Climate models miss most of the warming coarse dust in the atmosphere

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Take-home points:

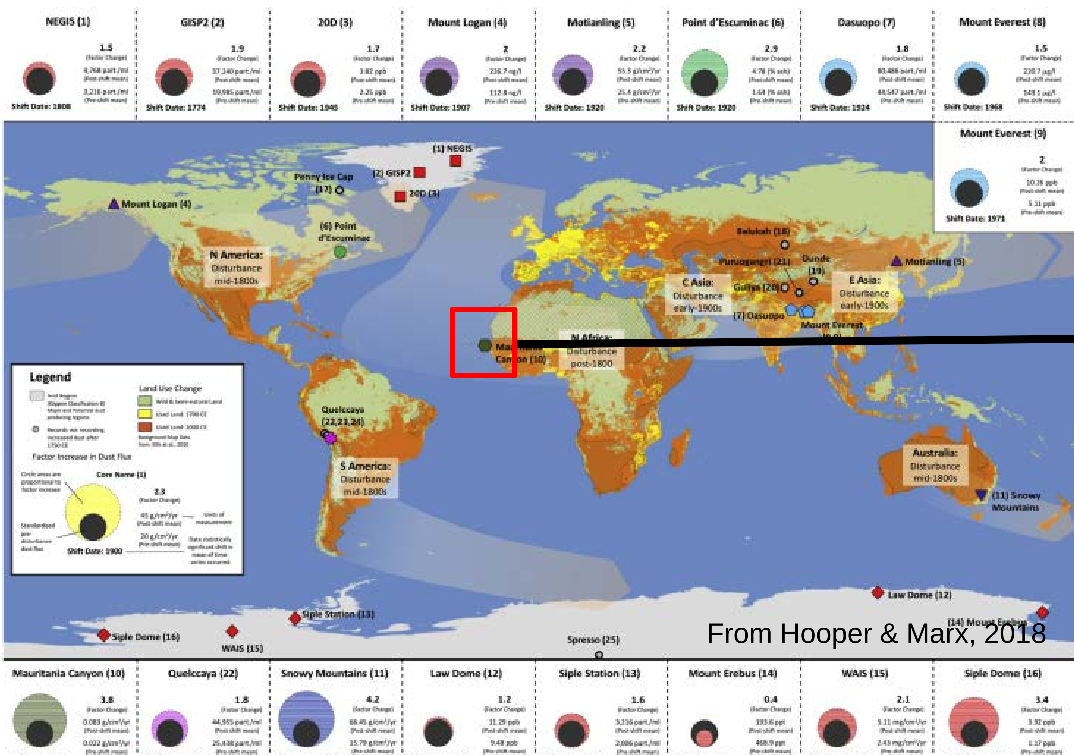
- **The atmosphere contains ~four times more coarse dust** (*D* > 5 μm) than included in models
- Accounting for the missing coarse dust **adds a direct radiative effect of 0.15 ± 0.06 W m^{-2}**

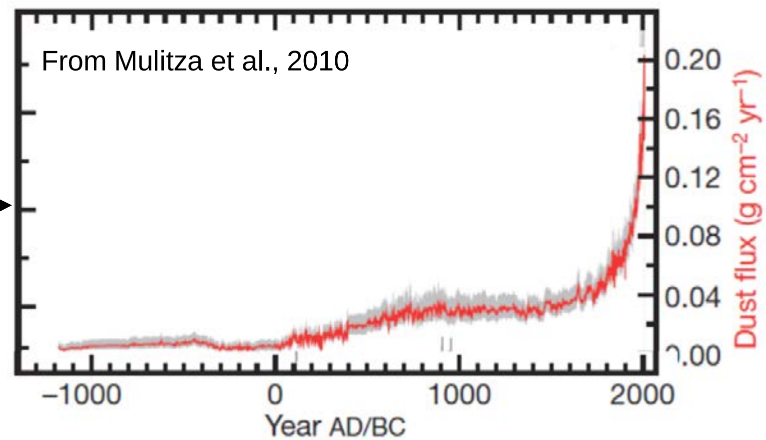
Collaborators: Chun Zhao, Akinori Ito, Pierre Nabat, David Ridley, and Yang Wang

Has dust exerted a substantial "missing" radiative forcing?

- **Dust increased strongly in many regions** since PI (Marx & Hooper, '18)
  - Might have globally ~doubled (Mahowald et al., '10; Marx & Hooper, '18)
  - Not represented well in current climate models

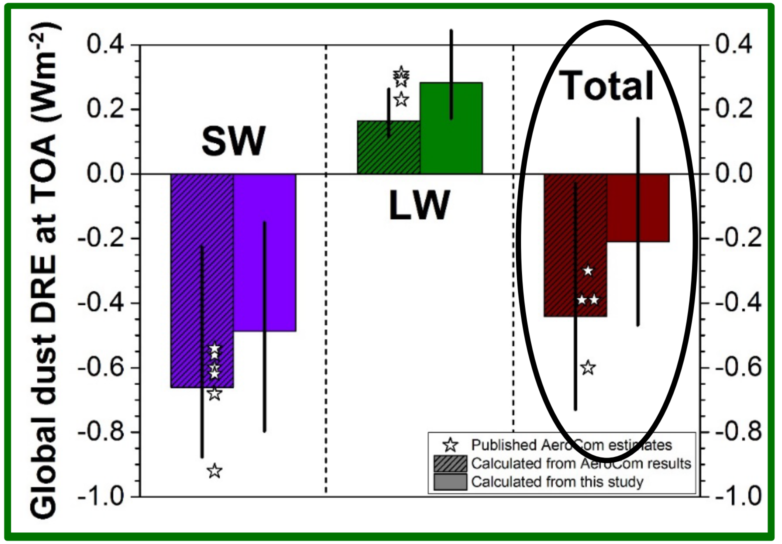
- Possibly substantial **"missing" radiative forcing**
  - Need to figure out **net direct (and indirect) radiative effect** of dust!





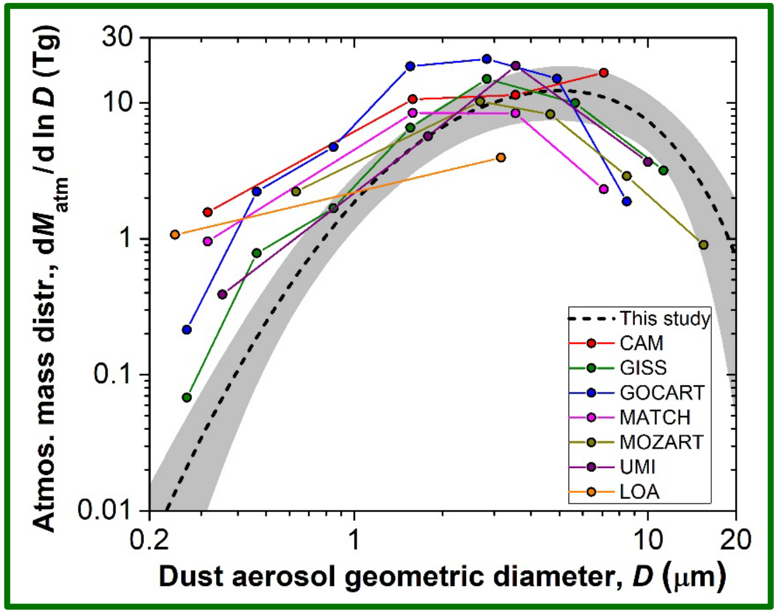
So does dust warm or cool? We don't know!

- 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**

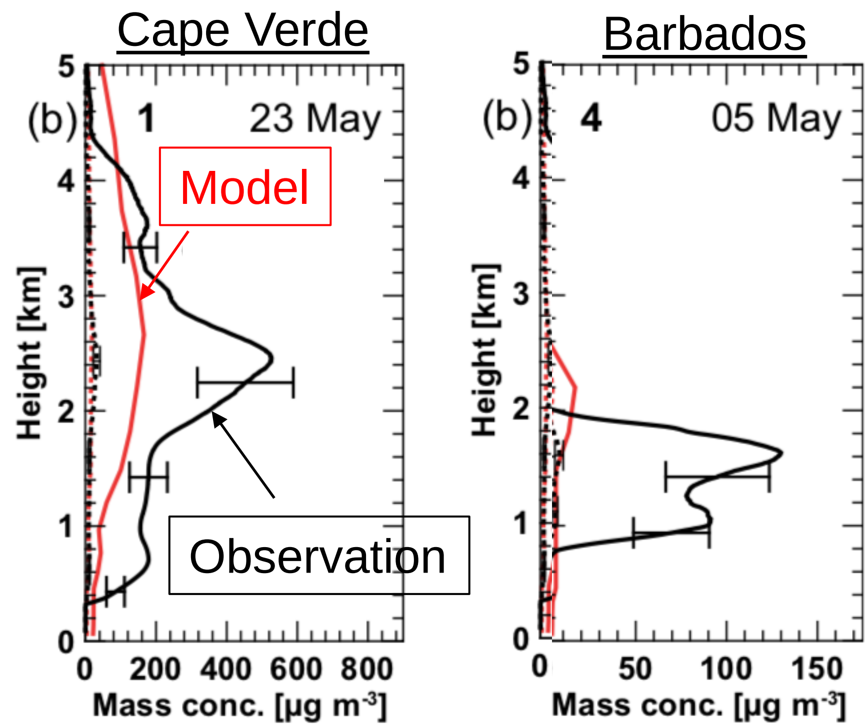


- Large uncertainties remain!
  - Optical properties, especially LW (Di Biagio et al., 2017)
  - Models still greatly **underestimate coarse dust** (e.g., Ryder et al., 2019)

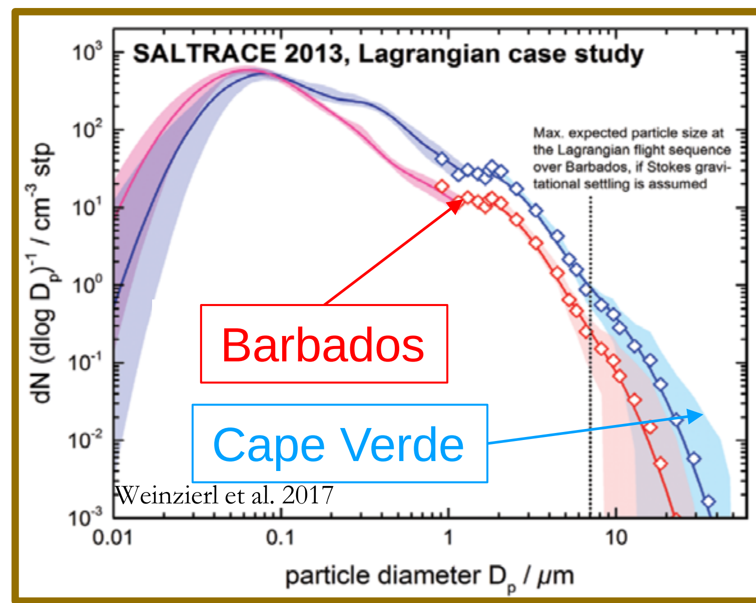
Several lines of evidence indicate that **models greatly underestimate coarse dust**

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).



Ansmann et al. 2017



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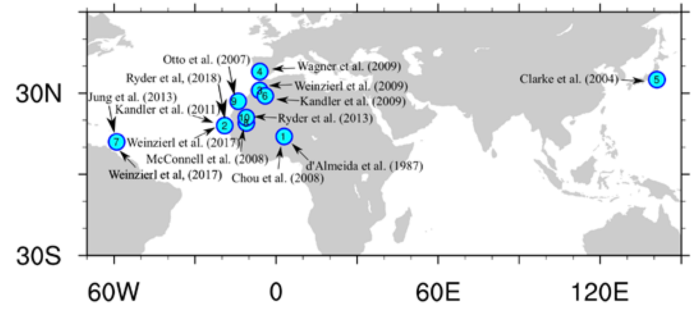
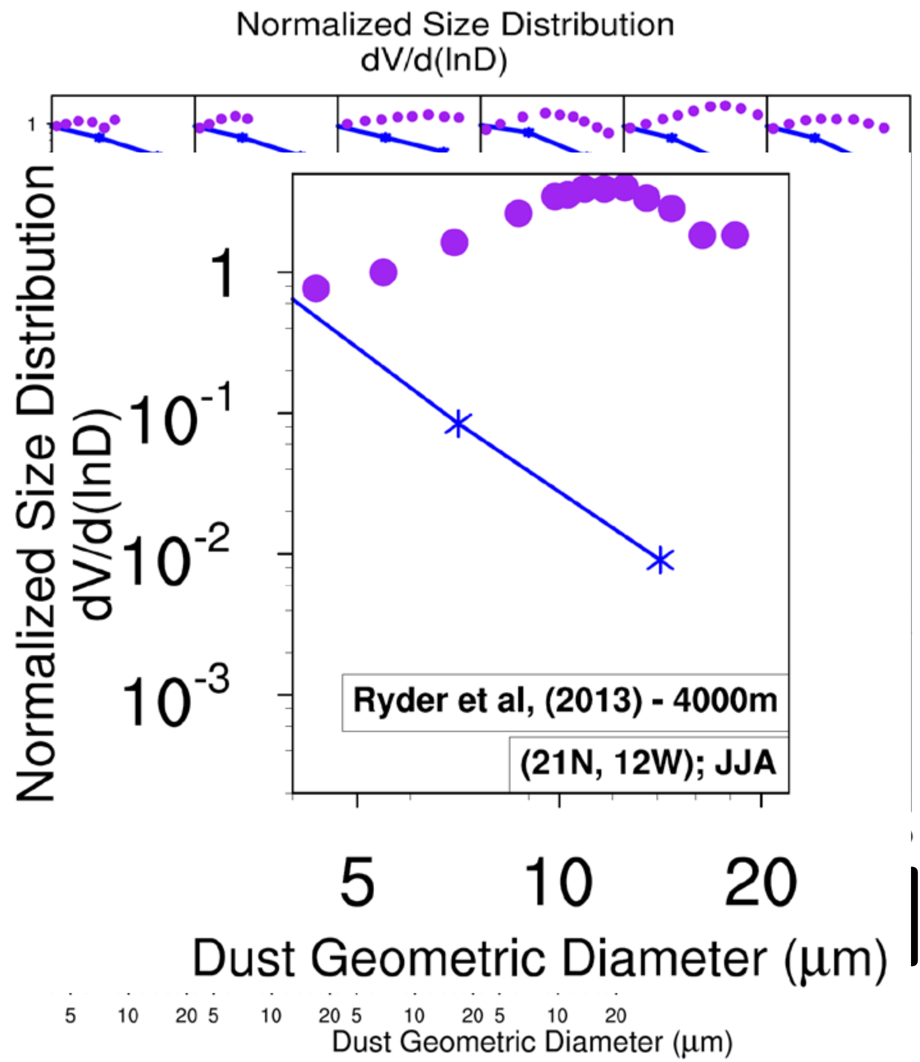
2. **Coarse dust particles are found at greater distances than possible from model simulations** (Maring et al., 2003, Weinzierl et al. 2017, van der Does et al. 2018)..

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



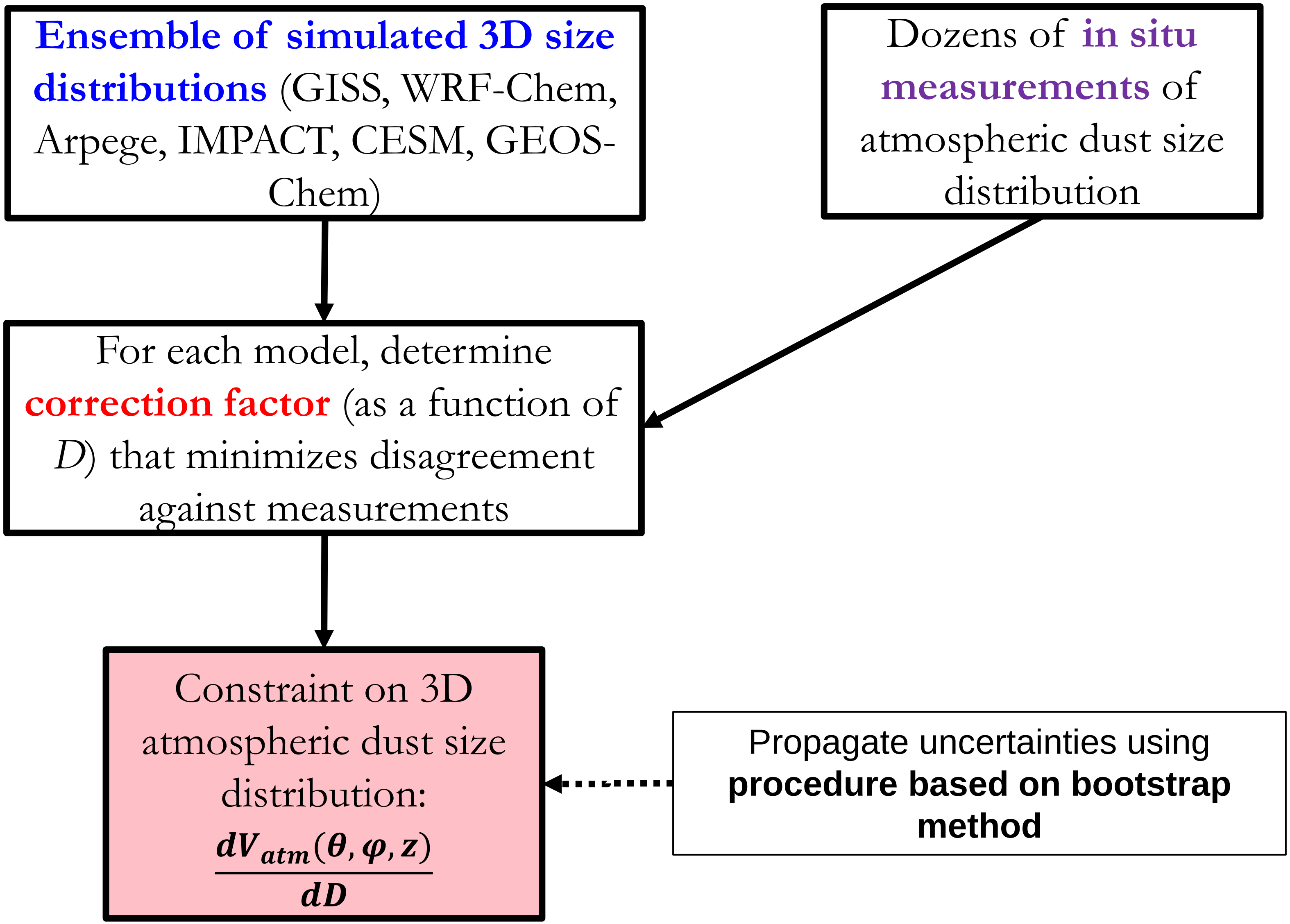


Central questions:

- How much coarse dust is missing from climate models?

- What is the direct radiative impact of the missing coarse dust?

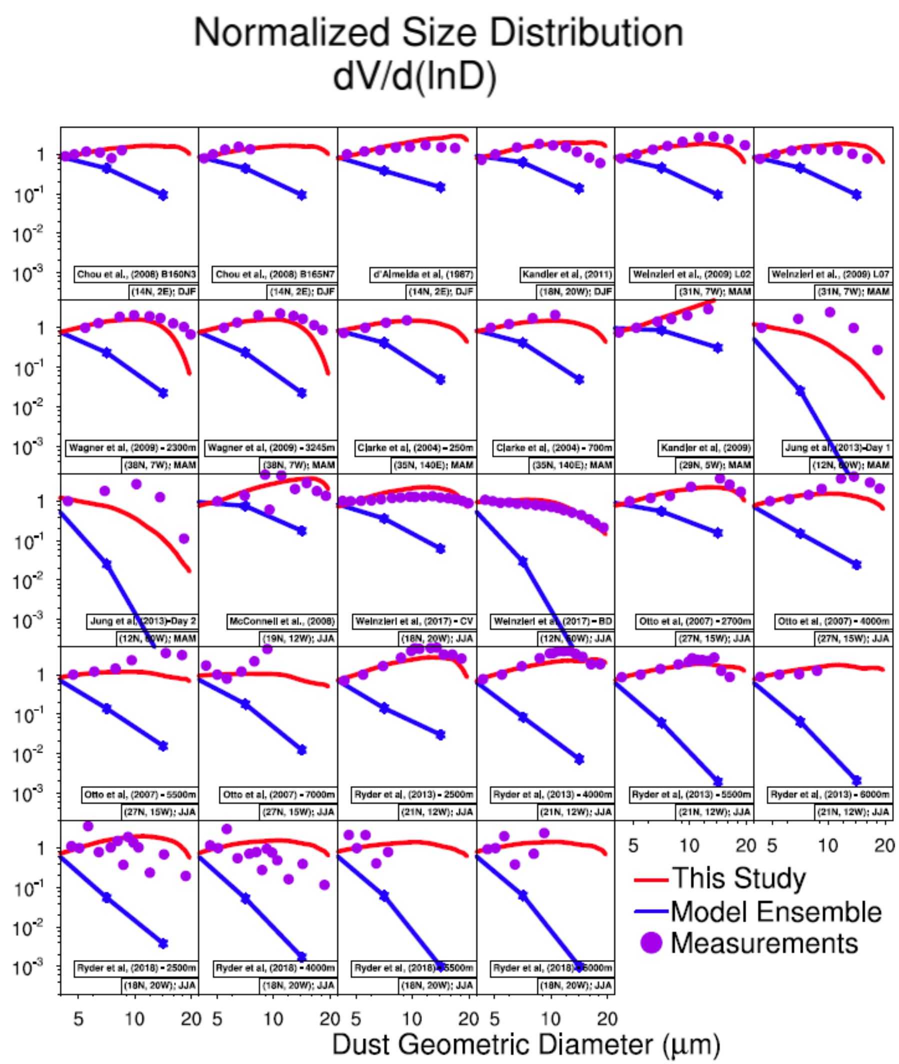
Joint experimental-modeling analysis to constrain 3D atmospheric dust size distribution

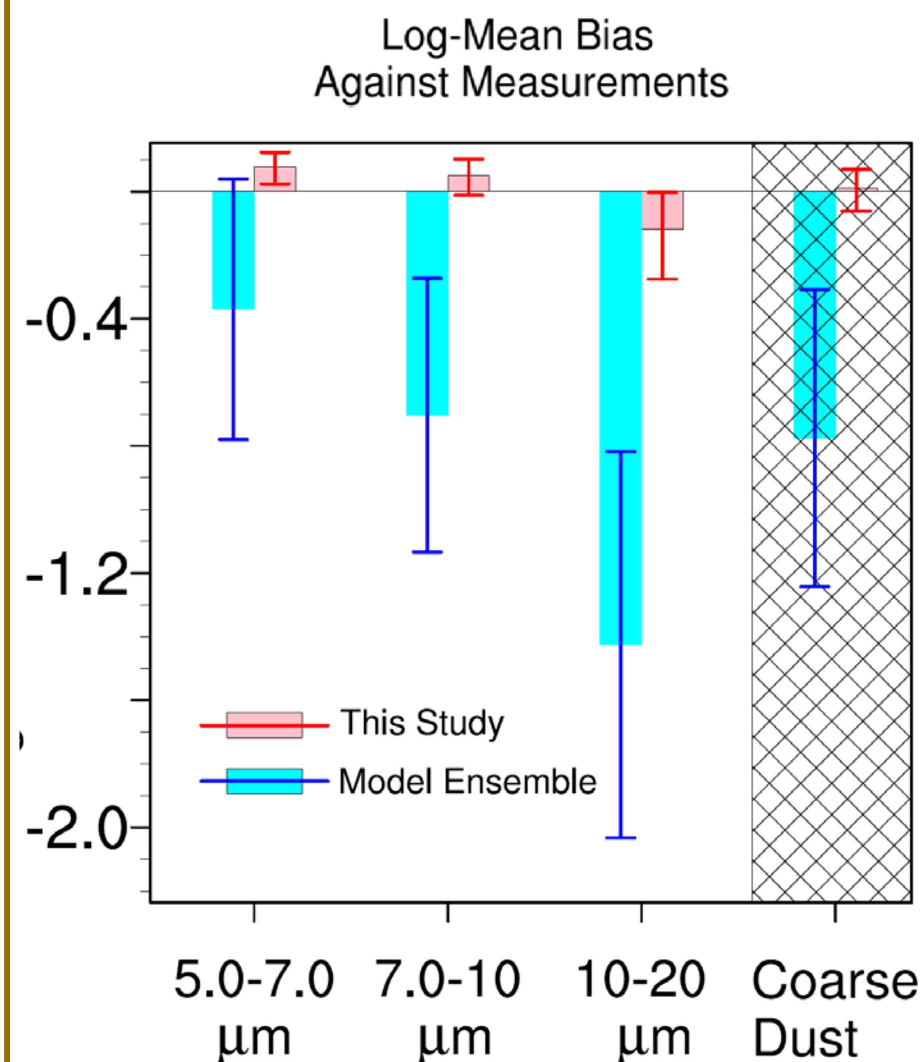


Our estimates agree better with measurements

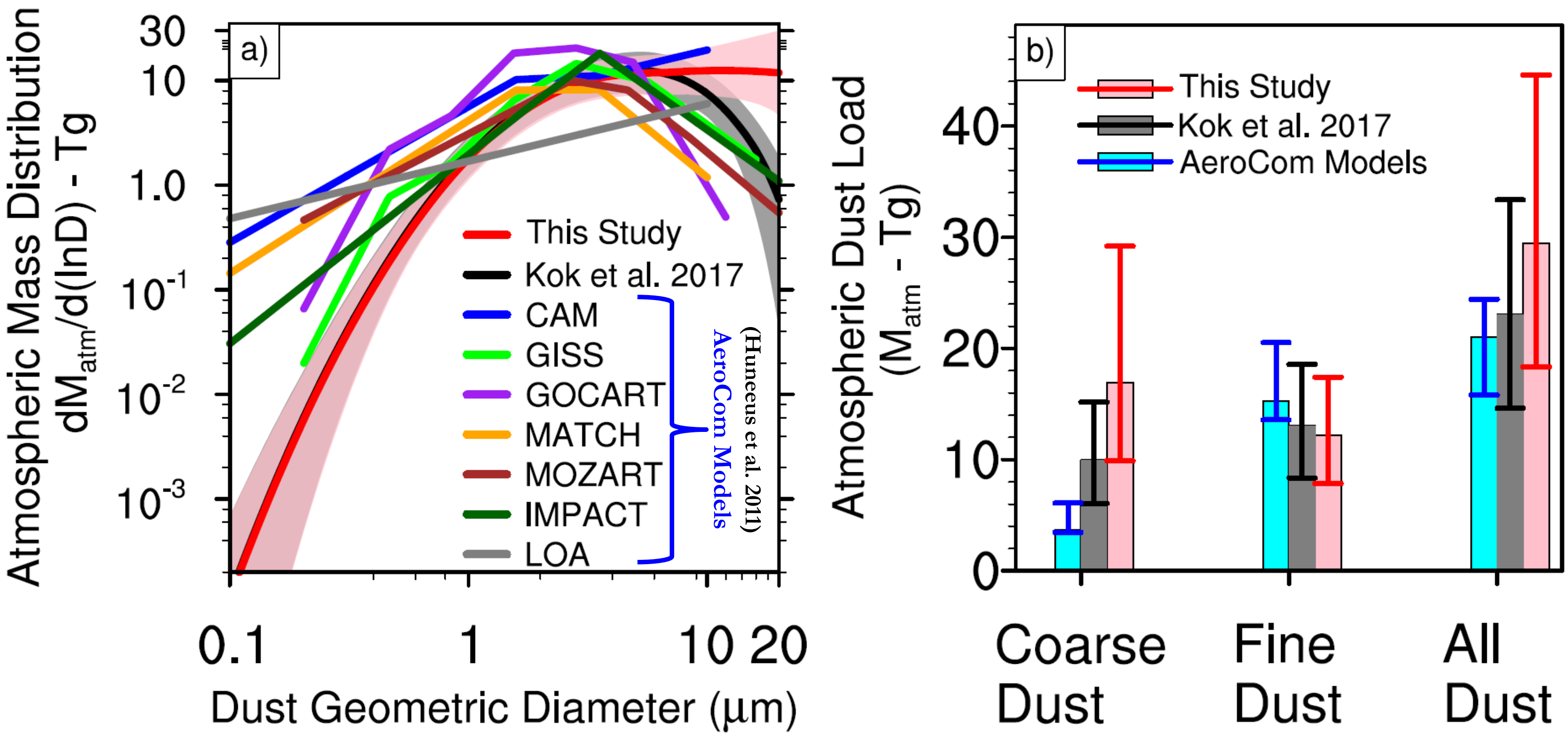
over different locations, height levels, and seasons

→ **Almost complete elimination of bias**





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



Central questions:

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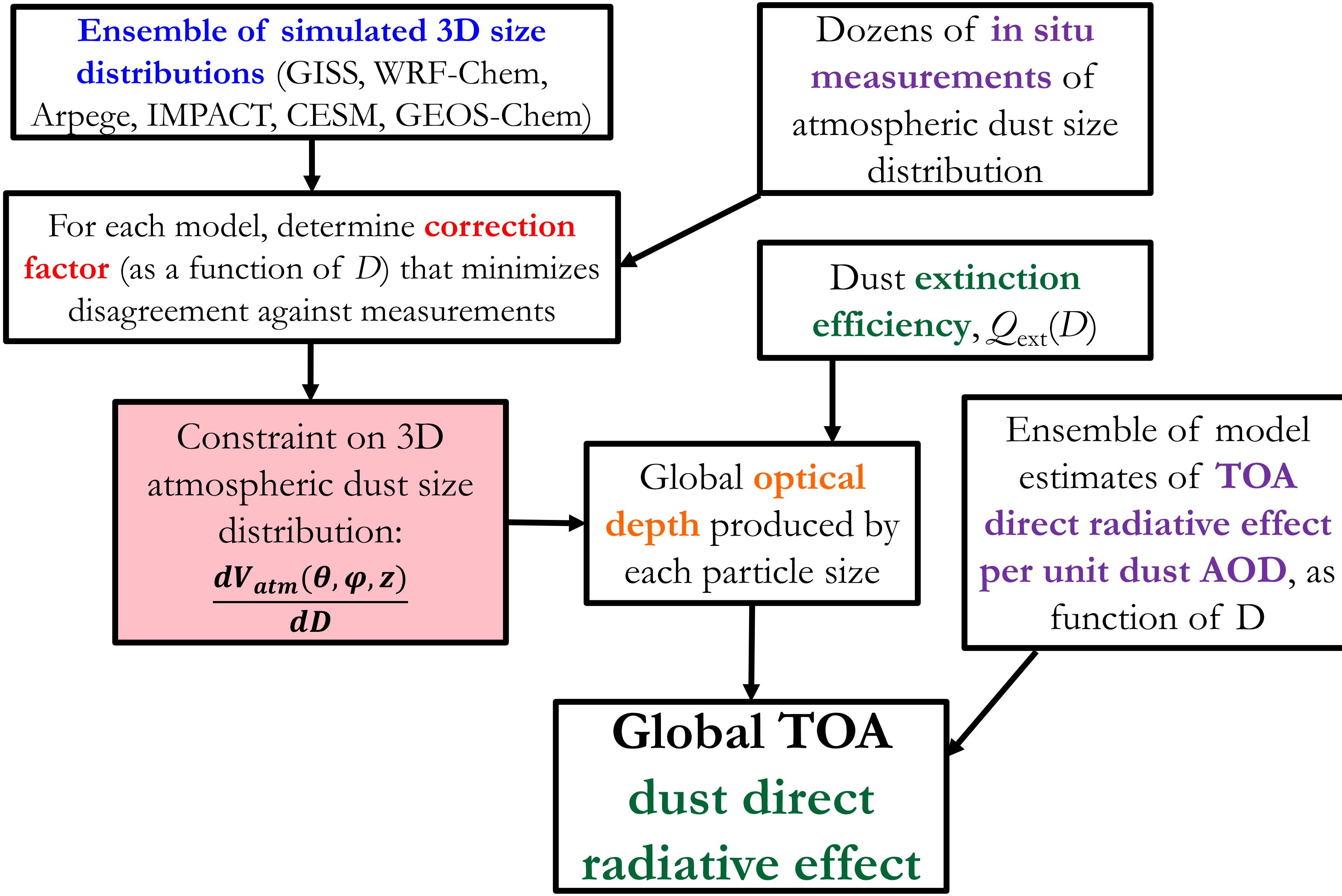
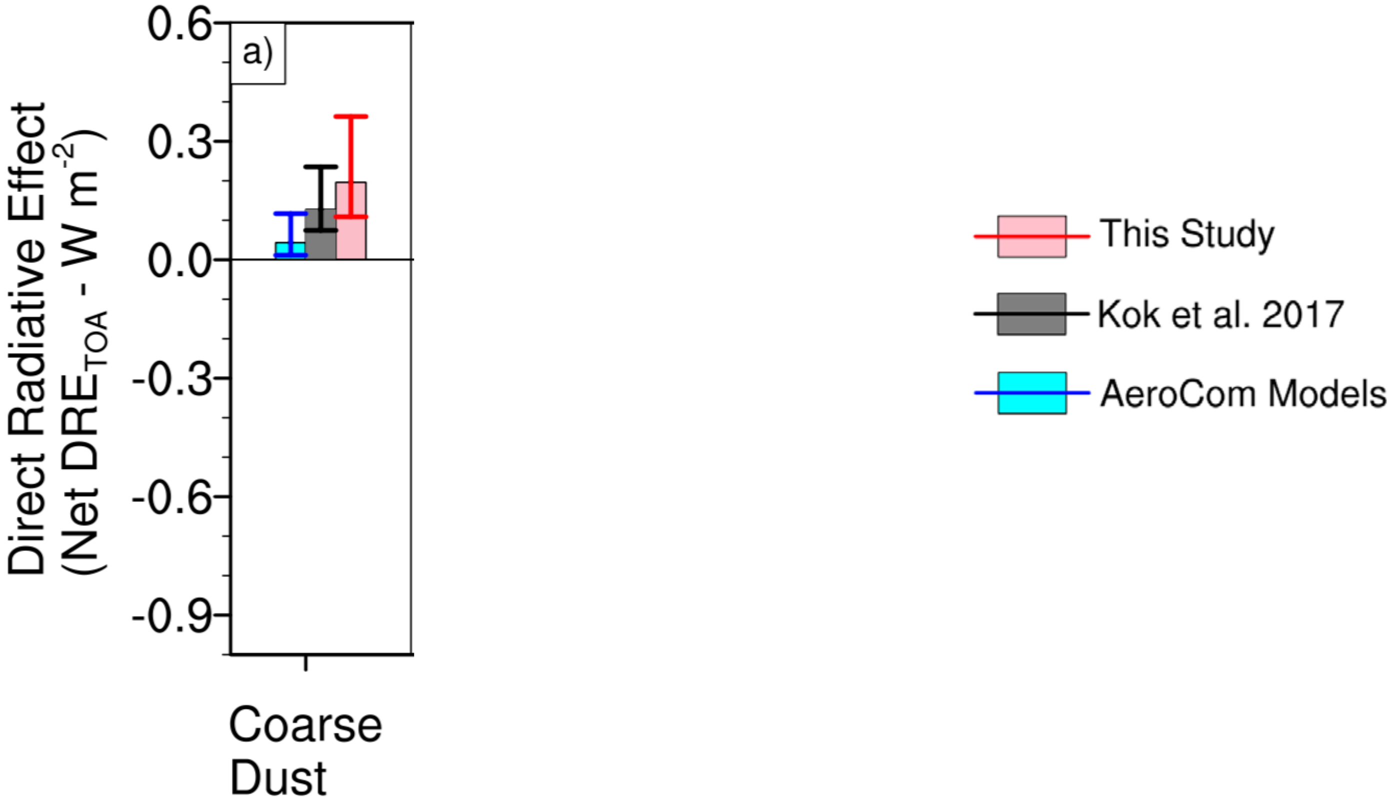
Joint experimental-modeling analysis to constrain dust direct radiative effect



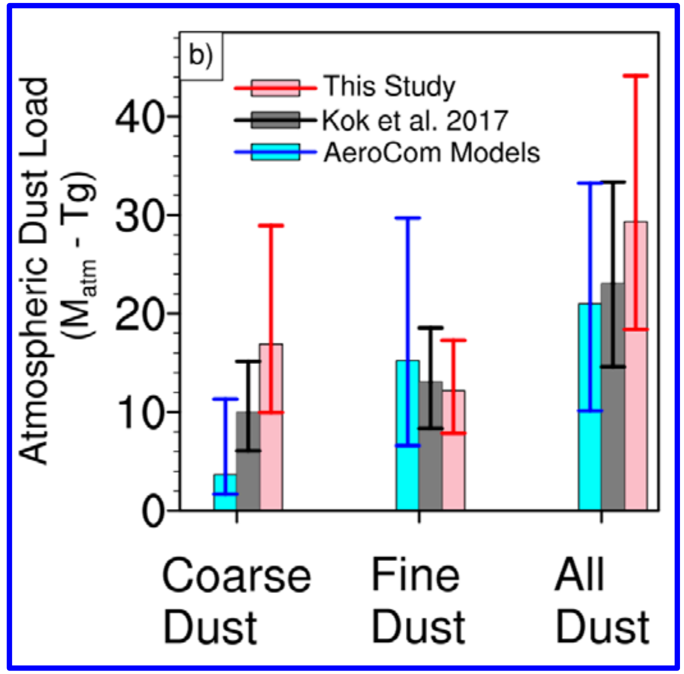
Missing coarse dust adds ~0.1 W/m^2 warming

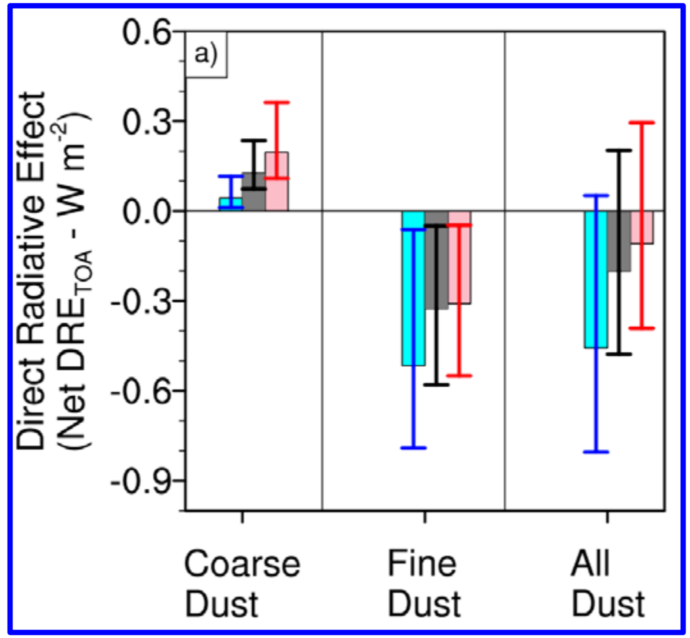


- Accounting for **missing coarse dust increases TOA warming by 0.15 ± 0.06 Wm^{-2}**
- Still unclear if dust direct radiative effect net warms or cools!

Summary

- The atmosphere contains **17 ± 5 Tg coarse dust**
  - **AeroCom (phase I) models account for only ~quarter of coarse dust**
- Missing coarse dust adds **0.15 ± 0.06 W m^{-2}** of TOA direct warming
  - Helps remedy model underestimation of absorption
- Missing coarse dust implies **important processes are missing** from current models!





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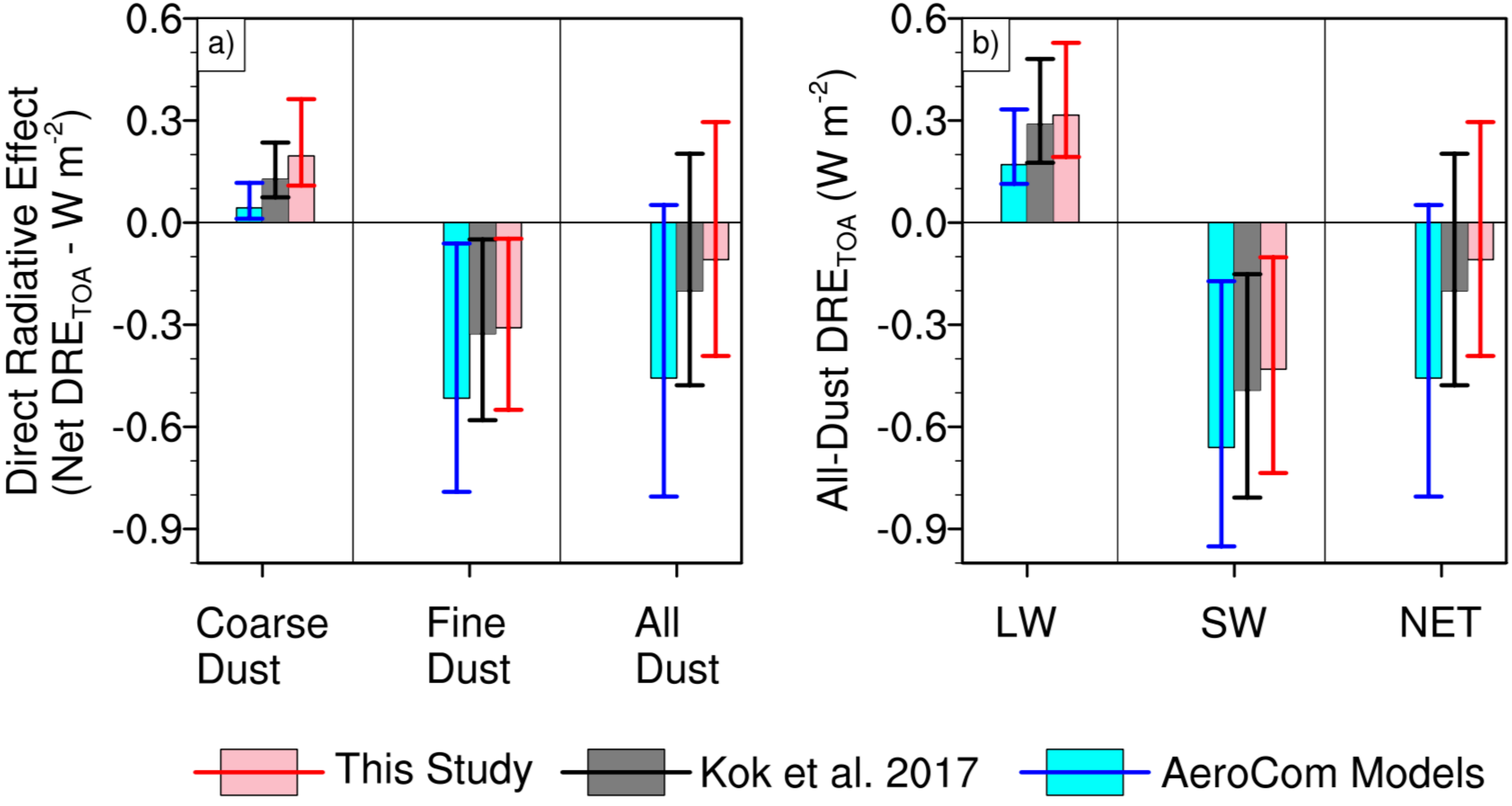
Okay, so WHY do models greatly underestimate coarse dust?

- Not enough coarse dust emitted
  - Likely because coarse particles are difficult to measure because of losses in inlet system for D > 5 um

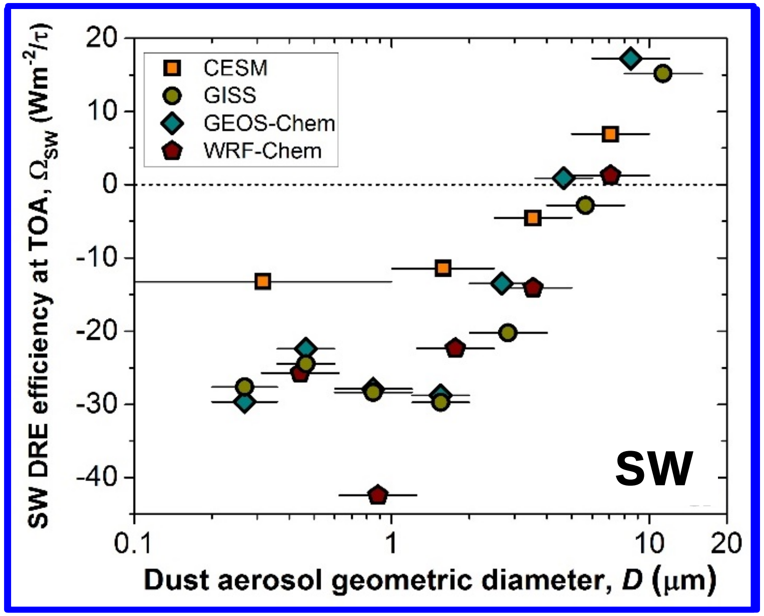
- But measurements show that coarse dust deposits too quickly in models (e.g., Weinzierl et al. 2017). Why?
  - Dust is highly aspherical → models overestimate settling speed by ~20% (Huang, Kok et al., in prep)
  - Turbulence in dusty layers can slow settling (e.g., Gasteiger et al., 2017)
  - Excessive numerical diffusion due to insufficient vertical resolution (Zhang et al., 2018) and/or diffusive advective schemes (Ginoux, 2003)
  - Electrification of dust might counteract gravitational settling (Ulanowski et al., 2007)

Coarse dust warms atmosphere more than previously estimated

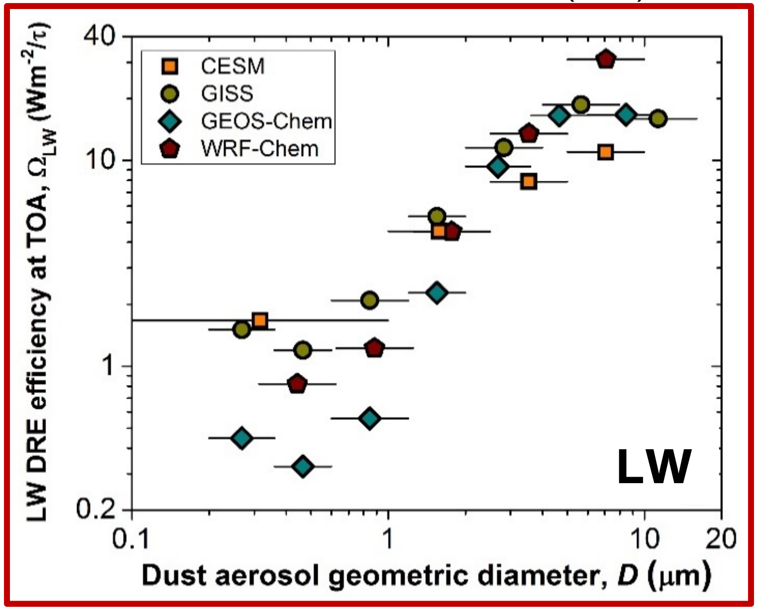


Radiative effect efficiency

- **Radiative effect efficiency (REE)** from simulations by four leading climate models
- **SW REE increases with D** (becomes more warming)
  - Greater fraction of extinction due to **absorption**
- **LW REE positive, and increases** as *D* → atmospheric window (~10 um)



From Kok et al., Nature Geoscience (2017)

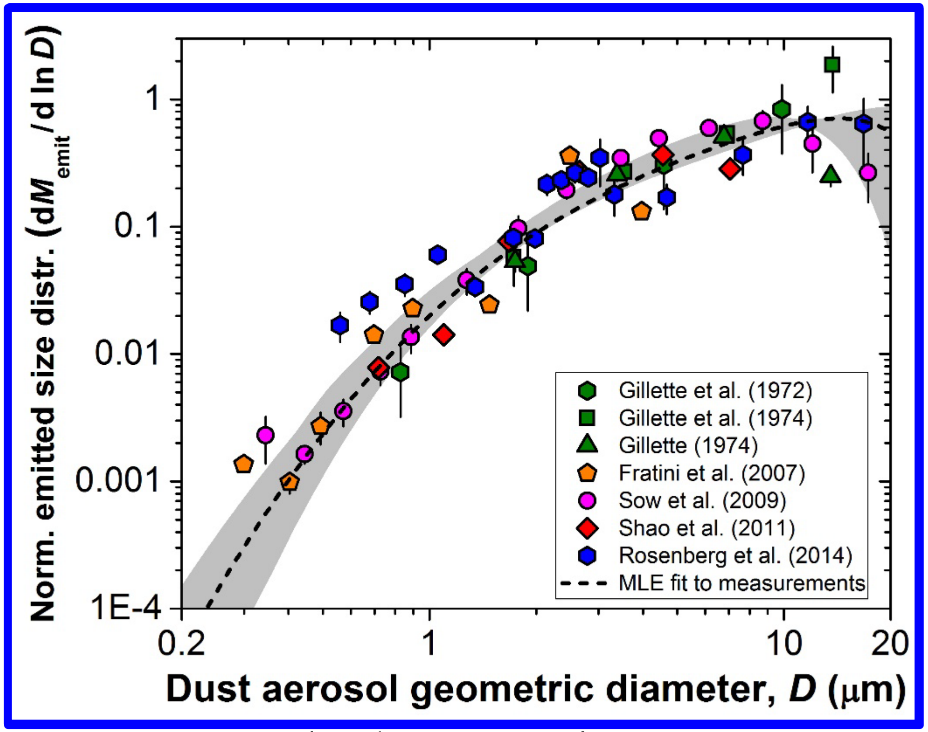


Globally-averaged emitted dust size distribution

- 7 studies of **size distribution of emitted dust**
  - **Limited dependence on wind speed and soil properties** (Gillette, 1974; Kok, ACP, 2011; Rosenberg et al., 2014)

  → Each data set is a measure of globally-averaged emitted dust size distribution

- **Most likely emitted size distribution and 95 % confidence interval** from maximum likelihood and bootstrap methods



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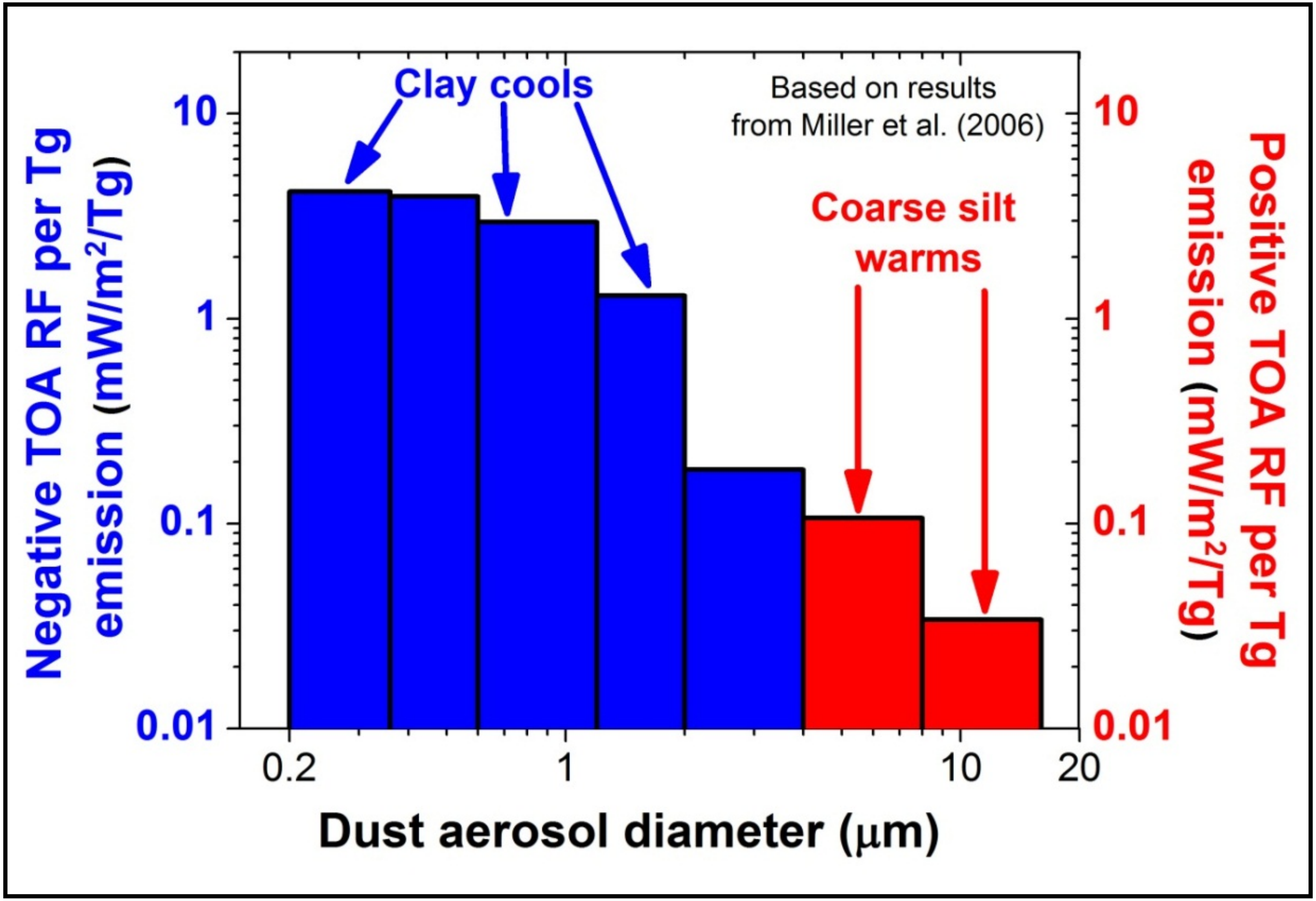
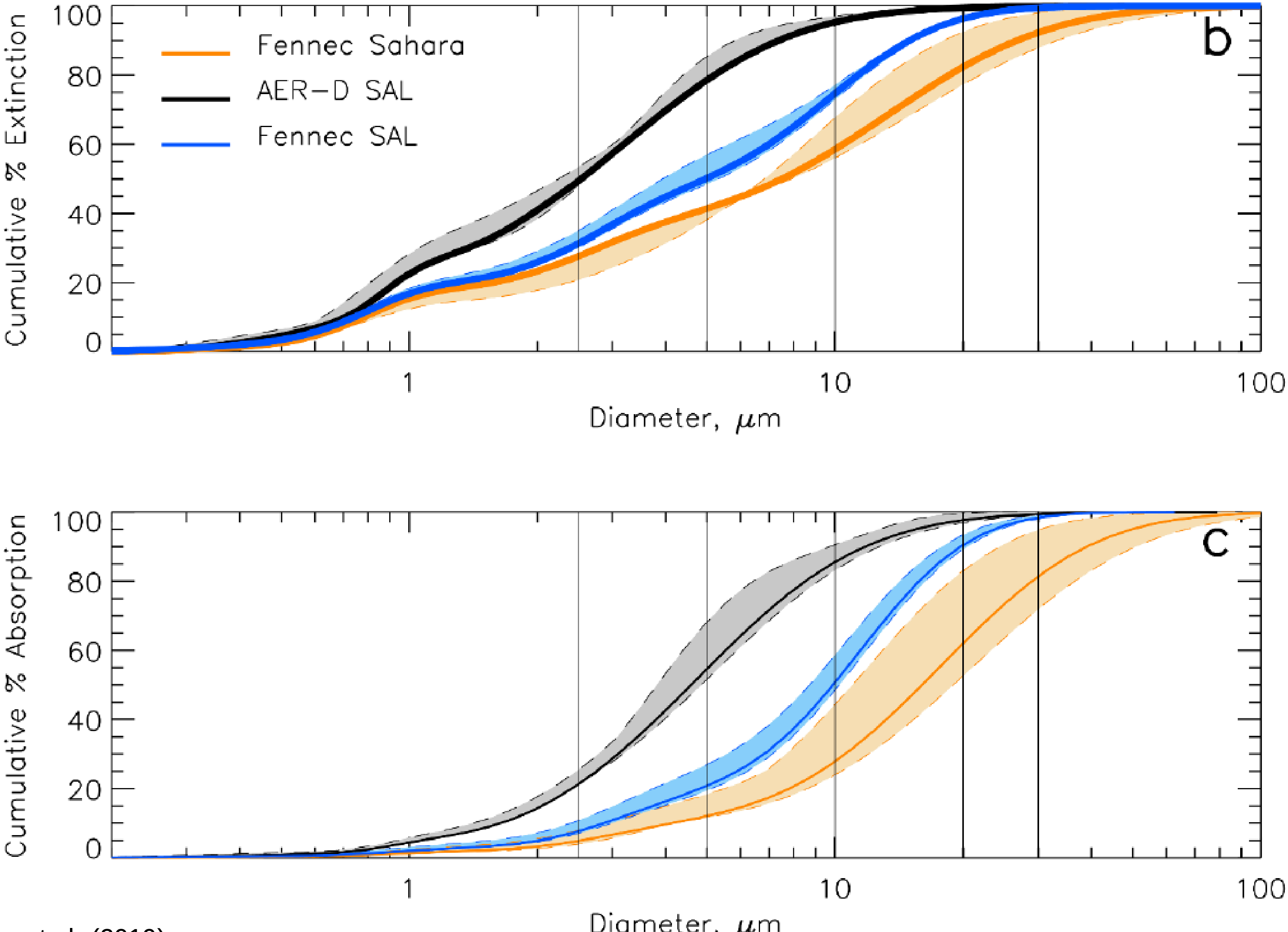
Fine dust cools; coarse dust warms



Measurements also show giant dust (D > 20 um) important to radiative budget



From Ryder et al. (2019)