The mysterious abundance of coarse desert dust in Earth's atmosphere

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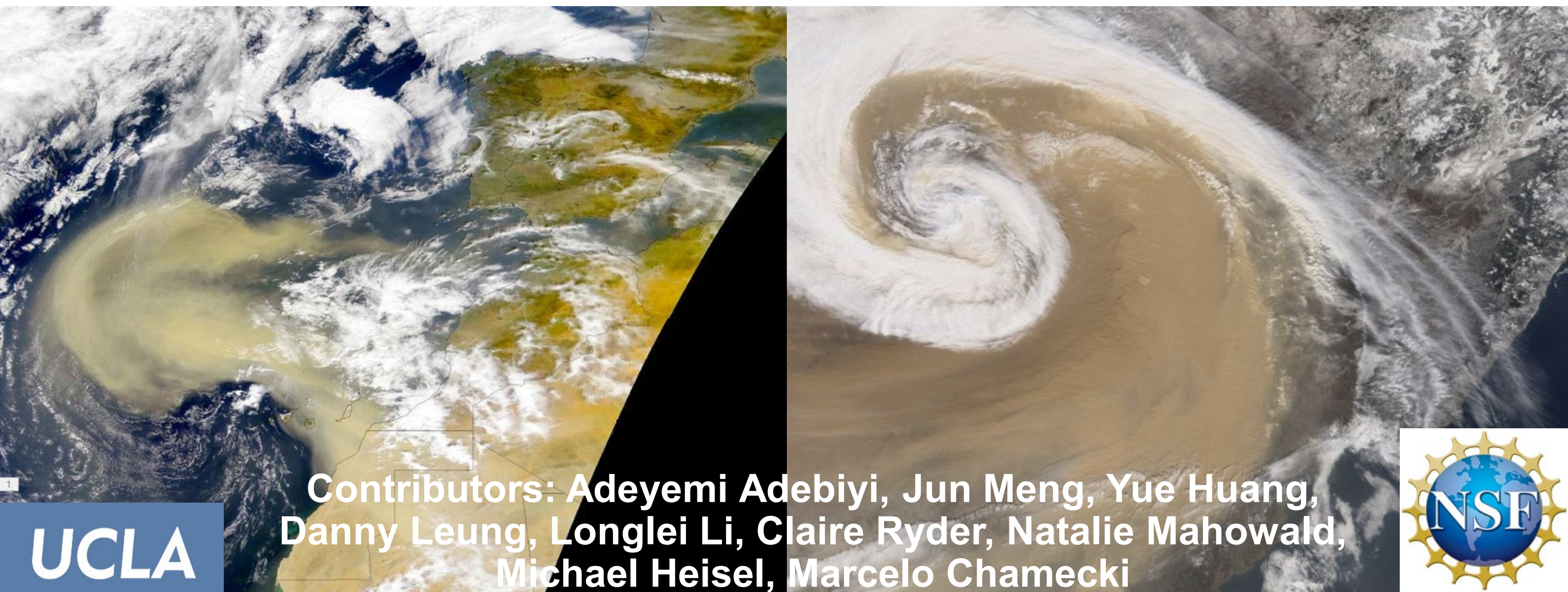
InDust virtual seminar, April 13, 2022



Contributors: Adeyemi Adebiyi, Jun Meng, Yue Huang, Danny Leung, Longlei Li, Claire Ryder, Natalie Mahowald, Michael Heisel, Marcelo Chamecki

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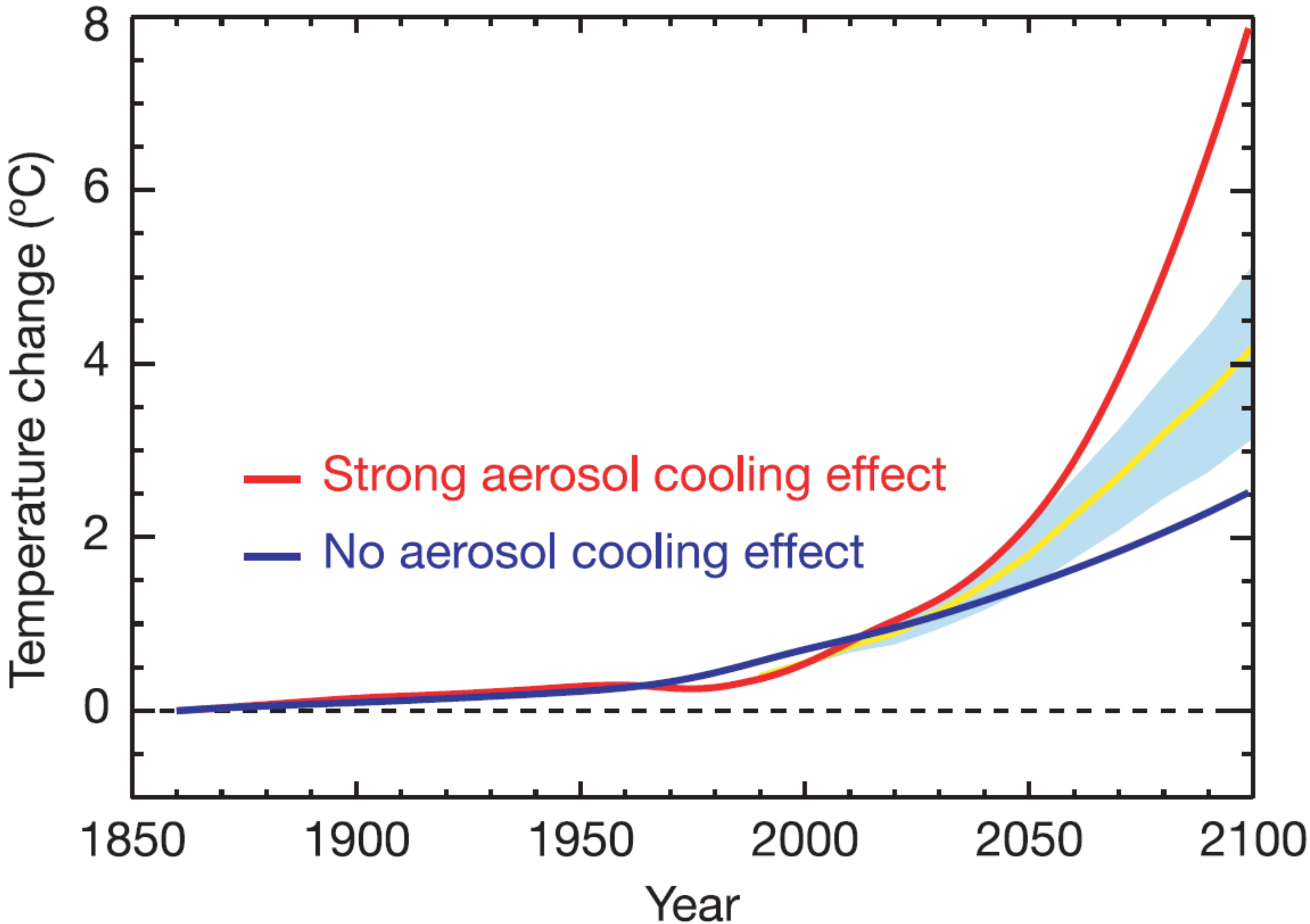
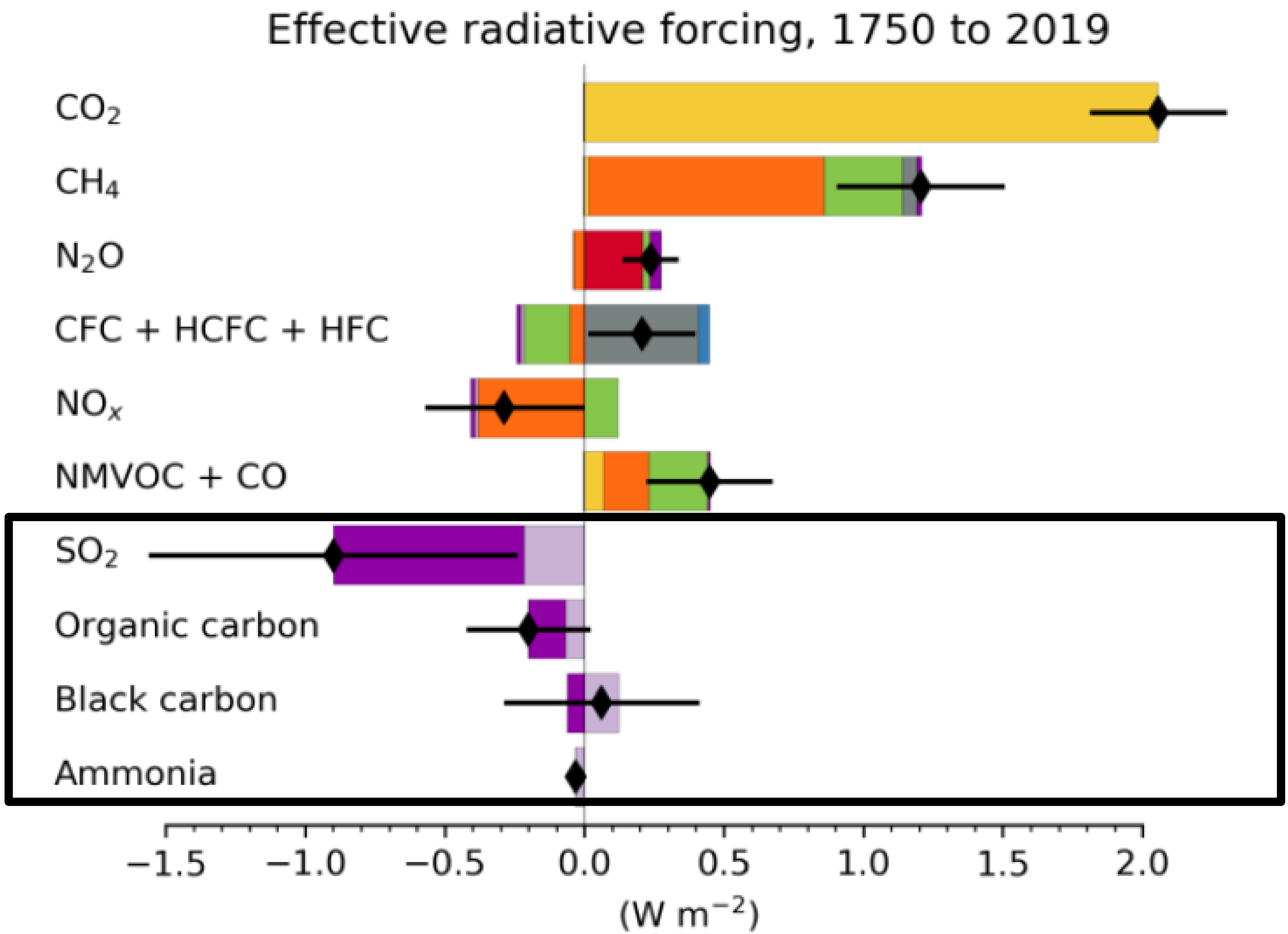
Aerosol radiative forcing co-determines our climate future



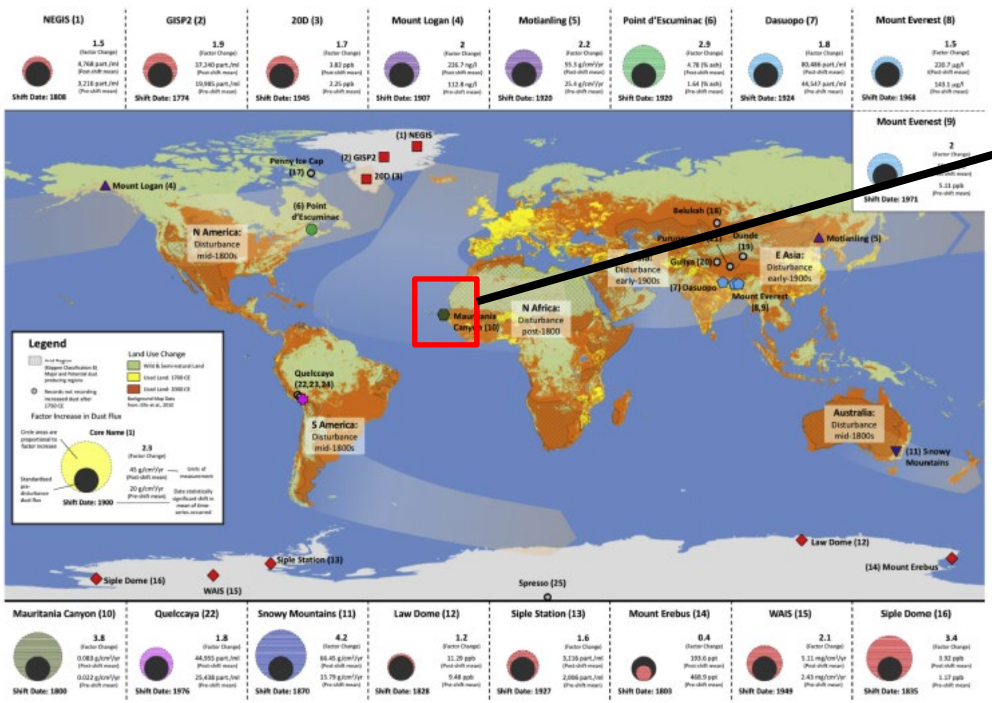
From Andreae et al., Nature (2005)



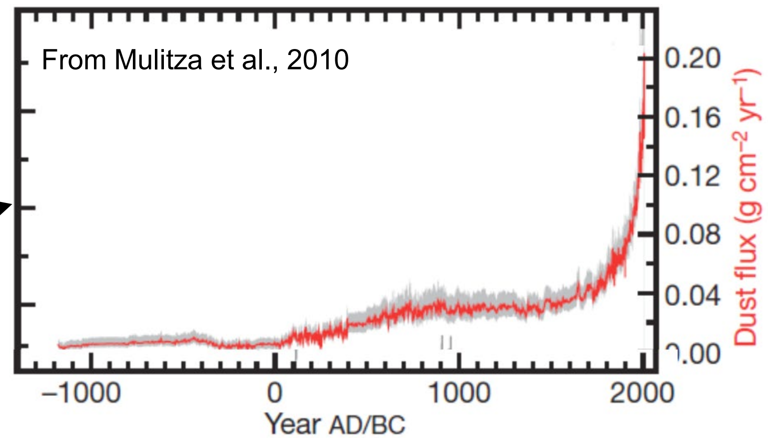
From IPCC Assessment Report 6, Working Group 1, Chapter 6: Short-lived climate forcers (2013)

Dust has increased strongly since pre-industrial times

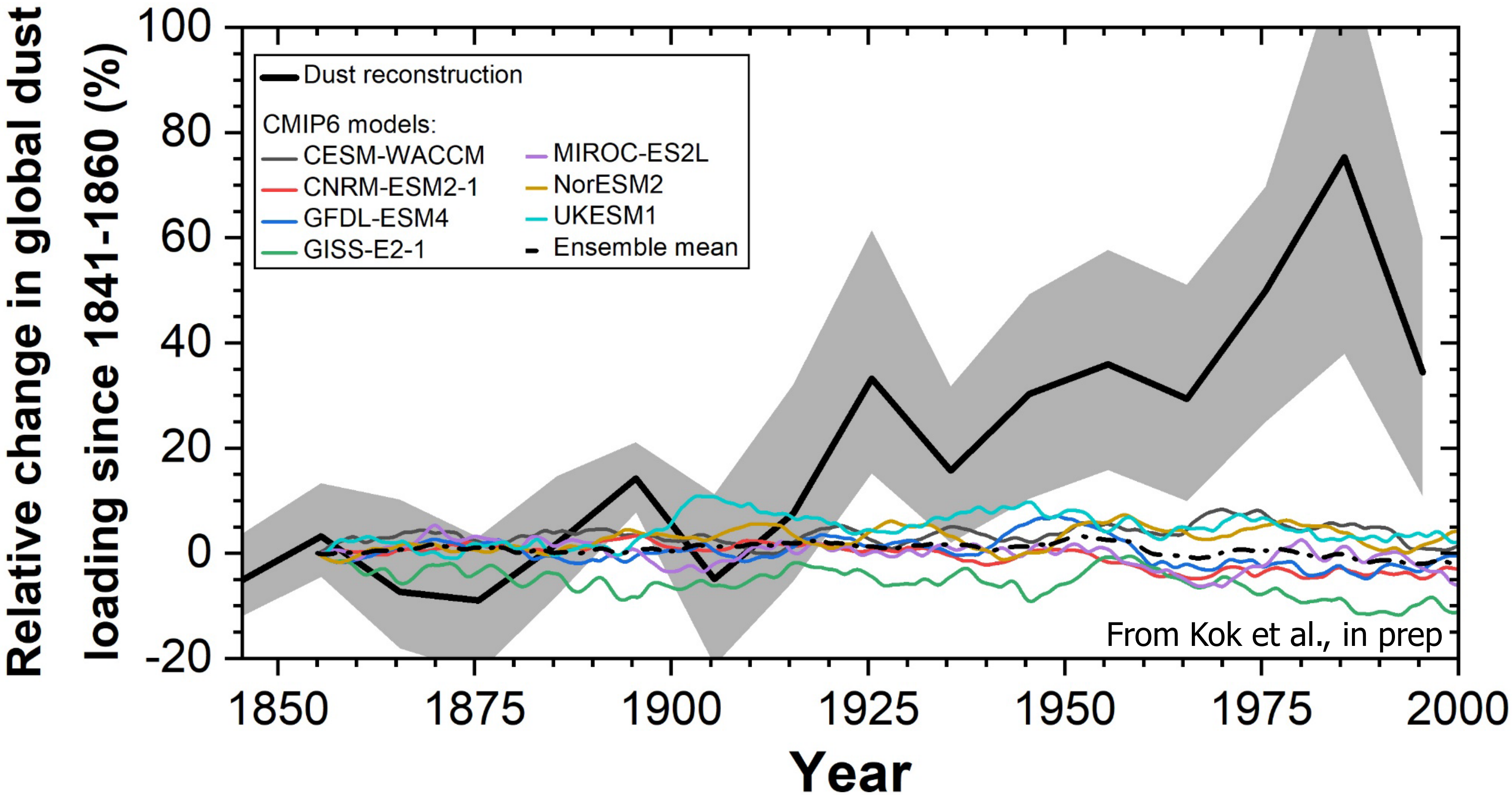
- Globally, atmospheric dust loading has increased by ~25-100% (Mahowald et al. ‘10; Hooper & Marx ’18; Kok et al., in prep)



From Hooper & Marx, 2018



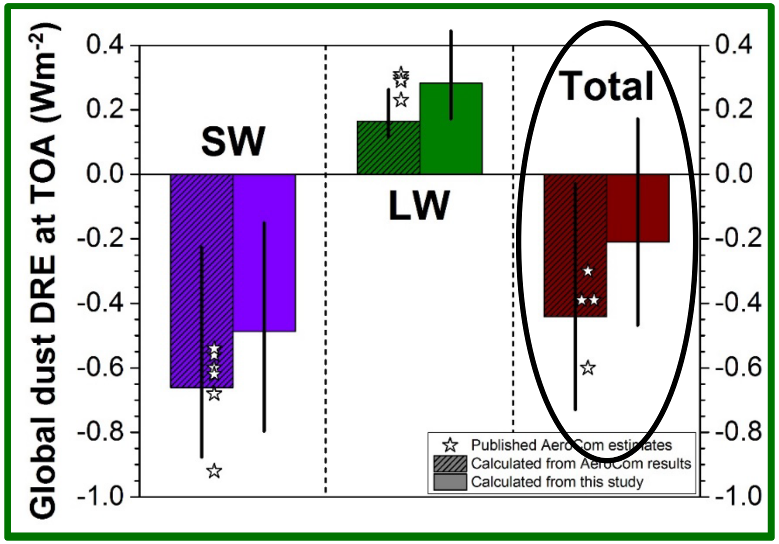
Current climate models miss "Anthropocene dust"



- Possibly substantial **"missing" radiative forcing?**
  - Need to figure out **net direct (and indirect) radiative effects** of dust!
  - Depends strongly on **dust size**!

Are models missing a substantial radiative forcing due to dust direct radiative effect?

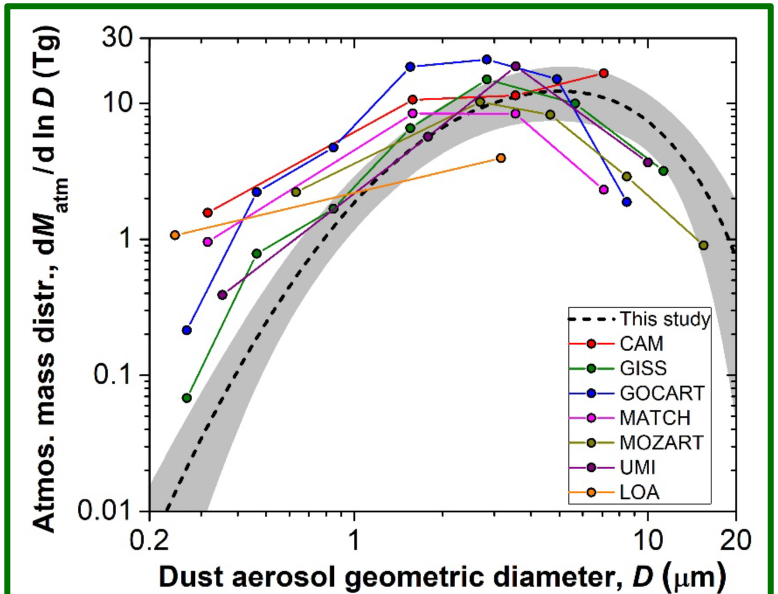
- Dust direct effect depends on dust sizes
  - Fine dust ($D \leq 5$ um) **cools by scattering SW**
  - Coarse dust ($D \geq 5$ um) **warms by absorbing SW and LW**
  - AeroCom phase 1 models indicated strong net cooling



Kok et al., Nature Geoscience, 2017

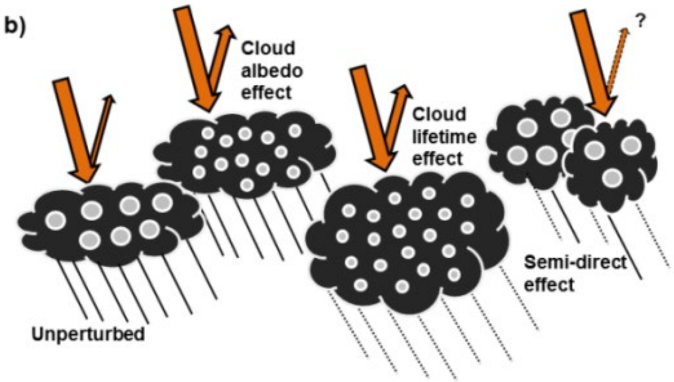
- But AeroCom models have **fine bias**
  - Emit too much fine dust, not enough coarse dust

  → Dust is **less cooling**, **could net warm**



Are models missing a substantial radiative forcing due to dust indirect radiative effect?

- **Fine dust cools** by seeding cloud droplets
- **Coarse dust warms** by reducing cloud droplet number concentrations as giant CCN
  - Produces warming of ~0.2 ± 0.1 W/m^2 (Klingmuller '20)
- Dust is main ice nucleating particle
  - Probably net cooling in global average (Liu et al., 2012; McGraw et al. 2020)



http://www.nature.com/scitable/knowledge/library/aerosols-and-their-relation-to-global-climate-102215345

De Mott et al. (2010); Heymsfield et al. (2017)

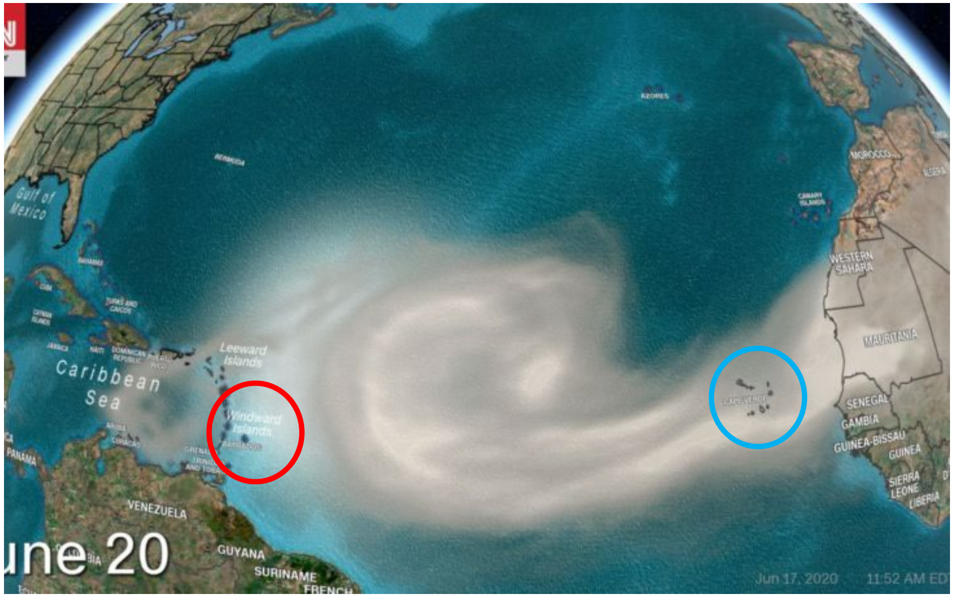
So “missing” radiative forcing by dust highly dependent on dust size:

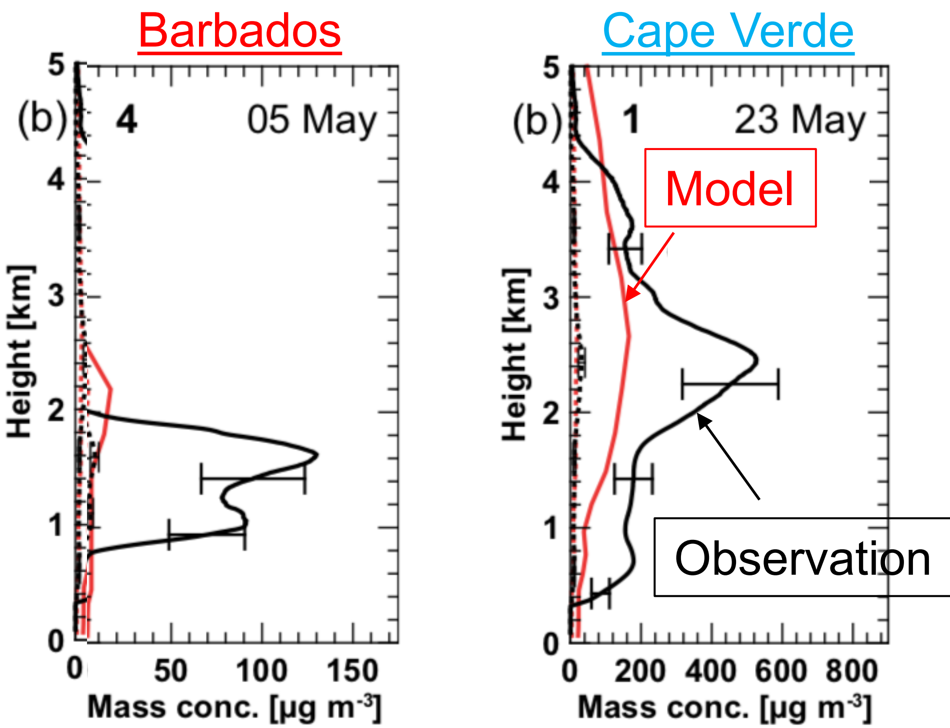
Fine dust cools (generally)

Coarse dust warms (generally)

Several lines of evidence indicate that **models greatly underestimate coarse dust**

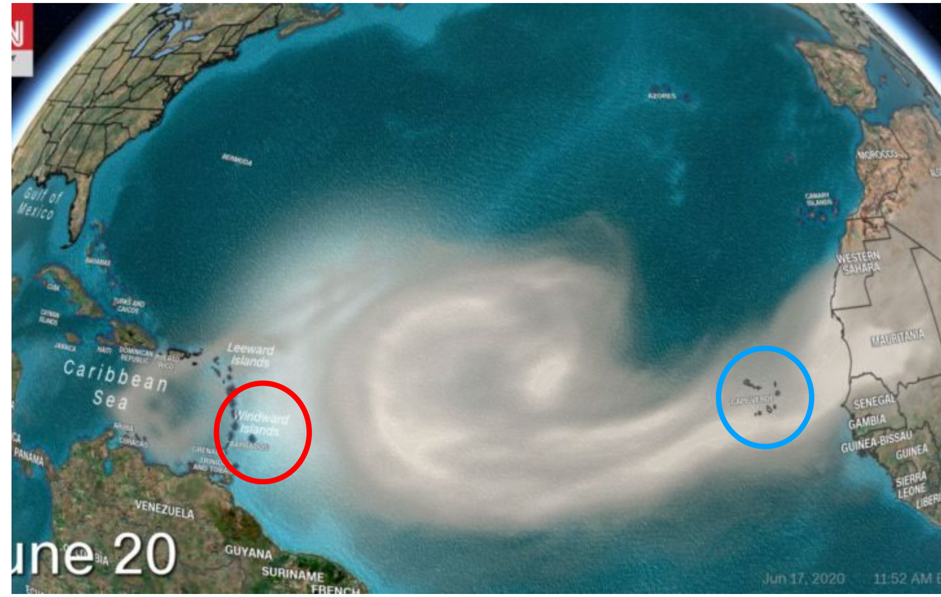
1. Lidar measurements show **models significantly underestimate coarse dust over North Atlantic** (Ansmann et al., 2017)





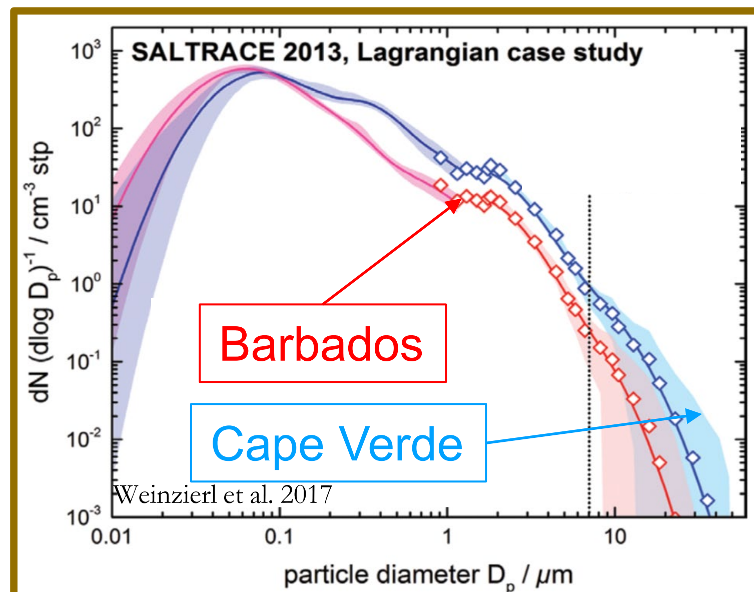
Ansmann et al. 2017

Several lines of evidence indicate that models greatly underestimate coarse dust



1. Lidar measurements show **models significantly underestimate coarse dust over North Atlantic** (Ansmann et al., 2017)

2. **Coarse dust particles are found at greater distances than possible from model simulations** (Maring et al., 2003, Weinzierl et al. 2017, van der Does et al. 2018).

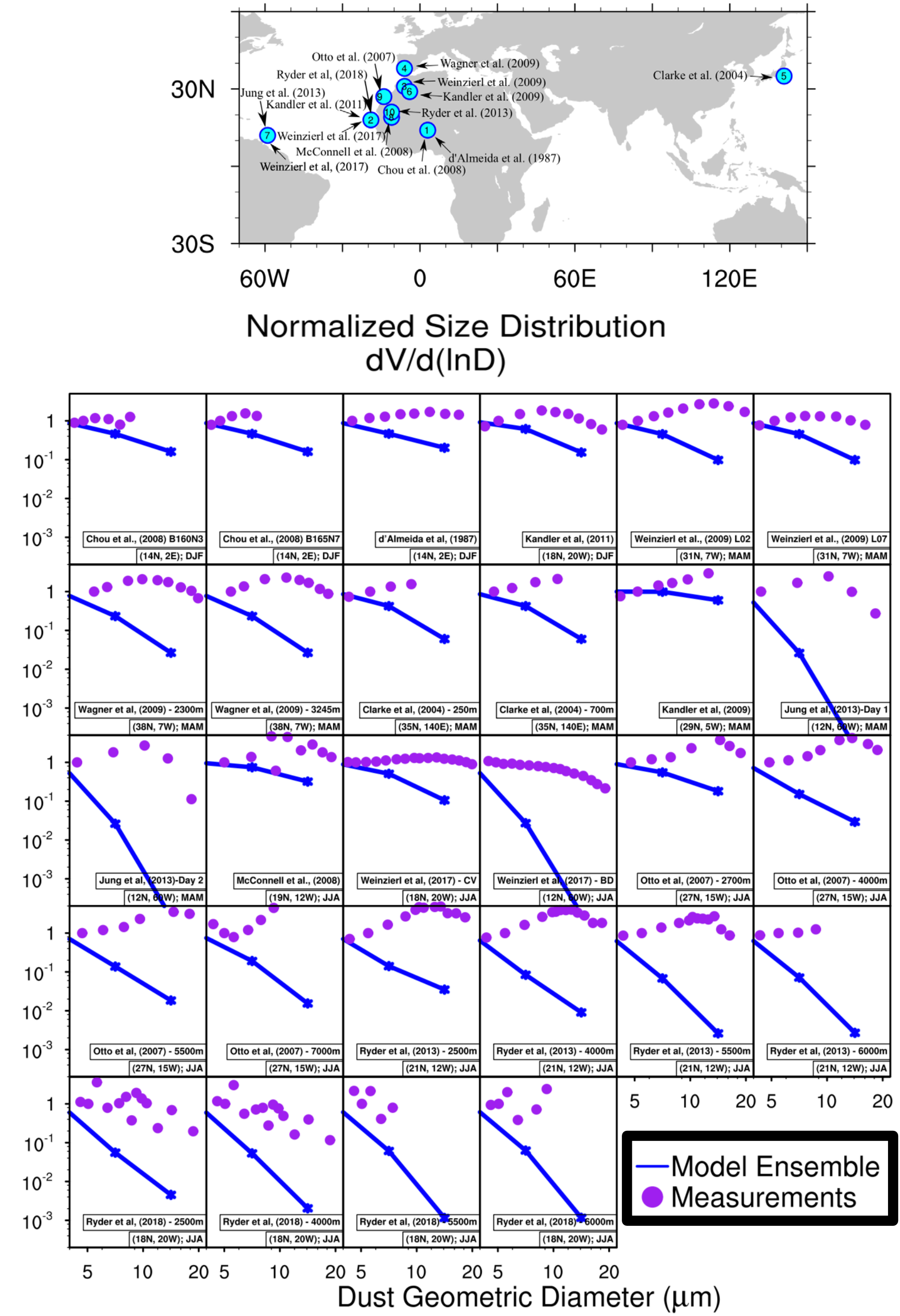


Several lines of evidence indicate that models greatly underestimate coarse dust

1. Lidar measurements show **models significantly underestimate coarse dust over North Atlantic** (Ansmann et al., 2017)

2. **Coarse dust particles are found at greater distances than possible from model simulations** (Maring et al., 2003, Weinzierl et al. 2017, van der Does et al. 2018)..

3. Dozens of **in situ measurements show much more coarse dust than simulated** in model ensemble



Adebiyi & Kok, Science Advances, 2020

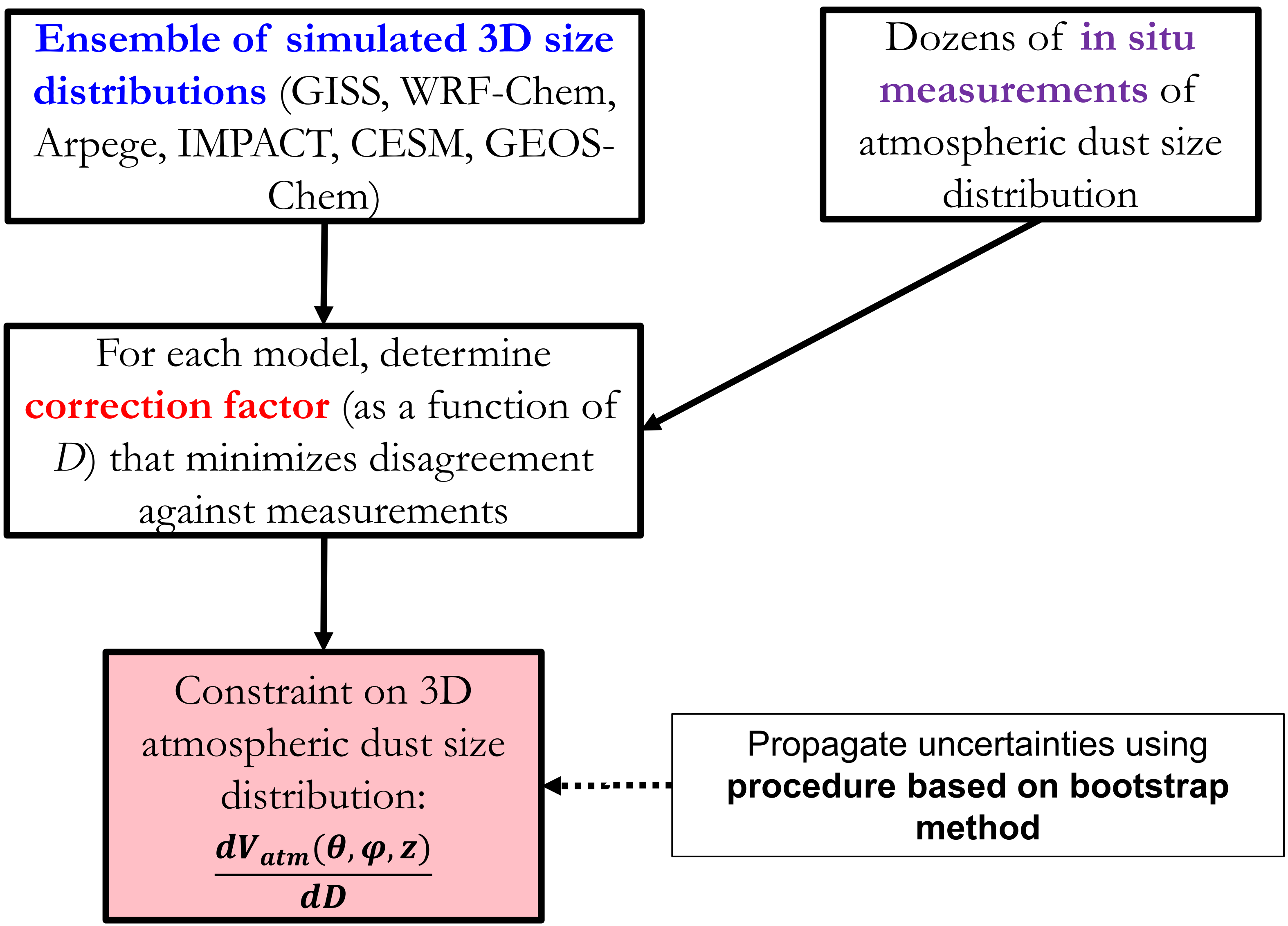
Overview

- **How much coarse dust is missing** from global models?

- What is the **direct radiative effect** of the missing coarse dust?

- What's causing models to underestimate coarse dust and how can we fix this?
  - Do models **underestimate coarse dust emission**?
  - Do models **overestimate coarse dust deposition**?

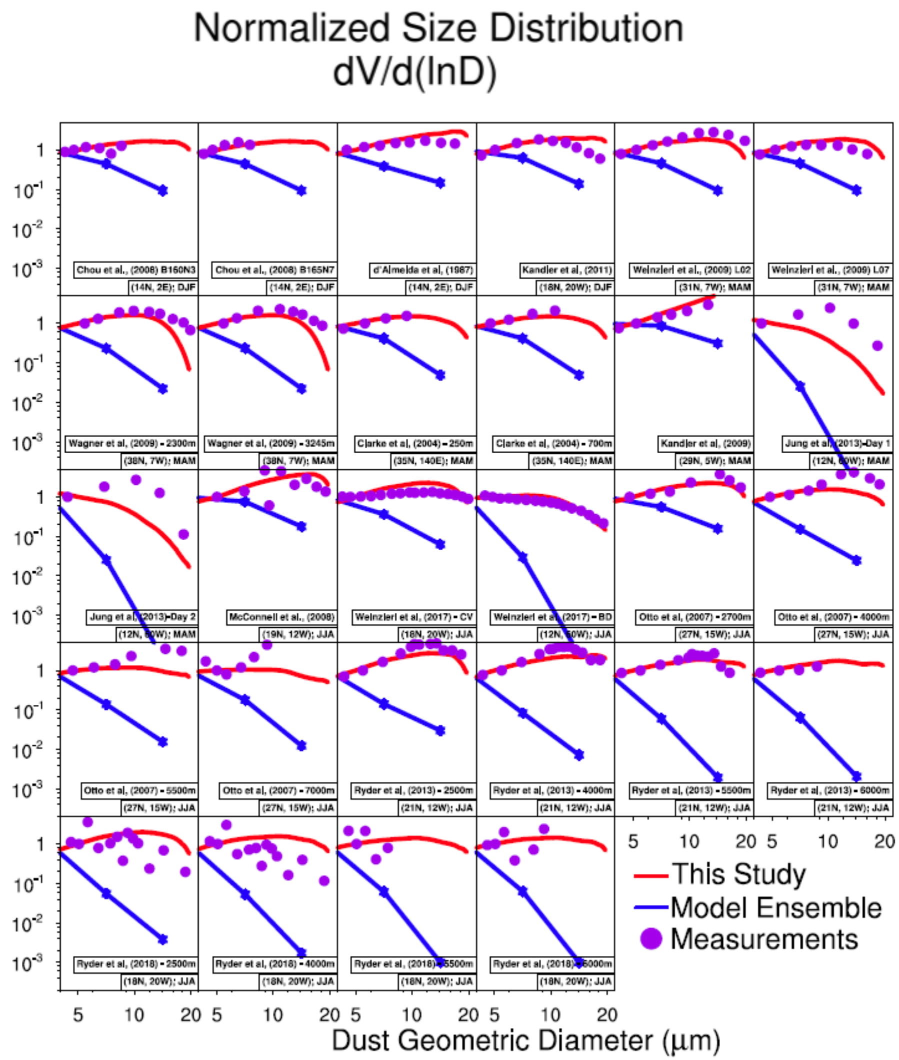
Joint experimental-modeling analysis to constrain 3D atmospheric dust size distribution

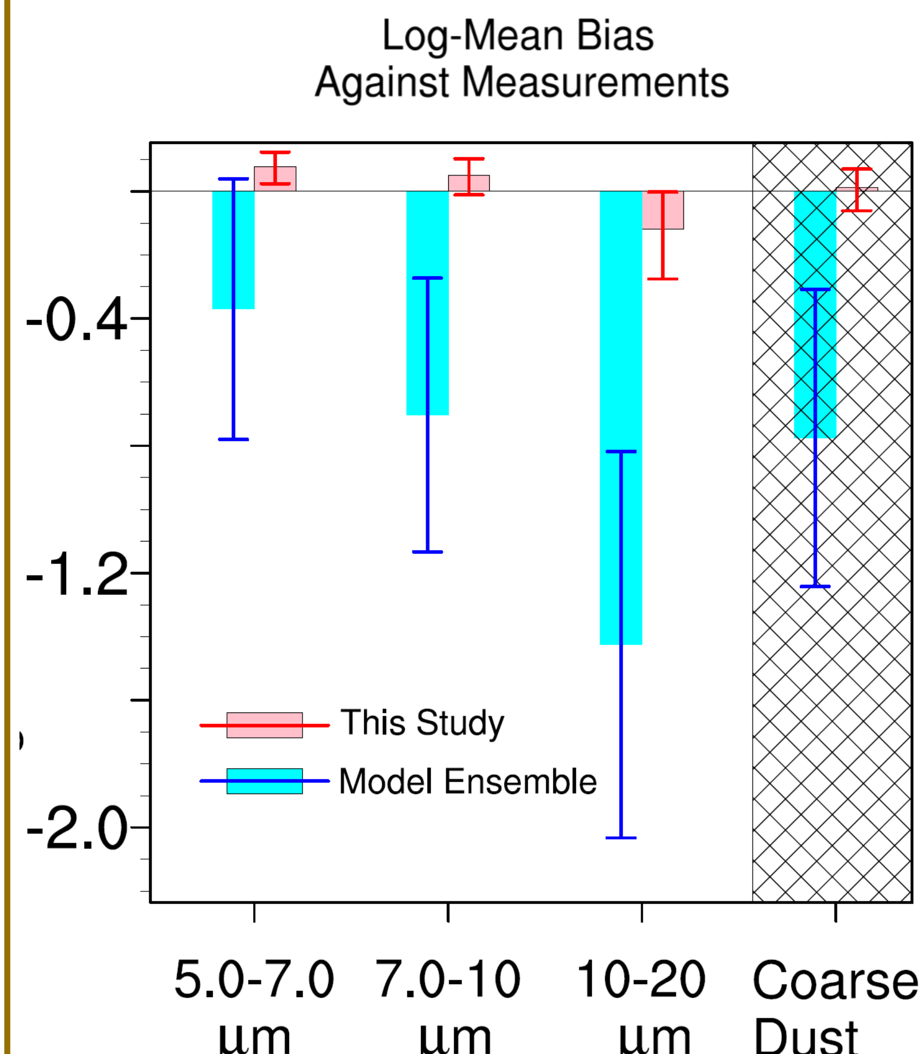


Our estimates agree better with measurements

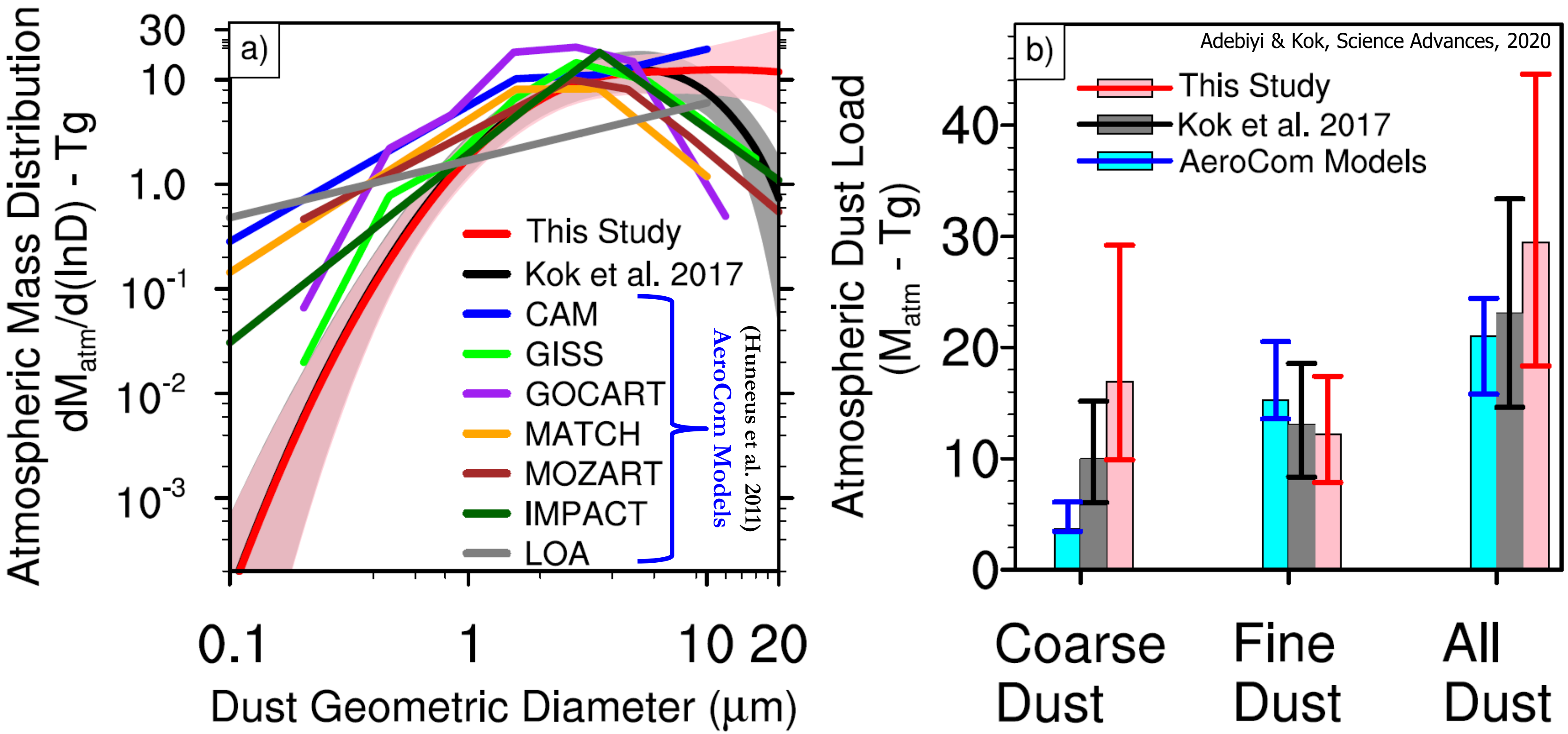
over different locations, height levels, and seasons

→ Almost complete elimination of bias





Most coarse dust mass is missing from (phase I) AeroCom models



- **The atmosphere contains 17 ± 5 Tg of coarse dust!**
- AeroCom models include only **3.7 ± 1.3 Tg**
  - About **3/4 of coarse dust is missing** from AeroCom models!

Overview

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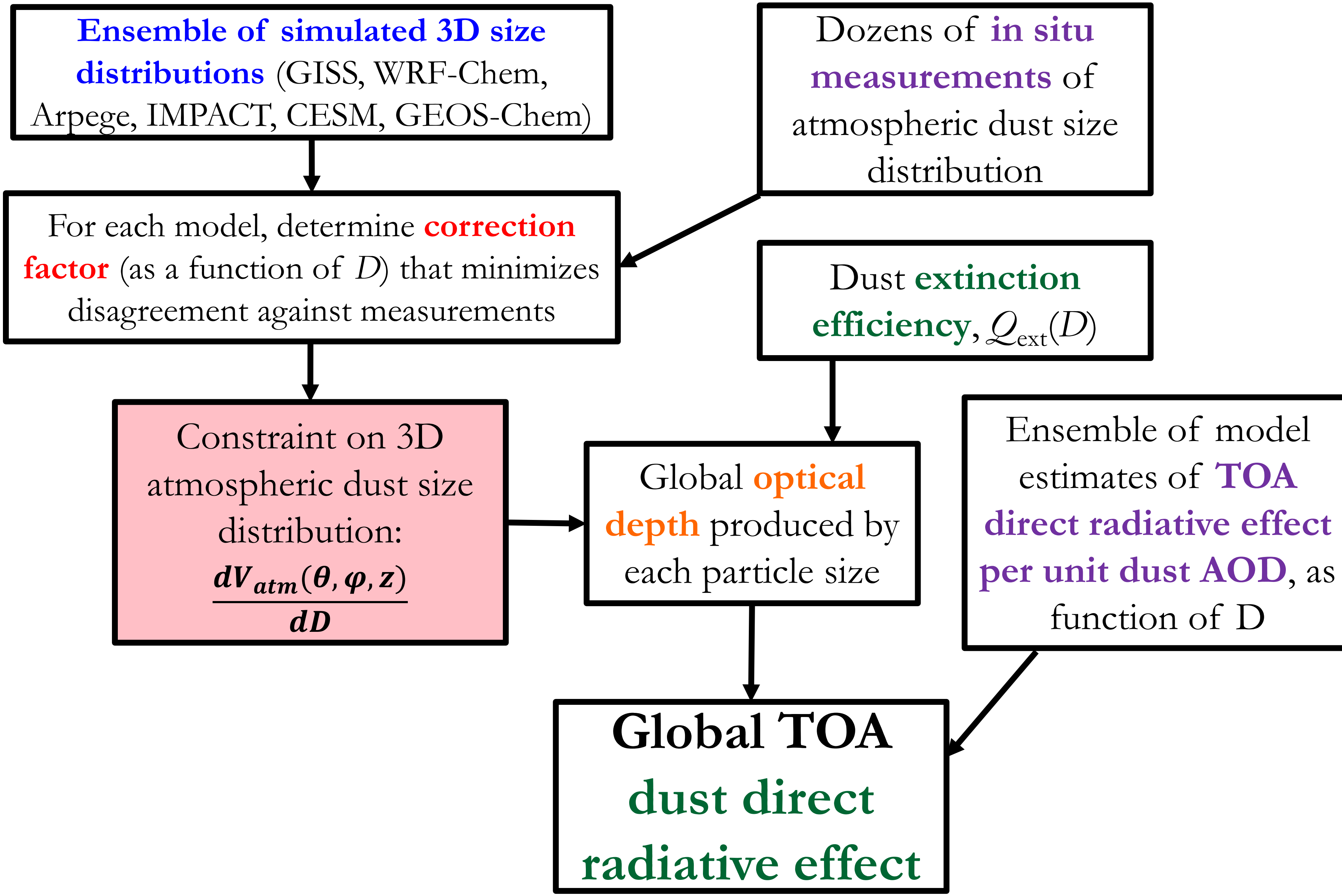
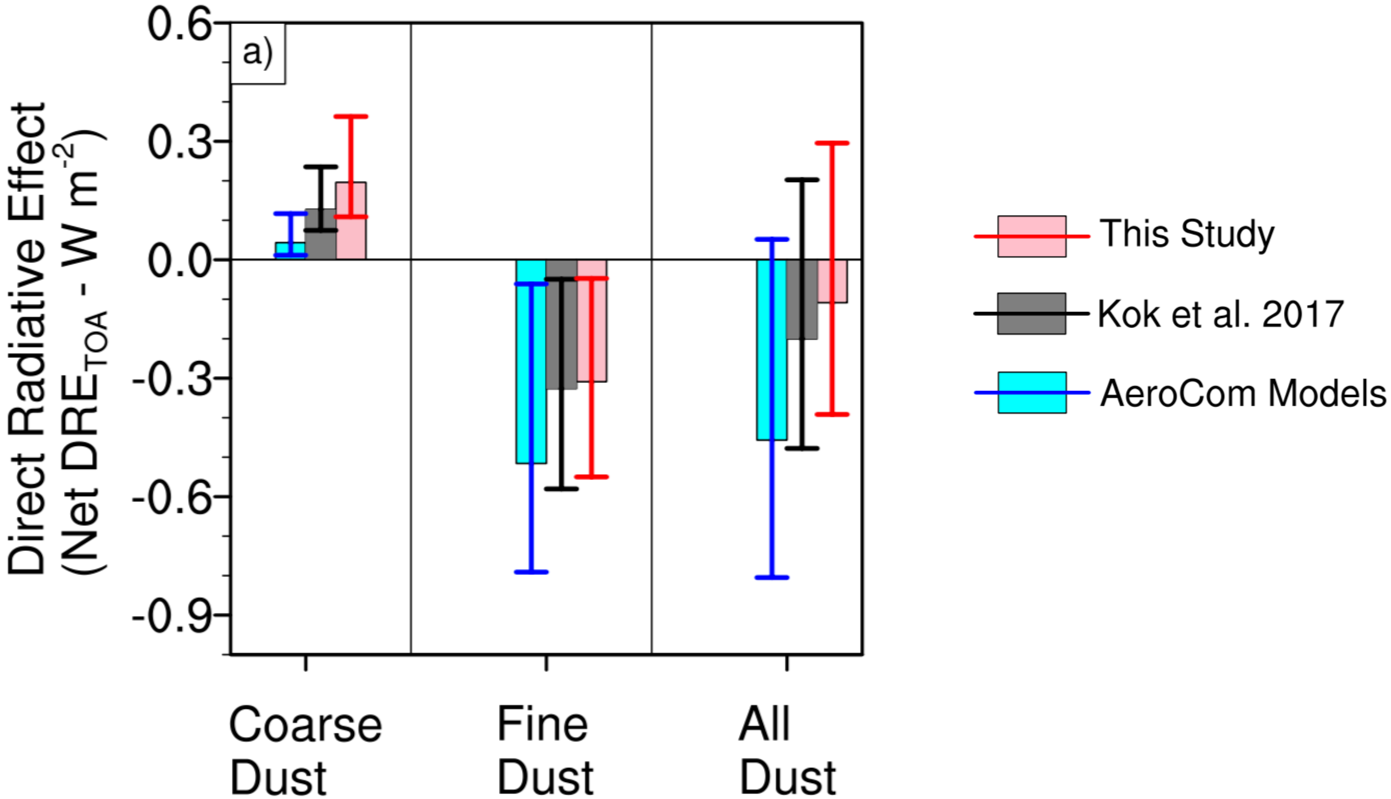
Joint experimental-modeling analysis to constrain dust direct radiative effect



Missing coarse dust adds ~0.1 W/m² warming



- Accounting for **missing coarse dust increases TOA warming by 0.15 ± 0.06 Wm^{-2}**
- Still unclear if dust direct radiative effect net warms or cools!

Overview

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- What is the **radiative effect** of the missing coarse dust?

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  - Do models **underestimate coarse dust emission**?
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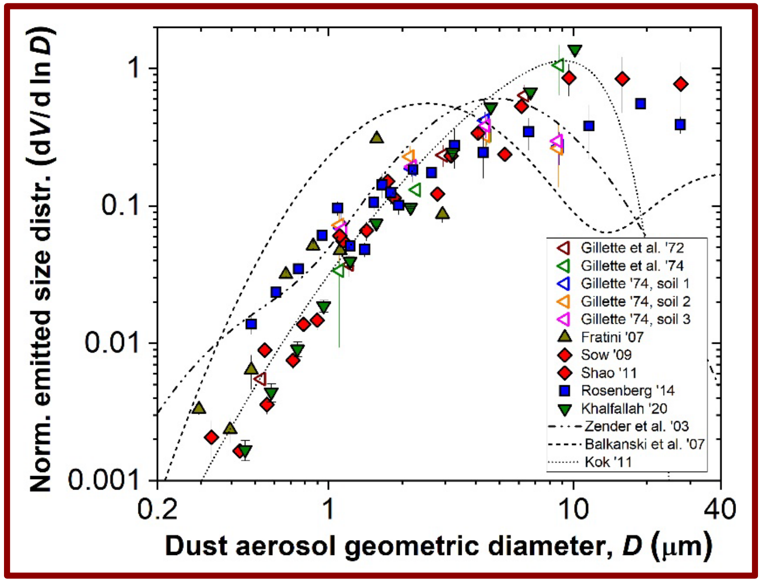
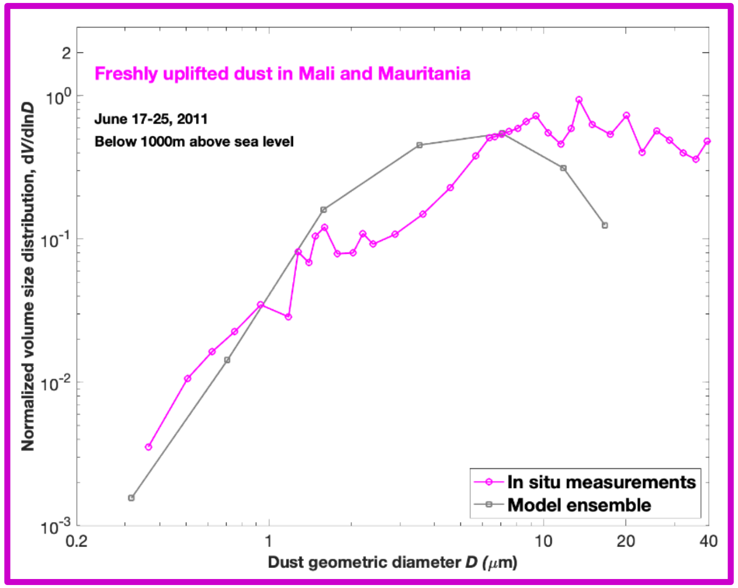
Models underestimate fraction of emitted dust that is coarse

- Modeled coarse dust depends on **size distribution of emitted dust** assumed in models
  - Measurements: vertical dust flux from eroding soil corrected to volume-equivalent diameter
- Models **underestimate emitted coarse dust**
  - Causes **underestimate of in situ measurements** of freshly lifted coarse dust
- Need to develop **improved parameterization**
  - What determines **size distribution of emitted dust**?



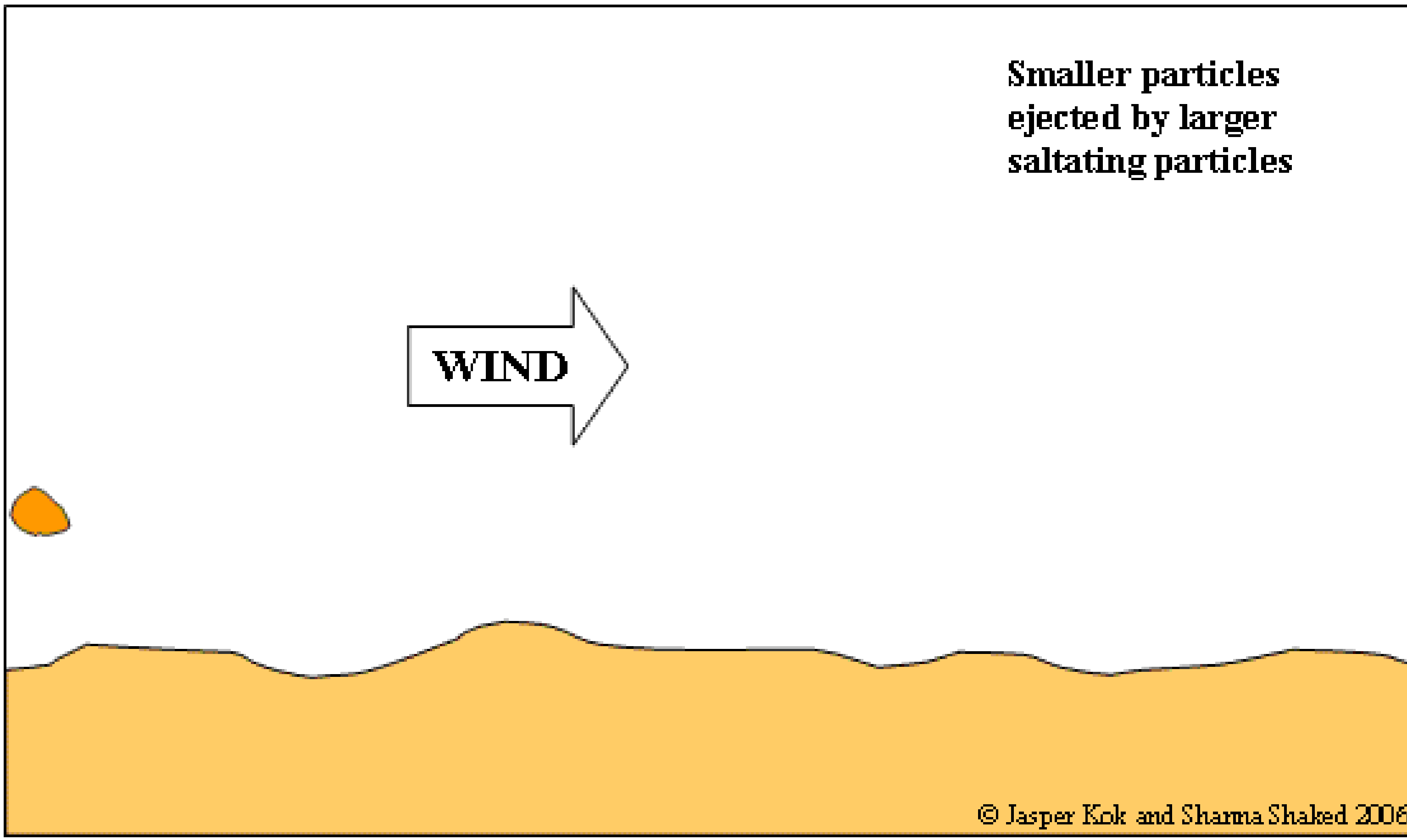
(Huang, Kok, et al., GRL, '21)



(Meng, Kok, et al, GRL, in press; measurements from Ryder '13)

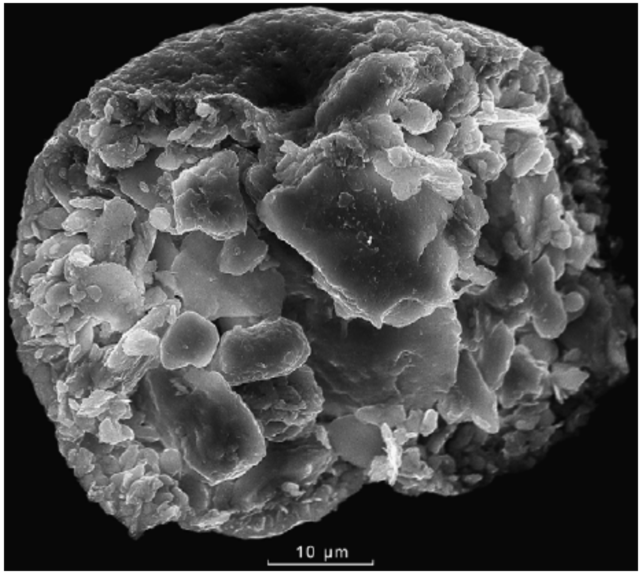
Macrophysics of dust emission: Saltation

- Dust aerosols (~0.1-50 μm) are emitted by **saltation**, the wind-driven hopping motion of sand grains (~250 μm)

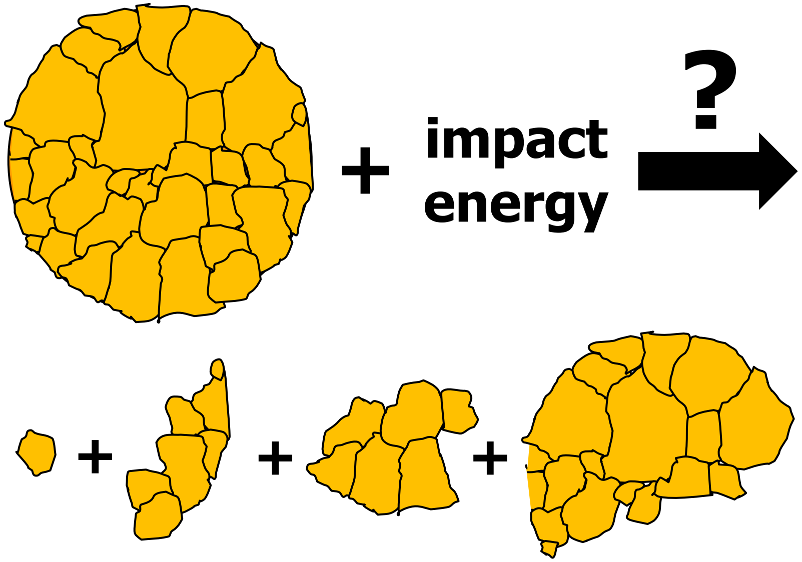


Microphysics of dust emission: Fragmentation of dust aggregates

- Small particles (< ~50 μm) in desert soils form **aggregates**
- Upon impact, **energy is transferred** from impactor to aggregate
  - What is final state of aggregate? Does it **fragment**? Into what particle sizes?



From Diaz-Hernandez and Parrage (2008)

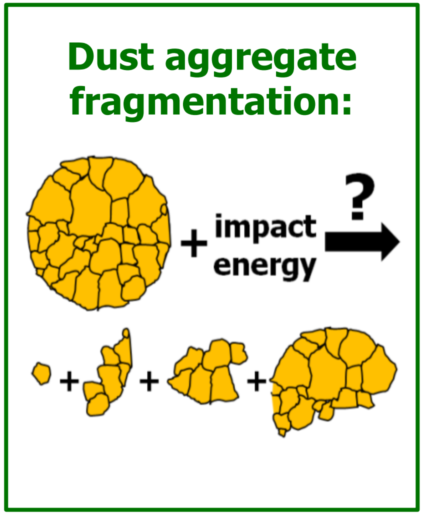


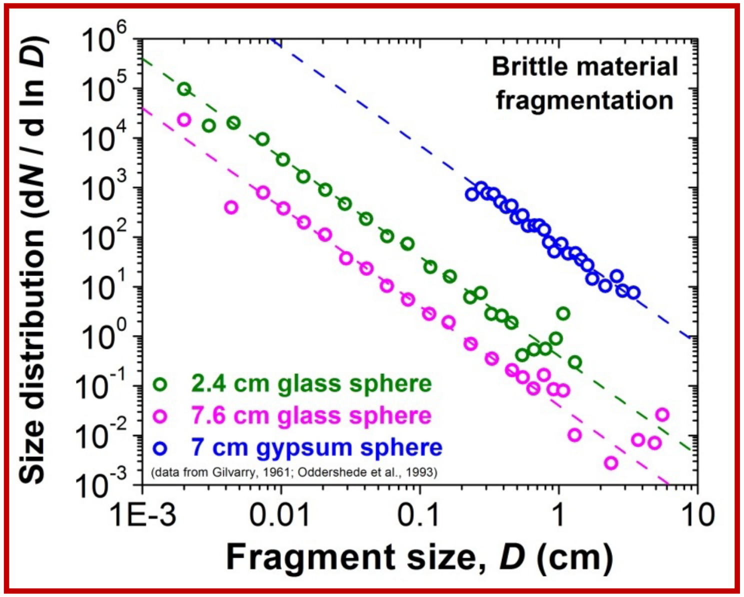
Analog: fragmentation of brittle materials

- **Dust aggregate fragmentation** is very complex problem
- Closest analog is **fragmentation of brittle materials** (e.g., glass)
- Measurements show size distribution is **scale-invariant** (a **power law**)
  - Resulting **size distribution**:

$$\boxed{\frac{dN}{d\log D_f} \propto D_f^{-2}}$$

- **Scale invariance occurs widely** in nature (many small, few large events)
- **What causes scale invariance** in brittle material fragmentation?





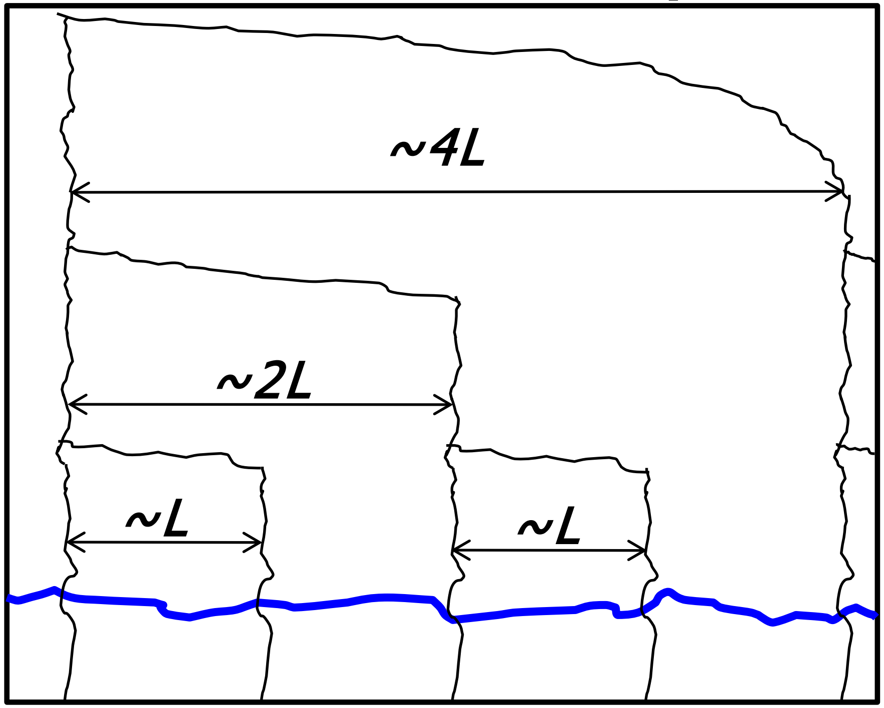
Kok, PNAS, 2011

Scale invariance due to crack merging

- Fragments are produced by **propagation and merger of cracks** in brittle material
- Main crack 'emits' **side cracks** at approximately regular intervals (*L*)
- Cracks are **attracted** to each other
- When **cracks merge**, fragments form
- In 1st 'generation': **N/2 fragments of typical size *L***
- In 2nd 'generation': **N/4 fragments of typical size 2*L*** and so on
- **Yields** $\mathbf{d}N/\mathbf{dlog}D_{\mathbf{f}} \sim D_{\mathbf{f}}^{-2}$ in 3D, as observed

Source: Astrom, 2006

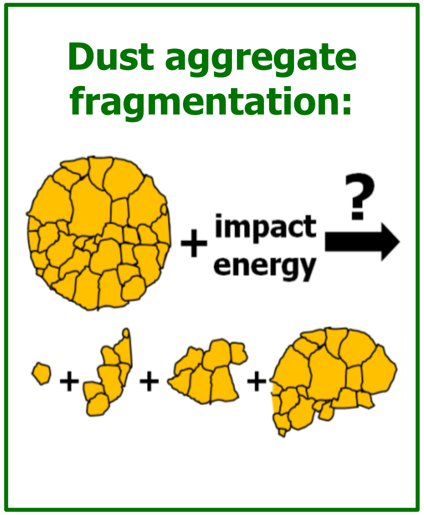
Brittle material sample

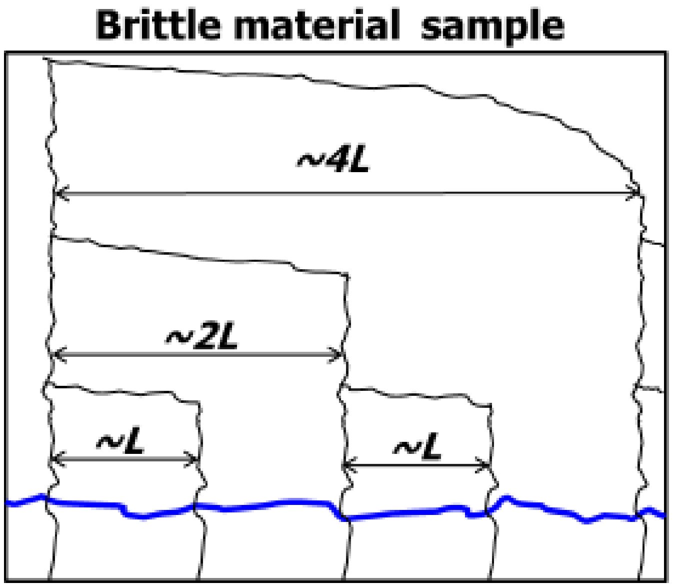


Limits to scale invariance

- Scale invariance can only hold for **limited size range**

- Cannot hold for sizes smaller than **indivisible constituents**
  - Size of **crystal unit or molecules** (~0.1 – 1 nm) for glass, gypsum
  - Size of **discrete dust particles** (~0.1 – 50 μm) for dust aggregates
    - Cracks will **propagate along surfaces** of discrete dust particles!





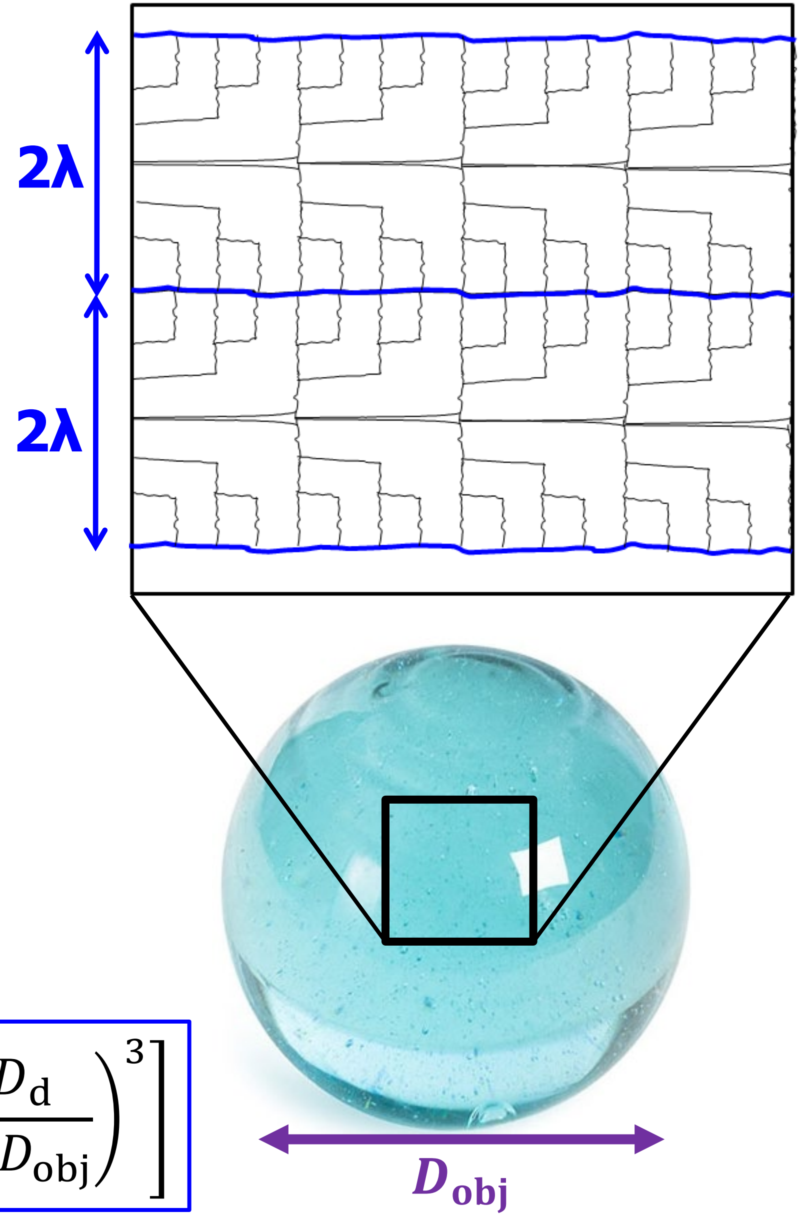
Largest fragments are ~10% of size of object

- Scale invariance cannot hold for sizes larger than **finite side crack propagation length (λ)**
- Measurements and models of brittle fragmentation (e.g., Astrom, 2006):

$$\frac{dN_\mathrm{d}}{d\ln D_\mathrm{d}} \propto D_\mathrm{d}^{-2}\exp\left[-\left(\frac{D_\mathrm{d}}{\lambda}\right)^3\right]$$

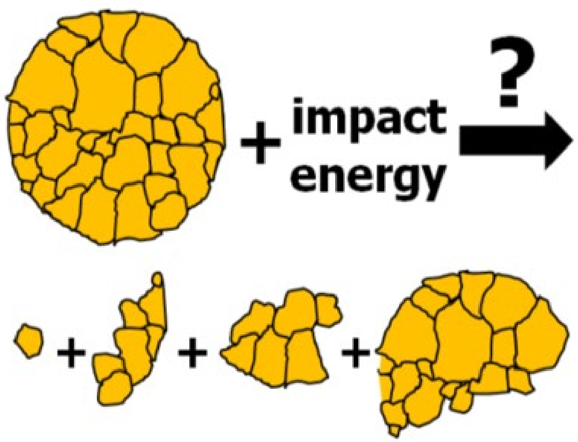
$$\lambda = f_\lambda D_\mathrm{obj};\quad f_\lambda \approx 0.1$$

$$\frac{dN_\mathrm{d}}{d\ln D_\mathrm{d}} \propto D_\mathrm{d}^{-2}\exp\left[-\left(\frac{D_\mathrm{d}}{f_\lambda D_\mathrm{obj}}\right)^3\right]$$



Let's apply this now to **derive the size distribution of dust produced by fragmentation of soil aggregates!**

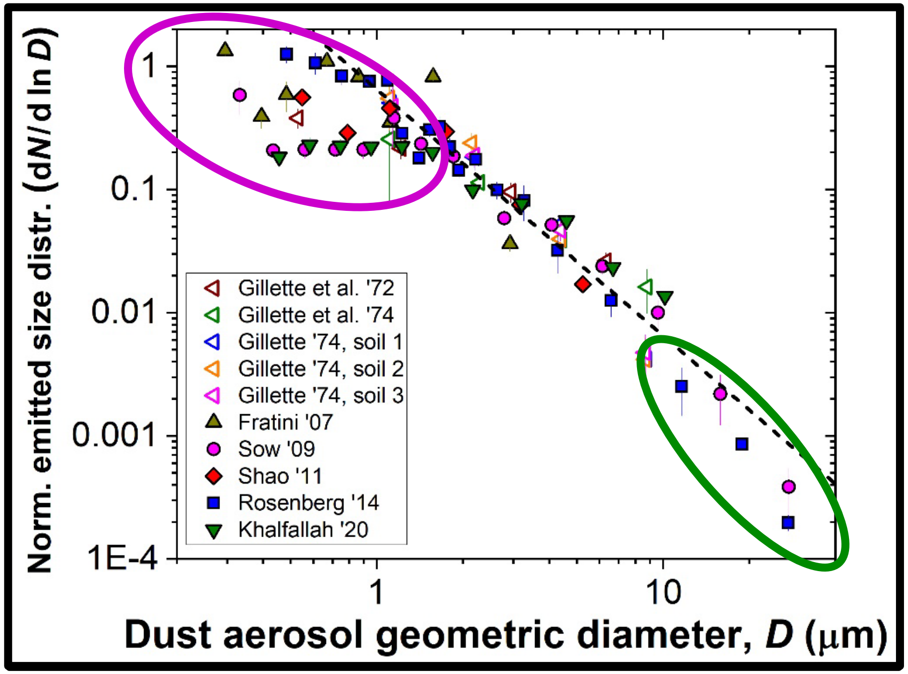
Dust aggregate fragmentation:



Analog: brittle fragmentation

Dust size distribution is consistent with brittle fragmentation physics

- Dust emission **follows brittle fragmentation power law** in ~1 – 10 μm range
- Emission of **finer dust reduced** from power law
  - Expected from >~1 μm size of **discrete dust particles**
- **Coarser dust also reduced**
  - From **finite distance between cracks**



Kok, PNAS, 2011; Meng et al., in prep

Expression for emitted dust size distribution

- Analytical expression:

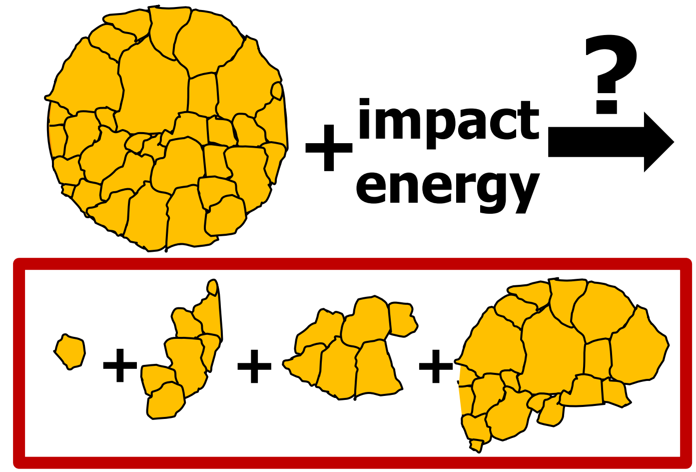
$$\frac{dN_{\mathrm{d}}}{d\ln D_{\mathrm{d}}} = \underbrace{\frac{c}{D_{\mathrm{d}}^2}}_{\text{Scale invariance}} \times \underbrace{\int_0^{D_{\mathrm{d}}} PSD\left(D_{\mathrm{soil}}; \overline{D}_{\mathrm{soil}}, \sigma_{\mathrm{soil}}\right) dD_{\mathrm{soil}}}_{\text{Soil cumulative mass fraction} \leq D_{\mathrm{d}}}$$

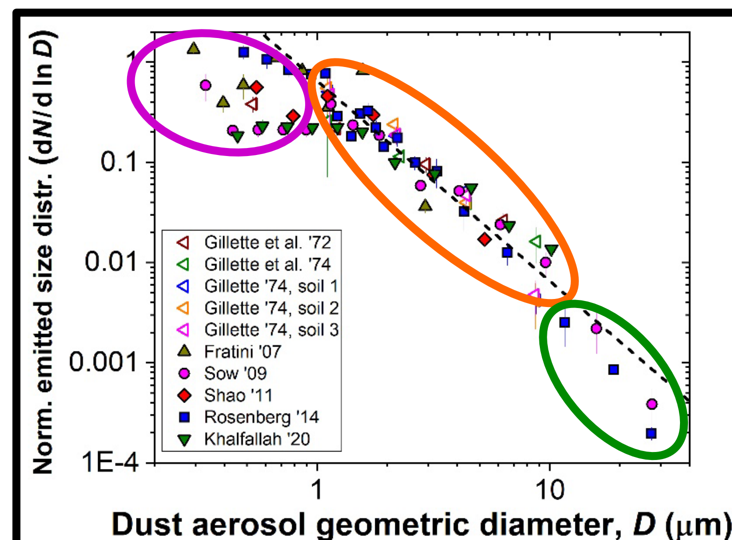
- Creation of smaller dust aerosols limited by **availability of discrete dust particles**

- Emitted fragment of size D_{d} is made up of **soil constituents ≤ D_{d}**
  → Amount of emitted D_{d} **proportional** to amount of soil constituents with $D_{\mathrm{soil}} \leq D_{\mathrm{d}}$

- Assume **log-normal distribution of dust particles** (≤ 50 μm) in soil
  - $\overline{D}_{\mathrm{soil}}$ and σ_{soil} describe distribution of **disaggregated** dust in soil

- Creation of larger dust aerosols limited by **finite distance between cracks**



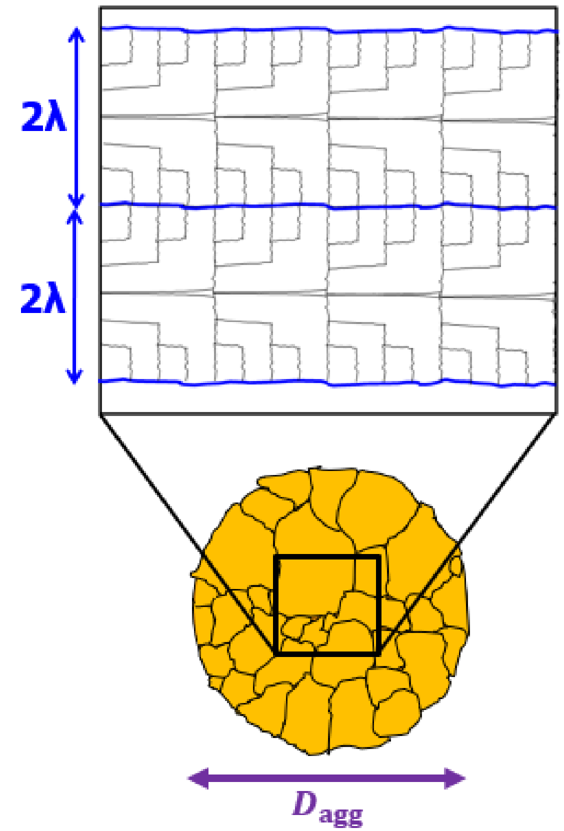


Kok, PNAS, 2011; Meng et al., in prep

Accounting for size distribution of soil aggregates

- Size distribution of soil dust aggregates ($PSD(D_{\mathrm{agg}})$) is lognormal

- For arid regions, no clear relation to soil properties. Measurement compilation:
  - $\overline{D_{\mathrm{agg}}} = 127 \pm 47\ \mu\mathrm{m}$
  - $\sigma_{\mathrm{agg}} = 3.0 \pm 1.0$



Size distribution from fragmenting **single soil aggregate**:

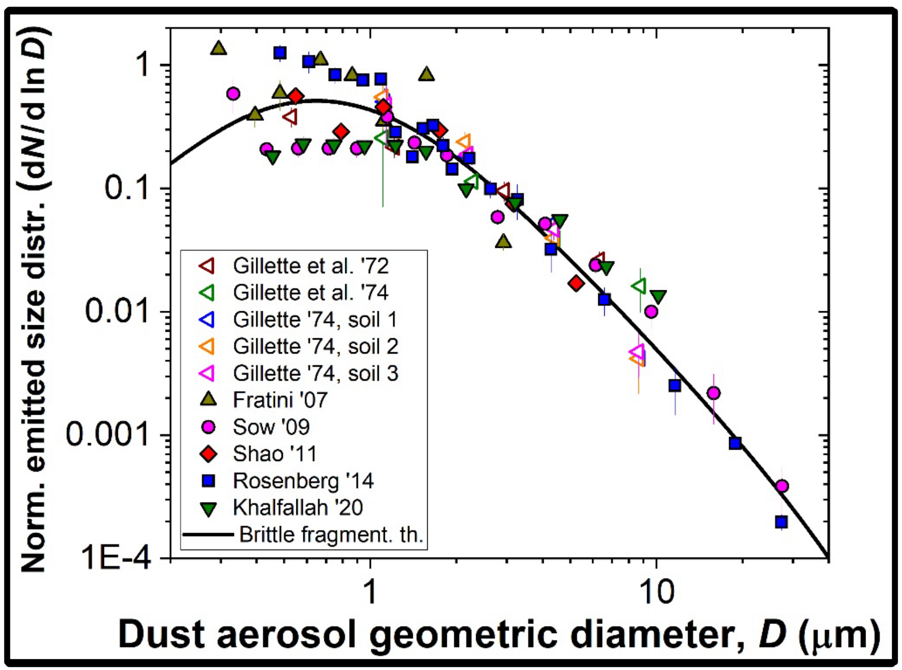
$$\frac{dN_{\mathrm{d}}}{d\ln D_{\mathrm{d}}} \propto D_{\mathrm{d}}^{-2} \exp\left[-\left(\frac{D_{\mathrm{d}}}{f_{\lambda} D_{\mathrm{agg}}}\right)^{3}\right]$$

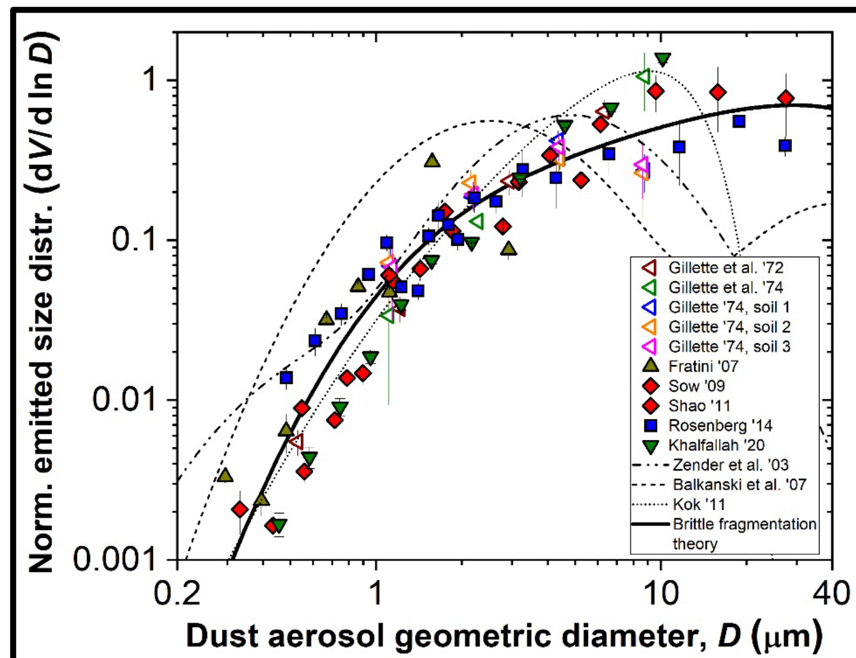
Size distribution produced by **soil with range of soil aggregates**:

$$\frac{dN_{\mathrm{d}}}{d\ln D_{\mathrm{d}}} \propto D_{\mathrm{d}}^{-2} \int PSD(D_{\mathrm{agg}}) \exp\left[-\left(\frac{D_{\mathrm{d}}}{f_{\lambda} D_{\mathrm{agg}}}\right)^{3}\right] dD_{\mathrm{agg}}$$

Expression for emitted dust size distribution

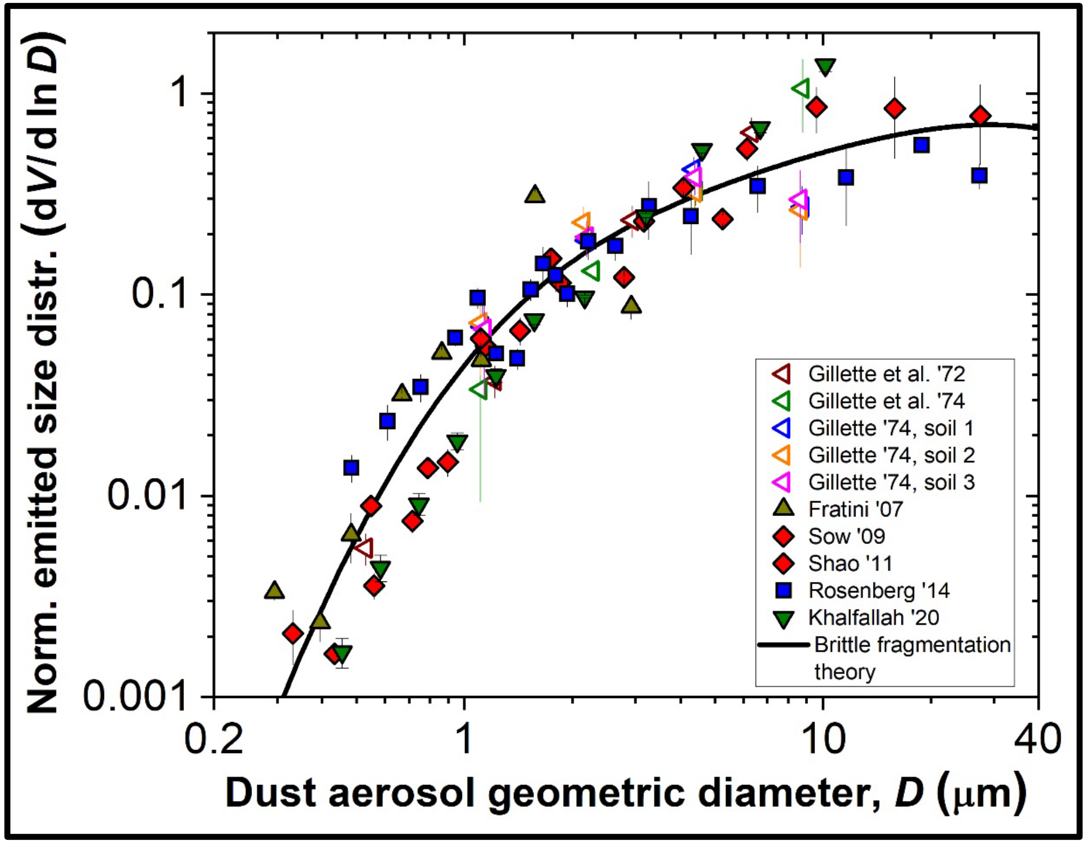
$$\frac{dN_{\mathrm{d}}}{d\ln D_{\mathrm{d}}} = \underbrace{\frac{c}{D_{\mathrm{d}}^2}}_{\text{Scale invariance}} \times \underbrace{\left\{0.5+\frac{\operatorname{erf}\left[\ln\left(D_{\mathrm{d}}/\overline{D}_{\mathrm{soil}}\right)\right]}{2\sqrt{2}\,\ln\sigma_{\mathrm{soil}}}\right\}}_{\text{Soil cumulative mass fraction} \le D_{\mathrm{d}}} \times \underbrace{\int PSD\left(D_{\mathrm{agg}}\right)\exp\left[-\left(\frac{D_{\mathrm{d}}}{f_\lambda D_{\mathrm{agg}}}\right)^3\right] dD_{\mathrm{agg}}}_{\text{Finite crack separation}}$$





Kok, PNAS, 2011; Meng et al., in prep

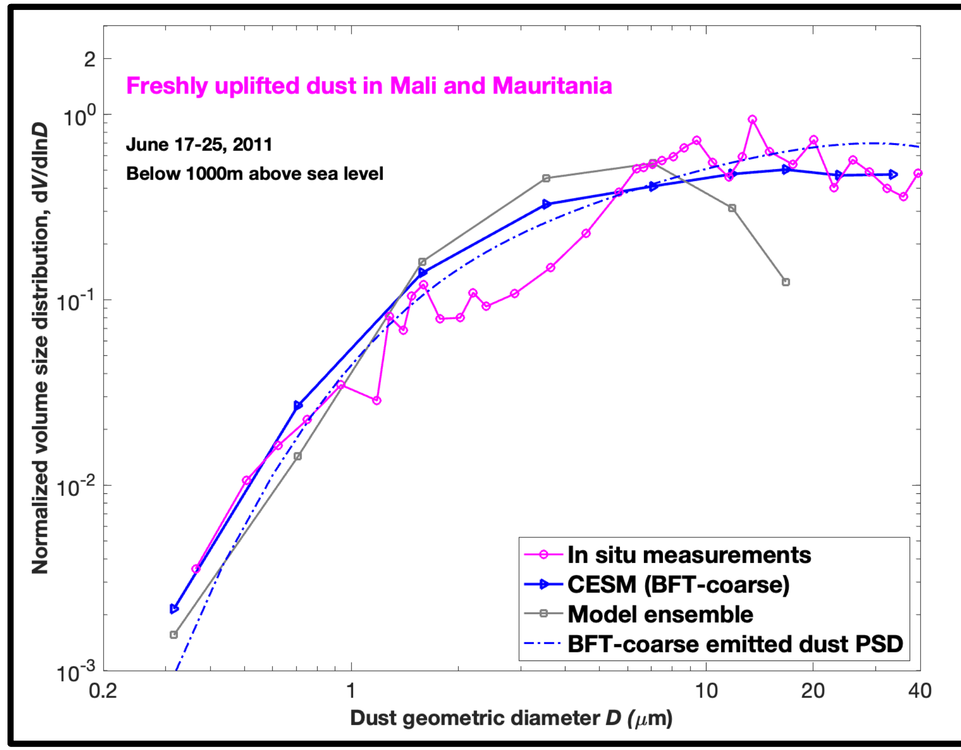
Can a global aerosol model with improved emitted dust PSD parameterization reproduce in situ measurements of coarse dust?



Model with parameterization reproduces freshly lifted coarse dust

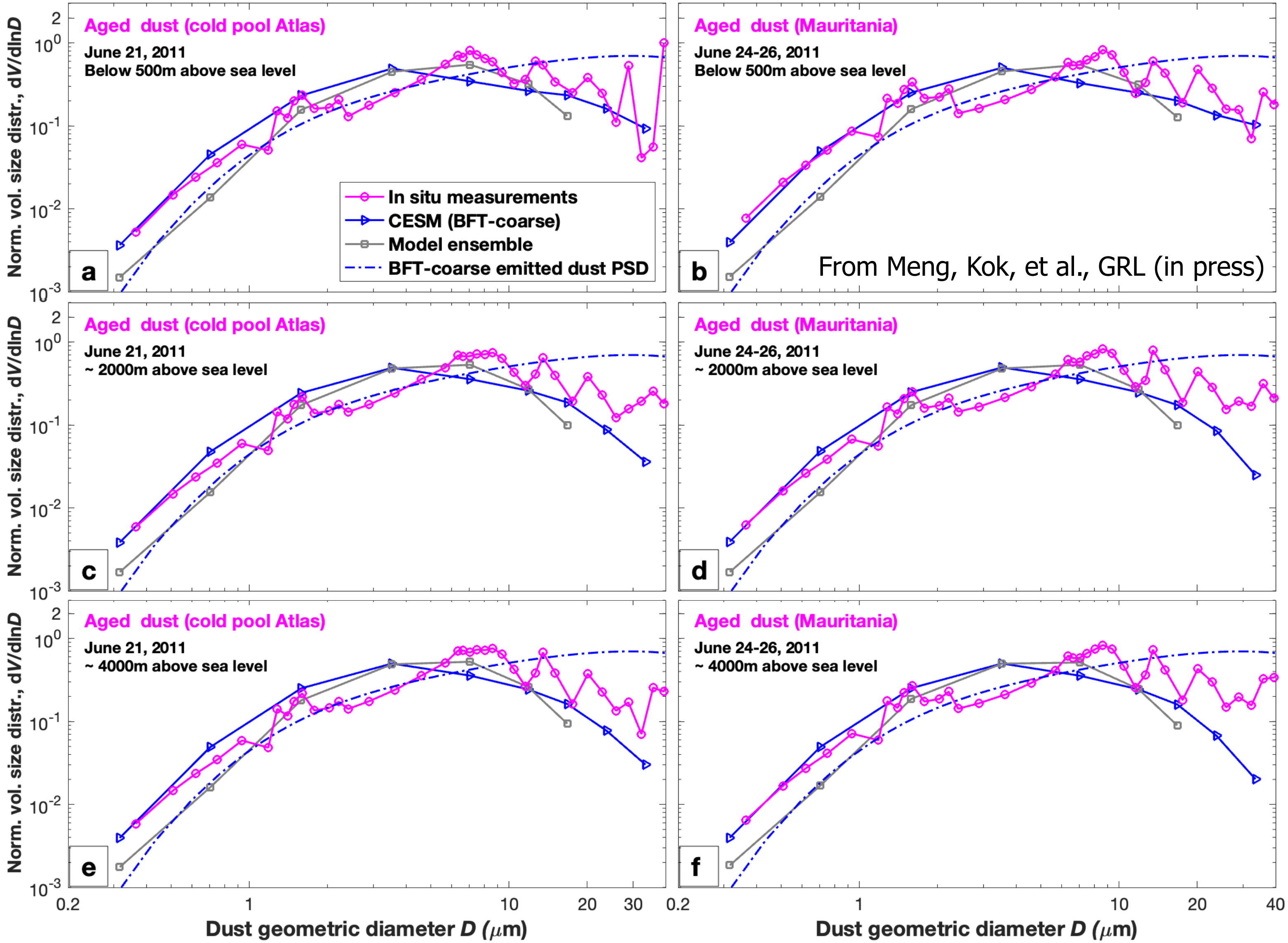
- Implemented parameterization into Community Earth System Model (CESM)

- Reproduces measured (normalized) size distribution of freshly lifted coarse dust



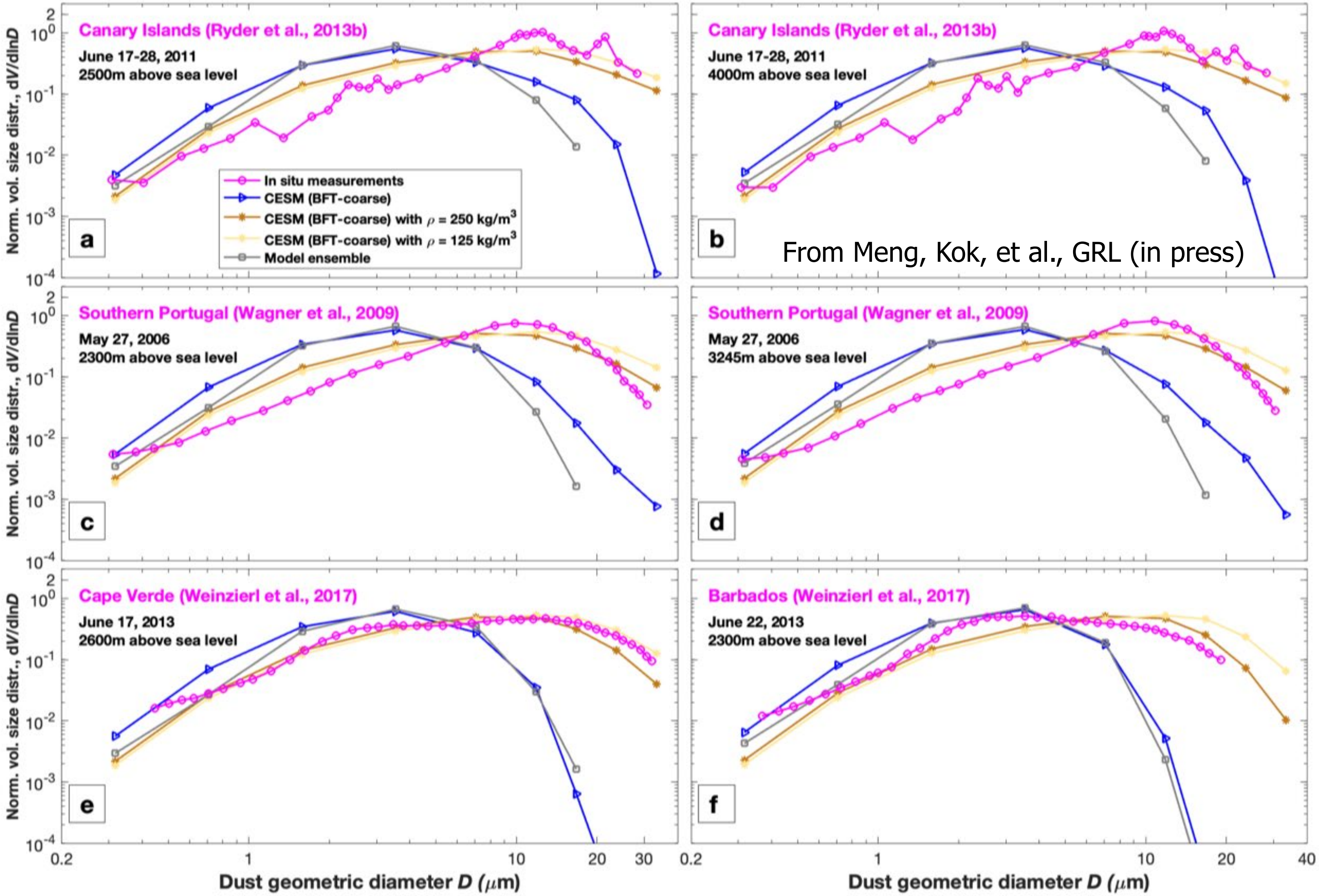
From Meng, Kok, et al., GRL (in press); measurements from Ryder et al '13, corrected to geometric diameter following Huang, Kok, et al '21

Model starts underestimating super coarse dust after aging



- The higher the altitude, the larger the underestimation

Model still greatly underestimates super coarse dust after long-range transport



From Meng, Kok, et al., GRL (in press)

- Need to reduce dust density by x10 to capture long-range transport!
- Similar conclusion by recent paper by Drakaki et al. (ACP, in discussion)

Overview

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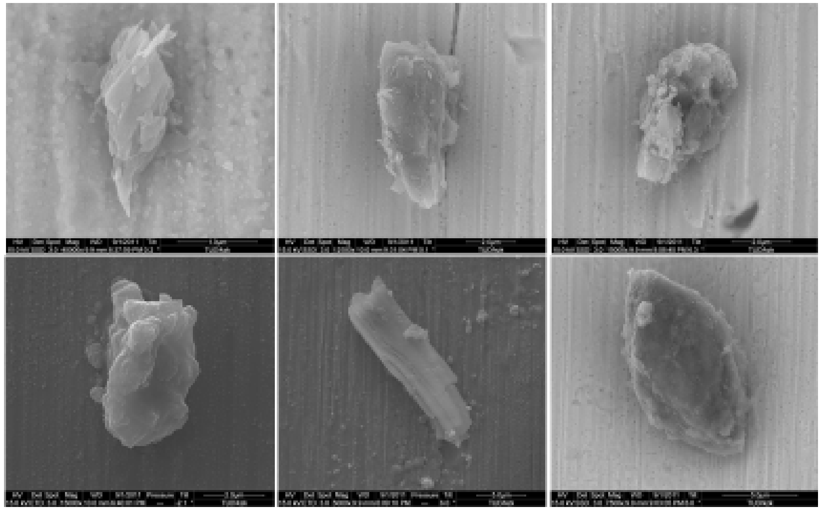
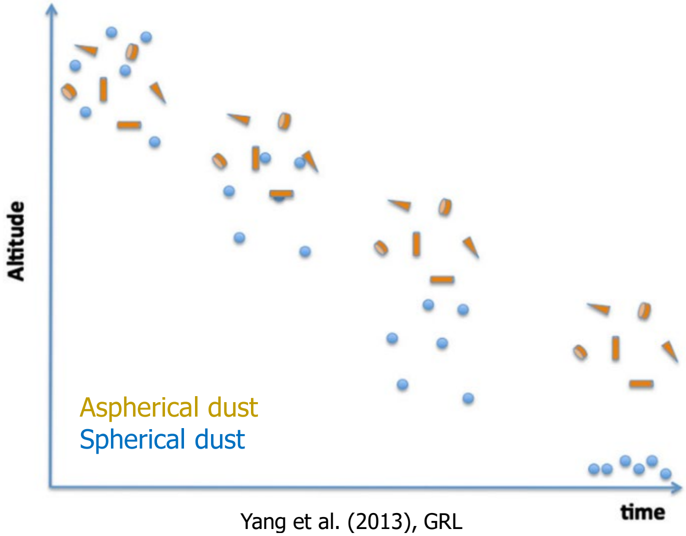
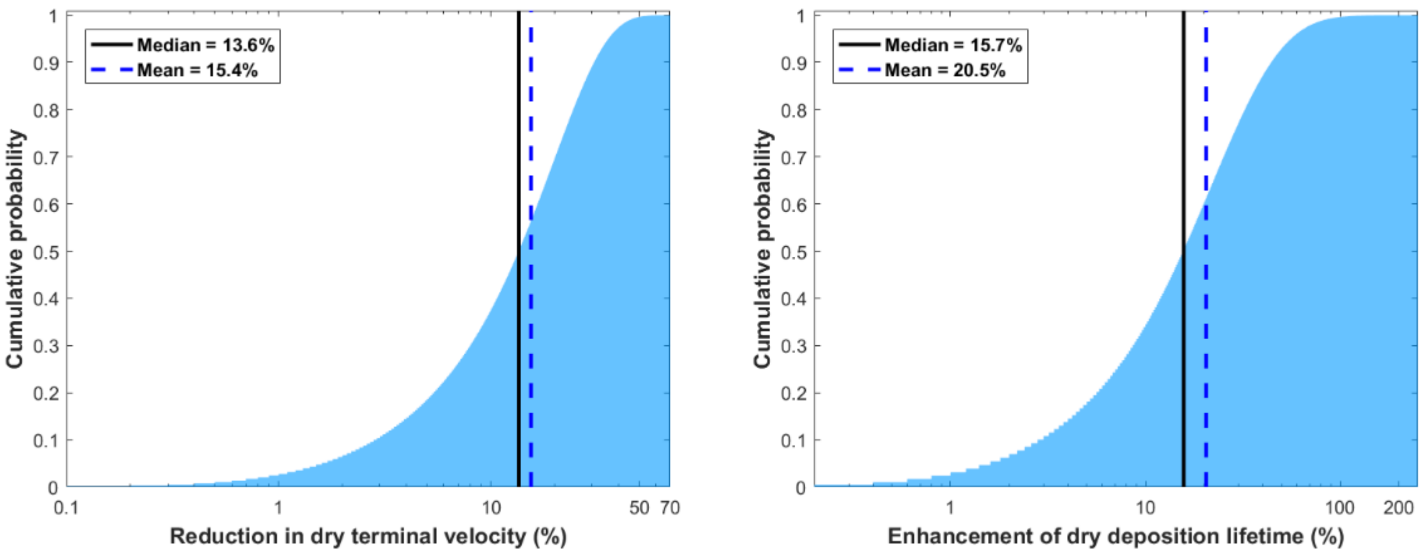
Partial explanation #1: Dust asphericity slows settling; increases lifetime by ~20%





Yang et al. (2013), GRL

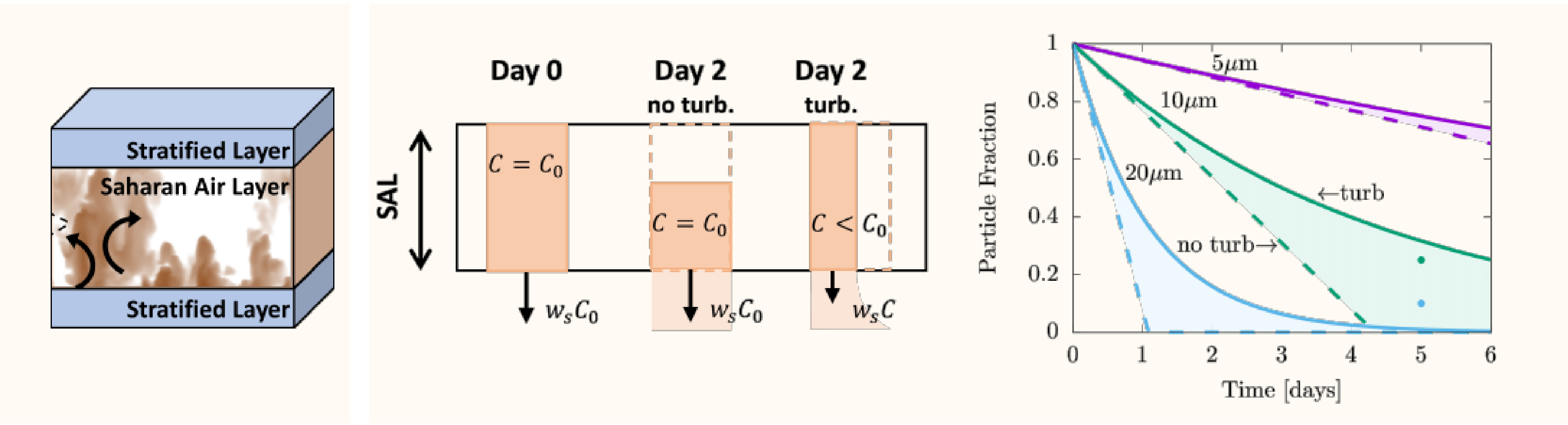


Huang, Kok, et al., GRL, 2020

Partial explanation #2: Gentle topography dramatically increases vertical transport of coarse dust in ABL

Heisel, Chen, Kok & Chamecki, JGR, 2021

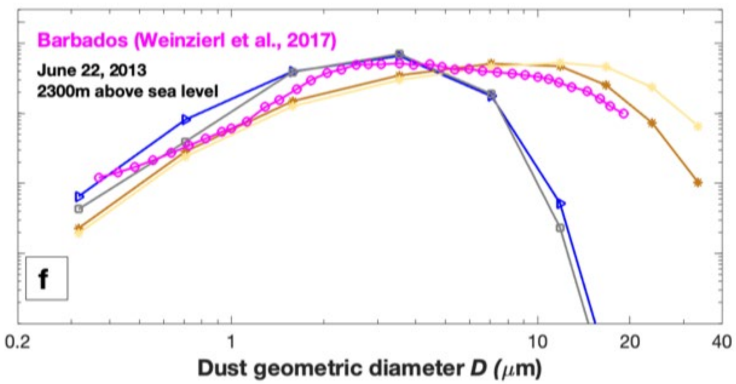
Partial explanation #3: Turbulence in Saharan Air Layer likely slows settling



- Turbulence could be generated by shear and buoyancy (dust SW warming and/or LW cooling)
- Simple model: turbulence has potential to decrease deposition flux and increase lifetime
  - Detailed LES study ongoing

Credit: Marcelo Chamecki

So what's causing models to overestimate coarse dust deposition?



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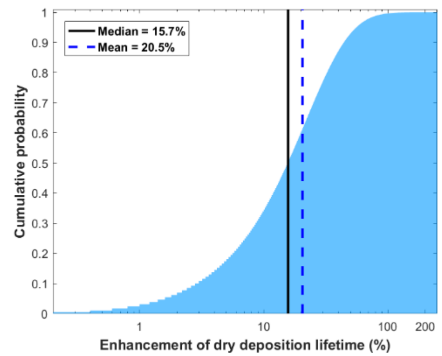

Dust asphericity slows settling

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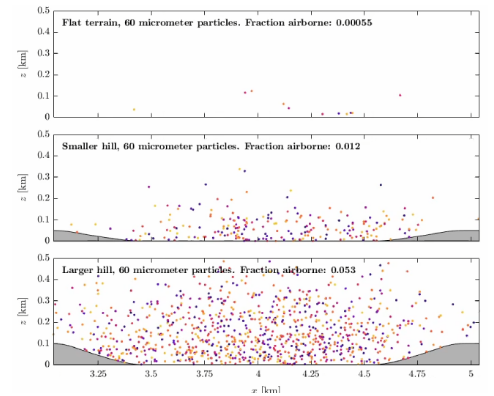

Gentle topography greatly enhances vertical transport of coarse aerosols

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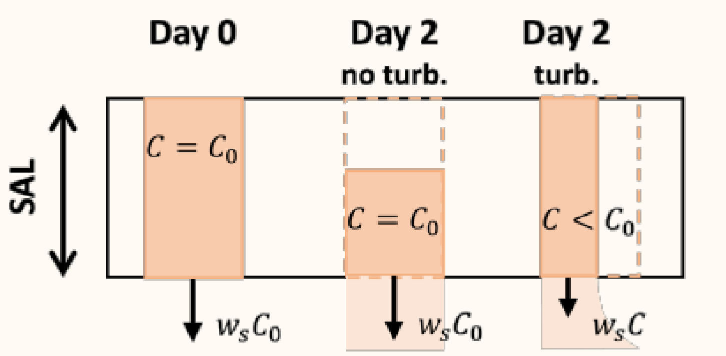


SAL turbulence slows settling

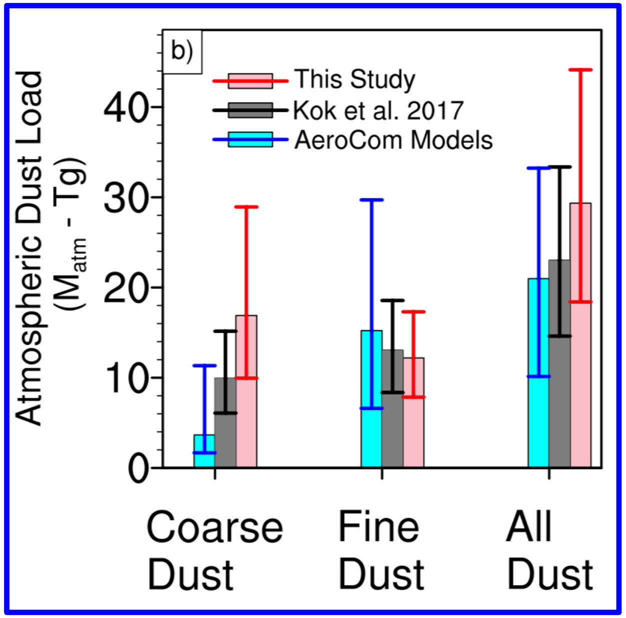
+

One or more other mysterious processes:

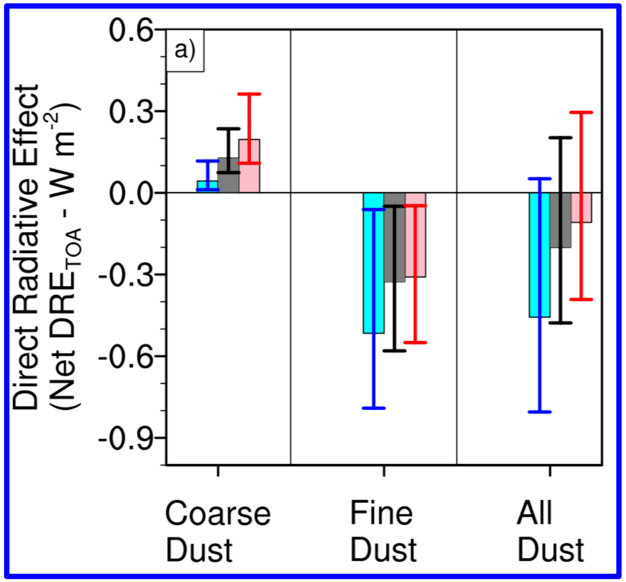
- Self-lofting
- Electrostatic forces
- Excessive numerical diffusion
- Convection events
- Etc

Summary and conclusions (1)

- The atmosphere contains **17±5** Tg of coarse dust
  - About a third of all PM by mass!
  - Models account for only ~quarter of this



- Adds **0.15 ± 0.06 W m^{-2}** of warming



Summary and conclusions (2)

- Models **underestimate coarse dust emission**
- Dust shatters like **glass**!
  - **New parameterization** captures coarse dust near source regions
- Models also **overestimate dust deposition**
  - Reasons not yet fully clear