Adjoint-Based Source Attribution of PM Health Impacts

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Introduction and Motivation

Long-term exposure to fine particulate matter has been associated with adverse health effects, including premature mortality. In 2006 the World Health Organization estimated that urban outdoor air pollution is the cause of approximately 1.3 million premature deaths worldwide per year [1]. Studies have suggested that PM mixtures with a high black carbon (BC) percentage may have greater effects on mortality than mixtures low in BC [3]. Quantifying the role of emissions from different sectors and different locations in governing the total health impacts is critical towards developing effective control strategies. To answer such questions, an adjoint model can provide sensitivities of estimated excess mortality with respect to emissions at a highly resolved spatial and sectoral level of specificity.

Motivation

- Some researchers have suggested that BC could account for all of the mortalities attributed to exposure to $PM_{2.5}$ [3]
- In August 2012, a US Court of Appeals overturned the Cross-State Air Pollution Rule
  - Court ruled that "under the Transport Rule, upwind States may be required to reduce emissions by more than their own significant contributions." [6]
- Forward CMAQ model simulations estimate that over 7,000 premature mortalities annually are attributed to BC exposure (Figure 1)
- Previous health effect studies of BC emissions used a forward sensitivity analysis approach [2]
  - Observed that majority of health benefits from BC emission reductions occur in the source region.
- The use of source-receptor modeling allows for similar studies to be performed at a highly resolved spatial level of specificity

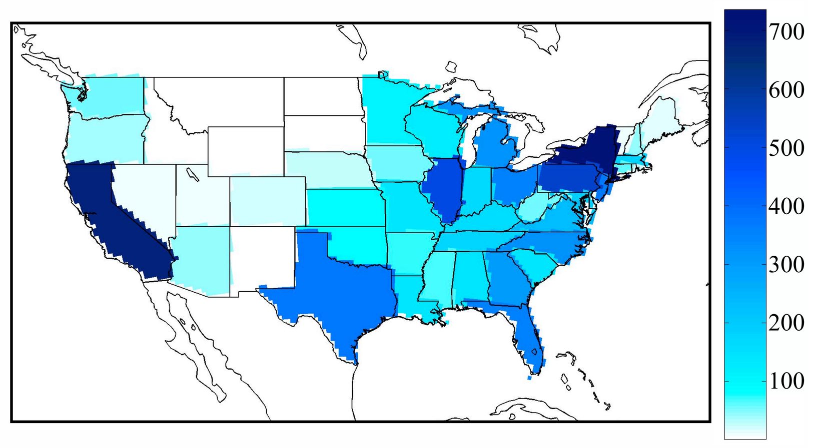


Figure 1: Yearly Mortalities Attributed to Exposure to BC

Objectives

Air quality models are an important tool utilized by the EPA in the development of emission regulations. This project focuses on the development of the CMAQ Adjoint model through the inclusion of an adjoint of aerosol microphysics. The CMAQ Adjoint model is then used to address the following issues:

1. Estimate the sensitivity of national mortality attributed to exposure to BC with respect to BC emissions in each and every state.
2. Estimate the contribution of emissions in upwind states to mortalities in downwind states.

What Are Adjoints?

- Forward sensitivity analyses are source-based.
  - Efficient for calculating sensitivities of large number of outputs with respect to small number of inputs
- Adjoint method provides receptor-based sensitivities.
  - Efficient for calculating sensitivities of small number of outputs with respect to large number of inputs
- Main advantage of adjoint method over finite difference is the ability to quickly calculate sensitivities with respect to all model parameters at the same time

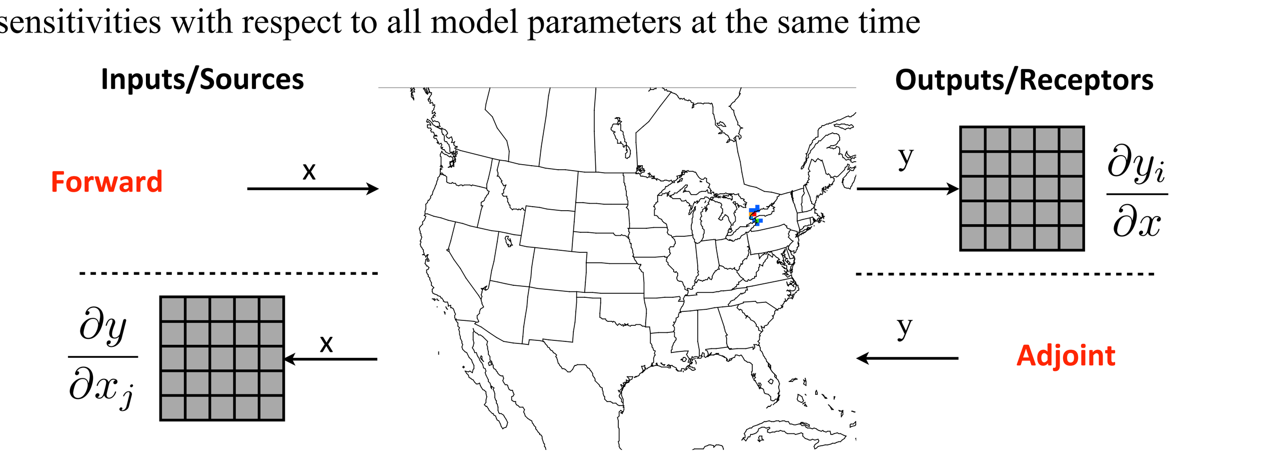


Figure 2: Schematic representation of differences between Adjoint and Finite Difference Method.

Adjoint Development and Validation

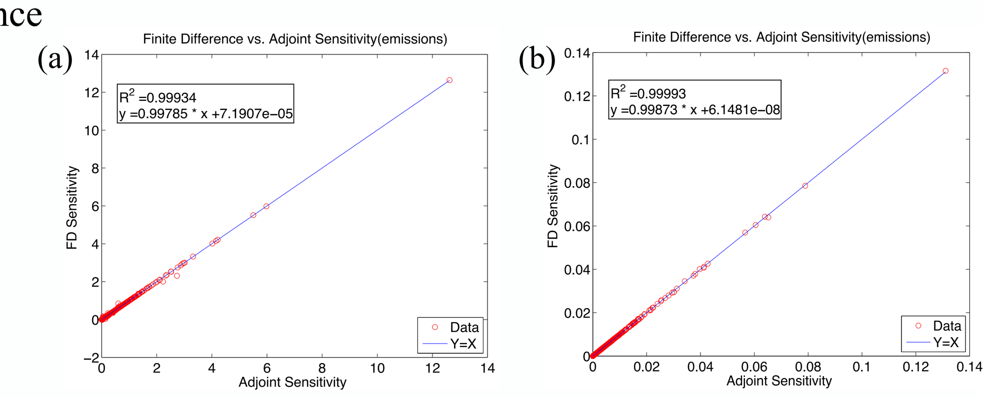
Development Goals

- Manually construct adjoints of aerosols and emissions
- Validate adjoints via comparison to finite difference

Validation

- Adjoint extended to include sensitivity with respect to emissions
- Aerosols included in emissions validation
  - Wet deposition omitted
- Validation performed for BC
- Comparison shows good agreement (See Figure 3)

Figure 3: Adjoint Validation, FD vs. ADJ Emission Sensitivities, (a) Layer 1, (b) all other layers. FD Perturbation = 0.01% $\frac{\partial J}{\partial emis}$



Adjoint Sensitivity of $PM_{2.5}$ Health Impacts

- Sensitivity studies performed with emphasis on continental US and States with a higher percentage of mortalities than emissions
- Cost Function defined to be health impact function for chronic premature mortality:

$$J = \sum_{i=1}^{N} Mort_i * (1 - \exp^{-\beta * Conc_i}) \qquad \beta = 0.005827$$

- Adjoint forcing (what drives the adjoint model) is derivative of cost function with respect to concentration:

$$\frac{\partial J}{\partial Conc} = \frac{Mort}{t} * \beta * \exp^{-\beta * Conc}$$

Mort = gridded annual mortalities for people over 30

t = # of timesteps in a year

Conc = gridded annual average BC concentration

β = concentration response factor

- Mortality information and concentration response factor [7] consistent with US EPA's BenMAP tool
- Simulations performed for April, 2008 on a 36km grid
- April, 2008 average concentration assumed to represent annual concentrations
- Simulations performed without wet deposition.

Sensitivity of BC Health Impacts - CONUS

- 7,827 annual mortalities attributed to exposure to BC in the continental US.
- States whose emissions contribute most to mortality are CA, NY, TX (See Figure 6)
- Figure 4 shows the effectiveness of BC emission control strategies for 15 states, sorted by emissions of BC.
  - Other states may have larger contributions, but are not top 15 emitters.
    - New York is the 2nd largest contributor to mortality with 589 annual mortalities attributed to exposure to BC
    - 18 states emit more BC annually than New York

Figure 4: Effectiveness of Black Carbon Control Strategies
% Mortality Contribution - % Emissions

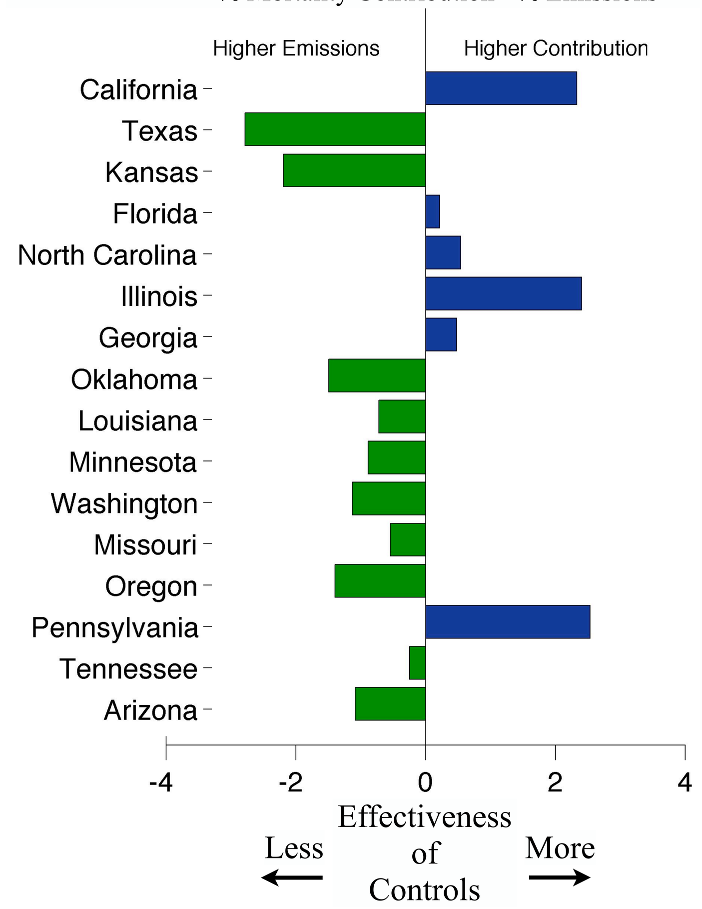


Figure 5: April 2008 Black Carbon Emissions, Summed by state.

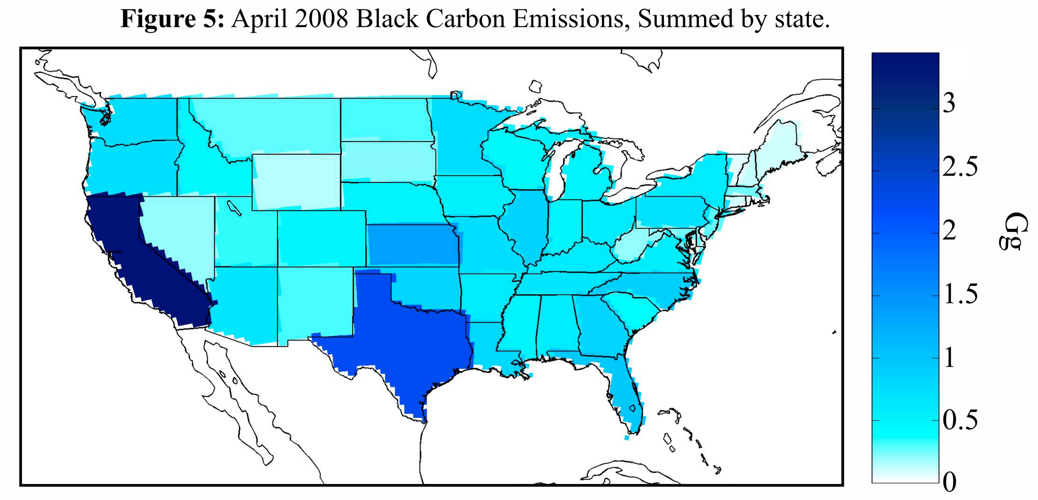
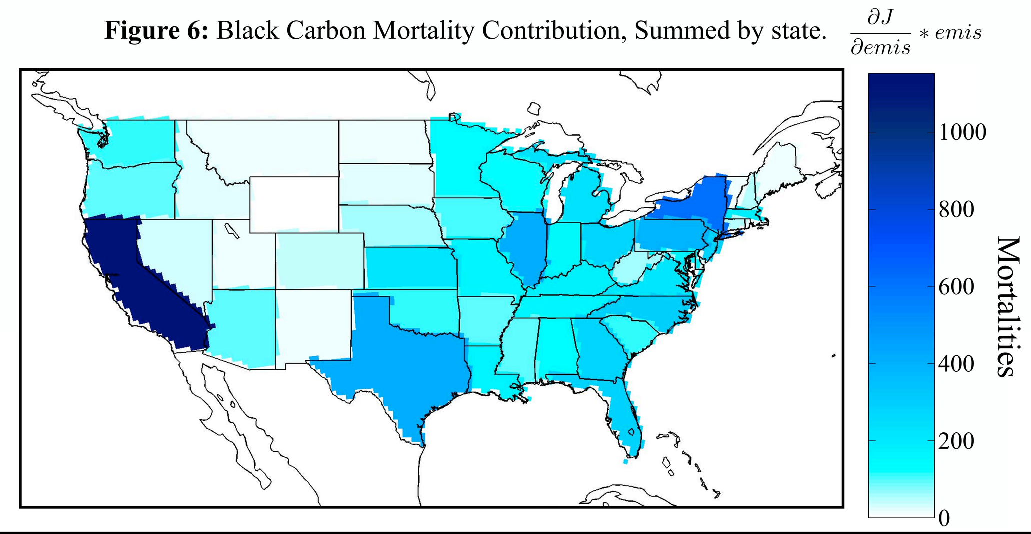


Figure 6: Black Carbon Mortality Contribution, Summed by state. $\frac{\partial J}{\partial emis} * emis$

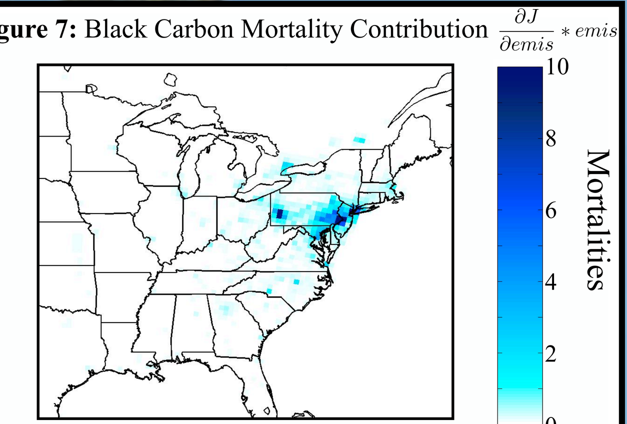


Sensitivity of BC Health Impacts

Pennsylvania

- Mortality contribution defined to be contribution of emissions in grid cell to mortality in defined region.
- Large contribution values seen near Trenton, NJ and New York City.
- To better understand impacts on the state level, results have been aggregated by state.

Figure 7: Black Carbon Mortality Contribution $\frac{\partial J}{\partial emis} * emis$



Pennsylvania Aggregated

- 530 annual mortalities attributed to BC exposure in Pennsylvania
  - Emissions in Pennsylvania account for 50% of mortalities.
  - Long range transport over estimated owing to lack of wet deposition

Figure 10: Mortality Contribution by State.

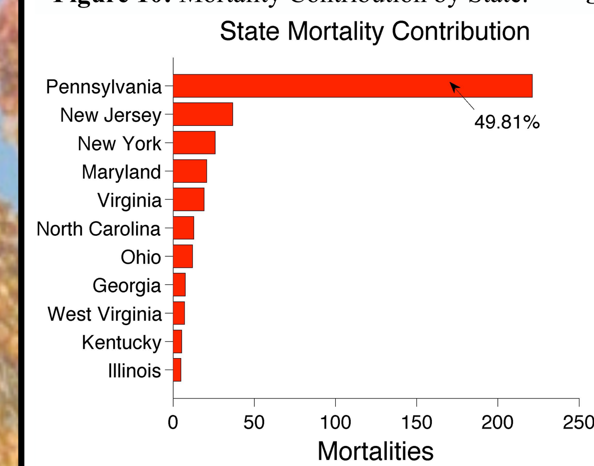
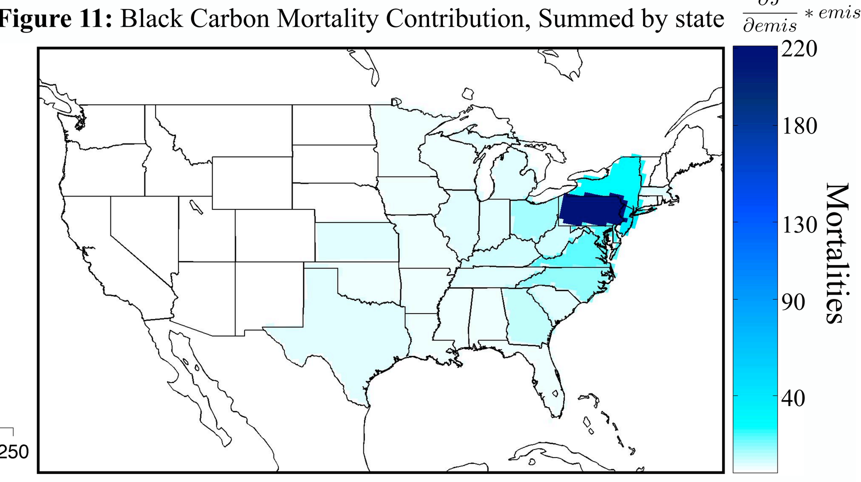


Figure 11: Black Carbon Mortality Contribution, Summed by state $\frac{\partial J}{\partial emis} * emis$



Illinois Aggregated

- 498 annual mortalities attributed to BC exposure in Illinois
  - Emissions in Illinois only account for 50% of mortalities
  - Long range transport over estimated owing to lack of wet deposition

Figure 8: Mortality Contribution by State.

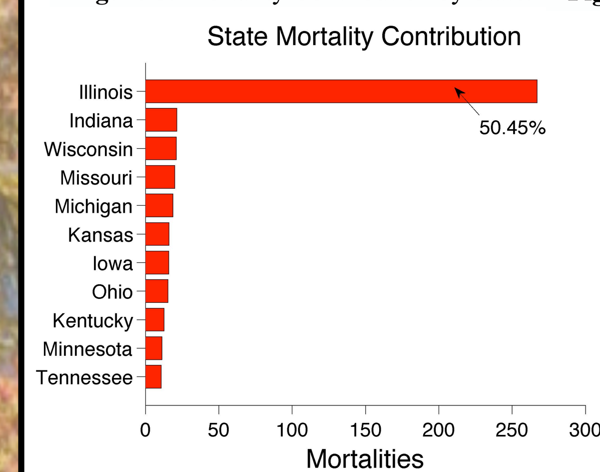
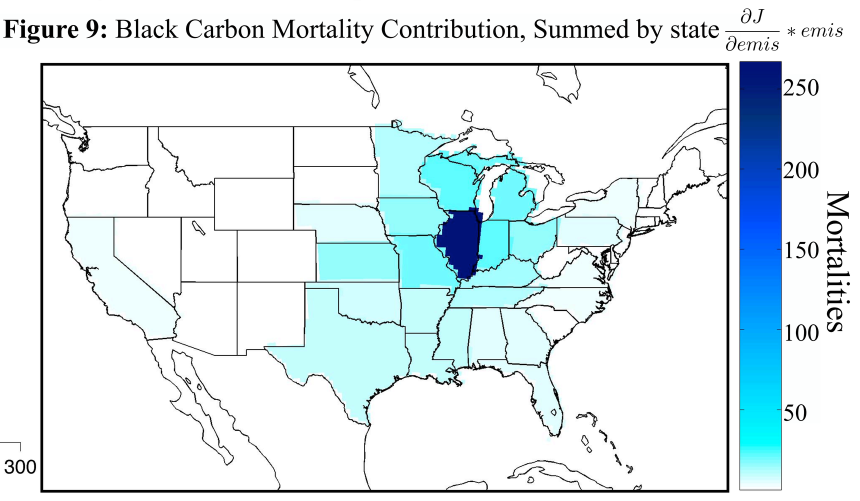


Figure 9: Black Carbon Mortality Contribution, Summed by state $\frac{\partial J}{\partial emis} * emis$



Conclusions

- Adjoint code has been generated and verified for both emissions and BC processes.
- Emission control strategies in certain states (CA, IL, PA) will be more effective on a per kg emission basis at reducing national mortality due to BC exposure.
  - States where control strategies would be most effective are not necessarily the highest emitters.
- Long range transport is over estimated due to omission of wet deposition
  - Only 50.5% of mortalities in Illinois due to exposure to BC are attributed to emissions in Illinois.
  - Only 49.8% of mortalities in Pennsylvania due to exposure to BC are attributed to emissions in Pennsylvania

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