Barcelona Supercomputing Center
Centro Nacional de Supercomputación

EXCELENCIA SEVERO OCHOA

Dust prediction models

Sara Basart (sara.basart@bsc,es)

6th Dust Training, 25-27 October 2017, Istanbul

Questions will be welcome!

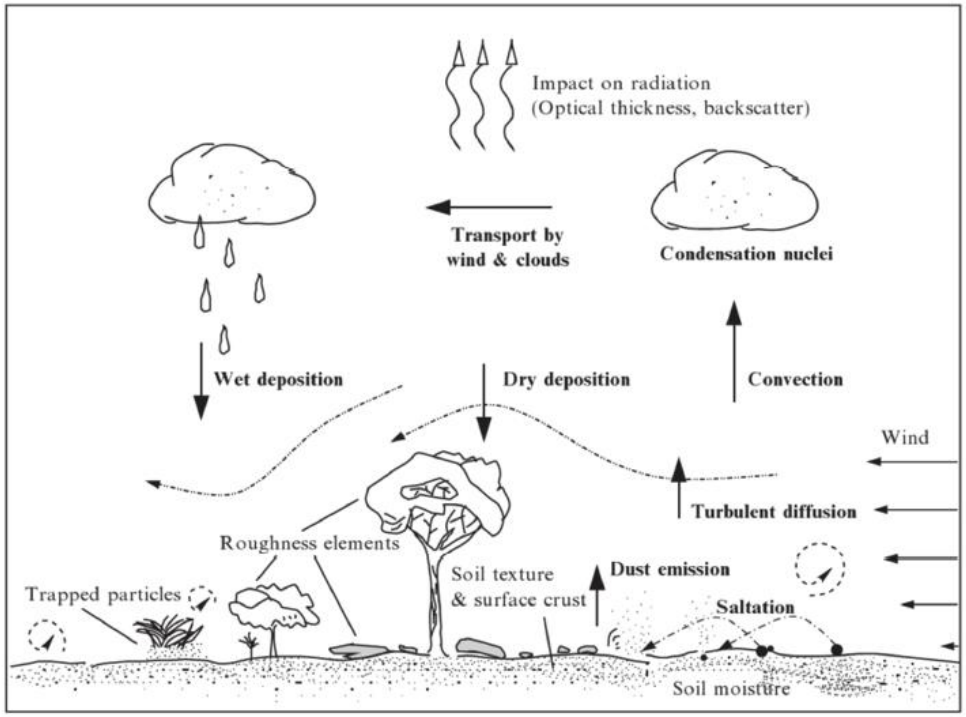
Introduction

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.

Dust forecasting models

Dust models are a mathematical representation of atmospheric dust cycle.



Extracted from Shao (2008)

- ✓ *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)*

Outlook

1. **Dust cycle and associated processes**

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

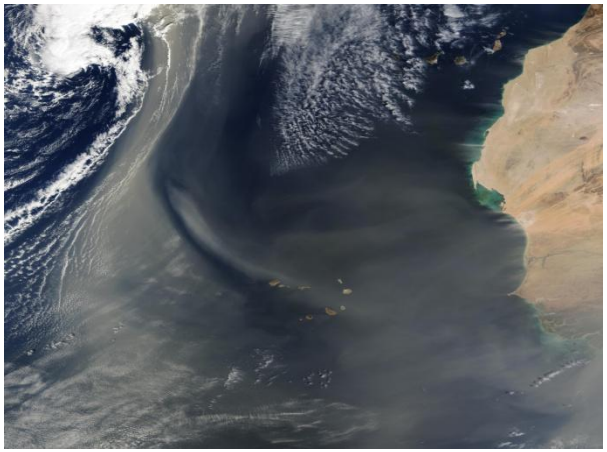
2. **Dust forecasting models**

   - *Dust emission schemes and dust sources*
   - *Dust transport*
   - *Dust deposition and sedimentation*

3. **Modeling the dust cycle at BSC: From R&D to operational**

Dust cycle and associated processes

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

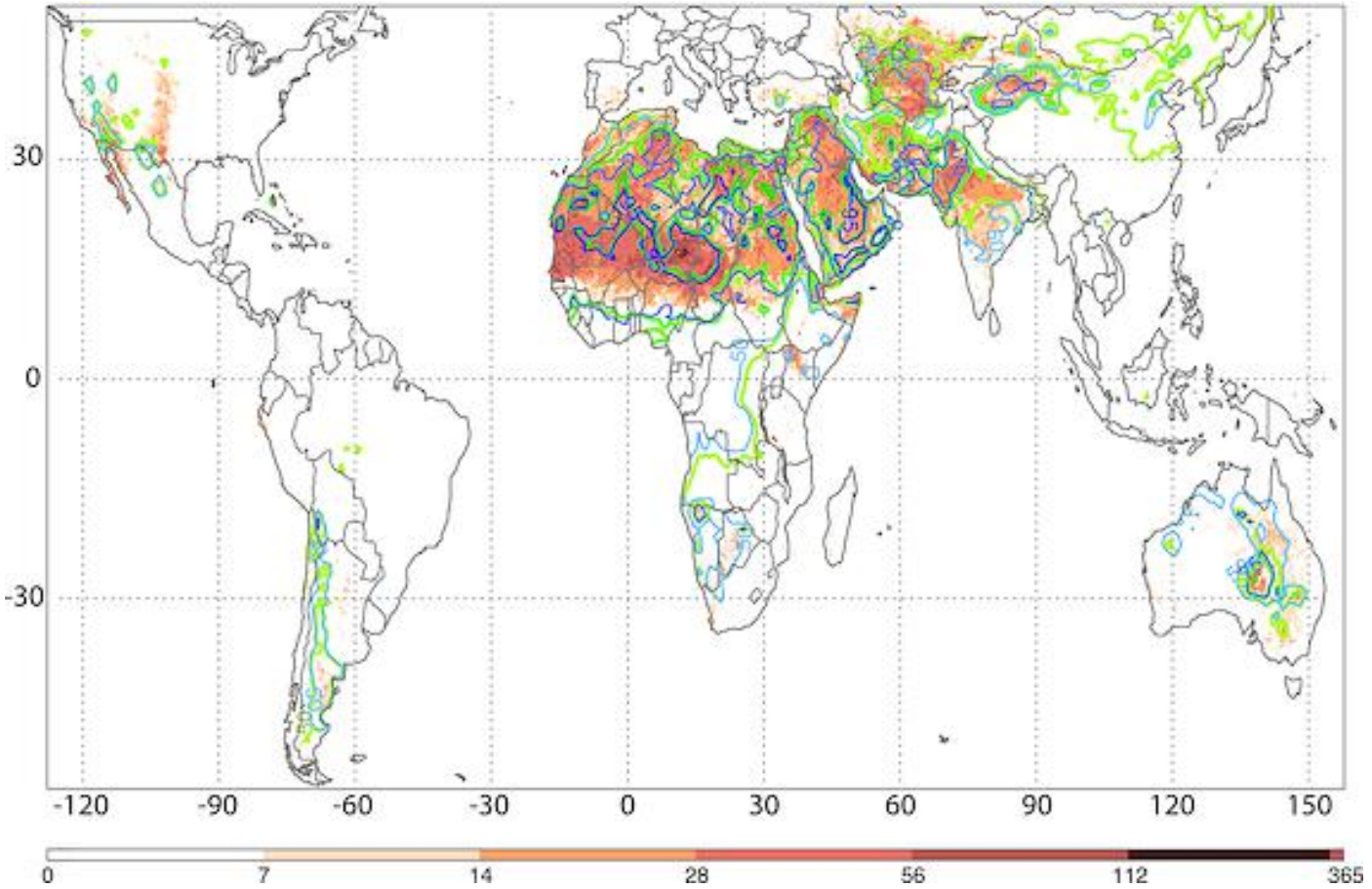


MODIS True color Western Africa – Altantic Ocean

People caught in a dust storm in Mali

Dust cycle and associated processes

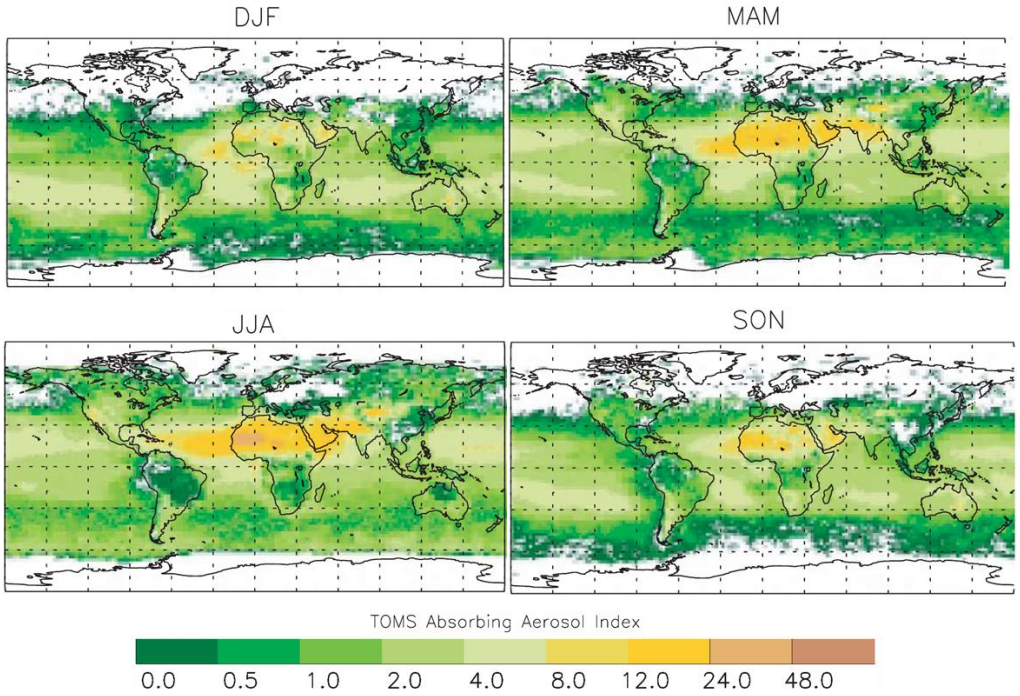
Dust global distribution



Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products by Ginoux et al. (2012)

Dust cycle and associated processes

Temporal changes in the dust distribution: SEASONAL and DECADAL CHANGES



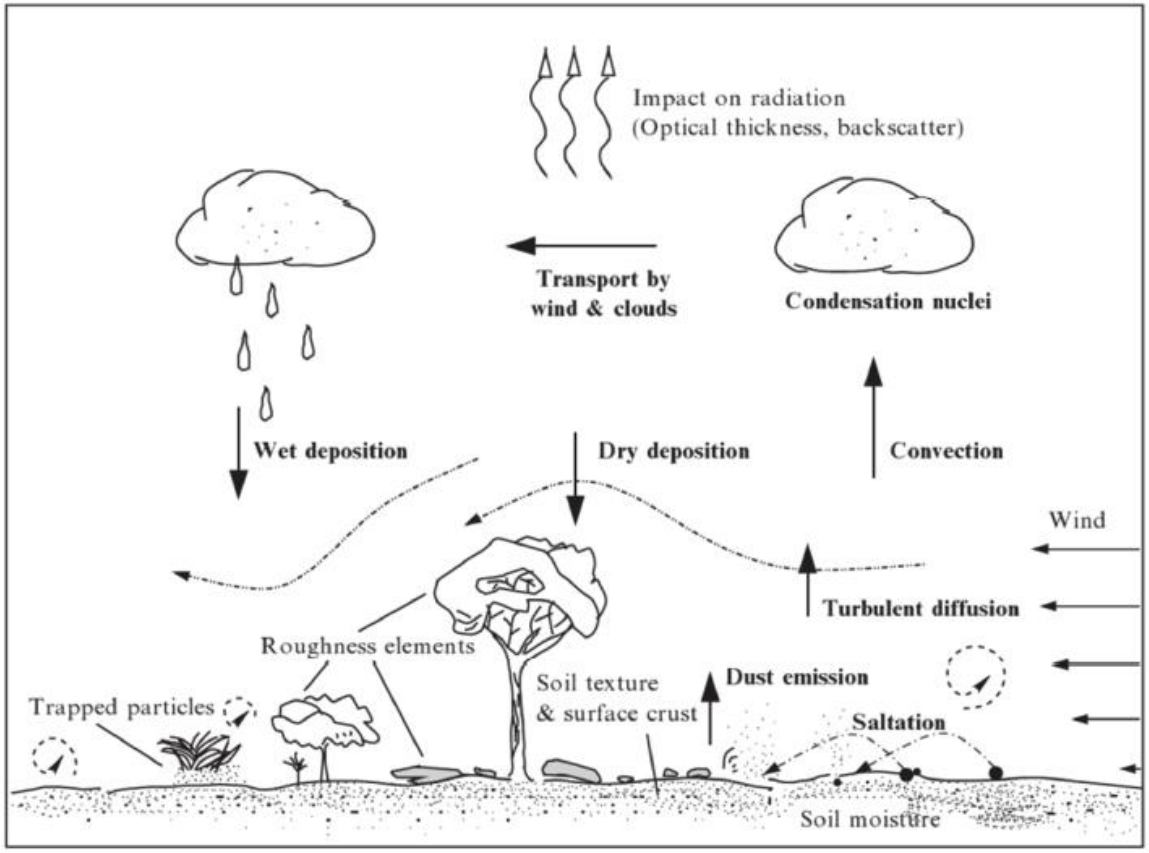
• Seasonal dust distribution changes well characterized. Follows seasonal changing weather regimes (mainly) and vegetation changes (in semi-arid areas)

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

Figure extracted from Tegen al. (2002)

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

Dust cycle and associated processes

Dust Impacts

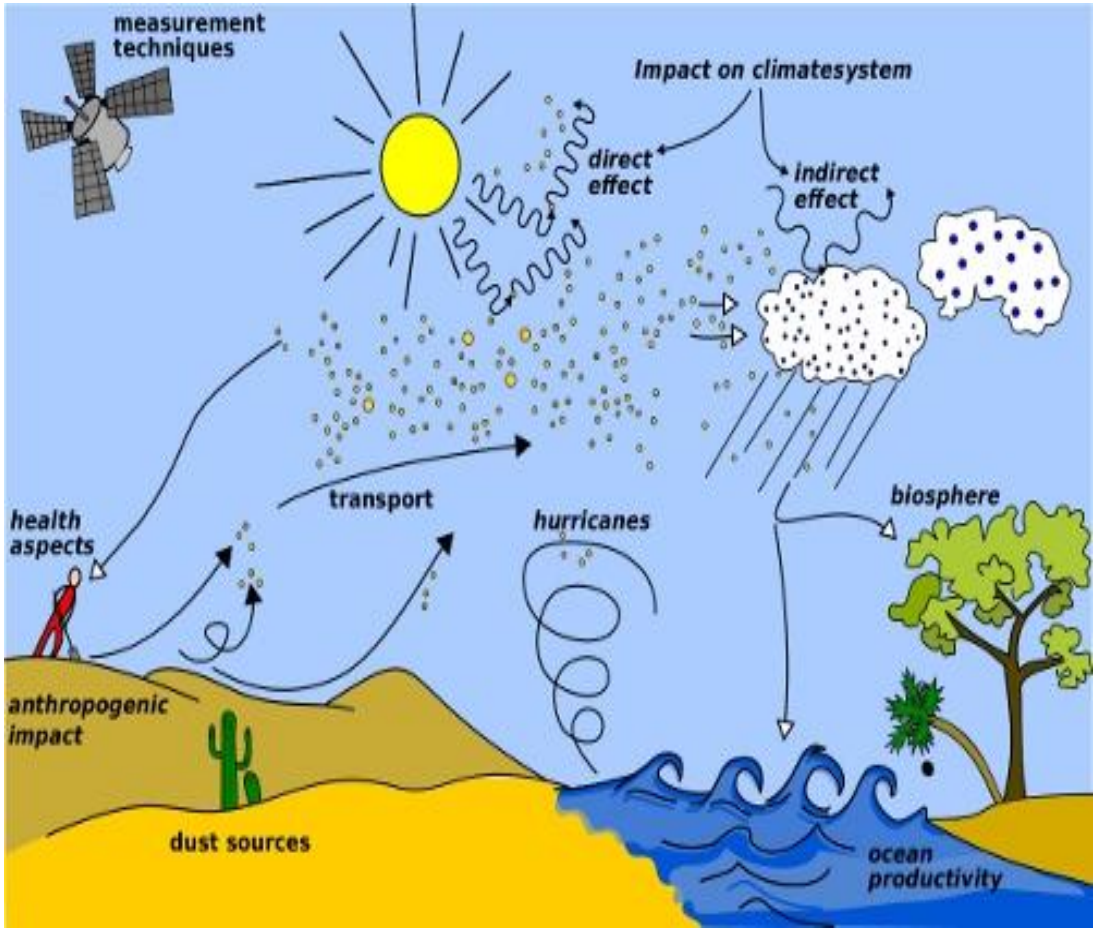


Image from WMO website (http://www.wmo.int/pages/prog/arep/wwrp/new/hurricanes.html)

Ecosystems, meteorology and climate

- *Marine productivity*
- *Coral mortality*
- *Hurricanes formation*

Air Quality and Human Health

- *Respiratory disease (asthma)*
- *Eye infections*
- *Meningitis in Africa*
- *Valley Fever in the Americas*

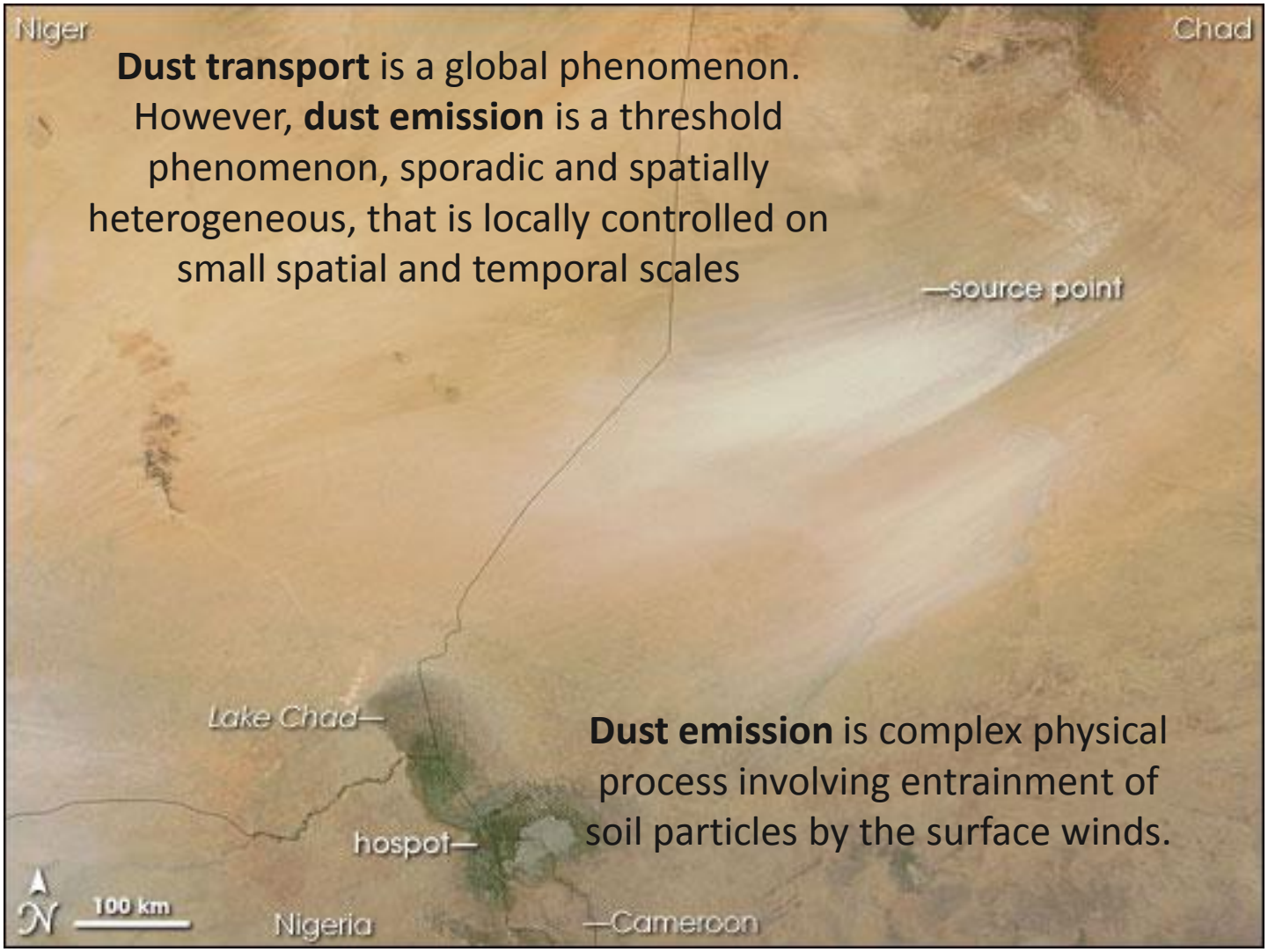
Aviation and Ground Transportation

- *Low visibility (i.e. air disasters)*

Agriculture and fishering

Energy and industry

Dust cycle and associated processes



Dust cycle and associated processes

Types of dust storms:

Synoptic dust storms (large scale weather systems)

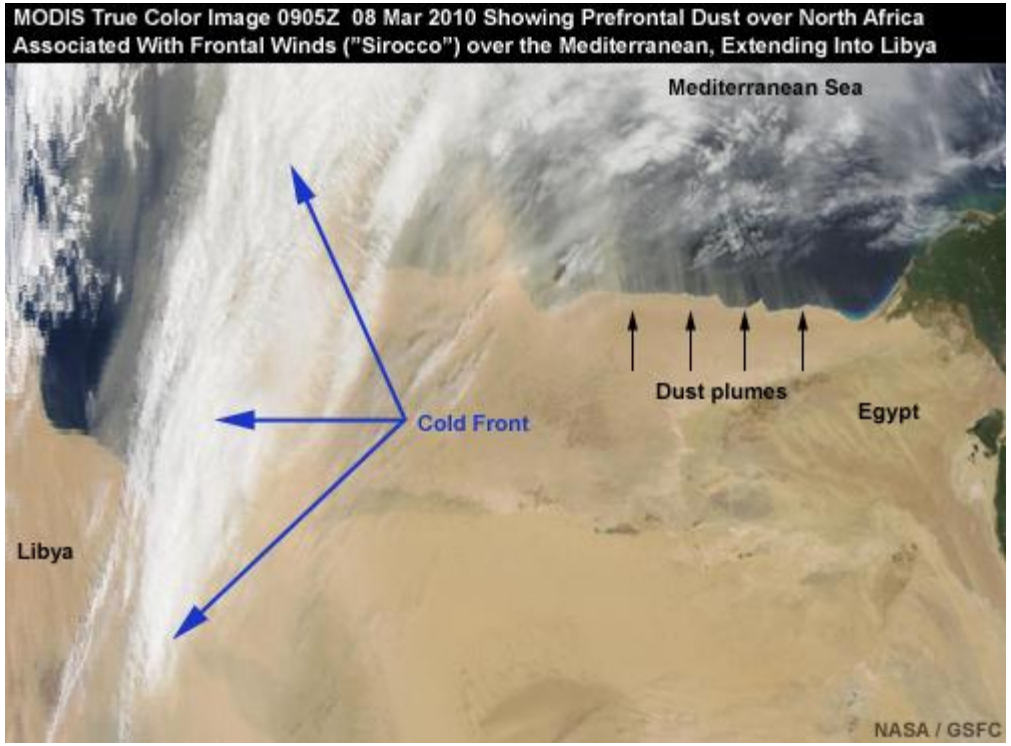
- Prefrontal winds
- Postprontal winds
- Large-scale Trade winds
- …

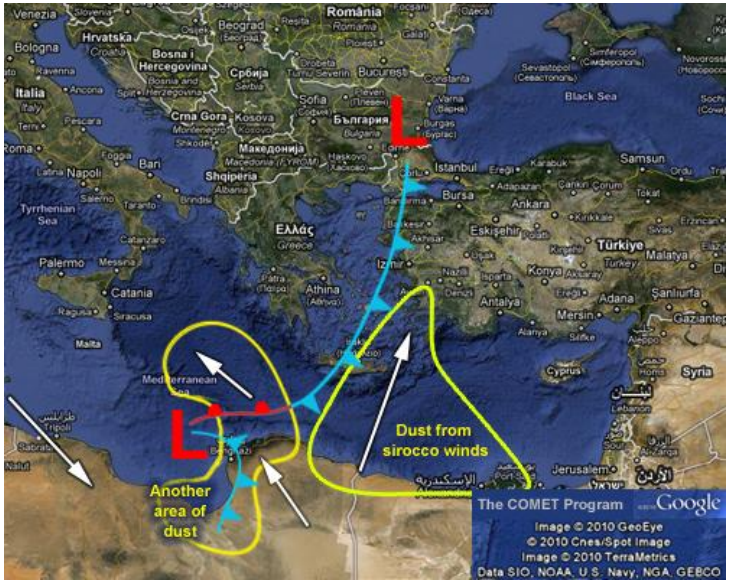
Mesoscale dust storms

- Downslope winds
- Gap flow
- Convection (dust devils and Haboobs)
- Inversion downburst storms
- …

Dust cycle and associated processes

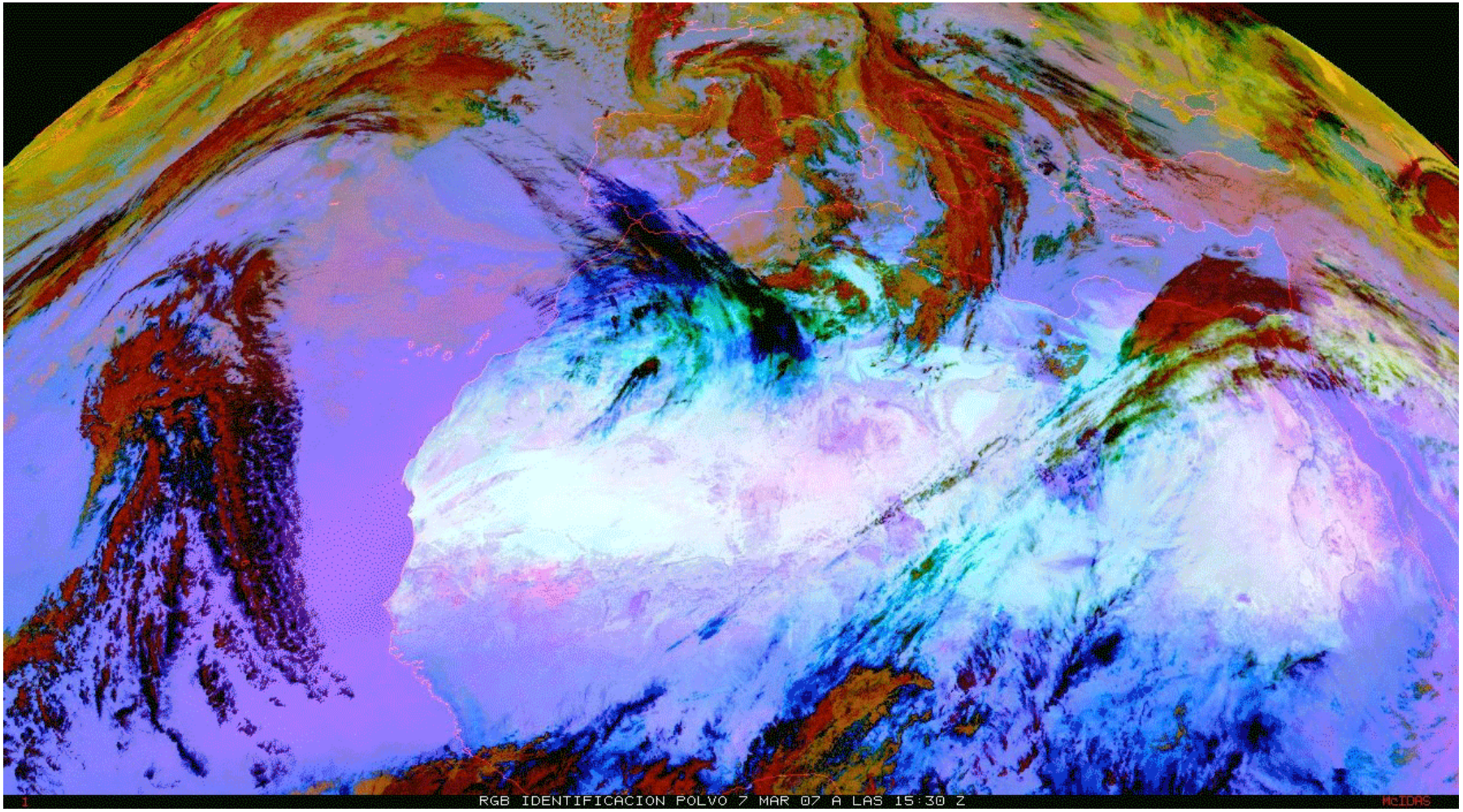
Synoptic dust storms: Pre-frontal





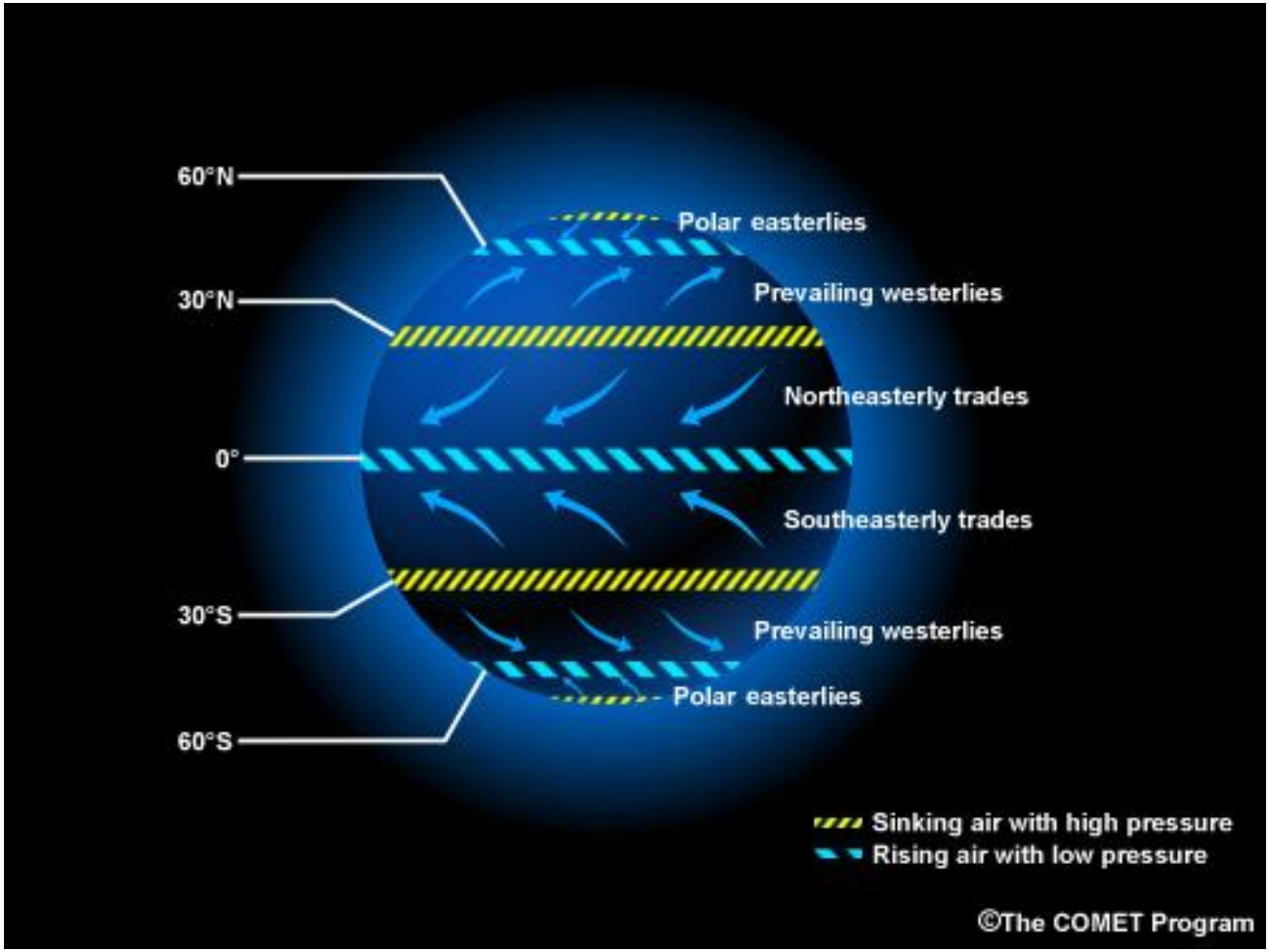
Dust cycle and associated processes

Synoptic dust storms: Post-frontal



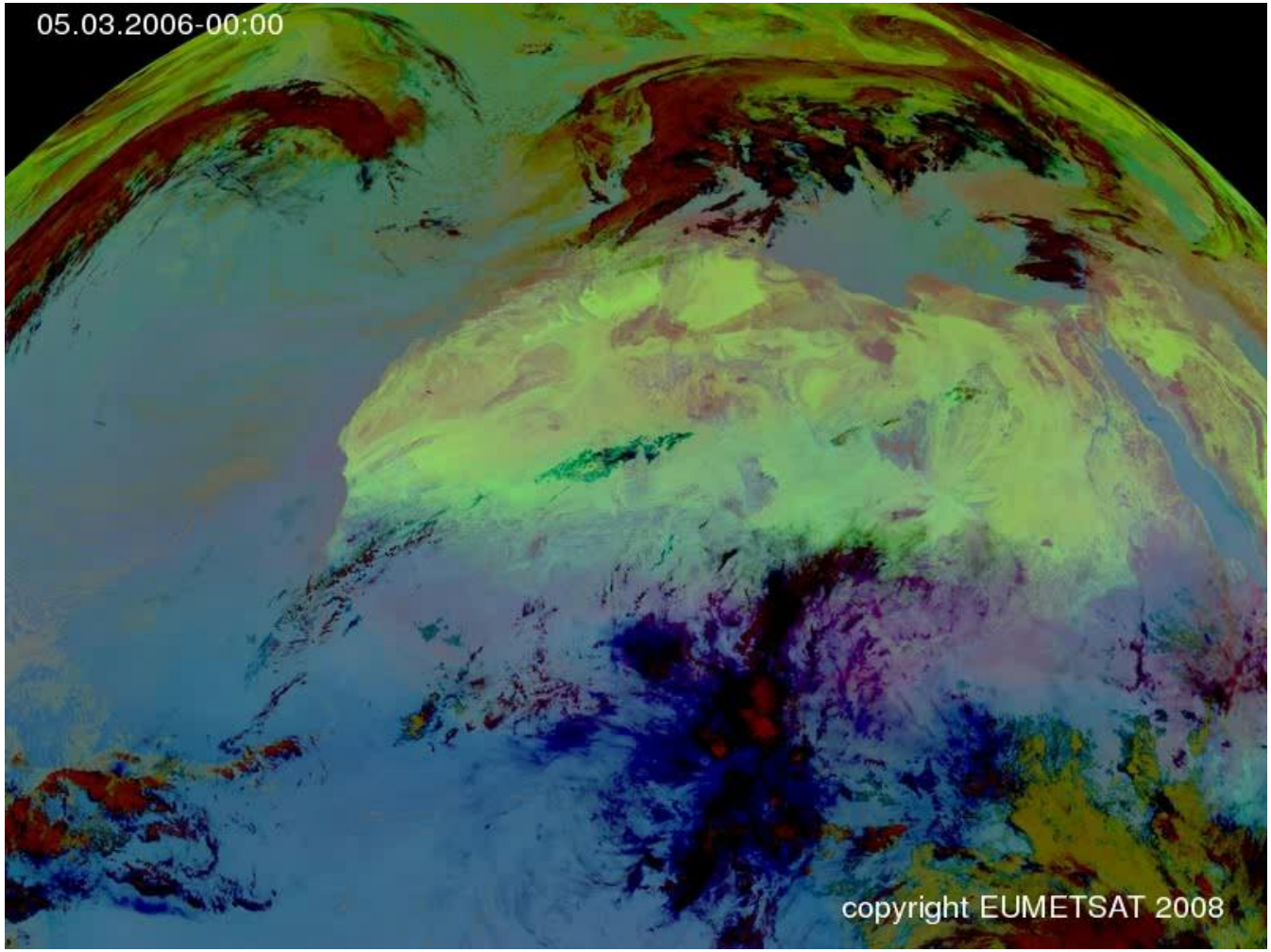
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



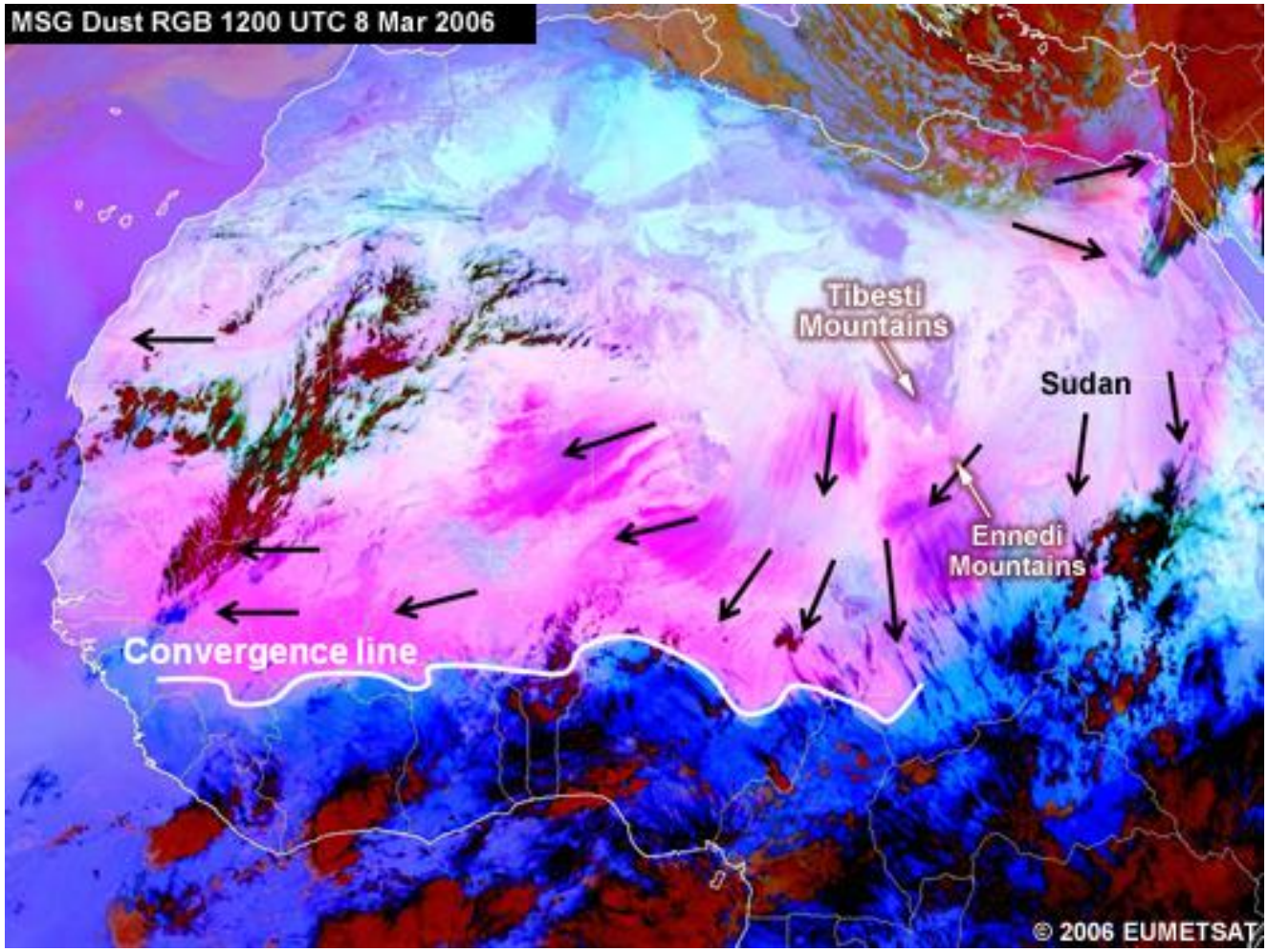
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



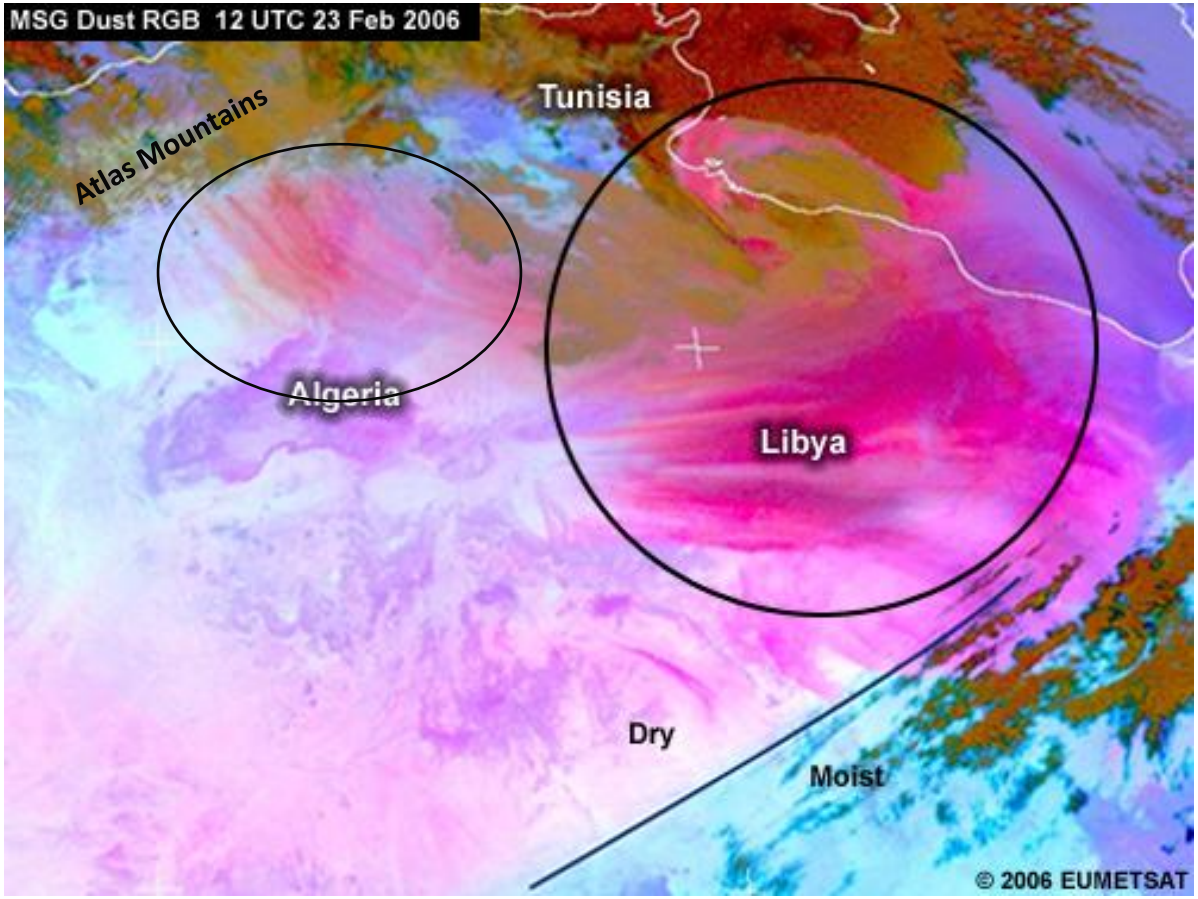
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



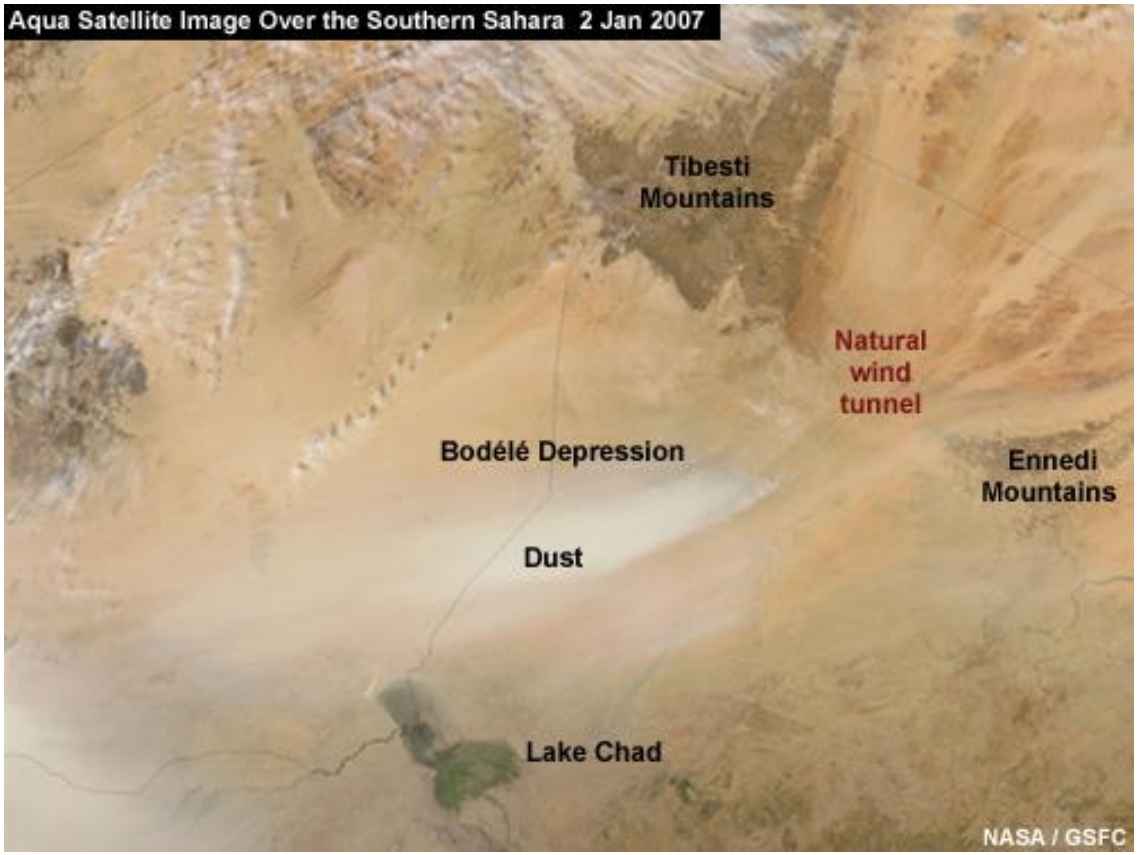
Dust cycle and associated processes

Mesoscale dust storms: Downslope winds



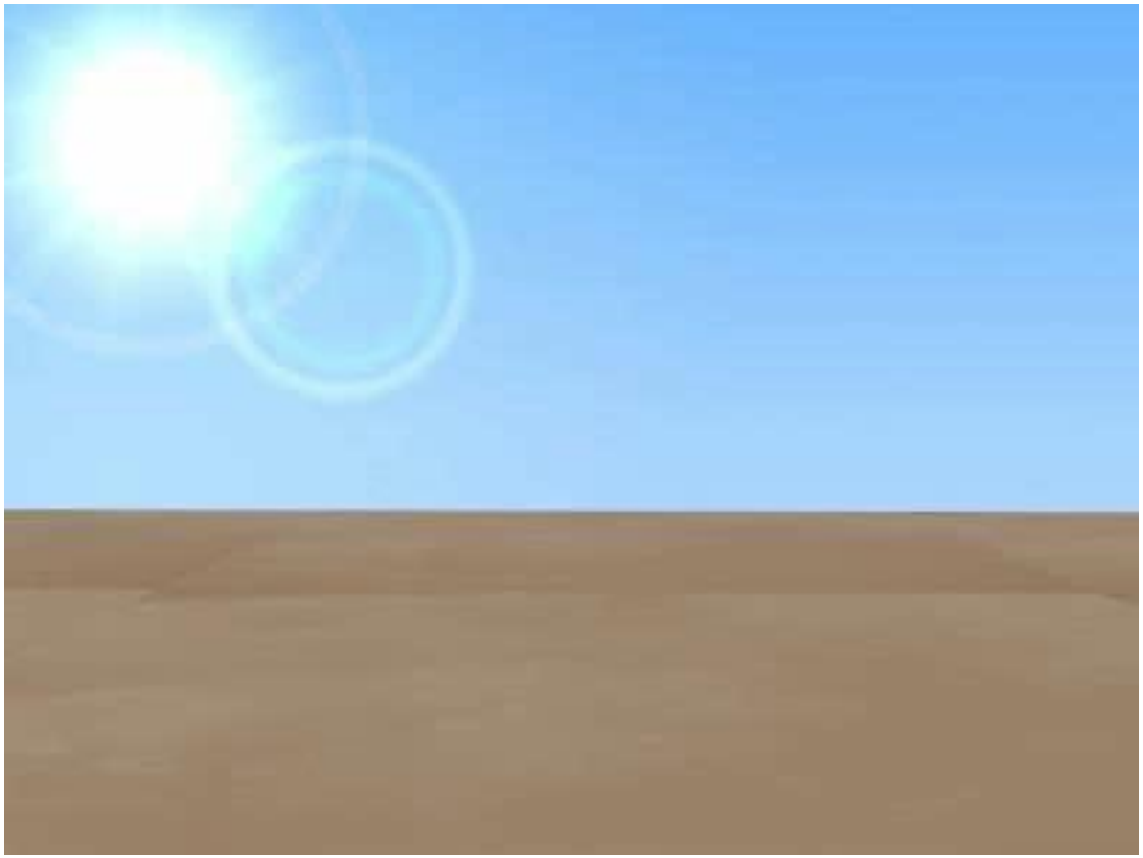
Dust cycle and associated processes

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)

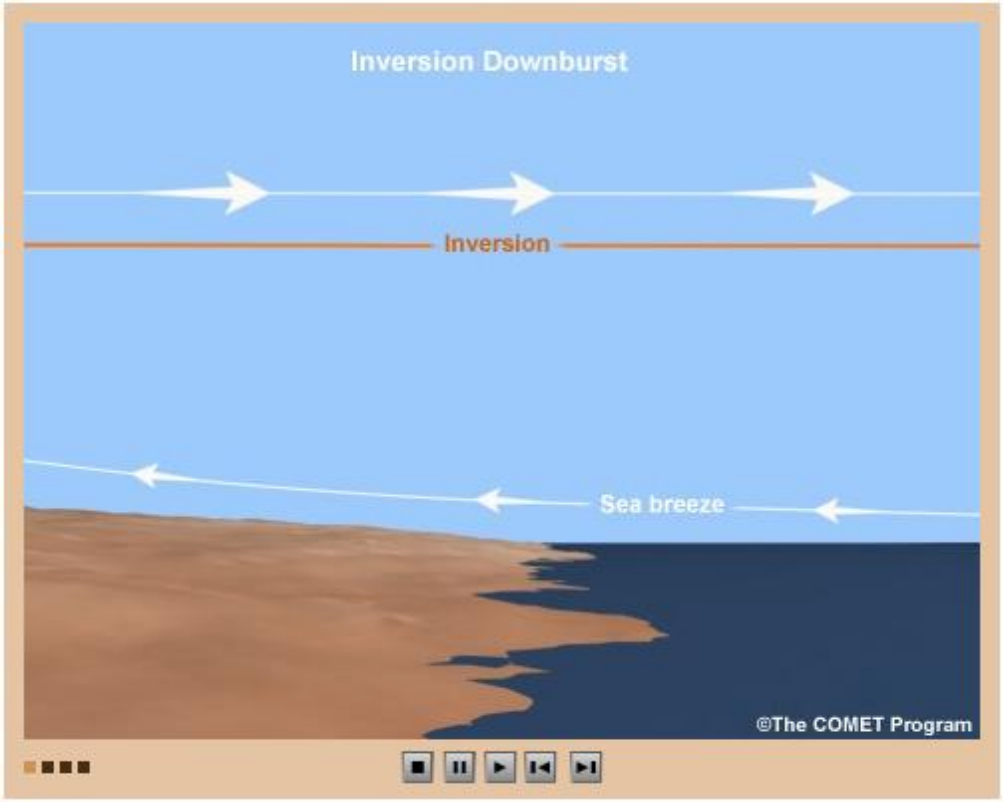
Dust cycle and associated processes

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

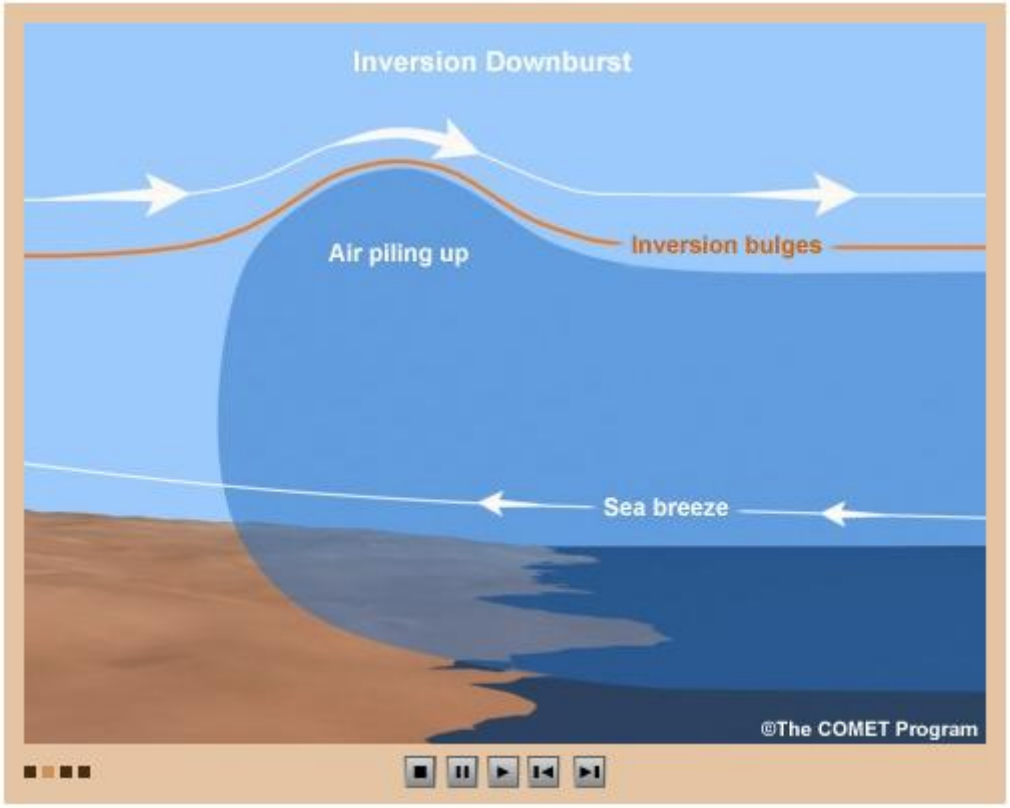
Mesoscale dust storms: Inversion downbursts



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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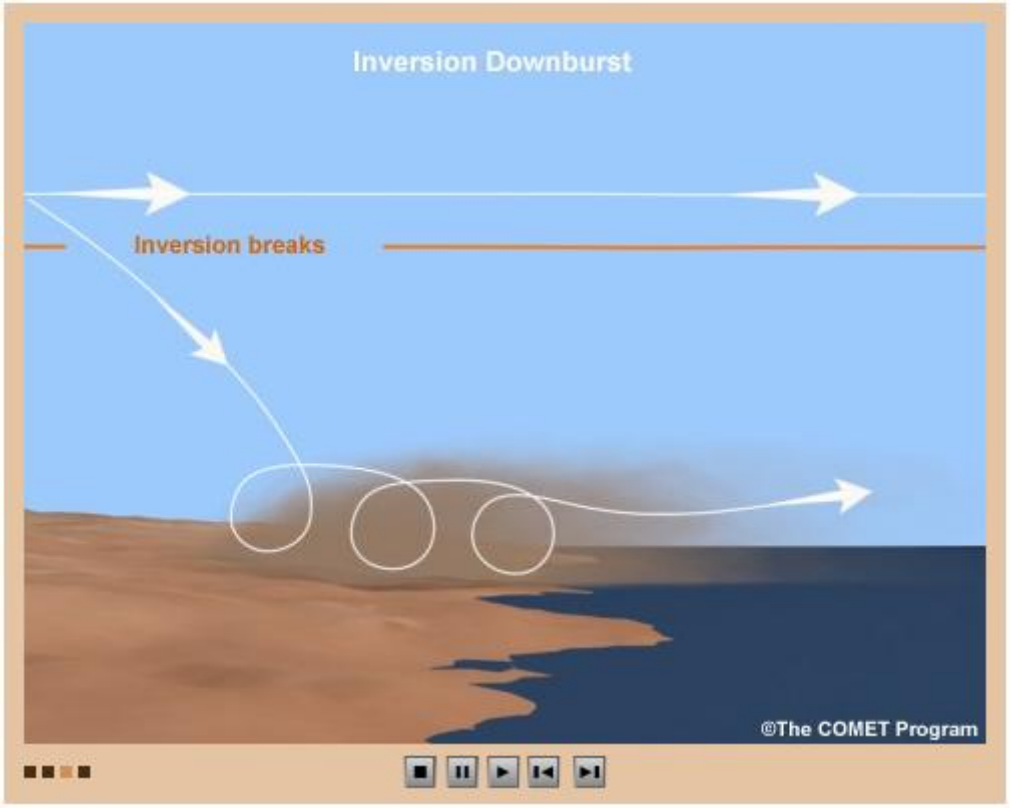
Dust cycle and associated processes

Mesoscale dust storms: Inversion downbursts



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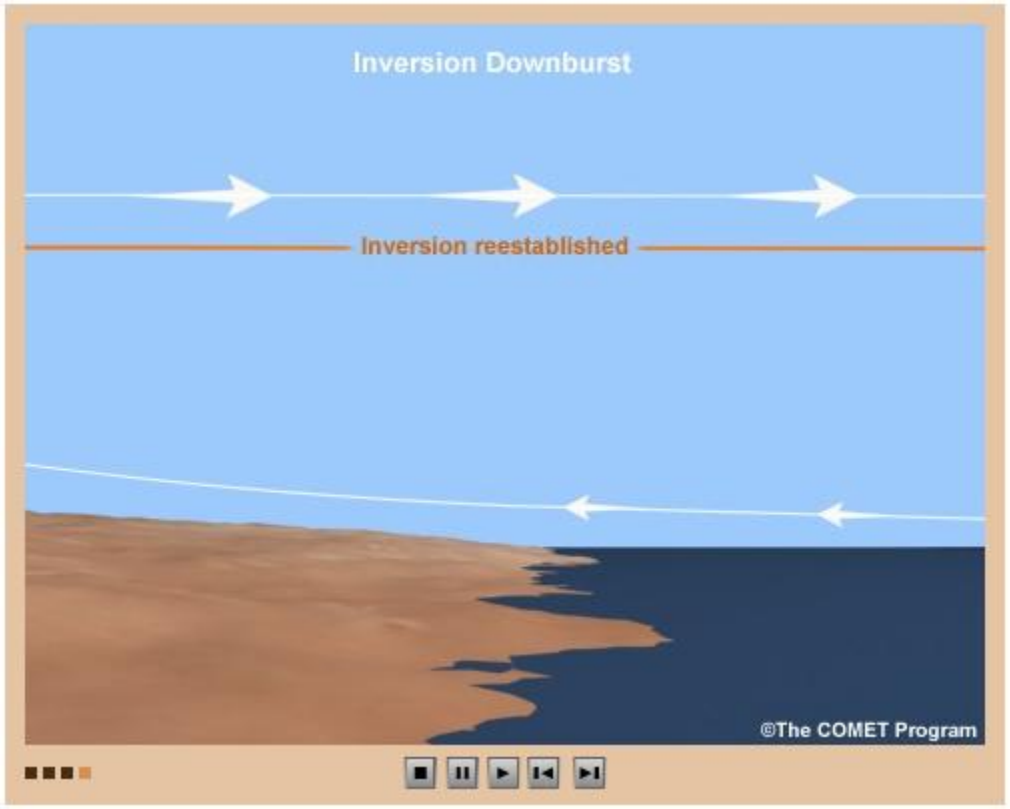
Dust cycle and associated processes

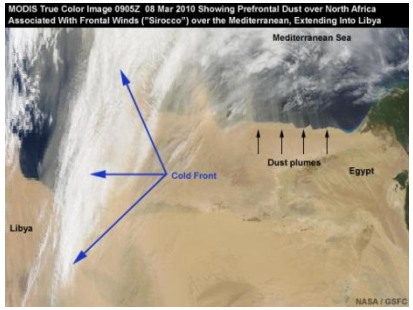
Mesoscale dust storms: Inversion downbursts



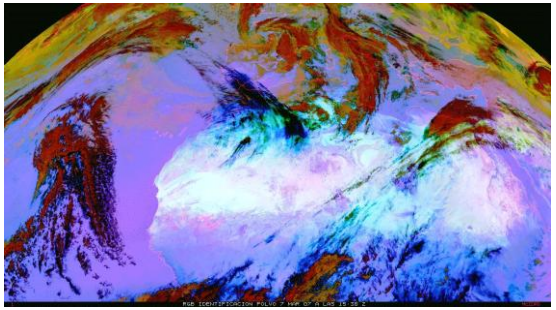
Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust cycle and associated processes

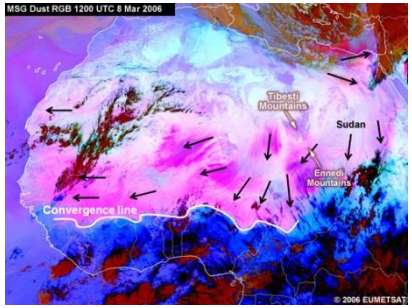
Synoptic dust storms (large scale weather systems) **Well captured by models.**



Pre-frontal winds

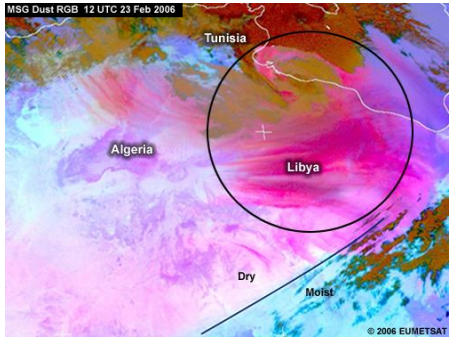


Post-frontal winds

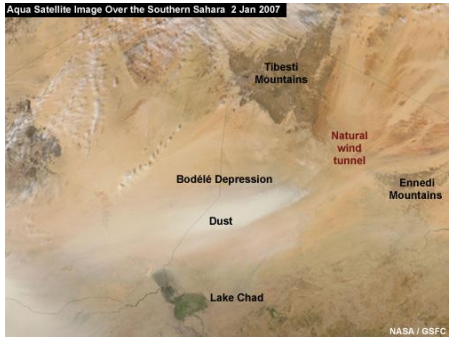


Large-scale trade winds

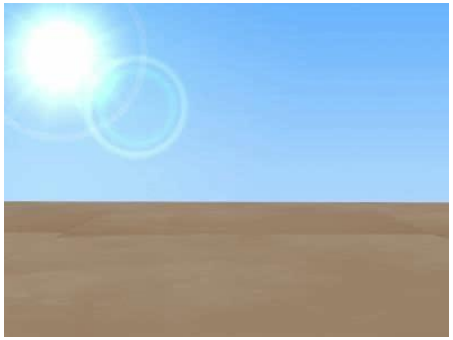
Mesoscale dust storms **Poorly captured by models.**
Some types improve in regional models.



Downslope winds



Gap flow



Dust devils

Haboobs

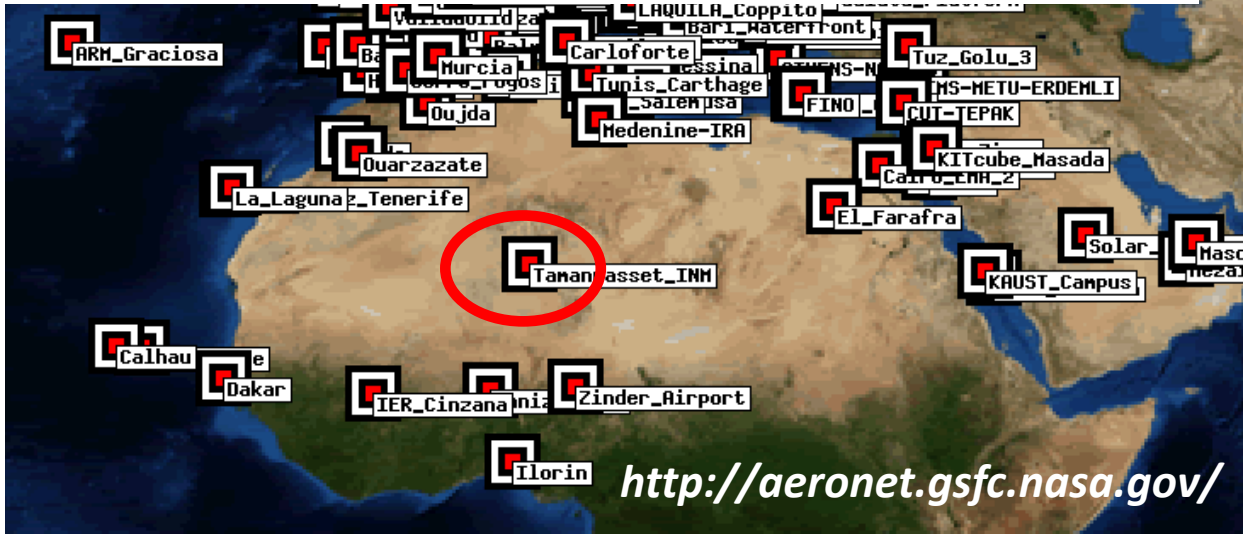
Dust forecasting models

Atmos. Chem. Phys., 14, 11753–11773, 2014
www.atmos-chem-phys.net/14/11753/2014/
doi:10.5194/acp-14-11753-2014

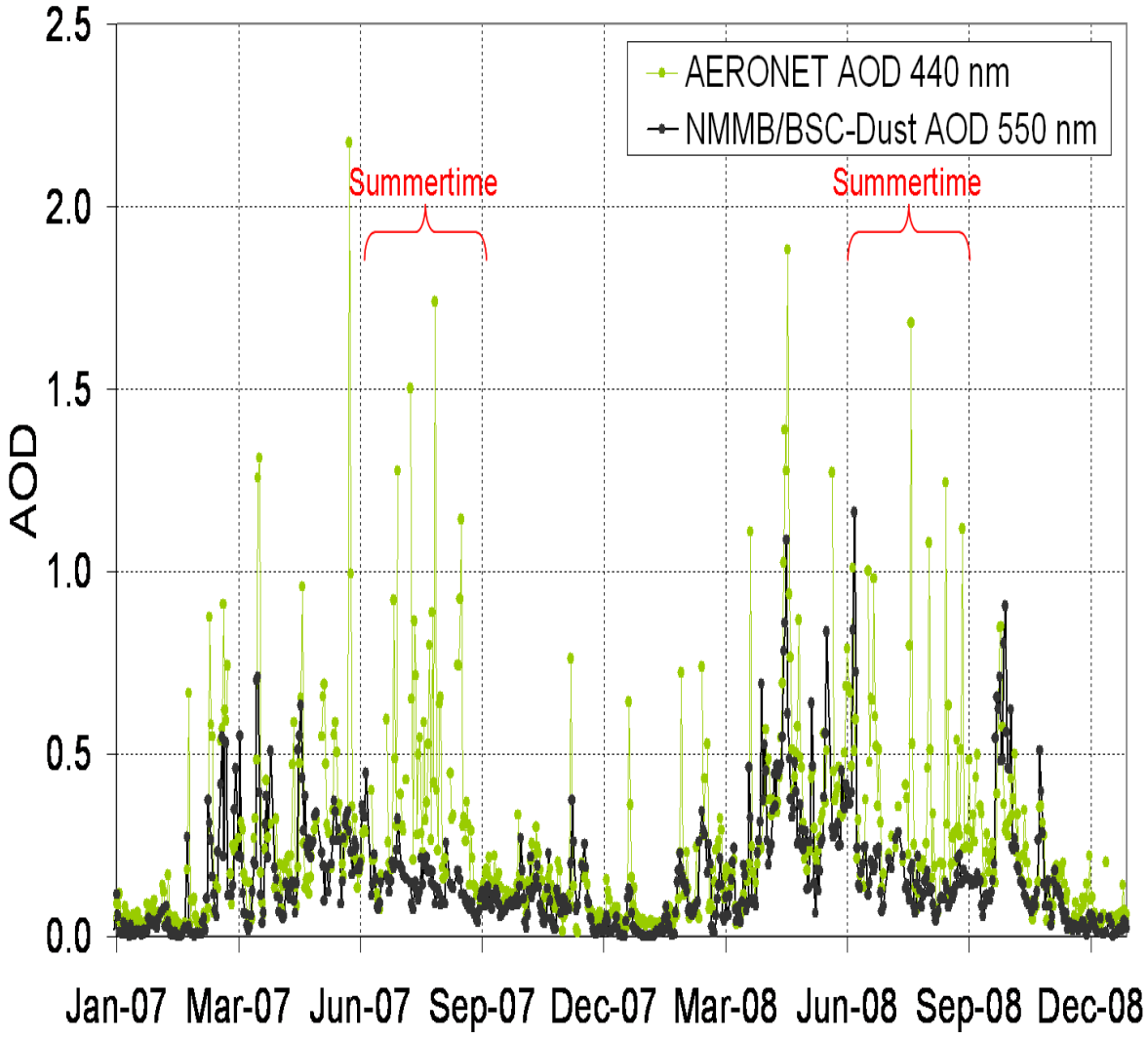
Atmospheric Chemistry and Physics
Open Access

Aerosol characterization at the Saharan AERONET site Tamanrasset

C. Guirado[1,2], E. Cuevas[2], V. E. Cachorro[1], C. Toledano[1], S. Alonso-Pérez[2,3,4], J. J. Bustos[2], S. Basart[5], P. M. Romero[2], C. Camino[2], M. Mimouni[6], L. Zeudmi[6], P. Goloub[7], J. M. Baldasano[5,8], and A. M. de Frutos[1]

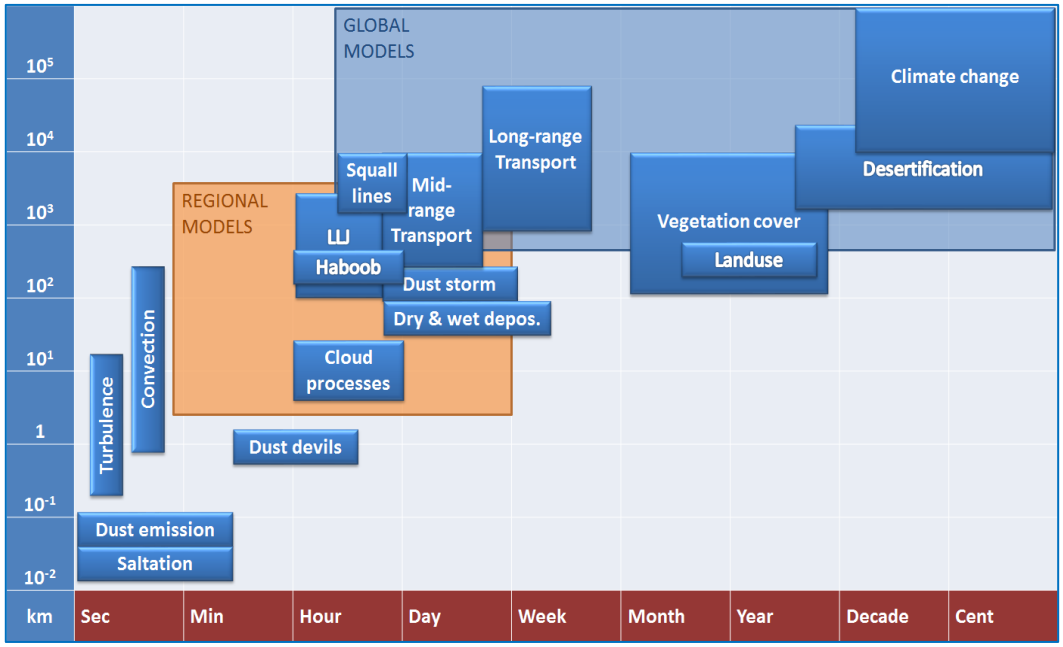


Dust forecasting models



Extracted from Guirado et al. (2014, ACP)

Dust forecasting models



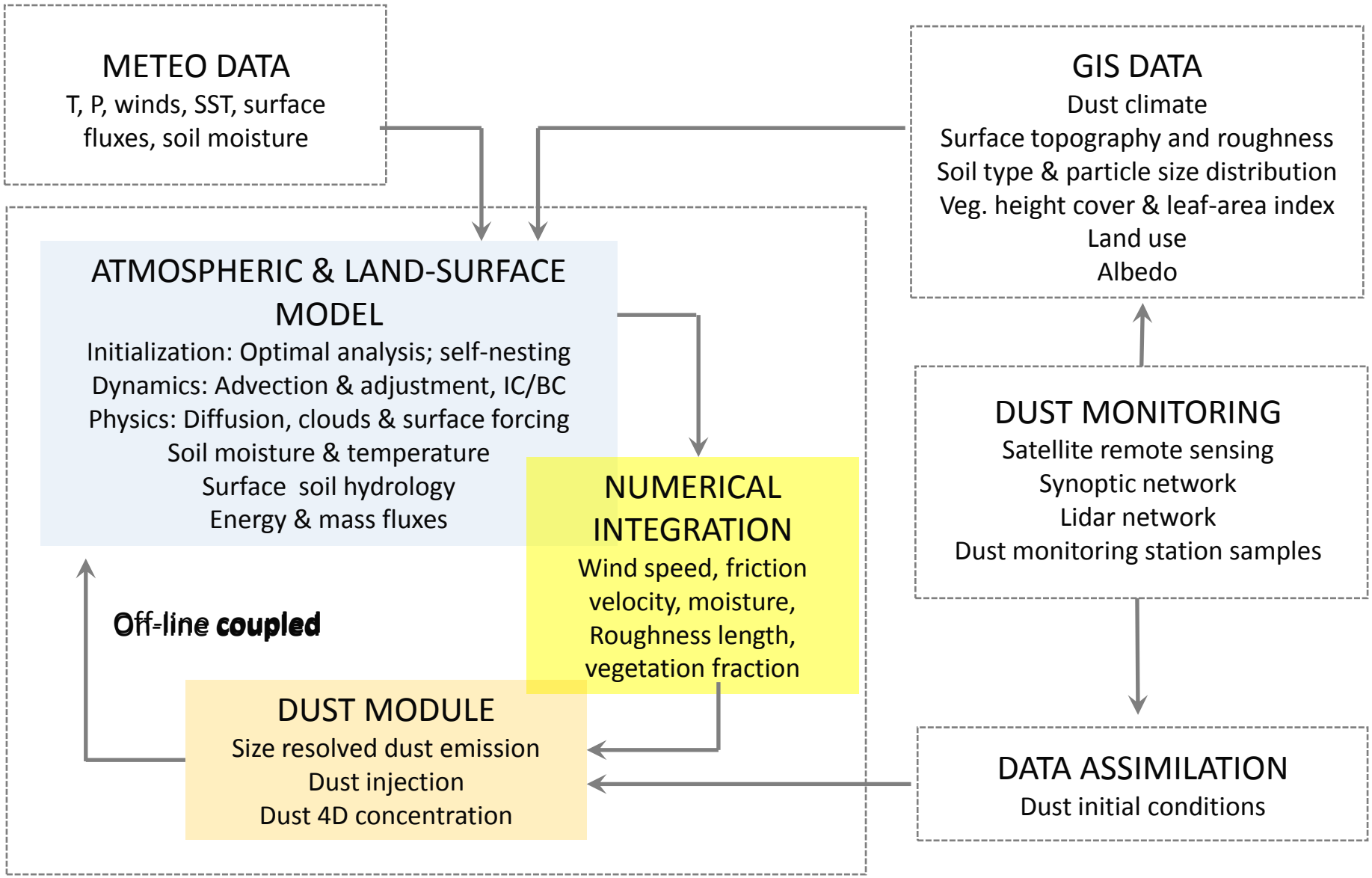
- Dust processes span over five orders of magnitude in space and time. **Dust transport** is a global phenomenon. However, **dust emission** is a threshold phenomenon, sporadic and spatially heterogeneous, that is locally controlled on small spatial and temporal scales.

- 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.

Adapted from Shao (2011)

Dust forecasting models



Dust forecasting models: Key words

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.

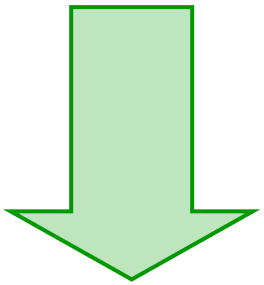
    II. **Pre-processing** of the operational system which includes a download, degrib and interpolation of the meteorological input data from the global meteorological model to this simulation domain, as well as, the initial and boundary conditions for the dust model.

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

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.*



Overall, **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

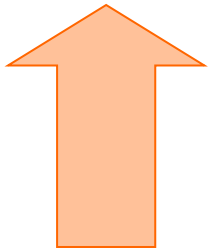
Vertical advection & gravitational settling

Horizontal diffusion

Vertical diffusion

Dust emission

Wet and dry deposition



Dust forecasting models: Emission

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;

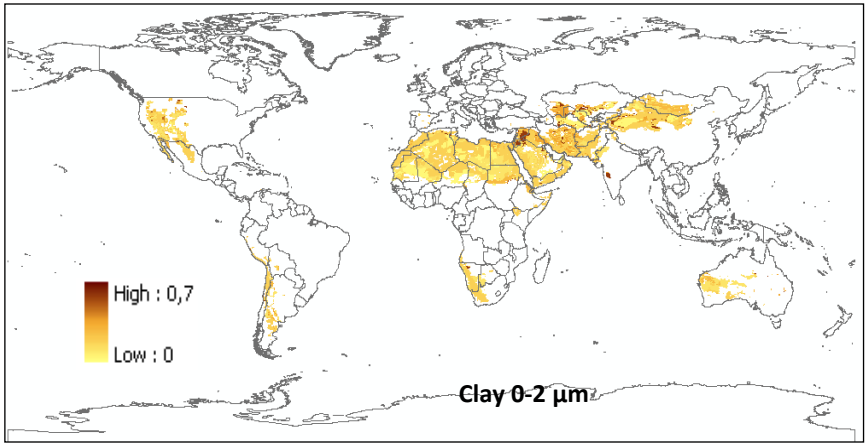
D) Daïa in the Mechfar, at Hassi Cheikh well;

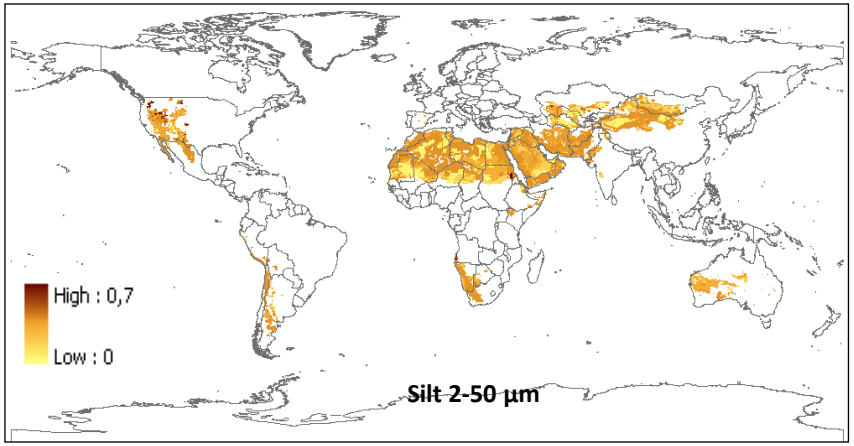
E) North-east of the Great Western Erg: coarse sand interdune corridor with deflation cauldron and palaeolake deposits;

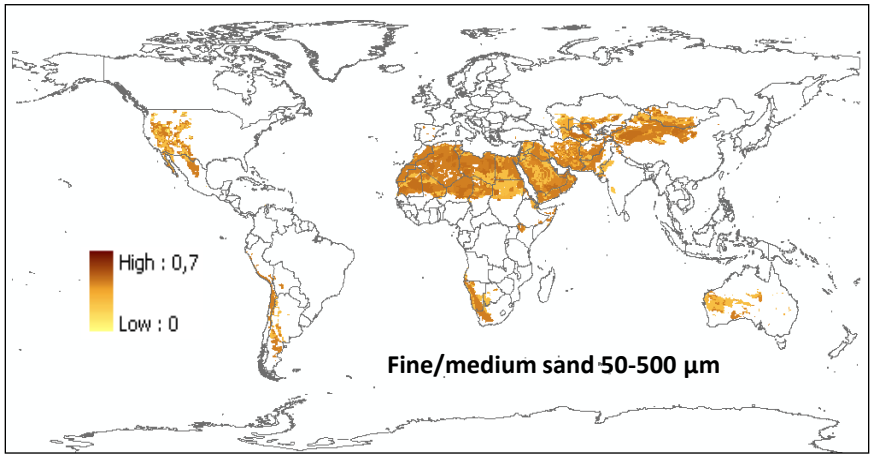
F) North-east of the Great Western Erg: great coarse sand dome dunes, covered by fine sand active dunes.

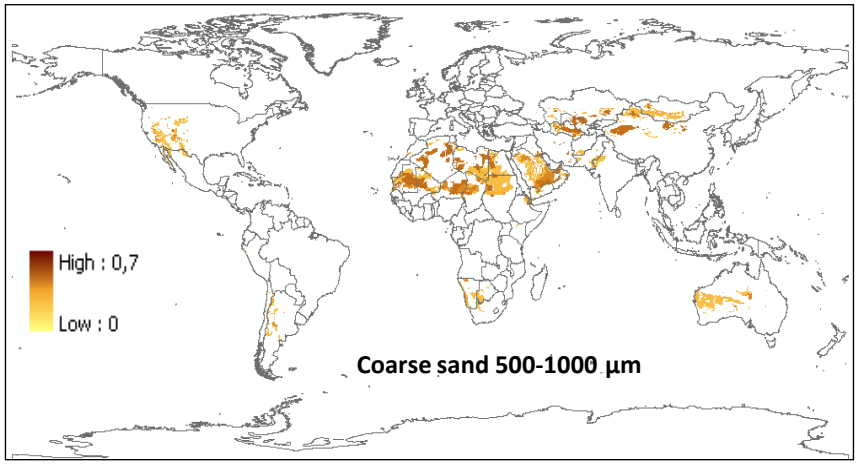
Dust forecasting models: Emission

Parent soil size distribution





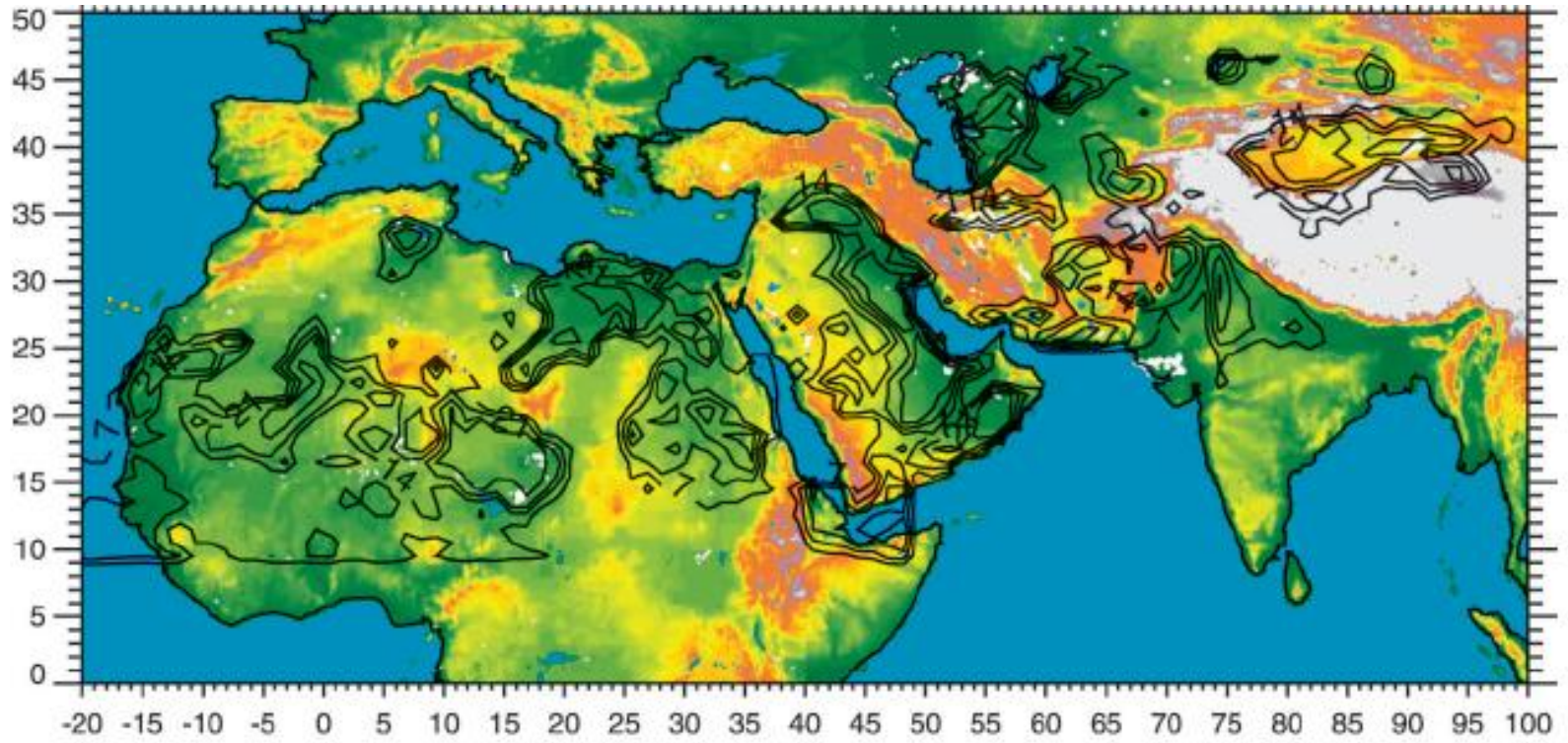




Four top soil texture classes according STASGO-FAO 1km database are converted to 4 parent soil size categories following Tegen et al. [2002]

Dust forecasting models: Emission

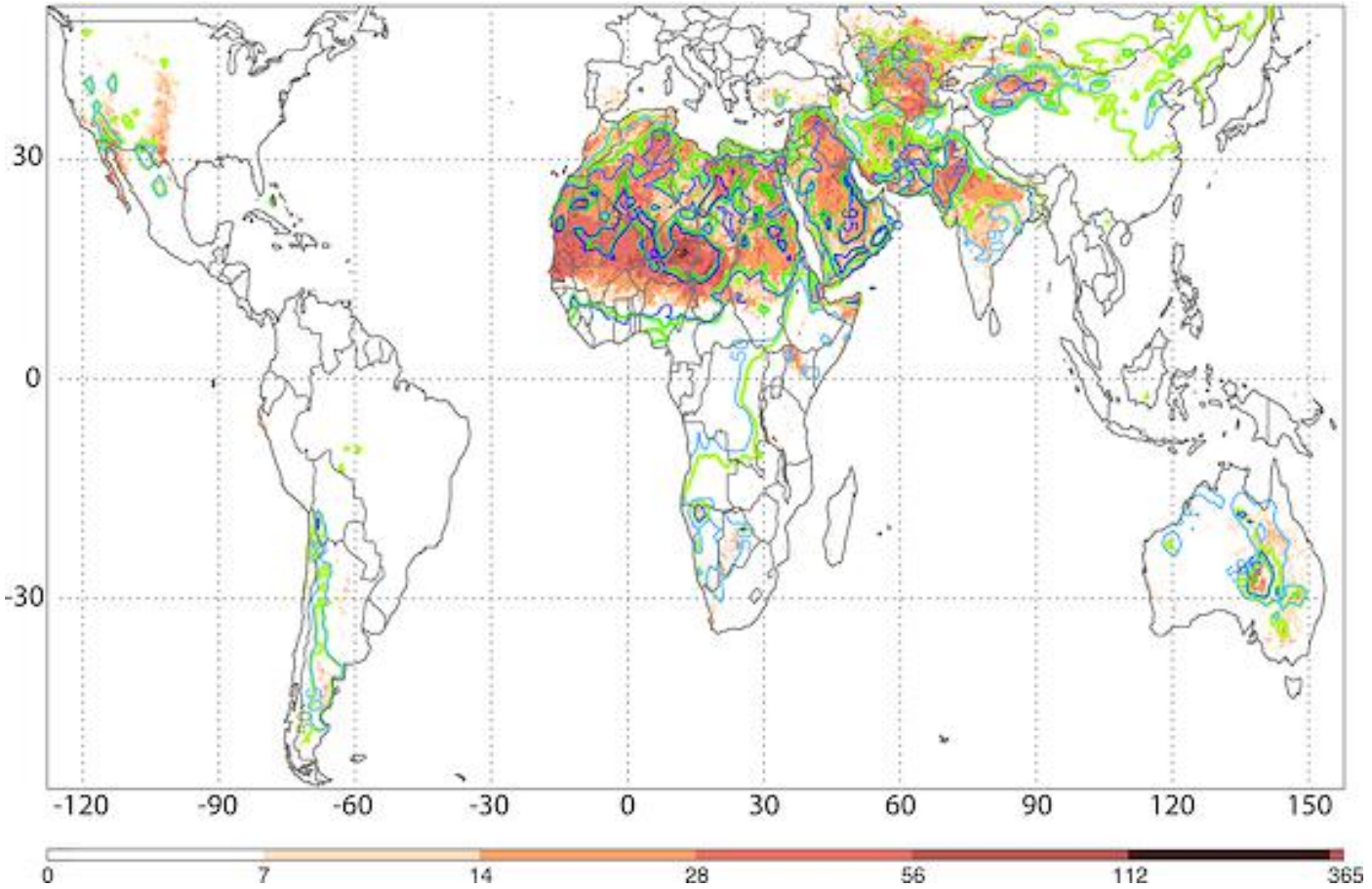
Dust source function



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

Dust forecasting models: Emission

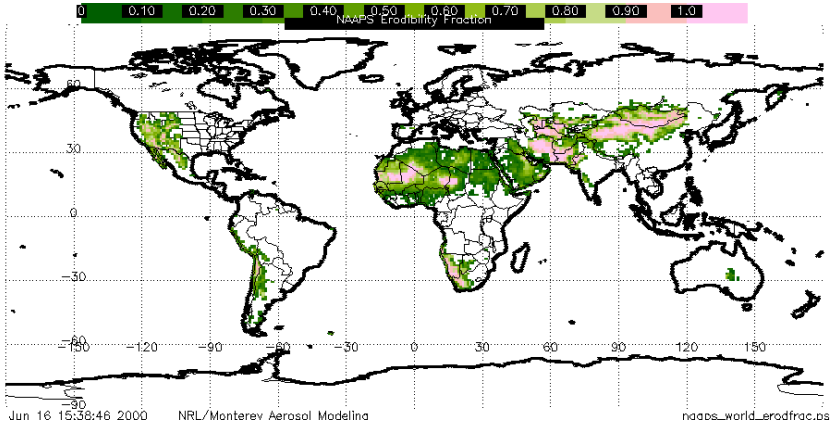
Dust source function



Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products by Ginoux et al. (2012)

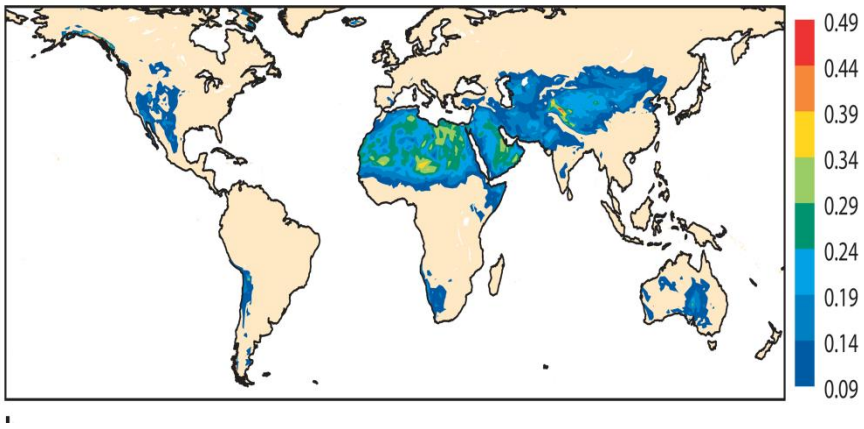
Dust forecasting models: Emission

Dust source function: Other approaches



NAAPS model

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

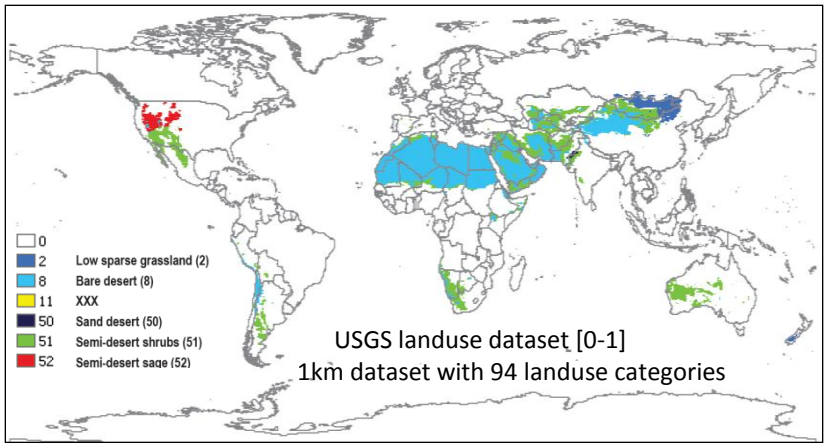


ECMWF-CAMS model

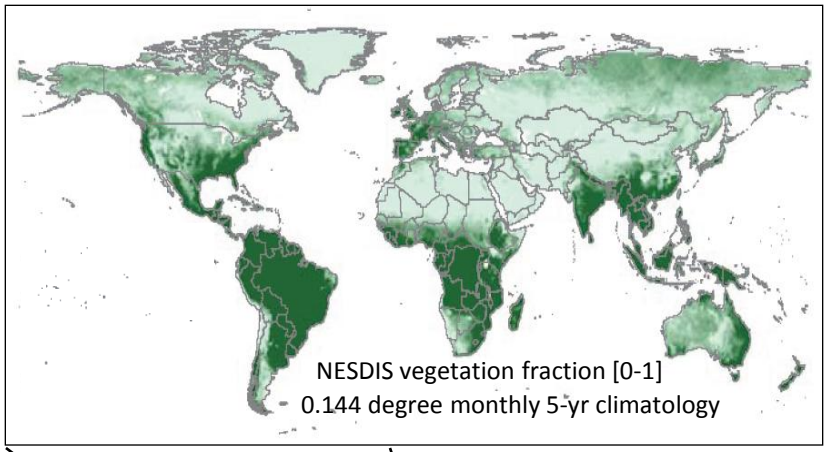
Background albedo in the ultraviolet-visible part of the shortwave spectrum. Only albedos with values between 0.09 and 0.54, assumed to be representative of light-colored soil and sparse vegetation are plotted.

Dust forecasting models: Emission

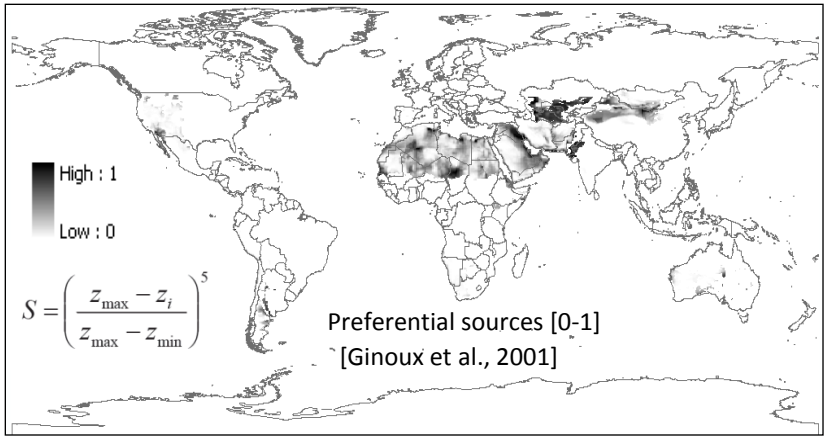
Dust source function: the NMMb/BSC-Dust model



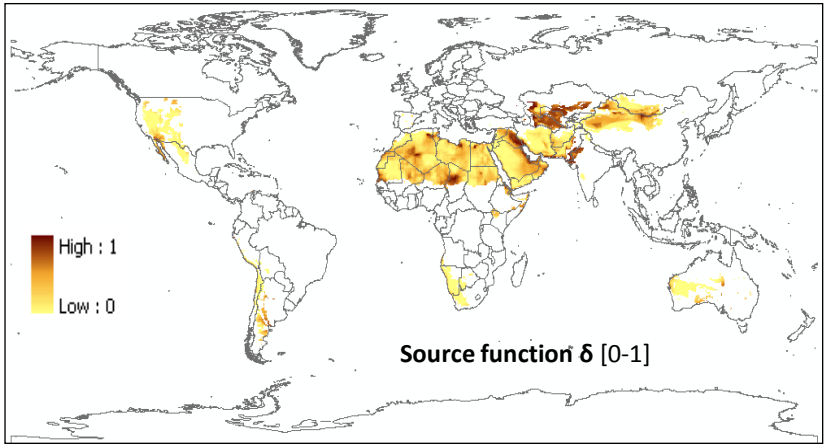
USGS landuse dataset [0-1]
1km dataset with 94 landuse categories



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



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

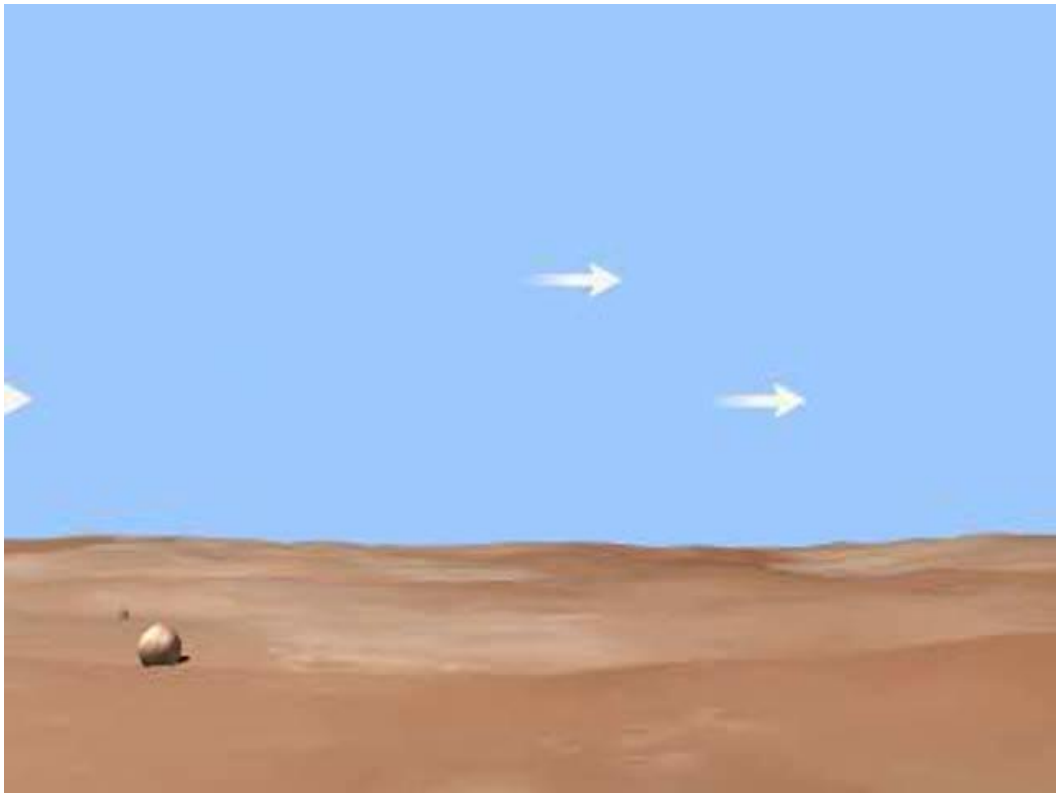


Source function δ [0-1]

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

Dust forecasting models: Emission

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



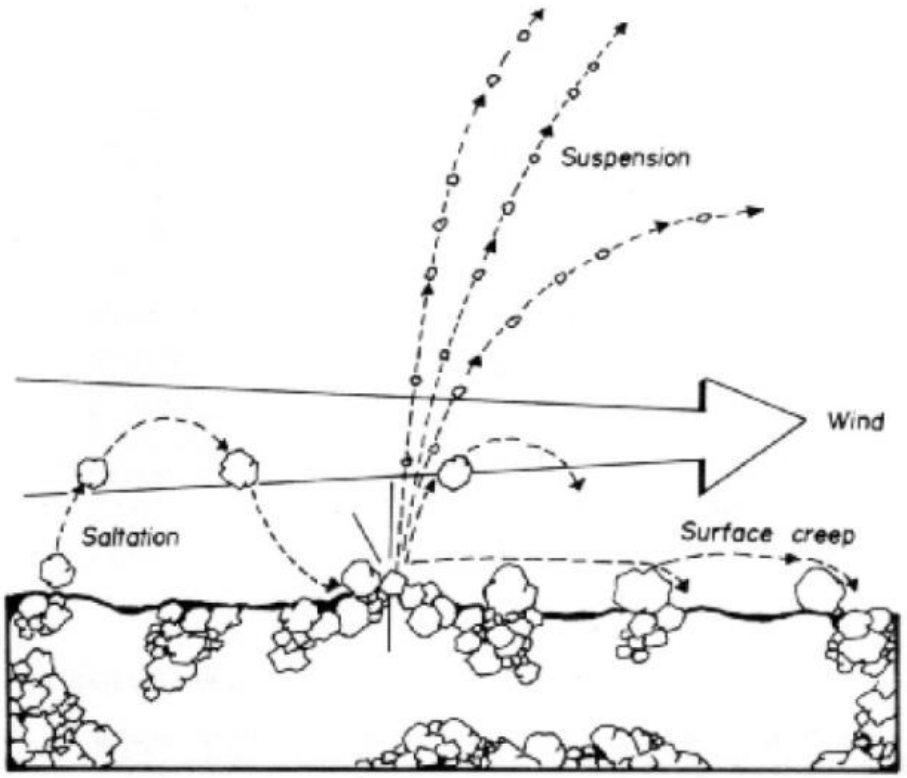
- Creep or rolling motion of the largest particles (> 500 um)

- 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



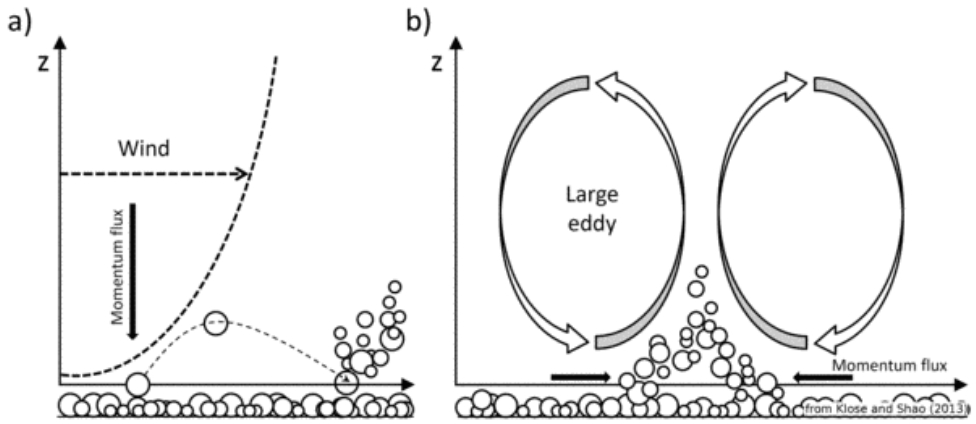
Scheme of the major wind erosion processes with saltation, creeping and suspension (due to sandblasting) in dependency of wind speed.

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

Dust forecasting models: Emission

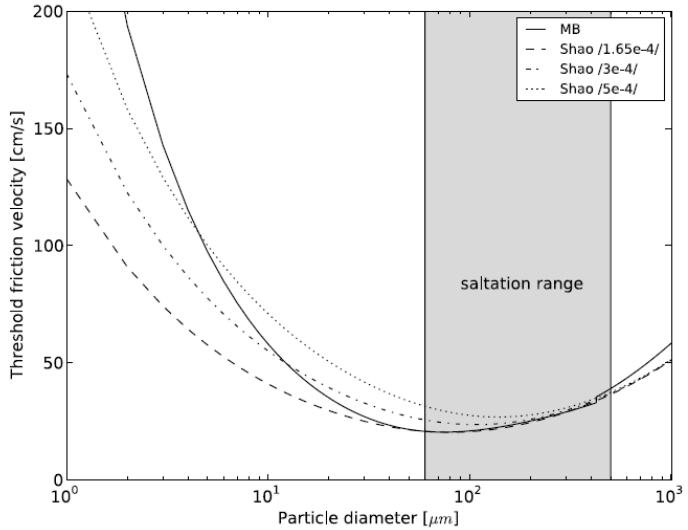
Dust storm generation requires:

- 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

Depends on **soil grain size, soil moisture and roughness** among others



Darmenova et al., 2009

Dust forecasting models: Emission

Simple schemes

Formulation of vertical dust flux (F)

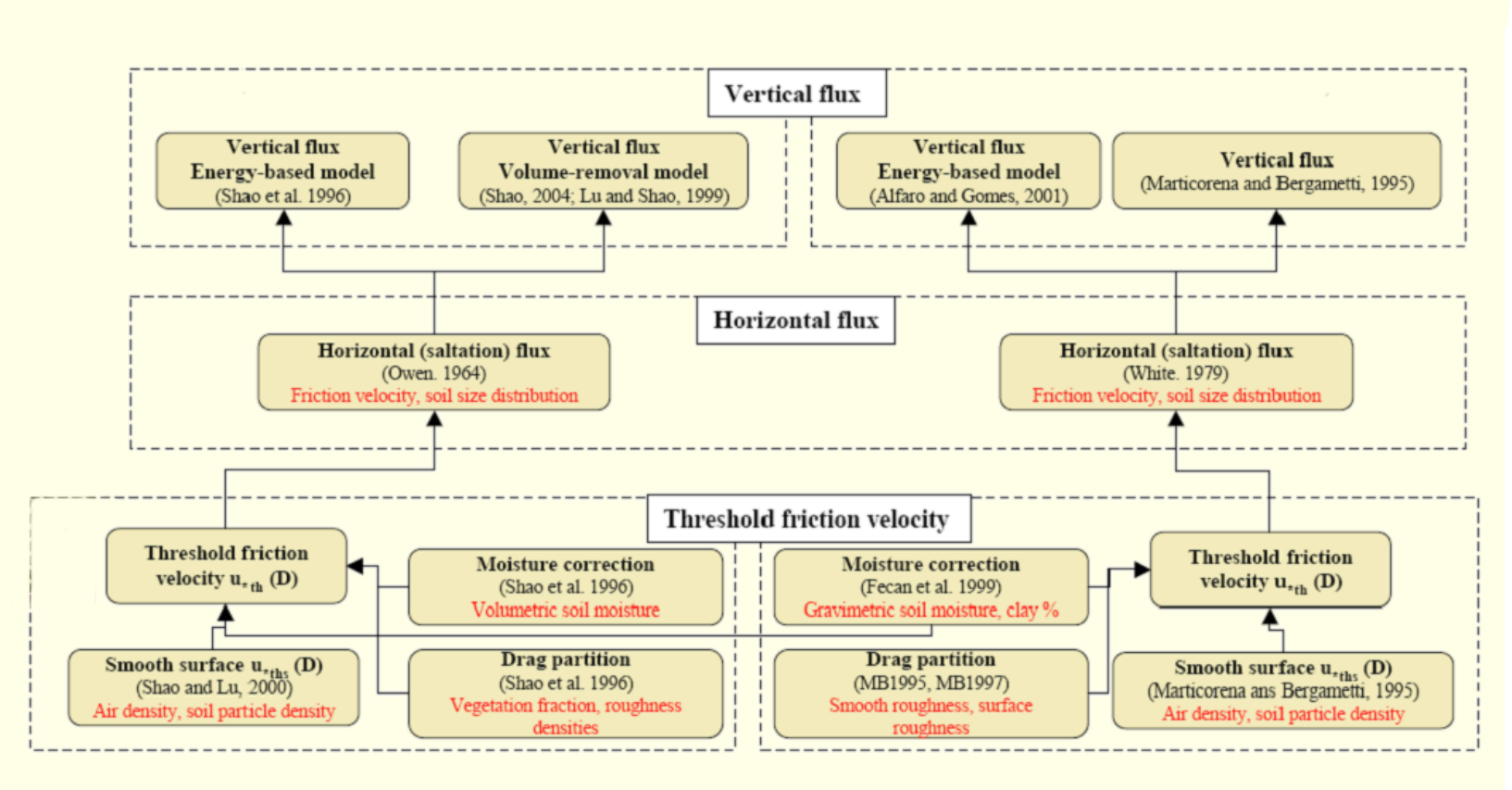
$$F = c \cdot f \cdot P(u_*^n, u_{*th}) \qquad \text{if} \quad u_* > u_{*t}$$

***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

Physically based schemes



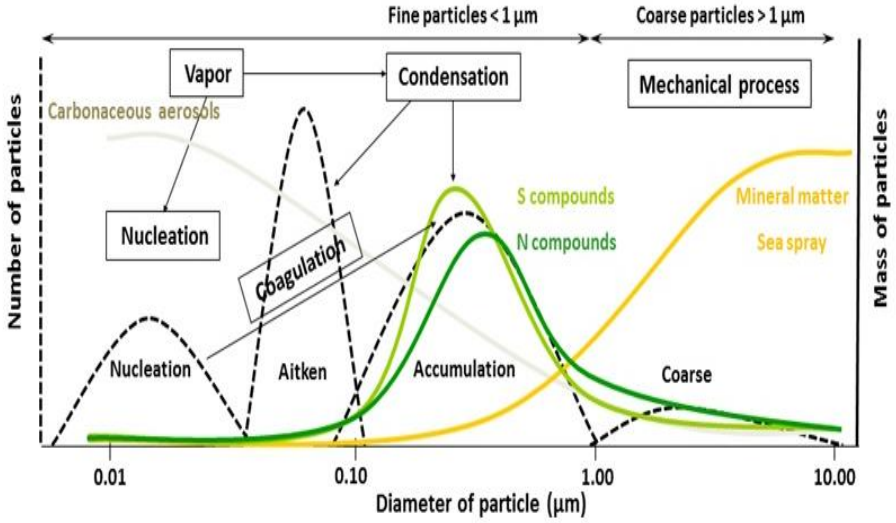
Physically-based **dust emission schemes** employ different parameterizations of the related physical processes, as well as require different input data.

Dust forecasting models: Emission

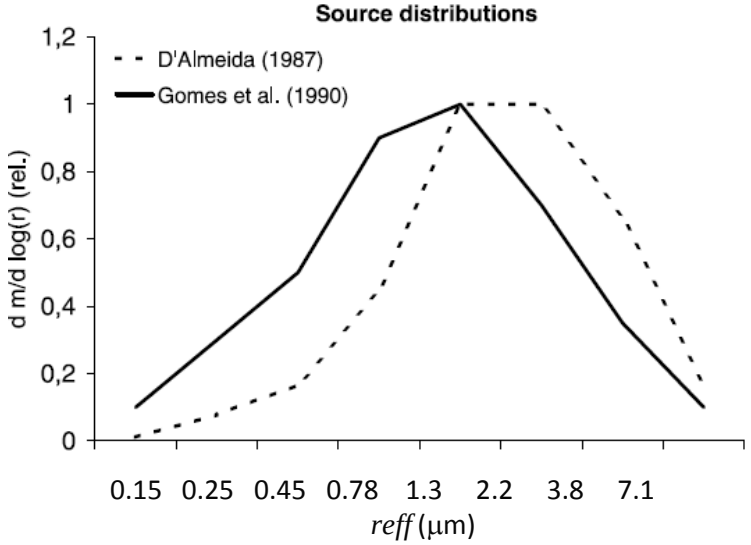
Dust **horizontal concentration** is calculated distributing the **vertical flux (F)** of the **first two parent soil categories** (clay and silt) over the **model particle bins.**

Parameterizations of mass size distribution of the model at sources

Modal



Sectorial



8 bin size distribution from Tegen and Lacis (1996)

Dust forecasting models

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

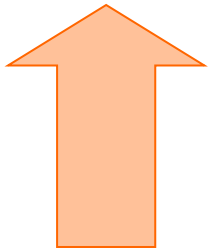
Vertical advection & gravitational settling

Horizontal diffusion

Vertical diffusion

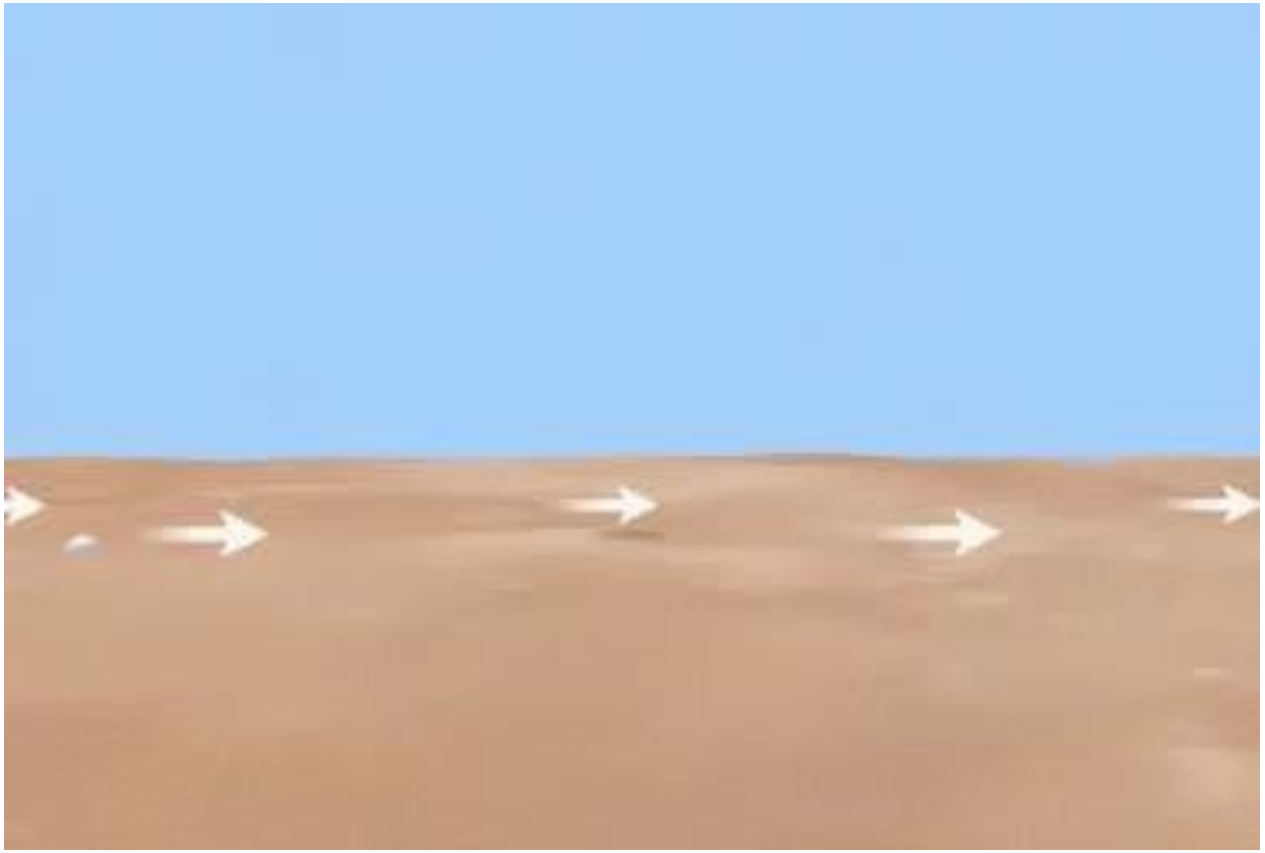
Dust emission

Wet and dry deposition



Dust forecasting models: Deposition

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: Deposition

Wet scavenging

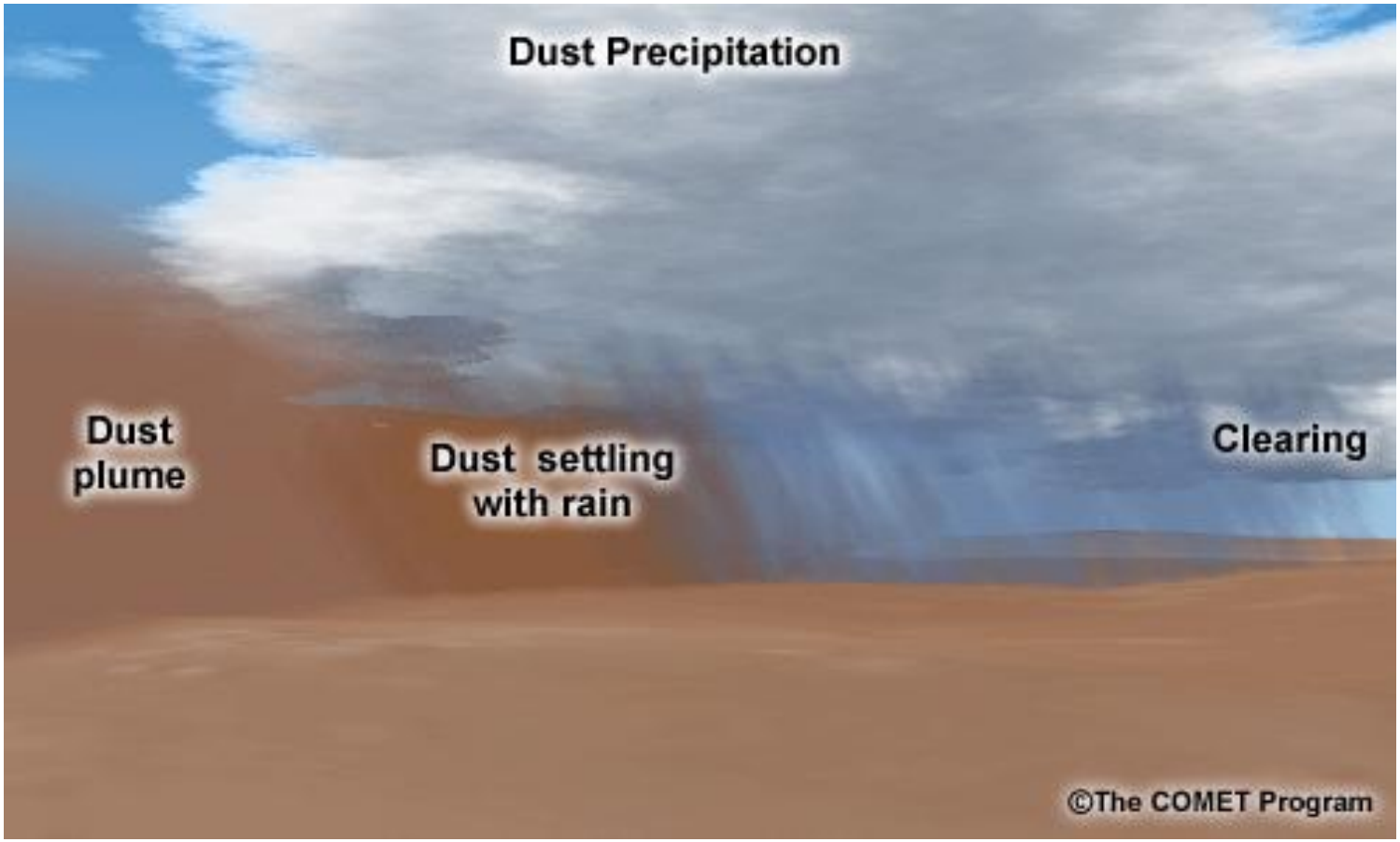


Image from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust forecasting models

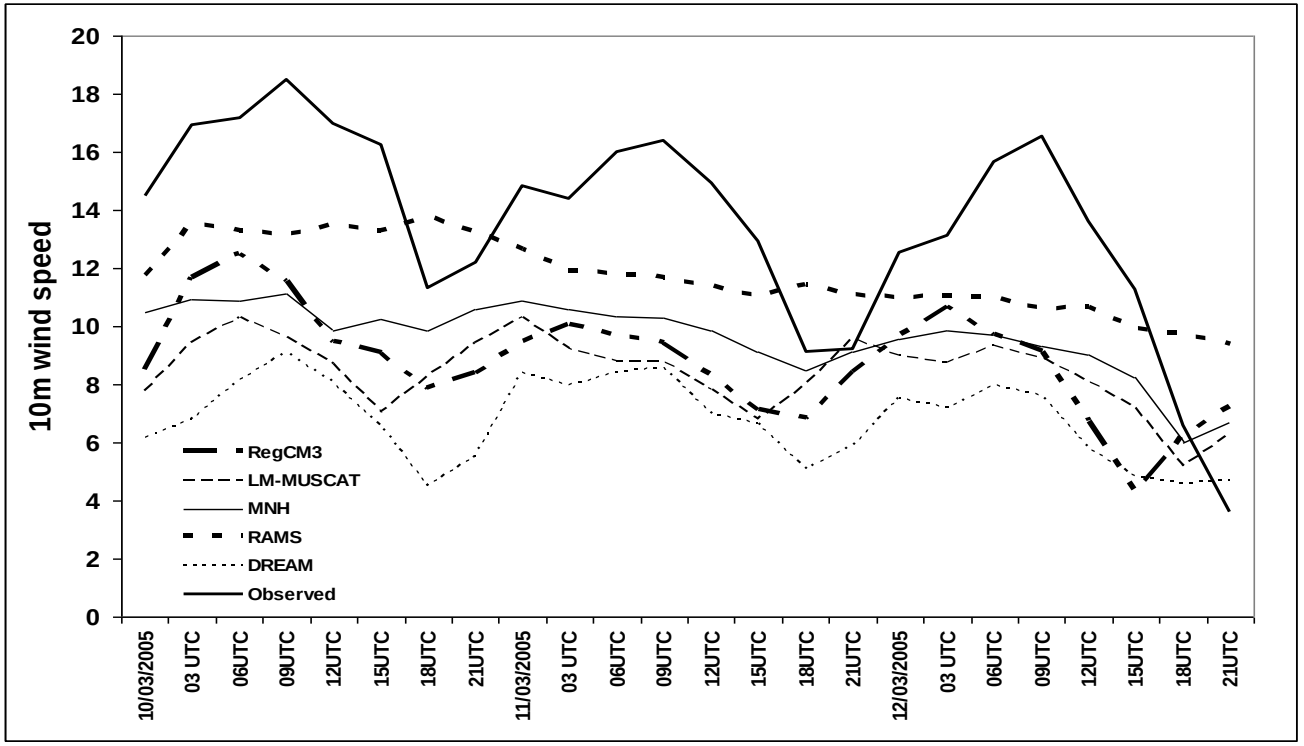
Main differences between dust models

1. *Meteorological driver*
2. *Meteorological input files IBC*
3. *Emission scheme*
4. *Geographic-information database (source mask)*
5. *Land-surface scheme*
6. *Dry deposition scheme*
7. *Wet depositioon scheme*
8. *Spatio-temporal resolution*
9. *Data assimilation*
10. *….*

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**

Barcelona Supercomputing Center
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EXCELENCIA SEVERO OCHOA

Thank you

Acknowlegde to Carlos Pérez García-Pando, Emilio Cuevas, Slodoban Nickovic, Francesco Benincasa, Enza DiTomaso, Oriol Jorba, Kim Serradell, Enric Terradellas as well as AERONET, MODIS, U.K. Met Office MSG, MSG Eumetsat and EOSDIS World Viewer principal investigators and scientists for establishing and maintaining data used in the present contribution. Also special thank to all researchers, data providers and collaborators of the WMO SDS-WAS NA-ME-E Regional Node.

sara.basart@bsc.es