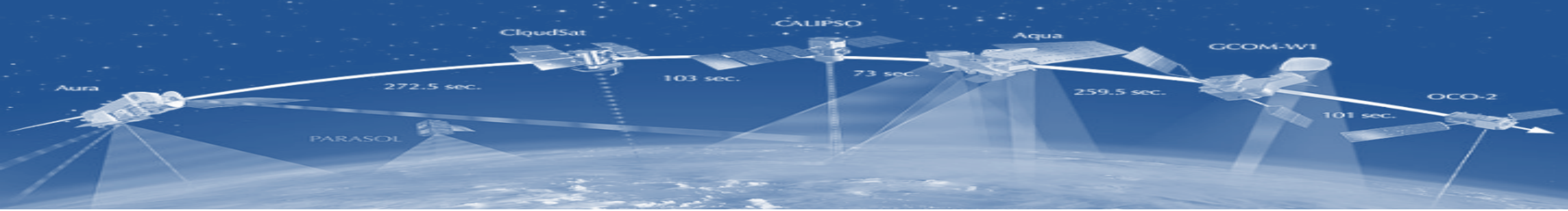

Implementing a sector-based inversion framework for top-down CO_2 emission estimates

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6/12/2025

Top-down Anthropogenic CO_2 Emission Estimates

Localized urban CO_2 emissions

(*Schwandner et al.*, 2017; *Wu et al*., 2020)

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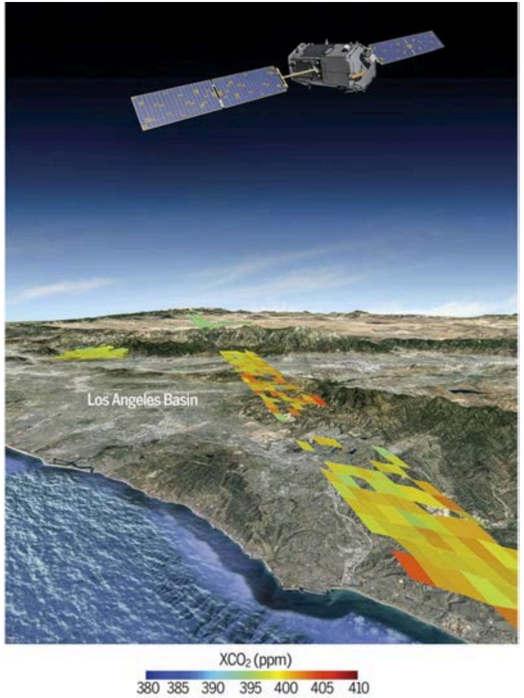
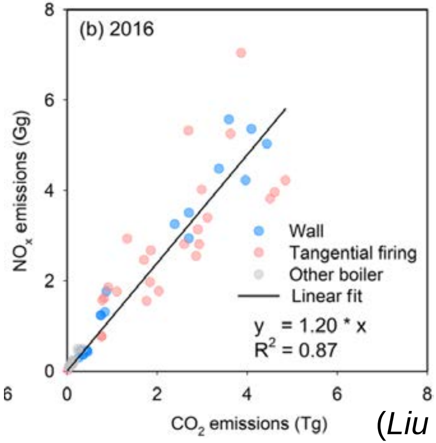


(*Schwandner et al.*, 2017; *Wu et al.*, 2020)

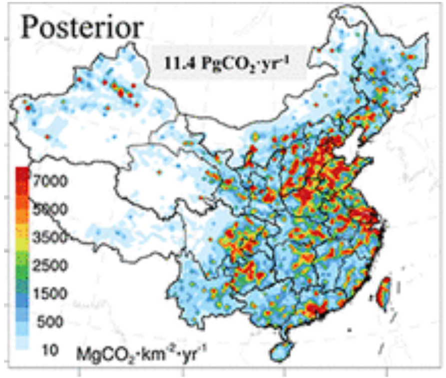
Use co-emitted air pollutant to estimate CO_2 emissions

Coal-fired power plant emissions using NO_x



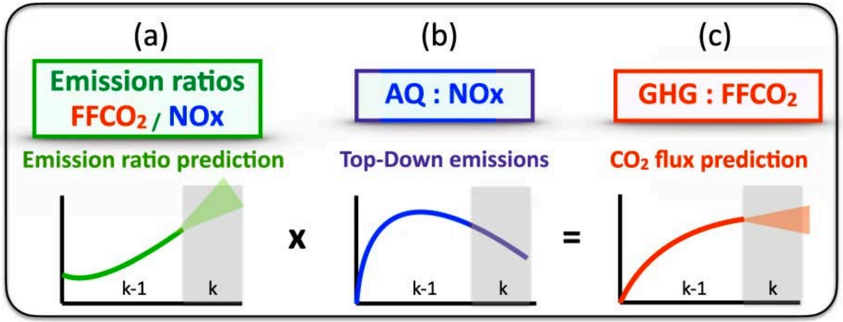
(*Liu et al.*, 2020)

Fossil fuel emissions using NO_x



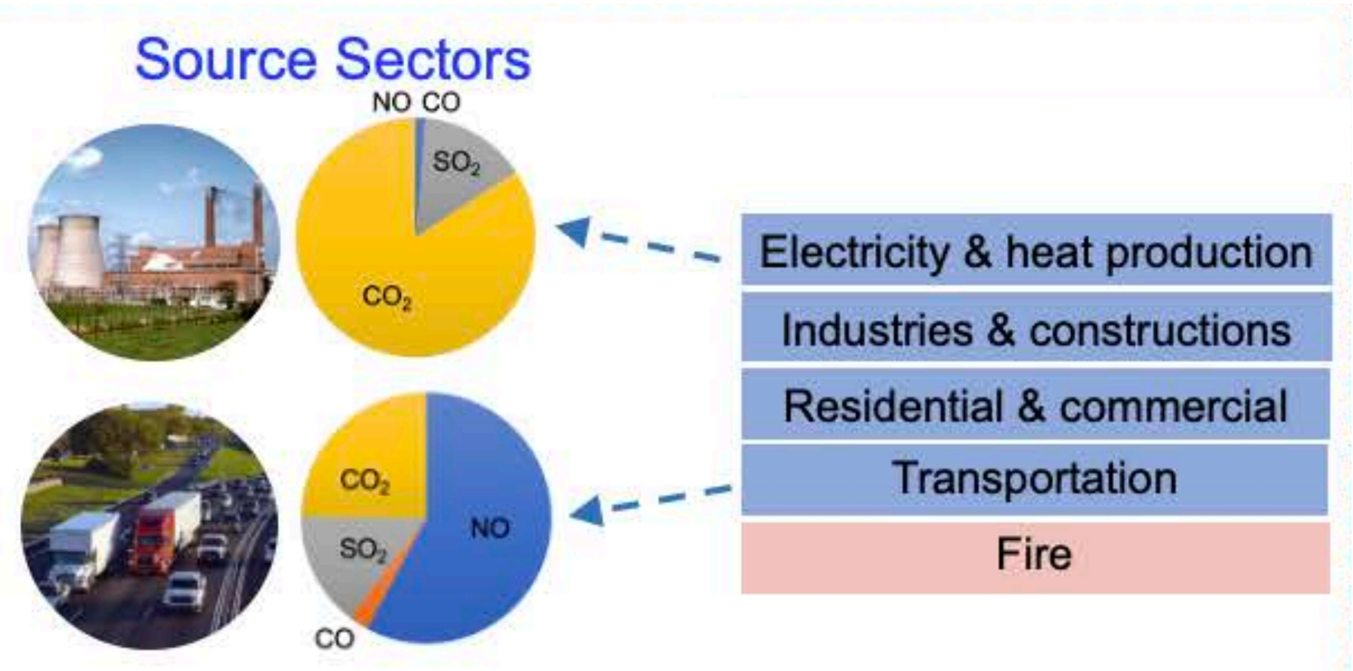
(*Feng et al.*, 2024)

Predict CO_2/NO_x emission ratio using Kalman Filter



(*Miyazaki & Bowman*, 2023)

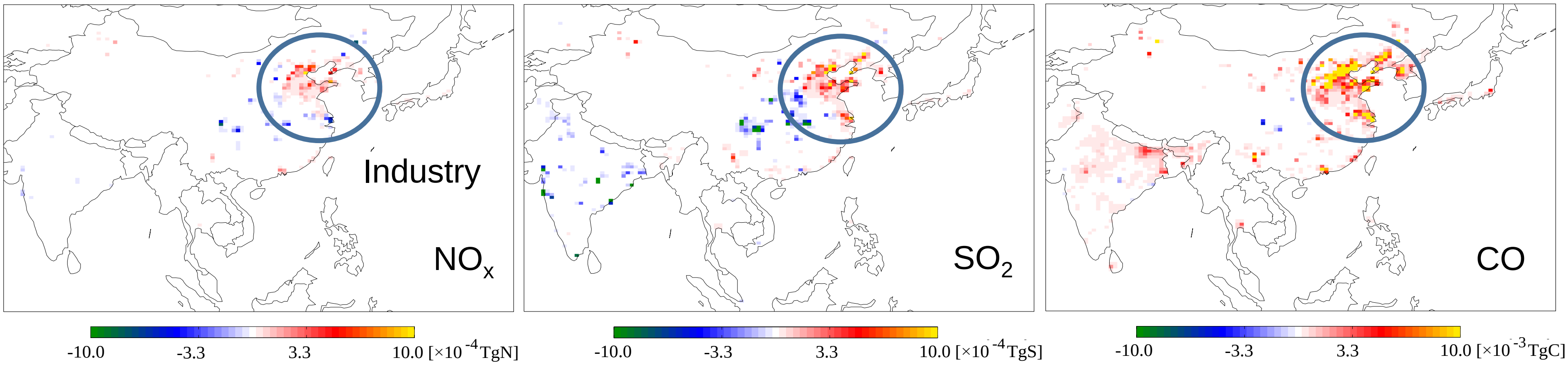
CO_2 and Air Pollutants Are Co-emitted From Human Activities



Emission = species emission factor × activity

Sector-based Inversion: Independent Adjustments for Each Source

Emission adjustments (Top-down – bottom-up, Jan, 2010)

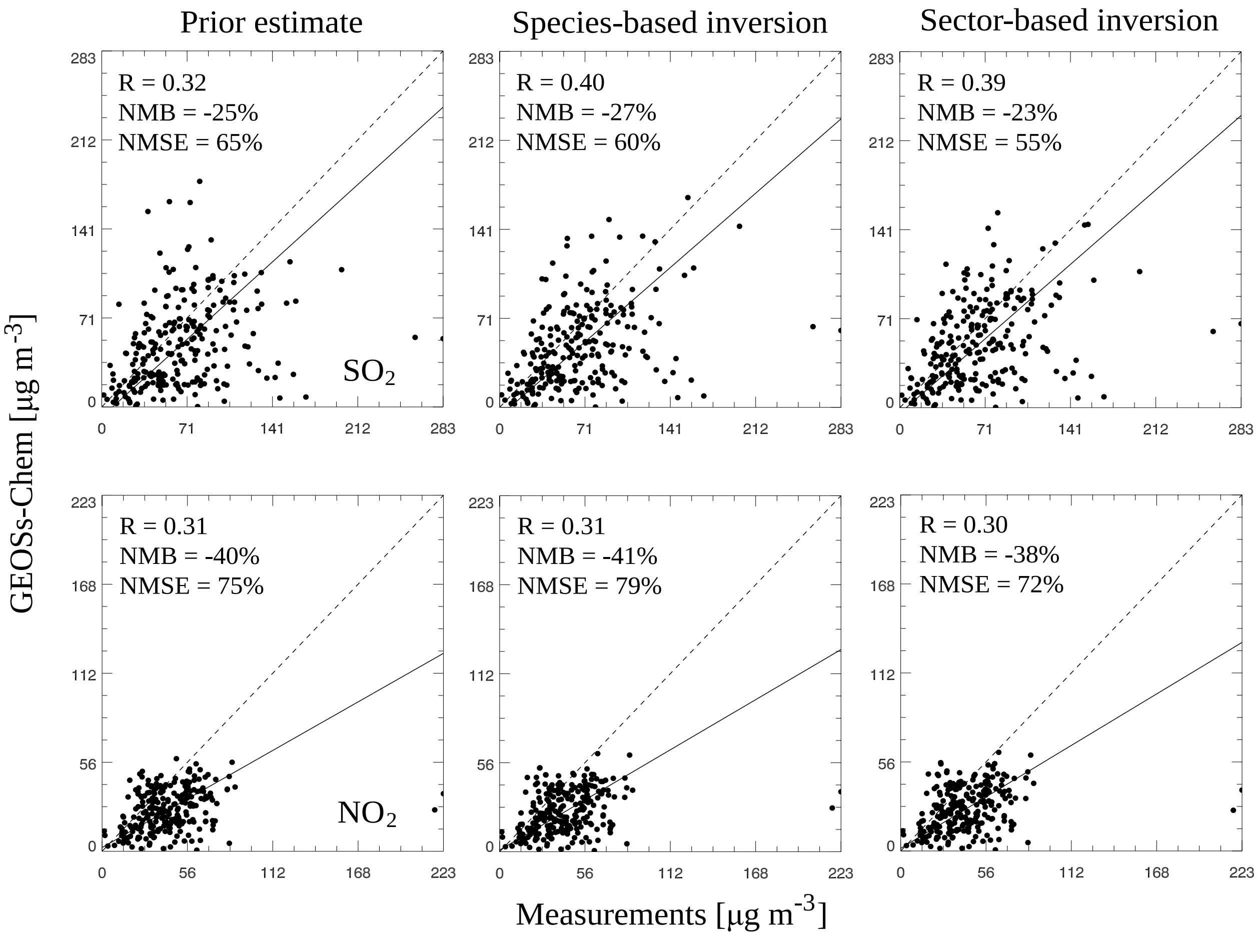


(*Qu et al.*, 2022)

Bottom-up emissions: overestimate underestimate

E = species emission factor × activity

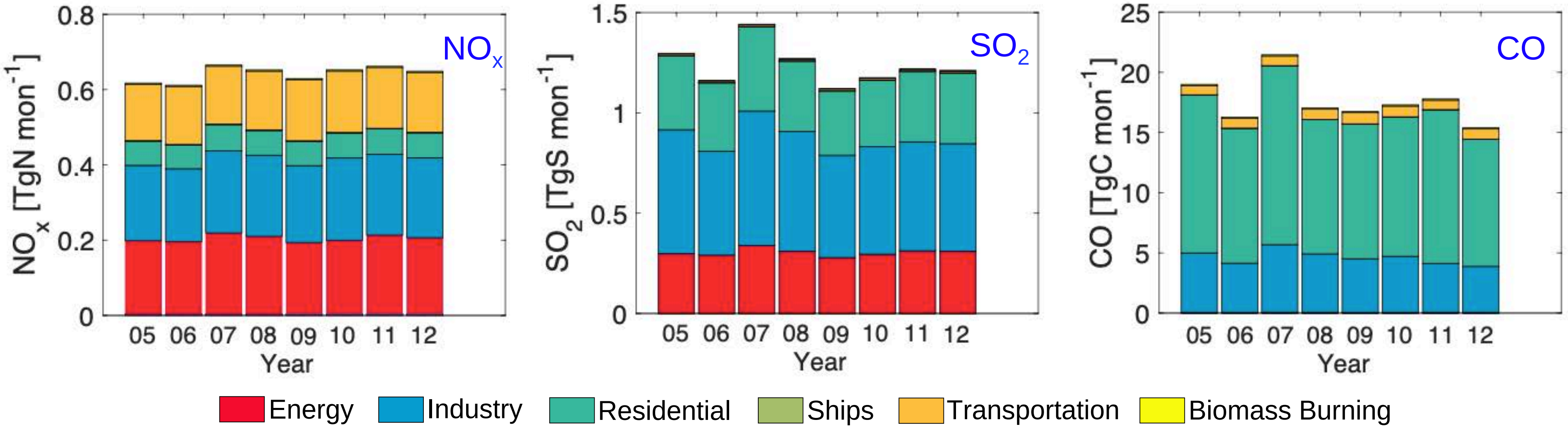
Sector-based Posterior Show the Best Agreement with Measurements



(*Qu et al.*, 2022)

Extend a Sectoral Air Pollutant Inversion Framework to CO_2 Emissions

Top-down emissions in China (Jan, 2005-2012)

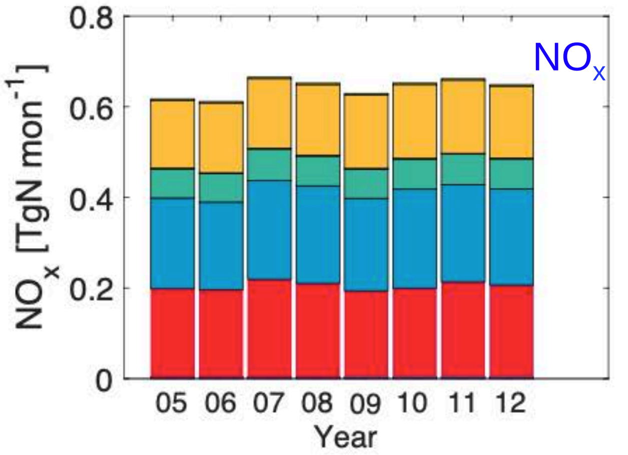


(*Qu et al.*, 2022)

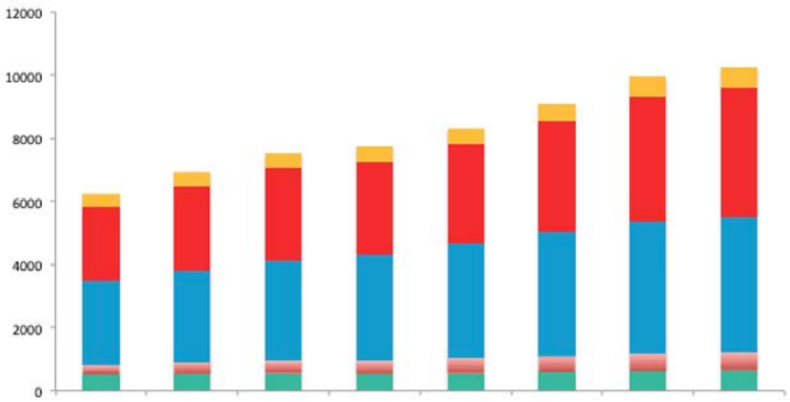
- Industry and energy sectors drive NO_x & SO_2 trends
- Residential and industry sectors drive CO trends

Extend a Sectoral Air Pollutant Inversion Framework to CO_2 Emissions

Top-down emissions



EDGAR CO_2 emissions in China (2005-2012)

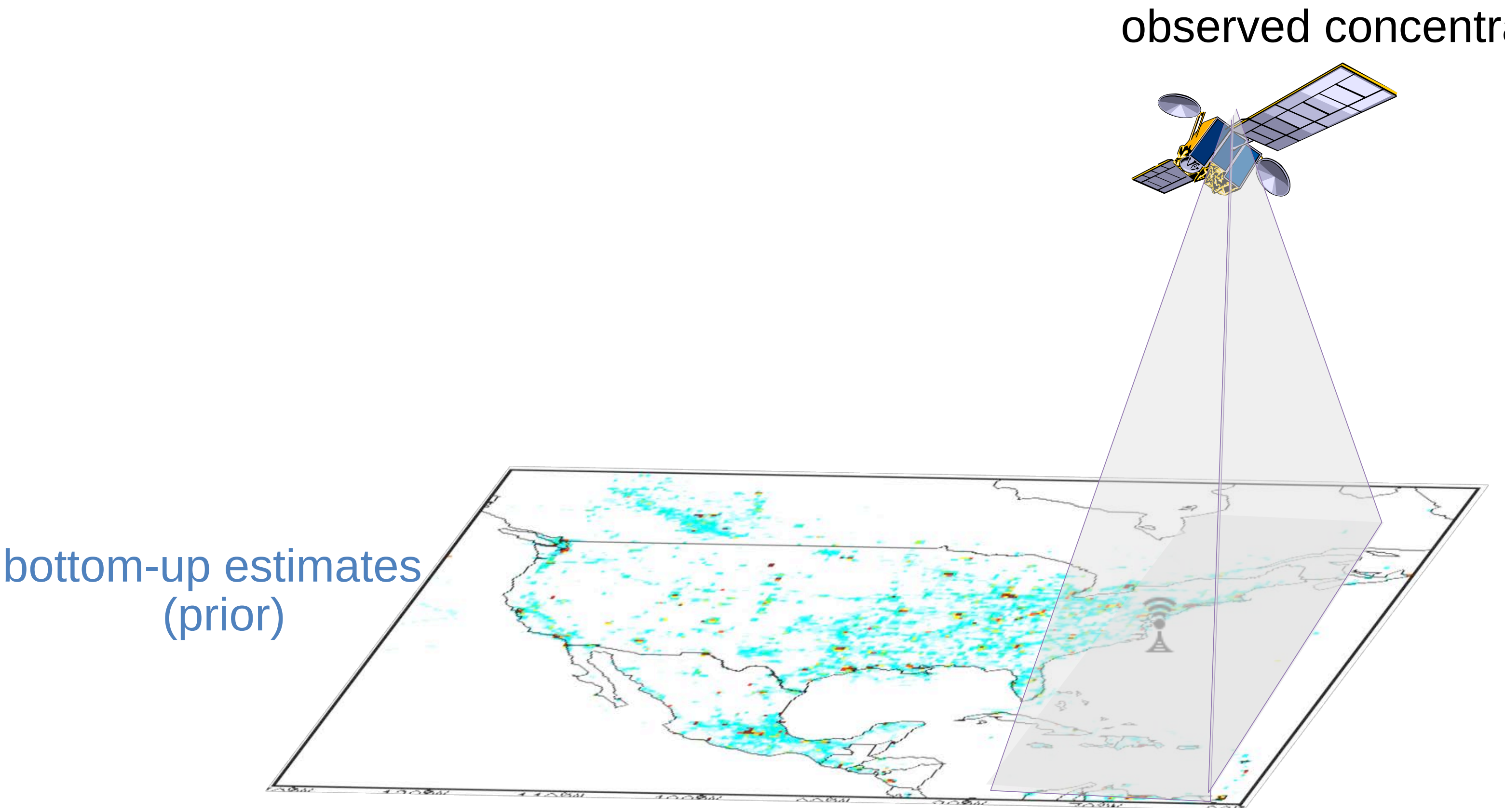


Energy Industry Residential Ships Transportation Biomass Burning

- Industry and energy sectors also drive CO_2 trends

Using Observations to Estimate Emissions Through Inverse Methods

Top-down estimate



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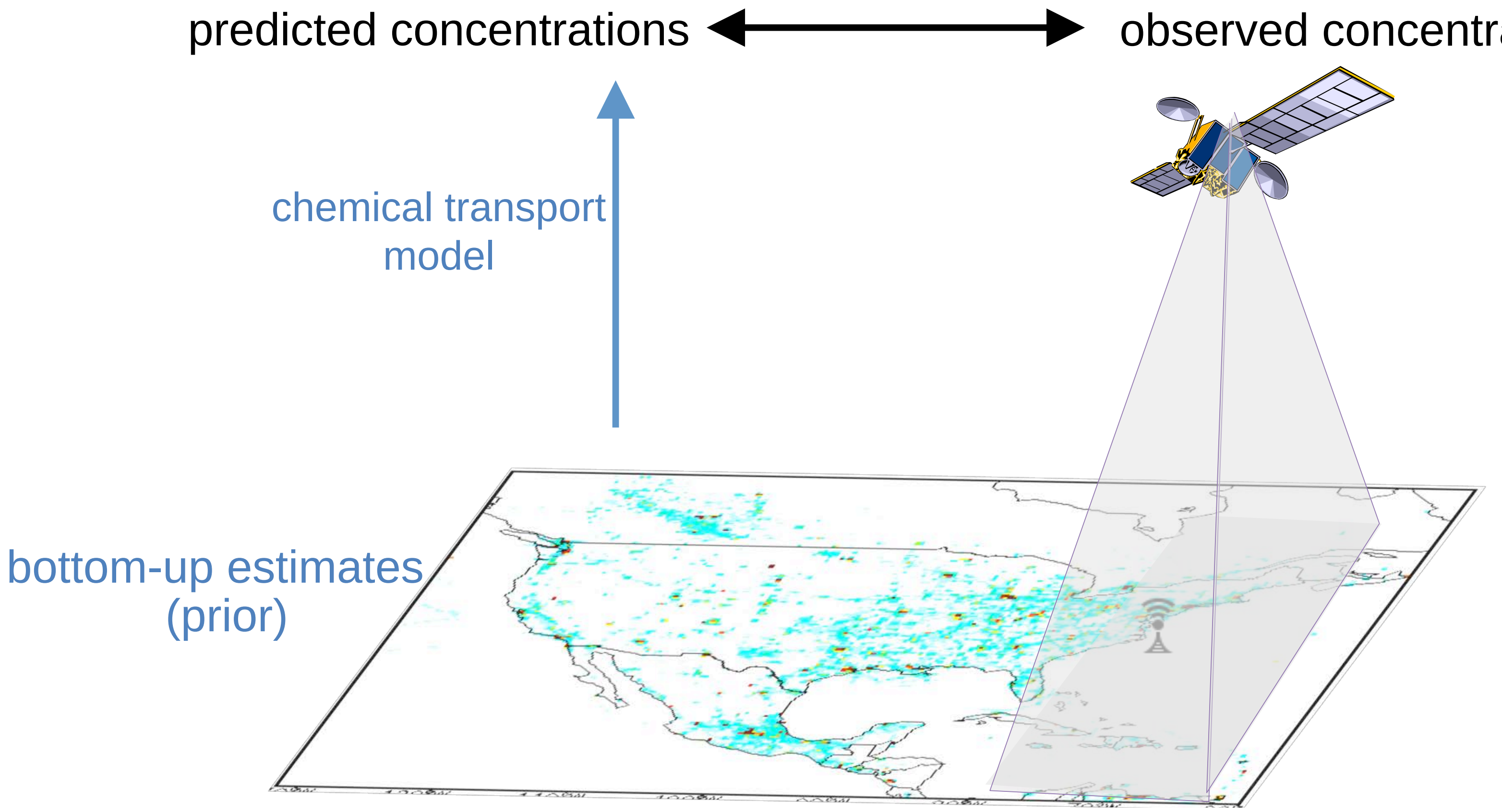

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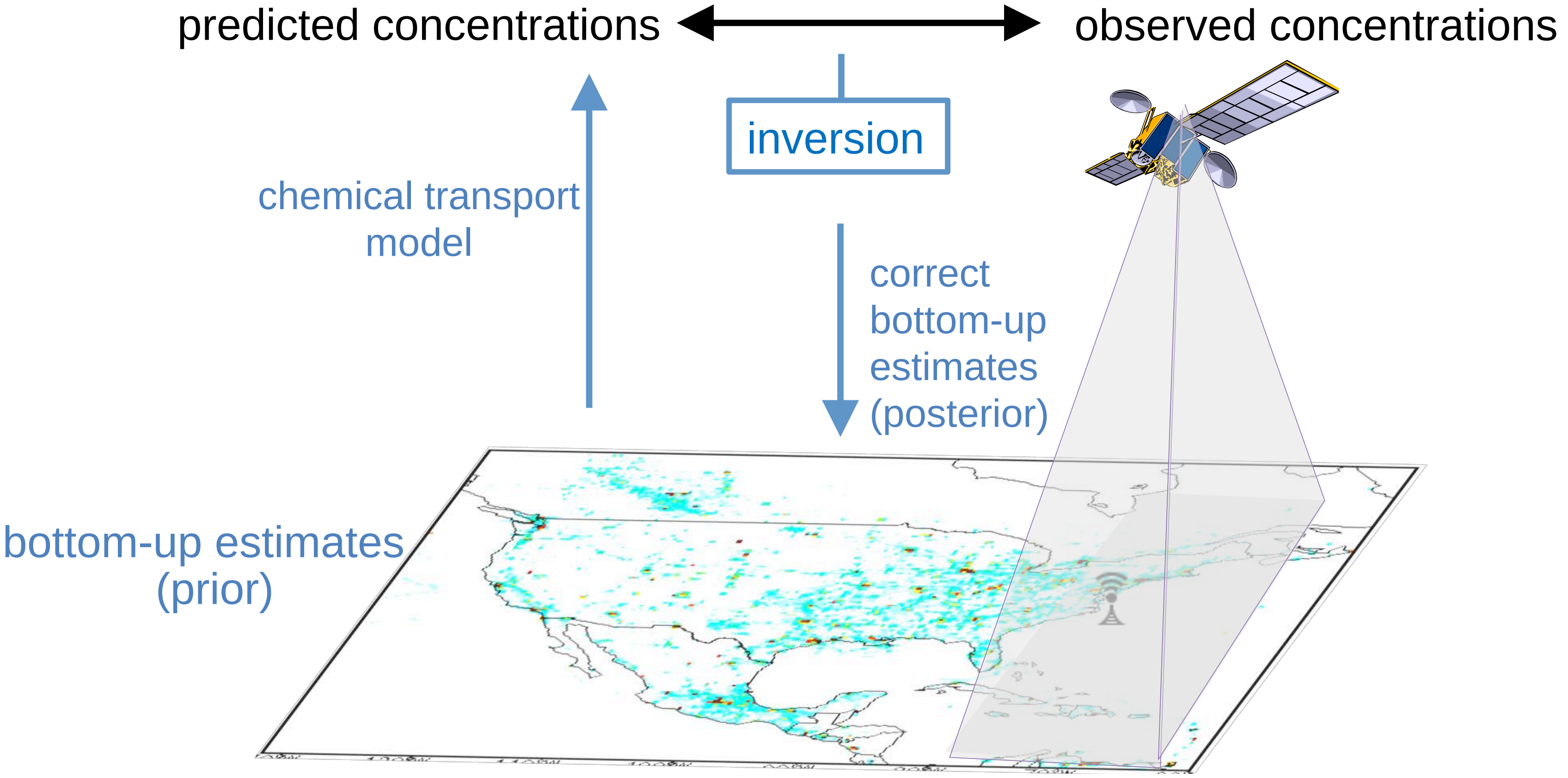

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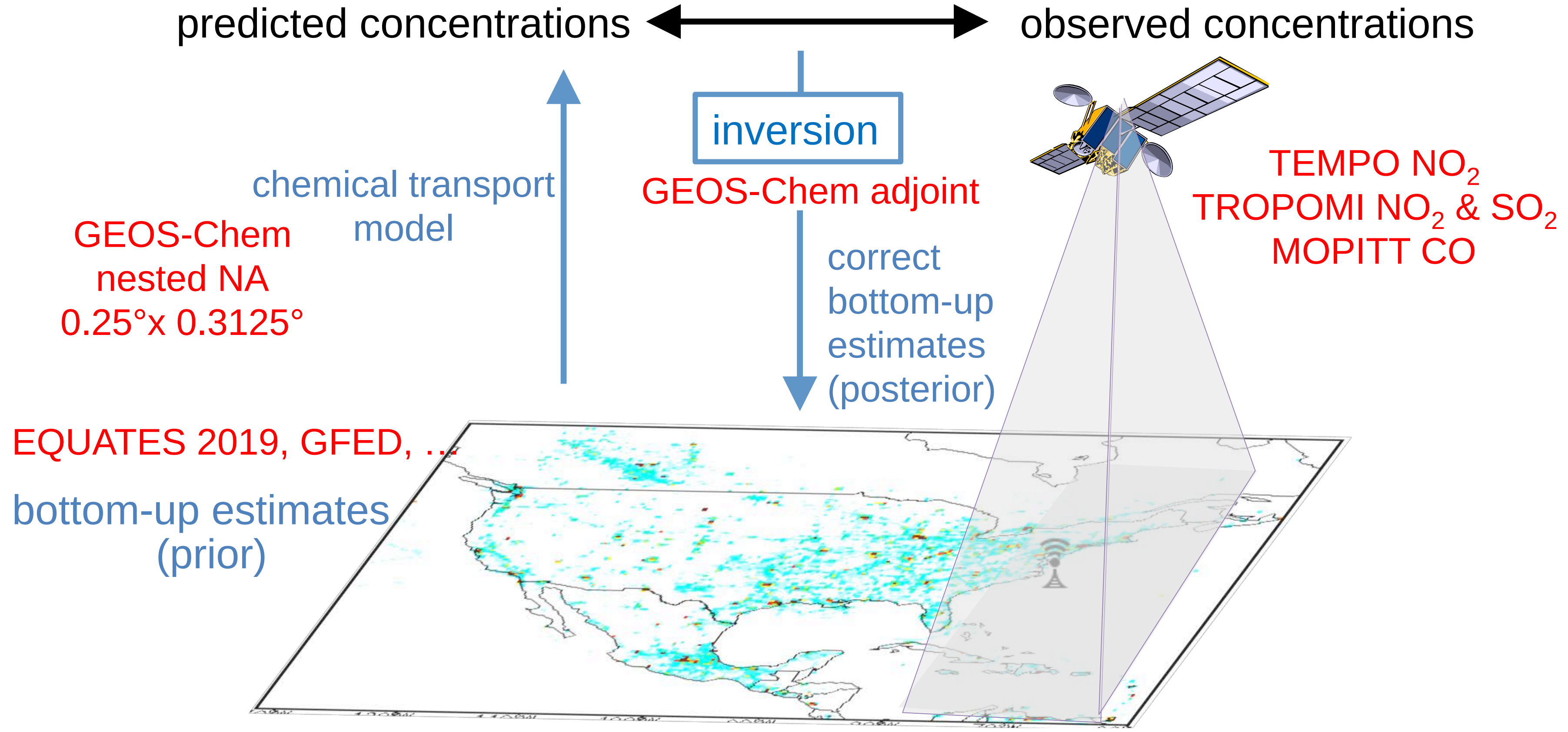
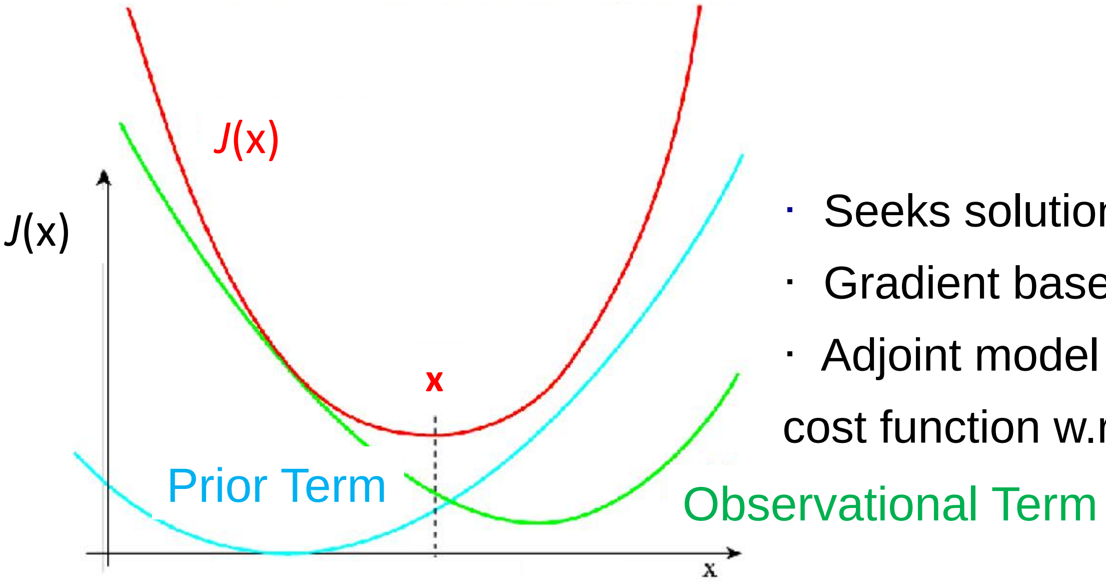


Bayesian Inference of Emissions: 4D-Var

Minimize cost Function:

$$J(x) = \underbrace{\frac{1}{2}(\boldsymbol{x}-\boldsymbol{x}_a)^T \mathbf{S_a}^{-1}(\boldsymbol{x}-\boldsymbol{x}_a)}_{\text{Prior Term}} + \underbrace{\frac{1}{2}\gamma(\boldsymbol{y}-\mathcal{H}\boldsymbol{x})^T \mathbf{S_o}^{-1}(\boldsymbol{y}-\mathcal{H}\boldsymbol{x})}_{\text{Observational Term}}$$



- Seeks solution iteratively
- Gradient based optimization
- Adjoint model calculates the sensitivity of cost function w.r.t. state vector

Formulation of a Sector-based Inversion

Existing multi-species inversion:

$E\_NO_x\_pos = SF\_NO_x \times E\_NO_x$

$E\_SO_2\_pos = SF\_SO_2 \times E\_SO_2$

$E\_CO\_pos = SF\_CO \times E\_CO$

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E = species emission factor × activity

New sector-based inversion:

$E\_NO_x\_pos = SF\_industry \times E\_NO_x\_industry + SF\_energy \times E\_NO_x\_energy + \ldots$

$E\_SO_2\_pos = SF\_industry \times E\_SO_2\_industry + SF\_energy \times E\_SO_2\_energy + \ldots$

$E\_CO\_pos = SF\_industry \times E\_CO\_industry + SF\_energy \times E\_CO\_energy + \ldots$

9 sectors: industry, transportation, residential, aviation, shipping, energy, biomass burning, lighting, and soil

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New sector-based inversion:

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$E\_CO\_pos = SF\_industry \times E\_CO\_industry + SF\_energy \times E\_CO\_energy + \ldots$

9 sectors: industry, transportation, residential, aviation, shipping, energy, biomass burning, lighting, and soil

Adjust sector and species emissions simultaneously

$E\_NO_x\_pos = SF\_industry \times E\_NO_x\_industry \times \boxed{SF\_NO_x\_industry}$

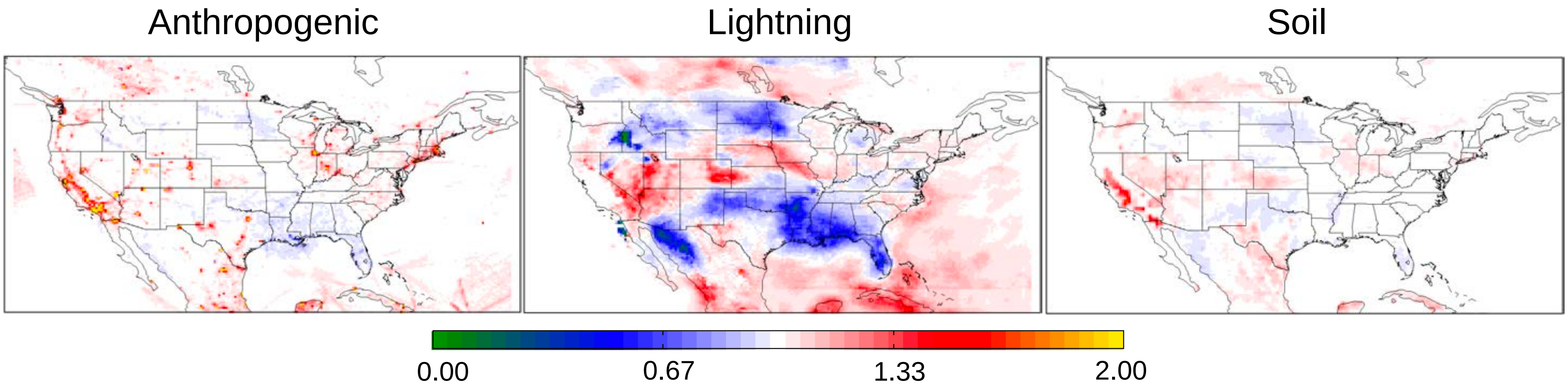
$E\_SO_2\_pos = SF\_industry \times E\_SO_2\_industry \times \boxed{SF\_SO_2\_industry}$

$E\_CO\_pos = SF\_industry \times E\_CO\_industry \times \boxed{SF\_CO\_industry}$

Step 1: Optimize Lightning and Soil NO_x emissions

Constrained by TROPOMI NO_2 observations:

Posterior / prior ratio of NO_x emissions (1st week of Aug, 2023)

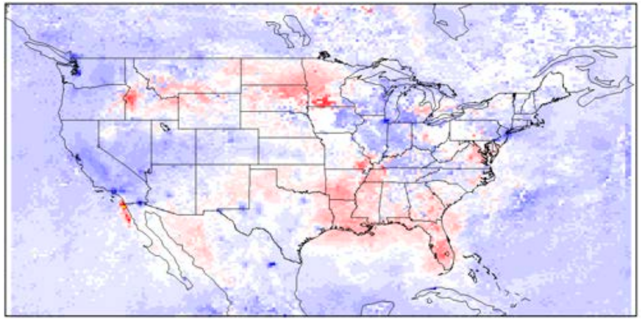


TROPOMI observations suggest large relative adjustments of natural emissions.

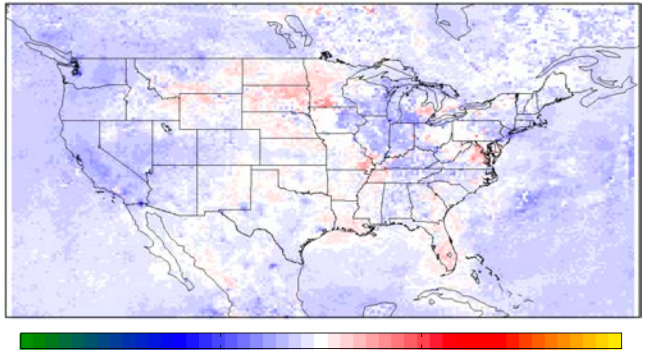
Reduced Biases in NO_2 After Optimizing Natural NO_x Emissions

GEOS-Chem - Observations

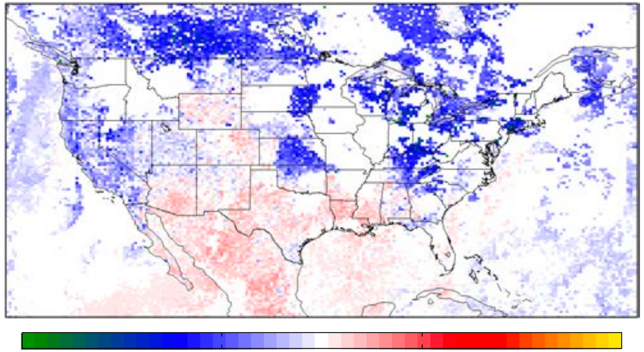
TROPOMI NO_2



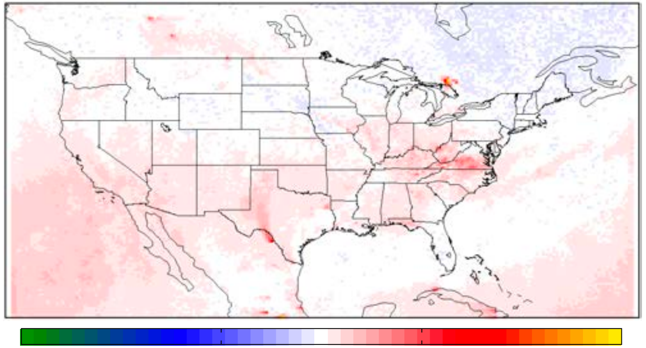
After optimizing lightning and soil



MOPITT CO

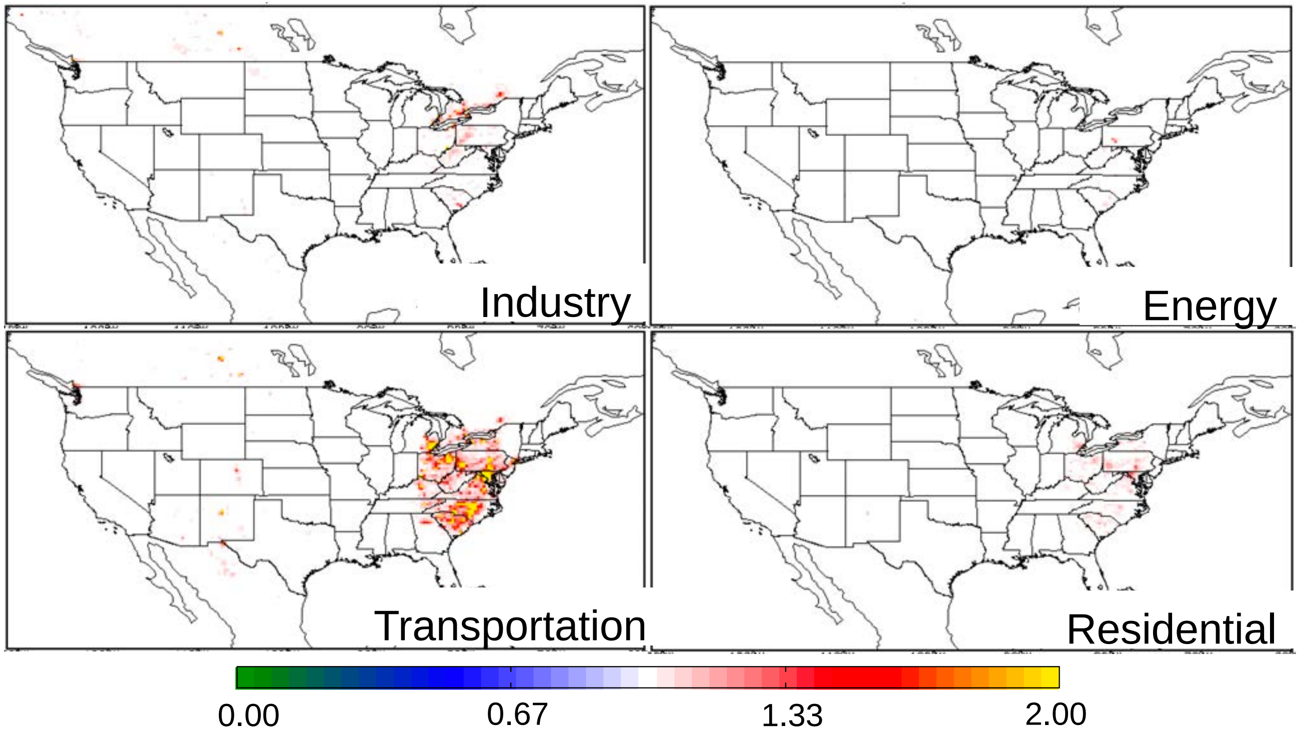


TROPOMI SO_2



Step 2: Optimize Sectoral Activity Rates

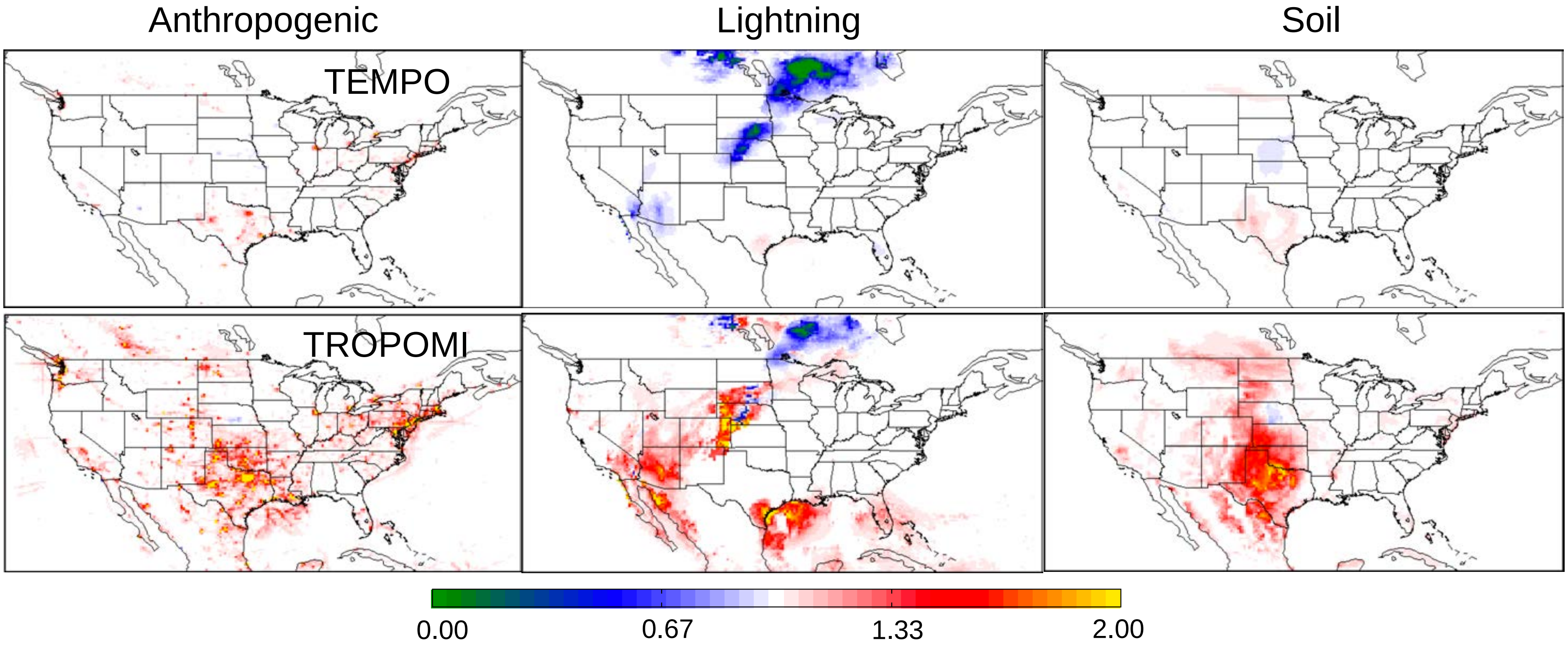
Posterior / prior ratio of activity rates (Sep 1, 2023)



Largest upward emission adjustments from the transportation and industry sector.

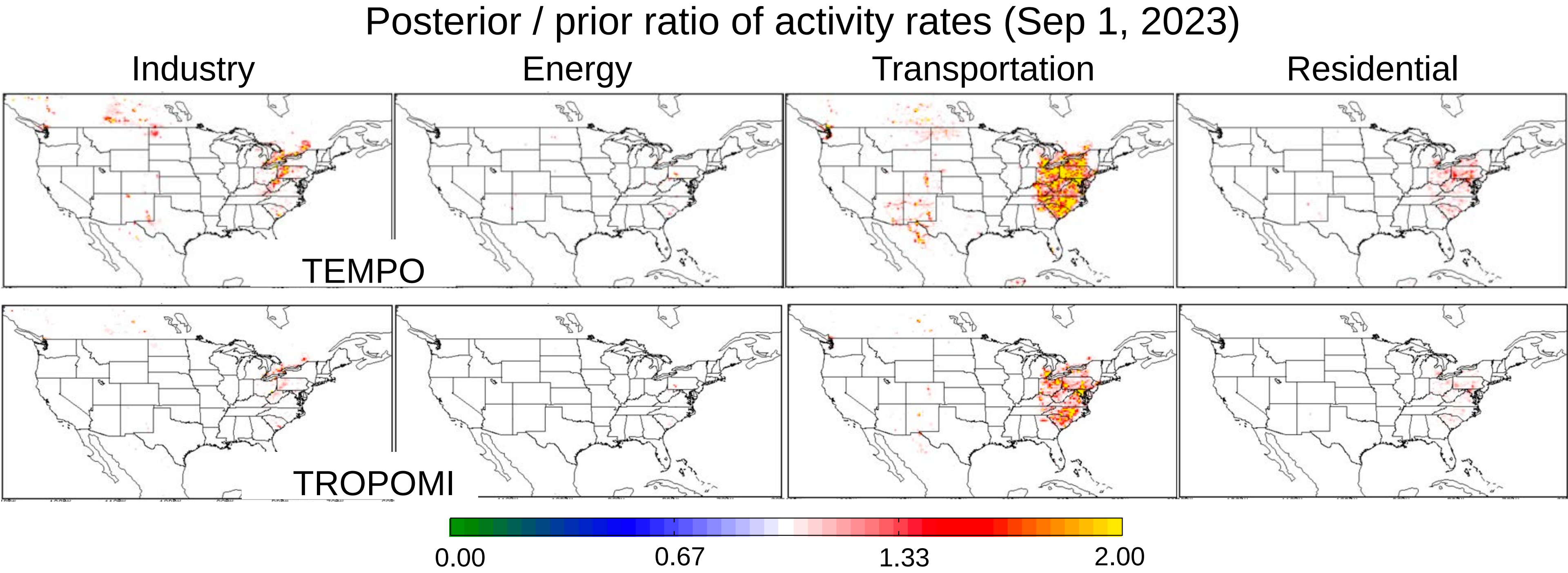
NO_x Emission Optimizations Using TEMPO

Posterior / prior ratio of NO_x emissions (Sep 1, 2023)



Sectoral Activity Rate Adjustments Using TEMPO and TROPOMI NO_2

Together with TROPOMI SO_2 and MOPITT CO observations:



Relatively consistent sectoral activity rate adjustments using TEMPO and TROPOMI NO_2.

Summary

- Top-down emissions from a sector-based inversion framework lead to the best agreement with independent surface measurements and provide a new perspective to evaluate bottom-up activity-based emission estimates.
- In the US, larger uncertainties in NO_x emissions are from lightning and soil; the inversion attributes most of the underestimates of anthropogenic air pollutant emissions to the transportation sector.
- Applying posterior scaling factors to sectoral activity rates has the potential to improve sector-specific anthropogenic CO_2 emission estimates.