Use of Adjoint Modeling with Satellite Data and CO_2 Control Benefits

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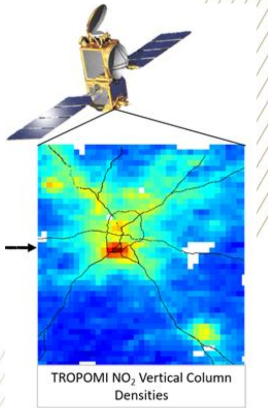

CRC-AQRN-Davis
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CREATING THE NEXT

Topics

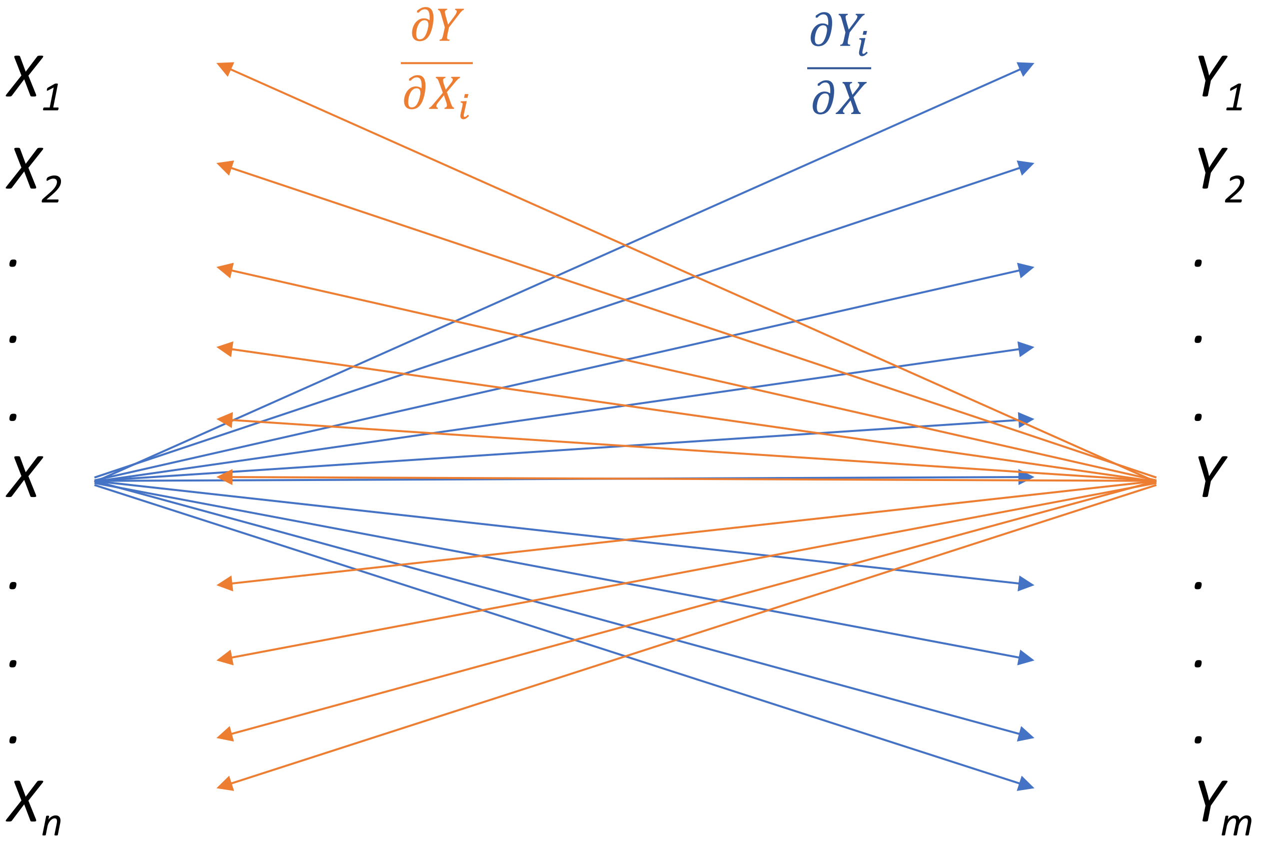
- Adjoint Air Quality Modeling
- Using the adjoint for top-down emissions inventory development
- Calculating spatially detailed and source specific co-benefits of CO2 reductions

Adjoint Modeling

- An “adjoint” modeling capability has been added to CMAQ and GEOS-Chem, and others
  - CMAQ adjoint a group effort across multiple universities/countries
  - Adjoint integrates backwards in time
- It extends model capabilities by adding “receptor-oriented” impact information
  - “What impact do sources located at what location and at what time, impact air quality (or health) at a specific receptor”
    - Receptor: a specific location, a population-weighted integral (and can include concentration response functions), or the model error across all monitors, …
  - It is a truly powerful capability that is not readily achieved by multiple applications of a model
    - Air quality management
    - Health
    - Emissions inventory analysis

Sensitivity Analysis: Forward (e.g., BF, DDM: source-) vs. Adjoint (Receptor-Oriented)

- Backward sensitivity analysis: Adjoint



Question: How will a source impact air pollution and health downwind?

Forward sensitivity (DDM)

Backward sensitivity (Adjoint)

Question: Where were the emissions that led to the concentration(s)/exposure/health observed?

Inputs/Sources (such as emissions)

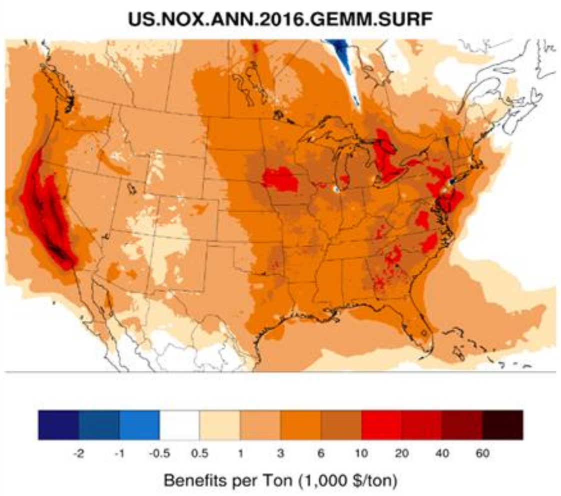
Outputs/Receptors/Outcome (such as concentration or health impact)

Adjoint Applications

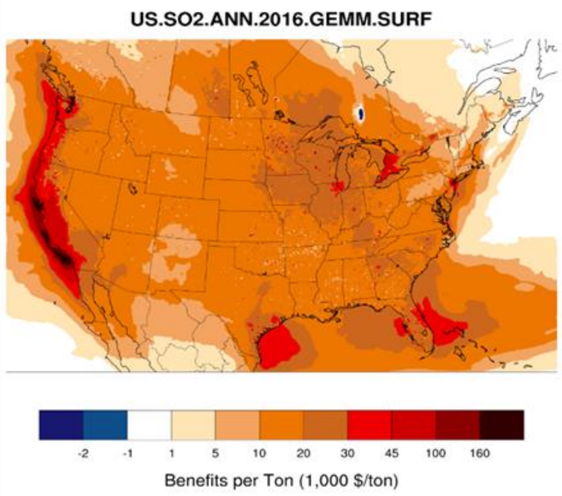
- Health impacts
  - “Value/Impact” of emissions from each location
    - E.g., health benefits per ton of emissions
      - A ton of NOx and SO2 is typically worth much more in CA than elsewhere
      - Note difference in relative values in NY & PA
  - Can also apply to look at air quality impact

- Emissions Inventory Assessment
  - Formal top-down approach taking advantage of adjoint’s spatial information
    - Use observations & model results to improve emissions estimates
  - NOx, NH3, CH4, Isoprene, SO2
    - Results still have a good deal of uncertainty, but improved satellite capabilities will address some of that

NOx

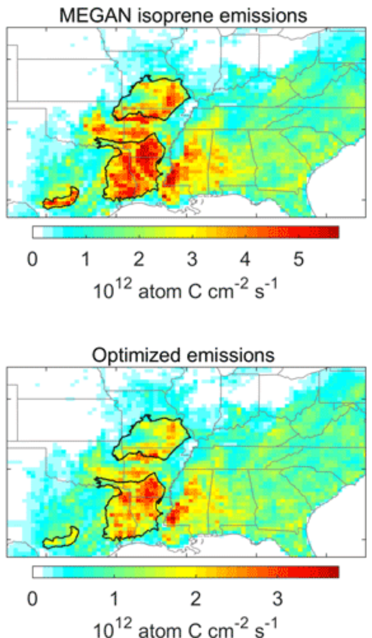


SO_2

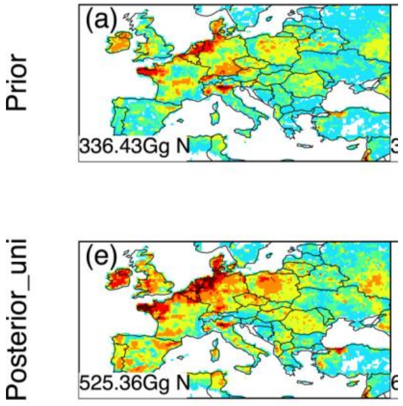


From Hakami et al., HEI report 2022

Isoprene Emissions in US
Kaiser et al., ACP 2018

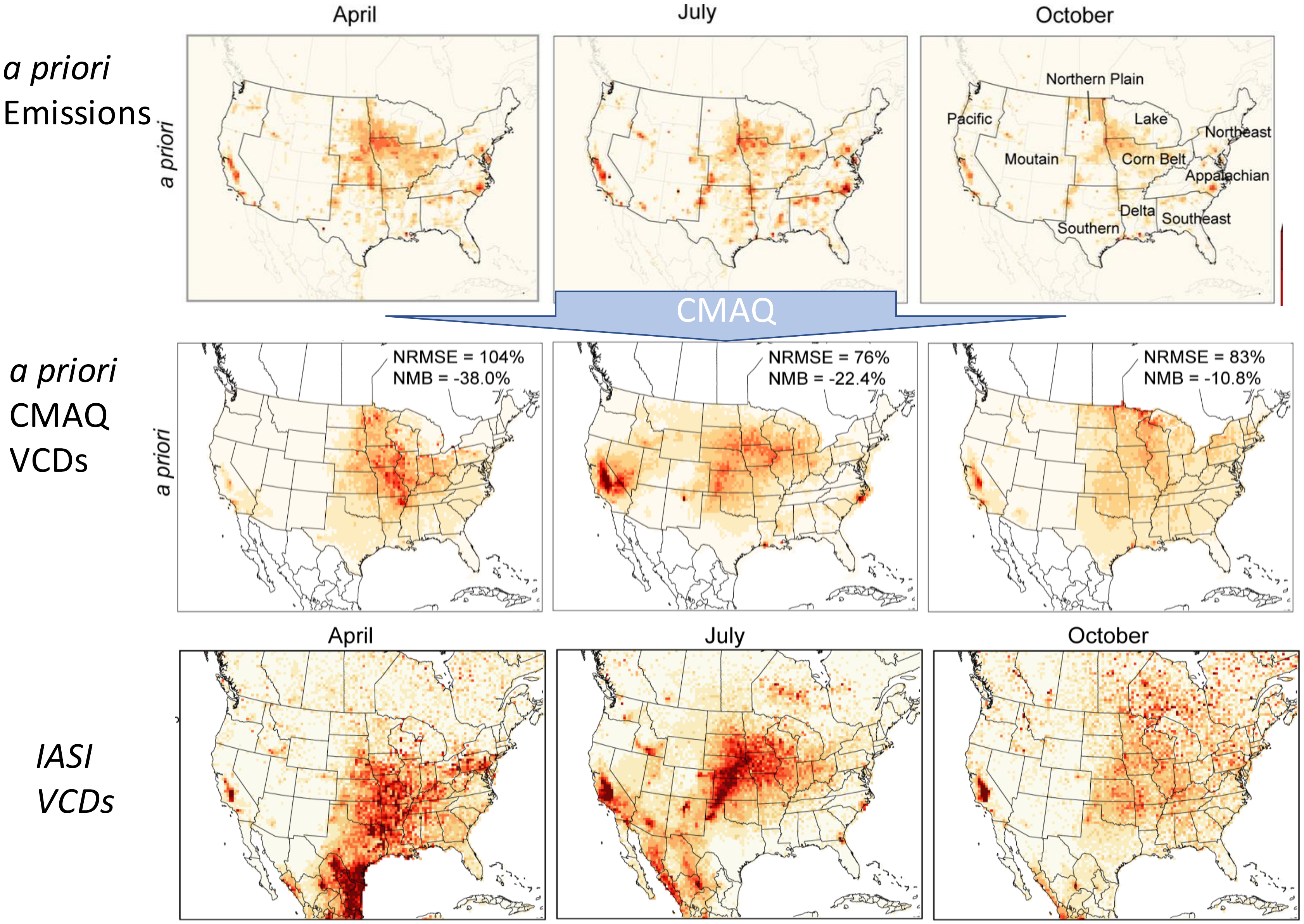


NH3 Emissions in Europe
Cao et al., JGR 2022



Top-down NH_3 emission estimation using the adjoint of CMAQ

- Modeled ammonia concentrations across US using CMAQ-ADJ
  - Compared with IASI and limited ground-based monitoring
- Adjusted emissions to improve spatial allocation of emissions
- Significantly reduced bias and improved spatial pattern
  - Still a long ways to go



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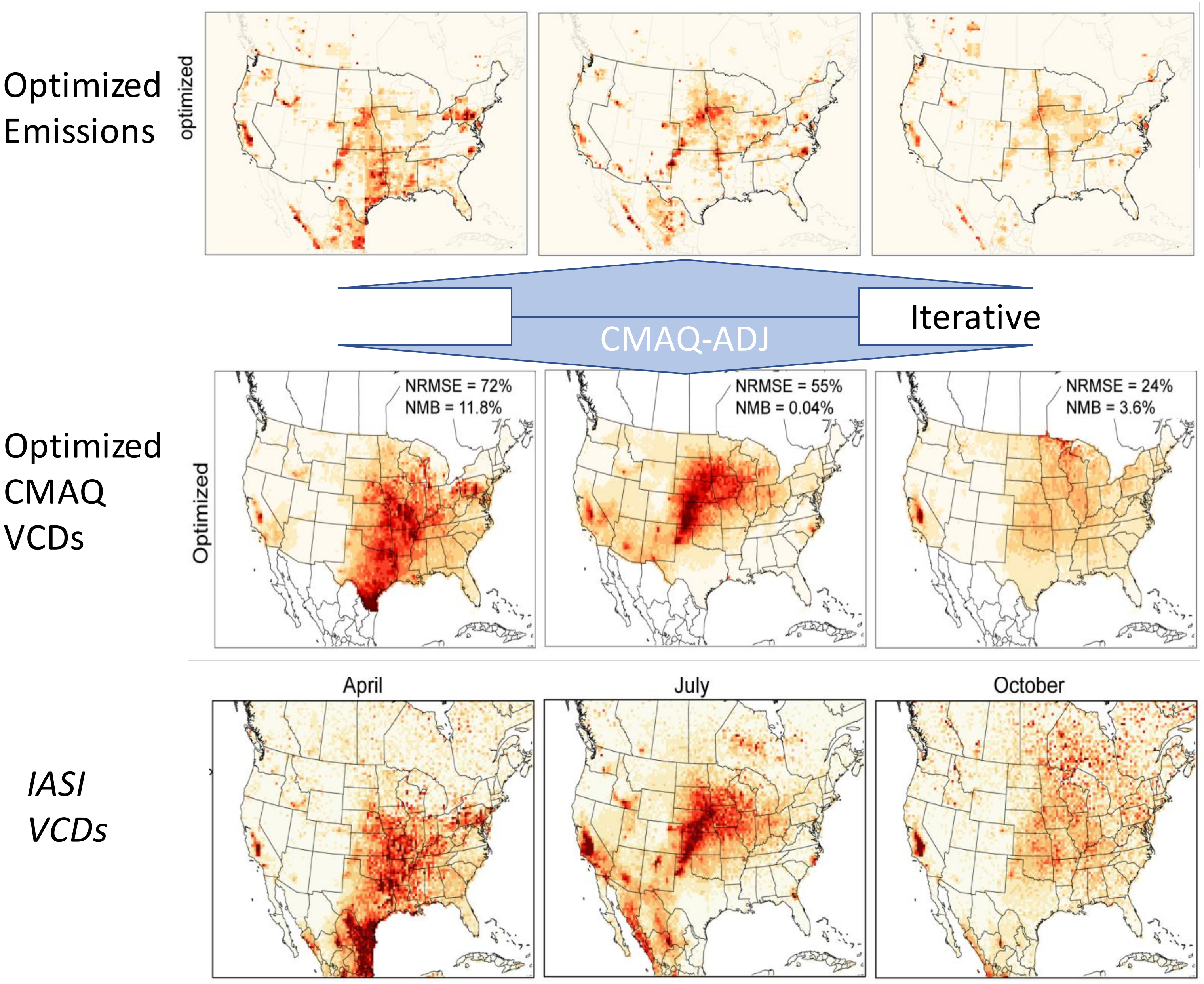

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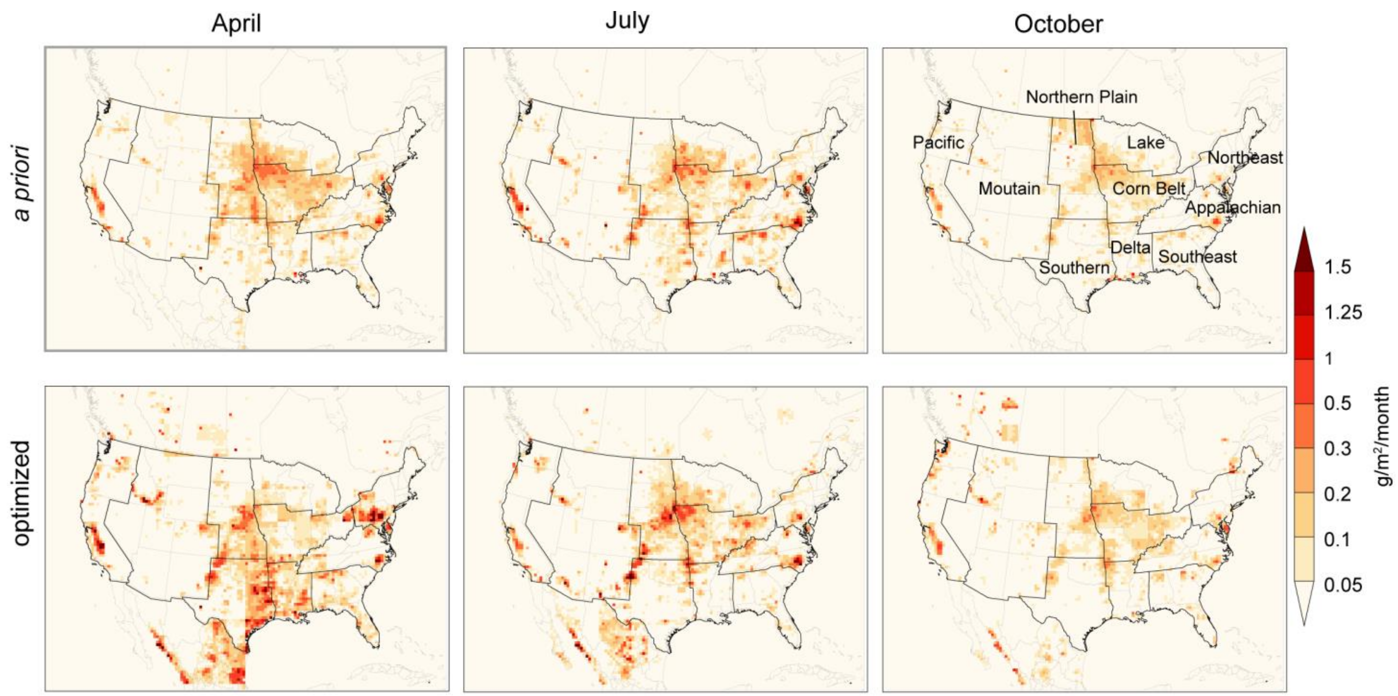
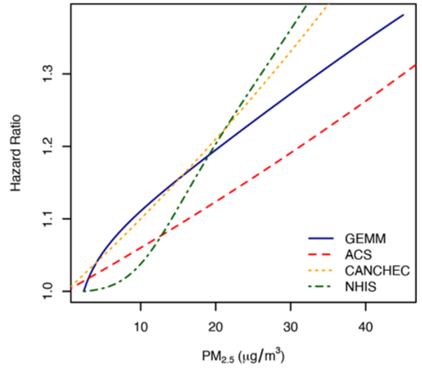
Before and After Ammonia Emissions

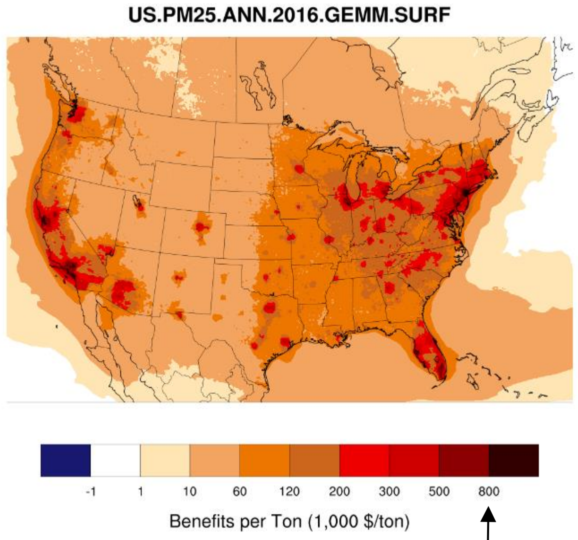


Application of CMAQ-Adjoint to provide spatially detailed, source specific benefits of reducing emissions and CO2 co-benefits

- CMAQ-ADJ provides location and species-specific sensitivities to chosen outcomes, including population exposure and health
  - Linked population health to health benefit to value emissions reductions
    - Value of reducing a ton of emissions
    - “Cost Function” $(\$'s) = V_{SL} \sum_i M_{0,i} \times P_i\left(1 - e^{-\theta T(z)}\right),$
      - VSL: Value of statistical life, $M_{0,i}$: baseline mortality rate in location i, P_i: population, $\left(1 - e^{-\theta T(z)}\right)$: GEMM concentration response function, T(z) nonlinear function of $PM_{2.5}$ concentration

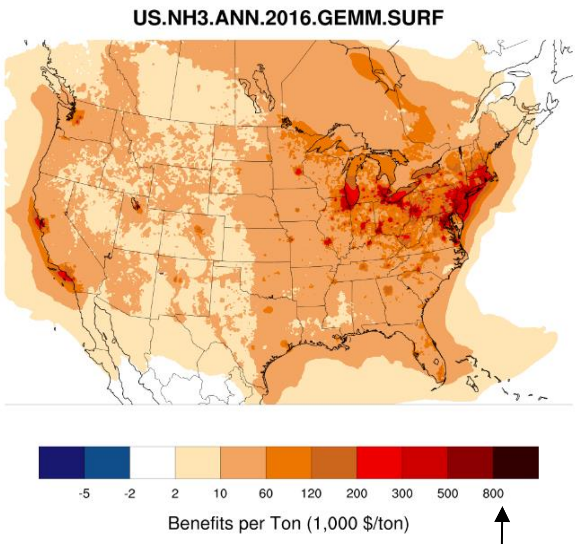


PM2.5 Emissions



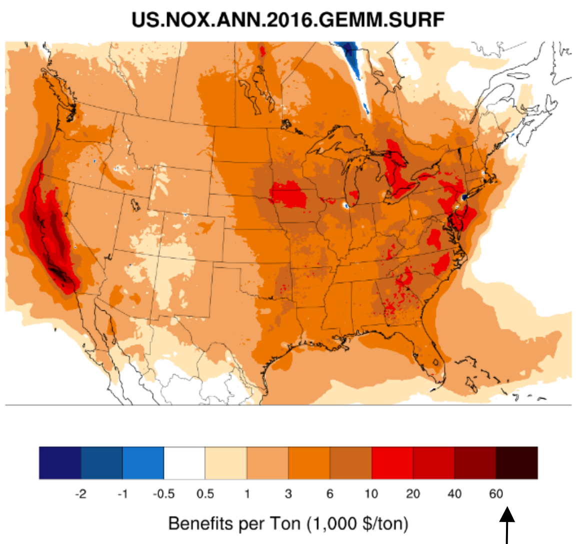
$800,000/ton

Ammonia Emissions



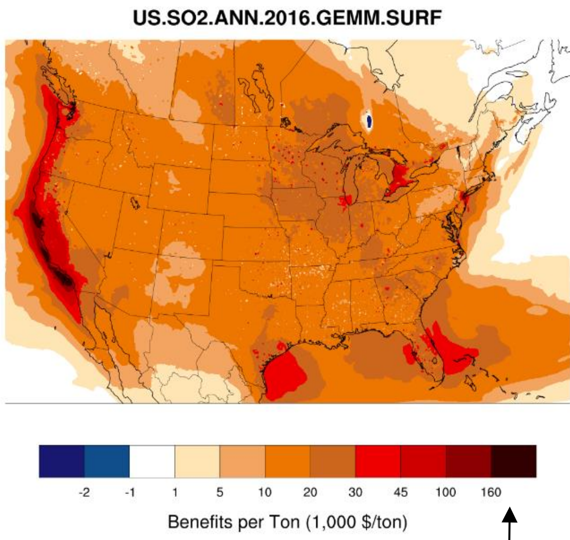
$800,000/ton

NOx Emissions



$60,000/ton

SO2 Emissions

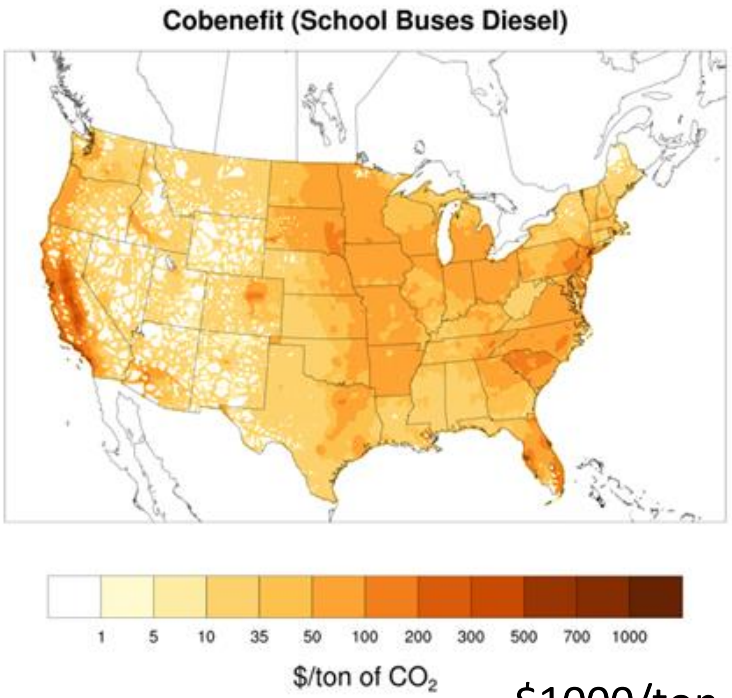


$160,000/ton

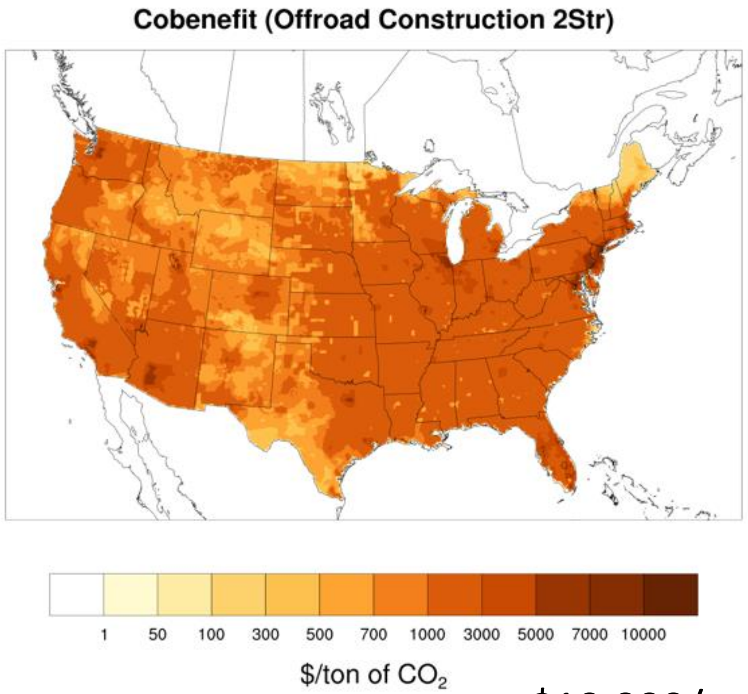
From Hakami, Russell, et al. (2023) Draft HEI report: Do not quote or cite

Co-benefits from CO2 reductions

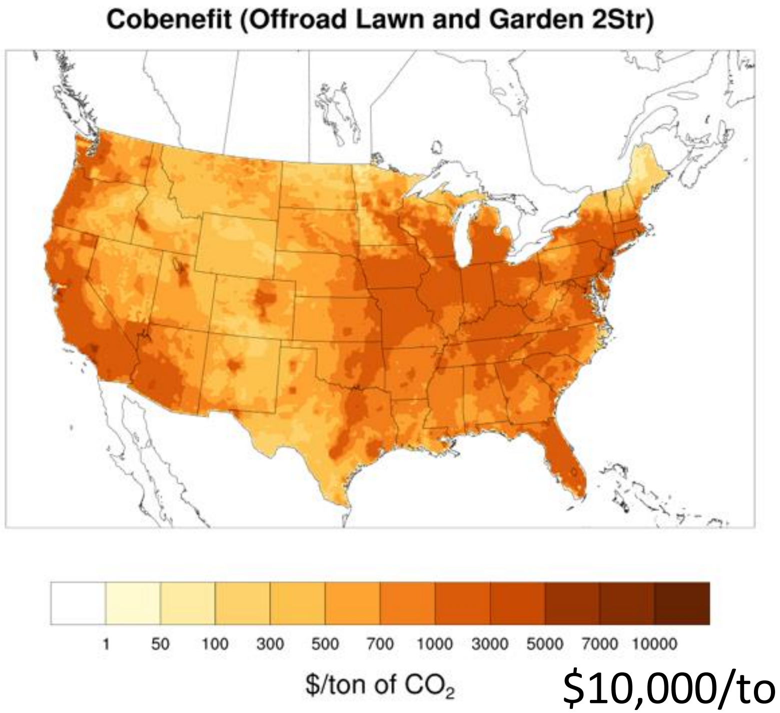
- What are the air quality benefits from location-specific CO_2 emissions reductions (and the associated traditional air pollutants) from specific sources
  - Accounts for how clean a vehicle is vs. fuel economy
  - Compare to Social Cost of Carbon: ($5-200+/ton)



$1000/ton



$10,000/ton



$10,000/ton

Benefits and co-benefits from cars

- Used MOVES to calculate model year specific CO_2 and traditional emissions

City	Co-benefit (\$/ton-CO_2)					Per-vehicle damage (\$/year)				
	1998	2002	2008	2012	2016	1998	2002	2008	2012	2016
Chicago	690	260	150	140	160	2100	900	700	700	700
Los Angeles	750	200	120	110	130	2200	700	500	500	600
New York	2060	840	490	450	530	6200	3100	2200	2100	2300
Seattle	280	110	60	60	60	800	400	300	300	300
Washington	340	130	80	80	80	1100	500	400	400	400

- Driving older cars have dramatically higher health impacts
    - ~$0.2/mile in a city (city dependent)

Summary

- Adjoint modeling has many scientific and policy applications
  - Unique, and powerful, information
    - Location and species specific impacts of emissions on outcomes
  - Improving emissions
  - Health benefit analyses
- Some caveats
  - Rather more computationally demanding
    - Mainly storage
  - Requires additional programming to add the adjoint to a model