Improving the desert dust emission representation in the Community Land Model (CLM5)

LMWG meeting
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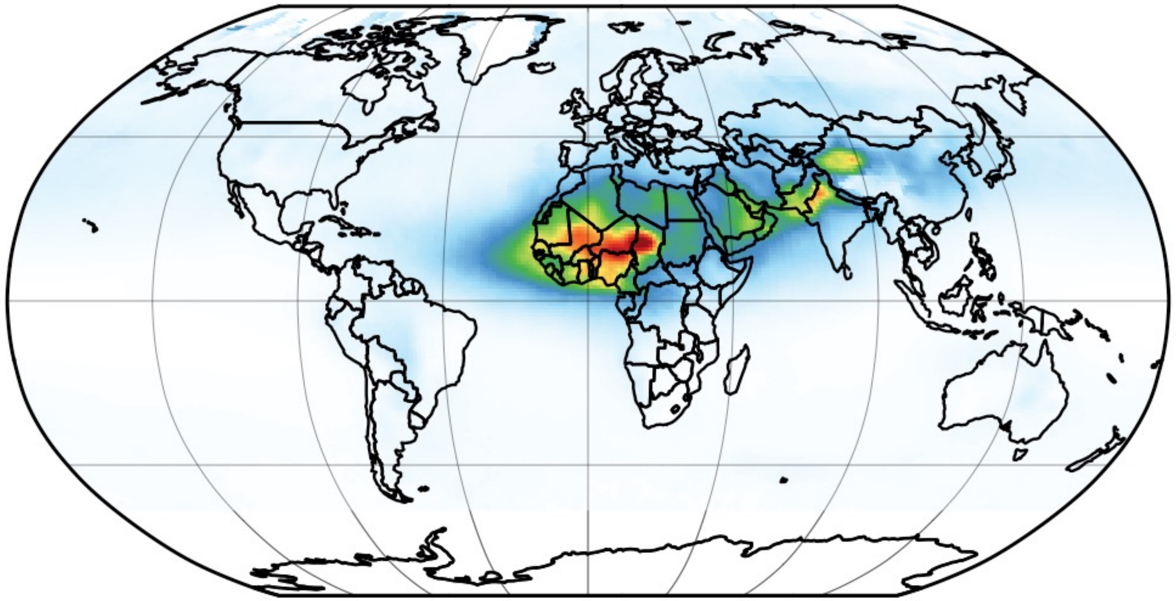
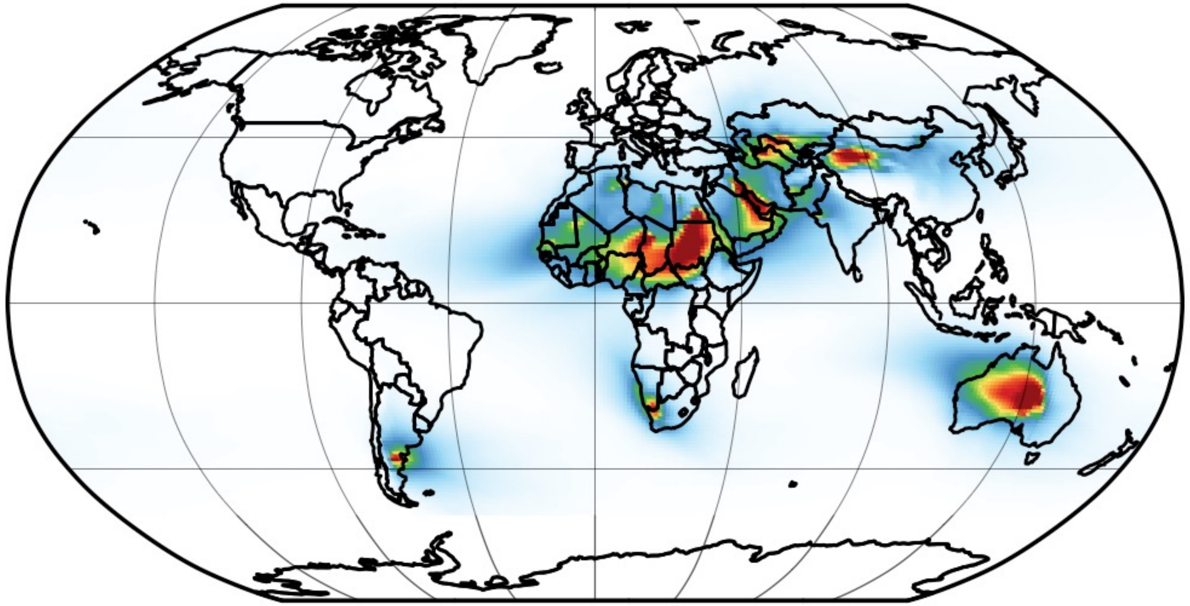
Modeled dust does not capture the spatial variability of dust well.

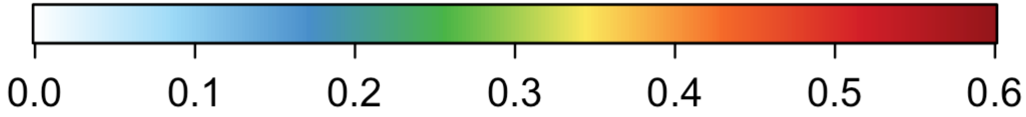
MODIS/Aqua 2004–2008 mean dust AOD



CESM2 2004–2008 mean dust AOD



Global mean = 0.033
(Gkikas et al. (2021)



Global mean = 0.030

- CESM2/CAM6 modeled dust aerosol optical depth (DAOD) overestimates dust over Taklamakan Desert, Sudan, and underestimates dust over El Djouf, Mauritania.

Making a new dust emission module in CLM

01 A new dust emission scheme (Kok et al., 2014; Li et al., 2022)

02 The soil PSD effects to dust emission threshold (Martin and Kok, 2017)

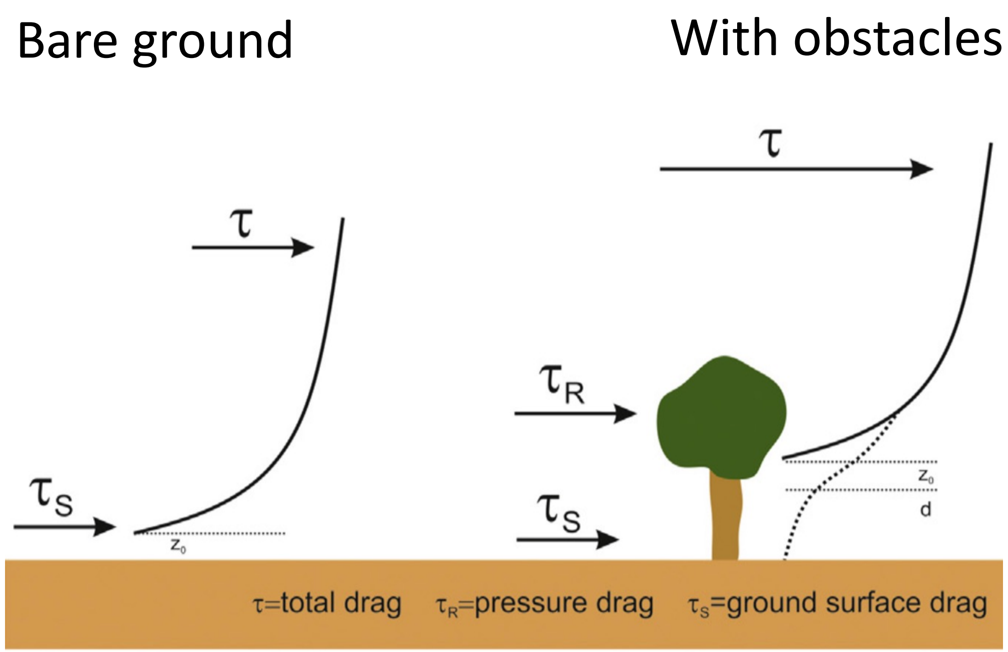
03 The wind drag partition effect by rocks/plants (Marticorena et al., 1995; Okin, 2008)

04 Dust emission intermittency due to PBL turbulence (Comola et al., 2019)

05 A correction map for high-resolution dust spatial variability

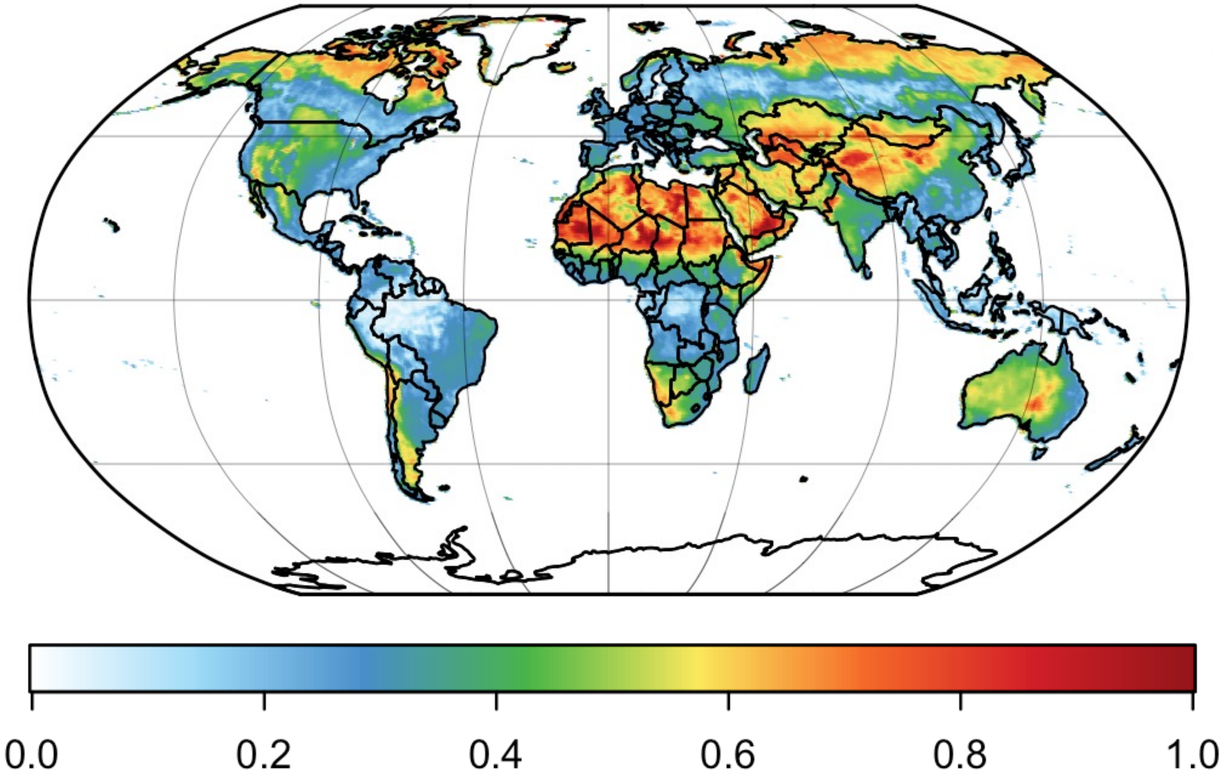
My additions (2–5) can also be applied to the default Zender et al. (2003) scheme also.

A3. We propose a novel approach combining drag partition effects due to rocks and plants on winds, shifting modeled dust to major source regions and coupling dust with dynamic vegetation.



Florian Betz et al. (2015)

Drag partition factor F_{eff} for 2004–2008



Wind stress absorbed by roughness elements:

$$\tau = \tau_{\mathrm{Obstacle}} + \tau_{Soil}$$

F_{eff} discounts the u_* reaching soil surface:

$u_{*s} = u_* F_{eff}$ $\qquad 0 \le F_{eff} \le 1$

$F_{eff} = F_{eff}(\mathrm{z_{0,rock}}, \mathrm{LAI}, frac_{bare}, frac_{veg})$

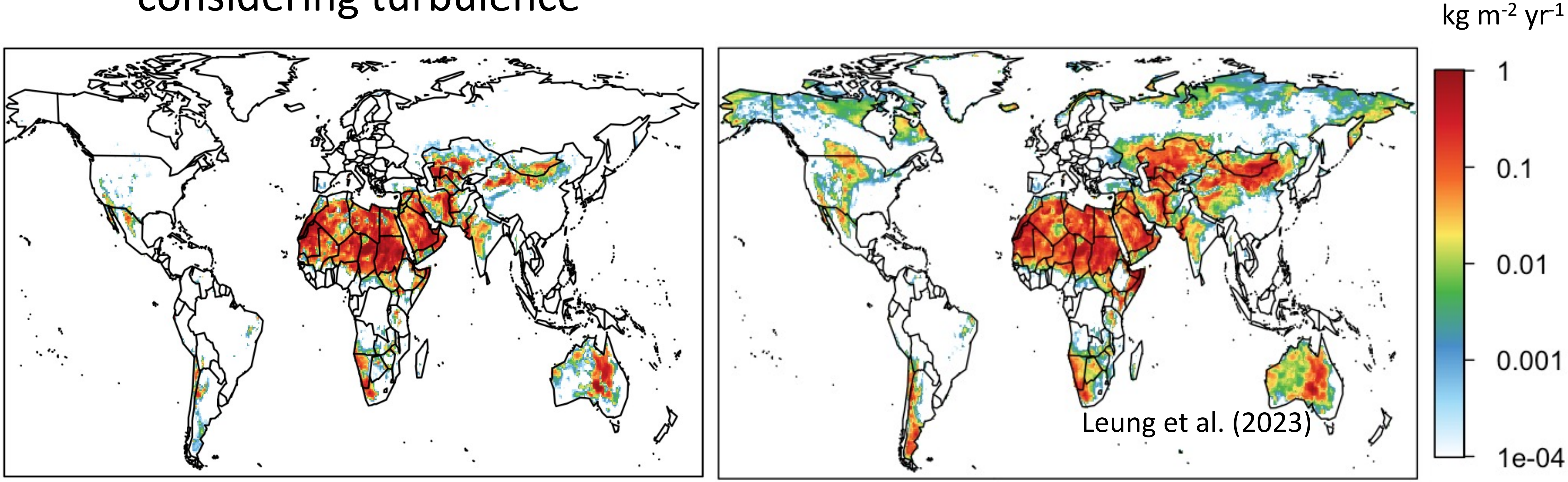
$F_d = F_d(u_* F_{eff})$ $\qquad F_d$ = dust emission (kg m^{-2} yr^{-1})

$\mathrm{z_{0,rock}}$: small-scale roughness (~ 1 cm) from Satellite (Prigent., 2005, 2012)

A4. We account for boundry-layer turbulence, which generates emissions over marginal and high-latitude regions and couples dust to boundary-layer dynamics.

Emissions without considering turbulence

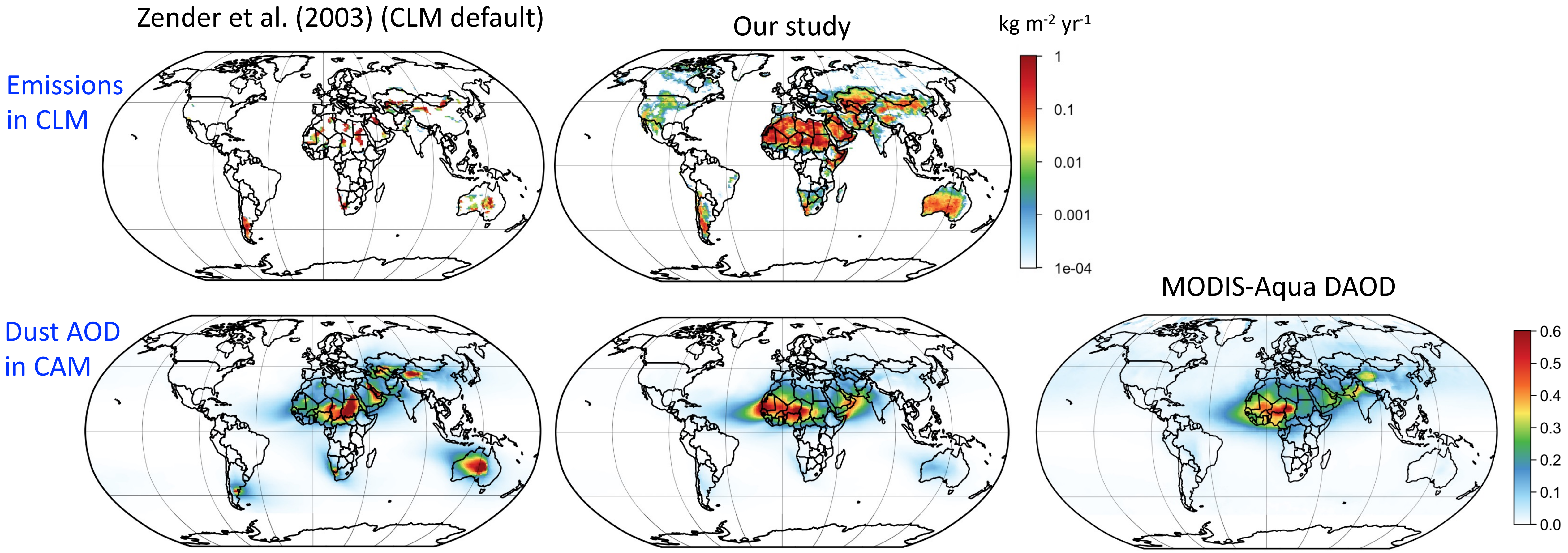
Emissions with turbulence effect



Turbulent wind fluctuations (m s^{-1}):

$$\sigma_{\tilde{u}} = u_{*s}\left(12 - 0.5\,\frac{z_i}{L}\right)^{1/3}$$ (similarity theory, Panofsky, 1979)

CLM dust emissions using different schemes (averaged over 2004–2008)

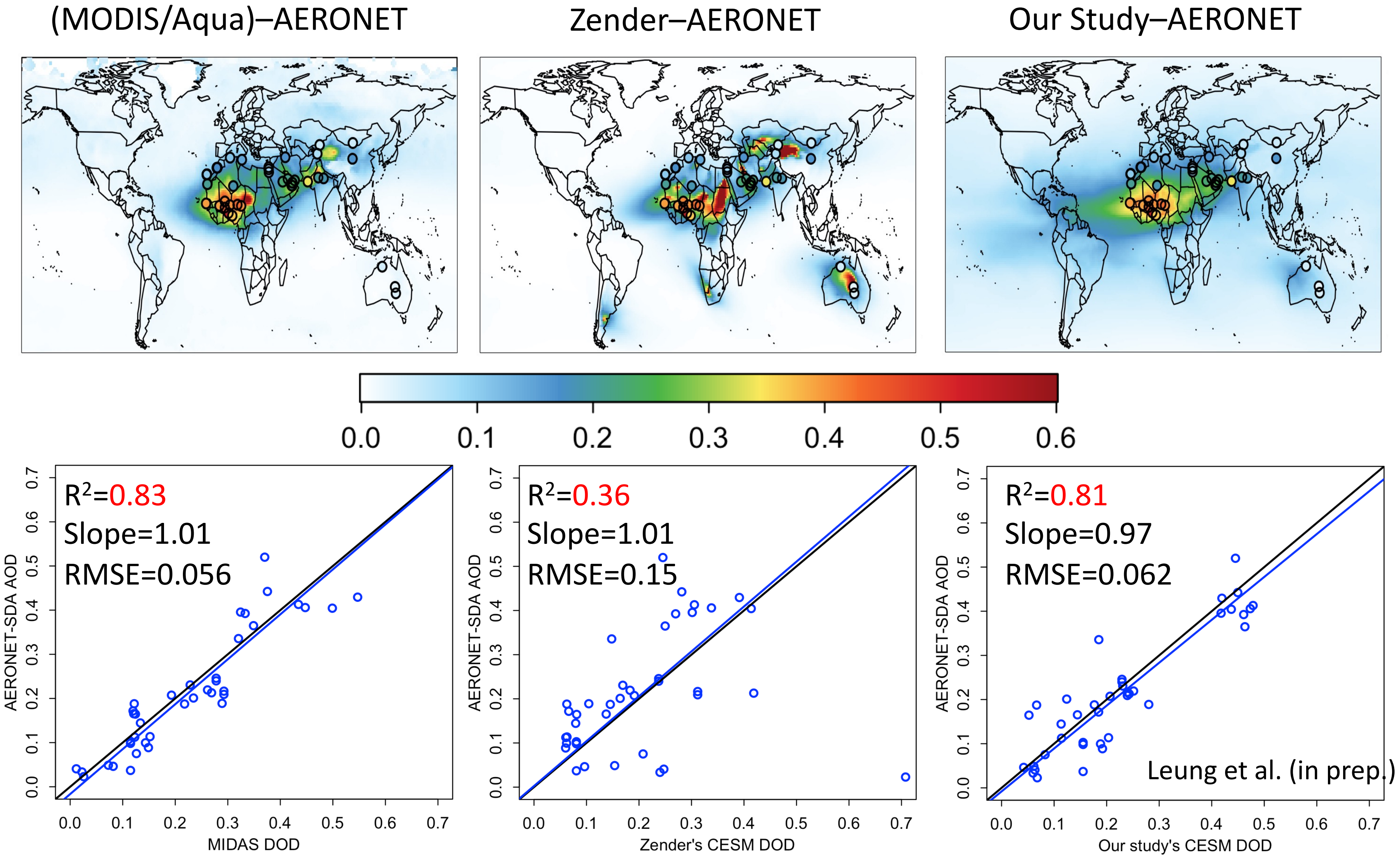


Leung et al. (in prep.)

Gkikas et al. (2021)

Compset: FHIST (transient land + atmosphere)
Land: CLM5 SP mode (ctsm5.1.dev106-14)
Atmosphere: CAM6 + Modal aerosol model (MAM4) (cam6_3_058)
Dynamics: FV, online nudging T, U, V (not PS and Q) toward MERRA-2 across all vertical levels

Comparison against AERONET–SDA shows our scheme has the best AOD spatial variability.



data are averaged across 2004–2008;
focus on spatial variability evaluations

Black: 1:1 line
Blue: fit line

Technical changes (see CTSM pull request #1897)

src/biogeochem/DUSTMod.F90:
- the old and the new emission schemes are here (users can choose)

user_namelist_clm:
- users can specify the new/old scheme here: ‘Leung2023’ or ‘Zender2003’

bld/namelist_files/namelist_defaults_ctsm.xml:
- path for the roughness length file
- use the new scheme as default

src/cpl/share_esmf/PrigentRoughnessStreamType.F90:
- where we read in the roughness length file as streams

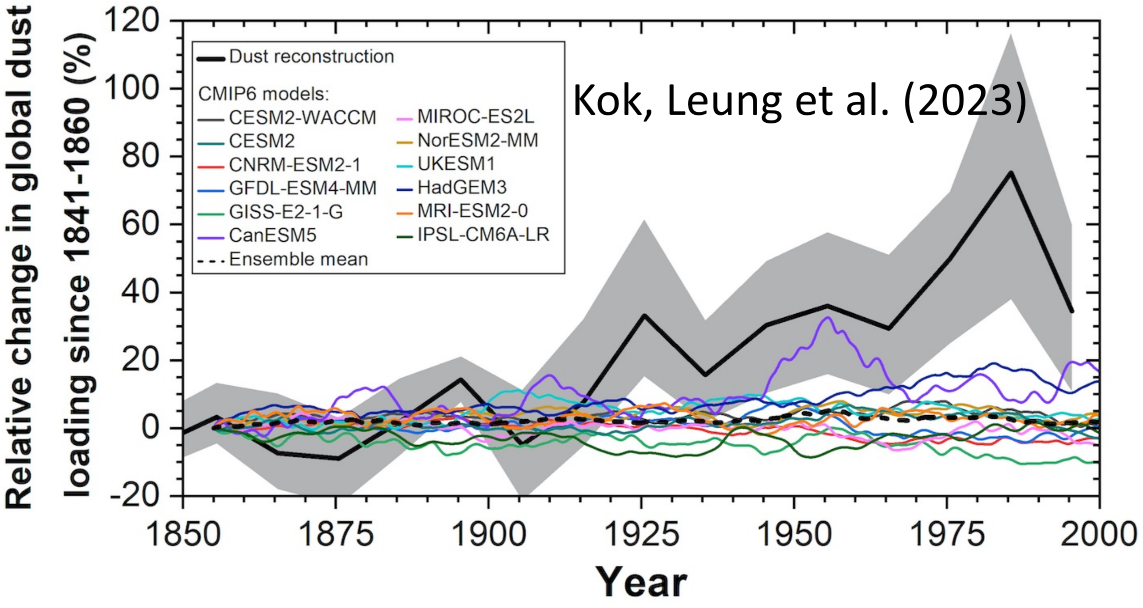
Our developments on the CTSM github:
https://github.com/ESCOMP/CTSM/pull/1897

Other files changed:
bld/CLMBuildNamelist.pm
bld/namelist_files/namelist_definition_ctsm.xml
src/main/clm_instMod.F90
src/biogeophys/SoilStateInitTimeConstMod.F90

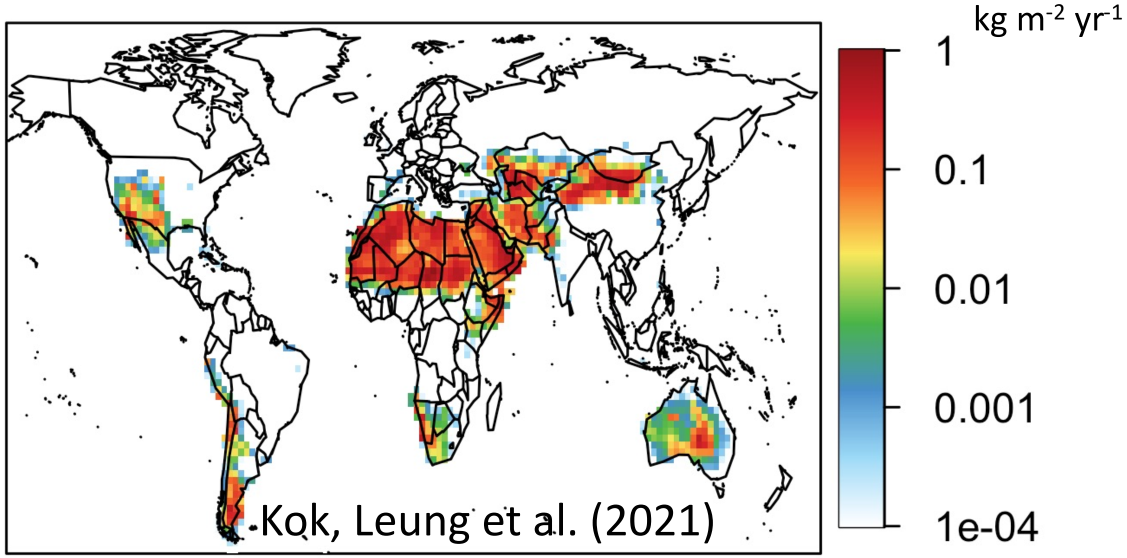
Other changes in progress:
We will move the Zender source function and the global tuning factor from CAM to CLM (https://github.com/ESCOMP/CAM/pull/748: Francis Vitt is responsible for removing them from CAM)
I will work on the putting them into CLM soon

Upcoming work – AeroCom Expt.: Investigate/improve long-term dust trend modeling

Historical dust loading from CMIP6 and ice core



Top-down emissions from the inverse analysis



CMIP6 models were not able to capture the long-term dust increase (~55 % from 1850s–2000s) in historical dust loading (RF = –0.07±0.18 W m^{-2}), likely since dust schemes are not well coupled with human-induced changes, LULCC/desertification and wind/moisture trends.

The 2023 AeroCom Dust radiative forcing (DURF) experiment is proposed by Jasper Kok (UCLA), Trude Storelvmo (UiO), Michael Schulz (UiO), and more.

We are implementing an 1850–2000 3-D gridded dust emission inventory into CLM to drive a coupled simulation, to

1) show how much dust scattering has masked the global warming in the past century; and
2) inform us what are the missing processes in the process-based dust emission scheme

We will possibly add this capacity into CLM, so users can choose between a “process-based” or “data-driven” approach.

Summary

- Developed an improved dust emission scheme with multiple key physics missed from the previous schemes

- More coupling with dynamic vegetation and boundary-layer dynamics improves the spatial and temporal variability of simulated dust; will perform a test on the long-term variability

- We are putting the new emission scheme into dev. version of CTSM. See the following link and QR code. It will be merged to the master branch likely within a few months

- We are working on putting the assimilated dust emission inventory for 1850–2020 to CLM5 and test the dust cycle response in CAM6 as part of the new AeroCom experiment.

Our developments on Github NCAR/CTSM:
https://github.com/ESCOMP/CTSM/pull/1897

What is needed to further improve the CLM5 and CAM6 dust modules?

Other processes needed:

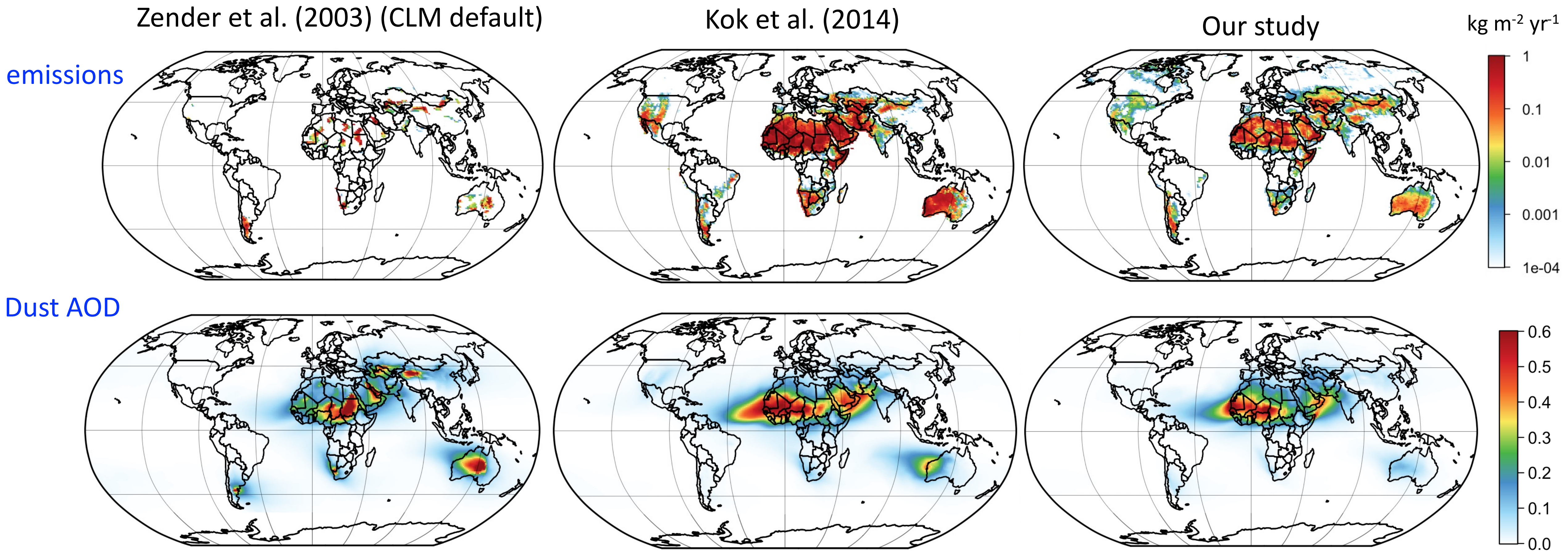
- CLM:
  - human effects (e.g., tillage, LU change) (Shi Yang, Xiaohong Liu's group)
  - subgrid wind and soil water variability due to orography/terrain/hillslope etc.
  - coupling dust emission physics (soil erosion) to changes in soil properties such as texture
  - convective dust emissions (haboobs)
  - electrostatic effect

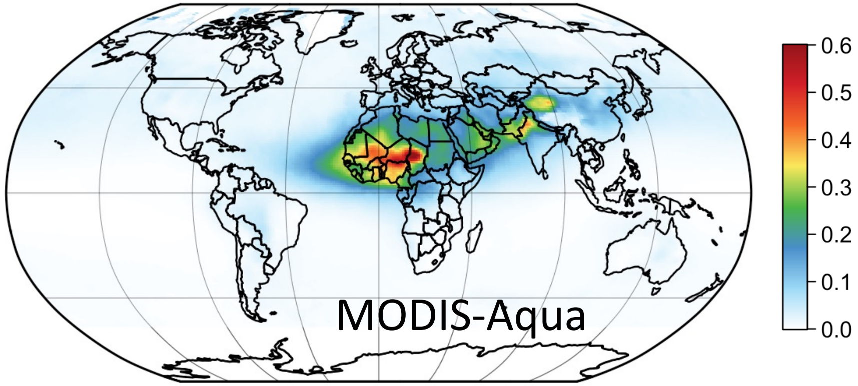
- CAM:
  - dust–cloud interactions
  - more modes for super coarse dust (> 20 μm)
  - a new dust deposition scheme + dust asphericity + a better spread of the log-normal distribution
  - mineralogy and size distributions

Model for our study: CESM2

Model: CESM v2.2
Compset: FHIST (transient land + atmosphere)
Land: CLM5 SP mode (ctsm5.1.dev106-14)
Atmosphere: CAM6 + Modal aerosol model (MAM4) + RRTMG (cam6_3_058)
Dynamics: FV, online nudging T, U, V (not PS and Q) toward MERRA-2 across all vertical levels
Other components: SGLC (I specified it), DOCN, CICE v5 (prescribed ice), MOSART, SWAV
Resolution: 0.9°x1.25°x32
Timestep: 1800 s (half an hour)
Simulation period: 2004–2008 (2003 spin up)

CLM dust emissions using different schemes (averaged over 2004–2008)





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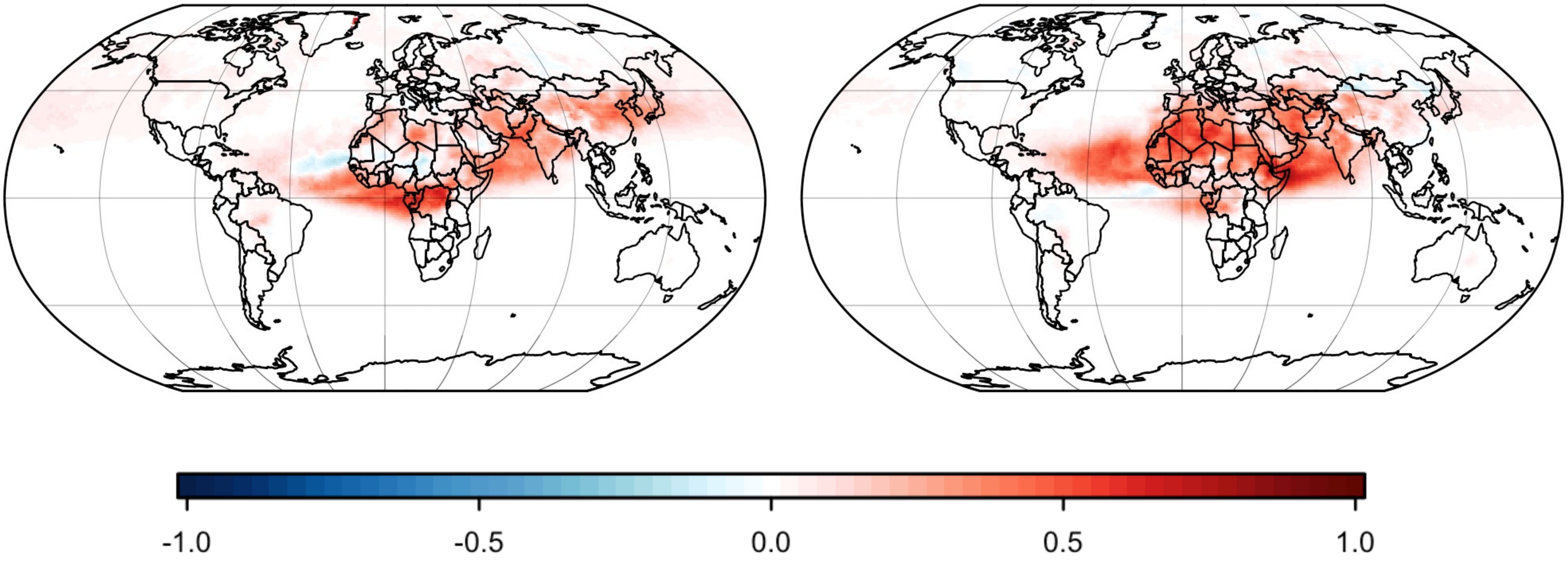
Our scheme shows improvements in day-to-day and seasonal dust variability.

(Default CESM)–(MODIS/Aqua)
dust AOD daily correlation

(Our model)–(MODIS/Aqua)
dust AOD daily correlation



- Our new scheme in CESM has a high grid-by-grid daily correlation with satellite-derived MODIS dust AOD, especially over the low-latitude dust belt over Africa and Asia.