Atmospheric dust aerosols: sources, properties, and impacts

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Multiple dust impacts

- Impact on clouds, and precipitation
- Impact on the radiative energy balance
- Impact on atmospheric composition and chemistry
- Impact on major biogeochemical cycles
- Impact on socioeconomic systems and human well-being
- Impact on ecosystem functioning
Observing and modeling capabilities
Climate radiative forcing of atmospheric aerosols can enhance or rival warming caused by GHGs

Intergovernmental Panel on Climate Change (IPCC, 2001)

The global mean radiative forcing of the climate system for the year 2000, relative to 1750

Intergovernmental Panel on Climate Change (IPCC, 2007)

Complexity of tropospheric aerosols:
- different types (distinct sources, varying emissions, differing physical and chemical processes, fine and coarse size modes)
- short lifetime (up to a few weeks)
- heterogeneous distribution of sources and varying transport pathways
- ageing (changes during transport)
- anthropogenic vs. natural aerosols
- light absorbing vs. scattering aerosols

Sulfates -0.4 (+/- 0.2)
Nitrates -0.1 (+/-0.2)
Fossil fuel OC -0.05 (+/- 0.005)
Fossil fuel BC +0.2 (+/- 0.15)
Biomass burning +0.03 (+/-0.12)
Dust -0.1 (+/-0.2) from -0.3 to +0.1
## Major radiative effects caused by atmospheric dust aerosols and their importance

<table>
<thead>
<tr>
<th>Impact</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct radiative impacts</strong></td>
<td></td>
</tr>
<tr>
<td>Cause the radiative forcing at the top of the atmosphere (SW and LW)</td>
<td>Affect energy balance of the Earth’s climate system (warming or cooling depending on the aerosol types and environmental conditions)</td>
</tr>
<tr>
<td>(IPCC considers SW forcing only!!!)</td>
<td></td>
</tr>
<tr>
<td>Alter the energy balance at the surface (SW and LW)</td>
<td>Affect surface temperature and surface-atmosphere exchange processes</td>
</tr>
<tr>
<td>Cause radiative heating or cooling within aerosol layers in the atmosphere</td>
<td>Affect temperature profile and atmospheric dynamics and thermodynamics</td>
</tr>
<tr>
<td>Affect PAR (400-700 nm)</td>
<td>Affect plant photosynthesis and influence the plant-air carbon/water exchange processes.</td>
</tr>
<tr>
<td><strong>Indirect radiative impacts</strong></td>
<td></td>
</tr>
<tr>
<td>Serve as ice nuclei</td>
<td>Affect the properties and amount of ice and water clouds and hence their radiative effects</td>
</tr>
<tr>
<td>Serve as cloud condensation nuclei</td>
<td></td>
</tr>
<tr>
<td>Promote or suppress precipitation</td>
<td>Affect the lifetime of clouds and their radiative effects</td>
</tr>
<tr>
<td>Alter actinic flux (UV-visible)</td>
<td>Alter the abundance of radiatively important atmospheric gases</td>
</tr>
<tr>
<td>Absorb chemically important gases</td>
<td></td>
</tr>
<tr>
<td>Provides particle surfaces for heterogeneous chemical reactions</td>
<td></td>
</tr>
</tbody>
</table>
Dust aerosol - ecosystem-energy/hydrological cycle linkages

Dust decreases surface SW radiation and increases LW radiation

Dust decreases or increases PAR (photosynthetically active radiation 400-700 nm): total PAR vs. diffuse PAR

Other impacts: dust deposition on vegetation; nutrient supply, etc.
Energy balance/Climate

Upward and downward radiative flux
\( F_{up}(\lambda, xy, z, t) \) and
\( F_{down}(\lambda, xy, z, t) \)

Remote sensing applications

Radiance
\( I(\lambda, xy, z, \theta, t) \)

Optical Properties

- optical depth \( \tau(\lambda, xy, z, t) \)
- single scattering albedo \( \omega_o(\lambda, xy, z, t) \)
- asymmetry parameter \( g(\lambda, xy, z, t) \)

Microphysical Properties

- particle number (and mass) size distribution \( N(r) = f(xy, z, t) \)
- refractive index (or composition) and mixing state \( m = n-ik; \quad m = f(\lambda, r, xy, z, t) \)
- particle shapes

Radiation transfer codes

- Mie theory, T-matrix, DDA, IGOM

Modified from Sokolik et al. (2001)
Sources

Transport
Spatiotemporal distribution

Dust load

Dust aerosol properties:
Size distribution
Composition
Particle shape

Regional and global impacts
Characterization of dust sources with satellite products

**TOMS Aerosol Index (AI)**
Prospero et al. (2002)
Washington et al. (2003)

**OMI Aerosol Index (AI)**

**Infrared Difference Dust Index**
Meteosat (geostationary)
Legrand et al. (2002)

**Meteosat Second Generation (MSG) Dust Index (SEVIRI)** –
Schepanski et al. (2009)

All satellite techniques are based on atmospheric dust signal (source + transport)
Characterization of dust sources with satellite products

Annual mean frequency distribution of MODIS (2003-2009) Deep Blue AOD (red field), TOMS (1980-1991) Aerosol Index >0.5 (blue), and OMI (2004-2006) Aerosol Index > 0.5 (green). The isocountours of TOMS and OMI have been removed over oceans for clarity.

Ginoux et al. (2012, RG)
A “simple type” dust emissions scheme:

\[ F = f \cdot C \cdot U_{10}^{3} \left( 1 - \frac{U_{10th}}{U_{10}} \right) \]

Critical assumptions:
1) Masking of dust sources (preferential dust sources, “hot spots”)
2) Assumes a mass normalization constant \( C \) (evaluated from satellite data)
3) Prescribed (fixed) threshold wind speed \( U_{th} \) (or friction velocity) (no dependence on land surface properties)
4) Bulk vertical dust flux (i.e., no size dependence or silt/clay-size fraction)
5) No information on dust composition
6)…..
## Physically-based dust emission schemes

Martiorena & Bergametti (MB)

<table>
<thead>
<tr>
<th>1a</th>
<th>Threshold friction velocity over smooth surface</th>
</tr>
</thead>
</table>
| $u_{*}(D) = \left\{ \begin{array}{ll}
\frac{0.129 \sqrt{d}}{K} & \text{for } 0.03 < \text{Re} < 10 \\
0.129 \sqrt{d G^{1/8}} & \text{for } \text{Re} > 10
\end{array} \right.$ |

<table>
<thead>
<tr>
<th>1b</th>
<th>Drag partition correction $R(D,w)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1: Manly (1953) &amp; $R(D,w) = \ln \left( \frac{D}{0.705 \cdot \theta_w} \right)$</td>
<td></td>
</tr>
<tr>
<td>Option 2: Swamee &amp; $R(D,w) = \ln \left( \frac{D}{0.305 \cdot \theta_w} \right)$</td>
<td></td>
</tr>
</tbody>
</table>

**Required parameters:**
- Air density
- Soil particle density
- Option 1: constant
- Option 2: spatially variable

**Required parameters:**
- Moisture correction $R(w)$
- $R(w) = \left\{ \begin{array}{ll}
1.2 + |w - w'| & \text{if } w < w' \\
1.2 - |w - w'| & \text{if } w > w'
\end{array} \right.$

<table>
<thead>
<tr>
<th>1c</th>
<th>Moisture correction $R(w)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w' = 0.0014 \text{ (g Cdm}^{-3}) \times 0.17 \text{ (mW/m2)}$</td>
<td></td>
</tr>
</tbody>
</table>

**Required parameters:**
- Soil clay content
- Soil organic content
- Option 1: constant
- Option 2: spatially variable

**Required parameters:**
- Eolian roughness length
- Marticorena & Bergametti (1995)

### Shao et al.

**Double dust particle**

<table>
<thead>
<tr>
<th>4a</th>
<th>Double dust particle</th>
</tr>
</thead>
</table>
| $R(D) = \left\{ \begin{array}{ll}
(1 - \sigma \gamma m_D \rho_D) & \text{if } m_D \rho_D \leq 1 \\
(1 - \gamma m_D \rho_D) & \text{if } m_D \rho_D > 1
\end{array} \right.$ |

**Required parameters:**
- Roughness density
- Vegetated surface
- Option 1: $A_D = A_D^C$ (constant)
- Option 2: Marticorena et al. (2006)

**Required parameters:**
- Eolian roughness length
- Marticorena & Bergametti (1995)

**Required parameters:**
- Moisture correction $R(w)$
- $R(w) = \left\{ \begin{array}{ll}
1.0 & \text{if } w < 0.23 \\
0.8 & \text{if } w > 0.23
\end{array} \right.$

**Required parameters:**
- Eolian roughness length
- Marticorena & Bergametti (1995)

### Calculation of dust emission flux

1. **Threshold friction velocity**
   $u_{*}(D, w) = \frac{u_{*}(D)}{R(D, w)} R(w)$

2. **Size resolved (sedimentation) flux**
   $Q(D) = \int_{D_{min}}^{D_{max}} Q(D) dD$

3. **Vertical flux**
   - Marticorena & Bergametti, 1995
     $F = \frac{D}{C} \int_{D_{min}}^{D_{max}} Q(D) dD$
   - Affouard & Gourcy, 2001
     $F = \frac{D}{C} \int_{D_{min}}^{D_{max}} Q(D) dD$

Darmenova, K., I.N. Sokolik, Y. Shao, B. Marticorena, and G. Bergametti, Development of a physically-based dust emission module within the Weather Research and Forecasting (WRF) model: Assessment of dust emission parameterizations and input parameters for source regions in Central and East Asia (2009, J. Geophys. Res.)
A fully-coupled regional modeling system WRF-Chem-DuMO

- **Terrestrial preprocessor**
  - Adjustable water/land cover mask to reproduce different historical LCLUC scenarios (Central and East Asia);
  - Land surface properties (aeolian roughness, soil size distribution, etc.)

- **Mesoscale atmospheric dynamics model (WRF-Chem)**
  - Flexible nesting capability (down to 1 km)
  - Driven by re-analysis data (NCEP or ECMWF)

- **Dust Module (DuMo)**
  - Physically-based dust emission schemes (coupled with the Noah land model)
  - Dust optics/Radiation
  - Dust-cloud interactions (via CCN and IN) (new dust CCN parameterizations Kumar, Sokolik, Nenes 2009)
Decadal dust emission in East Asia

Climatology of dust emission (f-g, April monthly mean fluxes, in g km$^{-2}$ s$^{-1}$) in East Asia for the 1950s – 1990s modeled with WRF-Chem-DuMo.

Sokolik et al. (2012), Book Chapter & Asian Dust Databank

East Asian regions which experienced extensive land cover change during the 1950-2000 period:
Estimated anthropogenic dust fraction for 1955 and 1998

<table>
<thead>
<tr>
<th>Study</th>
<th>Resolution</th>
<th>Region</th>
<th>Time period</th>
<th>$f_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tegen and Fung, 1995</td>
<td>8° x 10°</td>
<td>Global</td>
<td></td>
<td>30-50%</td>
</tr>
<tr>
<td>Mahowald and Luo, 2003</td>
<td>1.9° x 1.9°</td>
<td>Global</td>
<td>1980-2099</td>
<td>14-60%</td>
</tr>
<tr>
<td>Zhang et al., 2003</td>
<td>100 x 100 km</td>
<td>East Asia</td>
<td>1960-2002</td>
<td>14%</td>
</tr>
<tr>
<td>Tegen et al., 2004</td>
<td>3.75° x 5°</td>
<td>Global</td>
<td>1983-1992</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Yoshika et al., 2005</td>
<td>1.8° x 1.8°</td>
<td>North Africa</td>
<td>1984-1990</td>
<td>20-25%</td>
</tr>
</tbody>
</table>

$\textbf{f}_a (40\text{km resolution})$

<table>
<thead>
<tr>
<th>Year</th>
<th>W$^1$</th>
<th>W$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB95</td>
<td>1955</td>
<td>41.7%</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>60.2%</td>
</tr>
</tbody>
</table>

• Anthropogenic fraction varies between ~35% to 62% in Central Asia (Xi&Sokolik, 2012)

• Significant differences between studies: model- and definition-dependent
MISR stereo products: dust plume height and winds

Kalashnikova et al.

March 30, 2007, Gobi

MISR observed dust plumes, 2000-2006
Composition of atmospheric dust aerosols

Elemental
Mineralogical
Ionic
Isotopic

Size dependence:
  Bulk
  Size-segregated
  Individual particles
Importance of mineralogical composition

• Dust is a collective term referring to widely varying mixtures of minerals.
• Minerals each have different physical and chemical properties: size spectrum, particle shape, density, hygroscopicity, chemical reactivity, different abilities to serve as CCN and IN, etc.
• Spectral refractive indices vary widely from mineral to mineral. Optical properties of dust are determined by the relative abundance of each mineral and the details of how the minerals are mixed together.
• The abundance of various constituents depends on the region of dust origin, how it was mobilized, and chemical and physical transformation processes during dust transport.

Important minerals in atmospheric dust:
- Iron oxides (hematite and goethite)
- Clays (illite, kaolinite, montmorillonite)
- Quartz
- Calcite
- Gypsum
- Chlorite
- Feldspar

Clay-iron oxide aggregates control light absorption in SW
Control absorption in LW

Sokolik and Toon (1999, JGR)
Spectral normalized extinction coefficient of selected minerals
Regional radiative signature atmospheric dust aerosols

Sokolik (2002, GRL): predicted that satellite sensors operating in the thermal IR narrowbands and high spectral resolution sensors will be affected by dust composition.

High-resolution mineralogical database of dust-productive soils for atmospheric dust modeling

Nickovic et al. (2012, ACP) - 30s-resolution dataset GMINER30: 9 minerals (clay- and silt-sizes) for 28 FAO soil types (extension of Claquin et al., 1999)

"Bottom-up" approach

Global distribution of the effective mineral content in soil in percentages for (a) quartz, (b) illite, (c) kaolinite, (d) smectite, (e) feldspar, (f) calcite, (g) hematite, (h) gypsum and (i) phosphorus. The mineral fraction is weighted with the clay and silt content in soil. For minerals that are present in both clay and silt, the weighted values are summed.
Composition of atmospheric dust aerosols => potential sources

Formenti (2011, ACP)

“Top-down” approach

Fig. 1. Potential source areas in Northern Africa on work by Brooks and Legrand (2000, al. (2002), Prospero et al. (2002), Israe (2003), and Schepanski et al. (2009). M activations (DSA per day by Schepan their paper) were transferred to isoline tential source areas (shaded areas) are NAF-1: Zone of chotts in Tunisia and N2: Foothills of Atlas mountains (PSAN region (PSA NAF-2b: Western Sahara, NAF-3: Mali-Algerian border region; I PSA NAF-5: Bodélé depression (We Southern Egypt, Northern Sudan.

Fig. 3. Range of variability of illite/kaolinite (I/K) and chlorite/kaolinite (C/K) ratios for North African (NAF) and East Asian (EAS) mineral dust and source sediments. Light grey areas: single potential source areas which show deviations from the general trend (the range of the I/K ratios for PSA NAF-2 may extend to areas in Eastern Asia based on work by nt et al. (2006), Shao and Dong (2006), et al. (2008), and Zhang et al. (2003e). rcc areas (shaded areas) are drawn by wakan; PSA EAS-2: Gurbantunggut; PSA Hexi corridor; PSA EAS-4: Mongolian PSA EAS-5: Inner Mongolian (Southern and Tengger (PSA EAS-5a), Ulan Buh, -5b); PSA EAS-6: north-eastern deserts orquin Sandy Land, Hulun Buir Sandy

Nickovic et al. (2012)
Differences in mineralogy between parent soils and dust aerosols

Jeong (2008)

Transfer function?
Iron oxide speciation & Aggregates

- Nano iron oxides

- Iron in clays:
  
  Structural iron
  
  Iron oxides aggregated with clays:
  
  hematite and goethite
Quantification of iron oxides in atmospheric dust

Elemental analysis + CDB (chemical extraction method - selective dissolution of free-iron with citrate-bicarbonate-dithionite (CBD) reagent)

Lafon et al. (2004)
Mehra and Jackson (1960)
Single scattering albedo dust aerosols consisting of iron oxides-clay aggregates and non-absorbing minerals

Aggregates:  
Hematite-Illite (HI)  
Goethite-Illite (GI)  
Shale aggregates:  
Hematite-Illite (HI)  
Goethite-Illite (GI)  
Non-absorbing minerals:  
Quartz & calcite

Lafon, S., I.N. Sokolik, J.L. Rajot, S. Caquineau, and A. Gaudichet, Characterization of iron oxides: implications to light absorption by mineral dust aerosols (2006, JGR)
Differences in single scattering albedo caused by regional variability of iron oxides may affect the sign of radiative forcing (heating vs. cooling)
Region-specific composition of atmospheric dust aerosols

Compositions of five major minerals in size fractions of Asian dust (total 2871 particles). The particle size is the longest chord of the dust particles. Q, quartz; P, plagioclase; K, K-feldspar; Cl, clay partly mixed with nanosized calcite; Ca, calcite (Jeong 2008).

- Need for a unified, commonly accepted protocol (calibration standards for X-ray diffraction based techniques)
- Composition varies with particle size

Kandler et al. (2009, Tellus)
SEM/TEM images show complex morphology of dust aerosols.
Importance of particle morphology and major issues

- Shape is a fundamental physical characteristic of atmospheric aerosol.
- Growing evidence of a variety of complex, non-spherical shapes of mineral aerosol (dust) and carbonaceous aerosol.

Available data are mainly from SEM/TEM (but only 2D morphology!!!).

- Treatments of non-sphericity of dust particles:
  - **optics/remote sensing (optical equivalence):**
    - => introduce a mixture of spheroids (e.g., AERONET, Dubovik et al. 2006)
    - => use “actual” particle shapes from SEM/TEM (Kalashnikova and Sokolik, 2002, 2004…)
  - **chemical transport models and climate models (??? equivalence)**
    - assume spheres…but no explicit definitions of the “equivalence” and no consistency in treating dust non-sphericity in different processes (i.e., same spheres are used for optics/radiation, dry removal, heterogeneous chemistry, etc.)

spheres => surface area $S(R)$ => volume $V(R)$: $V = \frac{S^{1.5}}{6/\pi^{1/2}} = 0.094 S^{1.5}$  

Need for 3D particle morphology
Reconstruction of spheroids for optical modeling

50% prolate + 50% oblate: AERONET, Dubovik et al. (2006)


Prolate spheroids: Weigner et al. (2009), Otto et al. (2010), etc.
use distribution of AR measured in SAMUM

...but SEM/TEM see prolate spheroids only (cannot distinguish oblate spheroids)

Aspect ratio = length/width
AR = a/b

\[ c = b < a \Rightarrow \text{prolate (rugby ball-like) spheroids} \]
\[ c = b > a \Rightarrow \text{oblate (disk-like) spheroids} \]

SEM/TEM 2D particle image =>
fit with an ellipse =>
determine max dimension (length) and orthogonal dimension (width) =>
gives aspect ratio (AR) of the ellipse

!!! need to assume height (2c) = width (2b) to get volume of the spheroid
Height-to-width ratio

Frequency distribution of height-to-width ratio

Cumulative frequency distribution of height-to-width ratio

Okada et al. (2001): three samples of Asian dust (SEM: measurements of shadow length; Rpa<2μm)

Atomic Force Microscopy

Sokolik et al. (2011)
CALIPSO space lidar: a non-sphericity signature of dust
Saharan dust trans-Atlantic event (Aug. 17-23, 2006)

Liu et al. (2008)
Sizing methods used in atmospheric dust studies

**Geometric sizing:**
*Principle:* determines size from particle images taken with SEM or TEM

**Aerodynamic sizing:**
*Principle:* measures size of a spherical particle of unit density that has the same gravitational settling velocity as the particle in question
12-stage Micro Orifice Uniform Deposition Impactor (MOUDI)
DRUM impactor
Differential Mobility Particle Sizer (DMPS) for the mobility; size range of 20–800 nm
*APS:* Aerodynamic Particle Sizer; size range of 850 nm to 5μm

**Optical sizing:**
*Principle:* measures scattering from particles and assign their sizes based on calibration done with spherical particles of known ref. index (latex, at 0.635mm $n = 1.58 - i0$).
Different instruments have different viewing geometry and wavelengths
  *OPC:* optical particle counter,
  *FSSP:* Forward Scattering Spectrometer Probe, measured angles 5-12; size range d= 0.3-30 μm
  *PCASP:* Passive Cavity Aerosol Spectrometer Probe, measured angles 35-120; size range d=0.1–3 μm

**Remote sensing inversion:**
*Principle:* columnar mean sizes that give best fit to measured radiances
  *Sun/Sky radiometer (e.g., AERONET: retrieves parameters of two-lognormal modes)*
  *Satellite sensors (effective size; fine/coarse mode)*
Differences in sizing methods

Reid et al. (2003), PRIDE data
Regional variability of dust size distribution… or sizing biases?

Ground–based measurements of size distribution at different locations:
BG- background conditions;
DW - dust wind;
SS - sand storm.
Distances in parentheses are measurement altitudes above ground.
(a) Averages for meteorological conditions classified by d’Almeida (1987) from measurements at Matam/Senegal, Tombouctou/Mali and Agadez/Niger (d’Almeida and Schutz, 1983);
(b) Schütz and Jaenicke (1974);
(c) Gillette and Nagamoto (1993);

Kandler et al.(2009, Tellus)
Summary

- During the past decade, there has been a significant improvement in understanding the sources, transport, properties and impacts of atmospheric dust aerosols owing to diverse new data and advancements in modeling capabilities. At the same time, there has been a growing awareness about the complex nature of atmospheric dust aerosols and their multiple interrelated roles in the Earth systems.

- Key research needs & Challenges
  Need for systematic integration of observational and model data across nonuniform spatial and temporal sampling, scales, and coverages, including satellite, field, laboratory and model data

  Need for improved process-level understanding considering the coupling and feedbacks:
  - dust emission (influence of climate, land surface state, land use, etc.)
  - dust ageing (cloud processing, physical and chemical interactions with other aerosols&gases)
  - dust deposition

Modified from Shao et al.(2011)