Anthropogenic Aerosols as Drivers of Extreme Weather Risk

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E3SM All-Hands

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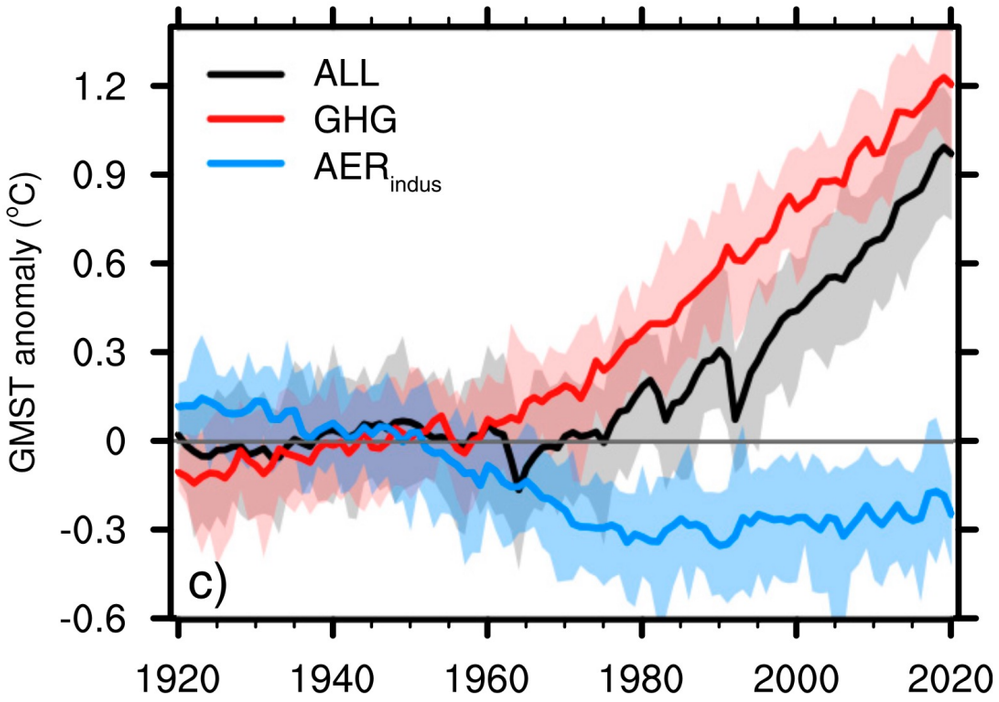
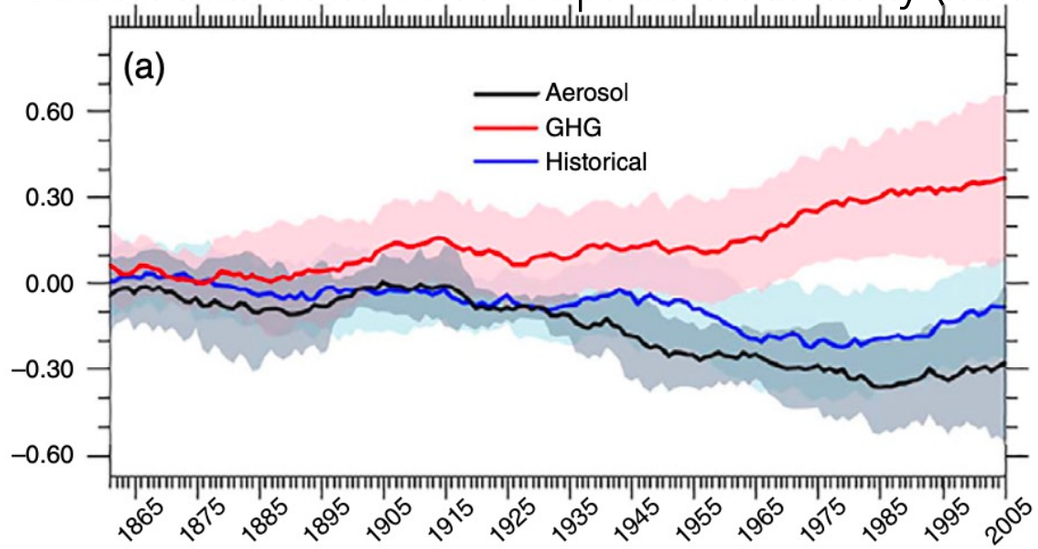
Aerosols impact global, regional, and local weather

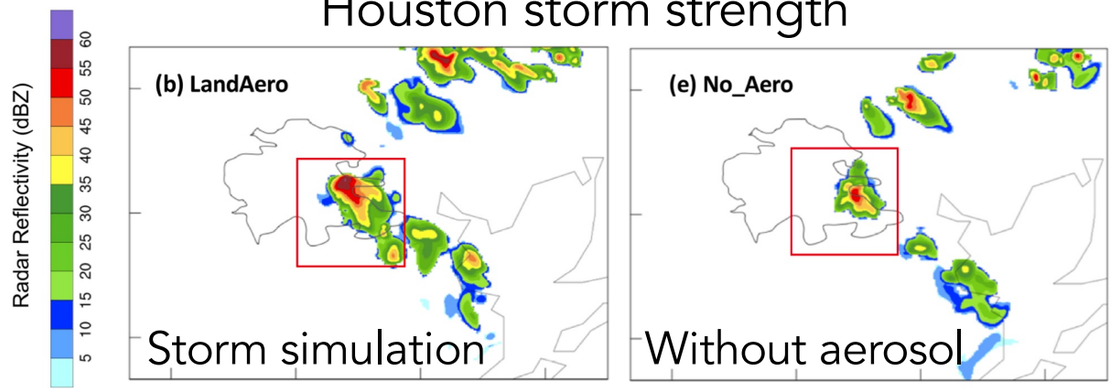
Global-Mean Surface Temperature Anomaly (°C)



South Asian Monsoon Precipitation Anomaly (mm/day)

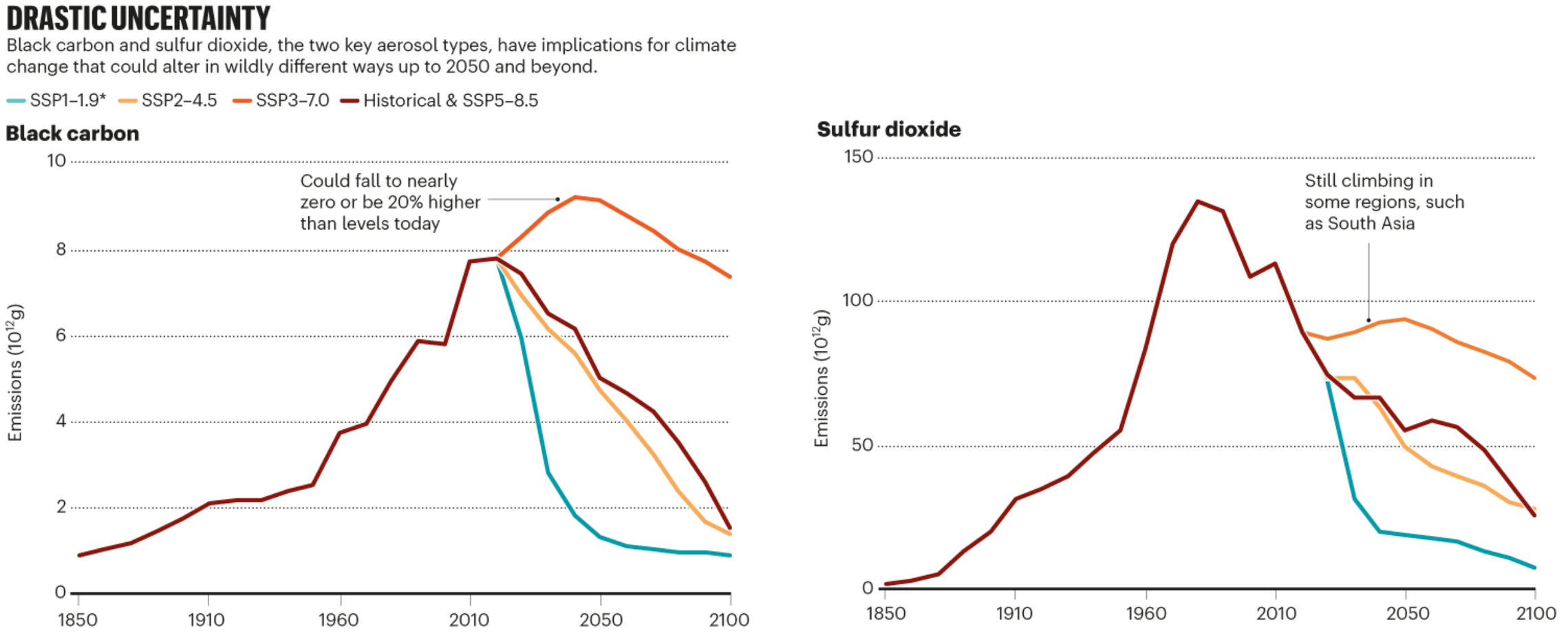


Houston storm strength



Deser et al. (2020), Singh et al. (2019), Fan et al. (2020)

Changes in regional aerosol emissions are a big uncertainty in the coming decades



Persad et al. (2022, *Nature*)

A call to action for the climate science, services, and decision-making communities

Aerosols must be part of climate risk assessments

Geeta G. Persad, Bjørn H. Samset & Laura J. Wilcox

Estimates of impending risk ignore a big player in regional change and climate extremes.

When Pakistan faced appalling floods in June this year, global attention focused on climate change as the culprit. The country had three times the usual rainfall in its summer monsoon, exacerbated by short spikes of extremely heavy rain. Riverbanks burst and more than 1,600 people died. Formal attribution studies and politicians alike blamed global warming for making such an event much more likely. Something else should have been mentioned, too: aerosols.

Aerosols are the miasma of soot (black carbon), sulfur dioxide, organic carbon and other compounds that drives poor air quality over many of the world's most-populated regions. Studies show that aerosols strongly affect the likelihood of extreme precipitation events[1], such as those that contributed to Pakistan's floods, and many other climate hazards.

Worse, it is not clear whether aerosols are set to rise, fall or stabilize. The amount of uncertainty about aerosol levels by 2050 is as large as the total increase since pre-industrial times (see 'Drastic uncertainty'). Over the next 20–30 years, we might – or might not – see aerosol-driven climate changes as large as those that have played out over the past 170 years, adding as much as 0.5 °C to global warming. That could rapidly change the likelihood of extreme events occurring in many regions.

Yet the impacts of aerosols on climate risk are often ignored. The issue was not

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- Aerosols have been major drivers of past climate change
- Aerosols are a major uncertainty in near-term climate forcing
- Aerosols' influence on climate change, climate impacts, climate risks differ drastically from greenhouse gases'
- Our current climate risk assessment frameworks, built for greenhouse gases, fail at capturing risks from changing regional aerosol emissions.
- Neglecting aerosols is therefore a major gap in near-term climate risk assessments.

Persad et al. (2022, *Nature*); Persad et al. (2023, *Environmental Research: Climate*)

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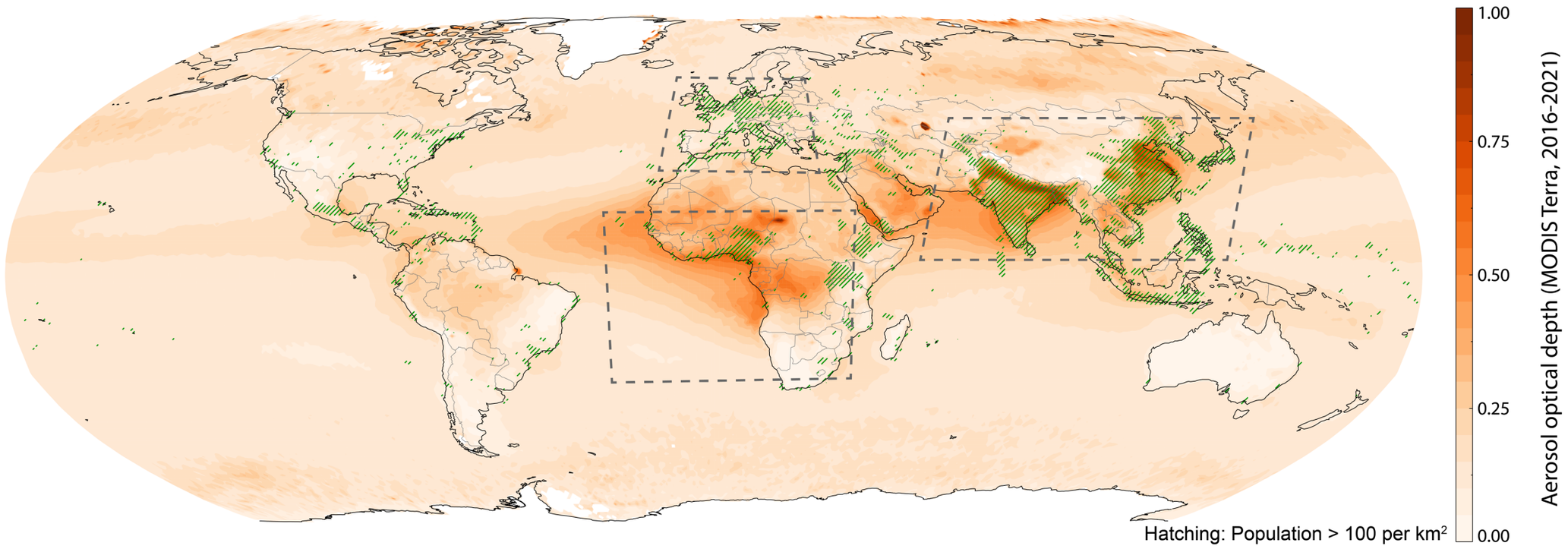
Aerosols are co-located with many of the most populated regions of the world

Atmospheric Aerosols (shading) and heavily populated regions (hatching)



Persad et al. (2023, *Environmental Research: Climate*)

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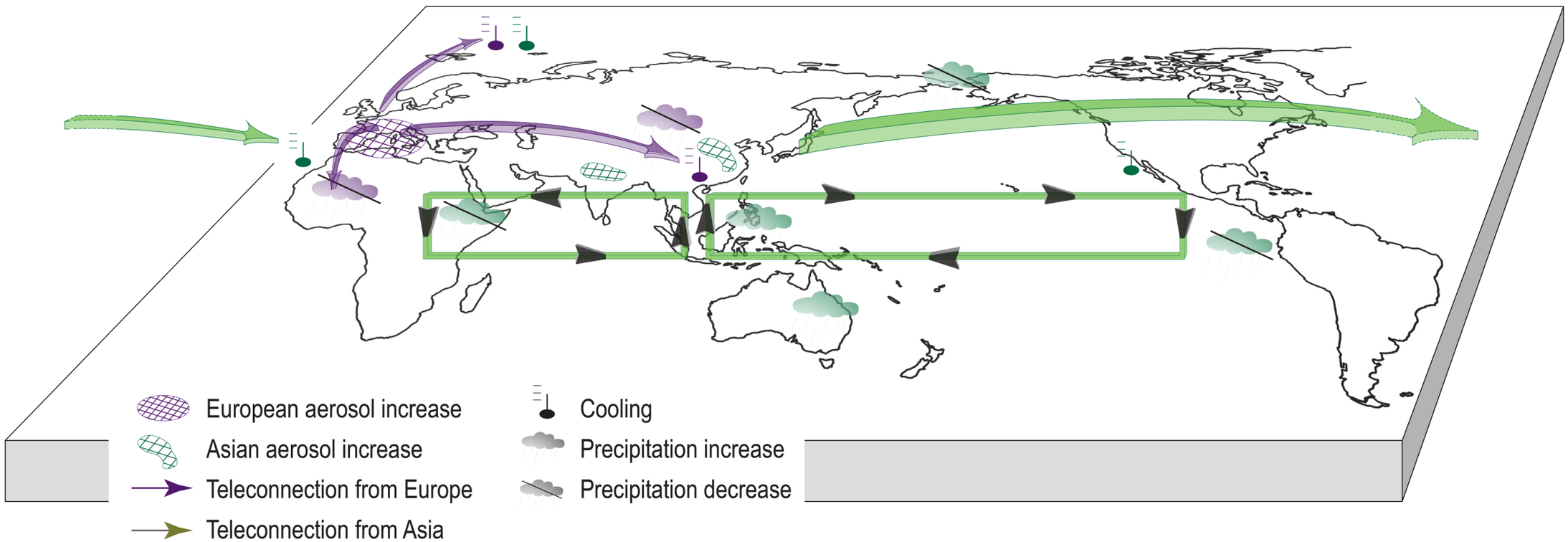
Aerosol emissions in one location can have impacts far away from the source



Persad et al. (2023, *Environmental Research: Climate*) from Acosta Navarro et al. (2016), Krishnan et al. (2022), Wilcox et al. (2019), Dow et al. (2021), Dong et al. (2014, 2015), Undorf et al. (2018), Westervelt et al. (2018, 2020), Persad and Caldeira (2018)

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Are we accounting for this adequately in our climate risk assessment frameworks? Probably not.

The standard framework developed to estimate GHG-driven near-term climate risk fails for regional aerosol emissions, creating blind spots

ESMs produce climate projections

Regional climate models (RCMs) and statistical algorithms

Often omit aerosol processes altogether

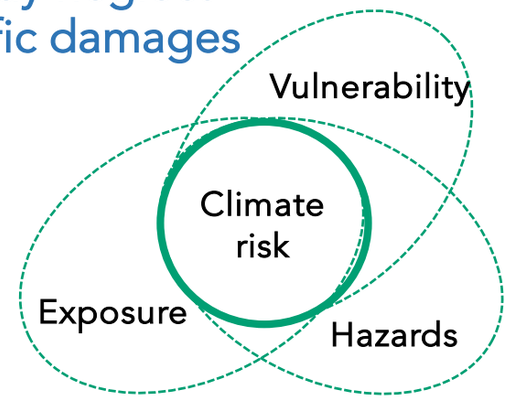
Emulators and simple climate models

Use global-averages or GHG-based pattern scaling

Obscure how regional aerosol emissions and their changes impact outcomes

Built around GHG-driven damages, may neglect aerosol-specific damages

Impact models, damage functions, & social cost calculations produce inputs to climate risk assessments

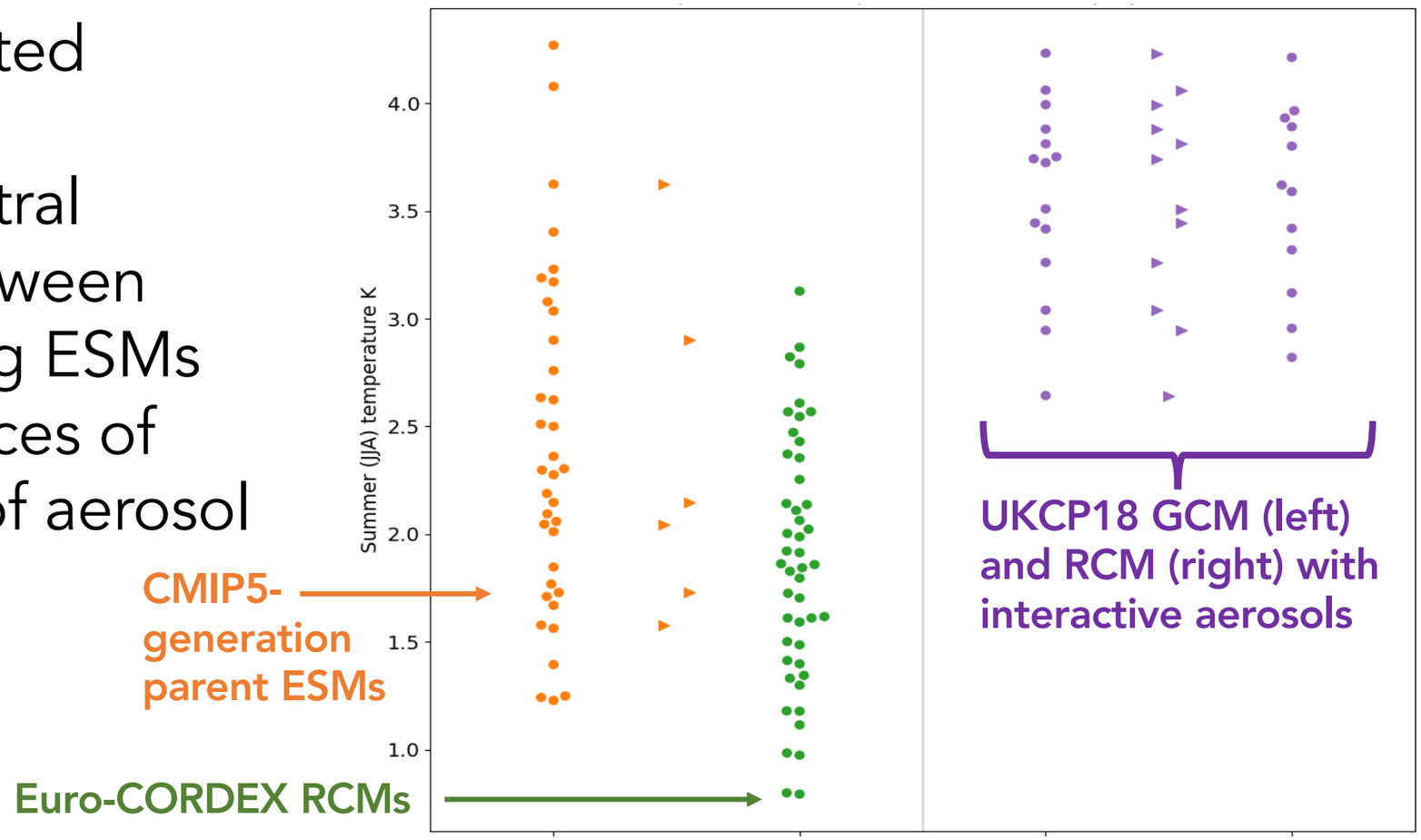


Near-term climate risk estimates rarely include aerosol effects or regard them as a global-mean offset to GHG-driven warming

Regional Climate Models often omit aerosol processes, obscuring aerosols' impacts in local-scale climate planning

Comparison of projected changes in summer temperature for a central European domain between RCMs and their driving ESMs shows the consequences of underrepresentation of aerosol processes in RCMs

See also Dominik Schumacher et al. 2024, *Nature Comms. E&E*



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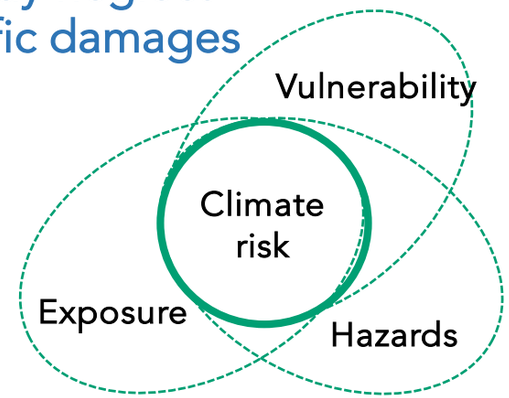

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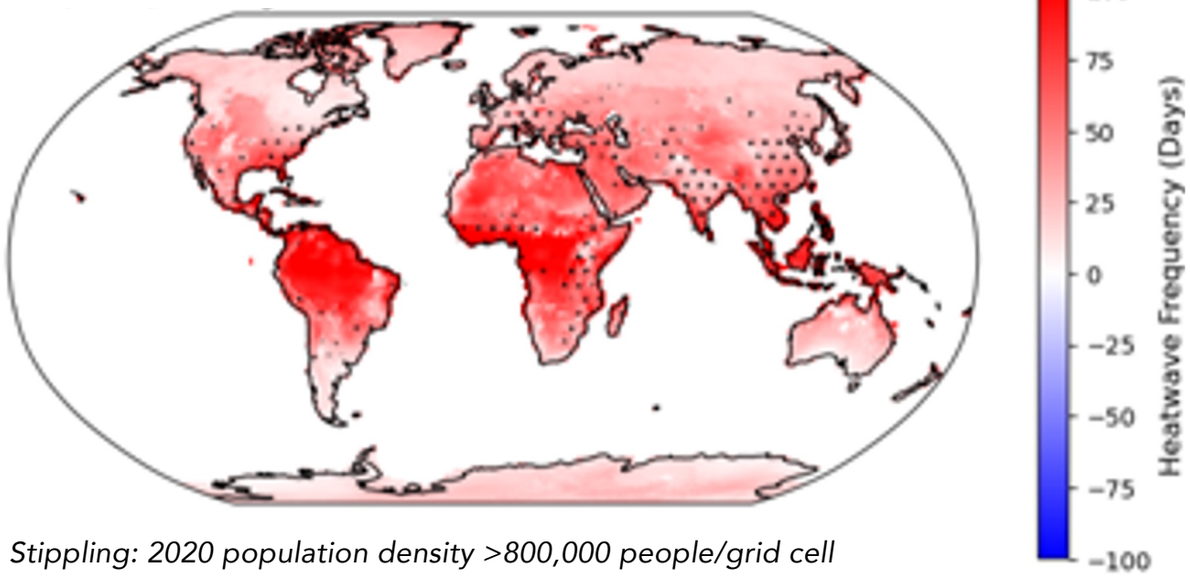
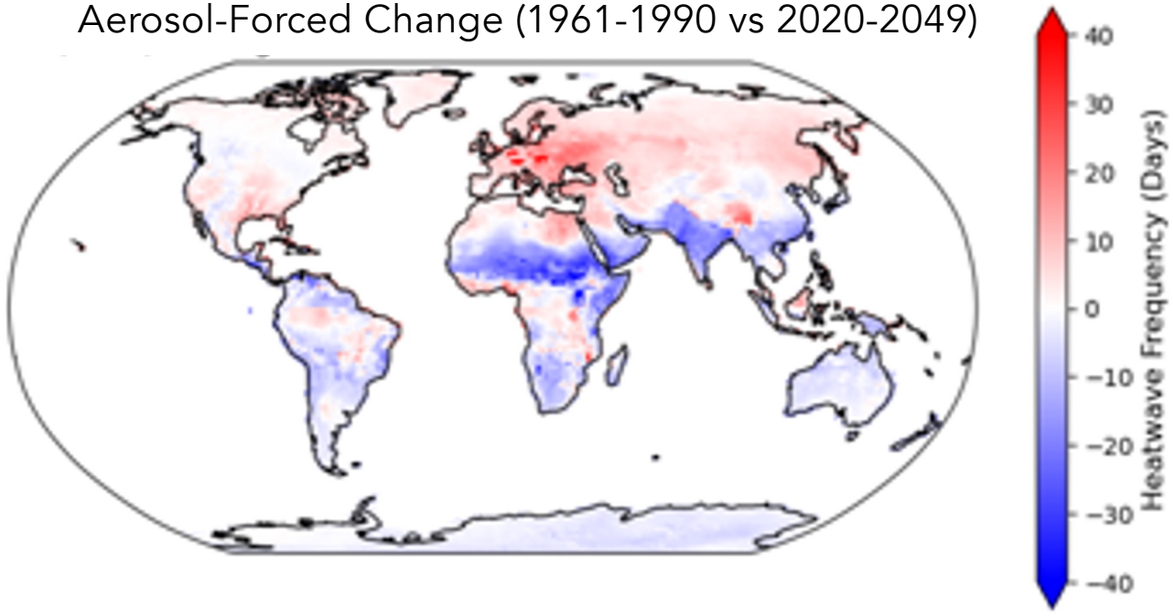
The spatial pattern of aerosol effects on heatwave hazard matters for exposure through time

All-Forced Change (1961-1990 vs 2020-2049)



Stippling: 2020 population density >800,000 people/grid cell

Aerosol-Forced Change (1961-1990 vs 2020-2049)



Persad et al. *(in revision at ERL)*
CESM1 Single Forcing Large Ensemble

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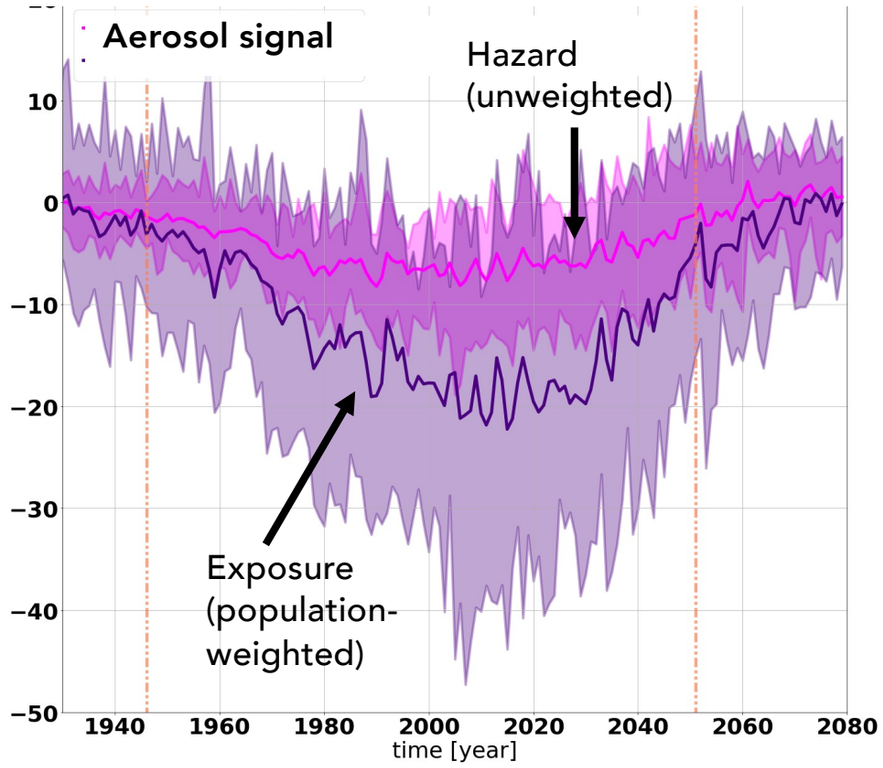
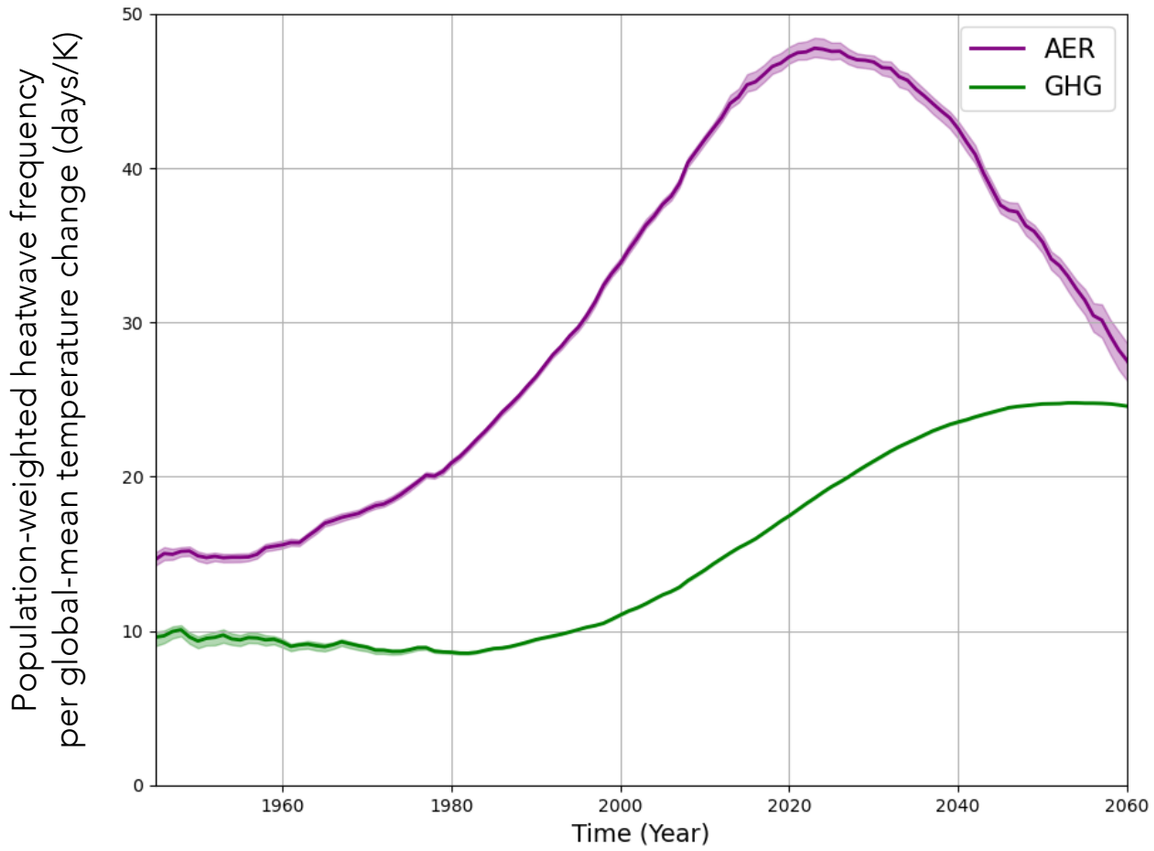
Aerosols have an outsized impact on global heatwave exposure per unit of global-mean temperature change

Global land-mean number of heatwave days per year



Heatwave Exposure per Global Mean Temperature Change



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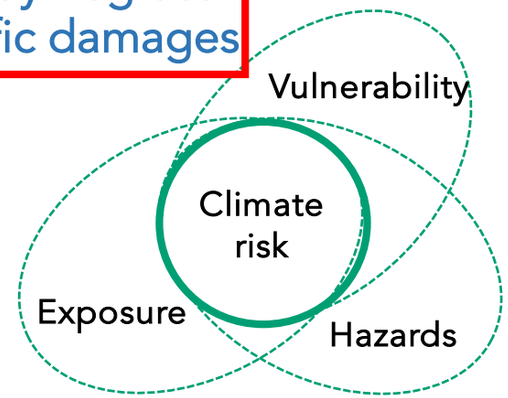

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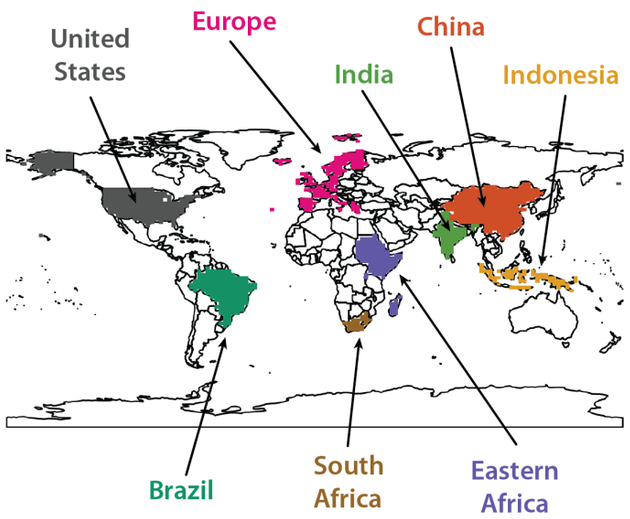
Connecting Physical System and Human System Impacts

Physical Responses from Climate Model Simulations



Total regional emissions change:
22.4 Tg sulfate precursor
1.61 Tg black carbon
4.03 Tg organic carbon

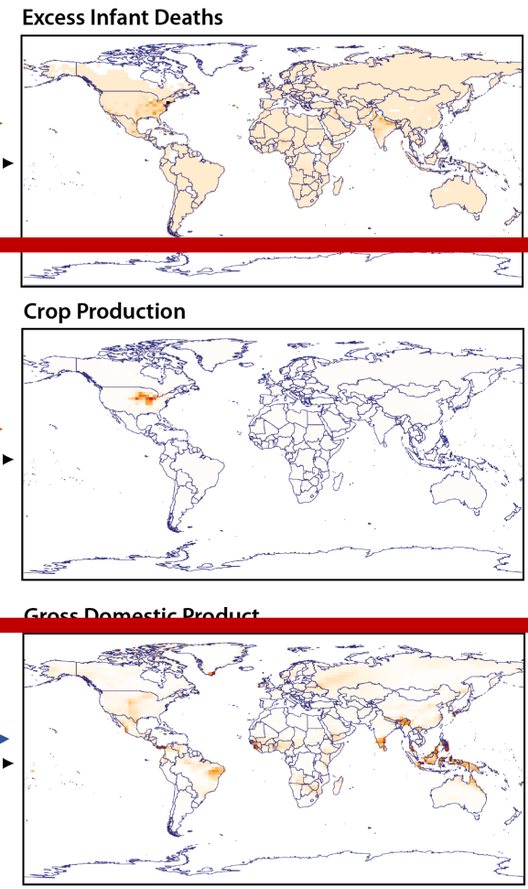
Damage Functions Based on Global Observations

Infant mortality impacts from surface air quality changes (Heft-Neal et al. 2018)

Crop yield impacts from aerosol optical depth and climate changes (Proctor et al., 2018)

Economic productivity impacts from climate changes (Burke et al., 2015)

Societal Impacts of Regional Aerosol Emissions



Burney, Persad et al. (2022, *Science Advances*), Persad and Caldeira (2018, *Nature Comms.*), Persad (2023, *ACP*)

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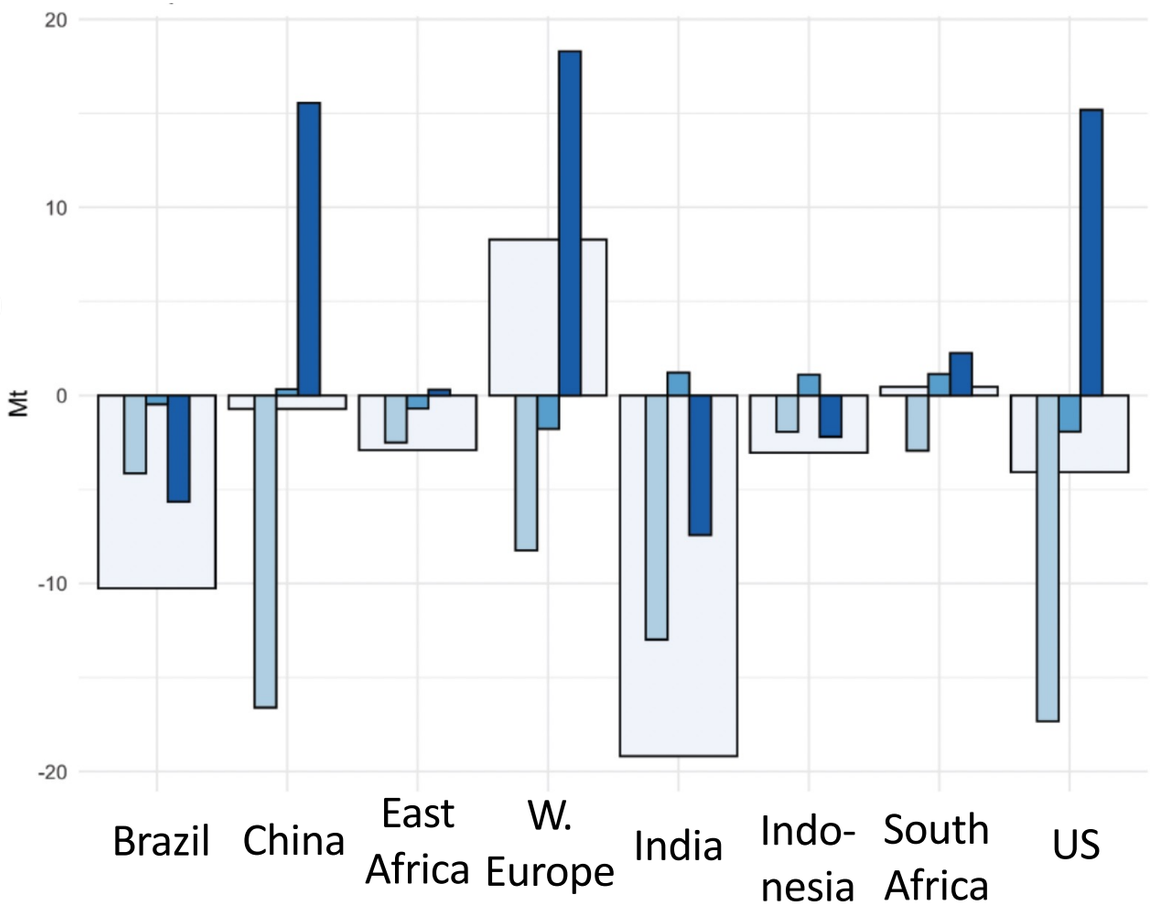
Impacts of regional aerosol emissions on agriculture highlight the importance of aerosol-aware impact modeling

Total Crop Yield Impacts (Mt)



AOD damages counteract cooling benefits, changing the sign of the total crop impacts

Total
AOD
Precipitation
Temperature

Burney, Persad et al. (2022, *Science Advances*)

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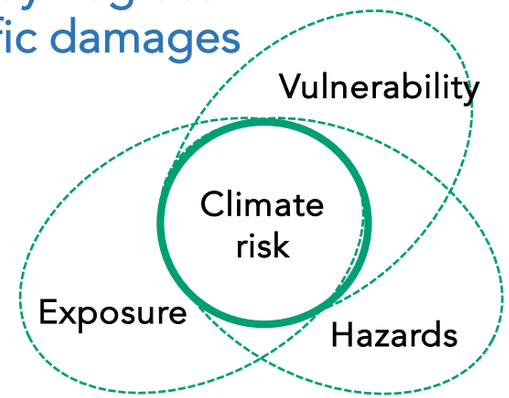

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Persad et al. (2023, *Environmental Research: Climate*)

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The way forward

Integrated assessment model developers

- Increased scenario diversity in regional patterns and composition of aerosol emissions **CMIP7**
- Greater intercomparison of assumptions driving aerosol emissions in future scenarios

Earth system modelers and aerosol-climate research community

- Continued improvement of aerosol representation and biases
- Dedicated earth system modelling efforts, such as Regional Aerosol MIP (**RAMIP**)

Persad et al. (2023, *Environmental Research: Climate*)

Regional Aerosol MIP

Coupled transient simulations (to February 2051)
SSP3-7.0 baseline, regional perturbations from SSP1-2.6
10 members ensembles

Tier 1

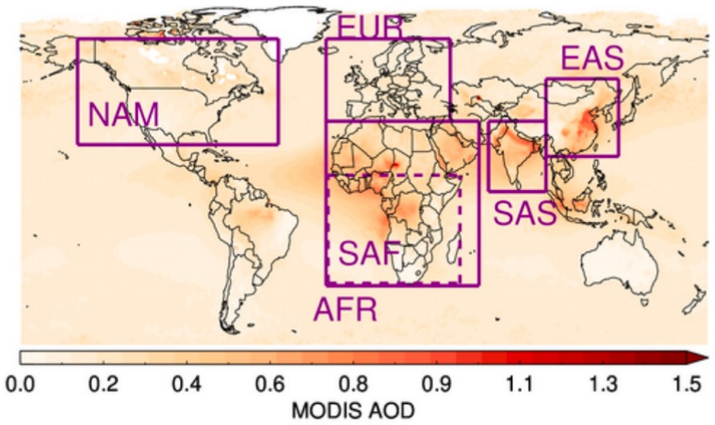
- Global
- Africa and the Middle East
- East Asia
- South Asia
- NAM + EUR

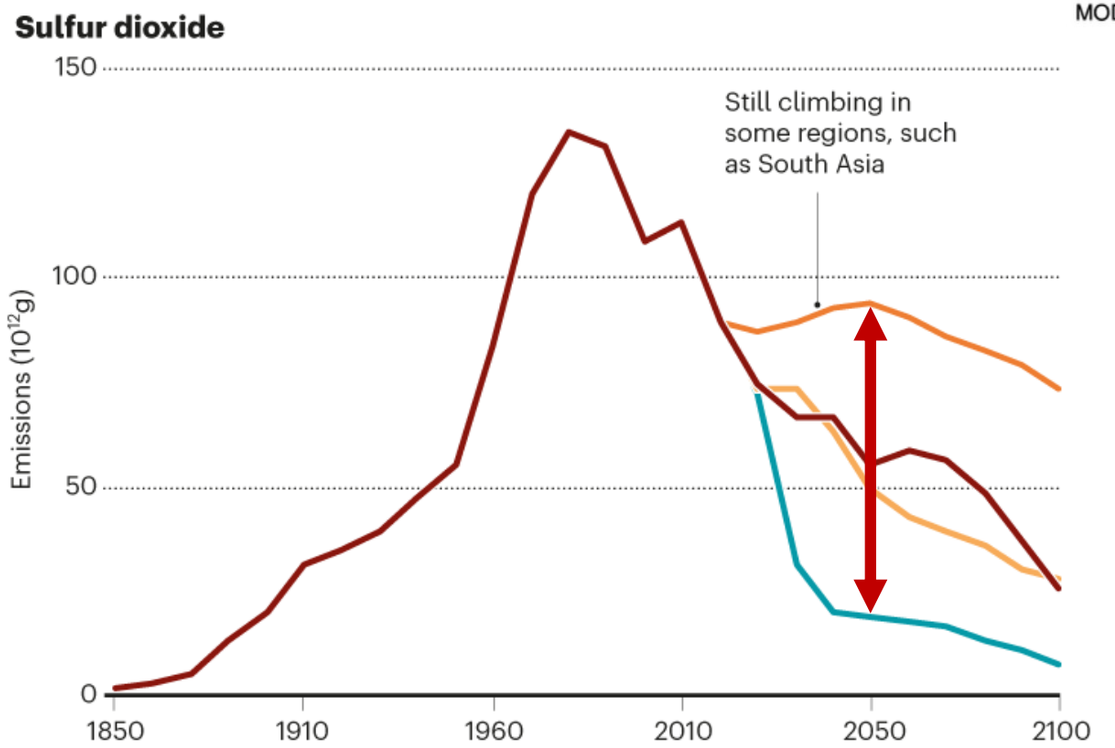
Tier 2

- South+East Asia
- Sub-Saharan Africa carbonaceous
- South Asia carbonaceous

10 Participating models

CanESM5, CESM2, CNRM-ESM2.1, EC-Earth3, GFDL-SPEAR, GISS-E2.1, MIROC6, MRI-ESM2, NorESM2, UKESM1





What does this uncertainty mean for near-term climate risk?

Wilcox et al. (2023, *Geosci. Model. Dev.*)
Laura Wilcox (lead), Robert Allen, Bjørn Samset, Camilla Stjern, Luke Fraser-Leach, Paul Griffiths Massimo Bollasina, Annica Ekman, James Keeble, Tyushi Koshiro, Molly MacRae, Risto Makkonen, Joonas Merikanto, Declan O'Donnell, Naga Oshima, Marianne Lund, David Paynter, Geeta Persad, Steve Rumbold, Toshi Takemura, Kostas Tsigaridis, Sabine Undorf, Daniel Westervelt

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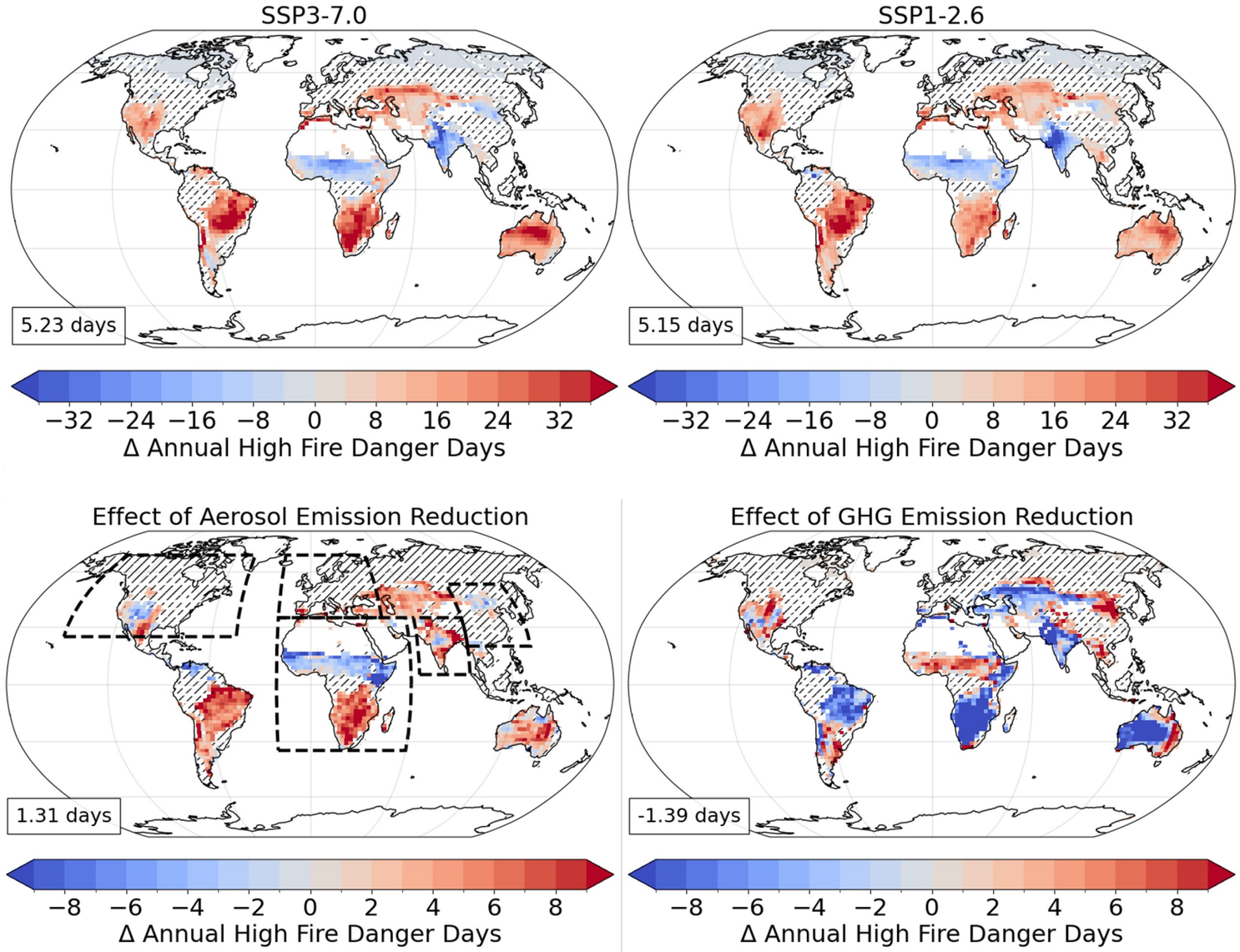
Aerosol reductions almost entirely counteract benefits of GHG mitigation for fire danger

Projected mid-century change (2041-2050) relative to historical (1961-1990)



Utama et al. (in prep.)

RAMIP results from GFLD SPEAR, NorESM2-LM, MRI-ESM2-0

Diagonal lines indicate regions with less than two models agreeing on sign of change

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Thank you!
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Impact researchers and climate service providers

- Pattern and variability aware emulators for translating ESM results into a larger scenario space
- Aerosol-aware impact modelling and risk assessment

Policymakers and stakeholders

- Demand aerosol-aware risk assessments
- Integrate findings into policy discussions; couple clean air/climate regulation

Funders, universities, and scientific societies

- Create new spaces for interdisciplinary interaction on aerosols and climate risk
- Prioritize funding in this area

Persad et al. (2023, *Environmental Research: Climate*)

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