The physics of dust emission
(and how to parameterize it in atmospheric models)

Jasper F. Kok
Associate Professor, Atmospheric & Oceanic Sciences
University of California – Los Angeles (UCLA)
jfkok@ucla.edu

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

Collaborators: Natalie M. Mahowald, Samuel Albani, Daniel S. Ward, Gerardo Fratini, John A. Gillies, Masahide Ishizuka, John Leys, Masao Mikami, Moon-Soo Park, Soon-Ung Park, R. Scott Van Pelt, Ted M. Zobeck
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?

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)
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:
    \[
    \frac{dN}{d \ln D_f} \propto D_f^{-2}
    \]
Theory in agreement with measurements

• Derived simple equation:

\[
\frac{dN}{d \ln D_d} = \frac{c}{D_d^2} \exp \left[ - \left( \frac{D_d}{\lambda} \right)^3 \right] \times \left\{ 1 + \frac{\text{erf} \left[ \ln \left( \frac{D_d}{D_{soil}} \right) \right]}{\sqrt{2} \ln \sigma_{soil}} \right\}
\]

- \( N = \) number of aerosols; \( D_d = \) aerosol size; \( c = \) normalization constant
- Only “fitting” parameter: \( \lambda \approx 12 \ \mu m \) from least squares fit to measurements
- \( D_{soil} \) and \( \sigma_{soil} \) describe soil size distribution

• Theory in good agreement with available measurements

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, $\sim -0.4$ W/m$^2$ at TOA
  - Correcting $\sim$**halves** dust direct radiative effect [95% CI: -0.48 to +0.20 W/m$^2$]

From Kok et al., Nature Geoscience, 2017
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)
Are current dust flux parameterizations missing important processes?

- 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”** \(=\text{dust flux per unit wind stress}\)

- 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?

![Graph showing dust aerosol optical depth over time](image)

- **Slope** = \((-0.047 \pm 0.011) / \text{decade}\)
- **Slope** = \((12.7\% \pm 3.0\%) / \text{decade}\)
- **Slope** = \((-0.017 \pm 0.005) / \text{decade}\)
- **Slope** = \((8.7\% \pm 2.5\%) / \text{decade}\)
Basic vertical dust flux equation

\[ F_d = n_s \times f_{\text{frag}} \times m_{\text{frag}} \]

- **Know** \( n_s \) and \( m_{\text{frag}} \) from theory (e.g., Shao et al., 1993; Kok et al., 2012):
  - \( n_s \propto \rho_a(u_*^2 - u_{*t}^2) \)
  - \( m_{\text{frag}} \propto f_{\text{clay}} \)

- **How does fragmentation fraction** \( f_{\text{frag}} \) **depend on wind** \( u_* \) **and soil** \( u_{*t} \) **conditions?**
  - Calculate \( f_{\text{frag}} = f(u_*, u_{*t}) \) using numerical saltation model COMSALT (Kok & Renno, 2009)
How does fragmentation fraction \( f_{\text{frag}} \) depend on friction velocity \( (u_*) \)?

- **For highly erodible soils:**
  - Most saltator impacts produce fragmentation
  - \( f_{\text{frag}} \approx \text{constant with } u_* \)

- **For erosion-resistant soils:**
  - Only energetic saltators emit dust
  - Their fraction increases with \( u_* \)
  - \( f_{\text{frag}} \) increases sharply with \( u_* \)

- \( f_{\text{frag}} \) scales with \( (u_*/u_{*t})^\alpha \)
  - 'Fragmentation exponent' \( \alpha \) scales with \( u_{*t} \)

- Confirmed by measurements

\[
\begin{align*}
  f_{\text{frag}} & = \left( \frac{u_*/u_{*t}}{u_{*t0}} \right)^\alpha \times f\left( \frac{u_*/u_{*t0}}{u_{*t1}} \right) \\
\end{align*}
\]

Due to increase in high-energy saltators with \( u_* \)
How does fragmentation fraction \( (f_{\text{frag}}) \) depend on threshold friction velocity \( (u_{*t}) \)?

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

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

\[
f_{\text{frag}} \propto \exp \left( -C_e \frac{u_{*t}}{u_{*t0}} \right) \times f(u_{*t})
\]

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

---

**Theory**

- **Highly erodible**
  \[ \sim (u_{*t}/u_*)^0 \]
  \[ \sim (u_{*t}/u_*)^{0.7} \]
  \[ \sim (u_{*t}/u_*)^{2.5} \]

**Measurements**

- \( u_{*t0} = 0.16 \text{ m/s} \)
- \( u_{*t0} = 0.25 \text{ m/s} \)
- \( u_{*t0} = 0.40 \text{ m/s} \)

**Dust emission coeff., \( C_d \) \( (\times 10^{-6}) \)**

- **GB04, Feb 16**
- **GB04, March 20**
- **ZP06, day 63**
- **ZP06, day 77**
- **SA09, ME1**
- **SA09, CE4**
- **SIL11**

**Wind friction speed, \( u_* \) (m/s)**

- **Due to increasing soil resistance to erosion with \( u_{*t} \)**
Proposed vertical dust flux parameterization

\[ F_d \propto \frac{\rho_a (u_*^2 - u_{*t}^2)}{u_{*t}} \times f_{\text{frag}} \times f_{\text{clay}} \]

- Vertical dust flux
- Scales saltator impact flux
- Fraction of impacts producing fragmentation
- Scales dust mass per fragmentation event

And \( f_{\text{frag}} \) is given by:

\[ f_{\text{frag}} \propto \left( \frac{u_*}{u_{*t}} \right) C_a \frac{u_{*t} - u_{*t0}}{u_{*t0}} \times \exp \left( -C_e \frac{u_{*t}}{u_{*t0}} \right) \]

Due to increase in high-energy saltators with \( u_* \)
Due to increasing resistance to erosion with \( u_{*t} \)

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)

\[
F_d \propto f_{clay} \frac{\rho_a (u_s^2 - u_{st}^2)}{u_{st}} \left( \frac{u_s}{u_{st}} \right)^{C_a \frac{u_{st} - u_{st0}}{u_{st0}}} \times \exp \left( -C_c \frac{u_{st}}{u_{st0}} \right)
\]

Due to increase in high-energy saltators with \( u_s \)
Due to increasing resistance to erosion with \( u_{st} \)

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)

\[ F_d = C_d f_{clay} \rho (u_*^2 - u_t^2) \frac{u_*}{u_{*m}} C_a \frac{u_{*m} - u_{*0}}{u_{*t}} \]

\[ C_d = \exp \left( -C_c \frac{u_{*t}}{u_{*0}} \right) \]

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)
Thank you!

Thoughts? Comments? → jfkok@ucla.edu

Presented work was from following references:
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: Astrom, 2006
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

### Table

<table>
<thead>
<tr>
<th>Soil number</th>
<th>Soil texture</th>
<th>Geographical location</th>
<th>Best fit $D_{soil}$ ($\mu$m)</th>
<th>Best fit $\sigma_{soil}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loam</td>
<td>Mali</td>
<td>2.6</td>
<td>2.9</td>
</tr>
<tr>
<td>2</td>
<td>Silt</td>
<td>Senegal</td>
<td>1.6</td>
<td>3.4</td>
</tr>
<tr>
<td>3</td>
<td>Sand</td>
<td>Mali</td>
<td>1.7</td>
<td>2.8</td>
</tr>
<tr>
<td>4</td>
<td>Loamy sand</td>
<td>Algeria</td>
<td>7.2</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>Sand</td>
<td>Niger</td>
<td>2.1</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Sources: d’Almeida and Schütz, 1983; Goldstein et al., 2005
Calculate **fraction of saltator impacts that produce fragmentation** and thus dust emission.

For highly **erodible (‘arid’) soils:**
- Threshold fragmentation energy $\sim$ mean impact energy.
- Fraction of impacts producing fragmentation $\sim$ constant with $u_*$.

For **erosion-resistant (‘semi-arid’) soils:**
- Threshold fragmentation energy $\gg$ 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 $u_{*t} \rightarrow$ 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 $\rightarrow$ 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**
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 ($u_*$)
  - **Statistically significant improvement** over other simulations (from bootstrap)
  - Also statistically significant improvements in **seasonal and daily AOD variations**

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