Sensitivity Assessment of Ozone and Fine Particulate Matter to Emissions Under the Influence of Future Climate and Emission Changes

Kasemsan Manomaiphiboon, Armistead G. Russell,
Sergey Nepelenok, Sun-Kyoung Park, Mehmet T. Odman
(School of Civil and Environmental Engineering, GaTech)
Jung-Hun Woo, Shan He, Praveen Amar
(NESCAUM)
Lai-Yung (Ruby) Leung
(Pacific Northwest National Laboratory)
and Chien Wang
(MIT)

September 2005
Annual Models3/CMAQ User's Conference
NC, USA

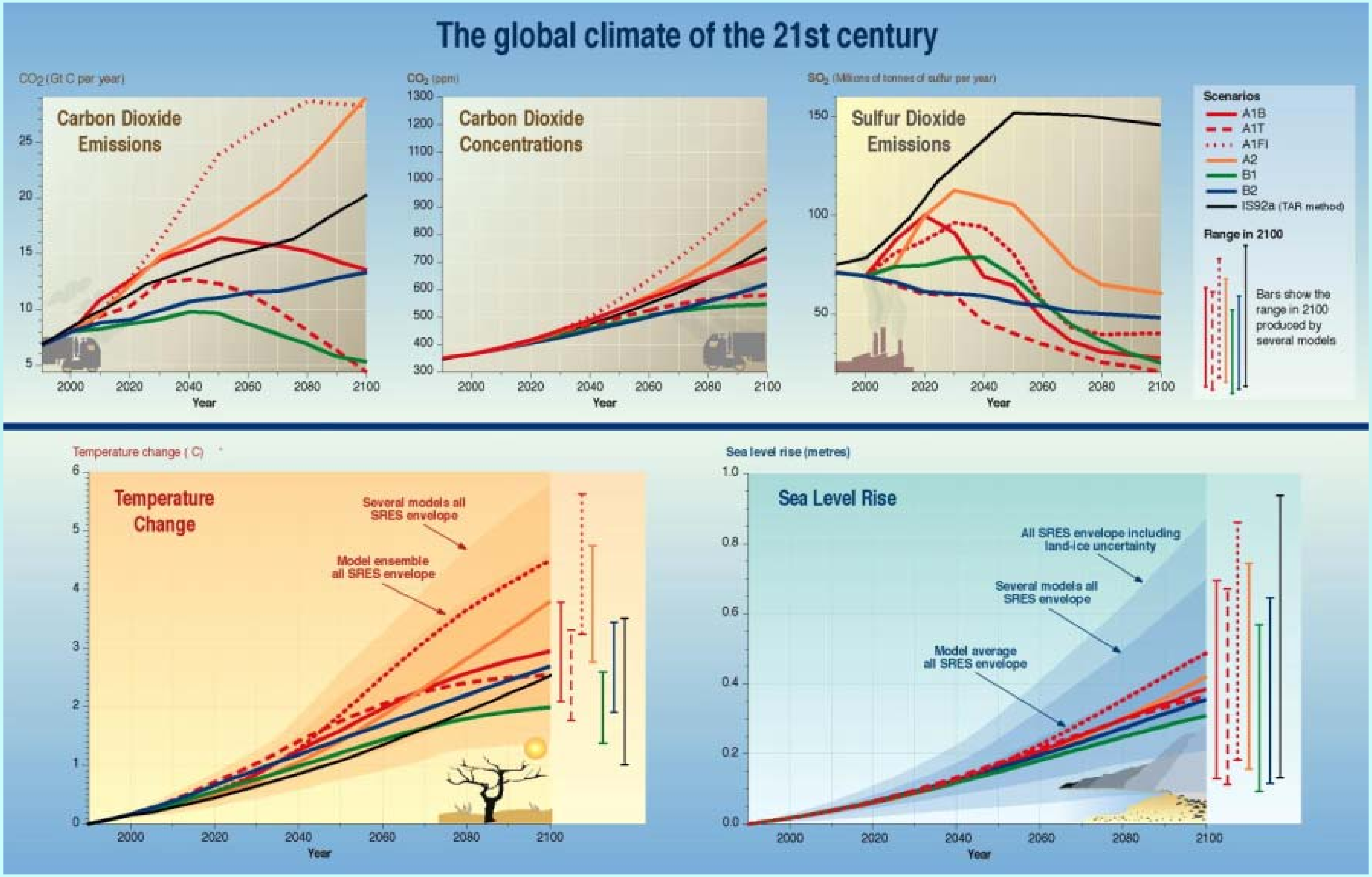
Issues

- **Global climate change potentially impacts regional air quality**
  - **Increased temperatures, changes in circulation, rainfall, etc.**
  - **Impacts emissions**
    - **Biogenic**
    - **Anthropogenic**
- **Significant uncertainties in future climate**
  - **Similar uncertainties in impacts on air quality**
- **Question relevant to air quality management: How does climate change affect the "response" of air quality to emissions?**
  - **Assess the effectiveness of current emission control strategies and how they will be impacted by climate change**
  - **Consider uncertainty in future climate and emissions on the effectiveness of control strategies**

Objectives

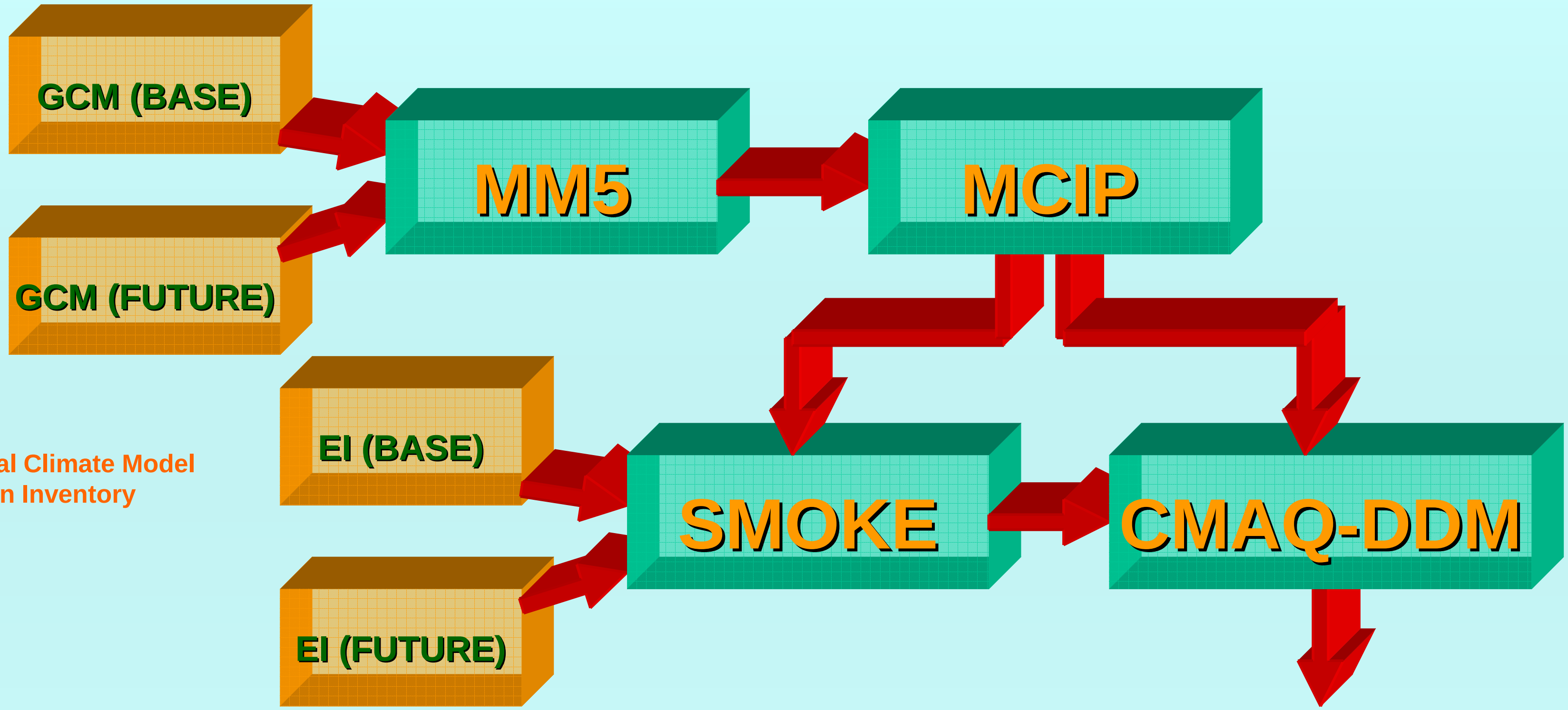
- Assess the impacts of both direct (i.e. from climate change) and indirect (i.e. from emissions changes) effects on regional air quality
  - Emphasis given to the response of air quality to emissions, i.e. the "sensitivity" of pollutant concentrations to emissions
- Assess if climate change forcing has a potentially significant and probable impact on the direction and magnitude of current emissions controls being considered in the U.S. for improving air quality
  - O_3 and fine particulate matter (FPM)

21st-Century Climate Study (IPCC)



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

Approach

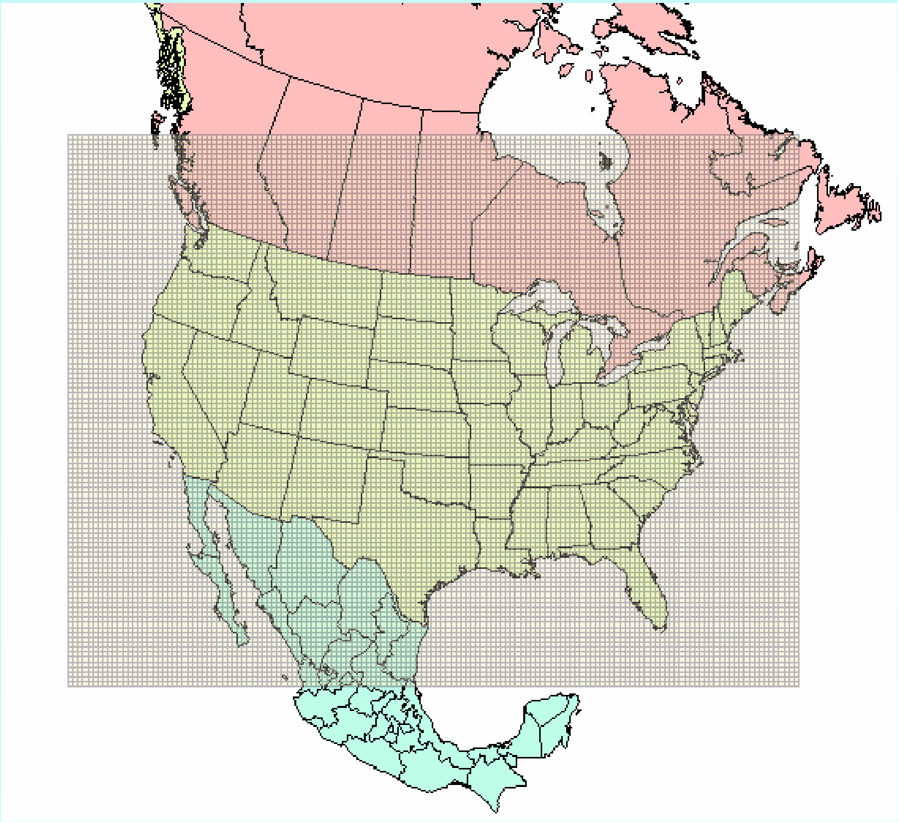


GCM: Global Climate Model
EI: Emission Inventory

- 2 Cases (summertime):
  a) Control (or base): Jun., 2000-2002
  b) Future: Jun., 2049-2051
- Climate-downscaled meteorological results by NASA's GISS GCM and MM5, based on Leung et al. (2005)

Leung et al., 2005: 85th Annual AMS Meeting, CA, USA

CMAQ Domain



- 147 x 111 grid domain
- 9 vertical layers
- 36-km grid size
- Continental US + Parts of CA & MX

Paradigm of Future-EI Development

Calculate combined factor of growth/control from EPA base year(2001) vs. future year (2020) emissions inventory

Calculate growth factor for Y2020-Y2050 (A1B) from IMAGE

Calculate growth factor for Y2001-Y2050 for Canada/Mexico from IMAGE

Compare EPA CAIR vs. IMAGE for Y2001-Y2020

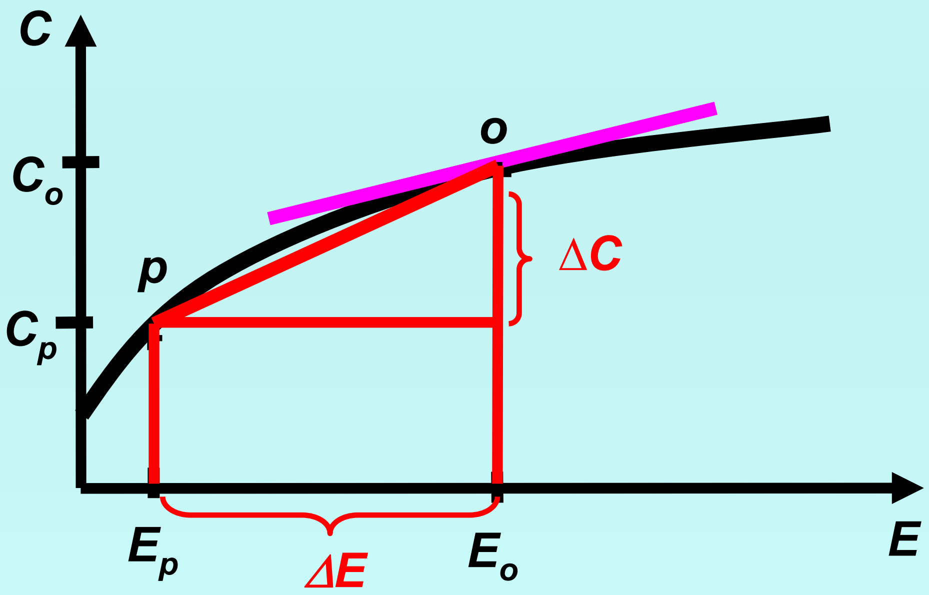
Develop SCC to IMAGE fuel/sector x-reference

Check/apply growth factors to 2020 EPA CAIR EI to get 2050 EI

<u>SRES A1B</u>: Future world of rapid economic growth and global population that peaks in mid-century and declines thereafter, rapid introduction of more efficient technologies, and balanced usage between fossil fuels and other energy sources

- ¾ of EI work completed
- Underway: Mobile-US, CA, and MX
- US:
  - 2001 → 2020 (EPA CAIR EI)
  - 2020 → 2050 (IMAGE w/ SRES A1B)
- CA & MX:
  - Adjusted to 2001 by GDP & pop.
  - 2001-2050 (using scaling factors from EGAS, GDP, pop., etc.) *- Not conducted yet*
- Land use:
  - BELD3 (held constant for future case)
- No future projection for geogenic and fire emissions
- MIMS spatial allocator with new EPA spatial surrogates

Sensitivity's Definitions



- In current context, Sensitivity (*S*) = Response of concentration (*C*) to change in emission (*E*)
- Brute Force (BF):
  1) $S = \Delta C \,/\, \Delta E$
- Decoupled Direct Method (DDM):
  With $\Delta \rightarrow 0$, equivalent to
  2) $S = \partial C \,/\, \partial E$

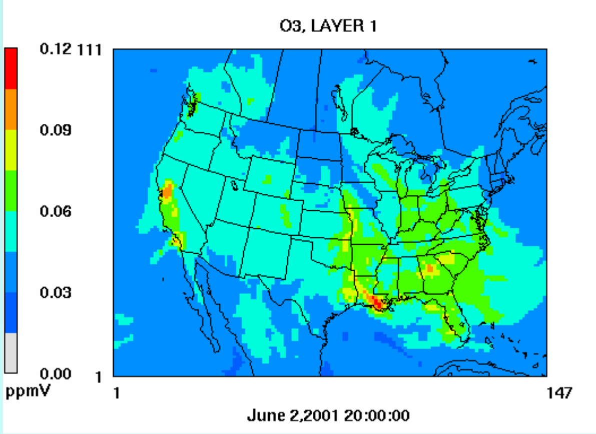
  Redefine by normalization
  3) $\varepsilon = \Delta E \,/\, E$

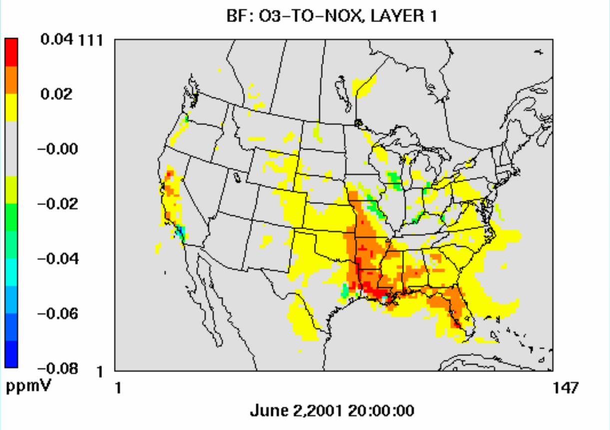
  Equivalent to
  4) $S = \partial C \,/\, \partial \varepsilon$

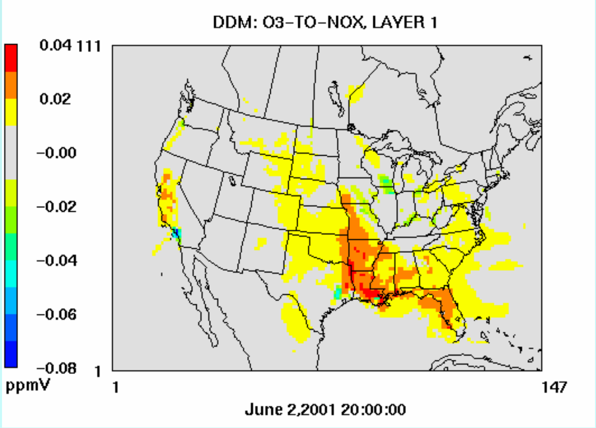
  By Eqs. 3-4, *S* and *C* have same unit

Sensitivity Calculation

- Sensitivity calculation: Useful analytical & application tool for AQM
- By DDM, sensitivity is numerically & directly solved
- DDM has been incorporated into several air quality models (e.g. CIT, URM, CAMx, and CMAQ)
- CMAQ-DDM: Based on Cohan et al. (2003) and Napelelok et al. (2005)



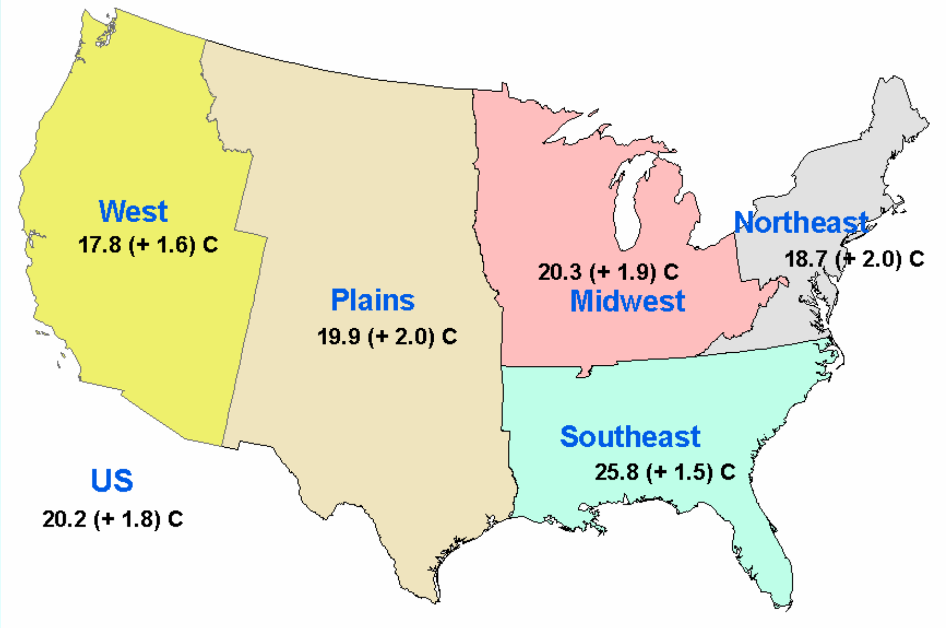




Cohan et al., 2003: 2nd Annual CMAS MODELS-3 User's Conference, NC, USA
Napelenok et al., 2005: Annual PM Supersites Conference, GA, USA

Temperature and Emissions Changes between Control and Future Cases

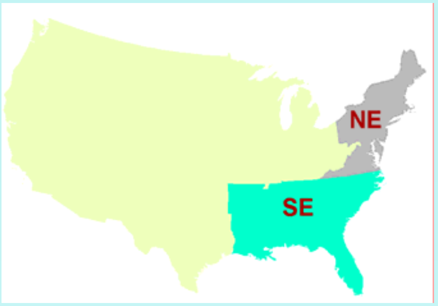
- <u>US regions:</u>
  WS (West)
  PL (Plains)
  MW (Midwest)
  NE (Northeast)
  SE (Southeast)
- Averaged by case and by region

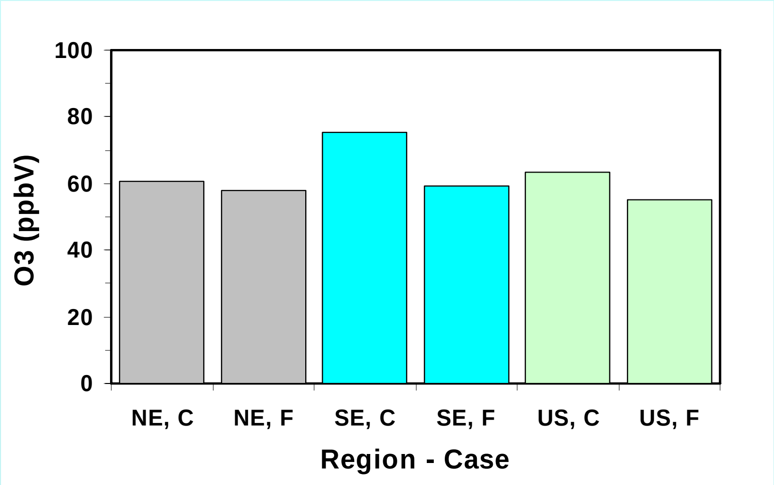


Region	Emission	Change (%)
WS	NOX	-51.8
	SO2	-49.3
	NH3	+4.1
	VOC	+9.0
	VOC (B)	+19.0
PL	NOX	-41.1
	SO2	-67.1
	NH3	+2.3
	VOC	+16.2
	VOC (B)	+27.0
MW	NOX	-52.7
	SO2	-60.1
	NH3	+5.1
	VOC	+8.1
	VOC (B)	+28.9
NE	NOX	-65.1
	SO2	-66.6
	NH3	+9.9
	VOC	-0.72
	VOC (B)	+29.6
SE	NOX	-62.8
	SO2	-60.5
	NH3	+4.6
	VOC	+7.0
	VOC (B)	+15.0
US	NOX	-54.1
	SO2	-62.2
	NH3	+4.5
	VOC	+8.6
	VOC (B)	+21.4
B: Biogenic		

O3: Concentration & Sensitivity

- Averaged by case and by region



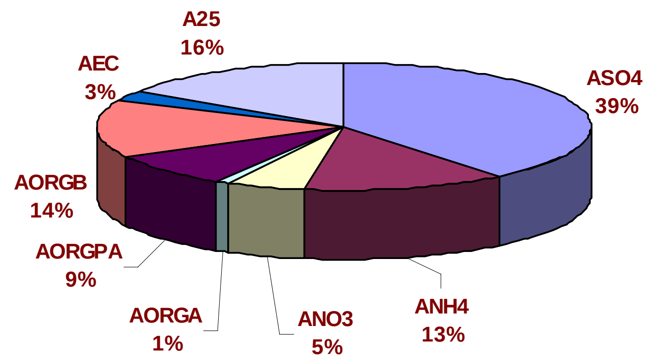


Region	Sensitivity*	Control	Future	Diff.
NE	O3 to NOX	11.1	17.3	6.2
	O3 to VOC	3.1	-2.0	-5.0
SE	O3 to NOX	24.0	21.7	-2.3
	O3 to VOC	0.5	-4.5	-5.0
US	O3 to NOX	15.3	15.1	-0.2
	O3 to VOC	1.4	-1.8	-3.2

*: ppbV

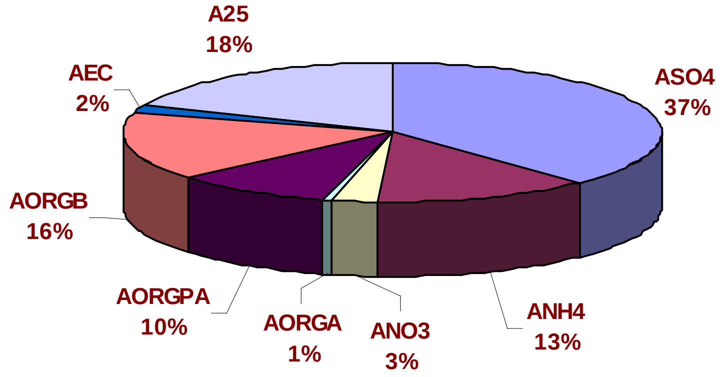
Fine Particulate Matter (PM2.5)

US (Control Case)



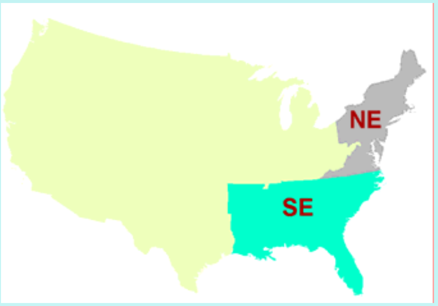
- Each PM2.5 species = I-Mode + J-Mode
- Averaged by case and by region
- ASO4 & ANO3 discussed here

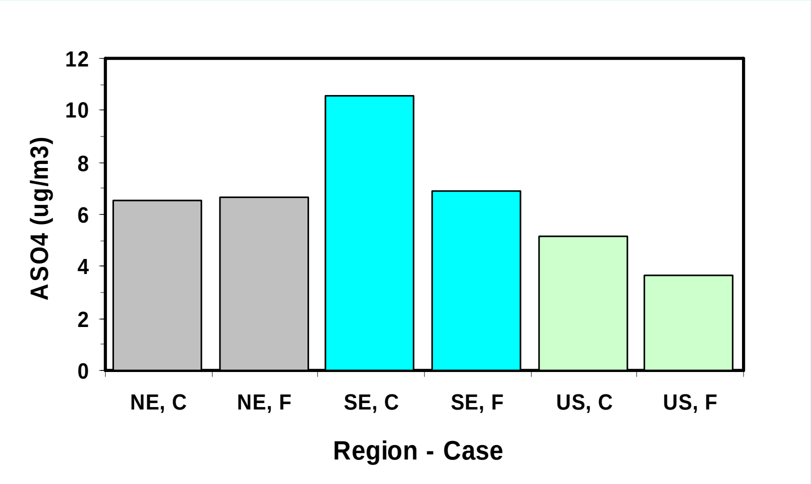
US (Future Case)



ASO4: Concentration & Sensitivity

- ASO4 = ASO4I + ASO4J
- Averaged by case and by region

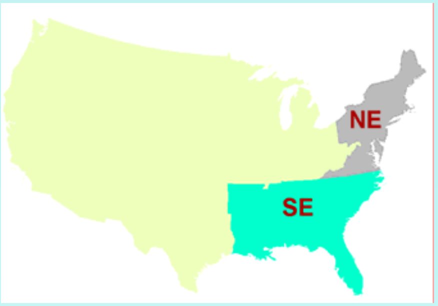


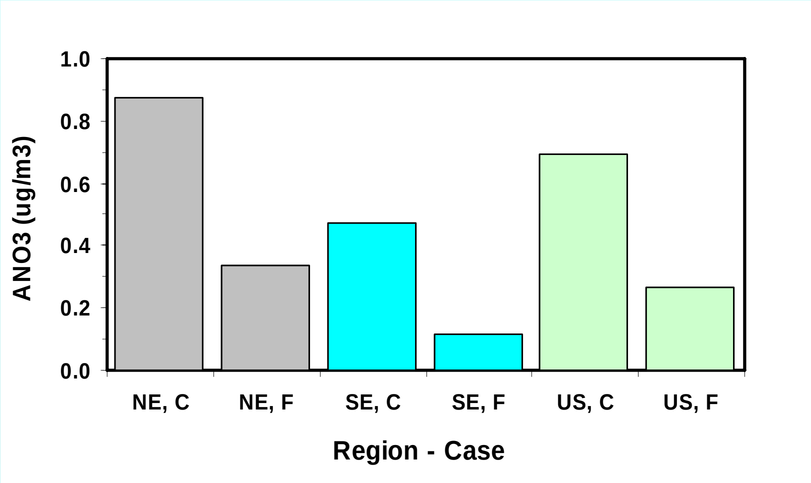


Region	Sensitivity*	Control	Future	Diff.
NE	ASO4 to SO2	4.779	4.468	-0.311
	ASO4 to NOX	0.504	0.741	0.237
	ASO4 to NH3	0.040	0.123	0.083
SE	ASO4 to SO2	8.325	5.062	-3.262
	ASO4 to NOX	0.939	0.691	-0.247
	ASO4 to NH3	0.043	0.155	0.111
US	ASO4 to SO2	3.970	2.455	-1.515
	ASO4 to NOX	0.398	0.296	-0.102
	ASO4 to NH3	0.078	0.190	0.111
*: ug/m3				

ANO3: Concentration & Sensitivity

- ANO3 = ANO3I + ANO3J
- Averaged by case and by region





Region	Sensitivity*	Control	Future	Diff.
NE	ANO3 to SO2	-0.672	-0.358	0.313
	ANO3 to NOX	0.691	0.419	-0.272
	ANO3 to NH3	1.244	0.562	-0.681
SE	ANO3 to SO2	-0.547	-0.162	0.386
	ANO3 to NOX	0.591	0.162	-0.429
	ANO3 to NH3	0.802	0.243	-0.559
US	ANO3 to SO2	-0.546	-0.187	0.359
	ANO3 to NOX	0.707	0.367	-0.340
	ANO3 to NH3	0.901	0.306	-0.595
*: ug/m3				

Conclusions

- **Sensitivity assessment:**
  - **Control and future cases (covering 6 one-month summer episodes)**
  - **Continental US (plus parts of CA & MX)**
  - **GISS-MM5/SMOKE/CMAQ-DDM**
- **Warmer climate around mid-century (+1.5-2.0 ºC)**
- **NOX & SO2 emissions reduced significantly in future case (~50-60%)**
- **Increased biogenic VOC emissions in future case (~15-30%)**
- **Decreased O3 in all regions (up to ~20% in SE)**
- **Decreased ASO4 and ANO3 in NE, SE, and US**
  - **Exception: ASO4 in NE due to unchanged SO2 emissions of CA**
- **<u>Sensitivity of O3 to emissions</u>:**
  - **No significant differences found between control and future cases**
  - **In NE, relatively larger changes in sensitivity (but their magnitudes are still much less than those of concentration)**
- **<u>Sensitivity of ASO4 and ANO3 to emissions</u>:**
  - **ASO4 most (positively) sensitive to SO2**
  - **ANO3 negatively sensitive to SO2 but positively sensitive to NOX & NH3**
  - **For some, fair-to-large changes in sensitivity**
- **Response of O3 and FPM to emissions changed but not too significantly under combined influence of both climate and emissions changes**

Future Work

- Examine and statistically evaluate climatology of meteorological variable of interest (particularly, temperature) and regional O3 & FPM levels (as discussed by Hogrefe et al., 2004)
- Complete EI development work for US, CA, and MX
- Comparison: Direct (alone) and combined (direct + indirect) effects
- Extended simulation and analysis: Annual simulations + More FPM species & sensitivity variables
- Large uncertainties exist for climate change prediction:
  - Account for and incorporate uncertainty information of climate change into meteorological modeling
  - Plan: Choose 5 modeling realizations (approx.) representing 5 different climate conditions (i.e. -extreme, -fair, typical, +fair, and +extreme)
  - Suggested by multi-dimensional cumulative density functions from MIT's ISGM GCM results (Webster et al., 2003)

Hogrefe et al., 2004: Atmos. Environ., 38, 2627-2638
Webster et al., 2003, Climatic Change, 61, 295-320

Acknowledgements

- Dr. Yongtao Hu, Dr. Efthimios Tagaris, and Kao-Jen Liao (GaTech) for assistance
- US EPA under STAR grant No. R830960