# Adjoint Estimates of Benefit per Ton of $PM_{2.5}$ and Precursor Emission Reductions in the U.S.

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# Benefit per Ton (BPT)

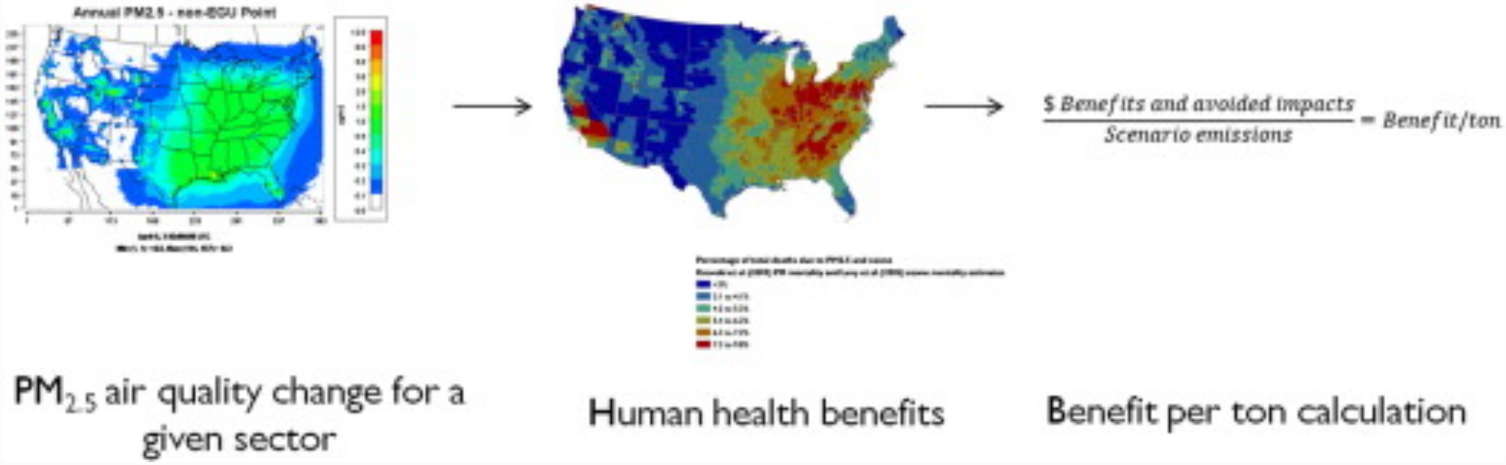
BPT is a term used to measure the dollar values of per-ton emission reductions (Fann et al., 2009)

BPTs depend on

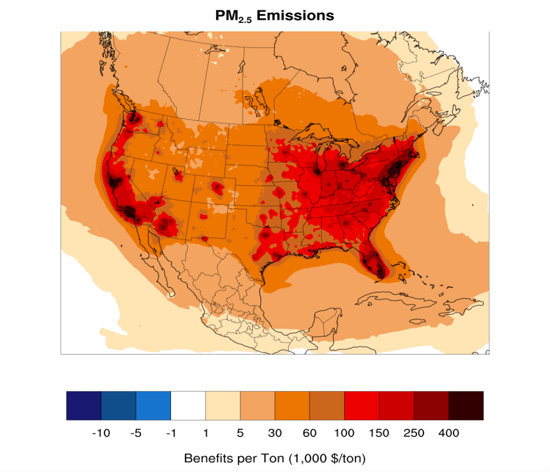
- Emission locations (metropolitan, remote areas)
- Emission sources (transportation, industry, agriculture, etc.)
- Emission types ($NH_3$, $SO_2$, $NO_x$, etc.)

**Goal:** Estimates of BPTs of $PM_{2.5}$ primary and precursor emissions, including primary $PM_{2.5}$, $NH_3$, $NO_x$, $SO_2$

# How to calculate BPTs?




- Forward approach (Fann et al., 2012)
- BPTs due to emission changes of a sector




- Backward adjoint approach
- BPTs of emissions at each location

# CMAQ adjoint model

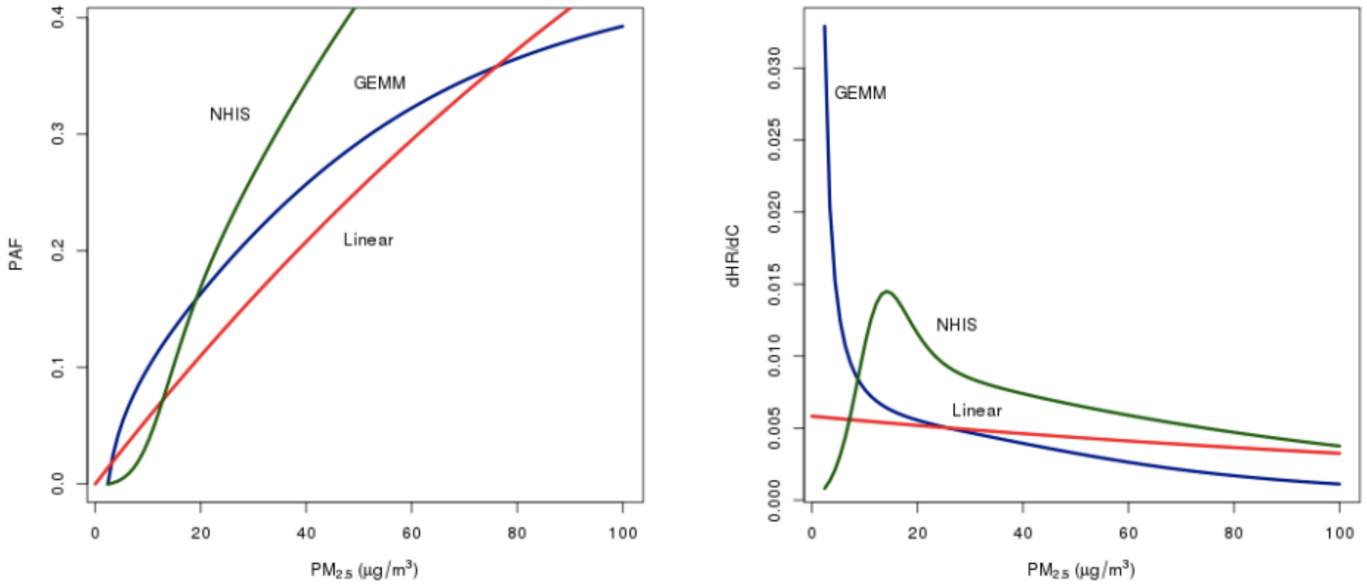
CMAQ simulates the evolution of pollutants

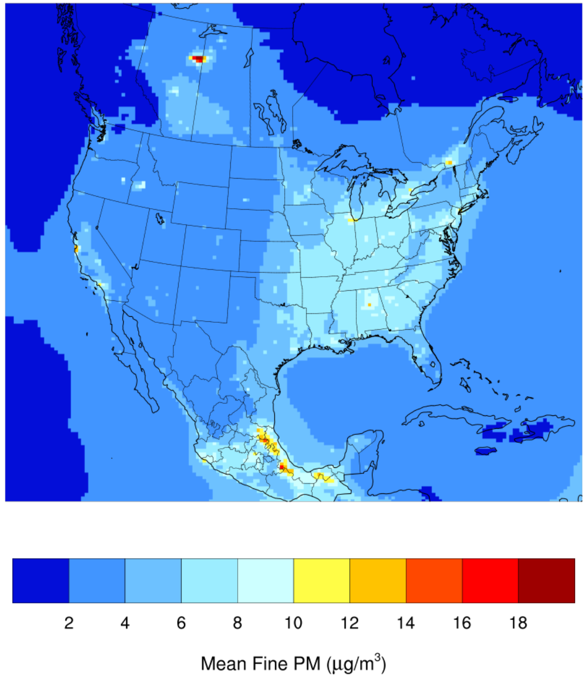
CMAQ adjoint calculates the gradients to pollutant concentrations/emissions, backward in time (Hakami et al., 2007; Zhao et al., 2020)

- The forward and backward components of the adjoint
- Checkpoint pollutant concentrations due to nonlinearity with the forward
- Define an air quality metric or adjoint cost function of pollutant concentrations
- Derive the adjoint forcing which drives the adjoint model
- Run the backward and calculate BPTs

# Adjoint cost function

Concentration response functions (CRFs), from air pollution to health and economic cost




- GEMM Global Exposure Mortality Model (Burnett et al., 2018)
- NHIS National Health Interview Surveys (Pope et al., 2018)
- Linear Linear in concentration (Krewski et al., 2009)

# Computational setup and cost

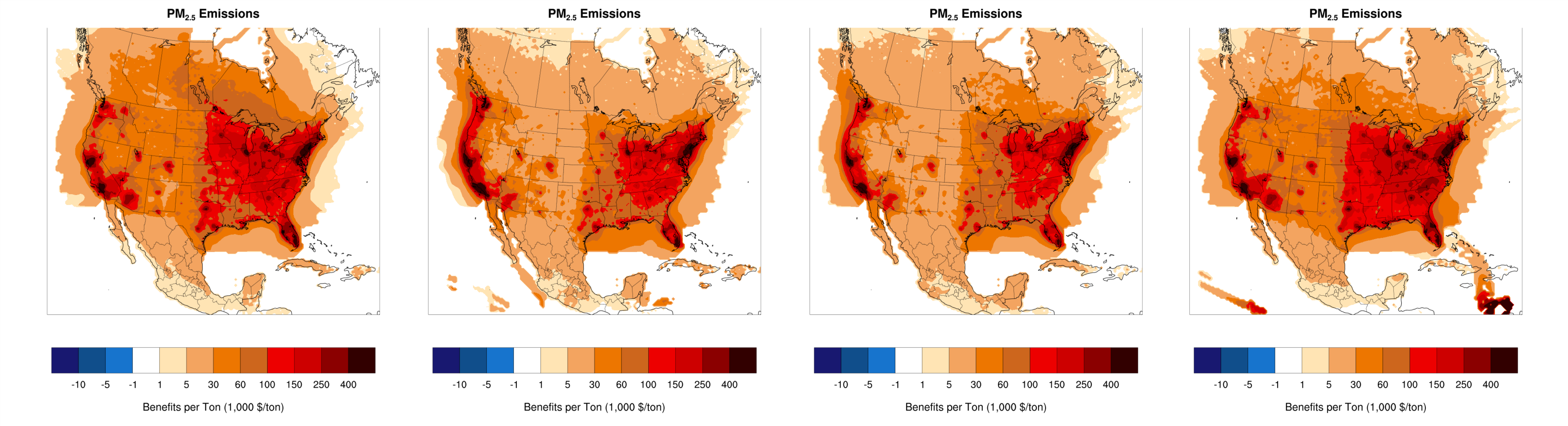
EPA 36US3 Domain: 172 columns x 148 rows x 35 layers

Synchronization time step: 12 minutes

Computational expenses on Compute Canada's Graham cluster

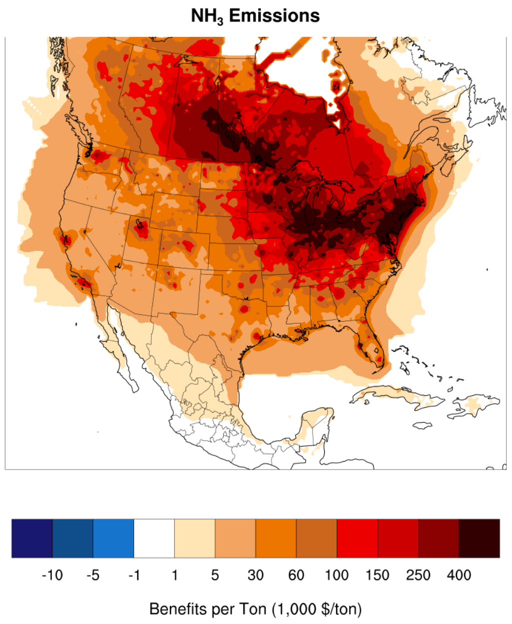
- Number of CPUs: 64
- Averaged elapsed time per day for the forward: 30 minutes
- Storage: 176 GB/day; 63TB/yr

# GEMM BPTs for $PM_{2.5}$ primary emissions

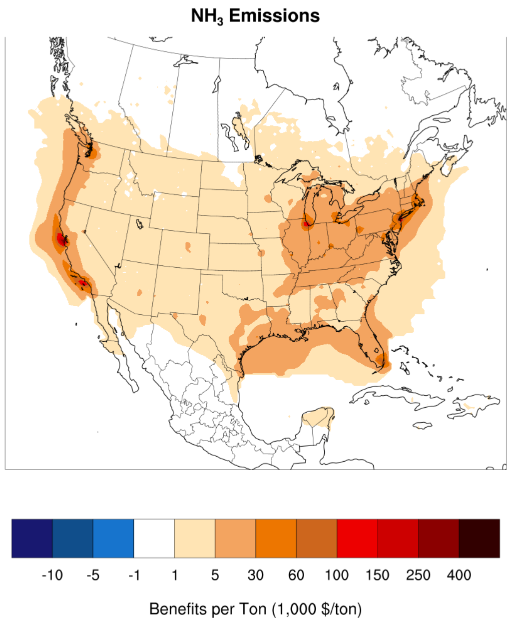



Winter Summer Spring Fall

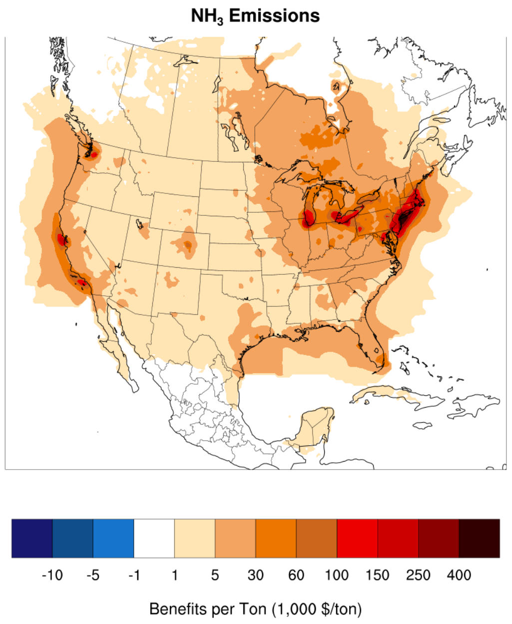
# GEMM BPTs for $NH_3$ emissions



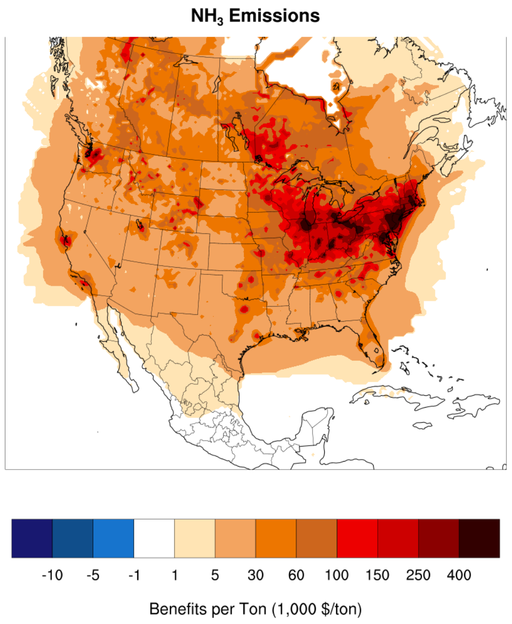

Winter




Summer

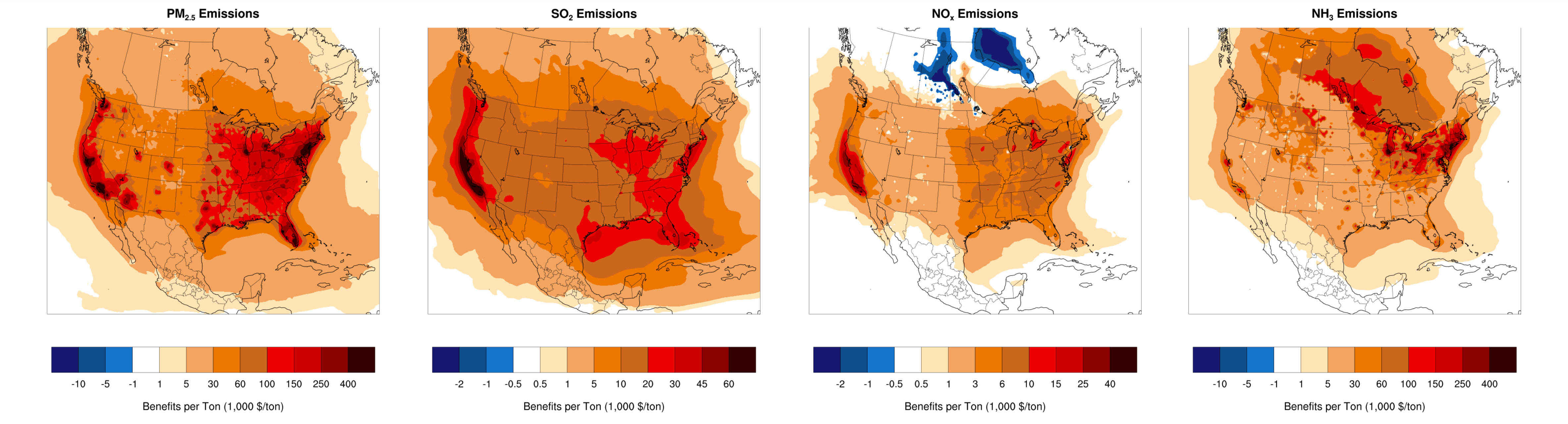



Spring




Fall

# Annual GEMM BPTs




$PM_{2.5}$ $SO_2$ $NO_x$ $NH_3$

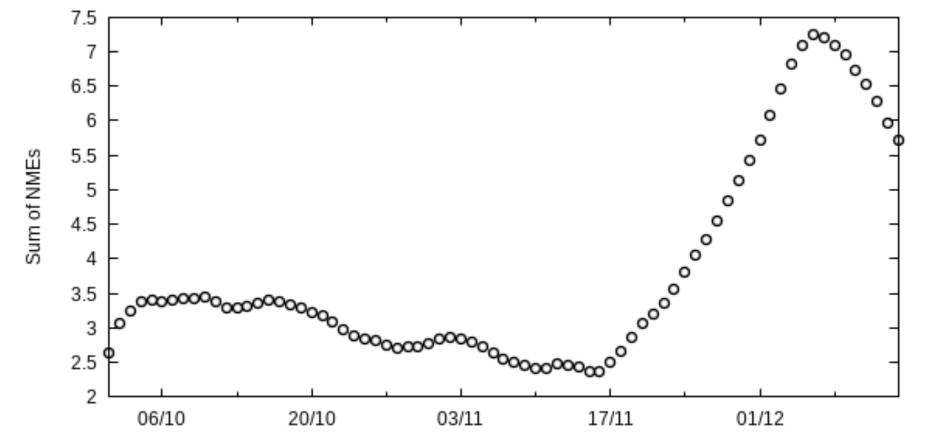
# Comparison with other models

(Industrial Economics, Incorporated, 2019)

| | CMAQ BENMAP | AP2 DIRECT | AP3 DIRECT | INMAP BENMAP | EASIUR DIRECT | SA DIRECT | CMAQ ADJ |
|---|---|---|---|---|---|---|---|
| Cement Kilns | $5,300 | $3,900 | $6,500 | $8,000 | $3,100 | $6,300 | $4,030 |
| CPP Proposal | $21,000 | $15,000 | $23,000 | $41,000 | $15,000 | $28,000 | $18,123 |
| Pulp and Paper | $2,600 | $1,400 | $2,400 | $3,500 | $1,600 | $2,800 | $1,797 |
| Refineries | $1,800 | $1,600 | $2,900 | $3,300 | $1,100 | $2,300 | $1,386 |
| Tier 3 | $4,100 | $11,000 | $18,000 | $13,000 | $5,300 | $6,800 | $4,156 |

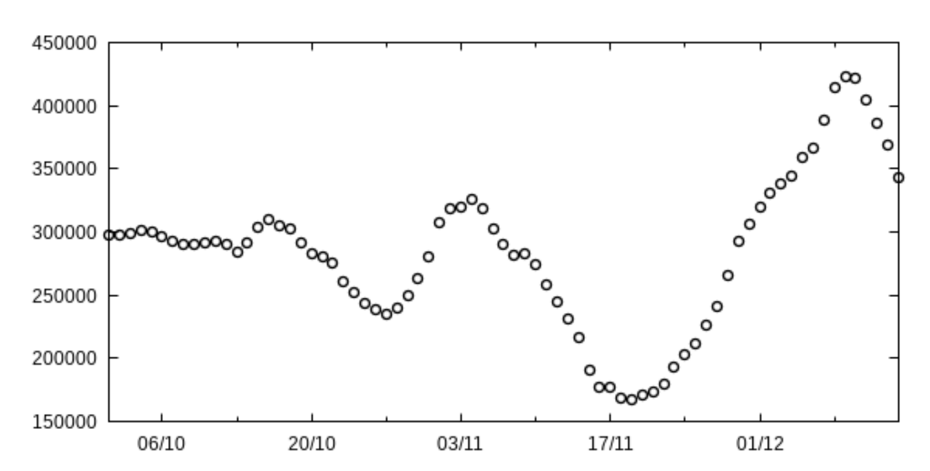
**National benefits by policy (Millions):** Different year (meteorology/emissions), different CRFs ...

# Episode selection



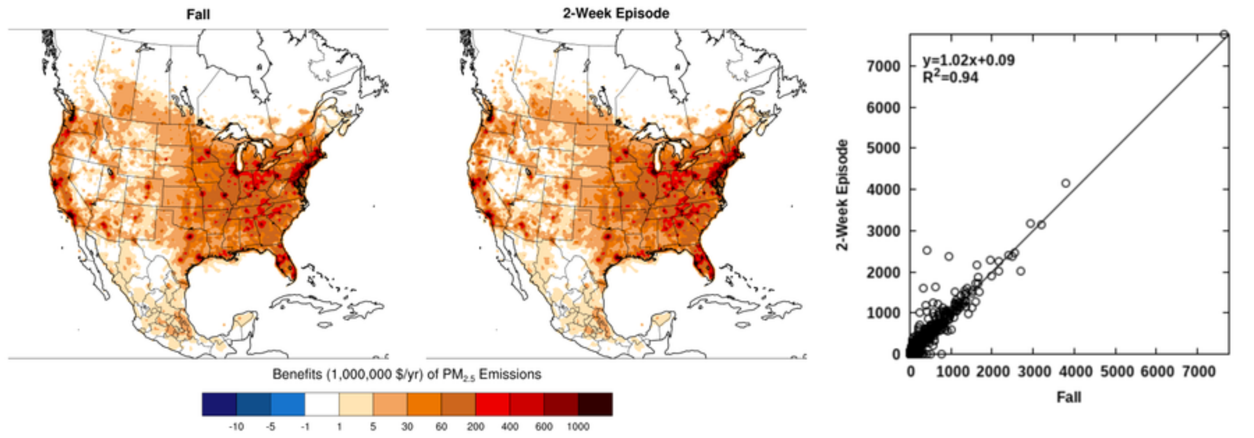

Normalized mean error for BPTs

$$NME = \frac{\sum_{i=1}^{N} |BPT_{w,i} - BPT_{s,i}|}{\sum_{i=1}^{N} |BPT_{s,i}|}$$

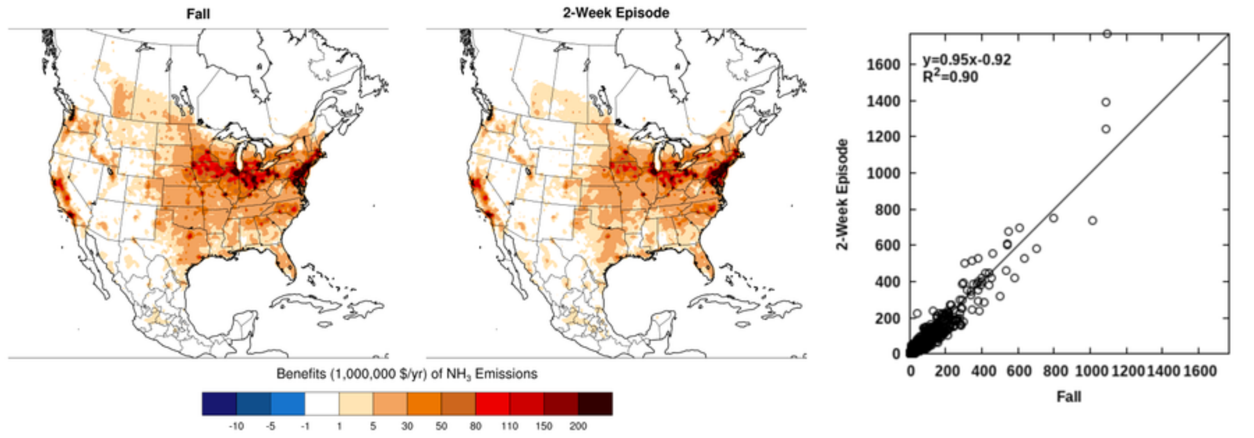



Mean error for total benefits

# Benefits: Episode versus full Season

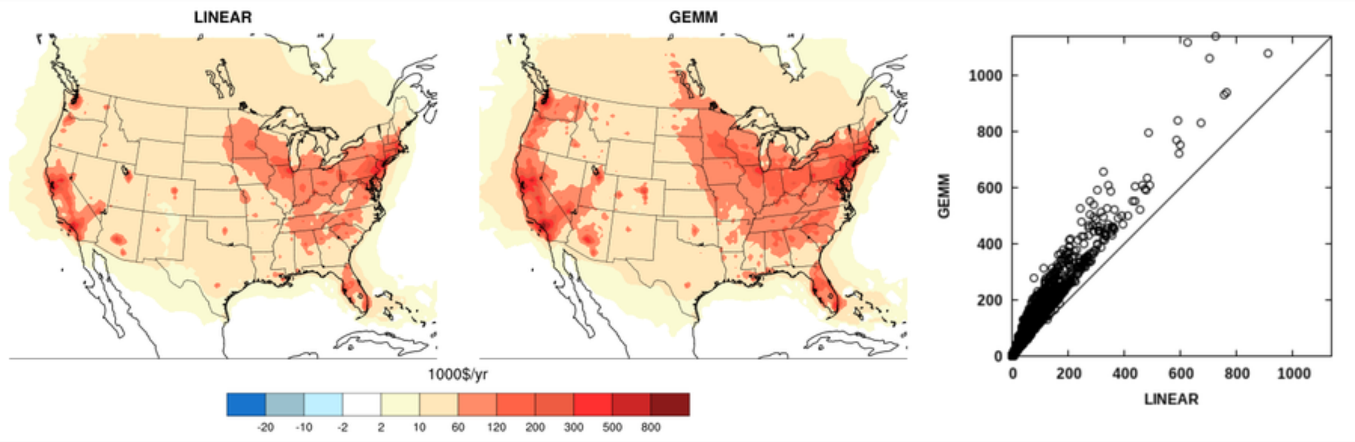



$PM_{2.5}$

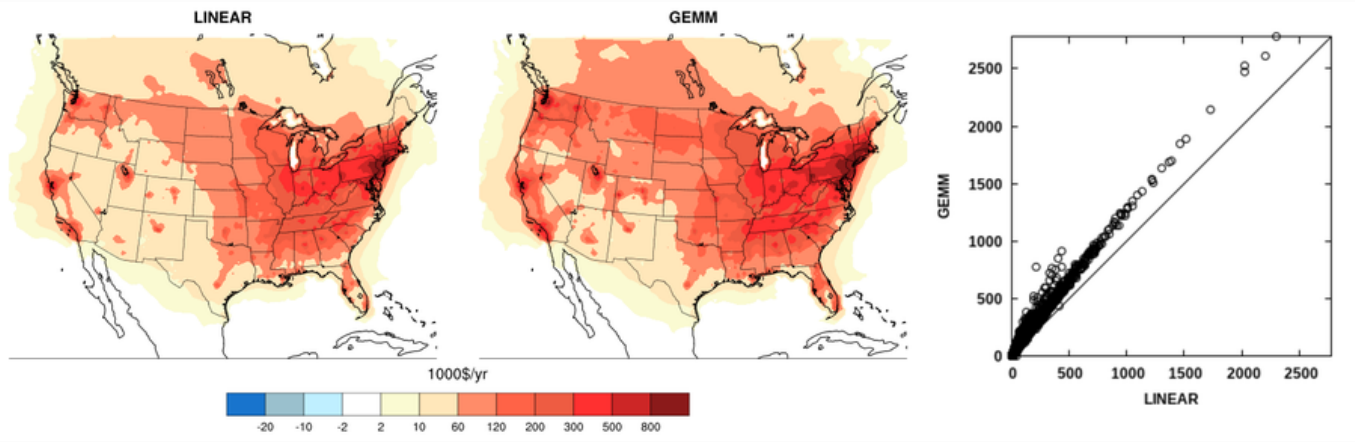



$NH_3$

# Preliminary results: Impact of CRFs

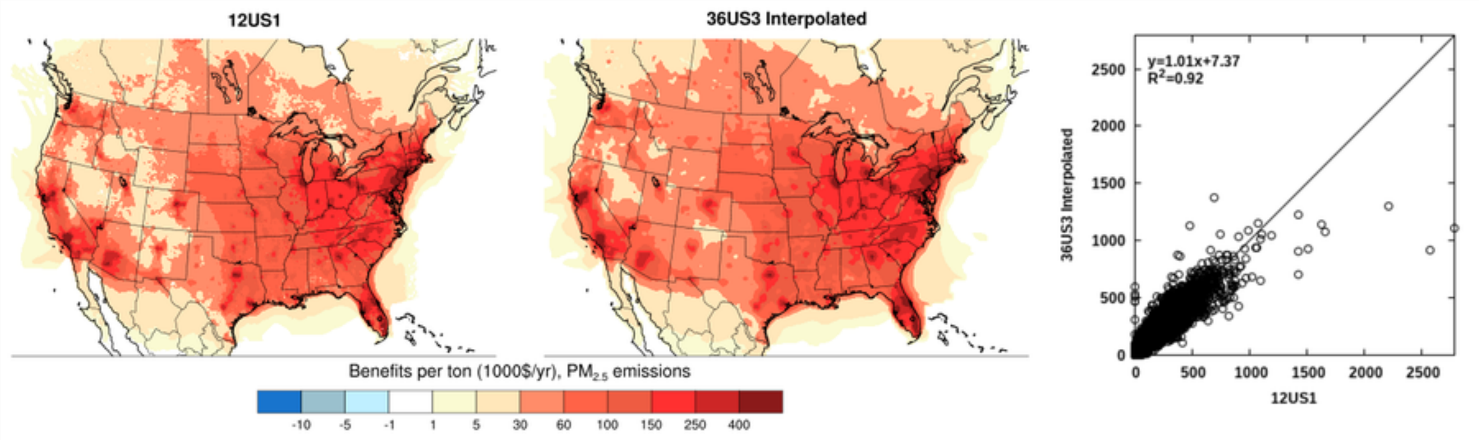



BPTs of $PM_{2.5}$ emissions

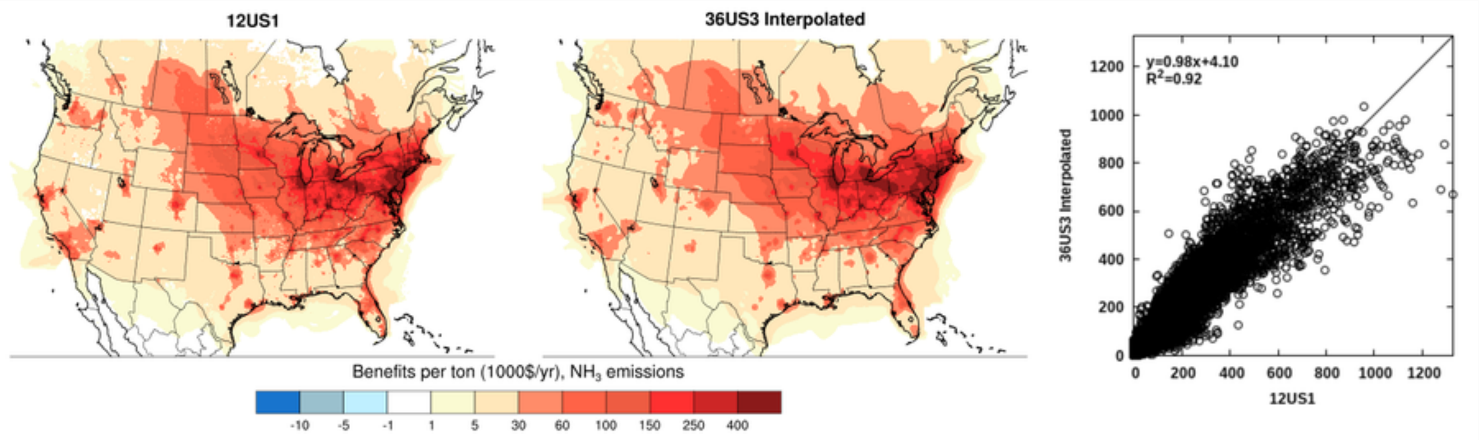



BPTs of $NH_3$ emissions

# Preliminary results: Impact of grid resolutions




BPTs of $PM_{2.5}$ emissions




BPTs of $NH_3$ emissions

# Concluding remarks and future work

- Seasonal adjoint simulations have been performed using the GEMM concentration response function to estimate benefits per ton of $PM_{2.5}$ primary and precursor emissions.
- Benefits per ton vary in time (seasonal variations), location and emission types; some emissions matter more than others.
- Despite the differences in setups, adjoint BPTs compare well with other models.
- 2-week episodes chosen based on BPTs and benefits have been used to study the impact of CRFs. For the U.S., GEMM BPTs are in general larger than Linear BPTs.
- Preliminary study of the impact of grid resolution shows that BPTs are consistent between 12KM- and 36KM-resolutions. Work with finer 4KM- and 1KM-resolutions is under way.
- Episode selection appears to be efficient and effective in studying the various scenarios with different CRFs and grid resolutions. Related uncertainties might need to be quantified.

# Acknowledgement


- We would like to thank Neal Fann and Kirk Baker from US EPA for their help with health assessment and RFM comparisons
- We would also like to acknowledge support from Health Effects Institute and Health Canada