Does the dust direct radiative effect (DRE) cool or warm the planet?

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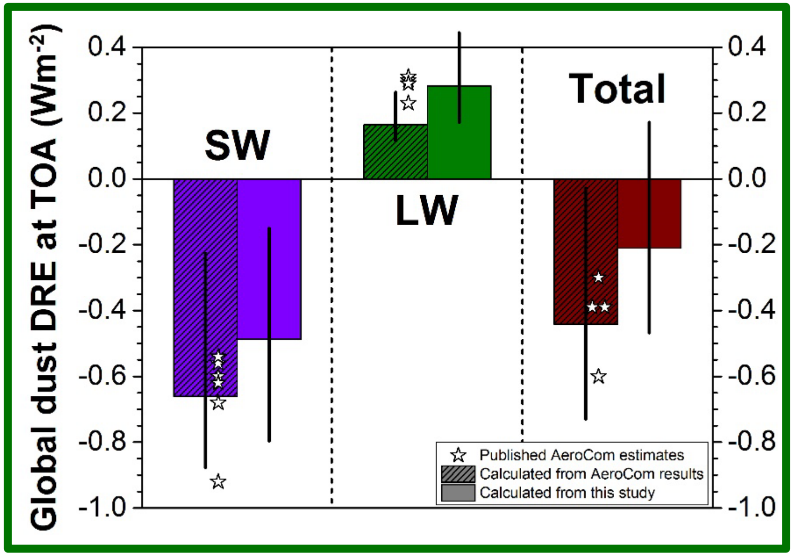
Main take-home points:

- New framework constrains the dust direct radiative effect (DRE) using experimental and observational constraints
- Bias towards fine dust causes models to overestimate dust cooling
- Dust DRE is about half of AeroCom models' estimate (~-0.20 W/m^2)



Collaborators: David Ridley, Qing Zhou, Chun Zhao,
Ron Miller, Colette Heald, Karsten Haustein, Samuel Albani, Daniel Ward

What determines the global dust direct radiative effect (DRE)?

- Global extinction of SW radiation by dust
  1. **Globally-averaged dust optical depth**

- Fraction of extinction produced by scattering (**cooling**) and absorption (**warming**)
  2. **Globally-averaged atmospheric dust size distribution**
  3. **Globally-averaged atmospheric dust optical properties**

- LW interactions (**warming**) that accompany the SW extinction
  2. **Globally-averaged atmospheric dust size distribution**
  3. **Globally-averaged atmospheric dust optical properties**

- Efficiency with which SW and LW interactions are converted to DRE
  4. **Radiative effect efficiency**

$$\left\{\begin{array}{c}\textbf{Dust Direct}\\ \textbf{Radiative}\\ \textbf{Effect (DRE)}\end{array}\right\} = f\left\{\begin{array}{c}\textbf{Dust}\\ \textbf{optical}\\ \textbf{depth}\end{array};\ \begin{array}{c}\textbf{Size}\\ \textbf{distribution}\end{array};\ \begin{array}{c}\textbf{Optical}\\ \textbf{properties}\end{array};\ \begin{array}{c}\textbf{Radiative}\\ \textbf{effect}\\ \textbf{efficiency}\end{array}\right\}$$

Are climate model estimates of dust direct radiative effect biased?

- Assessments of dust direct radiative effect (e.g., AeroCom and IPCC AR) are **currently based on global climate model simulations**
- **Reliance on models might be problematic**, because models need to **assume specific values for uncertain dust properties**, such as optical properties and size at emission
  - Models **do not represent experimental uncertainty** in dust properties and abundance
  - Chosen values are sometimes **inconsistent with experimental constraints**

→ model-simulated dust DRE might be affected by **substantial biases**

Traditional model-based DRE constraints:

$$\left\{\text{Dust Direct Radiative Effect (DRE)}\right\} = f_{\text{model}}\left\{\text{Dust optical depth};\ \text{Size distribution};\ \text{Optical properties};\ \text{Radiative effect efficiency}\right\}$$

Is there a better way?
A new theoretical framework

- I propose to instead **use model results only when experimental constraints are not available**
  - For instance, to simulate the radiative effect efficiency

- Other quantities can be **constrained more accurately with measurements and observations**
  - For instance dust size distribution and global dust optical depth
  - Direct **use of experimental constraints reduces effects of biases** in assumed dust properties and abundance on the resulting dust DRE

Proposed new framework to constrain DRE:

$$\left\{\text{Dust Direct Radiative Effect (DRE)}\right\} = f_{model}\left\{\text{Radiative effect efficiency}\right\} \times f_{meas}\left\{\text{Dust optical depth};\ \text{Size distribution};\ \text{Optical properties}\right\}$$

Theoretical framework for constraining the dust direct radiative effect

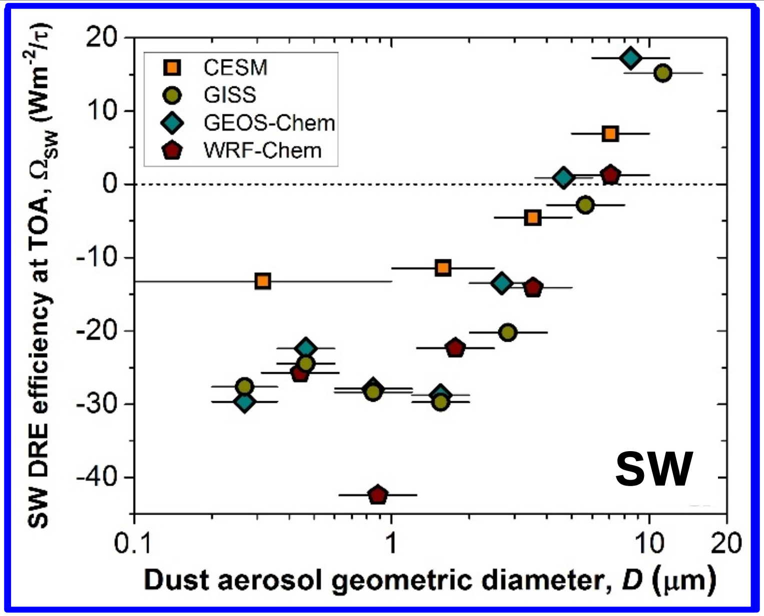
- Dust **direct radiative effect (DRE)** is caused by extinction (scattering + absorption) of radiation

$$\left\{ \text{Dust Direct Radiative Effect (DRE)} \right\} = \int \underbrace{\frac{d\tau_d}{dD}}_{\text{Global dust optical depth size distr.}} \underbrace{\left[\Omega_{\mathrm{SW}} + \Omega_{\mathrm{LW}} \right]}_{\text{Radiative effect efficiency}} dD$$

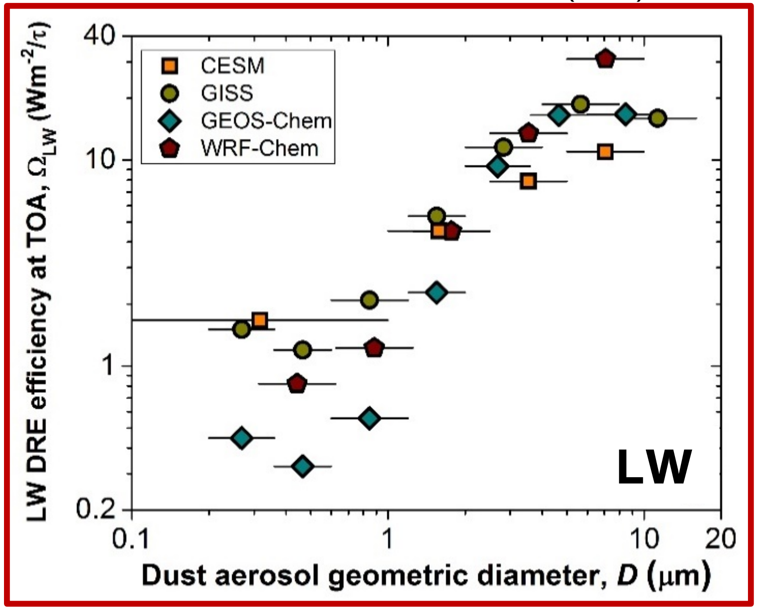
- Extinction of SW radiation by dust is quantified by τ_d, the globally-averaged **dust aerosol optical depth** at 550 nm
- **Ω is radiative effect efficiency** with which optical depth is converted to radiative effect at top of atmosphere
  - Depends on Earth's albedo, 4D distribution of dust, temperature profile, clouds, etc. → needs to be estimated with global model
- Must **integrate over particle size** because Ω depends strongly on particle size: small dust cools, coarse dust warms
  - Also must separate SW and LW components
- **Framework separates what needs to be simulated with global models** (Ω) **from what can be constrained with measurements** and observations ($\frac{d\tau_d}{dD}$)

Radiative effect efficiency

- **Radiative effect efficiency (REE)** from simulations by four leading climate models
- **SW REE increases with D** (becomes more warming)
  - Largely because greater fraction of extinction due to **absorption**
- **LW REE positive, and increases** as *D* become comparable to LW wavelength in atmospheric window (~8 – 13 um)



From Kok et al., Nature Geoscience (2017)



What is the global dust optical depth size distribution, $d\tau_d/dD$?

- **Size distribution of global dust AOD** depends on:
  1. **Global dust aerosol optical depth**
  2. **Globally-averaged atmospheric dust size distribution**
  3. **Globally-averaged extinction efficiency**

$$\{\text{Dust Direct Radiative Effect (DRE)}\} = \int \frac{d\tau_d}{dD}\left[\Omega_{SW} + \Omega_{LW}\right] dD$$

$\frac{d\tau_d}{dD}$: **Global dust optical depth size distr.**

$\left[\Omega_{SW} + \Omega_{LW}\right]$: **Radiative effect efficiency**

$$\frac{d\tau_d}{dD} = \tau_d \times \frac{dM_{atm}}{dD} \times \frac{A(D)}{m(D)} \times Q_{ext}(D) \times c_\tau$$

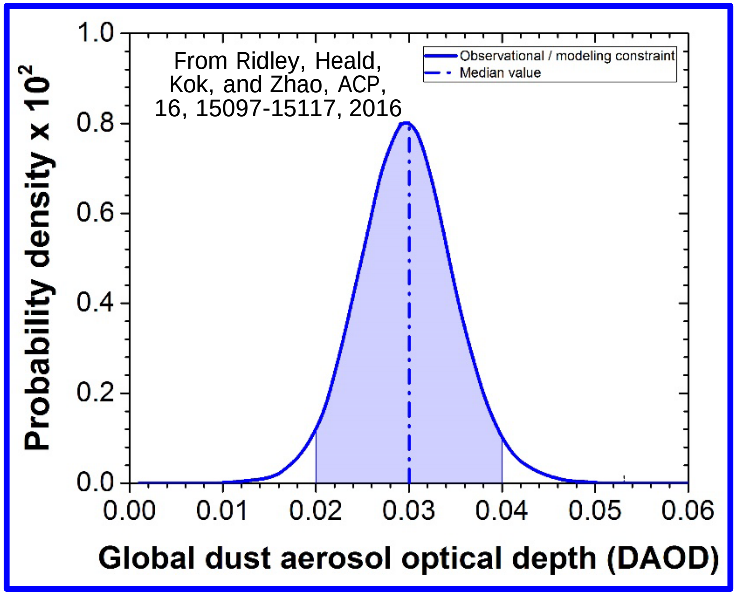
- $\frac{d\tau_d}{dD}$: **DAOD size distribution**
- τ_d: **Global DAOD**
- $\frac{dM_{atm}}{dD}$: **Atmospheric size distribution**
- $\frac{A(D)}{m(D)}$: **Surface-to-mass ratio**
- $Q_{ext}(D)$: **Extinction efficiency**
- c_τ: **Normali-zation factor**

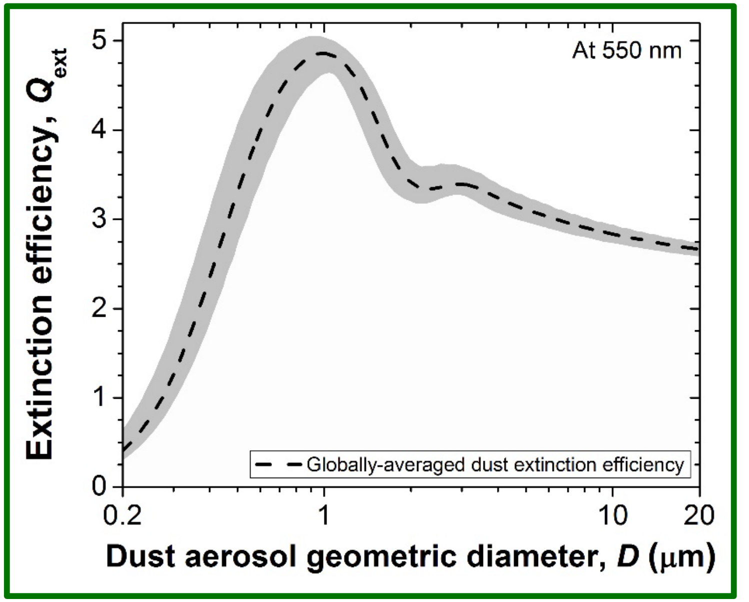
Constraints on global dust AOD and extinction efficiency

$$\underbrace{\frac{d\tau_d}{dD}}_{\text{DAOD size distribution}} = \underbrace{\tau_d}_{\text{Global DAOD}} \times \underbrace{\frac{dM_{atm}}{dD}}_{\text{Atmospheric size distribution}} \times \underbrace{\frac{A(D)}{m(D)}}_{\text{Surface-to-mass ratio}} \times \underbrace{Q_{ext}(D)}_{\text{Extinction efficiency}} \times \underbrace{c_\tau}_{\text{Normalization factor}}$$

- Ridley et al. (ACP, 2016) recently **constrained the global dust AOD**
  - From combination of MODIS and MISR satellite retrievals, AERONET data, and global model simulations
  - **Dust AOD = 0.030 ± 0.005**
  - Consistent with AeroCom ensemble result of 0.028 ± 0.011

- Used range of measured dust shapes and optical properties to **calculate corresponding range in globally-averaged Q_{ext} (D)** (e.g., Reid et al., 2003; Kandler et al., 2007; Chou et al., 2008)





What is the size distribution of atmospheric mineral dust?

$$\underbrace{\frac{d\tau_d}{dD}}_{\text{DAOD size distribution}} = \underbrace{\tau_d}_{\text{Global DAOD}} \times \underbrace{\frac{dM_{atm}}{dD}}_{\text{Atmospheric size distribution}} \times \underbrace{\frac{A(D)}{m(D)}}_{\text{Surface-to-mass ratio}} \times \underbrace{Q_{ext}(D)}_{\text{Extinction efficiency}} \times \underbrace{c_\tau}_{\text{Normalization factor}}$$

$$\underbrace{\frac{dM_{atm}}{dD}}_{\text{Atmospheric size distribution (normalized)}} = \underbrace{c_N}_{\text{Normalization factor}} \times \underbrace{\frac{dM_{emit}}{dD}}_{\text{Emitted size distribution (normalized)}} \times \underbrace{T(D)}_{\text{Size-resolved dust lifetime}}$$

- Globally-averaged **size distribution of atmospheric mineral dust** depends on:
  1. Globally-averaged **size distribution at emission**
  2. Globally-averaged **size-resolved dust lifetime**

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

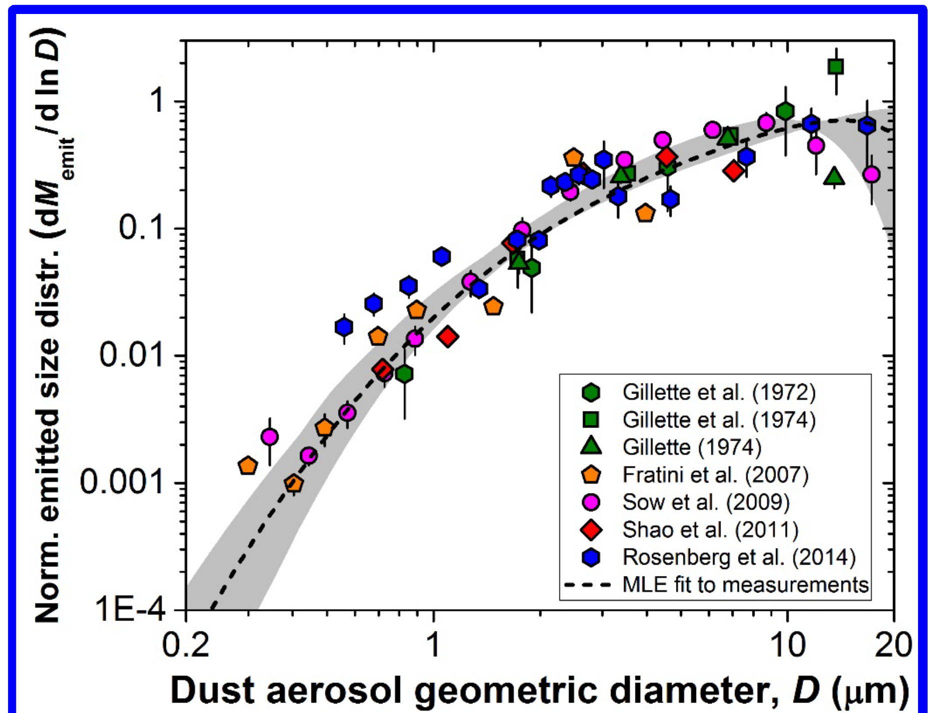
- Used statistical model (combination of maximum likelihood and bootstrap methods) to get **most likely emitted size distribution and 95% confidence interval**

$$\frac{dM_{atm}}{dD} = c_N \times \frac{dM_{emit}}{dD} \times T(D)$$

Atmospheric size distribution (normalized); Normalization factor; Emitted size distribution (normalized); Size-resolved dust lifetime

$$\frac{d\tau_d}{dD} = \tau_d \times \frac{dM_{atm}}{dD} \times \frac{A(D)}{m(D)} \times Q_{ext}(D) \times c_\tau$$

DAOD size distribution; Global DAOD; Atmospheric size distribution; Surface-to-mass ratio; Extinction efficiency; Normalization factor



From Kok et al., Nature Geoscience, 2017

Globally-averaged size-resolved dust lifetime

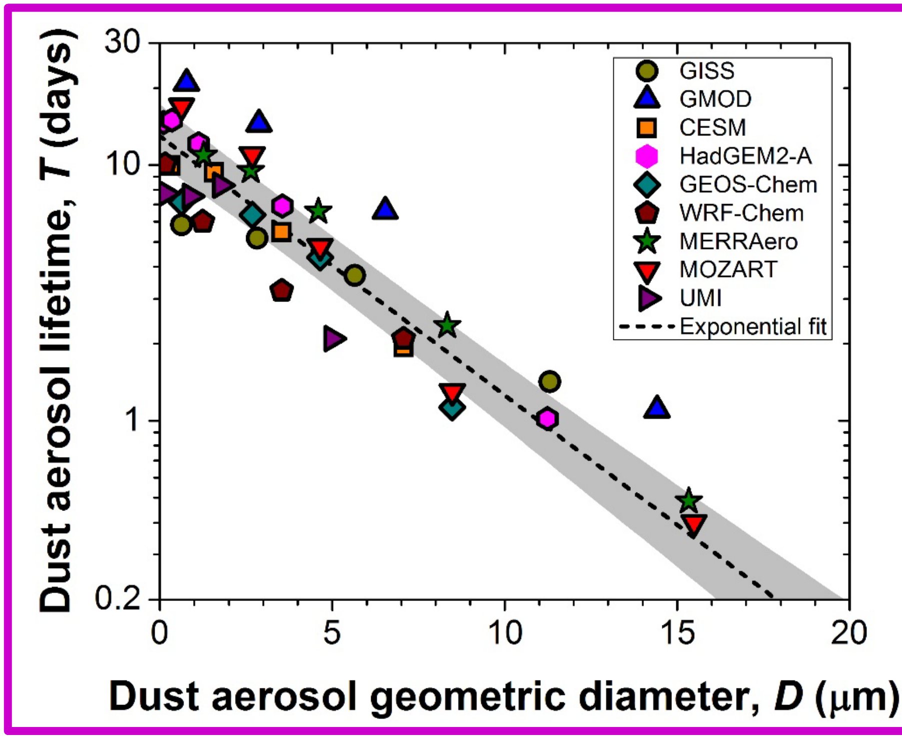
- No direct observational constraints
  - Best way to constrain T(D) is through **compilation of global model results**
  - → Obtained size-resolved dust lifetime from **9 (AeroCom) global models**
- **Most likely dust lifetime and 95% confidence interval** from maximum likelihood and bootstrap methods

$$\frac{dM_{atm}}{dD} = c_N \times \frac{dM_{emit}}{dD} \times T(D)$$

Atmospheric size distribution (normalized); Normalization factor; Emitted size distribution (normalized); Size-resolved dust lifetime

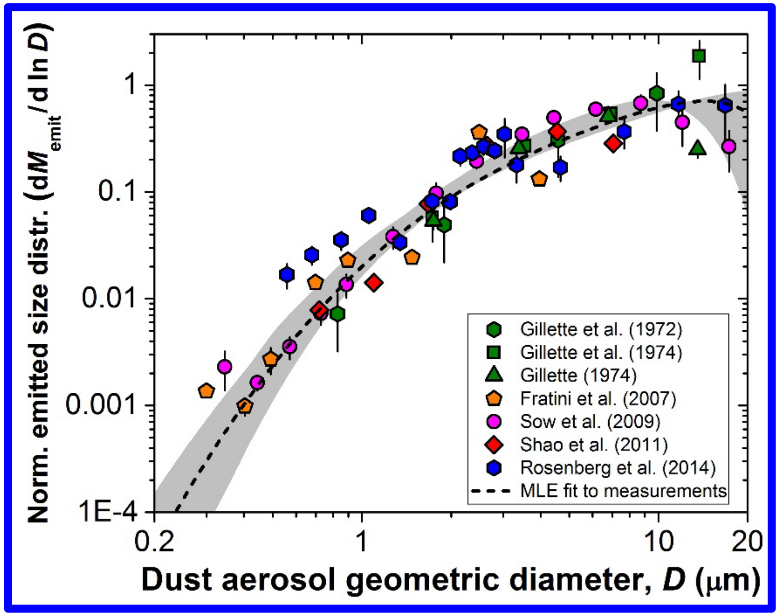
$$\frac{d\tau_d}{dD} = \tau_d \times \frac{dM_{atm}}{dD} \times \frac{A(D)}{m(D)} \times Q_{ext}(D) \times c_\tau$$

DAOD size distribution; Global DAOD; Atmospheric size distribution; Surface-to-mass ratio; Extinction efficiency; Normalization factor



From Kok et al., Nature Geoscience, 2017

Globally-averaged size distribution of atmospheric dust



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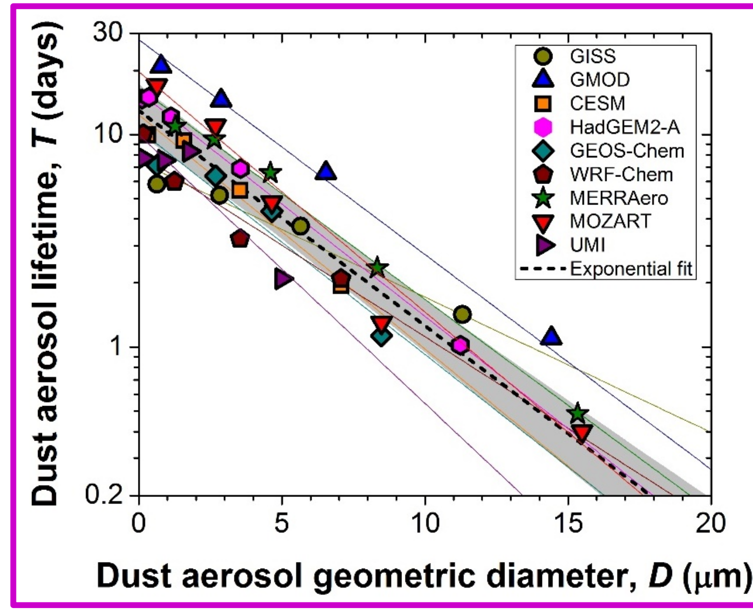

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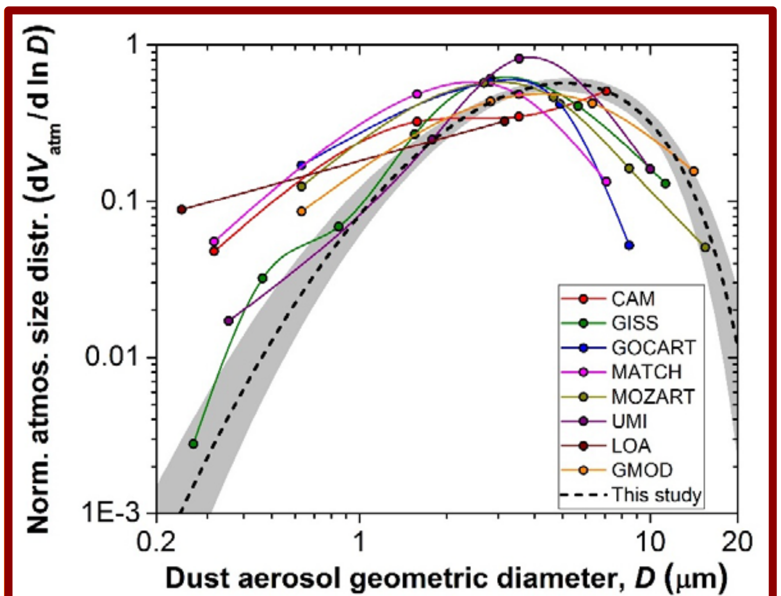


From Kok et al., Nature Geoscience, 2017

- Global models have **bias towards fine dust!**

$$\frac{dM_{atm}}{dD} = c_N \times \frac{dM_{emit}}{dD} \times T(D)$$

Atmospheric size distribution (normalized) — **Normalization factor** — **Emitted size distribution (normalized)** — **Size-resolved dust lifetime**

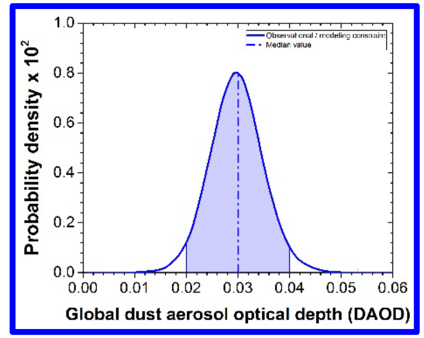
Models overestimate extinction by fine dust, underestimate by coarse dust

$$\underbrace{\frac{d\tau_d}{dD}}_{\text{DAOD size distribution}} = \underbrace{\tau_d}_{\text{Global DAOD}} \times \underbrace{\frac{dM_{atm}}{dD}}_{\text{Atmospheric size distribution}} \times \underbrace{\frac{A(D)}{m(D)}}_{\text{Surface-to-mass ratio}} \times \underbrace{Q_{ext}(D)}_{\text{Extinction efficiency}} \times \underbrace{c_\tau}_{\text{Normalization factor}}$$

- Combining constraints yields $\frac{d\tau_d}{dD}$

- Models overestimate extinction at small *D* (**cooling**), underestimate at large *D* (**warming**)

→ **Current (AeroCom) models overestimate cooling** from dust DRE!



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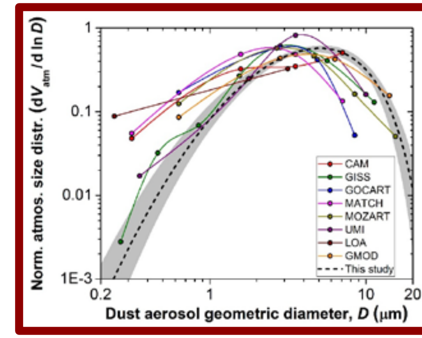

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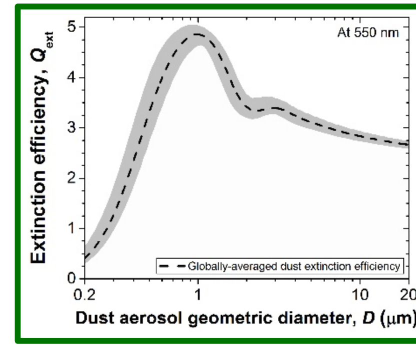

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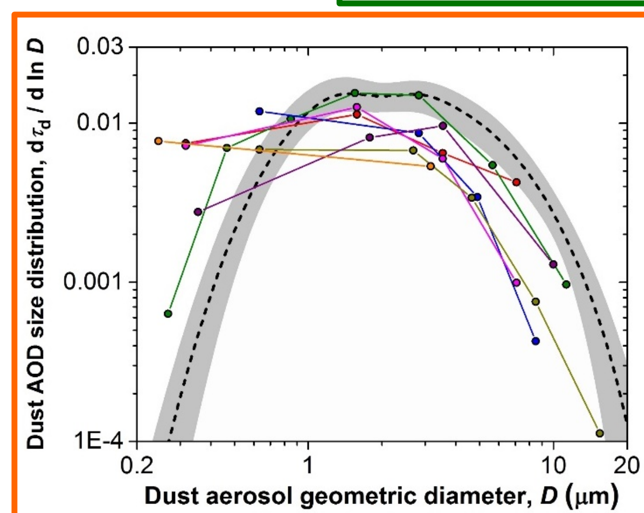
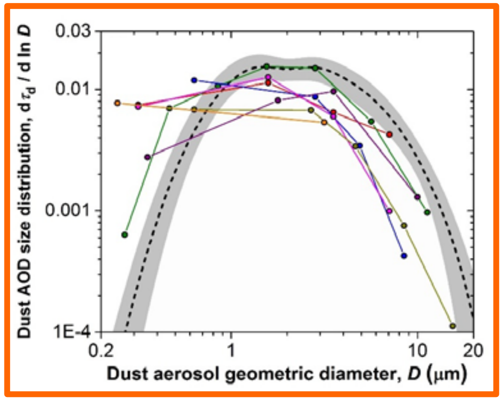


From Kok et al., Nature Geoscience, 2017

Constraints on global dust DRE

- Can now calculate DRE using $d\tau_d/dD$ from:
  1. AeroCom models
  2. Our constraints

$$\left\{\text{Dust Direct Radiative Effect (DRE)}\right\} = \int \underbrace{\frac{d\tau_d}{dD}}_{\text{Global dust optical depth size distr.}} \underbrace{\left[\Omega_{SW} + \Omega_{LW}\right]}_{\text{Radiative effect efficiency}} dD$$



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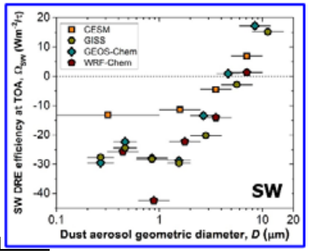

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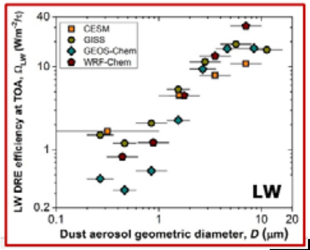

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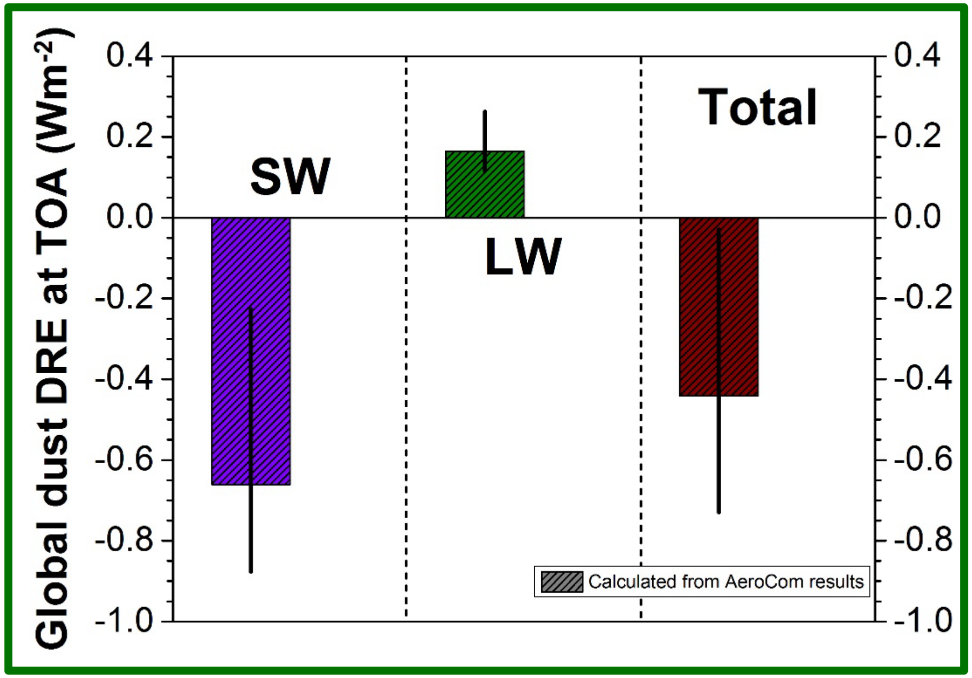


From Kok et al., Nature Geoscience, 2017

Constraints on global dust DRE

- DRE using $d\tau_d/dD$ from AeroCom models **consistent with published AeroCom estimates** (stars)

- Correcting fine dust bias **~halves the DRE cooling**:
  1. **Less SW cooling** (~0.15 W/m²) because of less fine dust
  2. **More LW warming** (~0.10 W/m²) because of more coarse dust

- **Constrained DRE to -0.20 (-0.48 to +0.20) W/m²**
  - Propagated all uncertainties in analysis

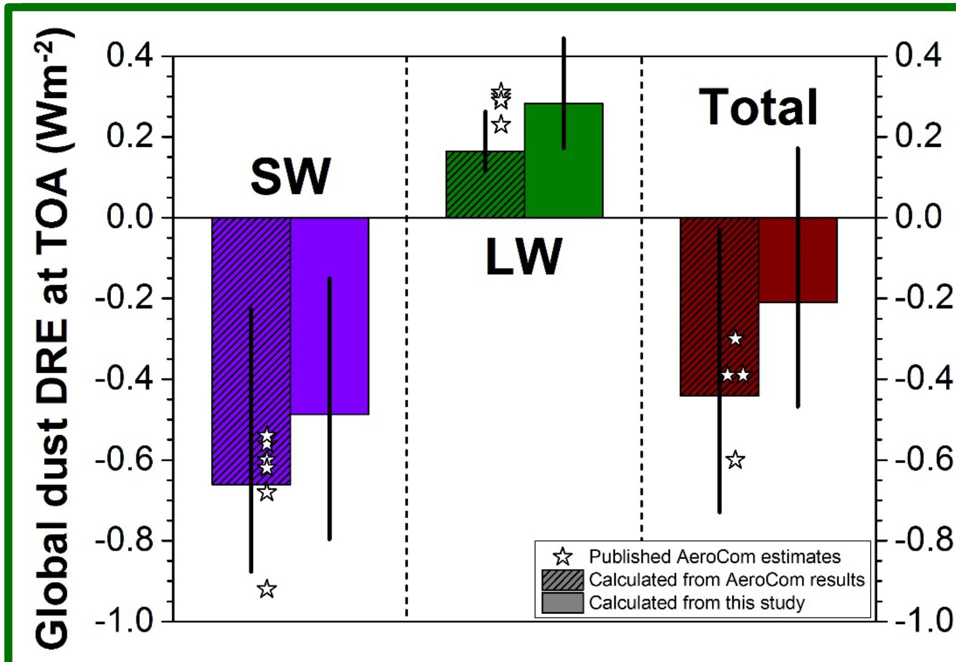
- **~one-in-four chance that DRE is actually net warming!**

Dust Direct Radiative Effect (DRE)

$$= \int \frac{d\tau_d}{dD}\left[\Omega_{SW} + \Omega_{LW}\right] dD$$

$\frac{d\tau_d}{dD}$: **Global dust optical depth size distr.**

$\left[\Omega_{SW} + \Omega_{LW}\right]$: **Radiative effect efficiency**



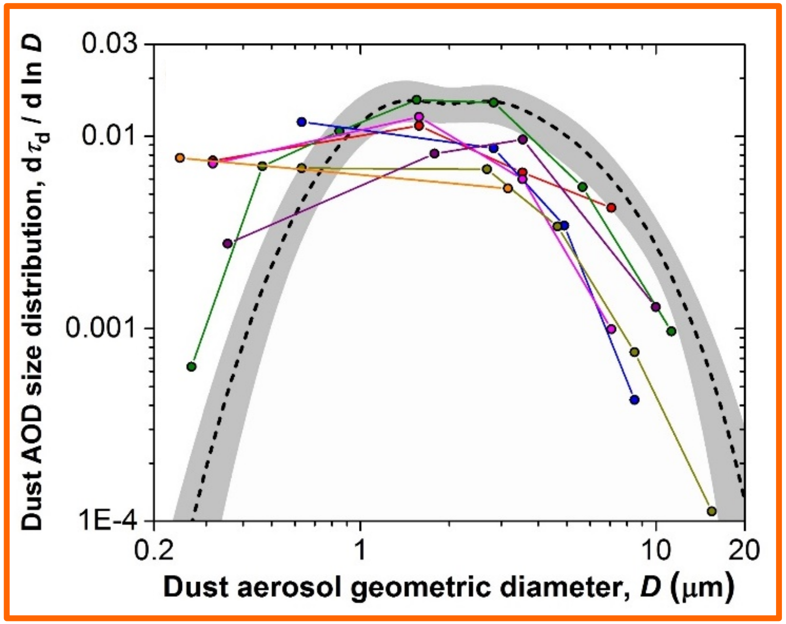
From Kok et al., in review

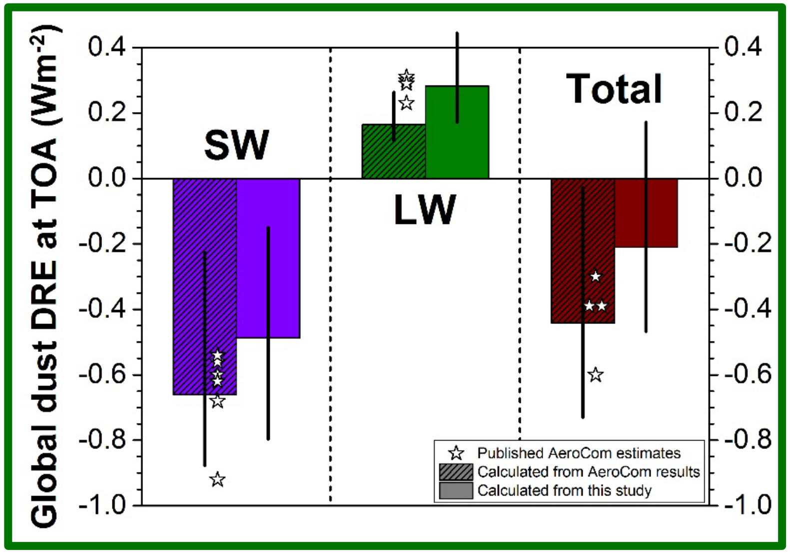
Summary and conclusions

- Developed **new framework to constrain dust DRE**
  - **Directly leverages experimental / observational constraints** on dust properties and abundances
  - **Reduces bias** in DRE

- Models have **too much fine (cooling)** and **too little coarse (warming)** dust
  - Current (AeroCom) models **overestimate dust cooling**!

- Correcting **~halves the dust DRE to -0.20 W/m^2**
  - **~one-in-four chance** that dust DRE net warms the planet





Thank you!

Thoughts? Comments? → jfkok@ucla.edu

Relevant references:

Kok, J. F., D. A. Ridley, Q. Zhou, C. Zhao, R. L. Miller, C. L. Heald, D. S. Ward, S. Albani, and K. Haustein (2017), Smaller desert dust cooling effect estimated from analysis of desert dust size and abundance, *Nature Geoscience*, 10, 274-278.

Ridley, D. A., C. L. Heald, J. F. Kok, and C. Zhao (2016), An Observationally-Constrained estimate of Global Dust AOD, *Atmospheric Chemistry and Physics*, 16, 15,097-117.

Main take-home points:

- New framework constrains the dust direct radiative effect (DRE) using experimental and observational constraints
- Bias towards fine particles causes current (AeroCom) models to overestimate dust cooling
- Dust DRE is about half of AeroCom models' estimate (~-0.20 W/m^2)
- ~One-in-four chance that dust DRE net warms the climate