The physics of dust emission

(and how to parameterize it in atmospheric models)

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ICAP 10th working group meeting
Seamless model development: Aerosol modelling across timescales
June 6th, 2018

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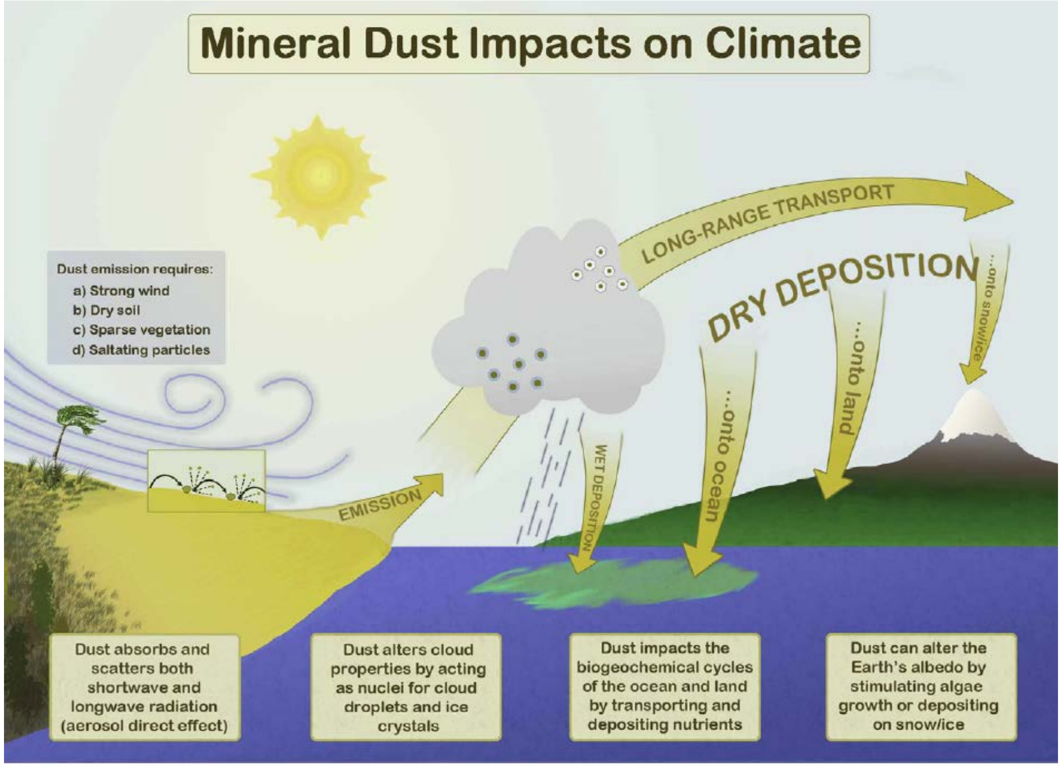
OUTLINE:

What do we need to know about physics of dust emission?

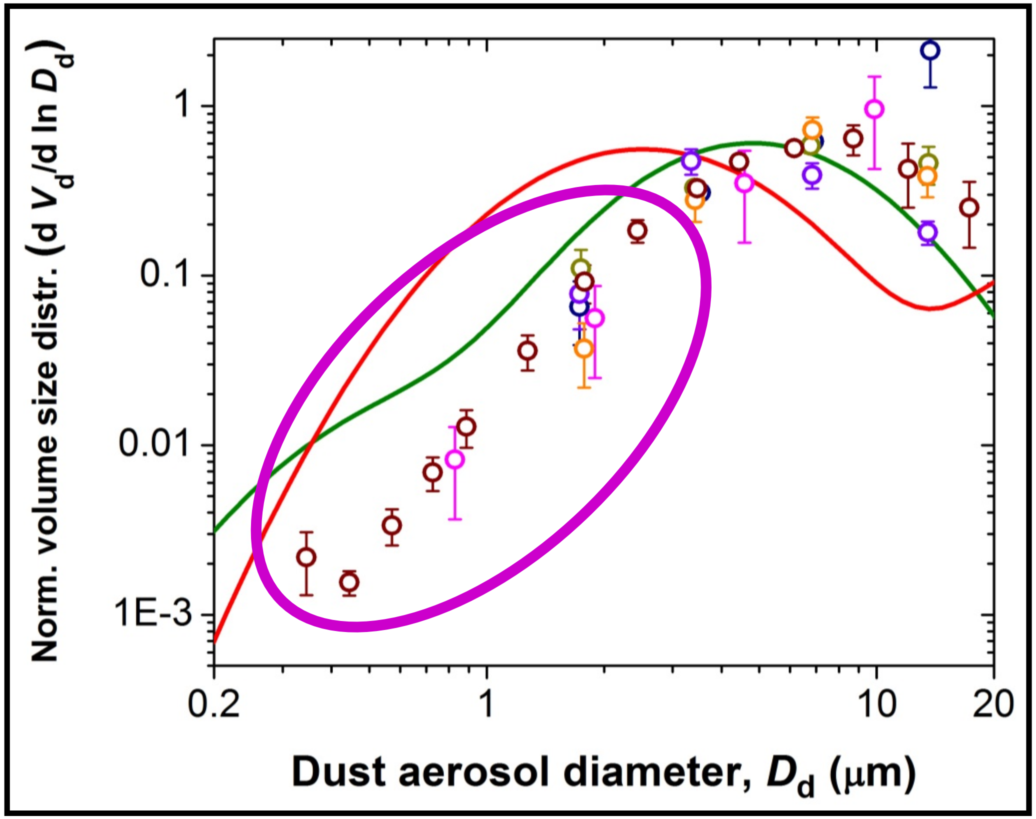
- **To represent dust effects** on weather and climate, models need to know:
  1. **What is size distribution** of emitted dust?
  2. **How much dust** is emitted? How does dust flux depend on wind speed and soil conditions?



From Mahowald et al. (2014)

Emitted dust size distribution in models

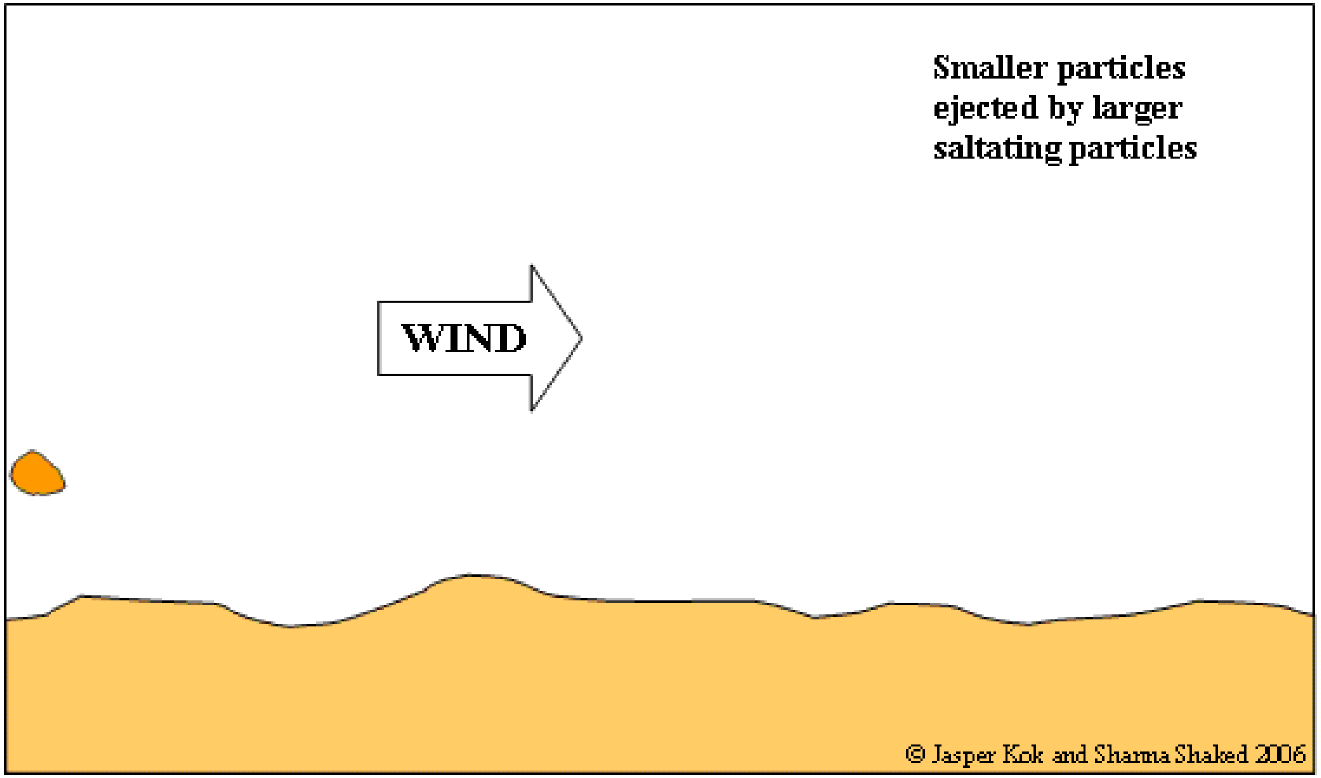
- Emitted dust size distribution **poorly understood**
  - Measurements: size-resolved **vertical dust flux** from eroding soil
  - Models **overestimate small particle fraction**
- **What determines dust size distribution**?



Measurements: Gillette et al. (1972, 1974), Gillette (1974), Sow et al. (2009)

Macrophysics of dust emission: Saltation

- Dust aerosols (~0.1-50 μm) are emitted by **saltation**, the wind-driven hopping motion of sand grains (~200 μm)
  - Dust aerosols experience **large cohesive forces** that generally **prevent direct lifting by wind** (e.g., Kok et al., 2012)



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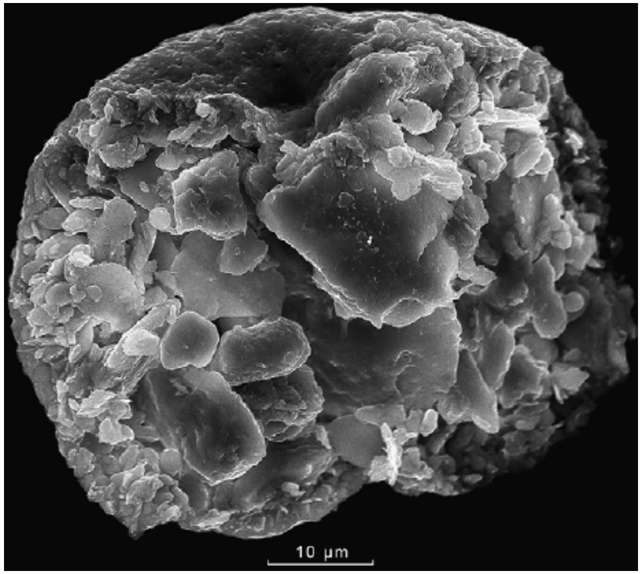
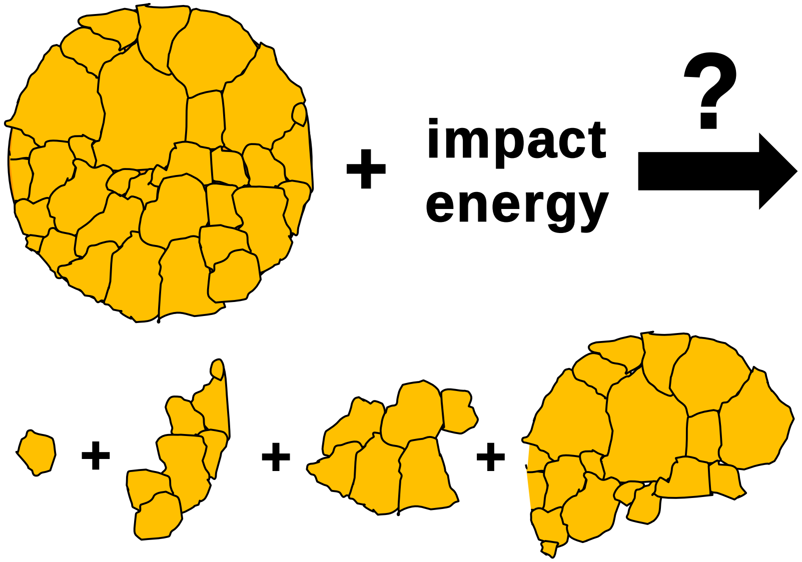
Microphysics of dust emission: Fragmentation of dust aggregates

- Small particles (< ~20 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)

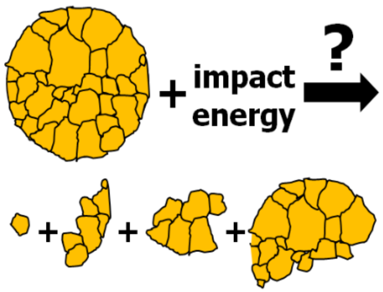


Analog: fragmentation of brittle materials

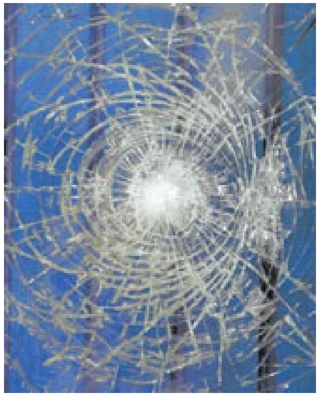
- **Dust aggregate fragmentation** is very complex problem
- Closest analog is **fragmentation of brittle materials** (e.g., glass)
- Measurements show brittle size distribution is **scale-invariant** (a **power law**)
  - Resulting **size distribution**:

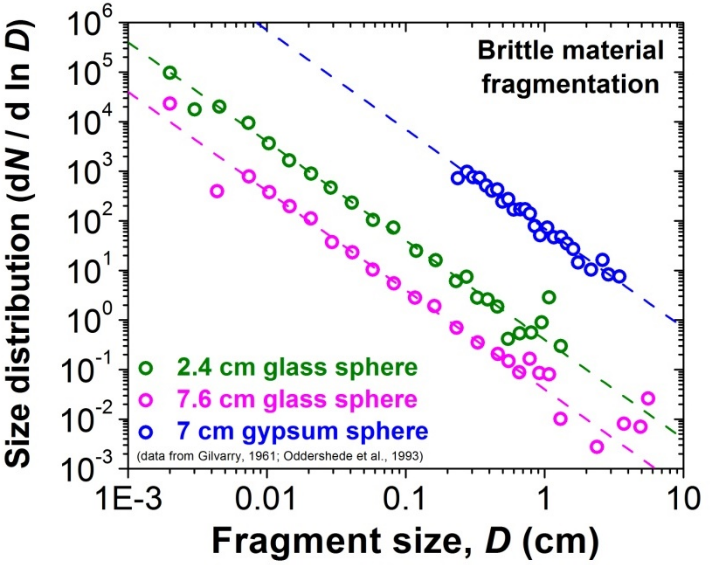
$$\boxed{\frac{dN}{d\ln D_f} \propto D_f^{-2}}$$

Dust aggregate fragmentation:



Analog: brittle fragmentation





(data from Gilvarry, 1961; Oddershede et al., 1993)

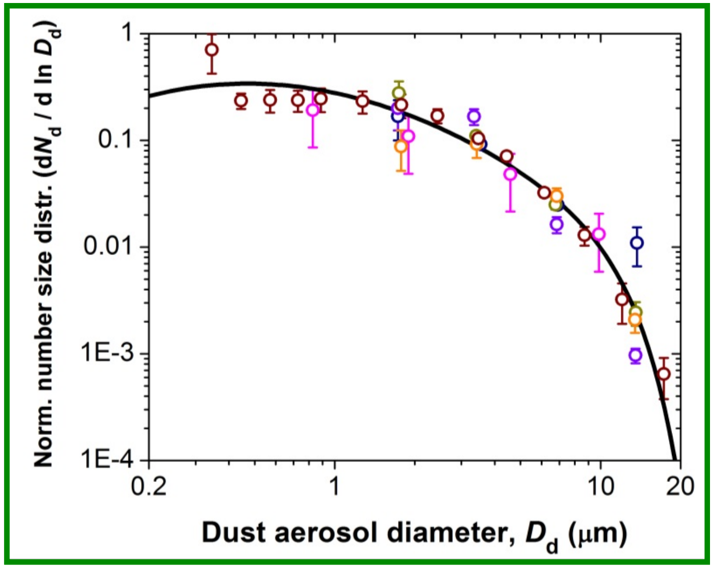
Theory in agreement with measurements

- Derived **simple equation:**

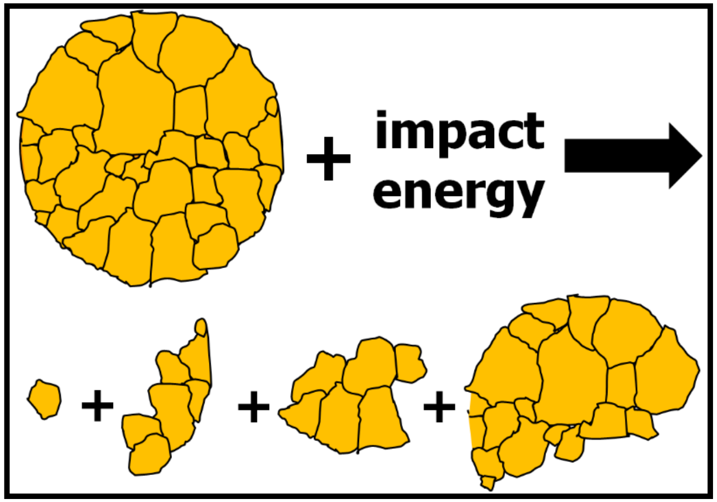
$$\frac{dN}{d\ln D_{\mathrm{d}}} = \underbrace{\frac{c}{D_{\mathrm{d}}^{2}}}_{\text{Scale invariance}} \times \underbrace{\exp\left[-\left(\frac{D_{\mathrm{d}}}{\lambda}\right)^{3}\right]}_{\text{Large-size cutoff}} \times \underbrace{\left\{1+\frac{\mathrm{erf}\left[\ln\left(D_{\mathrm{d}}/D_{\mathrm{soil}}\right)\right]}{\sqrt{2}\ln\sigma_{\mathrm{soil}}}\right\}}_{\text{Cumulative soil fraction (= correction for discrete particles)}}$$

  - N = number of aerosols; D_{d} = aerosol size ; c = normalization constant
  - Only “fitting” parameter: **λ ≈ 12 μm from least squares fit** to measurements
  - D_{soil} and σ_{soil} describe soil size distribution

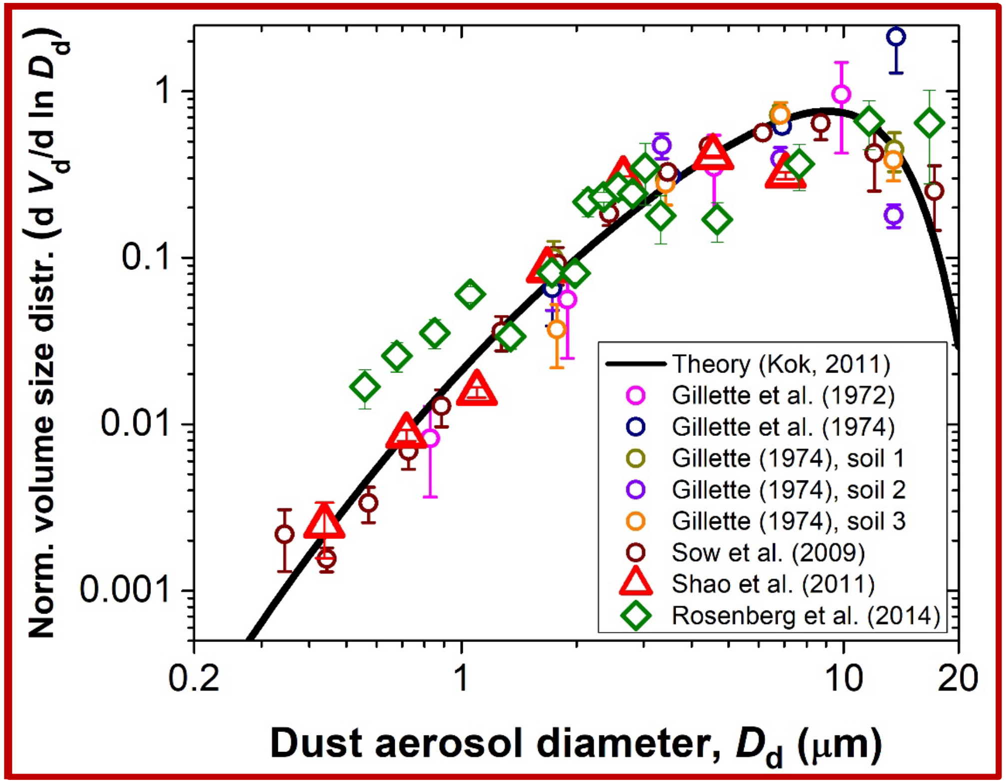
- Theory in **good agreement** with available measurements



Kok, J.F. (2011), *PNAS*, 108, 1016



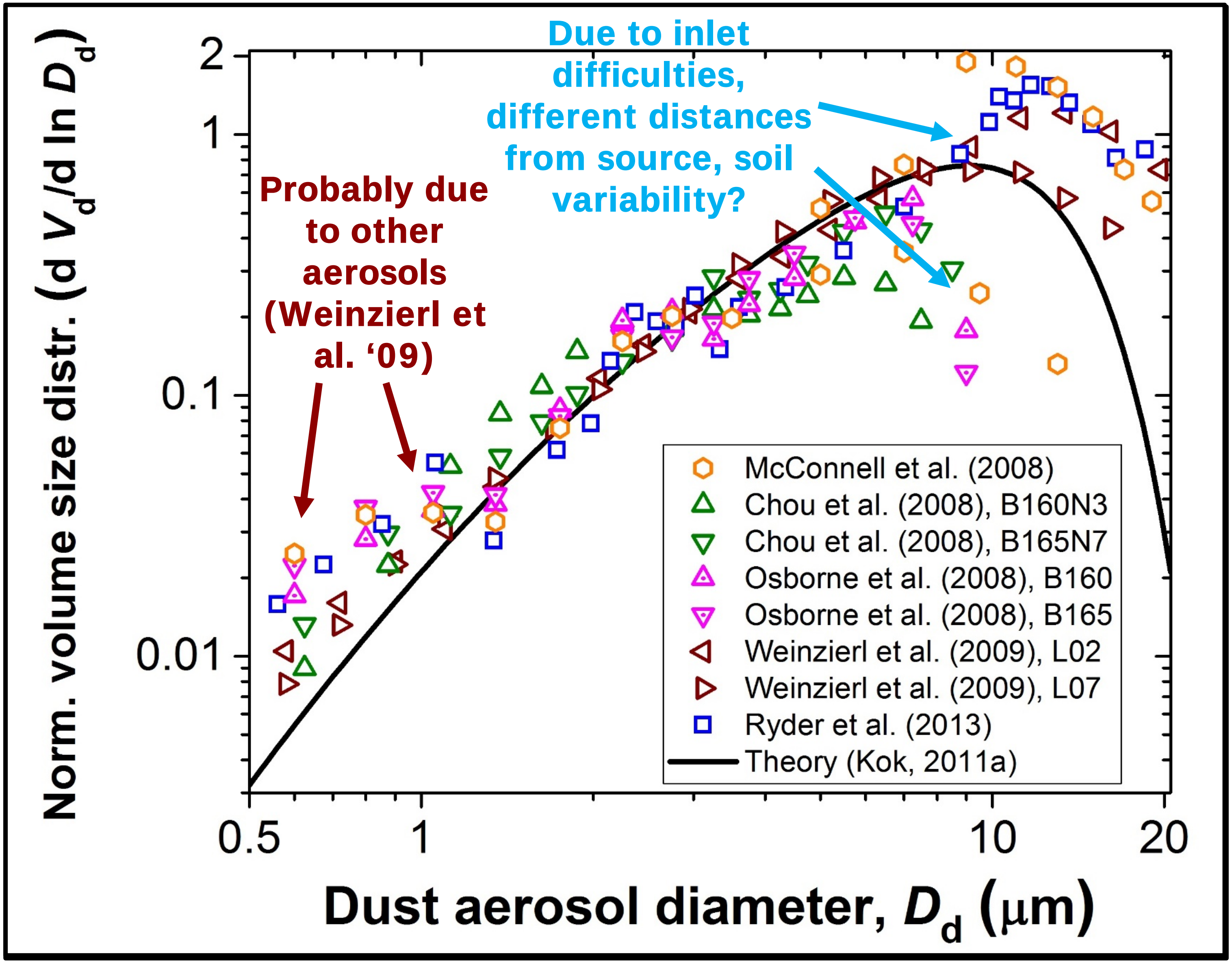
Theory consistent with subsequent measurements



- **New measurements** of emitted dust size distribution were published by Shao et al. (2011) and Rosenberg et al. (2014)

- In **agreement** with theory

Consistent with in situ measurements over North Africa



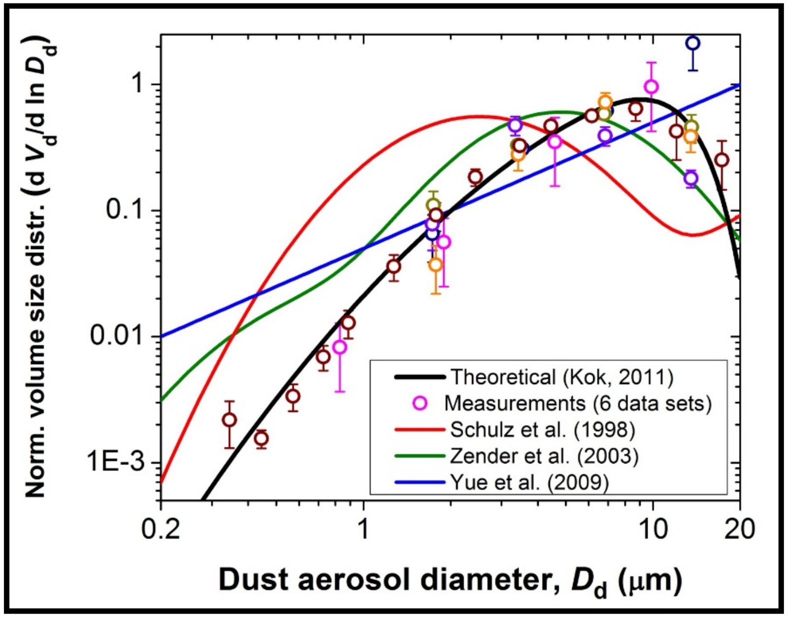
Due to inlet difficulties, different distances from source, soil variability?

Probably due to other aerosols (Weinzierl et al. '09)

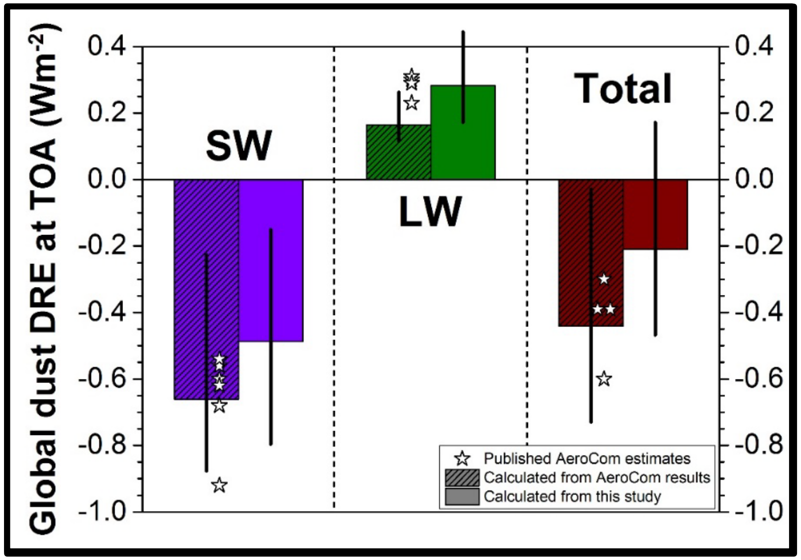
From Mahowald, Albani, Kok et al. (2014)

Implication: current models overestimate dust cooling

- Models have **too much fine dust**, **not enough coarse dust**
  - Since **fine dust cools** and **coarse dust warms**, models overestimate dust cooling



- AeroCom models: dust is strongly cooling, **~-0.4 W/m^2 at TOA**
  - Correcting **~halves** dust direct radiative effect [95% CI: -0.48 to +0.20 W/m^2]



From Kok et al., Nature Geoscience, 2017

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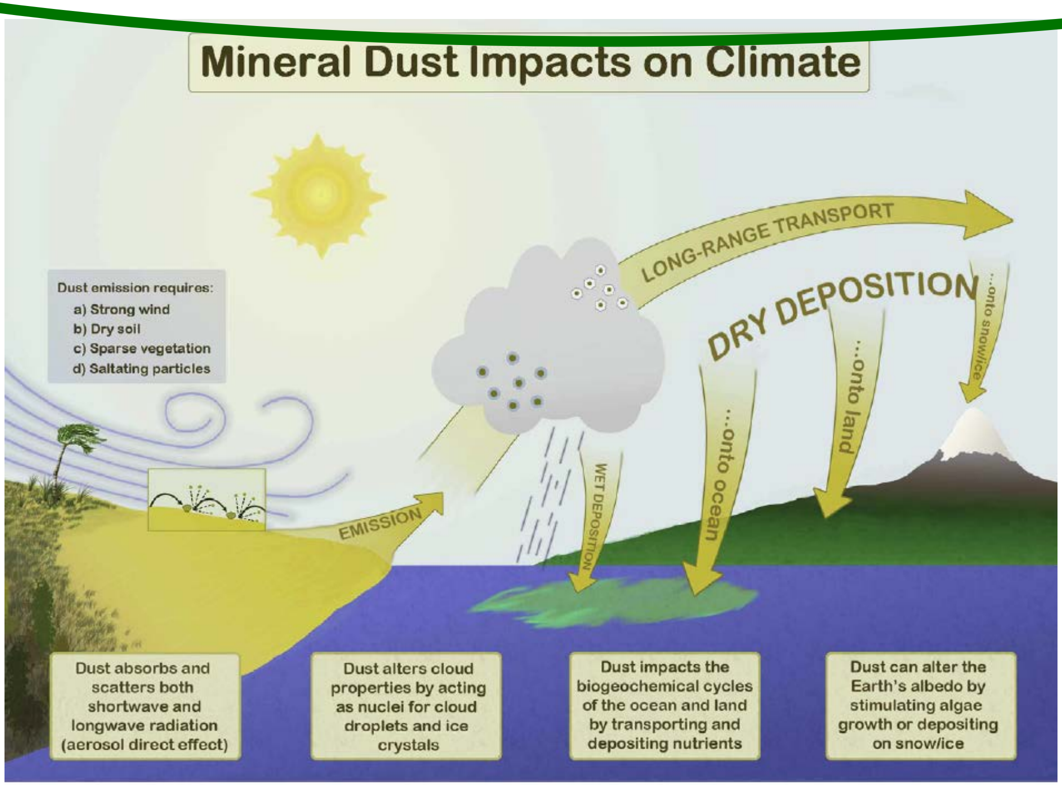


Dust emission requires:
a) Strong wind
b) Dry soil
c) Sparse vegetation
d) Saltating particles

Dust absorbs and scatters both shortwave and longwave radiation (aerosol direct effect)

Dust alters cloud properties by acting as nuclei for cloud droplets and ice crystals

Dust impacts the biogeochemical cycles of the ocean and land by transporting and depositing nutrients

Dust can alter the Earth's albedo by stimulating algae growth or depositing on snow/ice

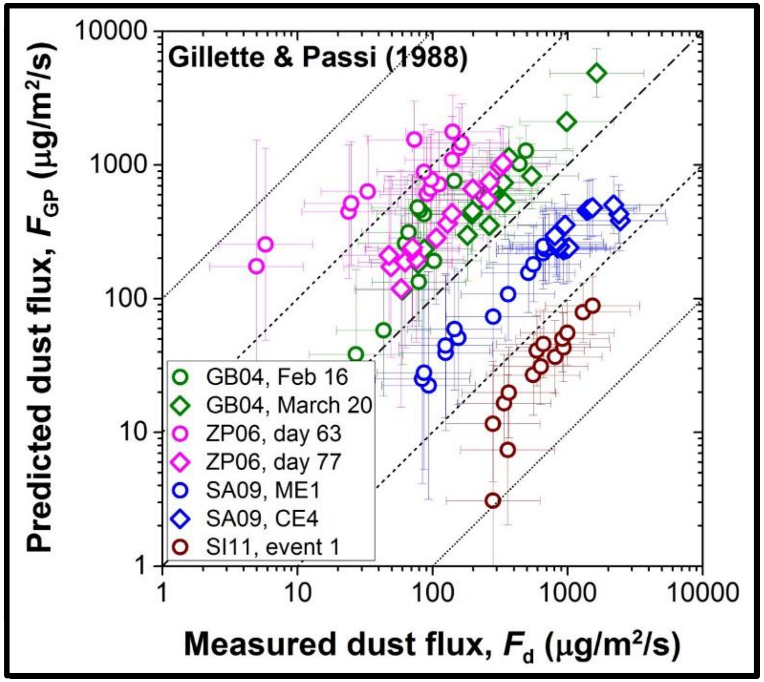
From Mahowald et al. (2014)

Are current dust flux parameterizations missing important processes?

$$\left\{\begin{matrix}\textbf{Dust flux}\\ \textbf{in model}\\ \textbf{grid cell}\end{matrix}\right\} = \boxed{\underbrace{F_d}_{\text{Vertical dust flux (small scale)}}} \times \underbrace{S}_{\text{Source function}} \times \underbrace{C_{\text{tune}}}_{\text{Global tuning const}}$$

- Dust flux measurements show **large spread**

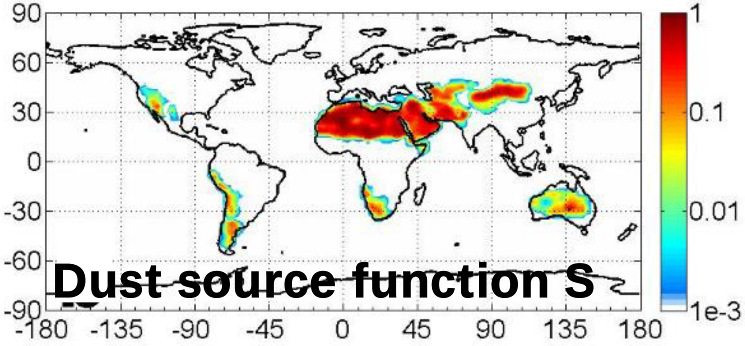
- Existing F_d parameterizations capture only part of spread
  - Must be **missing some important process(es)**
  - Can models capture dust **response to climate changes**?

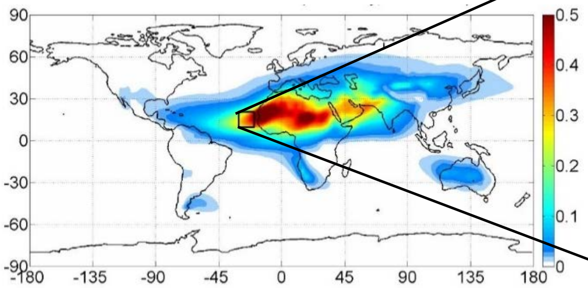


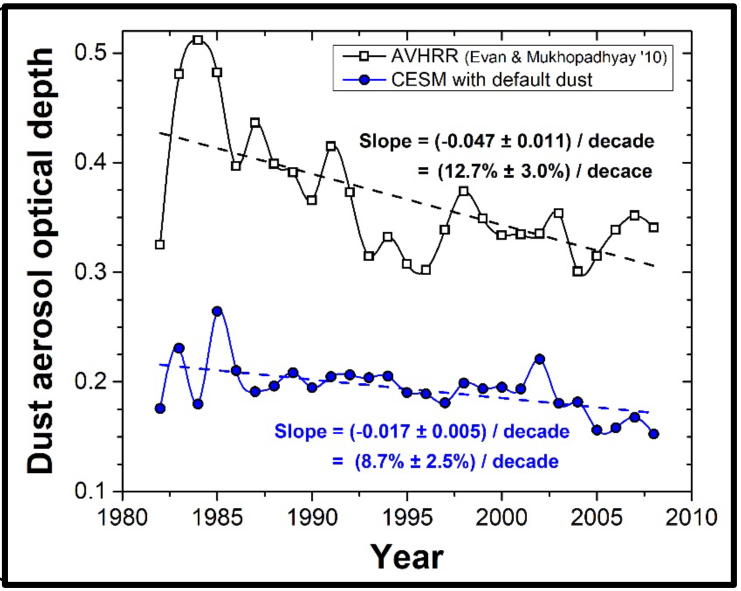
Most current dust modules use empirical source function

- “**Source function**” (**S**) parameterizes variability in “**soil erodibility**” (=dust flux per unit wind stress)

- Empirical source function **cannot capture full climate change response**
  - Current models **cannot capture decrease** in N.-African dustiness since ‘80s (Evan et al. 2014)
  - Due to missing processes?







Basic vertical dust flux equation

$$\underbrace{F_\mathrm{d}}_{\text{Vertical dust flux}} = \underbrace{n_\mathrm{s}}_{\text{Number of saltator impacts}} \times \underbrace{f_\mathrm{frag}}_{\text{Fraction of impacts producing fragmentation}} \times \underbrace{m_\mathrm{frag}}_{\text{Dust aerosol mass per fragmentation event}}$$

- Know n_s and m_frag from theory (e.g., Shao et al., 1993; Kok et al., 2012):
  - $\boxed{n_\mathrm{s} \propto \rho_\mathrm{a}\left(u_*^2 - u_{*\mathrm{t}}^2\right)}$
  - $\boxed{m_\mathrm{frag} \propto f_\mathrm{clay}}$
- How does **fragmentation fraction f_frag** depend on wind (u_*) and soil ($u_{*\mathrm{t}}$) conditions?
  - Calculate $f_\mathrm{frag} = f\,(u_*,\ u_{*\mathrm{t}})$ using numerical saltation model COMSALT (Kok & Renno, 2009)

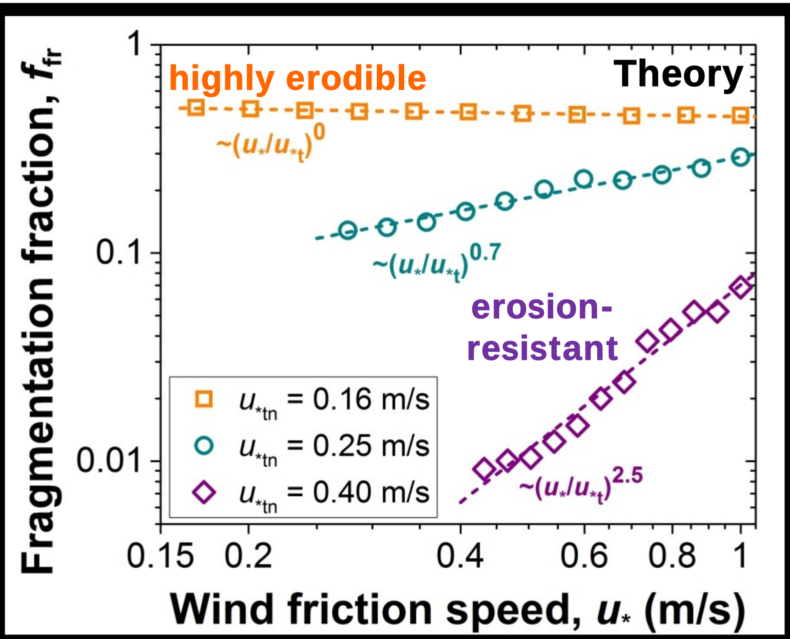
How does fragmentation fraction (f_{frag}) depend on friction velocity (u_*)?

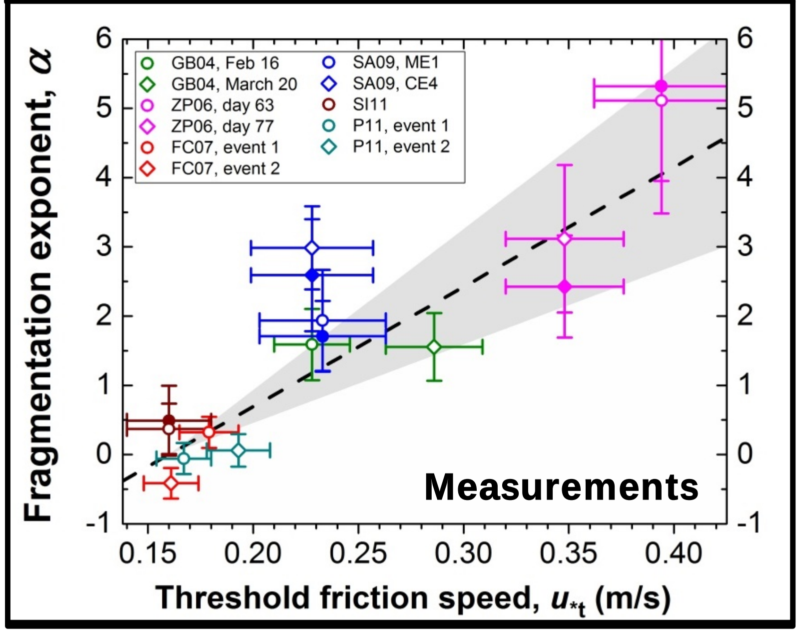
- For **highly erodible soils**:
  - Most saltator impacts produce fragmentation
  - → **f_{frag} ~constant with u_***
- For **erosion-resistant soils**:
  - Only energetic saltators emit dust
  - Their fraction increases with u_*
  - **f_{frag} increases sharply with u_*!**
- **f_{frag} scales with $(u_* / u_{*t})^{\alpha}$**
  - 'Fragmentation exponent' **α scales with u_{*t}**
- Confirmed by measurements

$$f_{frag} = \left(\frac{u_*}{u_{*t}}\right)^{C_a \frac{u_{*t} - u_{*t0}}{u_{*t0}}}$$

$$f_{frag} \propto \underbrace{f(u_*)}_{} \times f(u_{*t})$$

Due to increase in high-energy saltators with u*





How does fragmentation fraction (f_{frag}) depend on threshold friction velocity(u_{*t})?

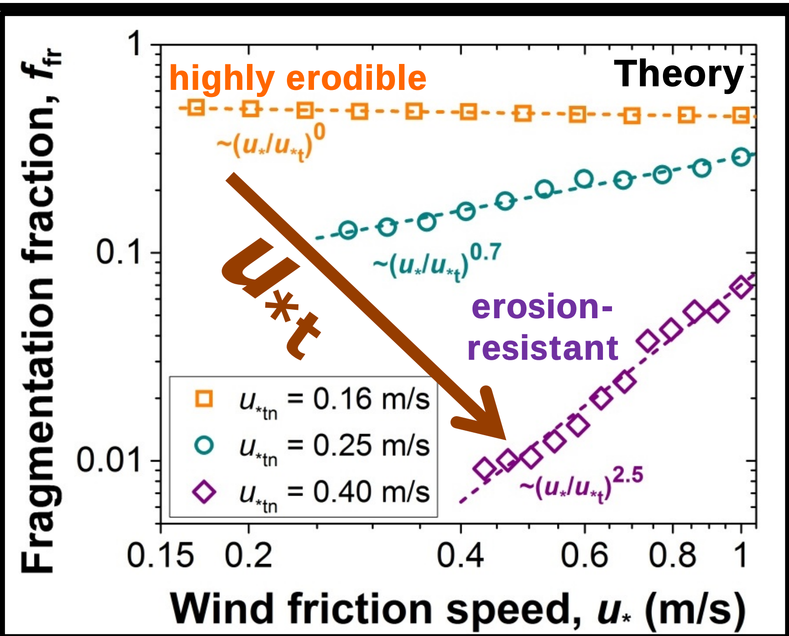
- Increase in u_{*t} makes soil **more resistant to erosion**
  → **Reduction in f_{frag}** as u_{*t} increases
- **f_{frag} decreases exponentially** with u_{*t}
  - Confirmed by measurements
- Larger u_{*t} → soil more erosion resistant
  - **Decrease in dust flux** for given saltator impact flux – not in current GCMs!
  - Climate partially determines u_{*t} → many **models underestimate dust cycle sensitivity to climate changes!**

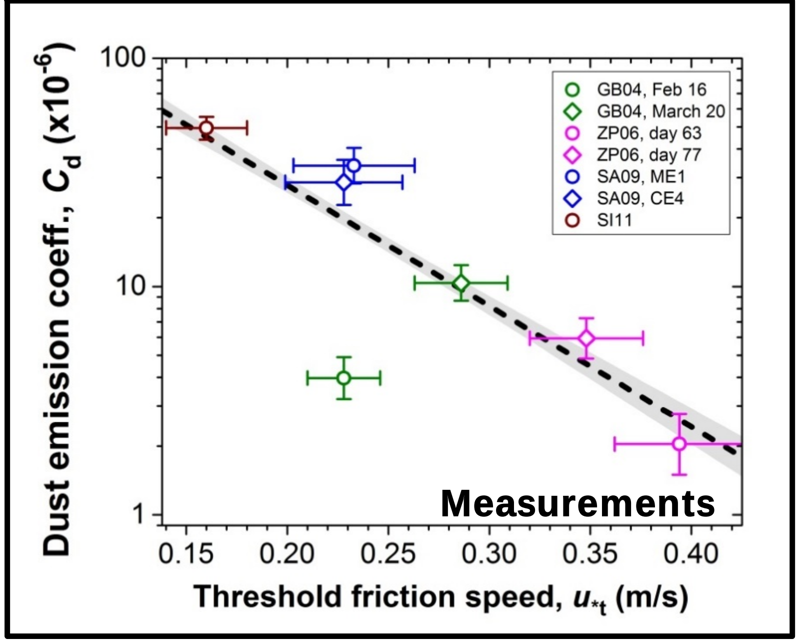
$$f_{\text{frag}} \propto \left(\frac{u_*}{u_{*t}}\right)^{C_a \frac{u_{*t} - u_{*t0}}{u_{*t0}}} \times C_d$$

$$f_{\text{frag}} \propto \left(\frac{u_*}{u_{*t}}\right)^{C_a \frac{u_{*t} - u_{*t0}}{u_{*t0}}} \times \boxed{f\left(u_{*t}\right)}$$

$$C_d = \exp\left(-C_e \frac{u_{*t}}{u_{*t0}}\right)$$

Due to increasing soil resistance to erosion with u_{*t}





Proposed vertical dust flux parameterization

$$\underbrace{F_{\mathrm{d}}}_{\text{Vertical dust flux}} \propto \underbrace{\frac{\rho_{\mathrm{a}}\left(u_*^2 - u_{*\mathrm{t}}^2\right)}{u_{*\mathrm{t}}}}_{\text{Scales saltator impact flux}} \times \underbrace{f_{\mathrm{frag}}}_{\text{Fraction of impacts producing fragmentation}} \times \underbrace{f_{\mathrm{clay}}}_{\text{Scales dust mass per fragmentation event}}$$

- And f_{frag} is given by:

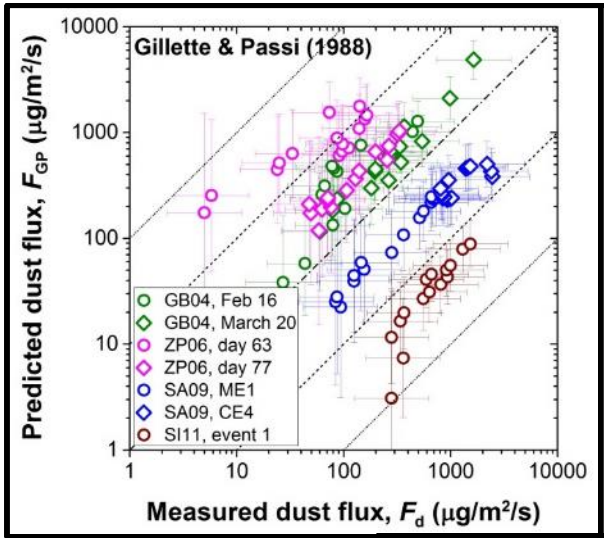
$$f_{\mathrm{frag}} \propto \underbrace{\left(\frac{u_*}{u_{*\mathrm{t}}}\right)^{C_{\mathrm{a}}\frac{u_{*\mathrm{t}}-u_{*\mathrm{t0}}}{u_{*\mathrm{t0}}}}}_{\text{Due to increase in high-energy saltators with } u*} \times \underbrace{\exp\left(-C_{\mathrm{e}}\frac{u_{*\mathrm{t}}}{u_{*\mathrm{t0}}}\right)}_{\text{Due to increasing resistance to erosion with } u_{*\mathrm{t}}}$$

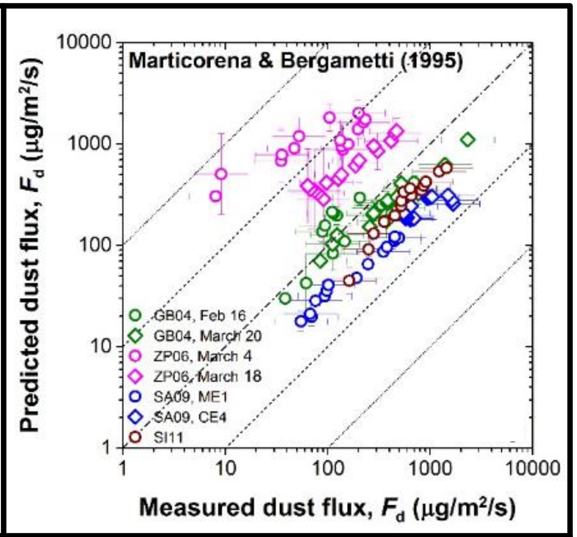
- Full details in Kok et al. (2014), Atm. Chem. Phys., Part 1, **14**, 13,023

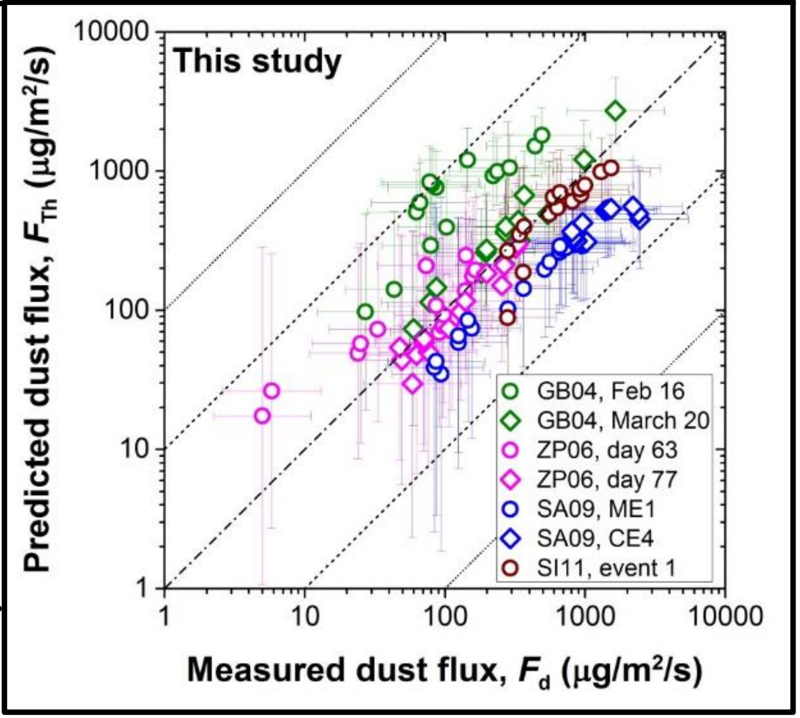
Comparison against dust flux measurements

- New parameterization **reduces** root mean square **error by ~40%**!
  - (Used cross-correlation technique)

$$F_{\mathrm{d}} \propto f_{\mathrm{clay}} \frac{\rho_{\mathrm{a}}\left(u_*^2 - u_{*\mathrm{t}}^2\right)}{u_{*\mathrm{t}}} \underbrace{\left(\frac{u_*}{u_{*\mathrm{t}}}\right)^{C_{\mathrm{a}} \frac{u_{*\mathrm{t}} - u_{*\mathrm{t}0}}{u_{*\mathrm{t}0}}}}_{\text{Due to increase in high-energy saltators with } u_*} \times \underbrace{\exp\left(-C_{\mathrm{e}} \frac{u_{*\mathrm{t}}}{u_{*\mathrm{t}0}}\right)}_{\text{Due to increasing resistance to erosion with } u_{*\mathrm{t}}}$$



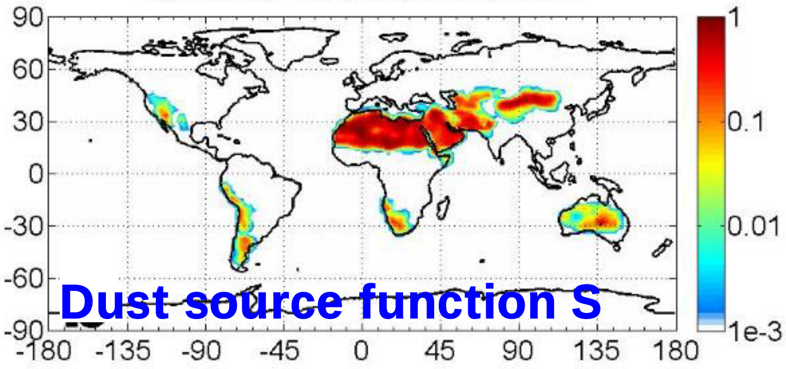




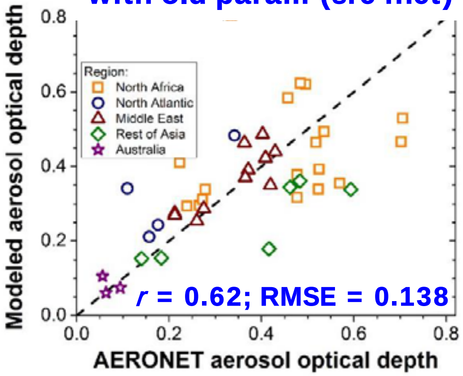
From Kok et al. (2014), Atm. Chem. Phys., Part 1, **14**, 13,023

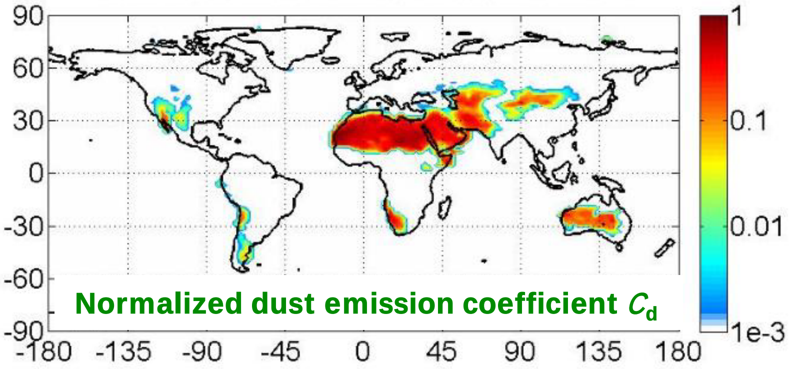
K14 parameterization improves CESM agreement with measurements

- Pattern of dust emission coefficient (C_d) similar to *S*
  - **Improves model agreement** against AERONET (in CESM)
  - Also improvement on seasonal and daily timescales
- K14 **eliminates need for source function** (in CESM)

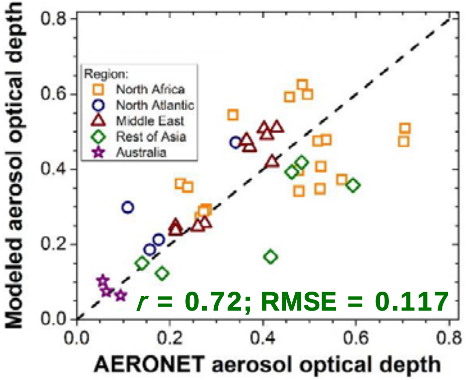


AERONET vs model AOD with old param (src fnct)





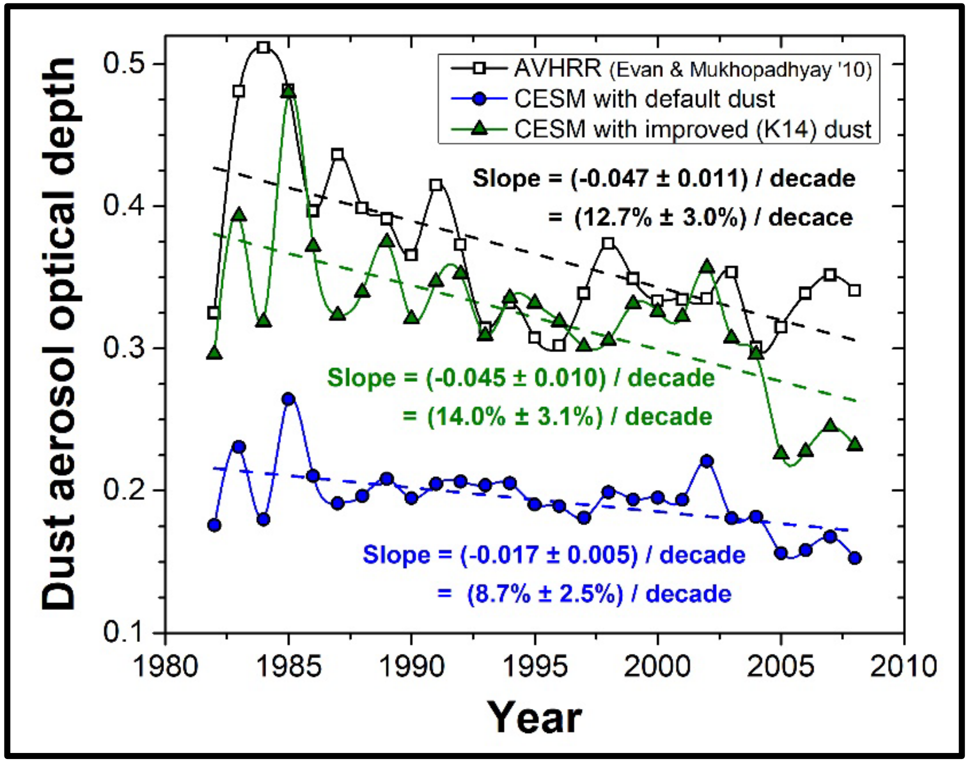
AERONET vs model AOD with new param. (no src fct)



$$F_d = C_d f_{\text{clay}} \frac{\rho_a\left(u_*^2 - u_{*t}^2\right)}{u_{*tn}} \left(\frac{u_*}{u_{*t}}\right)^{C_a \frac{u_{*tn} - u_{*t0}}{u_{*t0}}} \; ; \; \underbrace{C_d = \exp\left(-C_e \frac{u_{*t}}{u_{*t0}}\right)}_{\text{Due to increasing resistance to erosion with } u_{*t}}$$

K14 parameterization with CESM better captures historical record

- **CESM with K14** reproduces North African dust decline
  - Captures processes empirically parameterized by source function?

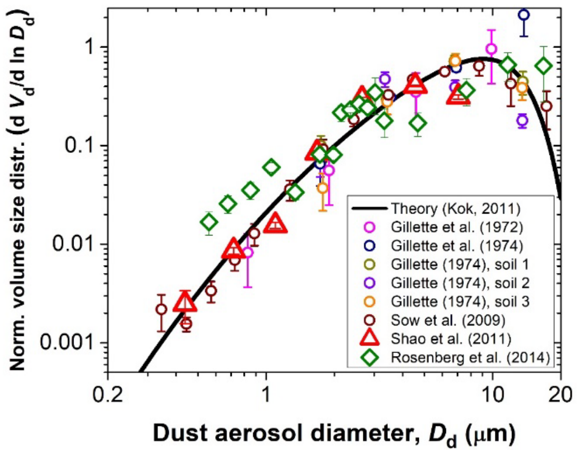


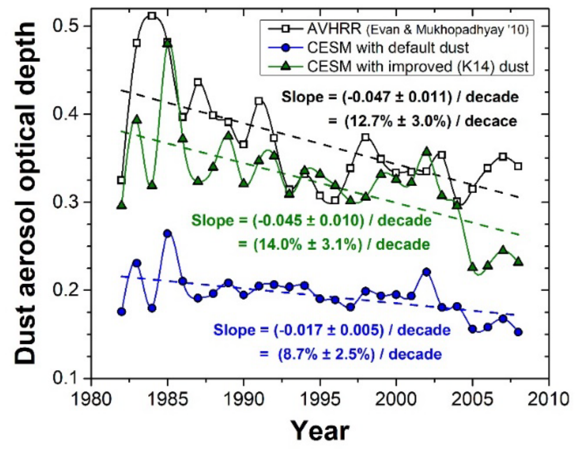
Kok et al., Nature Communications, 2018

Overview: Improving parameterization of dust emission in models

- Low-hanging fruit: implement **brittle fragmentation theory** for emitted size distribution
  - Substantial experimental support
  - Easy to implement (simple equation)
- To **improve dust cycle response** to changes in weather/climate (including diurnal, seasonal):
  - Kok et al. (2014) parameterization can give **more realistic response**
  - **Performance differs** between models
- Other improvements:
  - Aeolian roughness maps
  - Sub-grid scale variability (wind, surface)

$$\frac{dN_\mathrm{d}}{d\ln D_\mathrm{d}} = \underbrace{\frac{c}{D_\mathrm{d}^2}}_{\text{Scale invariance}} \underbrace{\exp\left[-\left(\frac{D_\mathrm{d}}{\lambda}\right)^3\right]}_{\text{Finite crack separation}} \underbrace{\left\{1+\frac{erf\left[\ln\left(D_\mathrm{d}/\overline{D}_\mathrm{soil}\right)\right]}{\sqrt{2}\ln\sigma_\mathrm{soil}}\right\}}_{\text{Soil cumulative mass fraction} \le D_\mathrm{d}}$$





Thank you!

Thoughts? Comments? → jfkok@ucla.edu

Presented work was from following references:

Kok, J. F. (2011), A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle, *Proc. Natl. Acad. Sci. USA*, 108, 1016-21

Kok, J. F., et al. (2014), An improved dust emission model – Part 1: Model description and comparison against measurements, *Atmospheric Chemistry and Physics*, 14, 13,023-41.

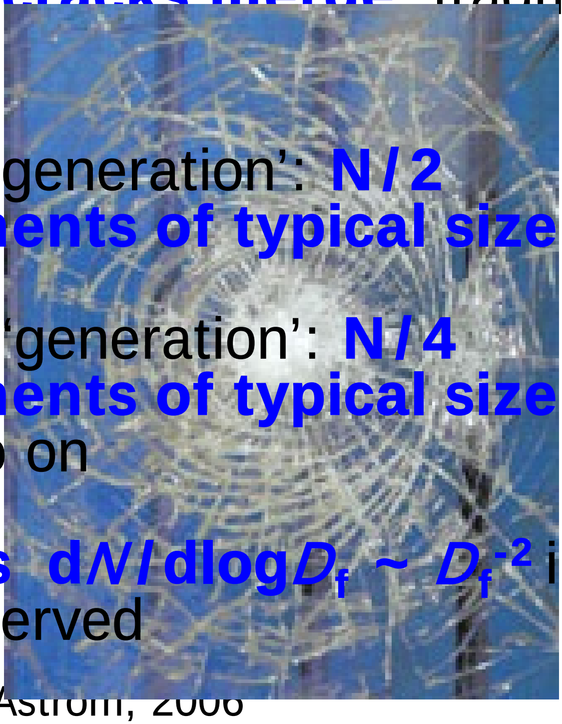
Kok, J. F., S. Albani, N. M. Mahowald, and D. S. Ward (2014), An improved dust emission model – Part 2: Evaluation in the Community Earth System Model, with implications for the use of dust source functions, Atmospheric Chemistry and Physics, 14, 13,043-61.

Kok, J. F., et al. (2017), Smaller desert dust cooling effect estimated from analysis of dust size and abundance, *Nature Geoscience*, 10, 274-8.

Kok, J. F., D. S. Ward, N. M. Mahowald, and A. T. Evan (2018), Global and regional importance of the direct dust-climate feedback, *Nature Communications*, 9, 241.

Scale invariance due to crack merging

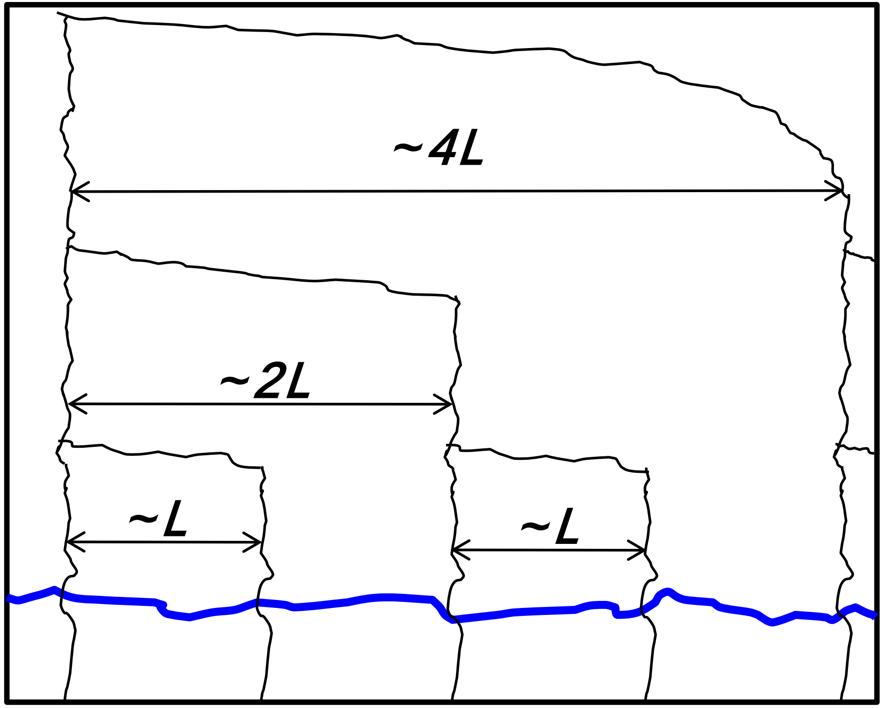
- Fragments are produced by **propagation and merger of cracks** in brittle material
- Main crack 'emits' **side cracks** at approximately regular intervals (*L*)
- Cracks are **attracted** to each other
- When **cracks merge**, fragments form



- In 1st 'generation': **$N/2$ fragments of typical size L**
- In 2nd 'generation': **$N/4$ fragments of typical size $2L$**
and so on
- **Yields $dN/d\log D_f \sim D_f^{-2}$** in 3D, as observed

Source: Åström, 2006

Brittle material sample



What is size distribution of PM20 dust in soils?

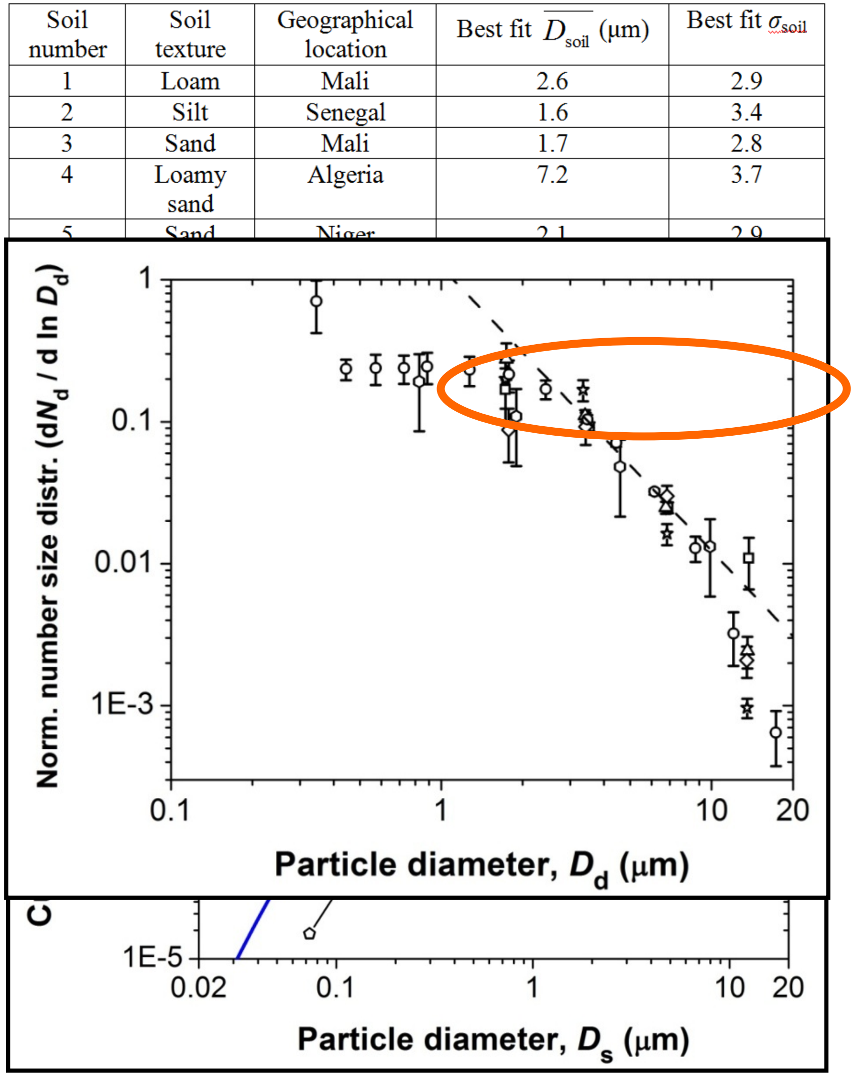
- Emitted dust size distribution depends on **size distribution of disaggregated dust** in arid soils

- Not many measurements (8 total)
  - Must define **typical disaggregated arid soil size distribution** for models
  - Those available have **similar log-normal distribution parameters**

- PM20 dust size distribution seems **relatively soil invariant**

- Emitted dust size distribution **relatively insensitive to soil type**

- Supported by
  - **Insensitivity** of dust aerosol size distributions to **source region** (Reid et al., 2003, 2008; Maring et al., 2003)
  - **Similarity** of 6 vertical dust data sets



Soil number	Soil texture	Geographical location	Best fit $\overline{D_{soil}}$ (μm)	Best fit σ_{soil}
1	Loam	Mali	2.6	2.9
2	Silt	Senegal	1.6	3.4
3	Sand	Mali	1.7	2.8
4	Loamy sand	Algeria	7.2	3.7
5	Sand	Niger	2.1	2.9

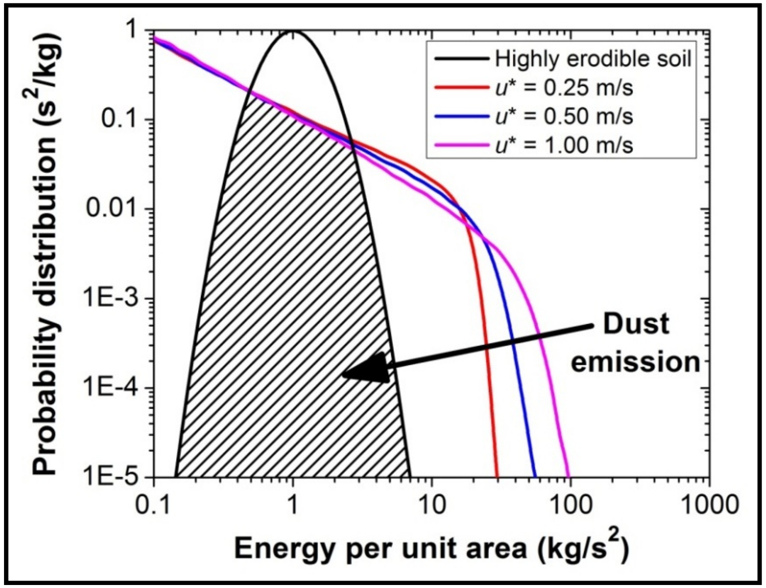
Sources: d’Almeida and Schütz, 1983; Goldstein et al., 2005

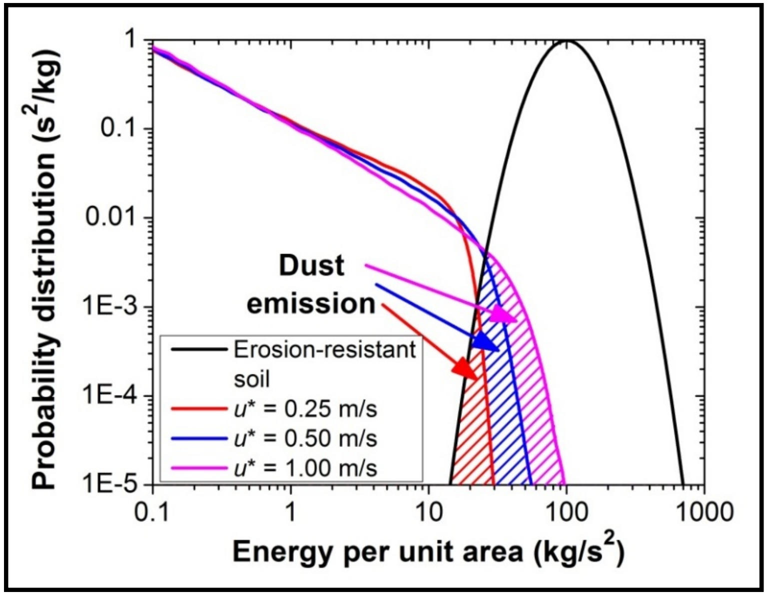
How does fraction of impacts that produce dust emission depend on wind speed?

- Calculate **fraction of saltator impacts that produce fragmentation** and thus dust emission

- For highly **erodible ('arid') soils**:
    - Threshold fragmentation energy ~ mean impact energy
    - Fraction of impacts producing fragmentation ~ constant with u_*!

- For **erosion-resistant ('semi-arid') soils**:
    - Threshold fragmentation energy >> mean impact energy:
    - Dust emission is due to **high-energy tail**
    - Fraction of impacts producing fragmentation **increases sharply with u_*!**

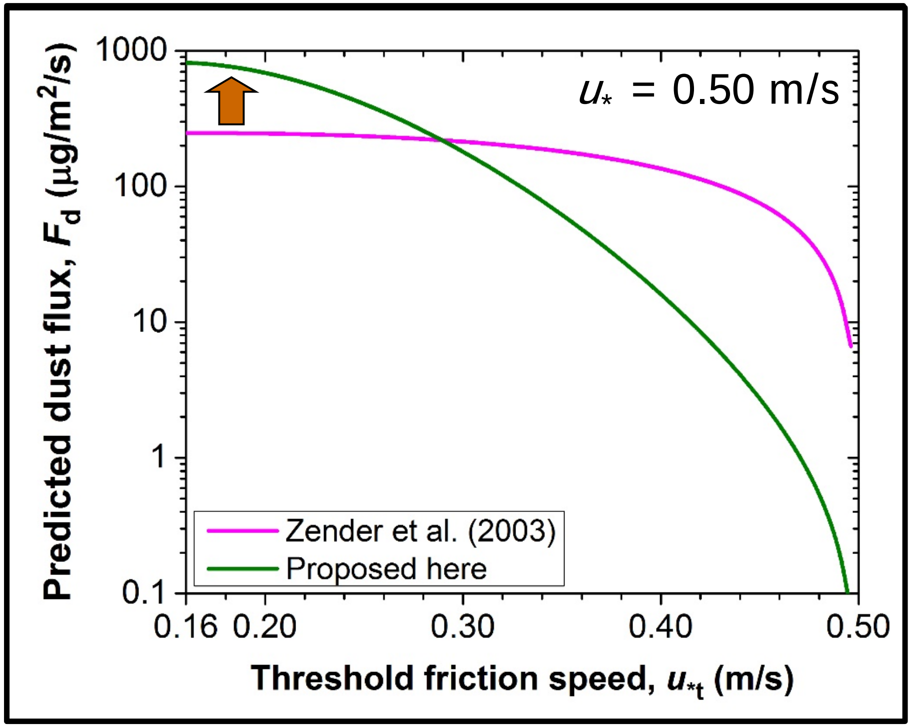




Implication: Dust cycle more sensitive to climate change than thought

Increase in **threshold** (u_{*t}) has **2 effects**:

1. **Decrease in wind stress available** for dust emission
   - Has been **widely recognized**
2. Larger u_{*t} → soil more resistant to erosion
   - **Decrease in dust flux** for given saltator impact flux
   - Recognized by Shao et al. '93, '96
   - **Not in GCM parameterizations** (e.g., Ginoux et al., 2001; Zender et al., 2003)



- Climate change → **drier deserts** (Solomon et al., 2007)
  - **Reduces u_{*t}** (e.g., Fecan et al., 1999)
  - **GCMs underestimate** resulting dust flux **increase**

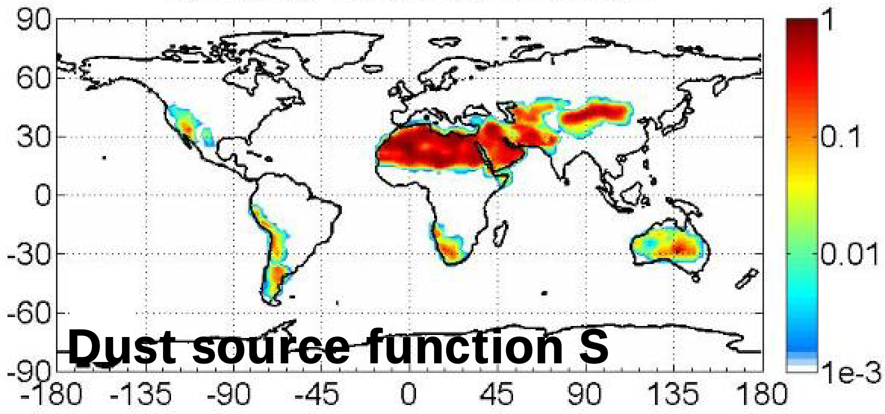
Q1: Does additional physics obsolete the empirical source function?

- Current parameterizations represent spatial variability in soil erodibility using **source function**
  - Shifts emissions to most erodible regions

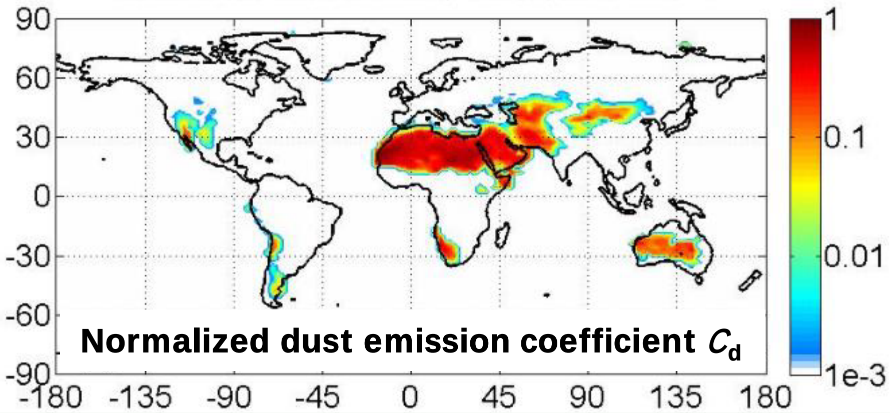
- In new parameterization, spatial variability in soil erodibility largely determined by **physically-derived "dust emission coefficient"**
  - Scales increase in dust flux per saltator impact as soil becomes more erodible

- Yields **remarkably similar shift of emissions** to most erodible regions!
  - From **greater sensitivity of dust flux to soil's threshold** wind speed for erosion (u_{*t})
  - u_{*t} mostly controlled by **soil moisture**

- New theory **replaces empirical result with physical model**



Dust source function S



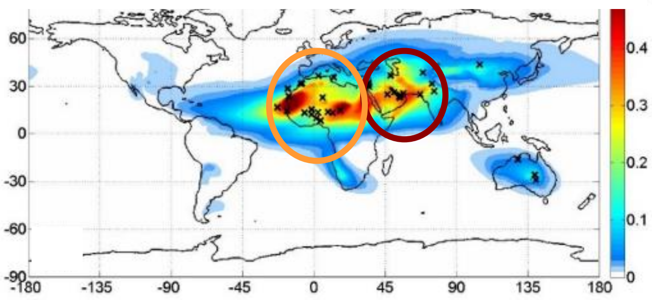
Normalized dust emission coefficient C_d

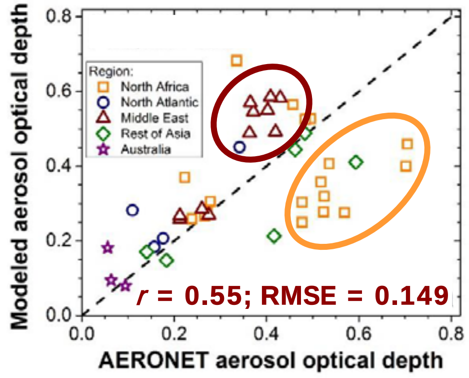
$$F_\mathrm{d} = C_\mathrm{d} f_\mathrm{clay} \frac{\rho_\mathrm{a}\left(u_*^2 - u_{*\mathrm{t}}^2\right)}{u_{*\mathrm{tn}}} \left(\frac{u_*}{u_{*t}}\right)^{C_\mathrm{a} \frac{u_{*\mathrm{tn}} - u_{*\mathrm{t0}}}{u_{*\mathrm{t0}}}} \; ; \; \underbrace{C_\mathrm{d} = \exp\left(-C_\mathrm{e} \frac{u_{*\mathrm{t}}}{u_{*\mathrm{t0}}}\right)}_{\text{Due to increasing resistance to erosion with } u_{*\mathrm{t}}}$$

Q2: does parameterization reproduce dust emission about as well as existing models?

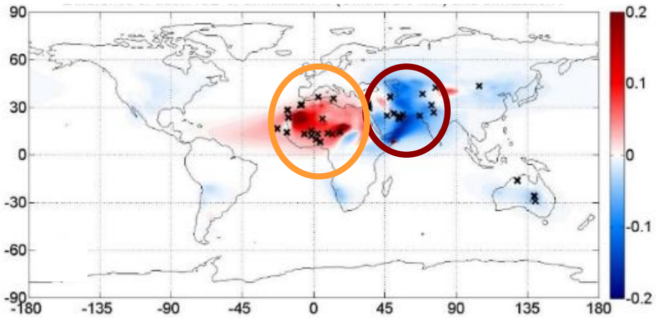
- AOD **underpredicted** in **Western Africa**, **overpredicted in ME**
- **Source function shifts emissions (and AOD)** from ME to Western Africa
  - Improves agreement
- New model produces **similar shift to most erodible regions**
  - Due to **increased dust flux sensitivity** to soil threshold (u_{*t})
  - **Statistically significant improvement** over other simulations (from bootstrap)
  - Also statistically significant improvements in **seasonal and daily** AOD variations

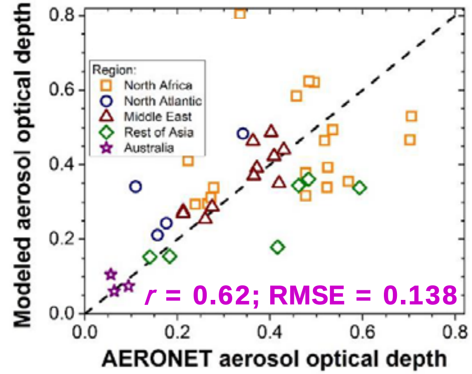
Dust AOD with old param., no src fnct



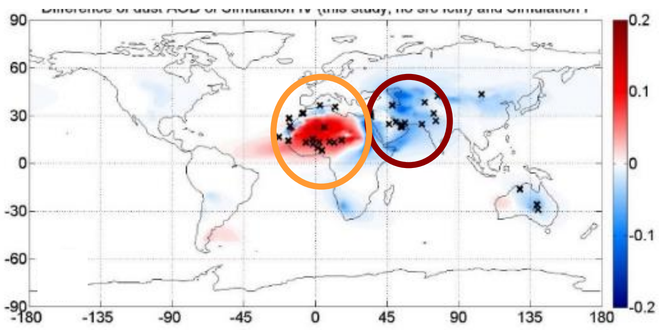


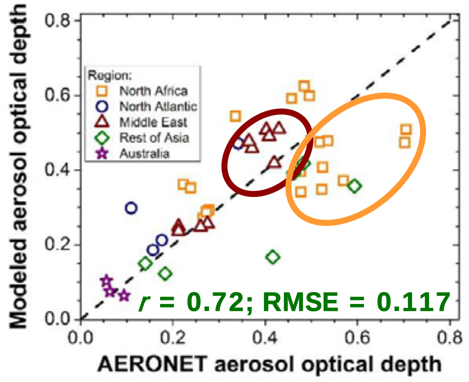
AOD change when adding src fnct





AOD change with new param. (no src fct)





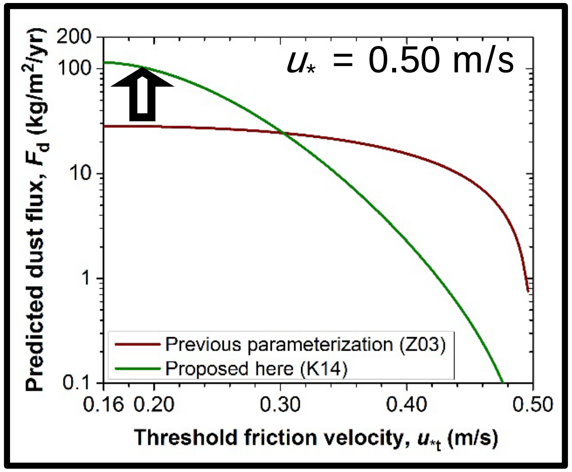
From Kok et al. (2014), Atm. Chem. Phys., Part 2, in press

Q3: Does new parameterization better reproduce historical dust emission trends?

- Empirical parameterizations use **source function** to parameterize part of dust flux sensitivity to soil state
  - Models **can capture only part of dust cycle response** to climate-induced soil state changes

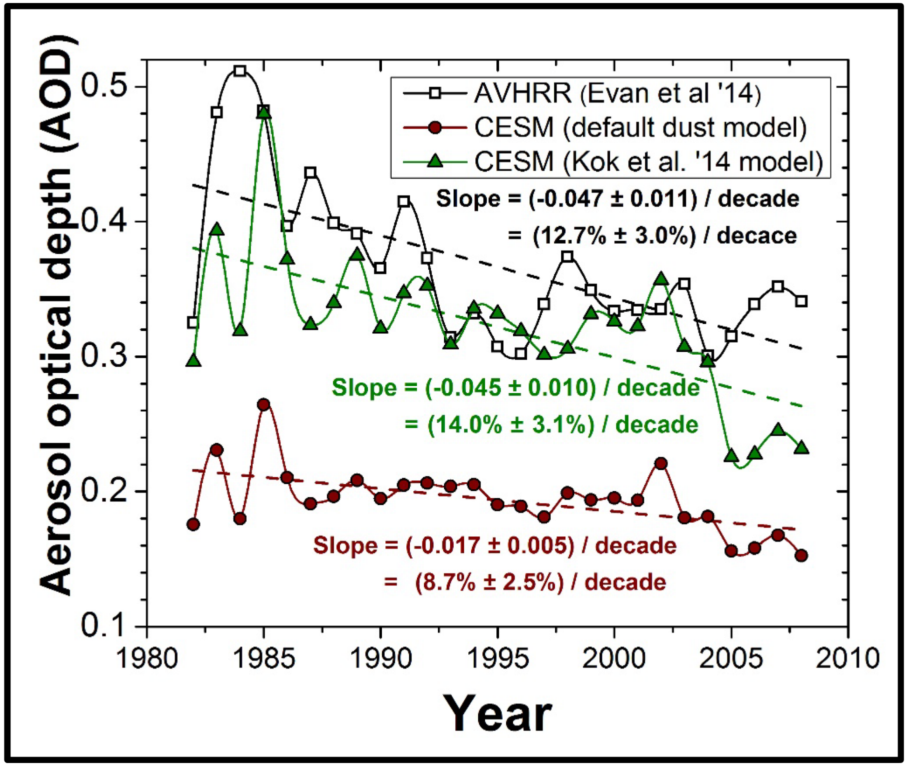
  → **Underestimation of climate sensitivity** of global dust cycle

  → Many models cannot capture decrease in African dust emission since 80s



- Additional physics in new parameterization **does account for effect of climate-induced soil state changes**

  → **Better agreement** with historical trend



- Also improvements in correlation of long-term AERONET AOD trends
  - But these records only go back ~15 years
  - More long-term records needed