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Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Dust forecasting models

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Questions will be wellcome!

Introduction

What do we need to forecast dust storms?

1. Satellites, surface observations, NWP models and dust models.
2. Good knowledge of the dust climatology in the region.
3. Good knowledge of observation limitations.
4. Good knowledge of the dust model limitations.

Outlook

1. **Dust cycle and associated processes**

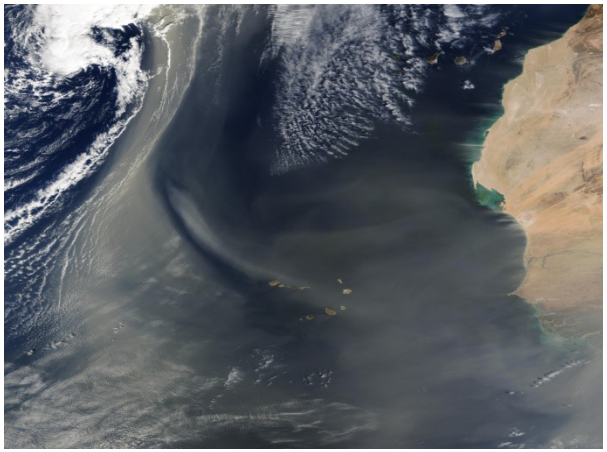
   - *The atmospheric dust cycle*
   - *Dust global climatology*
   - *Types of dust storms and model forecasting skills*

2. **Dust forecasting models**

   - *Dust emission schemes and dust sources*
   - *Dust transport*
   - *Dust deposition and sedimentation*
   - *Model evaluation and model intercomparison*

Dust cycle and associated processes

MODIS true colour composite image for March 2005 depicting a dust storm initiated at the Bodélé Depression (Chad Basin)

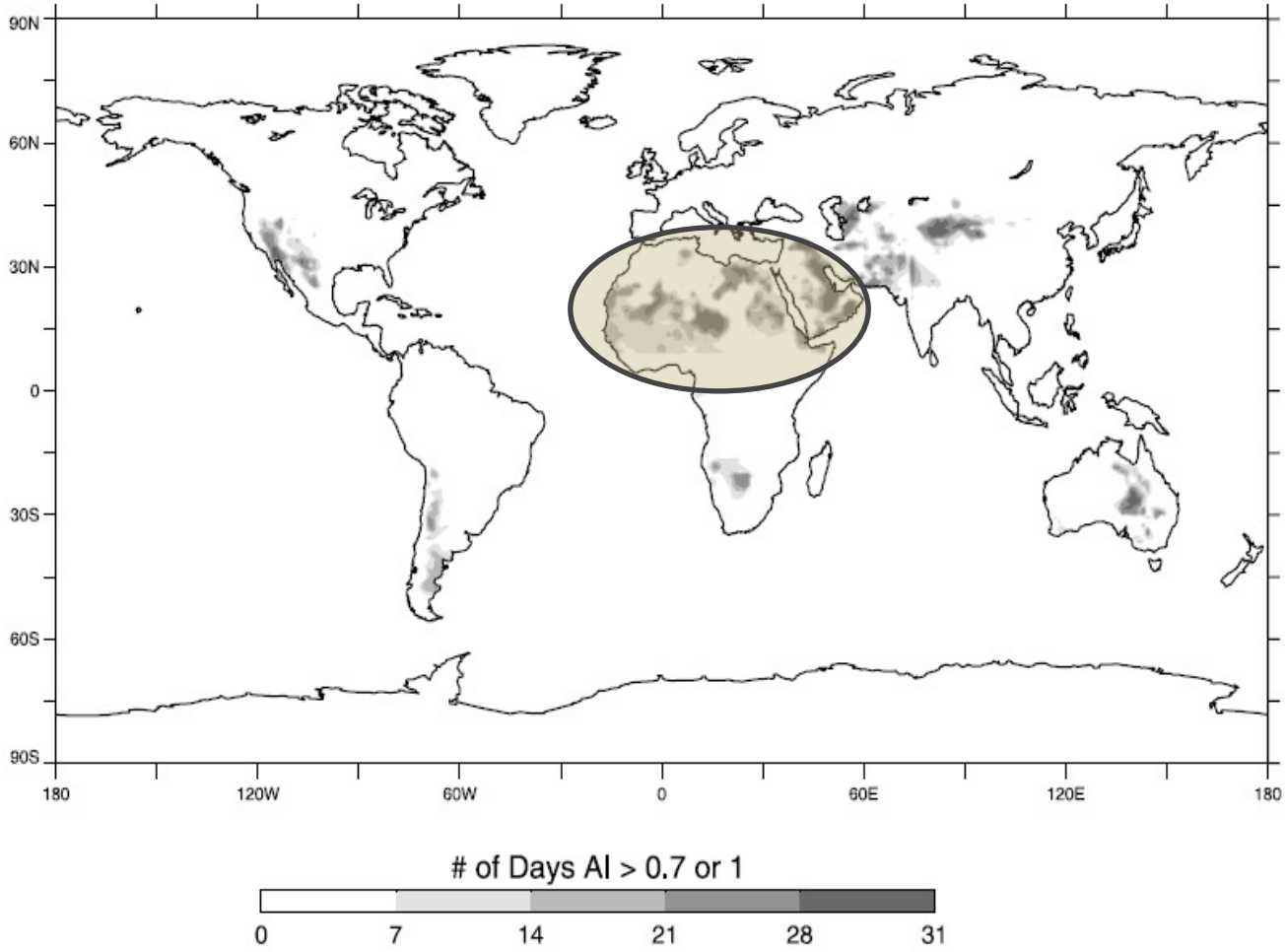


MODIS True color Western Africa – Altantic Ocean

People caught in a dust storm in Mali

Dust cycle and associated processes

Dust global distribution

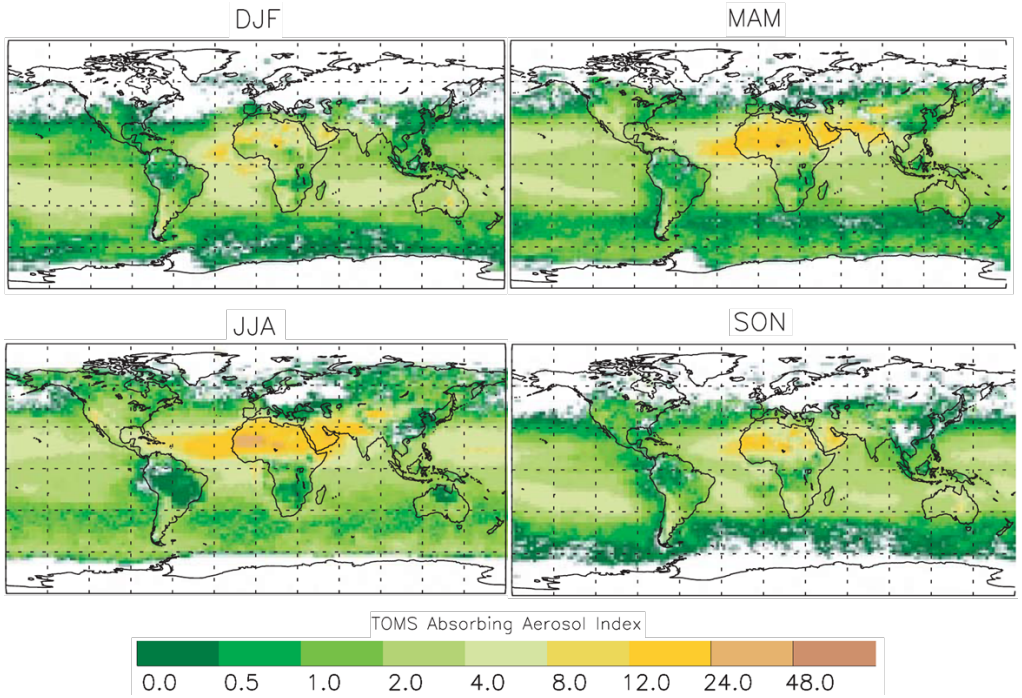


The global distribution of **TOMS** dust sources.

Extracted from Prospero et al. (2002, Rev. Geophys.)

Dust cycle and associated processes

Temporal changes in the dust distribution: SEASONAL and DECADAL CHANGES

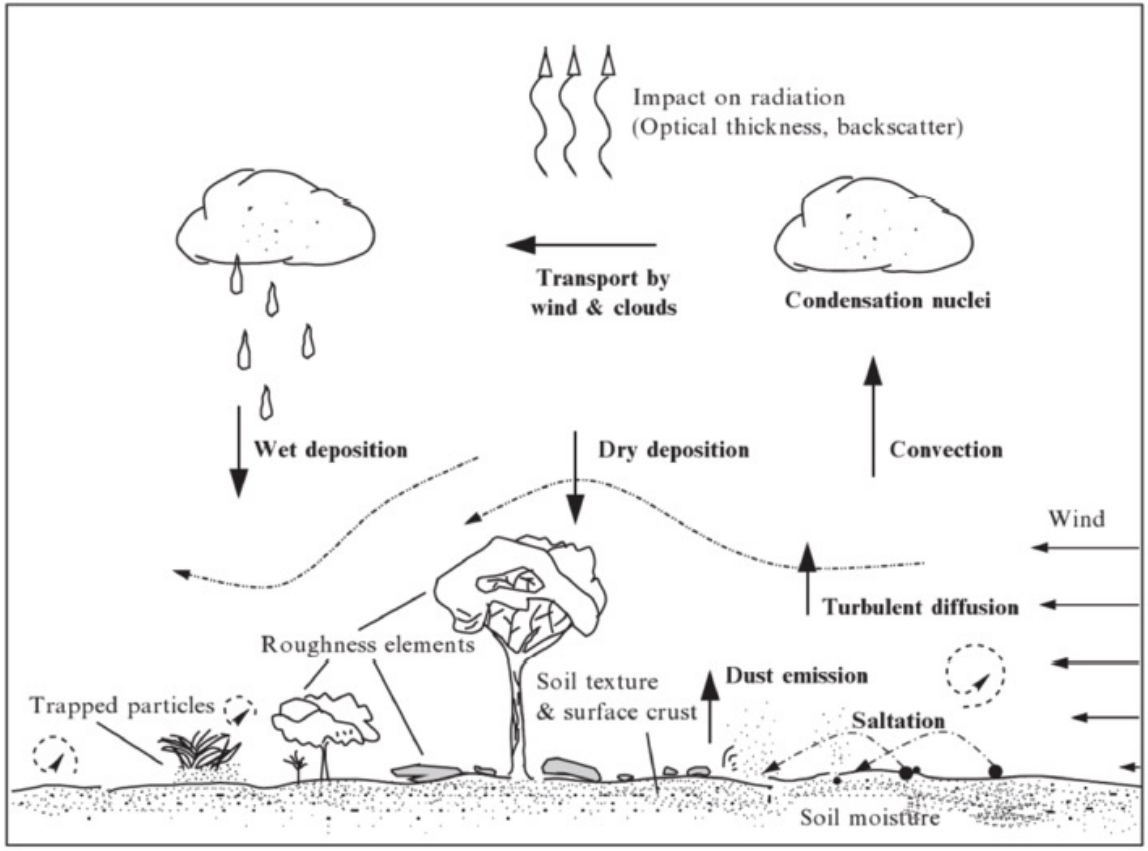


- Seasonal dust distribution changes well characterized. Follows seasonal changing weather regimes (mainly) and vegetation changes (in semi-arid areas)

- Interannual/decadal changes are controlled by climate and surface modification (land use, desertification). Decadal changes are not well captures by models

Dust cycle and associated processes

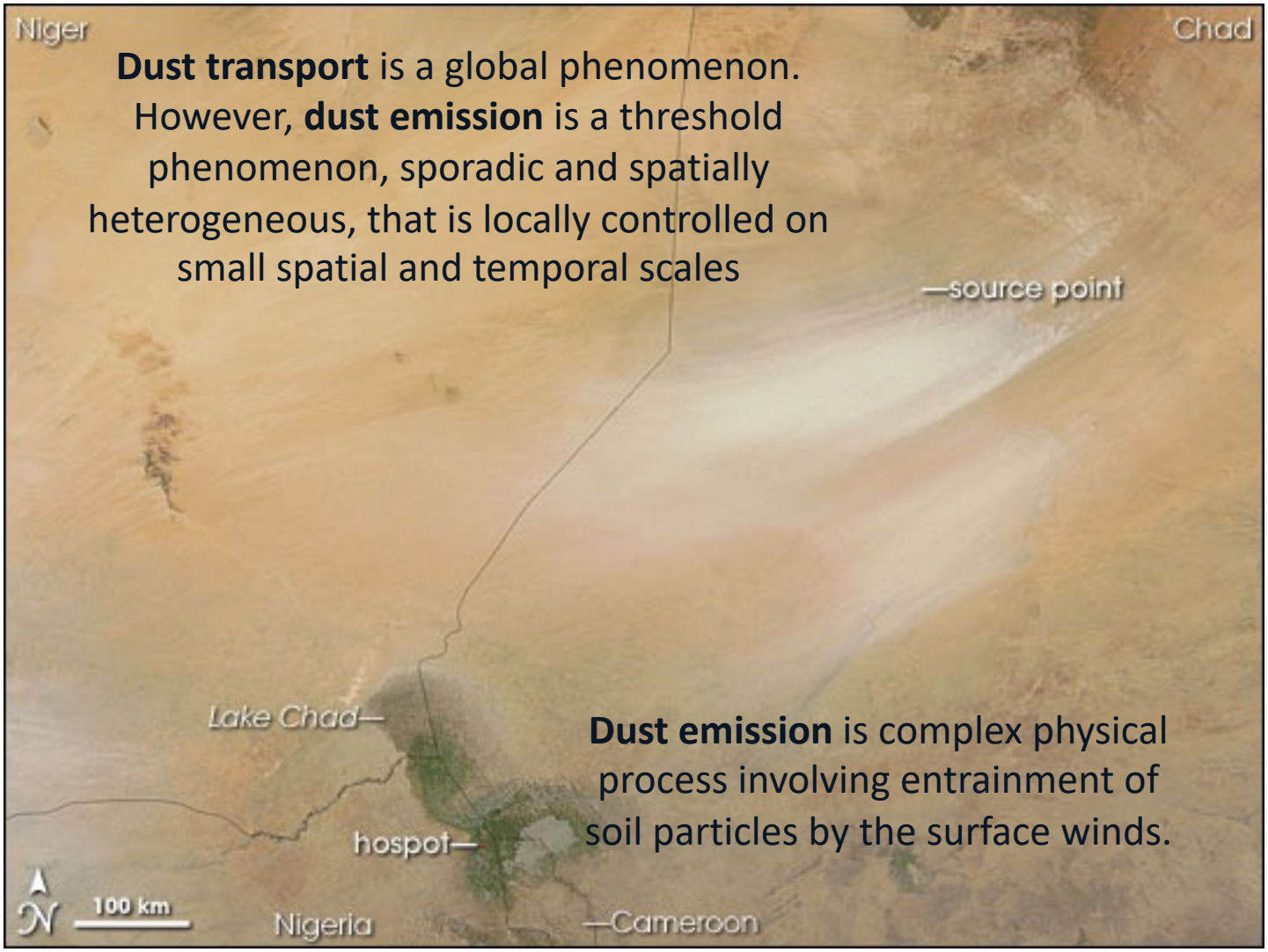
The atmospheric dust cycle and involves a variety of processes:



Extracted from Shao (2008)

- Dust emission from dry unvegetable surfaces (dust sources)
- Mid- and long-range transport
- Sedimentation, wet and dry deposition
- Impact on meteorology

Dust cycle and associated processes



Dust cycle and associated processes

Types of dust storms:

Synoptic dust storms (large scale weather systems)

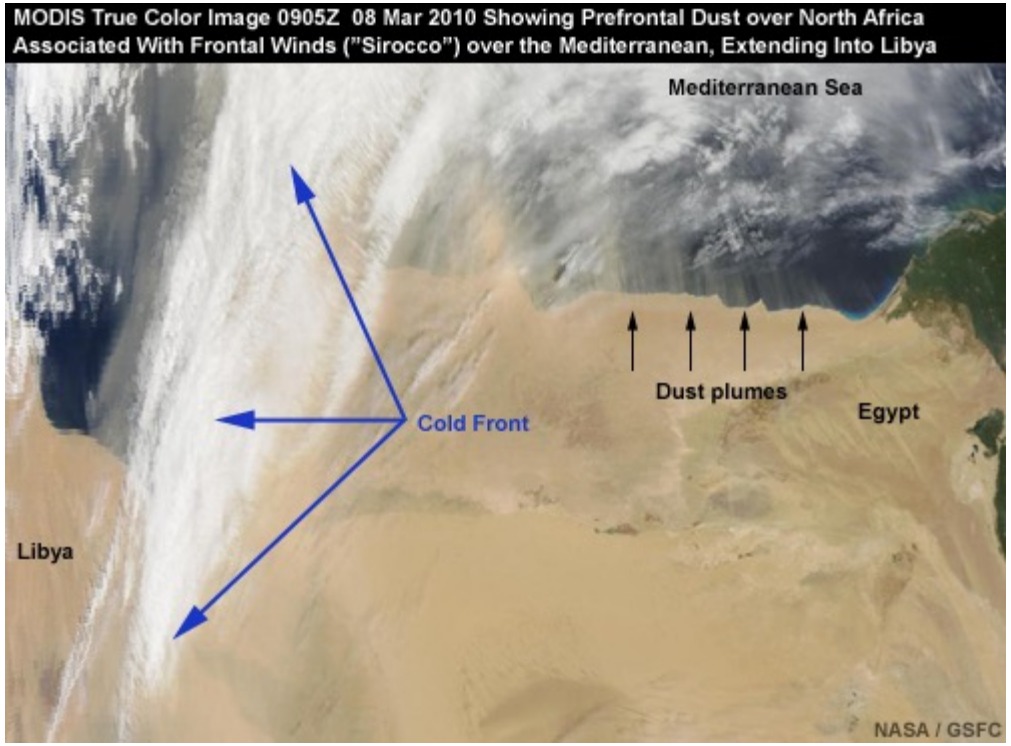
- Prefrontal winds
- Postprontal winds
- Large-scale Trade winds
- …

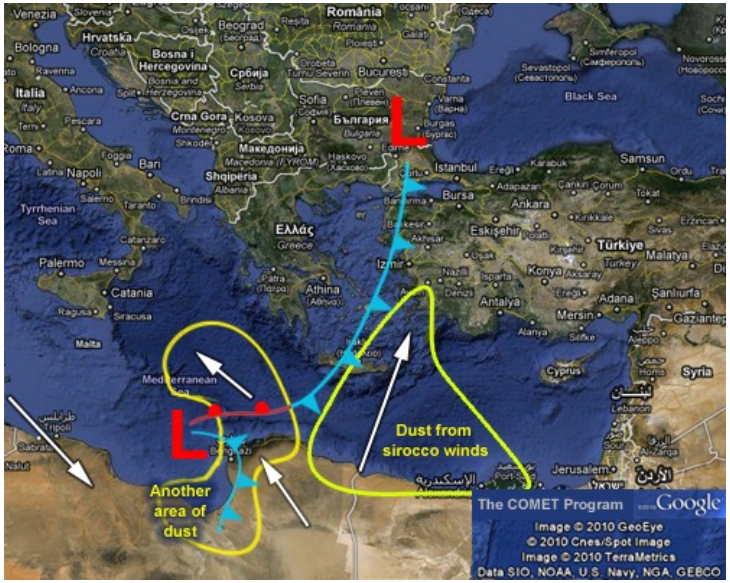
Mesoscale dust storms

- Downslope winds
- Gap flow
- Convection and Haboobs
- Inversion downburst storms
- …

Dust cycle and associated processes

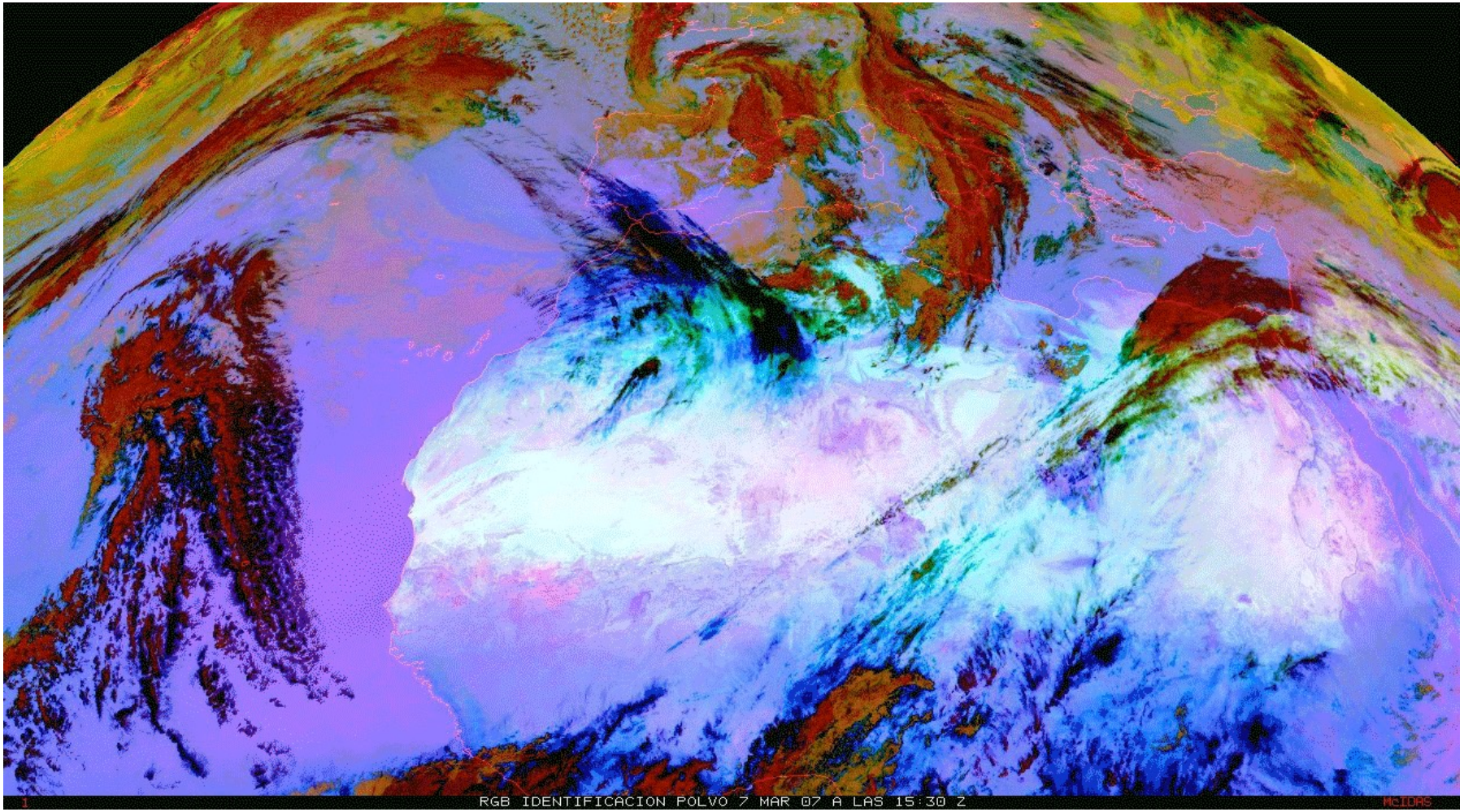
Synoptic dust storms: Pre-frontal





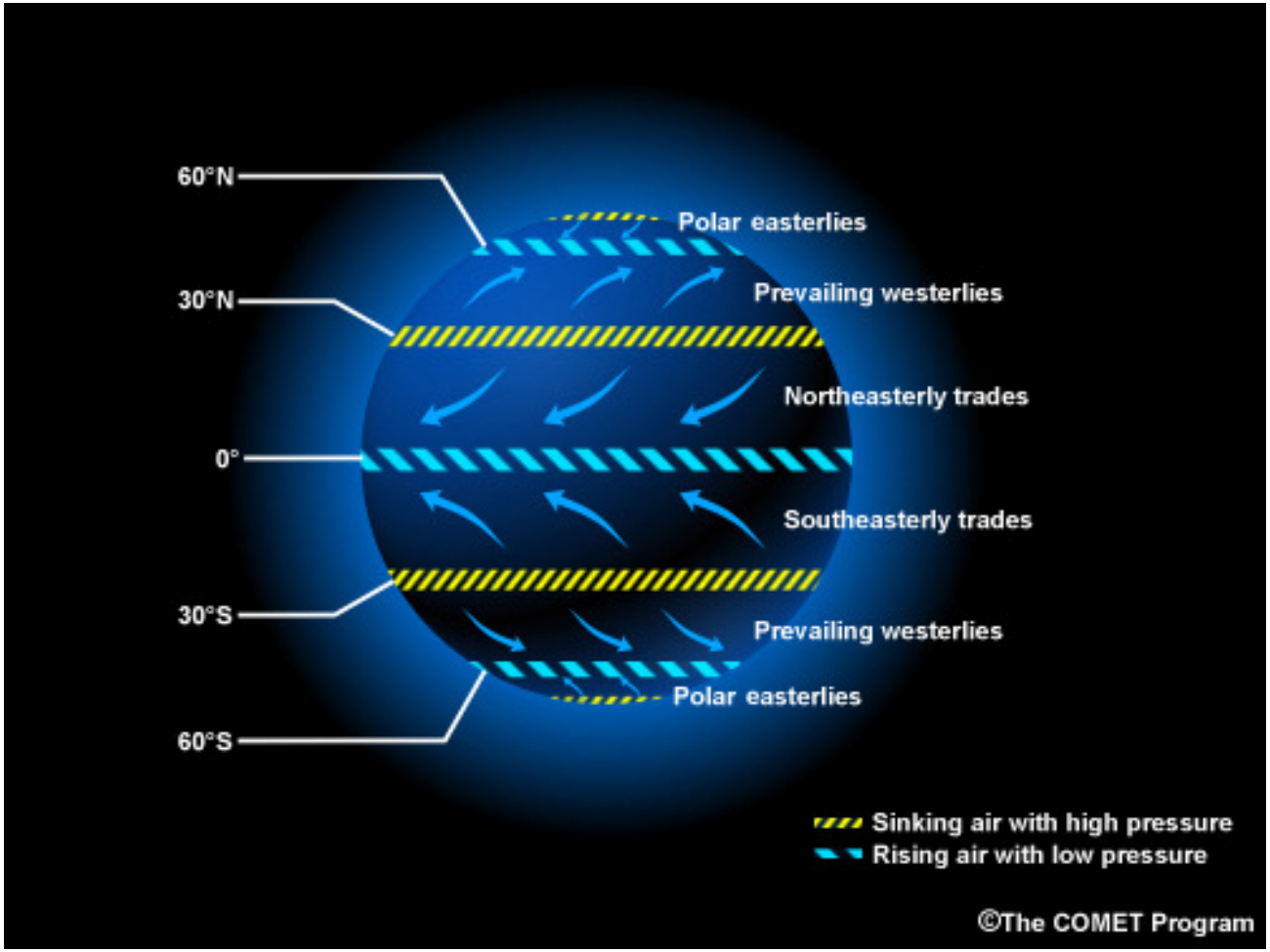
Dust cycle and associated processes

Synoptic dust storms: Post-frontal



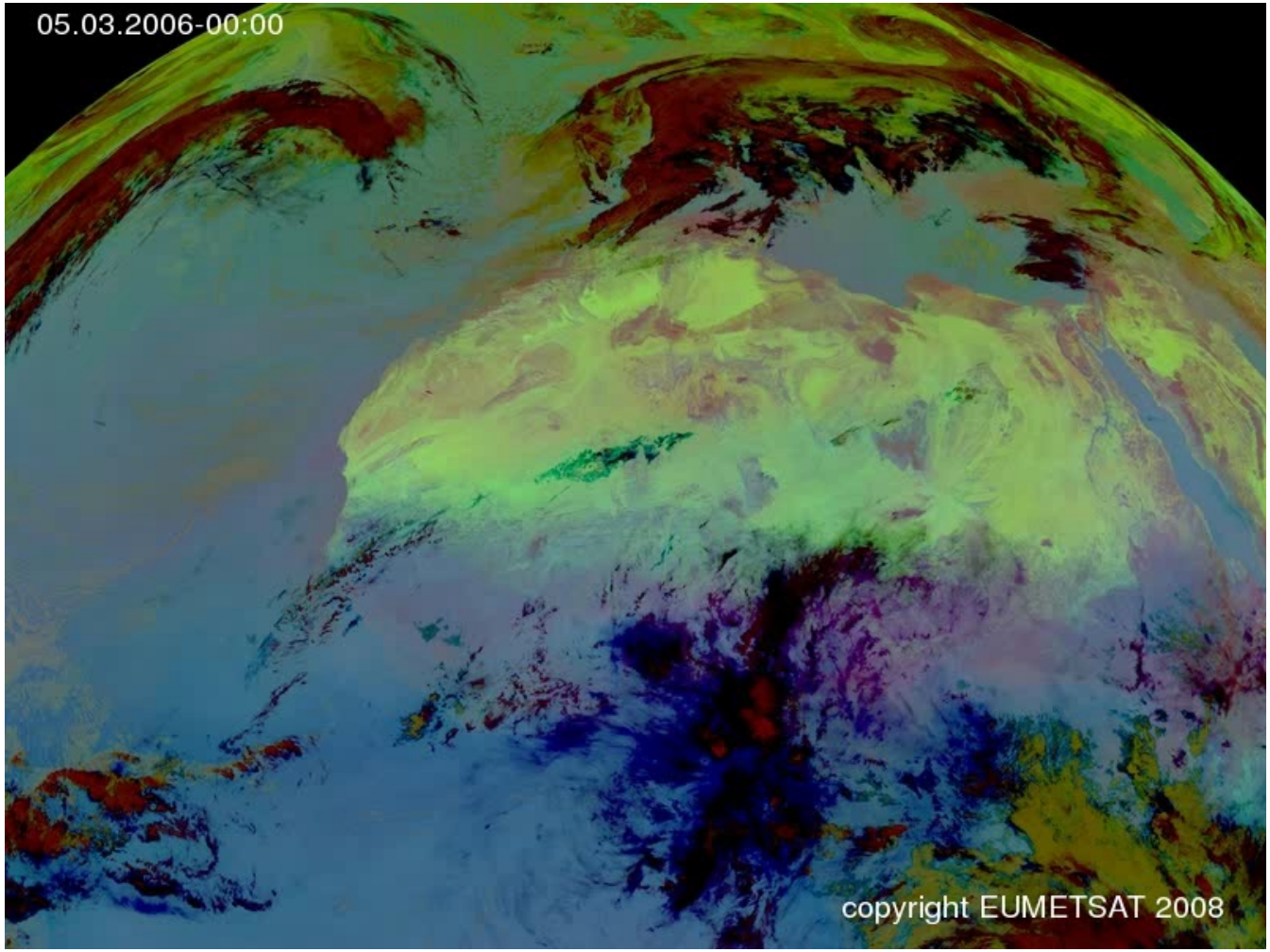
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



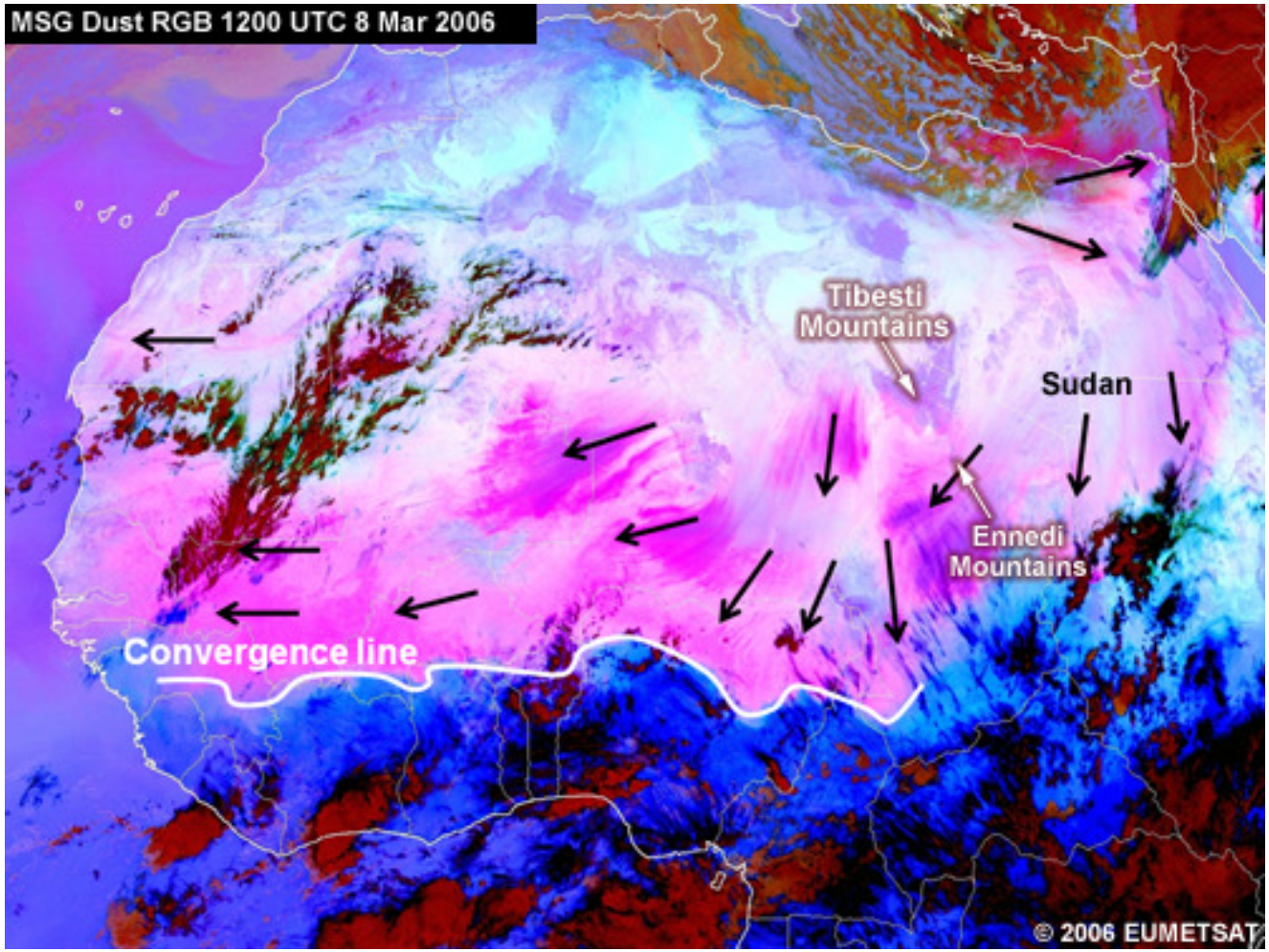
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



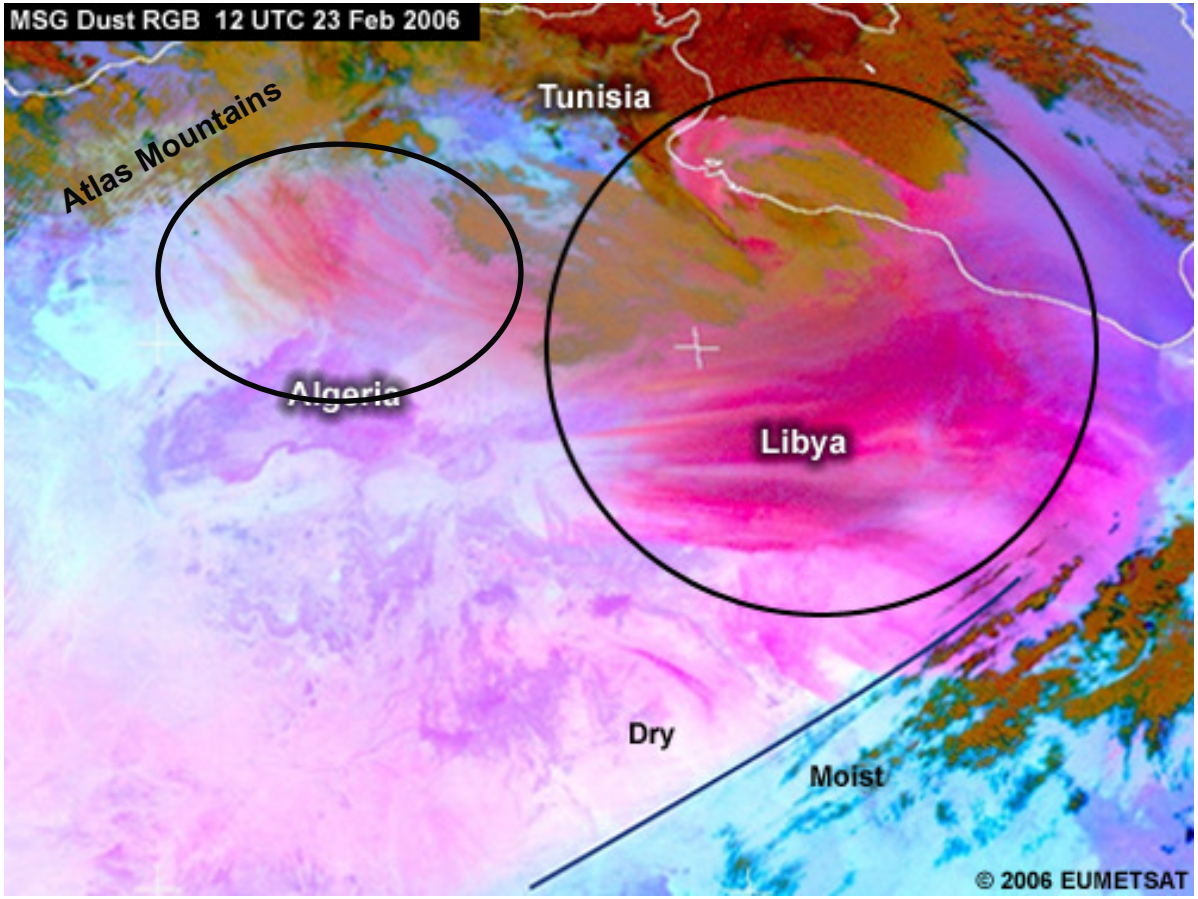
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



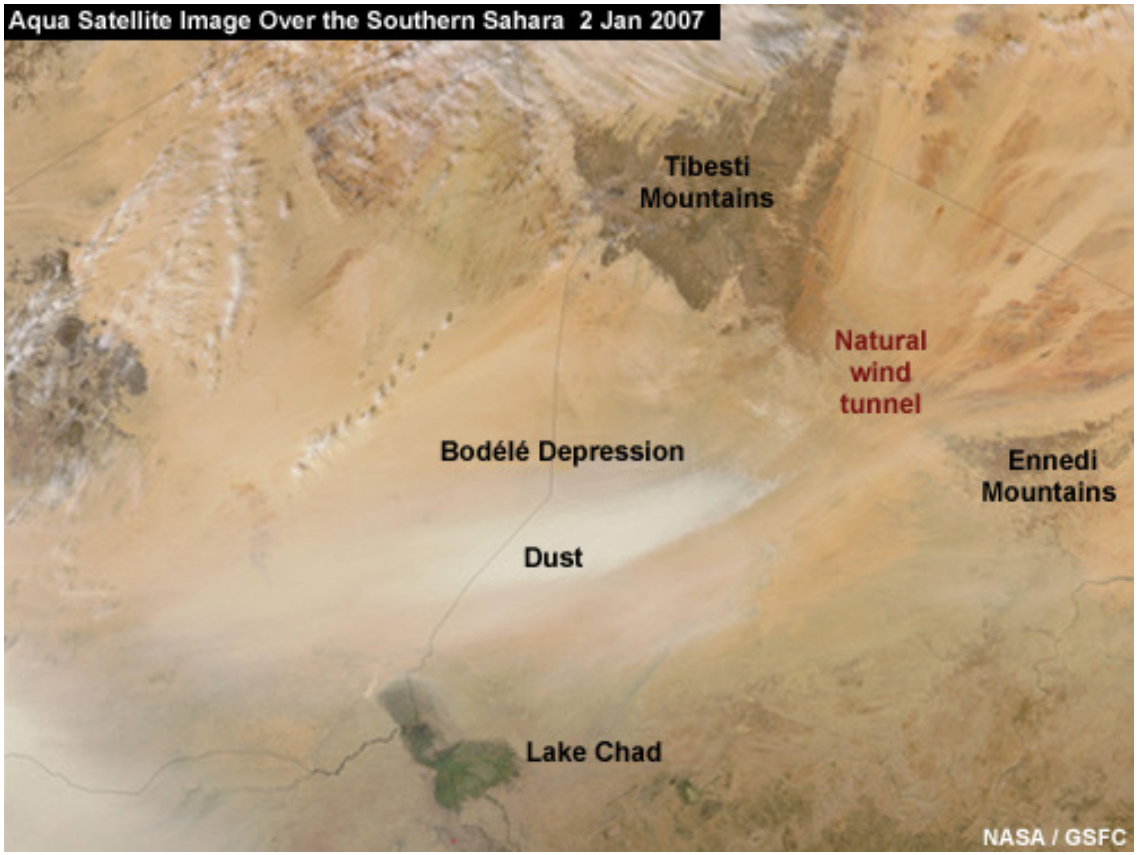
Dust cycle and associated processes

Mesoscale dust storms: Downslope winds



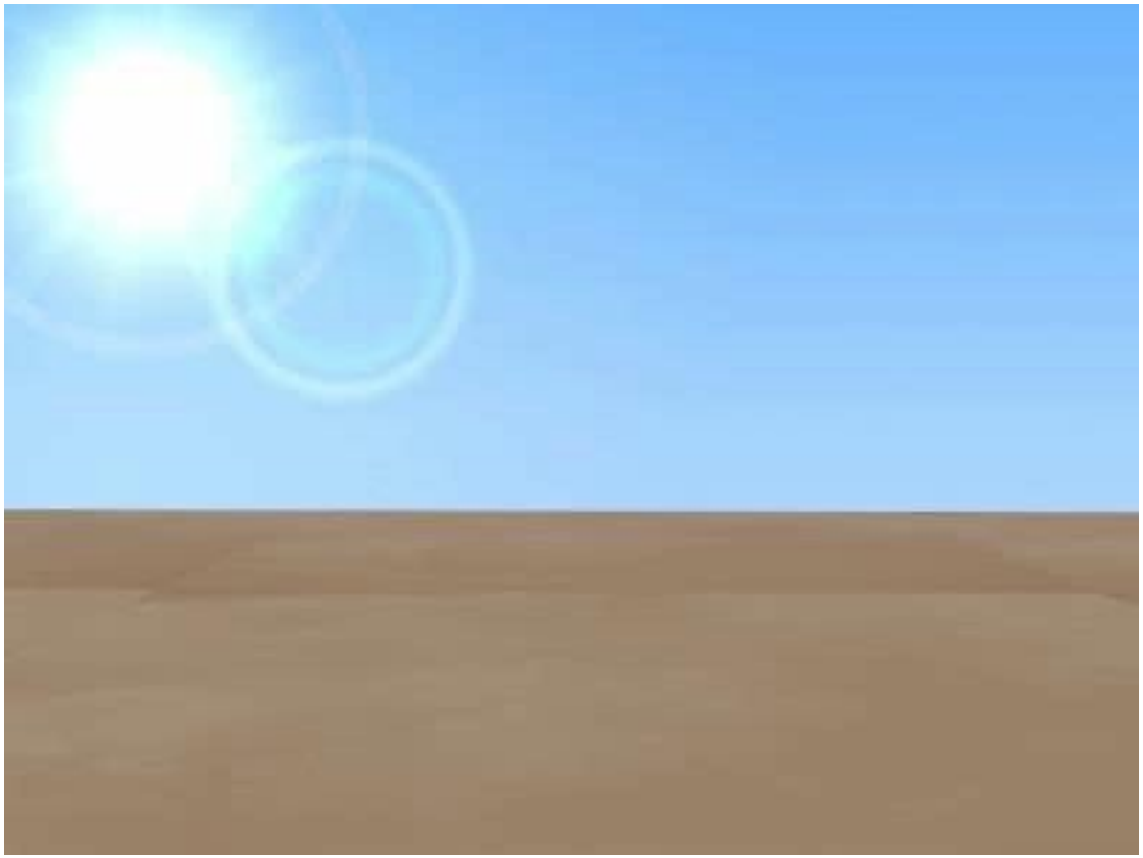
Dust cycle and associated processes

Mesoscale dust storms: Gap flow



Dust cycle and associated processes

Mesoscale dust storms: Dust devils (convection)



Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

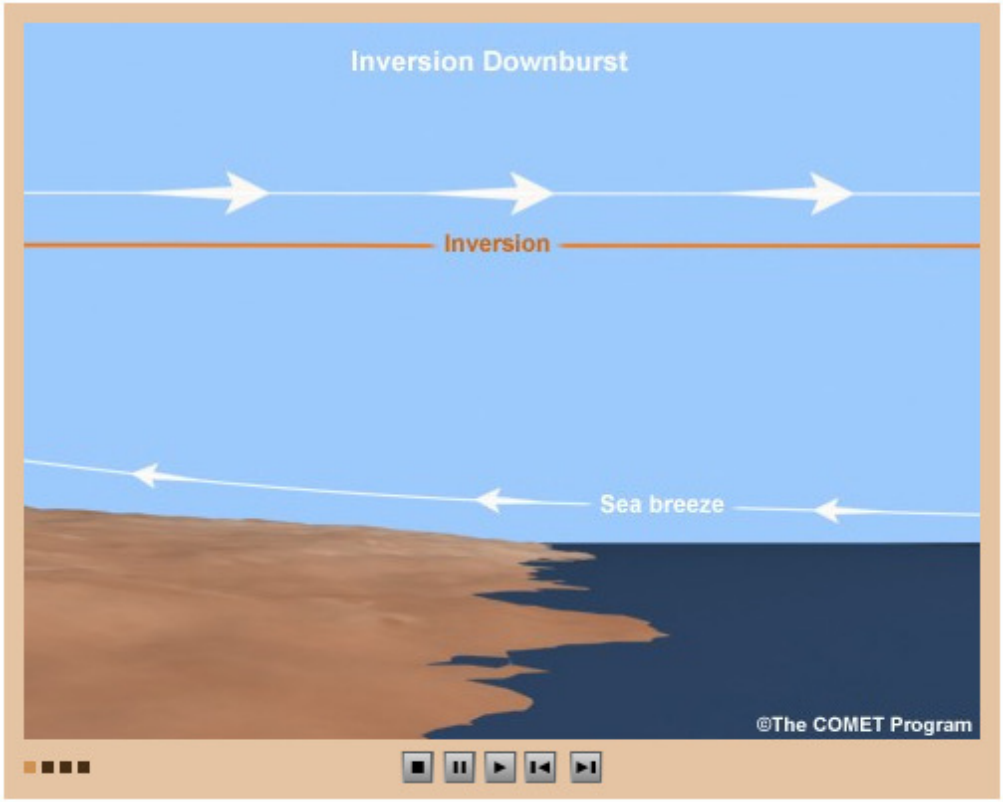
Dust cycle and associated processes

Mesoscale dust storms: Haboobs

Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust cycle and associated processes

Mesoscale dust storms: Inversion downbursts



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Dust cycle and associated processes

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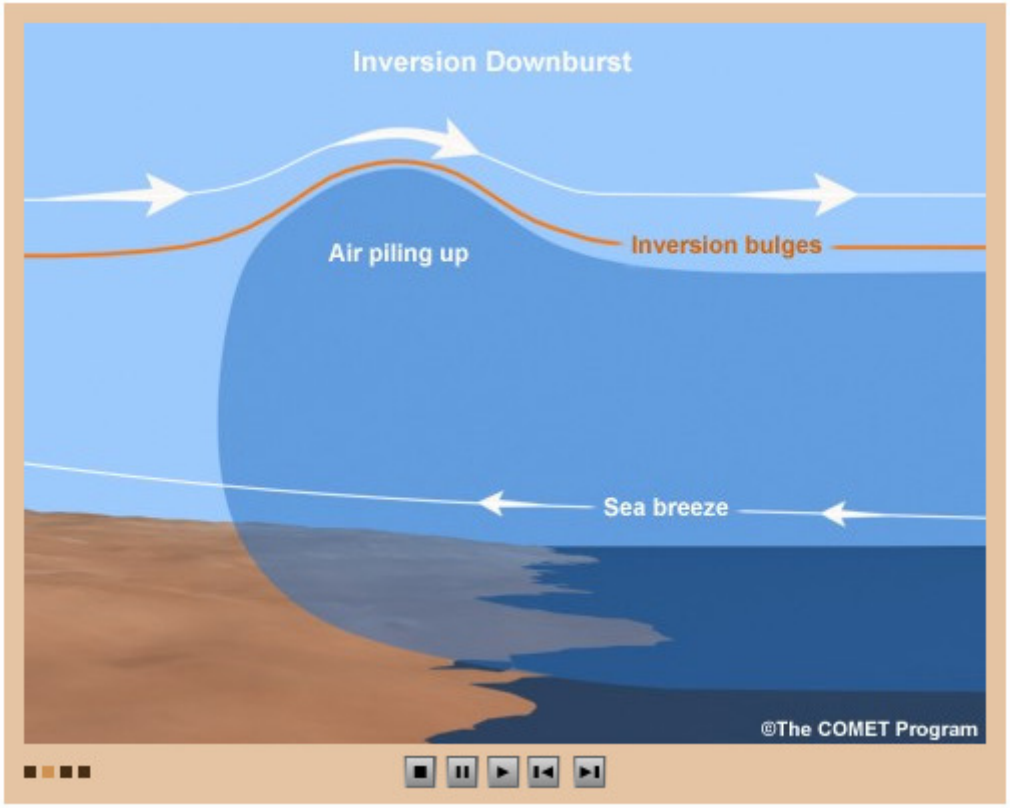

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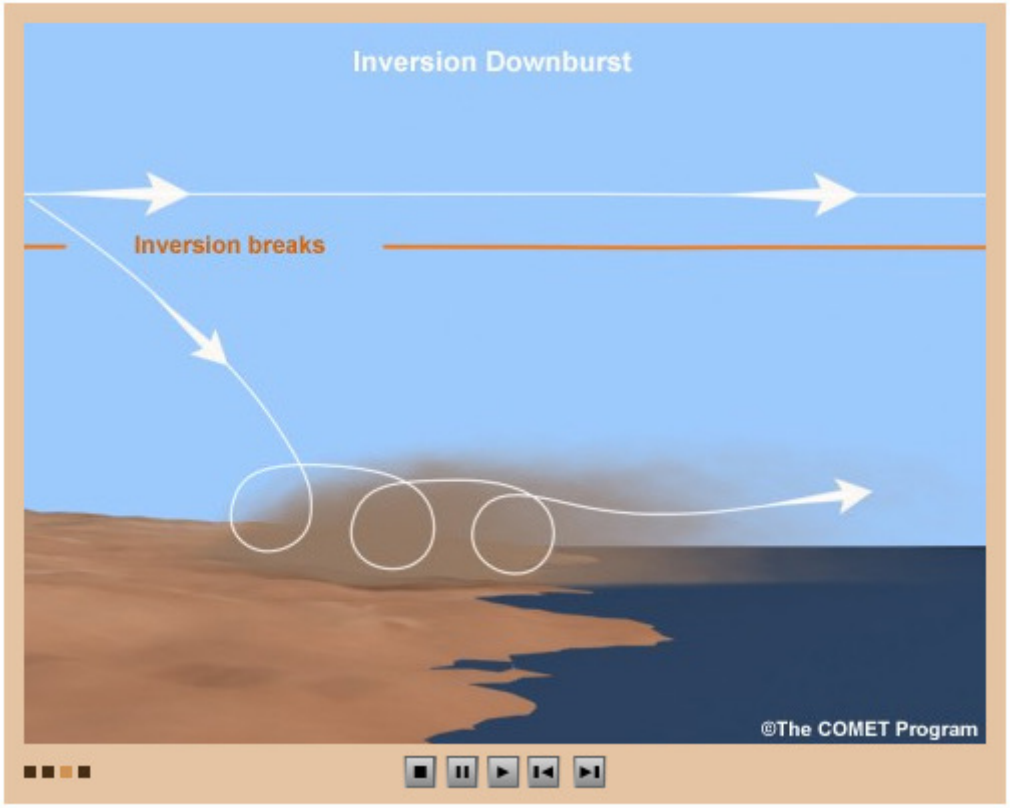
Dust cycle and associated processes

Mesoscale dust storms: Inversion downbursts



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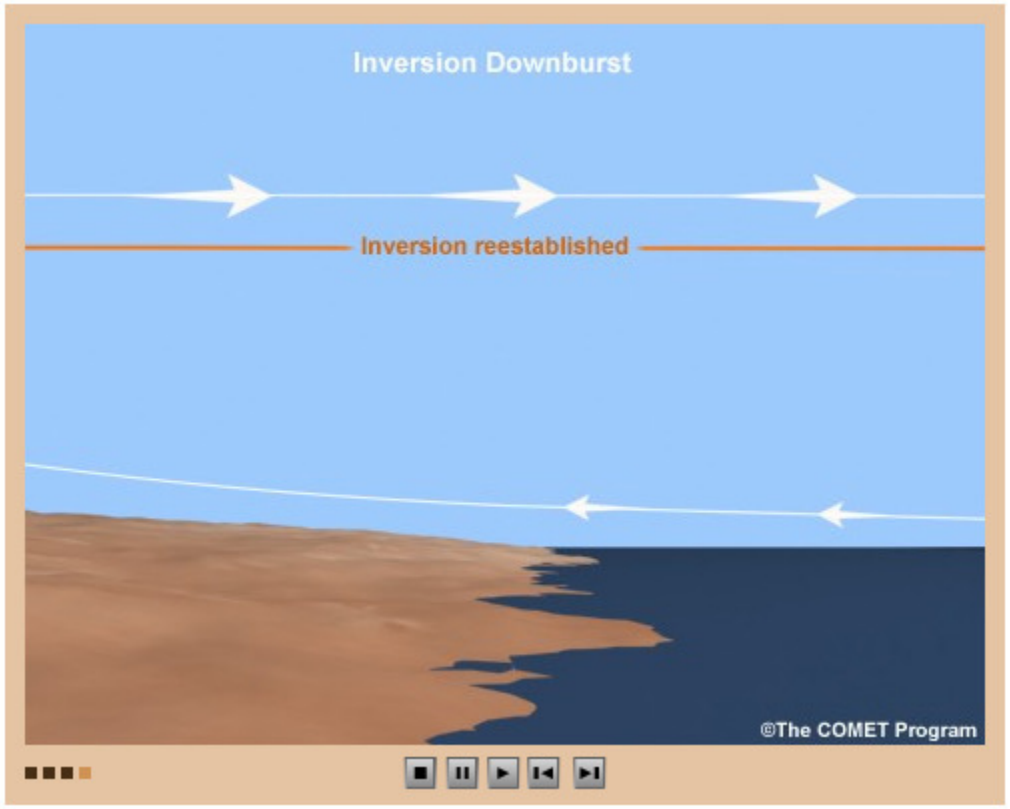
Dust cycle and associated processes

Mesoscale dust storms: Inversion downbursts



Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust cycle and associated processes

Types of dust storms:

Synoptic dust storms (large scale weather systems)

- Prefrontal winds
- Postprontal winds
- Large-scale Trade winds
- ….

Well captured by models.

Mesoscale dust storms

- Downslope winds
- Gap flow
- Convection and Haboobs
- Inversion downburst storms
- …..

Poorly captured by models. Some types improve in regional models.

Outlook

1. **Dust cycle and associated processes**

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2. **Dust forecasting models**

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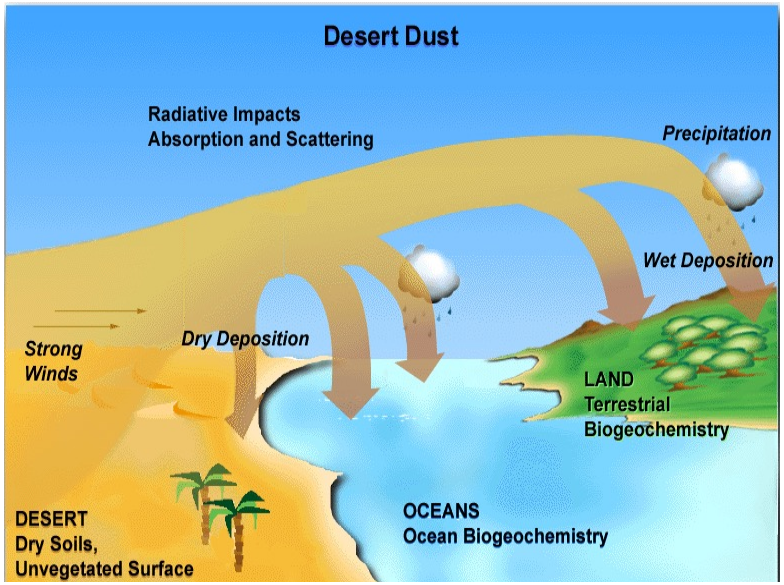
   - *Dust dry and wet deposition and sedimentation*
   - *Model evaluation and model intercomparison*

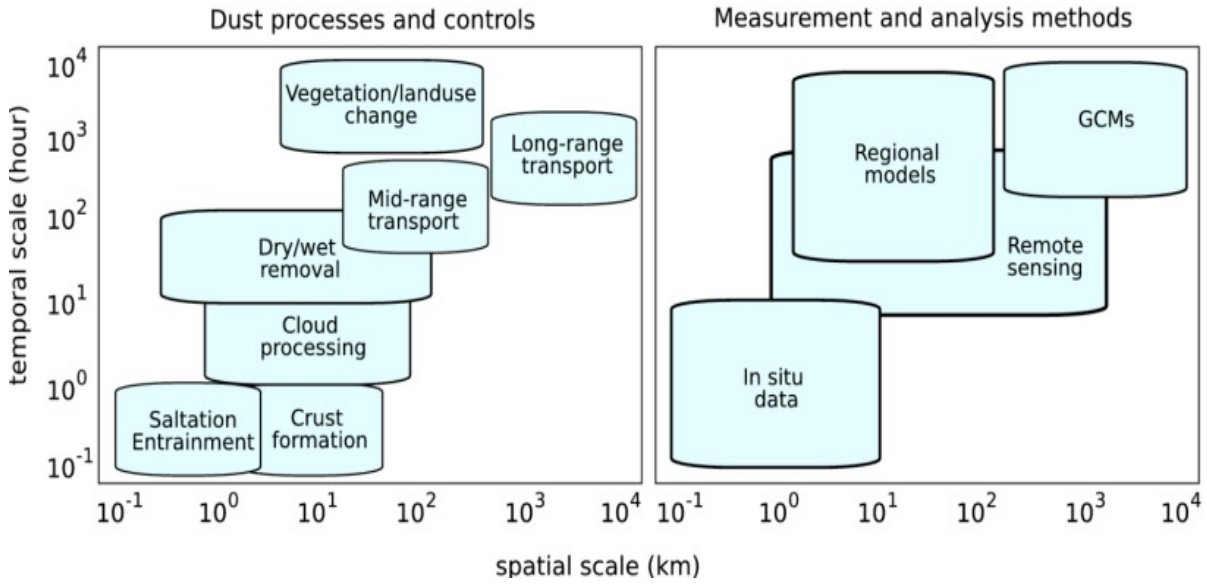
Dust forecasting models



Dust models are a mathematical representation of atmospheric dust cycle.

- ✓ To complement dust-related observations, filling the temporal and spatial gaps of the measurements.
- ✓ To help us to understand the dust processes and their interaction with climate and ecosystems.
- ✓ To predict the impact of dust on surface level concentrations used as SHORT-TERM FORECASTING TOOLS (3-5 days ahead)

Dust cycle and associated processes



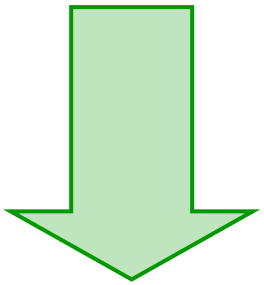
- Dust processes span over five orders of magnitude in space and time.
- To correctly describe and quantify the dust cycle, one needs to understand equally well local-scale processes such as saltation and entrainment of individual dust particles as well as large-scale phenomena such as mid- and long-range transport.

Accurate representation of dust sources and sinks is critical for providing realistic magnitudes and patterns of atmospheric dust fields.

Dust forecasting models: Global and regional models

Regional models offer a number of advantages in representation of dust compared to **Global models**.

- *Finer spatio-temporal resolution.*
- *Multiple physics parameterizations allow for more realistic representation of the topography, soil conditions and mesoscale circulations.*



Regional models are better suited for simulation of timing, duration and intensity of individual dust events.

Dust forecasting models

Dust models simulate the atmospheric dust cycle and involves a variety of processes:

$$\frac{\partial C_k}{\partial t} = -u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y} - \left(w - v_{gk}\right)\frac{\partial C_k}{\partial z} - \nabla\left(K_H \nabla C_k\right) - \frac{\partial}{\partial z}\left(K_z \frac{\partial C_k}{\partial z}\right) + \left(\frac{\partial C_k}{\partial t}\right)_{SOURCE} - \left(\frac{\partial C_k}{\partial t}\right)_{SINK}$$

Horizontal advection

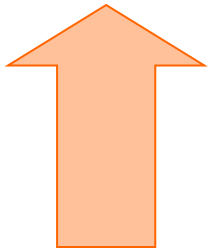
Vertical advection & gravitational settling

Diffusion

Dispersion

Dust emission

Wet and dry deposition



Dust forecasting models: Emission scheme

Dust source function

Main landscapes of the North Africa (Photos from Callot et al. 2000) :

A) Central part of Saharan Atlas. In the background, mountains, and in front, an overgrazed plain;

B) Northern part of Saharan Atlas. Esparto grass steppe degraded by a strong anthropic action. The sandy soil disappears, denuding the sandstone substratum;

C) The Great Hamada south-west of El-Abiodh-Sidi-Cheikh;

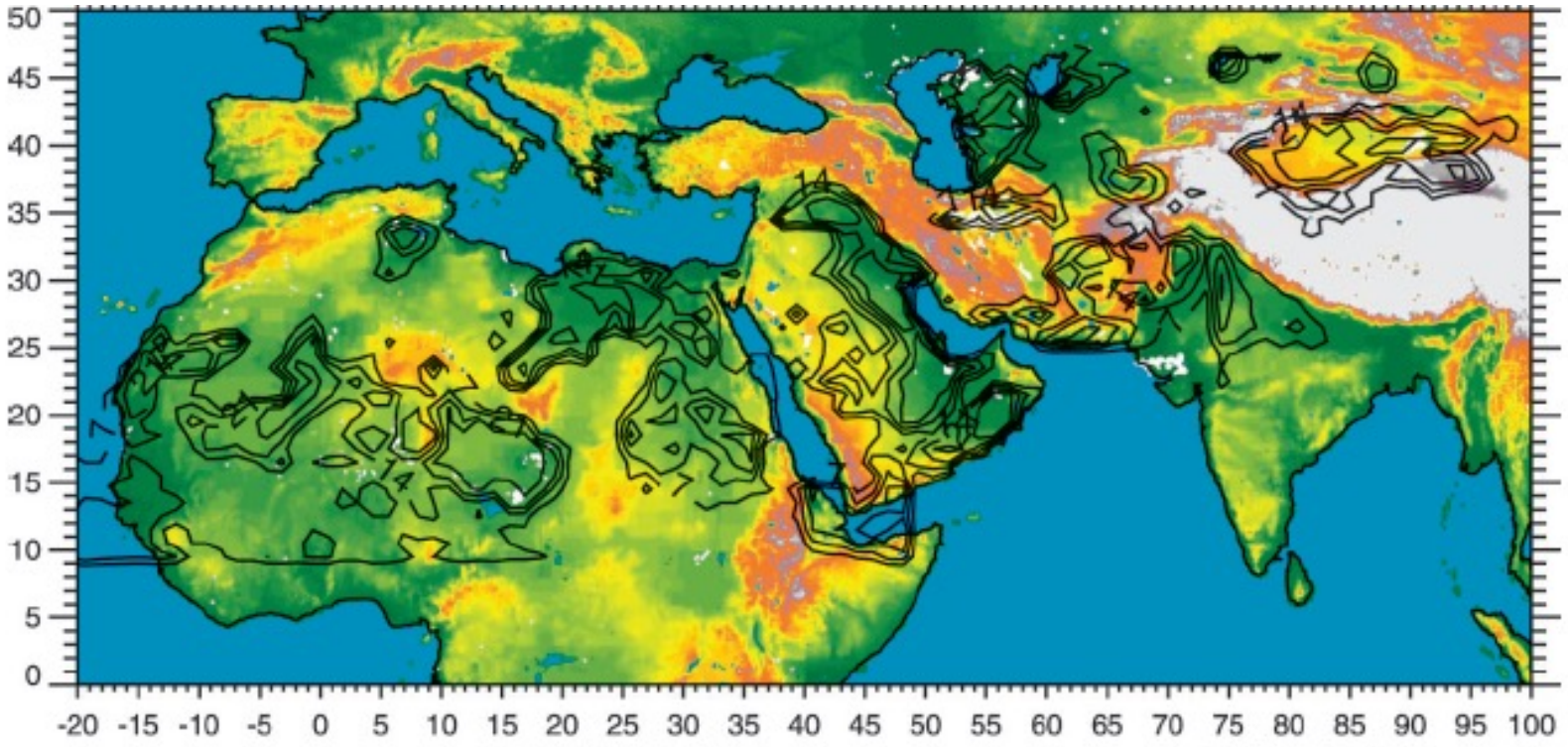
D) Daïa in the Mechfar, at Hassi Cheikh well;

E) North-east of the Great Western Erg: coarse sand interdune corridor with deflation cauldron and palaeolake deposits;

F) North-east of the Great Western Erg: great coarse sand dome dunes, covered by fine sand active dunes.

Dust forecasting models: Emission scheme

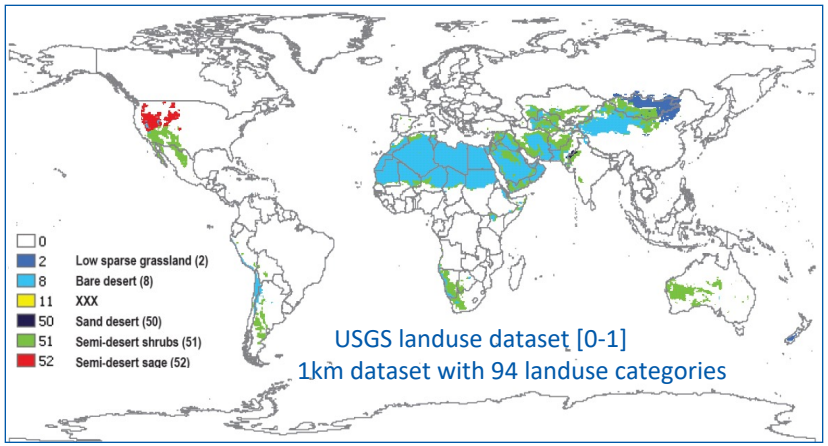
Dust source function



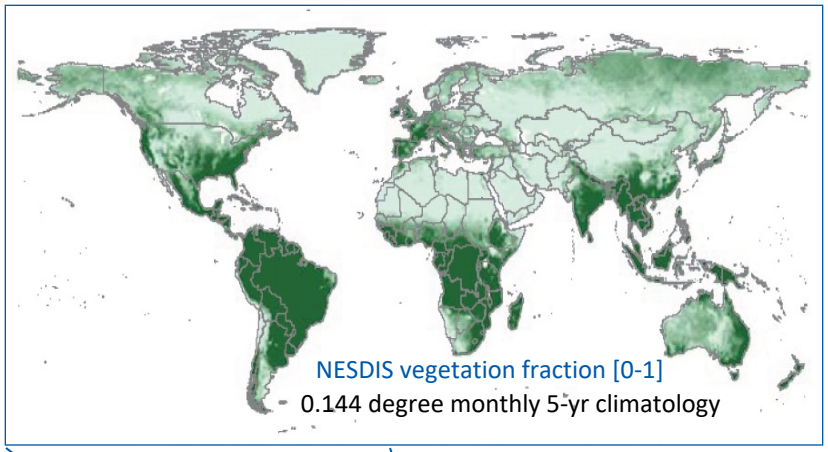
DUST HOT SPOTS ASSOCIATED WITH TOPOGRAPHIC DEPRESSIONS (Prospero et al., 2002)
Images show topography (color scale) and TOMS AI (contours)

Dust forecasting models: Emission scheme

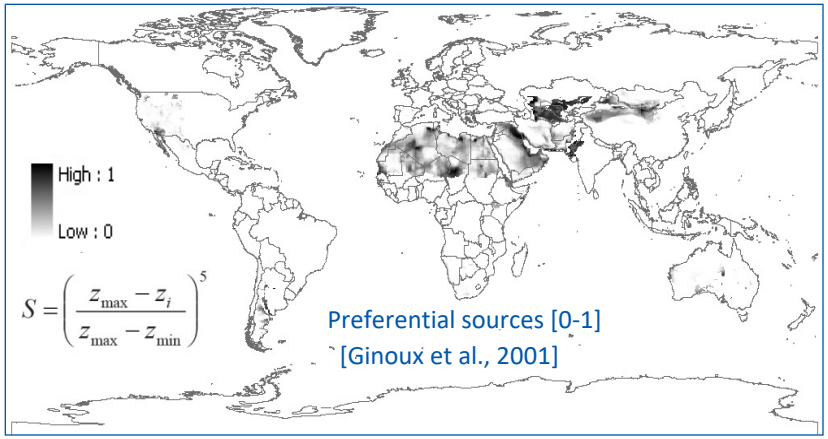
Dust source function: GOCART and NMMb/BSC-Dust models



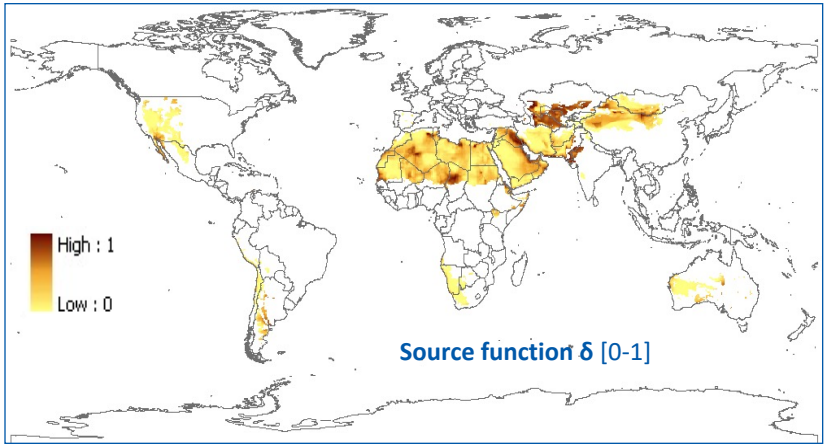
USGS landuse dataset [0-1]
1km dataset with 94 landuse categories



NESDIS vegetation fraction [0-1]
0.144 degree monthly 5-yr climatology



Preferential sources [0-1]
[Ginoux et al., 2001]

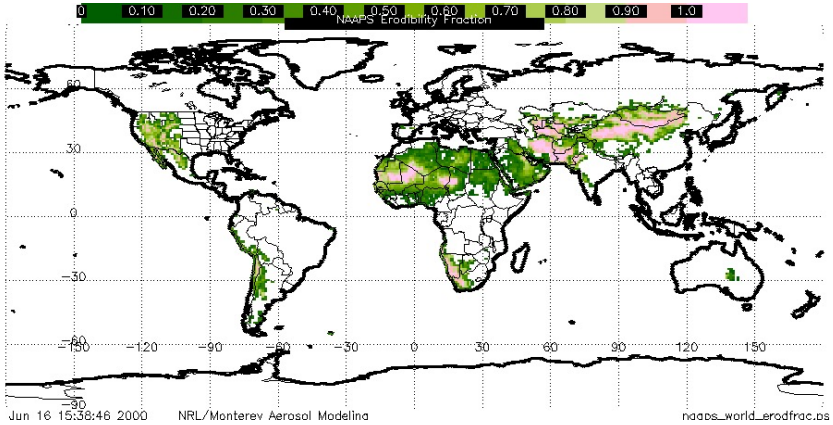


Source function δ [0-1]

$$\delta = USGS \cdot PREF \cdot (1 - VEGFRAC) \cdot (1 - SnowCover)$$

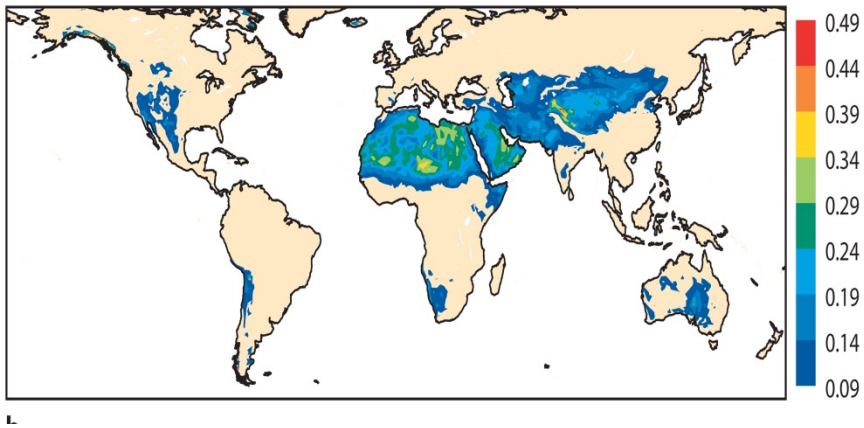
Dust forecasting models: Emission scheme

Dust source function: Other approaches



NAAPS model

Land use mask +
Erodibility map derived from TOMS
Satellite AI climatology

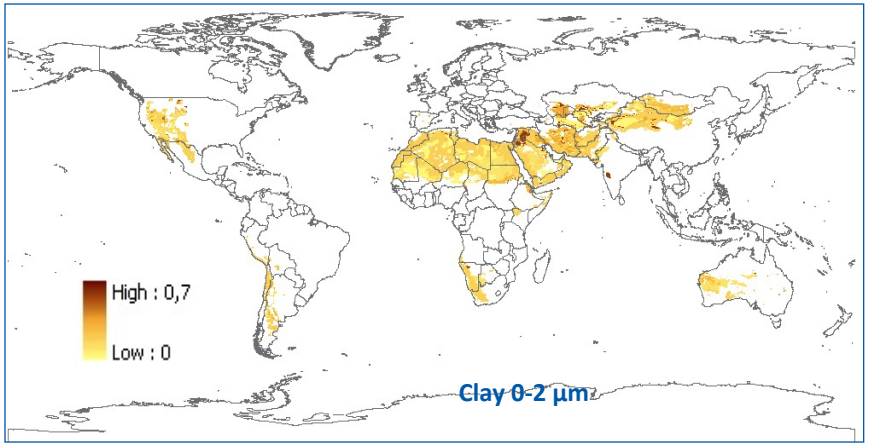


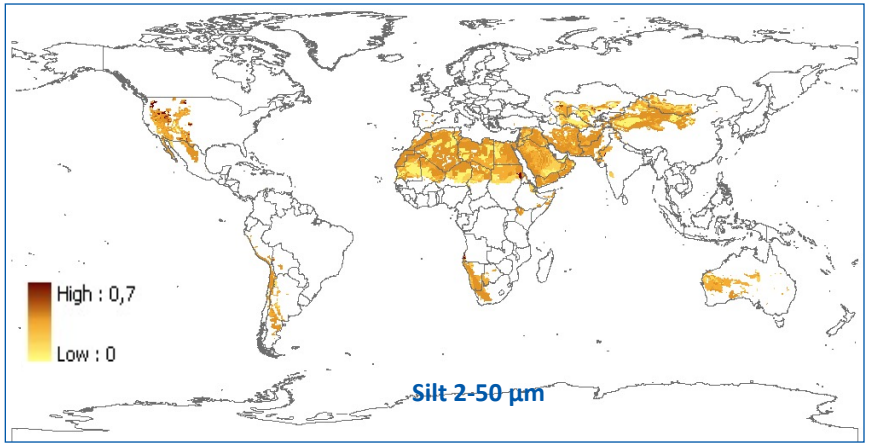
ECMWF-GEMS model

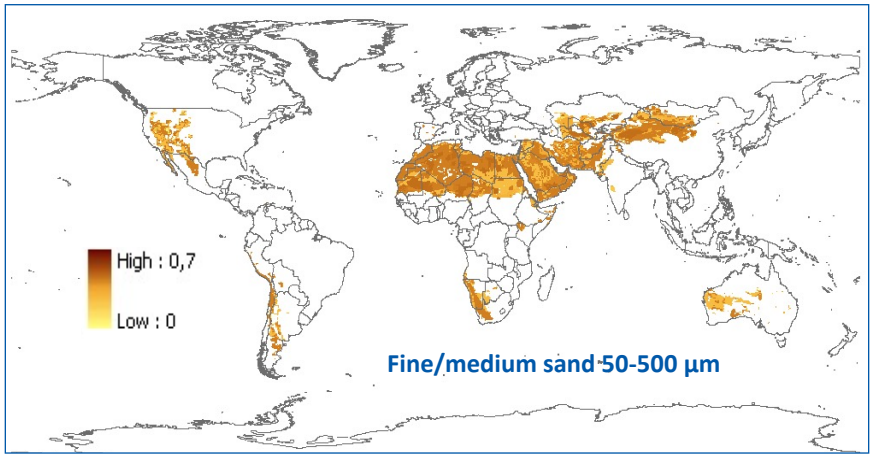
Background albedo in the ultraviolet-visible part of the shortwave spectrum. Only albedos with values between 0.09 and 0.54, assumed to be representative of light-colored soil and sparse vegetation are plotted.

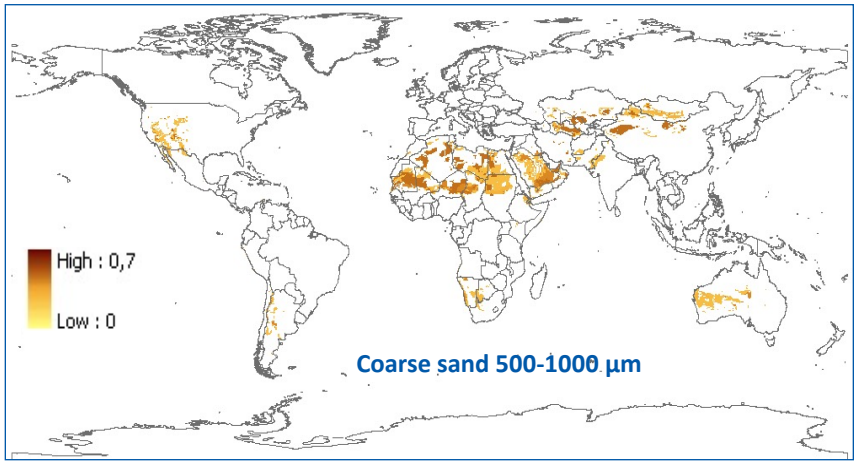
Dust forecasting models: Emission scheme

Parent soil size distribution





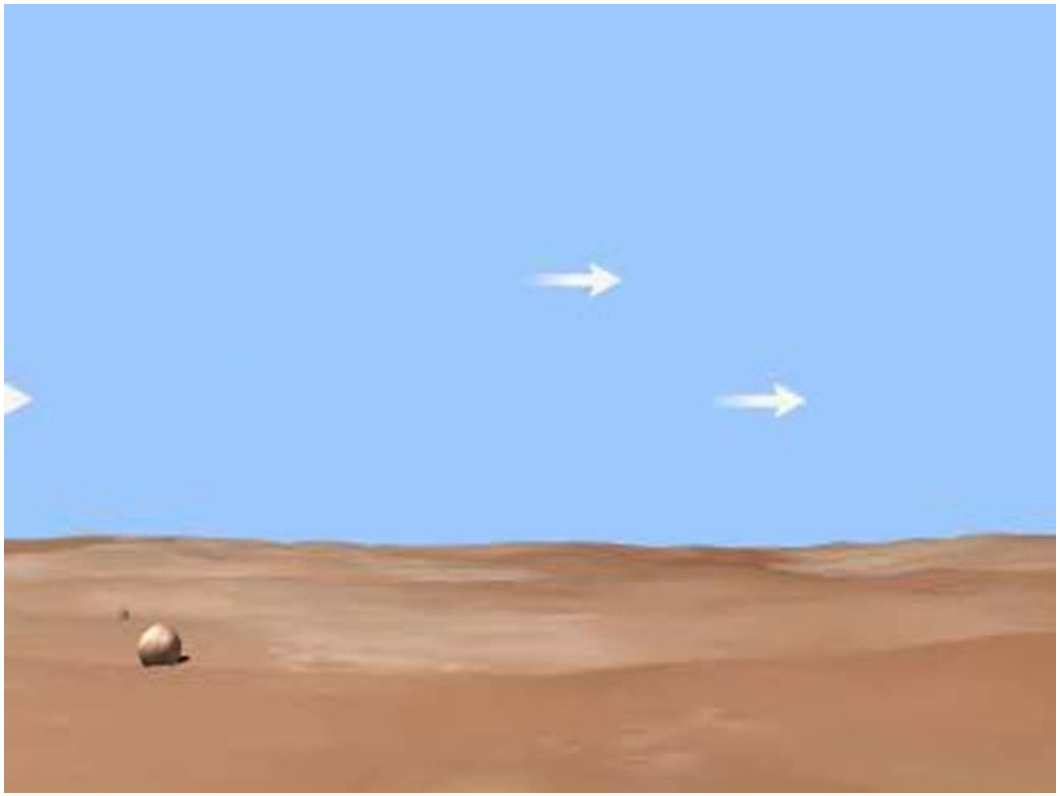




Four top soil texture classes according STASGO-FAO 1km database are converted to 4 parent soil size categories following Tegen et al. [2002]

Dust forecasting models: Emission scheme

- Complex physical process involving entrainment of soil particles by the surface winds.



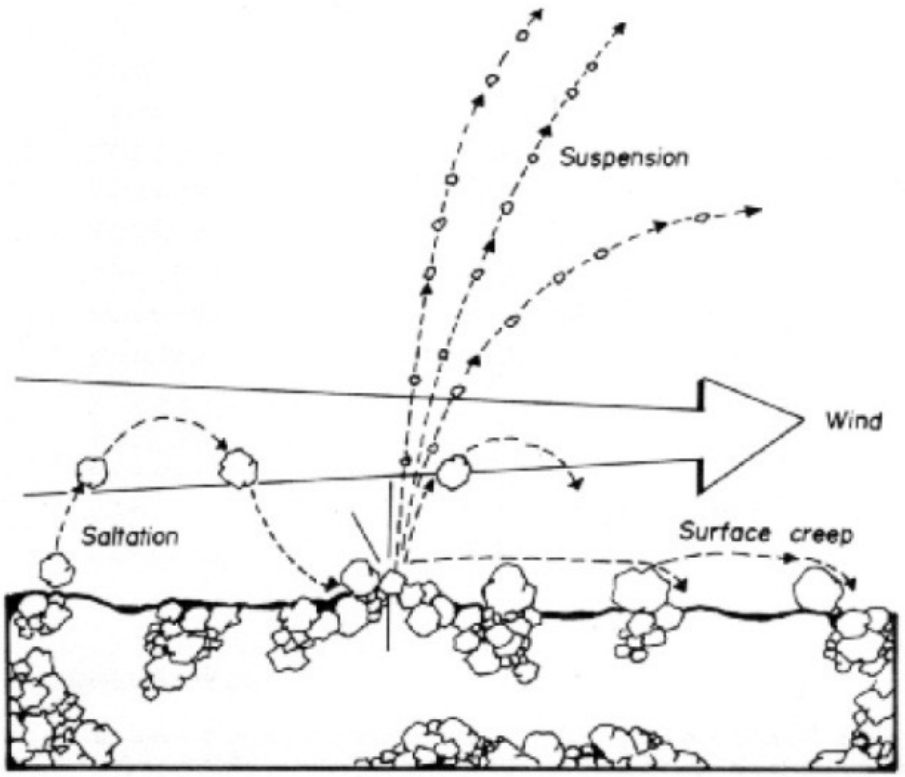
- Creep or rolling motion of the largest particles (> 500 um)

- Saltation or horizontal motion of large soil grains (sand) (50-500um)

- Suspension of dust (after sandblasting or saltation bombardment) (0.1-50 um)

Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust forecasting models: Emission scheme



Scheme of the major wind erosion processes with saltation, creeping and suspension (due to sandblasting) in dependency of wind speed.

Extracted www.extension.purdu.edu/extmedia/AY/AY-271.html

Dust forecasting models: Emission scheme

Simple schemes

Formulation of vertical dust flux (F)

$$F = c \cdot f \cdot P(u_*^n, u_{*th}) \qquad \text{if} \quad u_* > u_{*t}$$

***c*:** dimensional scale dependent constant proportinality
***f*:** relative surface area of each soil particle fraction (which includes de source function, δ)
u_***:** friction velocity
u_{*t}**:** threshold friction velocity
***P*:** polinomial of degree n

Study	Scheme
Uno et al. (2001) CFORS	$F = c u_{10}^2 (u_{10} - u_{10t})$
Liu and Westphal (2001) COAMPS	$F = f u_{10}^2 (u_{10} - u_{10t})$
Liu and Westphal (2001) COAMPS	$F = f c u_*^4$

Dust forecasting models: Emission scheme

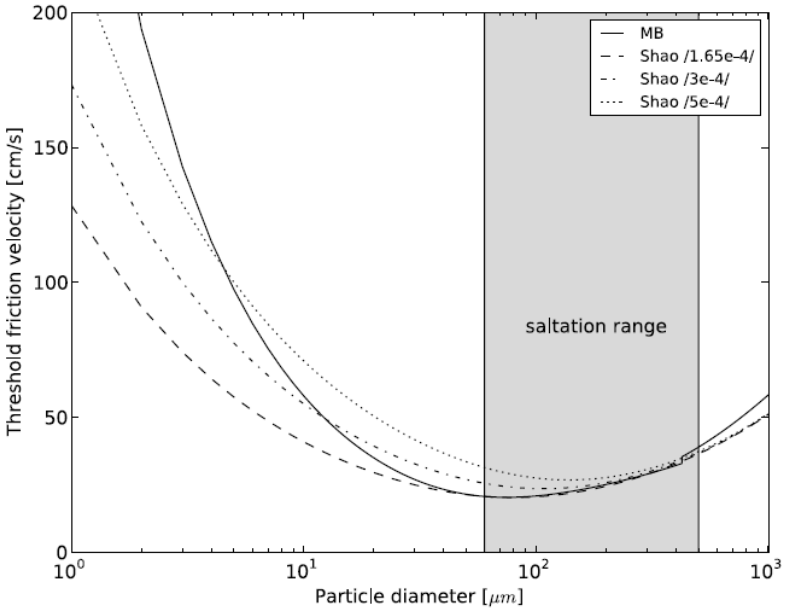
Threshold friction velocity

Dust storm generation requires:

- High wind
- Wind shear and turbulence
- Unstable boundary layer

Friction velocity is the parameter used by dust models since it expresses wind speed, turbulence and stability

Threshold friction velocity vs particle radius →



Darmenova et al., 2009

Dust forecasting models: Emission scheme

Simple schemes

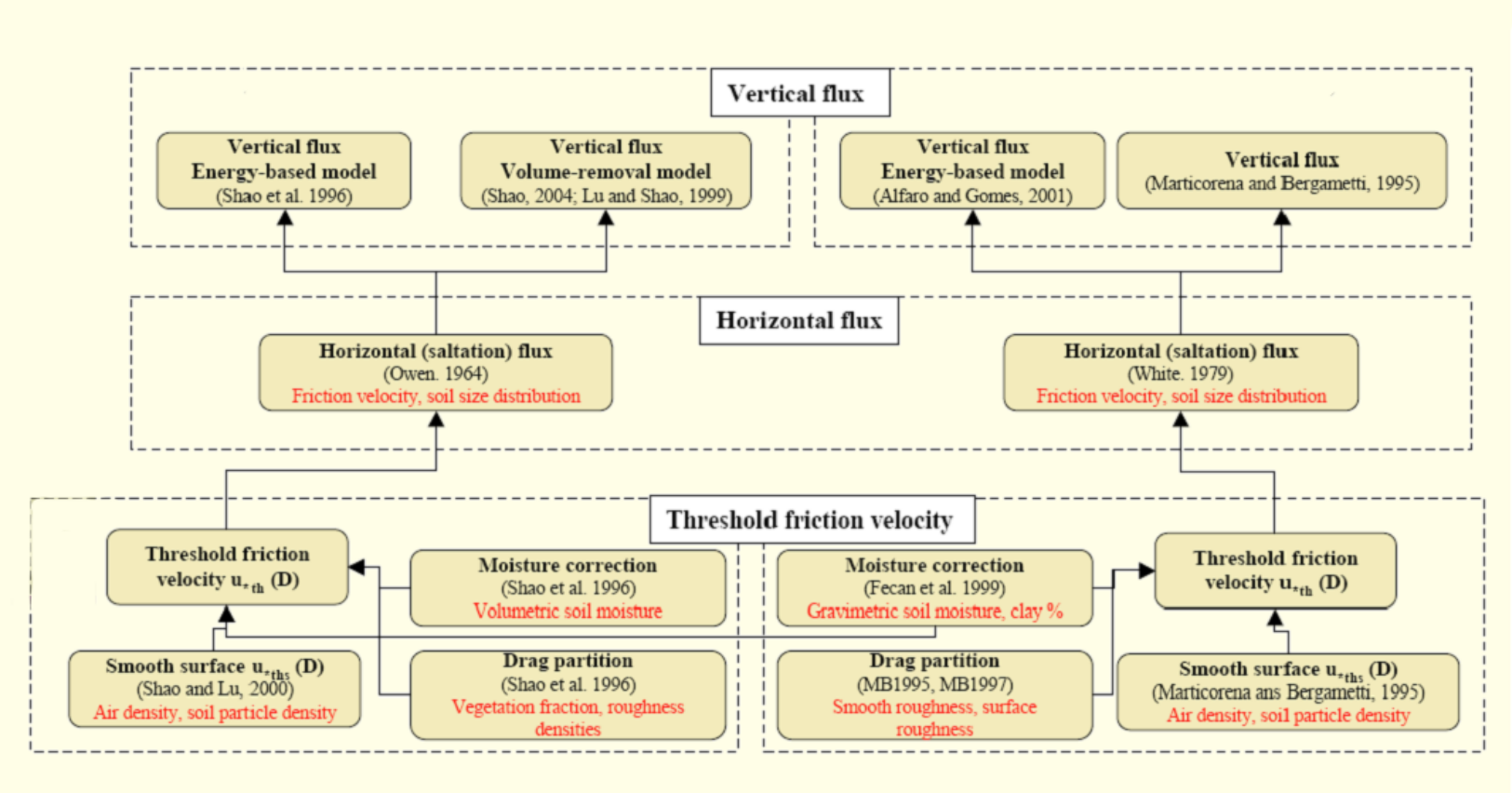
Limitations

- Oversimplified physical representation of dust emission.
- Normalization constant C is not known
- Erodible fraction is prescribed for predefined dust sources
- Threshold friction velocity is usually a fixed value (no dependence on the land surface properties)

- **Assuming constant threshold friction velocity will introduce bias in the modelling of the timing and intensity of dust events.**
- **The prescribed constant is model dependent and can result in large discrepancies in calculated dust loadings between different models.**

Dust forecasting models: Emission scheme

Physically based schemes



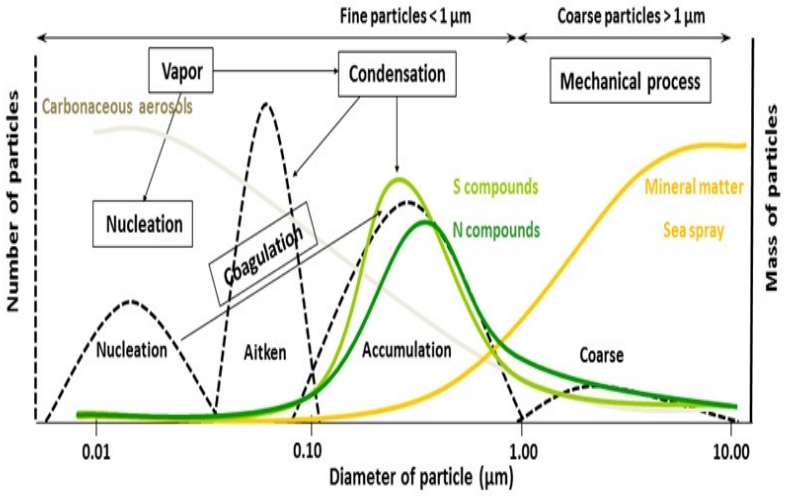
Physically-based **dust emission schemes** employ different parameterizations of the related physical processes, as well as require different input data.

Dust forecasting models: Emission scheme

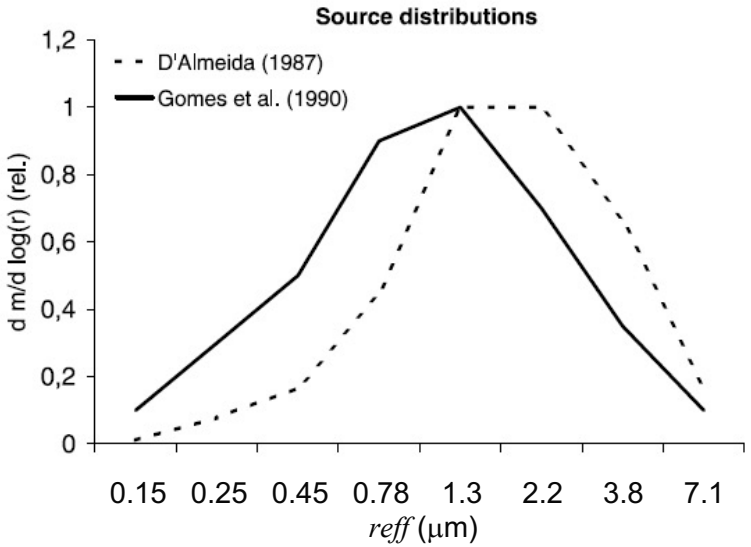
Parent soil size distribution are used to calculate **horizontal flux (H).**
Dust **horizontal concentration** is calculated distributing the **vertical flux (F)** of the **first two parent soil categories** (clay and silt) over the **model particle bins.**

Parameterizations of mass size distribution of the model at sources

Modal

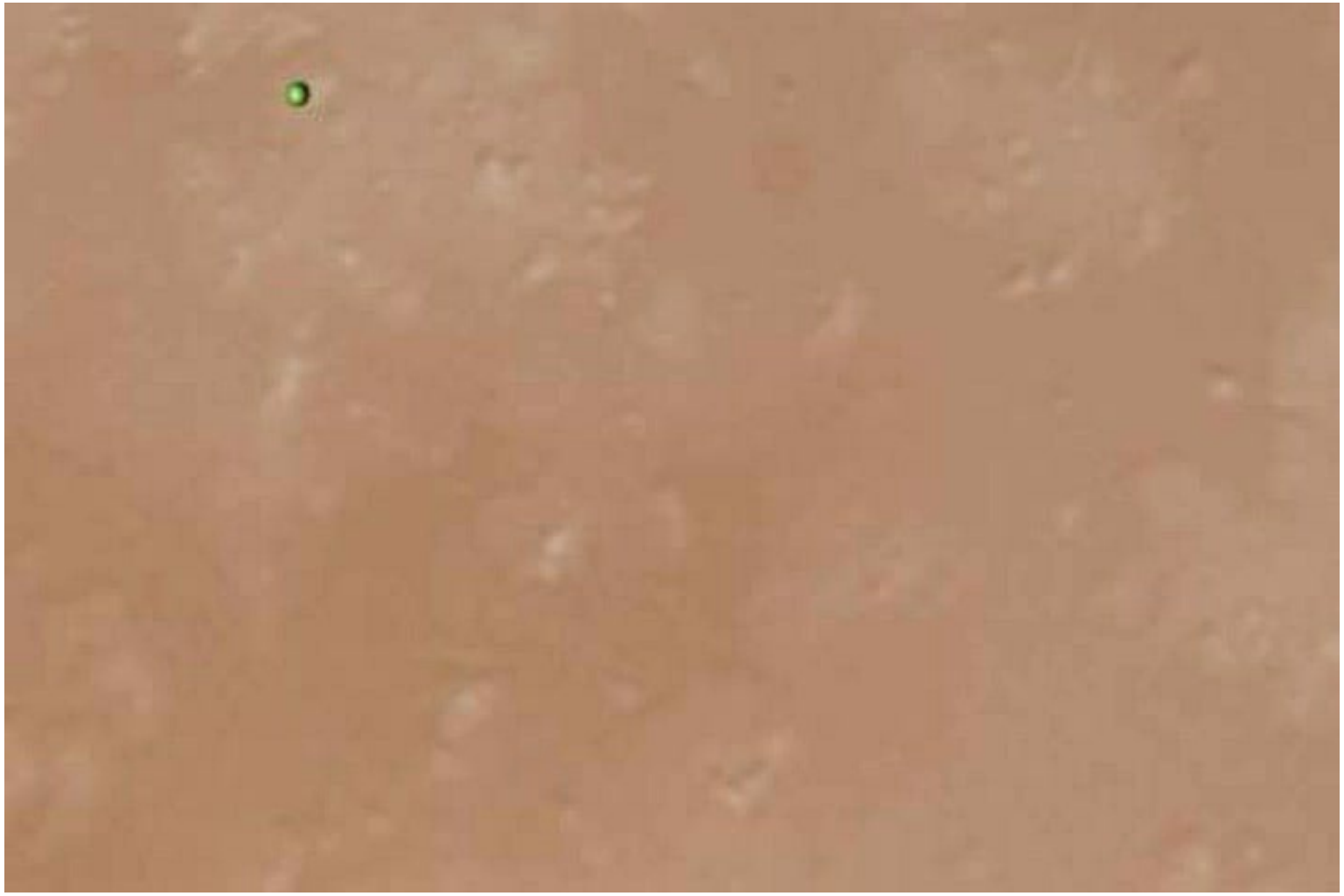


Sectorial



8 bin size distribution from Tegen and Lacis (1996)

Dust forecasting models: Dispersion



Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust forecasting models

Dust models simulate the atmospheric dust cycle and involves a variety of processes:

$$\frac{\partial C_k}{\partial t} = -u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y} - \left(w - v_{gk}\right)\frac{\partial C_k}{\partial z} - \nabla\left(K_H \nabla C_k\right) - \frac{\partial}{\partial z}\left(K_z \frac{\partial C_k}{\partial z}\right) + \left(\frac{\partial C_k}{\partial t}\right)_{SOURCE} - \left(\frac{\partial C_k}{\partial t}\right)_{SINK}$$

Horizontal advection

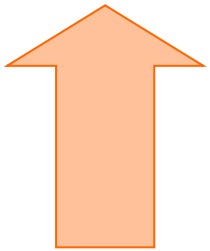
Vertical advection & gravitational settling

Diffusion

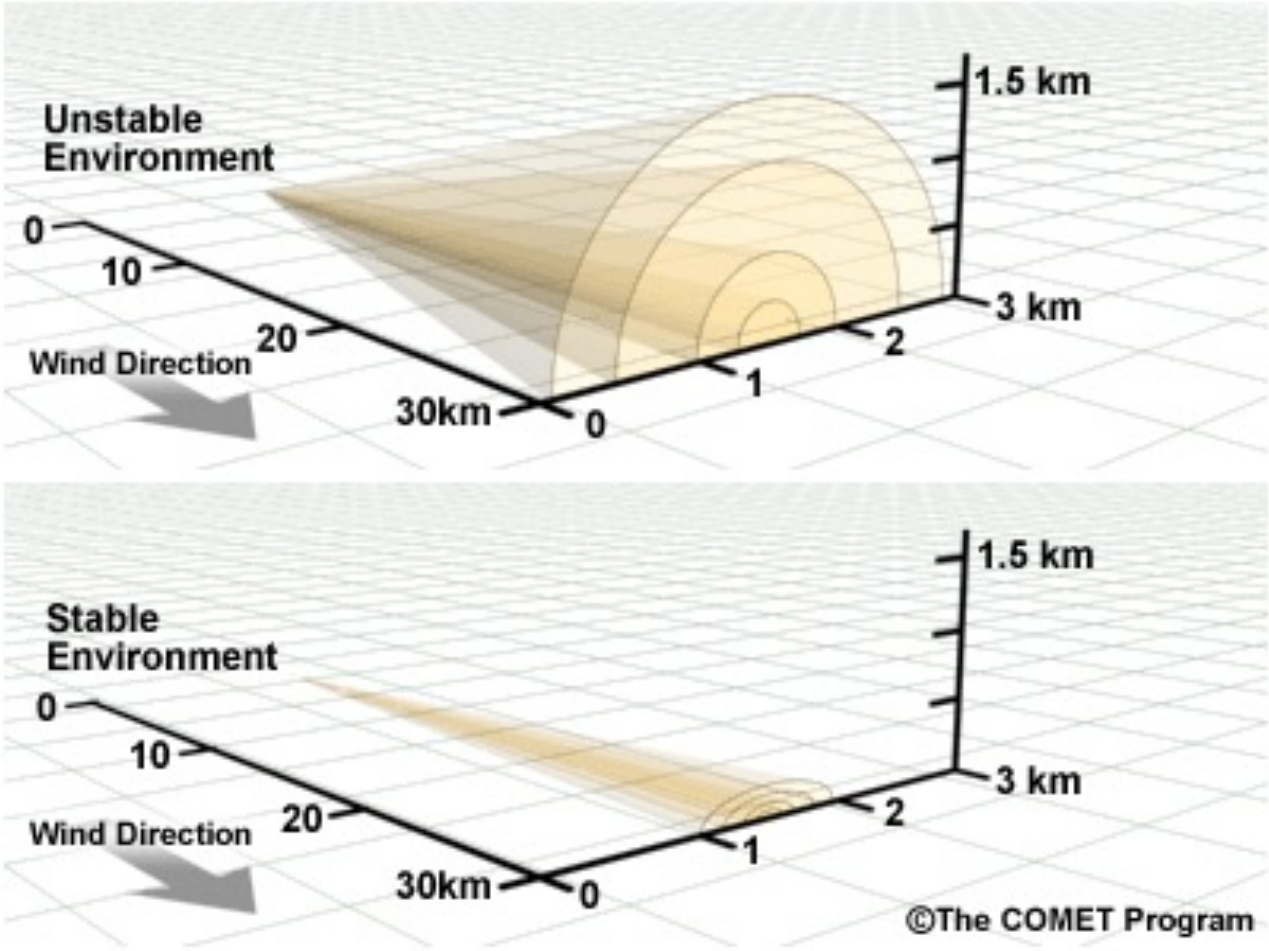
Dispersion

Dust emission

Wet and dry deposition



Dust forecasting models: Dispersion



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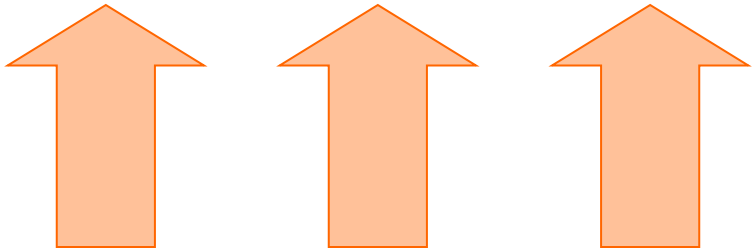
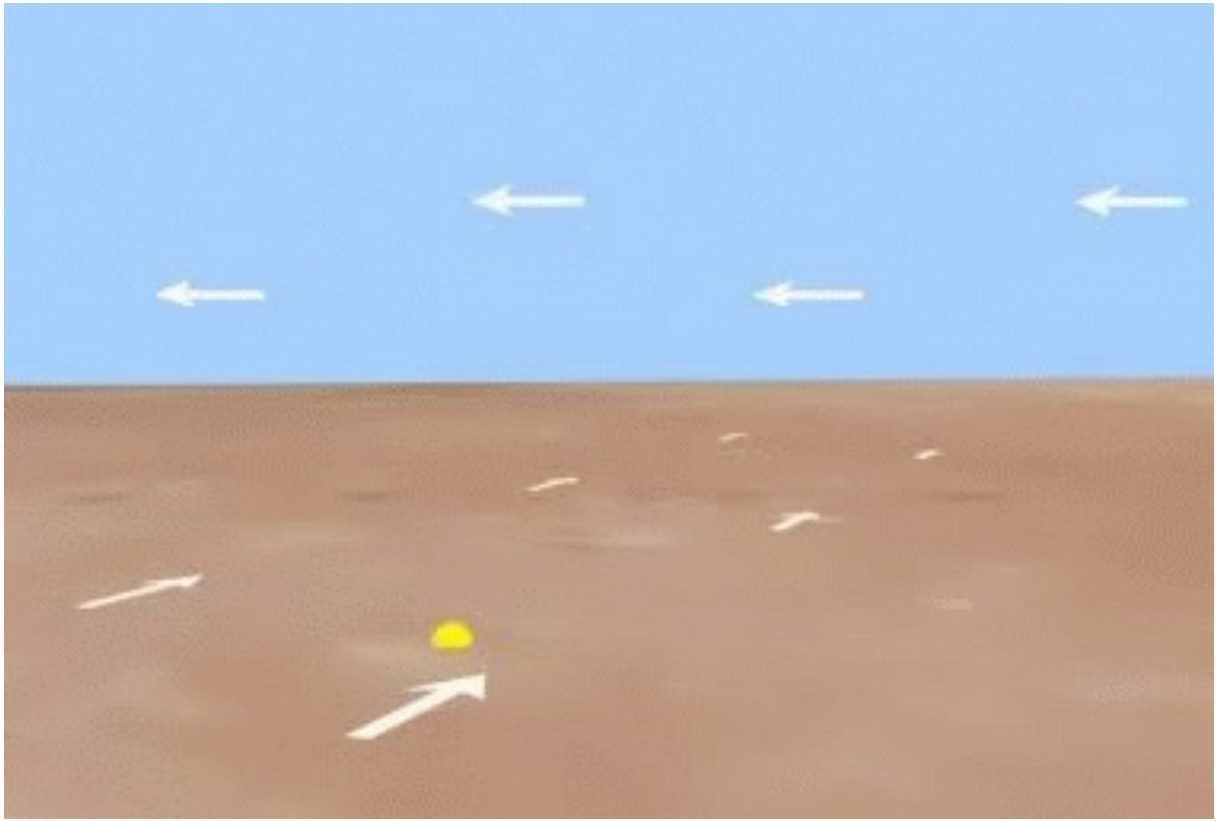


Dust forecasting models: Advection and diffusion



Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

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Horizontal advection

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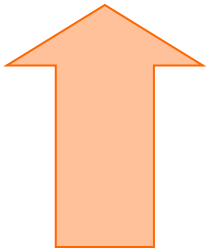
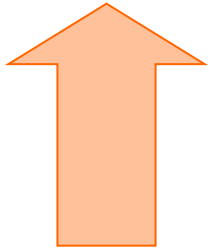
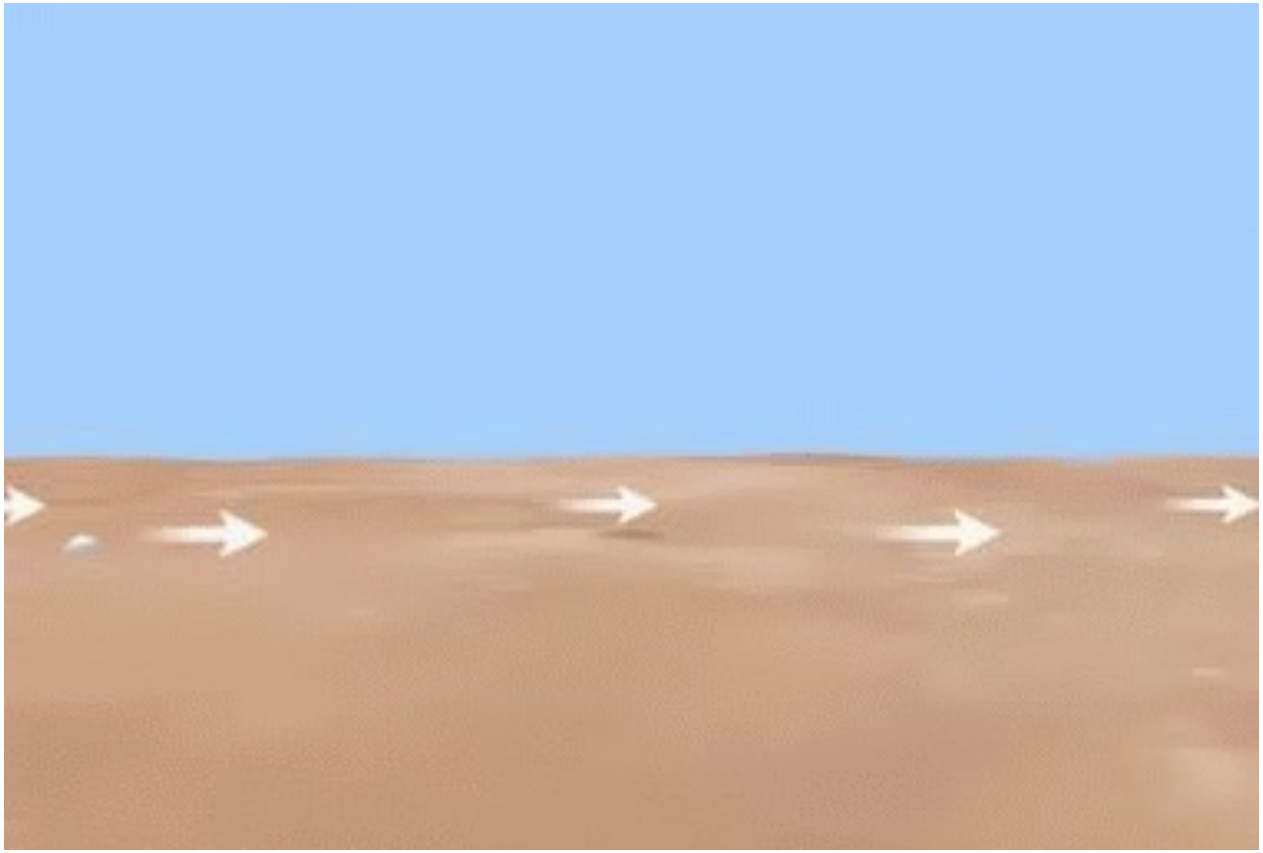




Dust forecasting models: Dry deposition scheme

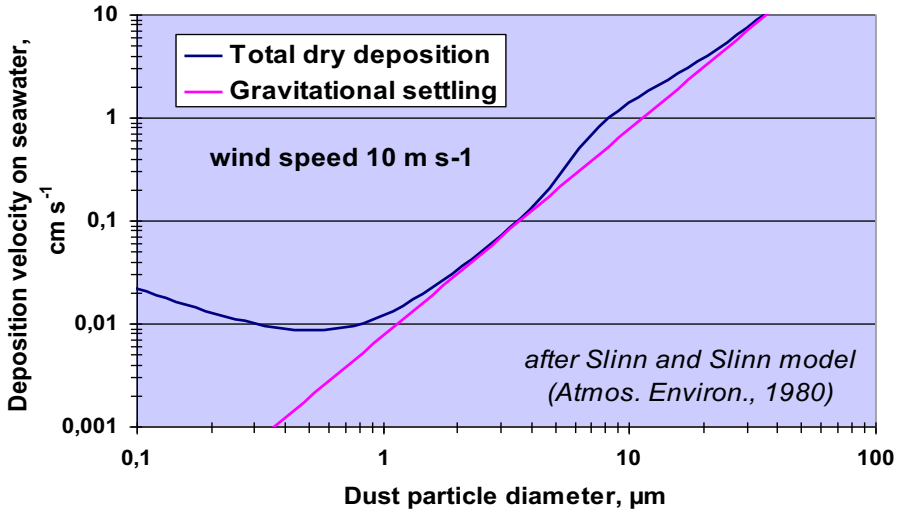
Sedimentation and dry deposition



Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust forecasting models: Dry deposition scheme

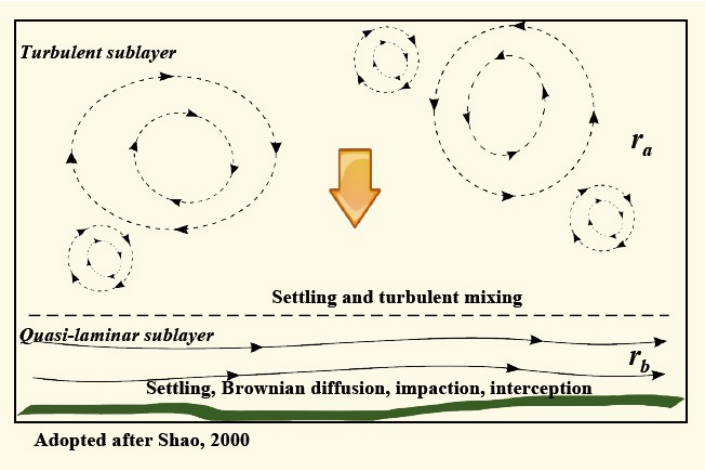
Dry deposition depends on the variety of factors such as meteorological conditions near the surface, physicochemical properties of mineral dust and the nature of the surface itself.



Dry deposition velocity is represented as 3 resistances in series parallel to a second pathway - gravitational settling velocity:

- Aerodynamic resistance to transfer (r_a)
- Quasi-laminar surface layer resistance (r_b)
- Resistance to surface uptake (r_c)

$$v_d = \frac{1}{r_a + r_b + r_c} \longrightarrow F_d = -C \cdot v_d$$



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Horizontal advection

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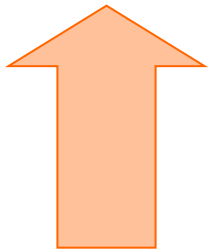
Wet and dry deposition



Dust forecasting models: Wet deposition scheme

Wet scavenging

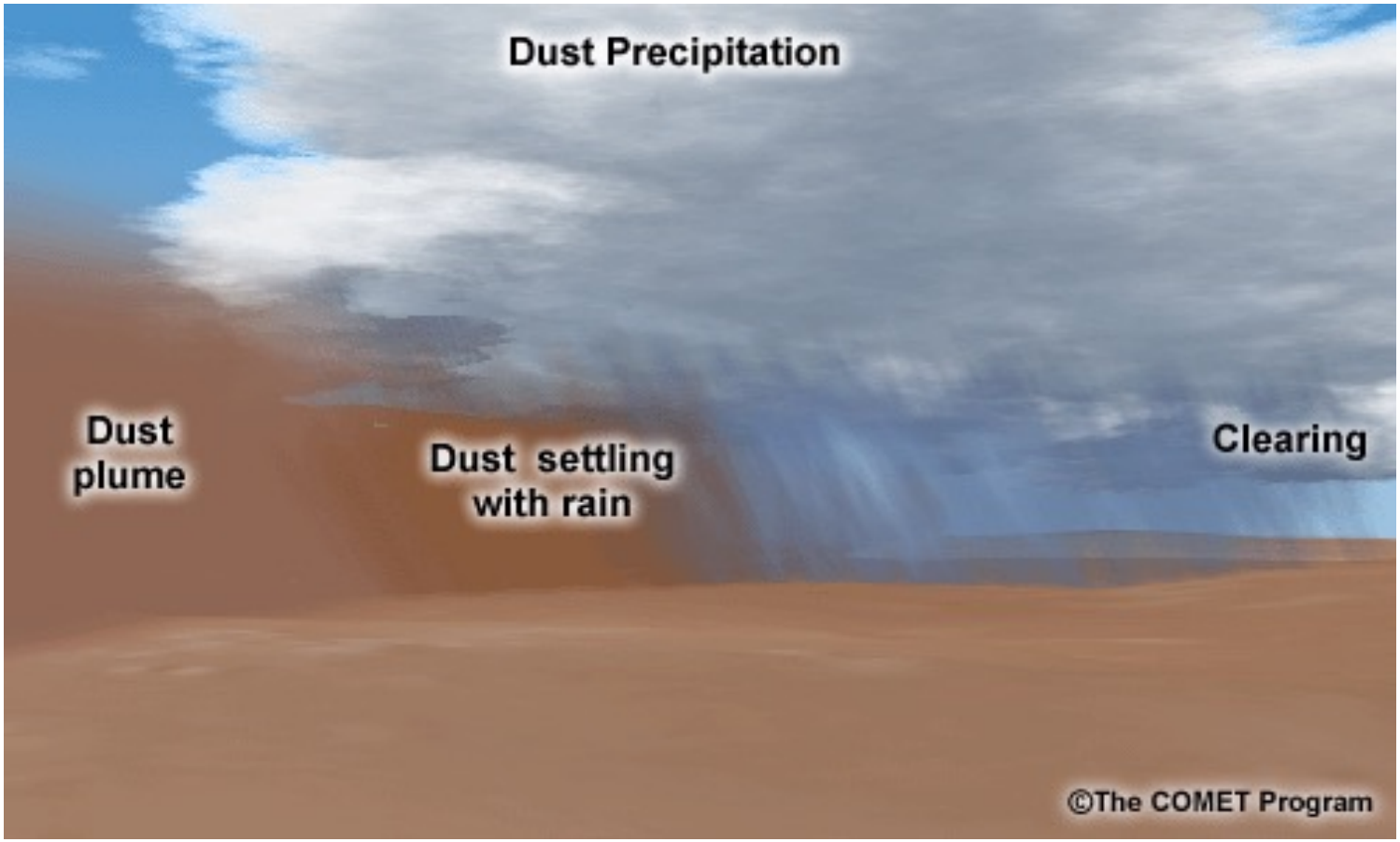
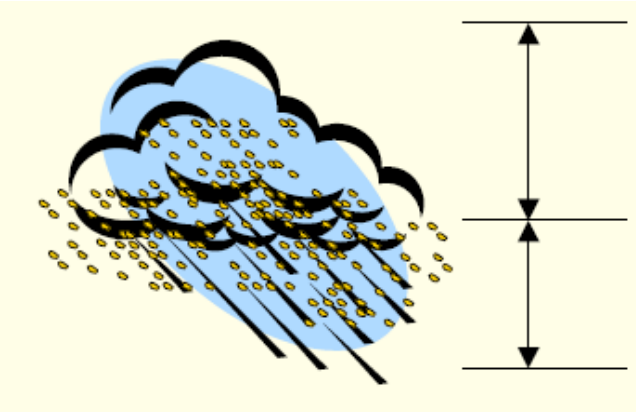


Image from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust forecasting models: Wet deposition scheme



In-cloud scavenging:

- **nucleation scavenging** by activation and growth of particles to cloud droplets
- **collection** of a non-activated fraction of particles by coagulation with cloud and rain droplets

Below-cloud scavenging:

Collection by falling raindrops of particles under their collision.

Decrease rate of the aerosol concentration due to **wet scavenging** in a layer with uniform concentration can be described by a first-order equation:

$$\frac{\partial C}{\partial t} = -\lambda C$$

The **scavenging coefficient (C)** depends on:

- the particle size and solubility
- the collectors size distribution and fall speeds
- precipitation rate and phase (rain or snow).

Dust forecasting models: Wet deposition scheme

Existing problems

- **Rainout:** The soluble fraction of dust is not well known, so assigned scavenging efficiencies do not reflect regional specifics of dust properties and their dynamics (i.e., mineralogical composition, aging, etc.)

- **Washout:** Problems in modelling of clouds and precipitation remain a long-standing issue. Precipitation rates during violent convective rains are often underpredicted.

- **Dry versus wet deposition:** The relative importance of dry or wet deposition processes differs regionally and depends on the meteorological conditions and used parameterizations.

Dust forecasting models

Consists of these 3 major parts:

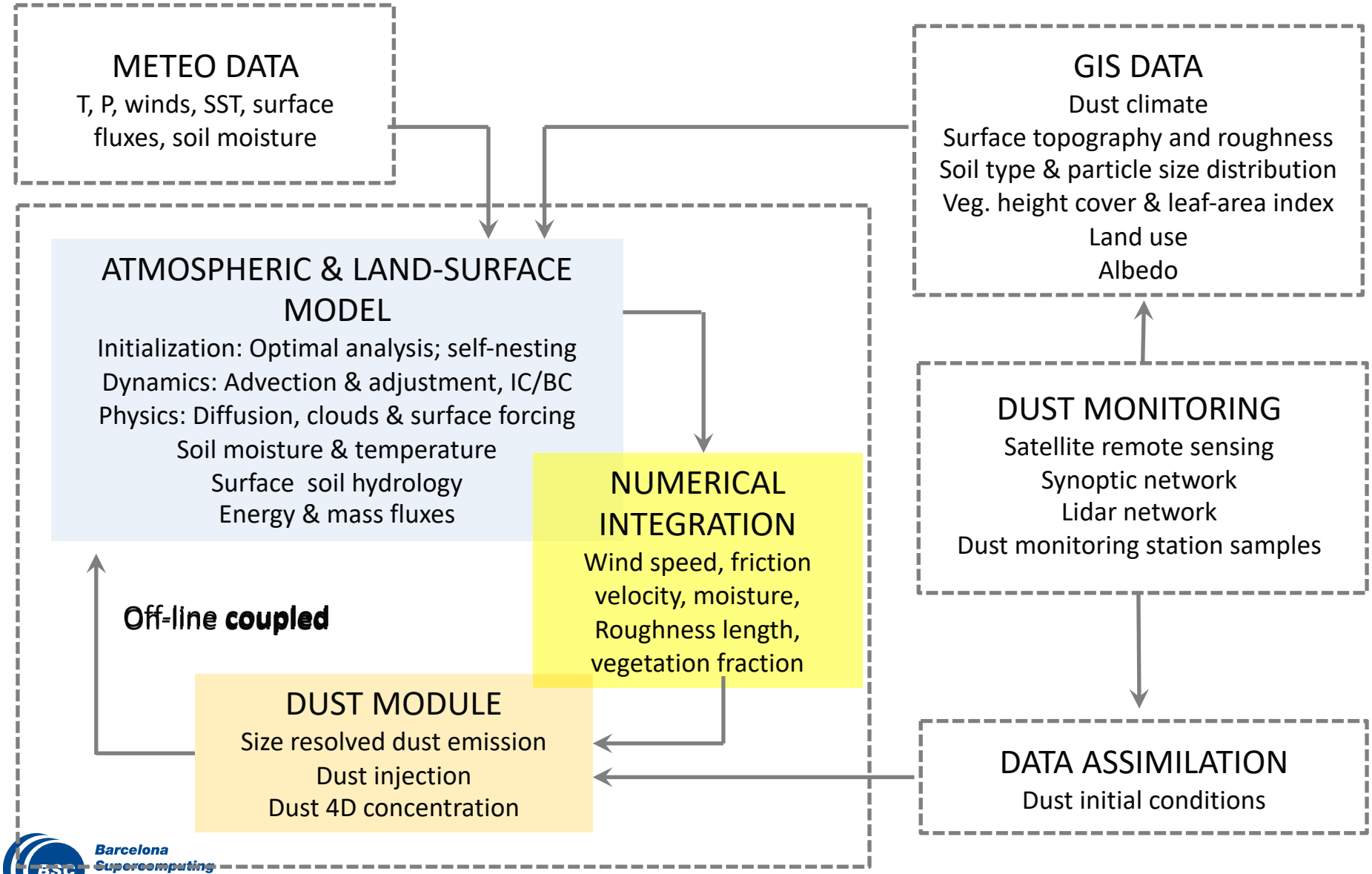
1. **Pre-Processing:** Its functions include two parts,

    I. The **Set-up** of the model which includes the definition of simulation domains and model configuration and the interpolation of terrestrial data (such as terrain, land use, and soil types) to the simulation domain.

    II. **Pre-processing** of the operational system which includes a download, degrib and interpolation of the meteorological input data from the global meteorological model to this simulation domain, as well as, the initial and boundary conditions for the dust model.

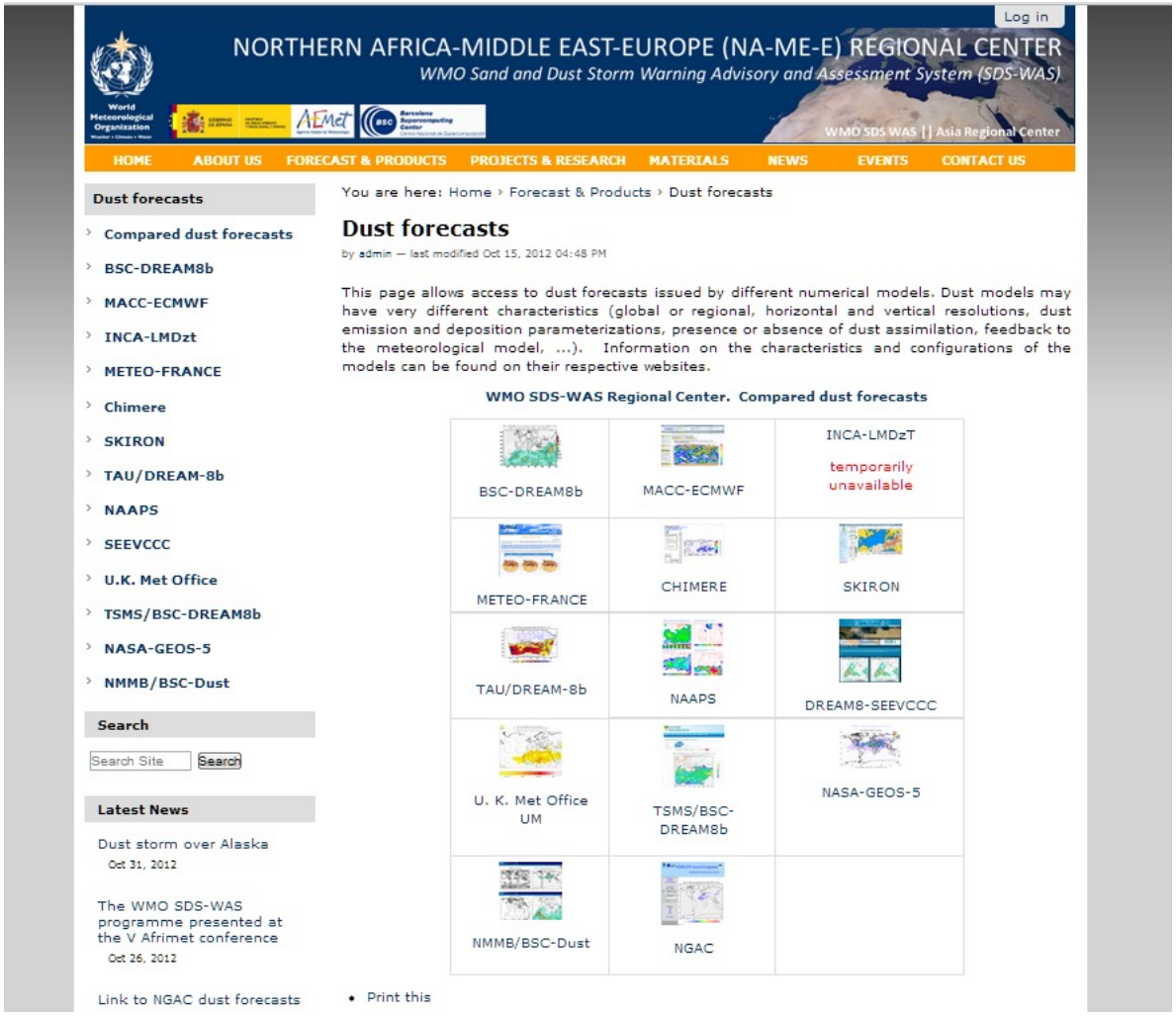
2. **Model:** This is the key component of the dust modelling system.
3. **Post-Processing & Visualization tools:** This includes the maps generation process.

Dust forecasting models



Dust forecasting models: SDS-WAS NA-ME-E RC

http://sds-was.aemet.es/



Dust forecasting models

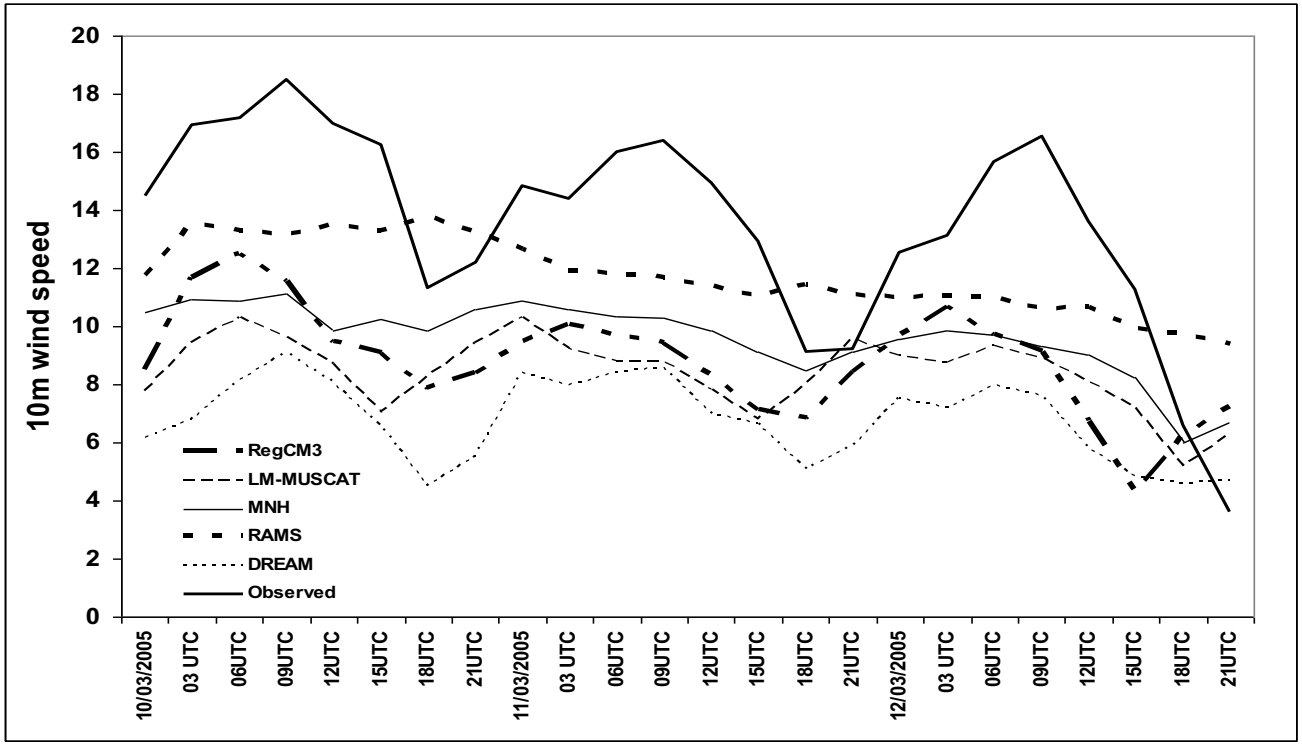
Main differences between models

1. *Emission scheme*
2. *Geographic-information database*
3. *Atmospheric driver and land-surface scheme*
4. *Spatio-temporal resolution*
5. *Meteorological input files*
6. *….*

Dust forecasting models

Experimental campaigns: BODEX 2005 (Todd et al. 2008, JGR)

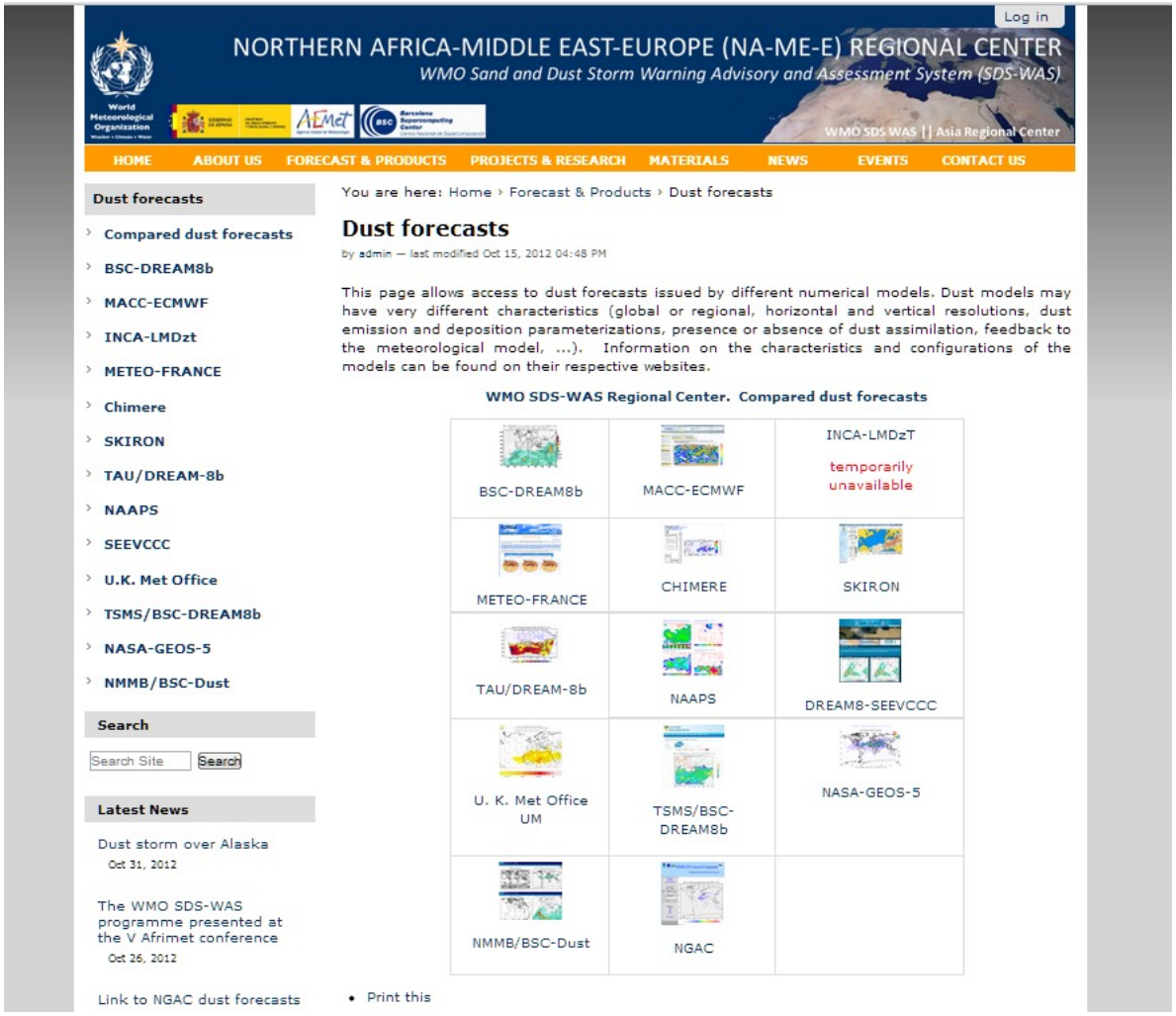
First regional model intercomparison in the Bodélé hot spot



Strong differences between models!!!! → **Meteorology** and **emission scheme**

Dust forecasting models: SDS-WAS NA-ME-E RC

http://sds-was.aemet.es/

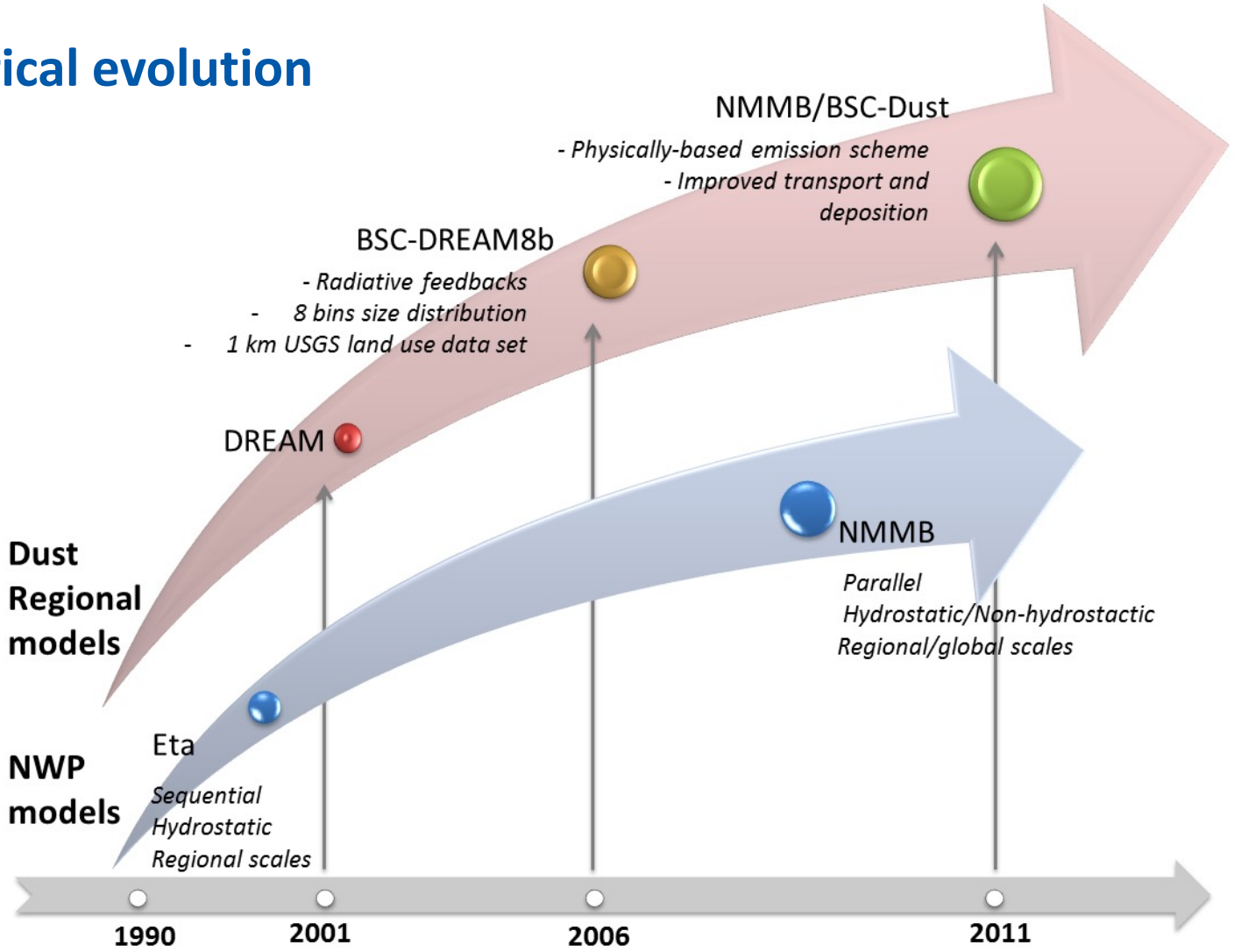


Dust forecasting models: SDS-WAS NA-ME-E RC

Atmospheric driver and dust model	Regional Global	Meteo. initial files	Radiation interaction	Horiz./Vert. resolution	Emission Scheme	Surface wind speed	Transport size bins	Data assimilation
ETA/NCEP BSC-DREAM8b	Regional	NCEP	radiation feedback	0.3ºx0.3º 24 η-layers	Uplifting SHAO	viscous sublayer	8 bins 0.1-10 μm	no
NMMB/NCEP NMMB/BSC-Dust	Regional /Global	NCEP	radiation feedback	0.25ºx0.25º 40 σ-layers	Uplifting MB	viscous sublayer	8 bins 0.1-10 μm	no
ECMWF MACC	Global	ECMWF	no	1ºx1º 91 layers	Uplifting GINOUX	surface wind field	3 bins 0.03-20 μm	yes
MetUM MetUM	Global	MetUM	no	0.35ºx0.23º 70 layers	Uplifting WOOD	surface wind field	2 bins 0.1-10 μm	no
NOGAPS NAAPS/COAMPS	Global	NCEP	no	1ºx1º grid 25 layers	Uplifting WEST	friction velocity	10 bins 0.05-35 μm	yes
GEOS-5/NASA GEOS-5/NASA	Global	NASA	radiation feedback	0.25ºx0.31º 72 layers	Uplifting GINOUX	friction velocity	5 bins 0.73 -8 μm	yes

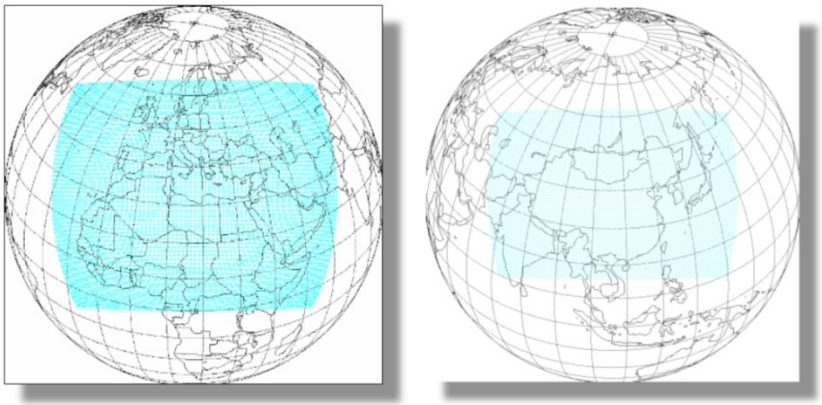
Dust forecasting models: BSC dust forecasting models

Historical evolution



Dust forecasting models: The BSC-DREAM8b v2.0

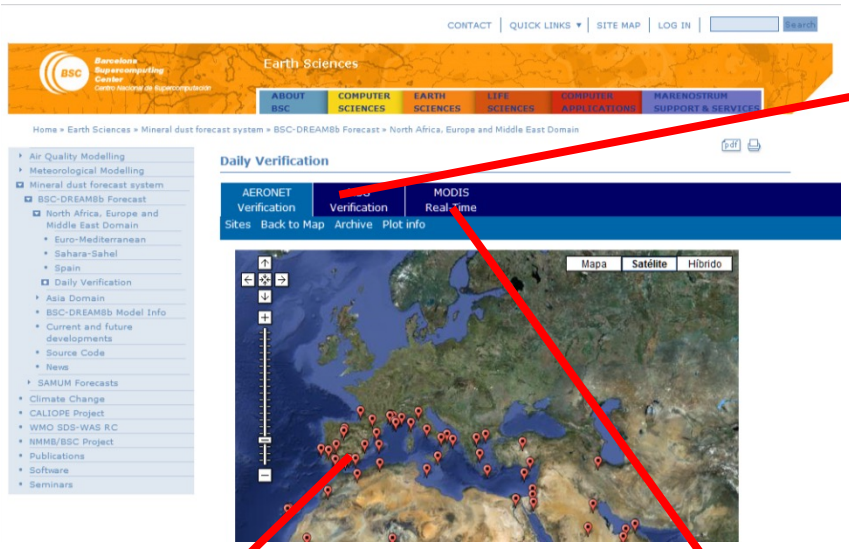
- Daily forecasts in 2 domains:
  - North Africa-Middle East-Europe (0.3º x 0.3º)
  - East Asia (0.5º x 0.5º)



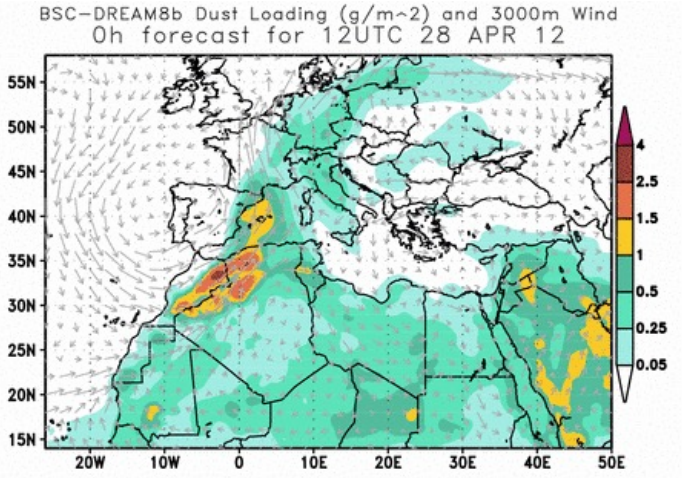
- Main features
  - 8 particle size bin distribution (0.1 -10 μm)
  - Dust radiative feedbacks (Pérez et al., 2006)
- Latest developments (version 2.0; Basart et al. 2012a)
  - Updated dry deposition
  - Inclusion of a preferential source mask

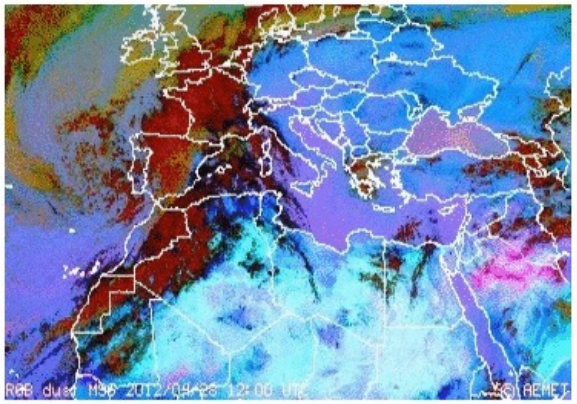
- Included in the CALIOPE AQ system
- Near-real time evaluation
- Dust forecast evaluation studies:
  - Single events in the ***Mediterranean*** (e.g., Papayannis et al., 2005; Pérez et al., 2006)
  - Experimental campaigns in ***source regions***
    - BoDEX 2005 (Todd et al., 2008)
    - SAMUM 2006 (Haustein et al., 2009)
  - Anual evaluation over North Africa, Mediterranean and Middle East (Pay et al., 2011; Basart et al., 2012b)

Dust forecasting models: The BSC-DREAM8b v2.0

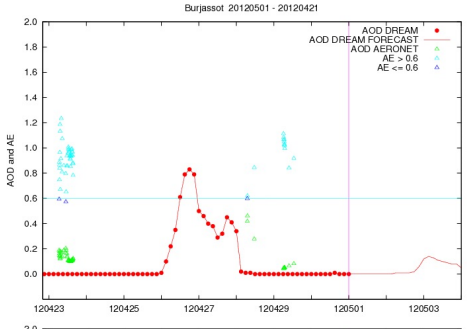


MSG/RGB

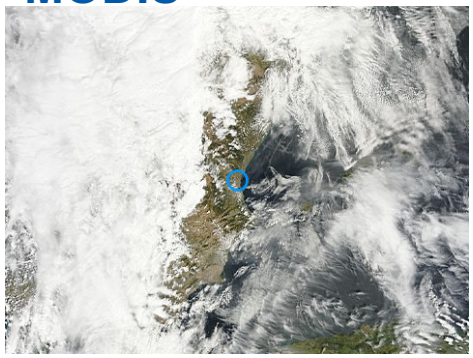




AERONET



MODIS

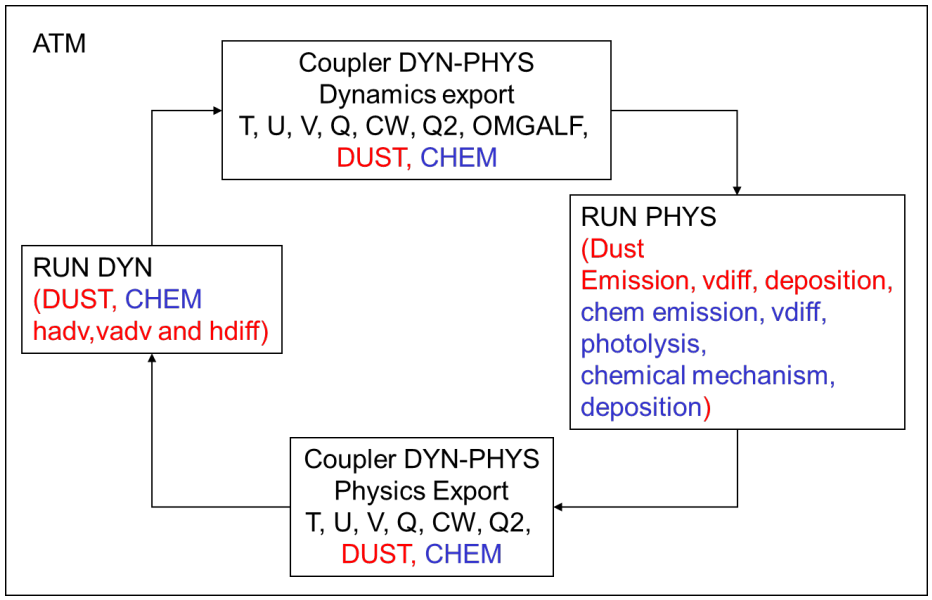


Inclusion of new satellite aerosol products: **OMI**, **CALIPSO** and **MISR**

Dust forecasting models: The NMMB/BSC-CTM project

The **N**on-hydrostatic **M**ultiscale **M**odel (**NMMB**) :

- Under development at NCEP (Janjic, 2005; Janjic and Black, 2007) as evolution of the ETA model
- Developed within the Earth System Modeling Framework (ESMF)
- Arakawa B grid and regular (global) or rotated (regional) lat/lon coordinate
- Unified model for a broad range of spatial and temporal scales
- NMMB is the regional operational meteorological model in NCEP since *October 2011*.



On-line approach:

SEA SALT (*Spada et al., 2012*), gas-phase **CHEM** (*Jorba et al., 2011; Badia et al., 2012*) and **Dust** (*Pérez et al., 2011; Haustein et al., 2012*) , modules fully embeded within the atmospheric driver.

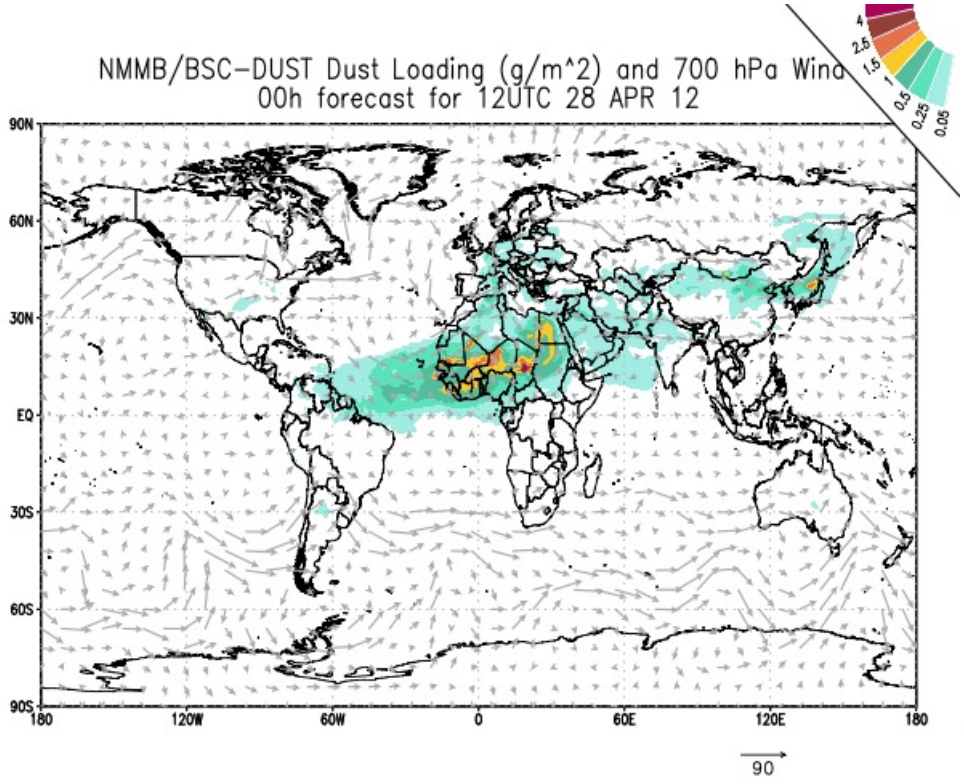
Dust forecasting models: The NMMB/BSC-Dust model

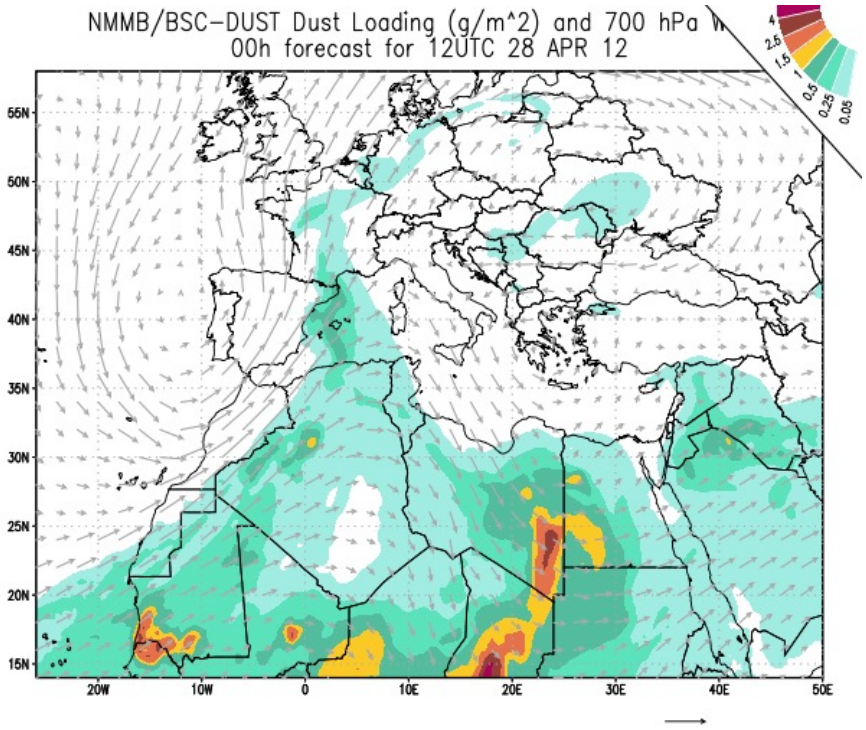
- Evolution of the BSC-DREAM8b model (Nickovic et al., 2001; Pérez et al., 2006)
- **NMMB/BSC-Dust** is embedded into the NMMB model and solves the mass balance equation for dust.
- **NMMB/BSC-Dust** (Pérez et al., 2011; Haustein et al., 2012) main features:
  - Implementation of all common **on-line dust modules** for global and regional simulations
  - Nested regional domains at very high resolution are available
  - The current DREAM dust emission scheme is upgraded to a physically based scheme
    → ***explicitly accounting for saltation and sandblasting***
  - New high resolution database for soil textures and vegetation fraction is included
- Pre-operational dust forecasts in the **BSC** website (global/regional) and participating in the **ICAP** initiative (global)

http://www.bsc.es/projects/earthscience/nmmbsc-dust-forecast

Dust forecasting models: The NMMB/BSC-Dust model

*Dust forecasts on **global** and **regional** domains are running in pre-operational in the **BSC***





Dust forecasting models: The NMMB/BSC-Dust model

Global configuration:

- Global domain at 1.4º x 1º horizontal resolution
- 24 vertical levels
- fundamental time step of 180s
- Cold start without data assimilation
- Initial conditions from NCEP meteorological analysis 1x1º and Meteorological fields updated with NCEP every 24 h

Annual simulation: 2000 (Pérez et al., 2011)

Regional configuration:

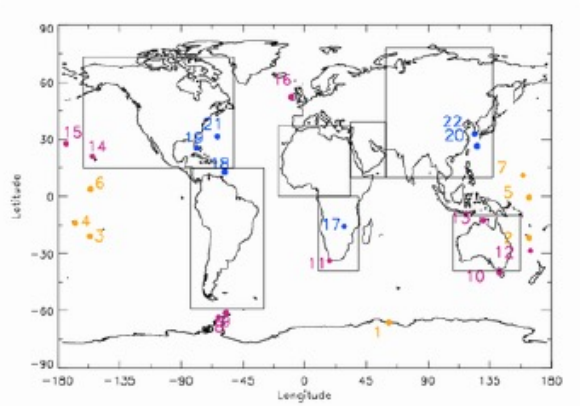
- North African domain at 0.25º x 0.25º horizontal spatial resolution
- 40 vertical layers
- fundamental time step of 40s
- Cold start without data assimilation
- Initial conditions from NCEP meteorological analysis 1x1º and meteorology fields updated boundary conditions every 6 h

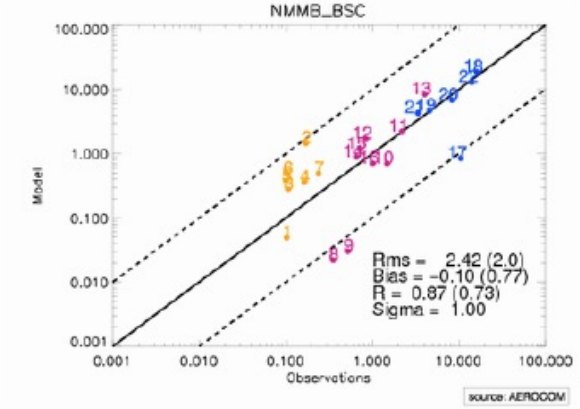
Annual simulation: 2006 (Pérez et al., 2011)

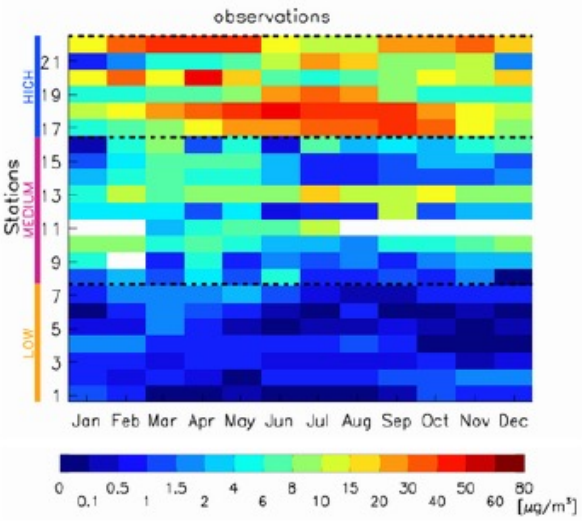
SAMUM-I May 2006 (Haustein et al., 2012)

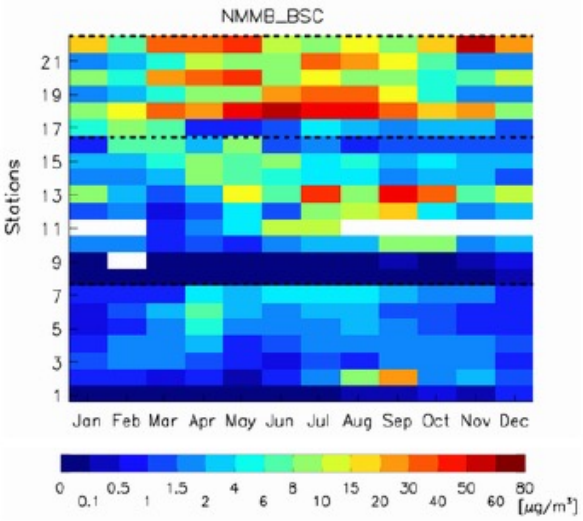
Dust forecasting models: The NMMB/BSC-Dust model

Surface concentration for global domain for 2000 (Pérez et al., 2011)





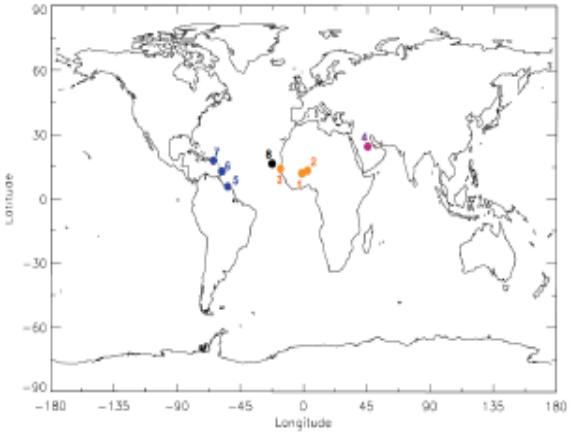




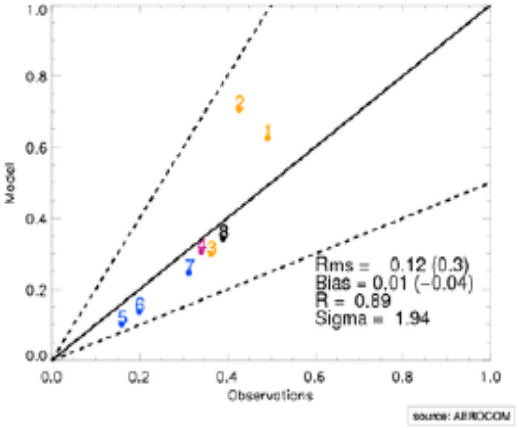
Dust forecasting models: The NMMB/BSC-Dust model

DOD for global domain for 2000 (Pérez et al., 2011)

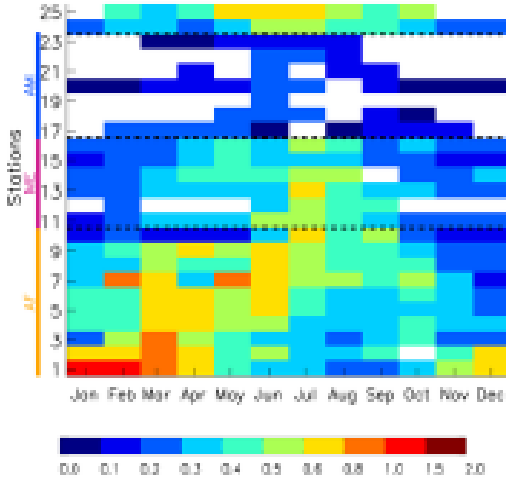
AERONET sites



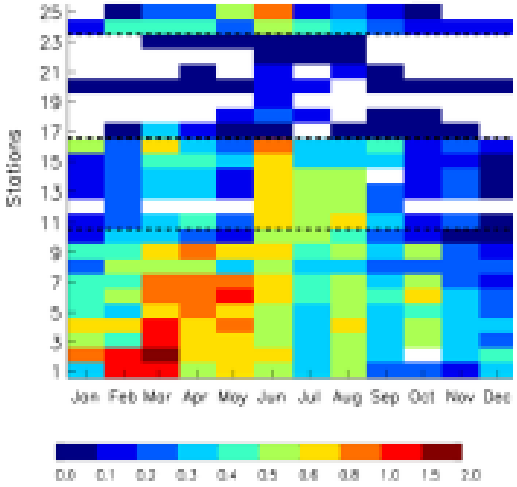
NMMB/BSC-DUST



Total AOD observations

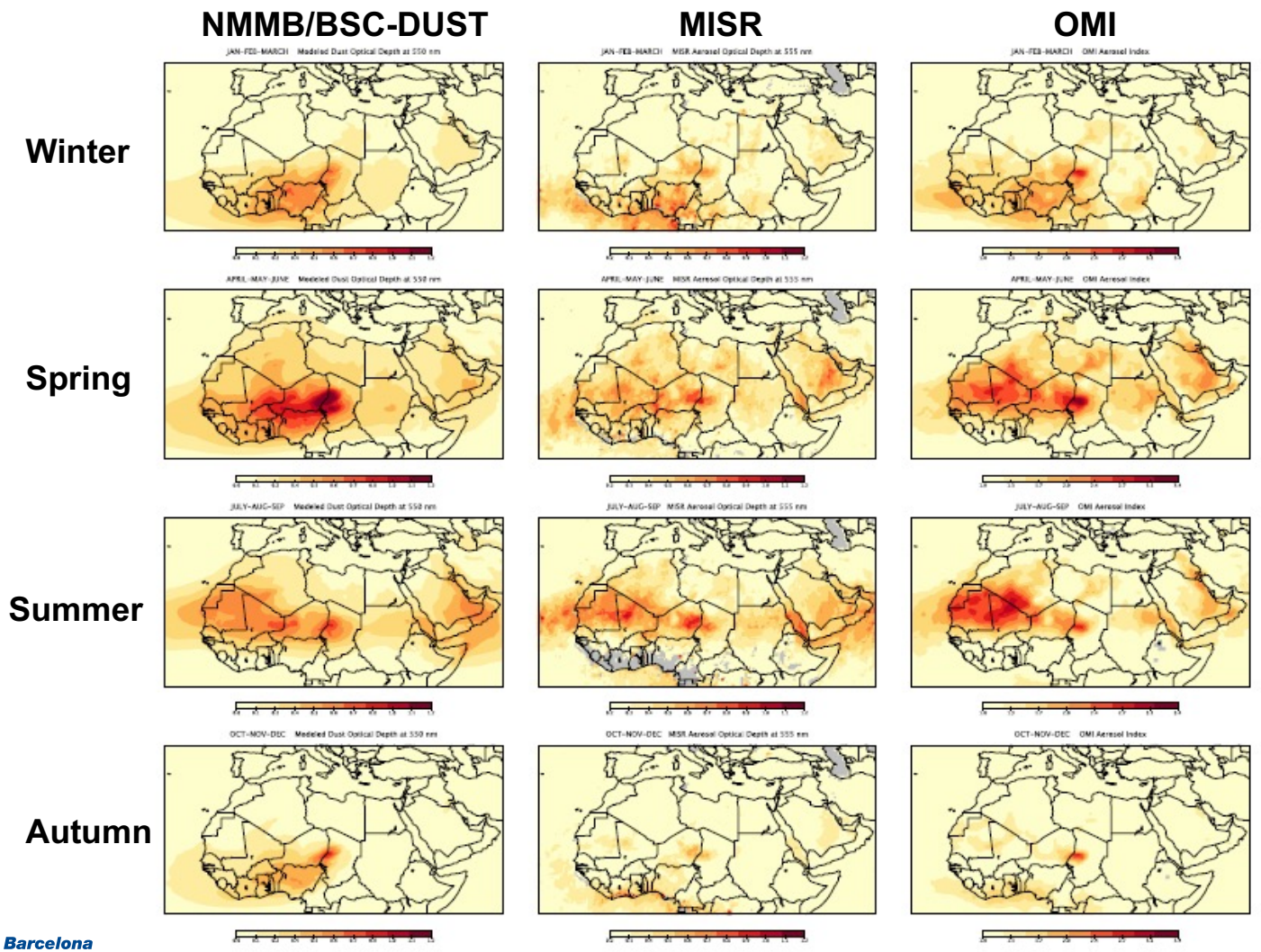


NMMB/BSC-DUST



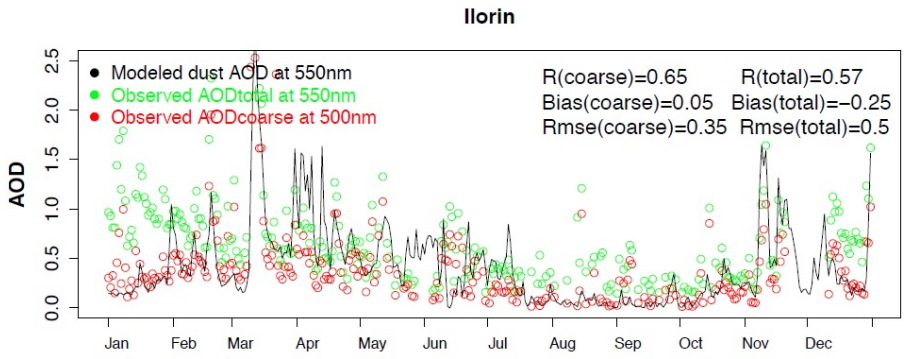
Dust forecasting models: The NMMB/BSC-Dust model

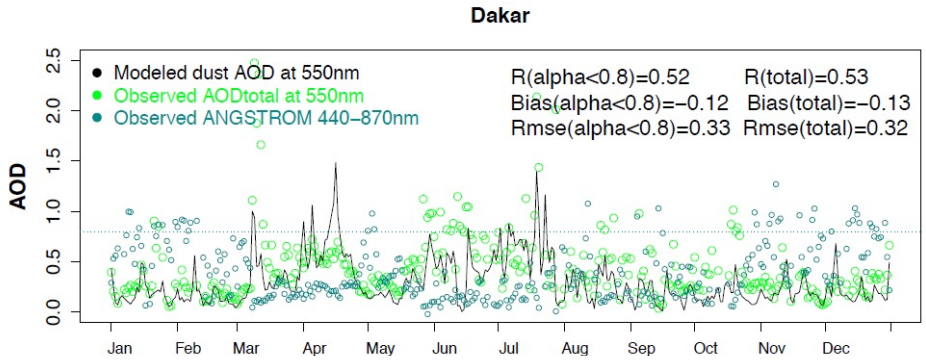
Satellite comparison for regional domain for 2006 (Pérez et al., 2011)

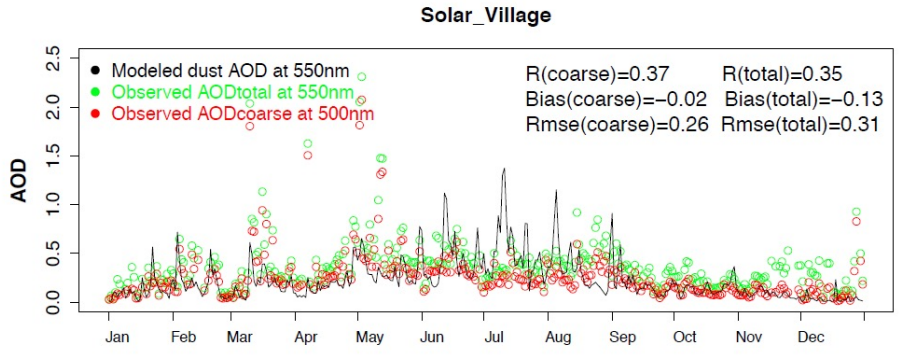


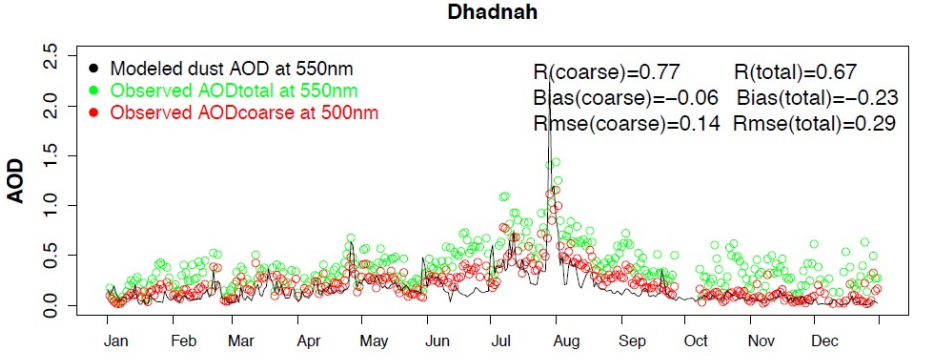
Dust forecasting models: The NMMB/BSC-Dust model

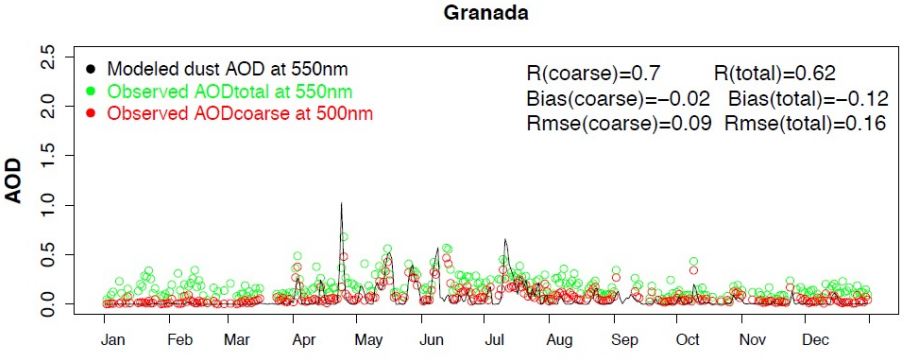
AERONET comparison for regional domain for 2006 (Pérez et al., 2011)

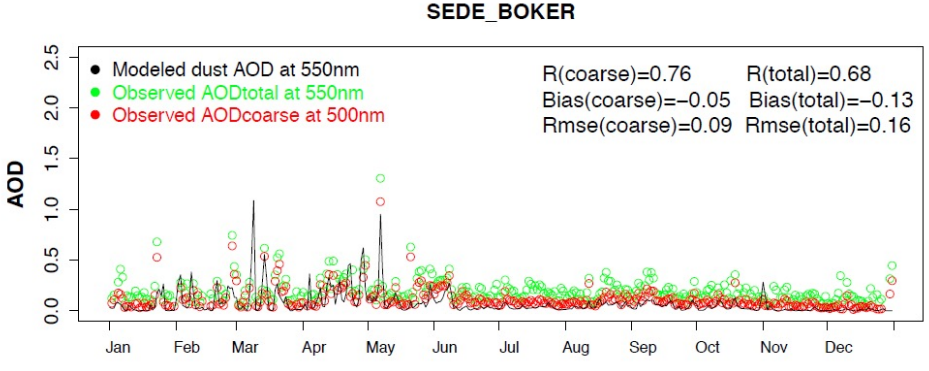






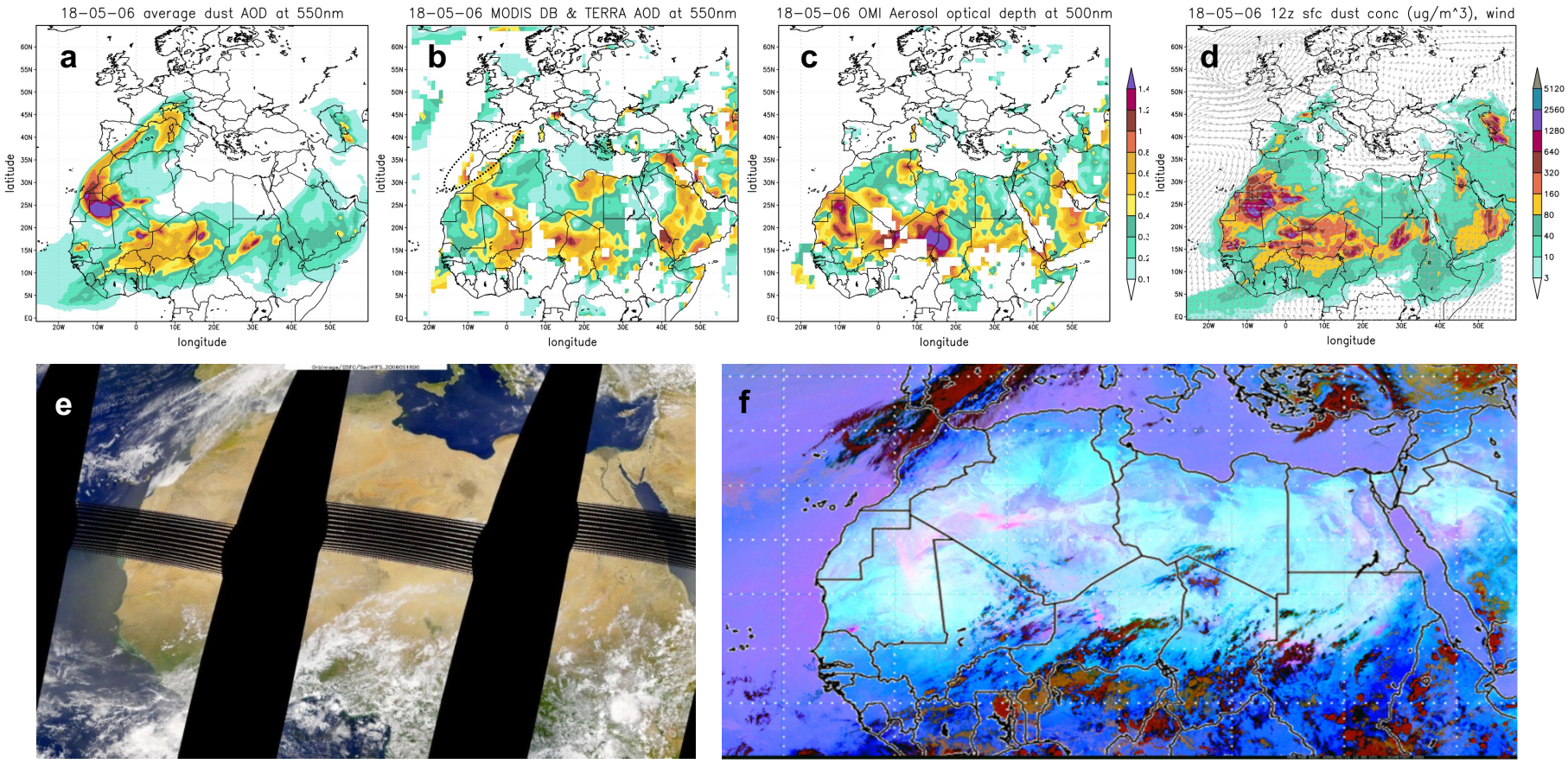






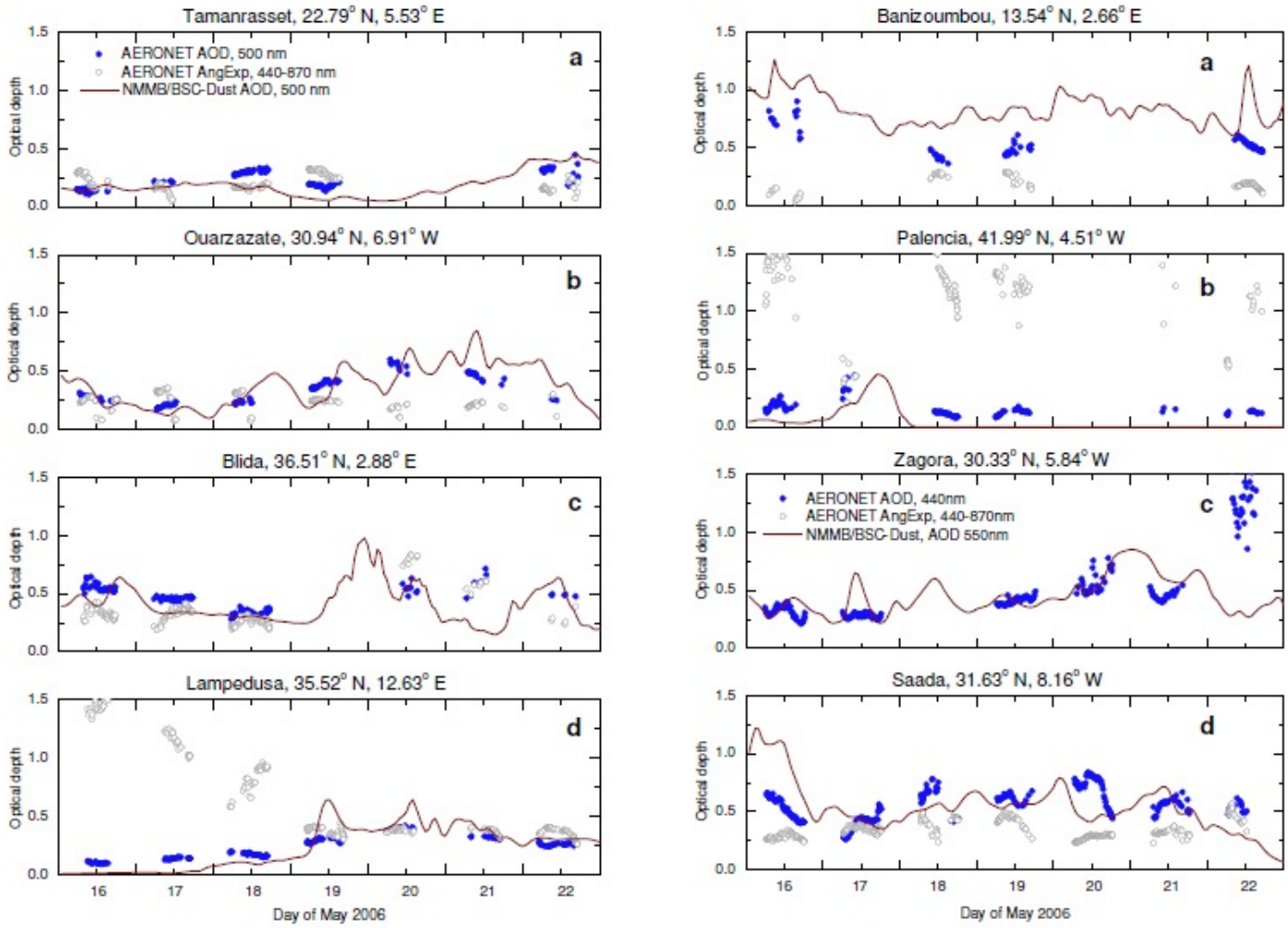
Dust forecasting models: The NMMB/BSC-Dust model

SAMUM-I on 18 May 2006 – Satellites (Haustein et al., 2012)

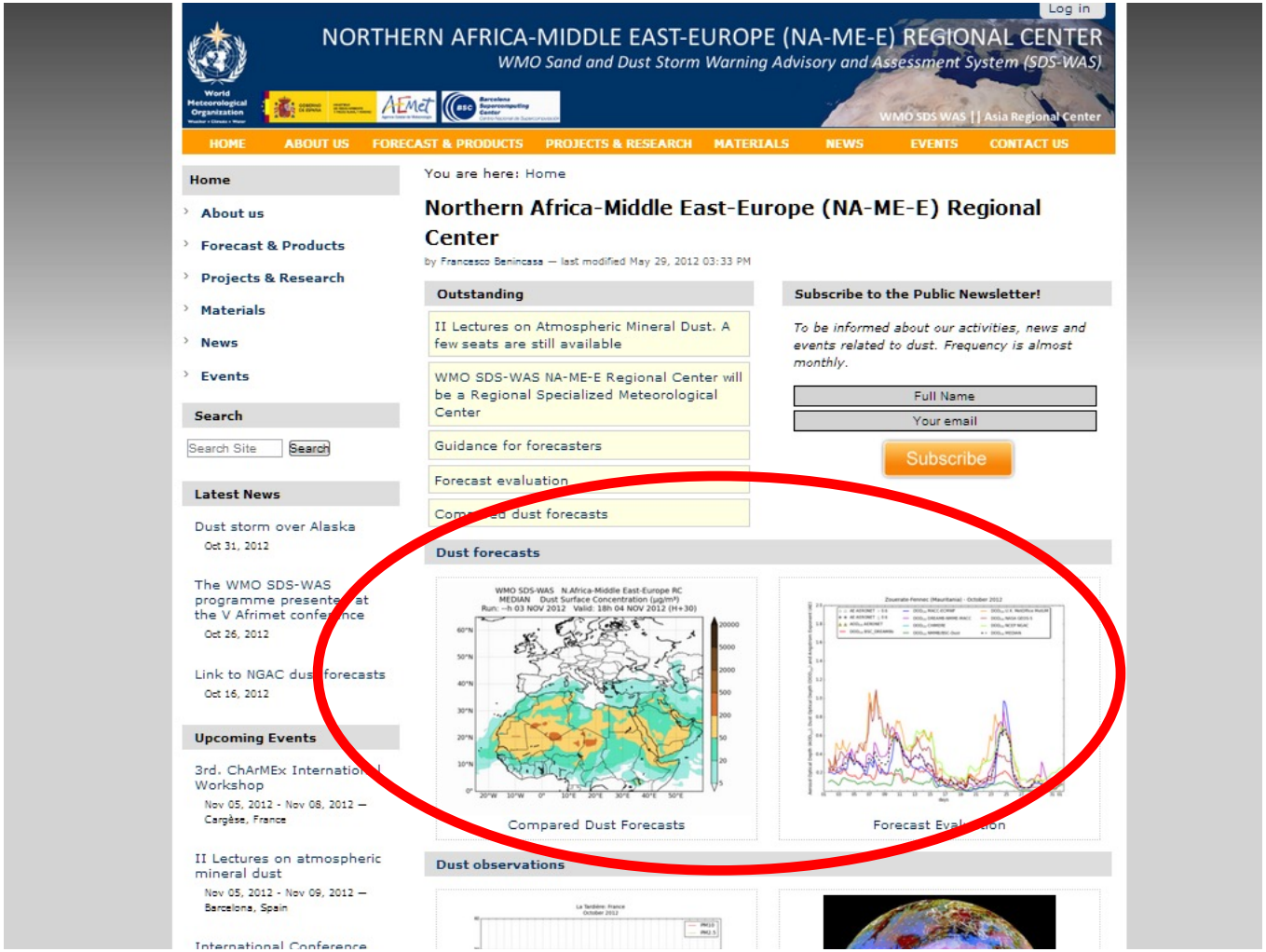


Dust forecasting models: The NMMB/BSC-Dust model

SAMUM-I May 2006 – AERONET (Haustein et al., 2012)

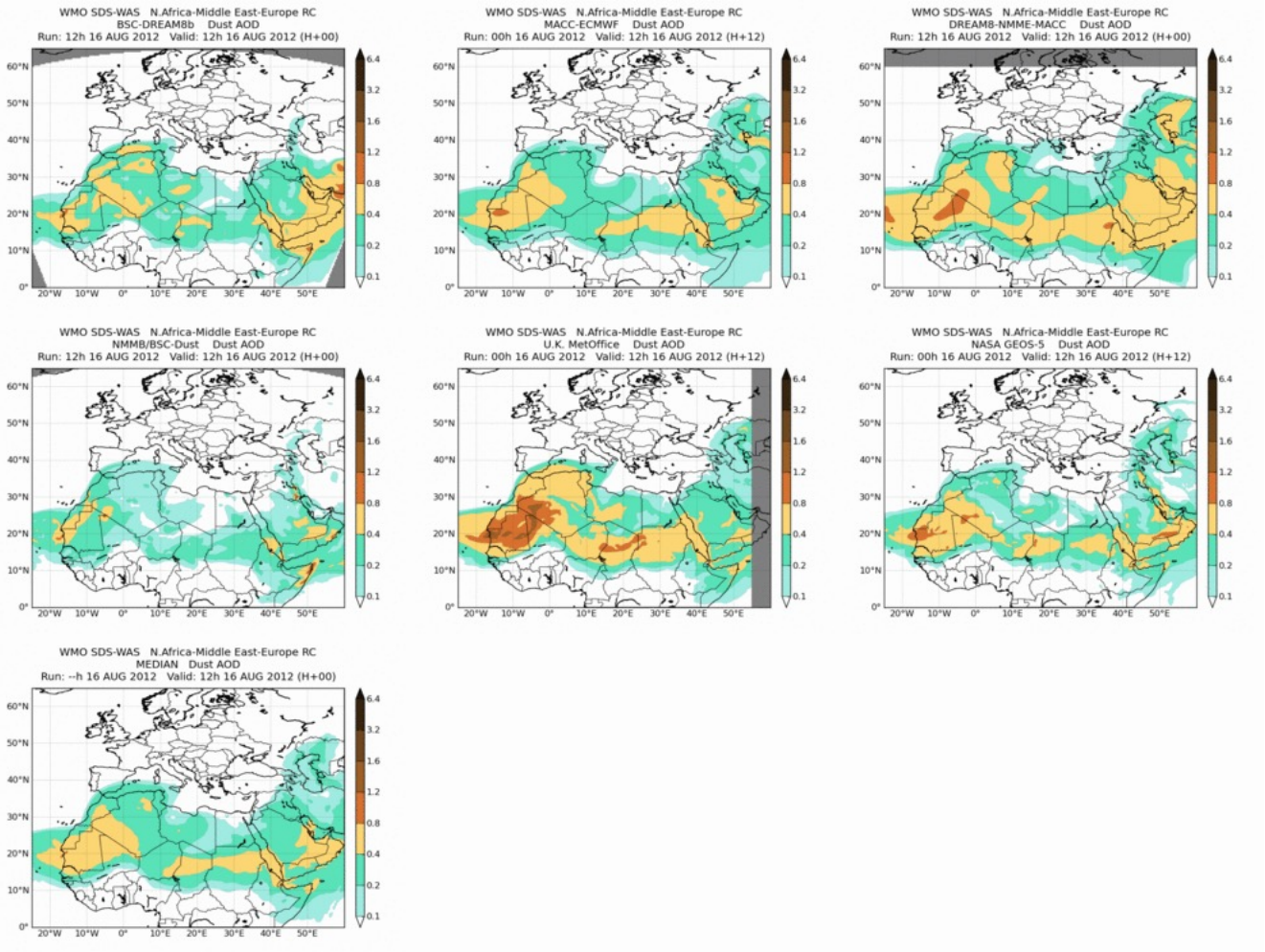


Dust forecasting models: SDS-WAS NA-ME-E RC



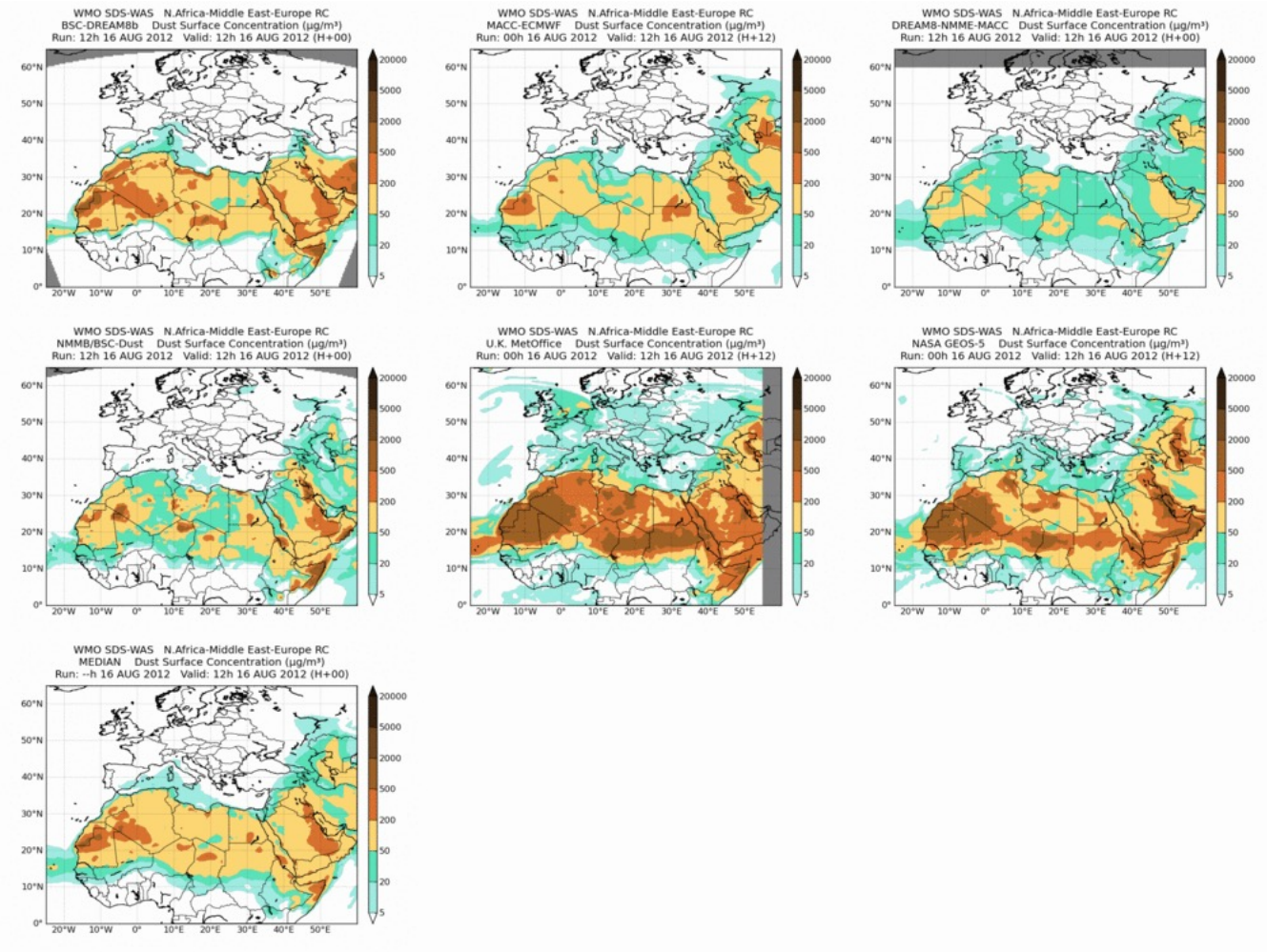
Dust forecasting models: SDS-WAS NA-ME-E RC

Compared AOD for 16 August 2012

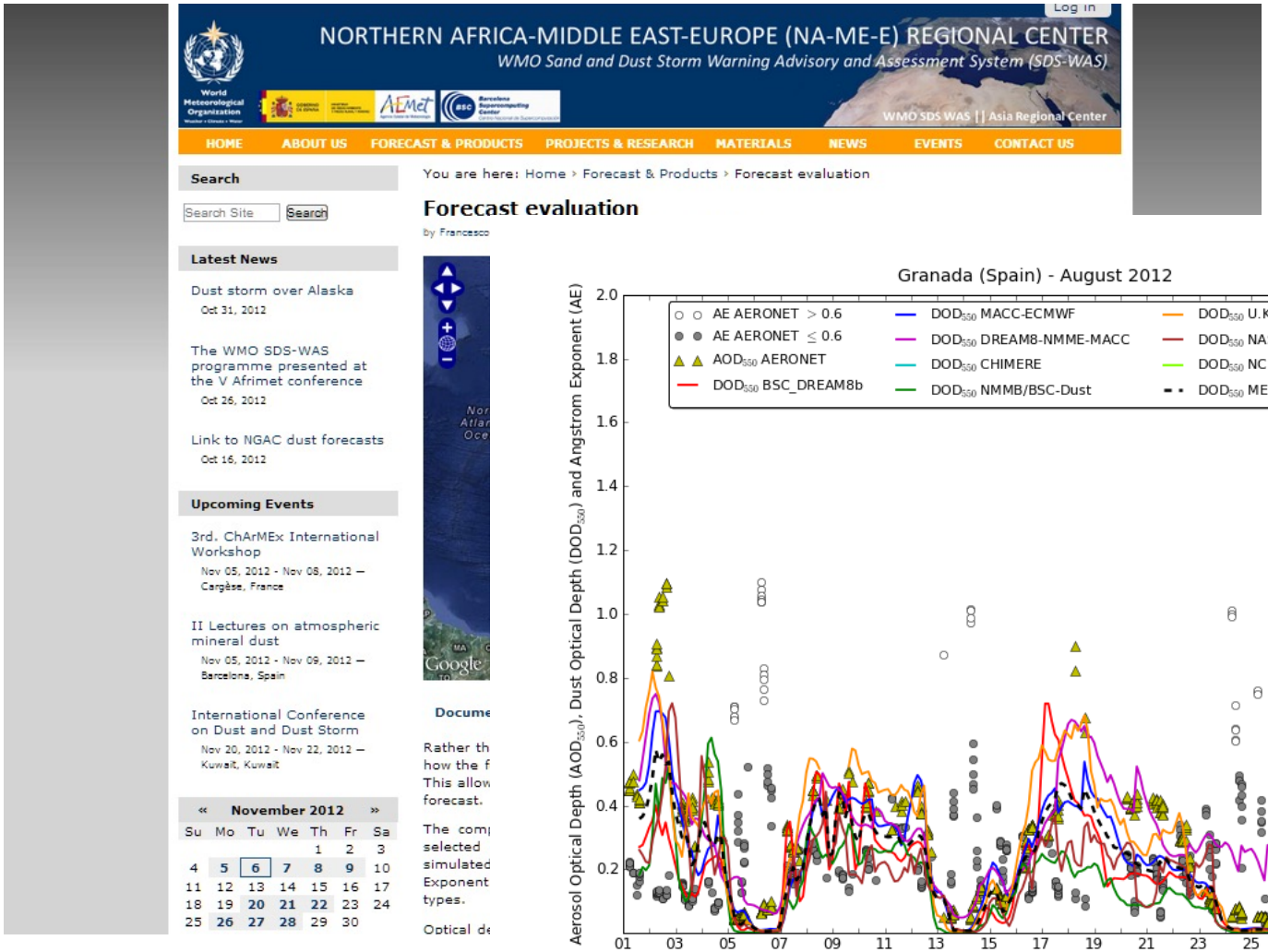


Dust forecasting models: SDS-WAS NA-ME-E RC

Compared SCONC for 16 August 2012



Dust forecasting models: SDS-WAS NA-ME-E RC



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