The dust cycle in the atmosphere

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Summary

- Atmospheric aerosol
- The cycle of mineral dust
- WMO SDS-WAS
- Dust observation
- Dust forecast
- Also...
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Atmospheric aerosol

Solid or liquid particles suspended in the air

- **Types**: primary / secondary, natural / anthropogenic particles
- **Size**: diameter between 0.001 µm (1 nm) and 100 µm approx.
- **Chemical and mineralogical composition**: diverse
- **Optical properties** (absorption, scattering): diverse
Sources

Year 2000 (Tg)
IPCC (2001)
Distribution

- Mineral dust (reddish)
- Sea salt (blue)
- Products from biomass burning (green)
- Sulphates (white)

https://youtu.be/oRsY_UviBPE
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The dust cycle
The dust cycle

- Emission
- Turbulent diffusion
- Transport
- Dry / wet deposition
Emission

- The wind moves the loose particles according to its speed and the size of those particles
- The process is similar to sediment transport by rivers
The threshold for particle mobilization is the result of the balance between the wind-shear stress and the forces acting to keep the particles on the soil (weight, cohesive forces between particles)

\[ u^* = \left( \frac{\tau}{\rho} \right)^{0.5} = \frac{ku}{\ln(z/z_0)} \]

Shao and Lu (2000)
Saltation & sandblasting

- Direct suspension is not so common, because it needs very strong winds.

- Normally, the dust emission is the result of the combination of two different physical processes: saltation (horizontal flux) and sandblasting (vertical flux).

- Sandblasting is a consequence of the breaking of particle aggregates.

Shao et al. (2011)
A crude estimation of the threshold wind speed for dust emission would be around 8 m/s, although it depends on many factors (soil nature and state, turbulence). Different elements modify this threshold.
Emission

Soil factors
- Soil texture (particle size)
- Soil moisture
- Vegetation
- Snow cover

Meteorological factors
- Wind speed
- Near-surface turbulence
Sources
A significant part (25-30%) of the dust sources are anthropogenic:

- Perturbed soils: dried lakes, marshes and other water bodies by water overuse, agricultural lands, etc.
- Direct human activity: overcast minery, construction, ...
Bodélé depression
Aral Sea
Total emission

~ 30–60 Tm/s
~ 1000–2000 Tg/yr

50,000,000 lorries

3,000 ULCC
SYNOPTIC SCALE
- Frontal systems
- Reinforcing trade winds

Meteorological conditions

22-24 Mar 2008
Meteorological conditions

MESOSCALE-MICROSCALE
- Convection
- Drainage winds
- Low-level jets (LLJ)
- Gap winds
- ...

29 Apr – 1 May 2007
Meteorological conditions
Transport

29 – 30 Jul 2013
Dust optical depth at 550 nm. Average value 2003-2015

Data: CAMS reanalysis
Picture: WMO SDS-WAS
The average particle size decreases
Chemical composition may vary
Optical properties may vary
Increasing ability of particles to act as CN
Increasing solubility of Fe
Deposition

<table>
<thead>
<tr>
<th>SIZE (µm)</th>
<th>AVERAGE LIFETIME (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 - 0.18</td>
<td>231</td>
</tr>
<tr>
<td>0.18 - 0.3</td>
<td>229</td>
</tr>
<tr>
<td>0.3 - 0.6</td>
<td>225</td>
</tr>
<tr>
<td>0.6 – 1</td>
<td>219</td>
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<tr>
<td>1 - 1.8</td>
<td>179</td>
</tr>
<tr>
<td>1.8 – 3</td>
<td>126</td>
</tr>
<tr>
<td>3 – 6</td>
<td>67</td>
</tr>
<tr>
<td>6 - 10</td>
<td>28</td>
</tr>
</tbody>
</table>

Tegen and Lacis (1996)

Settling Velocity Versus Particle Size (Zender, 2003)
Wet deposition

MODIS 12 Mar 2012

PM Ayia Marina, Cyprus, Mar 2012
Composition

MINERALOGICAL (X-ray diffractometry)
- Silicates: quartz, feldspar, phyllosilicates (illite, kaolinite, smectite)
- Carbonates (calcite, dolomite)
- Hematite, gypsum, halite, ... 

ISOTOPICAL (Sr, Nd, Pb)

CHEMICAL (spectroscopy)
- Si, Al, Ca, Mg, Fe, K, Na, Mn, Ti, P

- Information about the source region
- Influence on optical properties
- Influence the impact on health, ecosystems, ...
Particle size

\[ \tau = \ln\left( \frac{I_0}{I_1} \right) \cos(\theta) \]
Seasonal variability

1996-2010

Terradellas et al. (2012)
Impacts

- Air quality and health
- Weather and climate
- Transportation (visibility reduction)
- Energy
- Agriculture, fisheries…
Health impact

- Particle size
- Chemical and mineralogical composition
- Carrying bacteria, viruses, fungi, ...
- Time and intensity of exposure
Impact on weather and climate

Takemura et al. (2009)
Impact on transportation

D’Almeida (1986)
Ben Mohamed et al. (1992)

Arizona, 29 Oct 2013

Tunis, 7 May 2002
Solar energy

- Reduction of available energy
- Reduced efficiency due to dust deposition
Dust deposition
Jickells et al. (2005)

- Dust deposition is a source of micro-nutrients for continental and marine ecosystems
- Saharan dust has been shown to fertilize the Amazon rainforest
- The contribution of Fe and P benefits the production of marine biomass in oceanic areas that suffer from shortage of such elements
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Mission:
Enhance the capacity of countries to generate and distribute to end-users dust observations, forecasts, information and knowledge

Structure:
- Regional Center for Northern Africa, Middle East and Europe, Barcelona
- Regional Center for Asia, Beijing
- Regional Center for Pan-America, Bridgetown
- Regional Center for West Asia (??)
The Center is jointly managed by AEMET and the Barcelona Supercomputing Center

UPC Campus. Nexus II building

MareNostrum III supercomputer
SDS-WAS Regional Center NAMEE

https://sds-was.aemet.es
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Why do we need dust observation?

- Monitoring dust events
- Data assimilation into models
- Forecast verification
- Validation of other observations (i.e. ground observations to validate satellite products)
Monitoring: satellite products

- The basic tool for monitoring dust events is satellite imagery
- The EUMETSAT RGB dust product is a composition based on three infrared channels from SEVIRI (Meteosat Second Generation)

**Drawbacks:**
- Qualitative product
- Without information from cloudy areas
- Vertical integration. Without information on near-surface conditions

19 Mar 2017: The sandstorm named Madar, originated in Libya, swept through Egypt, Saudi Arabia, Iraq, Kuwait and Iran
Monitoring: AQ stations

Drawbacks:
- Few stations near dust sources
- No protocol for data exchange
- Lack of harmonization in measurements
- Integration of all particles
- Many stations located in urban environments

Average columnar dust contents 2003-2015 (WMO Airborne Dust Bulletin, 1)
Monitoring: meteorological reports

Drawbacks:
- Indirect estimation (not mass concentration)
- Subjective nature
- Limited to severe events

https://sds-was.aemet.es

19 Mar 2017
Data assimilation

Drawbacks:

- Lack of suitable observations
- Complexity of extracting the dust signal from the measured radiance
- Modellers often use processed products rather than raw observations
- They normally assimilate MODIS AOD using variational techniques (ECMWF) or EKF (JMA, BSC)
- Efforts are now aimed at assimilating products from GEO satellites and lidar/ceilometer profiles

MODIS AOD retrieval (DT+DB+O) 19 Mar 2017
Solar radiation at the top of the atmosphere is known
Airborne particles attenuate the direct radiation (absorption, scattering)
The sun-photometers measure the direct radiation that reach the surface
Measurement at different wavelengths allows retrieval of total aerosol contents and some of its properties (e.g. size spectrum)
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Dust prediction models

Meteorological model (NWP) + Parameterization of the dust cycle = Dust prediction model

- Emission
- Transport (diffusion, convection, advection)
- Dry / wet deposition
- Interaction with radiation
- Interaction with cloud droplets
- Atmospheric chemistry
- ...

Diagram showing:
- Horizontal advection
- Vertical advection and sedimentation
- Lateral diffusion
- Turbulent diffusion
- Wet deposition
- Dry deposition
- Mountain effects
- Desert
Problems

- Incomplete knowledge of the physical processes involved in the dust cycle
- Processes of very diverse scale
- Need for a very accurate wind forecast
- Lack of adequate observations for assimilation and verification

\[ F = \sum_{i} C_i u^2 (u - 6.5) \]

Tegen et al. (1994)

\[ F = \alpha \frac{\rho}{g} u^3 \sum_{i} s_i \left( 1 + \frac{u_{tri}}{u_*} \right) \left( 1 - \frac{u^2_{tri}}{u_*^2} \right) \]

Marticorena et al. (1997)

\[ F = CS \sum_{i} u^2 s_i w_0 (u - u_{tri}) \]

Ginoux et al. (2001)
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InDust

International Network to Encourage the Use of Monitoring and Forecasting Dust Products

MC chair: Sara Basart (BSC)

28 countries
Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Cyprus, Denmark, Finland, France, fYR Macedonia, Germany, Greece; Hungary, Iceland, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Spain, Switzerland, Turkey, United Kingdom

Near-neighbour countries:
Morocco (Min. of Health), Egypt (EMA, Cairo Univ.), Jordan (Univ. of Jordan)

International organizations:
World Meteorological Organization
Climate monitoring

Average dust AOD at 550 nm in 2016 and its anomaly

https://sds-was.aemet.es/materials/WMO_Airborne_Dust_Bulletin_No1_en.pdf
Dust Storms Assessment for the Development of User-oriented Climate Services in Northern Africa, Middle East and Europe

PI: Sara Basart (BSC)

https://sds-was.aemet.es/projects-research/dustclim
Early Warning System for Burkina Faso

This project covers the design, implementation and operation of an EWS for airborne dust at the thirteen regions in which Burkina Faso is administratively divided.
Early Warning Systems

- **Risk knowledge.** The impact of airborne dust on air quality, human health, weather and climate, the environment and different economic sectors is generally known, although some aspects require further investigation.

- **Monitoring and warning services.** Most NMHS have the ability to obtain and use the basic products of dust monitoring and prediction.

- **Dissemination and communication.** Warnings must reach those at risk. Clear messages containing simple, useful information are critical to enable proper responses.

- **Response capability.** It is essential that communities understand their risks; respect the warning service and know how to react.
Capacity building

TRAINING
Accra
Addis-Ababa
Ankara
Antalya
Barcelona
Cairo
Casablanca
Istanbul
Madrid
Muscat
Niamey
Ouagadougou
Sta. Cruz de Tfe.
Tehran
Tbilisi