Trends in PM air pollution in the context of internal climate variability

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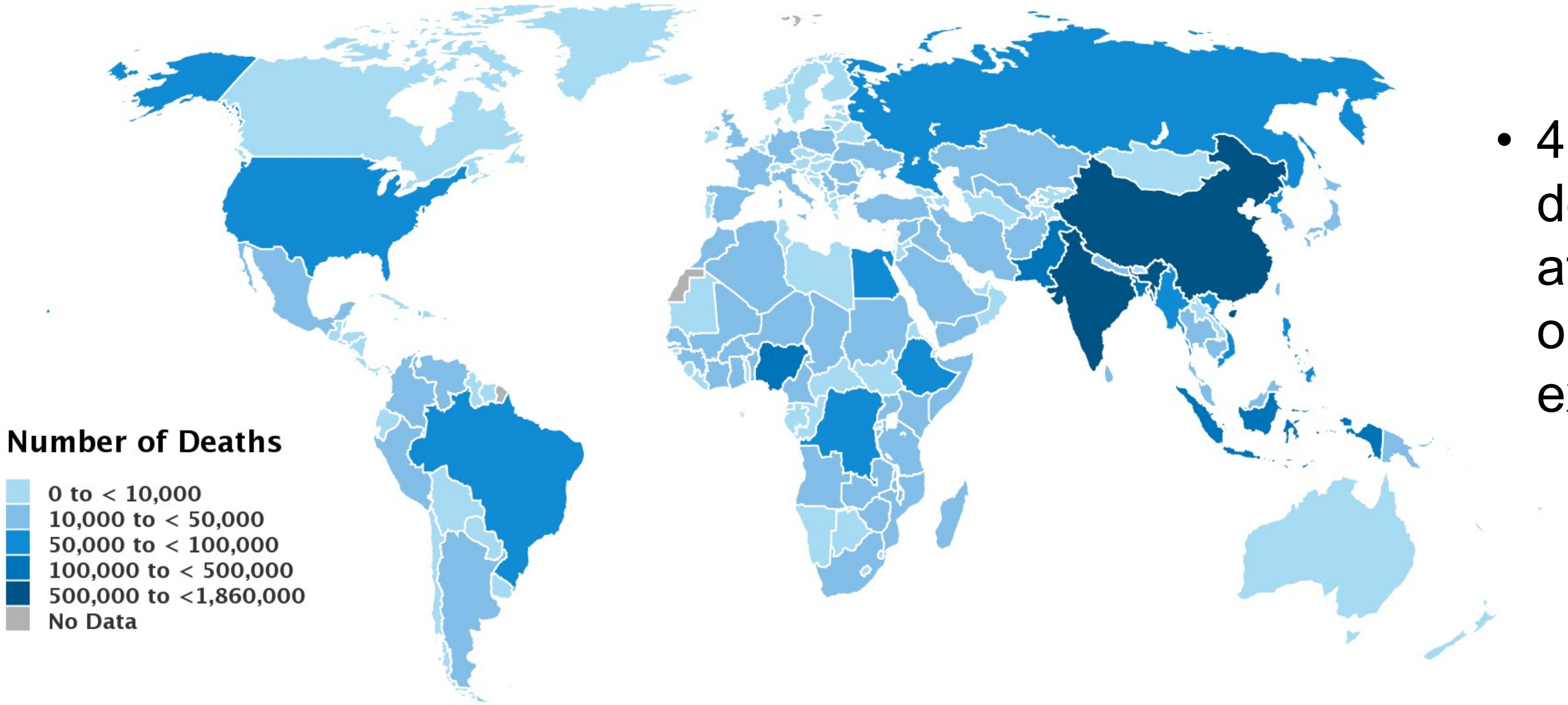
Air pollution leading cause of premature mortality globally

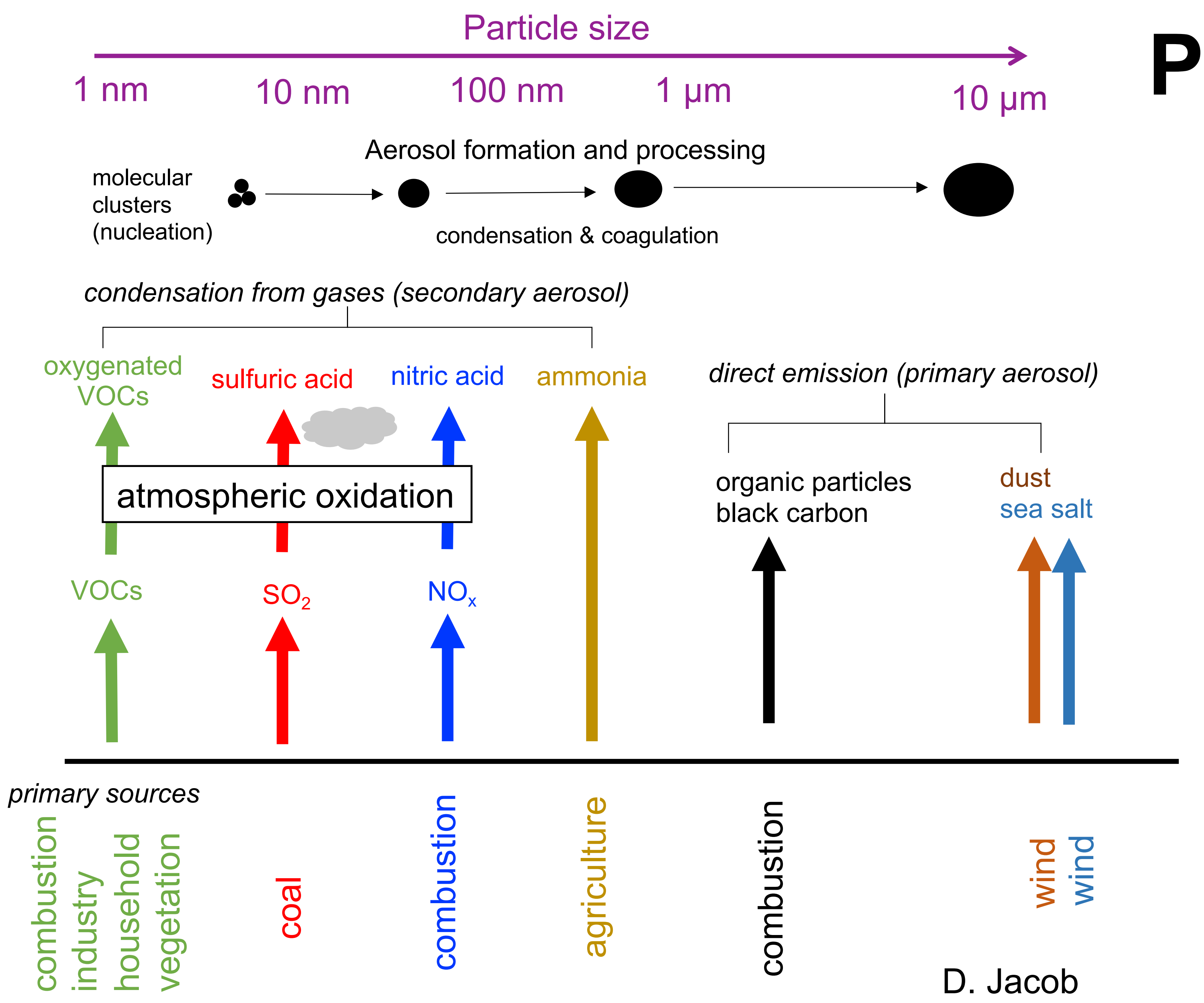
Premature deaths attributable to air pollution, 2019

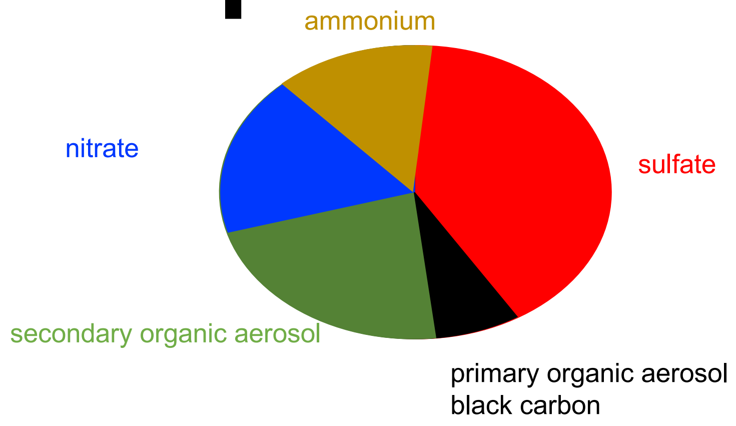


- 4.14 million deaths attributable to outdoor $PM_{2.5}$ exposure in 2019

State of Global Air, 2020

$PM_{2.5}$ sources & composition

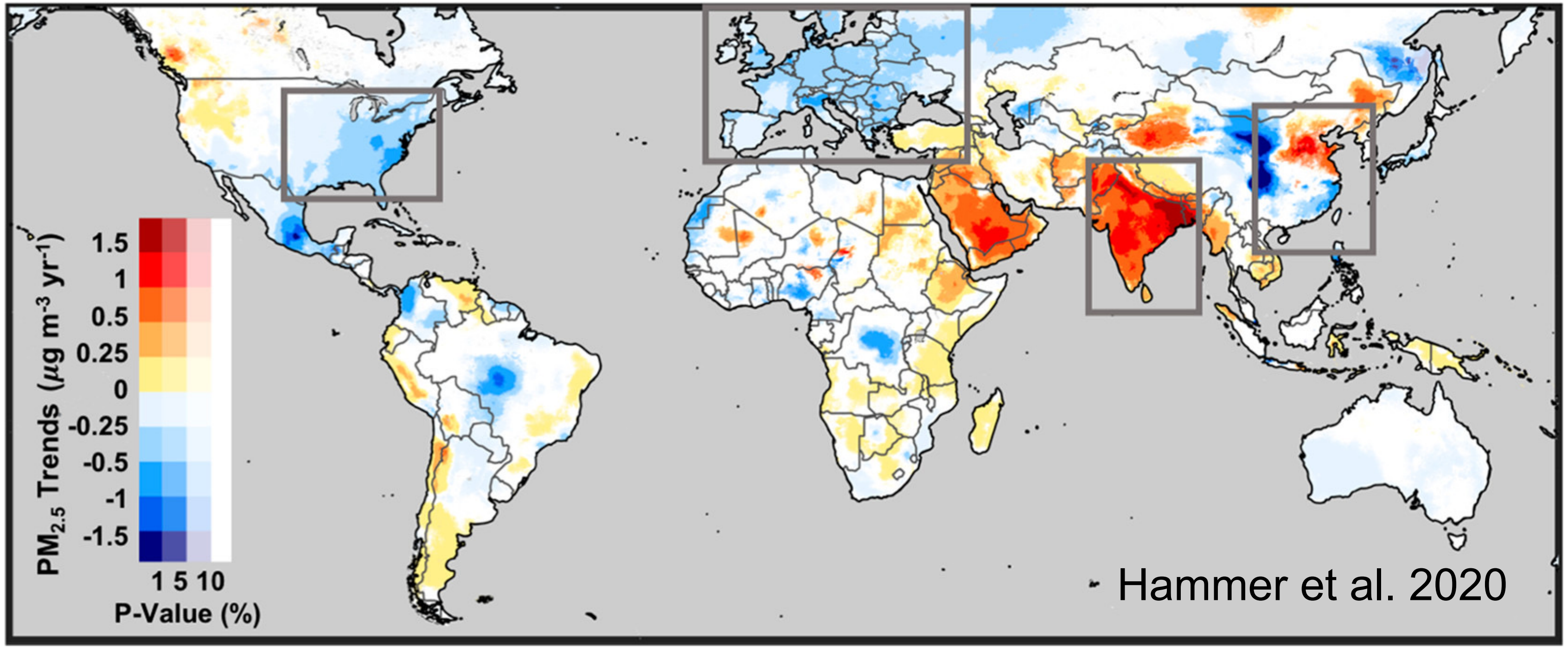




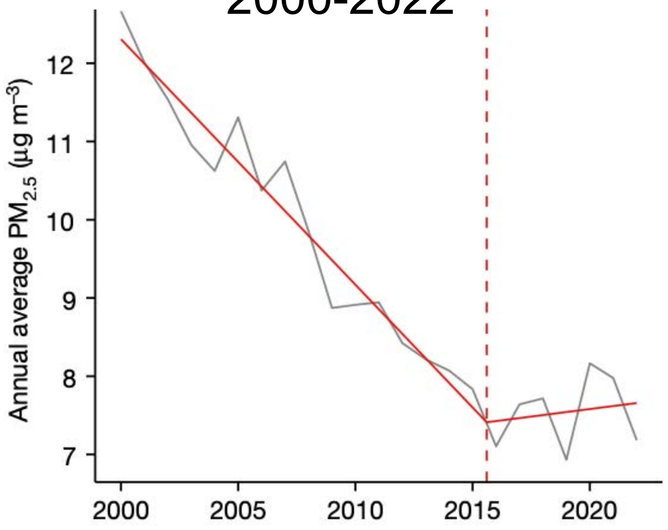
- $PM_{2.5}$ composition varies by location, season, etc.
- Different PM types have different sources, some overlapping
- Particles transported, removed by wet and dry deposition

Large, regionally distinct changes in $PM_{2.5}$ over the past few decades, corresponding mostly to anthropogenic emissions

Trends in satellite-based $PM_{2.5}$ over 1998-2018



Ground-based monitoring stations across CONUS over 2000-2022

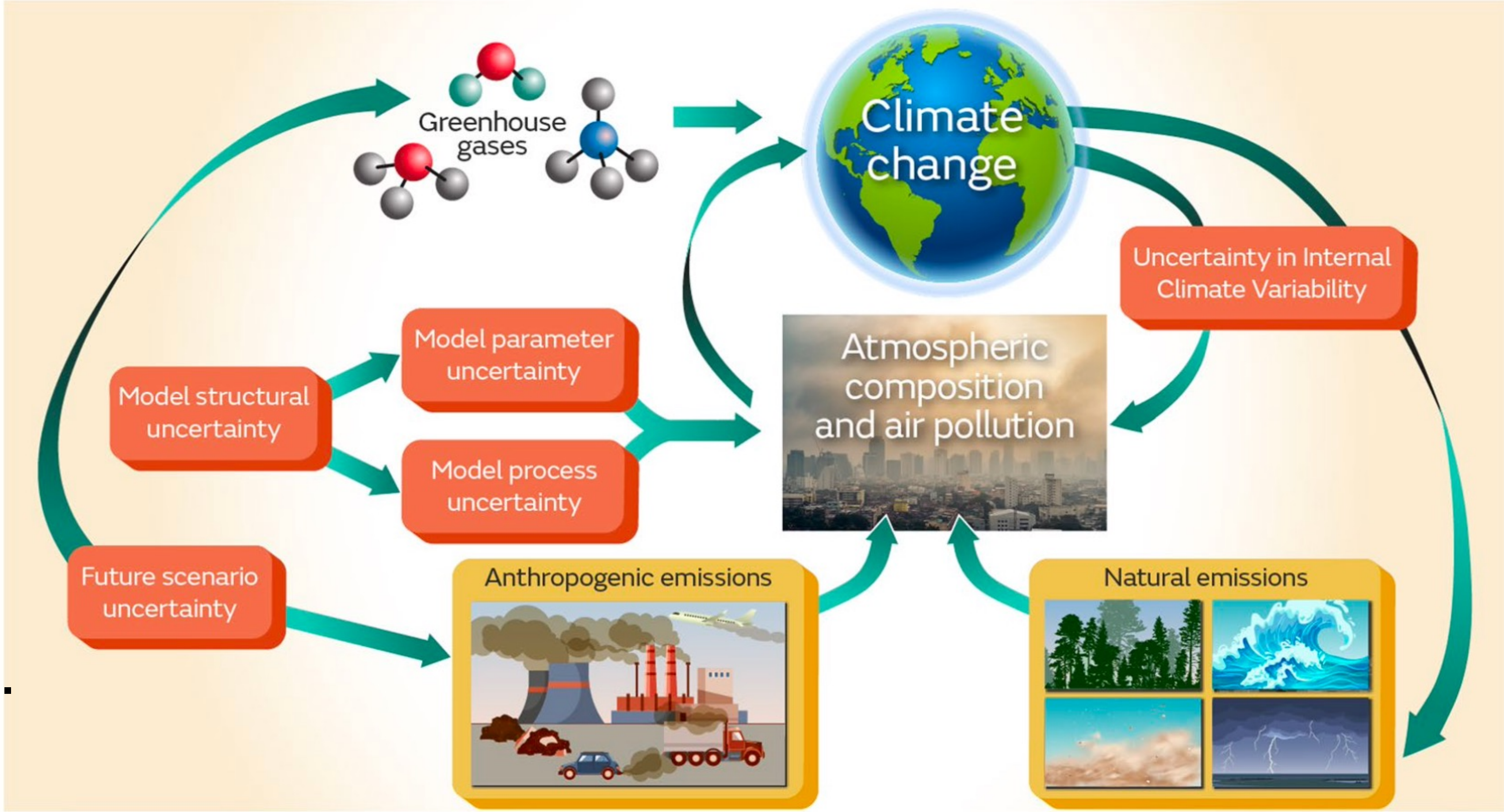


Burke et al. 2023

We rely on observational records of PM to estimate the efficiency of anthropogenic emission controls and advance process understanding of PM.

Internal climate variability = key, overlooked uncertainty for $PM_{2.5}$?

- Follows strong links with meteorology (e.g., transport, aerosol formation & processing, wet and dry deposition, natural emissions of PM & precursors inc. 🌳 & 🔥)



Doherty et al. JGR-A 2022

Overarching goal: Understand extent to which observed $PM_{2.5}$ trends are imprinted by climate variability

CMIP6 historical simulations with interactive aerosols

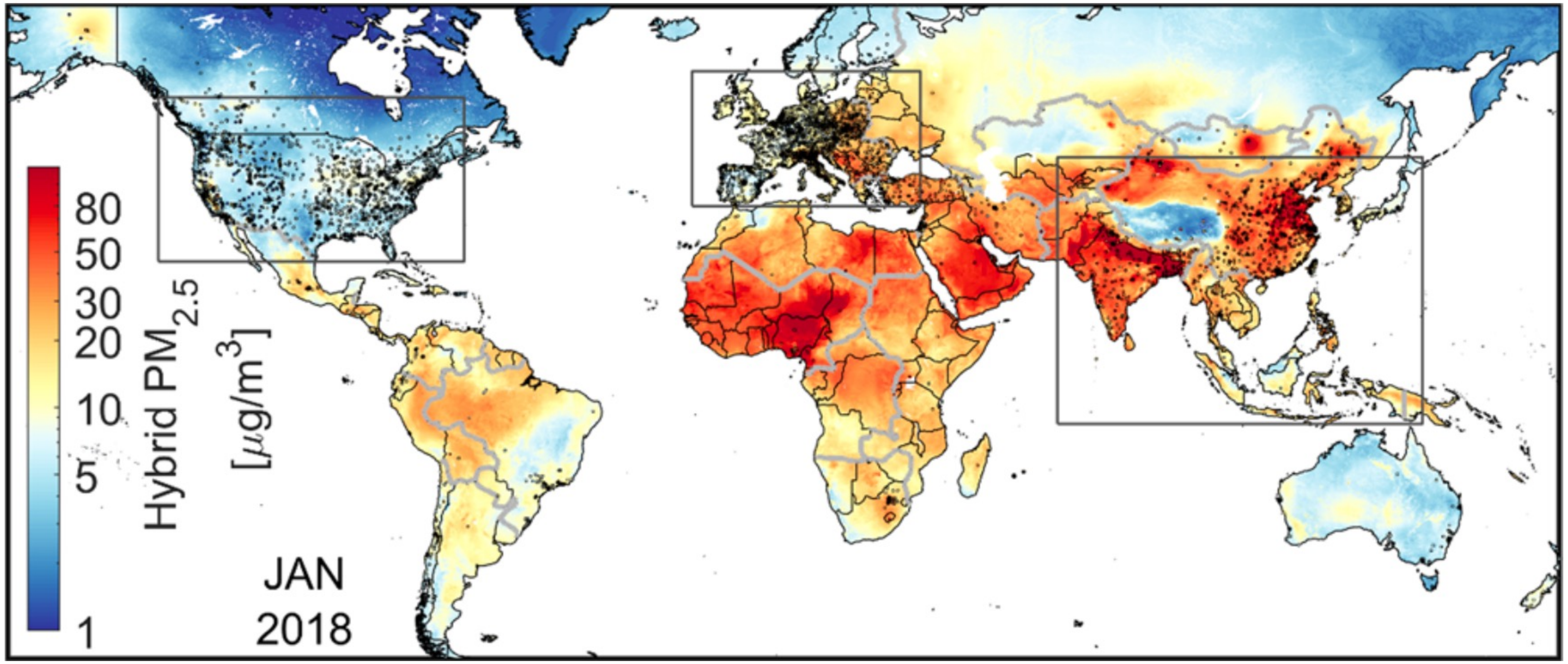
- GISS E2.1
  - Two aerosol configurations – OMA & MATRIX
  - 10 ensemble members each
- CESM2-WACCM6
  - 3 ensemble members in archive (expanded to 12 – Fiore et al., 2022)

First steps

1) Establish whether the set of simulations captures "observed" PM trends as well as the "observed" range of interannual variations.
2) Use this analysis to uncover model strengths and limitations.

$PM_{2.5}$ observation-***based*** products

- Few places have long-term ground-based observations of PM, but most places have none (or only starting in more recent years)
- Over two decades of satellite retrievals of quantities like aerosol optical depth (AOD) that can be linked to near-surface PM

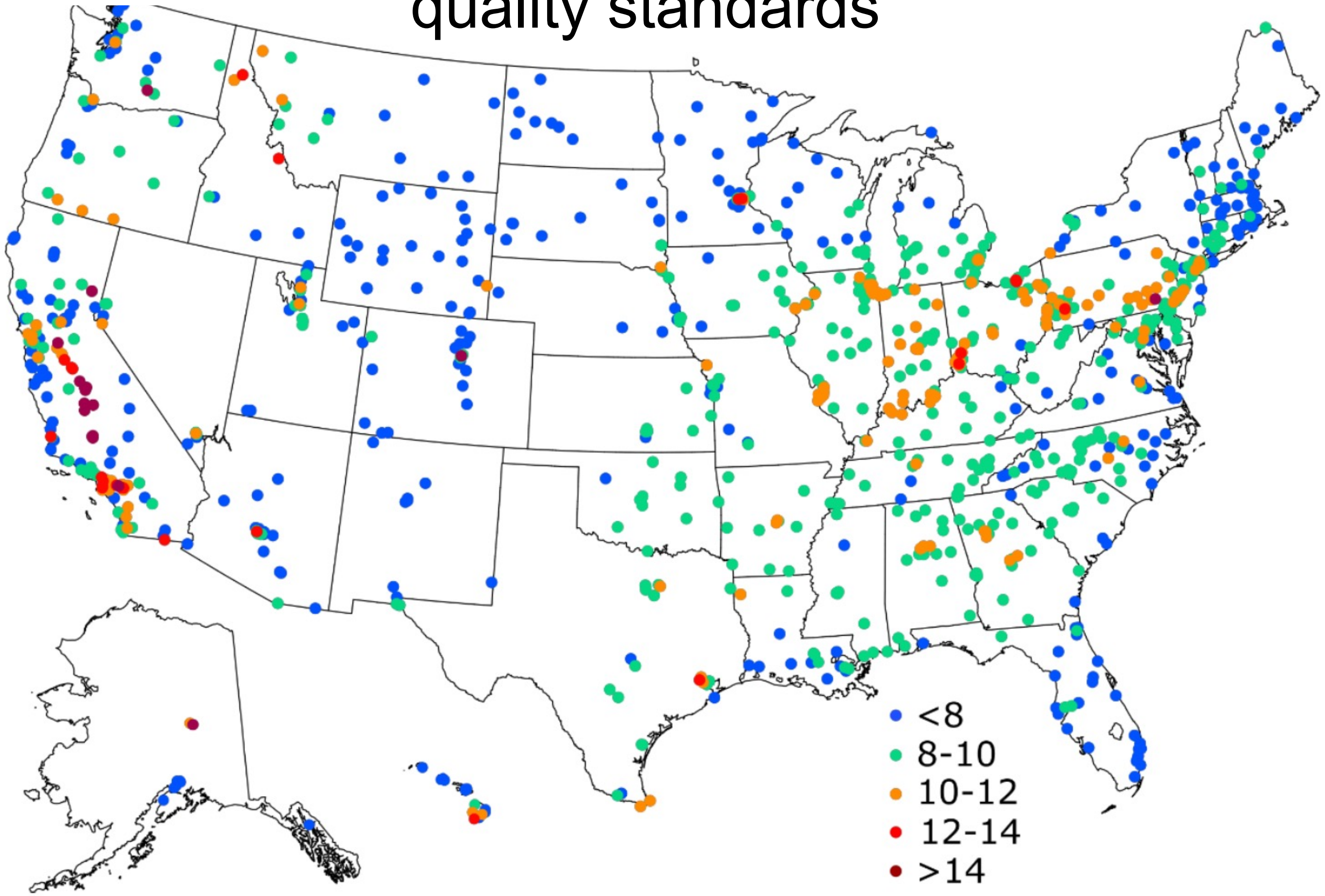


Global monthly $PM_{2.5}$ product (inc. uncertainty), from 1998 onwards (van Donkelaar et al. 2021)

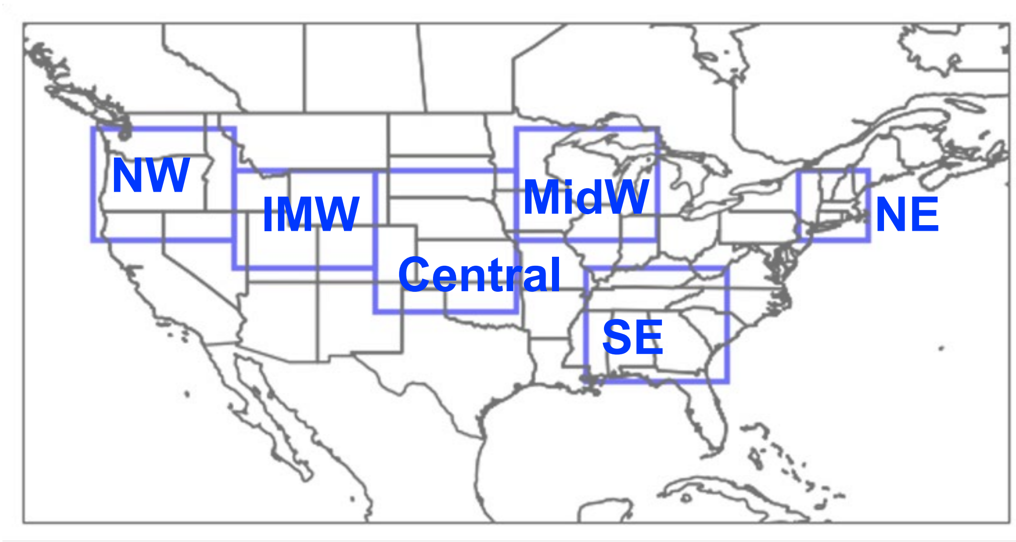
- Combines satellite retrievals of AOD, chemical transport modeling & ground-based measurements

$PM_{2.5}$ observation-***based*** products

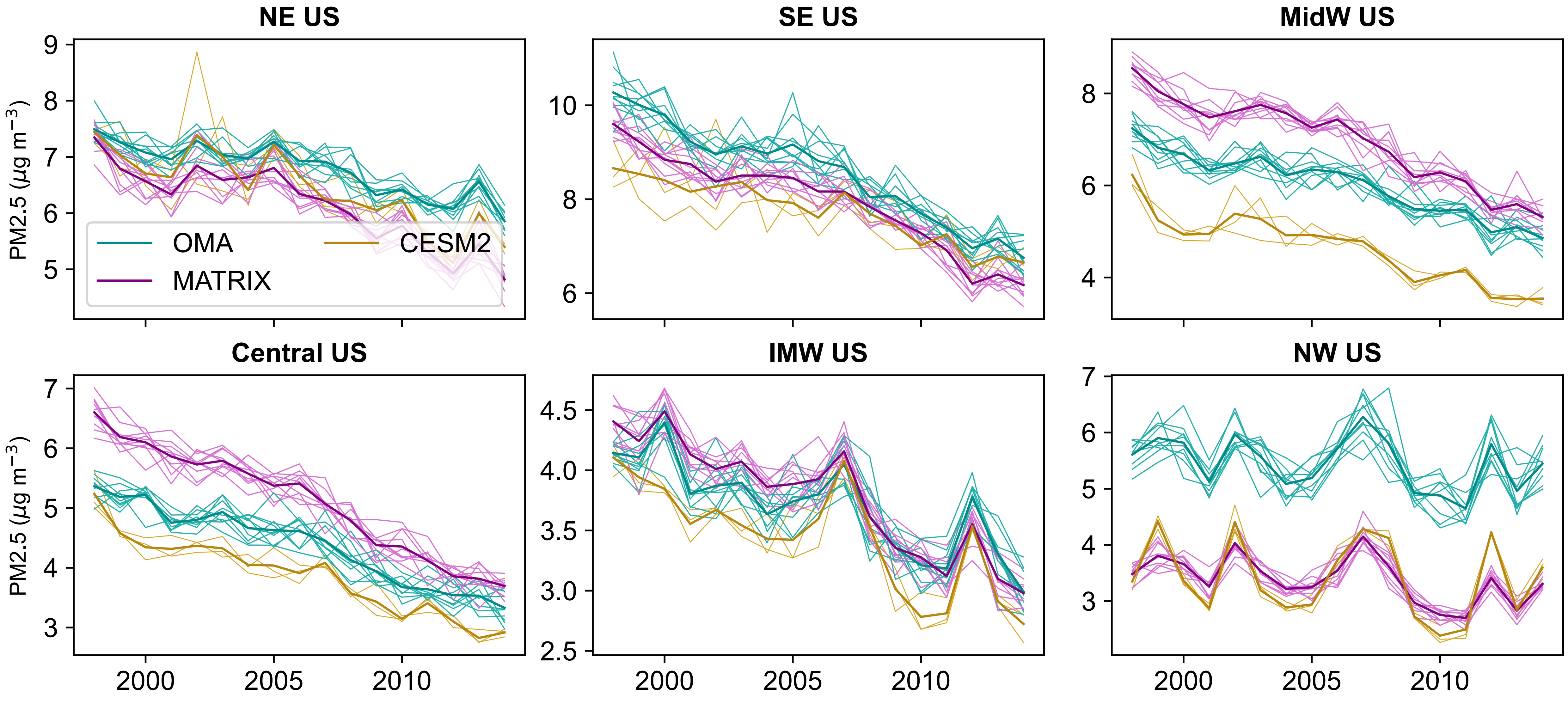
Annual $PM_{2.5}$ concentrations (μg m^{-3}) 2013-2015 at EPA monitoring sites used for air quality standards



- 2º by 2.5º gridded product of monthly mean $PM_{2.5}$ from sites
- 2003-2013
- Calculated by Klovenski et al. (2022) following methods of Schnell et al. (2015)



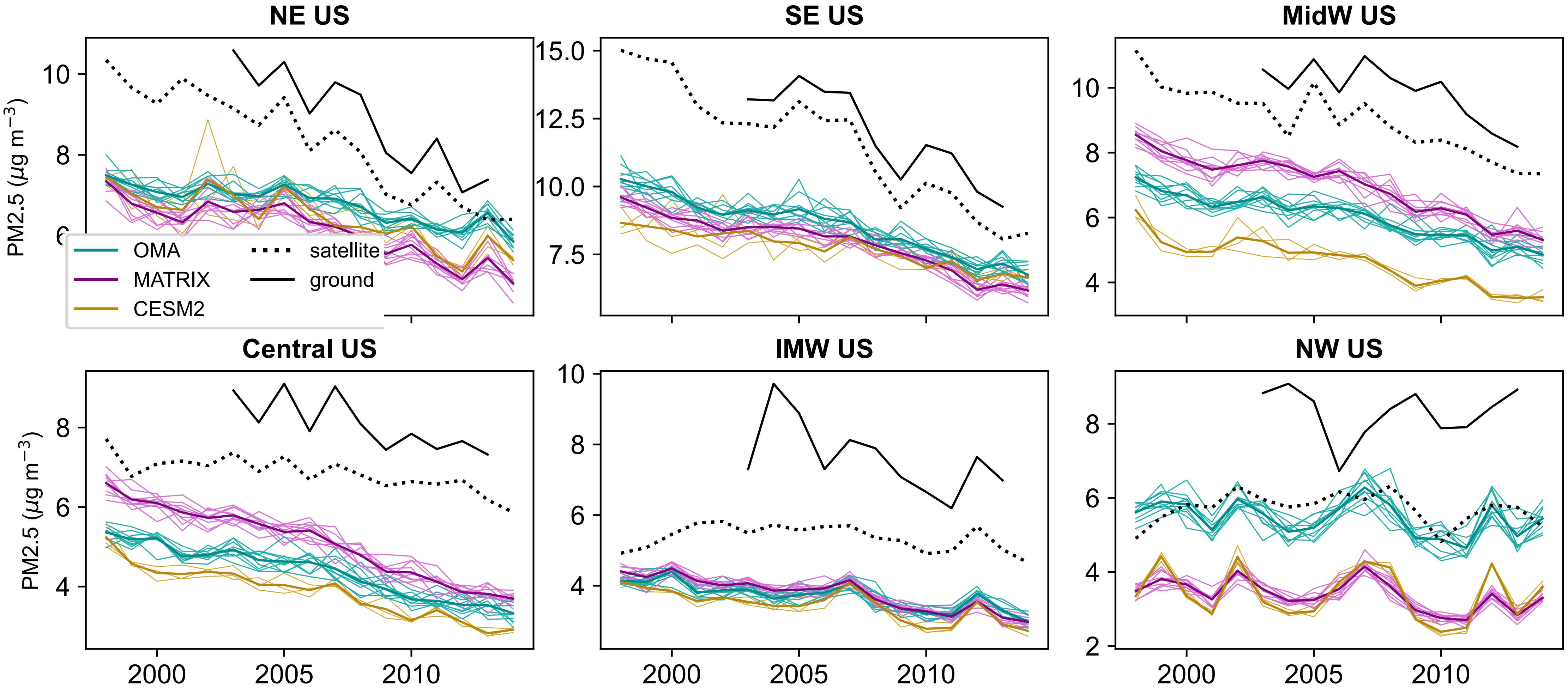
Annual $PM_{2.5}$ over U.S. regions, from 1998 to 2014



CMIP6 fully coupled historical sims

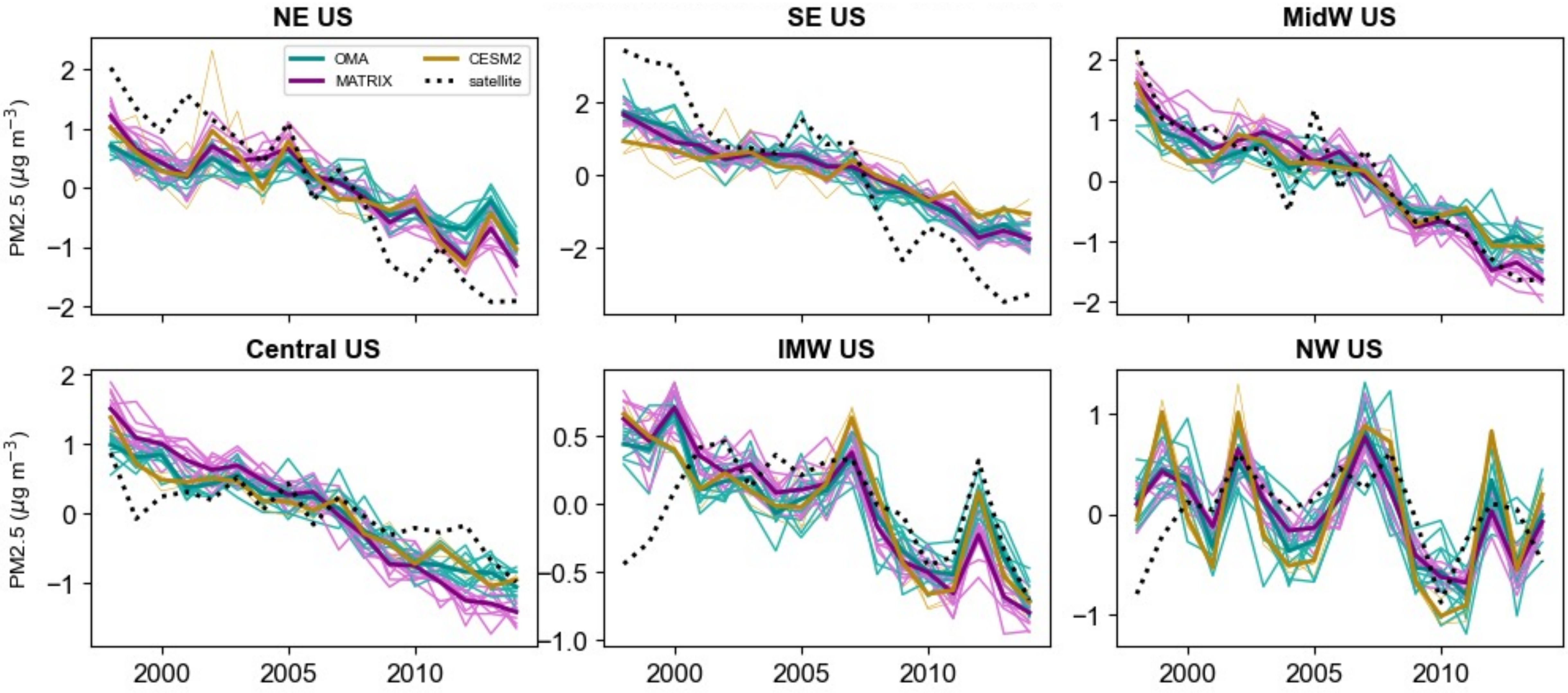
Thick – ensemble averages
Thin – individual ensemble member

Annual $PM_{2.5}$ over U.S. regions, from 1998 to 2014



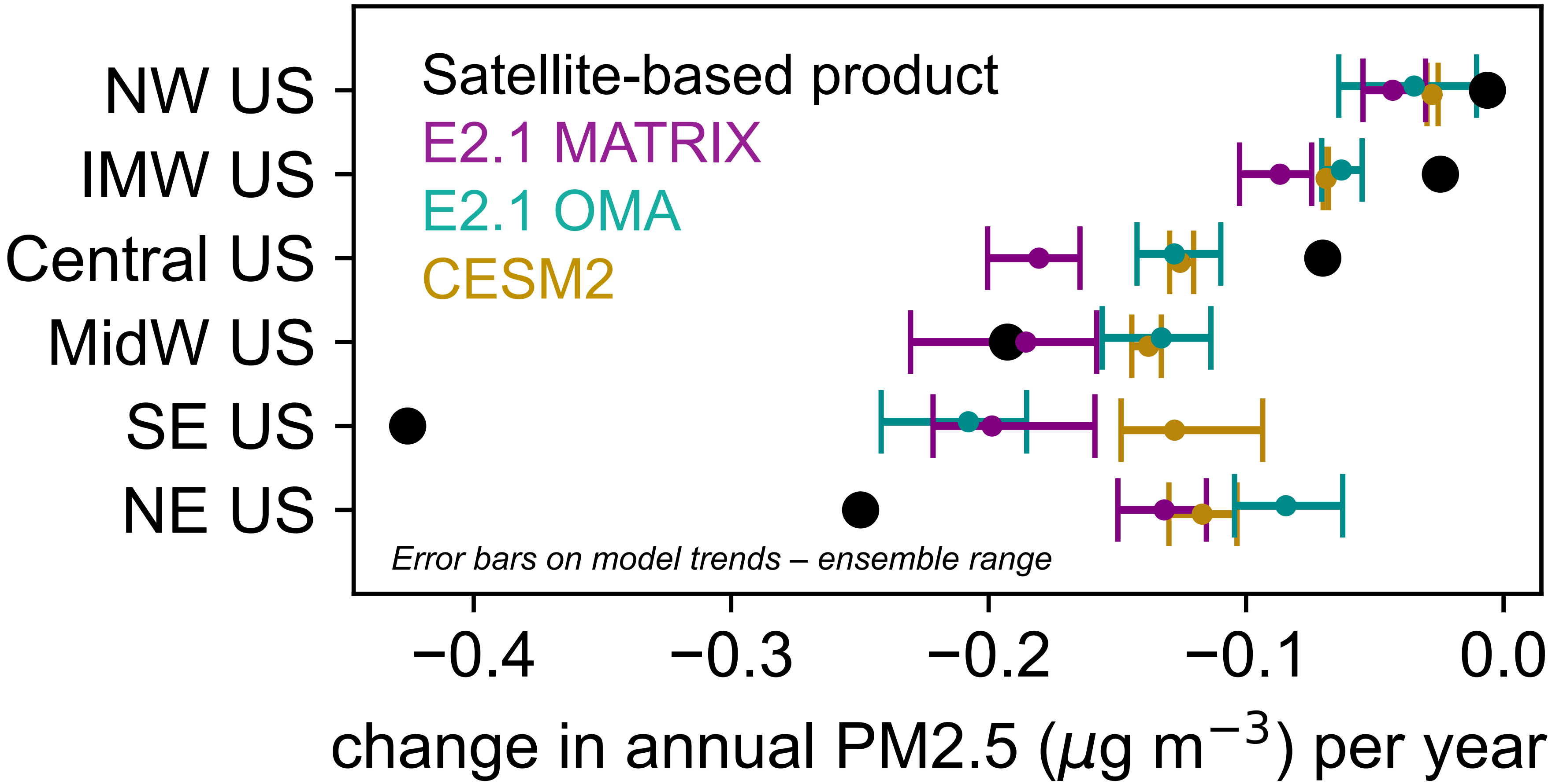
- Observation-based products similar for NE, SE, & MidW; different for Central & western US
- Low $PM_{2.5}$ in models relative to observation-based products

Annual anomalies in $PM_{2.5}$ over U.S. regions, from 1998 to 2014



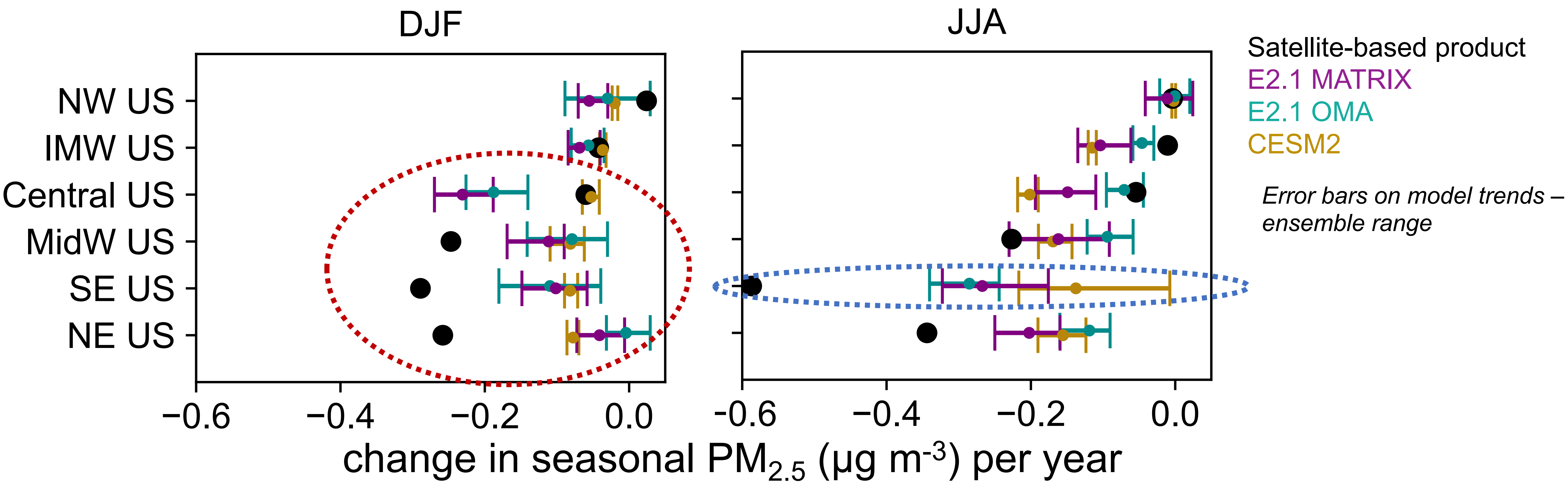
- Models largely capture degree of IAV in satellite product (but not always trend)
- Similar finding for ground-based product (not shown)

Annual trend in $PM_{2.5}$ over U.S. regions, from 1998 to 2014



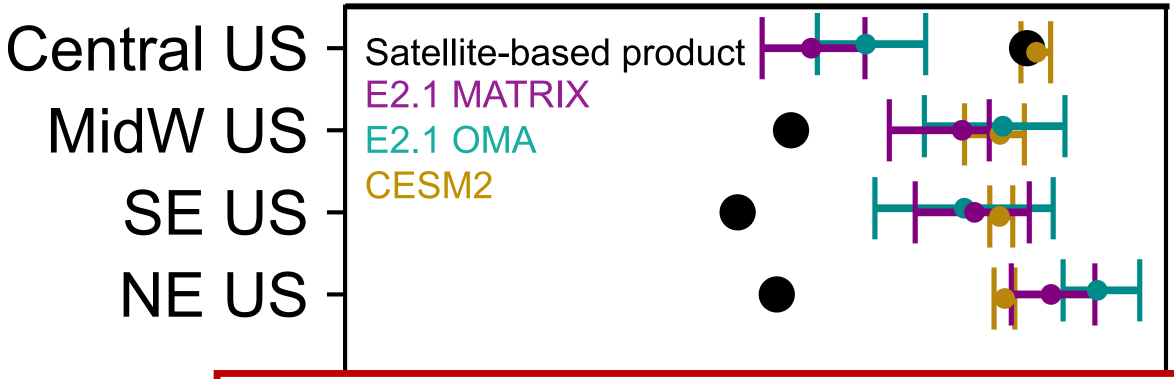
- Models slightly overestimate satellite-based trend over NW, IMW, & Central US
- MATRIX captures satellite-based trend for MidW
- Models strongly underestimate satellite-based trend over SE & NE

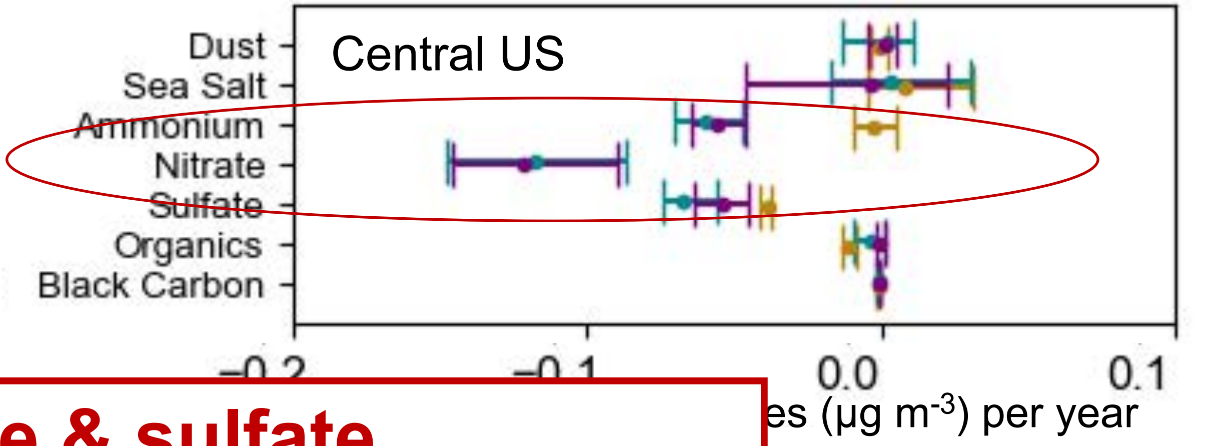
Seasonal trend in $PM_{2.5}$ over U.S. regions, from 1998 to 2014



- Models do well for western US during DJF but issue for Central, MidW, SE, & NE (CASE STUDY #1)
- Large uncertainty during JJA over SE points to role for vegetation emissions & secondary organic aerosol (CASE STUDY #2)

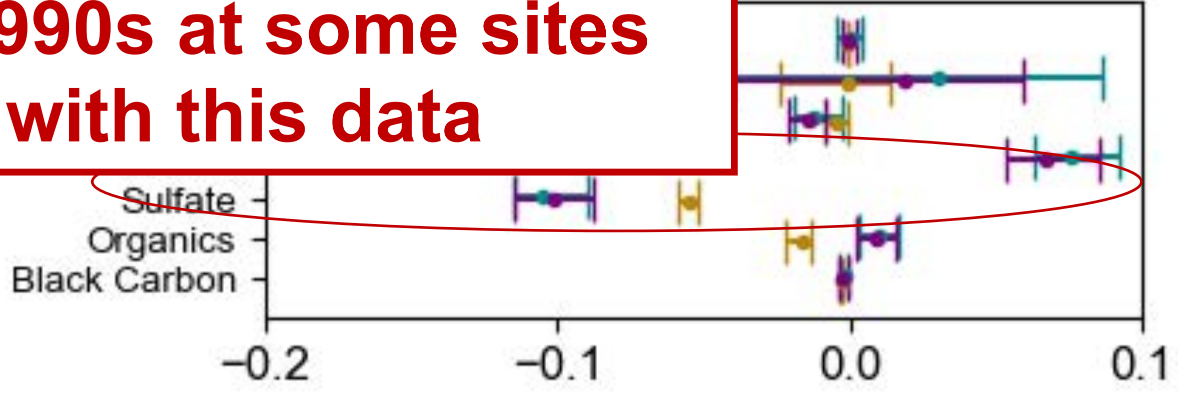
Case Study # 1: What is going on during winter over eastern, Midwest & Central US?





There are ground-based nitrate & sulfate measurements since the late 1990s at some sites across the US – next: evaluate with this data

- Centra
  - N
    decreases in $PM_{2.5}$
  - CESM does not have nitrate & shows no change in ammonium so weak decreases



DJF trends by PM species (µg m^{-3}) per year

- MidW, SE, & NE US
  - E2.1 increases in nitrate *temper* decreases in $PM_{2.5}$ driven by sulfate
  - CESM does not have nitrate & decreases in sulfate weaker than E2.1

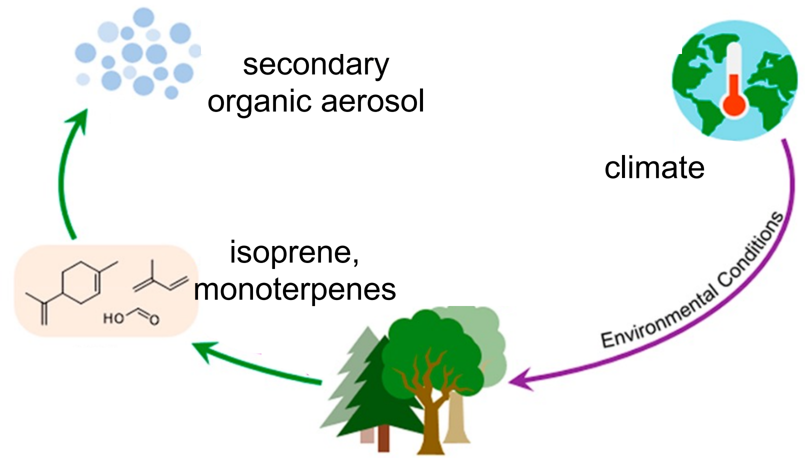
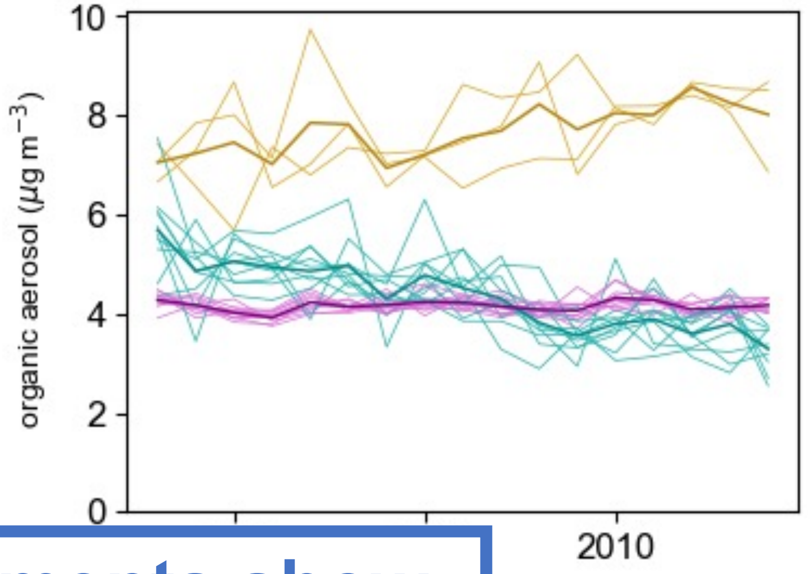
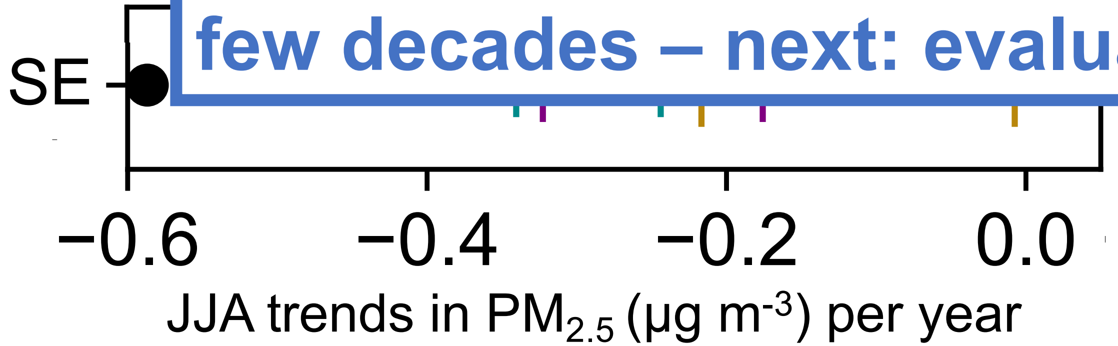


figure adapte

Case Study # 2: What is going on during summer over SE US?



Ground-based organic aerosol measurements show decreases during summer over the SE US over past few decades – next: evaluate with this data



- …weakens the decreasing trend in $PM_{2.5}$ in CESM2 and increases ensemble spread
- Lack of variability in organic aerosol in MATRIX due to strong tie to static monoterpene emissions

Takeaways

Ugly – $PM_{2.5}$ observational products are imperfect and uncertain as well as rather short-term

Bad – Representation of nitrate, sulfate, & secondary organic aerosol needs to be scrutinized

Bad/Good – Models too low in terms of magnitude of $PM_{2.5}$ but generally capture interannual variability and trends

Good – We can still learn from model-“observation” comparisons, esp. with a focus on seasons & species as well as inclusion of model structural uncertainty, even if observational products are imperfect

Good – We may be able to use climate models to understand extent to which observed $PM_{2.5}$ trends are imprinted by climate variability