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Effects of Climate Change and Greenhouse Gas Mitigation Strategies on Air Quality

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Project Overview – Goal and Objectives

Goal

Analyze air quality (AQ) impacts of climate change and various transportation and power sector GHG mitigation strategies in 2050

Objectives

1. **Establish rigorous analyses methodologies and adapt state-of-the-art models to evaluate future scenarios in 2050**

2. **Model air quality sensitivity to meteorological and boundary conditions affected by changes in global climate**

3. **Develop spatially and temporally resolved criteria pollutant emissions due to GHG reduction strategies in the transportation sector**

4. **Develop spatially and temporally resolved criteria pollutant emissions due to GHG reduction strategies in the power generation sector**

5. **Assess air quality impacts due to GHG reduction strategies**

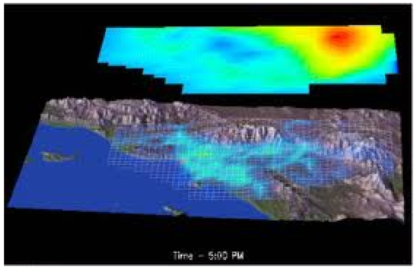
Outline – Tasks

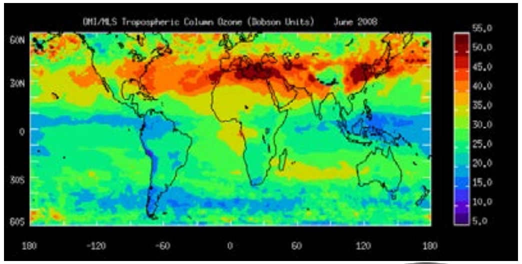
1. **Methodology Development**

2. Technology Assessment
   – Emphasis on power and transportation sectors

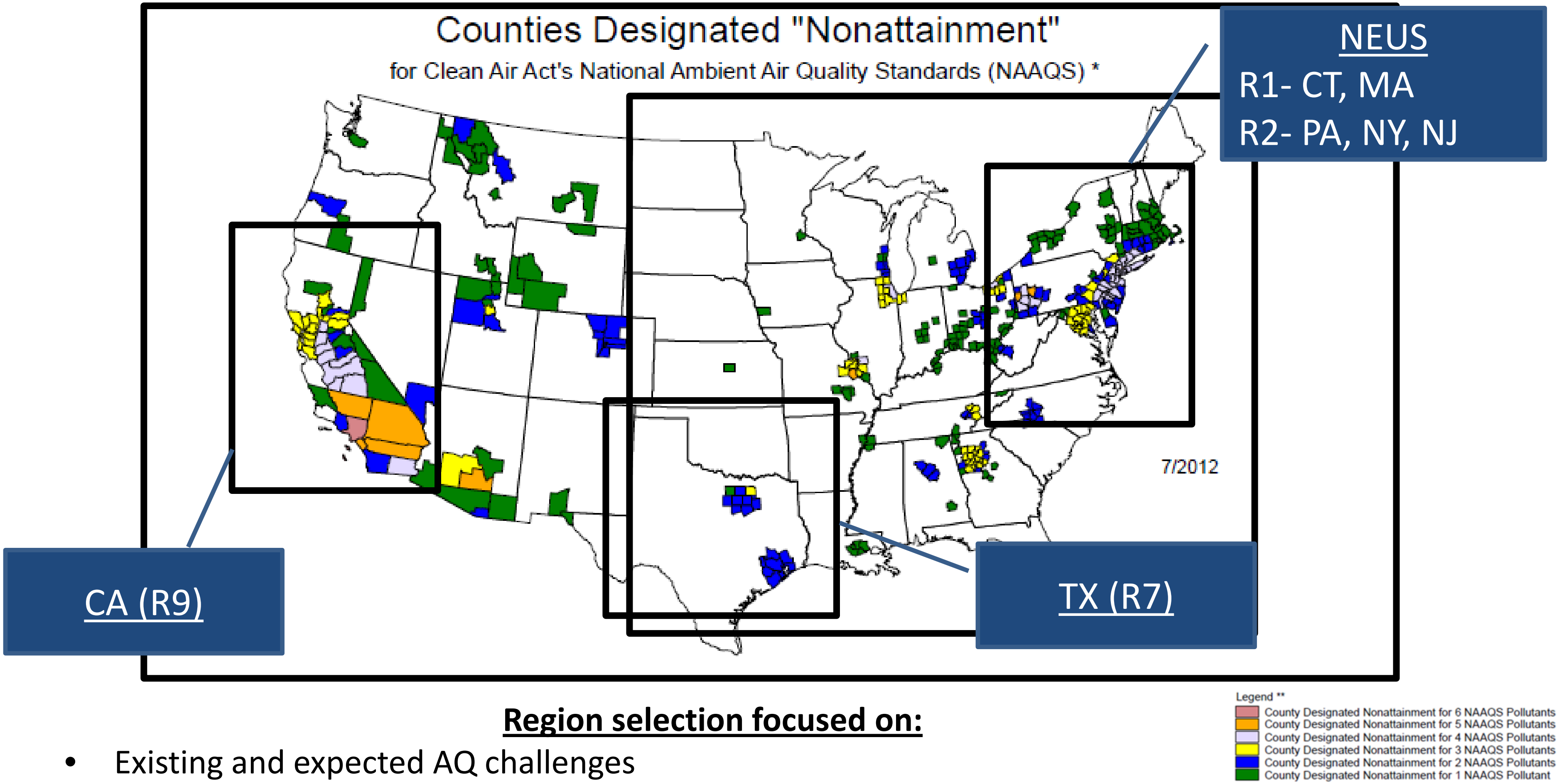
3. Evaluation of GHG and AQ Impacts
   – Development and assessment of scenarios

4. Air quality model sensitivity
   – Impacts of climate change





Regions of Interest



Region selection focused on:

- Existing and expected AQ challenges
- Similar/differing contributing sources to facilitate comparison and identify trends
- Current/expected focus on GHG mitigation and alternative technology deployment
  - CA, NEUS

Methodology

Identify/Assess Mitigation Strategies
- **Power sector**
- **Transportation sector**

Scenario Development
- **Range of potential futures**
- **Project to 2050**

Pollutant Emission Impacts

Spatial & Temporal Resolution

Simulations of atmospheric chemistry and transport

Air Quality Impacts

GHG Emission Impacts

Sparse Matrix Operator Kernel Emissions Model (SMOKE)
- Gridded, speciated, & temporalized emissions

Initial Scenarios
- Base Case
  - SCC-based emission growth factors
- 2005 National Emissions Inventory
- MARKAL – Base Case
- Alternative Case(s) – Scenario-specific

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Quantitative Impacts
- MARKAL-derived growth factors
- In-house methodologies
- GREET Model (Trans.)
- Literature review results

CMAQ Model
- 12 km Resolution (4 km CA)
- CB 05 Chemical Mechanism

Quantitative Impacts
- MARKAL outputs
- GREET Model (Trans.)
- In-house methodologies
- Literature review results

Outline – Tasks

1. Methodology Development

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   - **Emphasis on power and transportation sectors**

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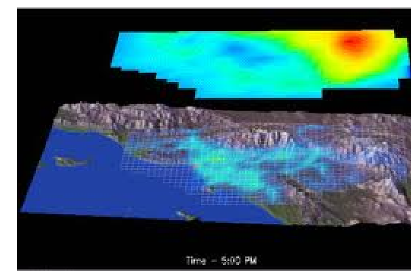

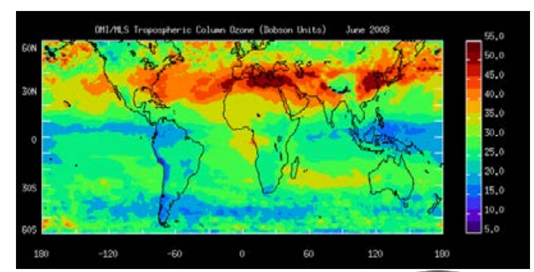

Mitigation Strategies: Transportation

Major drivers of transportation GHG emissions

- **Transport Demand**
  - Vehicle miles traveled (VMT)
- **Energy Intensity of Travel**
  - Unit fuel per mile (e.g., miles/gallon, kWhr, kg)
- **Fuel carbon intensity**
  - Life cycle GHG emission per unit fuel (e.g., gCO_2e/MJ)

Challenges

- **Current vehicles reject >60% of potential fuel energy**
  - Electric drive trains can improve efficiencies by 40-80%
- **Combustion of current fuels produces significant GHG emissions**
  - Conventional motor gasoline: 93 g CO_2eq /MJ
- **Significant growth in projected future transportation demand**
  - Growth in population, economic sectors

Mitigation Strategies: Transportation (LDV)

Life cycle GHG emissions dependent on:

– **Vehicle propulsion efficiency, utilized fuel, and production pathway**

Mitigation Strategy		Potential Reduction	Reference(s)
Efficiency Gains			
	Conventional	**5 to 50%**	[1-9]
	HEVs	**37 to 87%**	[1-3, 7, 8, 10, 11]
Hydrogen			
	HFCVs	**14 to 99%**	[1, 3, 7-24]
Electricity			
	PHEVs	**15 to 68%**	[1, 3, 7, 8, 10, 11, 25-31]
	BEVs	**28 to 99%**	[1, 7, 8, 10, 11, 32, 33]
Biofuels			
	Corn Ethanol	**+93 to 67%**	[4, 7, 11, 34-41]
	Cellulosic Ethanol	**+50 to >100%**	[3, 4, 7, 11, 35, 37, 39, 42-46]
Modal Shift		**Total Demand Reduction**	
	Various	**0.4-2%**	[47-50]

- **HDV**
  – **Increased vehicular efficiency**
  – **Transition to natural gas**

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LDV Mitigation Strategies: AQ Impacts

Fuel Production

- Spatial/temporal shift
  - PHEV, BEVs, HFCVs, Ethanol
- Paradigm shift
  - PHEV, BEVs, HFCVs, Ethanol
- Slight Reduction
  - HEV, PHEV,
- Significant Reduction
  - PHEV, BEV, HFCV, Ethanol
- Increase (potential)
  - PHEV, BEV, HFCV, Ethanol

Fuel Distribution

- Reduction in emissions
  - HEV, PHEV, BEV,
- Slight increase (potential)
  - Ethanol

Direct Vehicle

- Moderate reduction
  - HEV, PHEV, Ethanol
- Significant reduction
  - PHEV
- Complete reduction
  - BEV, HFCV
- Increase (potential)
  - Ethanol

LDV Mitigation Strategies: AQ Impacts

AQ Impacts of PHEV Deployment - EXAMPLE

- **Generally modest, but significant, spatially-dependent improvements**
  - Localized areas of worsening (power sector impacts)

Study	Direct NO_x	Direct SO_x	Direct VOC	Direct CO	Direct PM	Secondary PM	Ozone
EPRI 2007	D	D	D	N/A	I-10%	D	D -61% area I -1% area
Kintner-Meyer 2007	I- Coal D-No coal	I-75% area	D-93%	D-98%	I-67% area	N/A	N/A
Parks 2007	D- small	D-some I-some	N/A	N/A	N/A	N/A	N/A
Thompson 2009	I-night D- day	I-Potential	I-night D- day	I-night D- day	I-Potential D- Potential	I- SO_x related D- Potential	D- 2-6 ppb Localized I < 8 ppb
Brinkman 2010	D	N/A	N/A	N/A	N/A	N/A	D - <2-3 ppb Localized I- small

I: Increase
D: Decrease
N/A: Not studied

Mitigation Strategies: Power Sector

Major drivers of power sector GHG emissions

- **Power Demand**
  - Total demand for power (e.g., MWhr)
- **Efficiency of generation**
  - Unit power generated per unit fuel input (e.g., MWhr/MJ)
- **Fuel carbon intensity**
  - Life cycle GHG emission per unit fuel (e.g., gCO_2e/MJ)

Challenges

- **Current U.S. system dominated by fossil fuel generation**
  - 67% provided from coal(42%) and natural gas (25%)[1]
- **Combustion of current fuels produces significant emissions**
  - Coal: 944 g CO_2eq /MJ
- **Significant growth in projected future power demand**
  - Growth in population, economic sectors

[1] U.S. EIA 2012

Mitigation Strategies: Power Sector

Life cycle emissions dependent on fuel/conversion pathway

– **Traditional Coal: 687-1689 $gCO_2eq/kWhr$ (Average: 944) [1-8]**

Mitigation Strategy		LCA Emissions [$gCO_2eq/kWhr$]	GHG Reduction [Average Coal]	Reference(s)
Gas-Fired Power		390 to 682	**28-76%**	[1-4, 9-13]
Nuclear Power		3.5 to 220	**77% to >>99%**	[3, 4, 9, 11, 14-20]
Renewable Power				
	Wind	3 to 40	**96-99%**	[3, 4, 10, 11, 21-31]
	Solar PV	19 to 104	**89-98%**	[4, 30, 32-40]
	Solar CST	12 to 241	**74-99%**	[41-46]
	Biopower	-633 to 390	**62-100%, 163-245%**	[3, 30, 47-64]
	Geothermal	5 to 57	**94-99%**	[4, 27, 65, 66]
	Ocean	2-56	**94-99%**	[27, 67, 68]
CCS				
	Coal (PC)	41-844	**50-94%**	[6-8, 73-76]
	NG	47-280	**59-88%**	[7,8, 73-75]

- **Efficiency Improvements (Generation, T&D, End-use)**
  – **Reduce required generation ≤ 30% [77-85]**

Mitigation Strategies: Natural Gas

- **NG considered viable power mitigation strategy in select regions**
  - **Significant projected expansion from increased domestic production**
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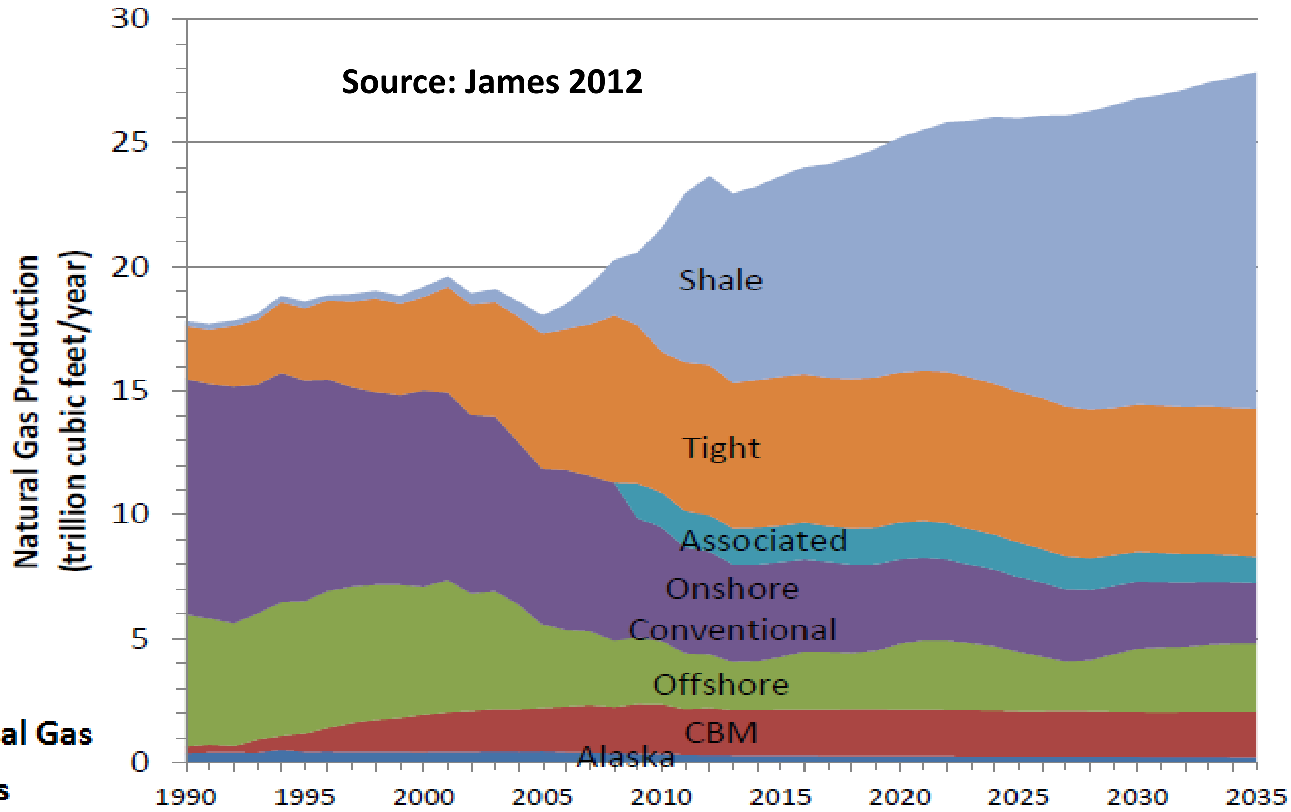

Traditional Gas
Shale Gas
Coal

NGCC:Natural Gas Combined Cycle
PC: Pulverized Coal
IGCC:Intergrated Coal Gasification Cycle
CCS: Carbon Captures Sequestration

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Power Mitigation Strategies: AQ Impacts

- **AQ impacts generally favorable**
  - **Efficiency measures reduce emissions via reductions in generation**
  - **Transition to low carbon fuels generally associated with reductions in criteria pollutant emissions**
    - Nuclear, renewable technologies
- **Dynamic power system impacts associated with intermittent nature of renewables necessitates co-deployment of back-up**
  - **Reduced net emission reductions of GHG and pollutants**
- **Impacts associated with deployment of CCS**
  - **Efficiency losses from associated processes**
    - Fleet-wide increases in emissions of some pollutants (e.g., NO_x)
  - **Impacts of capture processes reduces**
    - Generally associated with decreases in PM, SO_x

AQ Impacts: CCS Deployment

Potential for positive and negative impacts (species dependent)

- **Efficiency penalty necessitates increased fuel utilization**
  - Increased criteria pollutant emissions fleet-wide (NO_x ,CO)
- **Capture process effectively reduces some emissions**
  - PM, SO_2

Technology	Net CO_2 Reduction	NO_x	SO_2	CO	VOC	P.M.	References
Pulverized Coal	82-84%	+(24)%	-(61-96%)	---	---	-(29-35)%	[1,2,5]
Super-critical P.C.	72-87%	+(25-44)%	-(61-95%)	---	---	-(35-49)%	[2,3,5]
IGCC	81-88%	+(18-20)%	+(10-19%)	---	---	-(0-41)%	[2,3,5]
NGCC	59-83%	+(5-17)%	+(0-21%)	+0-19%	+(0-17%)	-42 to +25%	[1-5]

[1] Tzimas 2007, [2] Odeh & Cockerill 2008, [3] Singh 2011, [4] James, Ralph NETL 2012, [5] Sathre 2011

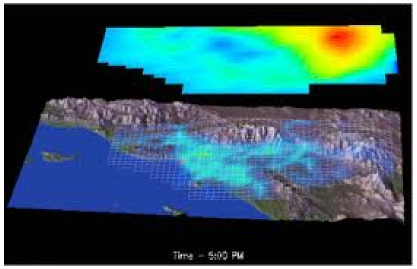
Outline – Tasks

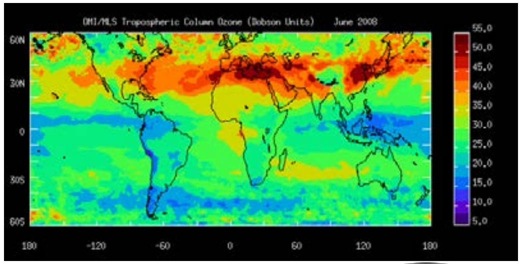
1. Methodology Development

2. Technology Assessment
   - Emphasis on power and transportation sectors

3. **Evaluation of GHG and AQ Impacts**
   - **Development and assessment of scenarios**

4. Air quality model sensitivity
   - Impacts of climate change



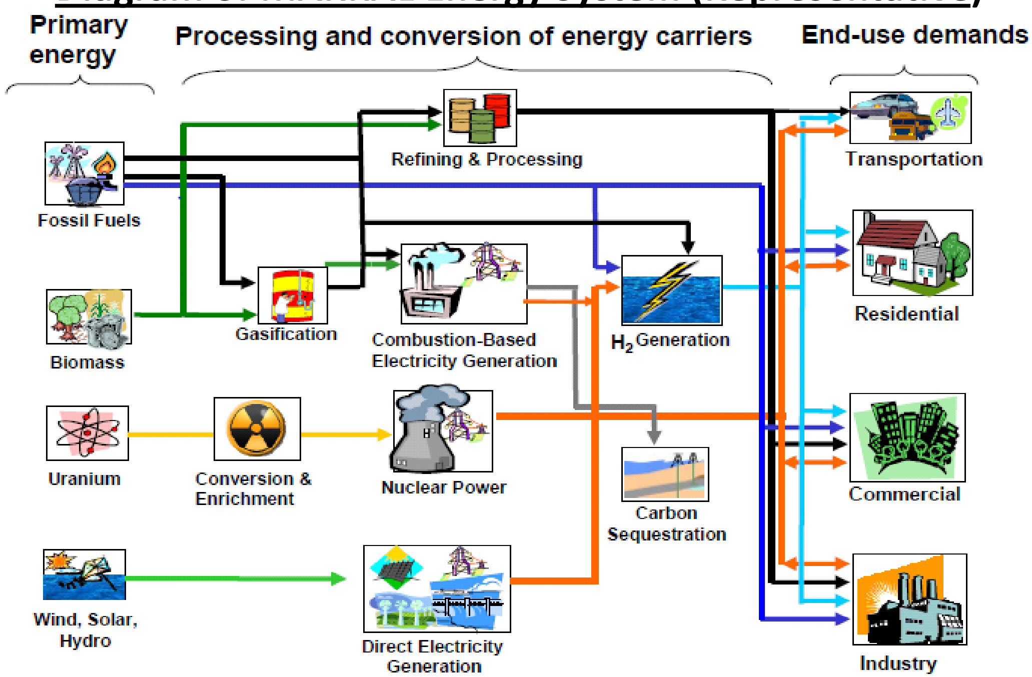


Base Case Development

Initial base case developed via MARKAL (Dan Loughlin, EPA)

- **Represents energy system evolution to targeted horizon (2050)**
  - EPA U.S. 9-region MARKAL database
- **Base case represents business-as-usual (BAU) assumptions**
  - Calibrated to AEO 2010, projected to 2055

Diagram of MARKAL Energy System (Representative)

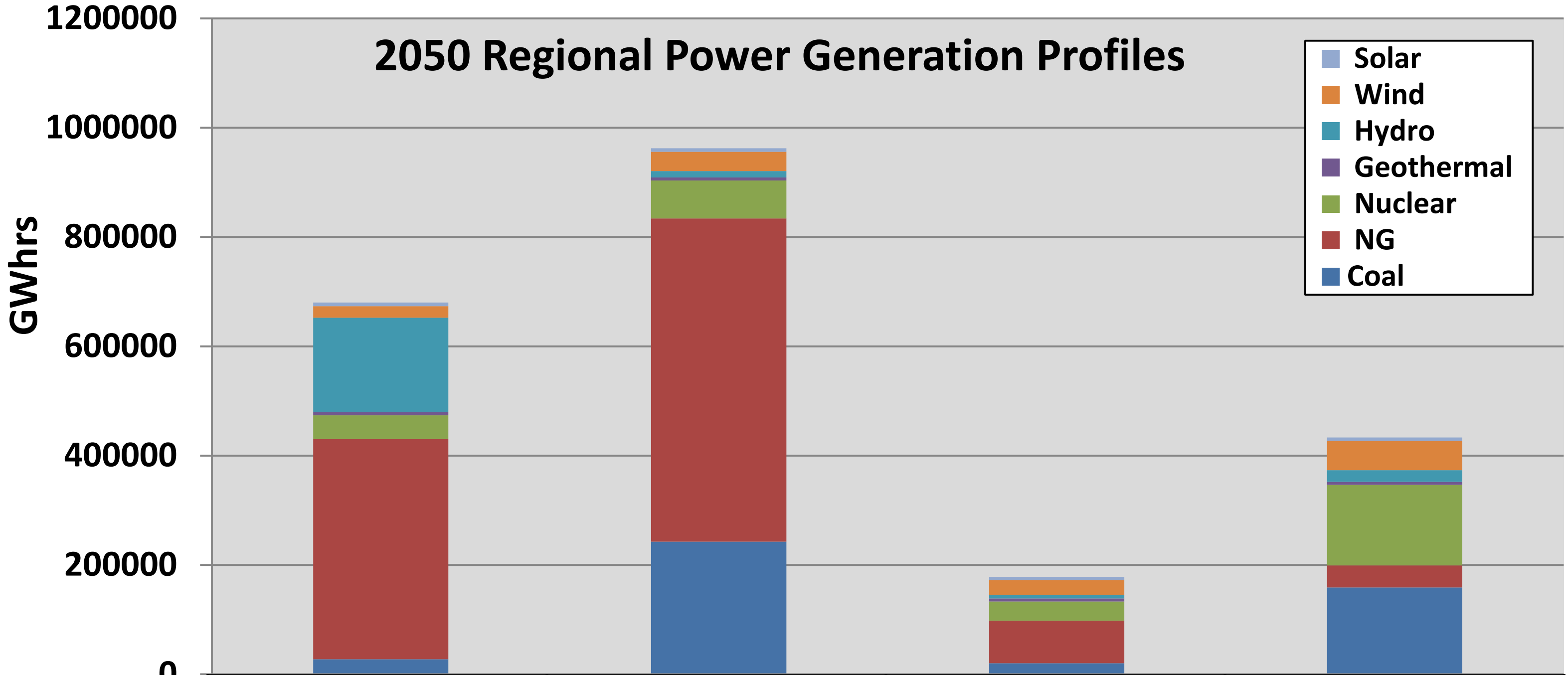


Source: Loughlin et al. 2011

Base Case Power Generation

Significant regional variation in technology and fuels

- Gas-fired generation growth substantial in most regions
- Coal in TX and NEUS R2 (offset in NEUS by significant nuclear power)
- CA and R1 relatively clean grid mixes

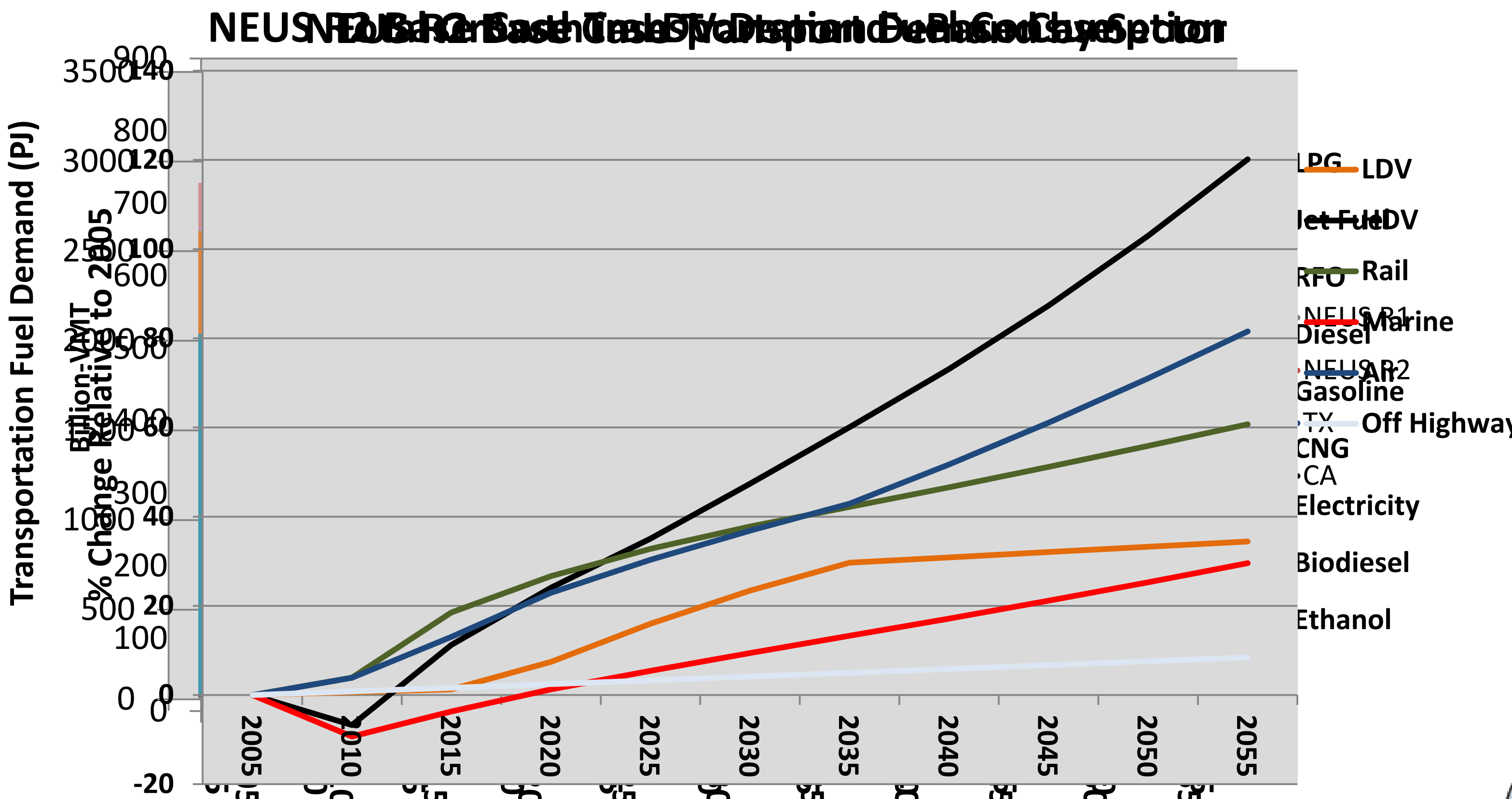


	CA (R9)	TX (R7)	NEUS (R1)	NEUS (R2)
g CO_2/kWh	243	466	228	310

Base Case Transportation

Regional demand increases significantly in Base Case

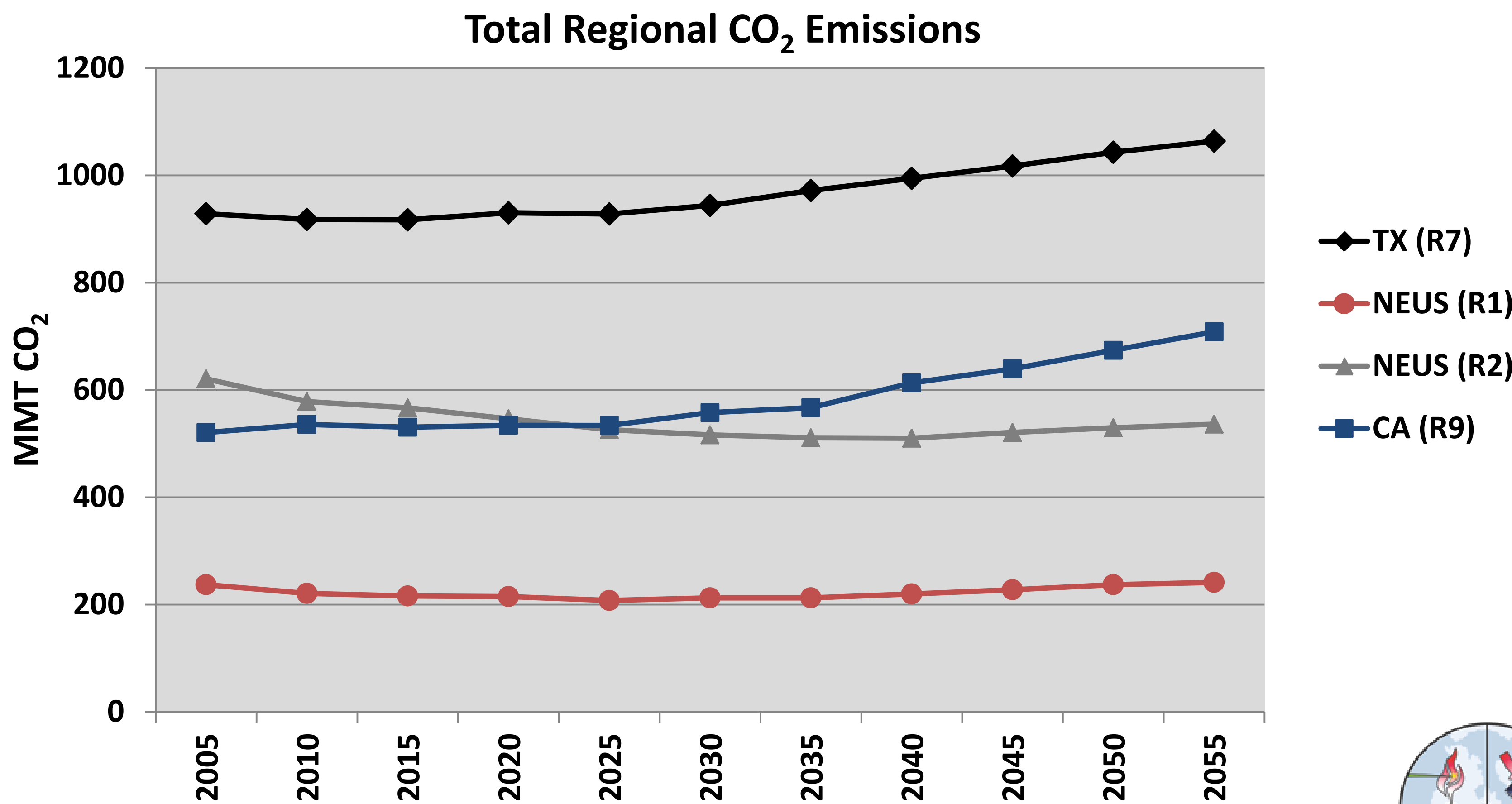
- Fuel consumption off-set by vehicle efficiency improvements
- Low penetrations of alternative fuel use in LDV sector



Base Case GHG Emissions

General moderate increases in regional CO_2 emissions in Base Case

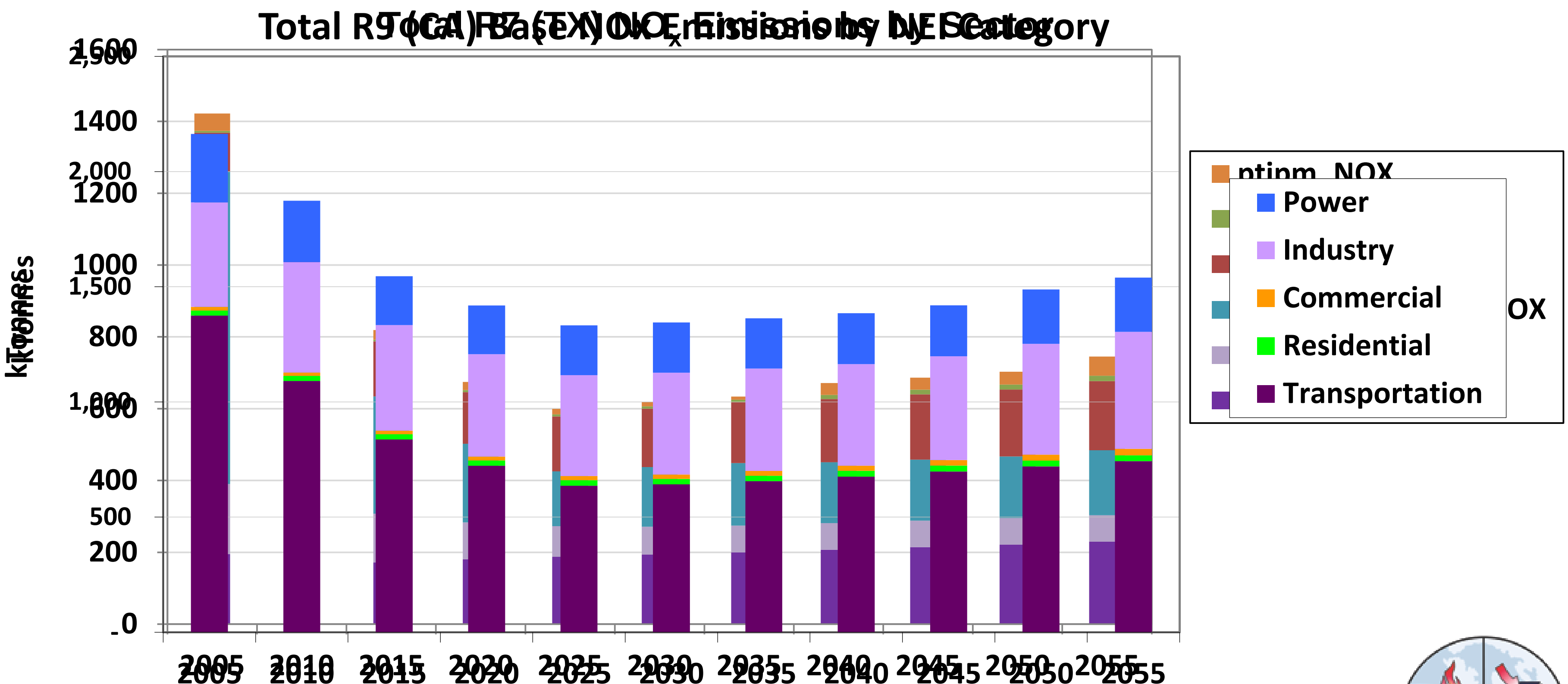
- NEUS R2 experiences moderate decrease



Base Case NO_x Emissions

Significant decrease in total regional emissions

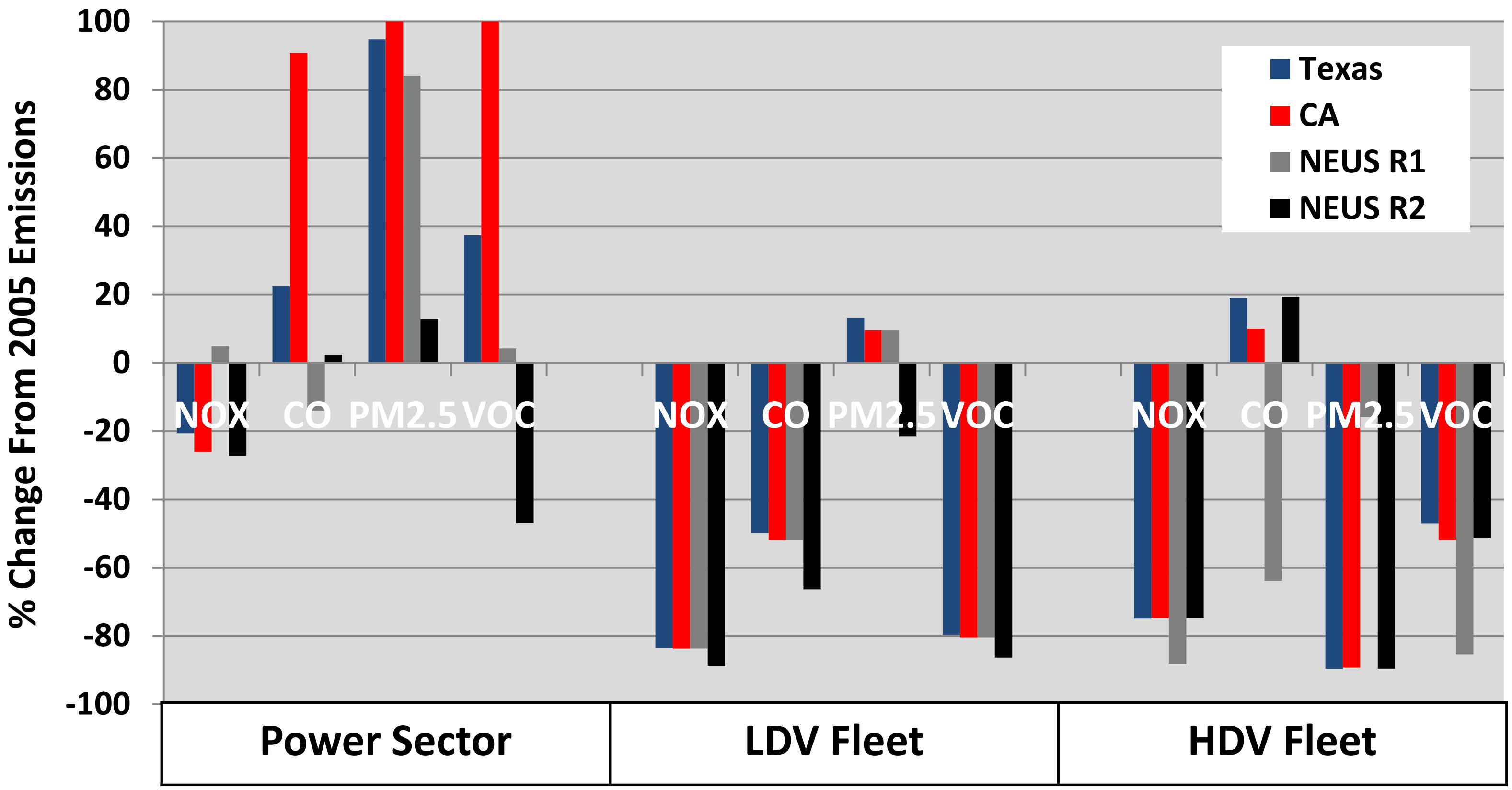
- **Large reduction from transportation sector**
  - On-road (LDV, HDV) contribute largest fraction



Base Case Pollutant Emissions

2050 Base Case Pollutant Emissions

- Power → reductions in NO_x, increases in other pollutant emissions (CSAPR)
- Transportation →significant reductions in LDV and HDV fleet emissions

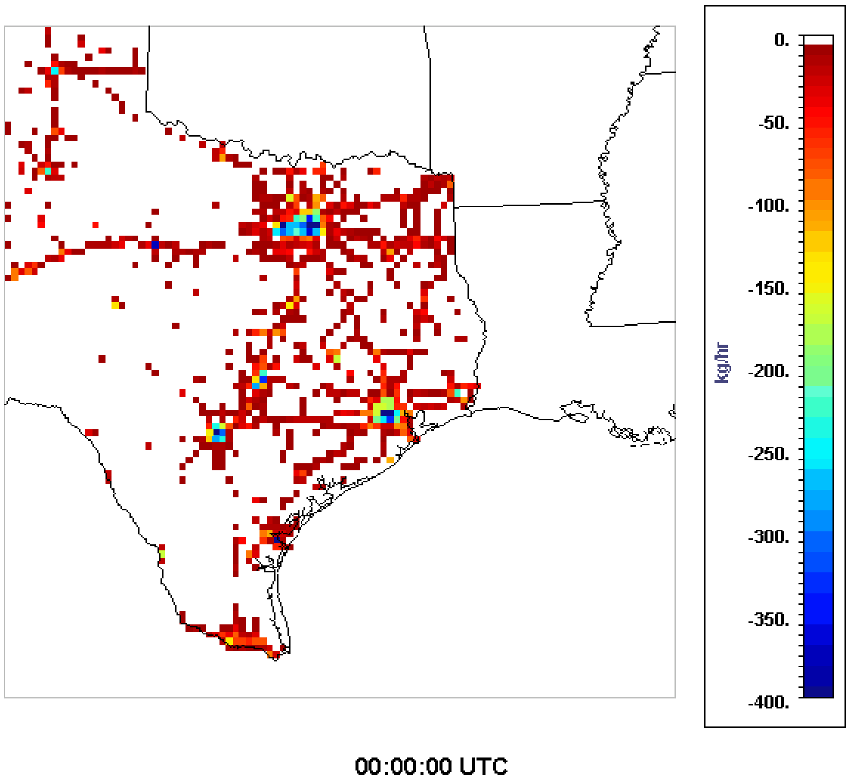


Base Case Pollutant Emissions (TX)

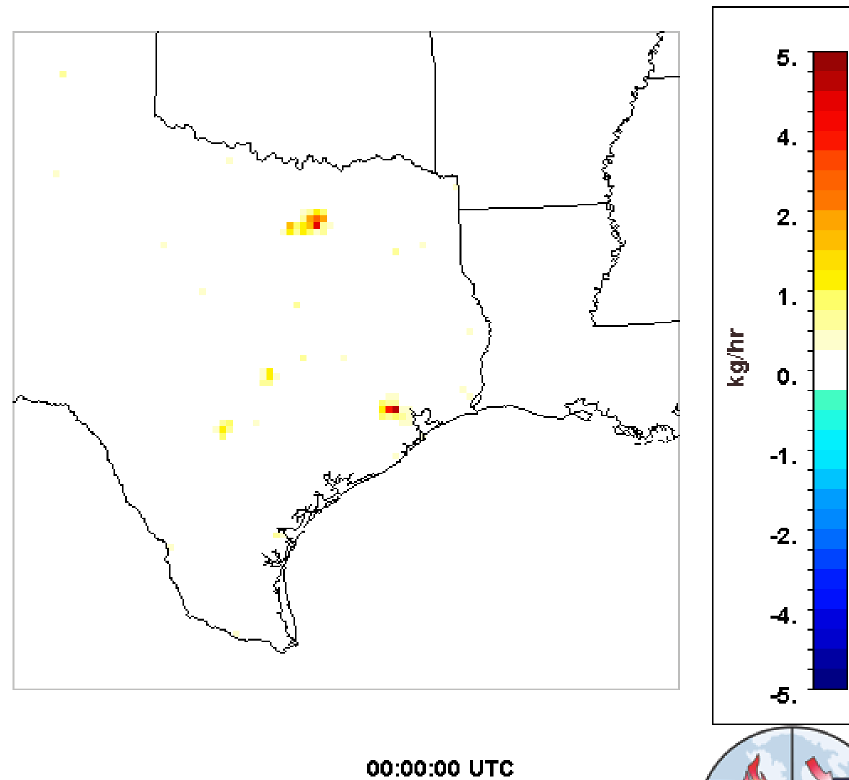
Species, spatial, and temporal-dependent increases & decreases

– **NO_x: ≤ -900 kg/hr**
– **Direct PM: ≤ +5 kg/hr**

Difference in NO_x Emissions (2005 to 2050)



Difference in PM Emissions (2005 to 2050)

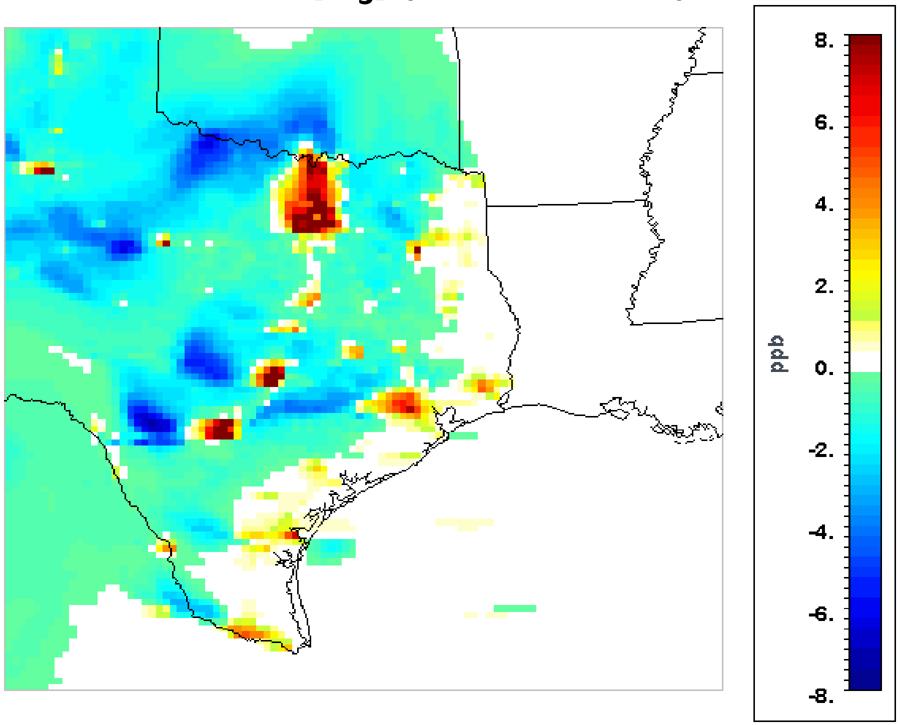


Base Case Air Quality (TX)

Base Case AQ from 2005 to 2050

- Ozone: -16 to +7.5 ppb
- $PM_{2.5}$: -3 to +.3 µg/m^3

Difference in $[O_3]$ (2005 to 2050)



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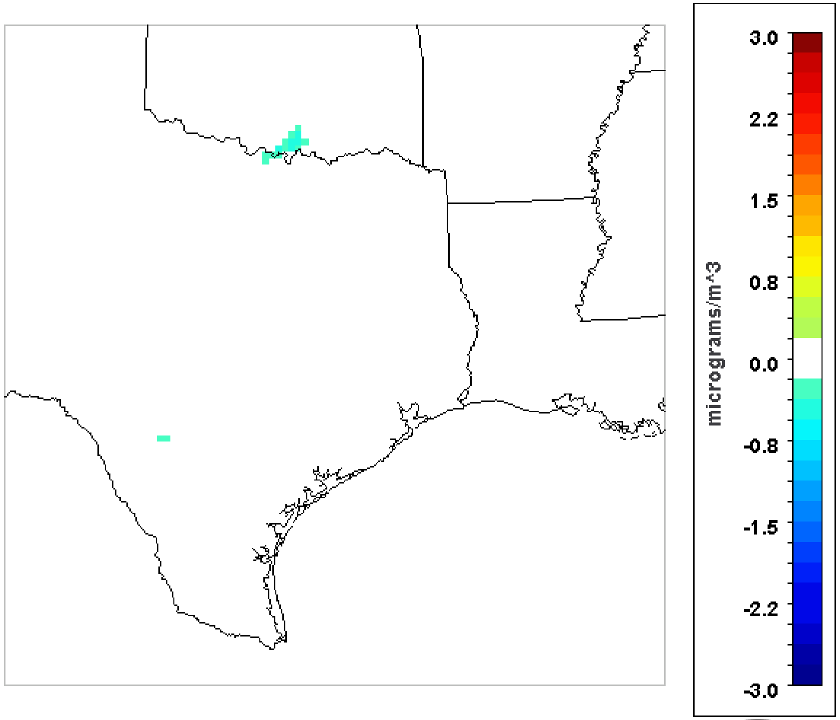
Difference in $[PM_{2.5}]$ (2005 to 2050)



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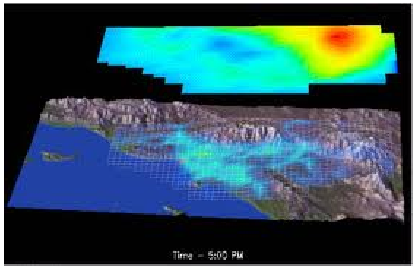
Outline – Tasks

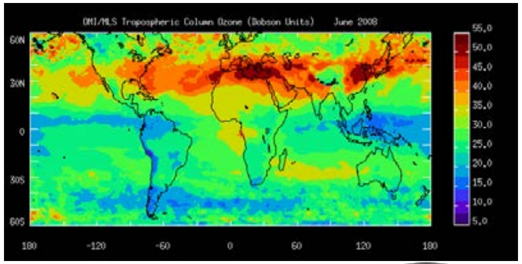
1. Development of methodologies to facilitate achievement of project objectives and goal

2. Assessment of technologies comprising GHG mitigation strategies
   – Emphasis on power and transportation sectors

3. **Assessment of GHG and AQ impacts from mitigation strategy deployment**
   – **Power generation sector**
   – **Transportation sector**

4. Air quality model sensitivity
   – Meteorological and boundary conditions affected by changes in global climate and the global economy

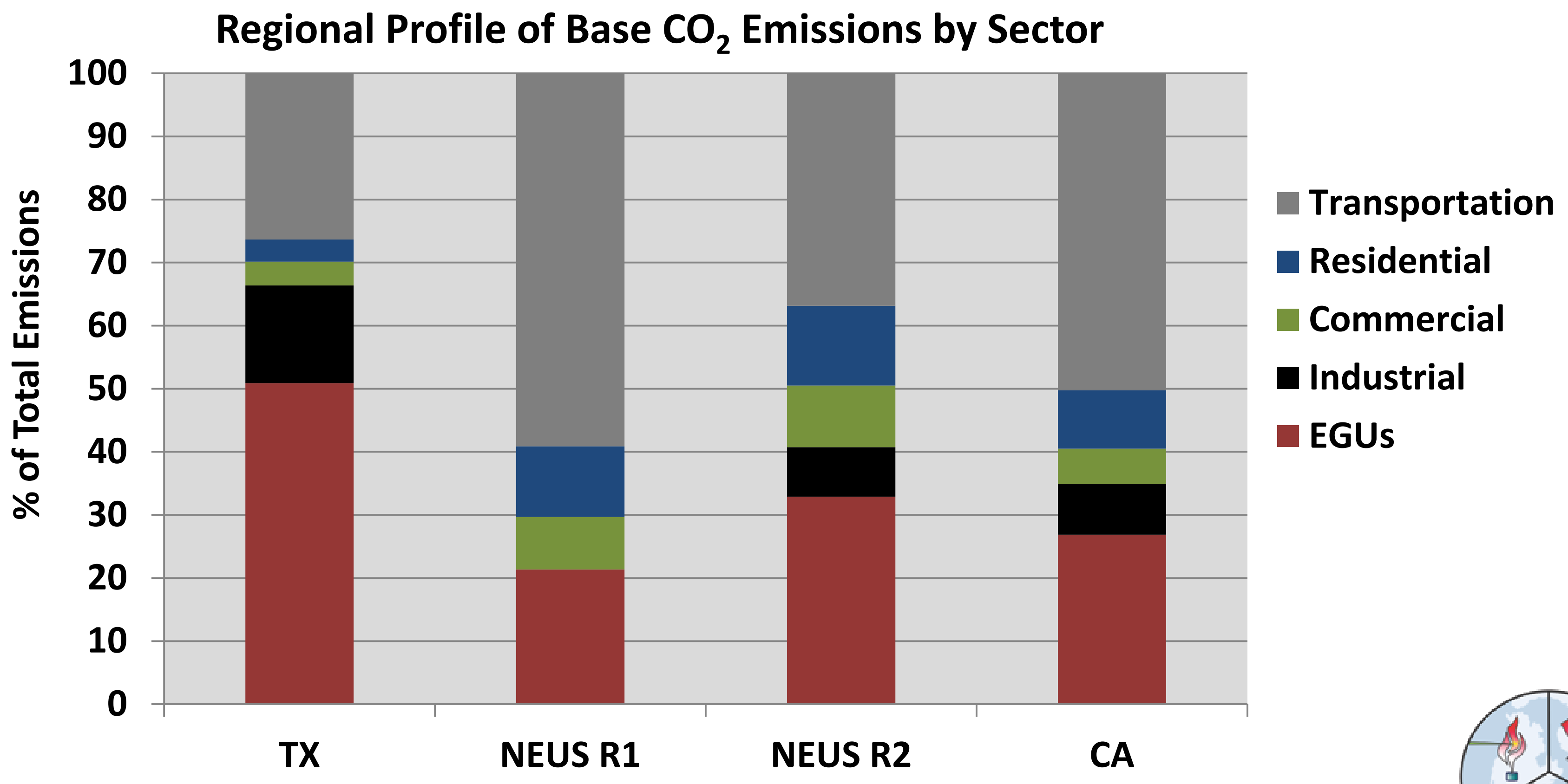




Base 2050 GHG Emissions

Initial focus on power and transportation sectors

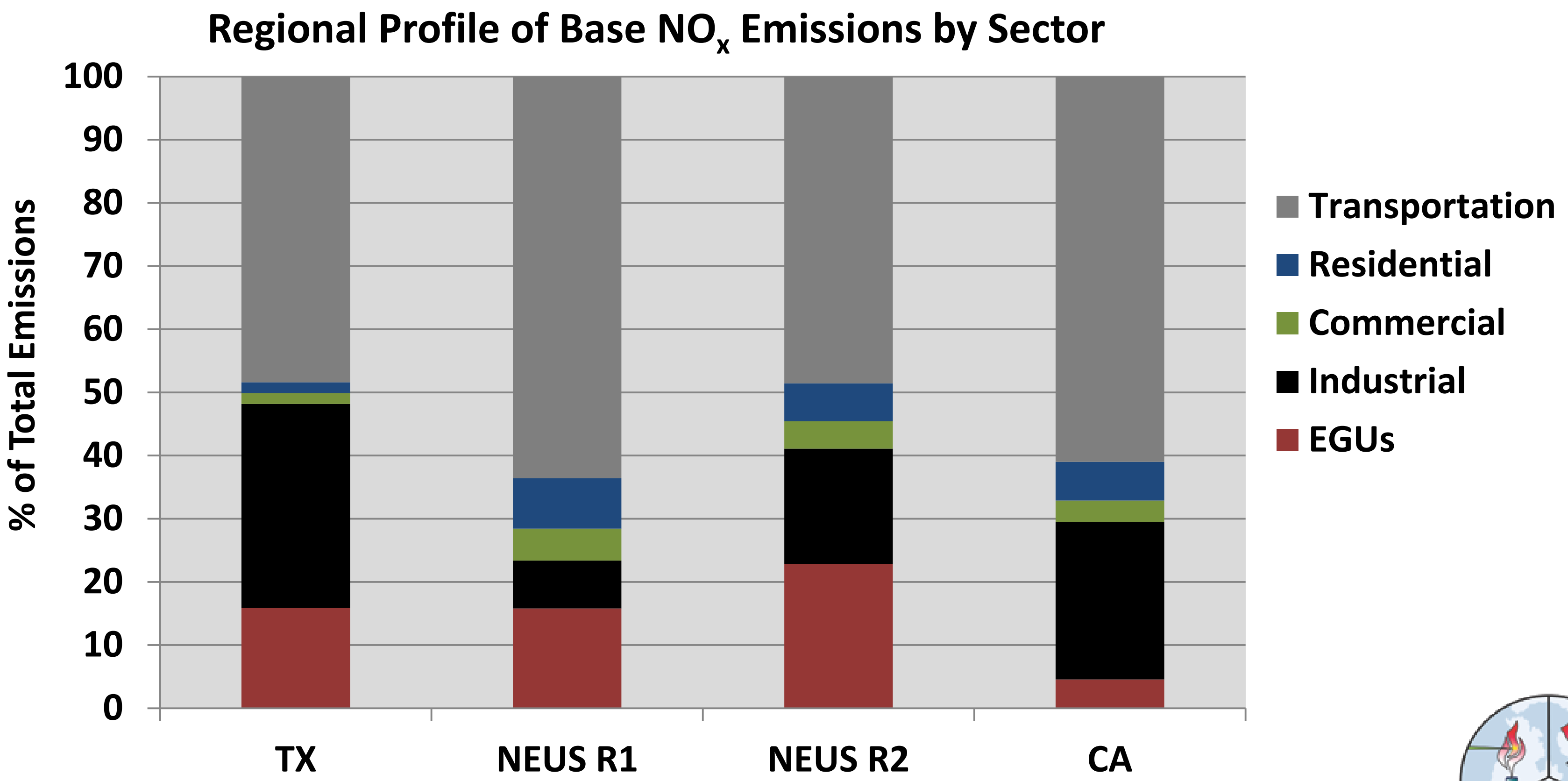
- **Other sectors have significant regional impacts**
  - Industrial (TX), Residential (NEUS)



Base 2050 NO_x Emissions

Transportation major contributor

– **Industrial emissions contribute significantly in all regions**



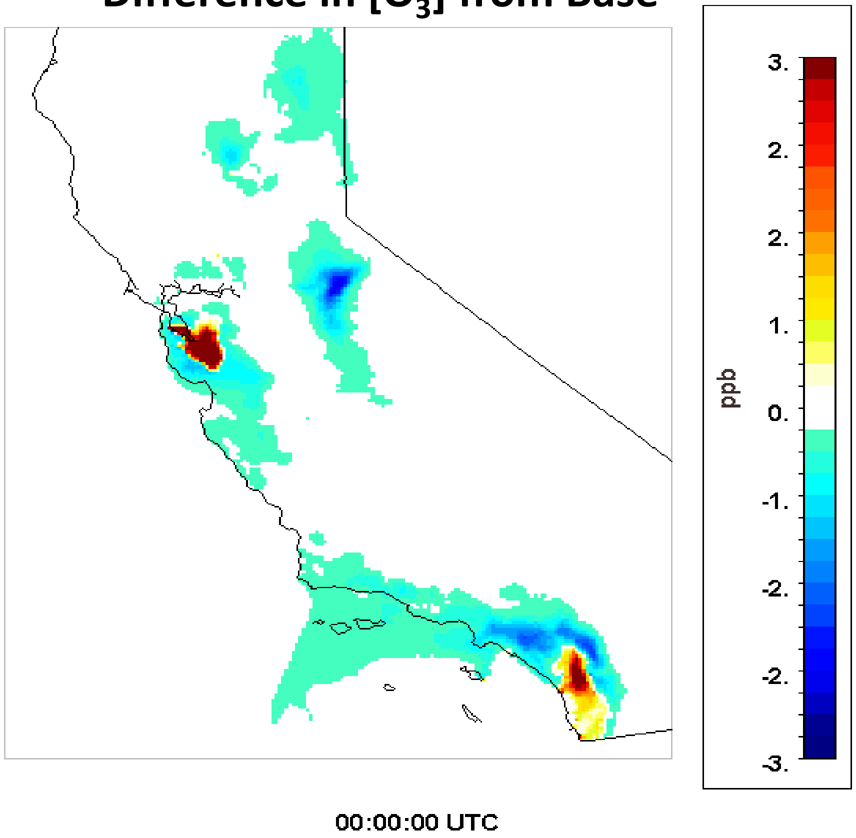
Power Sector AQ Impacts

AQ impacts driven by NO_x reduction

- **Reductions in Peak $[O_3]$**
  - CA: -3 ppb
  - TX: -16 ppb
  - NEUS: -9 ppb
- **Reductions in Peak $[PM_{2.5}]$**
  - CA: -6 µg/m^3 **(localized)**
  - TX: -2 µg/m^3
  - NEUS: -6 µg/m^3

- **Regional variation evident**
  - **CA impacts lower than other regions**
    - High penetration of renewables
  - **Impacts of coal power significant**
    - NEUS, TX

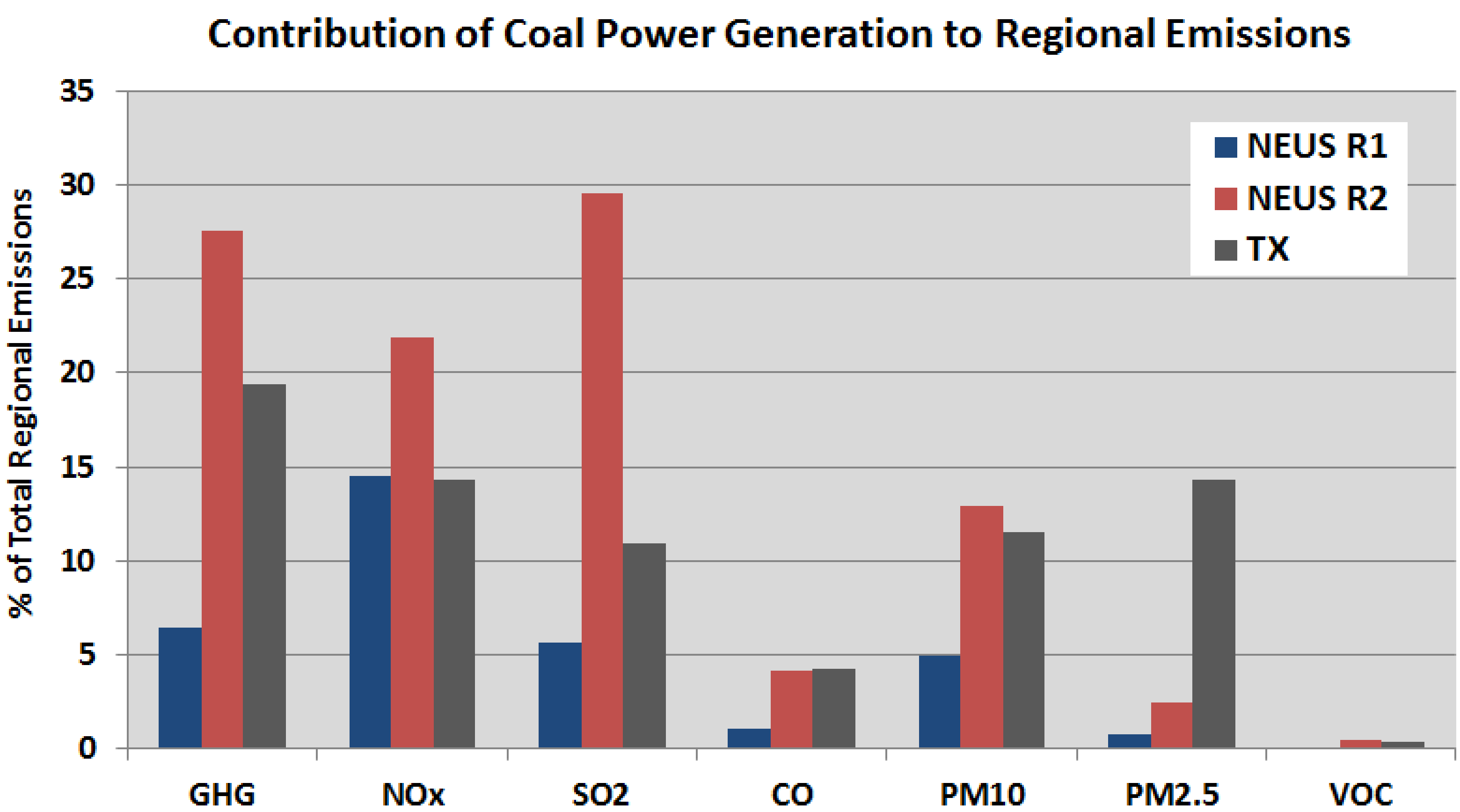
Difference in $[O_3]$ from Base



Impacts of Coal Generation

Impacts of coal power continue to be significant (NEUS, TX)

- **Share of total generation →TX: 25%, NEUS R1: 11%, NEUS R2: 36%**

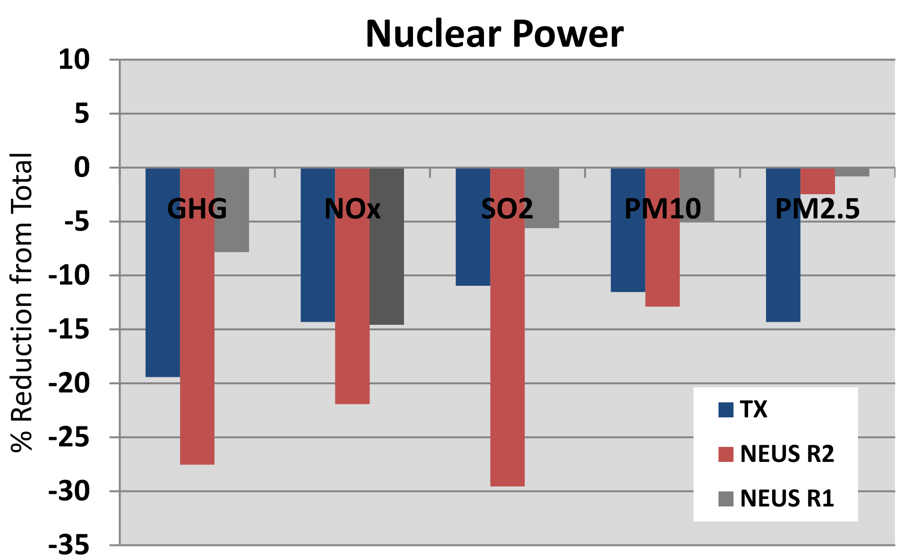


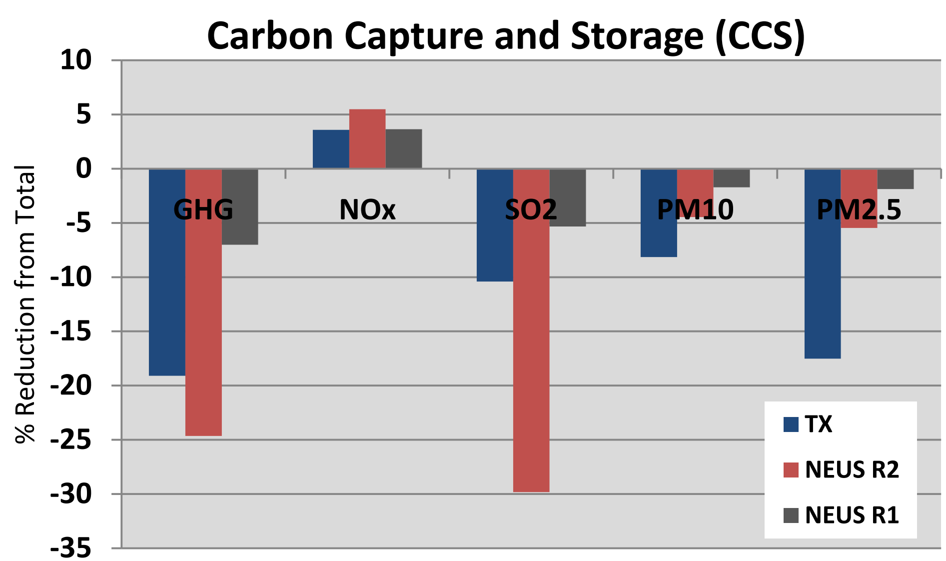
Power Sector Scenarios

Nuclear offers emissions benefits relative to CCS deployment

- **GHG emissions comparable to slightly favorable**
- **Criteria pollutant emissions generally favorable**
  - SO_2 equivalent, $PM_{2.5}$ reductions higher for CCS

Regional Emissions Impacts From Replacement of Coal Power



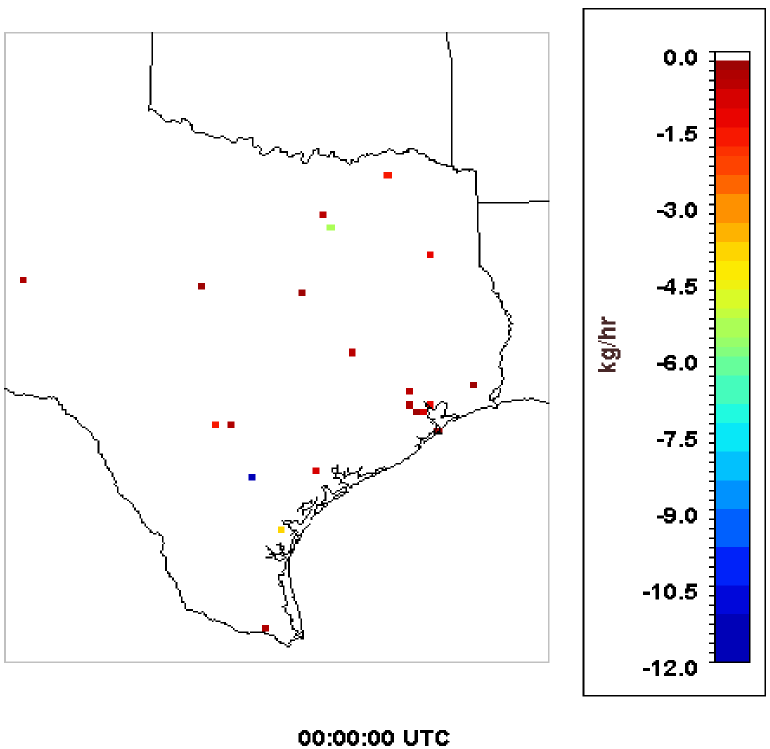


Nuclear Power AQ Impacts

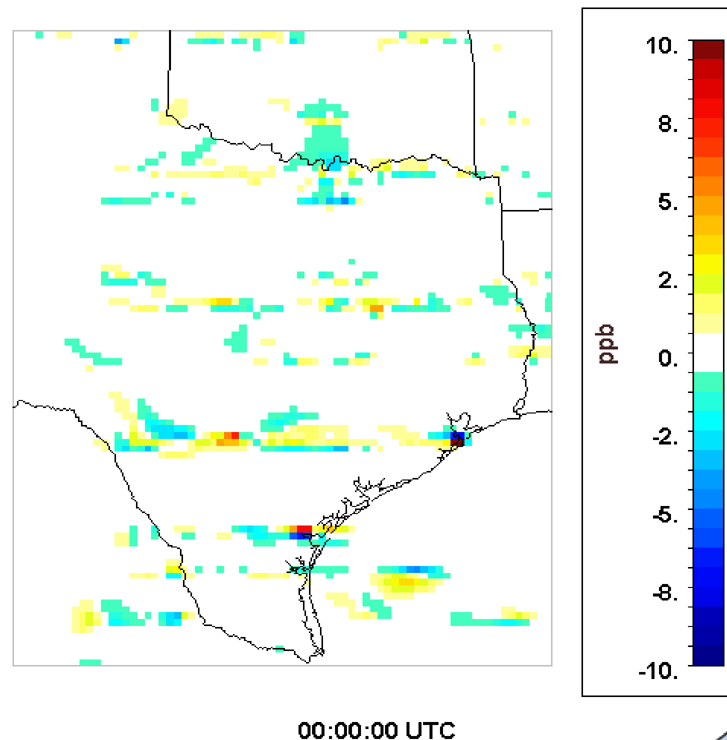
Improvements spatially correlated with coal plant locations

- Peak ozone: -12 ppb
- Peak $PM_{2.5}$: -4 μg/m^3

Difference in NO_x Emissions



Difference in $[O_3]$ From Base



Transportation Sector AQ Impacts

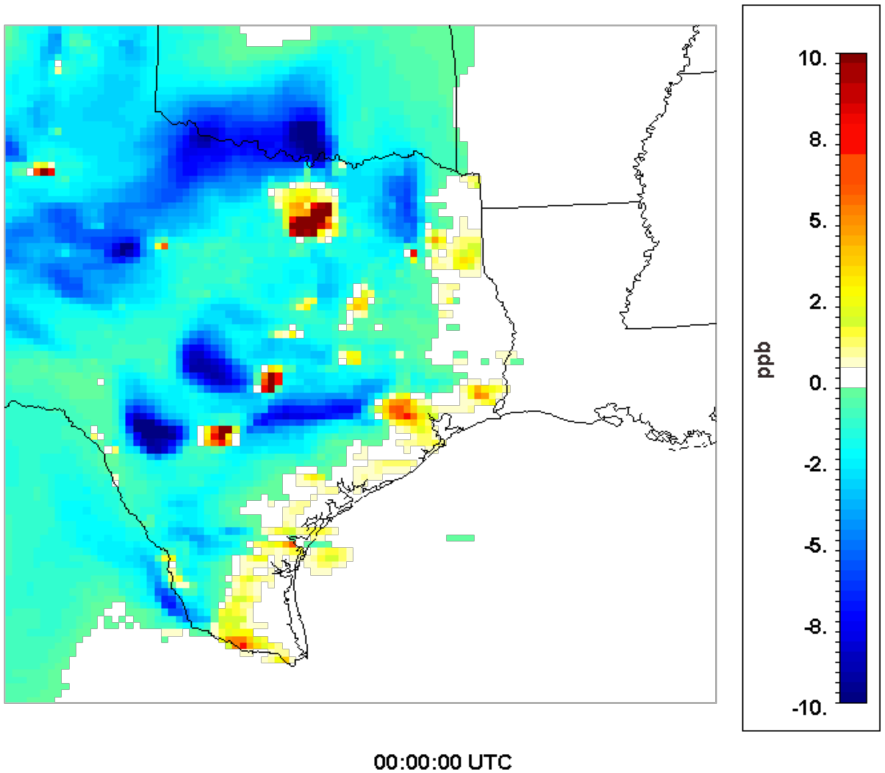
AQ significantly impacted despite net emissions reductions

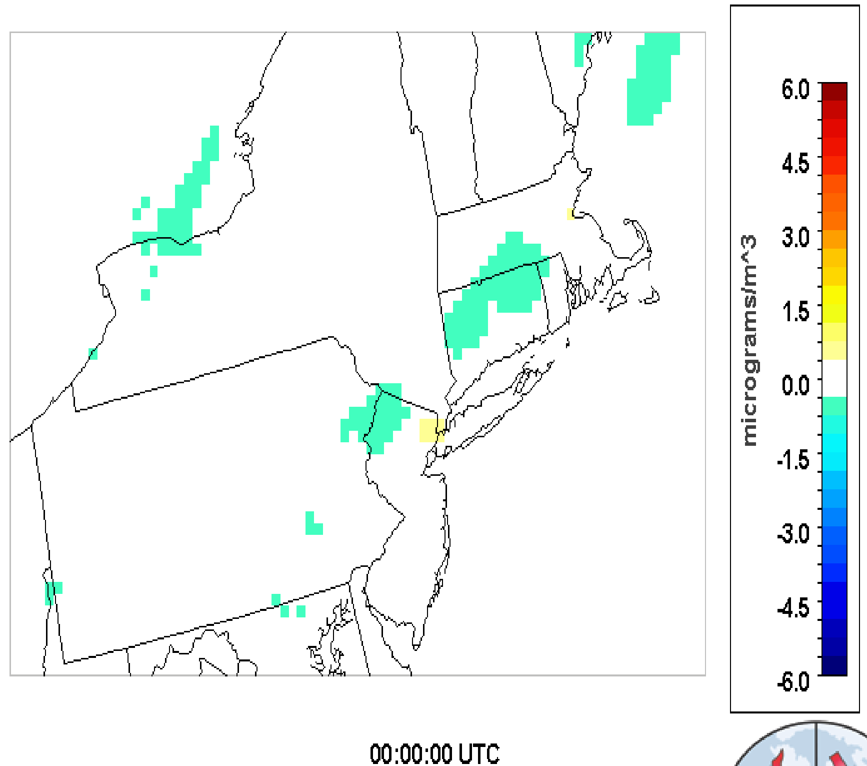
Reductions in Peak [O_3]

- CA: -6 ppb
- TX: -15 ppb
- NEUS: -24 ppb

Reductions in Peak [$PM_{2.5}$]

- CA: -6 μg/m^3
- TX: -4 μg/m^3
- NEUS: -8 μg/m^3



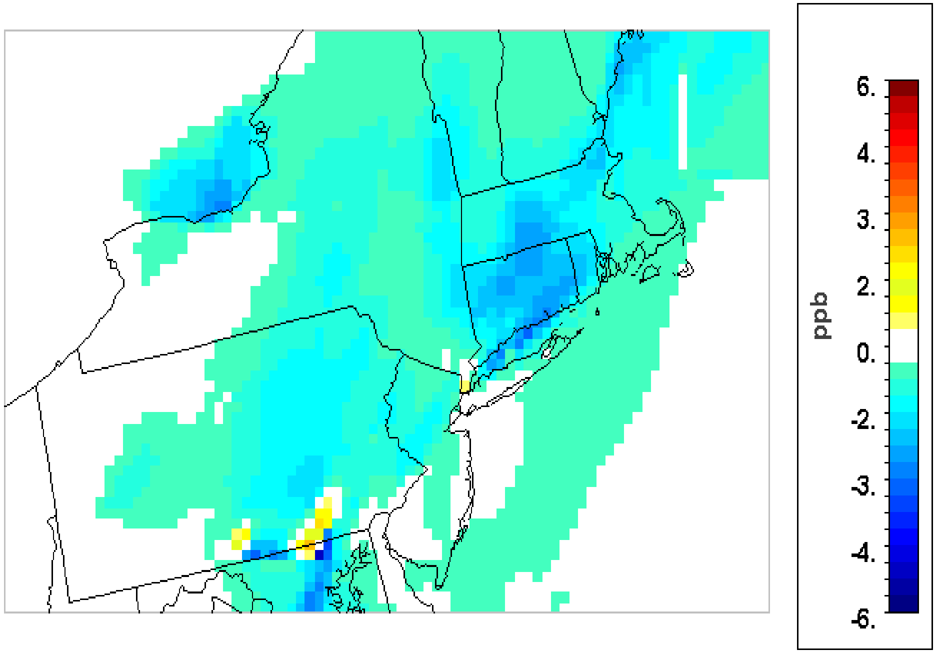


Transportation Sector AQ Impacts

AQ effects of LDV impacted by fleet evolution

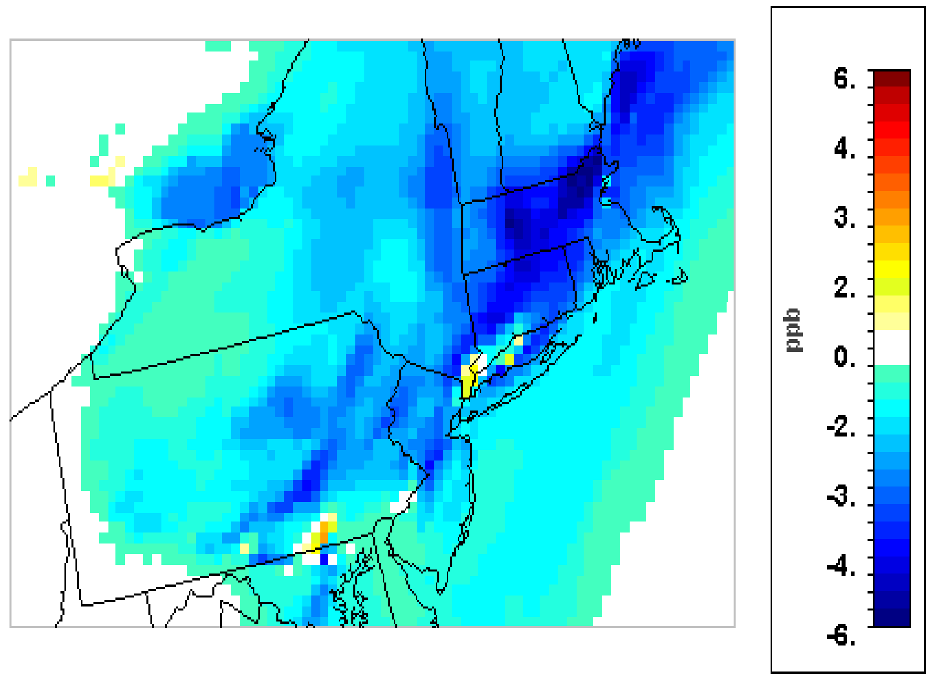
- **Improved conventional vehicle (CV) emissions performance**
  - Increases the relative importance of non-LDV transportation technologies

Difference in [O_3] (No LDV Relative to Base)



4 P.M.

Difference in [O_3] (No Non-LDV Relative to Base)



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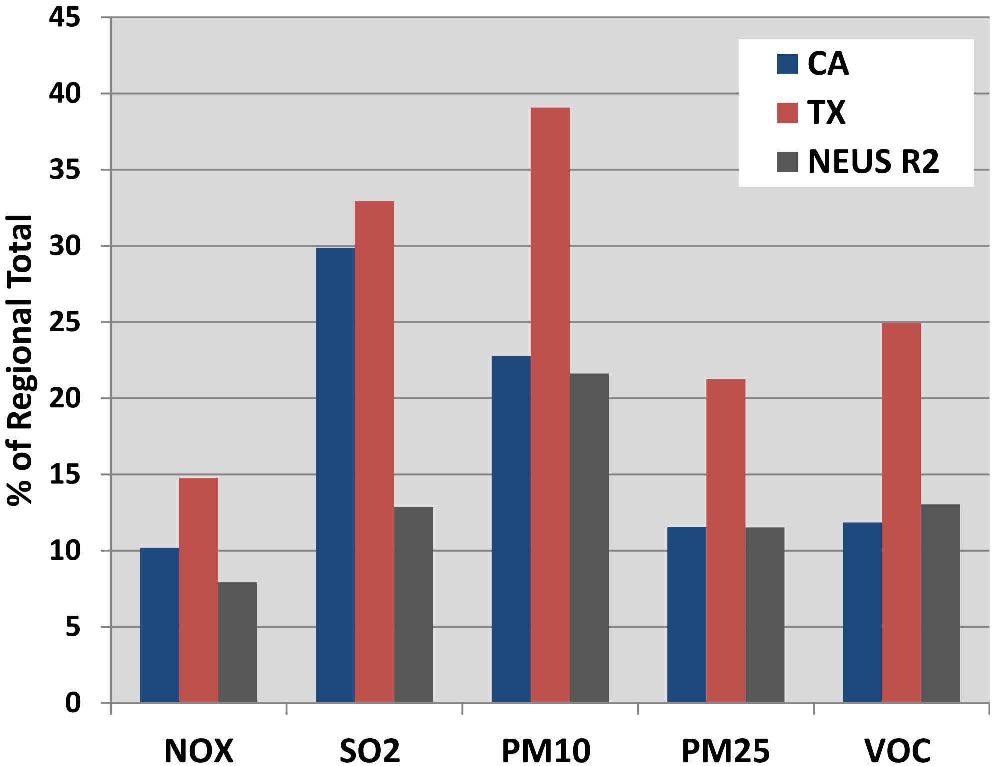
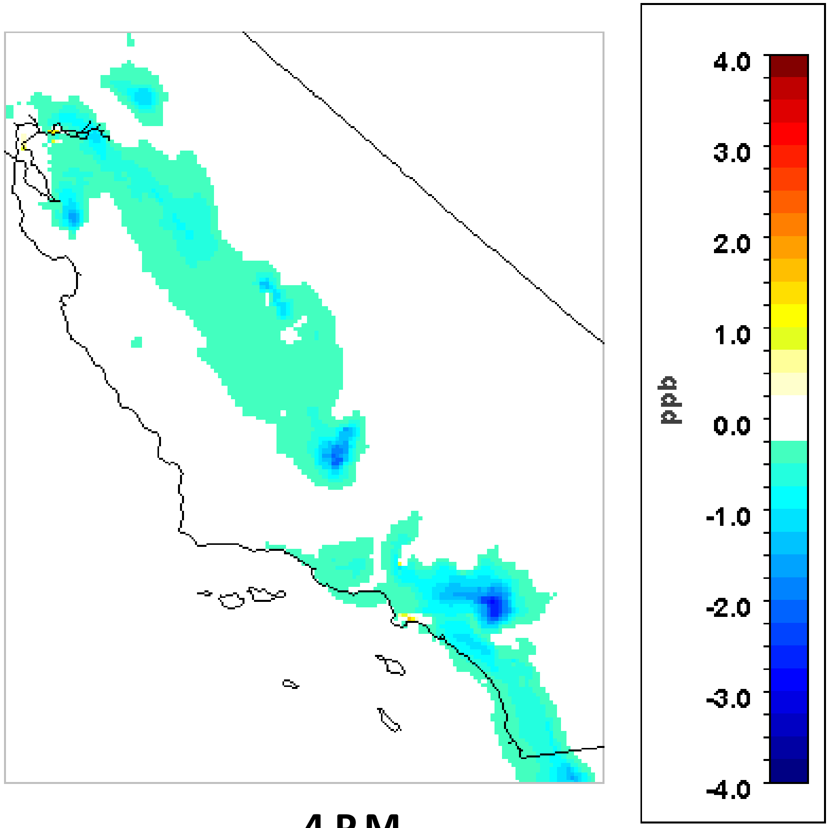
Transportation Sector AQ Impacts

Petroleum fuel refining activities significantly impact AQ

Contribution of Refinery Emissions to Regional Total



Difference in [O_3] (No Refining relative to Base)



4 P.M.

High Efficiency Case

Transportation

- **LDV[1-3]**
  - Fleet-wide efficiency 45 → 60 mpg (34% improvement)
  - Total demand (VMT) → 10% reduction [1-3]
- **HDV[1,4]**
  - Fleet-wide efficiency 23 →26 mpg (14% improvement)
  - Total demand → 20% reduction
- **Air, Marine, Rail, Off-road**
  - Total demand → 20% reduction
- **Refinery/Fuel Transport & Storage/Refueling Emissions**
  - -24% from decreased fuel usage

Power Generation

- **Total Demand →30% reduction[5-7]**

Residential/Commercial/Industrial

- **Total Demand →30% reduction**
  - E.g., lighting, appliances, heat/cool

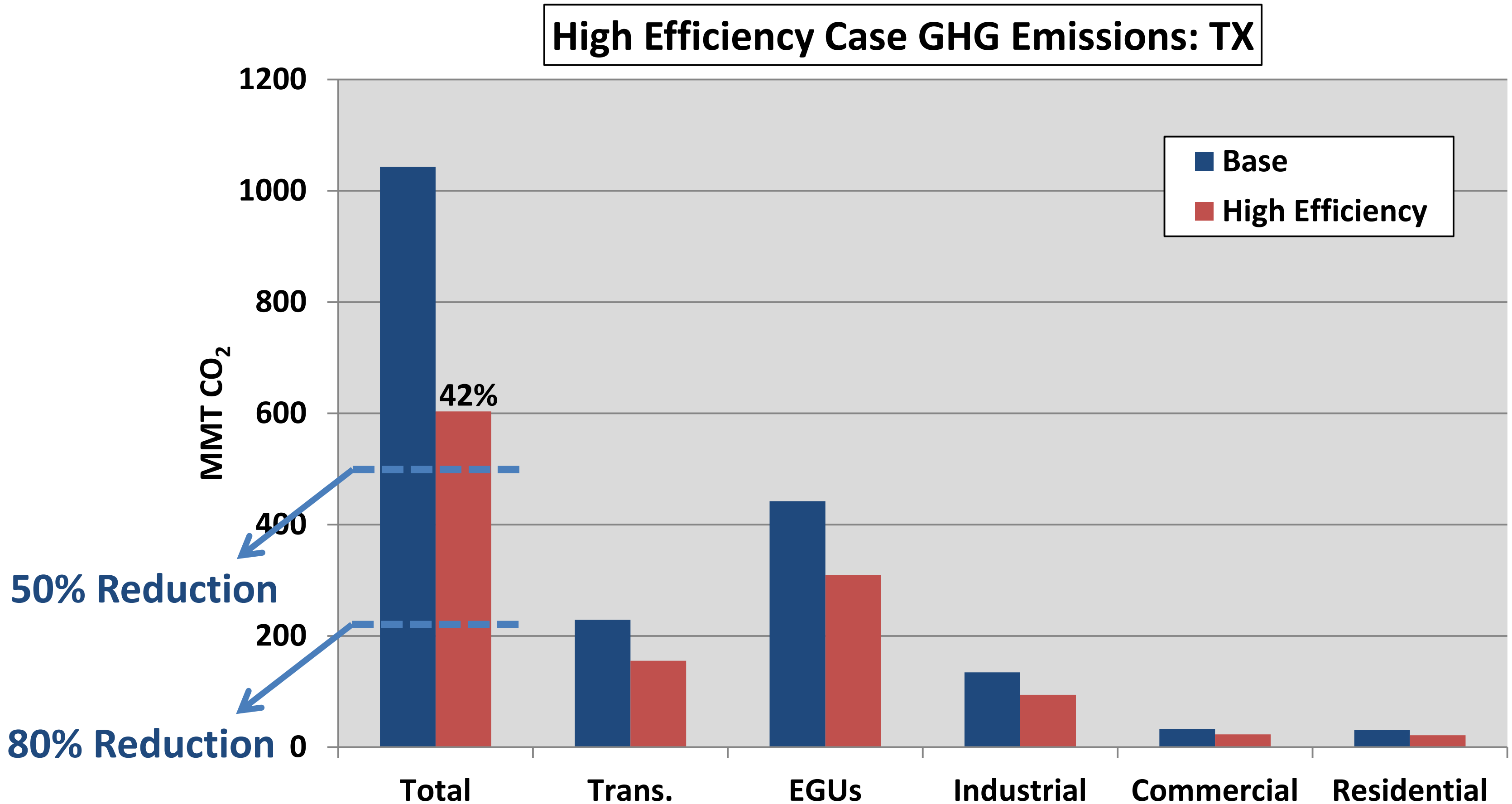
References

[1] Greene 2011
[2] Melaina 2011
[3] NRC 2009
[4] Williams 2012
[5] Google 2009
[6] U.C.S. 2009
[7] Greene 2009

High Efficiency GHG Impacts

Efficiency measures can significantly reduce emissions

- 42% reduction in total CO_2 emissions (TX)
- Upper bound case

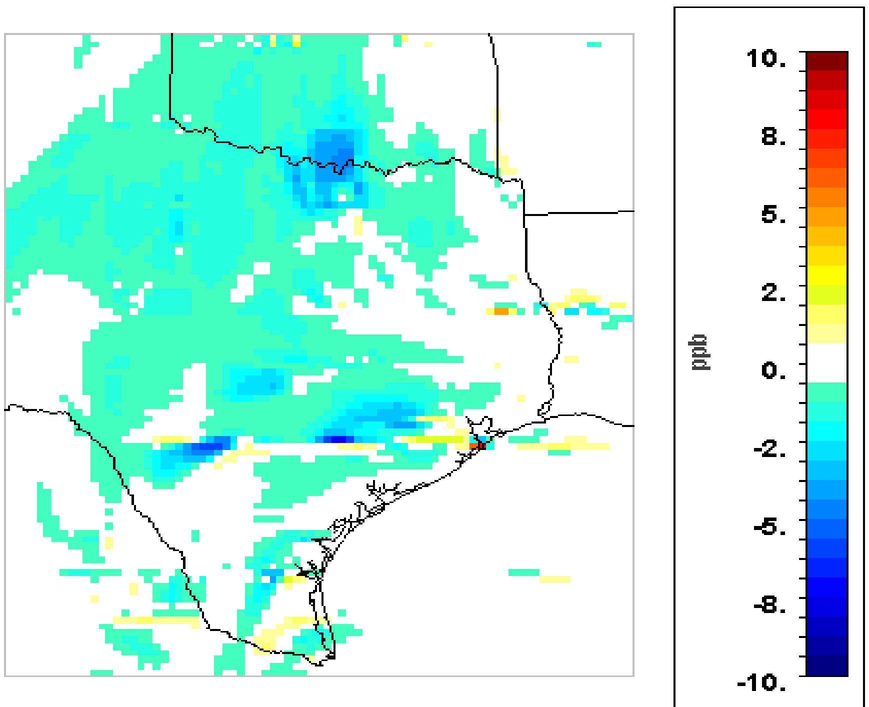


High Efficiency AQ Impacts

AQ improvements in HE Case Relative to Base Case

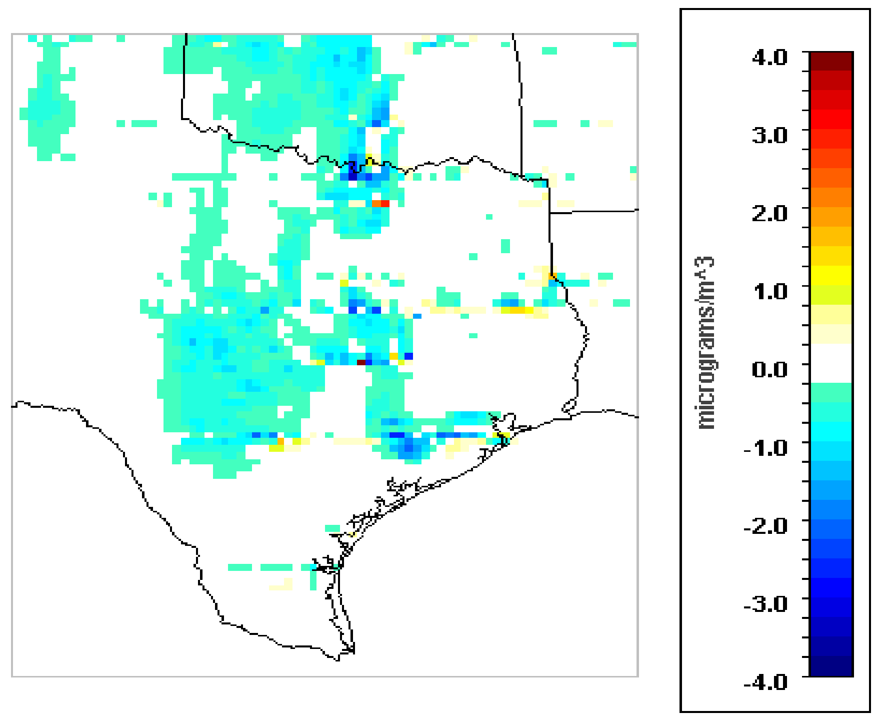
- Peak Ozone: -11 ppb
- Peak $PM_{2.5}$: -4 μg/m^3

Difference in [O_3] HE vs. Base



5 P.M.

Difference in [$PM_{2.5}$] HE vs. Base



7 A.M.

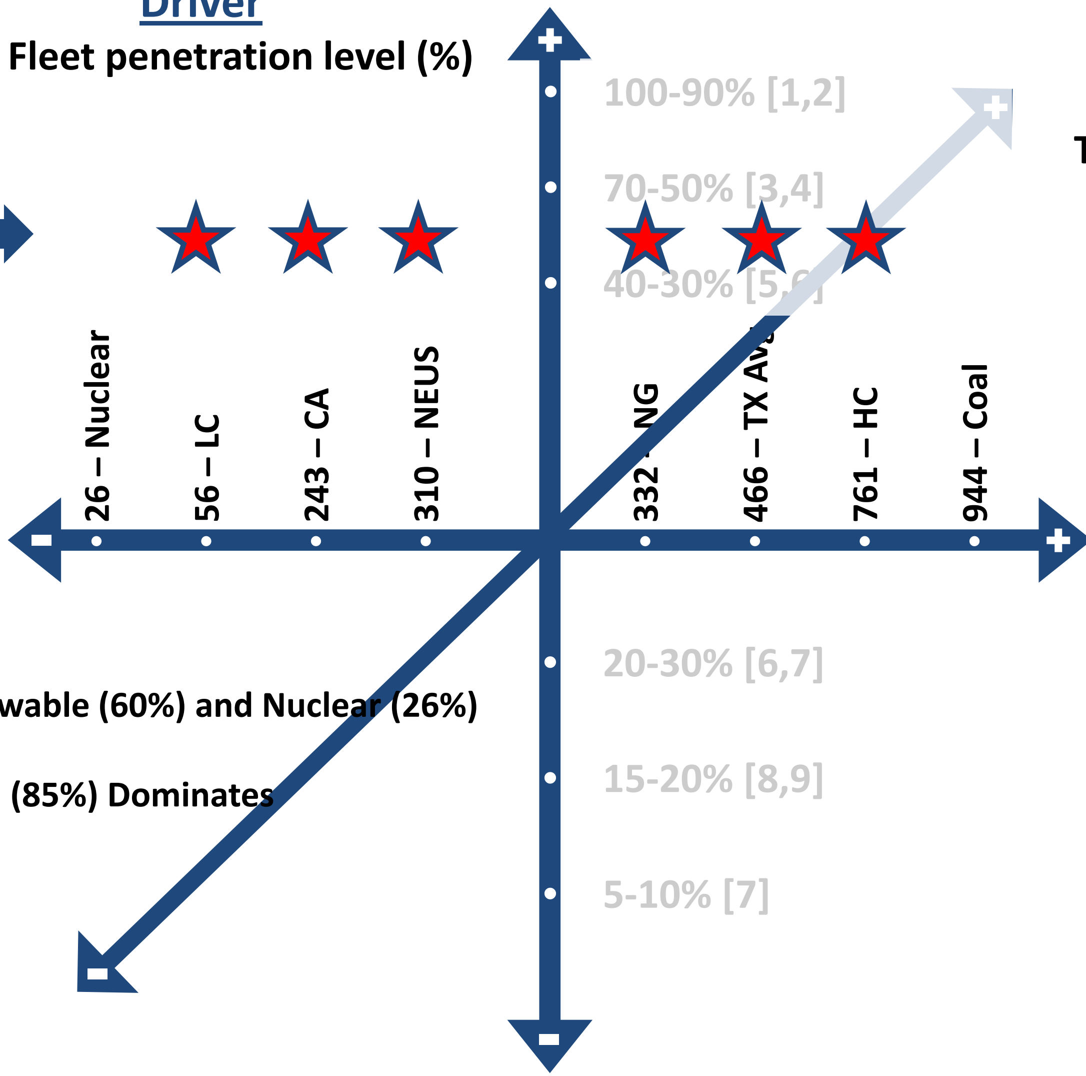
Scenario Development: EV

Driver
LDV Fleet penetration level (%)

EVM 1
30% EV
30% PHEV-40

Driver
Total LDV Demand (VMT)

Driver
Grid GHG intensity (gCO_2eq/kWh)



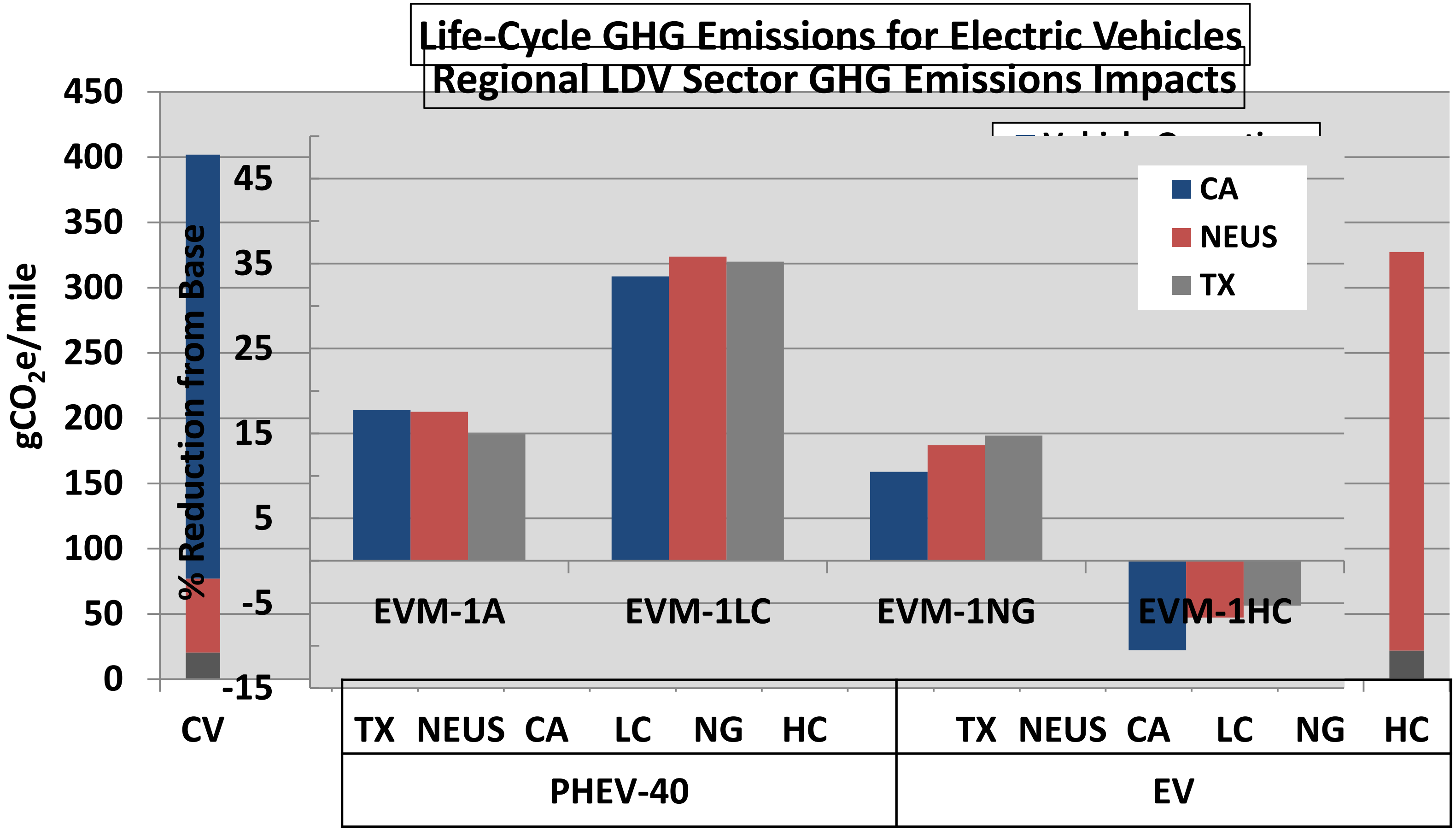
LC: Low Carbon, Renewable (60%) and Nuclear (26%)
NG: NGCC
HC: High Carbon, Coal (85%) Dominates

References
[1] Brinkman 2010
[2] Kintner-Myer 2007
[3] Kempton-Archer 2007
[4] Andress 2011
[5] EPRI 2007
[6] Reilly 2009
[7] NRC 2008
[8] McKinsey & Co 2007
[9] Alhajeri 2011

Electric Vehicle Scenario Impacts

GHG impacts dependent on power sector and region

- Per mile reductions from CVs range from 19 to 94%
- Total LDV impacts range from +10 to -35%



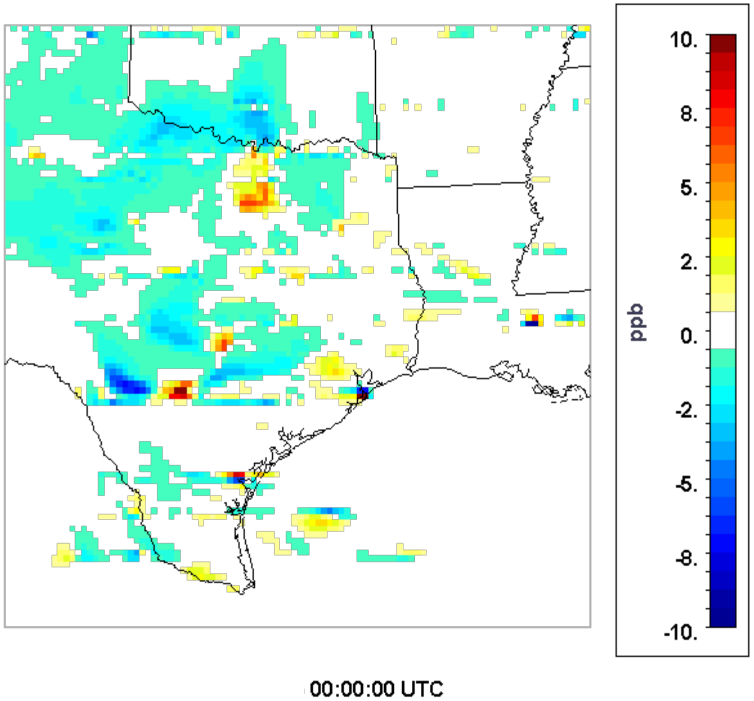
LC: Low Carbon
NG: NGCC
HC: High Carbon

EVM 1 Average (TX)

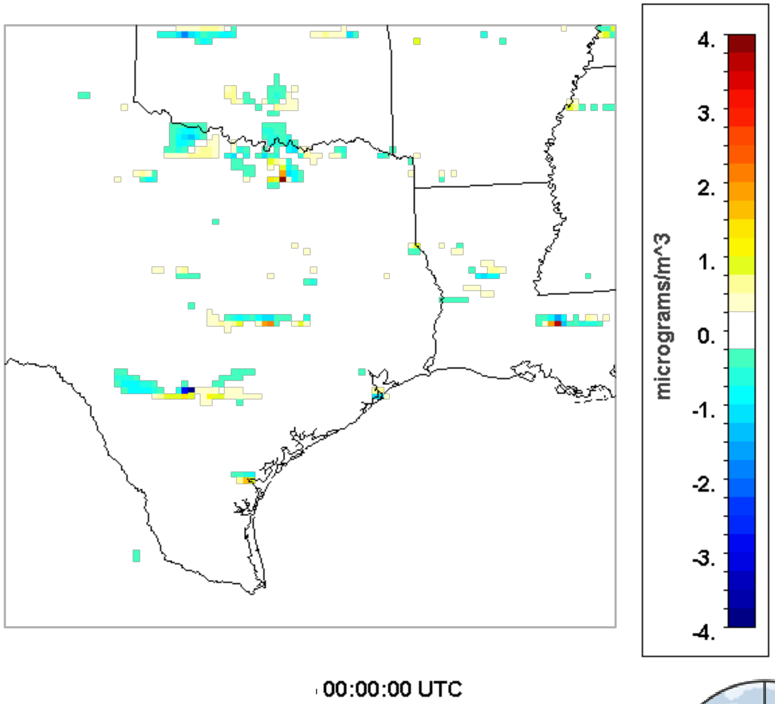
Spatially and temporally dependent AQ impacts

- **Peak ozone: -12 to +17 ppb**
- **Peak $PM_{2.5}$: -4 to +6 $\mu g/m^3$**

Difference in $[O_3]$ From Base



Difference in $[PM_{2.5}]$ From Base

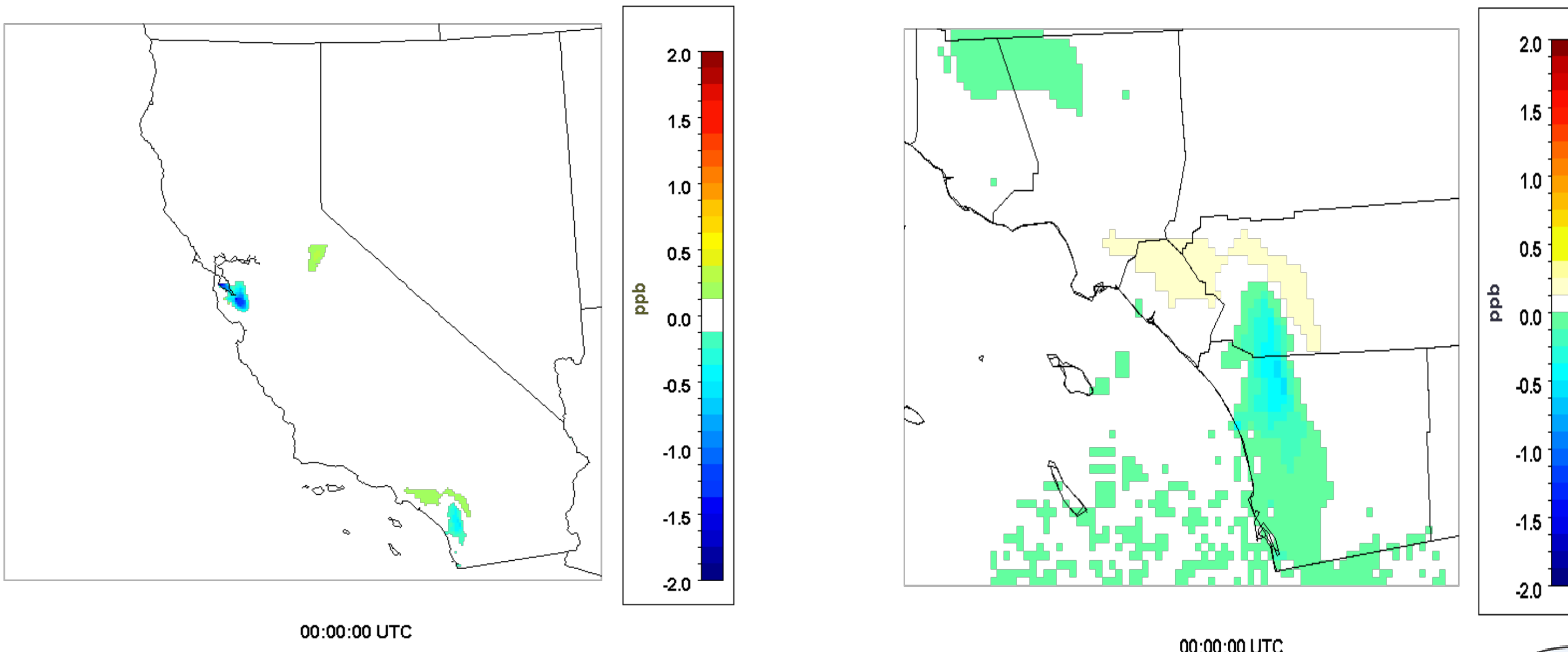


EVM 1 Average (CA)

Lesser state-wide AQ impacts relative to other study regions

- Peak ozone: -2 to + <1 ppb
- Slight increases in peak $PM_{2.5}$

Difference in $[O_3]$ From Base



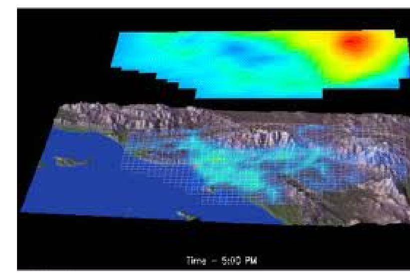
Outline – Tasks

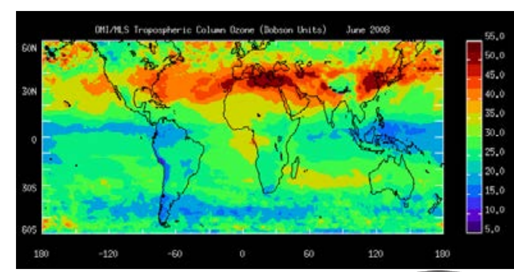
1. Methodology Development

2. Technology Assessment
   – Emphasis on power and transportation sectors

3. Evaluation of GHG and AQ Impacts
   – Development and assessment of scenarios

4. **Air quality model sensitivity**
   – **Impacts of climate change**



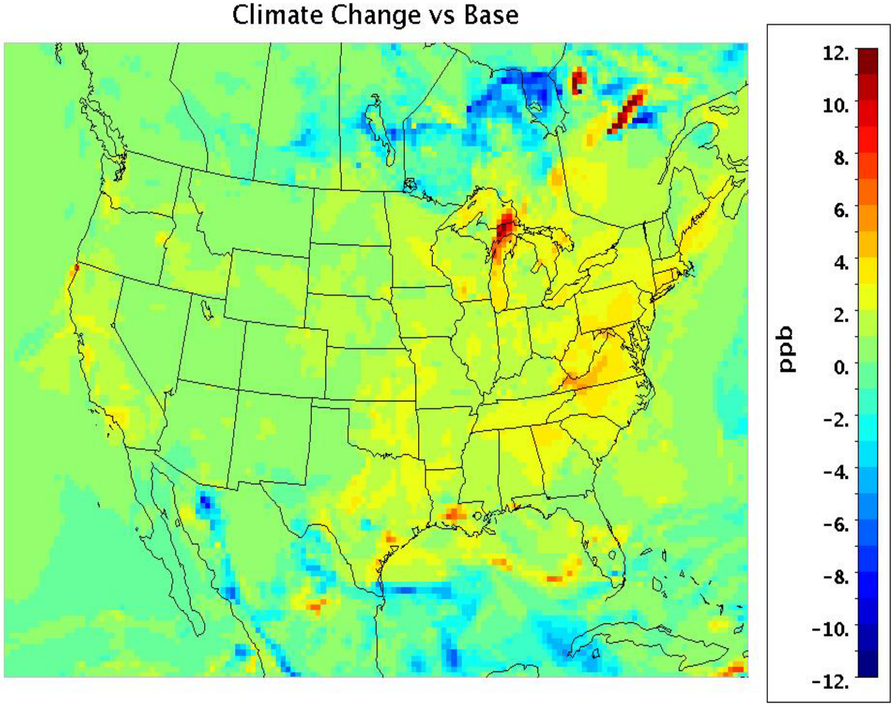


Air Quality Model Sensitivity

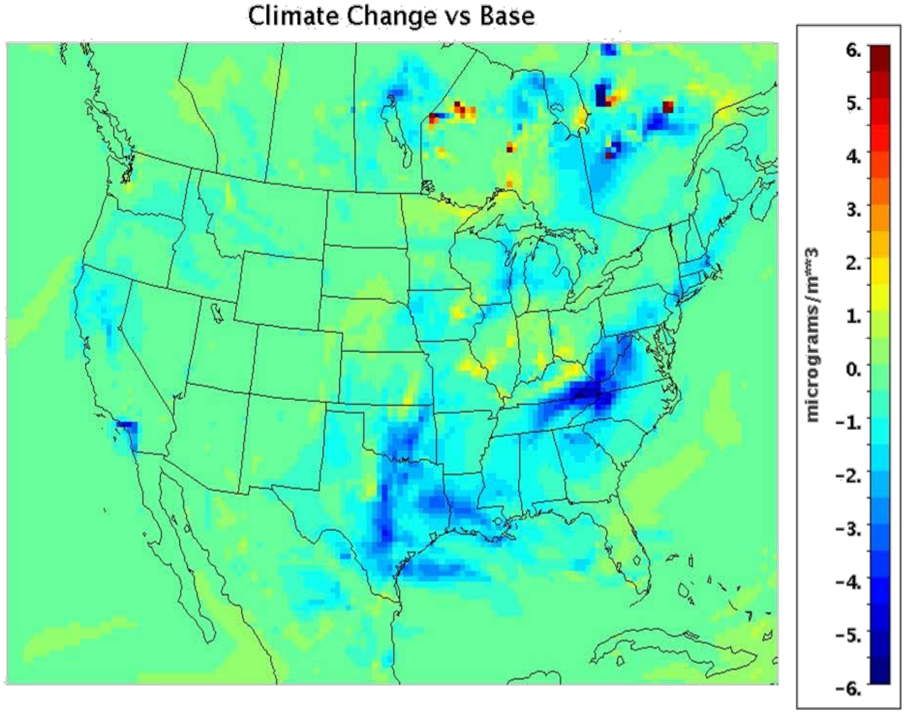
Initial work focused on impacts of climate change

– **Ozone and $PM_{2.5}$ formation sensitivity to temperature**
  - Increase of 2 °C in mean air and soil temperature

Impacts on peak O_3



Impacts on 24-hour $PM_{2.5}$



Initial Findings

- **GHG and AQ impacts experience different trends to 2050**
  - Effectiveness of mitigation strategies differs from present
  - Impacts of other (e.g., Industrial) sectors significant
- **Significant variability in regional impacts and strategy effectiveness**
  - CA region may require alternative strategies for significant improvements
- **Linkages between sectors important**
  - Co-deployment of GHG mitigation strategies across multiple sectors
  - Interactions between mobile and stationary sources
- **Impacts of climate change on AQ significant**
  - Similar in magnitude to technology driven perturbations

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