Wildfire Smoke Redefines $PM_{2.5}$ Compliance: Local and Transboundary Sources Driving $PM_{2.5}$ Exceedances under the Revised Annual NAAQS

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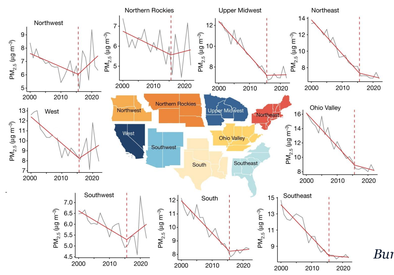
1. BACKGROUND

- Long-term declines in $PM_{2.5}$ (particulate matter with an aerodynamic diameter ≤2.5 μm) levels driven by reductions in anthropogenic emissions under the Clean Air Act enabled EPA to tighten the annual standard from 12 to 9 μg/m³ in February 2024.



Burke et al. (2023)

- However, regional $PM_{2.5}$ trends in the western U.S. began to reverse around 2016, coinciding with increasing contributions from local wildfire smoke.[1]
- More recently, large-scale Canadian wildfires have become a major driver of smoke pollutants in the northeastern U.S., with 2023 showing the most severe smoke influence recorded.[2,3]

2.AIMS

- Assess $PM_{2.5}$ compliance potential across the contiguous U.S. (CONUS) under the revised annual NAAQS for years 2021–2023, which capture variation in wildfire intensity across North America.
- Identify the emission sources driving regional $PM_{2.5}$ exceedances and apply compositional analysis to assess the seasonal variability of source contributions.

3. METHODS

Chemical transport model	GEOS-Chem was used to simulate annual mean $PM_{2.5}$ concentrations over CONUS at 50-km horizontal resolution
Simulations	For each year, we ran: (i) baseline scenario; Sensitivity simulations: (ii) Anthro_Off, (iii) BB_Off, (iv) Anthro&BB_Off, (V) Natural_Aerosols
Emission Inventories	Biomass Burning: GFAS *(emission-flux-weighted plume injection height)* Anthropogenic: CEDS + NEI *(implemented latest inventory versions in the model)*
Observational Dataset	Ground-based observations for total $PM_{2.5}$ and its chemical constituents from EPA's Air Quality System

4.1 RESULTS

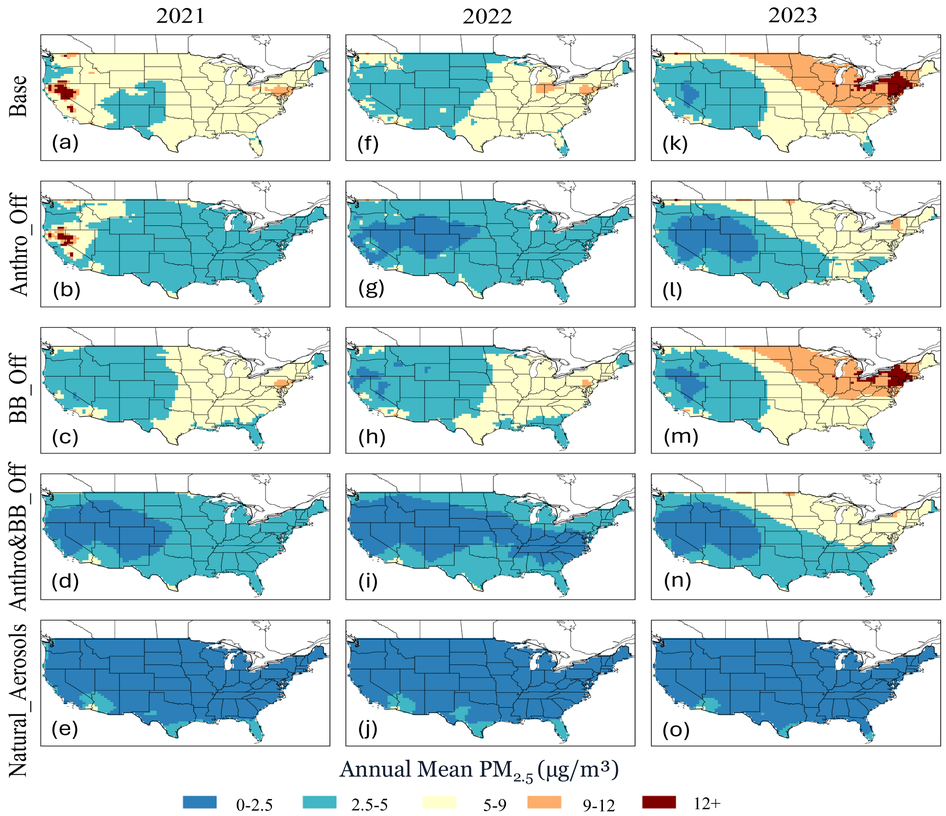


Fig.1: Simulated annual $PM_{2.5}$ concentrations for 2021-2023 under different scenarios

- Exceedances in the western U.S. were largely **driven by local wildfires**, while those in the eastern U.S. (2021 and 2022) were primarily associated with **anthropogenic emissions**.
- In 2023, widespread violations of the current standard were primarily driven **by transboundary transport of Canadian wildfire smoke**, with simulated peak annual mean concentrations reaching **35.4 μg/m³**.

4.2 RESULTS

Regional Characteristics of $PM_{2.5}$ Sources and Composition

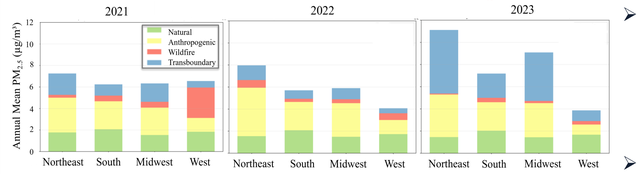


Fig.2: Source apportionment of annual mean $PM_{2.5}$ by region (shown in Fig. 5) over CONUS

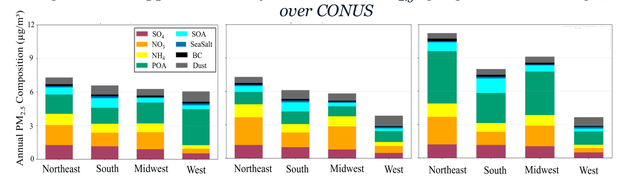


Fig.3: Area-weighted annual mean $PM_{2.5}$ composition by region (shown in Fig. 5) from the Baseline simulation for 2021-2023

- Anthropogenic emissions dominate eastern U.S. $PM_{2.5}$ in low-smoke years, while wildfire smoke drives regional enhancements during severe fire years.
- The influence of anthropogenic emissions on $PM_{2.5}$ peaks in winter, while wildfire-driven enhancements occur primarily in summer

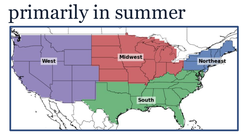


Fig. 5: Regional classification of the contiguous U.S

- Nitrate accounts for a significant fraction of the annual $PM_{2.5}$ in the Northeast (22.1–34.1%) and Midwest (20.4–35.6%, not shown), driven by pronounced wintertime nitrate enhancement (shown in Fig. 4)
- In wildfire-affected years, primary organics (POA) are the largest contributor in the impacted regions (e.g., 53% in the West in 2021).

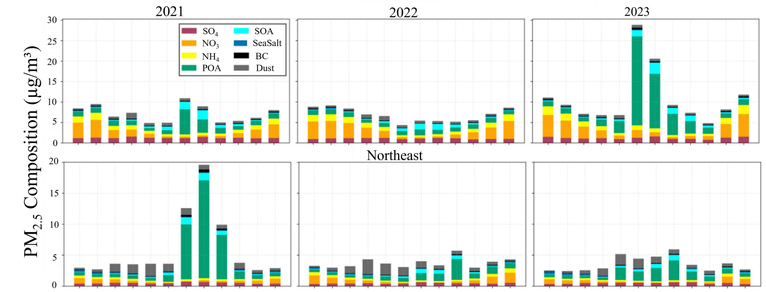


Fig.4: Area-weighted monthly mean $PM_{2.5}$ composition by region (shown in Fig. 5) from the Baseline simulation for 2021-2023

4.3 RESULTS

Population Exposure

In 2021, **46.9 million (14.6%)** people were exposed to simulated annual $PM_{2.5}$ above 9 μg/m³, whereas this number rises to **159.6 million (47.7%)** in 2023.

*[1]no US anthropogenic emissions
*[2]no US fire emissions
*[3]no US anthropogenic or fire emissions
*[4]no anthropogenic or fire emissions anywhere

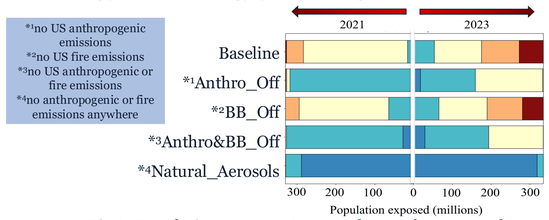


Fig.6: Population exposure to annual $PM_{2.5}$ for 2021 and 2023 under different emission scenarios

Model Evaluation

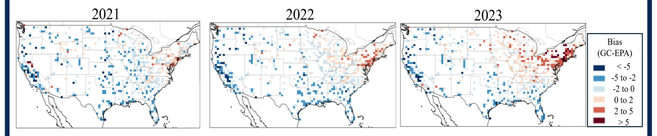


Fig.7: Population exposure to annual $PM_{2.5}$ for 2021 and 2023 under different emission scenarios

- The model exhibits a predominantly low bias across most of the CONUS throughout the study period.
- The Midwest and Northeast exhibit a persistent positive bias, which intensifies during the year affected by transported smoke from western Canadian wildfires.

5. IMPLICATIONS

- Attainment of the strengthened annual $PM_{2.5}$ standard depends not only on continued reductions in domestic anthropogenic emissions, but also on the occurrence, intensity, and transport of wildfire smoke.
- In 2023, transboundary Canadian wildfire smoke, combined with domestic anthropogenic contributions, exposed nearly half of the U.S. population to simulated annual $PM_{2.5}$ levels above μg/m³.
- Future PM2.5 attainment will depend on controlling anthropogenic precursors while preparing for increasingly influential wildfire smoke.

REFERENCES

[1] Burke et al. (2023). *Nature.*

[2] Zhang et al. (2025). *Nature.*

[3] Chen et al. (2025). *Atmospheric Environment.*

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