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 2012, Fann et al. estimated taht 130,000 to 320,000 premature mortalities were attributed to $PM_{2.5}$ exposure in the US [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 [2]. 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 12,000 premature mortalities annually are attributed to BC exposure (**Figure 1**)
- The benefit per amount emitted of reducing PM has been shown to vary by location and emission source [2].
- The use of source-receptor modeling allows for efficient analysis of the health impacts of all emission sectors and locations.

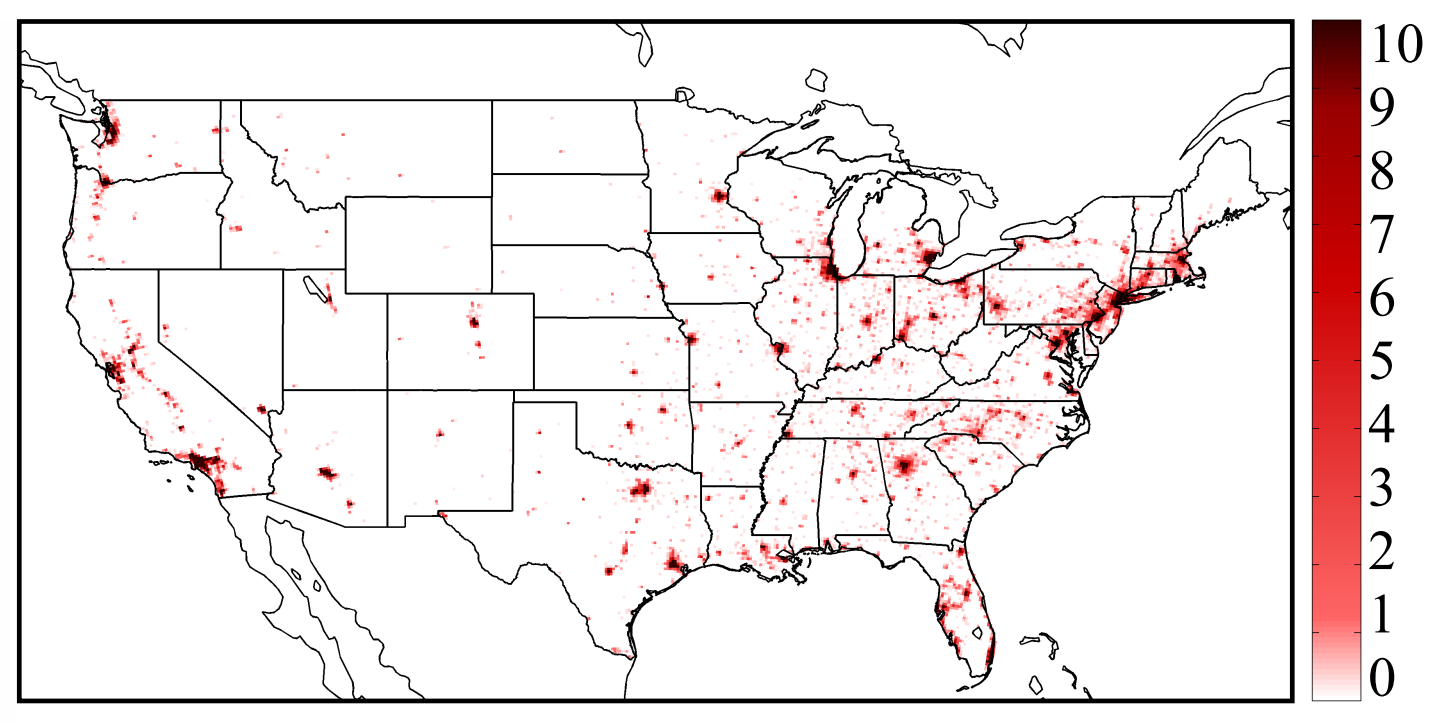


Figure 1: Yearly Mortalities Attributed to Exposure to BC. Maximum of **269** in NYC. Total Mortalities = **12,583** in 2007

Objectives

Air quality models are an important tool utilized by the EPA in the development of emission regulations. This project uses the recently updated CMAQ Adjoint model, which includes an adjoint of aerosol microphysics, to address the following issues:

1. Estimate the sensitivity of national mortality attributed to exposure to BC with respect to BC emissions in the entire domain.
2. Estimate the impact of each BC emission sector on mortality in the US.
3. Estimate the significance of transport of short-lived species in health effect analyses.

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.

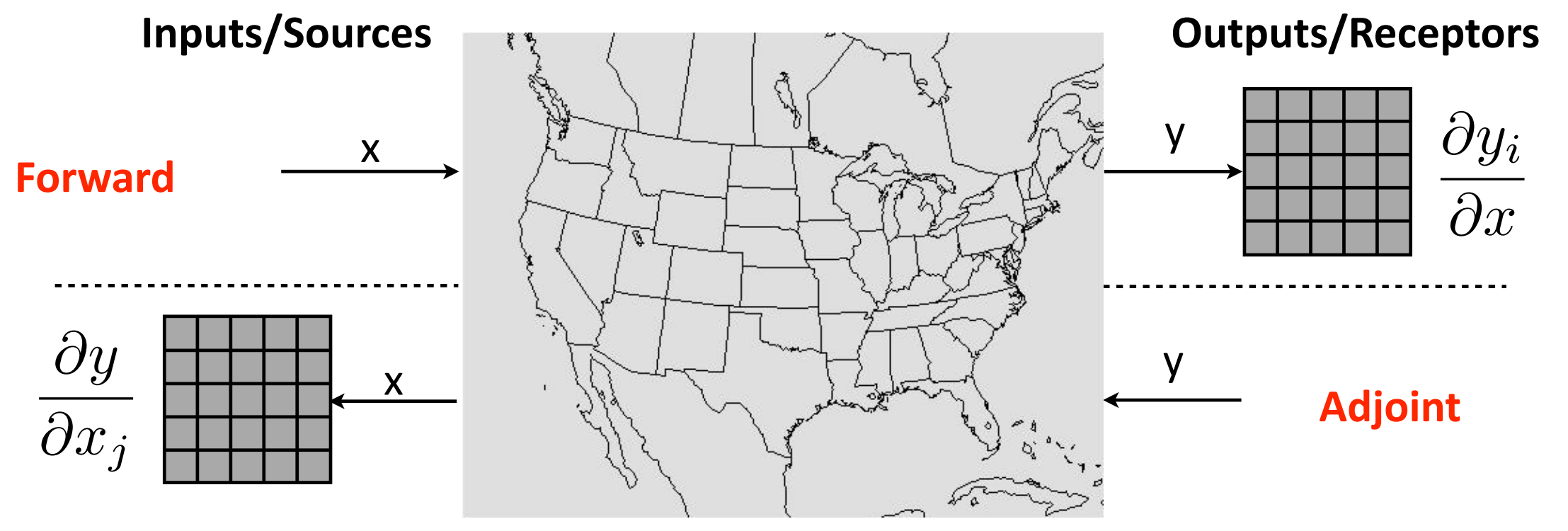


Figure 2: Schematic representation of differences between Adjoint and Finite Difference method.

Adjoint Sensitivity of BC Health Impacts

- Sensitivity studies performed with emphasis on continental US and regions similar to those in Fann et al. [3].
- Cost Function defined to be health impact function for chronic premature mortality:

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

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

$$\frac{\partial J}{\partial C_{i,t}} = \frac{Mort_i}{T} * \beta * exp^{-\beta * C_{av,i}}$$

- $Mort$ = gridded annual mortalities in the US
- C_{av} = gridded annual average BC concentration
- T = number of timesteps in a year
- i = grid cell index
- N = total number of grid cells for which cost function is calculated
- β = concentrations response factor (Krewski et al. [4])
- t = timestep index
- Forward simulations performed for every week of 2007 on a 12km grid
- 12 1-week adjoint simulations performed for first week of each month of 2007
  - Assumed to accurately represent year as a whole

Sensitivity of BC Health Impacts - National

- 12,583 annual mortalities attributed to exposure to BC in the continental US.
- Contributions ($\frac{\partial J}{\partial E_{i,k}} * E_{i,k}$) = Semi-normalized sensitivities with respect to emissions scaling factors
- Comparison of contribution percentage to emission percentage (**Figure 3**) shows locations in which emissions have the largest effect on health, on a per-unit-emission basis.
  - Allows one to predict locations where stricter BC controls would have the greatest benefit.

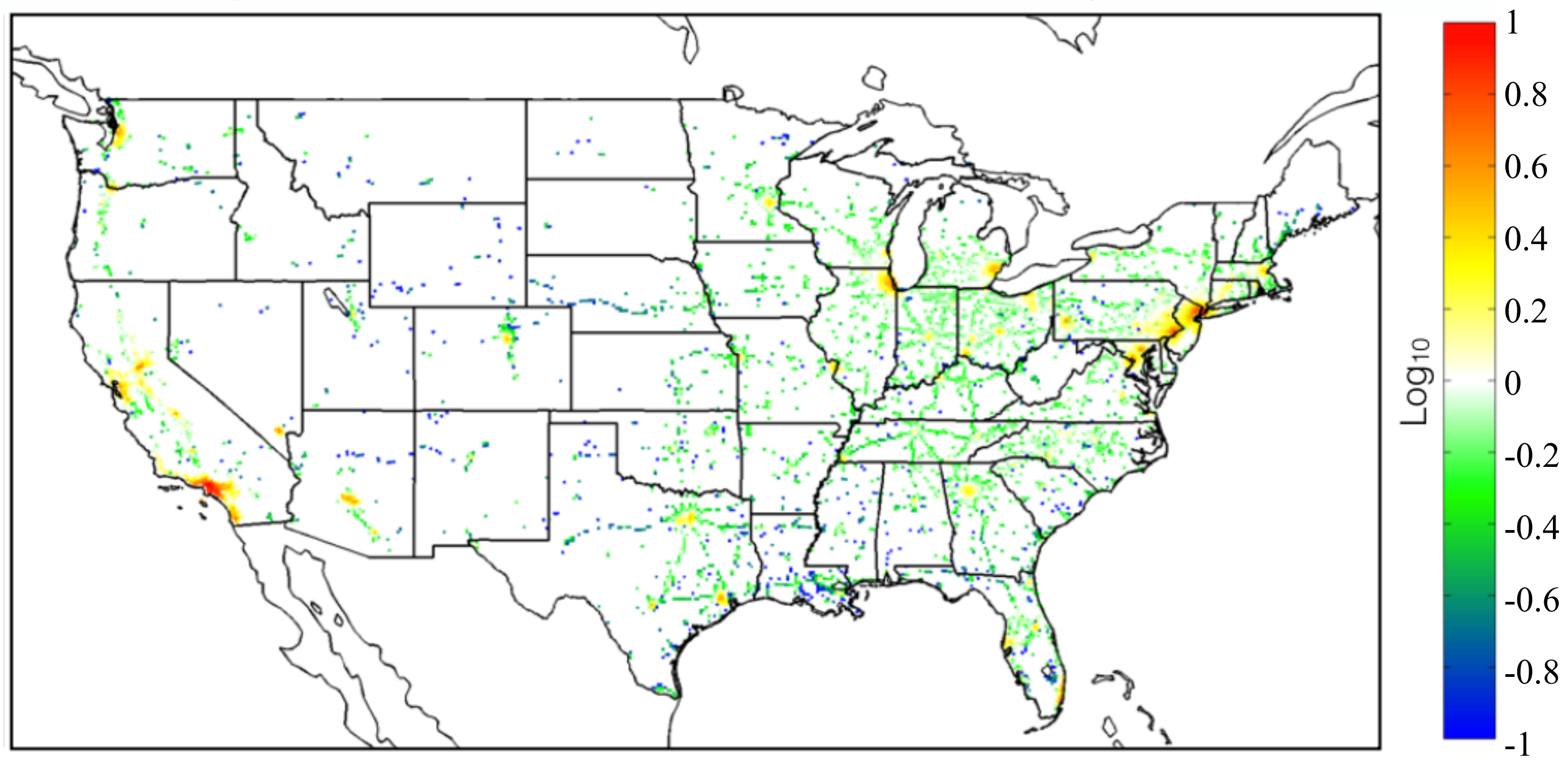


Figure 3: Ratio of Gridded Contribution Percentage from Anthropogenic Emissions to Gridded Anthropogenic Emissions, Plotted on a Log Scale

- Comparison of contribution percentage to mortality percentage (**Figure 4**) yields a spatial mapping of the import and export of death.
  - Grid cells shaded red and yellow have emissions that contribute to more mortalities than there are in the grid cell, essentially exporting death.
  - Shows the importance of transport for health effect analysis of short-lived species

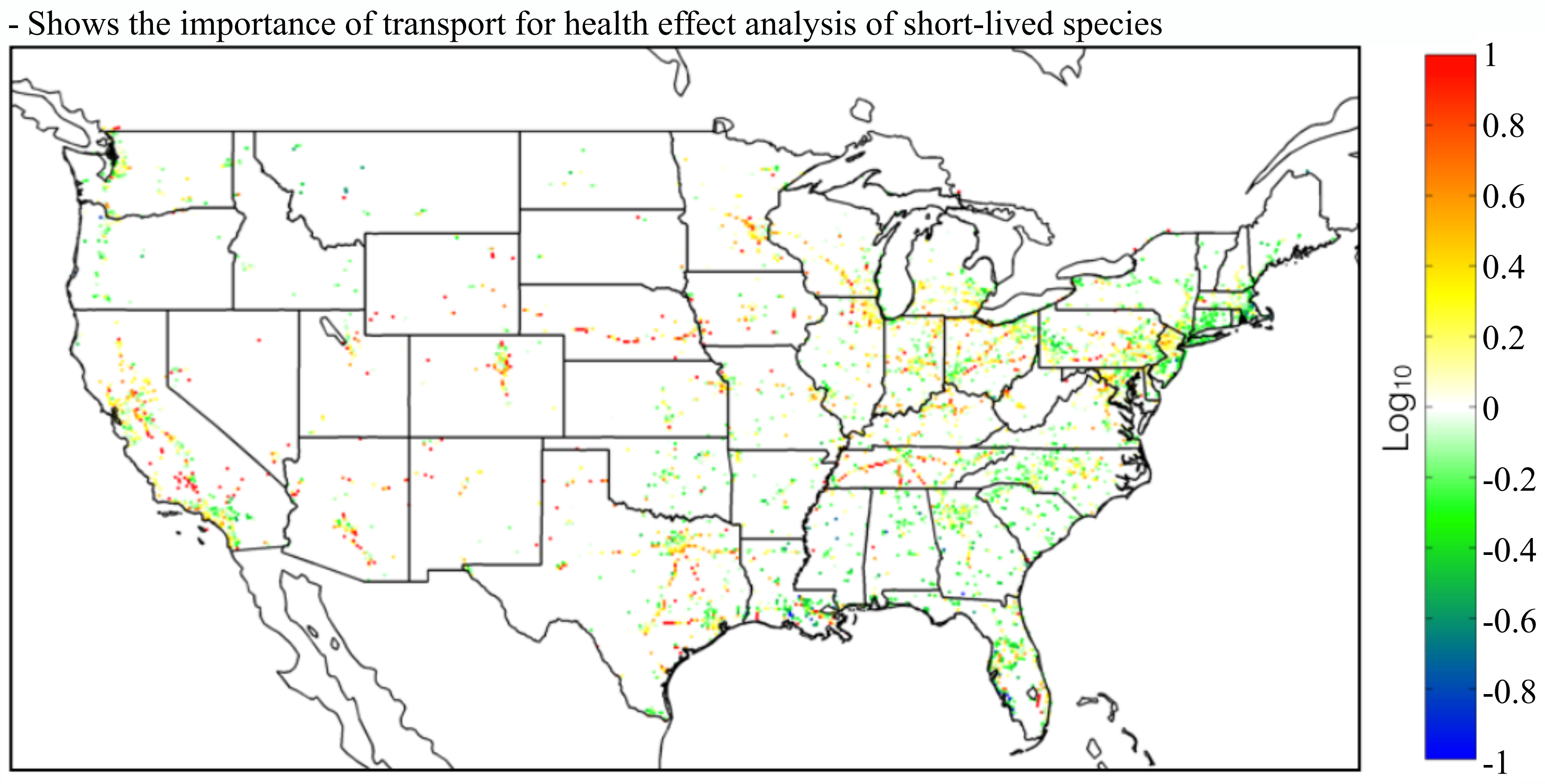


Figure 4: Ratio of Gridded Contribution Percentage from Anthropogenic Emissions to Gridded Mortality Percentages, Plotted on a Log Scale.

- Locations with the highest anthropogenic emissions do not correspond to the highest contribution values (**Figure 5d**).
- It is interesting to consider the most effective strategy for reducing health impacts if the highly spatially resolved analysis of this work was not available.
  - Most effective control strategies would apply stricter controls in locations with the highest mortalities (**Figure 5c**), rather than locations with the highest emissions (**Figure 5d**).

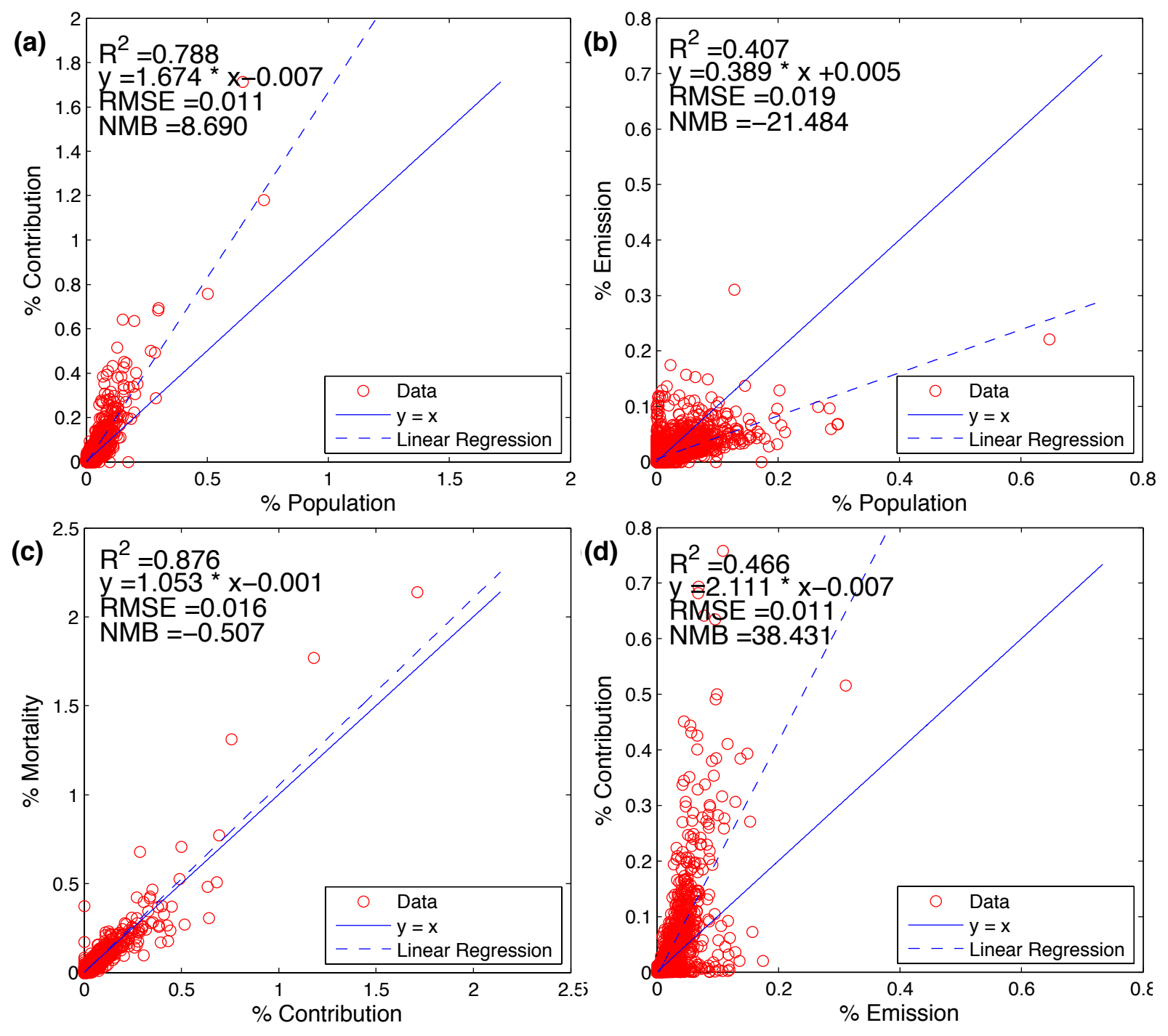
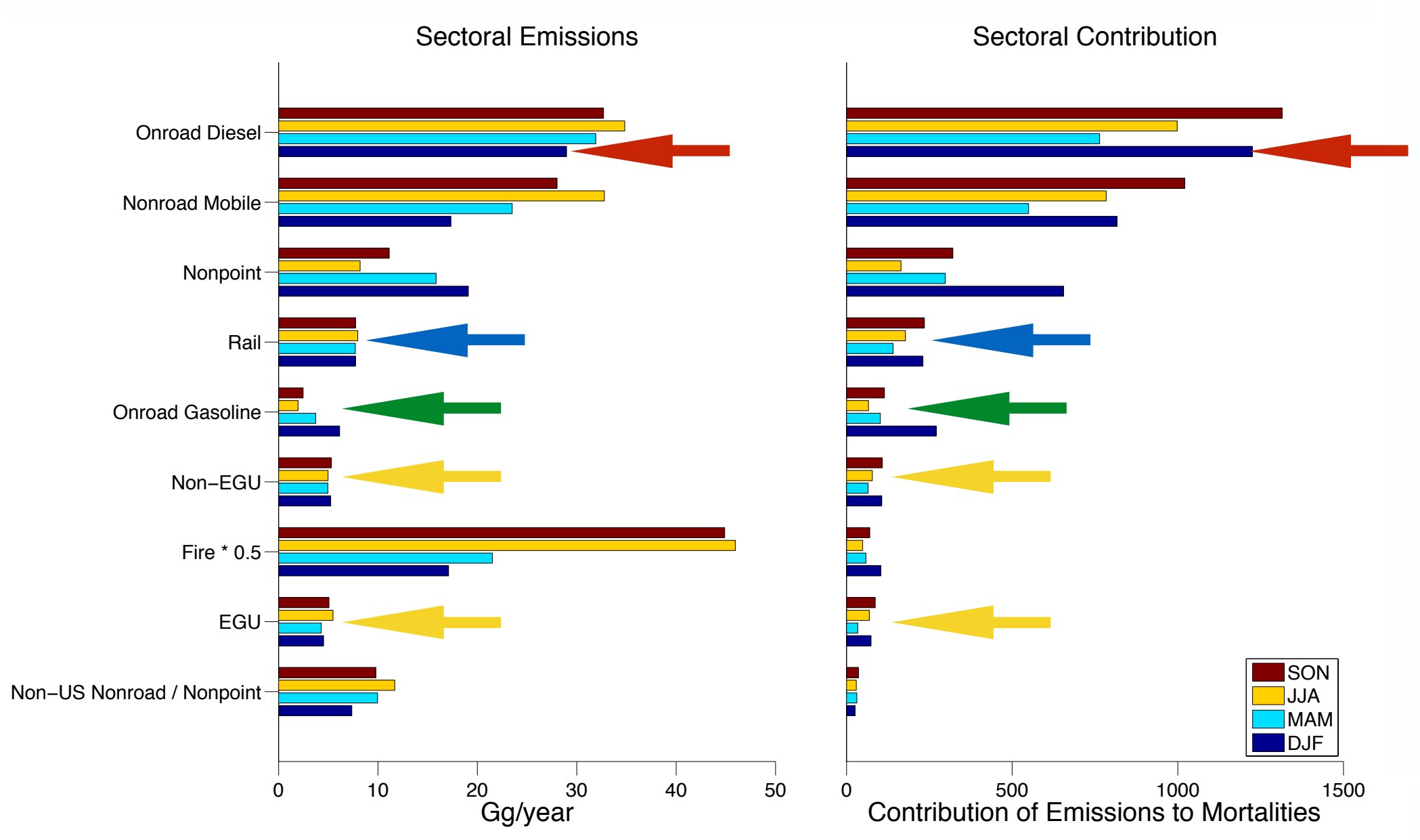


Figure 5: Comparison of (a) Contribution Percentage from Anthropogenic Emissions to Population Percentage, (b) Anthropogenic Emission Percentage to Population Percentage, (c) Mortality Percentage to Contribution Percentage, and (d) Contribution Percentage to Anthropogenic Emission Percentage.

Sectoral Emission Analysis - National

Figure 6: Seasonal Breakdown of Sectoral Emissions (left) and Contributions (right). Emission sectors with contributions smaller than Non-US Nonroad and Nonpoint emissions are not shown.



- Seasonal trends in contributions do not necessarily match seasonal trends in emissions (**Figure 6**).
  - Onroad diesel emissions are lowest in DJF period yet contributions from onroad diesel emissions for the same time period are nearly the highest (**red arrows**).
  - Rail emissions show no seasonality, yet contributions are higher in the cooler months and lower in the warmer months (**blue arrows**).
- Magnitude of emissions doesn't necessarily indicate magnitude of contributions.
  - Onroad gasoline emissions (green arrows) are smaller than Non-EGU and EGU emissions (yellow arrows), yet have larger contributions.

Sensitivity of BC Health Impacts - Regional

NY/PHI Region

- 1,923 annual mortalities attributed to exposure to BC in the NY/PHI region.

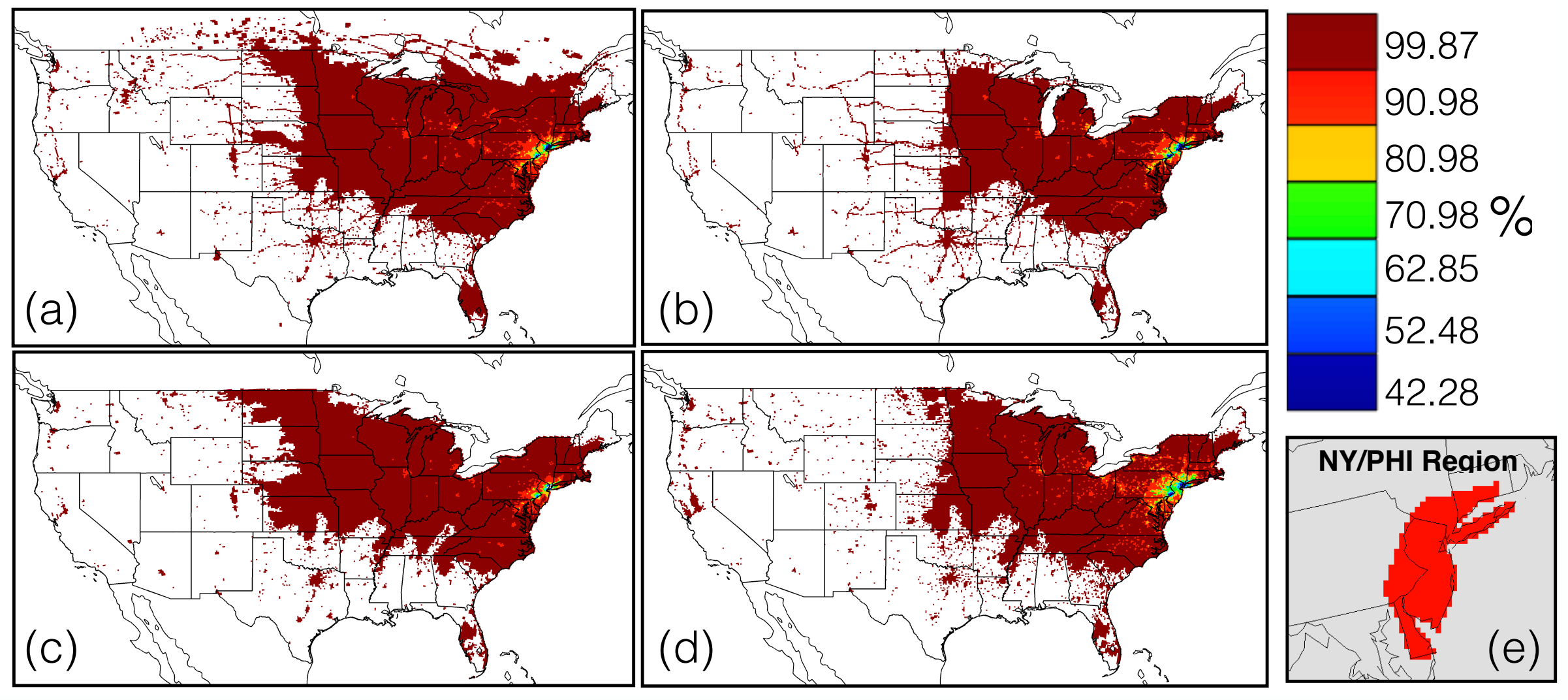


Figure 7: Contour Plots of Contributions to Mortalities in the NY/PHI Region (e) for all Emissions (a), Onroad Emissions (b), Nonroad Emissions (c), and Non-point Emissions.

- ~81% of mortalities in region are attributed to emissions within region.
- Largest percentage of contributions attributed to nonroad mobile emissions (**Figure 8**).
  - Nonroad mobile emissions have significantly larger contribution percentage than emission percentage.
- Transport shown to be significant for health impacts of BC emissions from many of the sectors with larger contributions.

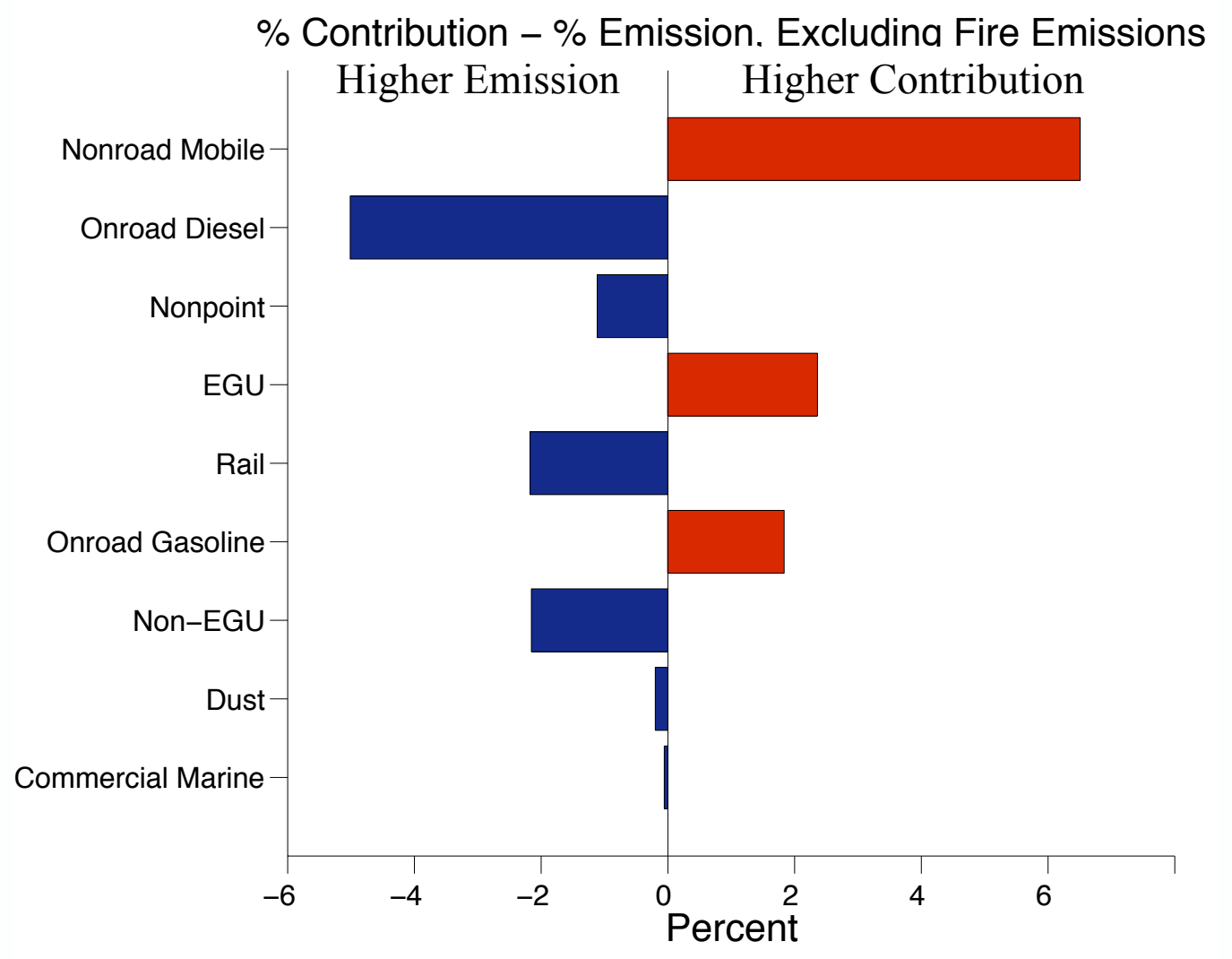


Figure 8: Difference Between Contribution Percentage and Emission Percentage in the NY/PHI Region

San Joaquin Valley Region

- 134 annual mortalities attributed to exposure to BC in the San Joaquin Valley region.

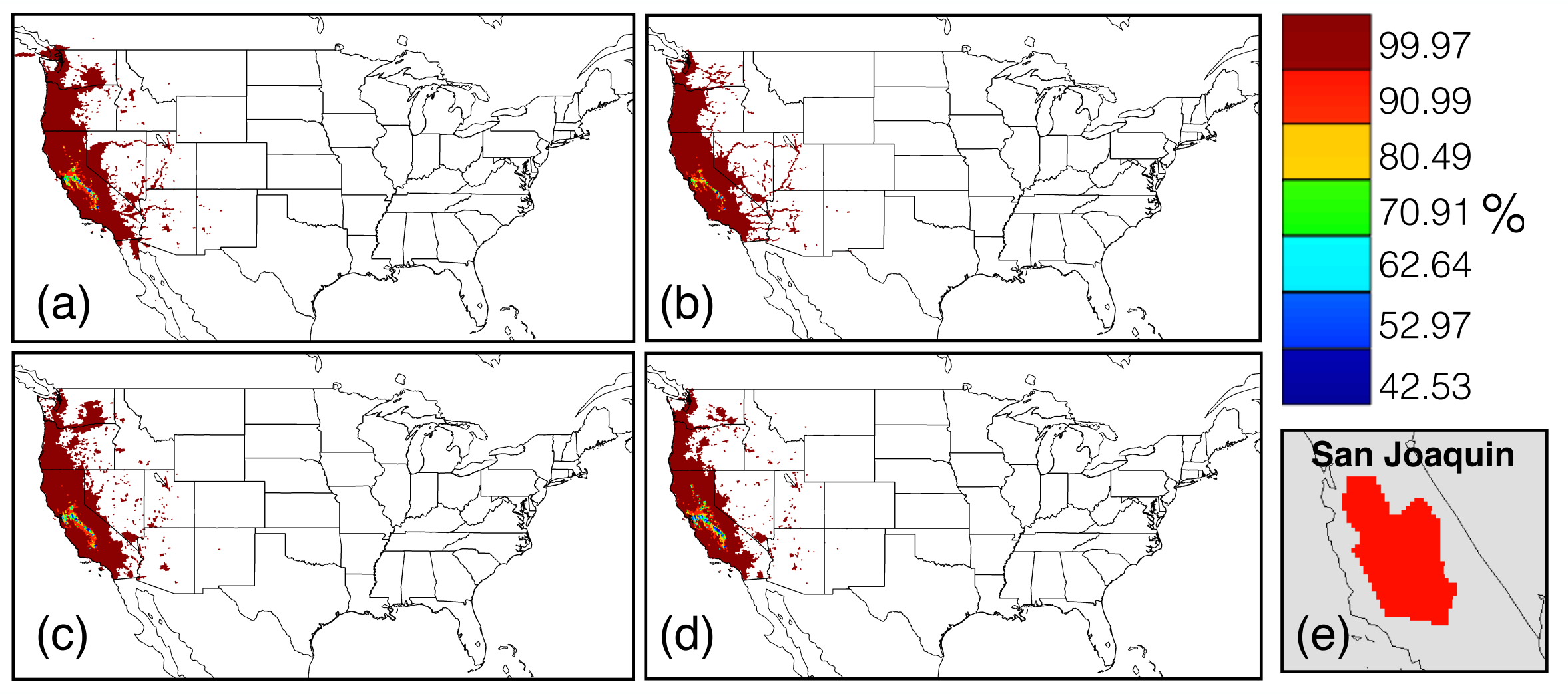


Figure 9: Contour Plots of Contributions to Mortalities in the San Joaquin Region (e) for all Emissions (a), Onroad Emissions (b), Nonroad Emissions (c), and Non-point Emissions.

- ~73% of mortalities in region are attributed to emissions within region
- Largest percentage of contributions attributed to onroad diesel emissions (**Figure 10**).
  - Non-point emissions have significantly larger contribution percentage than emission percentage.
- Emission sectors with larger contribution percentages would have greatest benefit from BC controls.

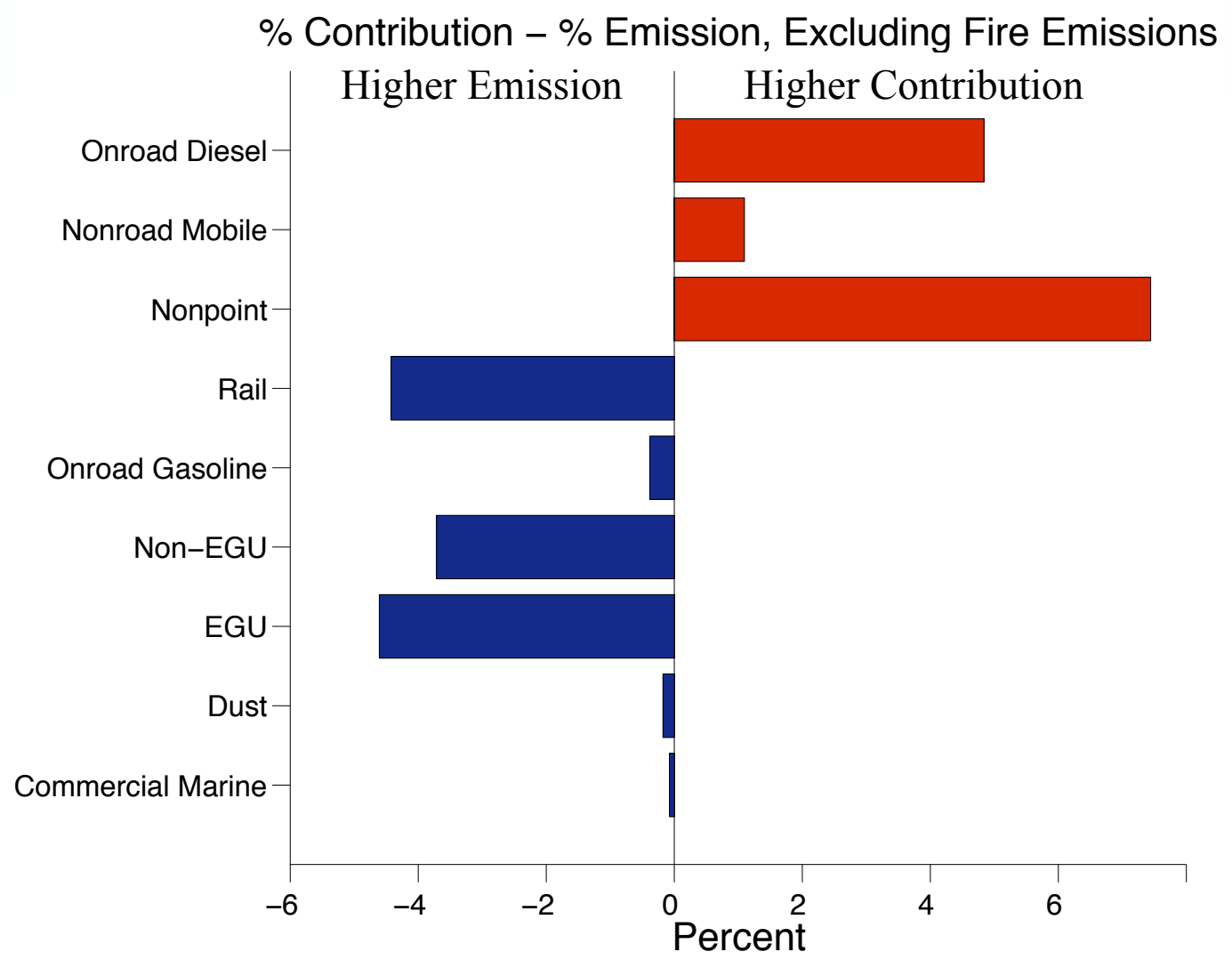


Figure 10: Difference Between Contribution Percentage and Emission Percentage in the San Joaquin Region

Conclusions

- Transport of short-lived species shown to be important for both national and regional studies.
  - Percentage of mortalities attributed to emissions outside of region ranges from 19% (NY/PHI Region) to 27% (San Joaquin Valley Region)
- Seasonal trends in emissions do not predict trends in contributions.
- Magnitude of emissions do not necessarily predict magnitude of contributions.

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This research is supported through NASA Applied Sciences Program grant NNX09AN77G.