A new mechanistic dust emission scheme: Updates in CESM3/CAM7

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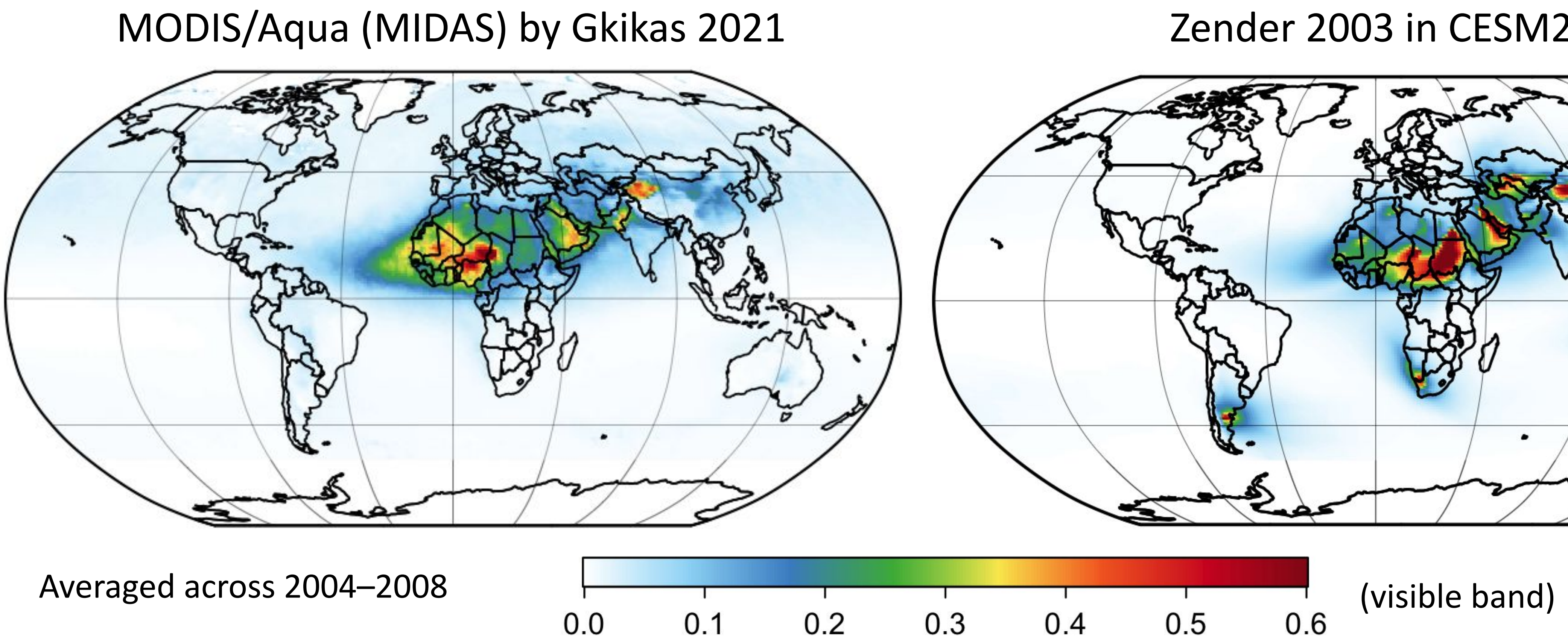
AMWG winter meeting

3 Feb 2025

Motivation: CESM dust does not capture the spatial variability of satellite dust AOD well.



- CESM2 dust AOD does not match well with MODIS/Aqua satellite dust AOD (MIDAS; Gkikas et al., 2021) in source regions.
- Dust sources are wrongly located, and new dust emission physics should be added to highlight the right source locations.

1) Dust scheme change: From Zender 2003 to Kok 2014 emission scheme

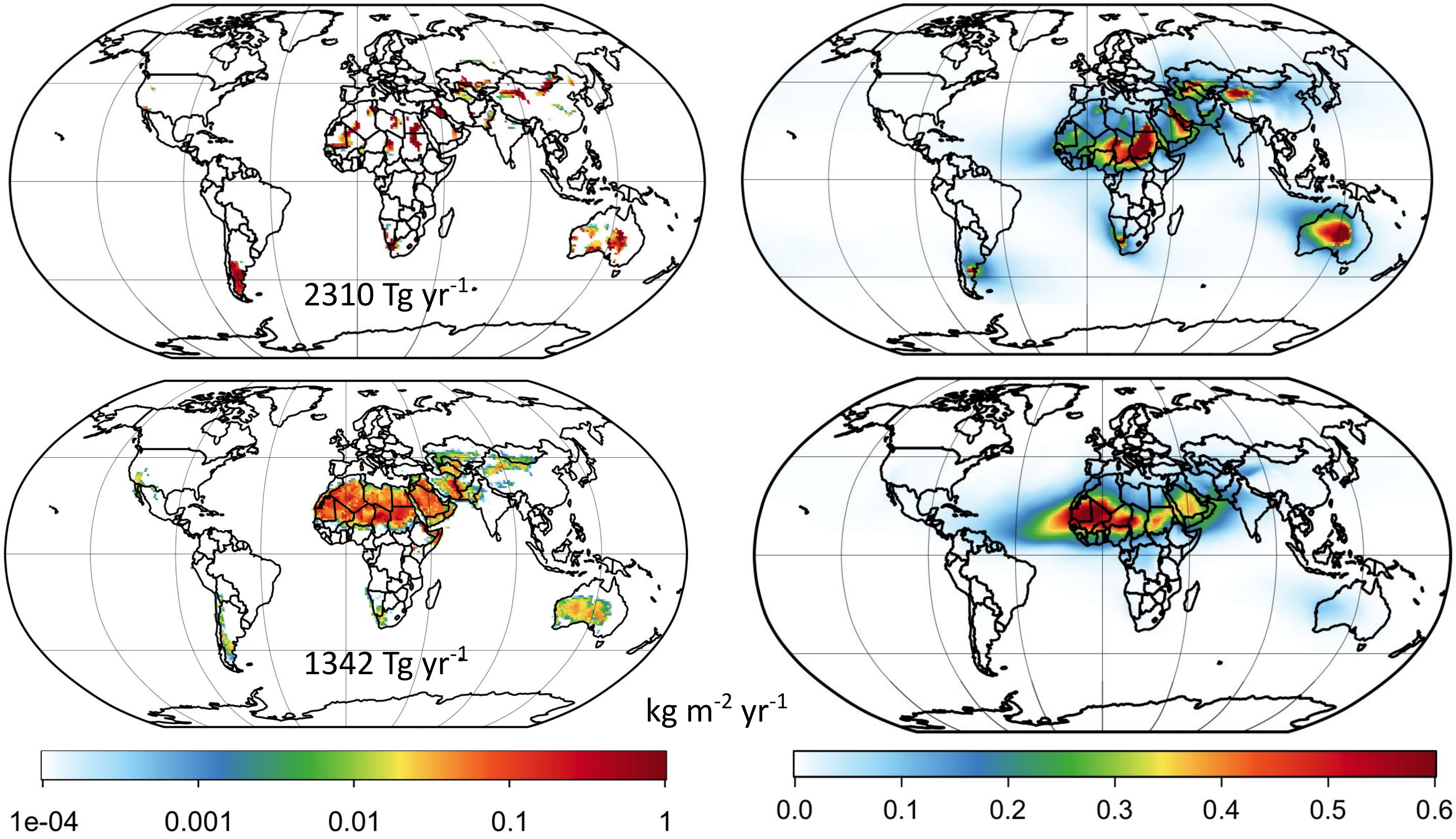
Threshold parameterization:
$F_{emis} > 0$
if $u_* > u_{*thr}$

CTSM5 Dust emission F_{emis}

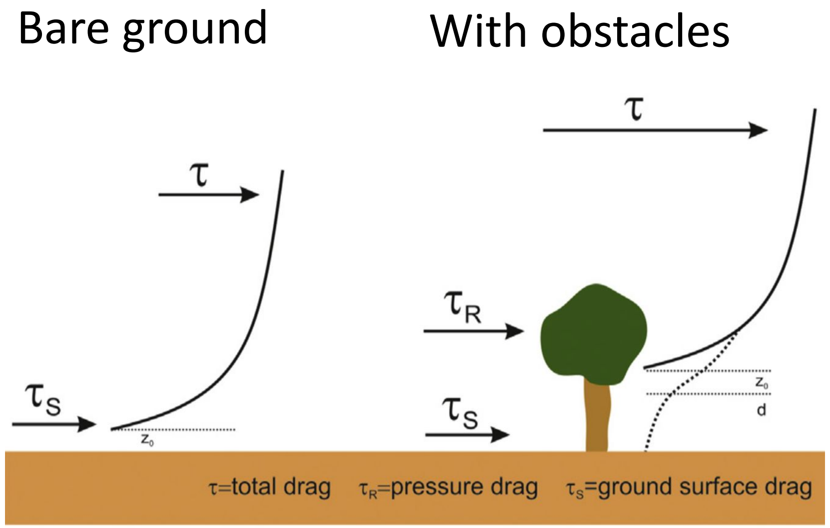
CAM6 Dust AOD
(2000s constraint: global mean = **0.03**)

Zender 2003; DEAD
CESM2 default

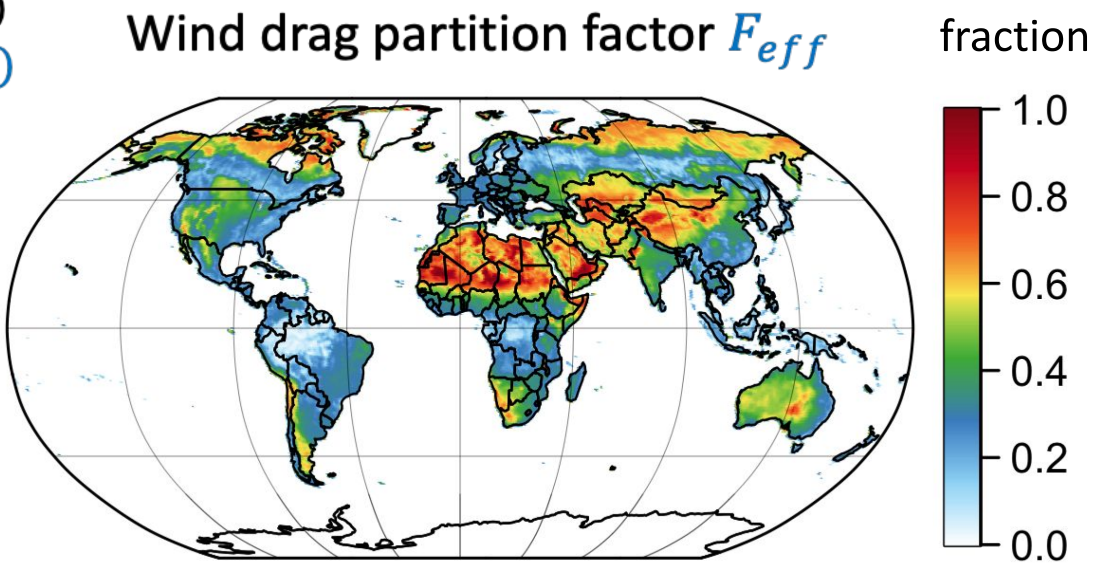
Kok 2014; K14
Base scheme for
Leung 2023

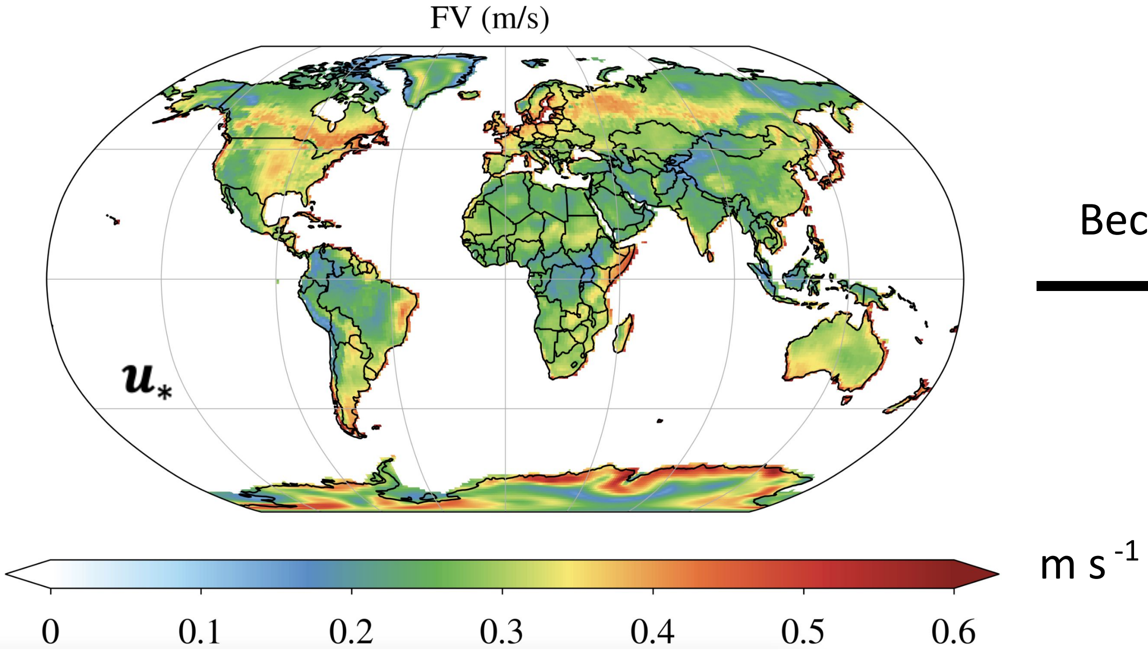


2) Leung 2023 added process: wind partition due to surface roughness (rocks + vegetation)

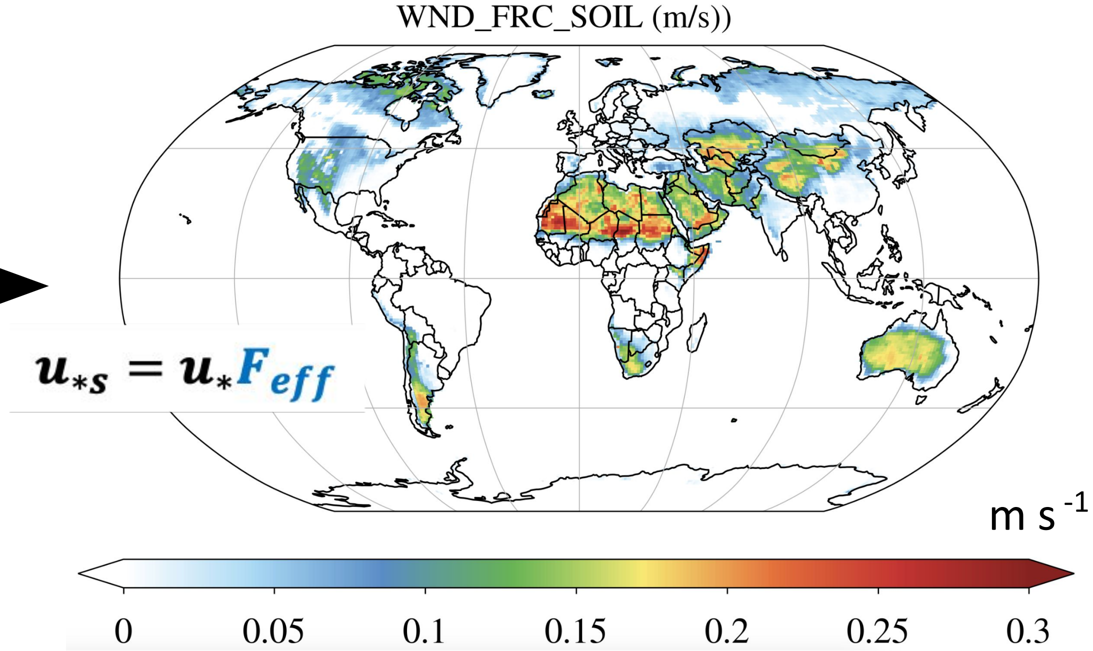


$$F_{emis} = F_{emis}(u_* \times F_{eff})$$
$$F_{eff} = F_{eff}(z_{0,rock}, LAI)$$





Becomes



3) Leung 2023 added process: sub-timestep emissions due to high-frequency (< 1 min) turbulent wind gusts

Why are turbulence-driven wind gusts important for dust emissions over **marginal dust source regions** (e.g., **N America, S Africa**)?

Because those places regularly have timestep-mean $u_{*s} < u_{*thr}$
➔ Mean winds cannot trigger emission over marginal sources
➔ no emissions
➔ Low dust biases over marginal source regions
turbulence can, so we need **sub-timestep wind gustiness.**

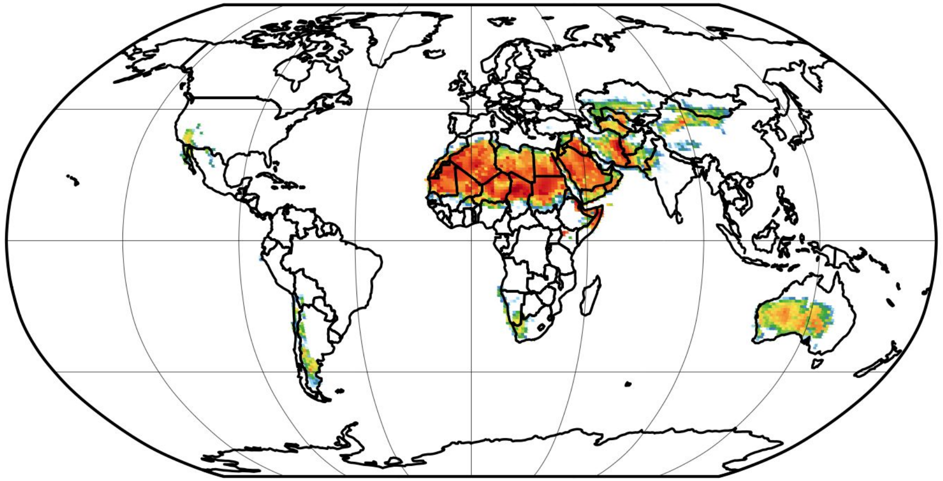
Overestimated dust over the dustiest regions and **underestimated dust over semiarid regions** for all CMIP6 models.

Comola 2019's statistical description to account for **sub-timestep wind spread** for generating emissions:

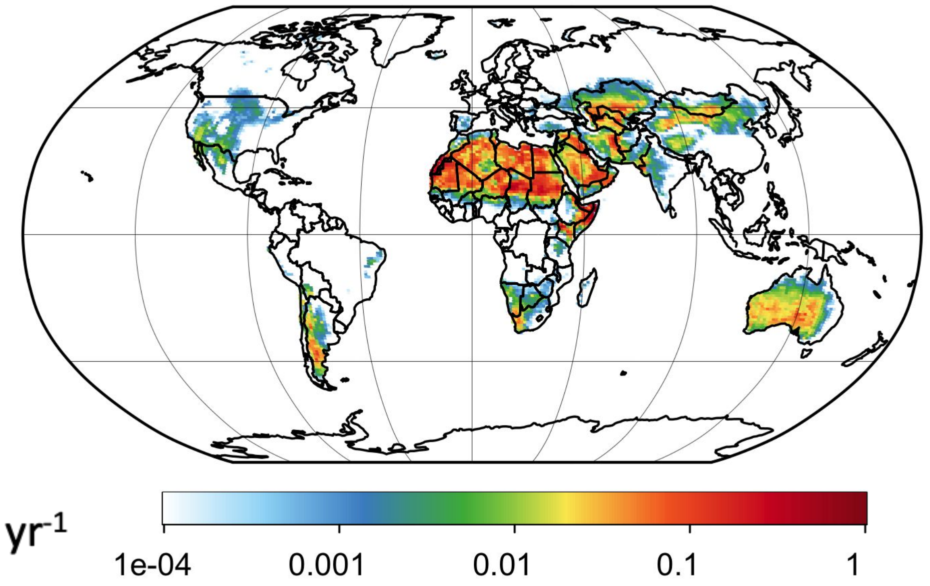
Similarity theory: $\sigma_{\tilde{u}_s} = u_* \left(12 - 0.5\frac{z_i}{L}\right)^{1/3}$

See Leung et al. (2023) for details

Kok 2014: weak emissions from semiarid areas.

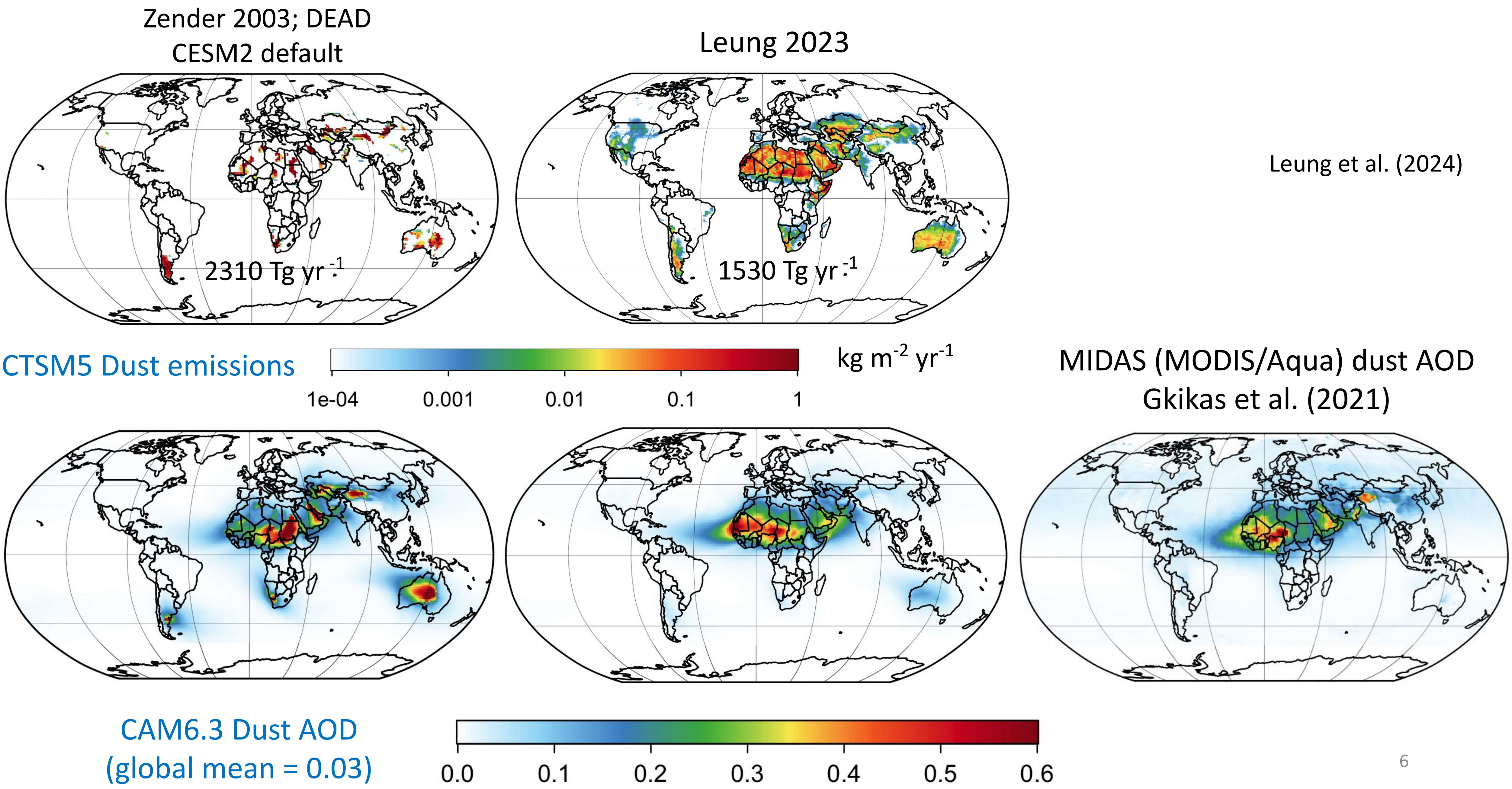


Leung 2023 (using C19): **reduced dust underestimations** from semiarid areas

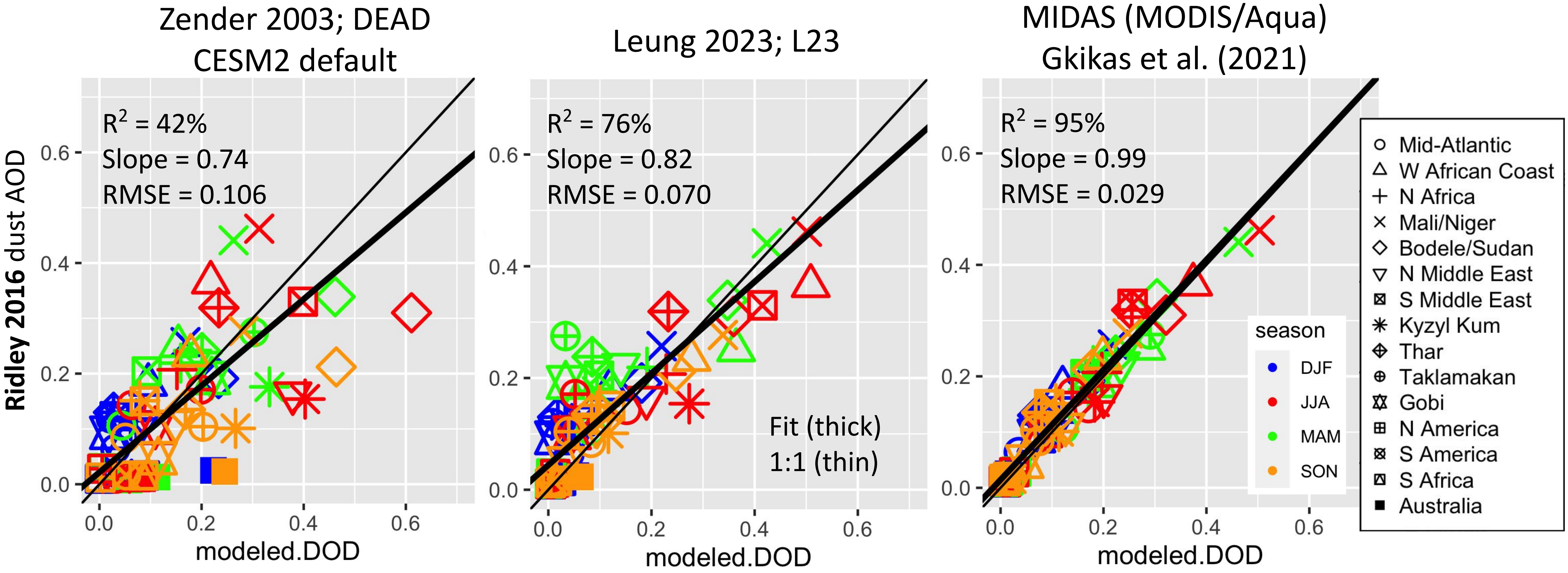


F_{emis} in kg m^{-2} yr^{-1}

Evaluation in CESM2.2: dust emissions and AOD (2004–2008)



Leung2023 is better in dust AOD seasonality and regional variability than Zender.



Leung et al. (2024)

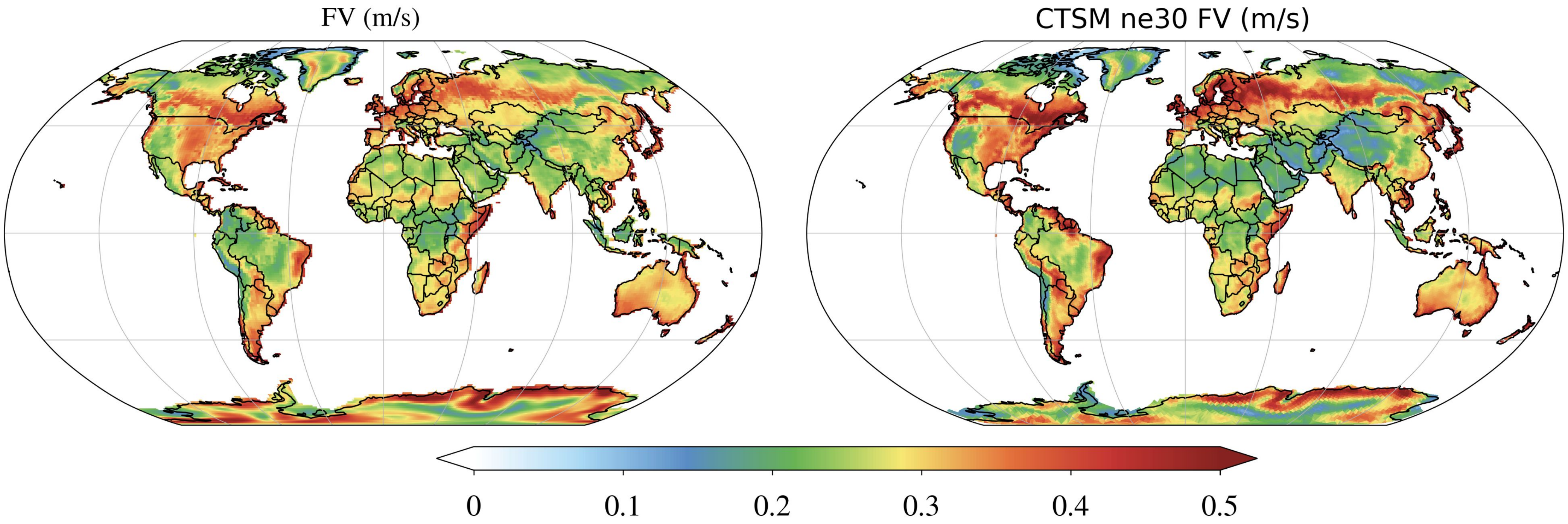
Regional dust biases improve with a closer to 1 reduced major axis (RMA) regression slope.

Our scheme have the largest errors compared with Ridley’s DAOD values over the springtime Taklamakan and the Gobi deserts (green). Biases in wind/soil moisture?

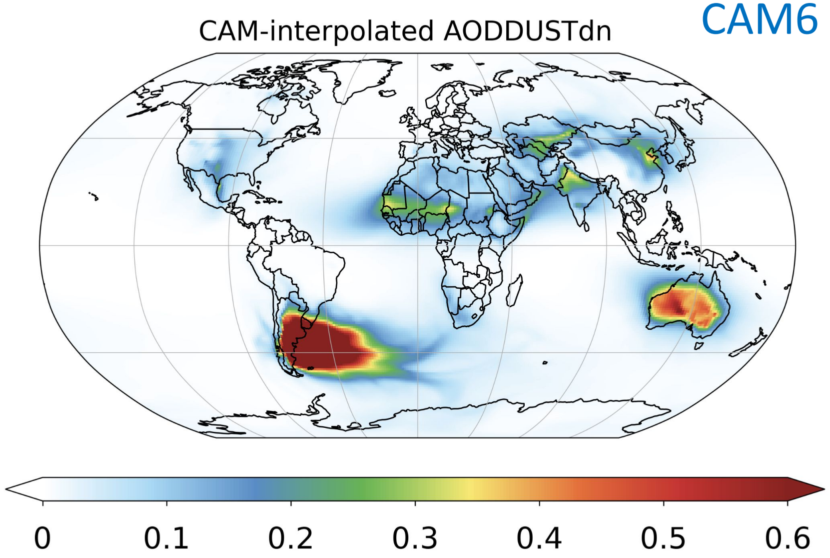
Dust emission tuning in CESM3/CAM7: Many things changed but the biggest issue is $\boldsymbol{u_*}$

CESM2.2 friction velocity $\boldsymbol{u_*}$ (m s^{-1})

CESM3 friction velocity $\boldsymbol{u_*}$ (m s^{-1})



CAM6 Dust AOD



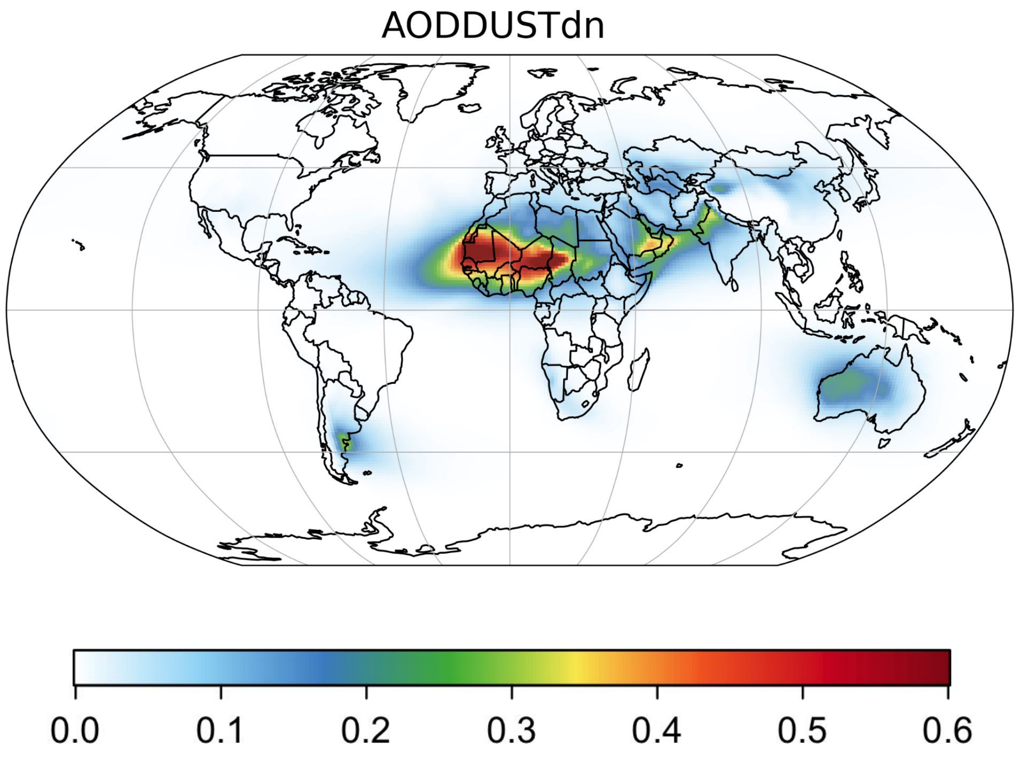
- u_* reductions over arid regions: e.g., the Sahara, W China
- u_* increases over vegetated regions: e.g., Australia, forests

- This is due to the switch in the CTSM roughness scheme (ZengWang2007 to **Meier2022**)

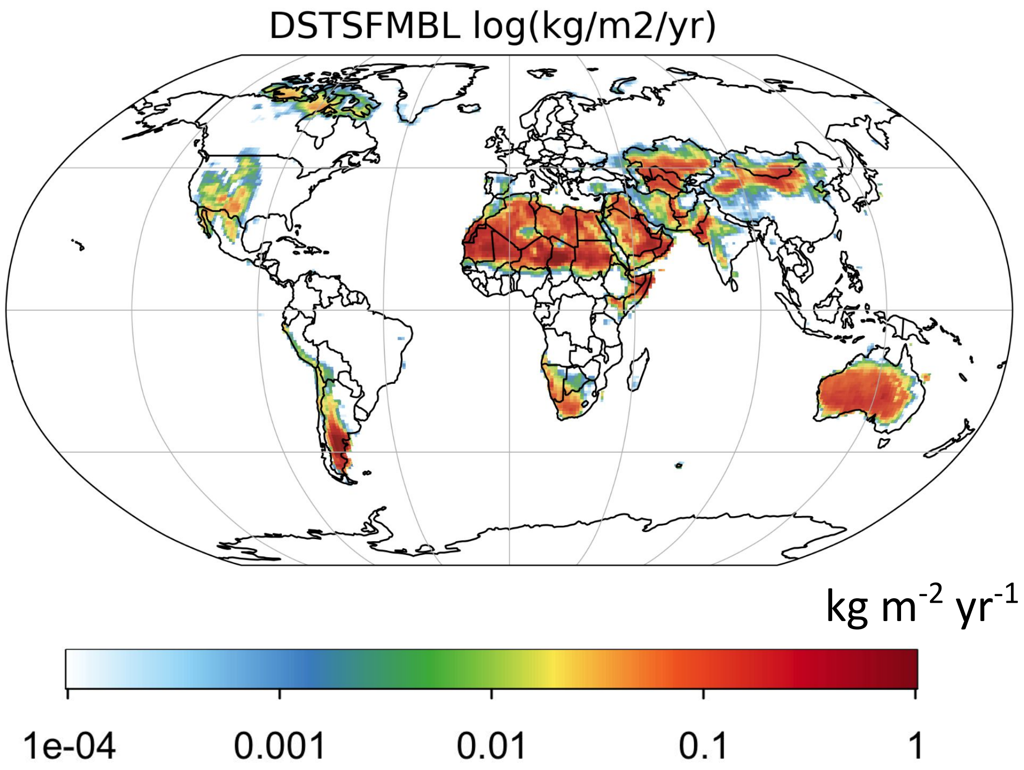
I tune dust by reducing the sensitivity of emission to u_{*s}: $F_{emis} \propto u_{*s}^7$ to $F_{emis} \propto u_{*s}^3$

- $F_{emis} \propto u_{*s}^7$ is allowed in Kok's theory, but now we cap it at $F_{emis} \propto u_{*s}^3$.
- If input fields are changed (improved?) with CESM updates, we tweak the equation in the range that the theory allows.
- Dust emission is very sensitive to met fields, so more vulnerable to CESM updates and more tuning is needed.
- I tried my best this time to reduce the emission sensitivity to met fields to save work for the future.

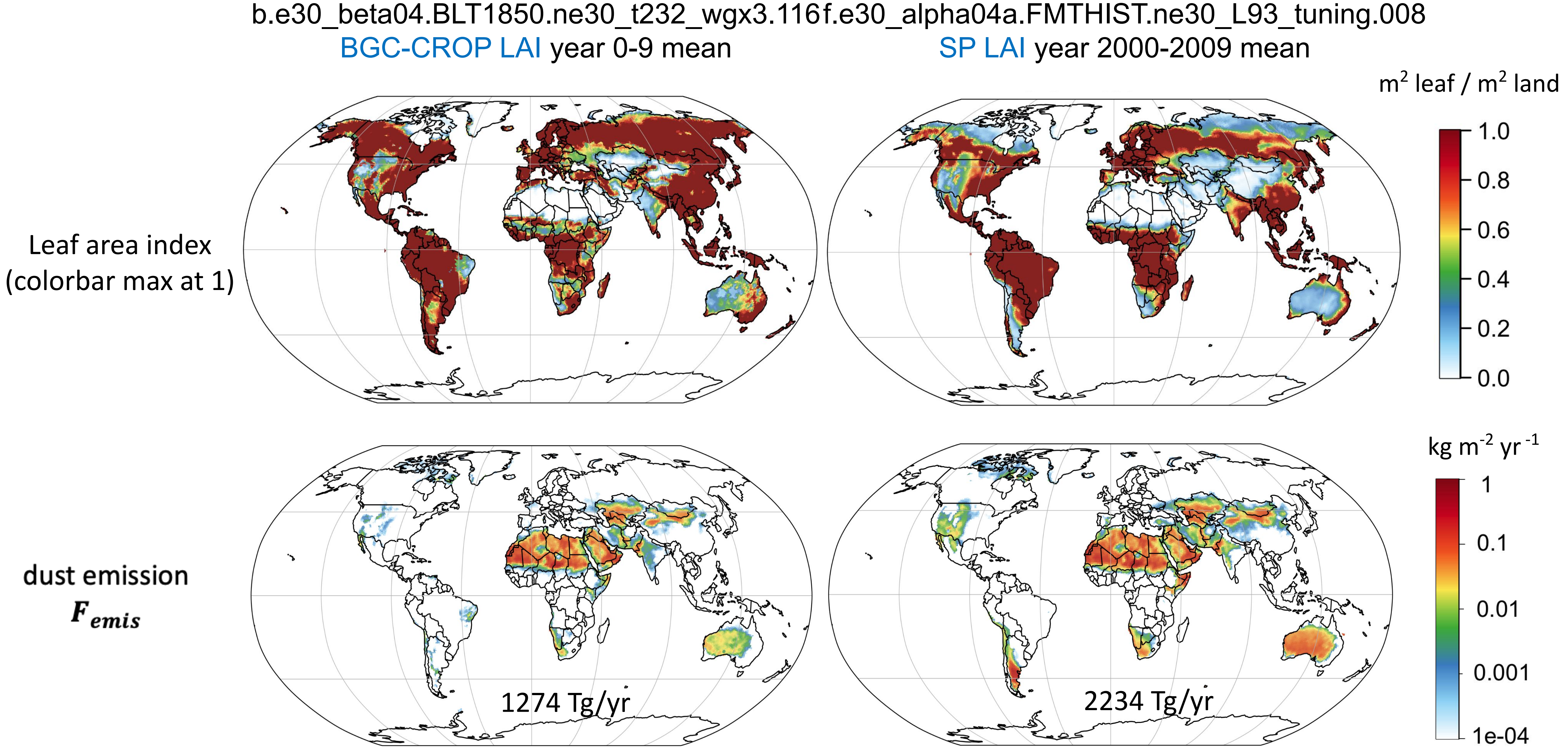
CAM7 dust AOD (global mean = 0.03)



CTSM dust emissions



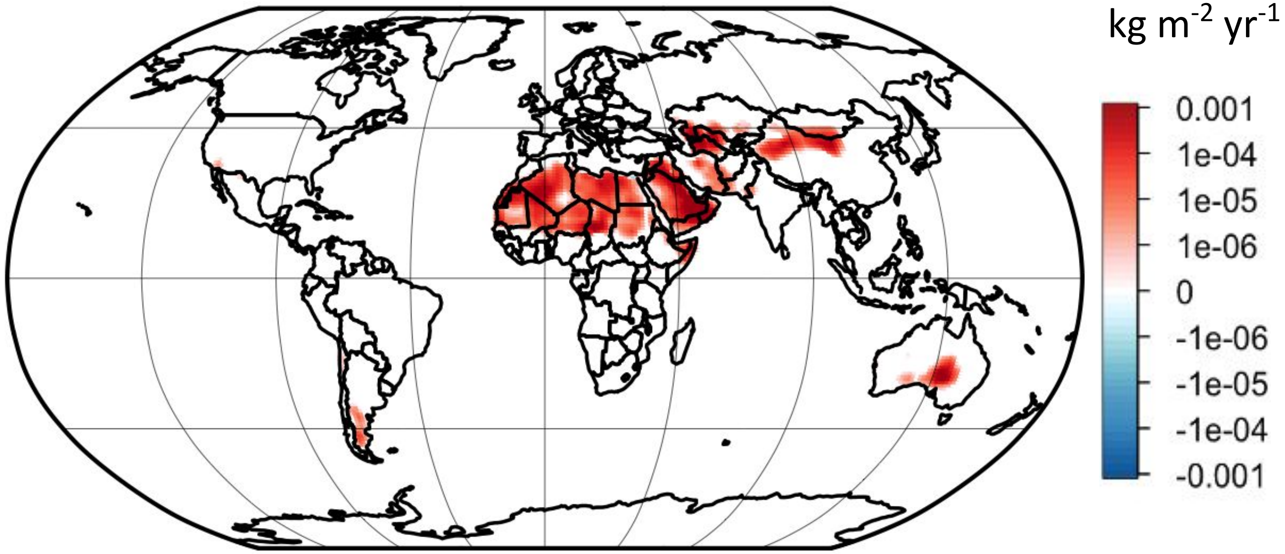
Dust emission behavior in CESM3/CAM7: Sensitivity to different LAI across compsets



Ongoing dust developments
(for future CESM)

We derive historical decadal dust emissions for 1850–2100.

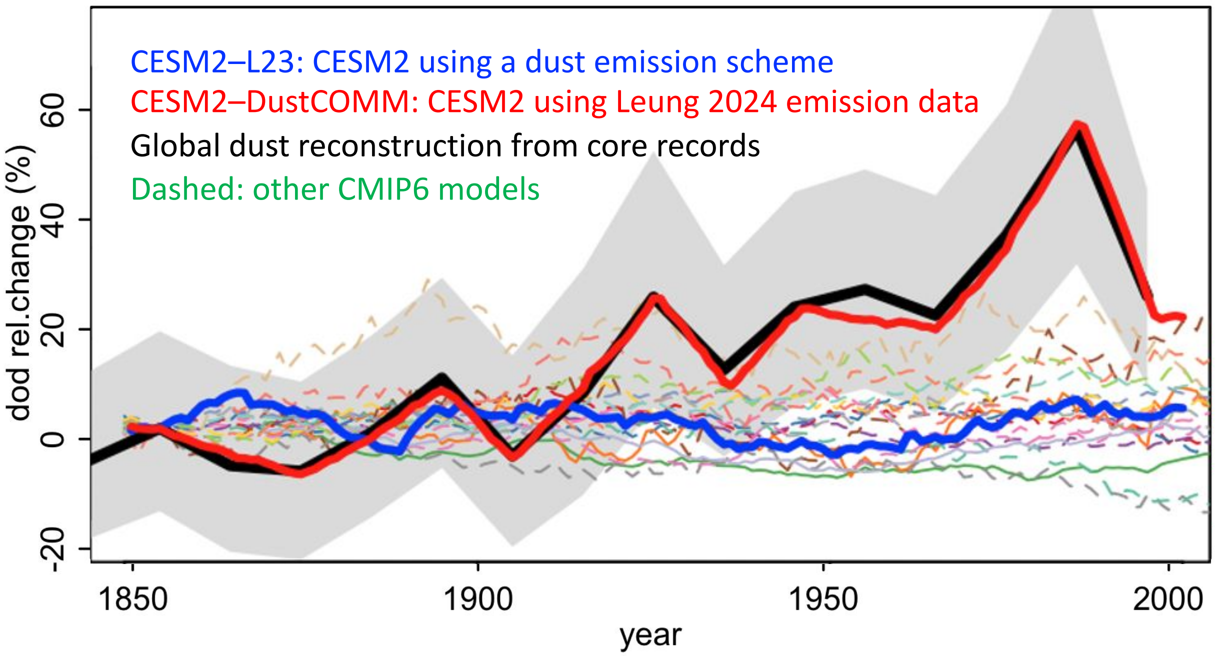
1981–2000 minus 1851–1870 inverse modeled dust emissions



+742 Tg / yr

Leung et al. (2024b)

1850–2000 Dust AOD historical variability CMIP6 models and our CESM runs



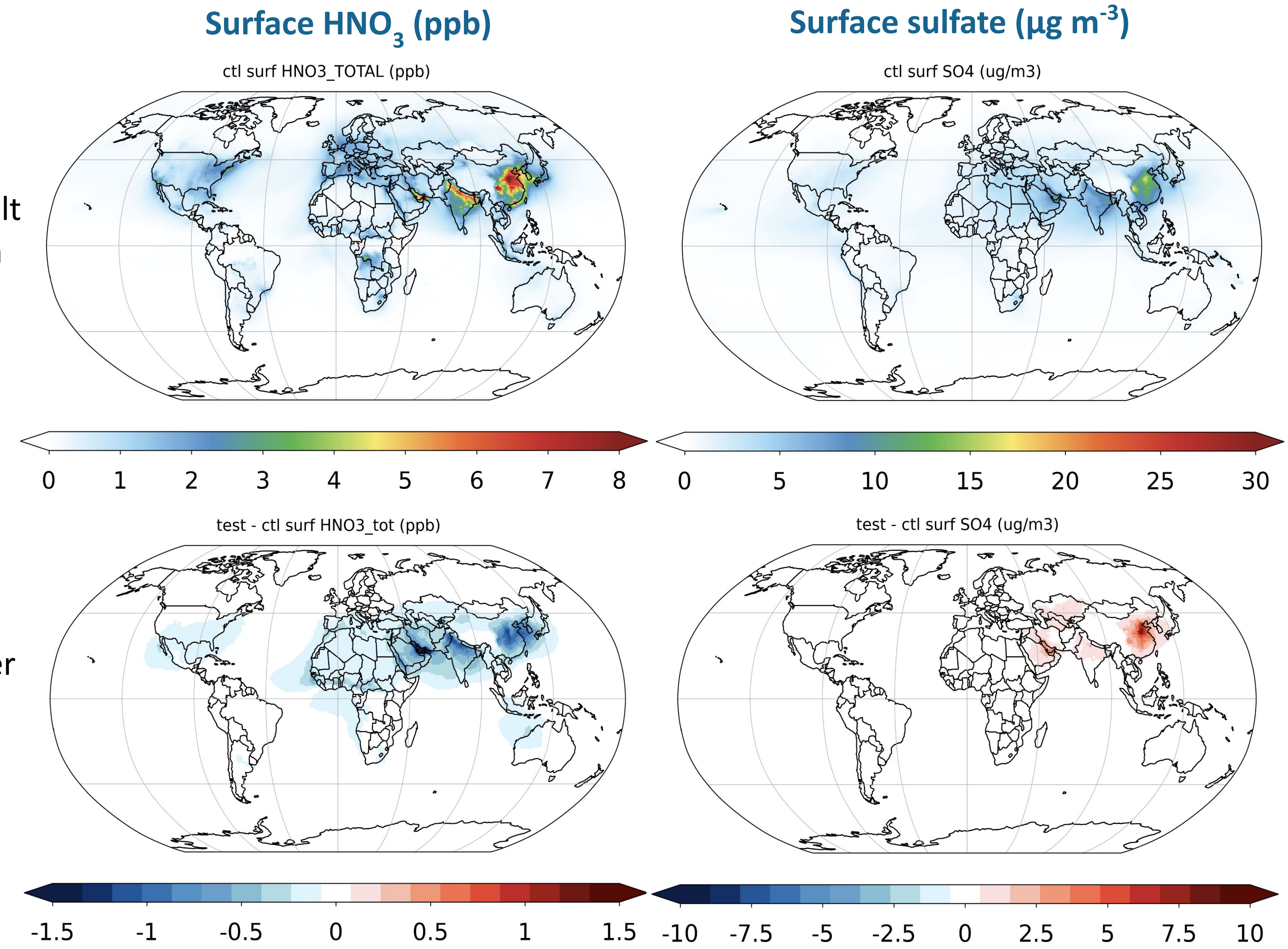
- **More in the LMWG meeting**
- Leung et al. (2024) used core records with an inverse modeling approach to constrain 1850–2000 emissions.
- **No CMIP6 models could capture the historical dust trend as shown by the core records. Why?**
- We did an AeroCom experiment on historical dust variability by putting Leung 2024 inverted emissions into many ESMs.
- Need to think: how to mechanistically model this variability in CESM (coupling with LULC/LAI)?

We include heterogeneous dust reactions for the chemistry model of CAM (CAM-Chem).

CESM2.2 default concentration

Dust uptakes acid (e.g., SO_2 and HNO_3) and converts them into nitrate and sulfate PM.

Difference after adding dust chemistry



Take-home messages: a new mechanistic dust emission scheme for CESM3/CAM7

$F_{emis} = F_{emis}(u_*, w, \mathrm{LAI})$ becomes $F_{emis} = F_{emis}(u_*, w, z_{0,\mathrm{rock}}, \mathrm{LAI}, \sigma_{\tilde{u}})$

(Zender 2003;
CESM2/CAM6 default)

(Leung 2023;
CESM3/CAM7 default)

Drag partition due to surface roughness

Subtimestep wind spread following the similarity theory

w = soil moisture

1. Leung_2023 dust emission is available since CTSM5.2.019. If you want a CESM2.2.2 sandbox with Leung, let me know. Leung_2023 is also being added into other models like GEOS-Chem, MONAN, GISS-GC, etc.
2. In CESM3/CAM7, users can switch dust_emis_method='Leung_2023' or 'Zender_2003' (thanks to Erik Kluzek).
3. We suggest always tuning dust to a global mean of **0.03±0.005** in the **2000s** (Ridley, Heald et al., 2016) for air quality modeling and climate-scale simulations, regardless of the choice of Leung or Zender.
4. For regional refinement, one can further tune it to minimize regional biases, although it is good that we talk first.
5. More developments in dust cycle modeling on the way in future CESM versions.

Paper on Leung_2023 evaluation in CESM2

GitHub description of Leung_2023 tuning for CAM7

Download CTSM5.3 with Leung_2023 dust emissions