Peak value	99.5%	# of days over 80 ppb	Peak value
West / Los Angeles	82	2	82	82	6	84	82	7	91
Plains / Houston	82	5	87	82	10	90	84	24	98
Midwest / Chicago	84	3	87	84	4	89	86	6	97
Northeast / New York	84	0	68	84	0	70	85	0	74
Southeast / Atlanta	85	0	75	85	0	78	86	2	85

Conclusions

- Combining the effect of emission changes and climate change, future O₃ and PM_{2.5} concentrations over U.S. are expected to be lower *but* the effects are more pronounced for regional PM_{2.5} concentrations
- Organic carbon could become the most important PM_{2.5} component
- Regionally, the Eastern U.S. shows more benefits than the rest of the regions
- The contribution of anthropogenic NO_x emissions to O₃ formation is more important than VOCs. Reductions in anthropogenic NO_x emissions will continue to be effective for reducing regional ozone concentrations
- Uncertainties of predicted O₃ and PM_{2.5} concentrations due to climate change are larger in the “high-extreme” meteorology case
- Uncertainties of predicted O₃ and PM_{2.5} concentrations due to climate change are regional in nature: Plains have higher uncertainties than elsewhere because temperature predictions are more uncertain there
- Emission controls have larger impact than climate change