The dust cycle in the atmosphere

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7th Training Course on WMO SDS-WAS Products, Ahvaz, Iran, 10-14 November 2018

Summary

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

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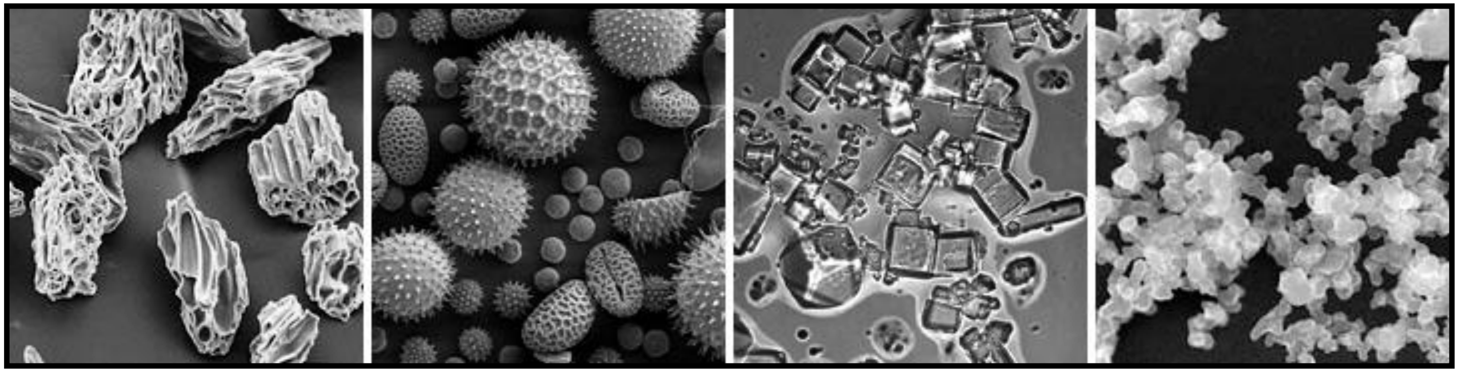
Atmospheric aerosol

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

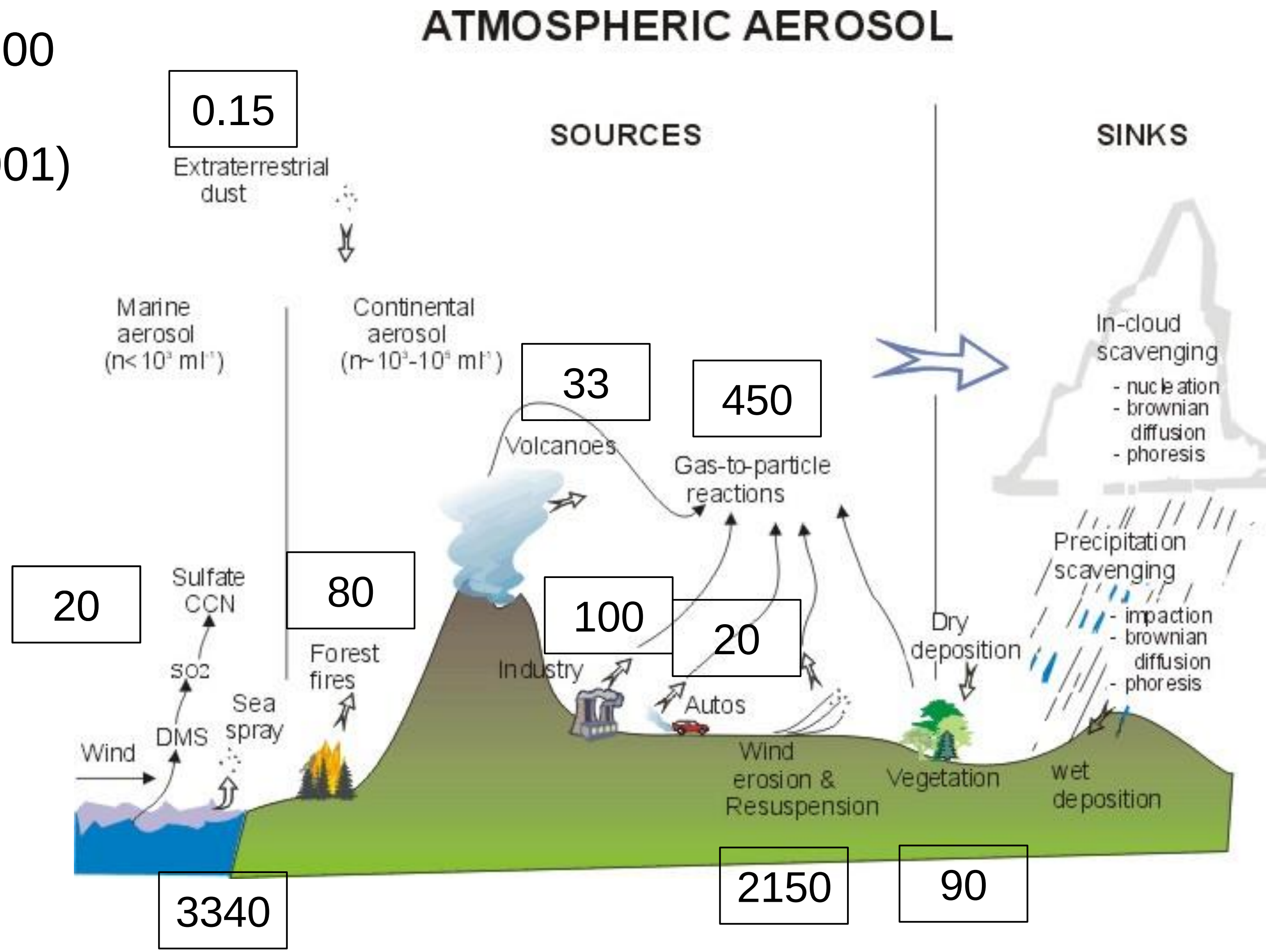


USGS science for a changing world

ASU Arizona State University

Sources of atmospheric aerosol

Year 2000
(Tg)
IPCC (2001)



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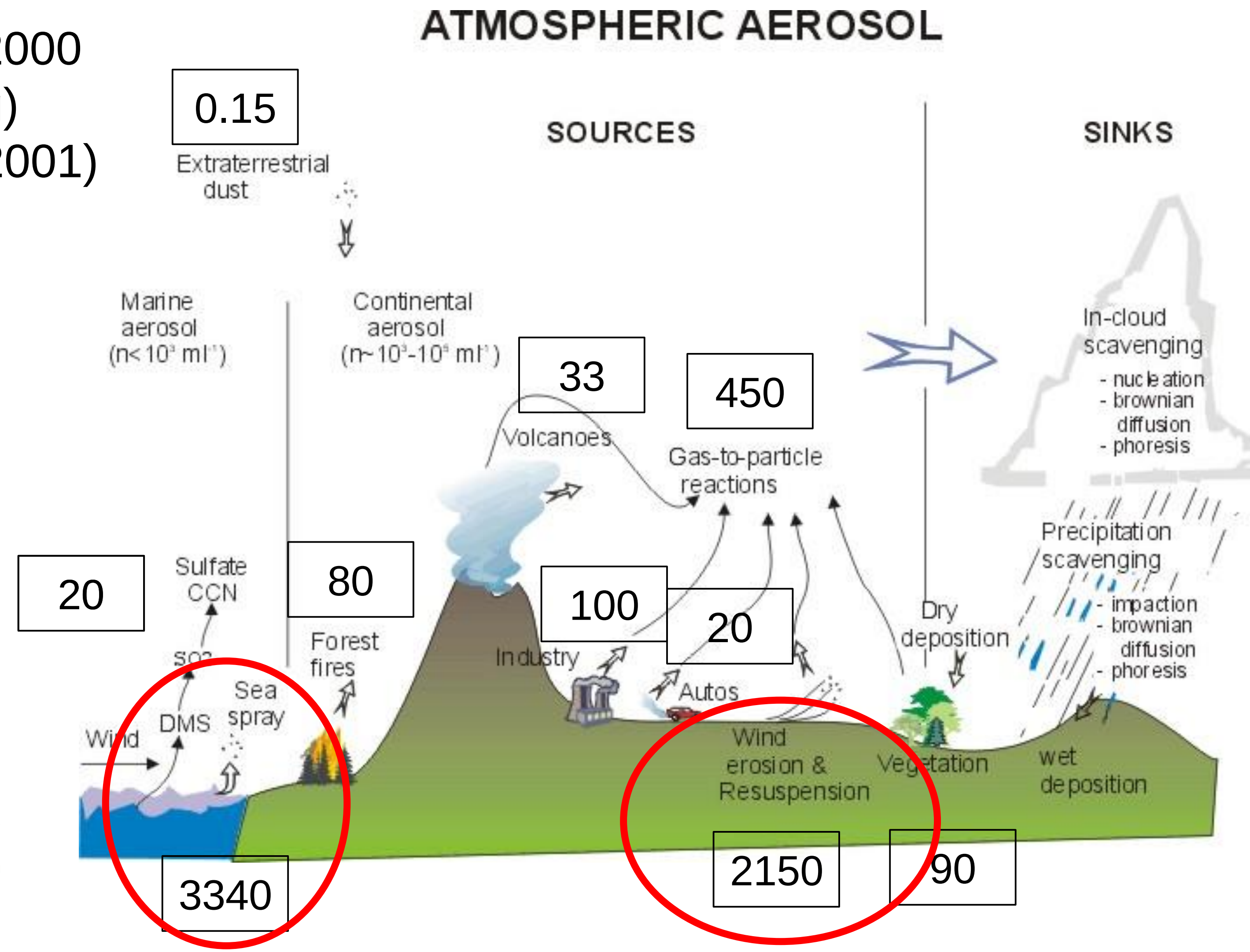
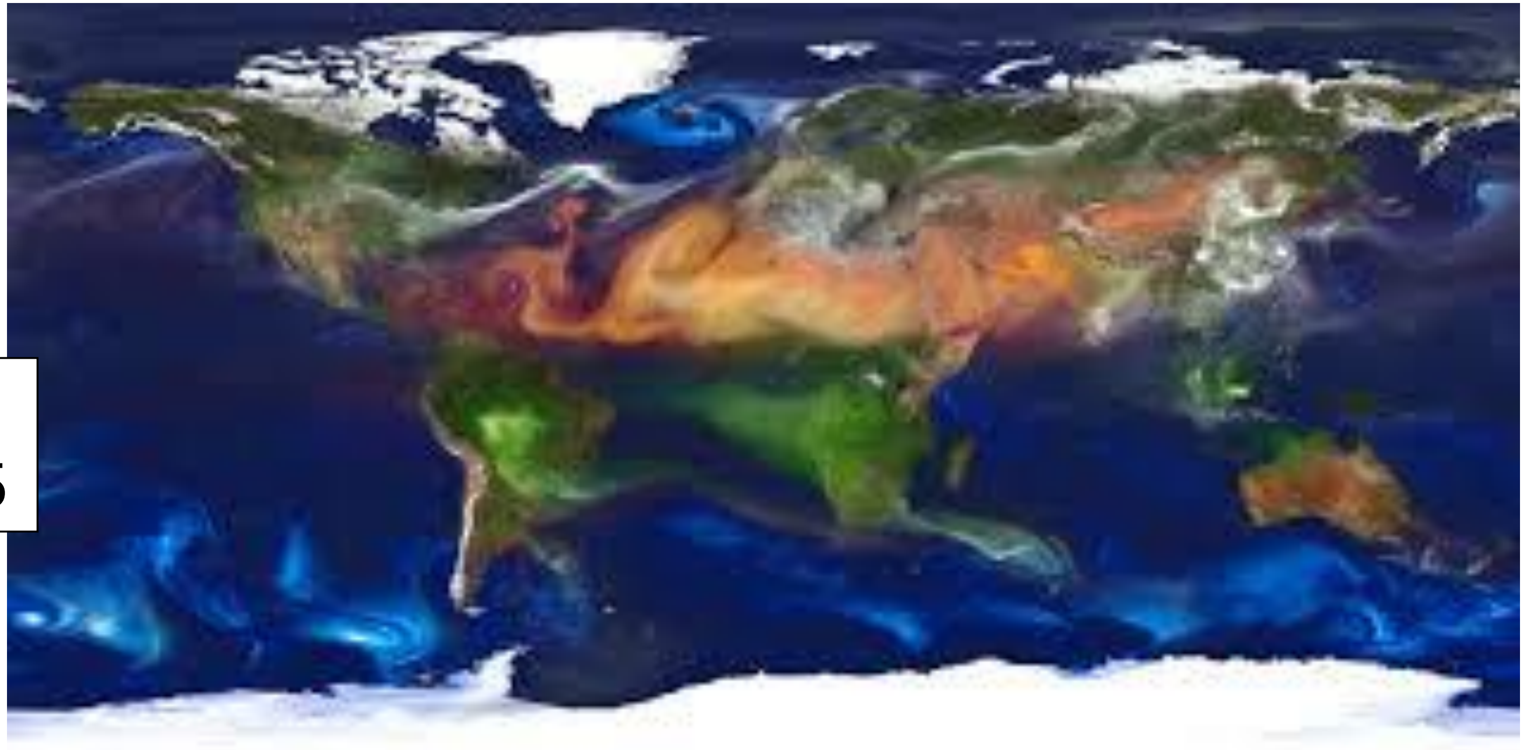


Distribution

NASA
GEOS-5

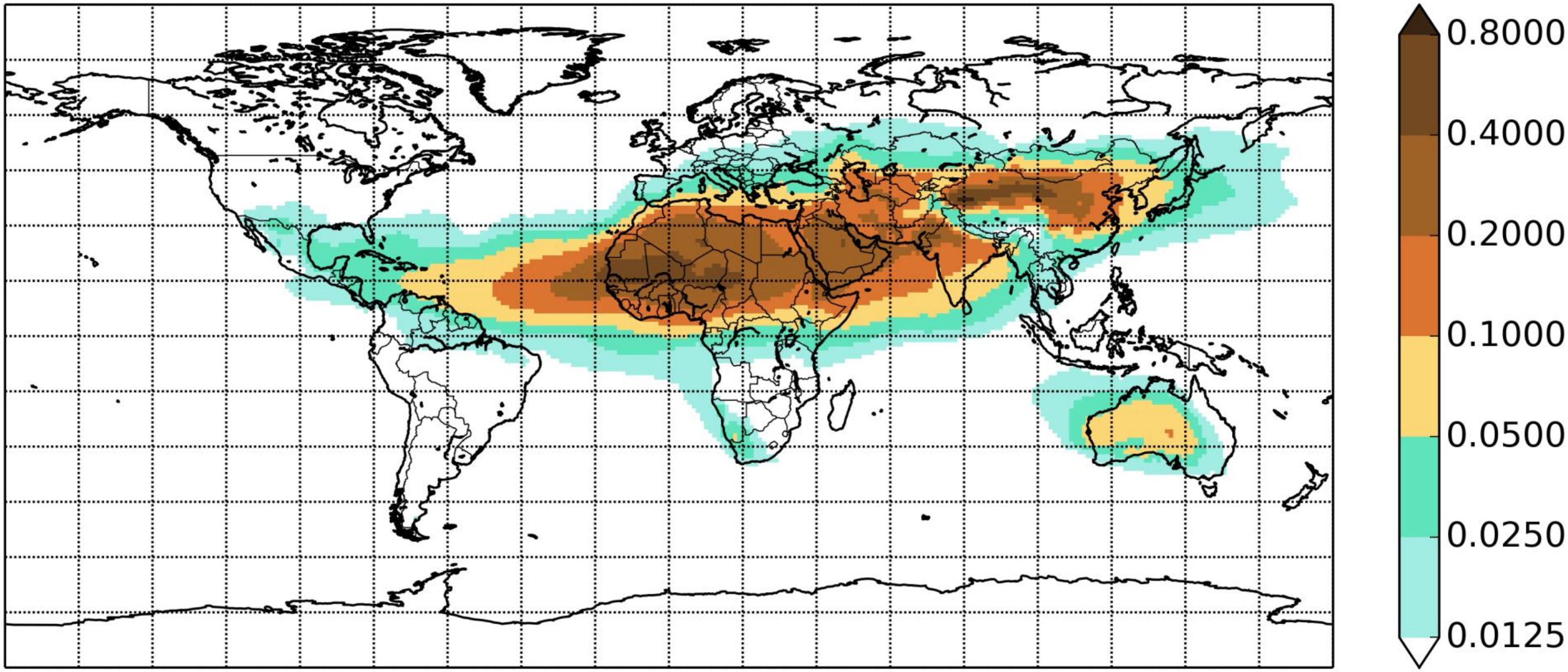


- Mineral dust (reddish)
- Sea salt (blue)
- Products from biomass burning (green)
- Sulphates (white)

https://youtu.be/oRsY_UviBPE

Grographical distribution of dust

Dust optical depth at 550 nm. Average value 2003-2015



Data: CAMS reanalysis
Picture: WMO SDS-WAS

WMO AIRBORNE DUST BULLETIN Sand and Dust Storm Warning Advisory and Assessment System

Summary

- Atmospheric aerosol
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- WMO SDS-WAS
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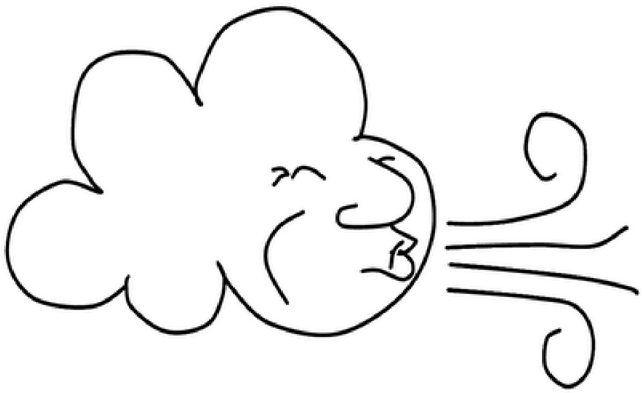
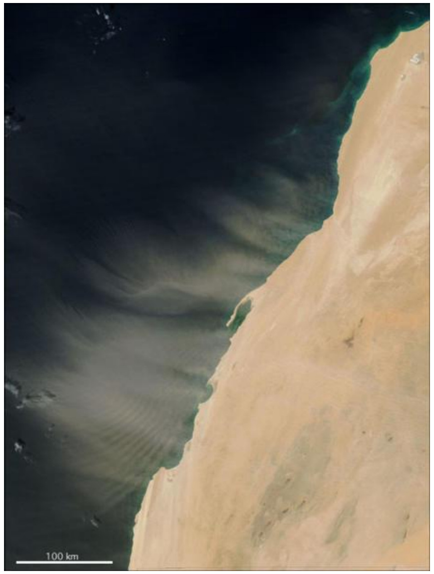
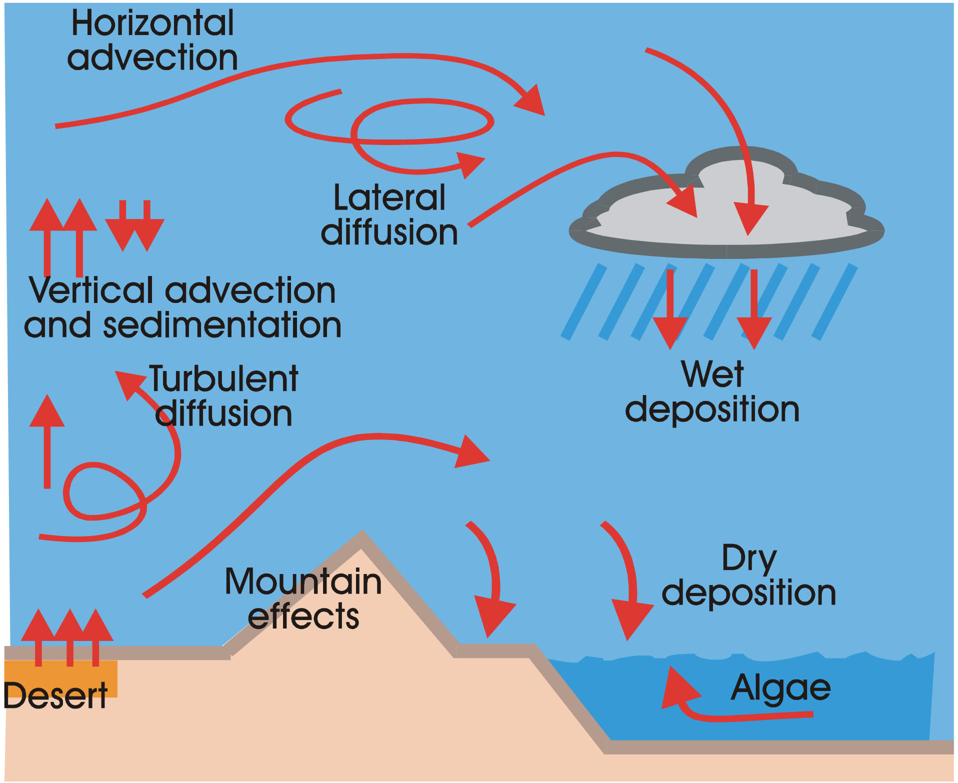
- Dust forecast

The dust cycle



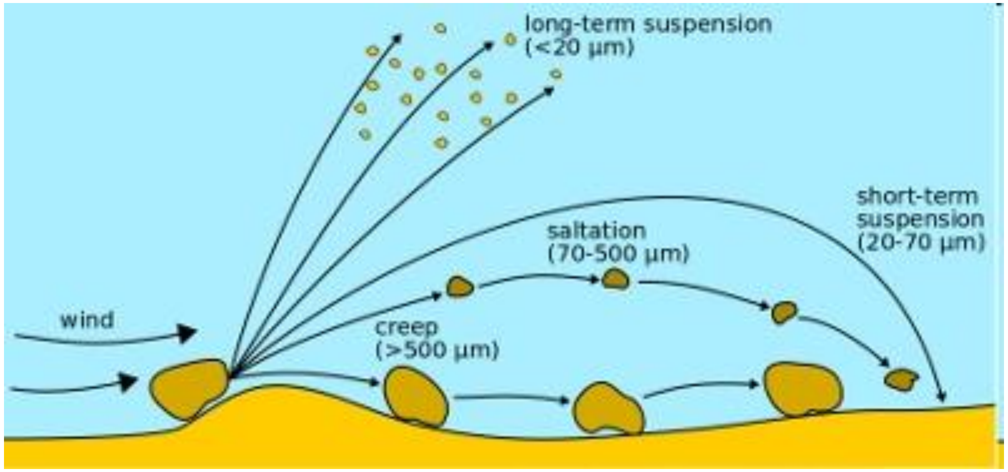


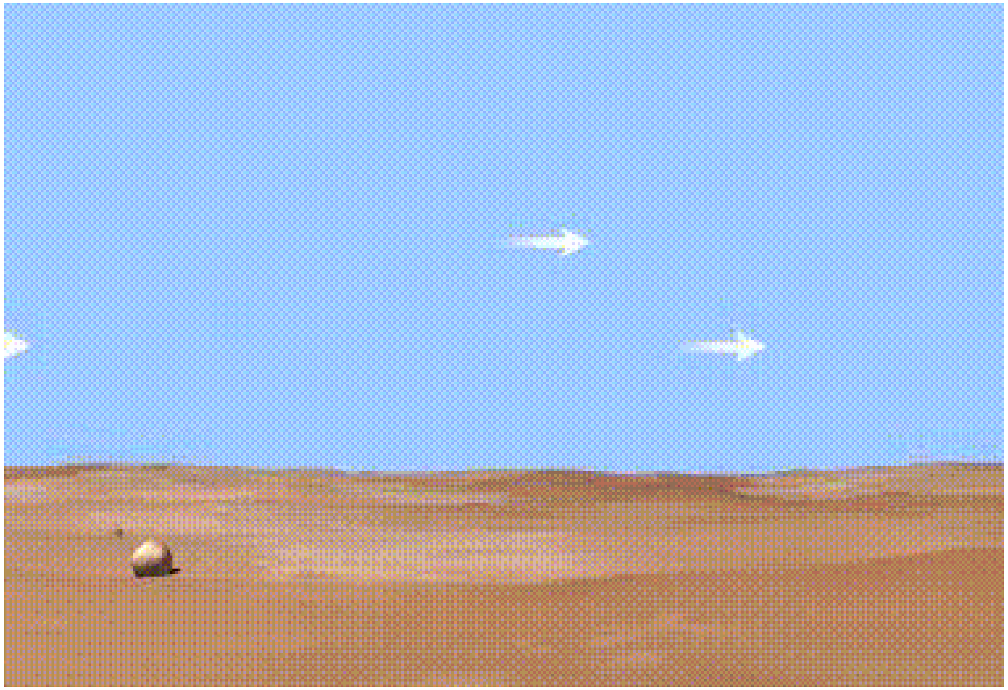
The dust cycle



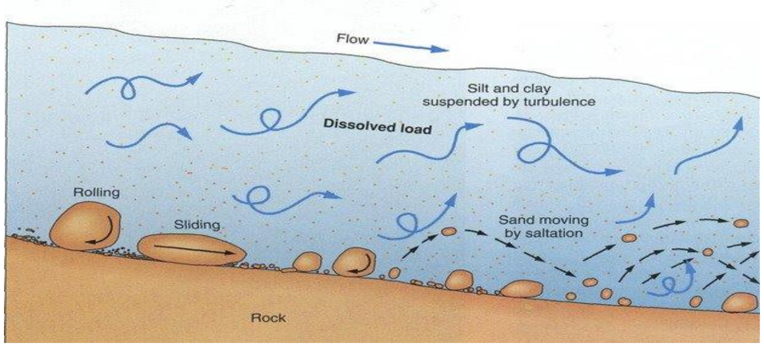
- Emission
- Turbulent difussion
- Transport
- Dry / wet deposition

Emission



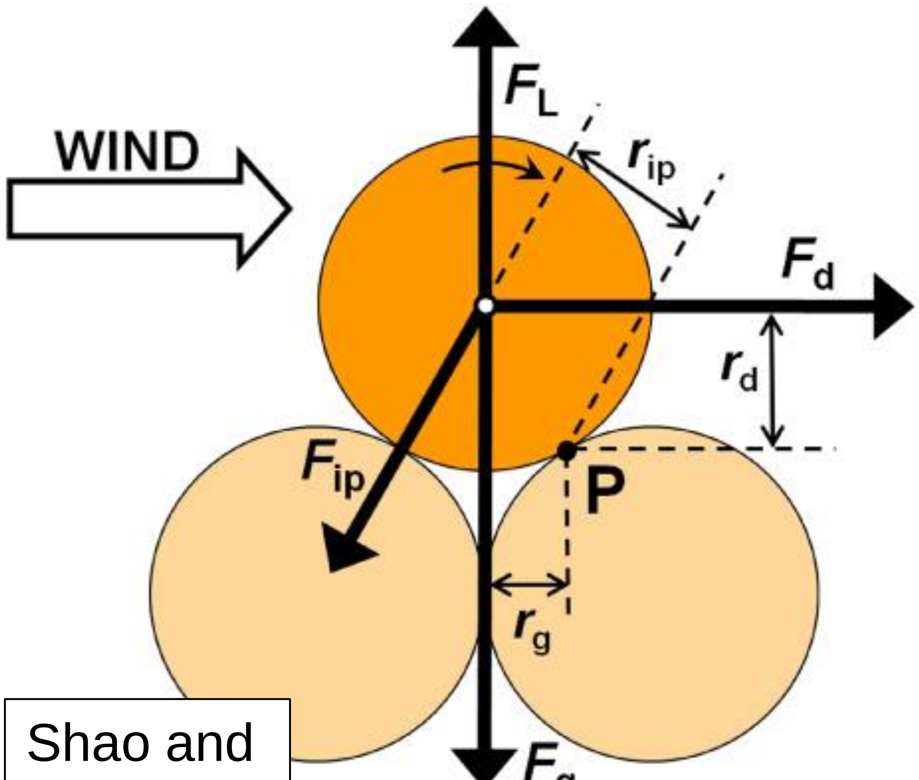


- The wind moves the loose particles according to its speed and the size of those particles
- The process is similar to sediment transport by rivers



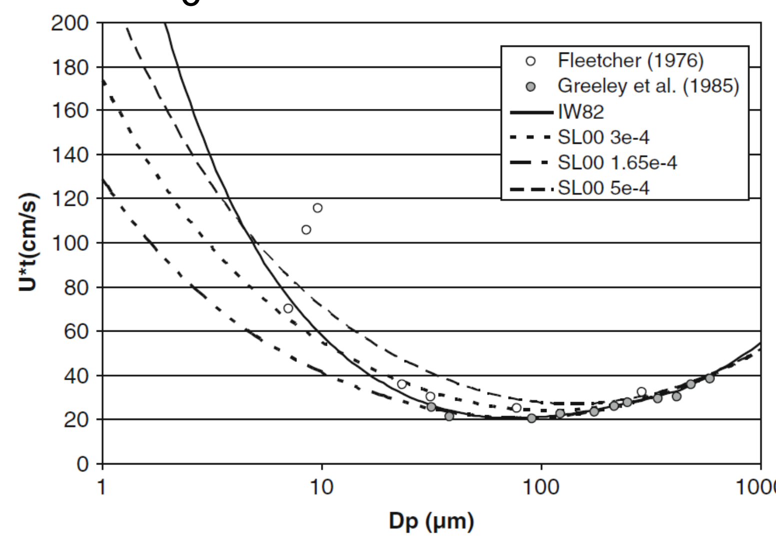
Erosion threshold

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)

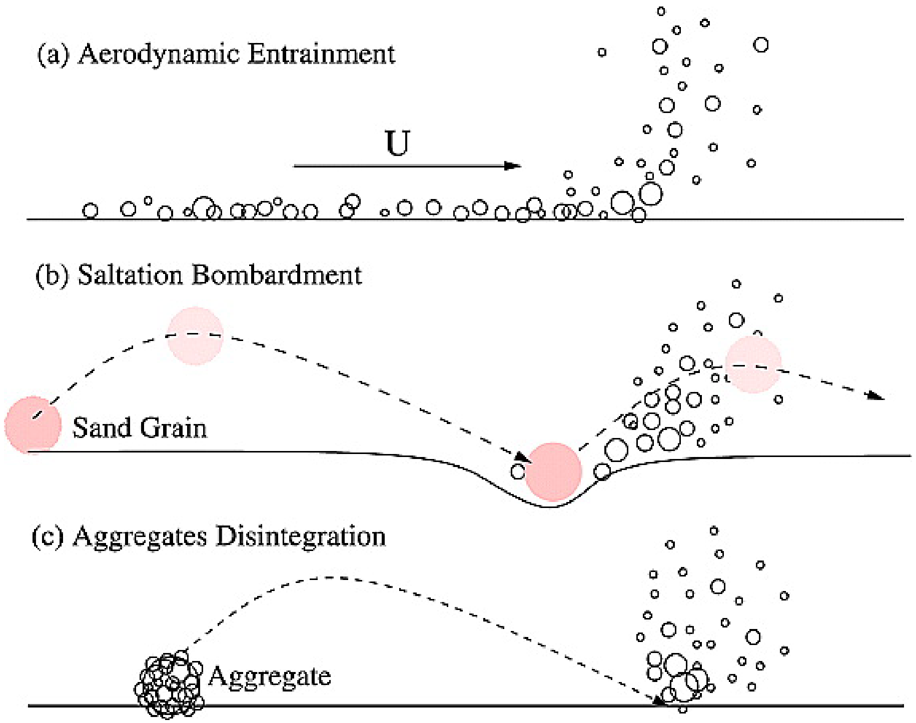


Shao and Lu (2000)

$$u^* = (\tau/\rho)^{0.5} = ku / \ln(z/z_0)$$



Saltation & sandblasting



Shao et al. (2011)

- 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.

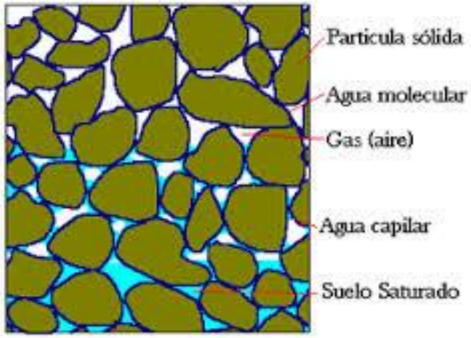
Erosion threshold

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

Non-erodible elements (i.e. vegetation)

Crusted soils

Soil humidity



Emission

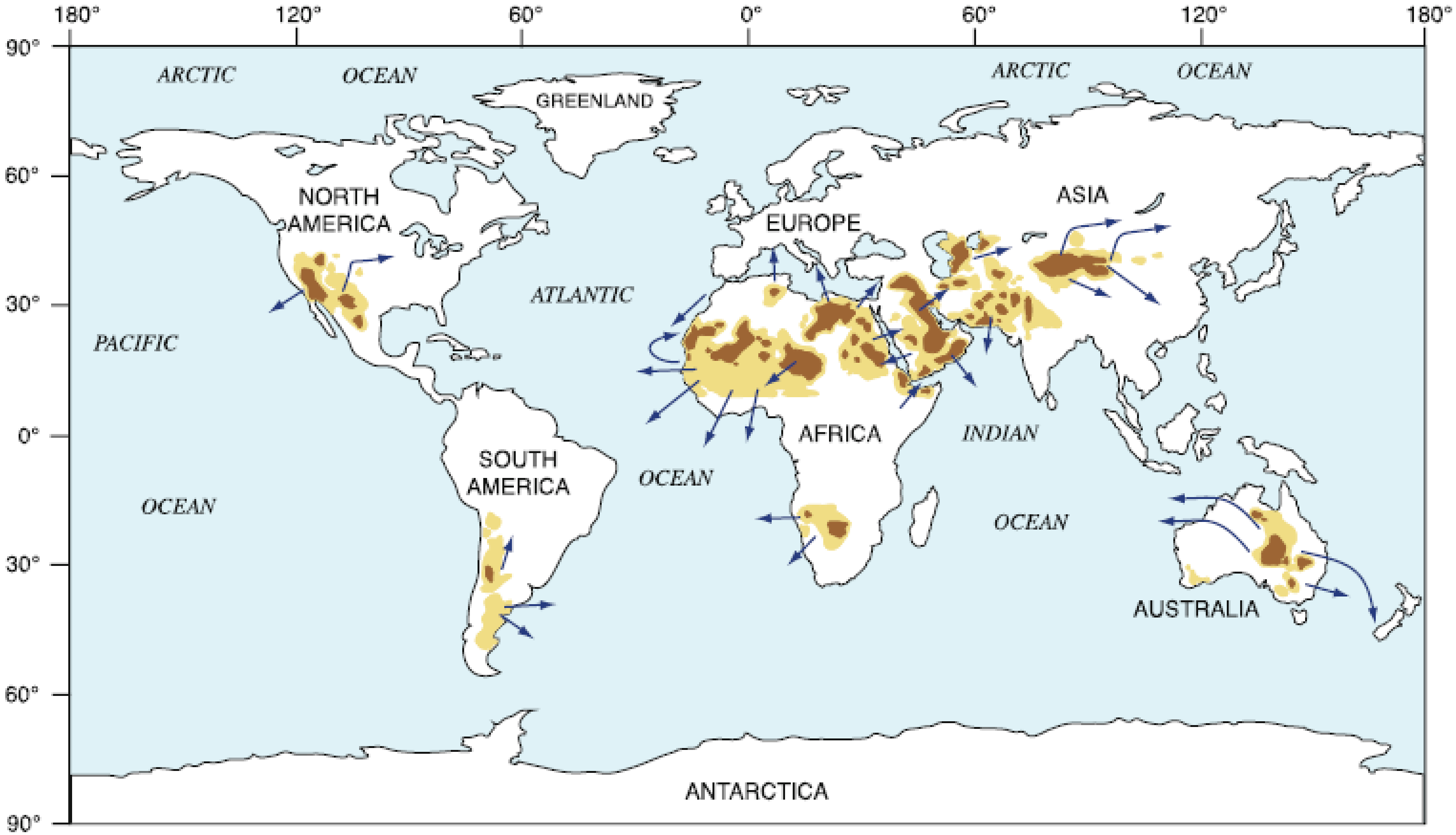
Soil factors

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

Meteorological factors

- Wind speed
- Near-surface turbulence

Sources



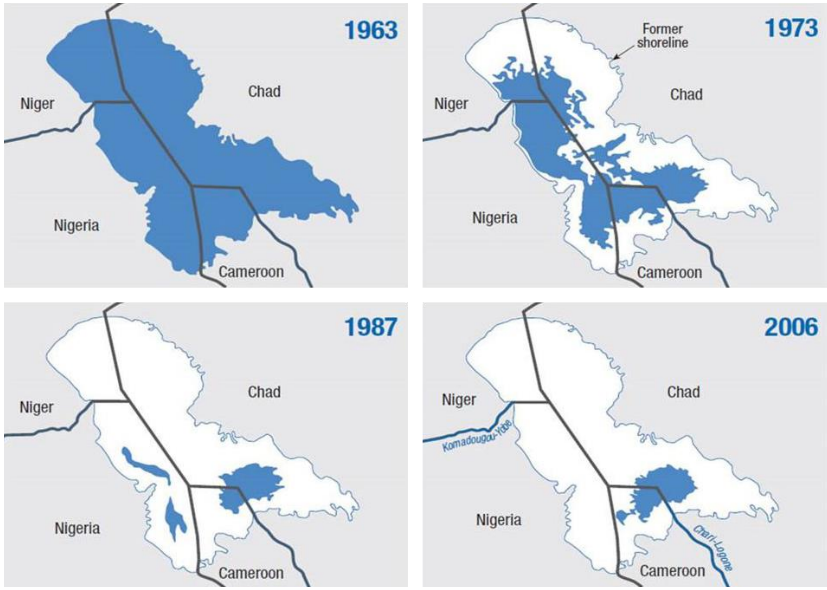
180°
120°
60°
0°
60°
120°
180°
90°
60°
30°
0°
30°
60°
90°
ARCTIC
OCEAN
GREENLAND
ARCTIC
OCEAN
NORTH
AMERICA
EUROPE
ASIA
ATLANTIC
PACIFIC
AFRICA
INDIAN
SOUTH
AMERICA
OCEAN
OCEAN
OCEAN
AUSTRALIA
ANTARCTICA

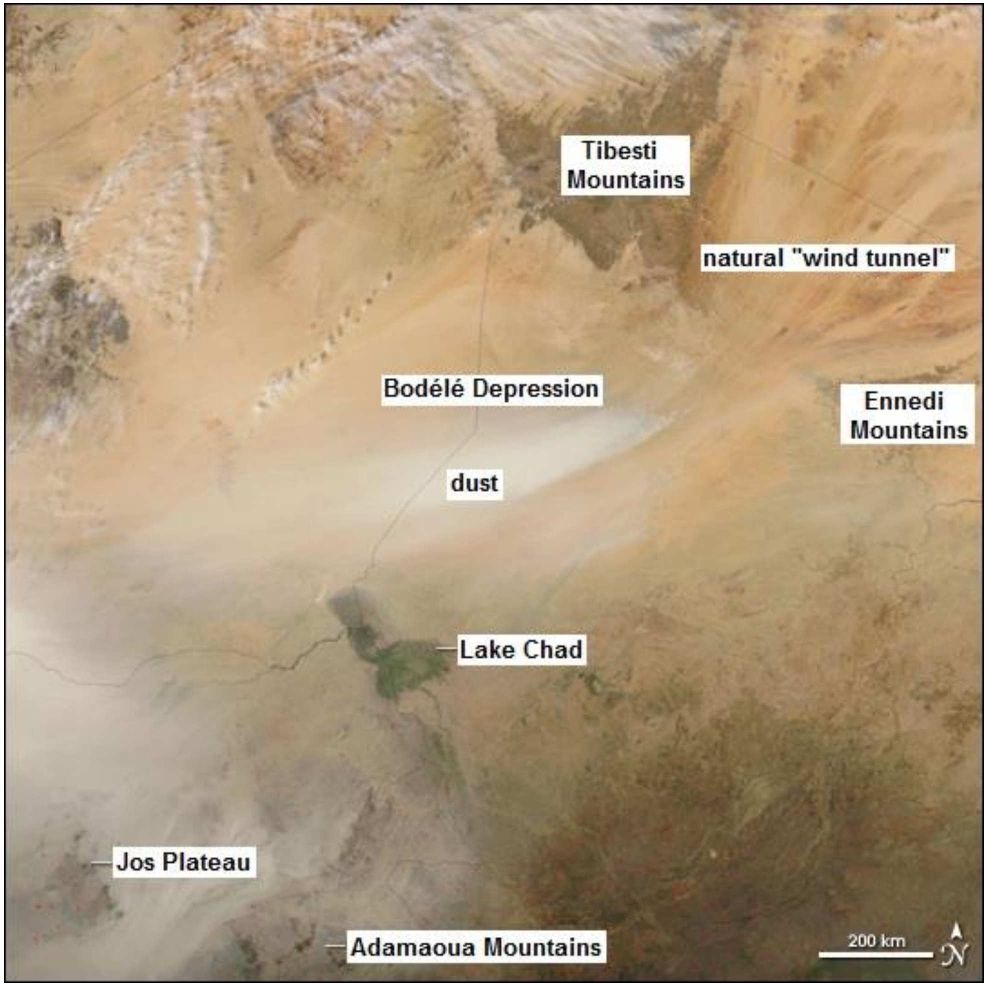
Anthropic sources of dust

Anthropic sources are responsible of a significant part (25-30%) of dust emissions

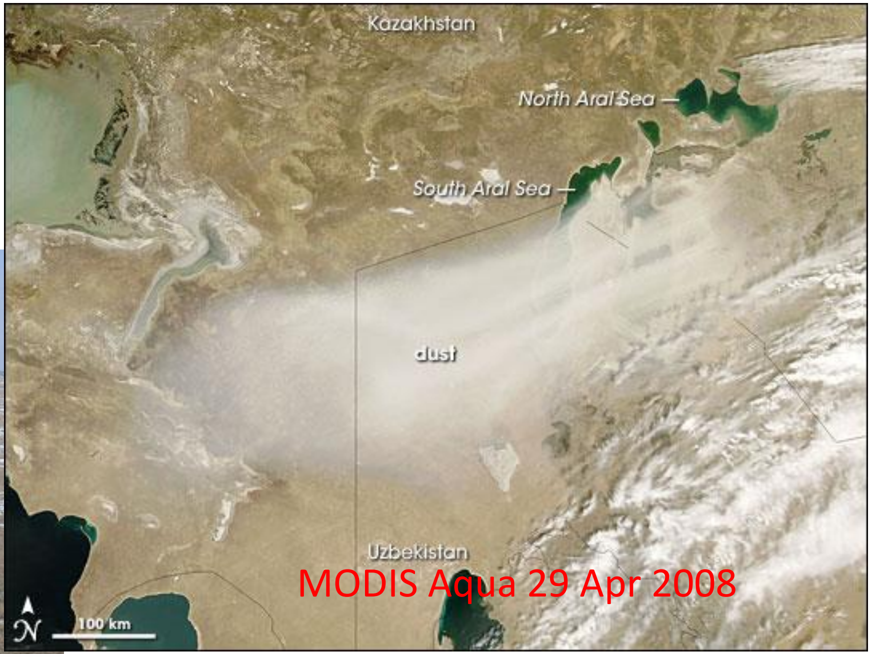
- Perturbed soils: dessicated lakes and marshes consequence of water overuse, agricultural lands, etc..
- Direct human activity: opencast mining, construction, driving on unpaved roads, ...

Bodélé depression



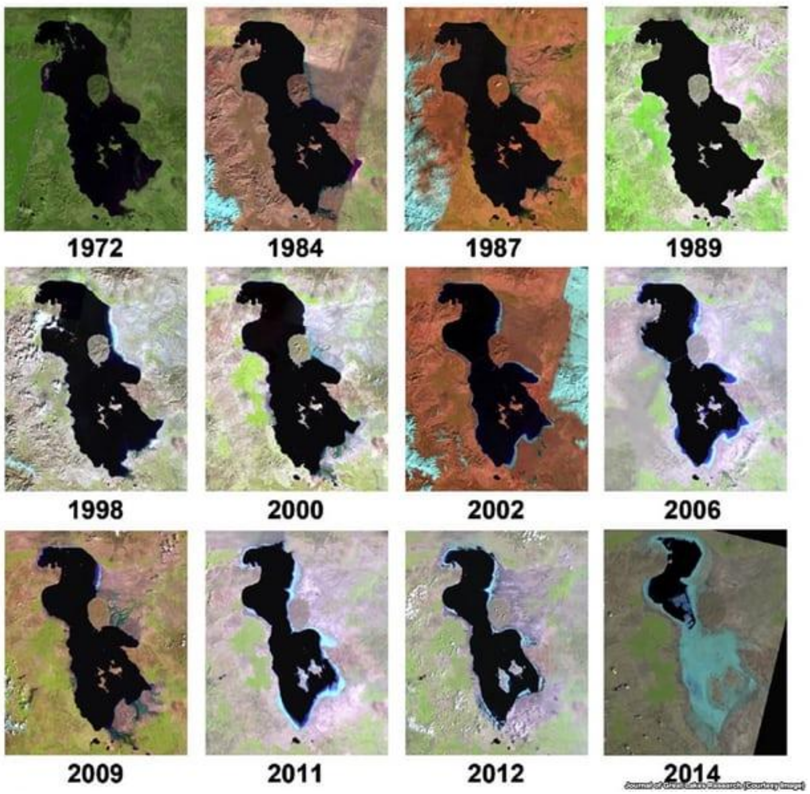


Aral Sea


Kazakhstan
North Aral Sea
South Aral Sea
dust
Uzbekistan
MODIS Aqua 29 Apr 2008
N
100 km

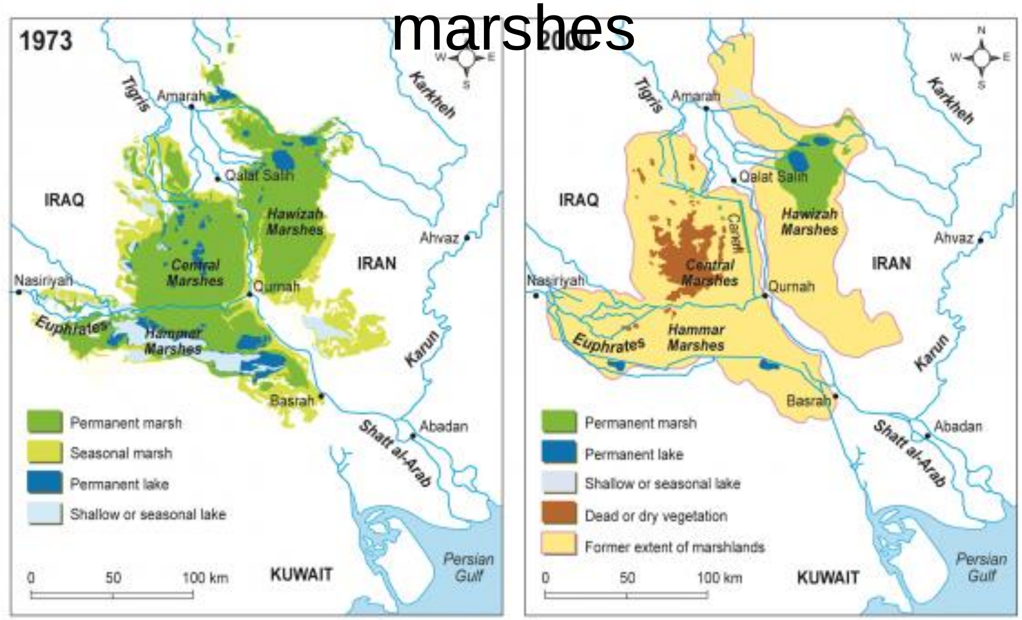
Dessicated lakes, marshes, ...

Urmia Lake

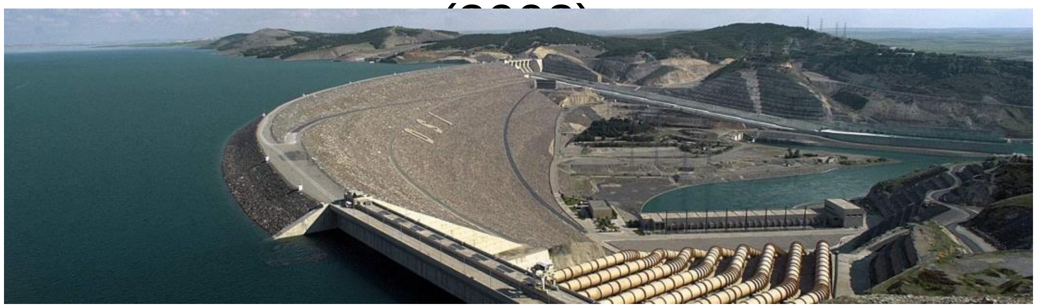


The Guardian

Mesopotamian marshes



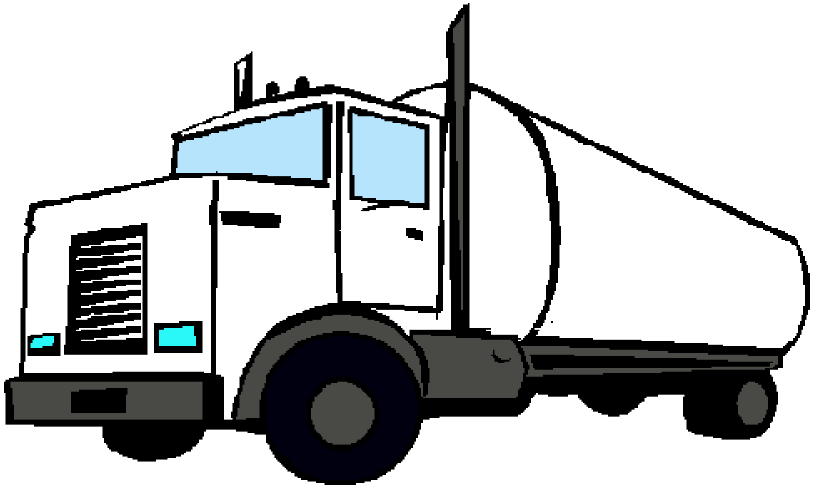
Partow (2001) modified by Rekacevicz



Total emission

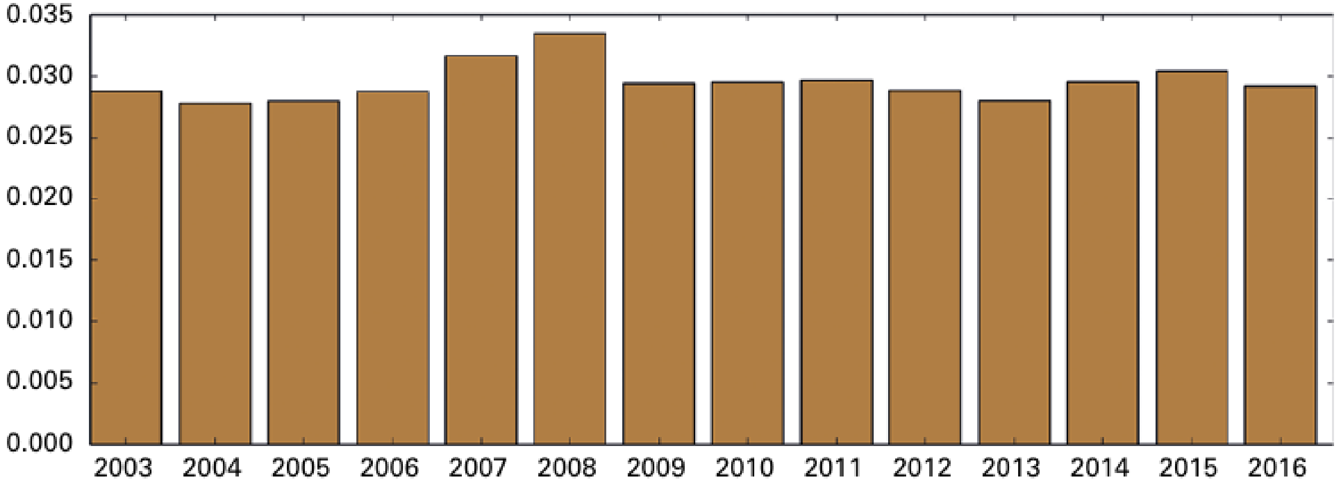
~ 30–60 Tm/s
~ 1000–2000 Tg/yr

50,000,000 lorries



3,000 ULCC

Long-term trends

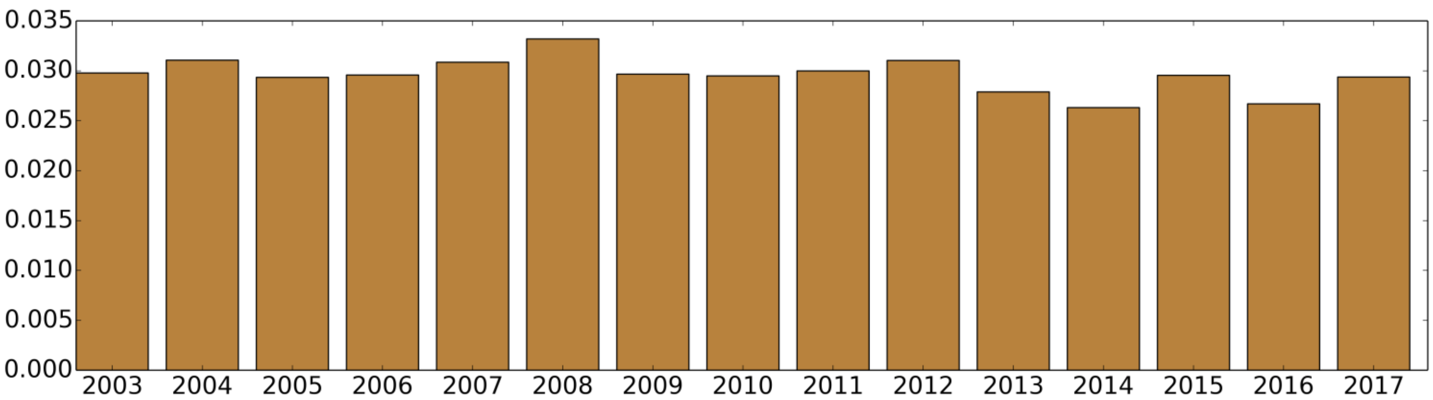


WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION | GLOBAL ATMOSPHERE WATCH | WWRP

WMO AIRBORNE DUST BULLETIN

Sand and Dust Storm Warning Advisory and Assessment System



Future trends

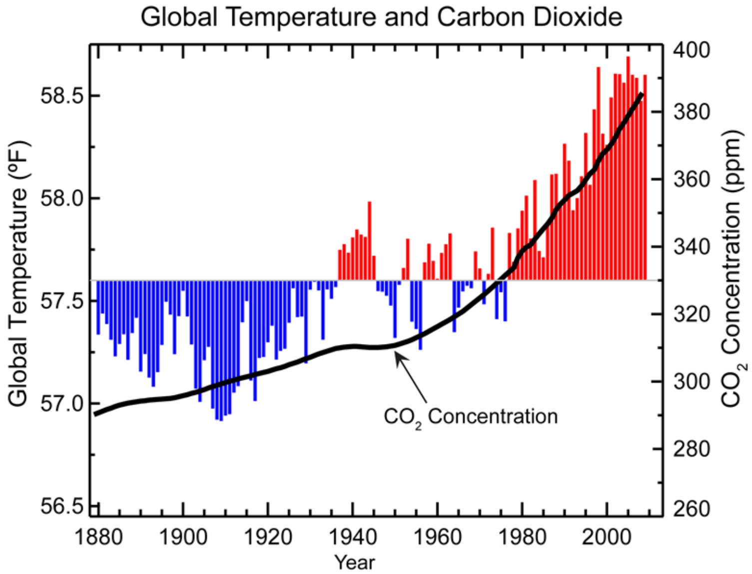
Dust emission depends on:

- Meteorological factors (wind, near-surface turbulence)
- Soil factors (texture, humidity, vegetation cover, …)

Land use and, therefore, soil conditions evolve much faster then climate. However, spatial scale is typically smaller

Changes in land use:

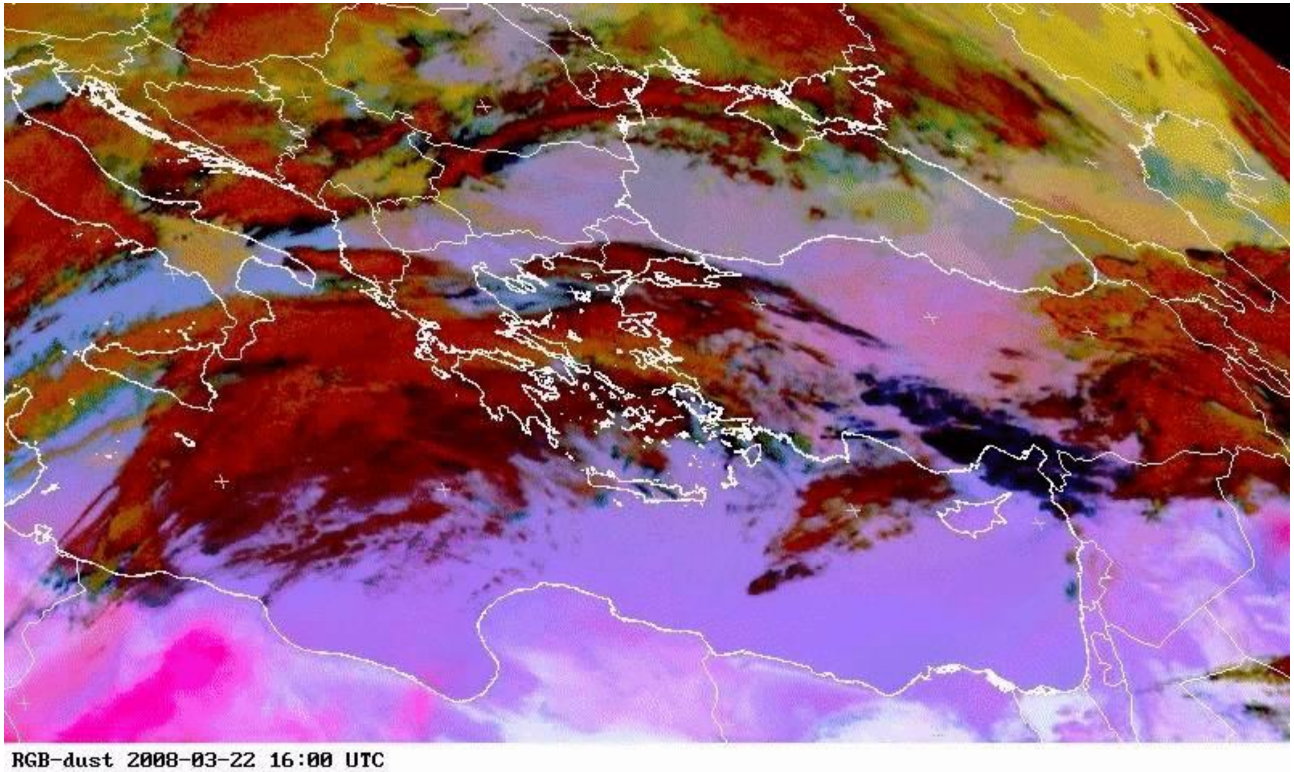
- Fast evolution
- Local to regional scale



Climate change

- Relatively slow
- Regional to global scale

Meteorological confitions



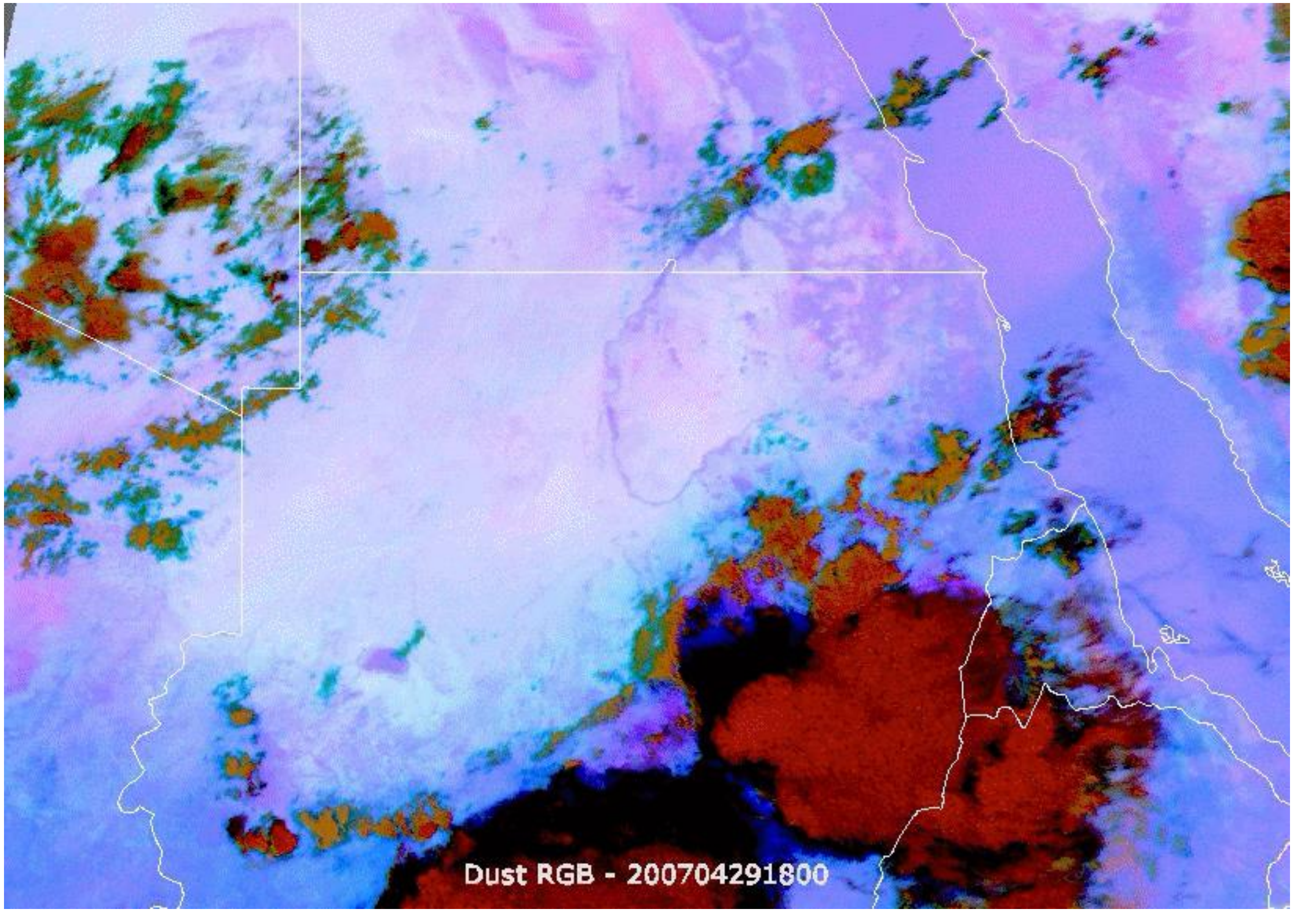
22-24 Mar 2008

EUMETSAT

SYNOPTIC SCALE

- Frontal systems
- Reinforced trade winds

Meteorological conditions

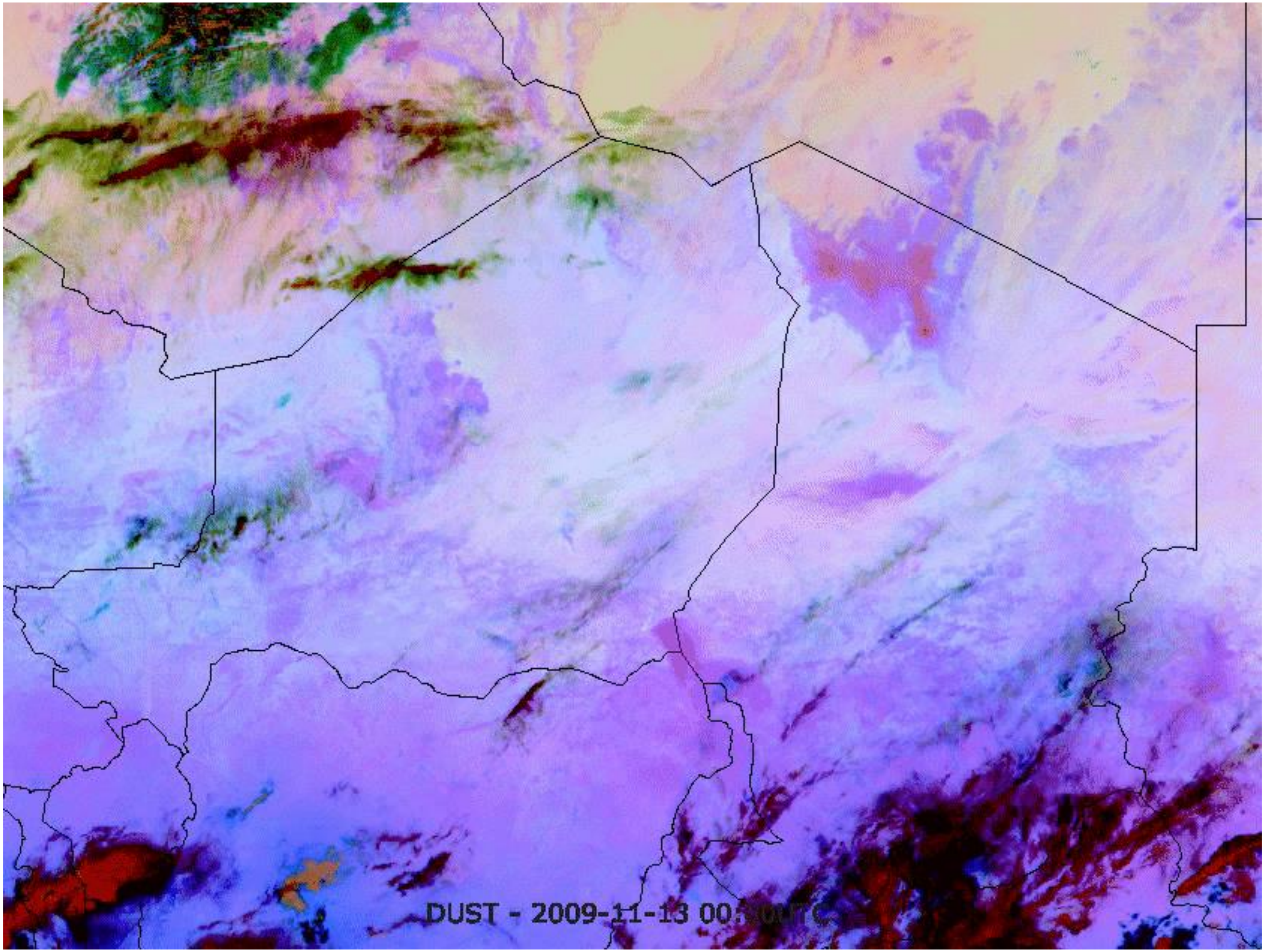


29 Apr – 1 May 2007

MESOSCALE-MICROSCALE

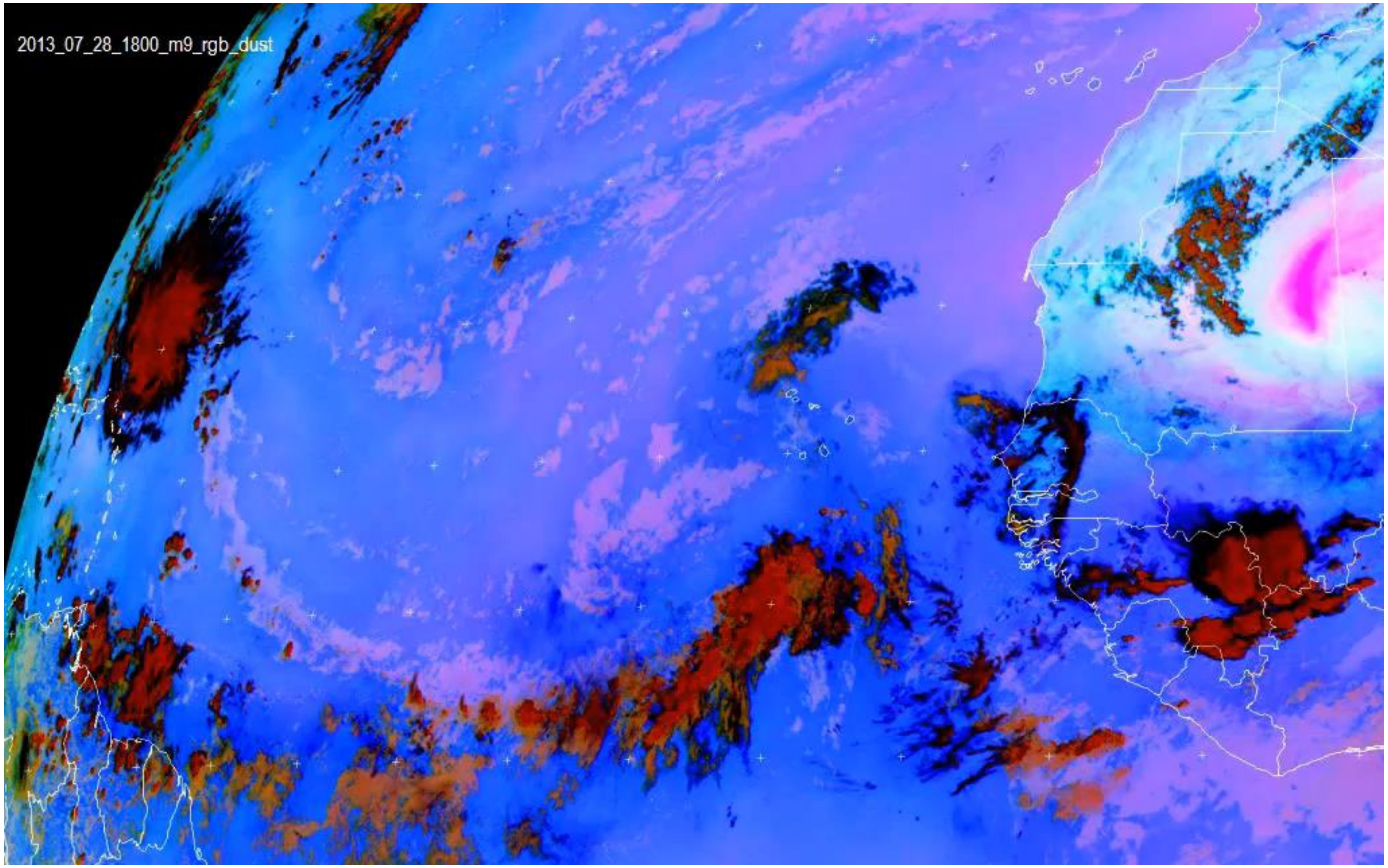
- Convection
- Drainage winds
- Low-level jets (LLJ)
- Gap winds
- ...

Meteorological conditions



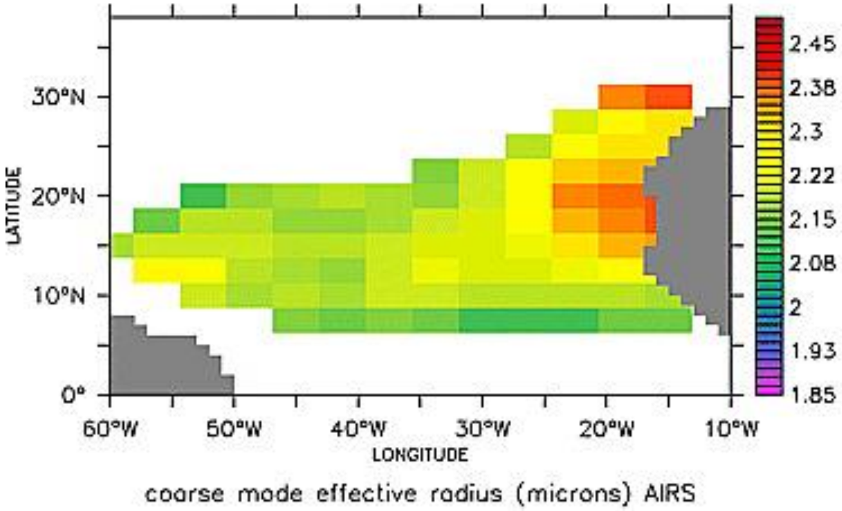
13 – 14 Nov 2009

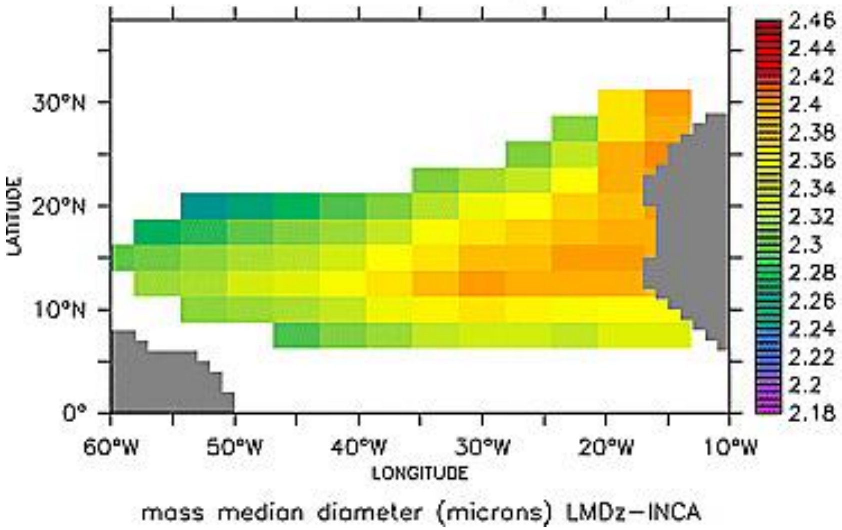
Transport



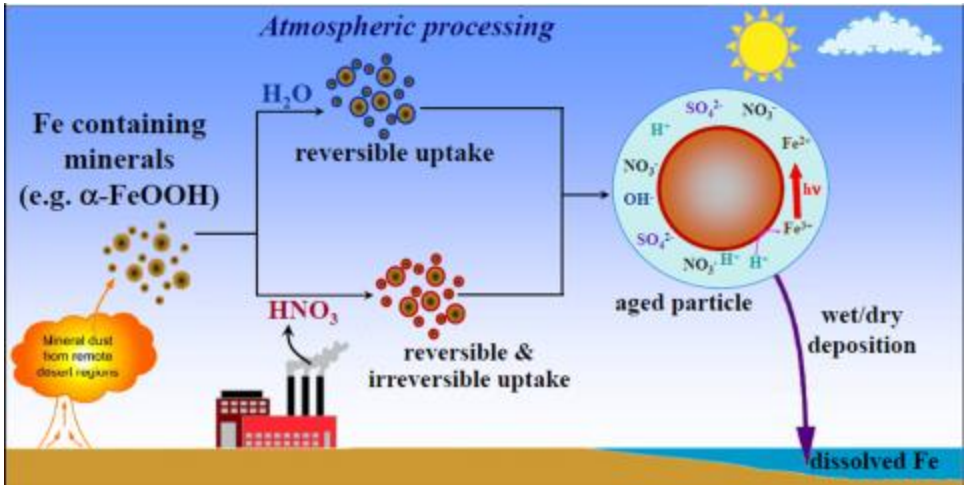
29 Jul – 2 Aug 2013

Transport



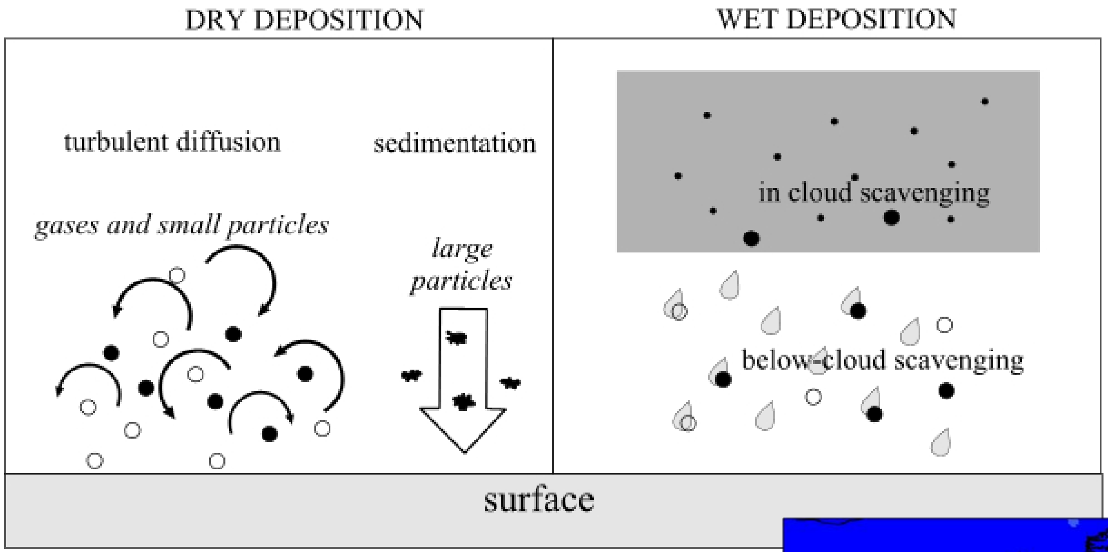


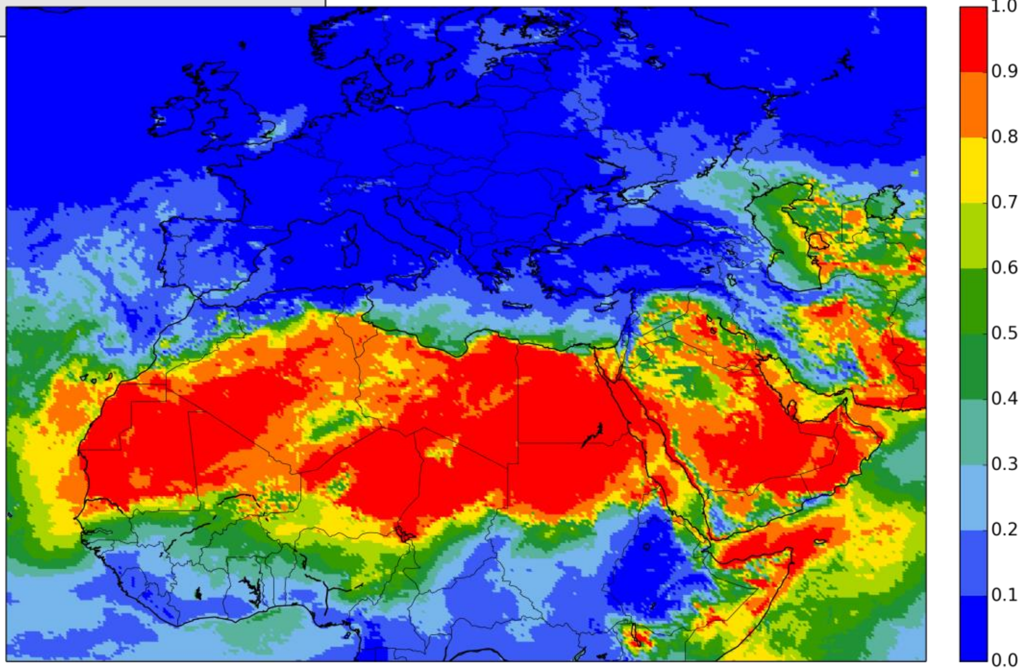
Pierangelo et al. (2005)



- 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

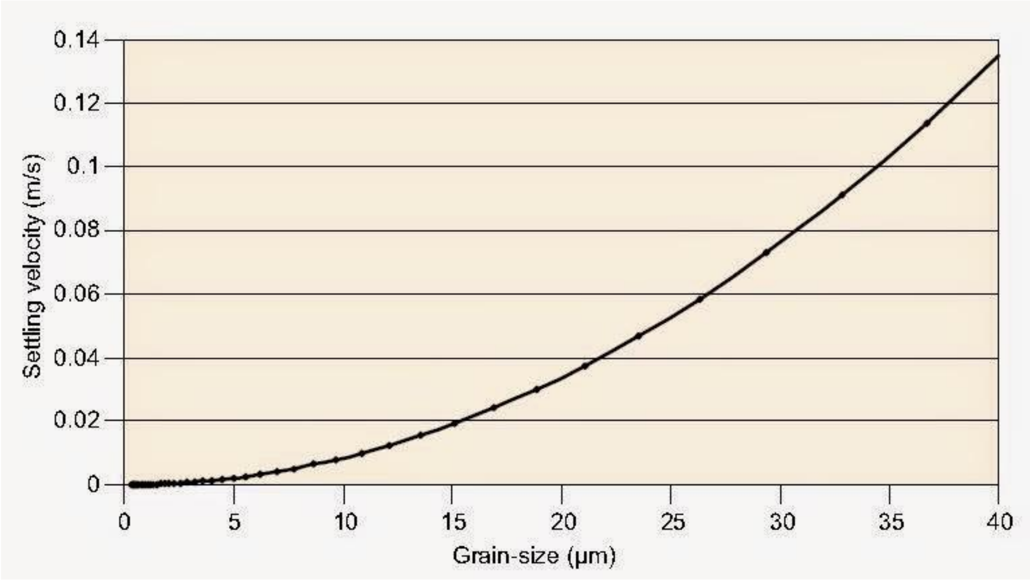
Deposition





Ratio between dry and total deposition

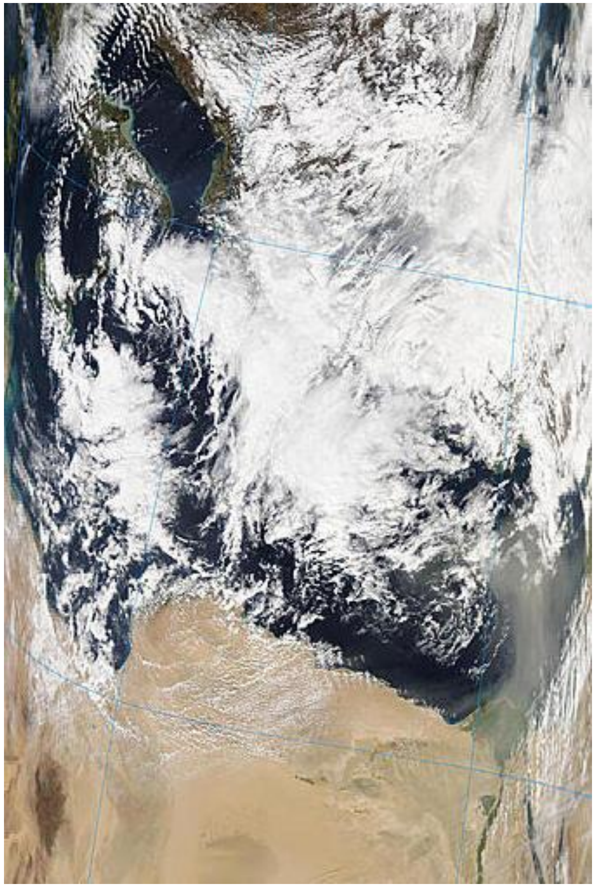
Deposition



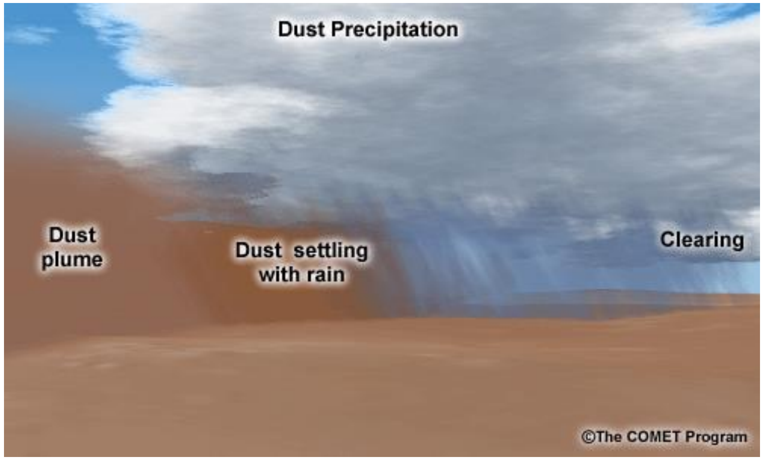
SIZE (µm)	AVERGE LIFETIME (h)
0.1 - 0.18	231
0.18 - 0.3	229
0.3 - 0.6	225
0.6 – 1	219
1 - 1.8	179
1.8 – 3	126
3 – 6	67
6 - 10	28

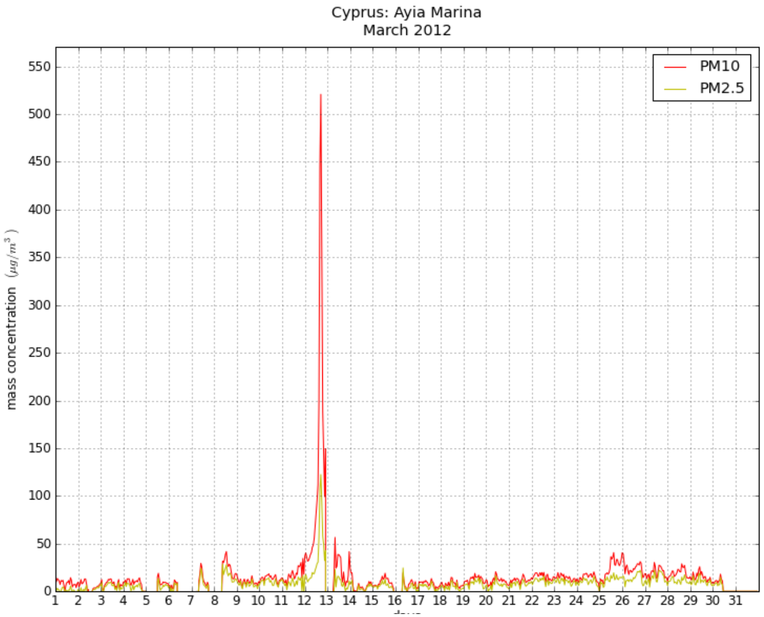
Tegen and Lacis (1996)

Wet deposition



MODIS 12 Mar 2012

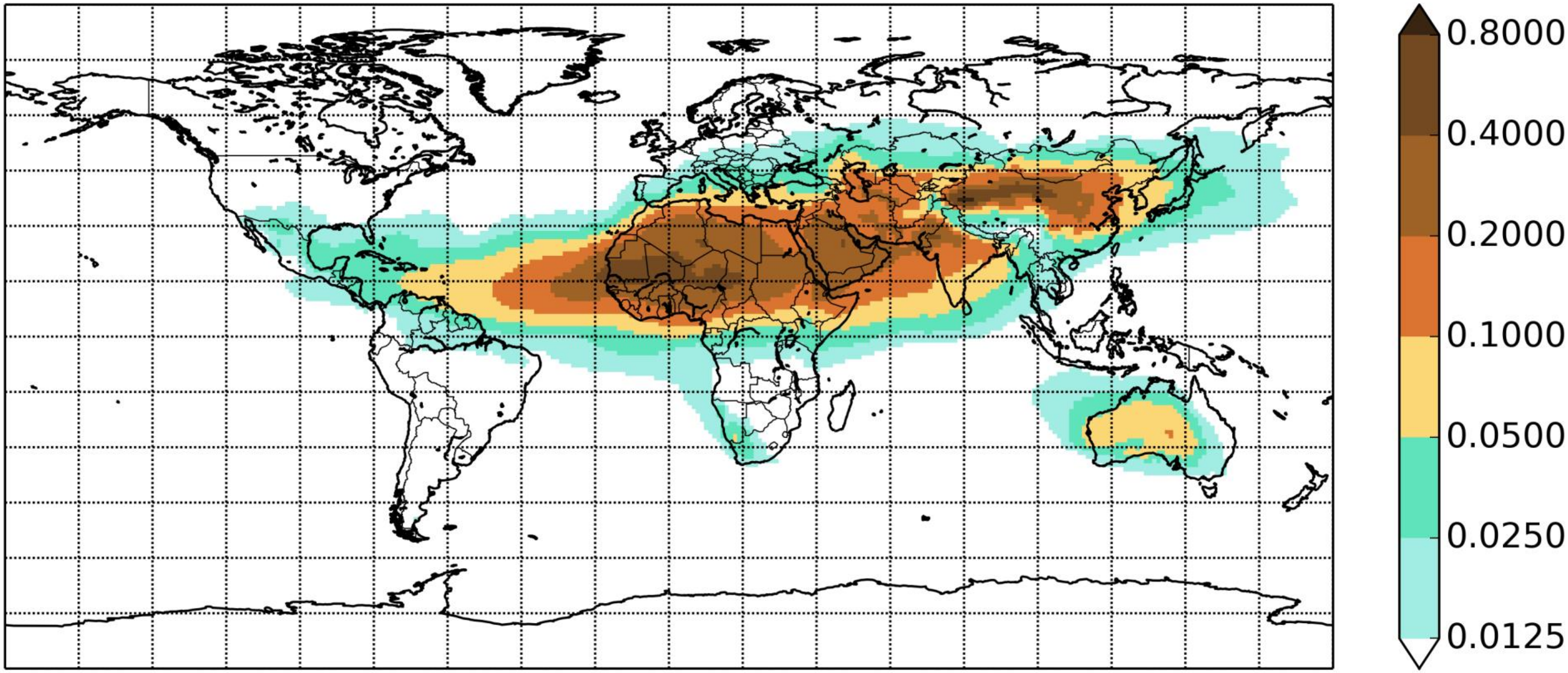




PM Ayia Marina, Cyprus, Mar 2012

Average distribution

Dust optical depth at 550 nm. Average value 2003-2015



Data: CAMS reanalysis
Picture: WMO SDS-WAS

WMO

Composition

MINERALOGICAL (X-ray diffractometry)

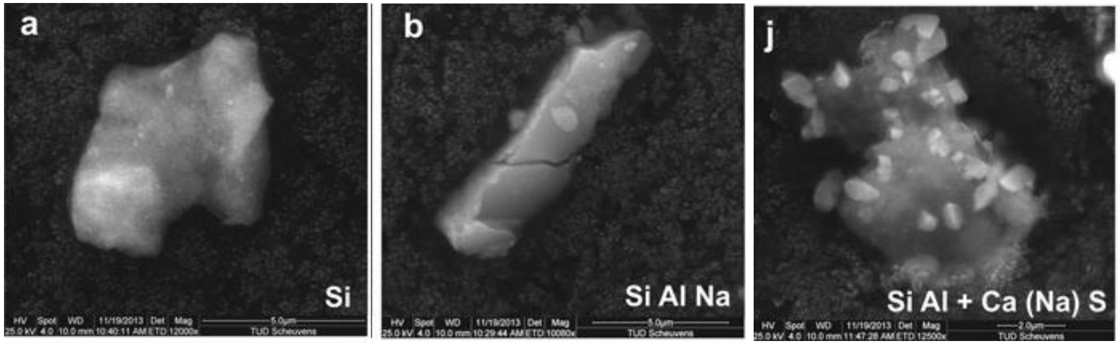
- Silicates: quartz, feldspar, phyllosilicates (ilite, kaolinite, smectite)
- Carbonates (calcite, dolomite)
- Hematite, gypsum, halite, …

ISOTOPICAL (Sr, Nd, Pb)

CHEMICAL (spectroscopy)

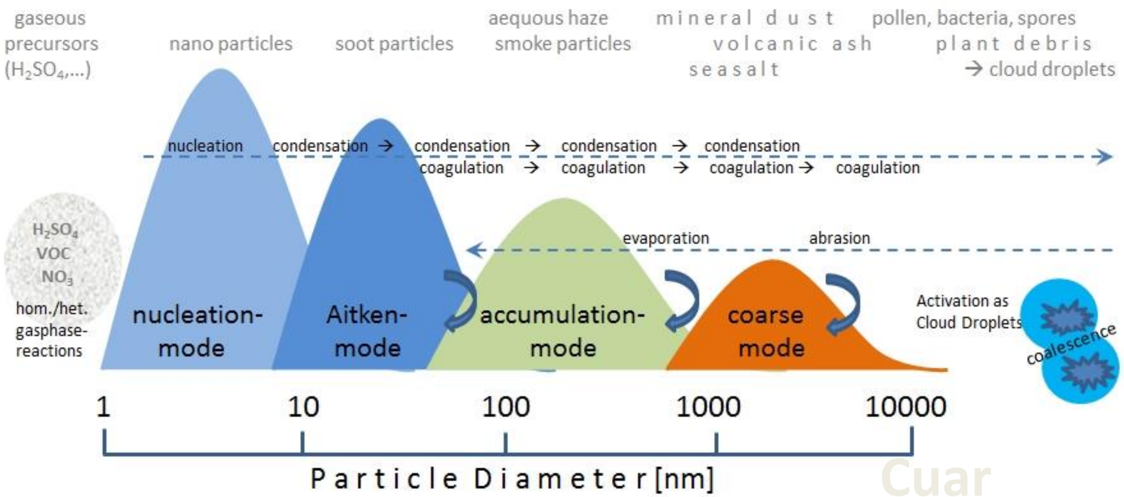
- Si, Al, Ca, Mg, Fe, K, Na, Mn, Ti, P

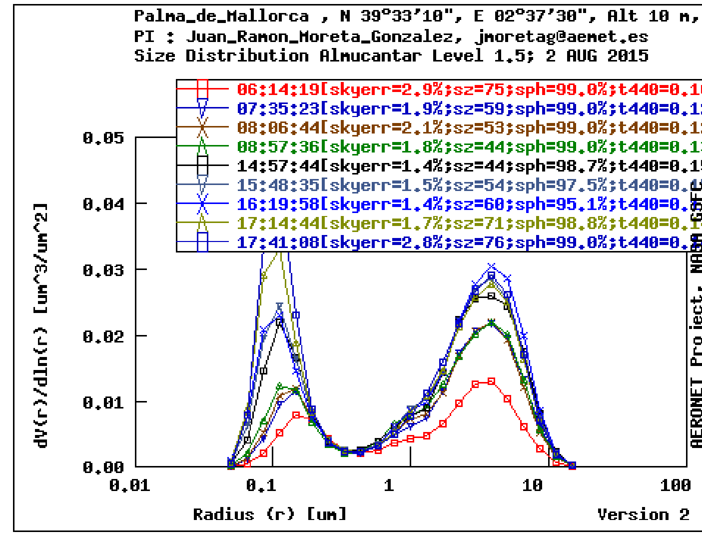
- Information about the source region
- Influence on optical properties
- Influence the impact on health, ecosystems, ...

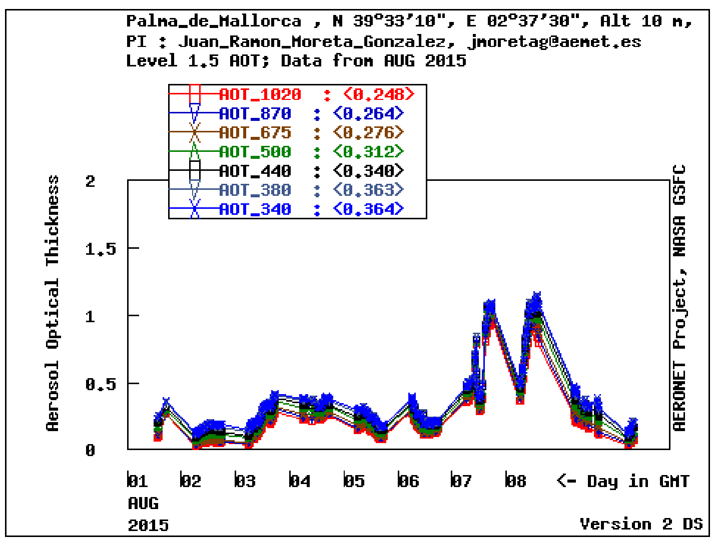


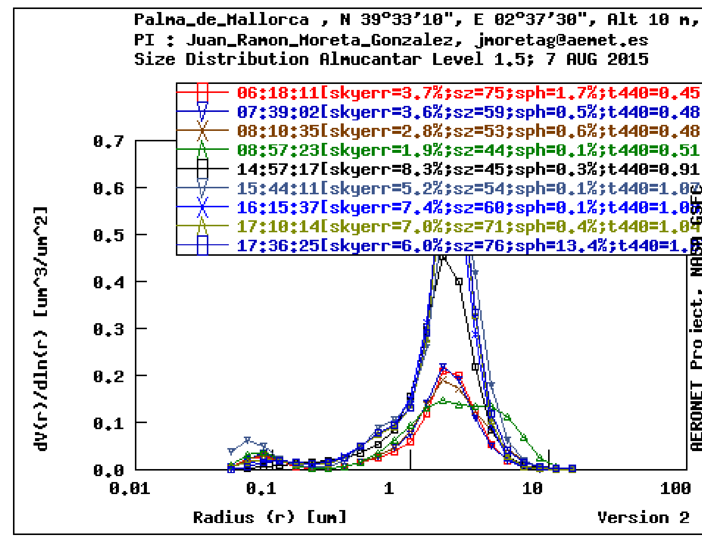
Quartz Albite Gypsum

Particle size







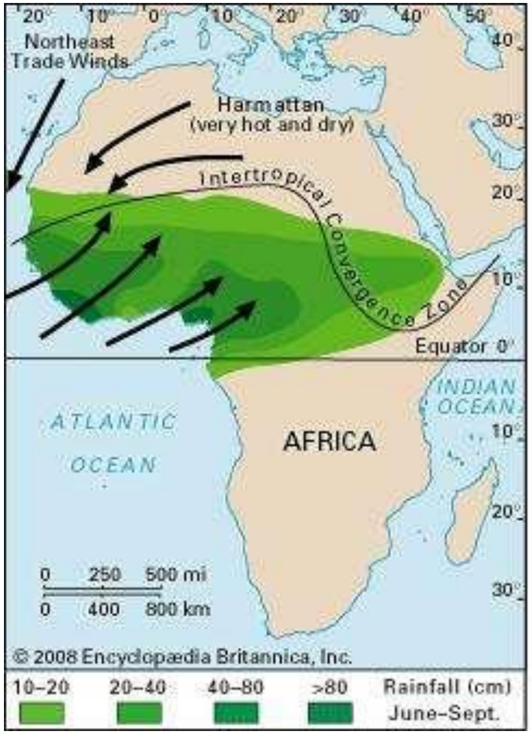


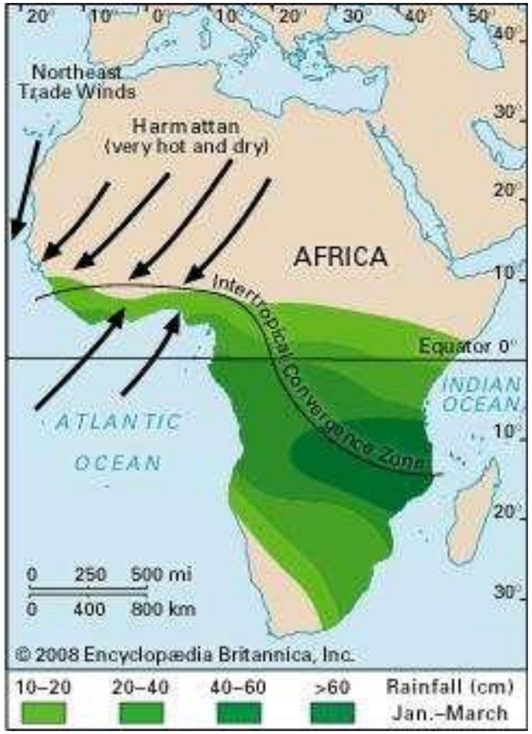
$$\tau = \ln\left(\frac{I_0}{I_1}\right)\cos(\theta)$$

AOD. Palma de Mallorca. Aug 2015

Palma de Mallorca 2 / 7 Aug 2015

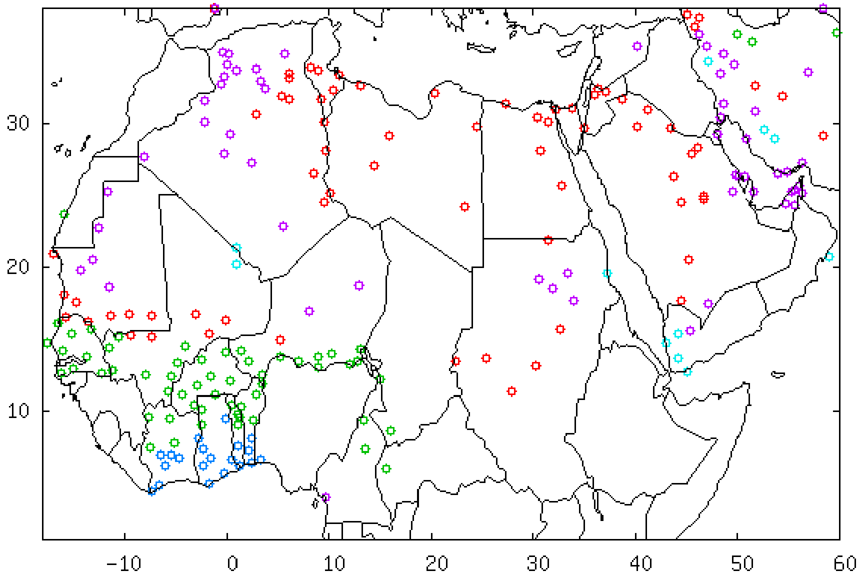
Seasonal variability



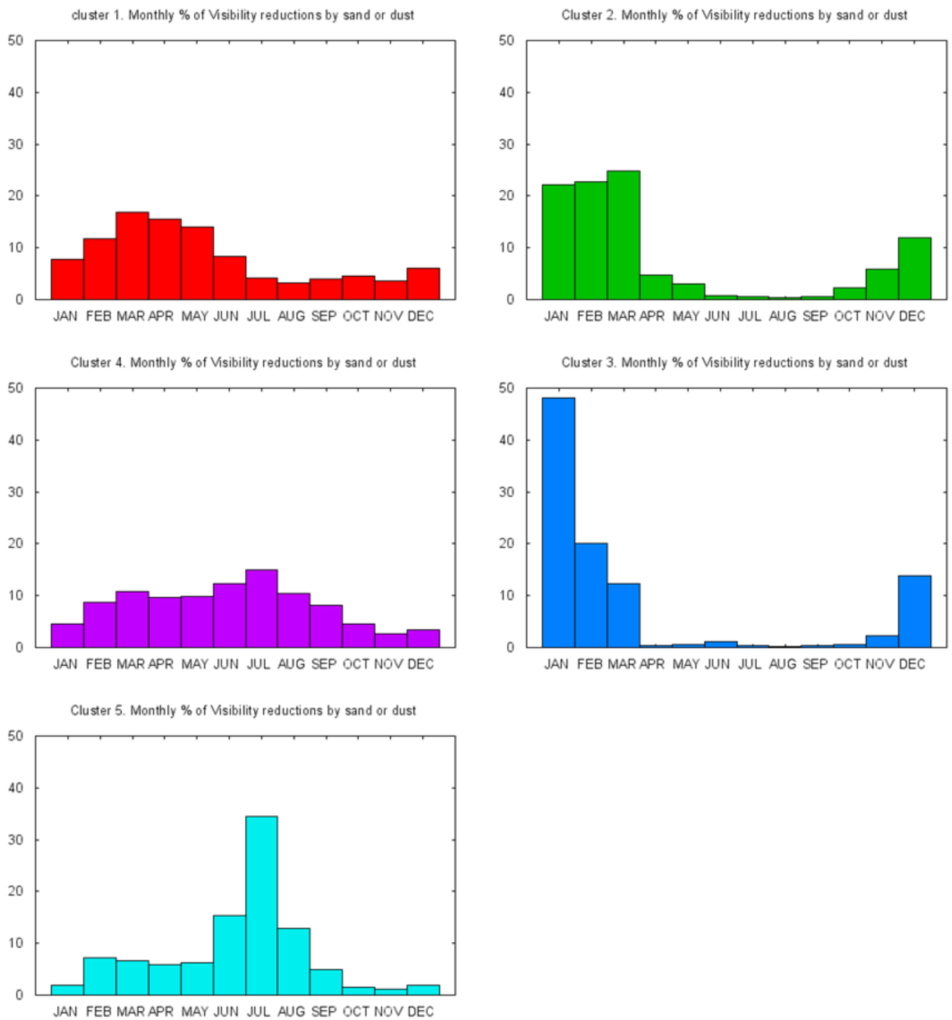


NH summer / winter

Seasonal variability



1996-2010



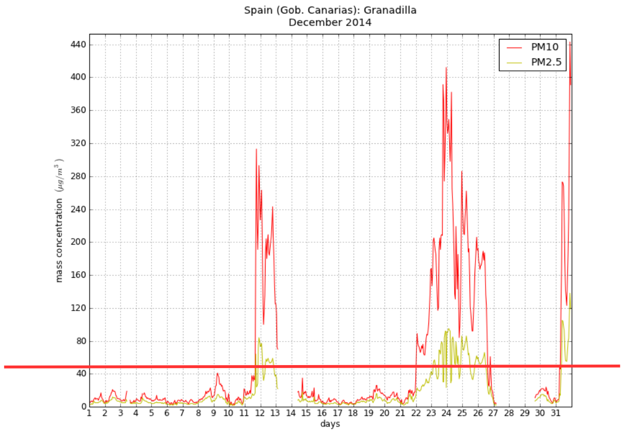
Terradellas et al. (2012)

Impacts

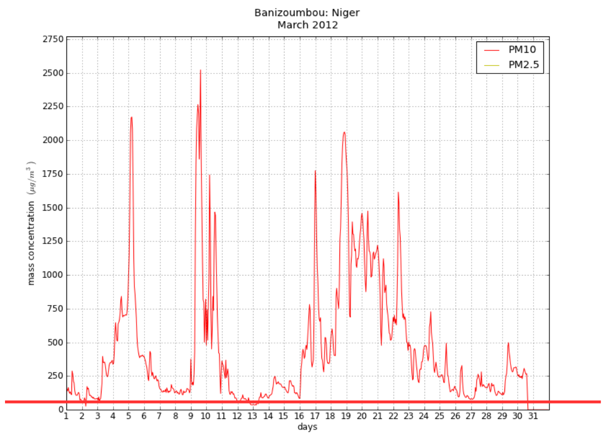
- Air quality and health
- Weather and climate
- Transportation (visibility reduction)
- Energy
- Agriculture, fisheries…

Impact on air quality

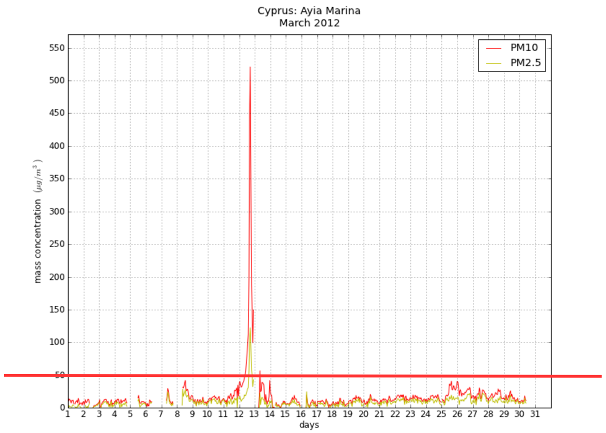
PM10	24-h avg.	50 µg/3	35 exceed.
	Year avg.	40 µg/m3	-
PM2.5	Year avg.	25 µg/m3	-



Granadilla, Spain
Dec 2014

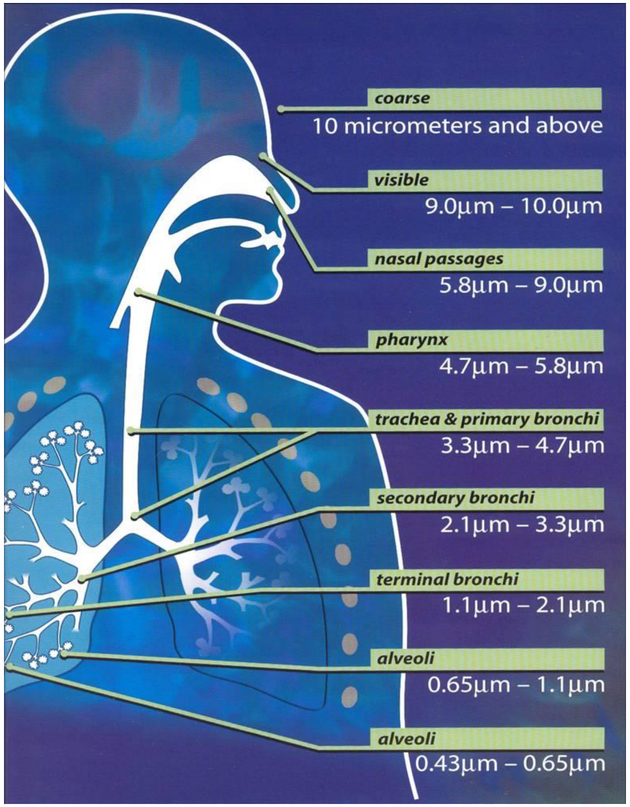


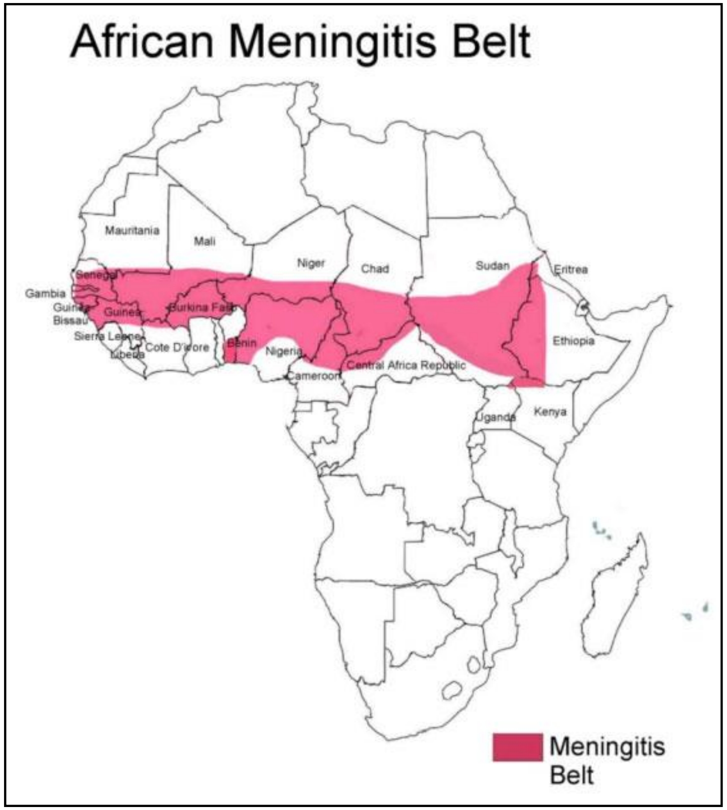
Banizoumbou, Niger
Mar 2012



Ayia Marina, Cyprus
Mar 2012

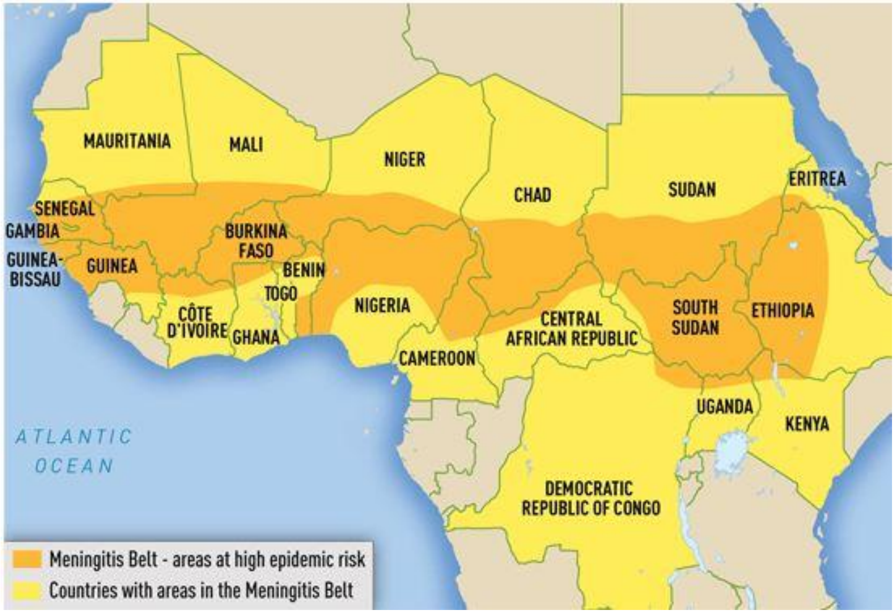
Health impact

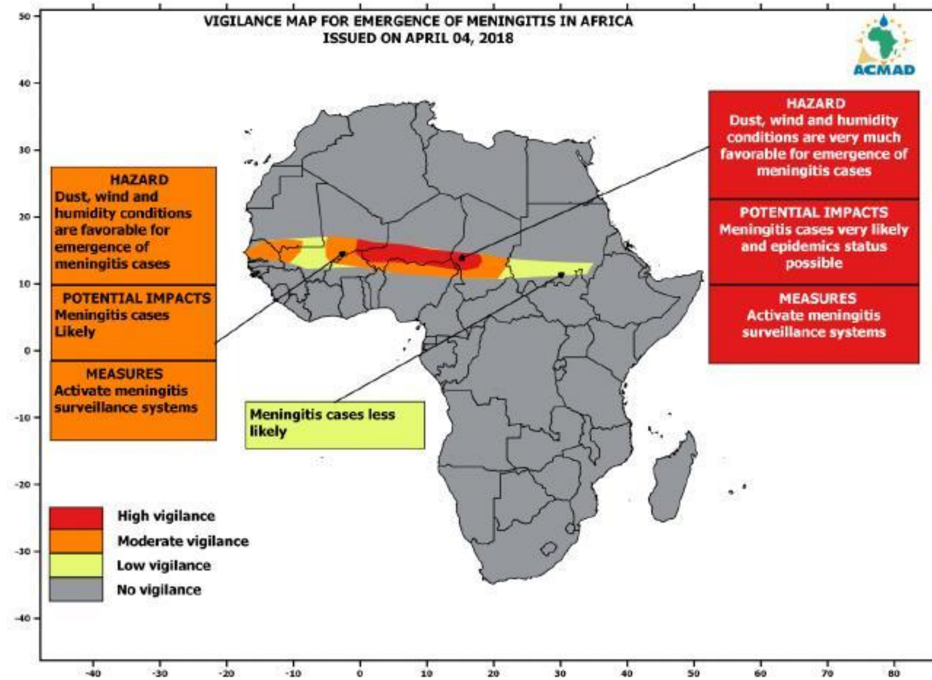


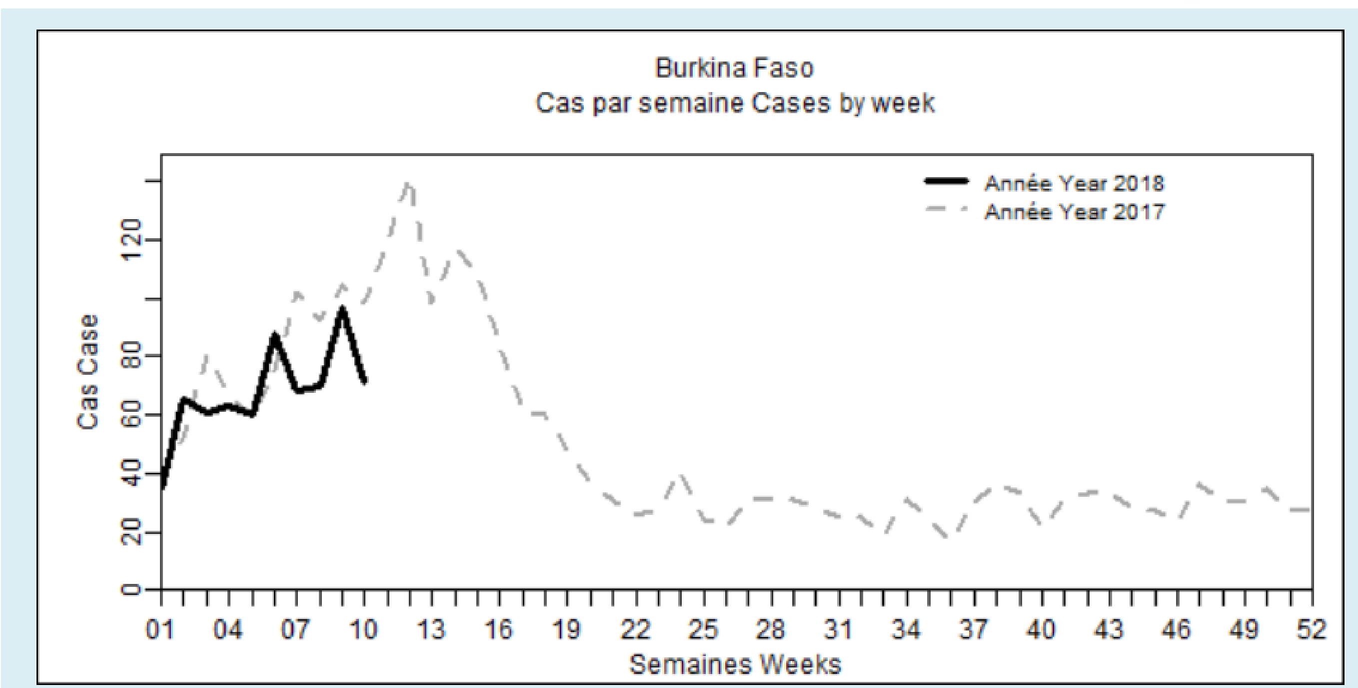


- Particle size
- Chemical and mineralogical composition
- Carrying bacteria, viruses, funghi, ...
- Time and intensity of exposure

Map 3-11. Areas with frequent epidemics of meningococcal meningitis



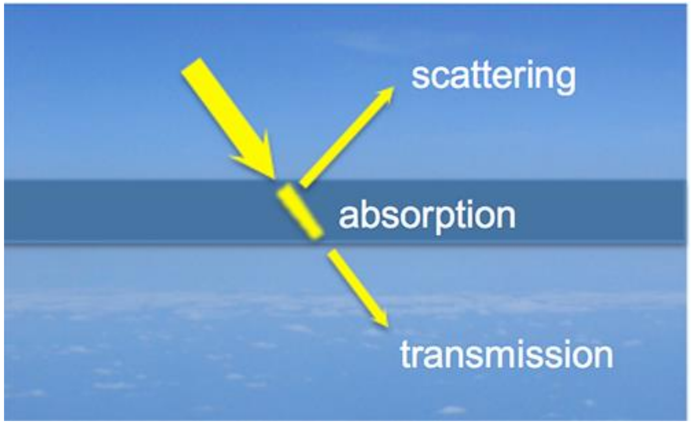


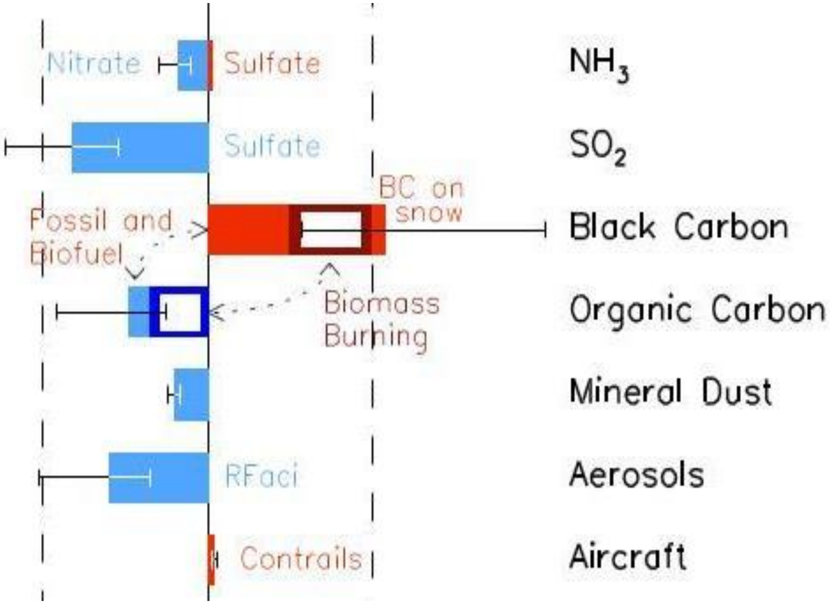


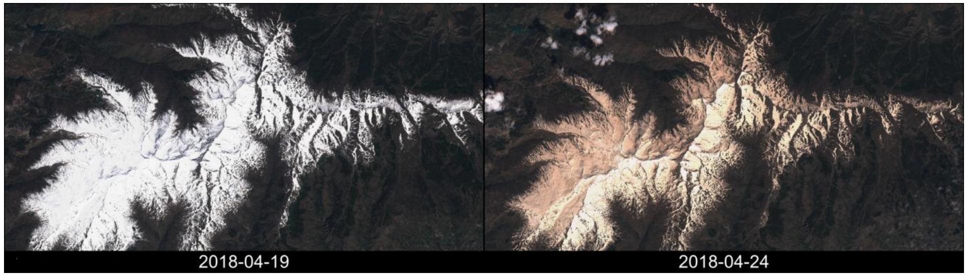
ACMAD

World Health Organization

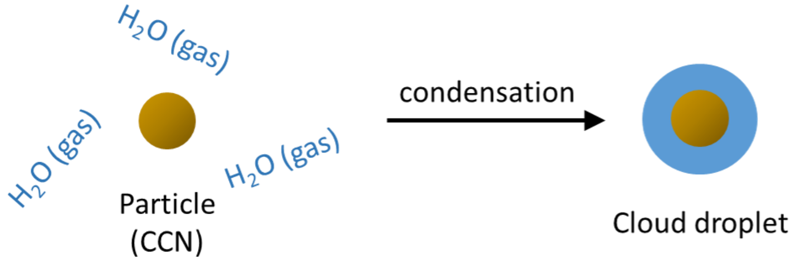
Impact on weather and climate

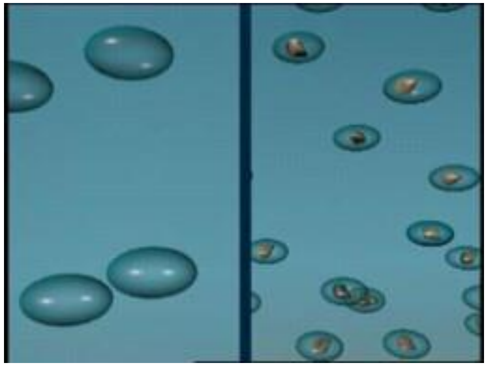




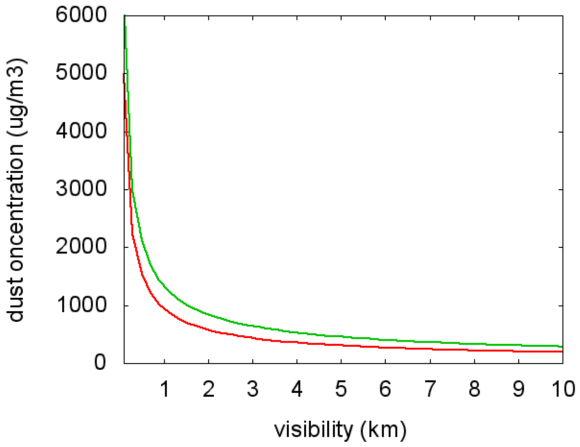


Sentinel-2 images of Sierra Nevada, Spain, on 19 and 24 April 2018





Impact on transportation

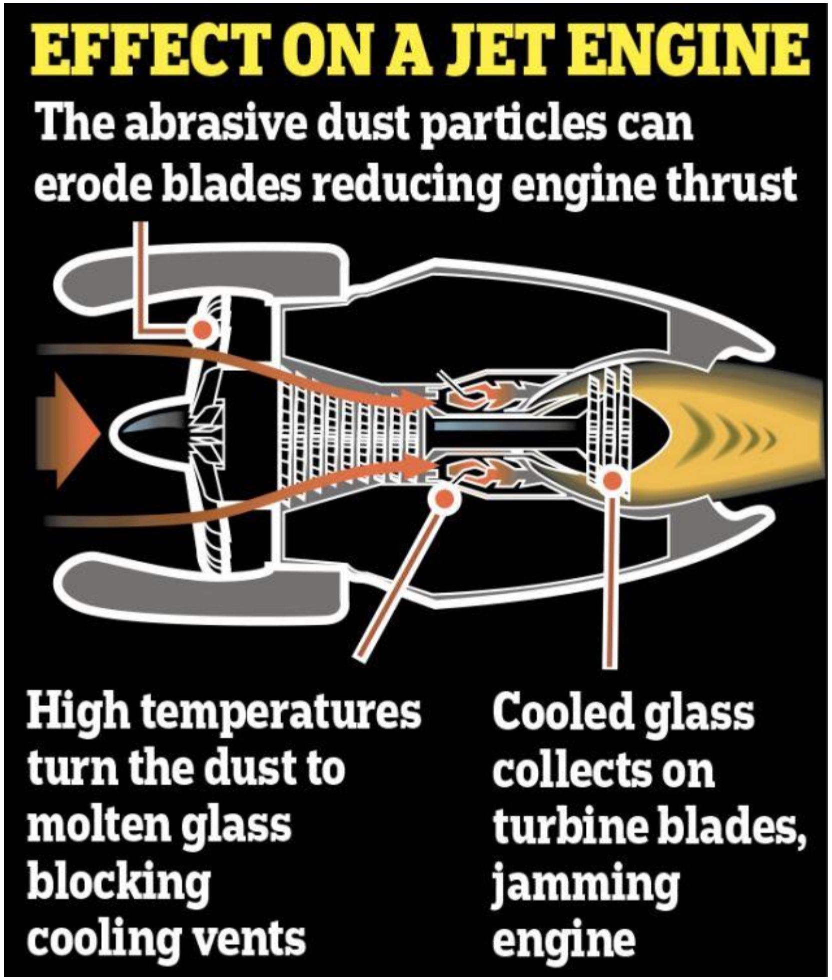


D’Almeida (1986)
Ben Mohamed et al. (1992)

Arizona, 29 Oct 2013

Tunis, 7 May 2002

Impact on transportation



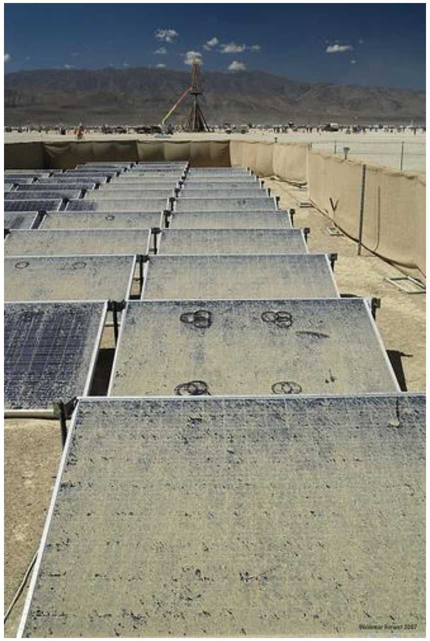
Volcanic ash is very dangerous for aviation because it melts at less than 1400º, the temperature at which the aircraft engines operate, and can cause flares.

Dust particles melt at about 1700º and do not cause such flares, but problems of erosion in the engine and on external surfaces of the aircraft.

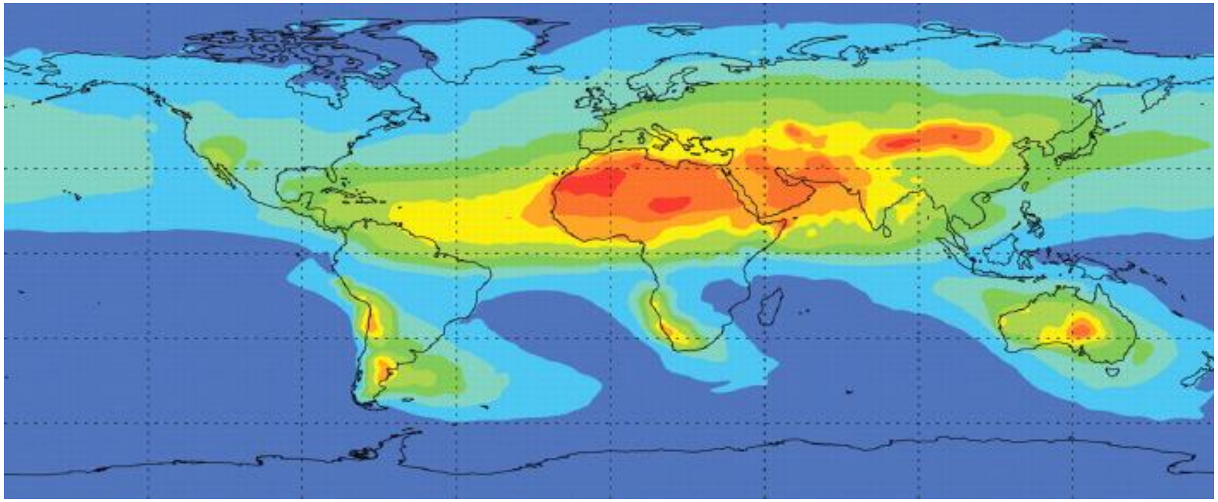
More frequent maintenance tasks

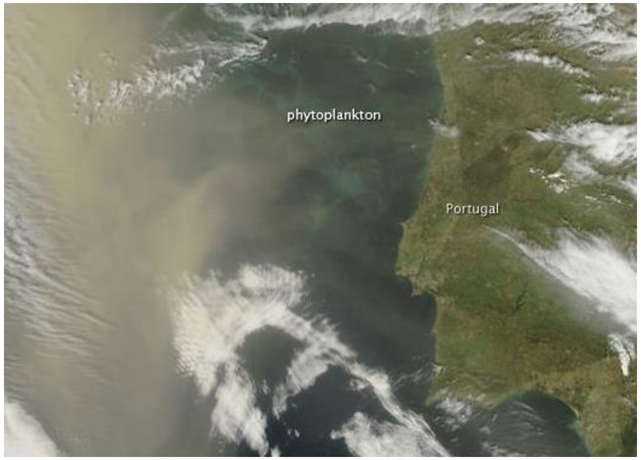
Solar energy

- Reduction of available energy
- Reduced efficiency due to dust deposition
- Impact on cloud formation



… also positive impacts





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

Summary

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

WMO SDS-WAS

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 (??)

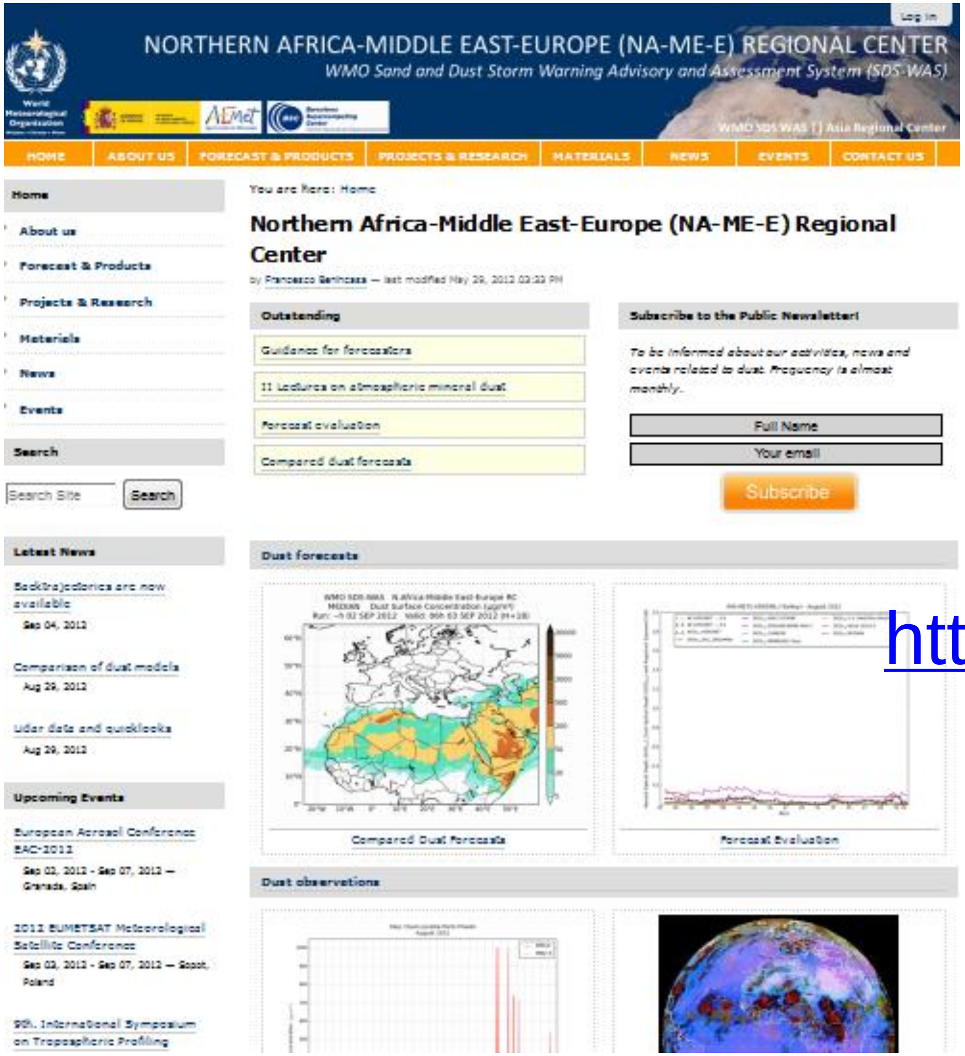
SDS-WAS Regional Center NAMEE

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

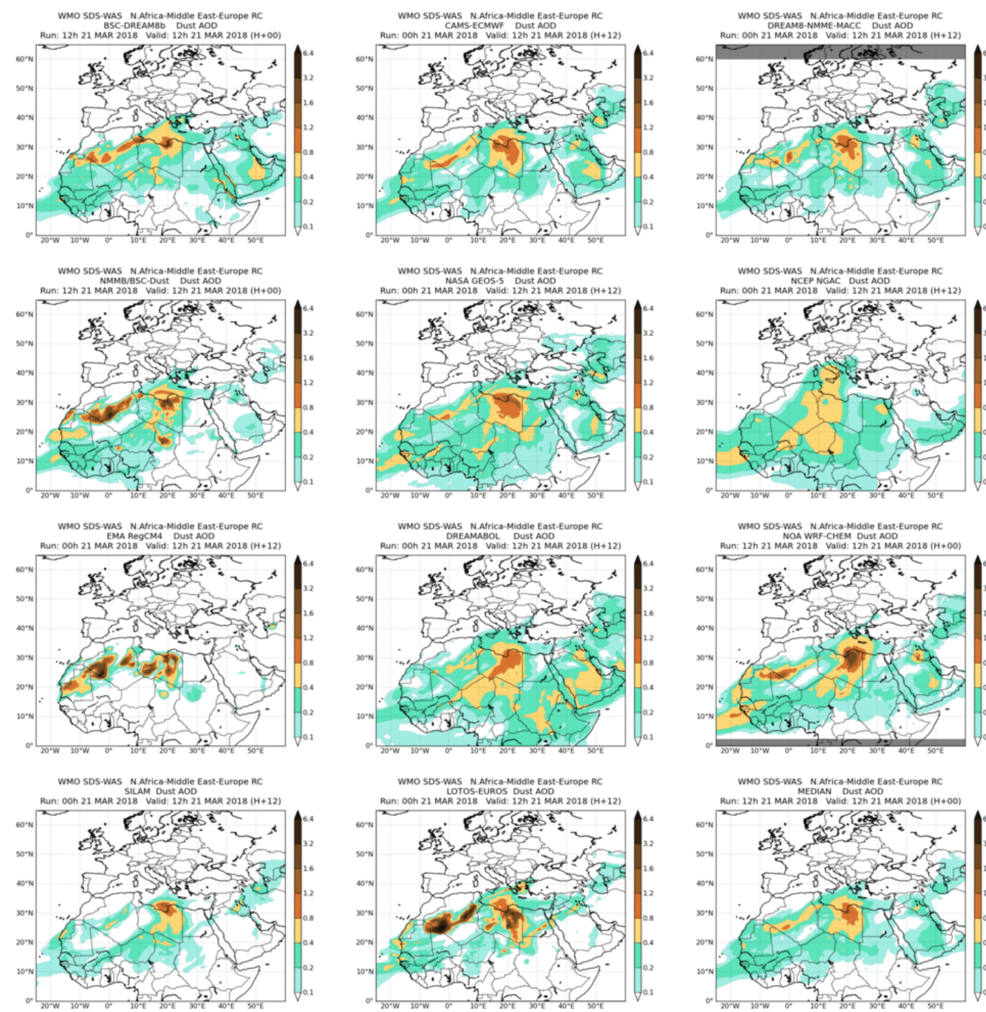


https://sds-was.aemet.es

sdswas@aemet.es

Forecast intercomparison

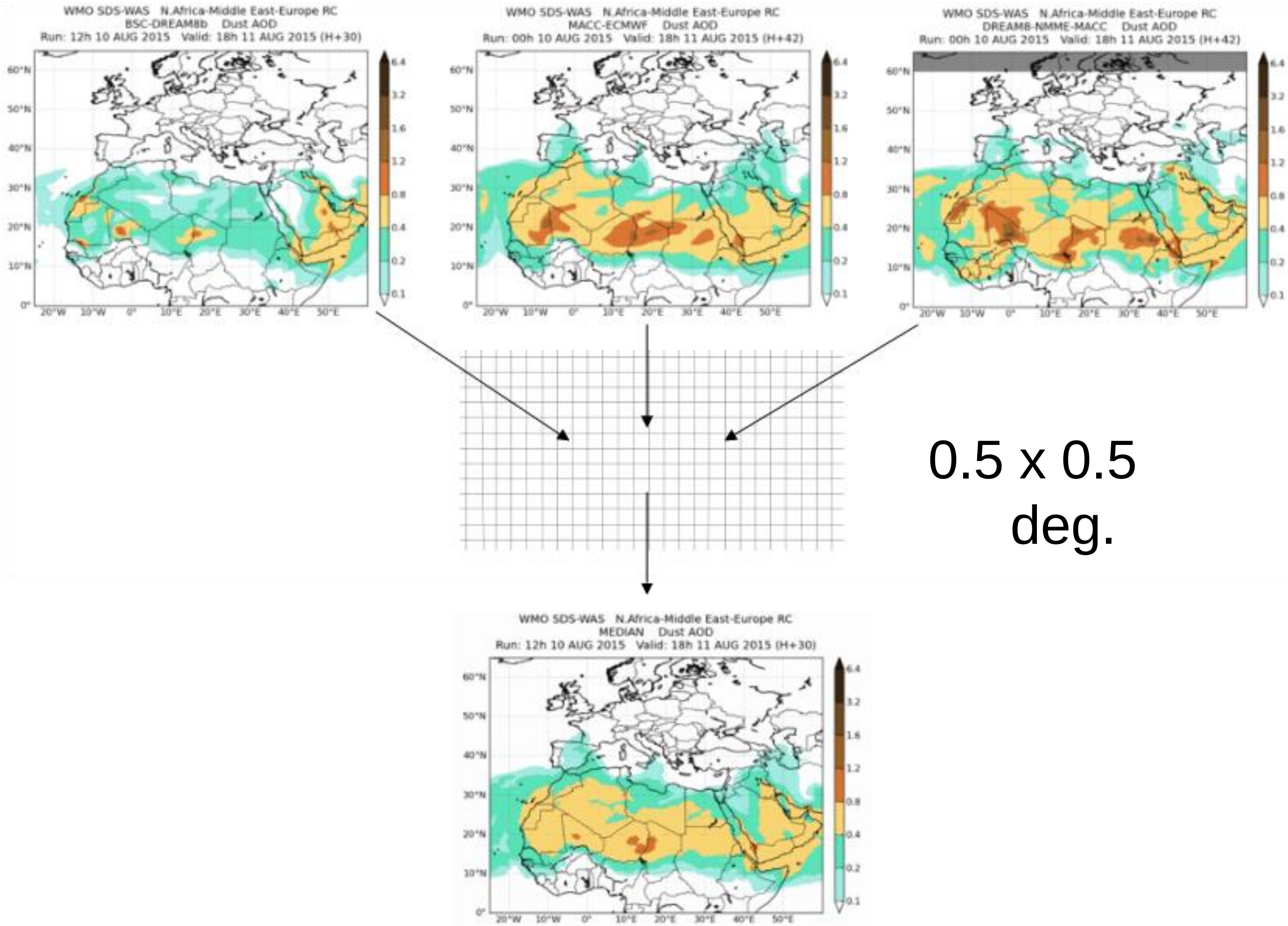
MODEL	INSTITUTION	DOMAIN
BSC-DREAM8b	BSC	Regional
CAMS	ECMWF	Global
DREAM-NMME-MACC	SEEVCCC	Regional
NMMB/BSC-Dust	BSC	Regional
MetUM	Met Office	Global
GEOS-5	NASA	Global
NGAC	NCEP	Global
RegCM4	EMA	Regional
DREAMABOL	CNR	Regional
NOA WRF-CHEM	NOA	Regional
SILAM	FMI	Regional
LOTOS-EUROS	TNO	Regional



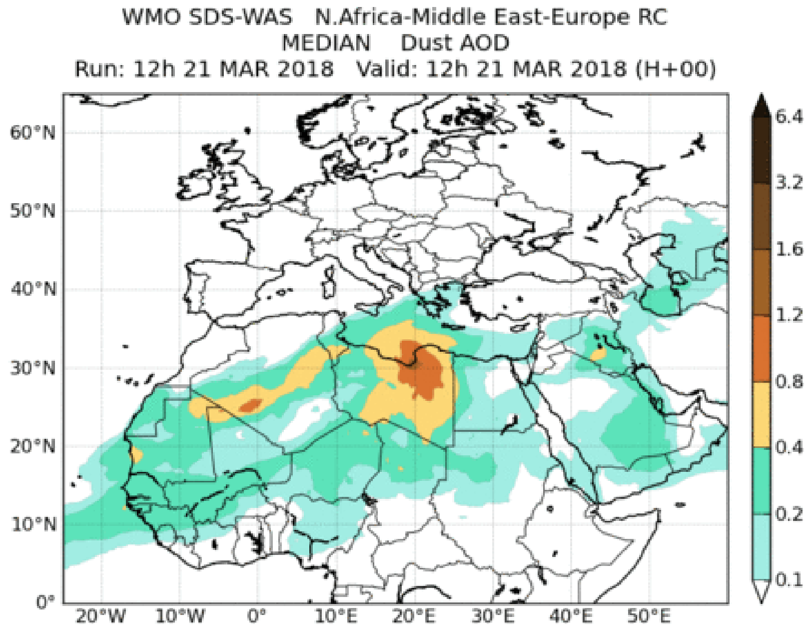
Forecasts of dust surface concentration and optical depth at 550 nm until 72 hours

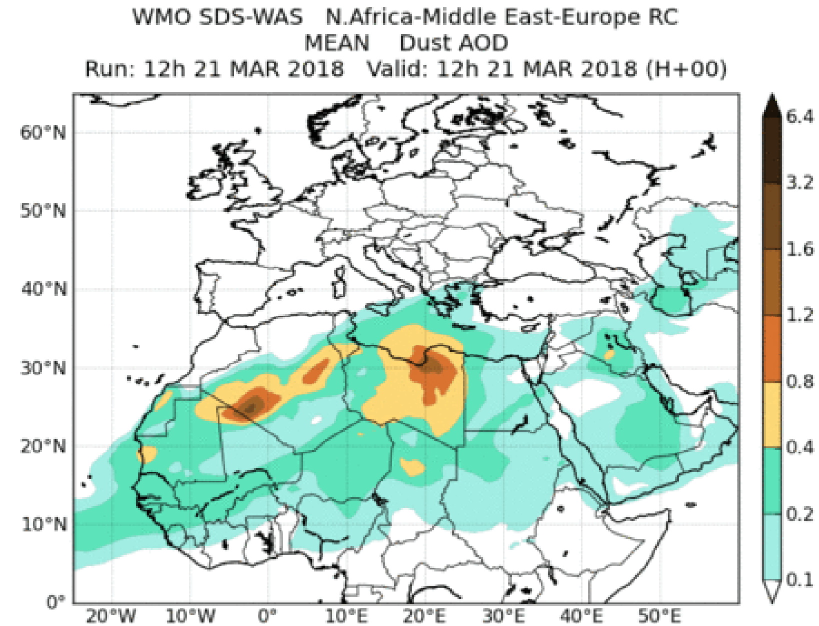
21 Mar 2018

Multi-model ensemble



Multi-model ensemble





- Forecasts of 12 models are daily interpolated to a common grid mesh. Then ensemble multi-model products are generated.
- Multi-model median yields better verification scores than any individual model

21 Mar 2018

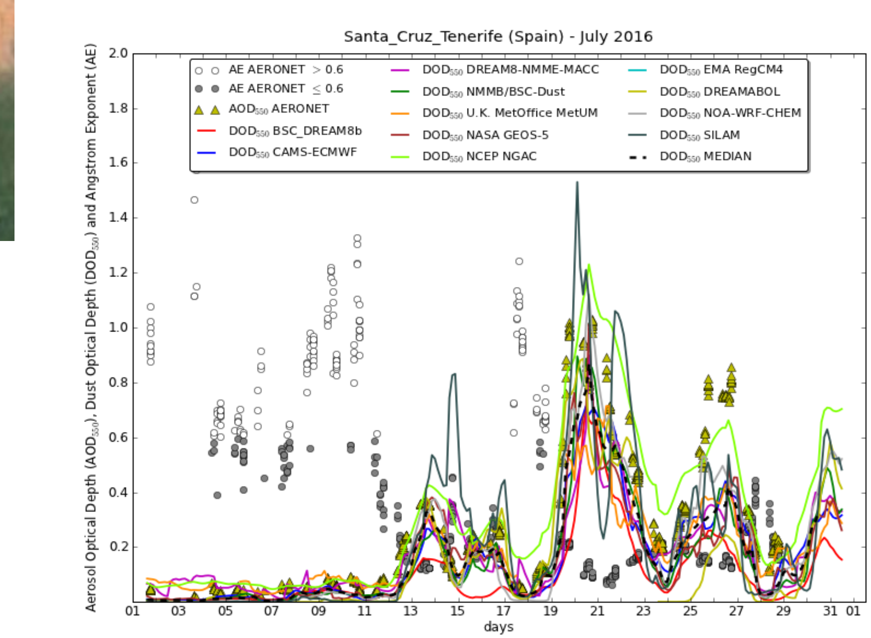
GOBIERNO DE ESPAÑA MINISTERIO DE AGRICULTURA Y PESCA, ALIMENTACIÓN Y MEDIO AMBIENTE

AEMet Agencia Estatal de Meteorología

BSC Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Verification

Santa Cruz de Tenerife
July 2016

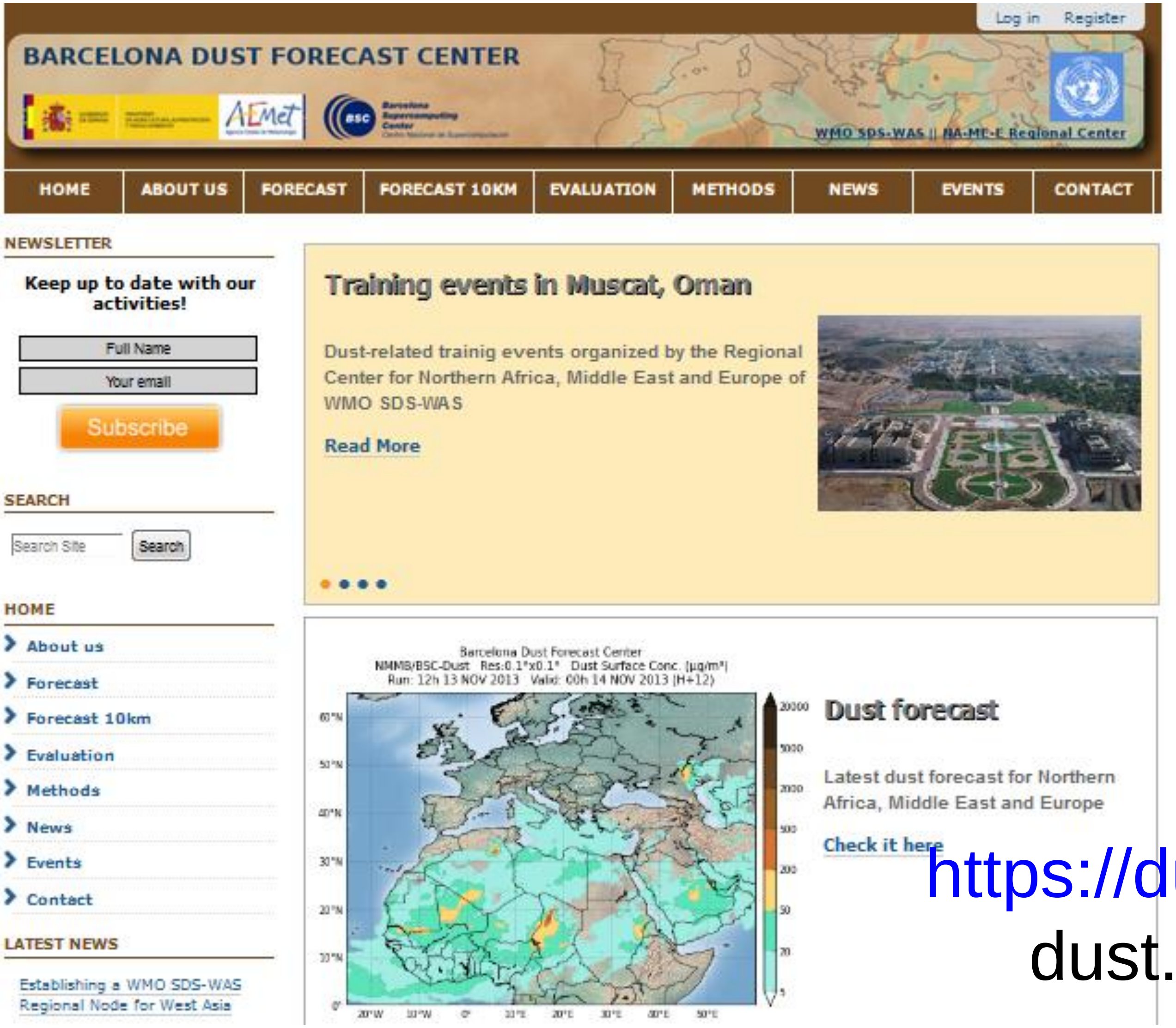


Capacity building

TRAINING

Accra
Addis-Ababa
Ahvaz
Ankara
Antalya
Barcelona
Cairo
Casablanca
Istanbul
Madrid
Muscat
Niamey
Ouagadougou
La Laguna
Tehran
Tbilisi

Barcelona Dust Forecast Center



https://dust.aemet.es

dust.aemet.es

Summary

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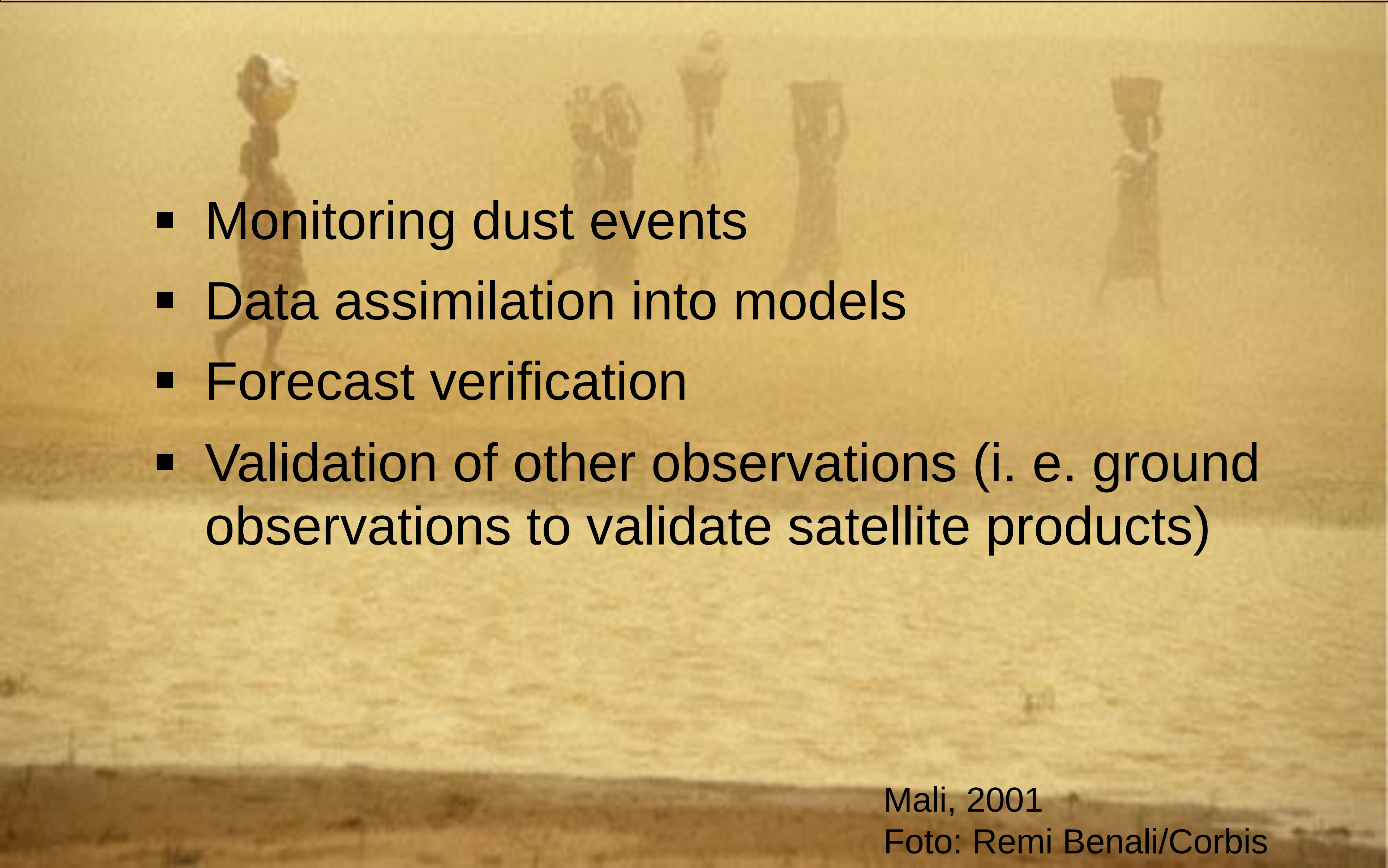
- Dust forecast

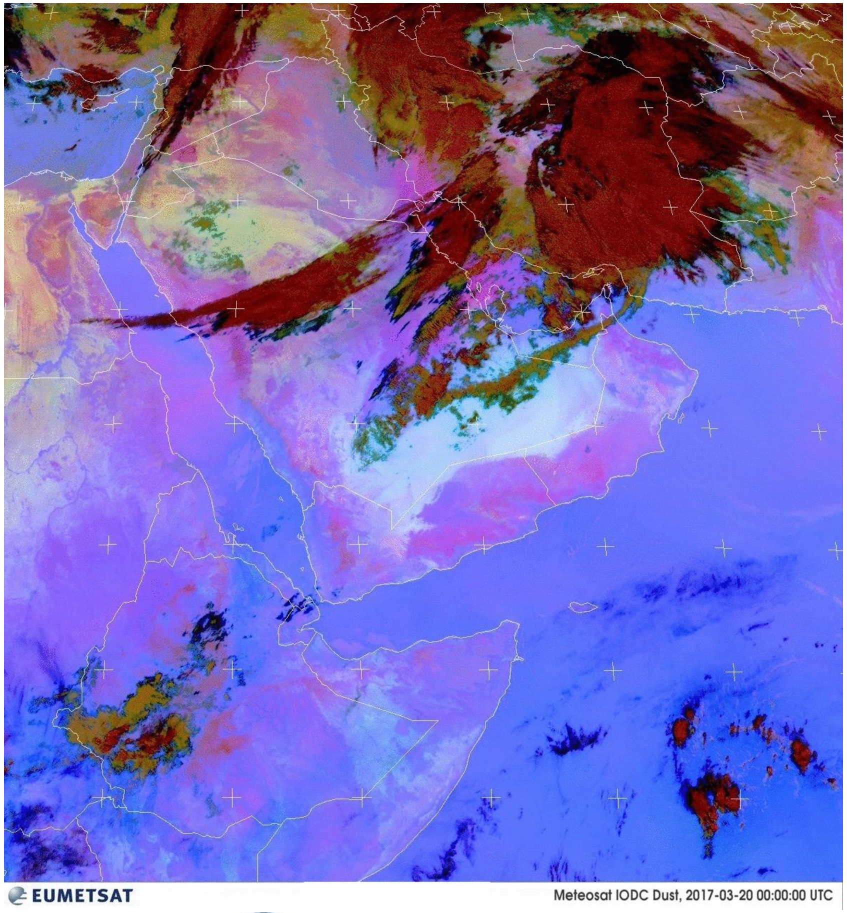
Why do we need dust observation?

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



Mali, 2001
Foto: Remi Benali/Corbis

Monitoring: satellite products



EUMETSAT

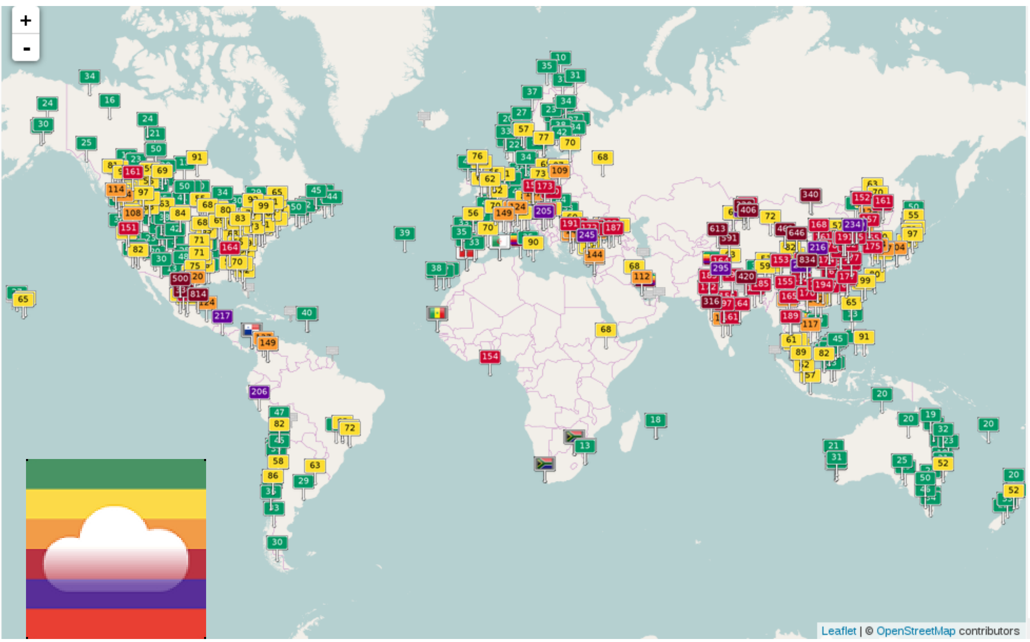
19 Mar 2017: The sandstorm named Madar, originated in Libya, swept through Egypt, Saudi Arabia, Iraq, Kuwait and Iran

- 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

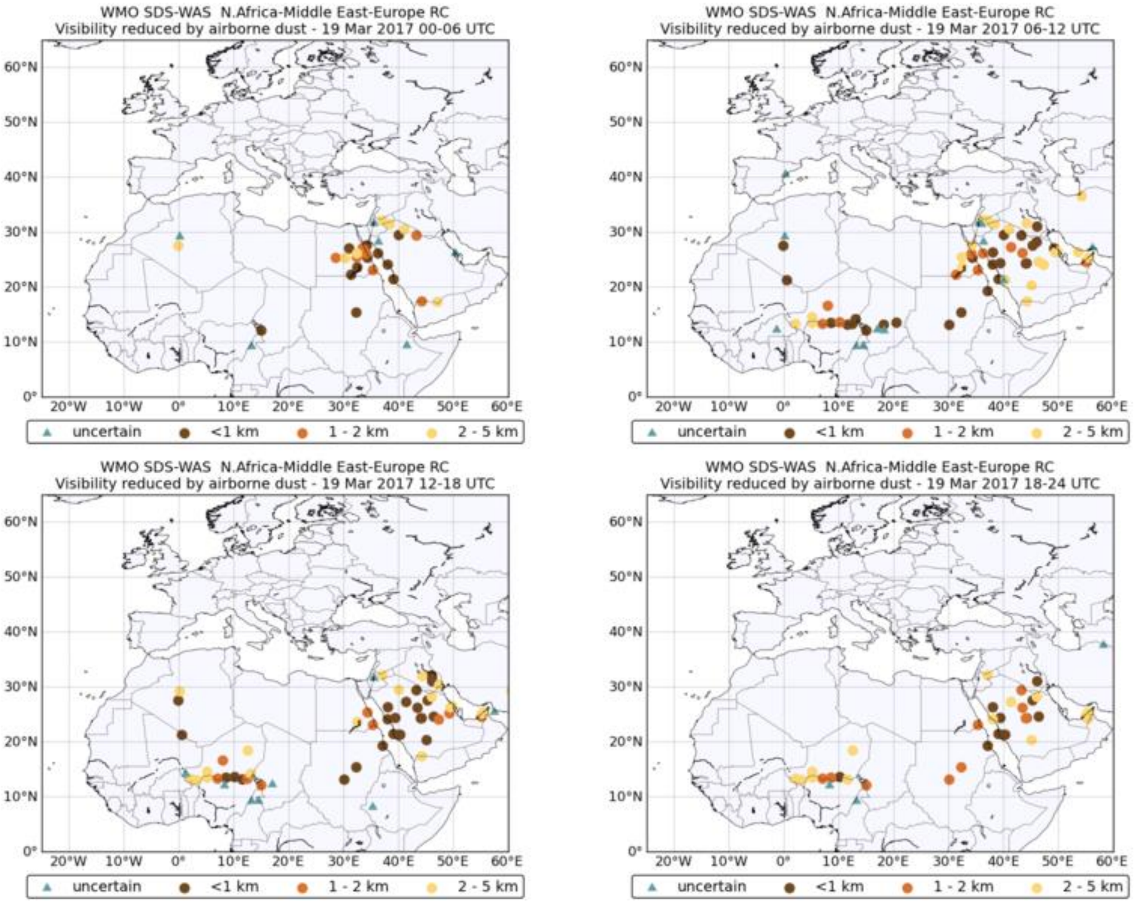
Air-quality monitoring stations



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

Visibility from meteorological reports



19 Mar 2017

Drawbacks:

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

https://sds-was.aemet.es

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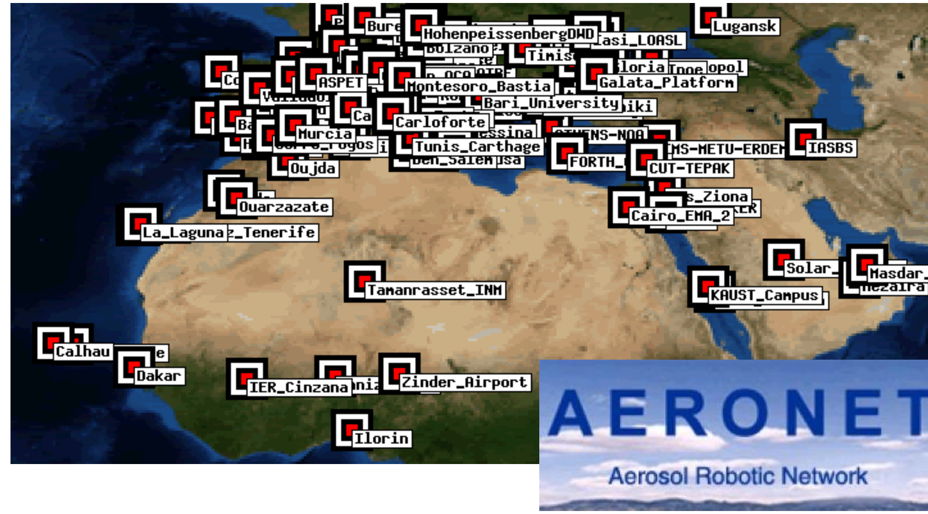
AEMet Agencia Estatal de Meteorología
Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Sun photometers

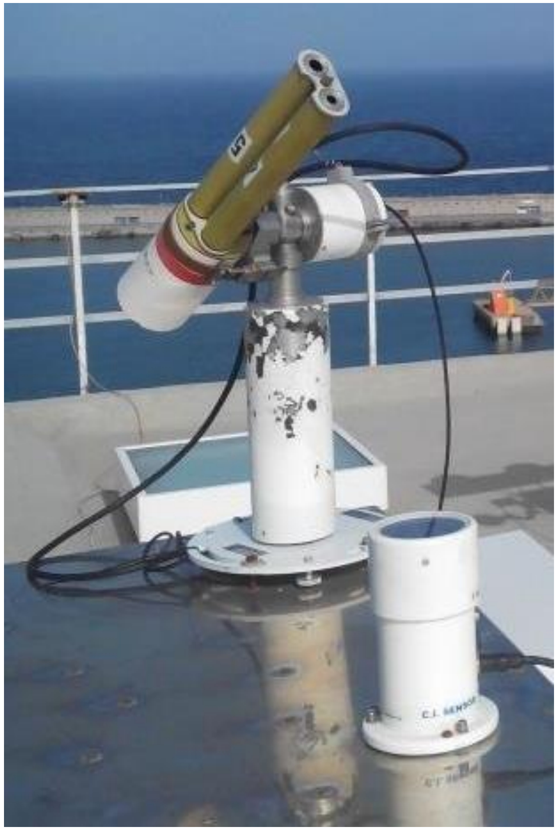


- Solar radiation at the top of the atmosphere is known
- Airborne particles attenuate the direct radiation (absorption, scattering)
- The sun-photometers measure the direct radiation that reach the surface
- Measurement at different wavelengths allows retrieval of total aerosol contents and some of its properties (e. g. size spectrum)

Drawbacks:

- Few stations close to the dust sources
- No retrievals in cloudy conditions
- Integration of all aerosol species

Low-cost instruments



ZEN R41
Stand alone
Robust
Low cost
Low maintenance
(Almansa et al., 2017)

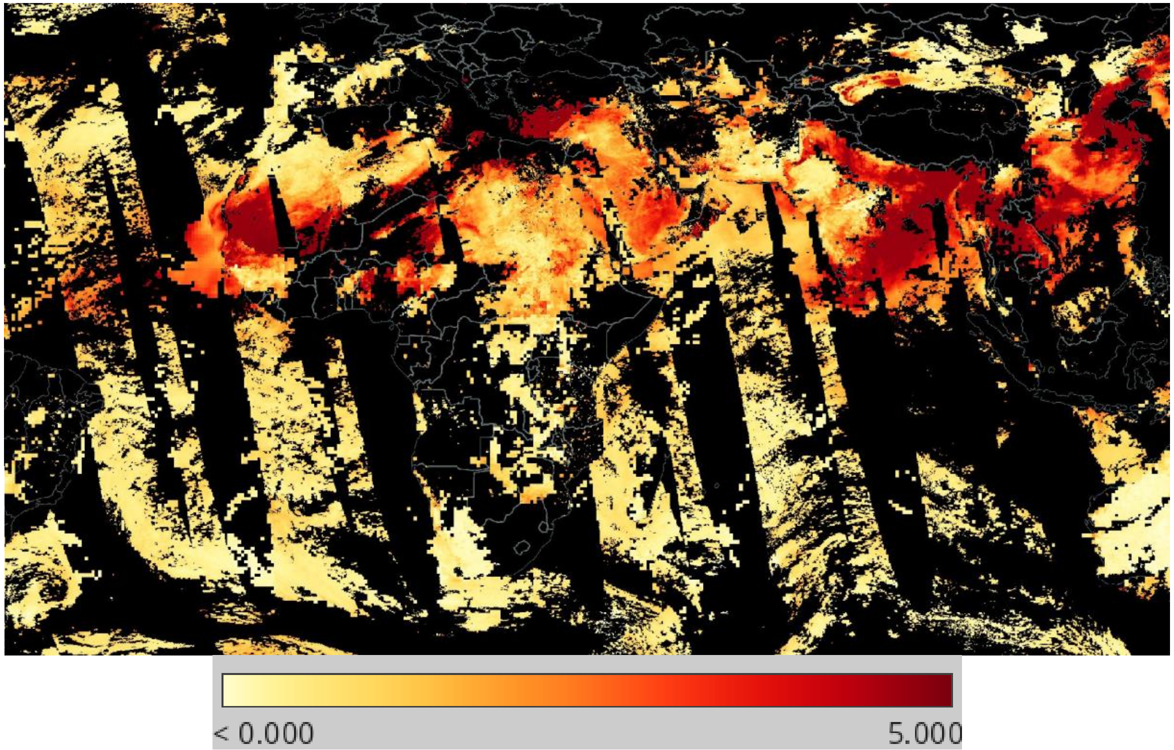
CALITOO

AEMet
Agencia Estatal de Meteorología

THE GLOBE PROGRAM
Comunidad virtual de la Red Canaria de Centros GLOBE

Satellite retrievals of AOD

MODIS AOD (DT+DB)
22 Mar 2018

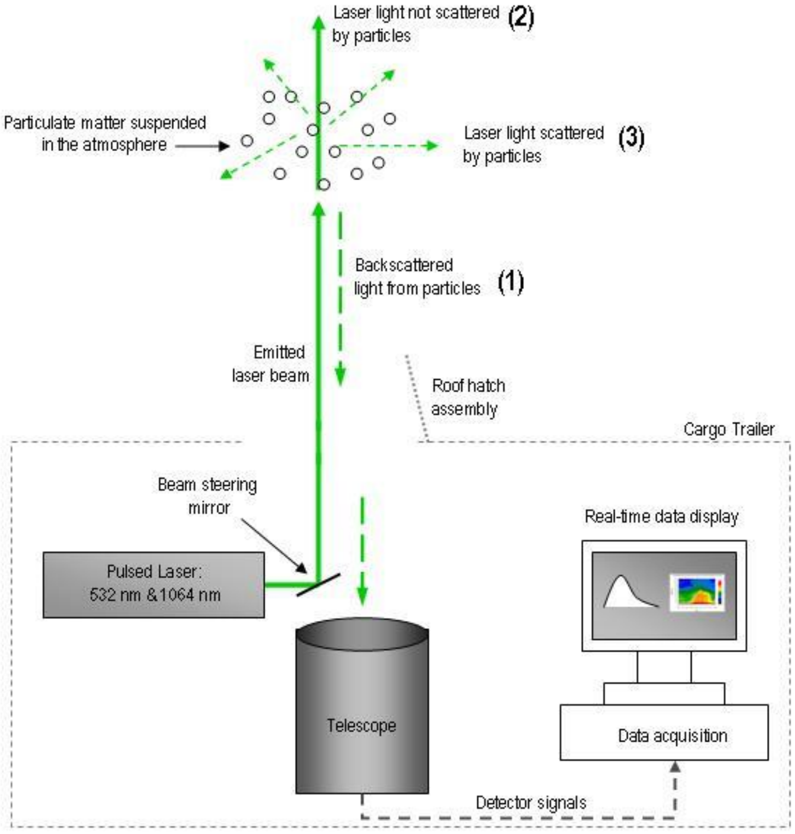


MODIS fly onboard Terra and Aqua in near-polar sun-synchronous orbits.

Drawbacks:

- Without information from cloudy areas
- Poor information from areas with relatively large viewing angles
- Poor time resolution
- Vertical and species integration

Lidar - ceilometer



University of British Columbia

- Lidar systems retrieve vertical profiles of aerosol optical properties. They measure backscatter and need the lidar ratio to obtain extinction profiles. Further hypotheses to get mass profiles.
- Depolarization ratio provides information on sphericity
- Raman lidars provide better estimations of extinction
- Space borne CALIOP (CALIPSO satellite) and CATS (ISS)
- Ceilometer (more robust and less expensive) can potentially be installed in remote sites

Drawbacks:

- Expensive equipment
- Few systems close to the sources

Summary

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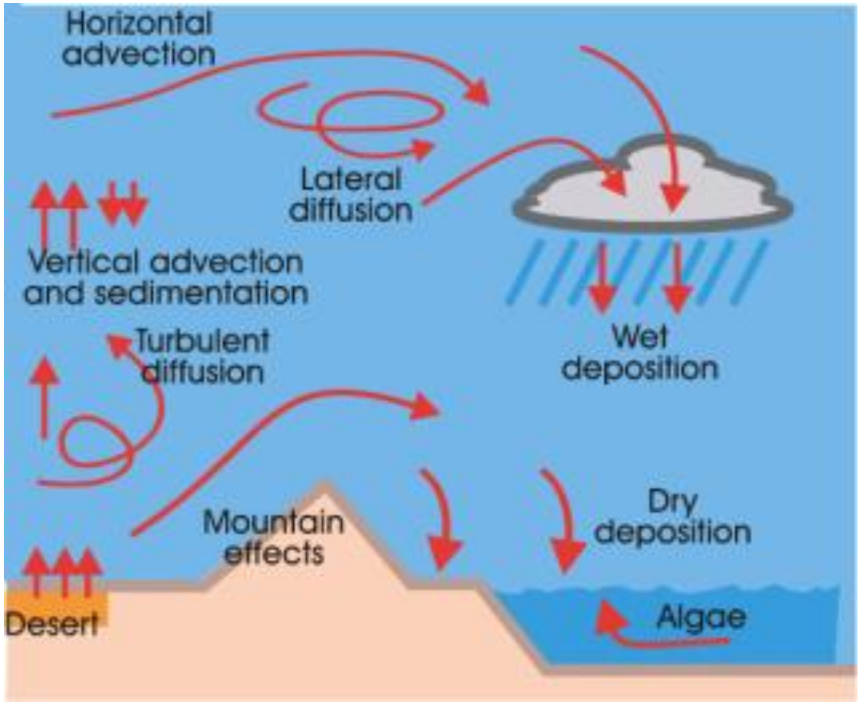
Dust prediction models

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



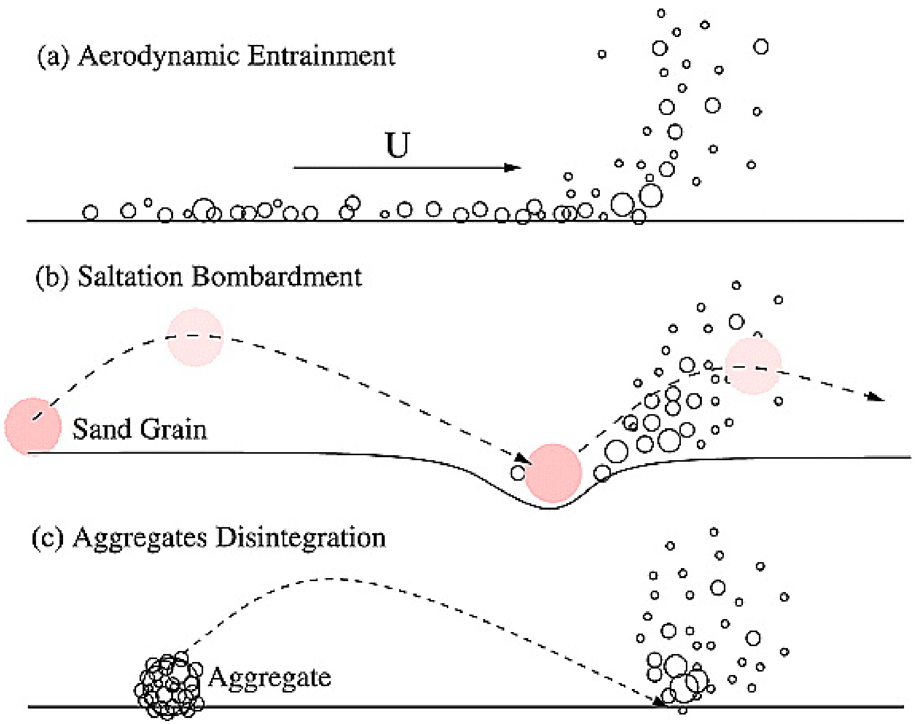
- Emission
- Transport (diffusion, convection, advection)
- Dry / wet deposition

- Interaction with radiation
- Interaction with cloud droplets
- Ice nucleation
- Atmospheric chemistry
- …

Dust models. Main problems

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

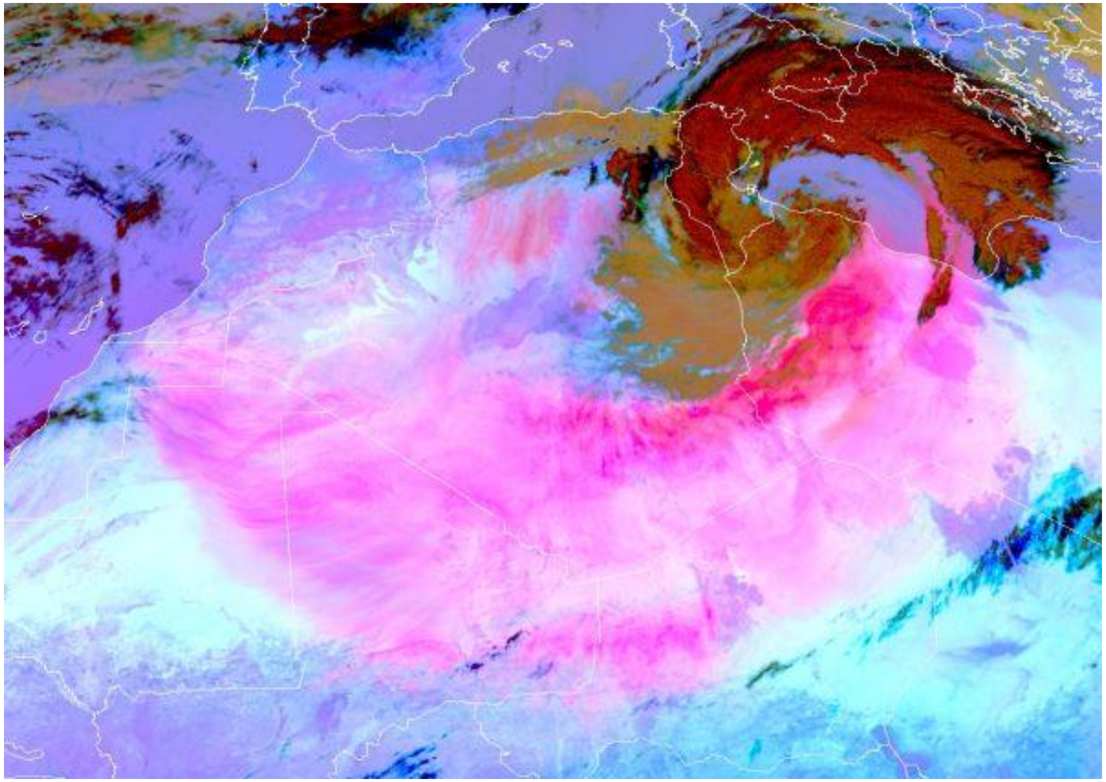
Incomplete knowledge of physical processes



Shao et al. (2011)

- 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.

Processes of diverse scale



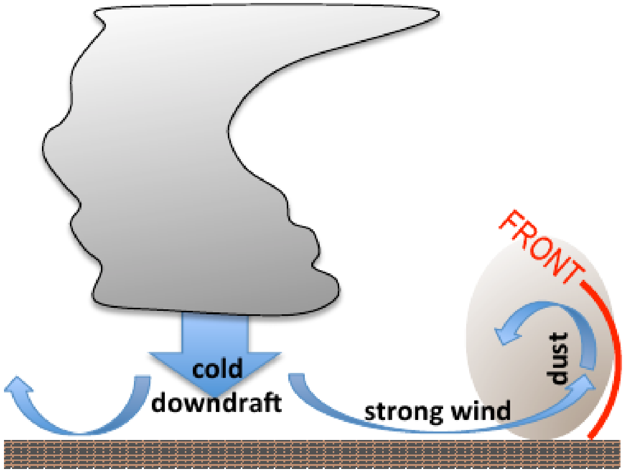
State-of-the-art models are able to predict synoptic-scale or meso-alfa scale dust events, but they suffer when emission happens at smaller scales (meso-gamma and microscale)

Incomplete information on soil state and nature

Tehran haboob, 2nd June 2014 – Ana Vukovic

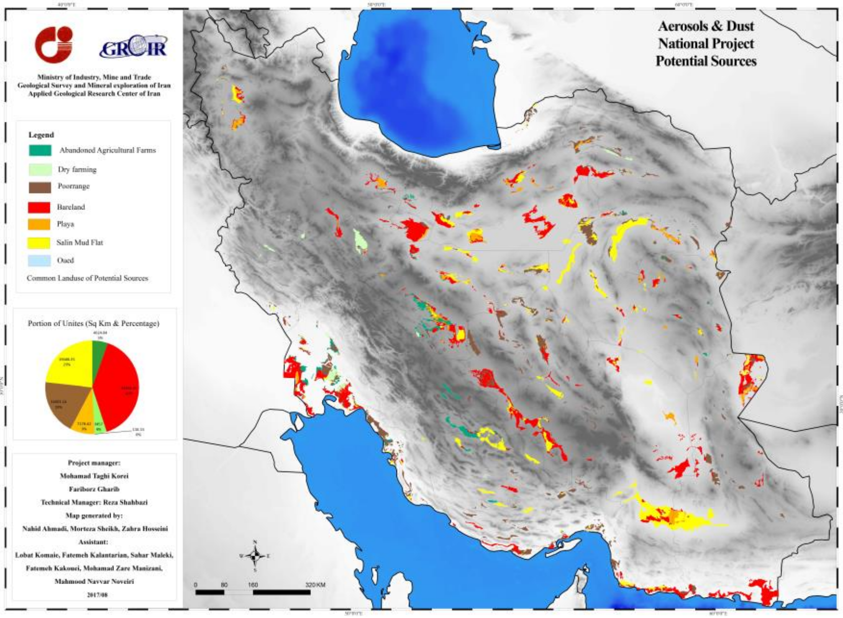
RHMSS

SEEVCCC



Better information on dust sources provided by the Applied Geological Research Center of Iran significantly improves the forecast.

Potential dust sources include abandoned agricultural fields, dry farming lands, bareland, playas, ...



Need for a very accurate wind forecast

Tegen et al. (1994) $$F = \sum_i C_i u^2 (u - 6.5)$$

Marticorena et al. (1997) $$F = \propto \frac{\rho}{g} u_*^3 \sum_i s_i \left(1 + \frac{u_{*tri}}{u_*}\right)\left(1 - \frac{u_{*tri}^2}{u_*^2}\right)$$

Ginoux et al. (2001) $$F = CS \sum_i u^2 s_i w_0 (u - u_{tri})$$

Different parameterizations agree taht dust emission is proportional to the third power of wind speed