Advances in Earth system modeling of dust aerosol: Bridging gaps for comprehensive understanding

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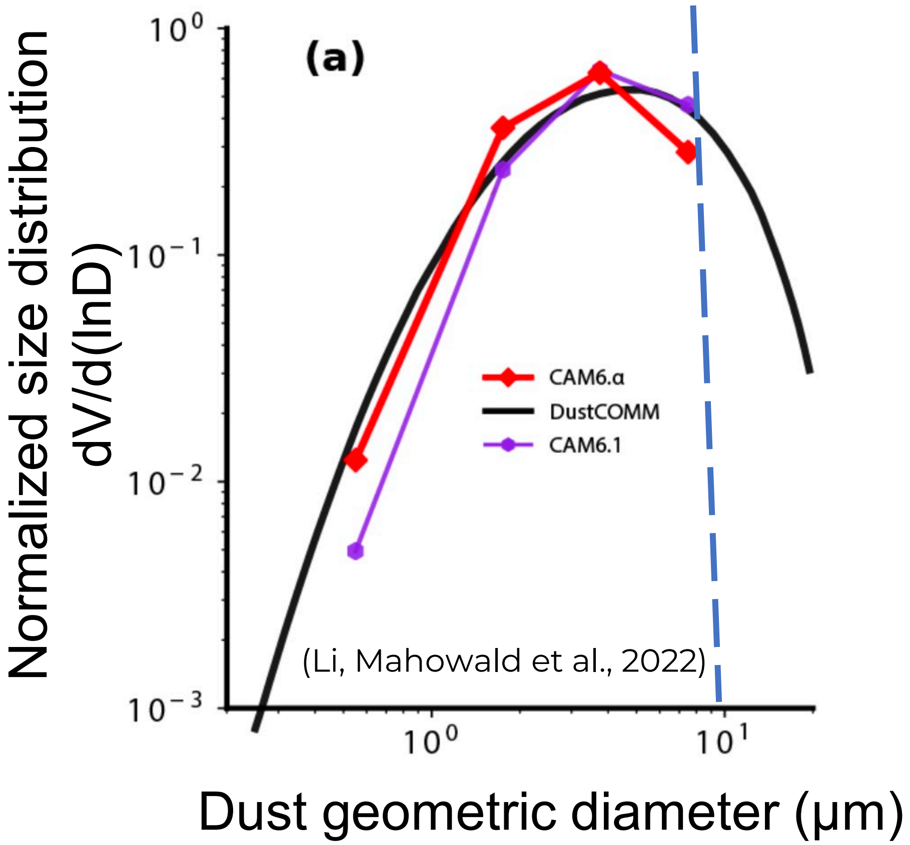
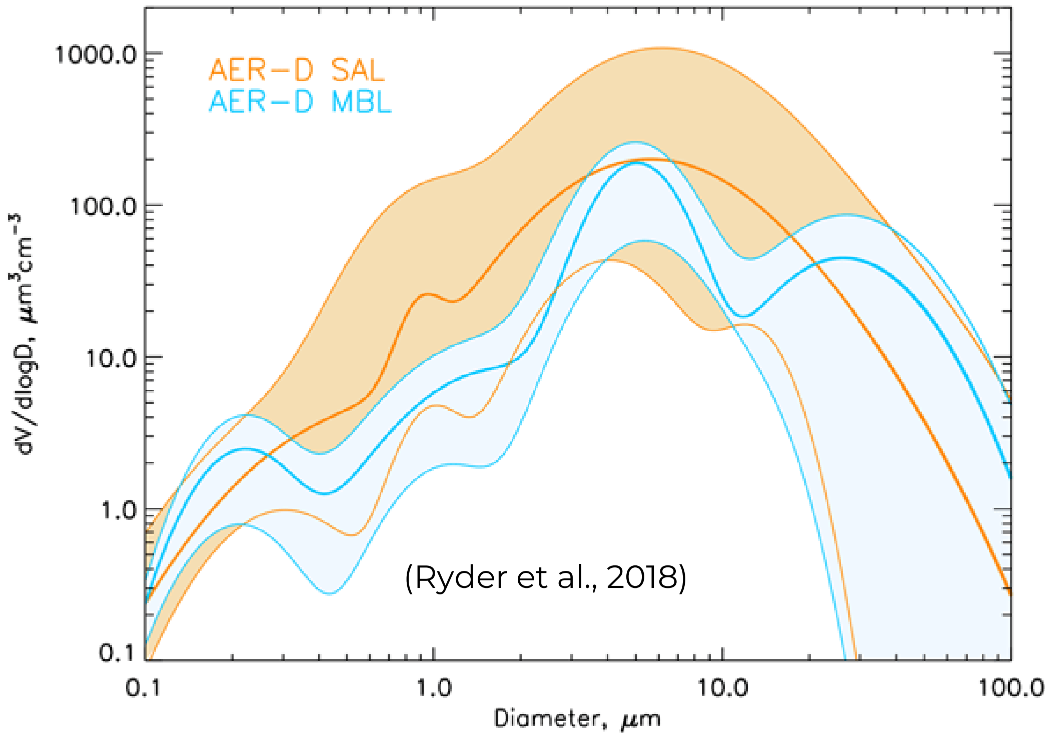
A long-standing assumption: Negligible influence of dust particles > ~10 μm on climatic effects

- ✓ Most climate models including CESM of different versions simulating only dust particles < 10 μm
- ✓ Rare dust particles coarser > 10 μm because of large-sized particles being removed quickly by gravitational settling



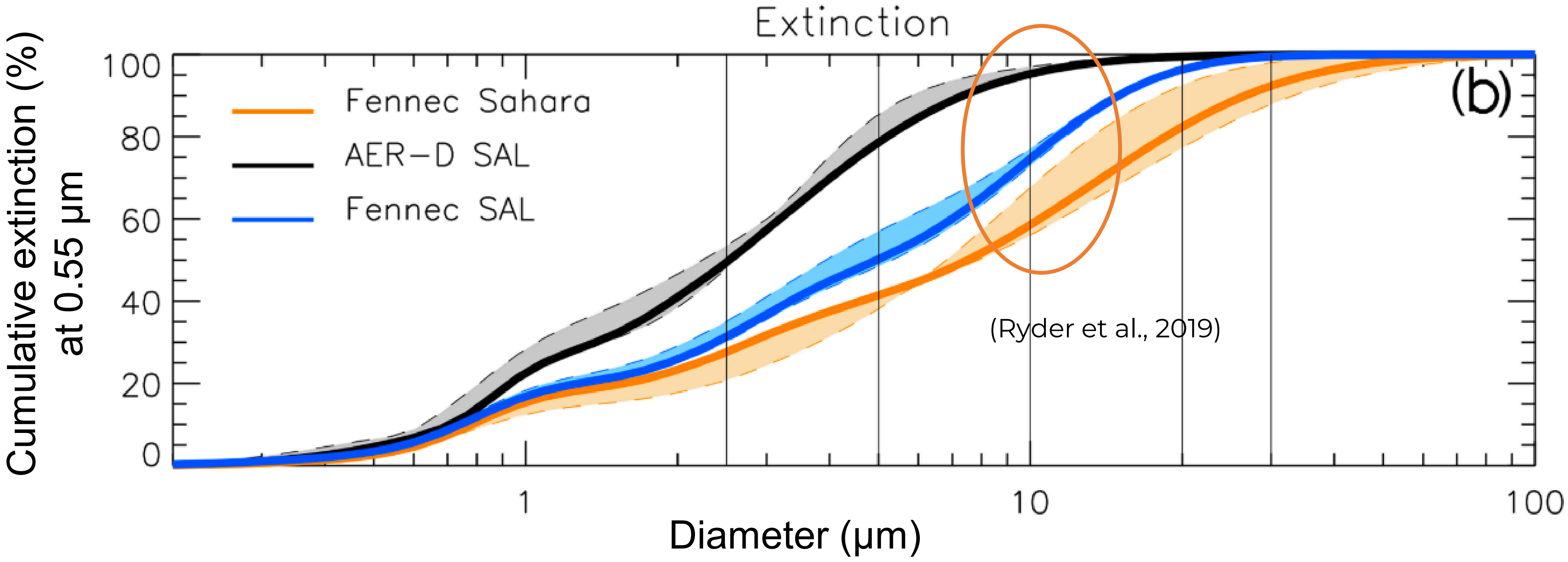
Significant mass presence in dust particles > ~10 µm

- ✓ Recent campaign measurements undertaken downwind of North Africa finding that large-sized dust particles contribute more than expected to total dust mass (Weinzierl et al., 2009, 2017;Ryder et al., 2013, 2018, 2019)
- ✓ Dust particles up to 40 µm frequently present as far as 2000 km downwind of North Africa



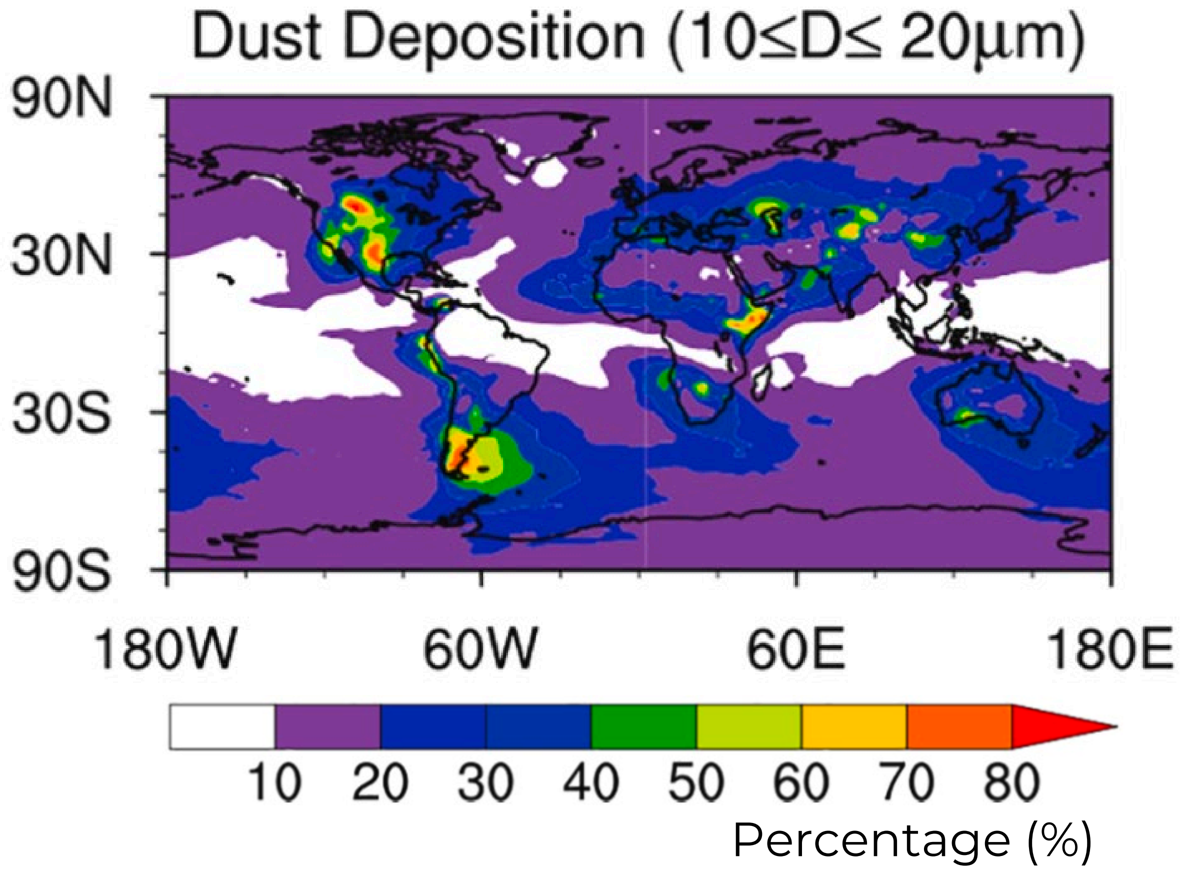
Challenging assumptions: dust particles > ~10 μm as a large contributor to dust extinction at 0.55 μm

- ✓ Up to 40% contribution to the extinction and thus dust optical depth at 0.55 μm (Ryder et al., 2019)



Continued: Non-negligible impacts on the climate system

- ✓ A positive DRE of +0.03 [+0.01, +0.06] W/m^2 (Kok et al., 2017)
- ✓ An important contribution (>30 %) to the dust deposition over some ocean areas (Meng, et al., 2022; Adebiyi et al., 2023)
- ✓ A missing source to bioavailable nutrients (Adebiyi et al., 2023)



(Adebiyi, et al., 2023)

Model development

- ✓ An innovative model framework that integrates recent dust modeling advancements with our own into a dust-speciated version of the CESM 2-CAM6 (8 separate mineral tracers).
  - Large-sized dust particles (Ke et al., 2023) in CAM5 with an extension to 70 μm by introducing a new dust mode: A5 (0.1-1.0 μm), A7 (1.0-5.0 μm), A8 (5.0-10 μm), A9 (10-20 μm), and A10 (20-70 μm)
  - The intermittency effect (Leung et al., 2023, 2024)
  - The surface roughness effect (Leung et al., 2023, 2024) with revised calculations using modeled leaf area index
  - Revised dust size distribution upon emissions (Meng et al., 2022)
- ✓ A novel tuning method designed to artificially address the underrepresentation of coarse and giant dust particles, such that the model with offline dynamics can better match
  - Size distribution measurements (Ryder et al., 2013, 2018, 2019)
  - Retrievals of DAOD at longwave band (Zheng et al., 2023)
  - Retrievals of effective diameter (Zheng et al., 2023)

Model evaluations

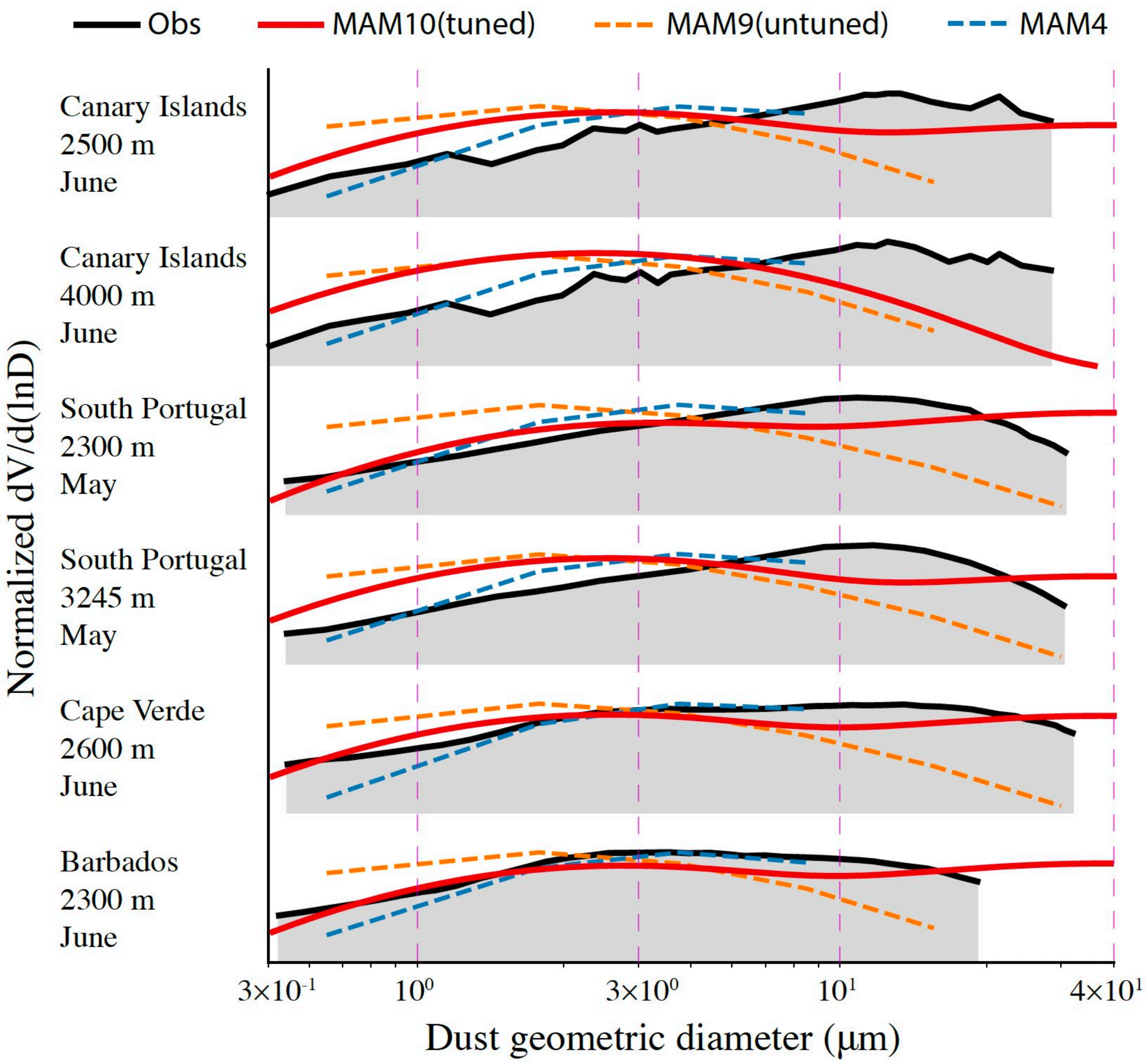
- ✓ Traditional model-data comparison (Albani et al., 2015)
  - Optical depth: Model (visible band) vs. AERONET (0.55 μm)
  - Surface concentrations
  - Deposition flux rates
- ✓ Radiative effect efficiency (Di Biagio et al., 2020; Li et al., 2022)
- ✓ Wet to total deposition ratio (Mahowald, et al., 2011)
- ✓ Size distribution
  - Data reported in Mahowald et al. (2014)
  - Aircraft measurements near western North Africa (Ryder, et al., 2013; Weinzierl et al., 2017)
- ✓ Particular Mass (PM)
  - Recent and comprehensive compilation of station-based measurements worldwide (Mahowald et al., 2024)
  - Aircraft measurements near western North Africa (Ryder et al., 2019): vertical profile

Scientific goals

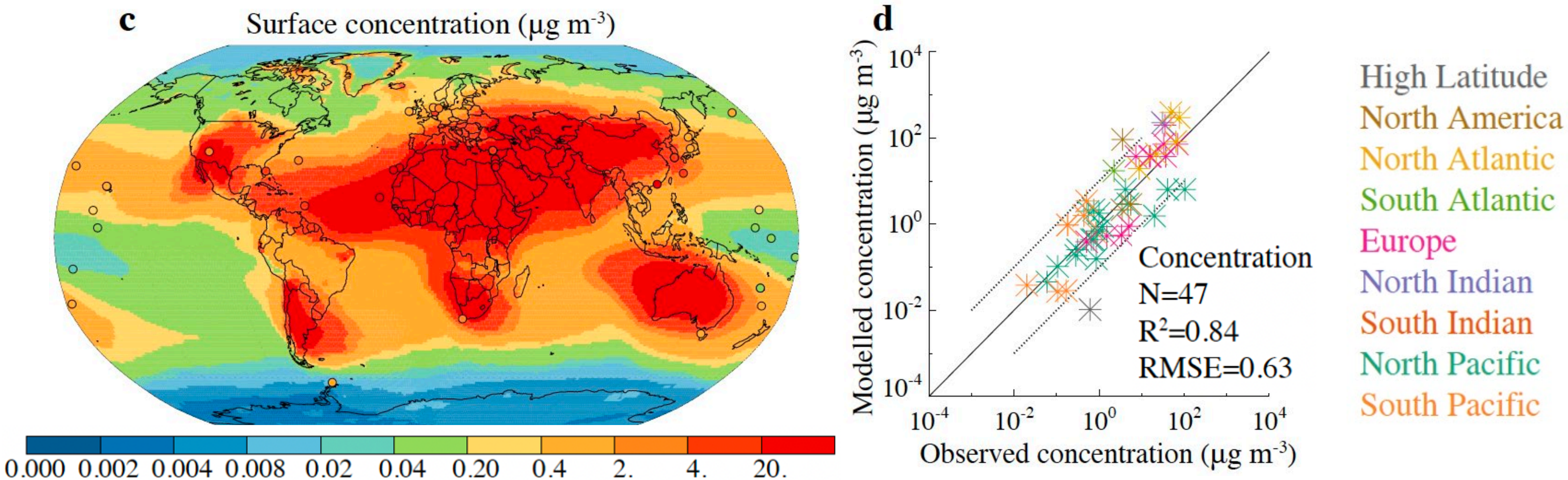
- ✓ Revisiting the modeled dust cycle: dust emissions, abundances (optical depth, loading, etc.), and deposition
- ✓ Revisiting the climatic impacts of dust: dust-radiation and -cloud interactions
  - Biogeochemistry (iron nutrients)
  - Air quality (mortality)
- ✓ Evaluating importance of coarse and giant dust particles

Dust size distribution tuning

- Measurements include the dust particle size distribution over the Canary Islands (~28°N, 16°W) at two altitudes (2500 and 4000m) (Ryder, et al., 2013), over southern Portugal (~38°N, 8°W) at two altitudes (2300 and 3245m) (Wagner et al., 2009), and at Cape Verde (~15°N, 23°W) and Barbados (~12°N, 60°W) (Weinzierl et al., 2017). All curves are normalized to yield unity when integrated over the whole diameter range (Meng et al., 2022)
- Recreating look-up table for interpolations of aerosol optical properties using the Mie Theory



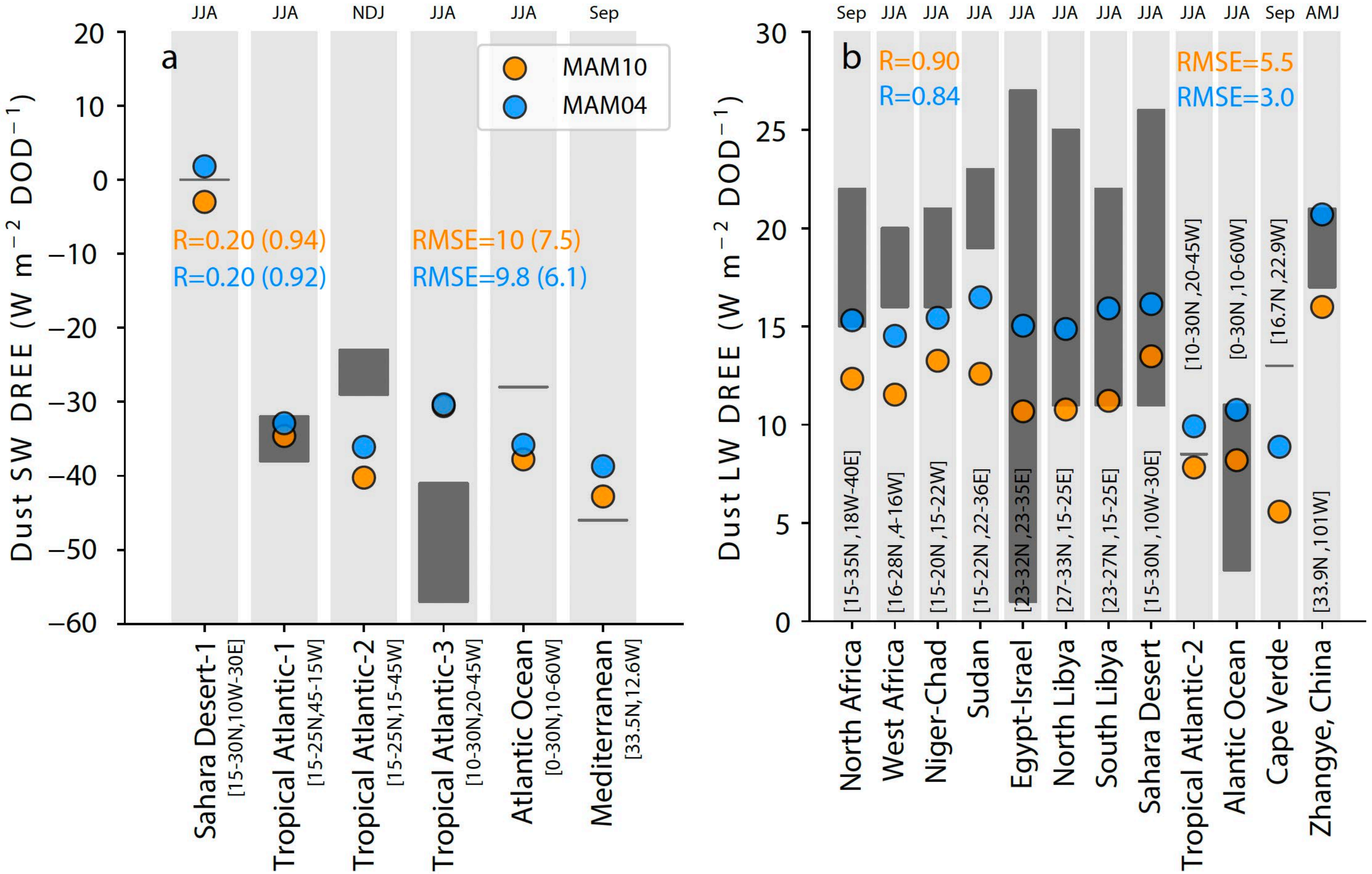
Traditional model-data comparison: Surface dust concentration matching observed data within one order of magnitude across most sites



- Reproducing 1) the observed dust optical depth (AERONET and MODIS) (0.55 μm) reasonably well, but 2) overestimating dust deposition within across many sites
- No significant improvements compared to MAM4

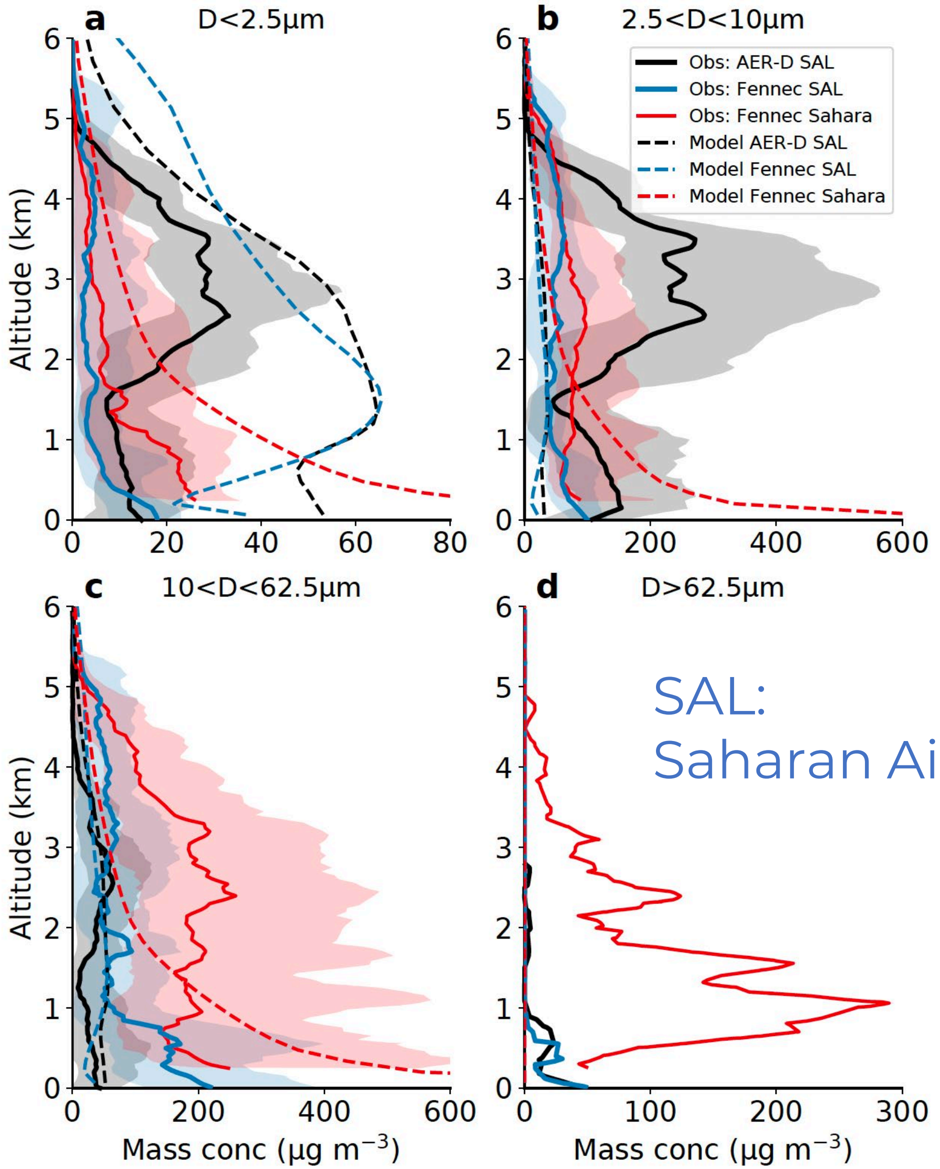
Challenges persist in accurately replicating the satellite-based dust radiative effect efficiency (DREE) under clear-sky conditions

- ✓ Shortwave DREE
  - No significant change between MAM10 and MAM4
- ✓ Longwave DREE
  - Considerable change toward higher bias in amplitude
  - Spatial variation well-reproduced



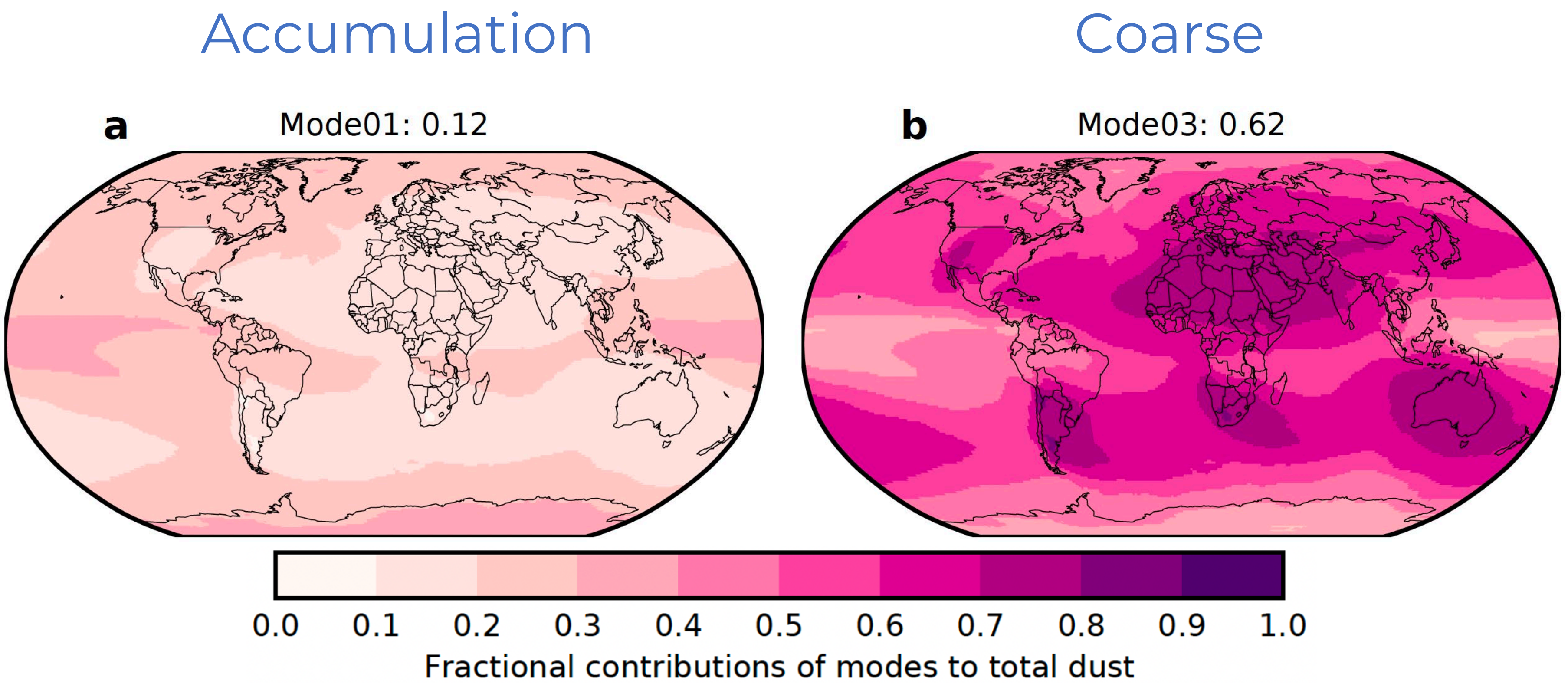
Vertical profile of size resolved dust Mass Concentration (MC: μg m^{-3})

- ✓ Sustainably high MC for dust < 2.5 μm (modeled values rescaled down by a factor of 6)
- ✓ Sustainably low MC for dust between 10 and 62.5 μm (modeled values rescaled up by a factor of 4)
- ✓ Insufficient vertical transport of dust across all size ranges for both MAM10 and MAM4

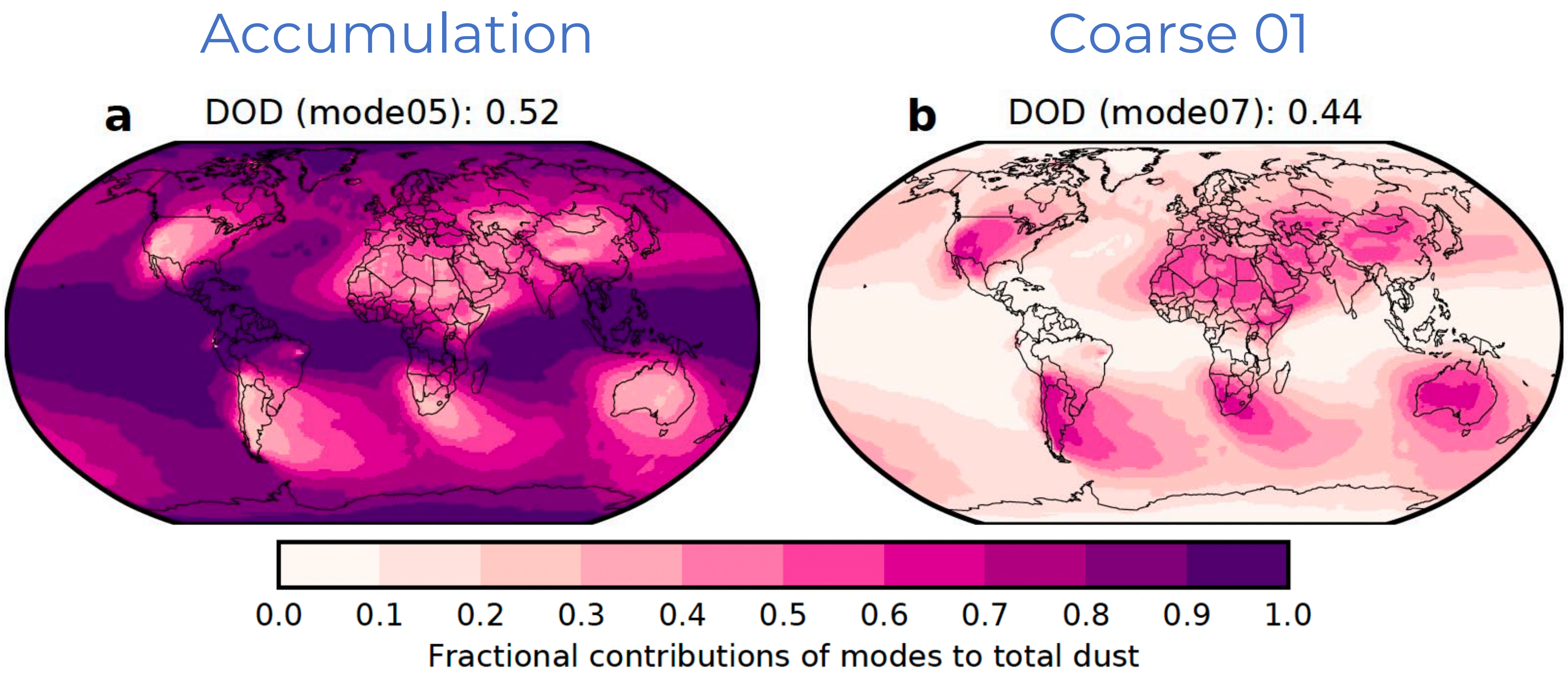


SAL:
Saharan Air Layer

Accumulation dust contributing little to total dust optical depth in visible band compared to coarse dust: MAM4



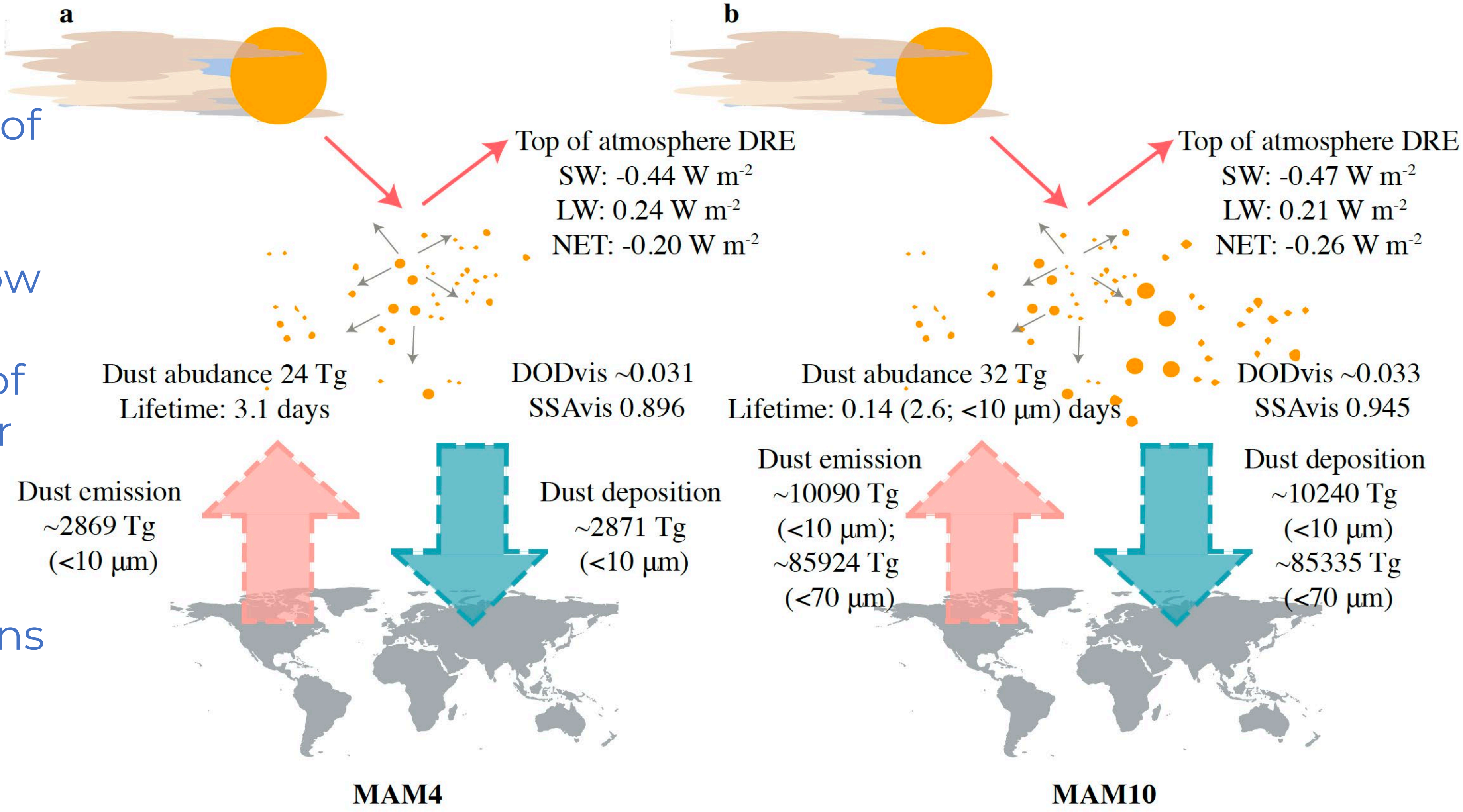
Accumulation dust in MAM10 contributing >3 times more to total dust optical depth in visible band compared to MAM4



Accumulation dust contributing disproportionally less to total deposition compared to dust optical depth in visible band!

MAM10 vs. MAM4: global quantities for the period of 2007-2011

- Much higher emissions because of including particles >10 µm
- Disproportionally low loadings compared to MAM4 because of low dust lifetime for particles > 10 µm
- Stronger cooling effect due to dust-radiation interactions



Conclusions

- ✓ Integrating recent model developments into the dust model within CESM2-CAM6, prioritizing the incorporation of missing components pertaining to dust particles larger than 10 μm
- ✓ Stronger dust cooling due to the competition effect between fine-sized dust and dust > 10 μm in MAM10 compared to MAM4
- ✓ The new model with constrained the coarse and giant dust particles fairly reproducing some (e.g., surface concentrations) within an order of magnitude but not all the observations (e.g., vertical profile of mass concentrations) for different dust quantities, highlighting the need for further refinement

Thank you for your attentions!