The dust cycle in the atmosphere

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MINISTERIO DE AGRICULTURA Y PESCA, ALIMENTACIÓN Y MEDIO AMBIENTE
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6th Training Course on WMO SDS-WAS products, Istanbul, Turkey, 25-27 Oct 2017

Summary

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

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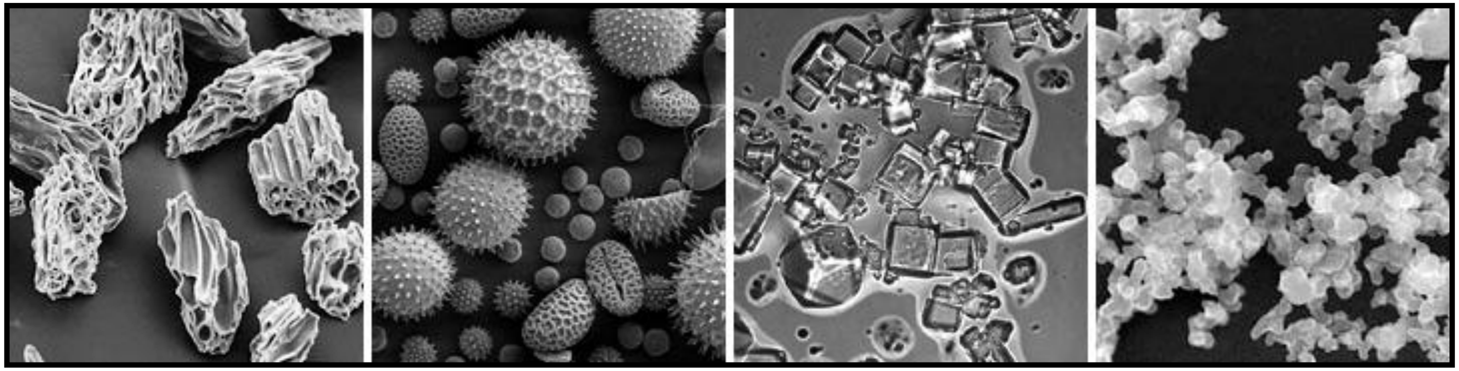
Atmospheric aerosol

Solid or liquid particles suspended in the air

- Types: primary / secondary, natural / anthropogenic particles
- Size: diameter between 0.002 and 100 μm approx.
- Chemical and mineralogical composition: diverse
- Optical properties (absorption, scattering): diverse



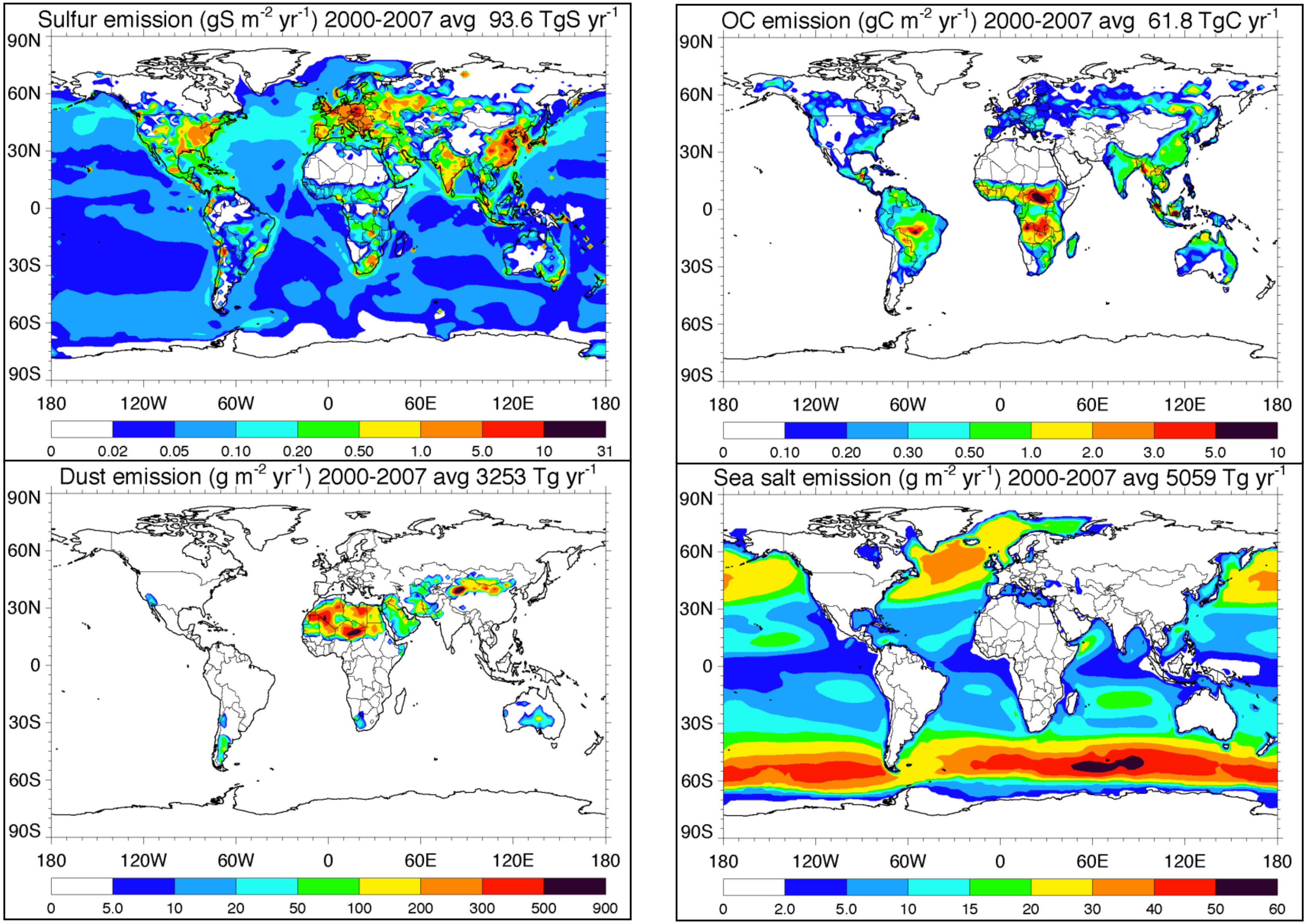
Sources






Volcanoes, sea salt, products from biomass burning, anthropogenic particles, organic compounds, mineral dust

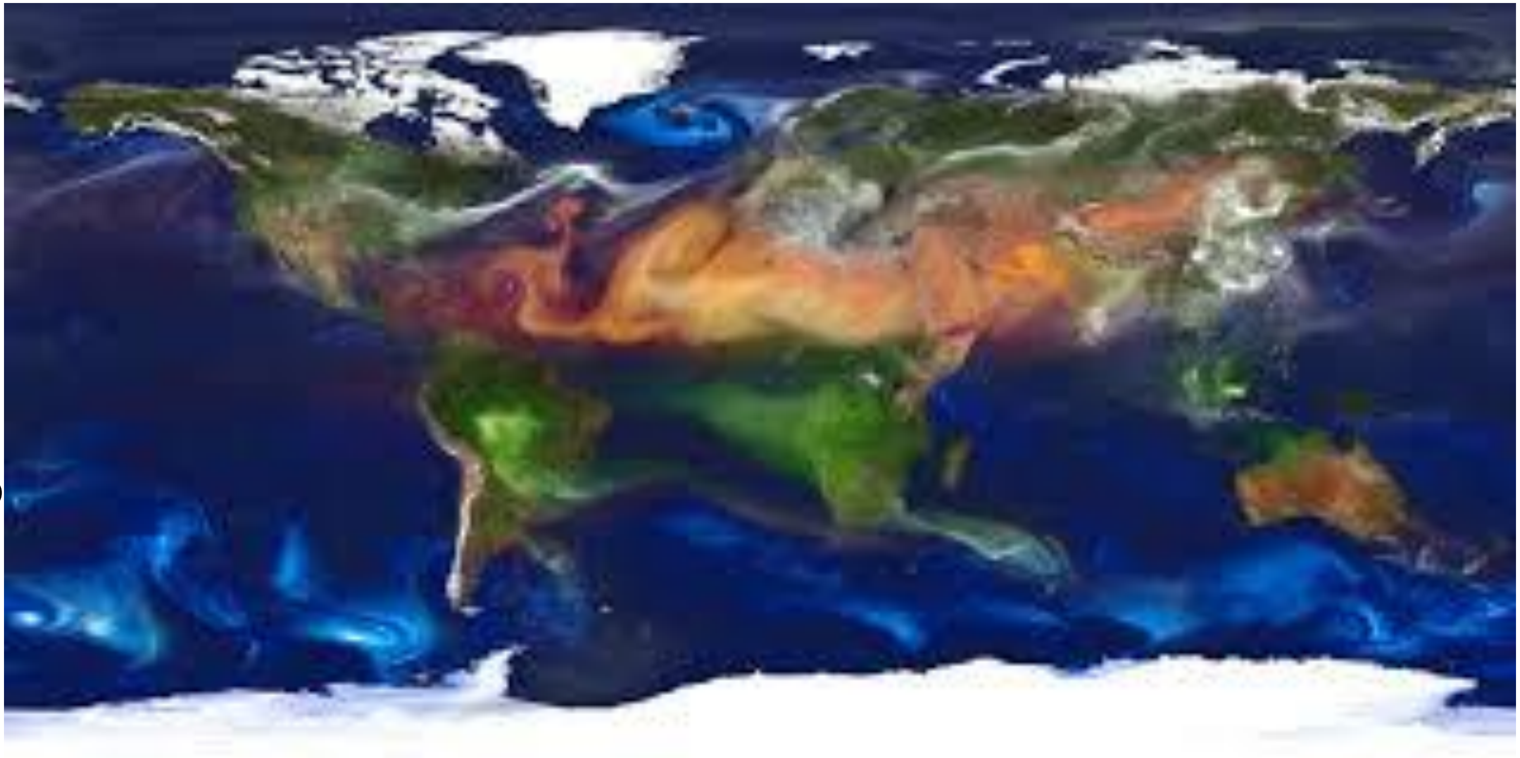
Emissions



Chin et al. (2009)

Distribution

NASA
GEOS-5



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

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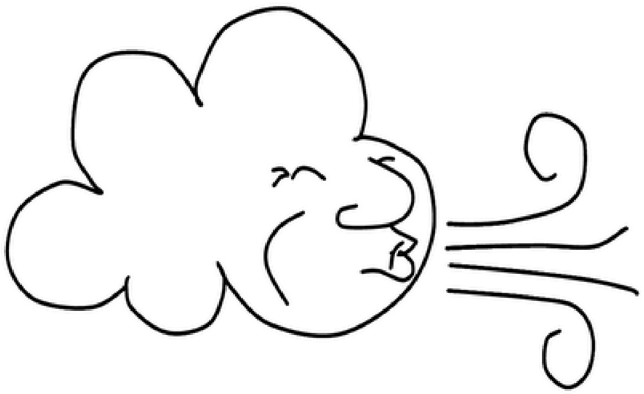
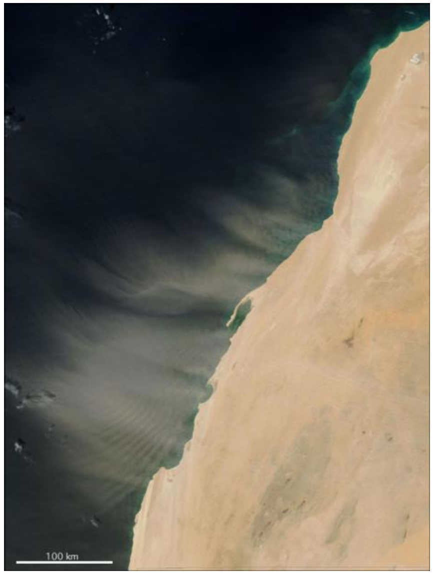
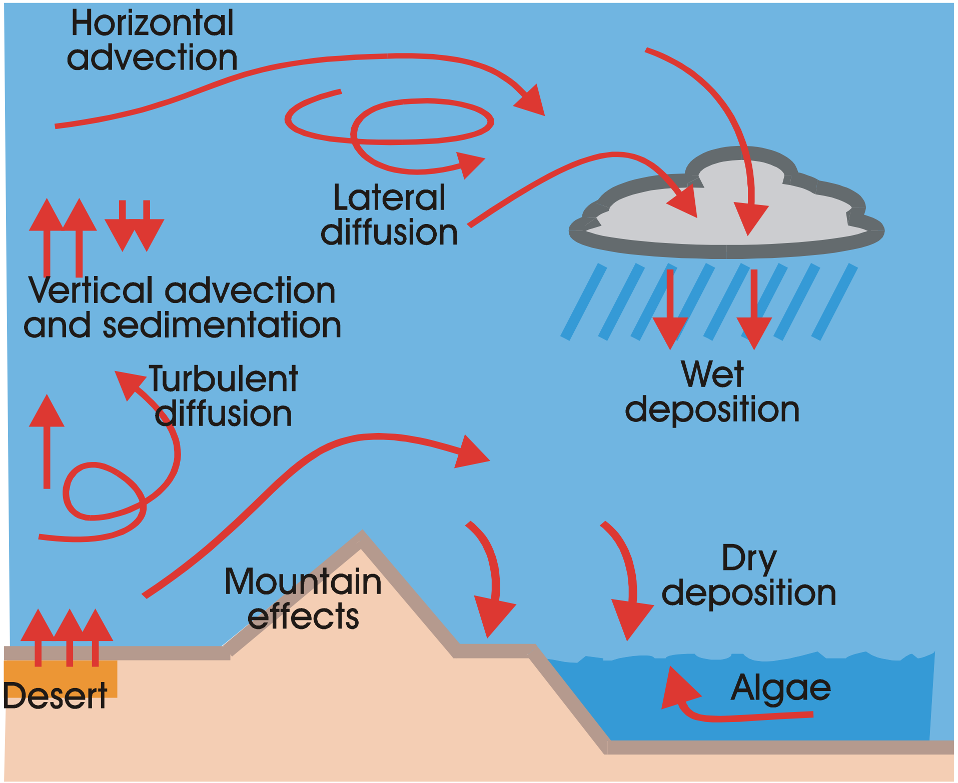
The dust cycle



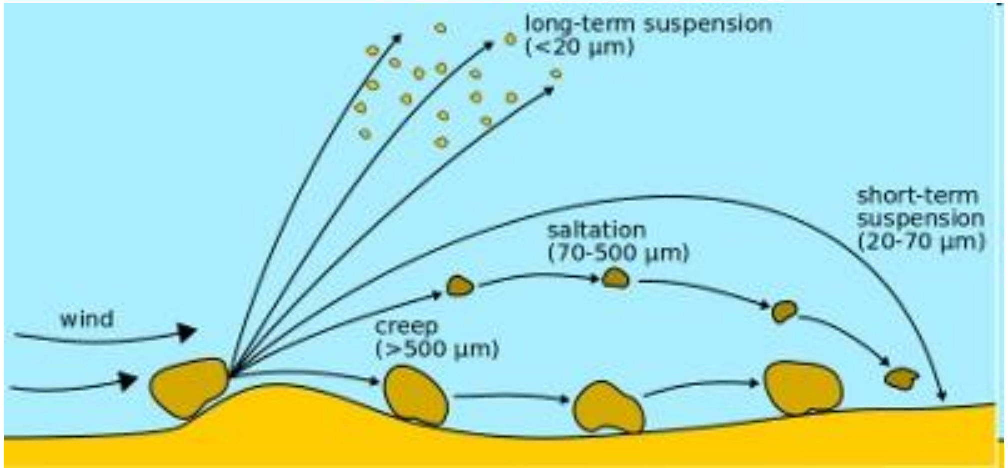


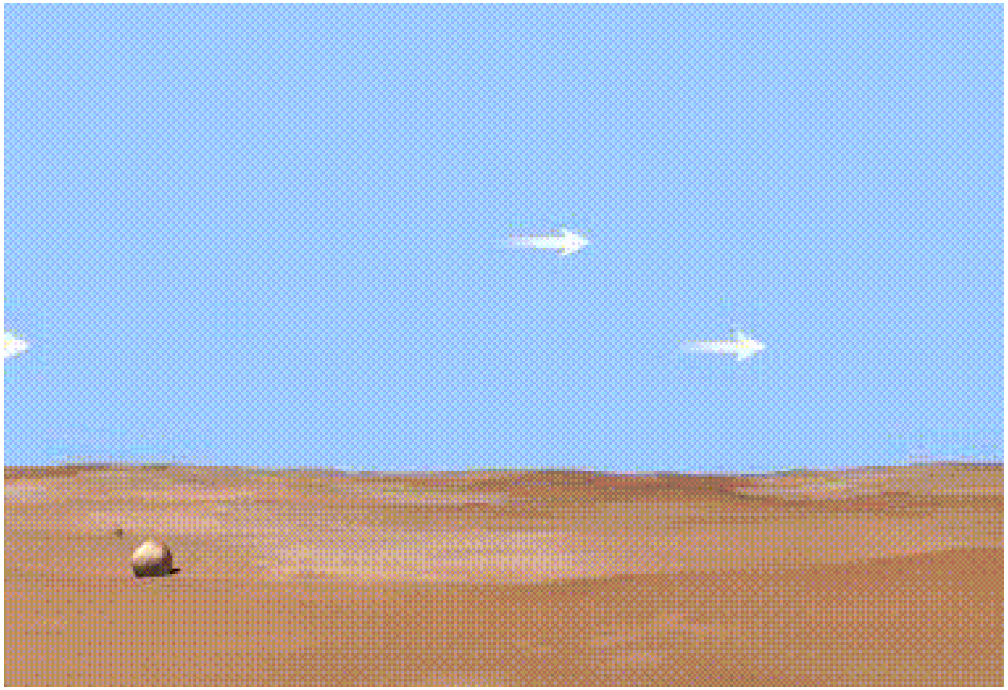
The dust cycle



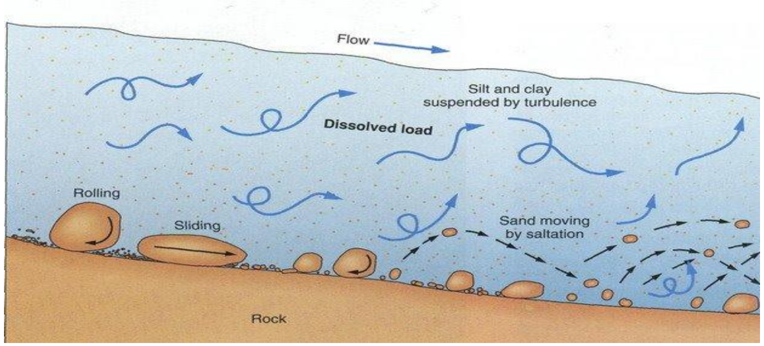
- Emission
- Turbulent difussion
- Transport
- Dry / wet deposition

Emission

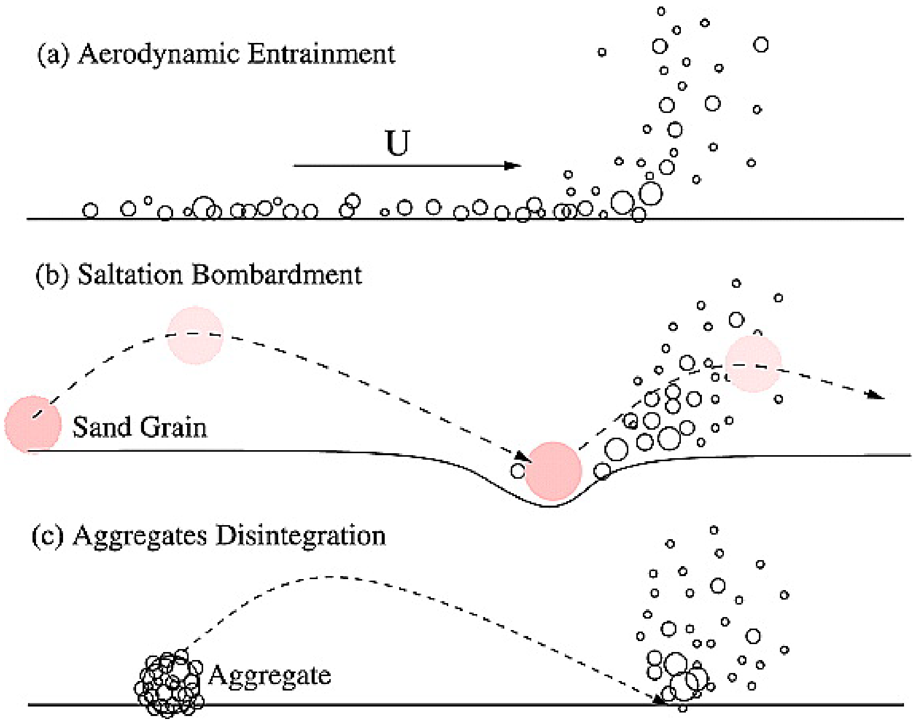




- The wind moves the loose particles according to its speed and the size of those particles
- The process is similar to sediment transport by rivers



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.

Horizontal flux

$$Q = c\frac{\rho}{g}U^{*3}\left(1 - \frac{U_t^*}{U^*}\right)\left(1 + \frac{U_t^{*2}}{U^{*2}}\right)$$

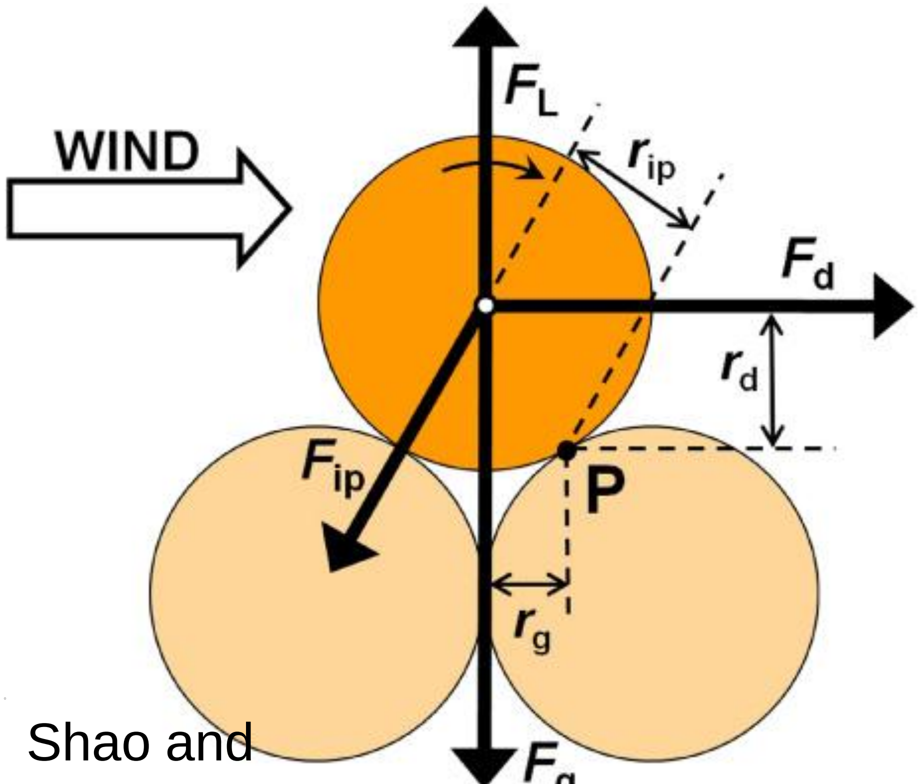
White (1979

- Strong dependence on wind speed (proportional to u^{*3})
- Strong dependence on partícle size (through u^*_t)

- Need for a very precise wind forecast
- The horizontal flux must be calculated for different size bins

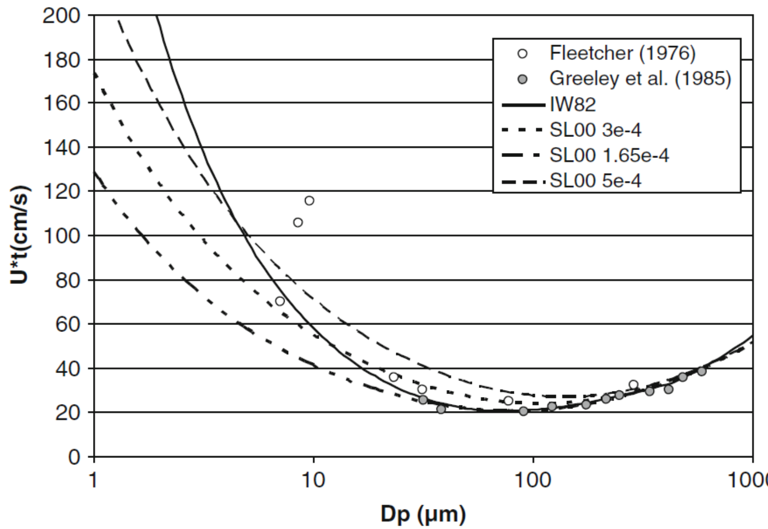
Erosion threshold

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)

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



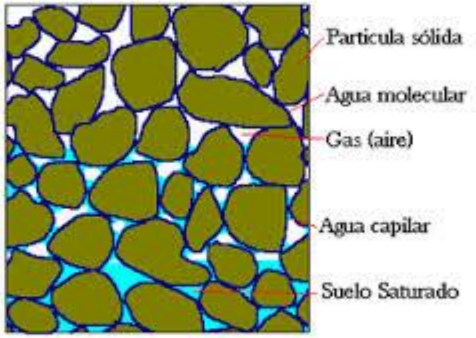
Erosion threshold

Elements that modify (increase) the erosion threshold

Non-erodible elements
(i.e. vegetation)

Crusted soils

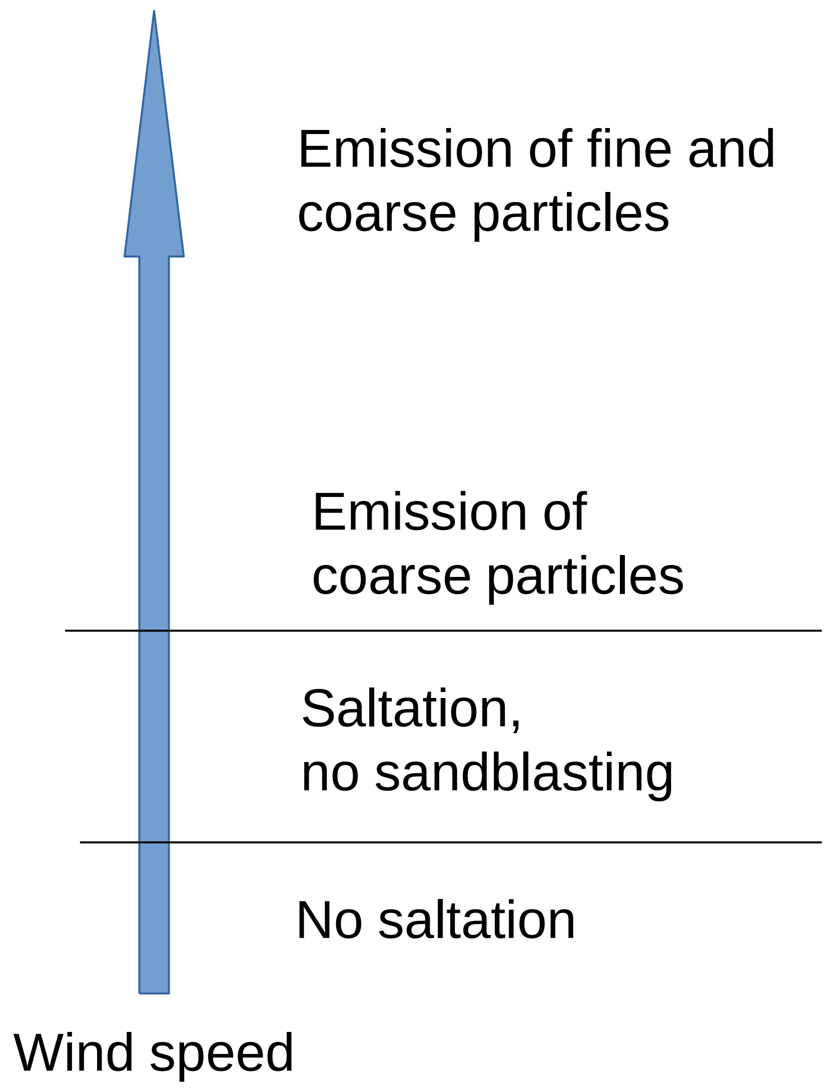
Soil humidity



Snow

Vertical flux

- The kinetic energy of saltation breaks the aggregates of particles and causes a vertical flux (sandblasting)
- A threshold kinetic energy is required to trigger the sandblasting
- Larger particles are less cohesive and are the first to be emitted
- Fine particles are only emitted in the most intense episodes



Emission

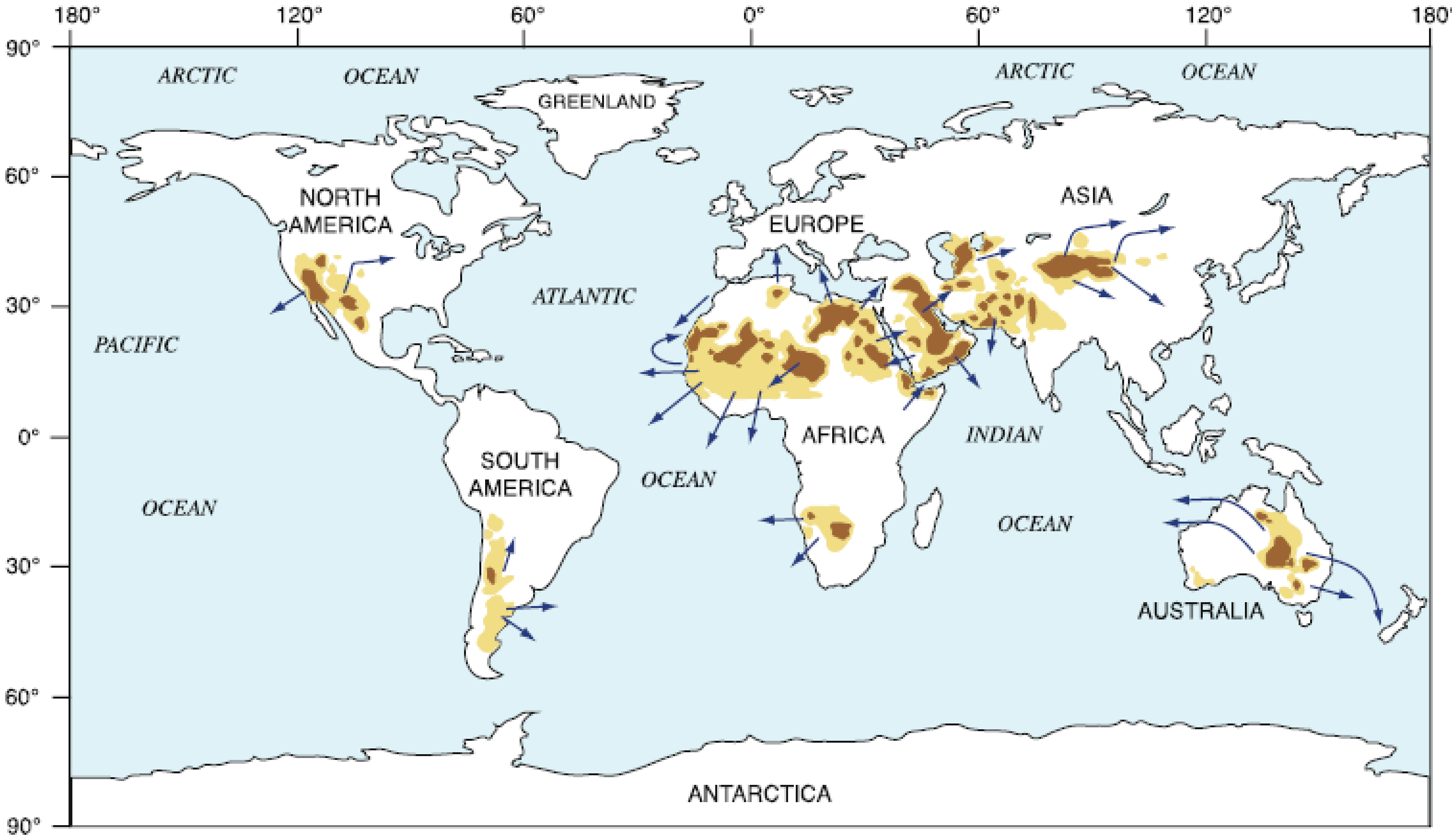
Soil factors

- Soil texture
- Soil moisture
- Vegetation
- Snow cover

Meteorological factors

- Wind speed
- Near-surface turbulence

Sources



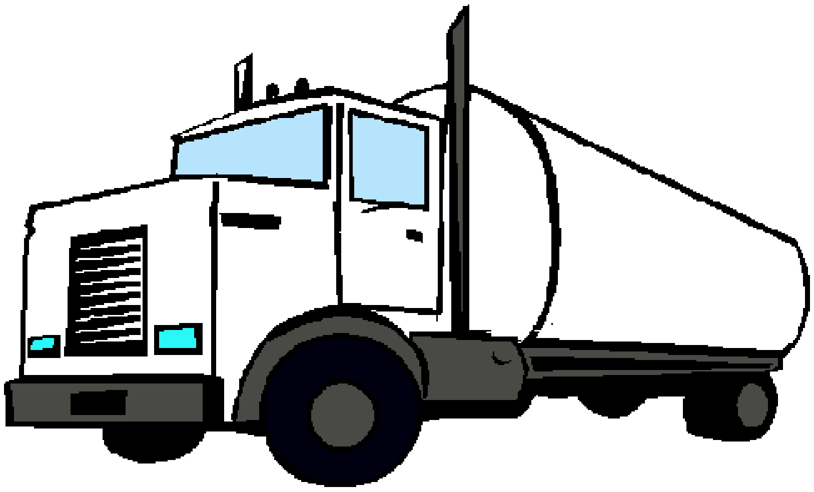
180°
120°
60°
0°
60°
120°
180°
90°
60°
30°
0°
30°
60°
90°
ARCTIC
OCEAN
GREENLAND
ARCTIC
OCEAN
NORTH
AMERICA
EUROPE
ASIA
ATLANTIC
PACIFIC
AFRICA
INDIAN
SOUTH
AMERICA
OCEAN
OCEAN
OCEAN
AUSTRALIA
ANTARCTICA

Anthropogenic sources

Total emission

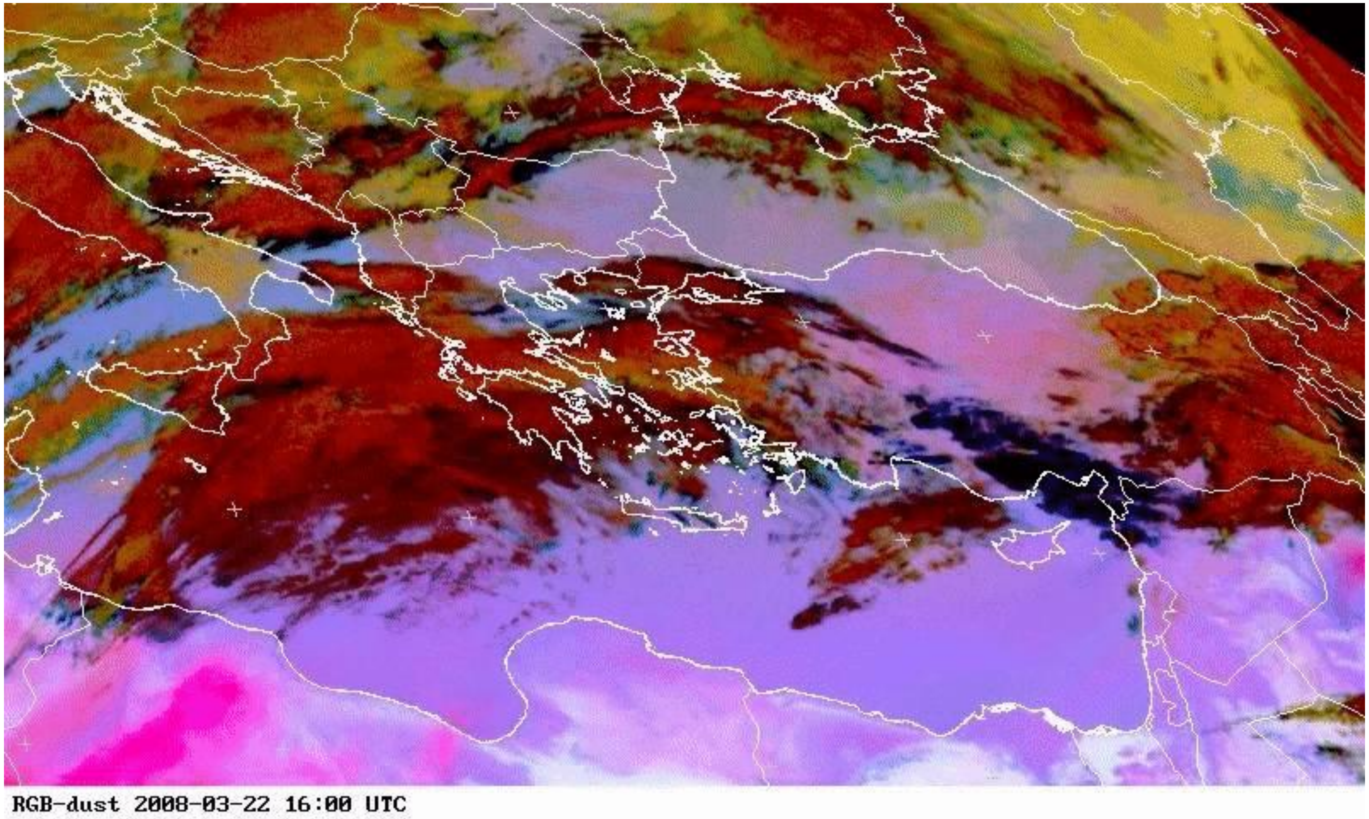
~ 30–60 Tm/s
~ 1–2 Pg/yr

50,000,000 lorries



3,000 ULCC

Meteorological confitions



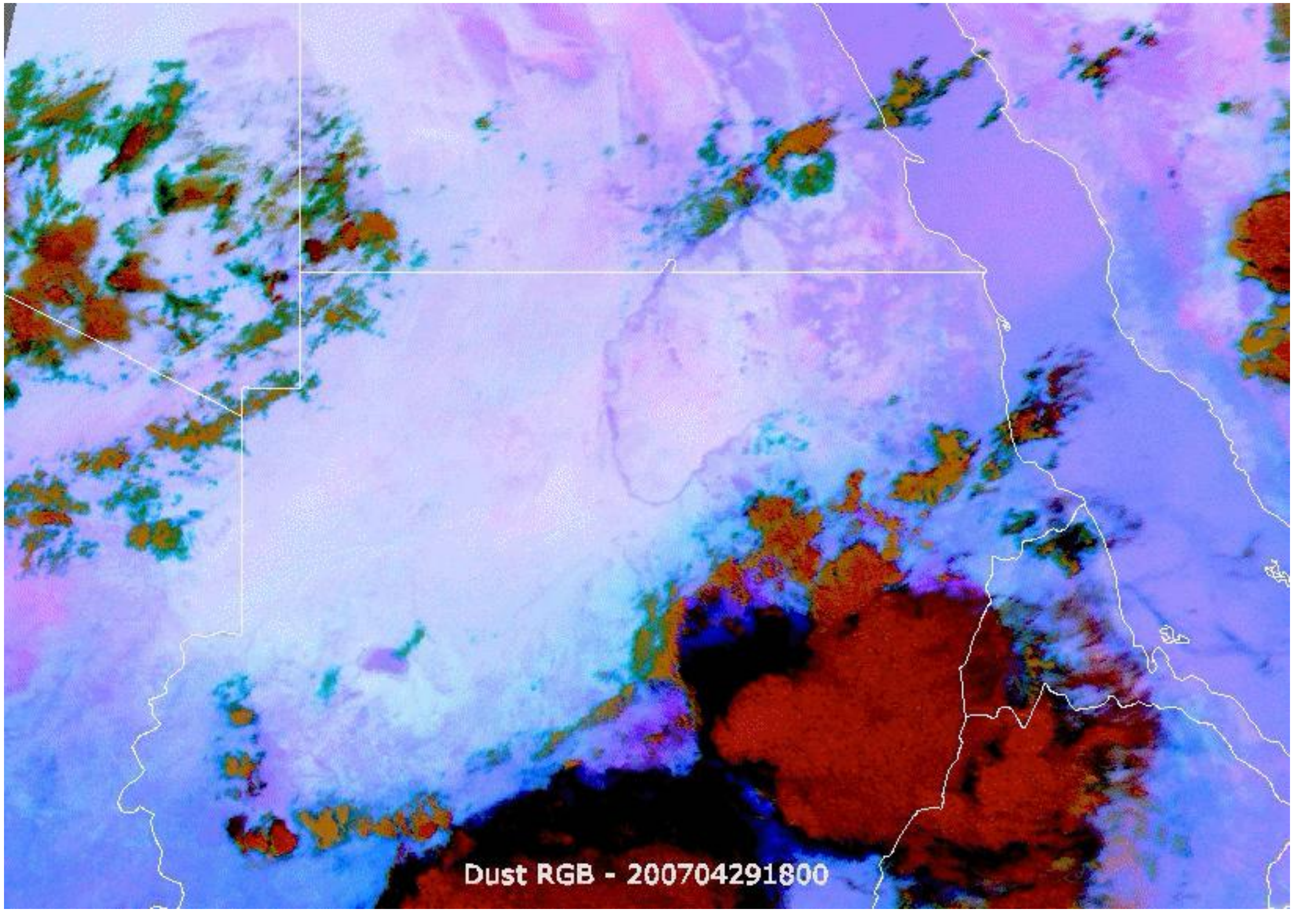
EUMETSAT

22-24 Mar 2008

SYNOPTIC SCALE

- Frontal systems
- Reinforcing trade winds

Meteorological conditions

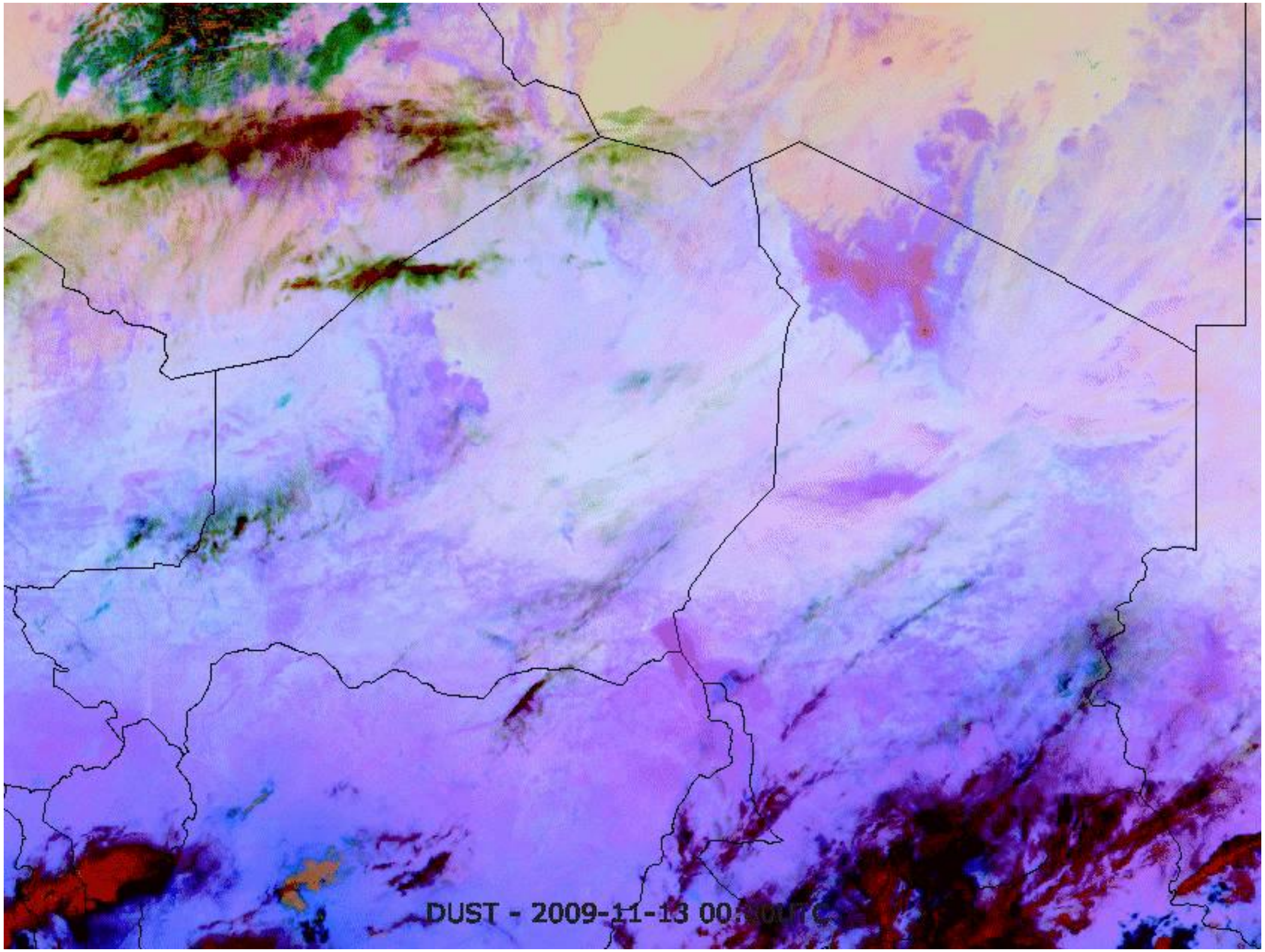


MESOSCALE-MICROSCALE

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

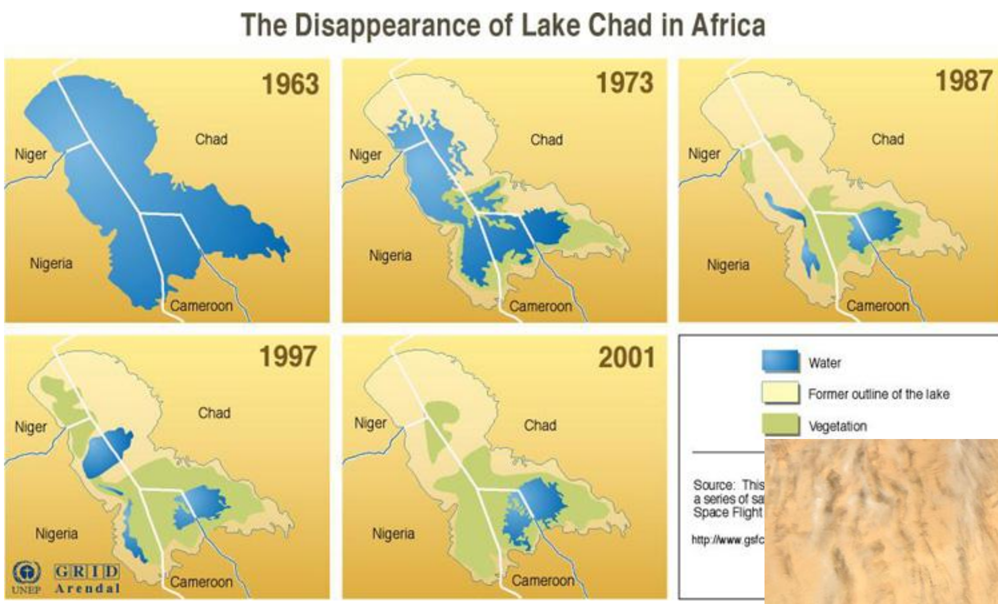
29 Apr – 1 May 2007

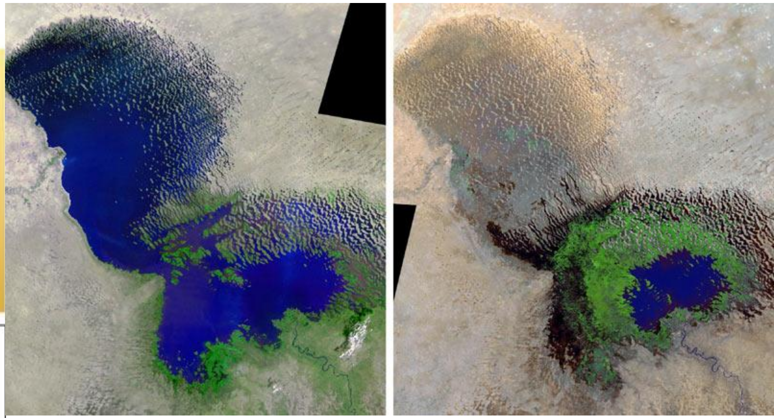
Meteorological conditions

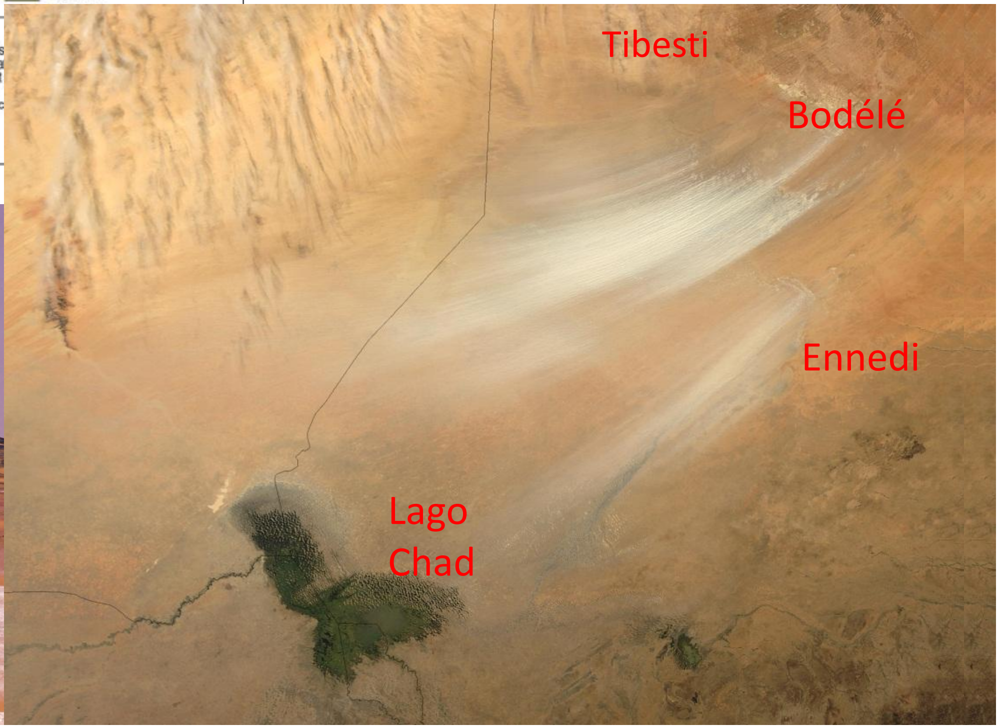


13 – 14 Nov 2009

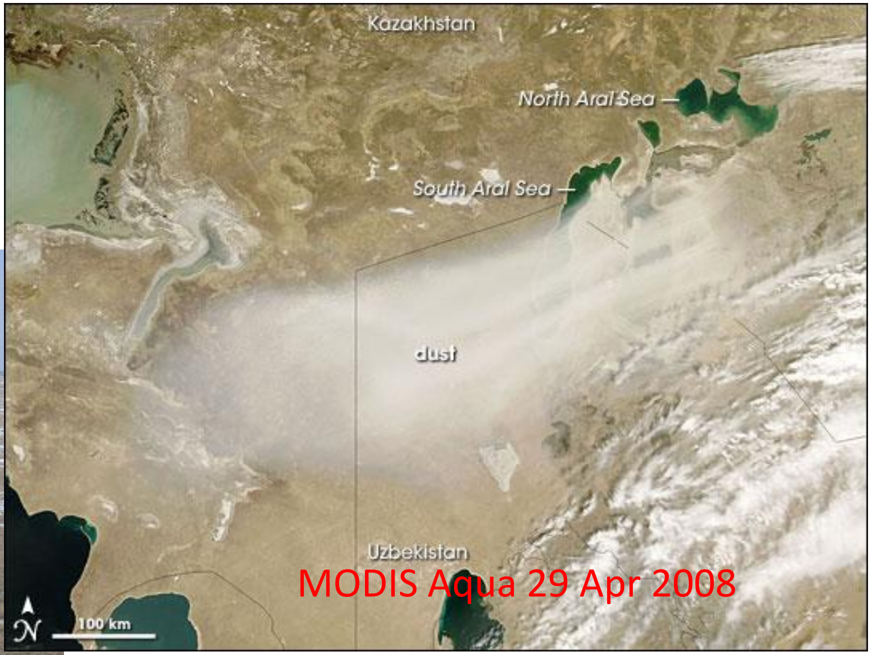
Bodélé depression



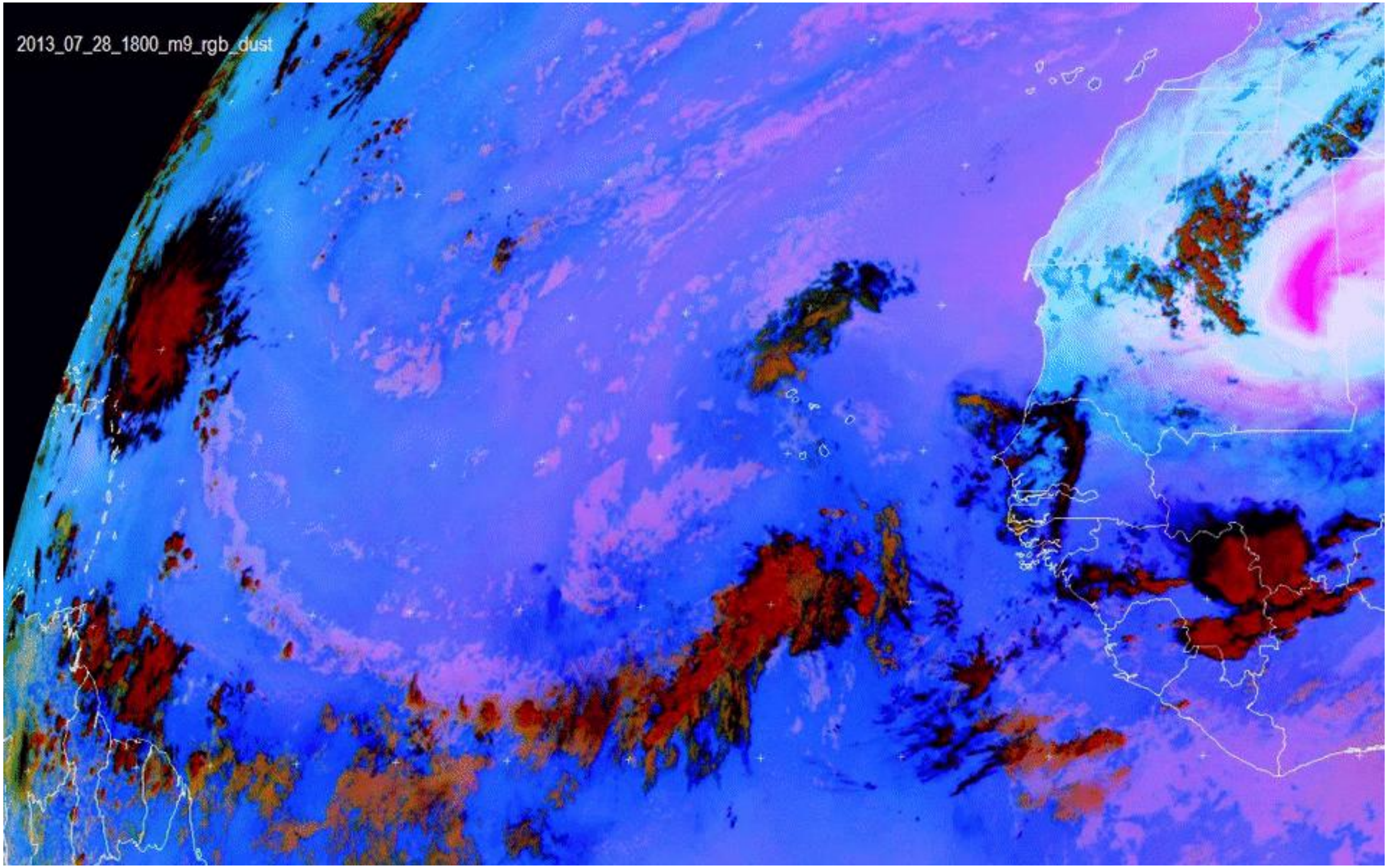




Aral Sea


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

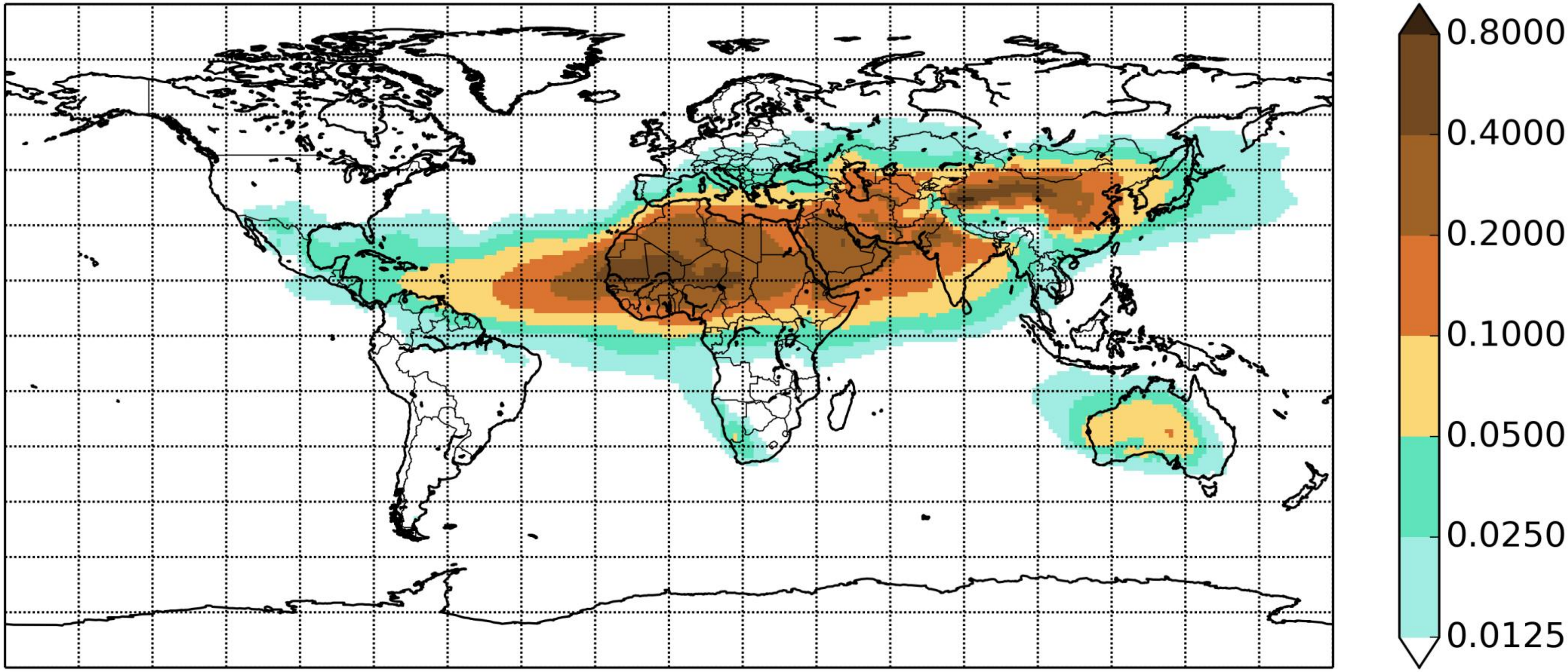
Transport



29 – 30 Jul 2013

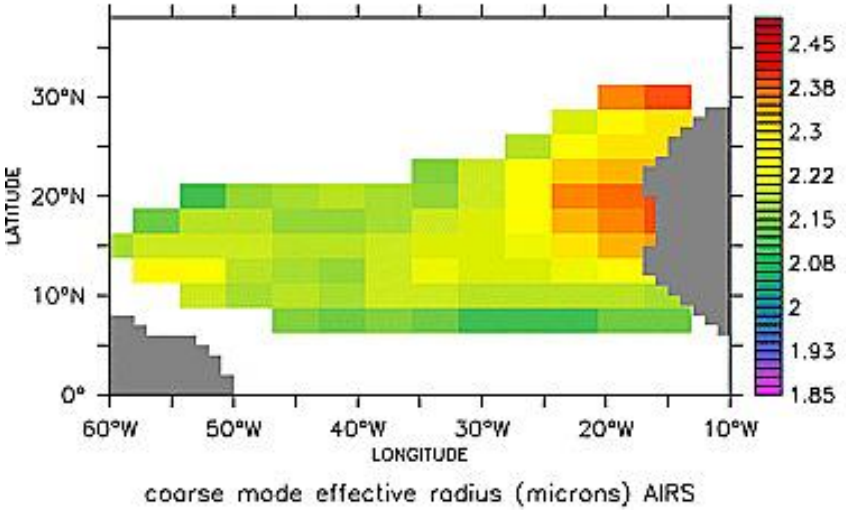
Average distribution

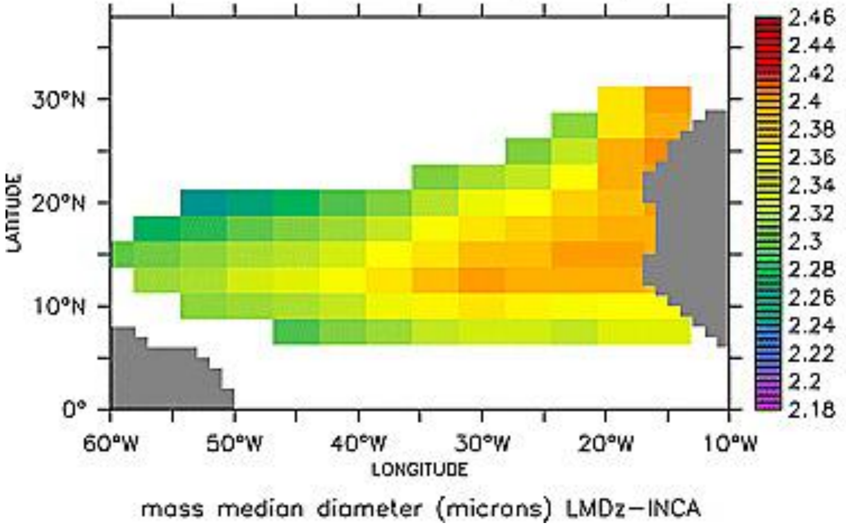
Dust optical depth at 550 nm. Average value 2003-2015



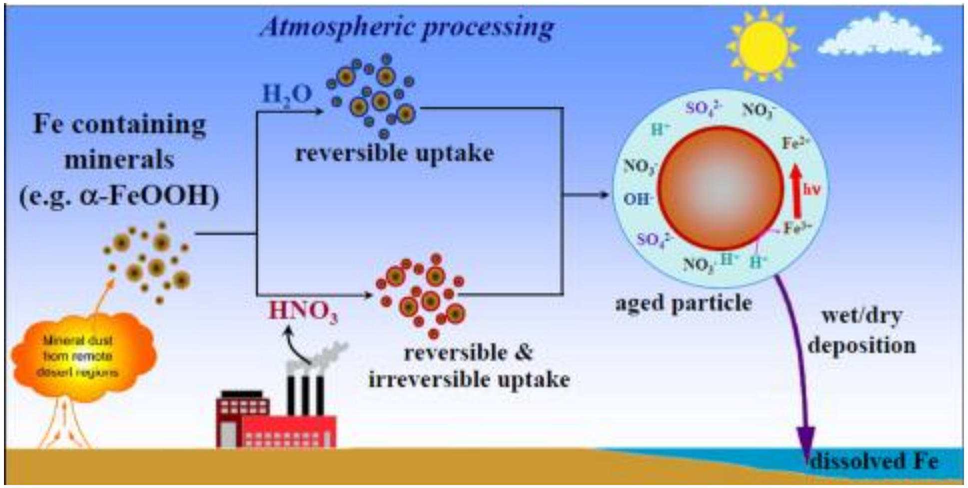
Data: CAMS reanalysis
Picture: WMO SDS-WAS

Transport



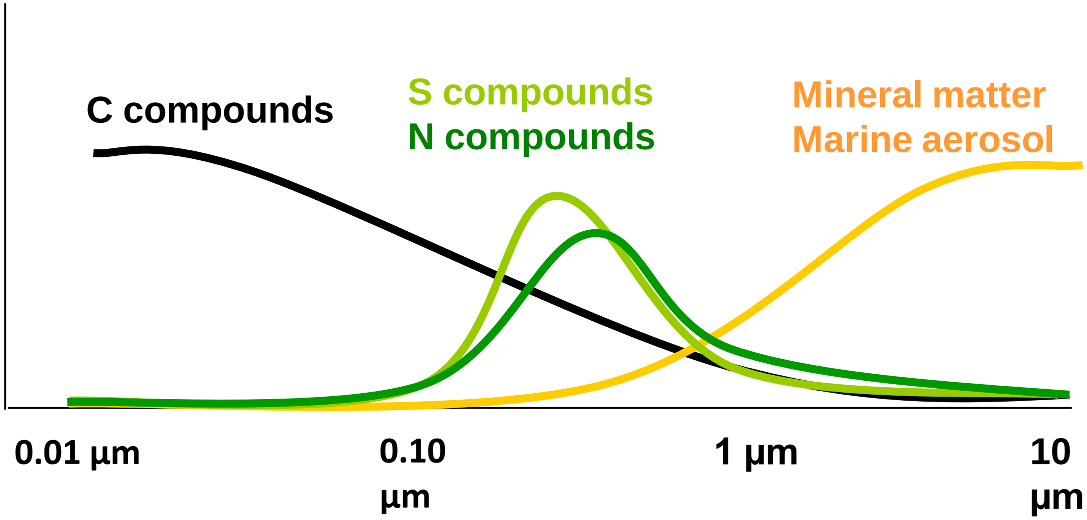


Pierangelo et al. (2005)



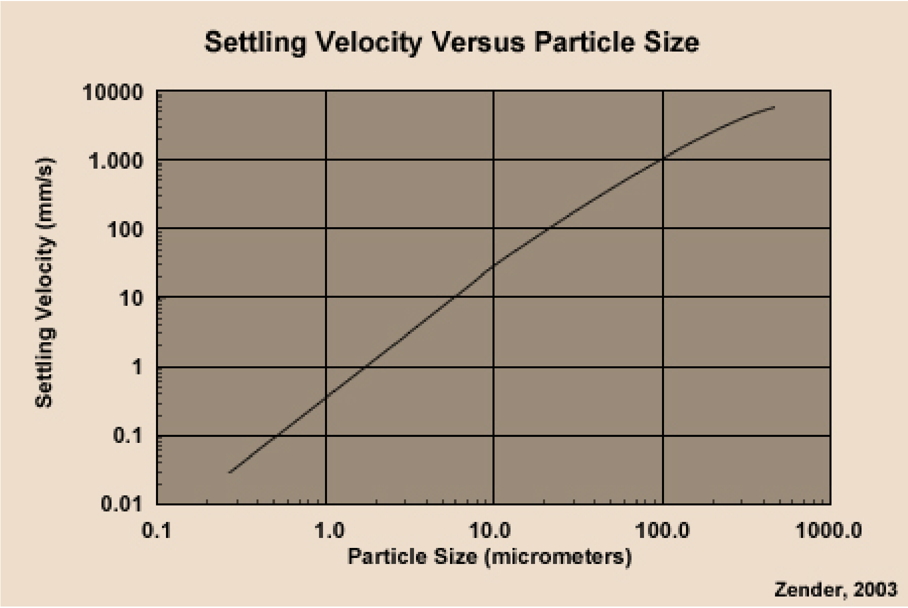
- The average particle size decreases
- Chemical composition may vary
- Optical properties may vary
- Increasing ability of particles to act as CN
- Increasing solubility of Fe

Deposition

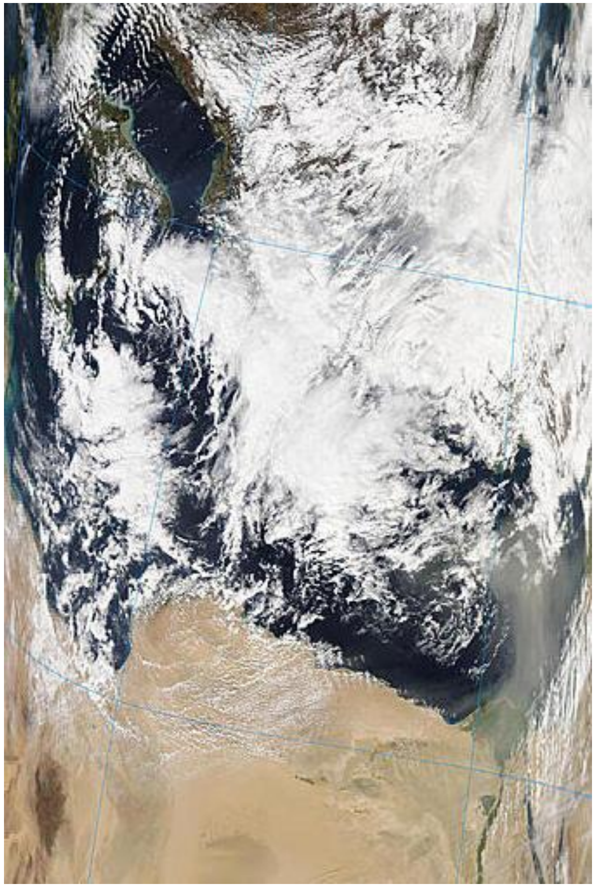


SIZE (µm)	AVERGE LIFETIME (h)
0.1 - 0.18	231
0.18 - 0.3	229
0.3 - 0.6	225
0.6 – 1	219
1 - 1.8	179
1.8 – 3	126
3 – 6	67
6 - 10	28

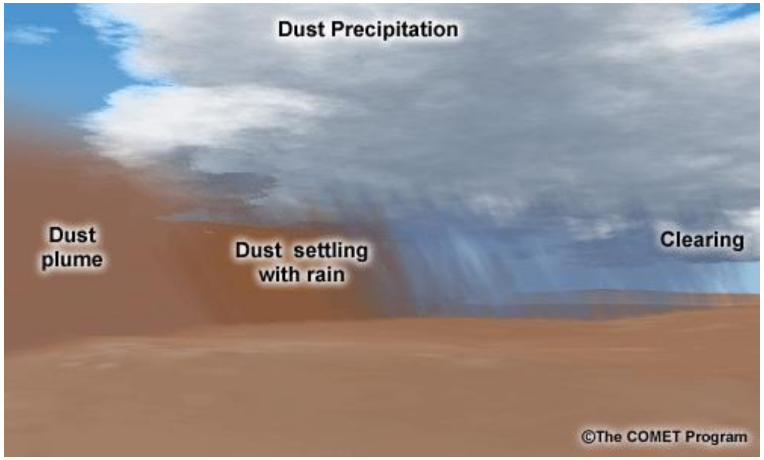
Tegen and Lacis (1996)

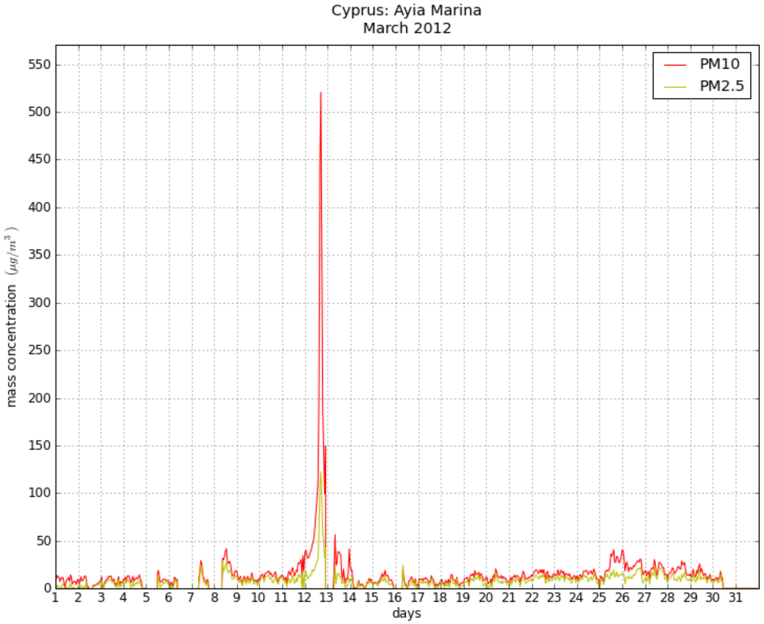


Wet deposition



MODIS 12 Mar 2012





PM Ayia Marina, Cyprus, Mar 2012

Composition

MINERALOGICAL (X-ray diffractometry)

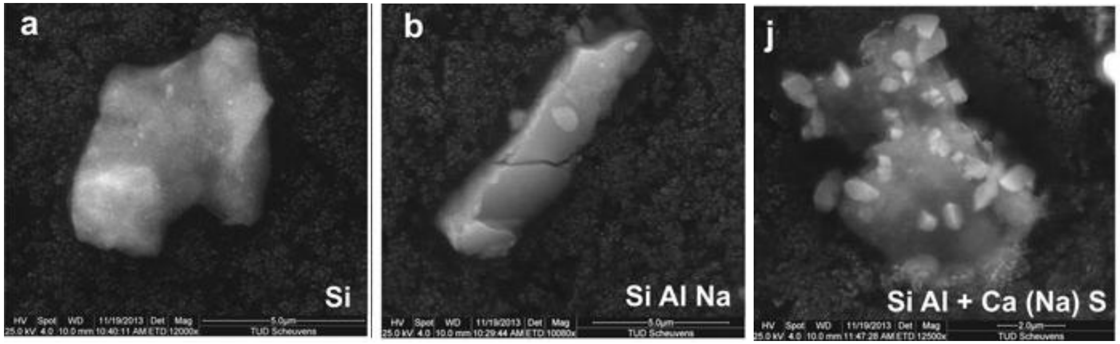
- Silicates: quartz, feldspar, phyllosilicates (ilite, kaolinite, smectite)
- Carbonates (calcite, dolomite)
- Hematite, gypsum, halite, …

ISOTOPICAL (Sr, Nd, Pb)

CHEMICAL (spectroscopy)

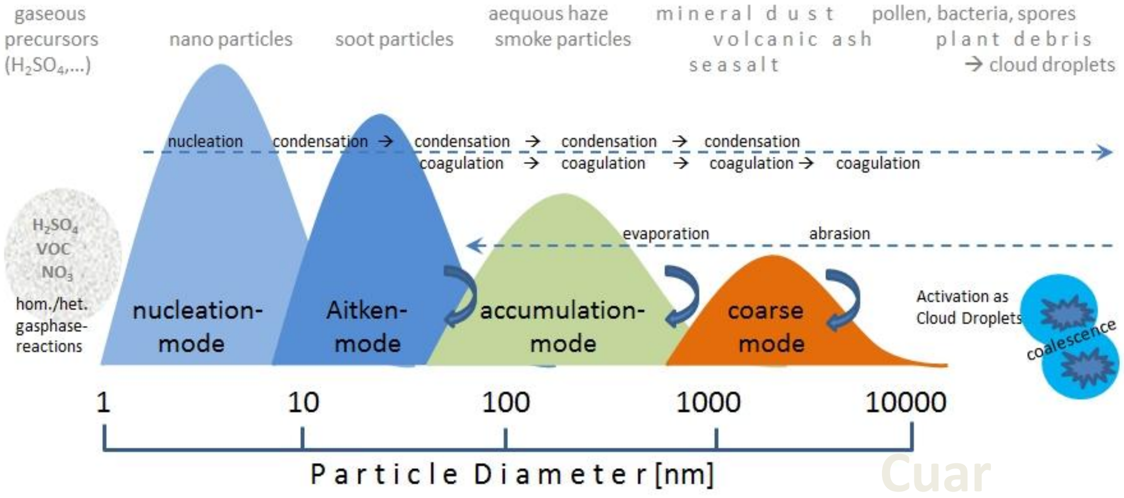
- Si, Al, Ca, Mg, Fe, K, Na, Mn, Ti, P

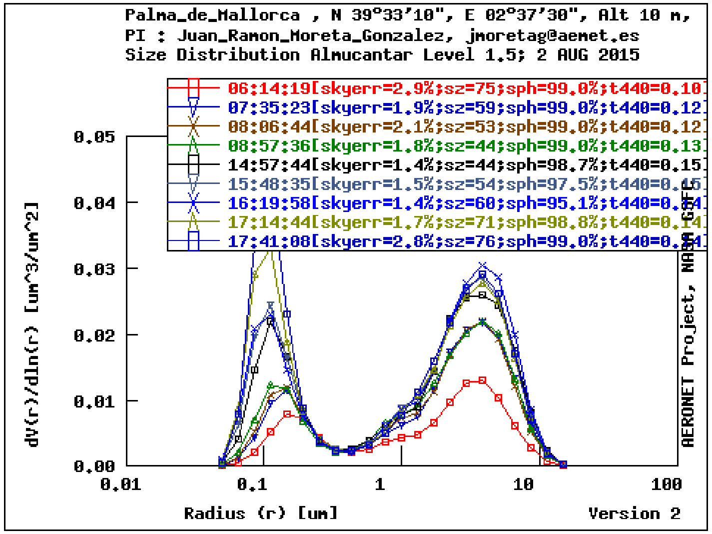
- Information about the source region
- Influence on optical properties
- Influence the impact on health, ecosystems, ...



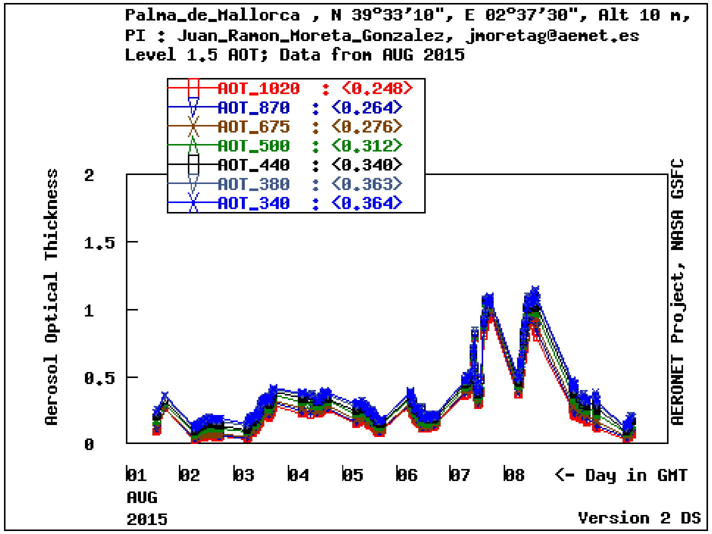
Quartz Albite Gypsum

Particle size

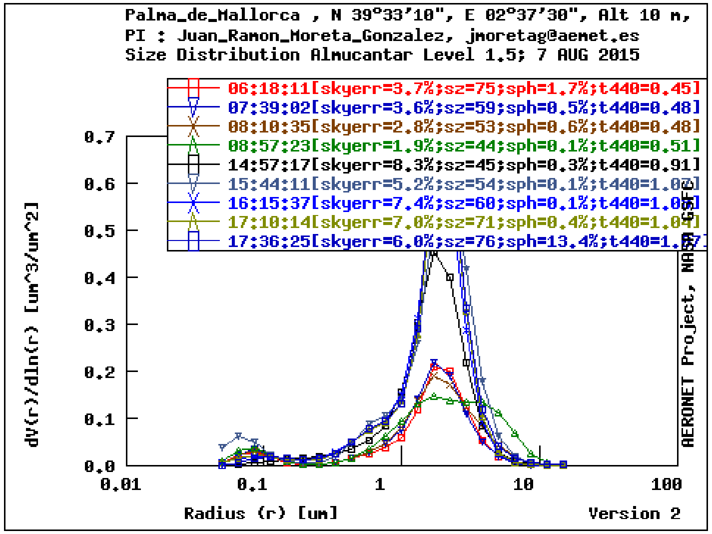




$$\tau = \ln\left(\frac{I_0}{I_1}\right)\cos(\theta)$$

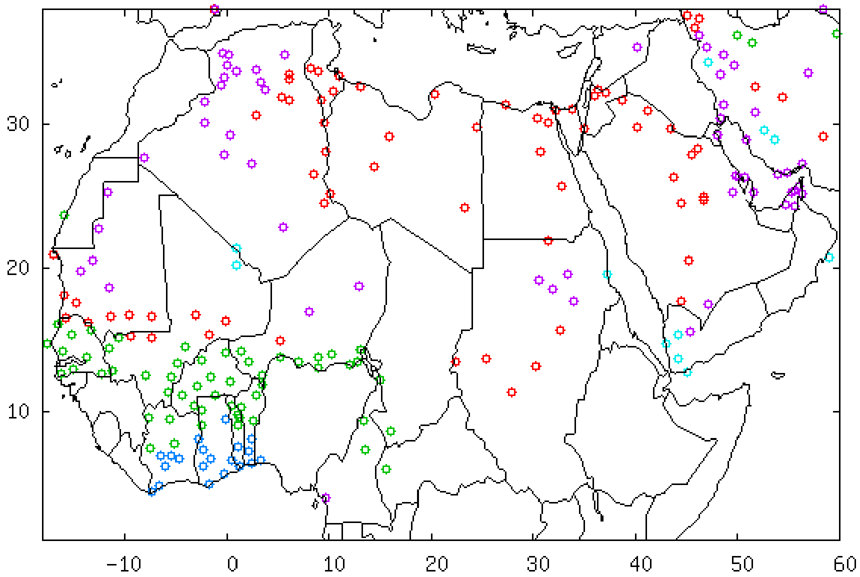


AOD. Palma de Mallorca. Aug 2015

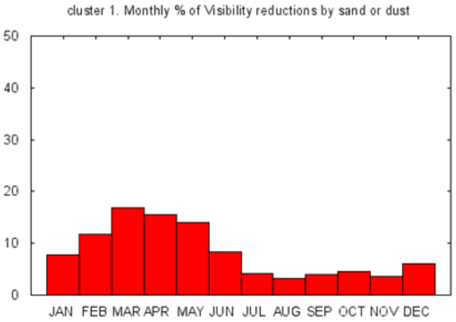


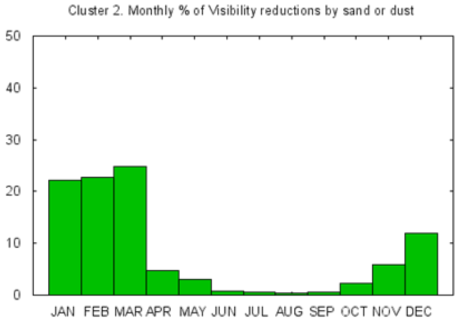
Palma de Mallorca 2 / 7 Aug 2015

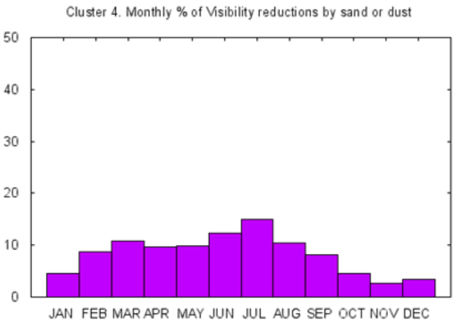
Seasonal variability

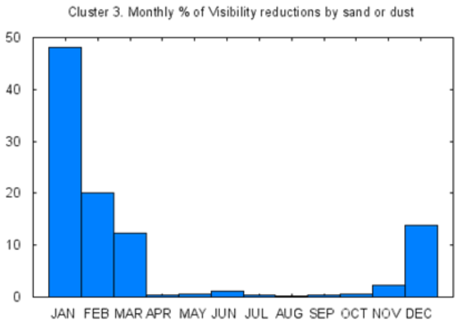


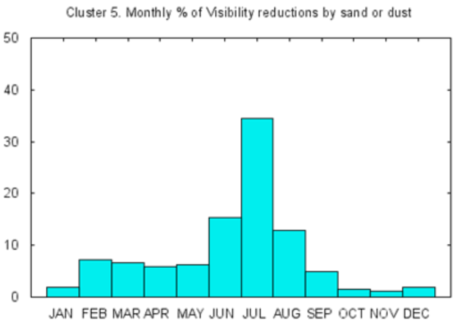
1996-2010









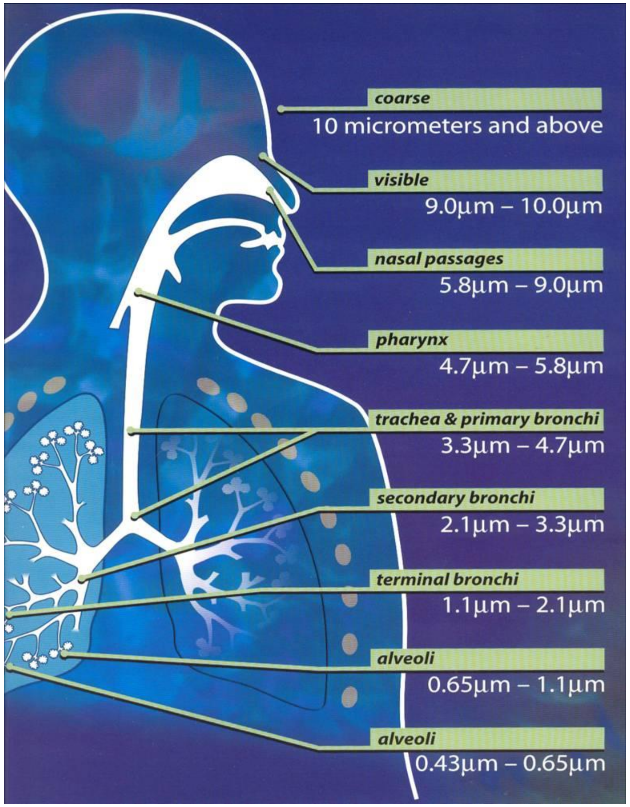


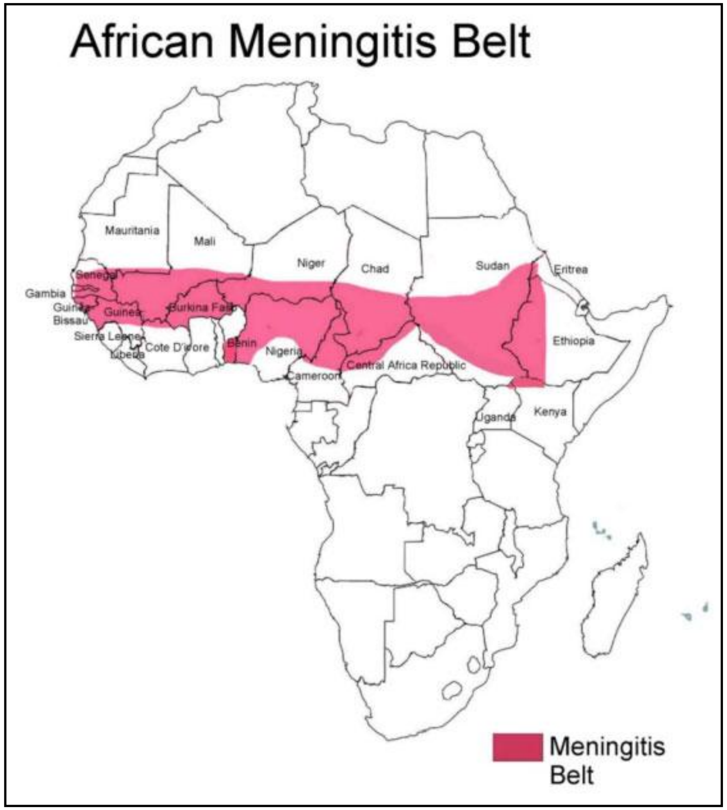
Terradellas et al. (2012)

Impacts

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

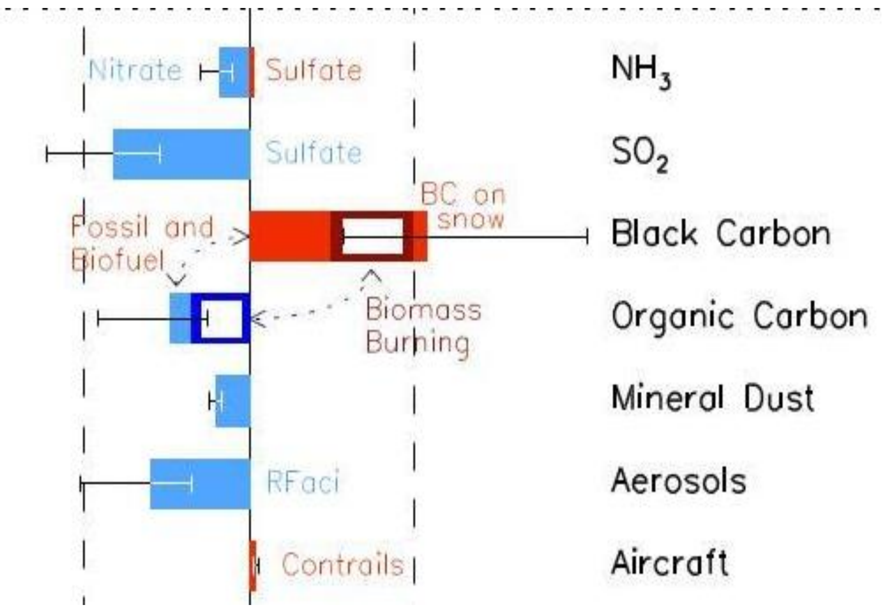
Health impact

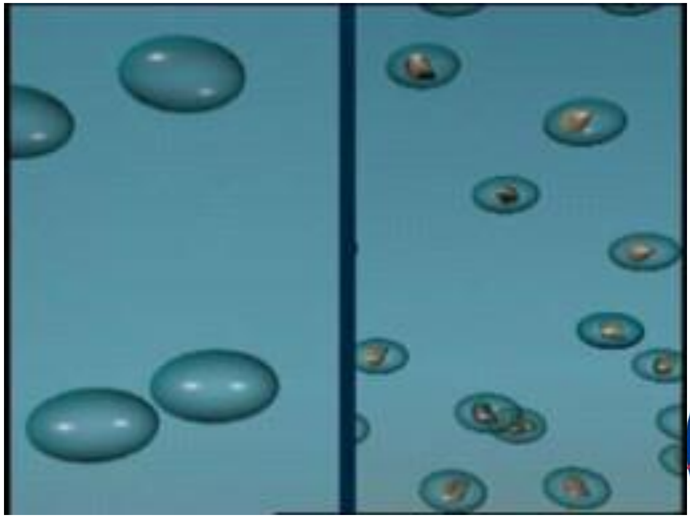


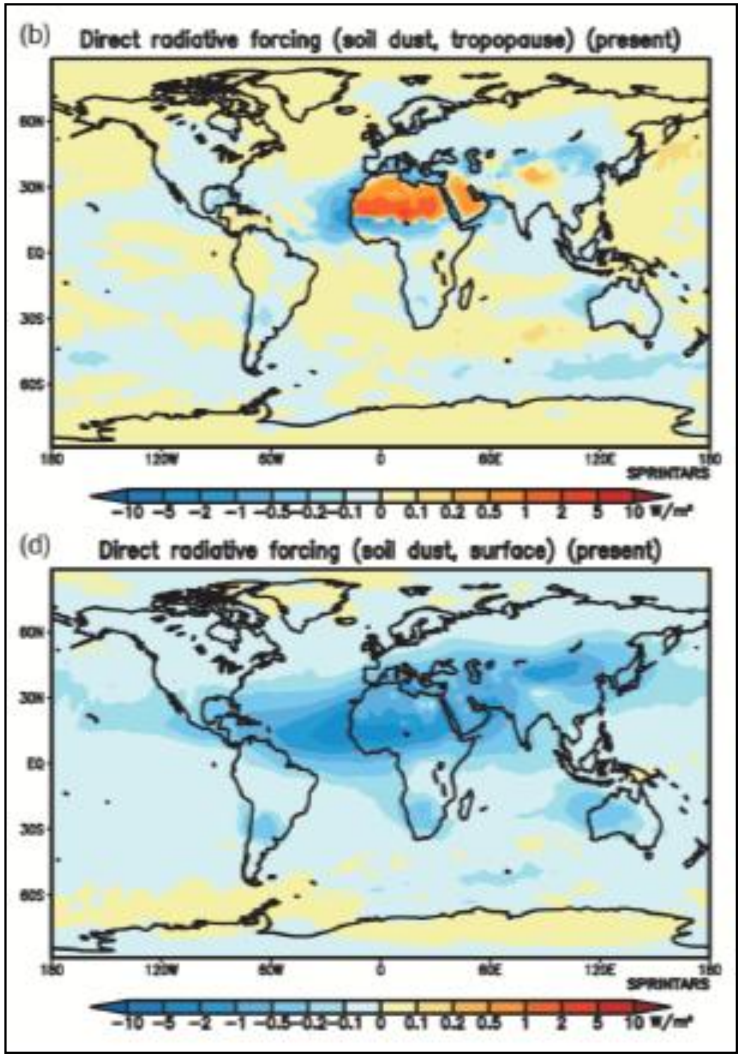


- Particle size
- Chemical and mineralogical composition
- Carrying bacteria, viruses, fungi, ...
- Time and intensity of exposure

Impact on weather and climate

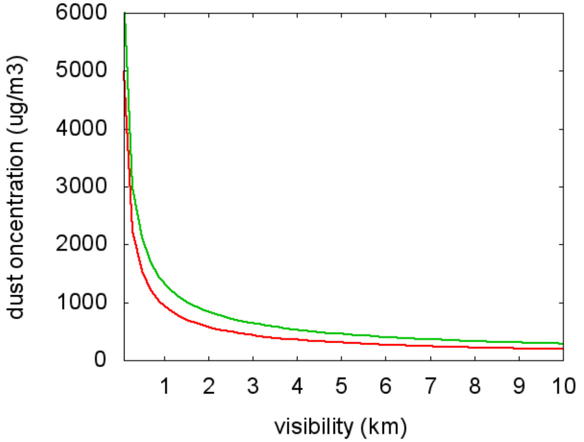






Takemura et al. (2009)

Impact on transportation



D'Almeida (1986)

Ben Mohamed et al. (1992)

Arizona, 29 Oct 2013

Tunis, 7 May 2002

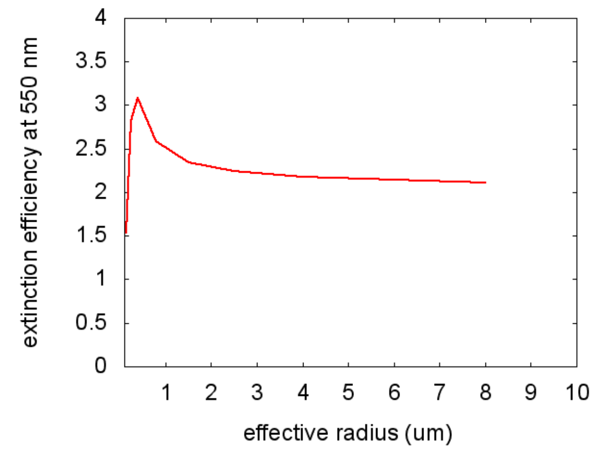
Visibility

Koschmieder formula

$$V = \frac{3.912}{\beta}$$

$$\beta_\lambda = \sum_{k=1}^{N} \sigma_k Q_{k\lambda}$$

$$\beta_\lambda = \sum_{k=1}^{N} \frac{3}{4} \frac{C_k Q_{k\lambda}}{r_k \rho_k}$$

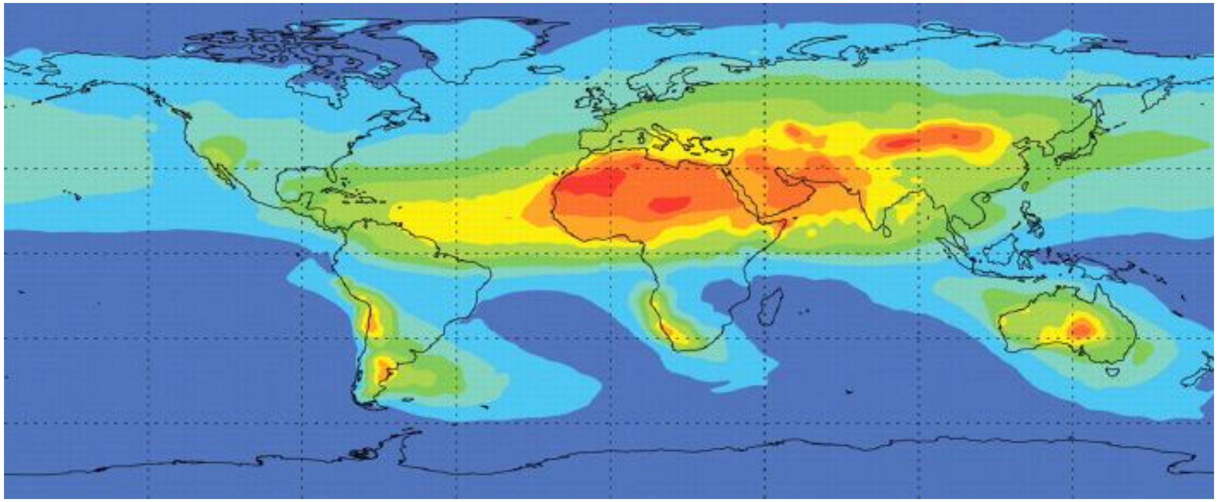


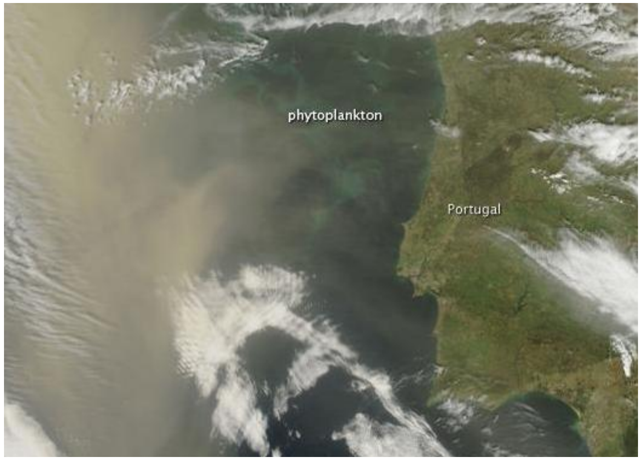
Tegen and Lacis (1996)

Solar energy

- Reduction of available energy
- Reduced efficiency due to dust deposition

… 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
- Barcelona Dust Forecast Center
- 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 (??)

Regional Center NAMEE

The Center is jointly managed by AEMET and the Barcelona Supercomputing Center

UPC Campus. Nexus II building

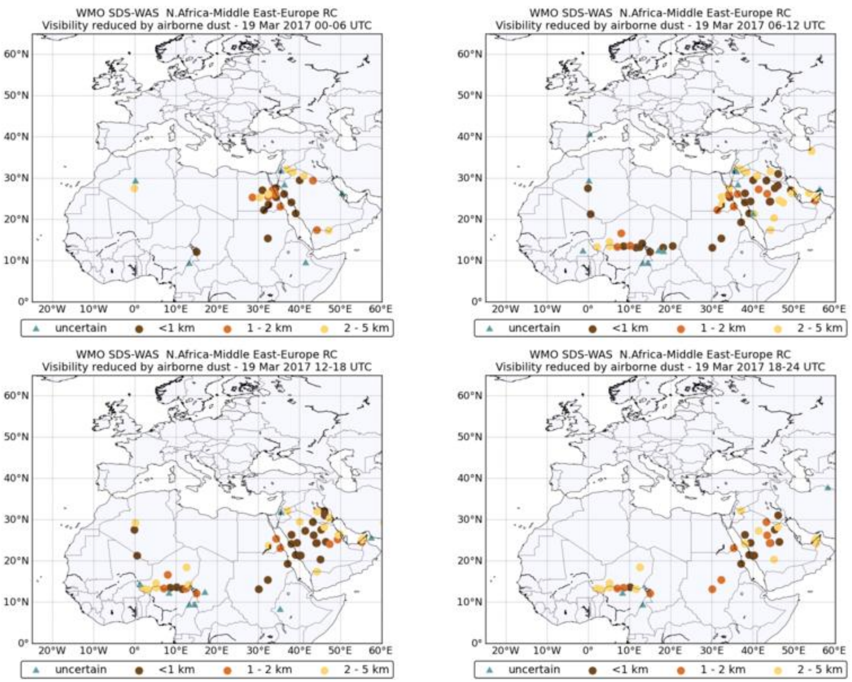
MareNostrum III supercomputer

Regional Center NAMEE

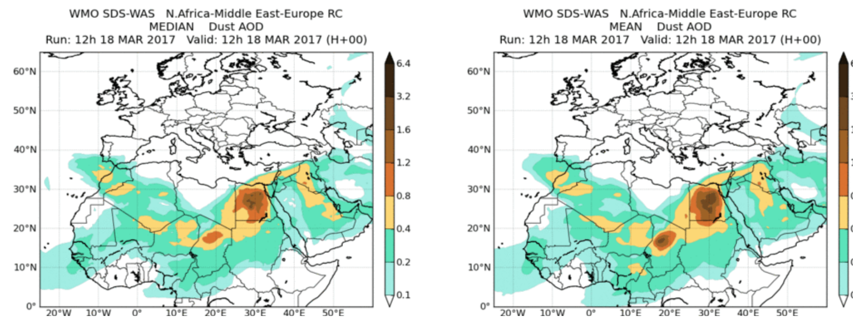
OBJETIVES:

- **Identify and improve products for observation and prediction of airborne dust, in collaboration with research and operational institutions, as well as with end users**
- **Facilitate user access to information**
- **Develop the capacity of countries to use the products supplied**

Obj. 1: Identify, improve productos



19 Mar 2017

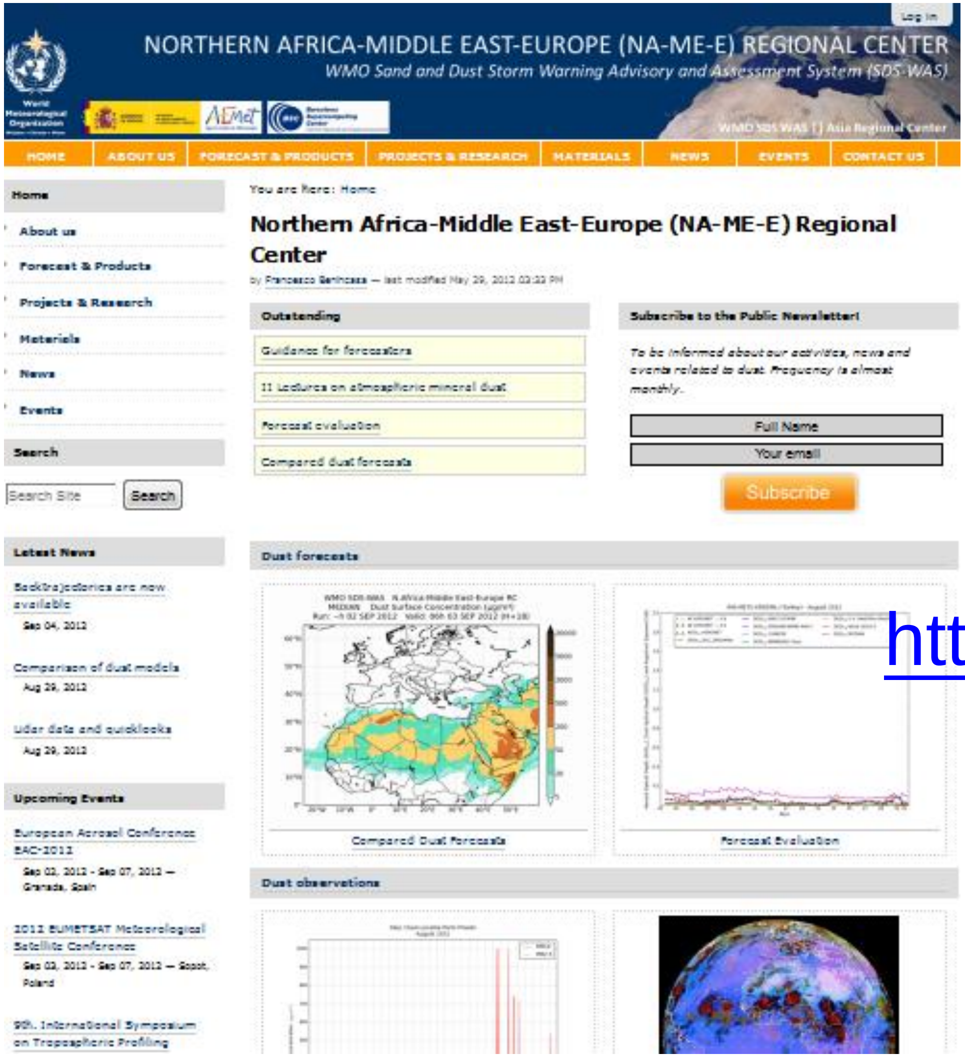


18-21 Mar 2017

OBSERVATION. Stations with visibility reduction to less than 5 km by sand or dust

PREDICTION. Ensemble prediction (EPS) from 12 different models

Obj. 2: Facilitate user access



https://sds-was.aemet.es

sdswas@aemet.es

Obj. 3: Build capacity

EUMETSAT

WMO

GHANA METEOROLOGICAL AGENCY

TURKISH STATE METEOROLOGICAL SERVICE TSMS

CILSS

GOBIERNO DE ESPAÑA MINISTERIO DE MEDIO AMBIENTE Y MEDIO RURAL Y MARINO

AEMet Agencia Estatal de Meteorología

UPC UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATEC

Sultan Qaboos University

BSC Barcelona Supercomputing Center Centro Nacional de Supercomputación

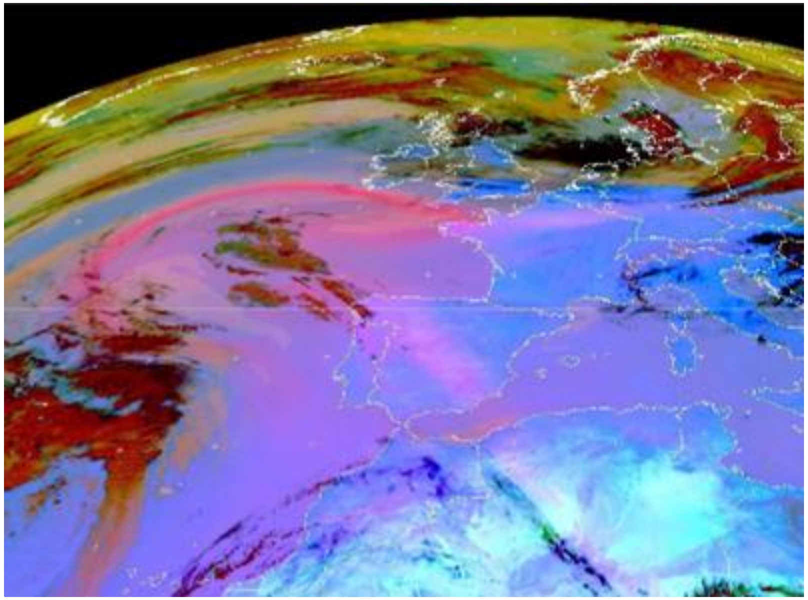
MAROC METEO

Atmospheric Science & Meteorological Research Center ASMERC

TRAINING

Accra
Addis-Ababa
Ankara
Antalya
Barcelona
Casablanca
Istanbul
Madrid
Muscat
Niamey
Ouagadougou
Tehran
Tbilisi

Collaborative research

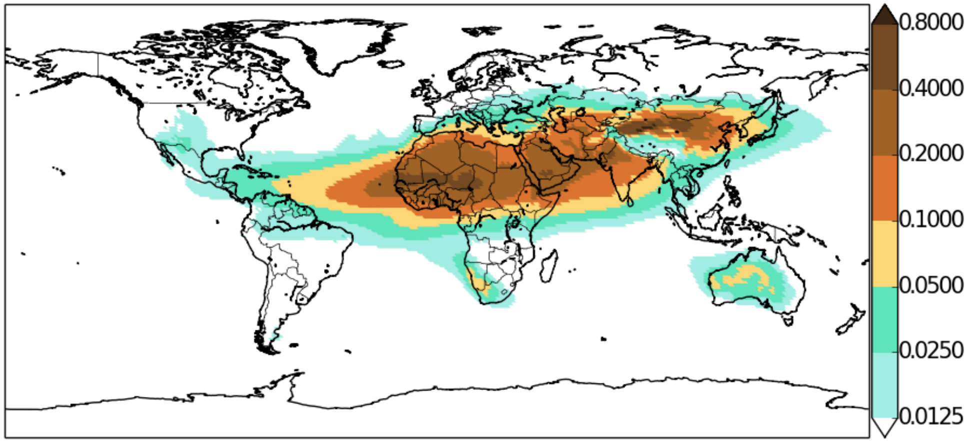


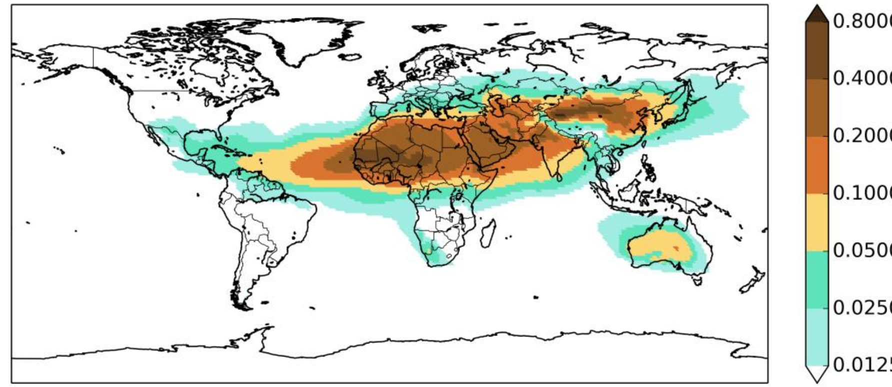
Prediction of the dust outbreak to Europe of April 2011 (Leader: Nicolas Huneeus)

Model-lidar comparison (Leader: Ioannis Binietoglou)

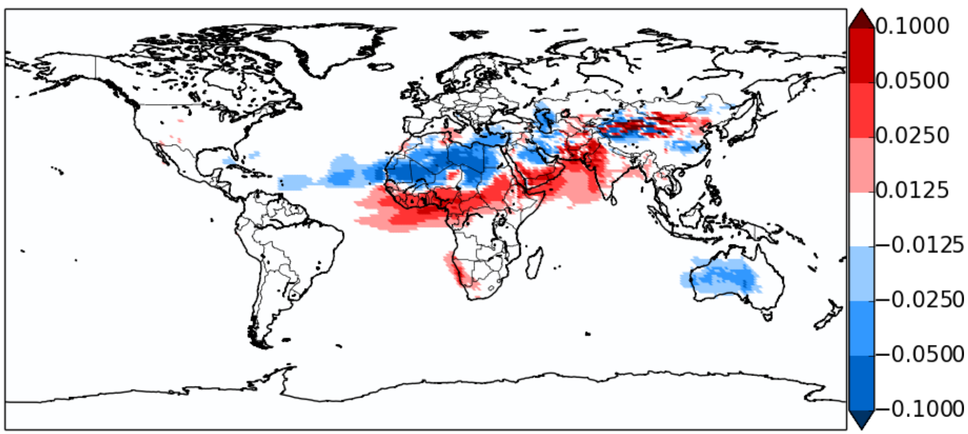
Study of a haboob in Tehran (Leader: Ana Vukovic)

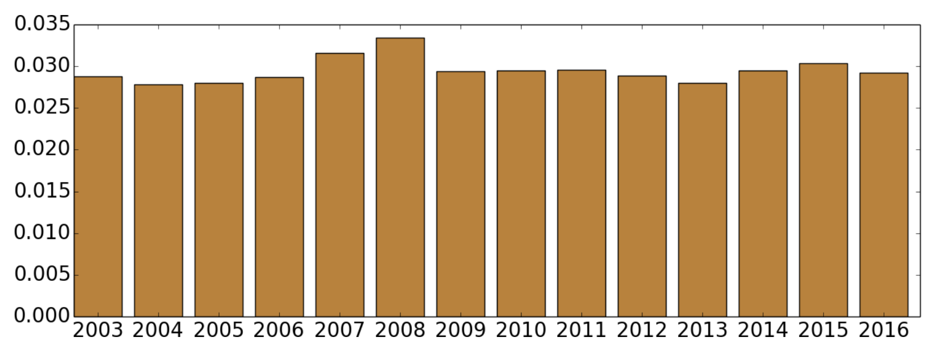
Climate monitoring





Average dust AOD at 550 nm 2003-2015. Based on CAMS reanalysis





Average dust AOD medio at 550 nm in 2016 and its anomaly. Based on CAMS forecasts. Source: WMO Airborne dust bulletin N. 1

Summary

- Atmospheric aerosol
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- Barcelona Dust Forecast Center
- Dust observation
- Dust forecast

Barcelona Dust Forecast Center

May 2013

WMO designates the consortium of AEMET and the BSC to host the first operational center of dust prediction (RSMC-ASDF). The Center shall operationally generate and distribute dust forecasts for Northern Africa, Middle East and Europe

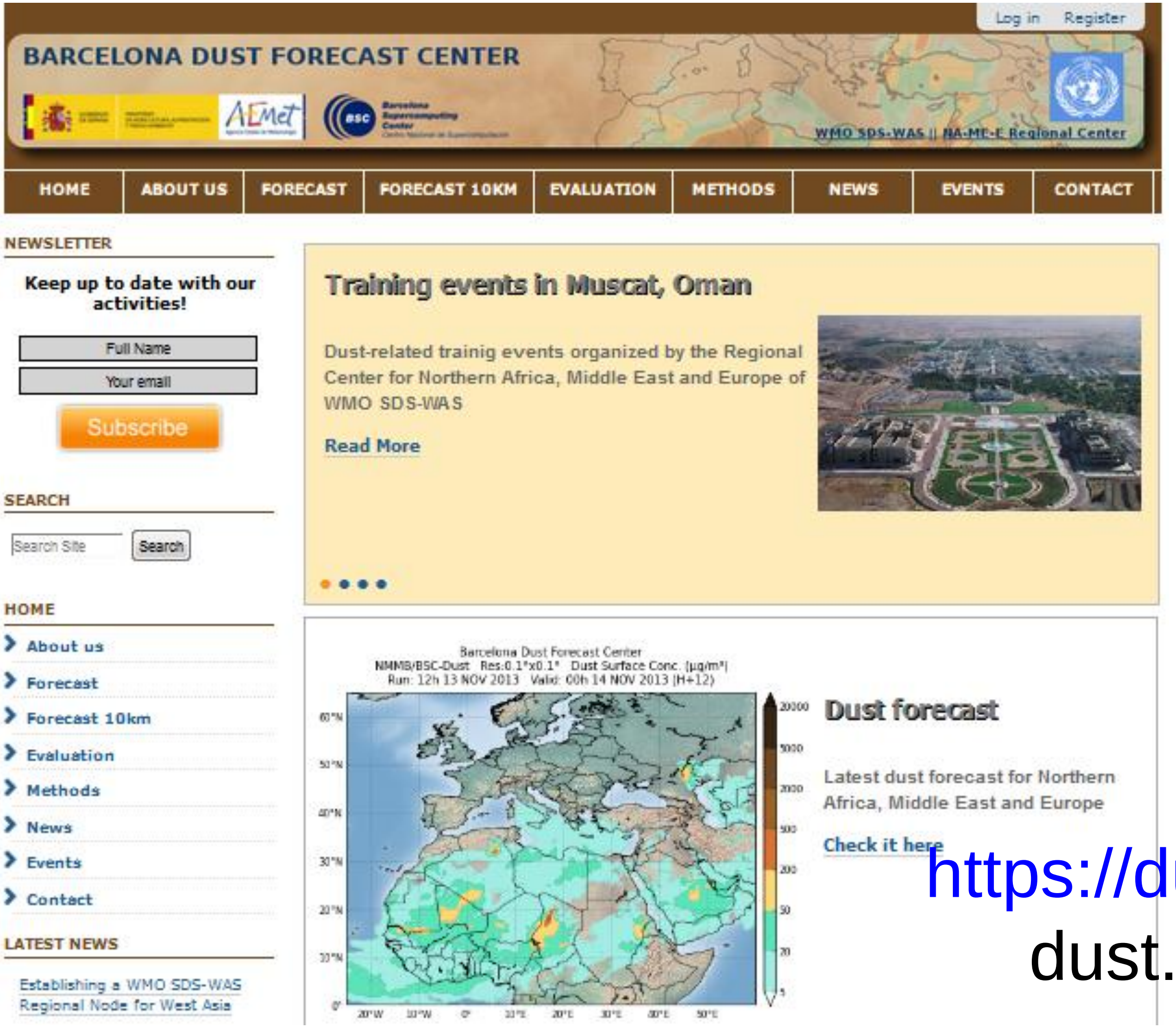
Feb 2014

The Center starts operations under the name of Barcelona Dust Forecast Center (BDFC)

Jun 2017

WMO designates CMA to host a similar center for Asia

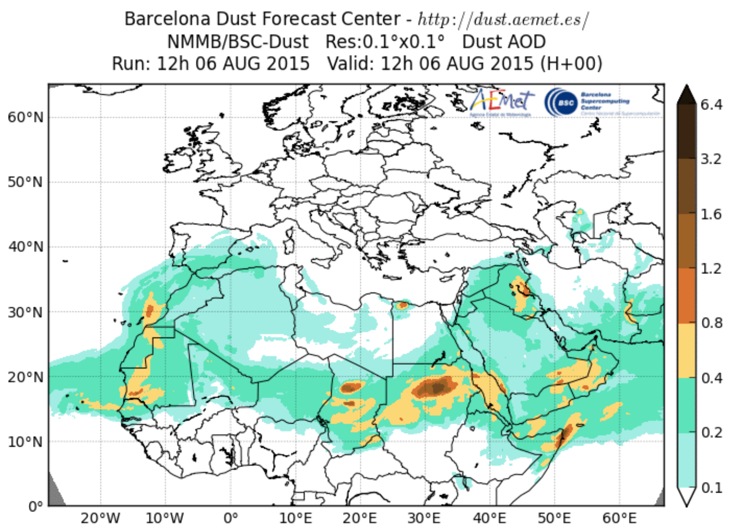
Barcelona Dust Forecast Center

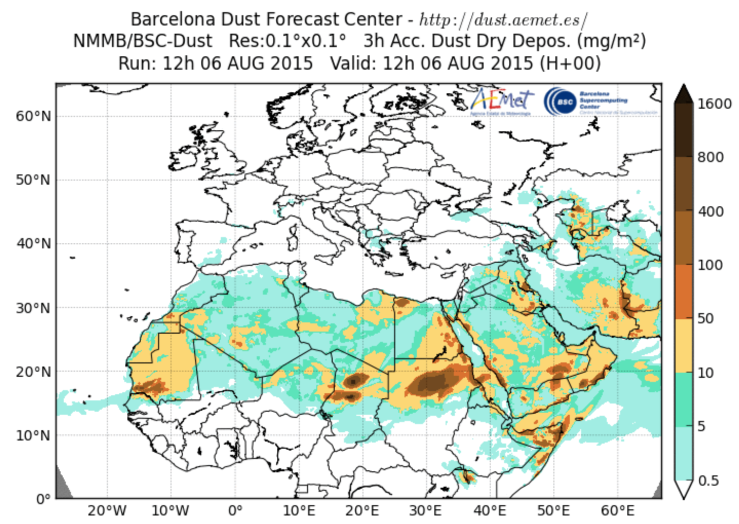


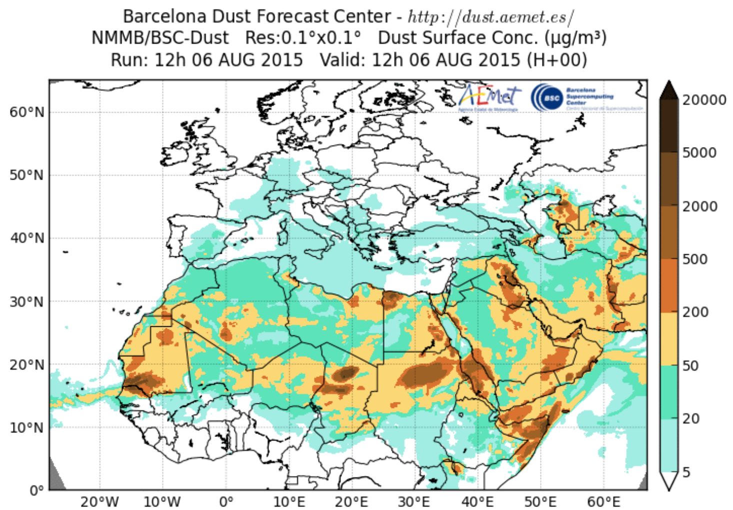
https://dust.aemet.es

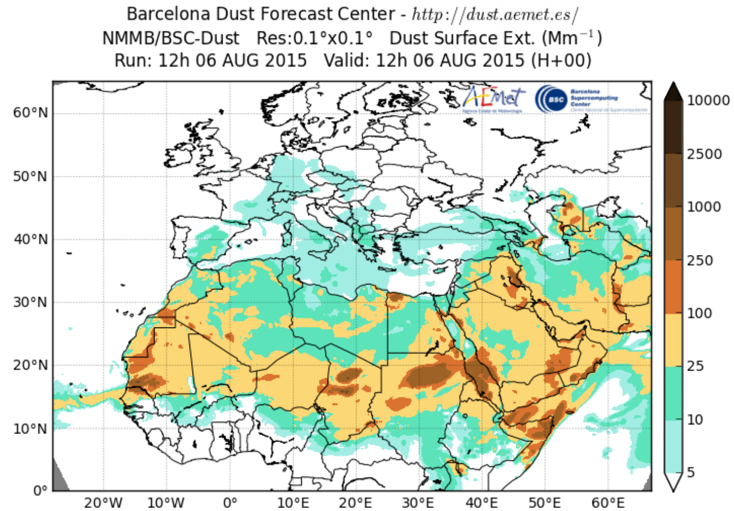
dust.aemet.es

Products



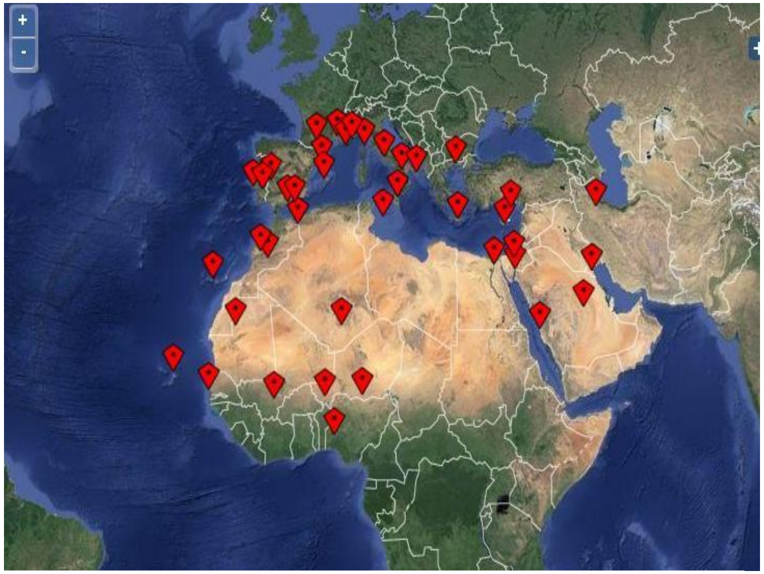


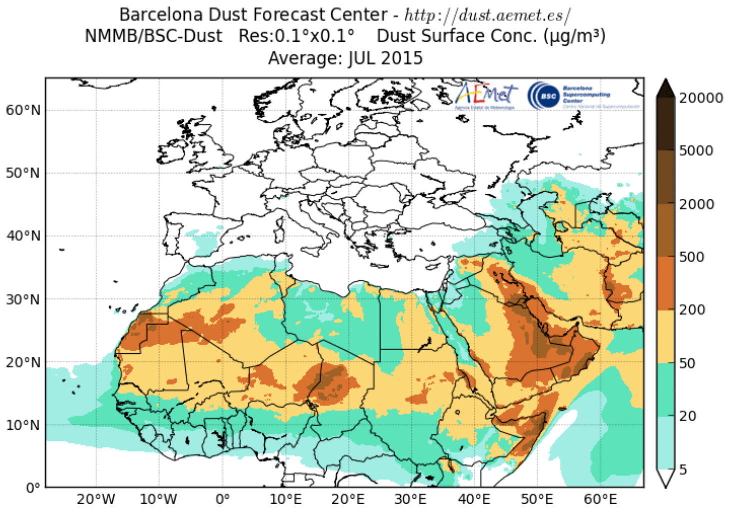


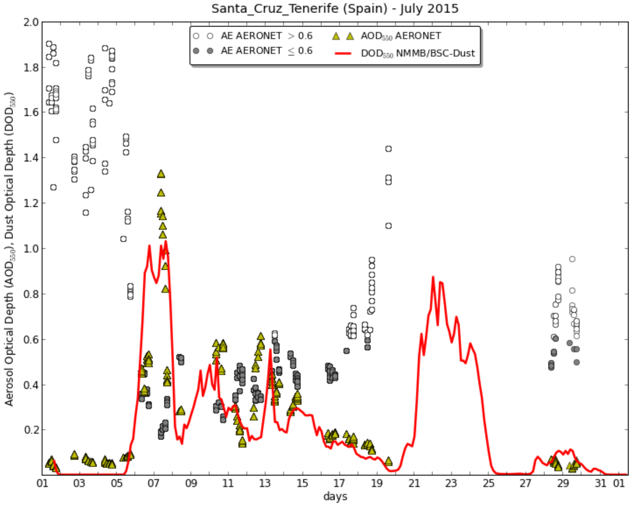


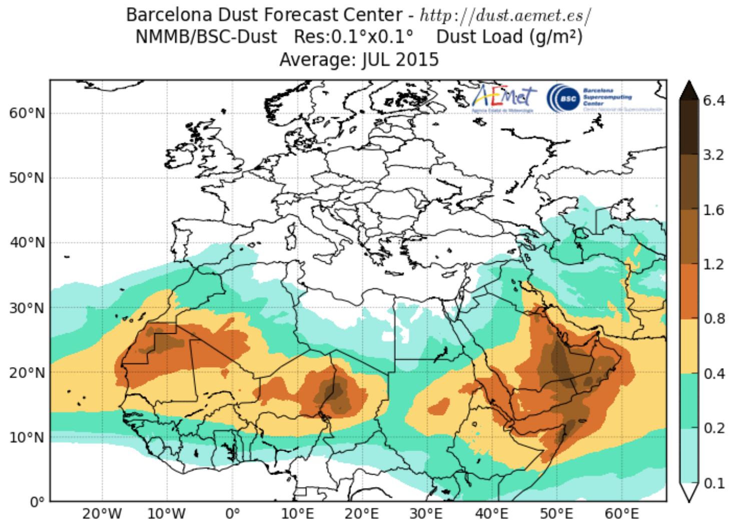
6 variables
Prediction: 0-72h

Other products

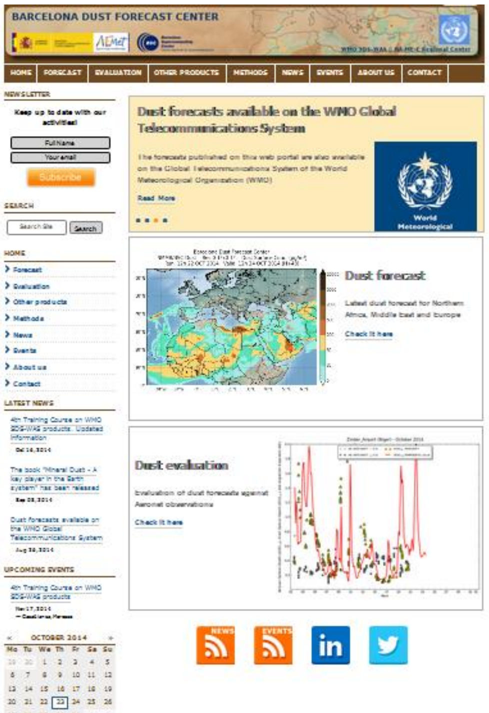








Dissemination

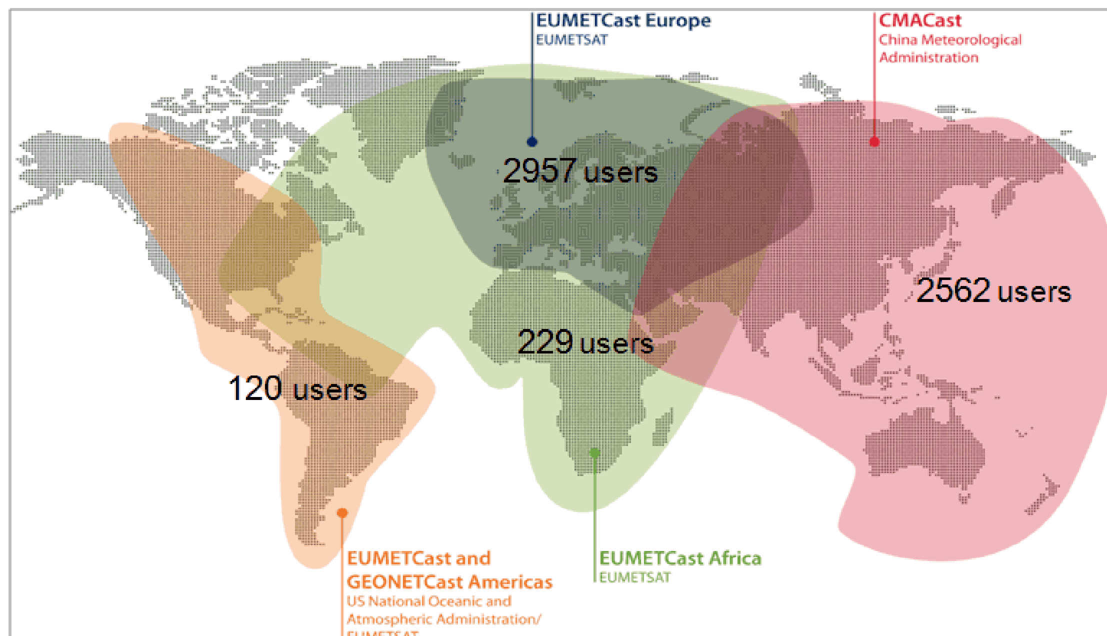


https://dust.aemet.es

WMO Global Telecommunications System

World Meteorological Organization

EUMETCast



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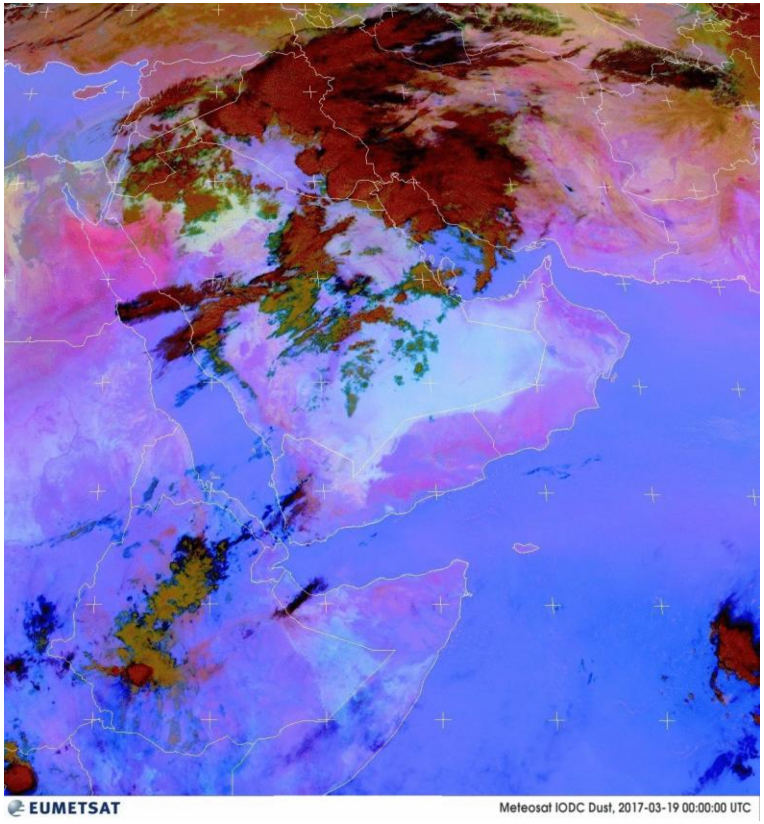
Why do we need dust observation?

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

Mali, 2001
Foto: Remi Benali/Corbis

Monitoring: satellite products



EUMETSAT

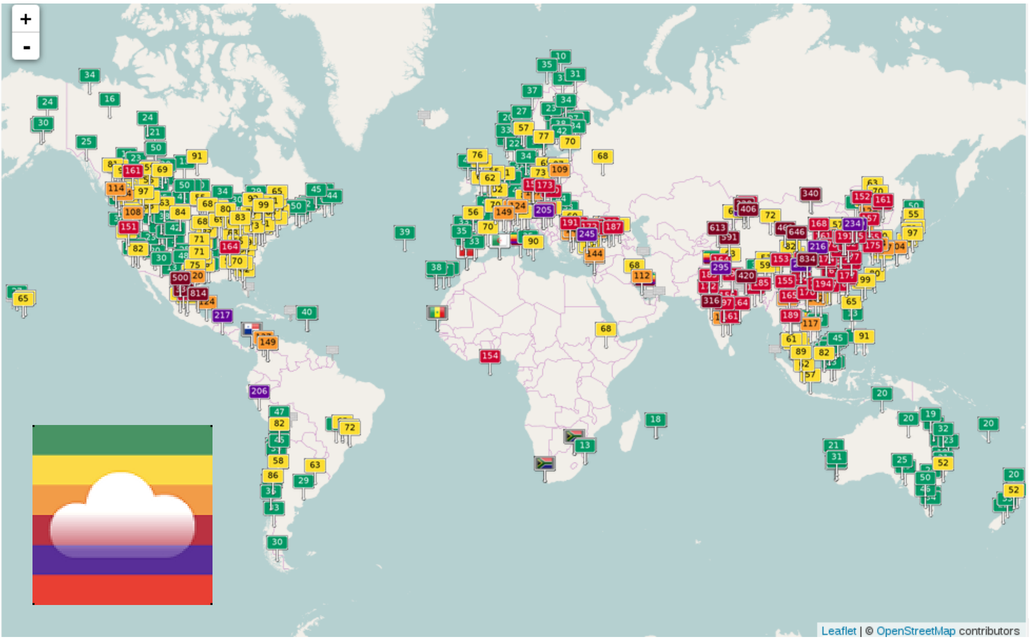
19 Mar 2017: The sandstorm named Madar, originated in Libya, swept through Egypt, Saudi Arabia, Iraq, Kuwait and Iran

- 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:

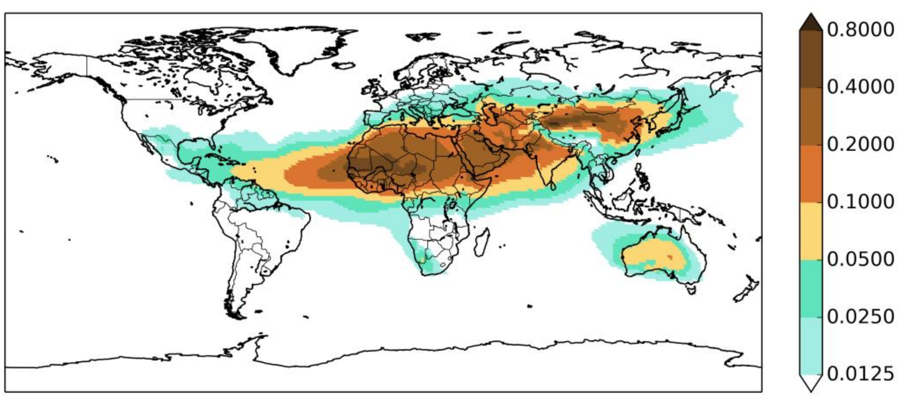
- Qualitative product
- Without information from cloudy areas
- Vertical integration. Without information on near-surface conditions

Monitoring: AQ stations



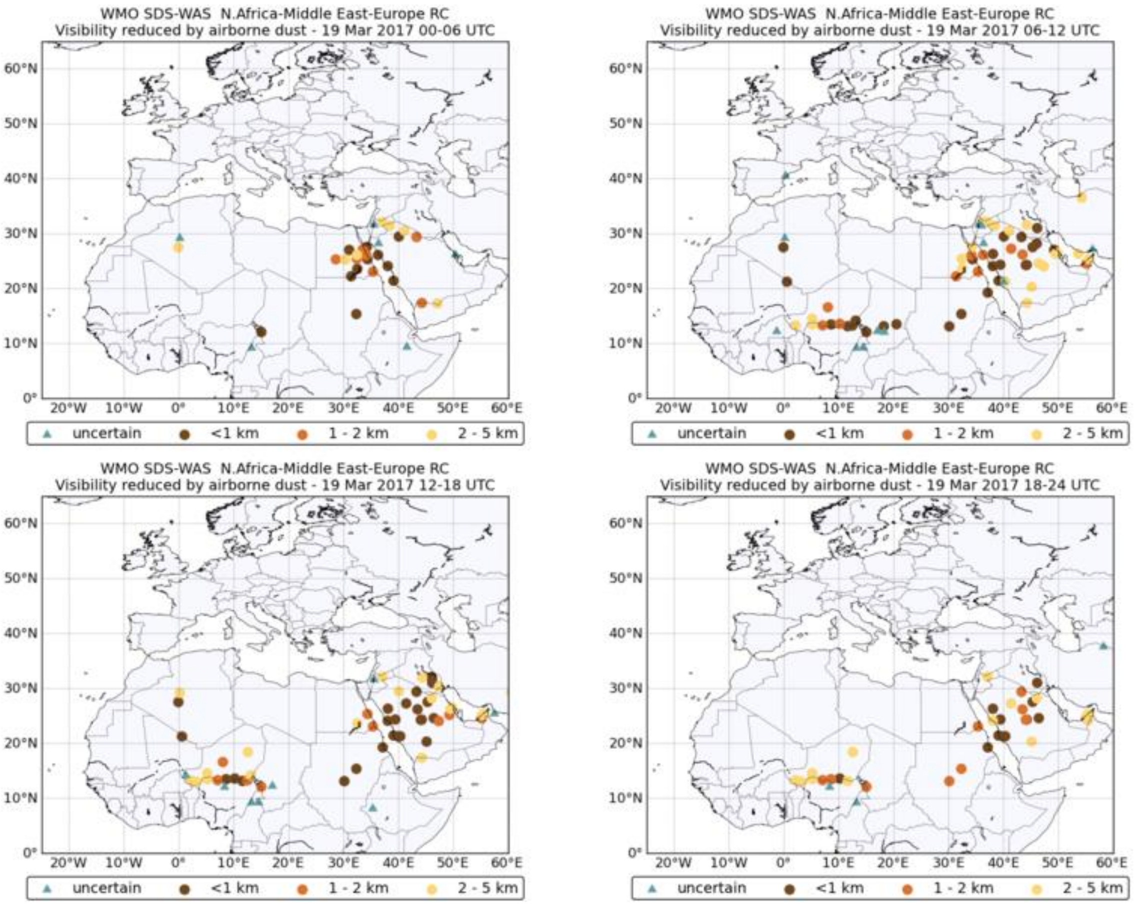
Drawbacks:

- 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



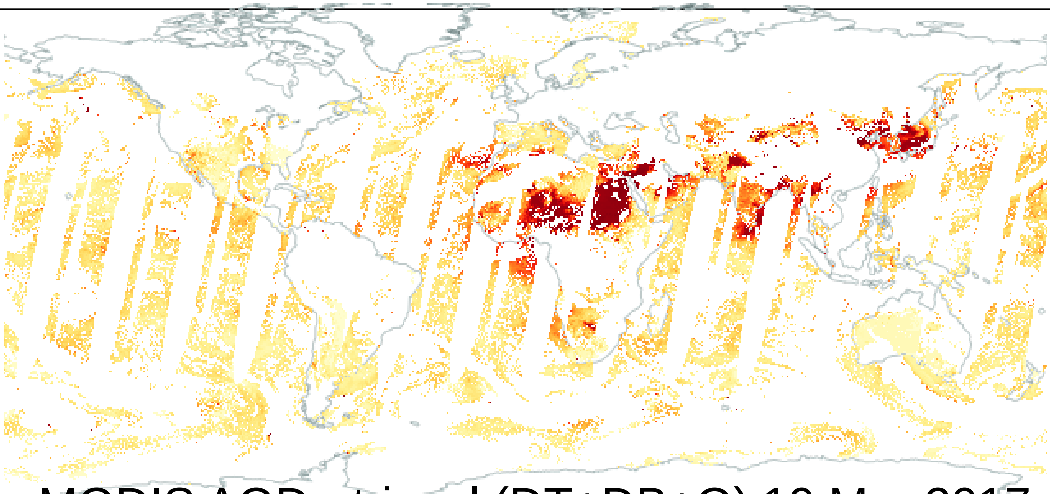
19 Mar 2017

Drawbacks:

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

https://sds-was.aemet.es

Data assimilation

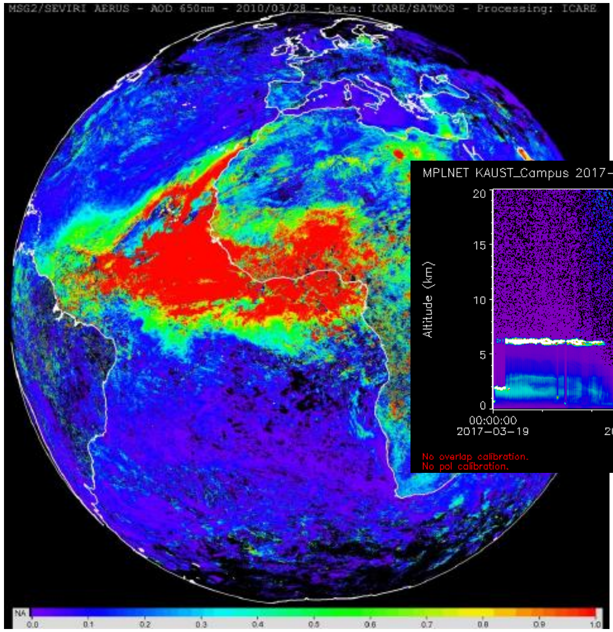


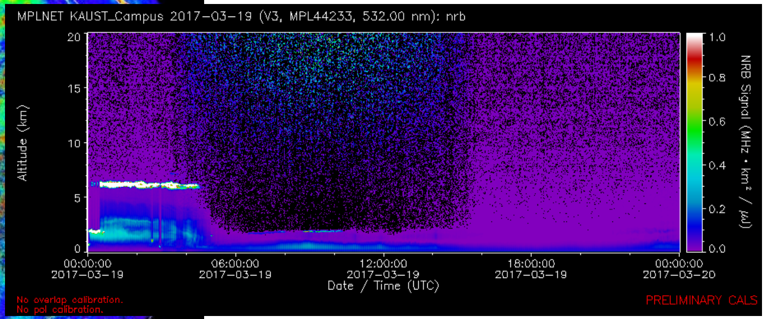
MODIS AODretrieval (DT+DB+O) 19 Mar 2017

Drawbacks:

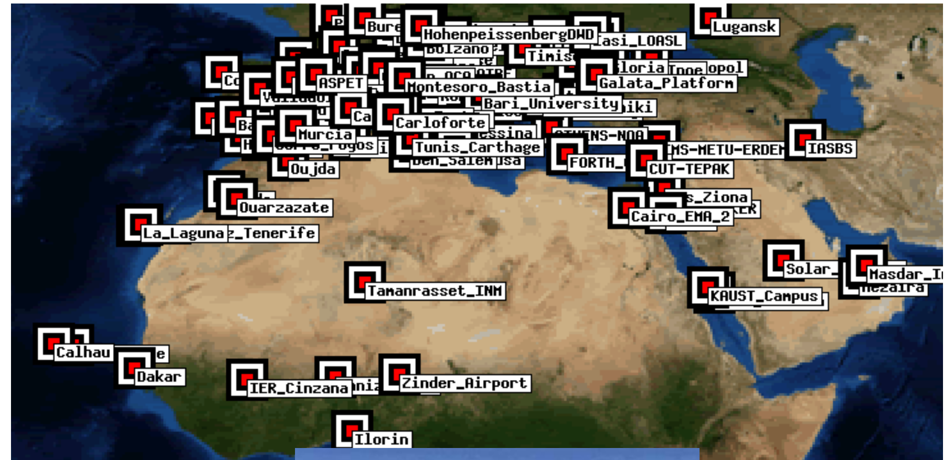
- Lack of suitable observations
- Complexity of extracting the dust signal from the measured radiance

- 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





Verification: sun photometers



AERONET
Aerosol Robotic Network

- 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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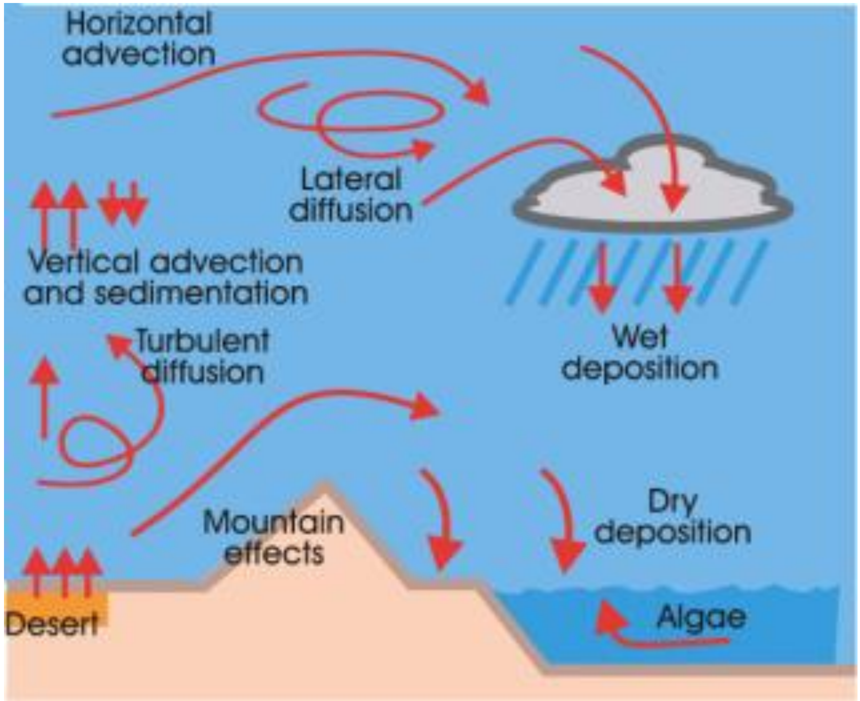
Dust prediction models

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
- …

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

Tegen et al. (1994)

$$\boldsymbol{F = \sum_i C_i u^2 (u - 6.5)}$$

Marticorena et al. (1997)

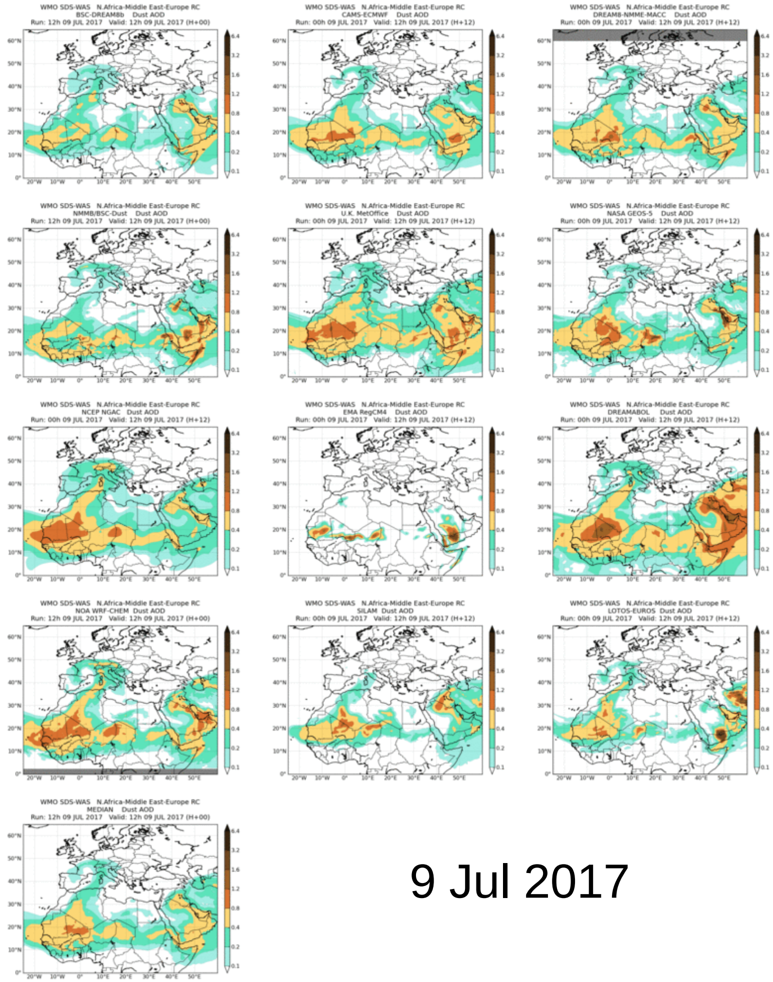
$$\boldsymbol{F = \propto \frac{\rho}{g} u_*^3 \sum_i s_i \left(1 + \frac{u_{*tri}}{u_*}\right)\left(1 - \frac{u_{*tri}^2}{u_*^2}\right)}$$

Ginoux et al. (2001)

$$\boldsymbol{F = CS \sum_i u^2 s_i w_0 (u - u_{tri})}$$

Dust model intercomparison

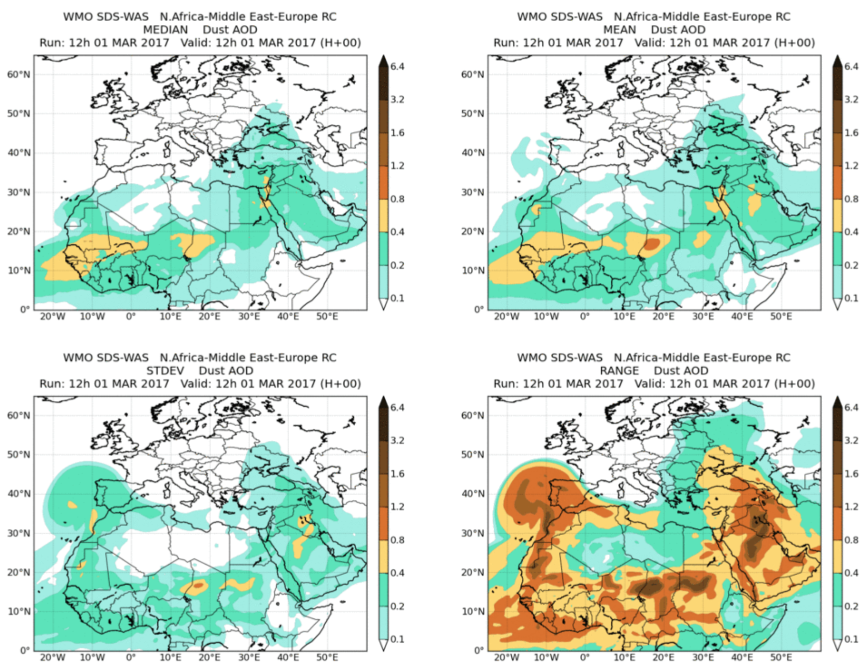
MODEL	INSTITUTION	DOMAIN	DATA ASSIMILATION
BSC-DREAM8b	BSC-CNS	Regional	No
CAMS	ECMWF	Global	MODIS AOD
DREAM-NMME-MACC	SEEVCCC	Regional	MACC analysis
NMMB/BSC-Dust	BSC-CNS	Regional	No
MetUM	Met Office	Global	MODIS AOD
GEOS-5	NASA	Global	MODIS reflectances
NGAC	NCEP	Global	No
RegCM4	EMA	Regional	No
DREAMABOL	CNR	Regional	No
NOA WRF-CHEM	NOA	Regional	No
SILAM	FMI	Regional	No
LOTOS-EUROS	TNO	Regional	No



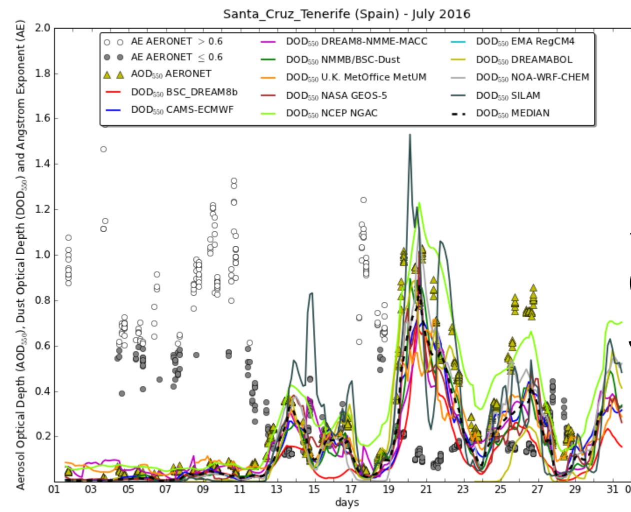
9 Jul 2017

Daily predictions of dust surface concentration and optical depth from 12 models are collected by the SDS-WAS Regional Center

EPS / Verification



- A monthly, seasonal and annual routine evaluation is conducted using AOD data from 40 AERONET stations
- Only observations with an Angstrom exponent of less than 0.6 are used in order to rule out those cases where dust is not the dominant aerosol type
- Models are also evaluated with MODIS AOD (only those that do not assimilate this product)



Santa Cruz de Tenerife Jul 2016

- The predictions of the 12 models are interpolated to a common grid mesh. Then, multi-model products are generated.
- The median presents better verification scores than any of the models