CESM LWMG meeting

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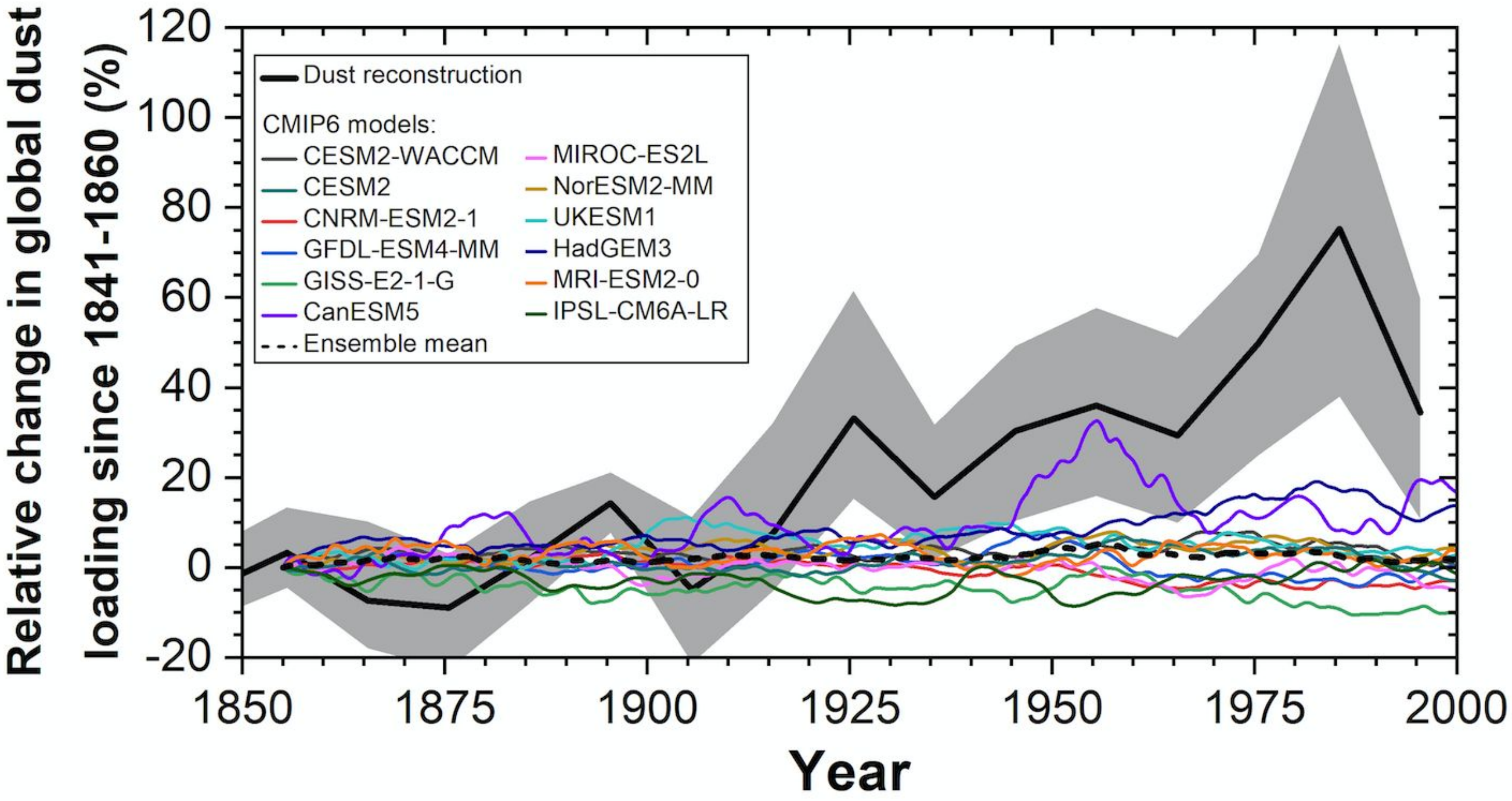
24 Feb 2025

Climate models fail to capture the observed historical dust aerosol trend.



19 paleo core records of decadal dust depositions for dust reconstruction (black solid).

Kok et al. 2023

- CMIP6 ESMs could not replicate the ~55 % dust increase -> biased aerosol forcings.
- ESM aerosol schemes (e.g., dust, fire) are biased towards present day and cannot be extrapolated to other climates.

ESMs need to follow the observational constraints to evaluate aerosol radiative forcings (RF).

ESMs have biased aerosol radiative forcings (RFs).

Long-term solution: Couple mechanistic aerosol schemes better with climate / land use changes.
Near-term solution: Force ESMs to follow observed aerosol variability?

The AeroCom Phase III project used following approaches:

1) Use paleo core records to globally tune ESM dust decadally;
2) Use paleo core records to derive global dust emissions for driving ESM simulations;

This talk focuses on developing and testing 2) historical gridded dust emissions.

Goal: use core records of dust depositions to optimize 7 regional dust emissions decadally.

Inverse method:

- Observations: 19 core records of decadal dust depositions time series β_j for 1850–2000; $j = 1,\ldots,19$
- States: 7 emission time series from 7 defined regional dust source regions λ_i; $i = 1,\ldots,7$
- Jacobian: Dust deposition-to-emission sensitivity $f_{i,j} = \partial\beta_j/\partial\lambda_i$ (from an ensemble of 6 climate models).

Use 19 β_j time series with $f_{i,j}$ to solve for decadal regional emissions $\lambda_i(d)$:

$$\lambda_i = f_{i,j}^{-1}\beta_j$$

By optimizing the cost function for decade d : $\chi(d)^2 = \sum_j^{19}\left[\sum_i^7 \lambda_i(d) f_{ij} - \beta_j(d)\right]^2$

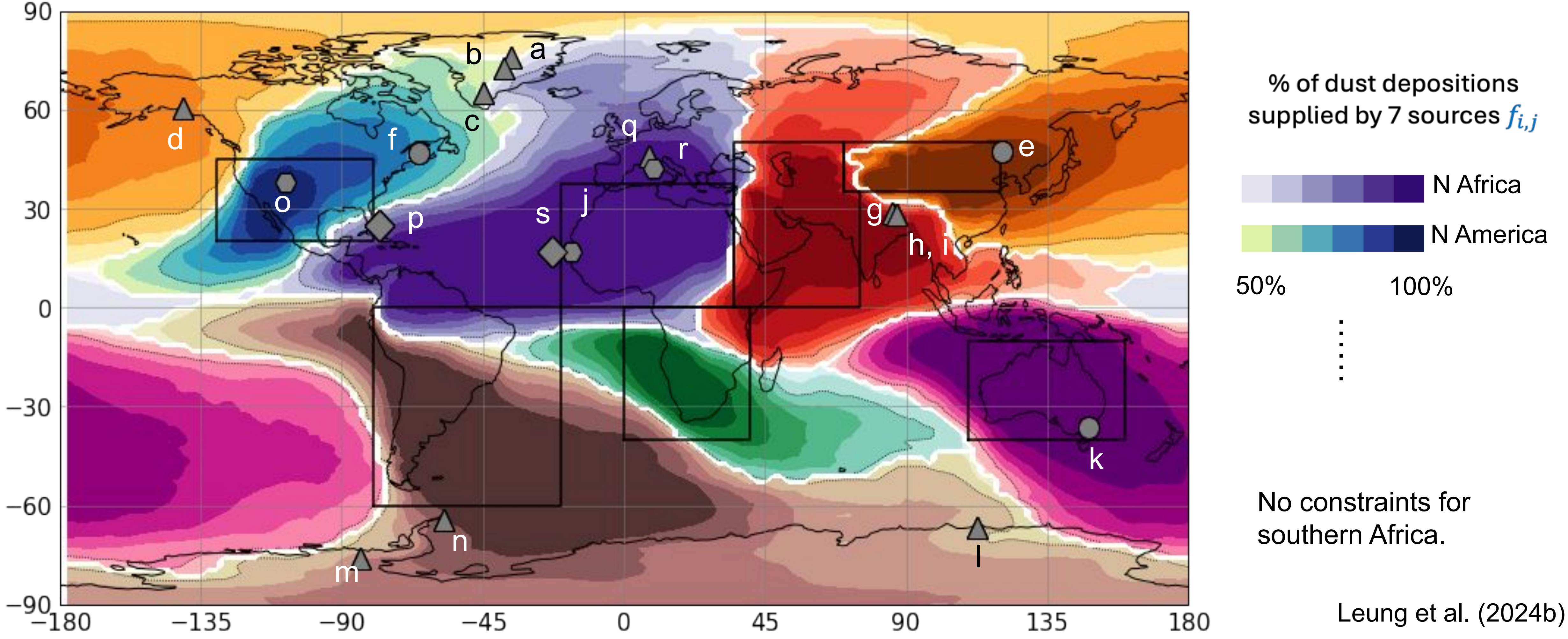
Multiply regional λ_i by the spatially gridded present-day emission patterns $F_i(\text{lon}, \text{lat})$ from the model ensemble:

$$F_{\text{DustEI}}(\text{lon}, \text{lat}, d) = \sum_{i=1}^{7} \lambda_i(d) F_i(\text{lon}, \text{lat})$$

$F_{\text{DustEI}}(\text{lon}, \text{lat}, d)$: gridded DustCOMMv1 emission dataset

Goal: use multiple records of dust depositions to optimize 7 regional dust emissions decadally.

Simulated fraction of dust depositions (colors) supplied by 7 emission sources (rectangles)



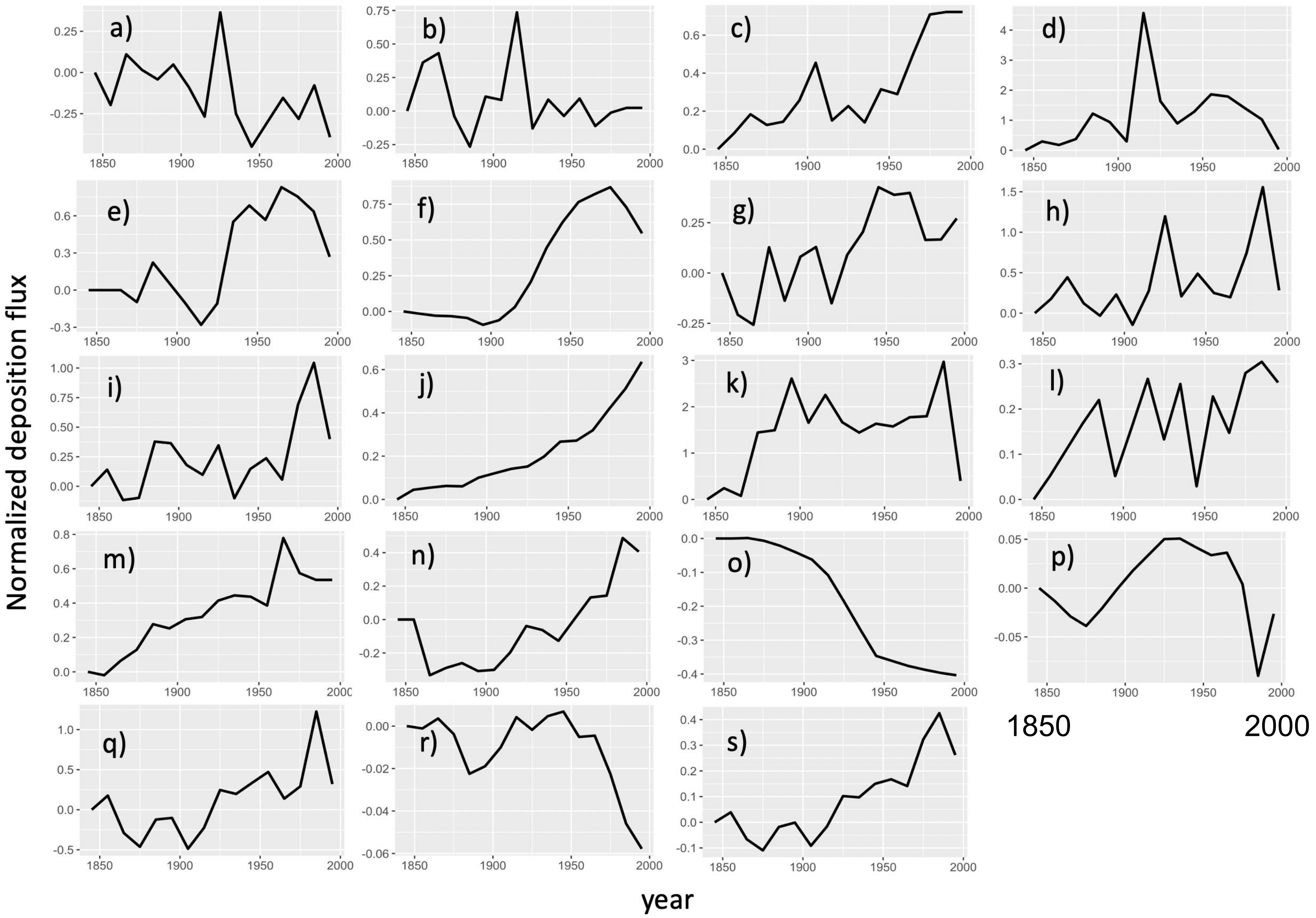
Colors: Reanalyzed fraction of dust depositions supplied by 7 emission sources $f_{i,j}$ (by an ensemble of 6 models)

Rectangular regions: 7 defined emission sources λ_i in this study

Dots: 19 sites of sedimentary records of dust deposition time series β_j

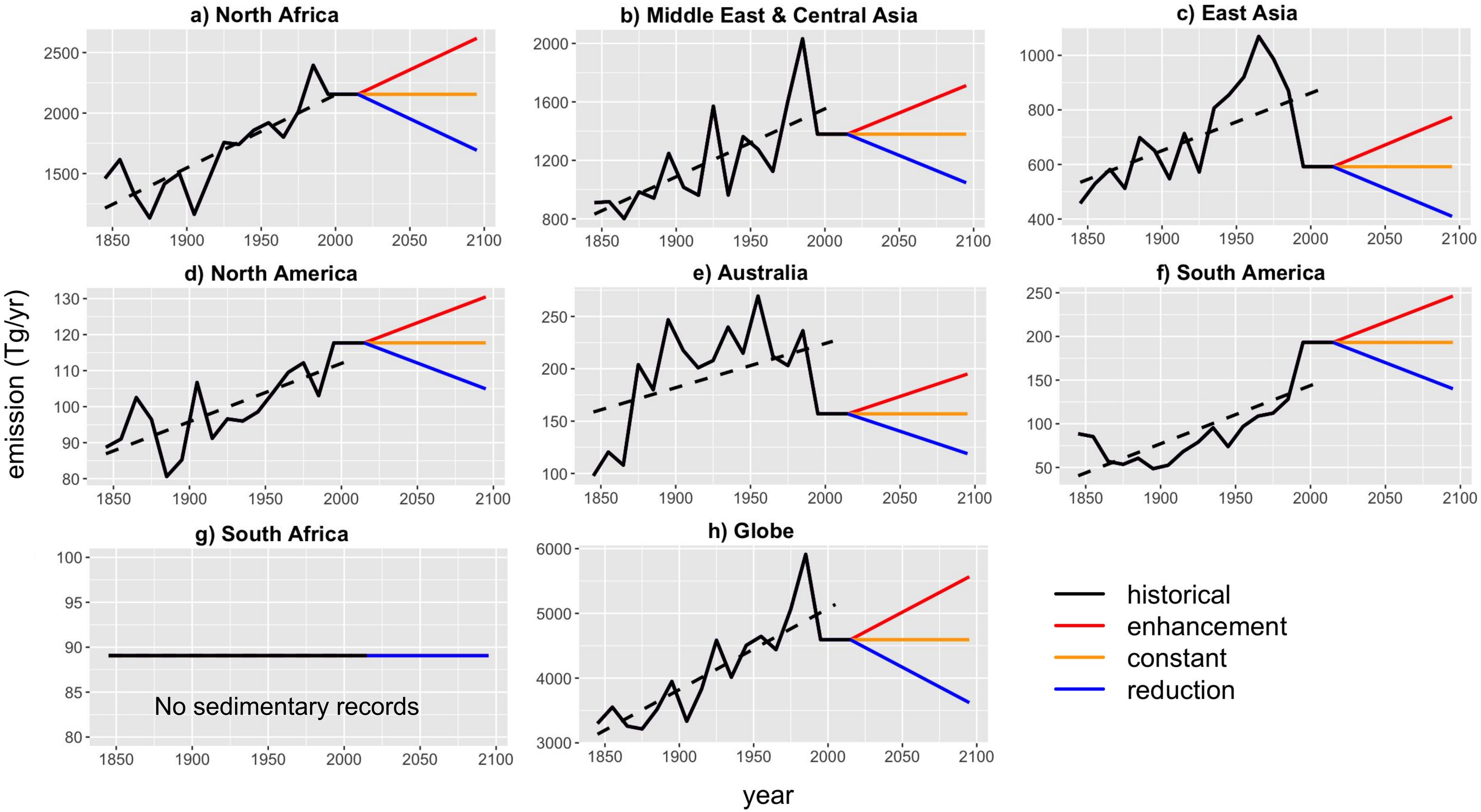
Goal: use multiple records of dust depositions to optimize 7 regional dust emissions decadally.

19 normalized core records of decadal dust depositions β_j for 1850–2000



- Substitute 19 β_j to solve $\lambda_i = f_{i,j}^{-1}\beta_j$ and obtain 7 λ_i.
- β_j at each site is indicative of dust variability from a source of λ_i.

DustCOMMv1 regional emissions $\boldsymbol{\lambda_i}$ for dust PM_{20}



Three future scenarios:

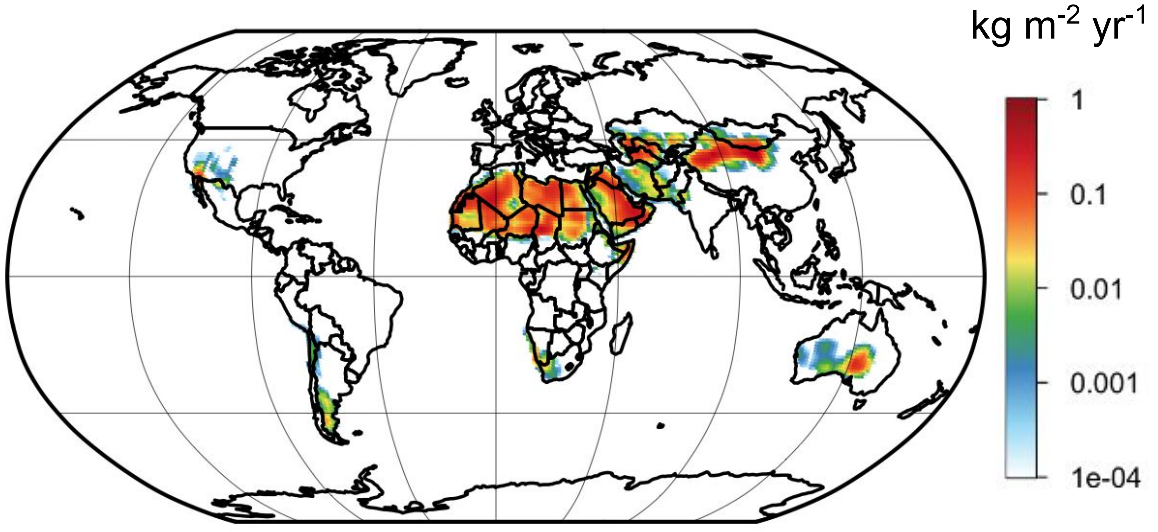
- Enhancement: same increasing rate
- Constant: no change
- Reduction: same rate but decreasing

Leung et al. (2025)

- We successfully rederived dust emissions that increased by ~55 % over 1850–2000
- For 2000–2020, satellite shows mild interdecadal variability -> for now assume no change
- 500 ensemble members for uncertainty characterization

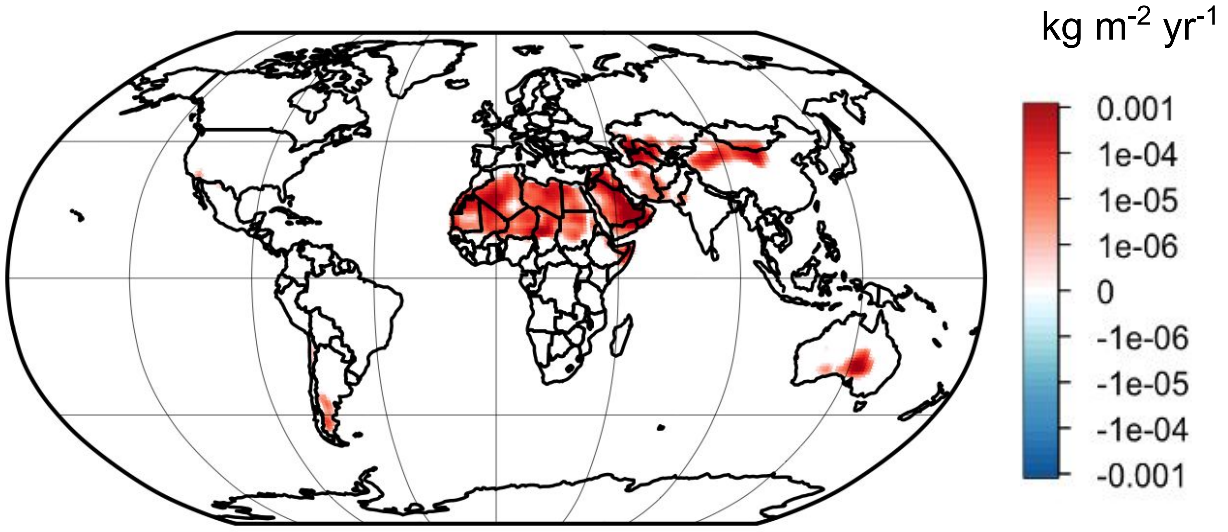
DustCOMMv1 gridded emissions $\mathbf{F}_{\mathbf{DustEI}}$ for dust PM_{10}

1851–1870 emissions



1406 Tg / yr

1981–2000 minus 1851–1870 emissions



+742 Tg / yr

Leung et al. (2025)

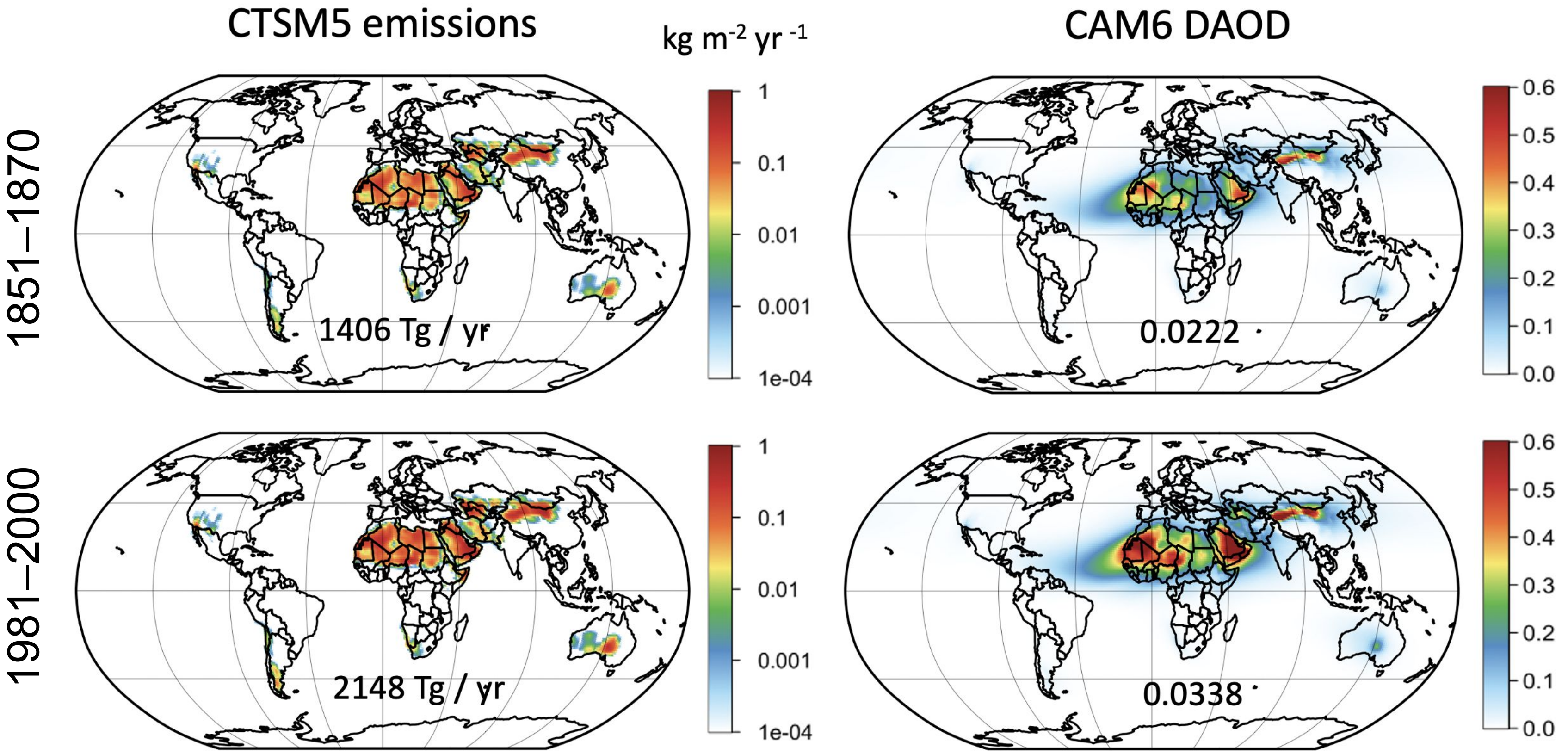
Project regional emission $\lambda_i(d)$ on model ensemble of spatial emission patterns $F_i(\text{lon}, \text{lat})$ to yield DustCOMMv1:

$$F_{\text{DustEI}}(\text{lon}, \text{lat}, d) = \sum_{i=1}^{7} \lambda_i(d) F_i(\text{lon}, \text{lat})$$

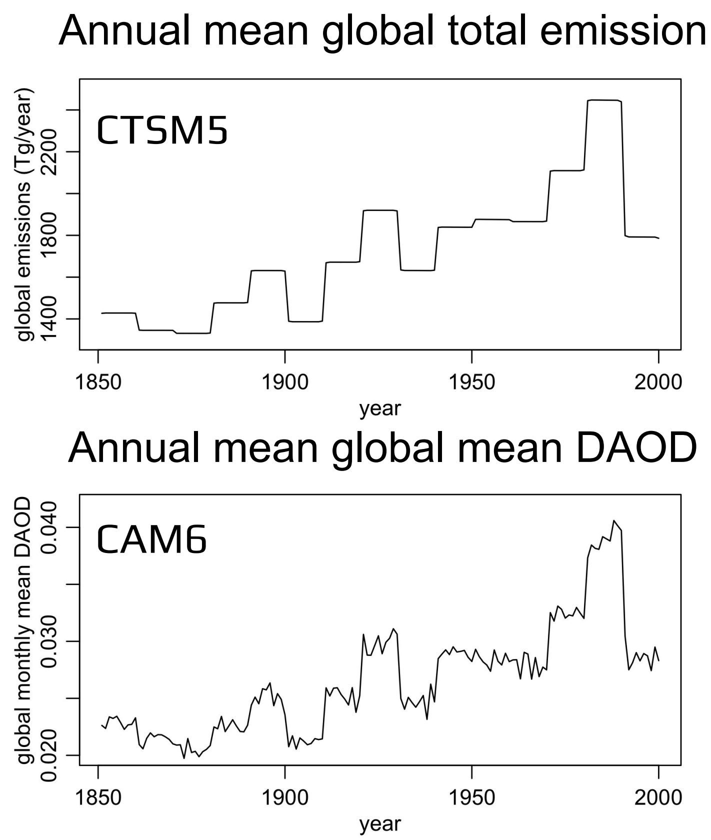
- Horizontal resolution: 1.9°x2.5°
- Temporal coverage: 1851–2000 decadal emissions.

Goal: We use F_{DustEI} to drive CESM2.2 1851–2000 land–atmosphere coupled simulations.

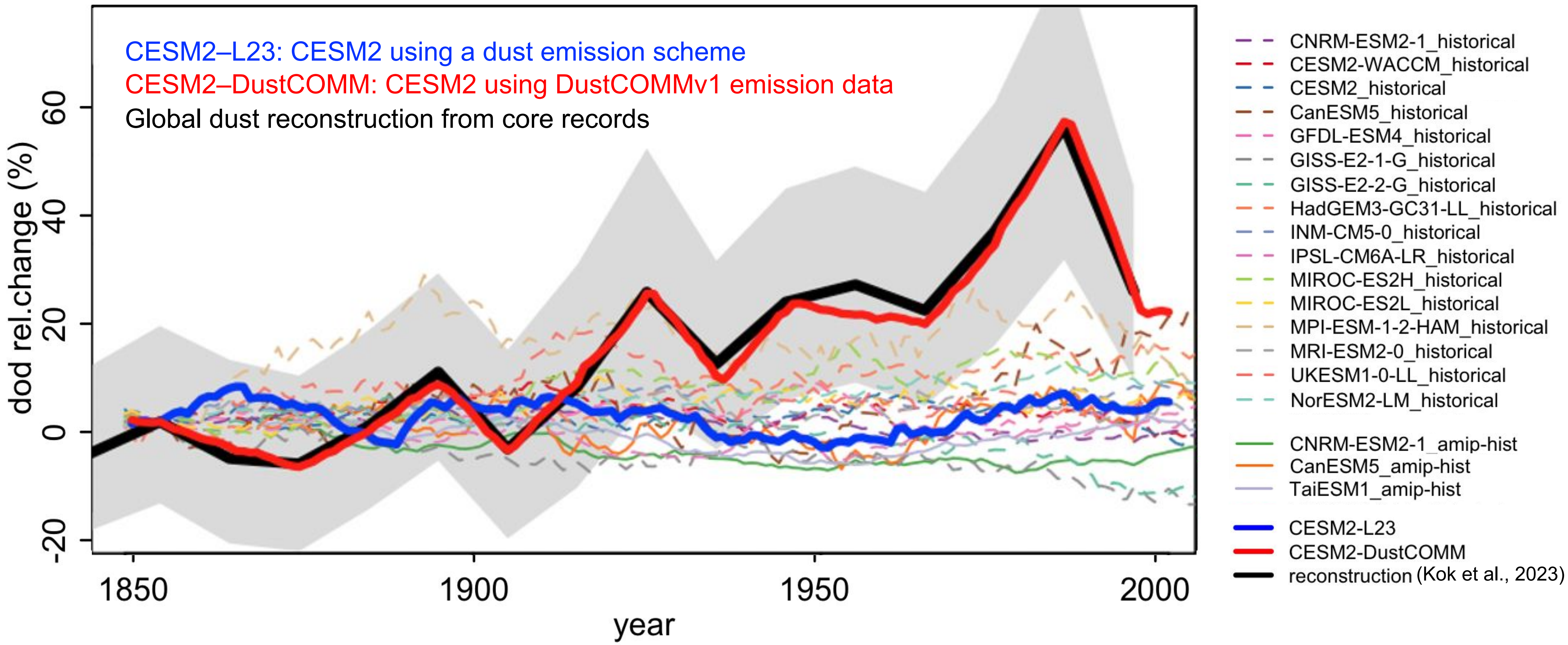
Spatial variability



Temporal variability



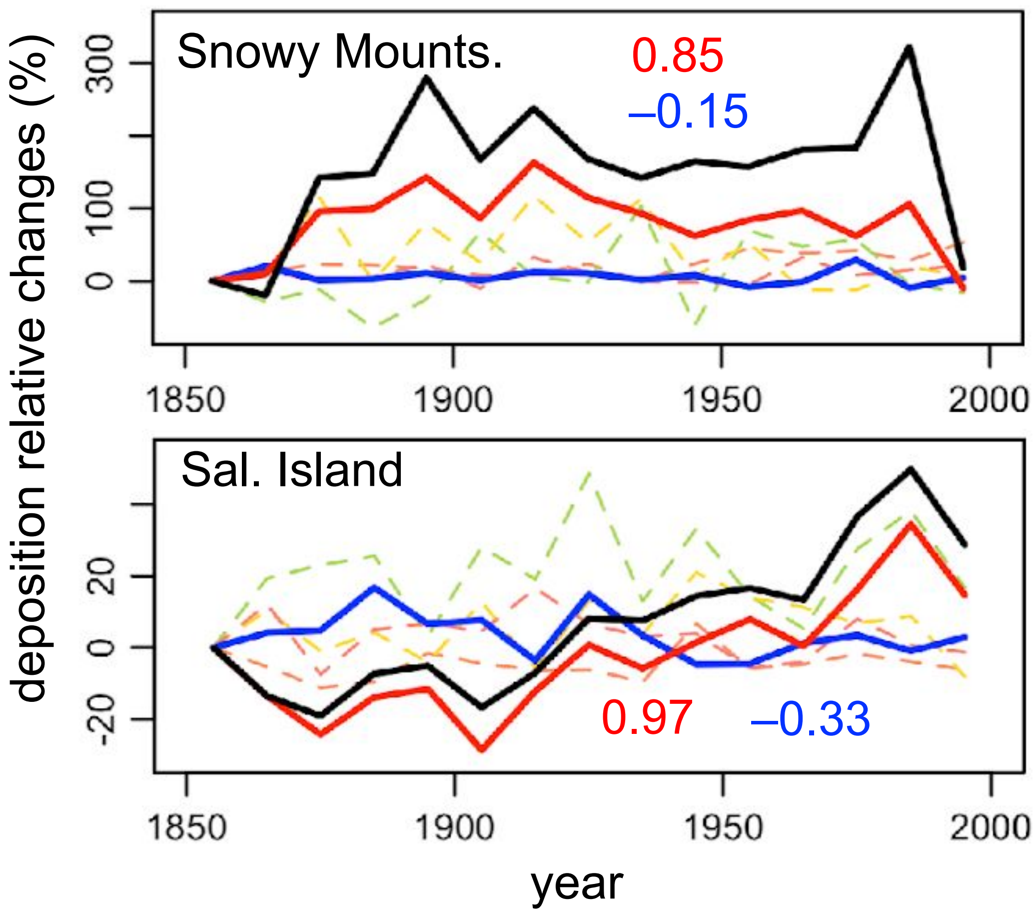
Comparison of 1851–2000 dust DAOD from our CESM2 runs and CMIP6 runs.



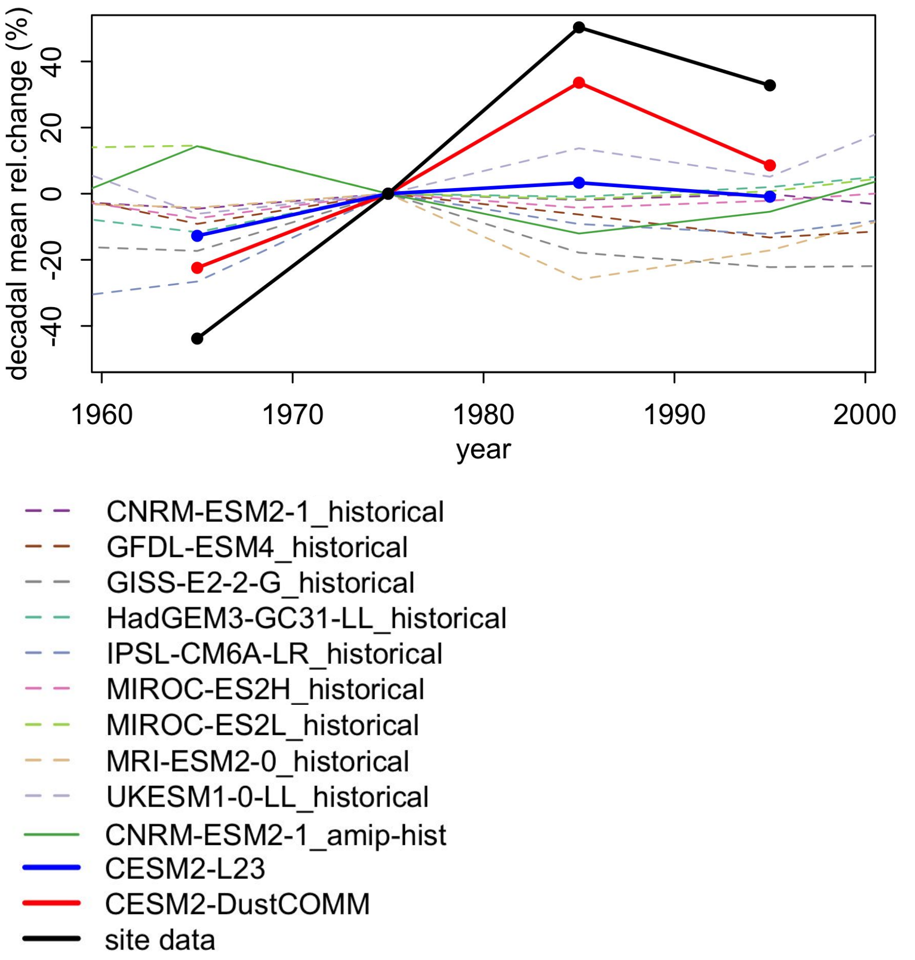
The CESM2–DustCOMM run matches the Kok et al. (2023) global dust trend reconstructed from the sedimentary records.

Evaluation: CESM using DustCOMM emissions gives better dust variability.

Decadal mean dust deposition
(relative to the 1850s)

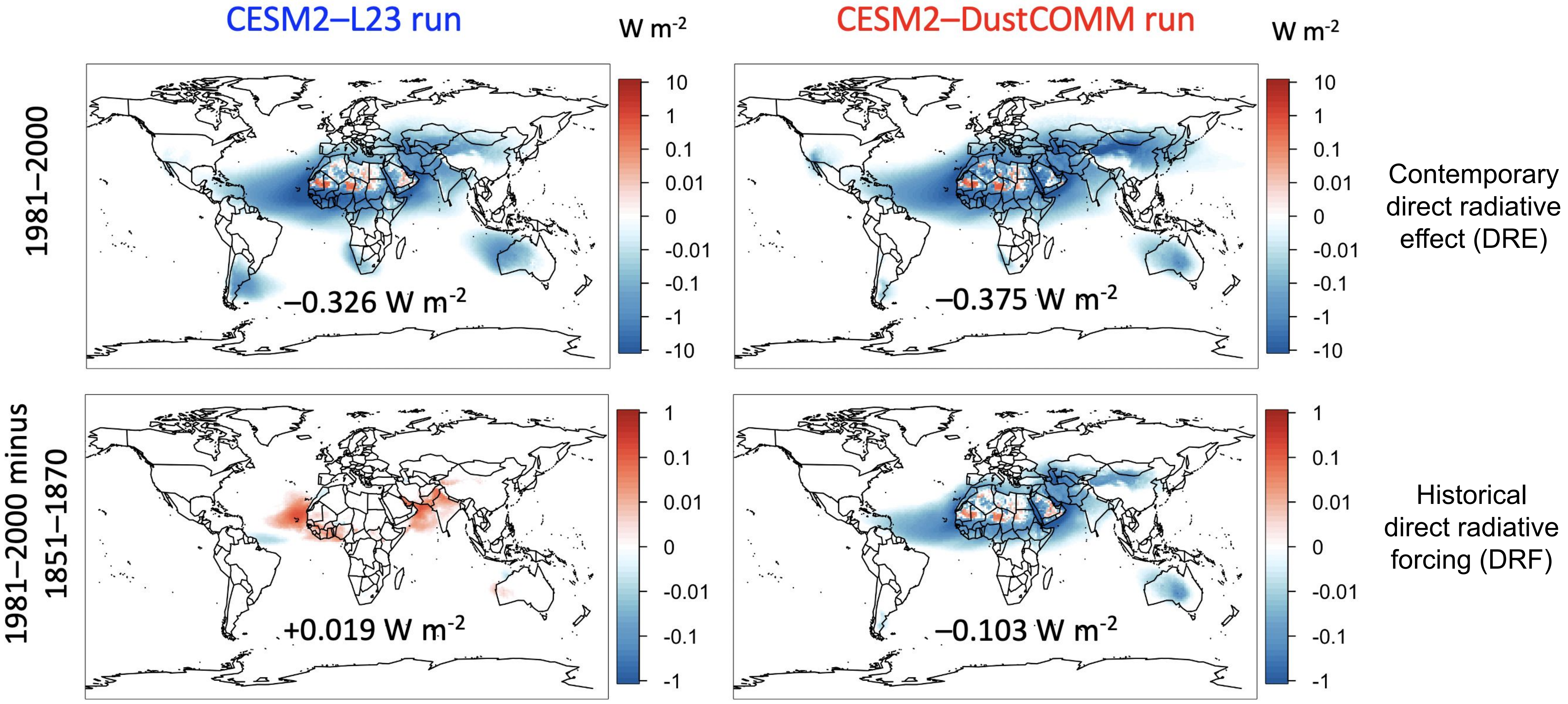


Decadal mean Barbados dust concentration
(relative to the 1970s)



Leung et al.
(2025)

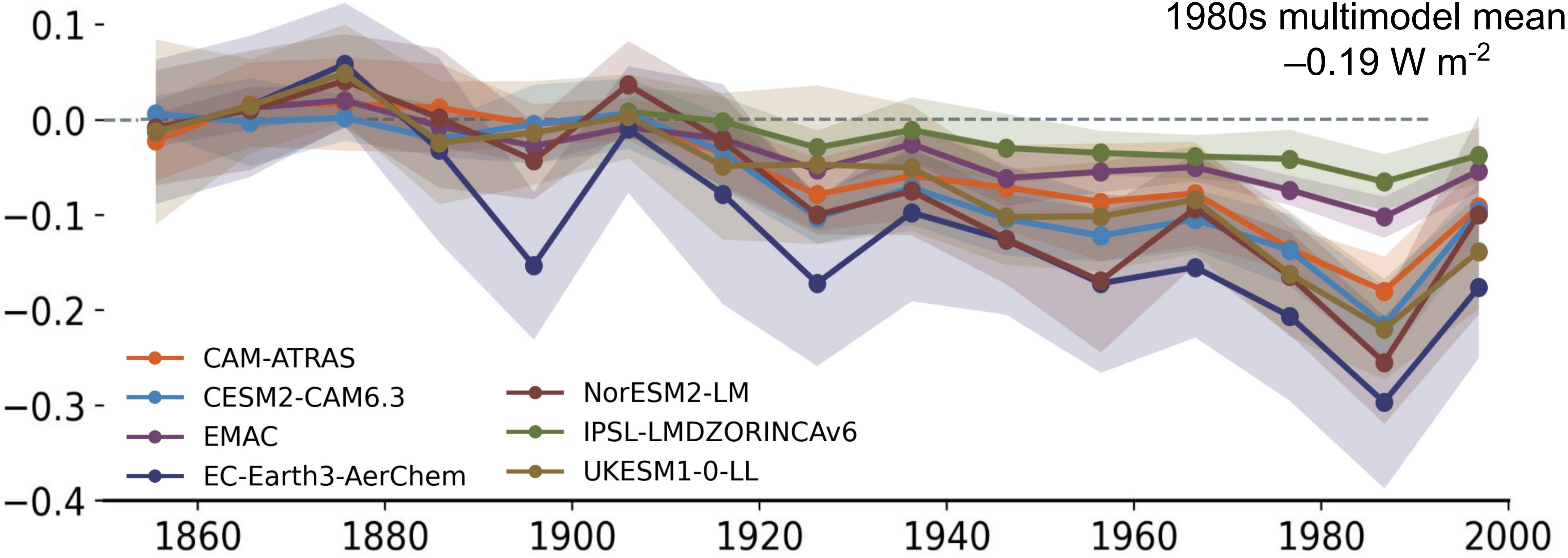
CESM2 historical dust PM_{10} direct radiative effects (REs) and forcings (RFs)



- We show ~an order of magnitude larger direct dust RF.
- The dust direct RF is ~20 % of total aerosol direct RF (~ –0.5 W m^{-2}; Bellouin et al., 2020).

AeroCom Phase III dust radiative forcing (DURF) experiment

Organizers: Trude Storelvmo (U Oslo), Jasper Kok (UCLA), Michael Schulz (U Oslo), Ove Haugvaldstad (U Oslo)
Purpose:
- Use historical dust emissions (DustCOMMv1) to compute dust RF (direct + indirect);
- Get a model ensemble to better constrain historical aerosol RF and climate sensitivity
Simulation year: 1850–2000



1980s multimodel mean: –0.19 W m^{-2}

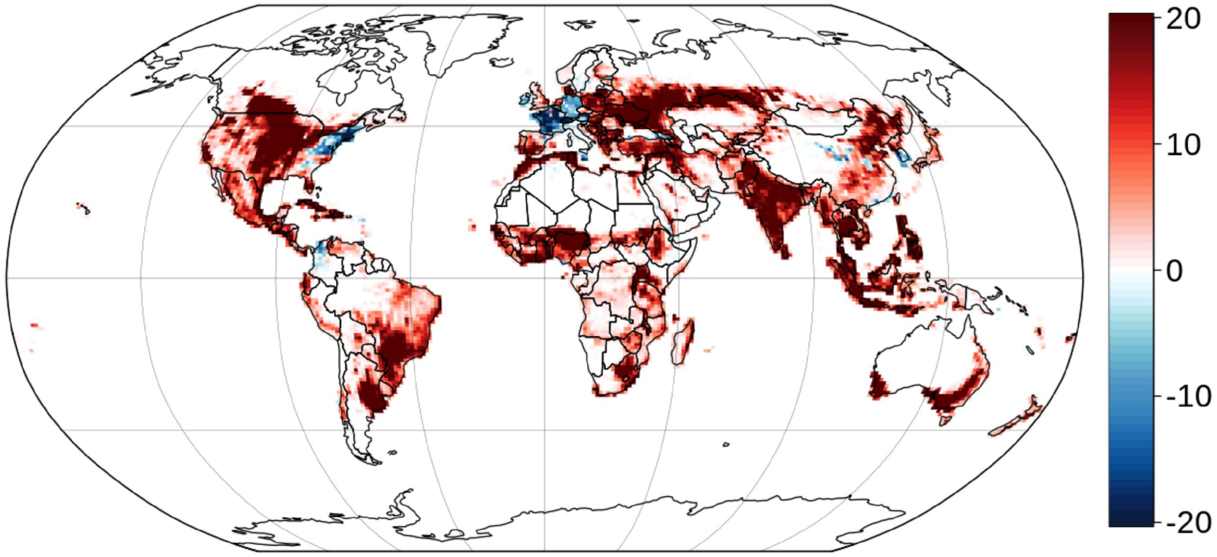
AerChemMIP2 on the way

Figure credit: Ove W. Haugvaldstad (U Oslo)

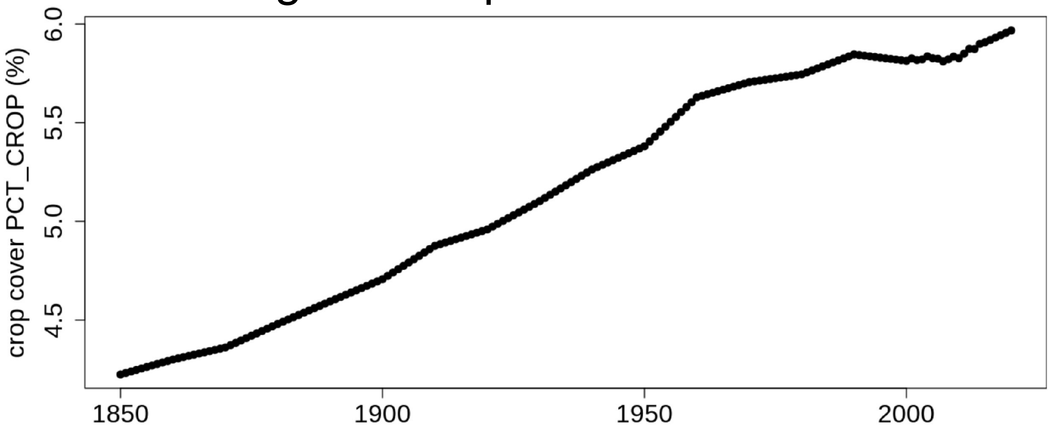
Speculation on how to improve ESM mechanistic dust on long-term variability

Suspected reasons for dust increase: land use change, desertification, deforestation, water use management, warming…

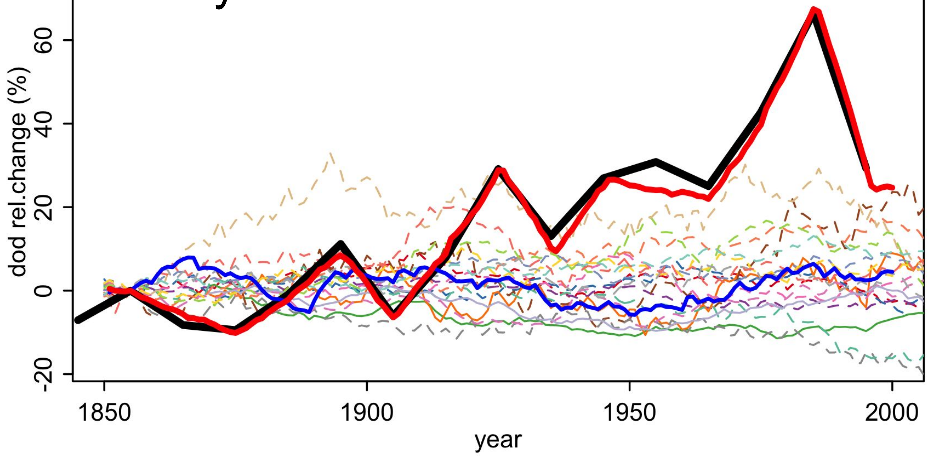
CTSM 2000s minus 1850s crop % cover



CTSM global crop % cover time series



Observed and modeled global dust variability



- ESM dust schemes might want to improve coupling with historical land use datasets.
- Historical LAI and soil moisture variability?

Summary

1. We derive 1851–2000 dust emissions (DustCOMMv1) with a historical increase of ~55 %. We are getting more core records to make DustCOMM further realistic.

2. We successfully generate a reasonable historical interdecadal dust variability in ESMs (e.g., CESM).

3. AeroCom experiment using our hist dust emissions gives a 1850–2000 dust direct radiative forcing (RF) of about –0.19 W m^{-2} (cooling), which is ~30–40 % of historical aerosol direct RF of –0.5 W m^{-2} (Bellouin).

4. Mechanistic dust schemes need to improve their interdecadal variability performance.

5. Same for other aerosols, e.g., Douglas Hamilton is developing a historical fire emission dataset using charcoal records and the inverse analysis.

Decadal global dust variability data