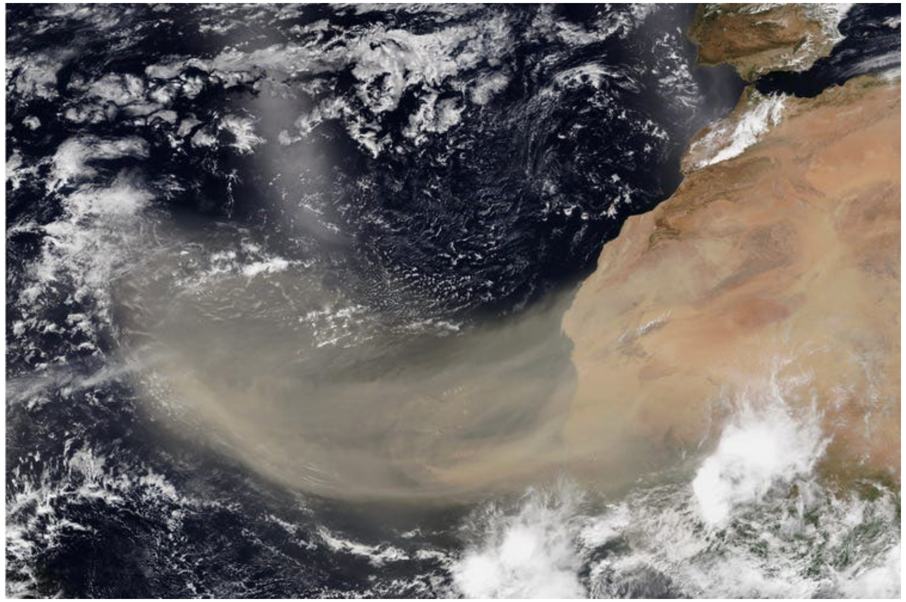
A new mechanistic dust emission scheme: Updates in CESM2

AMWG winter meeting
13 Feb 2024

Danny M. Leung[1,2], Jasper Kok[2], Longlei Li[3], Natalie Mahowald[3], David Lawrence[4], Simone Tilmes[5], Erik Kluzek[4], Gregory Okin[2], Martina Klose[6], Catherine Prigent[7], Laurent Menut[7], Carlos Pérez García-Pando[8]
[1]ASP | [2]UCLA | [3]Cornell | [4]CGD | [5]ACOM | [6]KIT Karlsruhe | [7]CNRS Paris| [8]BSC Barcelona



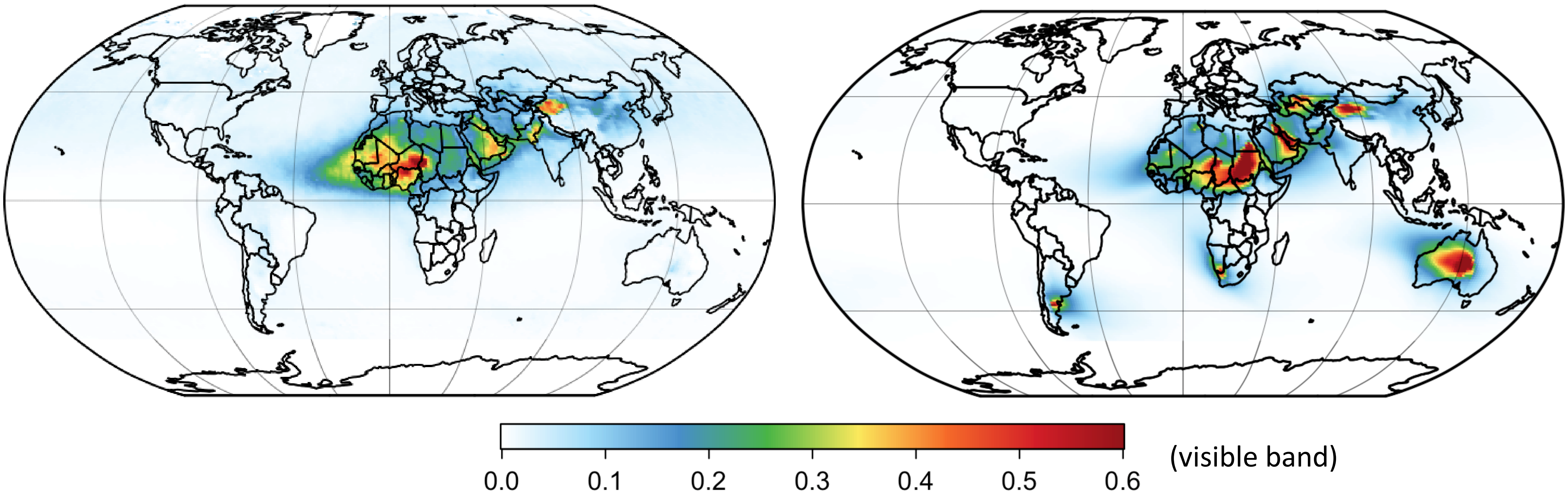
NASA worldview MODIS aerosol image for the Godzilla dust event, 18 June 2020

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

Averaged across 2004–2008

MODIS/Aqua (MIDAS) by Gkikas et al. (2021)

Zender et al. (2003; DEAD) in CESM2.2



- The CESM2 dust AOD does not match well with MODIS/Aqua satellite DAOD (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.

Model for our study: CESM2.2

Compset: FHIST (transient land + atmosphere coupled; other ES components inactive)
Land: Community Terrestrial System Model (CTSM5) Satellite Phenology (SP) mode
Atmosphere: Community Atmosphere Model (CAM6) + Modal aerosol model (MAM4); MAM5 in last slide
Dynamics: FV, online nudging T, U, V toward MERRA-2; SE-CSLAM in last slide
Resolution: 0.9°x1.25°x32 (-f09_f09_mg17, -nlev 32)
Timestep: 30 minutes
Simulation period: 2004–2008 (2003 spin up)

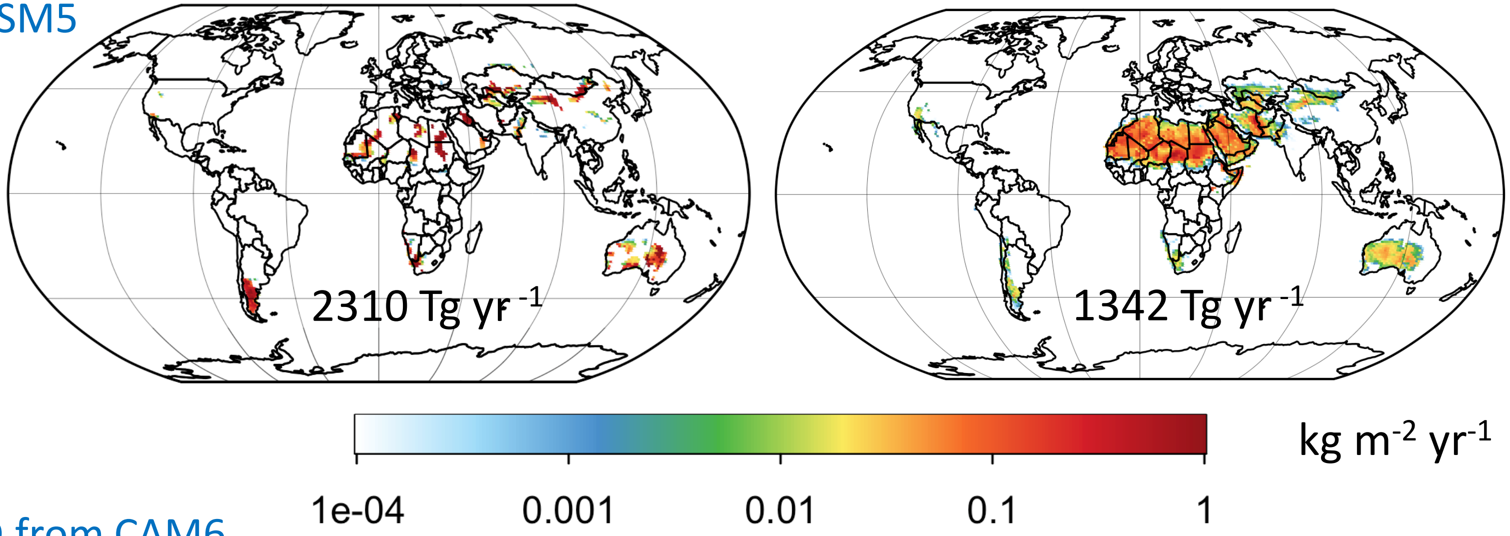
We make most modifications of the dust emission process in the land model (CTSM5).
We evaluate the dust cycle variables in CAM6.

Existing dust emission schemes are mostly dependent on wind speed and soil moisture.

Dust emissions from CTSM5

Zender et al. (2003; DEAD)
CESM default

Kok et al. (2014; K14)
Base scheme for Leung



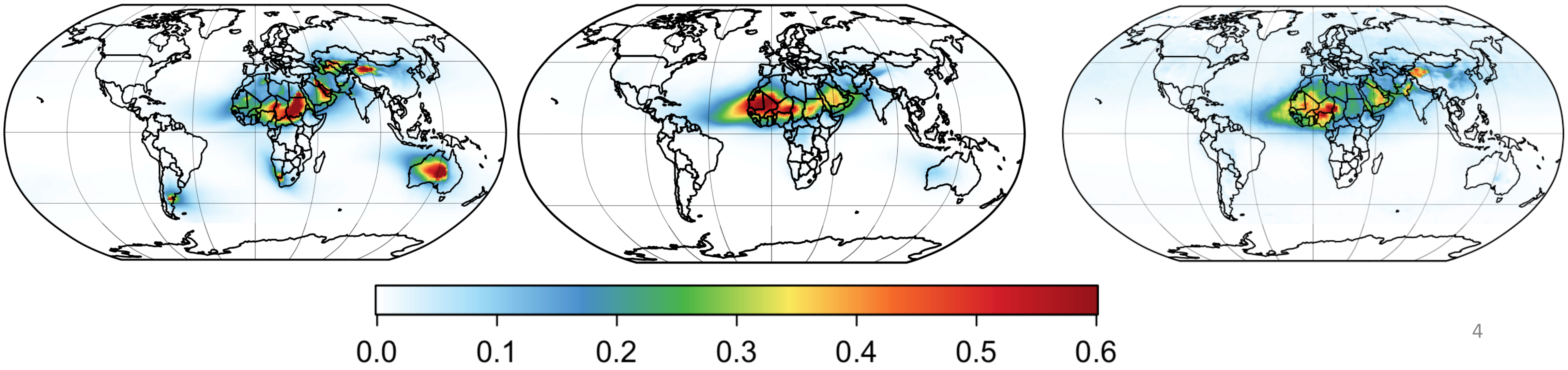
Threshold parameterization:

$$F_{dustemis} > 0 \qquad \text{if } u_* > u_{*t}(w)$$
$$F_{dustemis} = F_{dustemis}(u_*, w)$$

Leung 2023 chose to base the new developments on top of Kok 2014.

Dust AOD from CAM6
(global mean = 0.03)

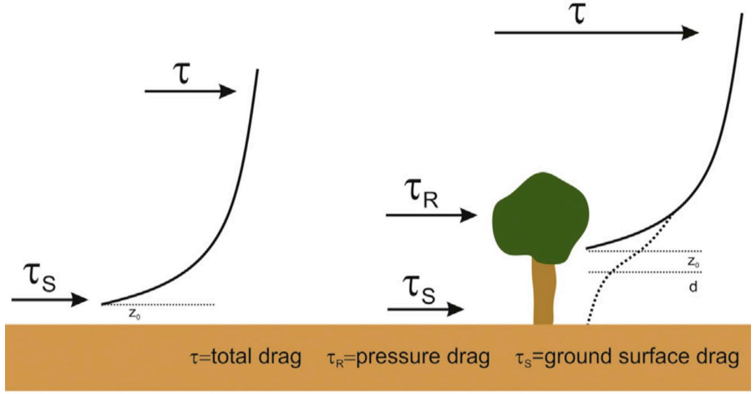
MIDAS (MODIS/Aqua)
Gkikas et al. (2021)



Two additional physics in the CESM2 dust emission scheme: 1) wind partition by surface roughness and 2) sub-timestep wind gusts due to high-frequency (<1 min) PBL turbulence

1. Wind momentum partition by rocks/plants

Bare ground With obstacles

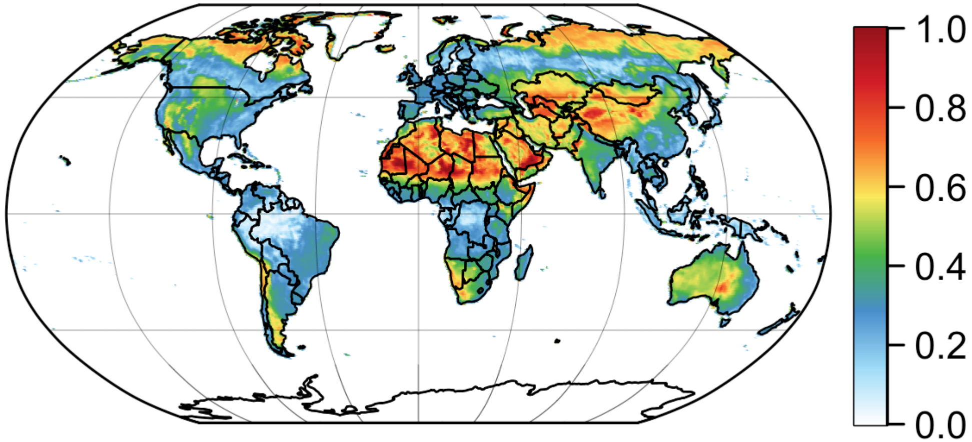


$F_{dustemis} = F_{dustemis}(u_* \times F_{eff})$

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

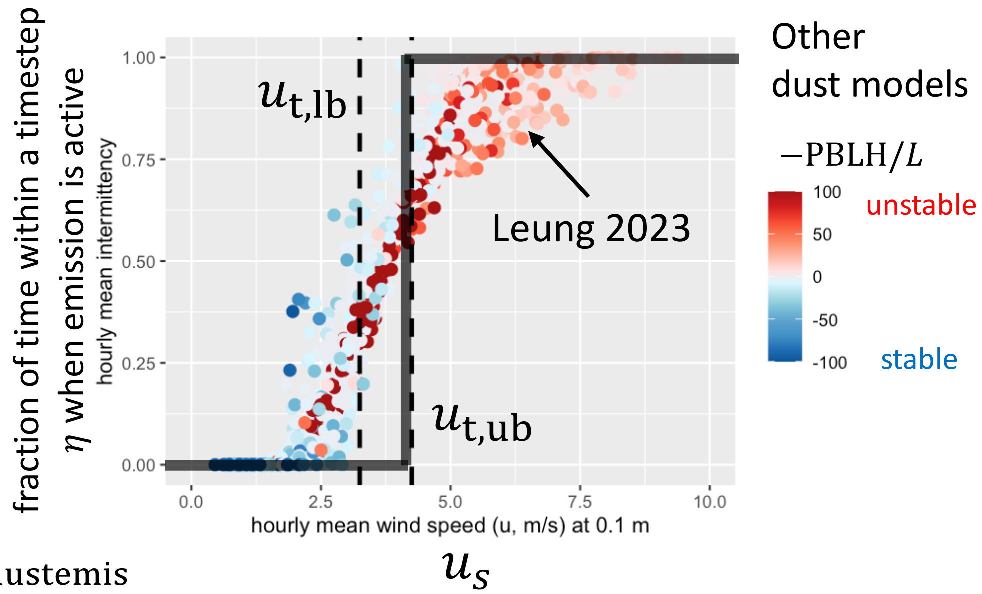
Highlighting the main dust sources

Wind partition factor F_{eff}



2. Sub-timestep (<30 min) wind fluctuations due to high-frequency (<1 min) PBL turbulence

fraction of time η within a timestep with active emission

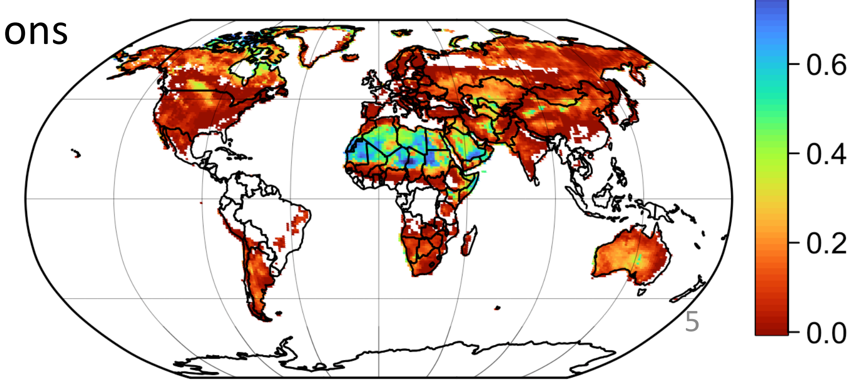


$F_{\mathrm{dustemis},\eta} = \eta \times F_{\mathrm{dustemis}}$

$\eta = \eta(u_*, \sigma_{\tilde{u}}, u_{\mathrm{t}})$

Semiarid/high-latitude emissions

annual mean η

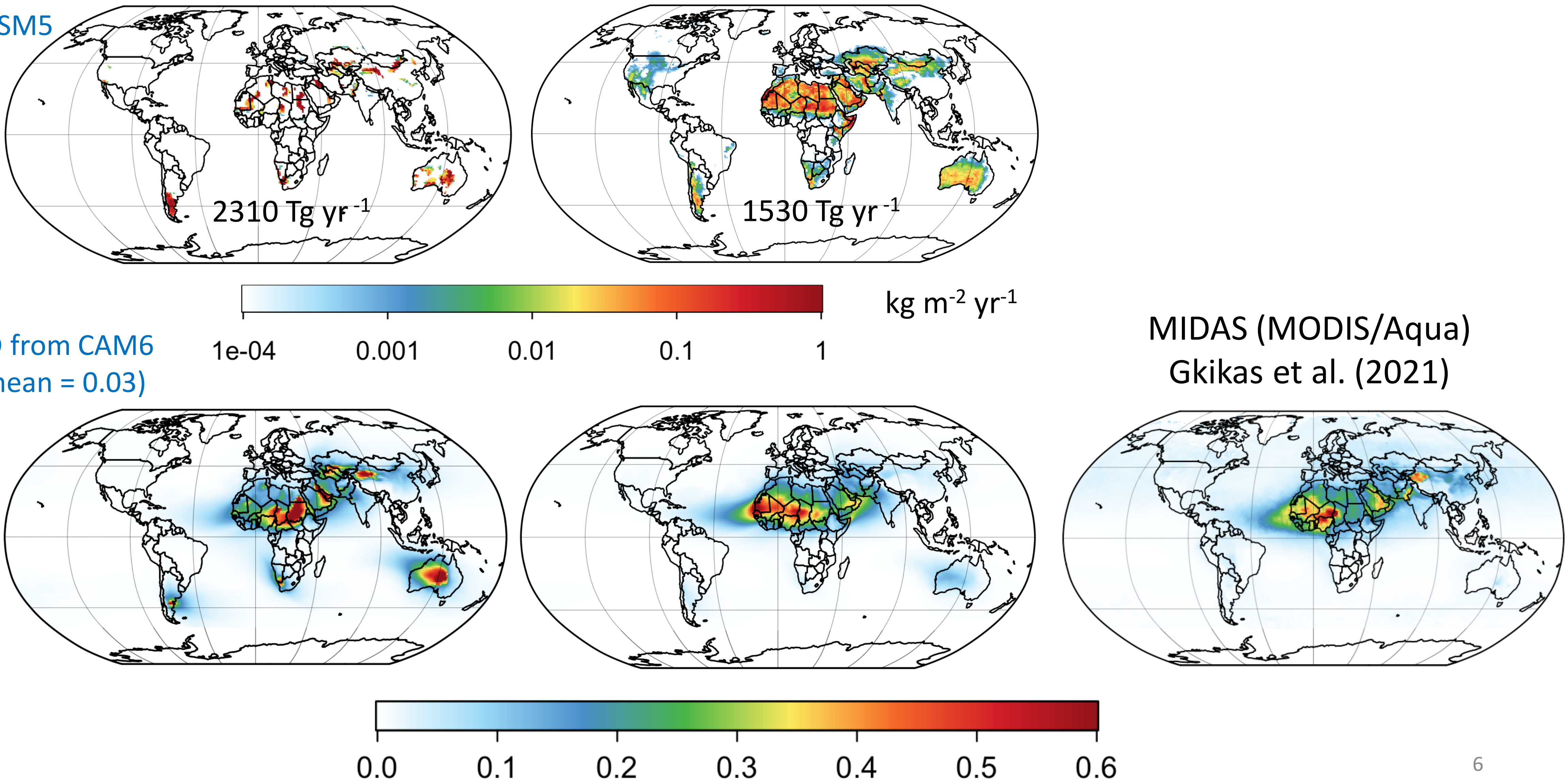


Evaluation in CESM: dust emissions and AOD using different schemes (2004–2008)

Dust emissions from CTSM5

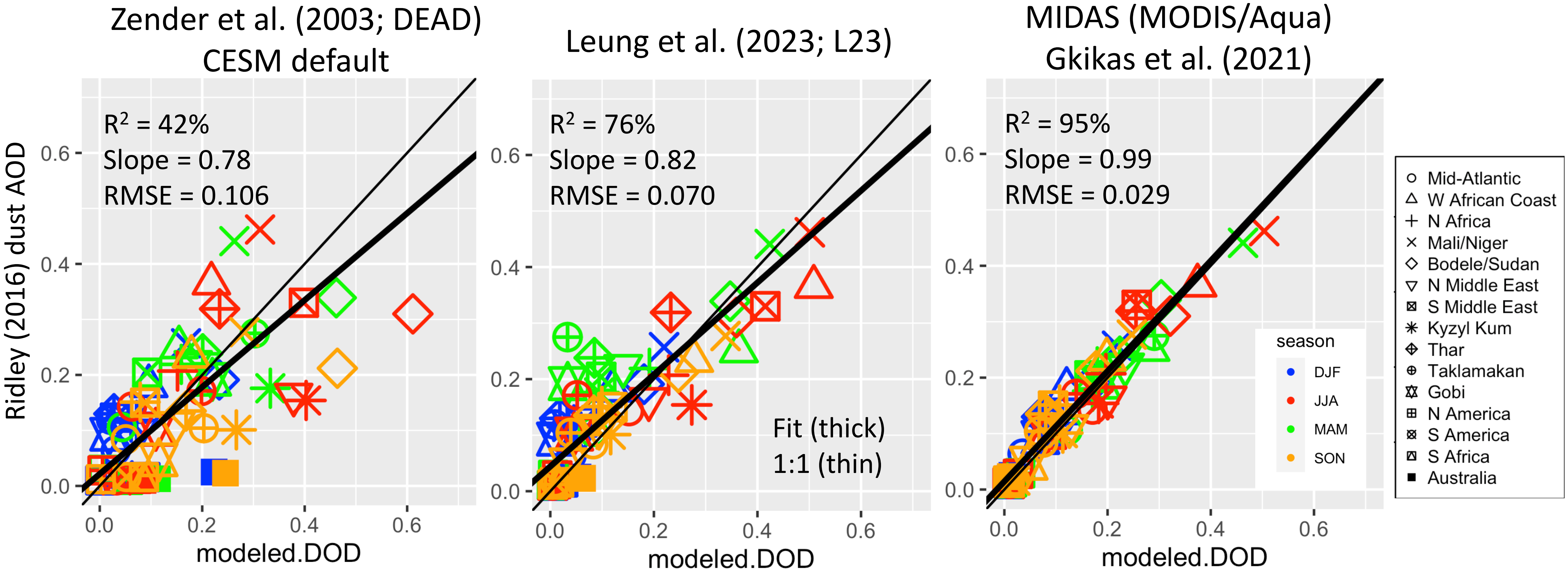
Zender et al. (2003; DEAD) CESM default

Leung et al. (2023)



Dust AOD from CAM6 (global mean = 0.03)

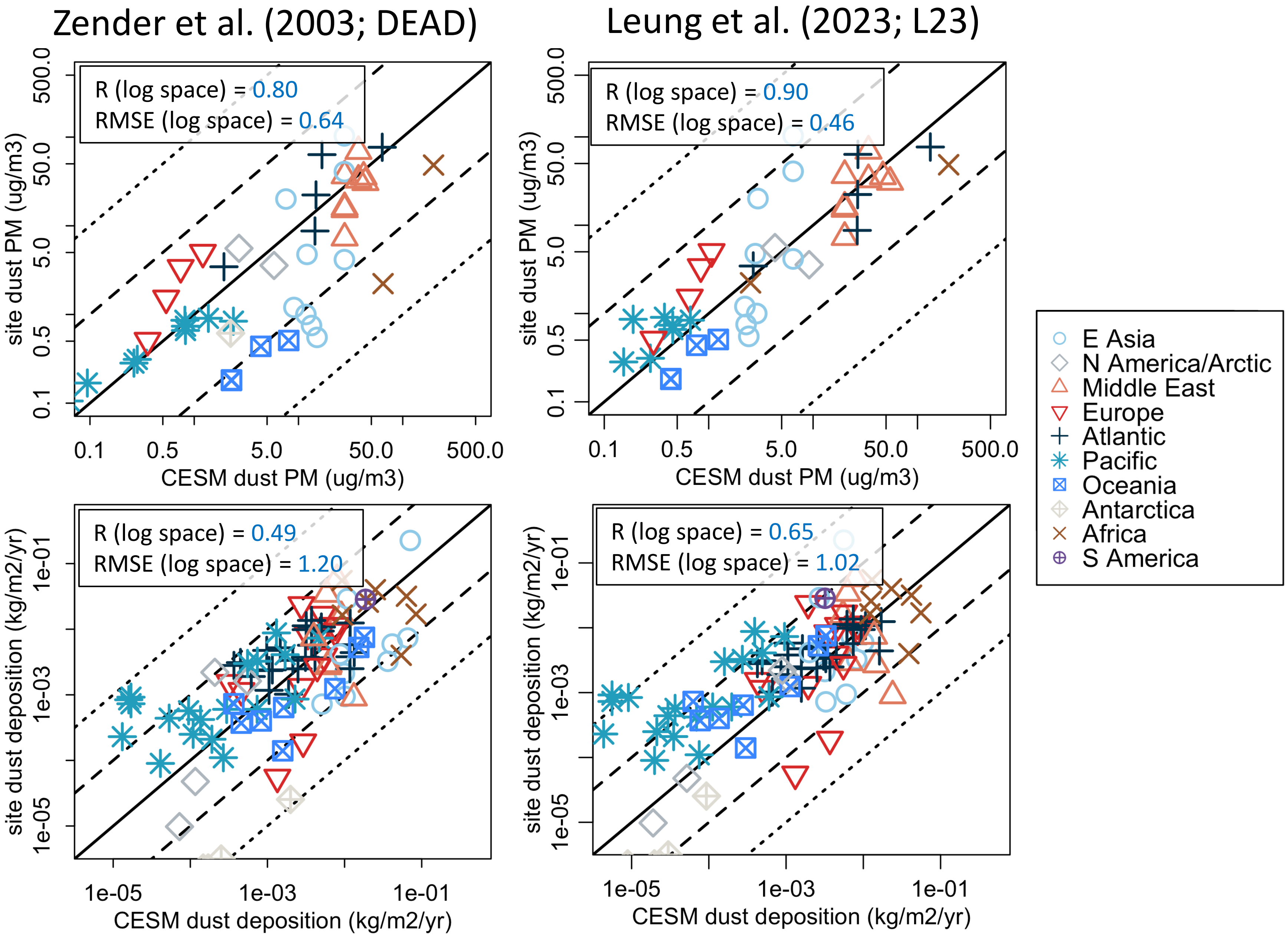
L23 does better in dust AOD seasonality and regional spatial variability than DEAD.



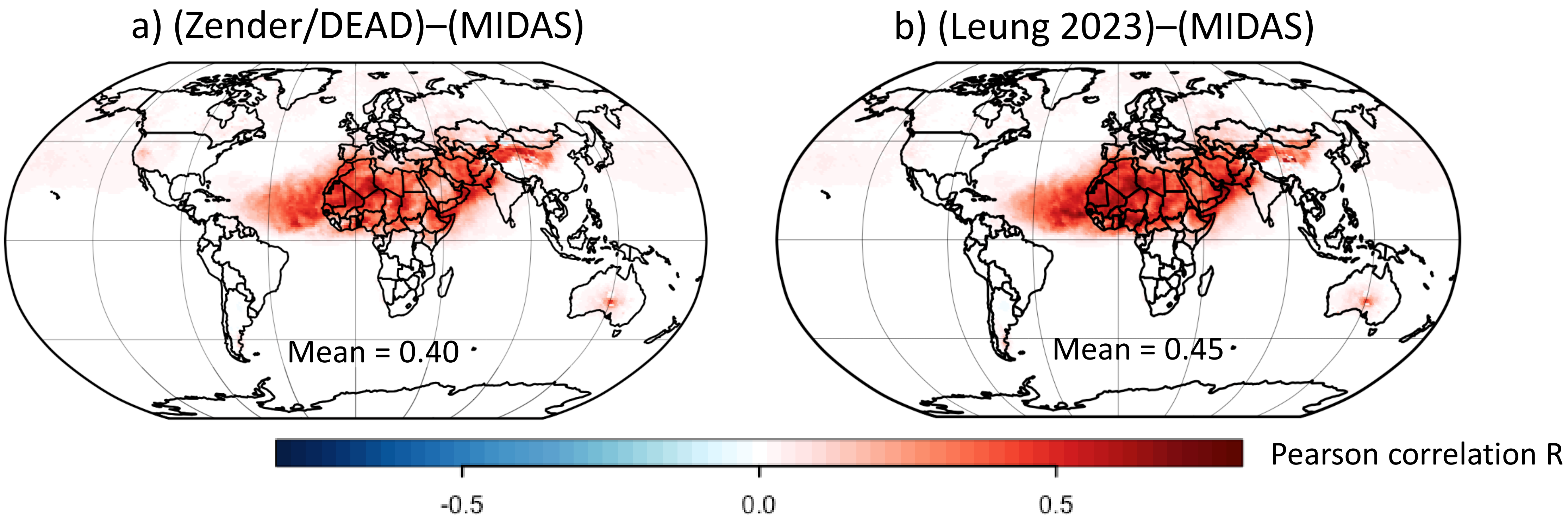
Ridley, Heald et al. (2016) optimized regional DAOD values (y-axis) are good for model evaluations.

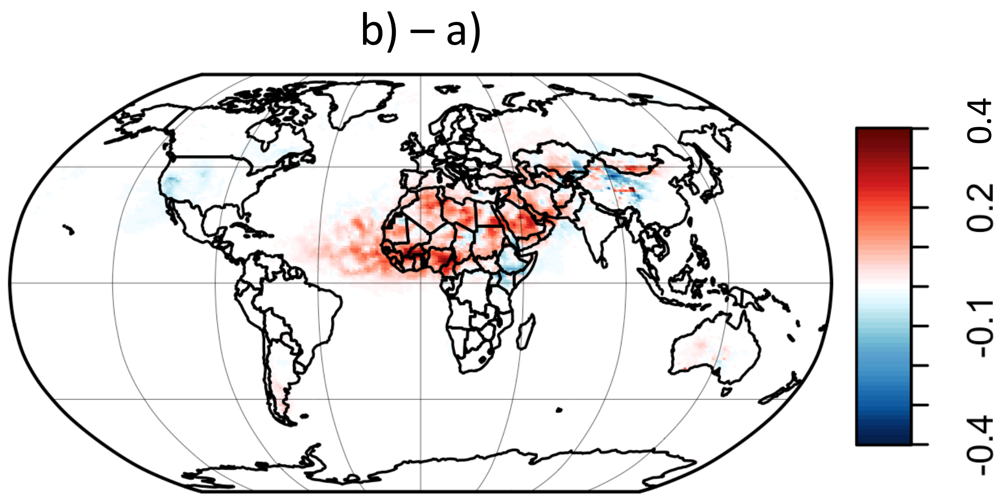
Our scheme have the largest errors compared with Ridley's DAOD values over the springtime Taklamakan and the Gobi deserts (green).

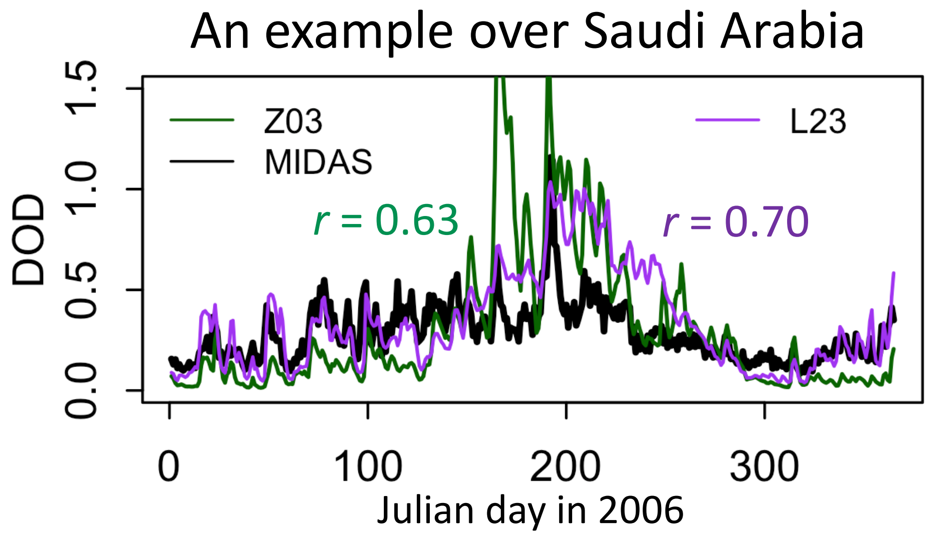
Comparison against in situ observations of dust PM and deposition fluxes



Daily dust AOD temporal (day-to-day) variability against MODIS/Aqua (MIDAS).

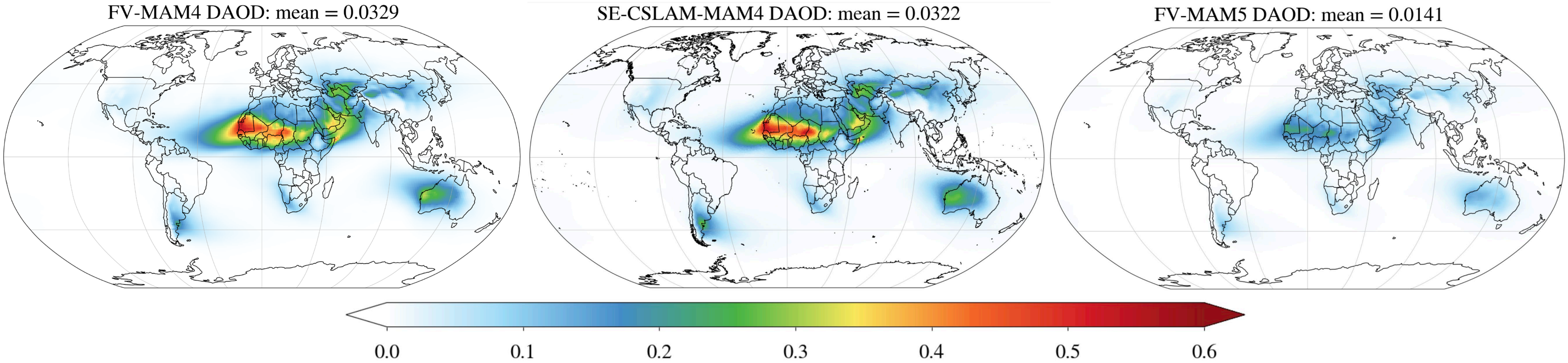


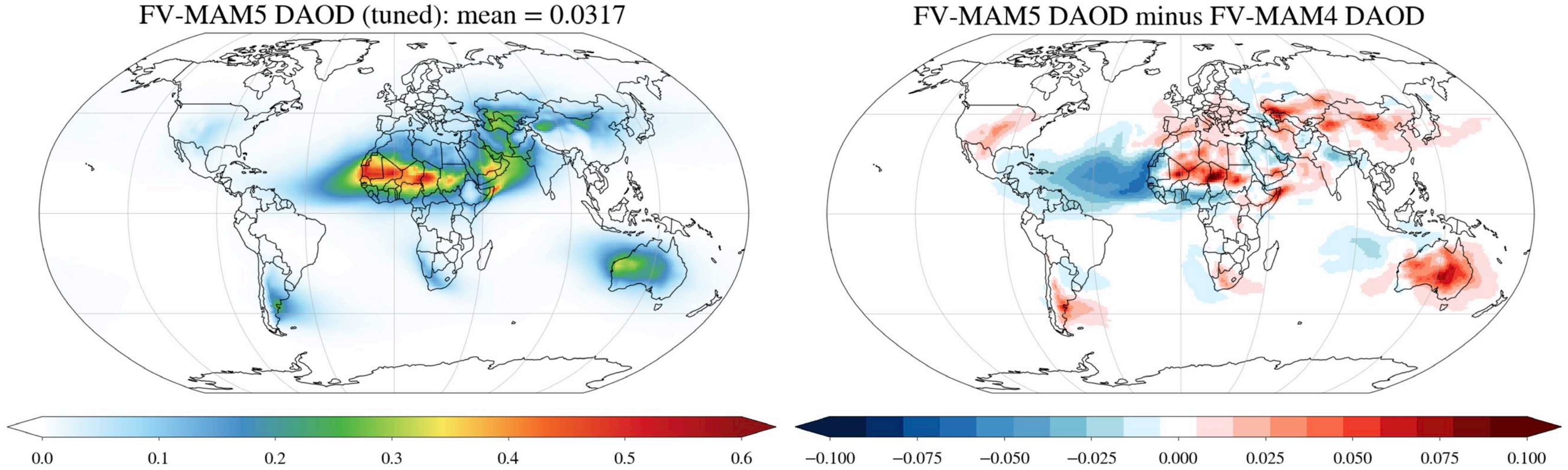




Going into CESM3: Leung 2023's behavior in different configurations (FHIST, no nudging)

FV: f09 (0.9°x1.25°) grid vs. SE-CSLAM: ne30pg3 grid
MAM4: coarse mode GSD σ = 1.2 vs. MAM5: coarse mode GSD σ = 1.8



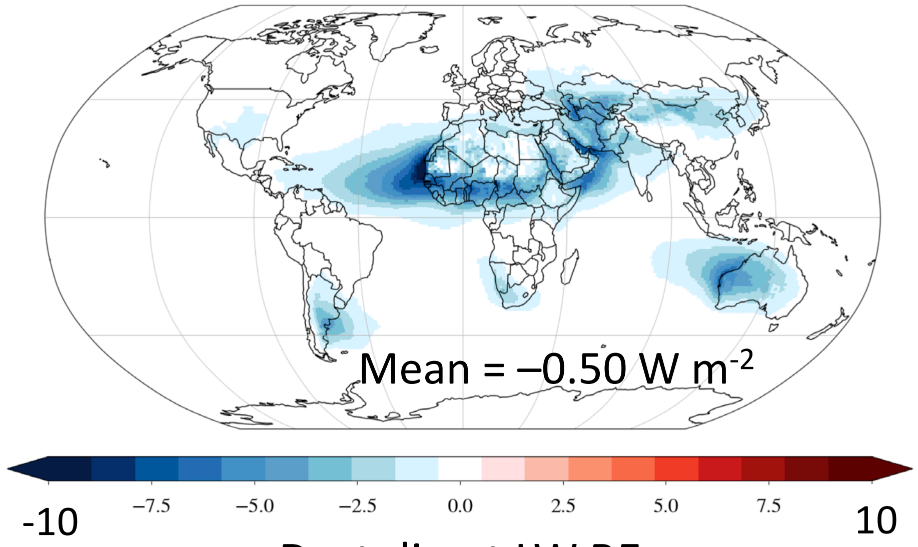


- The FV and the SE dycores give similar dust AOD.
- Using a larger GSD gives a smaller dust load as the coarse mode has bigger dust particles –> deposit faster.
- Retune CAM7/MAM5 in CESM3… Dust is slightly closer to source regions.

Dust direct RE (FSNTOA) and shortwave cloud RE (SWCF) using Leung 2023

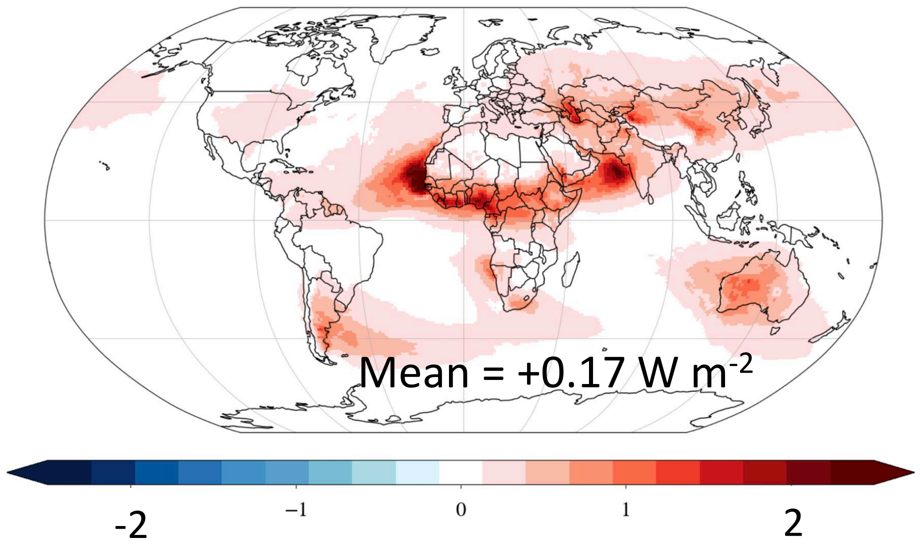
Dust direct SW RE

FSNTOA – FSNTOA_d1; W m^{-2}



Dust cloud SW RE

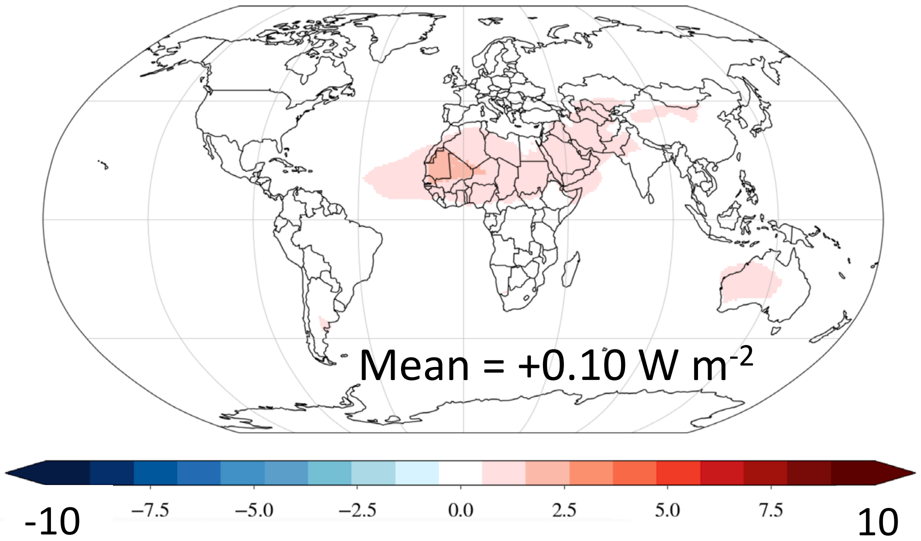
SWCF – SWCF_d1 ; W m^{-2}



(Note different color scales)

Dust direct LW RE

– (FLNT – FLNT_d1); W m^{-2}



Blue means dust is cooling; red means dust is warming.

d1 (rad_diag_1) is radiation without dust.

Take-home messages: a revised the mechanistic dust emission scheme for CESM

$F_{dustemis} = F_{dustemis}(u_*, w)$ becomes $F_{dustemis} = F_{dustemis}(u_*, w, \underbrace{\mathrm{z_{0,rock}}, \mathrm{LAI}}_{\text{Drag partition due to surface roughness}}, \sigma_{\tilde{u}})$

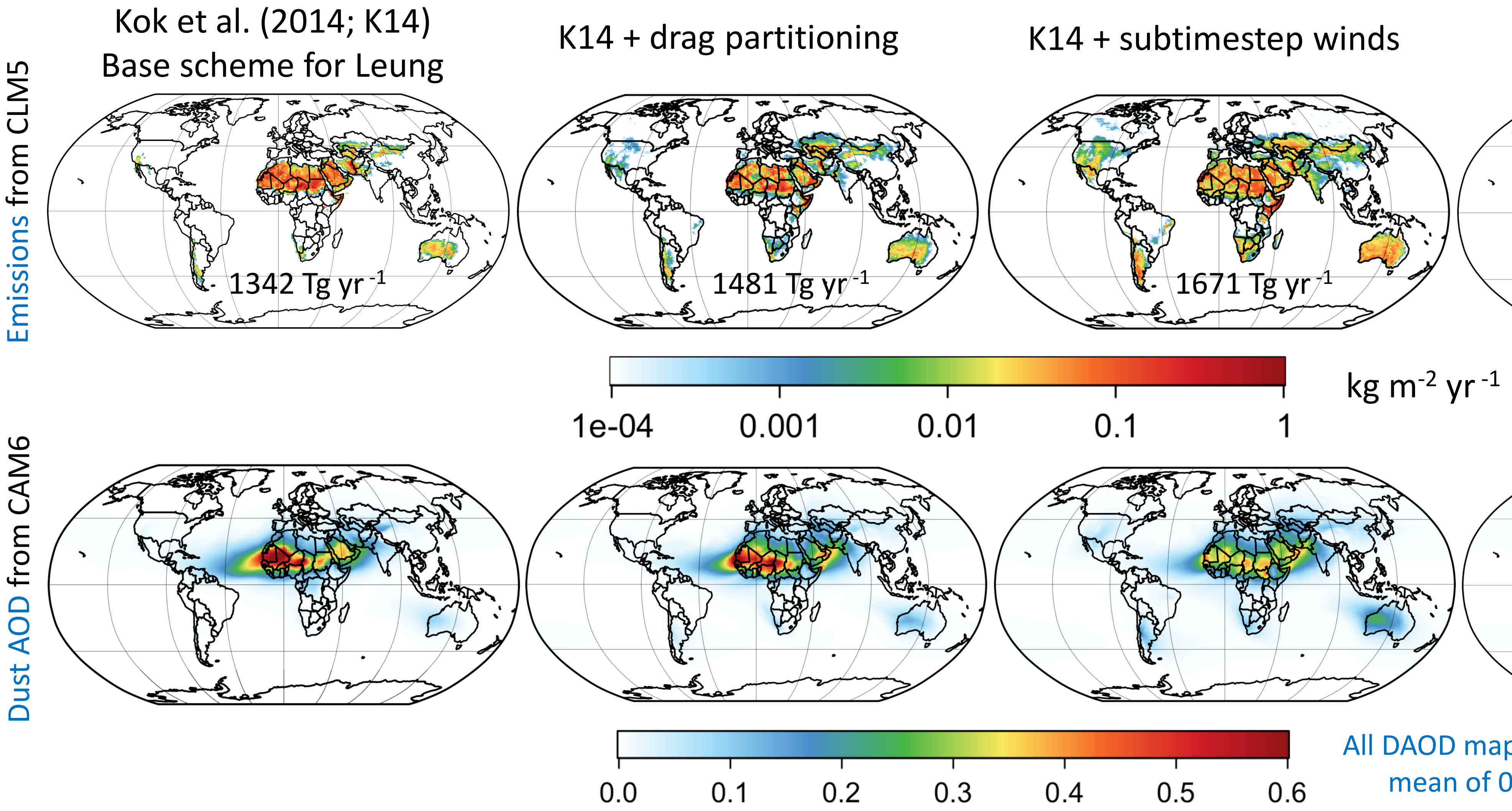
(CESM default)

(Leung 2023)

Subtimestep wind following the similarity theory

1. The new Leung 2023 emission scheme is implemented in the land model (CTSM). It is planned to be available in CESM3 (ESCOMP/CTSM PR #1897). If you want a CESM2.2.2. sandbox with Leung 23, let me know.
2. *In CESM3, users can switch between 'Leung 2023' (default) and 'Zender/DEAD 2003' (thanks to Erik Kluzek).
3. *We are moving the Zender soil erodibility map from CAM to CTSM. The dust tuning factor will be kept in CAM (ESCOMP/CTSM PR #1967).
4. *We suggest tuning dust to a global mean of 0.03 (±0.01) in the 2000s (Ridley, Heald et al., 2016) for air quality modeling and climate-scale simulations, no matter which dust emission scheme is used.
5. *For regional refinement, we suggest using the SE-CSLAM tuning factor. One can further tune it to minimize regional biases, although this is not highly recommended.
6. CESM3/CAM7 will use a wider coarse mode in the new MAM5. That makes dust overall deposit faster and stay close to source regions.
7. *The evaluation in this talk in CESM2. A lot of things will change in CESM3. Continuous and updated testings and tunings before the CESM3 code freeze.

Global dust emissions and dust AOD considering different effects (separating contributions).

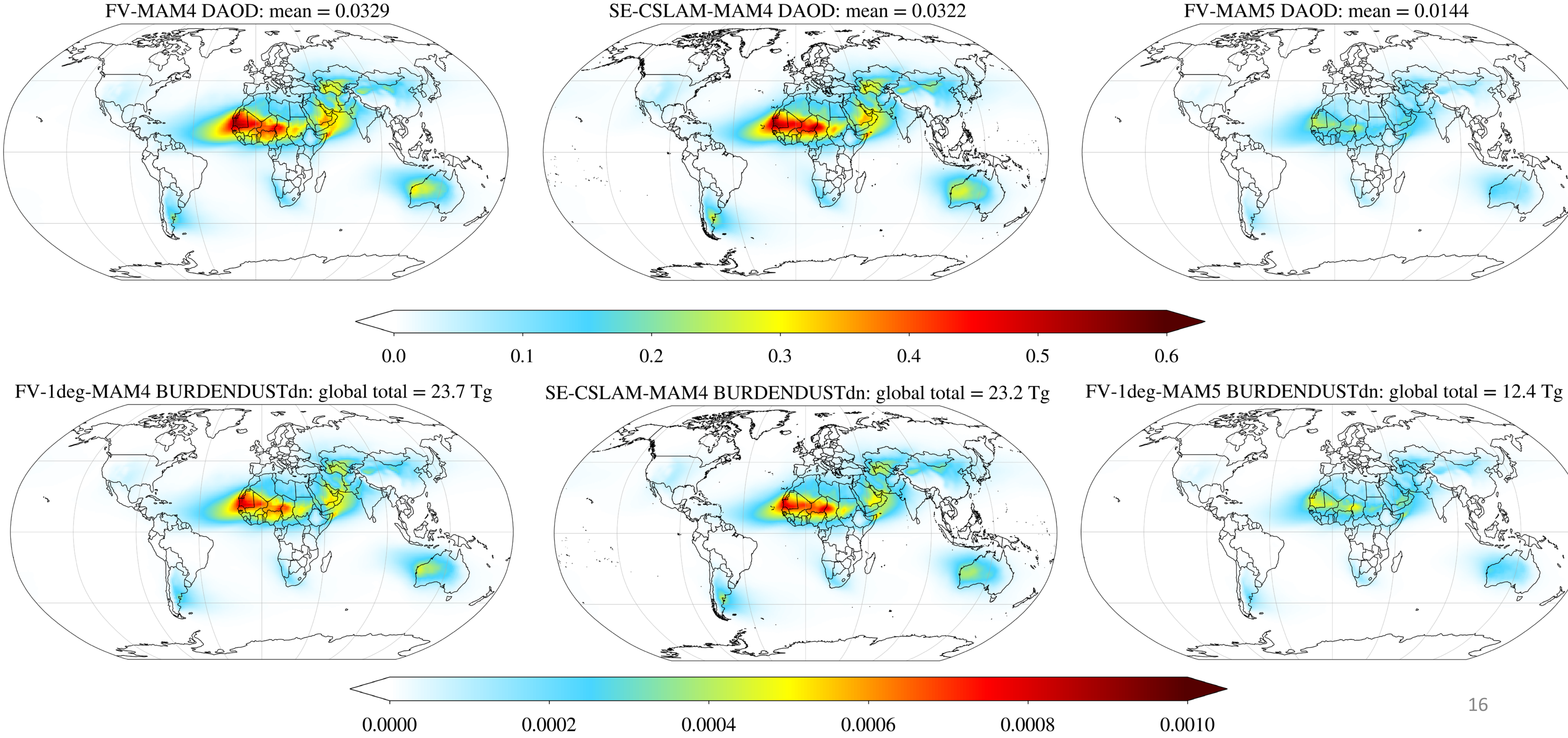


All DAOD maps are tuned to have a global mean of 0.03 (Ridley, Heald, 2016)

- The wind drag partitioning effect shifts dust emissions to major source regions (more exposed bare soils).
- Considering PBL turbulence (high-frequency wind fluctuations) generates more dust emissions from semiarid/marginal source regions (e.g., USA, South America, high-latitudes).

Update: testing the new dust emission scheme in different CESM configurations

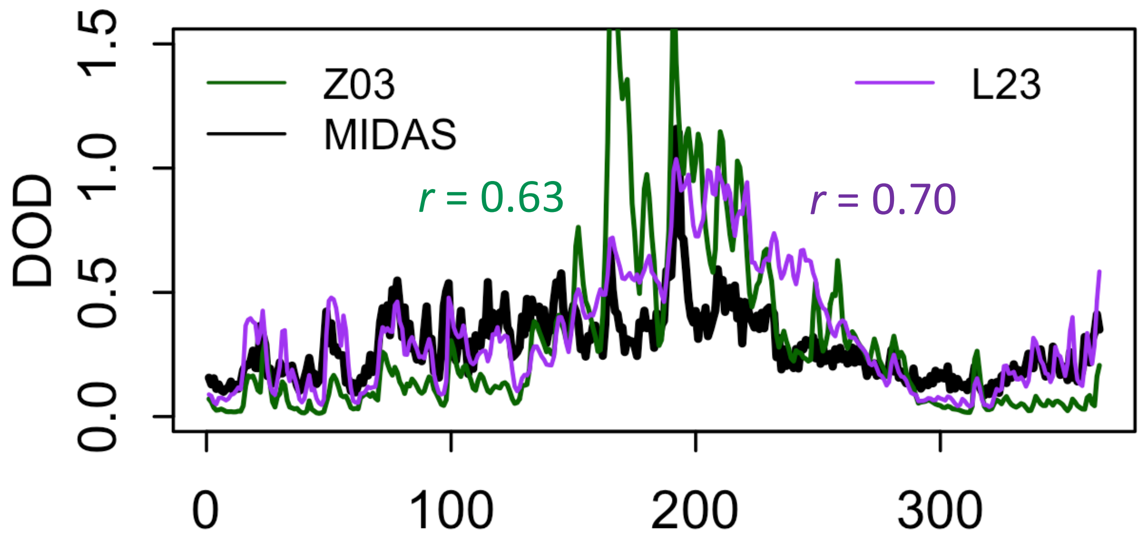
Finite volume (FV; 0.9°x1.25°) grid vs. spectral element (SE-CSLAM; ne30pg3) grid
4-mode modal aerosol model (MAM4) vs. 5-mode MAM (MAM5)



Daily dust AOD predictions in CESM2–L23 are generally better than in CESM2–Z03.

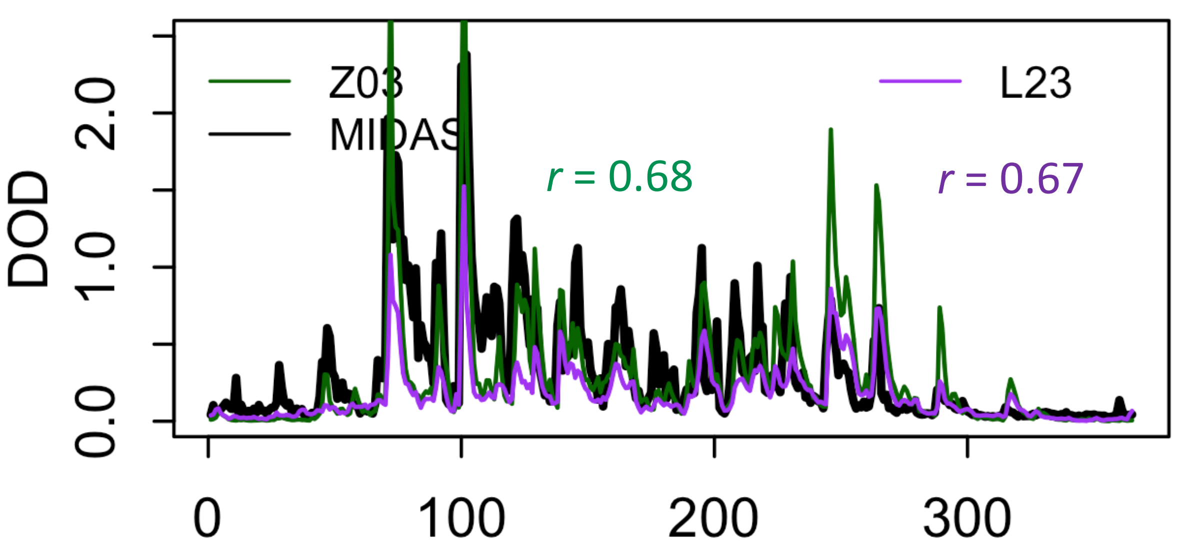
Dust AOD predictions in in 2006 using different schemes.

The Arabian Desert (Saudi Arabia)



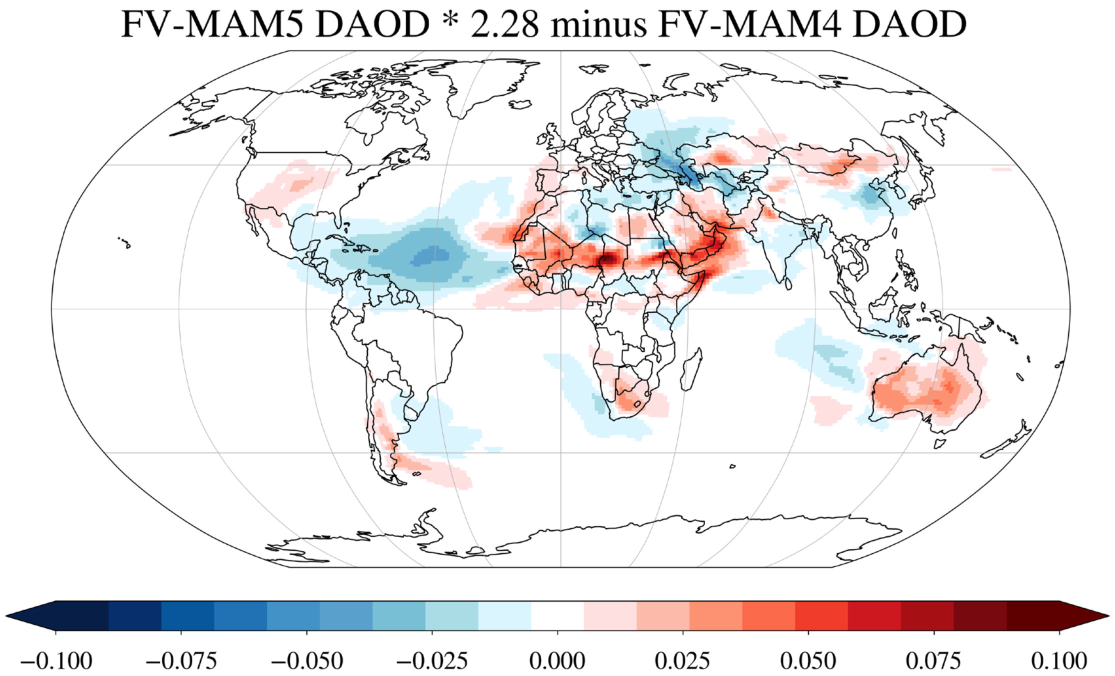
Julian day in 2006

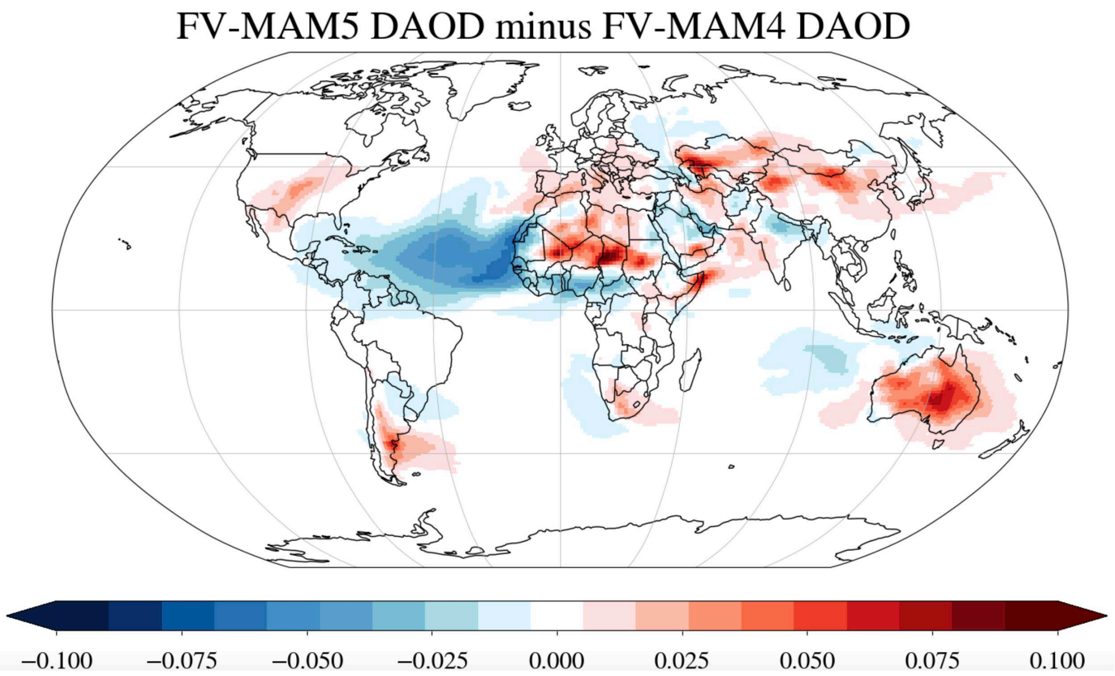
The Taklamakan Desert (China)



Julian day in 2006

MAM5 uses a wider coarse mode, making coarse mode dust deposit faster.





MAM5 dust is more concentrated over the source regions (topright), because MAM5 has more coarse dust, which deposits faster.