Simulation of mineral dust emissions in arid and semi-arid areas:

Recent advances and present limitations

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**Dust emissions are the main source of tropospheric aerosols in mass!!**

⇒ Dust both scatter and absorb the solar and Earth radiations

⇒ Dust are supports for chemical reactions in the atmosphere

⇒ Dust are one of the main sources of nutrients for oligotrophic oceanic surface water

None of these impacts exhibits a linear dependence with the dust concentrations!
Variability of the mineral dust concentration in the Sahel

A huge variability at the annual, monthly and daily time scale!

Such a temporal resolution is not well resolved by models
Why do the models fail in reproducing dust concentrations fields?
Modeling dust emissions is a key point to reproduce atmospheric concentrations:

- Sporadic in time and space
- The surface features are a controlling factor in dust emissions
- The dust emissions are highly sensitive to wind velocity
Modeling dust emissions with relevant temporal and spatial scale requires:

- A **physical, processes oriented, dust emissions module** allowing to account for the surface features characteristics, soil properties and required meteorological parameters.

- **Precise input data** that allow to document these surface features and meteorological parameters at the relevant scales.
Main processes involved in dust emissions

- Wind shear stress
- Vertical dust flux
- Suspension
- Saltation
- Sandblasting
- Erosion Threshold
- Horizontal Flux
Modeled dust emission processes

Emission processes

- Erosion threshold
- Saltation
- Sand-blasting

Model outputs

- Location and periods
- Emission flux intensity
- Size-distribution
- Composition
Modeled dust emission processes

**Emission processes**
- Erosion threshold
  - Saltation
    - Sand-blasting

**Main uncertainties**
- Vegetated, cultivated crusted surfaces
- Dust size-distribution
- Dust composition
Modeled dust emission processes

Vegetated, cultivated crusted surfaces

Estimation of the dust emissions from semi arid areas

Dust size-distribution

Dust composition

Assessment of any dust impact (radiative forcing, biogeochemical cycles, heterogeneous chemistry, ...)

Modeled dust emission processes

Dust Emissions in the Northern Chihuahuan Desert

\[\text{Gillette and Pitchford, 2004}\]

⇒ Aeolian erosion is measured over vegetated surfaces that partition models predict as non erodible!!
High resolution of the wind pattern
To estimate the erosion flux

Measured versus modelled erosion fluxes

Using a high resolution model to establish quantitative relationship between the erosion thresholds and fluxes as a function of vegetation amount, height, spacing including arrangement.

Bowker et al., Env. Fluid Mech., 2006
Modeled dust emission processes

Erosion threshold and fluxes over vegetated surfaces?

- Adapted drag partition models
- Aerodynamic properties of vegetation
  - porosity
  - flexibility
  - arrangement
- Temporal and spatial variability
Modeled dust emission processes

Roughness length and erosion fluxes over ploughed surfaces

Roughness length

\[ z_0 = 1.2736 \frac{R_H^2}{RS} - 0.005 \]

\[ r = 0.97 \]

Erosion flux

Operational relationship with the geometric characteristics of the ridges established in wind tunnel
Using tillage technics developed for temperate regions soils can increase local erosion and thus dust production
Dust emissions from cultivated surfaces?

- Systematic relationship between erosion processes and cultivated surface properties
- Field measurements over representative surfaces
- Land use data sets
Dust emissions from semi-arid areas

- Dust emissions from vegetated or ploughed surfaces is much lower than from bare surfaces !!

- Changes in vegetation cover or vegetation type is a critical issue

- Changes in agricultural technics can be as critical as change from natural to agricultural surfaces
Vertical dust flux: sandblasting process

Conceptual understanding

- Kinetic energy provided by the saltating particles
  \[ Q = f(U^*, D_p) \]

- Binding energy of the dust particles
  \[ e_d = f(D_d) \]

Operational parameterisation \( \alpha = F/Q \)

- Lu and Shao (2001)
  \[ \alpha = f(p) ; p: \text{plastic flow pressure} = \text{soil hardness} \]

- Alfaro et al. (1996; 1998)
  \[ \alpha = f(e_d) ; \text{Cohesion energy of the particles} \]

- Size-distribution of the emitted dust aerosol
  Chemical and mineralogical composition
Modeled dust emission processes

Dust emission model
(Shao, 2001)

» Soil size distribution control the aerosol size distribution
Modeled dust emission processes

Sand-blasting model *(Alfaro & Gomes, 2001)*

- Kinetic energy of saltating particles: \( e_c = f(D_p, U^*) \)
- Cohesive forces of aggregates: \( e_d = f(d) \)

⇒ Soil size distribution and dust binding energy control the aerosol size distribution
Modeled dust emission processes

Sensitivity of the dust flux to the soil size distribution

3 orders of magnitude
Modeled dust emission processes

Sensitivity of the vertical dust to the binding energy

<table>
<thead>
<tr>
<th></th>
<th>p1</th>
<th>p2</th>
<th>p3</th>
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<tbody>
<tr>
<td>$D_{med}$ (µm)</td>
<td>1.5</td>
<td>6.7</td>
<td>14.2</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>1.7</td>
<td>1.6</td>
<td>1.5</td>
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Fine sand ($D_{med}=210$ µm)

Coarse sand ($D_{med}=690$ µm)
What are the big remaining uncertainties?

1. Sanblasting process =
   - Validation of both mass flux and size distribution
   - Relation soil and aerosol composition?

2. Specific processes of dust emissions from semi-arid areas:
   - Vegetated surfaces
   - Cultivated surfaces
   - Crusted soil and supply limitation

→ Necessity of additional experimental data!!
Input data for dust emission models

- **Surface characteristics**
  - Local surface roughness
    - Aerodynamic properties
    - % covered surface

- **Soil**
  - Size-distribution
  - Texture
  - Composition

- **Meteorological data**
  - Wind friction velocity
  - Soil moisture

- Soil types maps
- Relations between the soil types and the required parameters
- Surface wind velocity
- Roughness length
- Precipitation
- Soil texture = f (depth)
Input data for dust emission models

Surface roughness → Location and occurrence of the dust emissions

Soil size-distribution → Intensity of the dust emissions and size distribution
Input data for dust emission models

SURFACE ROUGHNESS MAPPING

Radar measurements: in arid areas, the radar backscatter coefficient is proportional to the roughness of the surface (resolution is of the order of 30x30 m); (Marticorena et al., 2006)

BRDF: the bi-directional reflectance distribution function can be related to roughness length over desert surfaces during clear sky periods. Polder satellite provides very precise measurements of BRDF since at each orbit, it observes the same surface under 14 different angles of view. Resolution is 6kmx6km; (Marticorena et al., 2004, Laurent et al., 2005)
Protrusion Coefficient (PC) derived from POLDER-1 measurements of bidirectional reflectance

Laurent et al., JGR, 2005

[Marticorena et al., Int. J. Remote Sensing, 2004]
Simulated erosion thresholds

In the Taklimakan:
- median ~7 m.s\(^{-1}\)
- Wind velocities associated with dust storms: 6-8 m.s\(^{-1}\) [Wang et al., Water, Air, and Soil Poll., 2003]

In the Gobi:
- median ~15 m.s\(^{-1}\)
- Wind velocities associated with dust storms: 11-20 m.s\(^{-1}\) [Natsagdorj et al., Atmos. E., 2003]

Simulated erosion thresholds

[Laurent et al., J.G.R., 2005]
Mapping of the soil size-distribution

Only **soil texture maps** are available at global scale data that gives a soil classification based on a fully dispersed sediment (using wet method)

- Relationship between undisturbed size distribution and soil texture ?
No relation between soil texture and soil grain size distribution!!!!

Laurent et al., GPC, 2006

Fig. 3. Clay (a) and silt (b) contents as a function of the mass median diameter MMD of the finer mode of the soil size distribution for individual samples collected in the main desert areas of China (data from Mei et al., 2004).
Soil size-distributions derived from dry sieving of samples from the Chinese deserts

Adapted from Mei et al., Chinese Science Bulletin, 2004
Simulation of dust emissions from NE-Asian deserts 1996-2001

Annal dust Emissions t.y⁻¹

Annual number of days with dust emission

Laurent et al, GPC, 2006
Interannual variability of the dust emissions from NE-Asian deserts 1996-2001

Dust emissions occurrence
(number of events)

Dust emissions intensity
(Mt)

[Laurent et al., GPC, 2006]
Simulation of dust emissions from North Africa 1996-2001

All simulated source areas are observed by IDDI (Meteosat) and/or by TOMS AI.

The simulation exhibits significant bias in some locations:
- Underestimation for the Bodele depression area
- Overestimation on the West Coast

[Laurent et al., in prep.]
Simulation of dust emissions from North Africa 1996-2001

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Comparison of surface wind fields from meteorological models

Occurrence of wind velocities > erosion threshold

Occurrence of strong wind velocities > 9 m.s⁻¹

(Courtesy of C. Bouet)
Strong Local erosion is related to convective system with or without rainfall

Dust emissions in the Sahel

Highest surface concentrations = local dust emissions
Convective events reaching Banizoumbou

11 July 2006, 00h30 Local
Simulation of mesoscale convective systems

Without refined convection

With a refined convection

Vmax < 6 m/s = no dust emissions

Vmax > 16 m/s : huge dust emissions

500 km x 500 km centered on Niamey (June 30, 2006)  (Courtesy of C. Bouet)
What are the main uncertainties?

1. Surface roughness = operational mapping technics available; scaling issues to be investigated

2. Soil size distribution =
   - Constitution of a global data set
   - Comprehensive relationship between soil size-distribution and soil texture?

3. Surface wind velocity = THE MAJOR LIMITATION
   a critical issue a key issue that must be addressed at different scale!!
Concluding remarks

• **Most of the key physical processes involved in dust emissions are quite well-known.** Most of the future efforts should be dedicated to the specific processes acting in semi-arid areas (crust, anthropogenic surfaces, aerodynamic interactions with vegetation...) and to the validation of the modeled size distributions of the dust flux.

• **During the last 15 years, we have been able to develop physical models allowing to account for the influence of surface features**

• **Our capabilities in providing relevant surface data have also increased, but important caveats remain (i.e. soil grain size distribution) and must be resolved.**

• **The accuracy of the wind velocity fields is presently the most limiting factor in our capability to progress towards better dust emissions in transport models. Regional or nested models should help to resolve a part of the problem but probably only a part...**