The global atmospheric loading of mineral dust aerosols

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To **determine global dust impacts on the Earth system**, must answer two primary questions:

1. What is the **size distribution** of atmospheric mineral dust? (determines type of dust impact)

2. **How much dust** is in atmosphere? (determines magnitude of dust impacts)

Reference: Kok et al., Nature Geoscience, 10, 274-278 (2017)

UCLA

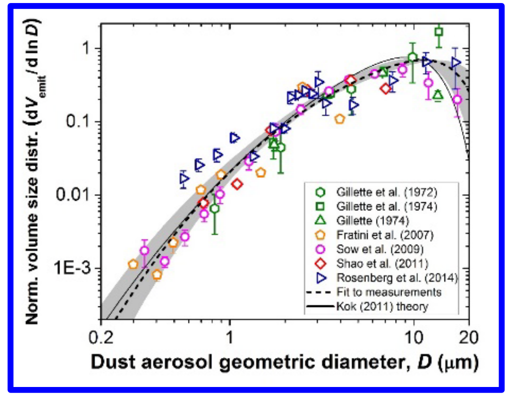
Collaborators: David Ridley, Chun Zhao, Ronald Miller, Karsten Haustein, Qing Zhou, Colette Heald, Daniel Ward, Samuel Albani

NSF

Question 1: What is the size distribution of dust in the atmosphere?

- Used constraints on **emitted dust size distribution** and **atmospheric lifetime** to constrain the **atmospheric dust size distribution**

- Current Earth system models have **bias towards fine dust**



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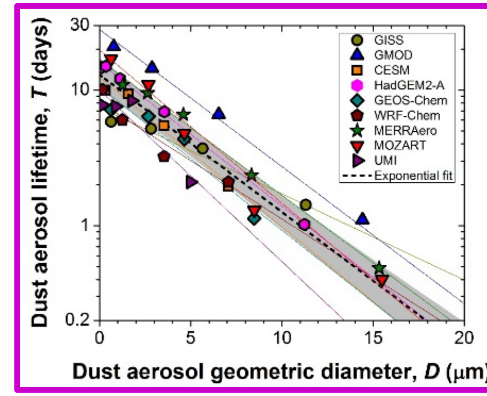

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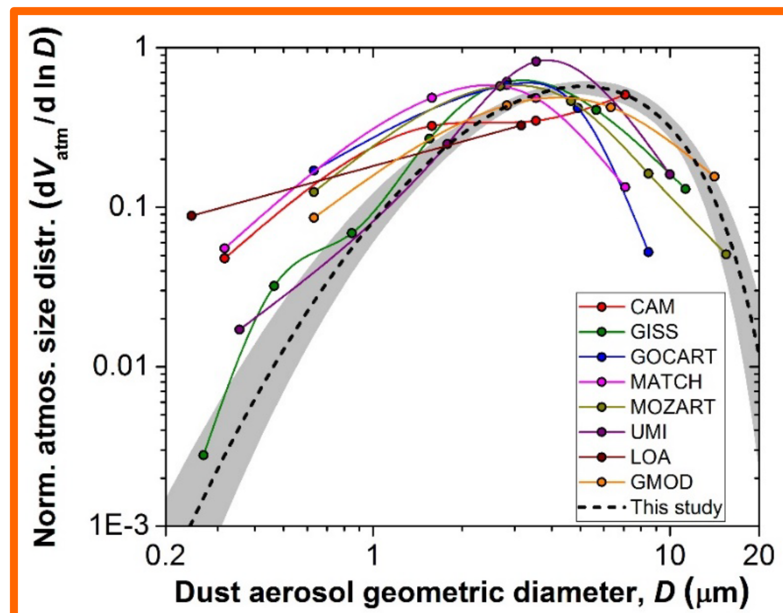
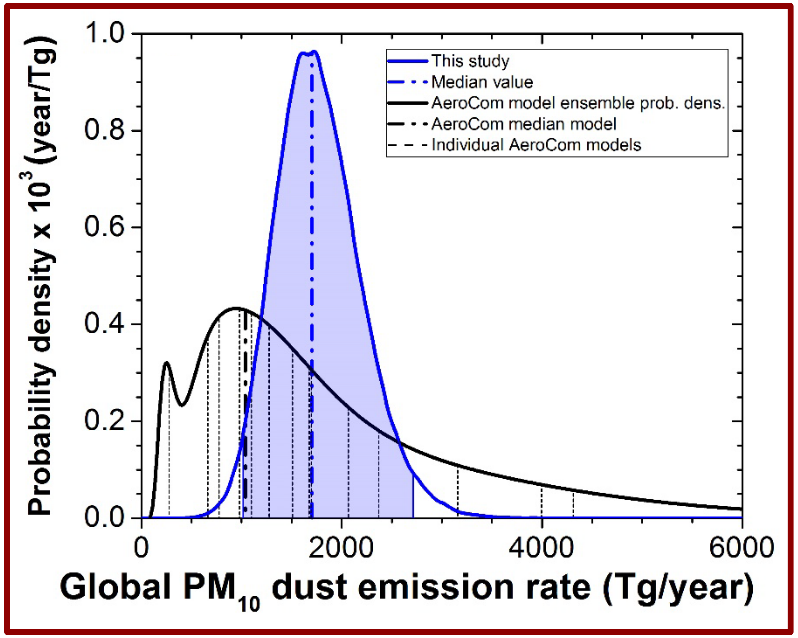
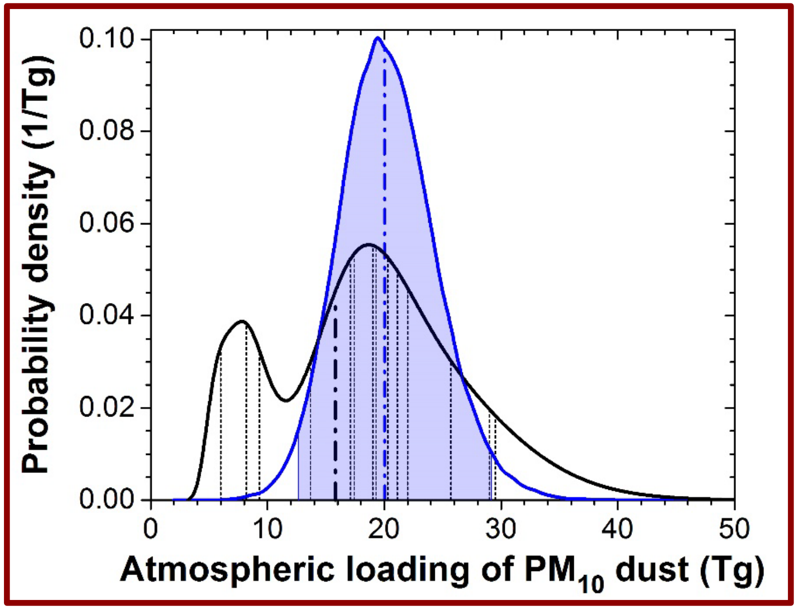


Question 2: How much dust is in the atmosphere?

- Used **constraints on dust AOD** and **extinction efficiency** to constrain global dust emission and atmospheric loading
  - **F_{emit} = 1700 (1000 - 2700) Tg/year**
  - **L_{atm} = 20 (13-29) Tg**
  - Current **models underestimate dust loading** (and emission rate)

- Can use constraints on size-resolved dust loading to **determine dust DRE**
  - See talk in room F1 today at 15:45!





Q1: What is the size distribution of atmospheric mineral dust?

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

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

- What is **emitted dust size distribution**?

Globally-averaged emitted dust size distribution

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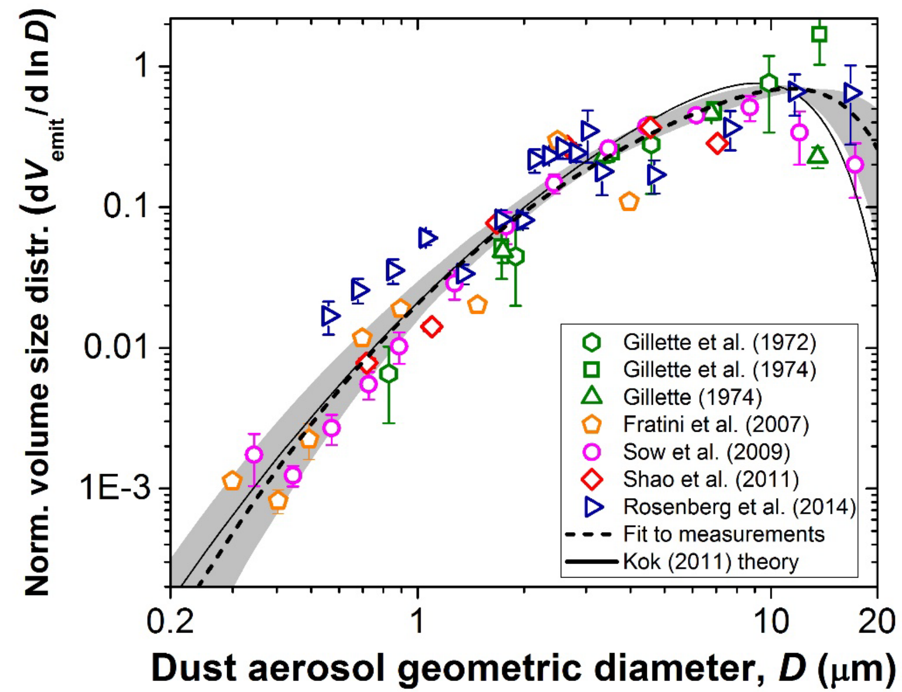
- 7 studies of **size distribution of emitted dust**
  - **Limited dependence on wind speed and soil properties** (Gillette, 1974; Kok, ACP, 2011; Rosenberg et al., 2014; Denjean et al., 2016)
  - So each data set is a measure of globally-averaged emitted dust size distribution

- **Most likely emitted size distribution** from maximum likelihood method
  - **Bootstrap method provides 95% confidence interval**
  - Explicitly accounts for measurement uncertainties
  - Consistent with Kok (PNAS, 2011)



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

Globally-averaged size-resolved dust lifetime

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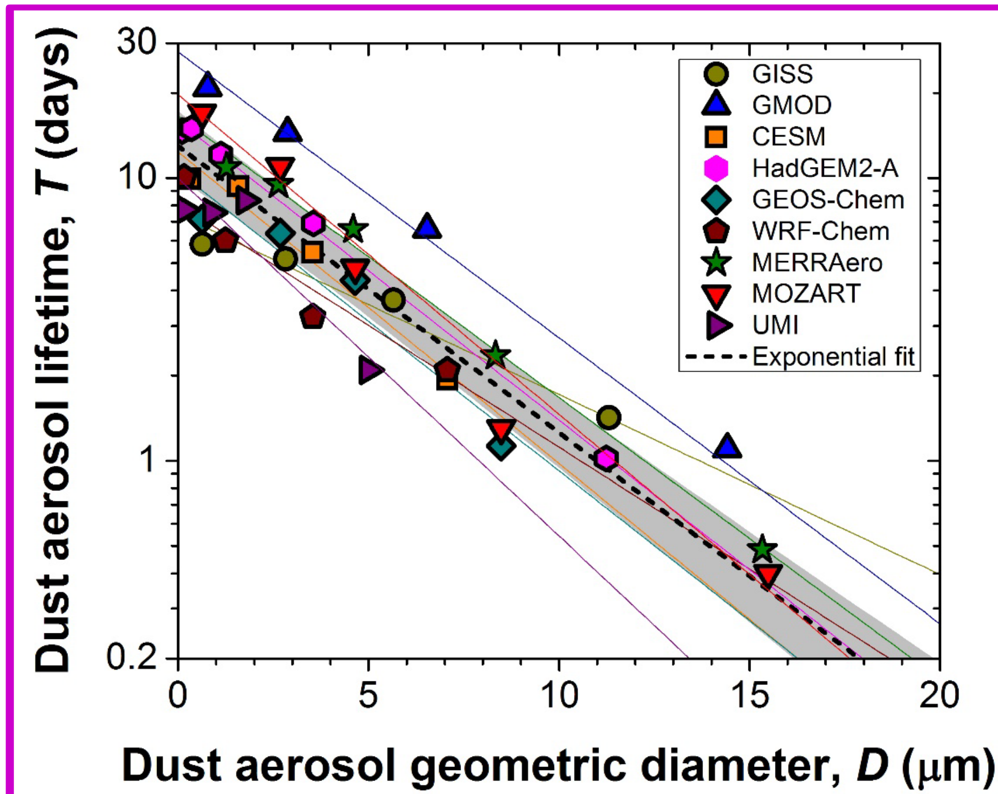
- No direct observational constraints
  - Best way to constrain *T* is through **compilation of climate model results**
  - → Obtained size-resolved dust lifetime from **9 (AeroCom) global models**

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



- Dust **lifetime decreases ~exponentially** with size

- **Most likely dust lifetime** from maximum likelihood method
  - 95% confidence interval from bootstrap method

Globally-averaged size distribution of atmospheric dust

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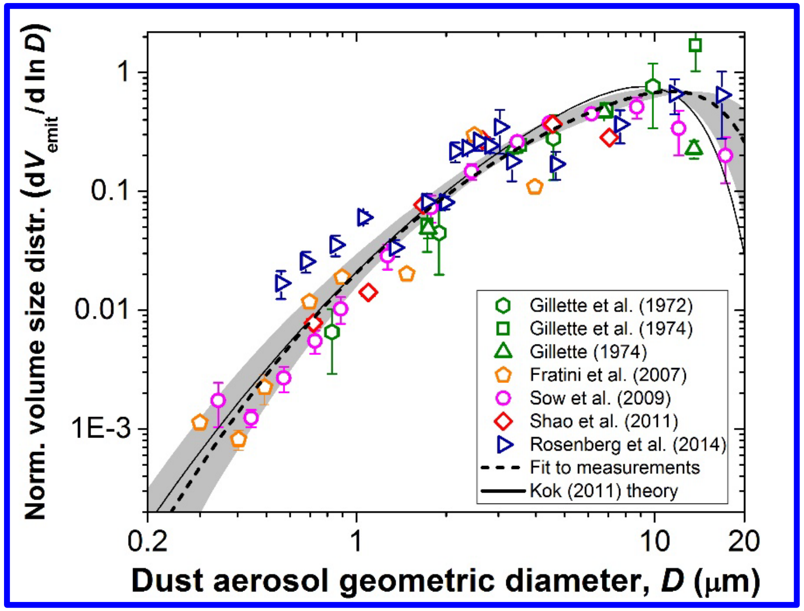

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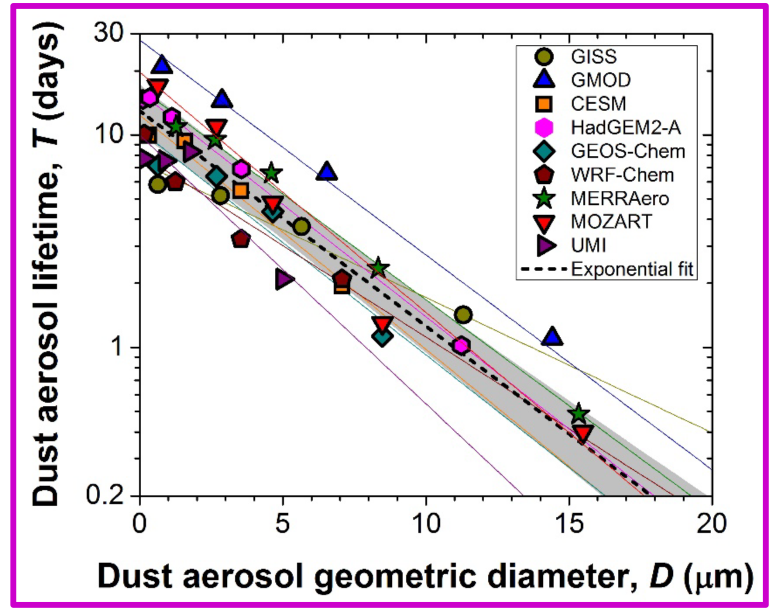

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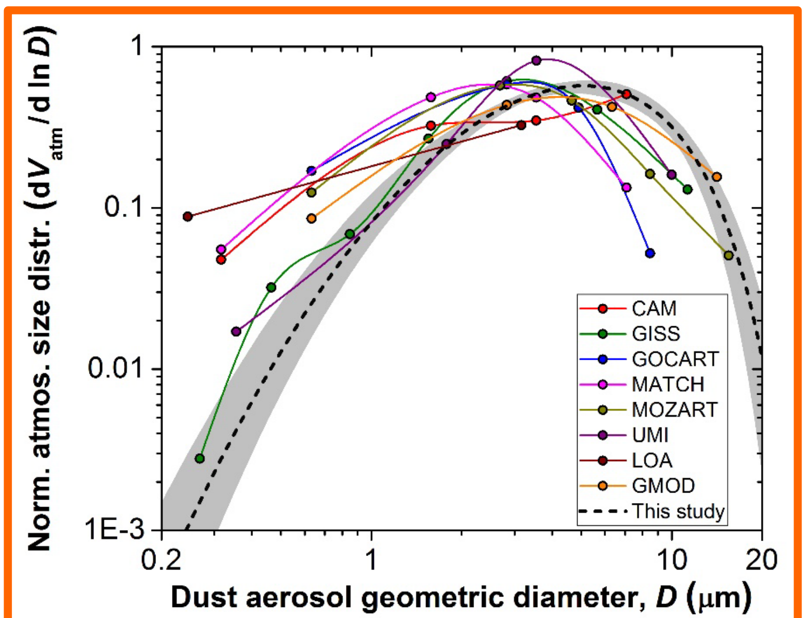

- Earth system models have **bias towards fine dust!**

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

Q2: How much dust is in the atmosphere?

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- **Atmospheric dust loading** (L_{atm}) depends on:
  1. **Global extinction of solar radiation by dust (dust aerosol optical depth = dust AOD)**
     - This is our strongest observational constraint on the global dust cycle
  2. **Optical depth produced per unit mass of dust loading**
     - In turn depends on the **atmospheric dust PSD**

$$\underbrace{L_{atm} = \int_0^{10} \frac{dL_{atm}}{dD} dD}_{\text{Atmospheric dust loading}} = \left\{ \textbf{Global dust AOD} \right\} \Big/ \left\{ \textbf{AOD per unit mass of dust loading} \right\}$$

Constraint on global dust AOD

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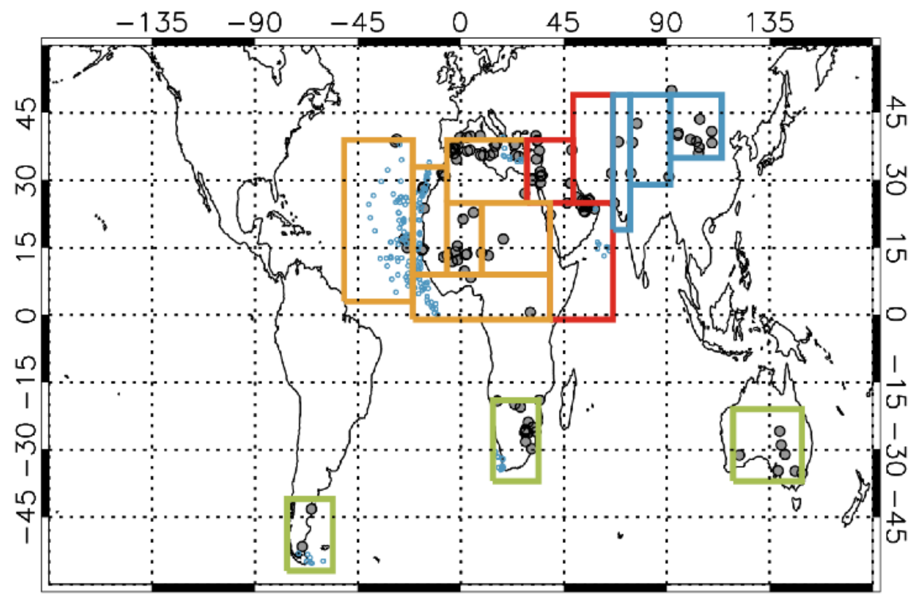
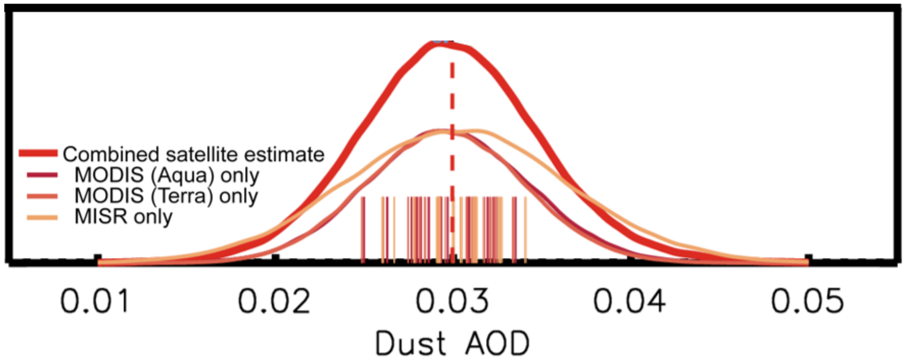
- Collaborated with David Ridley & Colette Heald (MIT) to constrain **global dust AOD**
  - Used MODIS (Aqua/Terra) and MISR AOD satellite retrievals **(superior coverage)** in 15 dust-dominated regions
  - Calibrated result to AERONET ground-based sun photometers **(superior accuracy)**
  - Used ensemble of simulations to **subtract non-dust AOD**
  - Used ensemble of simulations to calculate **ratio of global DAOD to DAOD within the 15 regions** only (x 1.3 ± 0.1)
  - Propagated uncertainties using bootstrap
- **Dust AOD = 0.030 ± 0.005**



From Ridley et al., in review



From Ridley, Heald, Kok, and Zhao, ACP, 16, 15097-15117, 2016

Global AOD per unit mass of PM_{10} dust loading

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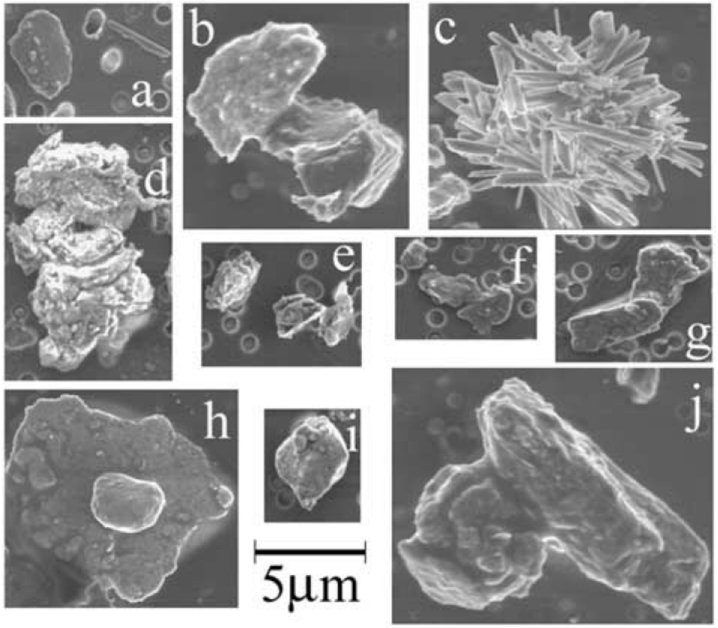
$$\underbrace{\text{AOD per unit mass of dust loading}} = \frac{1}{A_{\text{Earth}}} \int \underbrace{\frac{dV_{atm}}{dD}}_{\text{Atmospheric size distribution (already known)}} \times \underbrace{\frac{A(D)}{m(D)}}_{\text{Surface-to-mass ratio}} \times \underbrace{Q_{ext}(D)}_{\text{Extinction efficiency}}\, dD$$

- **Extinction efficiency** = extinction cross section per geometrical cross-sectional area
- Extinction efficiency difficult to calculate for dust, because **irregular and diverse** optical properties



From Reid et al., JGR, 2003

Extinction efficiency of irregular dust

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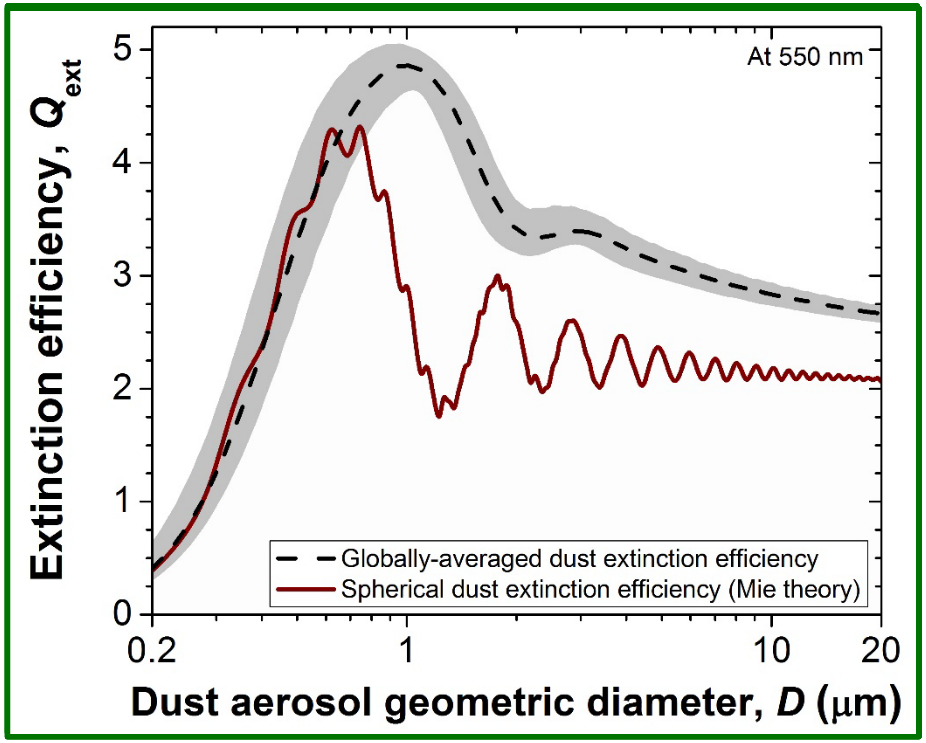
- Use range of measured dust shapes and optical properties to **calculate corresponding range in Q_{ext} (D)** (e.g., Reid et al., 2003; Kandler et al., 2007; Chou et al., 2008)
  - Used database of dust extinction efficiency of single particles to **convert to ensemble of Q_{ext}(D) values** (Meng et al., 2010)
  - Plotted is **mean of ensemble and 95 % CI**



- Extinction efficiency of irregular dust is **29 ± 5 % greater than for spherical particles** with same volume!
  - Consistent with recent lab measurements (Potenza et al., 2016)

$$\left\{\text{AOD per unit mass of dust loading}\right\} = \underbrace{\frac{1}{A_{\text{Earth}}}\int \frac{dV_{atm}}{dD}}_{\text{Atmospheric size distribution (already known)}} \times \underbrace{\frac{A(D)}{m(D)}}_{\text{Surface-to-mass ratio}} \times \underbrace{Q_{ext}(D)}_{\text{Extinction efficiency}}\, dD$$

Global AOD per unit mass of PM_{10} dust loading

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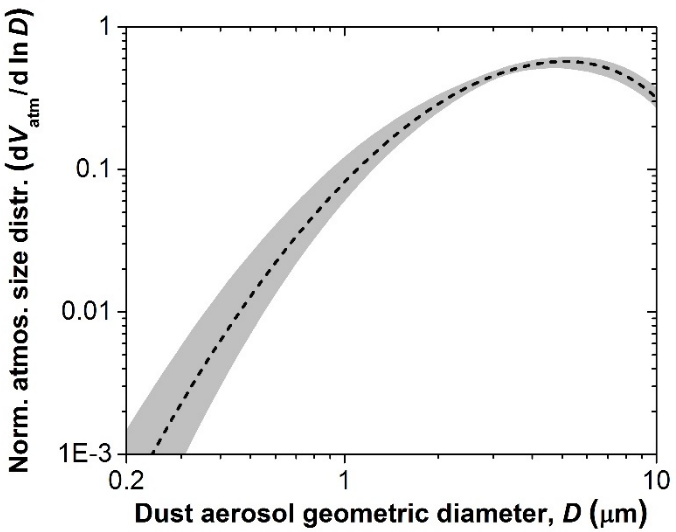
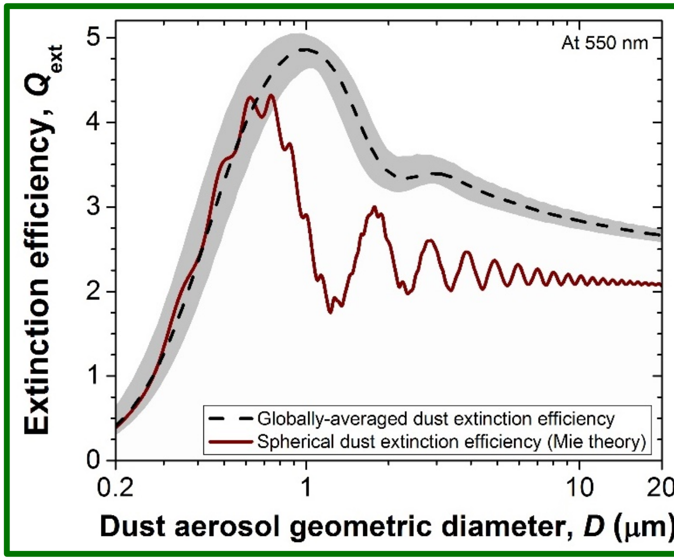


$$\times \boxed{\frac{(\pi/4)D^2}{\rho_d(\pi/6)D^3}} \times$$



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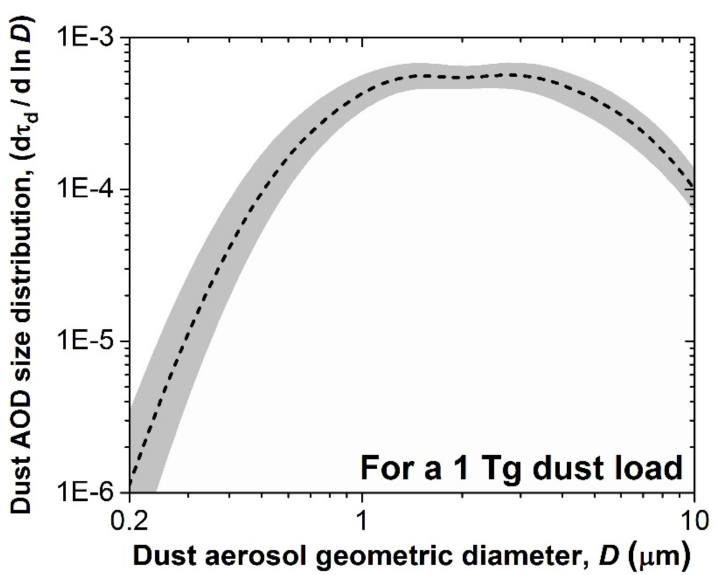

- **Global dust AOD generated per Tg** of PM_{10} dust loading is:

$$\boxed{(1.5 \pm 0.3) \cdot 10^{-3}\ \tau / \mathrm{Tg}}$$

$$\left\{\text{AOD per unit mass of dust loading}\right\} = \frac{1}{A_{\mathrm{Earth}}} \int \underbrace{\frac{dV_{atm}}{dD}}_{\text{Atmospheric size distribution (already known)}} \times \underbrace{\frac{A(D)}{m(D)}}_{\text{Surface-to-mass ratio}} \times \underbrace{Q_{ext}(D)}_{\text{Extinction efficiency}}\ dD$$

Global dust loading and emission rate

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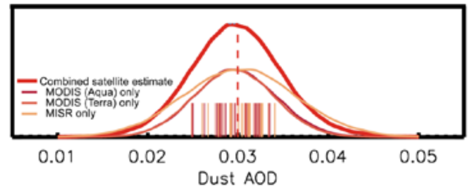
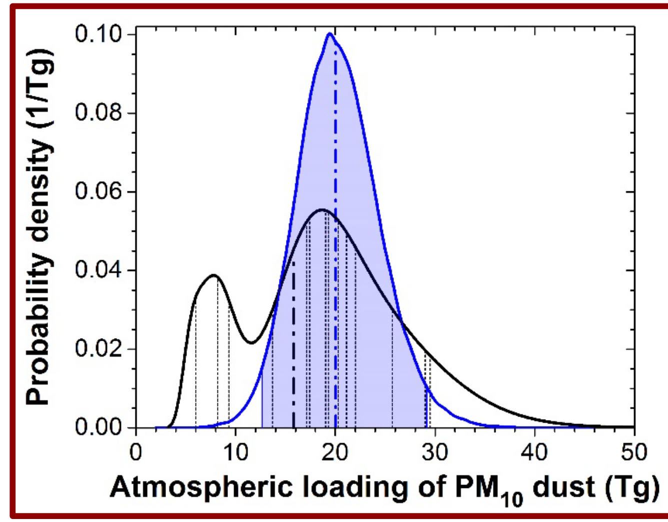
- Can now **constrain atmospheric loading of PM10 dust**
- PDF obtained from **bootstrap**
  - **Accounts for uncertainties** in emitted PSD, lifetime, Q_{ext}, DAOD
  - Does not account for possible systematic bias in model lifetimes; changes in optical properties during transport
  - **L_{atm} = 20 (13 – 29) Tg**
  - Loading of all other aerosols combined is ~10 Tg (Kinne et al., 2006) → **dust dominates aerosol mass**
  - Global dust emission rate **F_{emit} = 1700 (1000 – 2700) Tg/year**
- Many current Earth system models **underestimate global dust emission and loading**

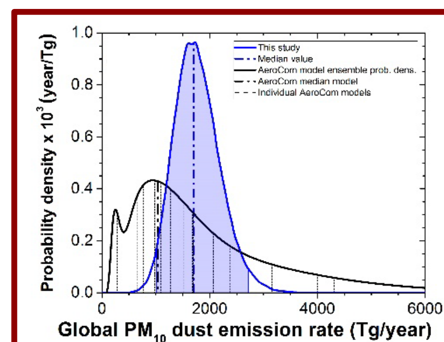
$$\underbrace{L_{\mathrm{atm}} = \int_0^{10} \frac{dL_{\mathrm{atm}}}{dD}\, dD}_{\text{Atmospheric dust loading}} = \left\{\text{Global dust AOD}\right\} \Big/ \left\{\text{AOD per unit mass of dust loading}\right\}$$



$$/ \quad (1.5 \pm 0.3) \cdot 10^{-3}\ \tau / \mathrm{Tg}$$

$$=$$





From Kok et al., Nature Geoscience, 2017