Observacion y prediccion del contenido de polvo mineral en la atmosfera,
Barcelona, Spain, 18 October 2017

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

EXCELENCIA SEVERO OCHOA

Dust prediction models

Sara Basart (sara.basart@bsc.es)

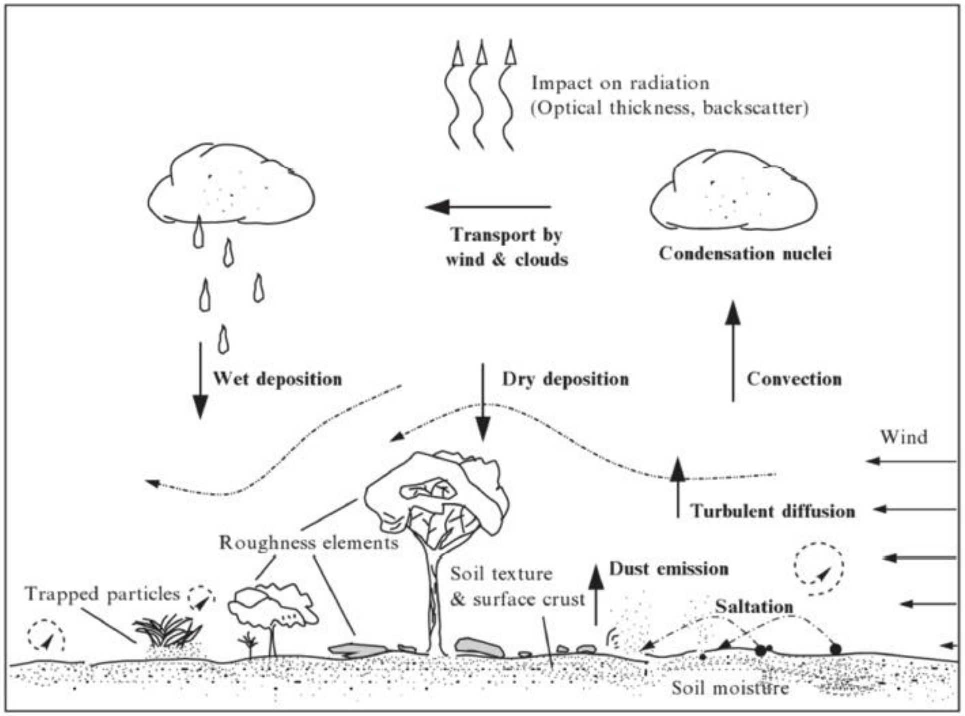
Questions will be welcome!

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)*

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Outlook

1. **Dust cycle and associated processes**

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

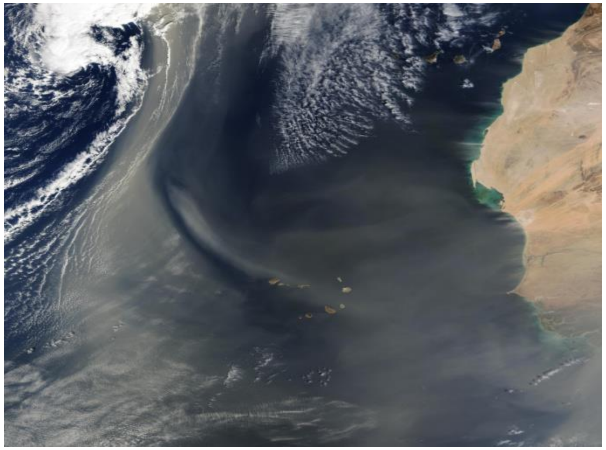
2. **Dust forecasting models**

    - *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)

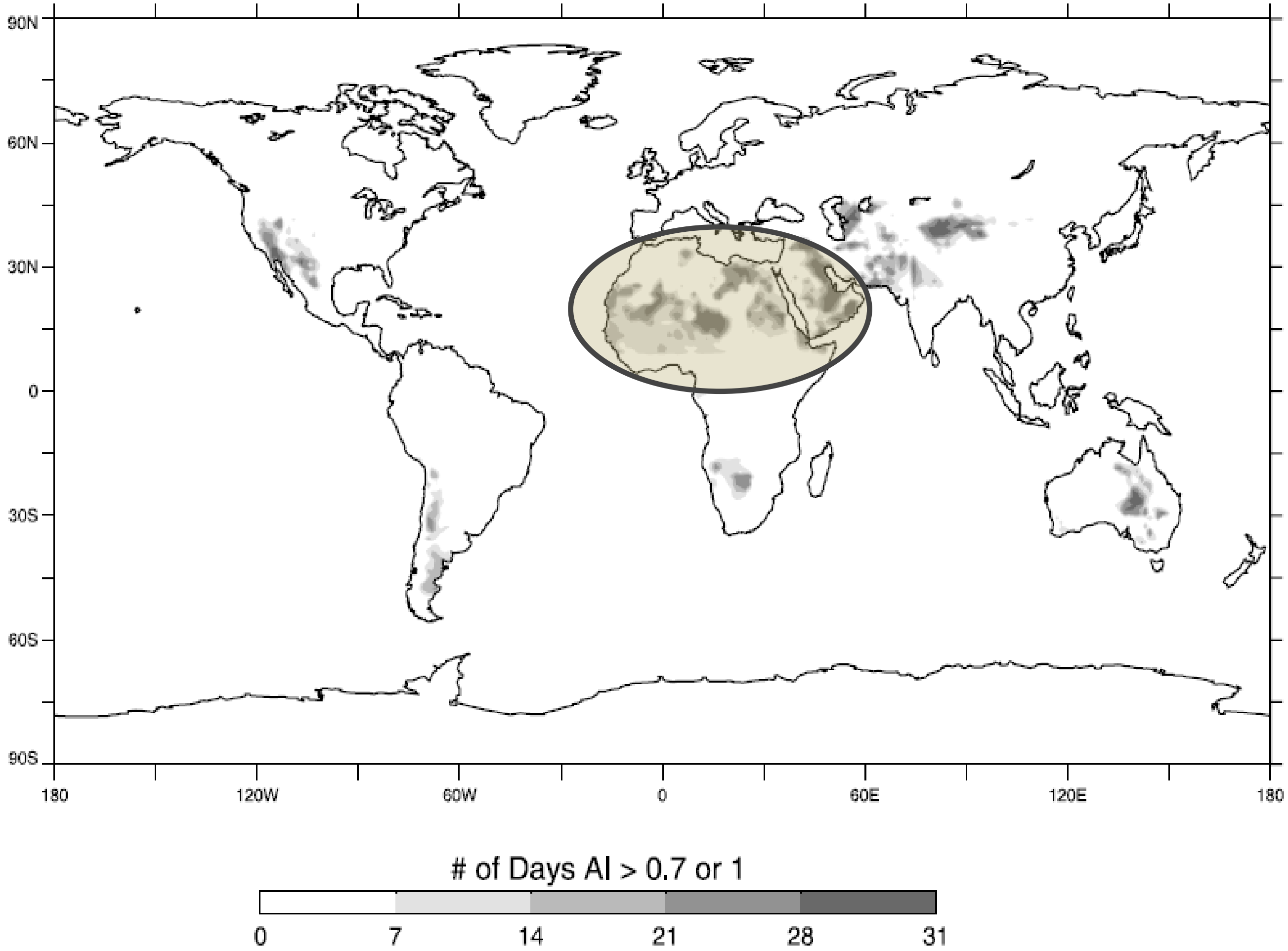


MODIS True color Western Africa – Altantic Ocean

People caught in a dust storm in Mali

Dust cycle and associated processes

Dust global distribution

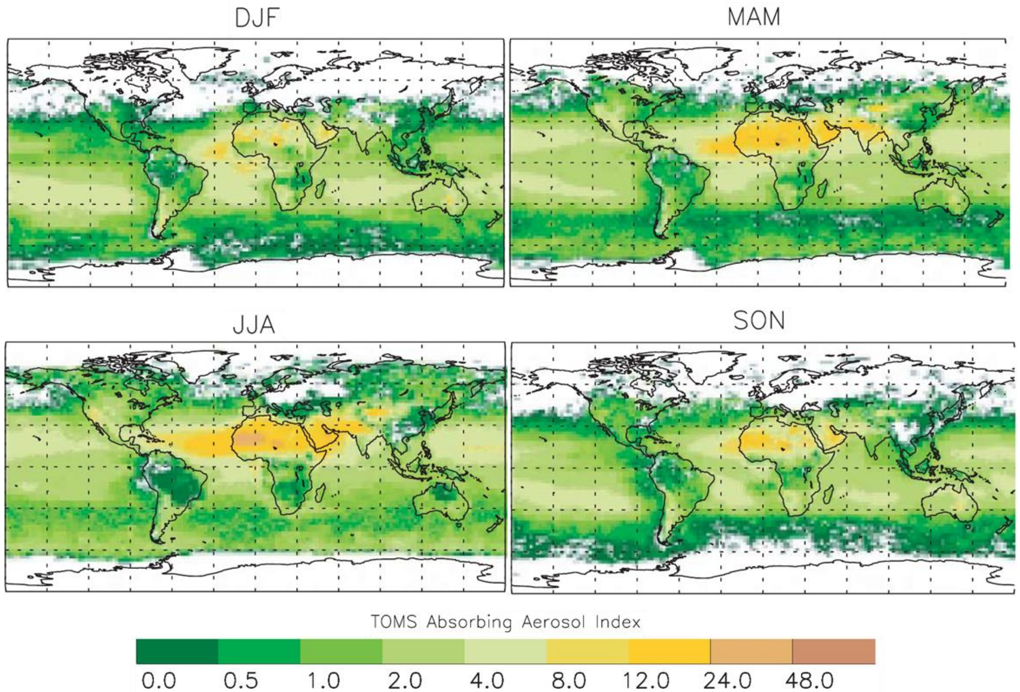


The global distribution of **TOMS** dust sources.

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

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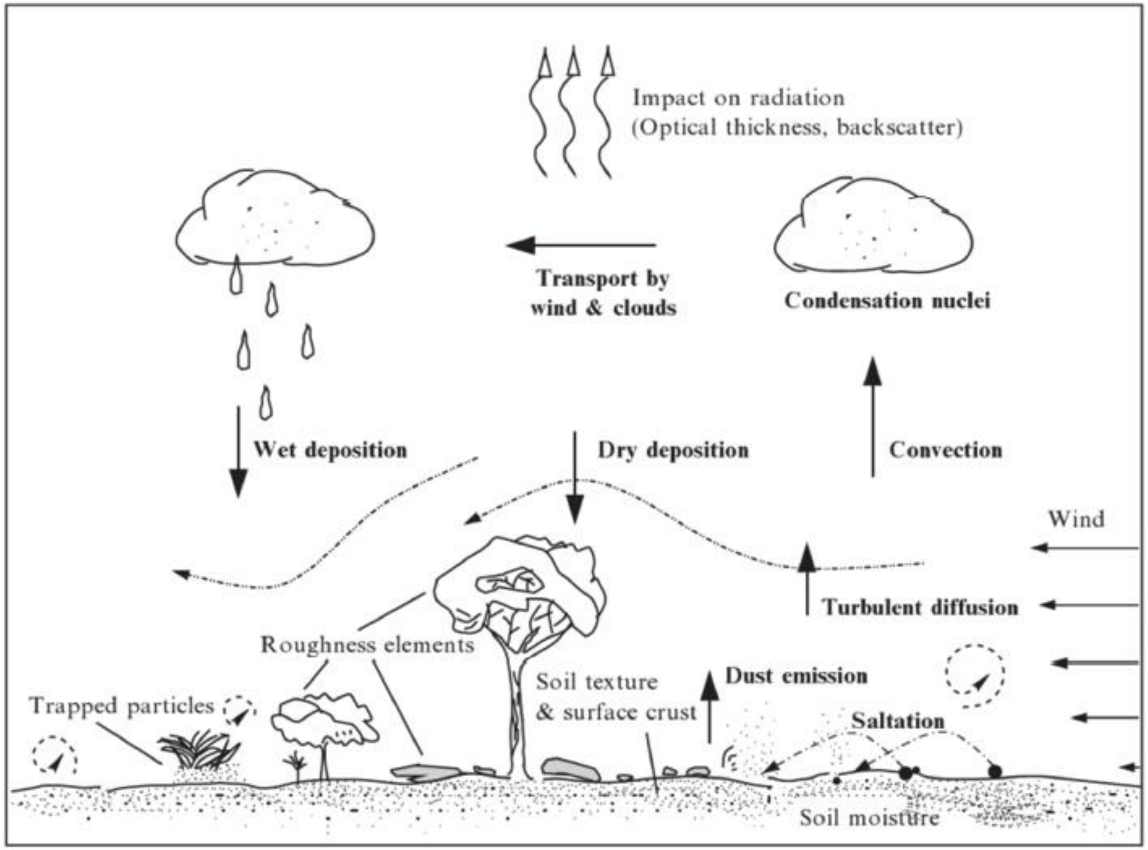
Figure extracted from Tegen al. (2002)

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

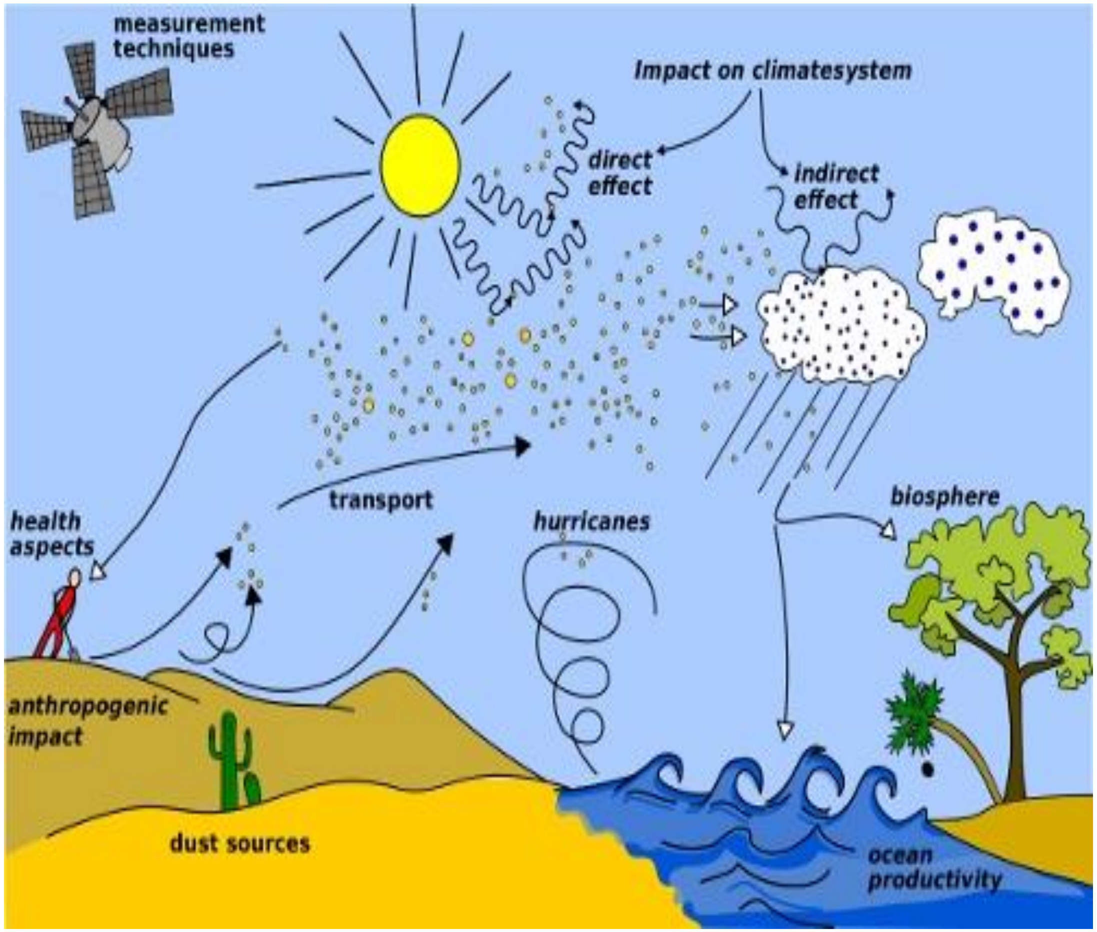


Image from WMO website (http://www.wmo.int/pages/prog/arep/wwrp/new/hurricanes.html)

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*

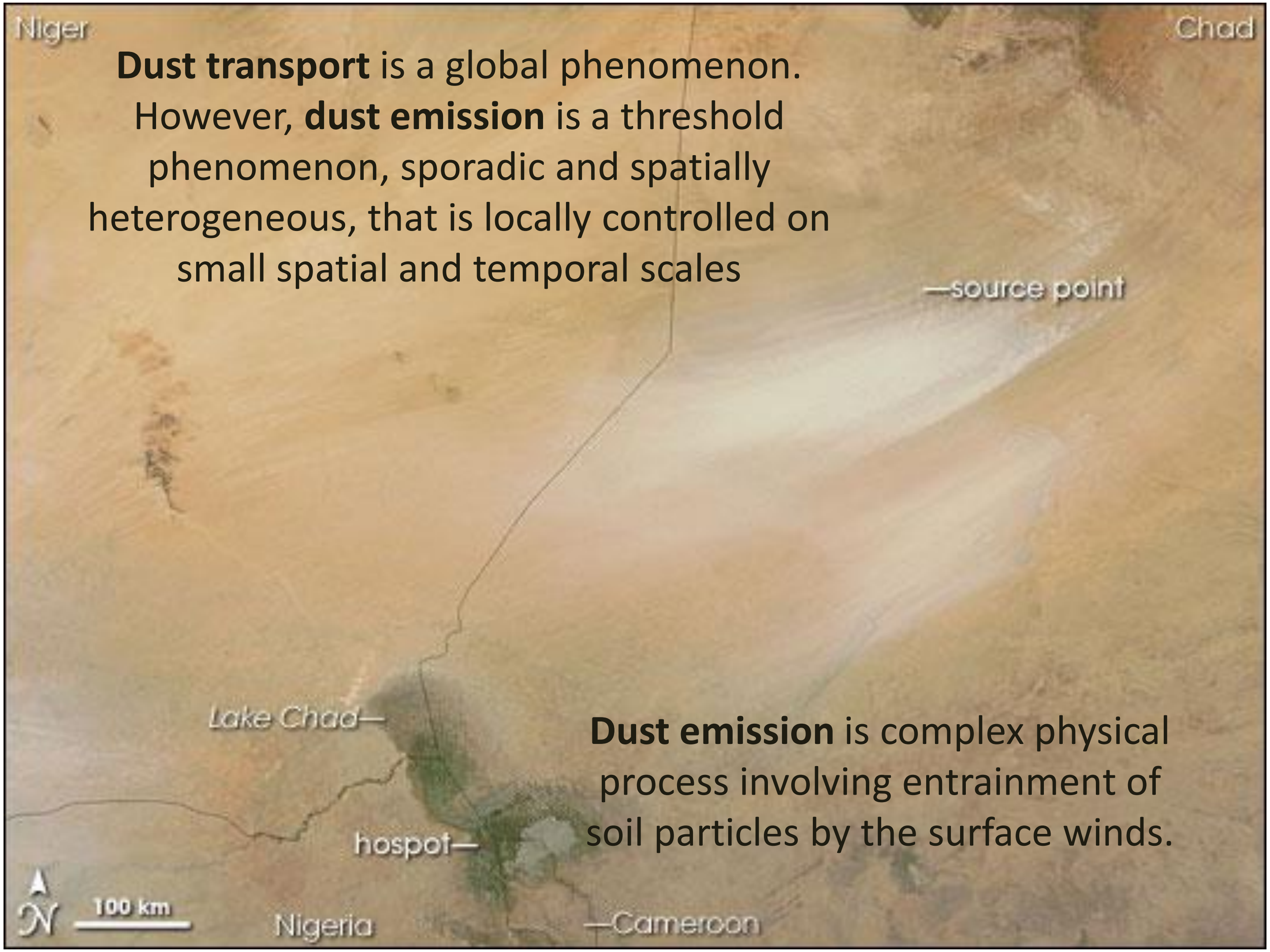
Aviation and Ground Transportation

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

Agriculture and fishering

Energy and industry

Dust cycle and associated processes



Dust 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

Dust emission is complex physical process involving entrainment of soil particles by the surface winds.

Types of dust storms:

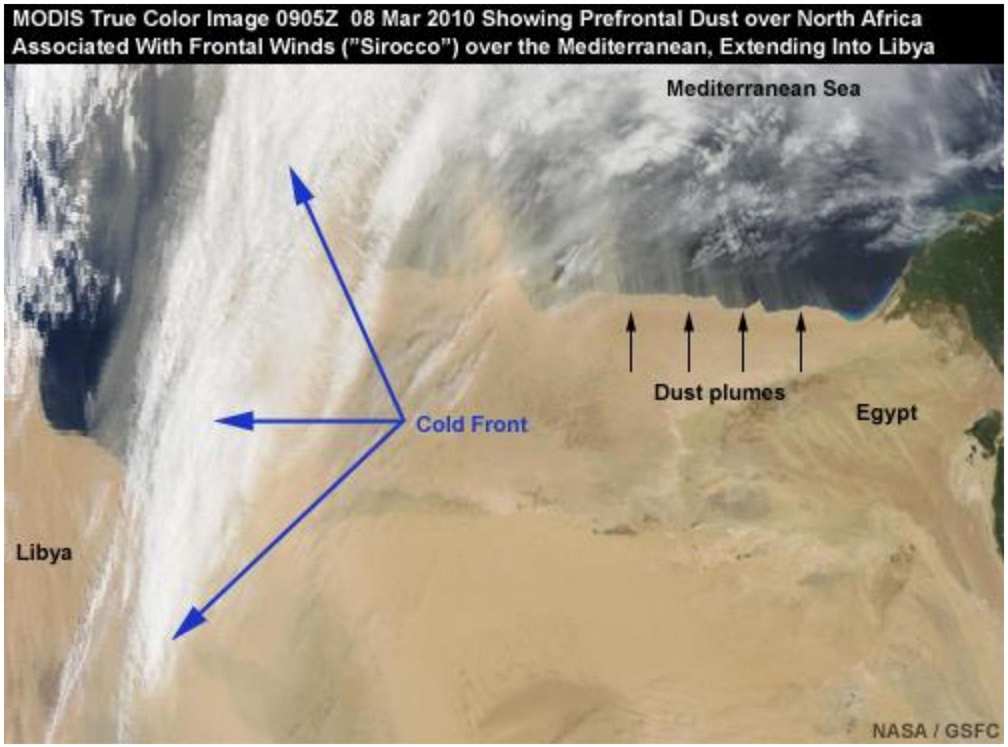
Synoptic dust storms (large scale weather systems)

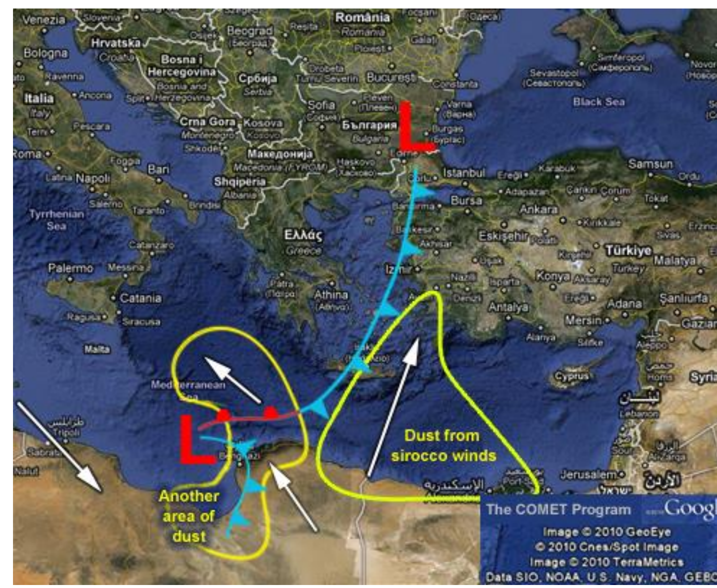
- Prefrontal winds
- Postprontal winds
- Large-scale Trade winds
- …

Mesoscale dust storms

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

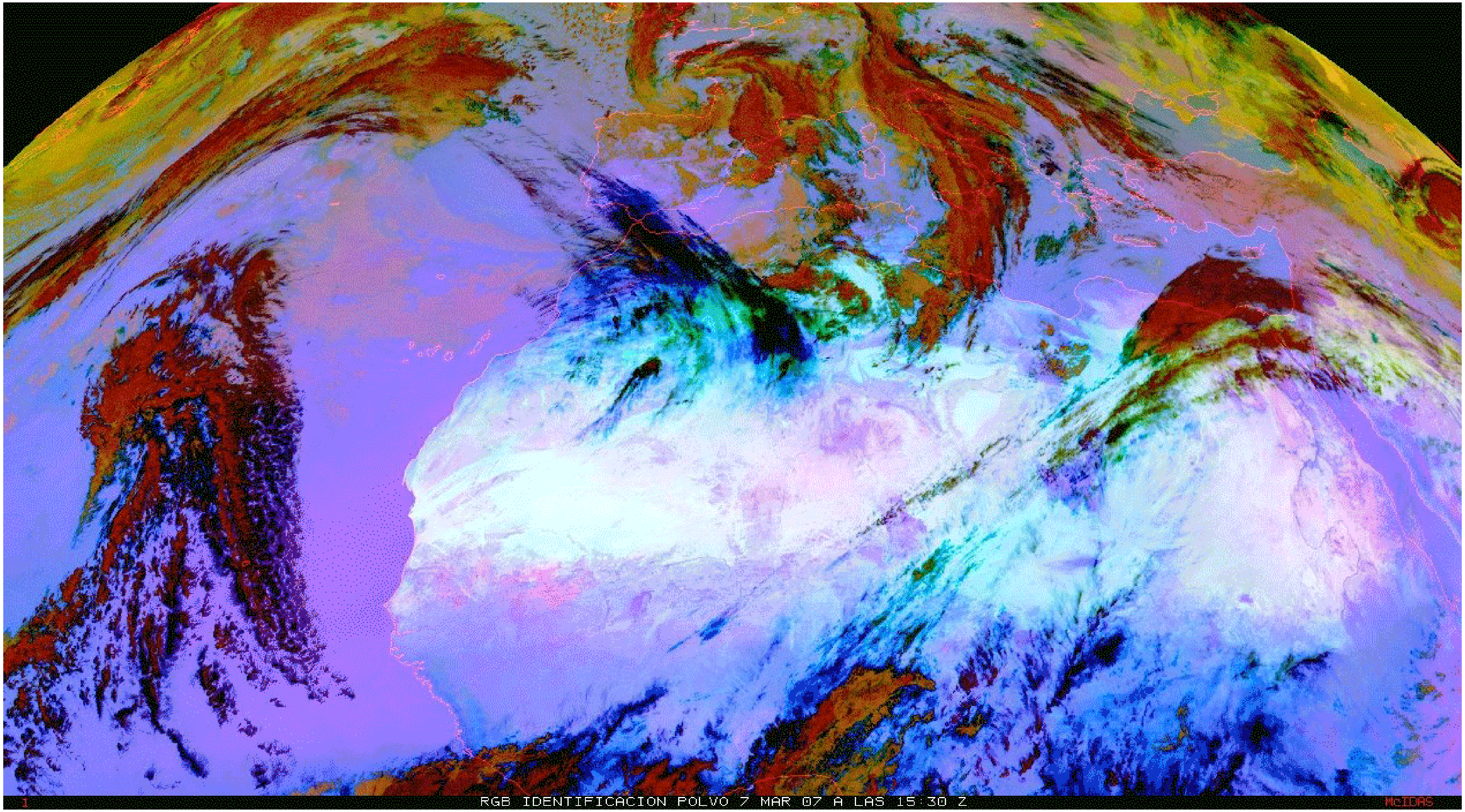
Synoptic dust storms: Pre-frontal





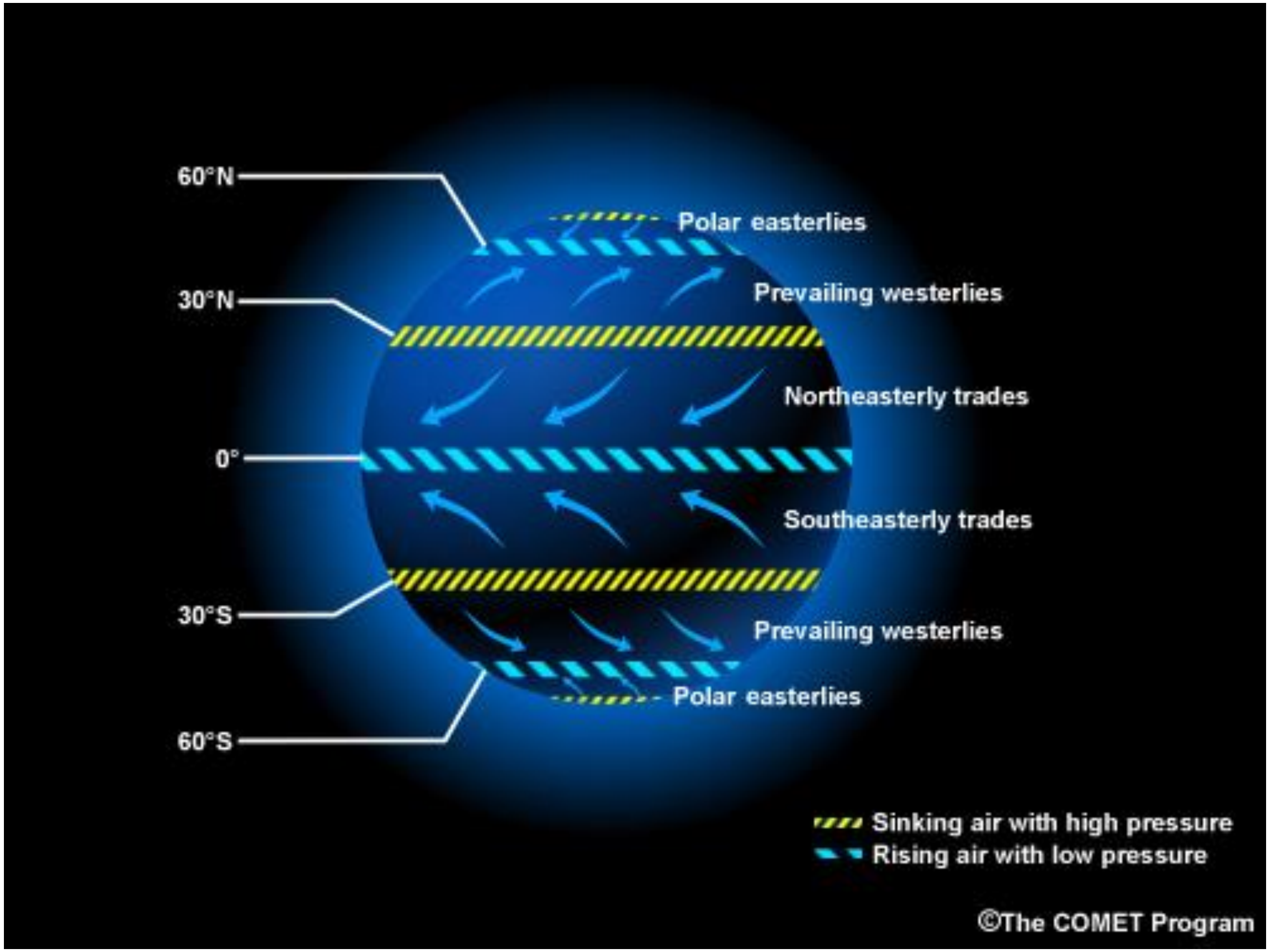
Dust cycle and associated processes

Synoptic dust storms: Post-frontal



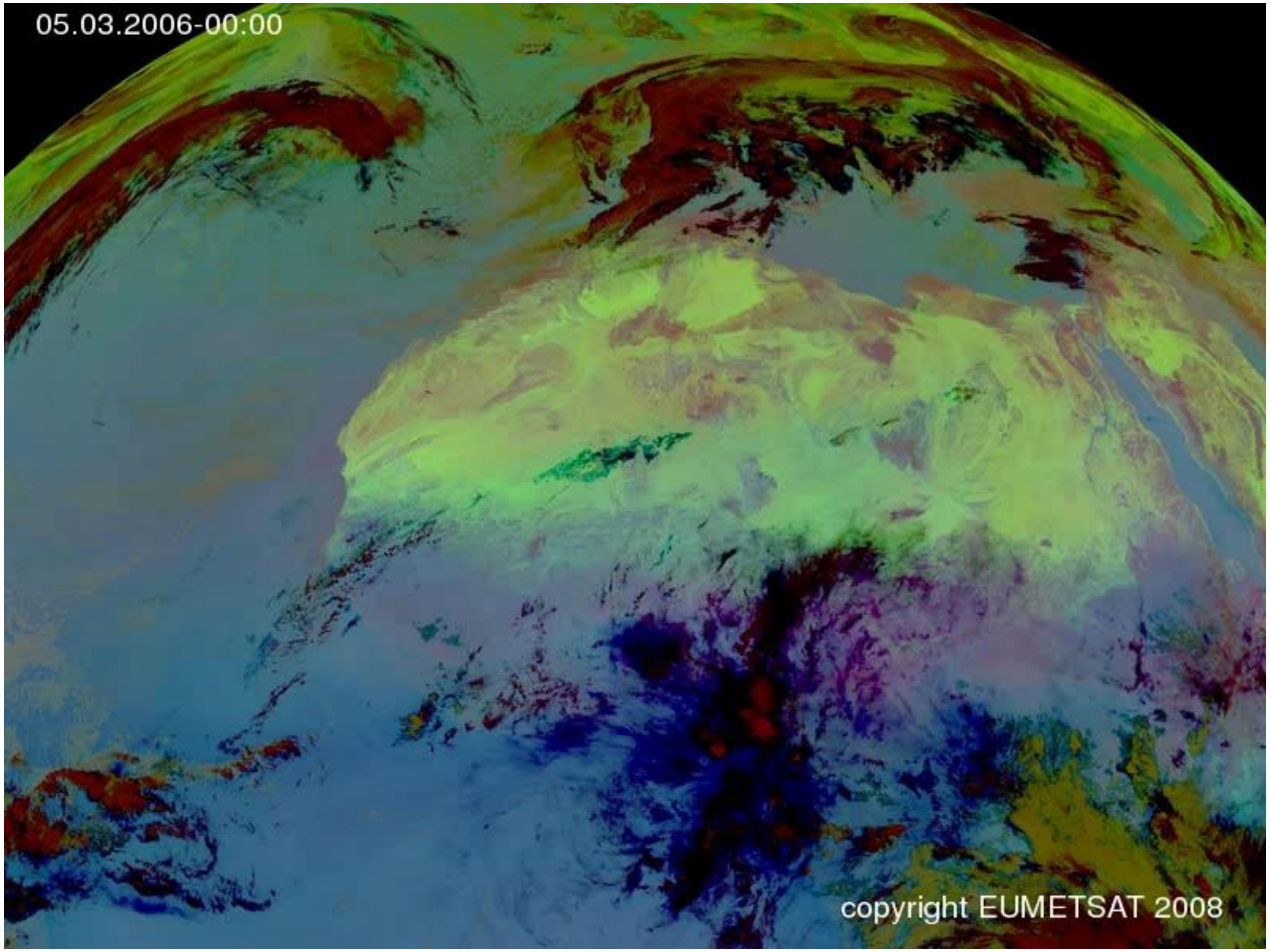
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



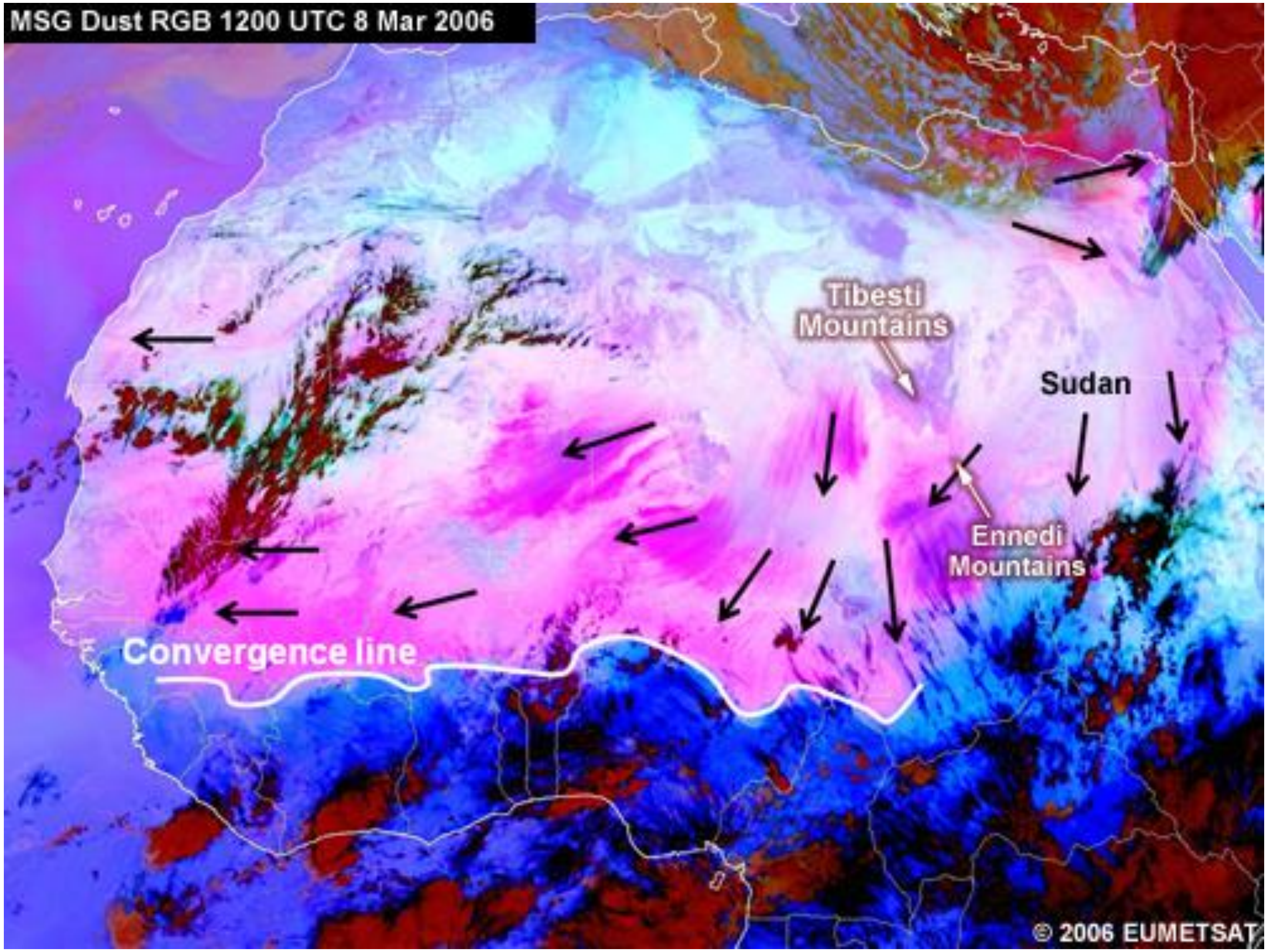
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



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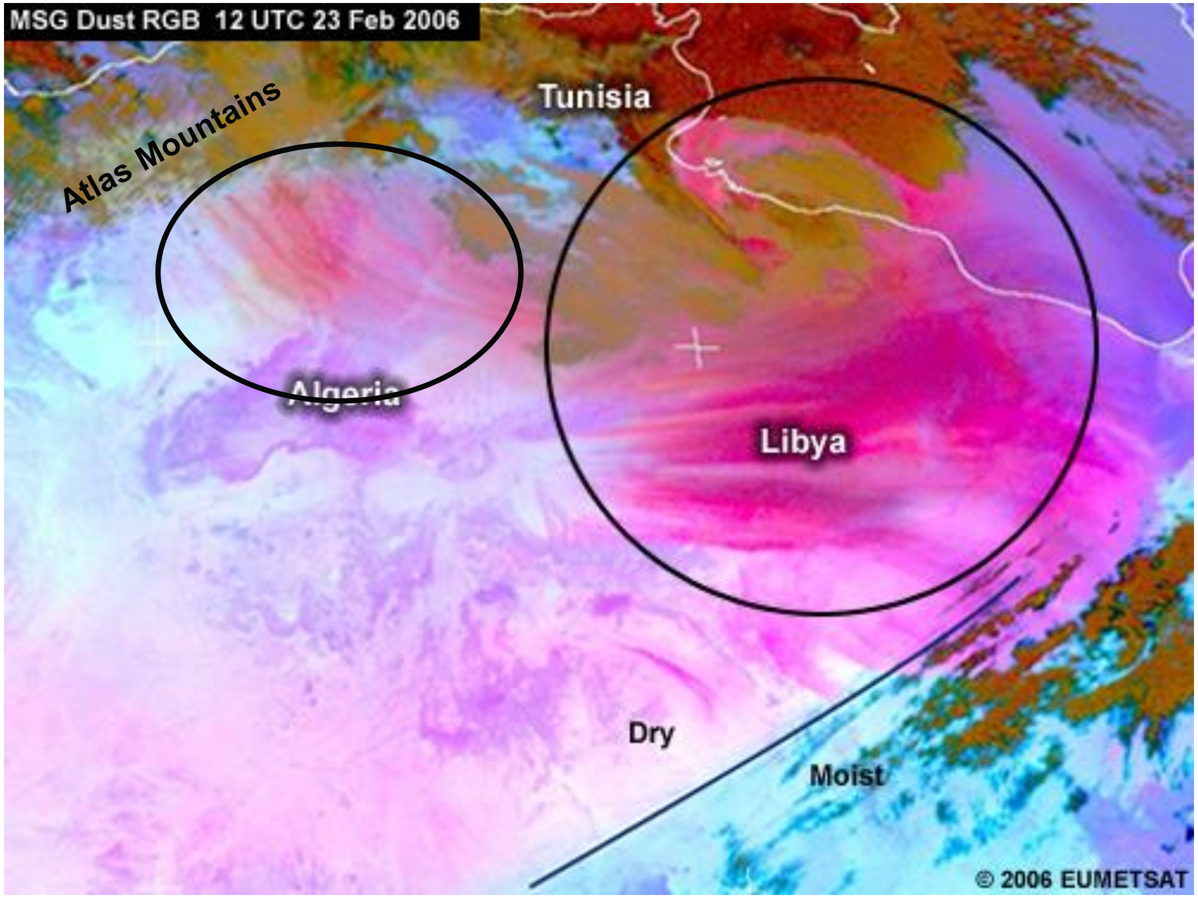
Dust cycle and associated processes

Mesoscale dust storms: Downslope winds



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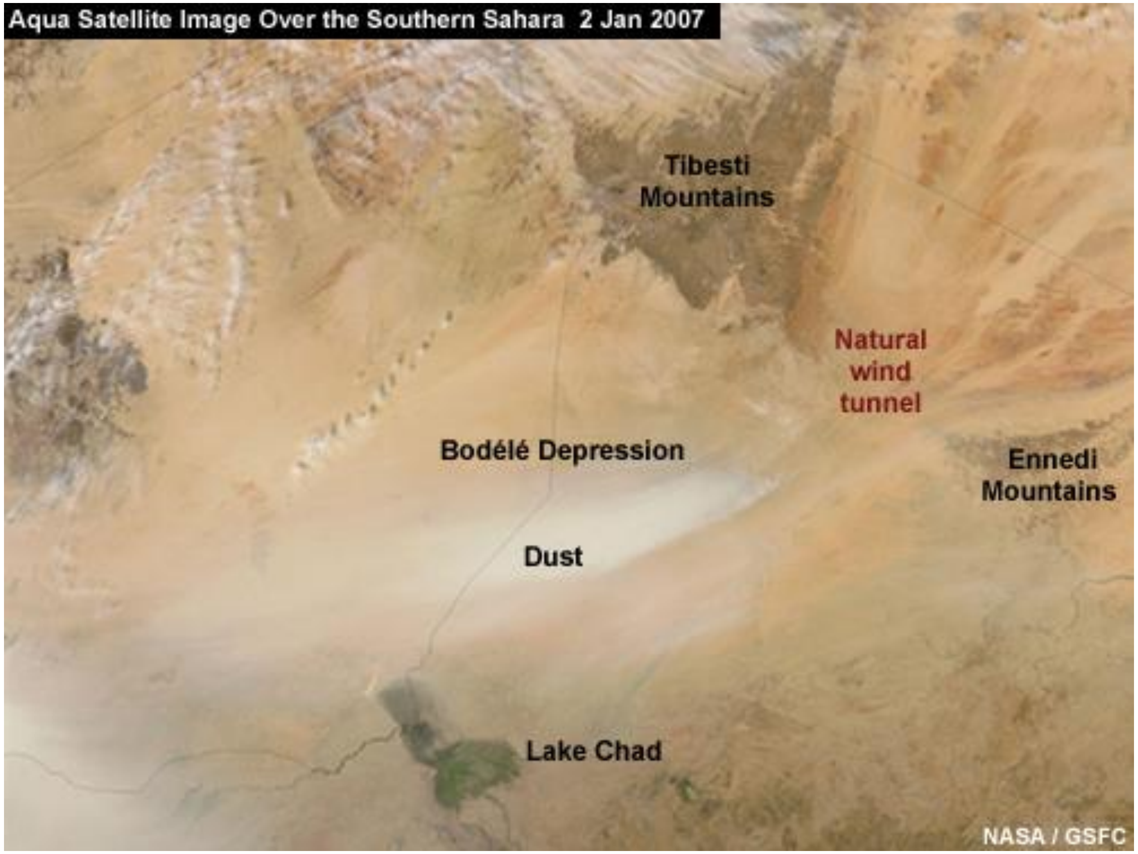
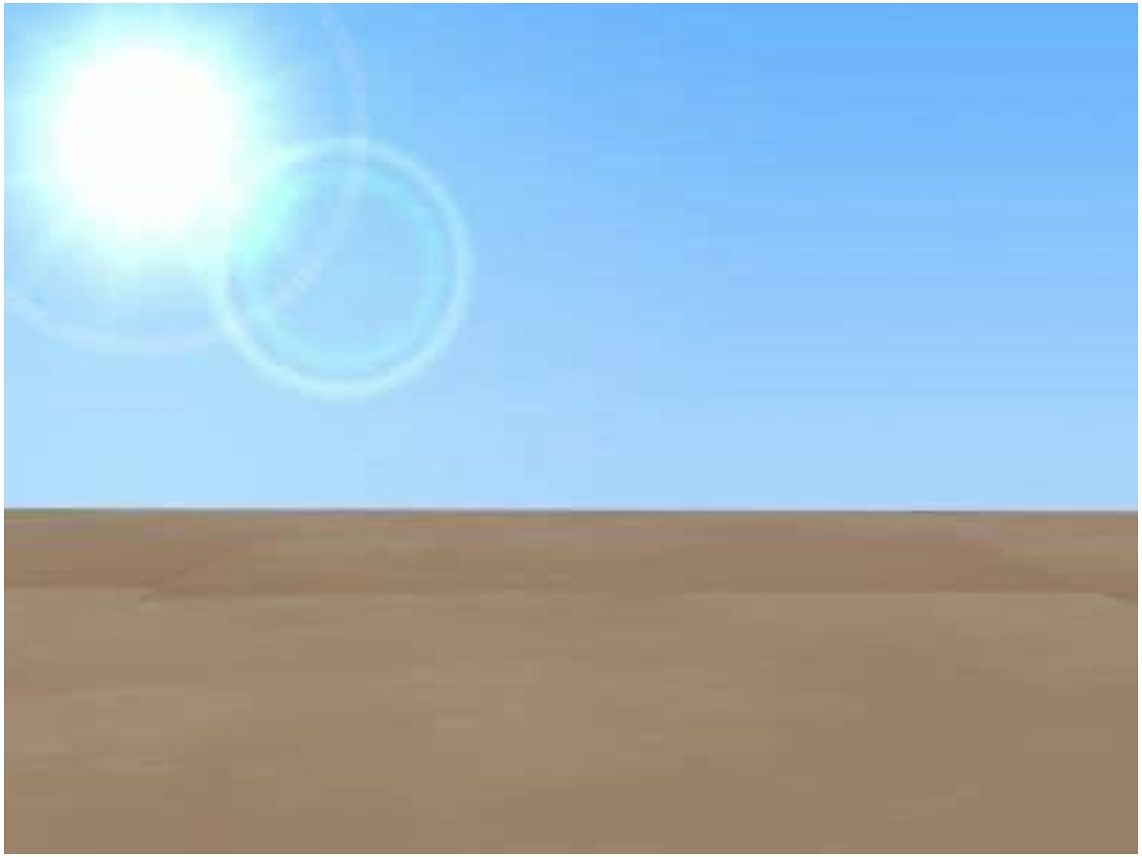
Mesoscale dust storms: Gap flow



Dust cycle and associated processes

Mesoscale dust storms: Dust devils (convection)



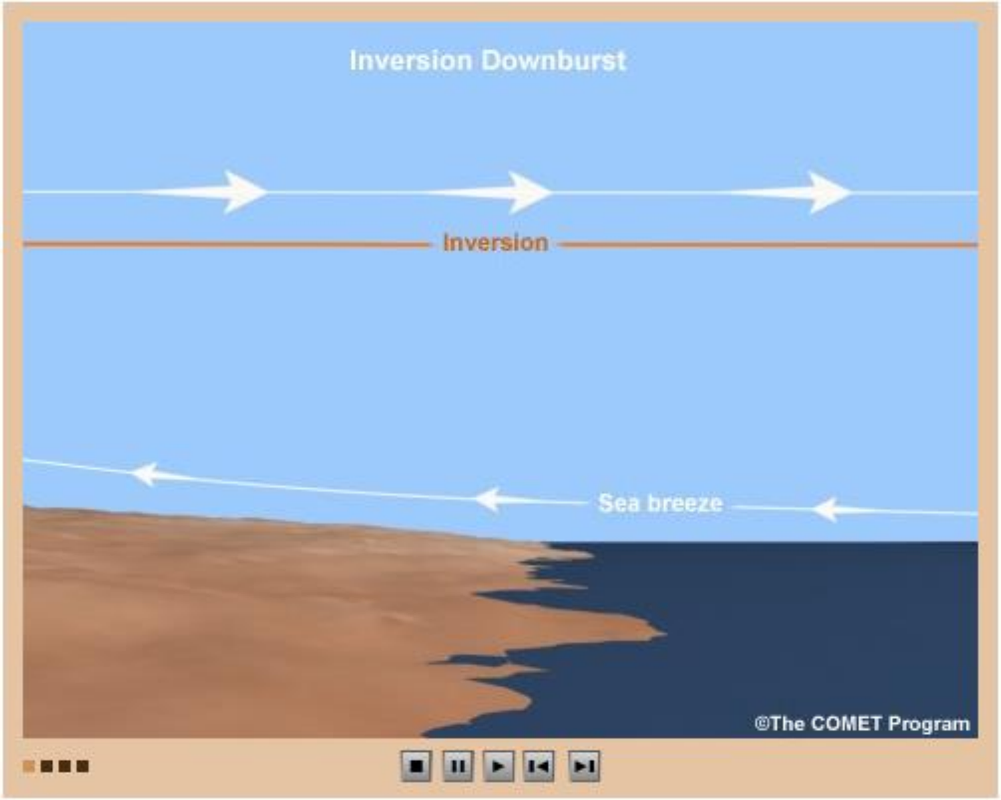
Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Mesoscale dust storms: Haboobs

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

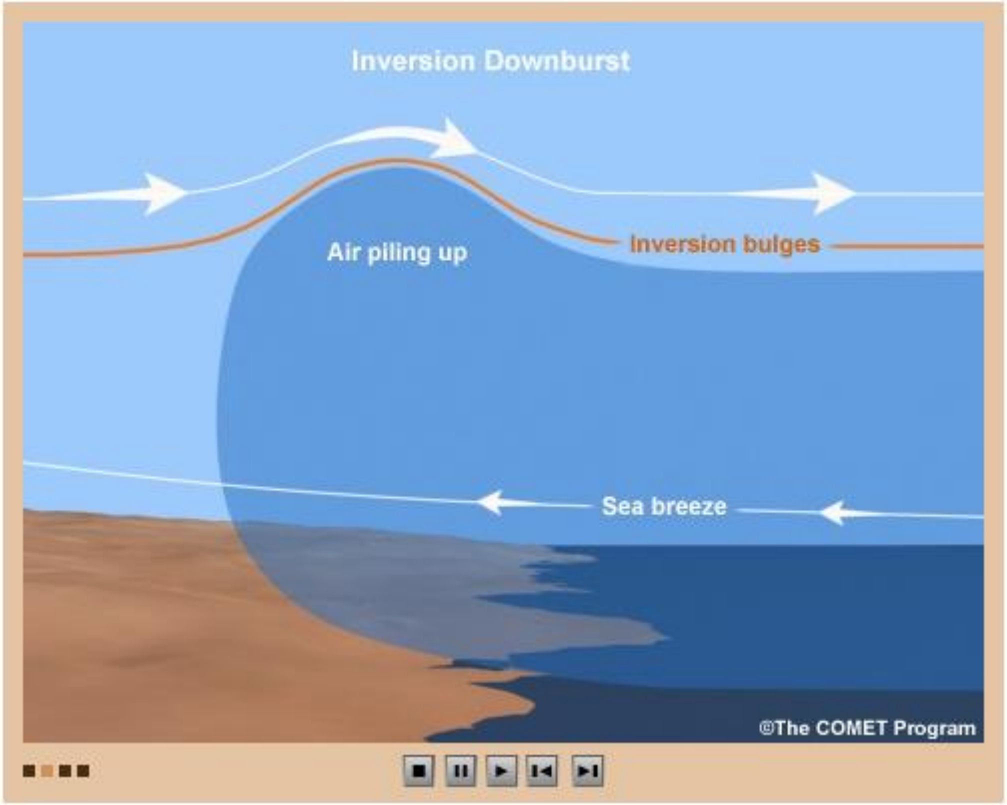
Dust cycle and associated processes

Mesoscale dust storms: Inversion downbursts



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

Mesoscale dust storms: Inversion downbursts



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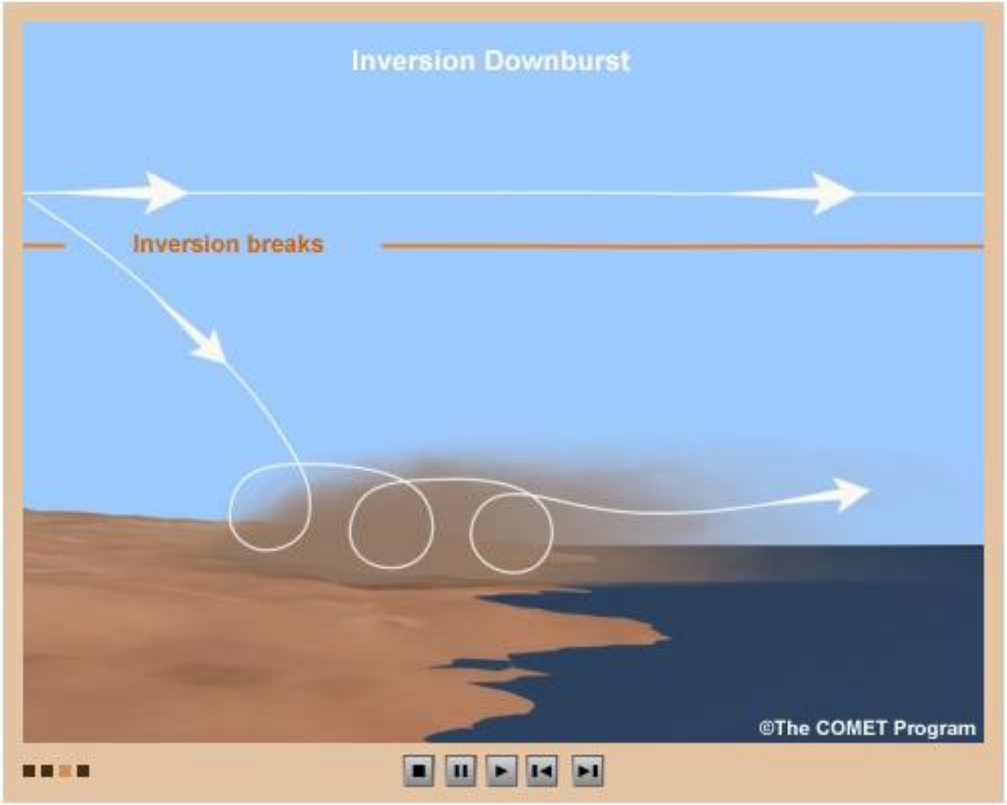
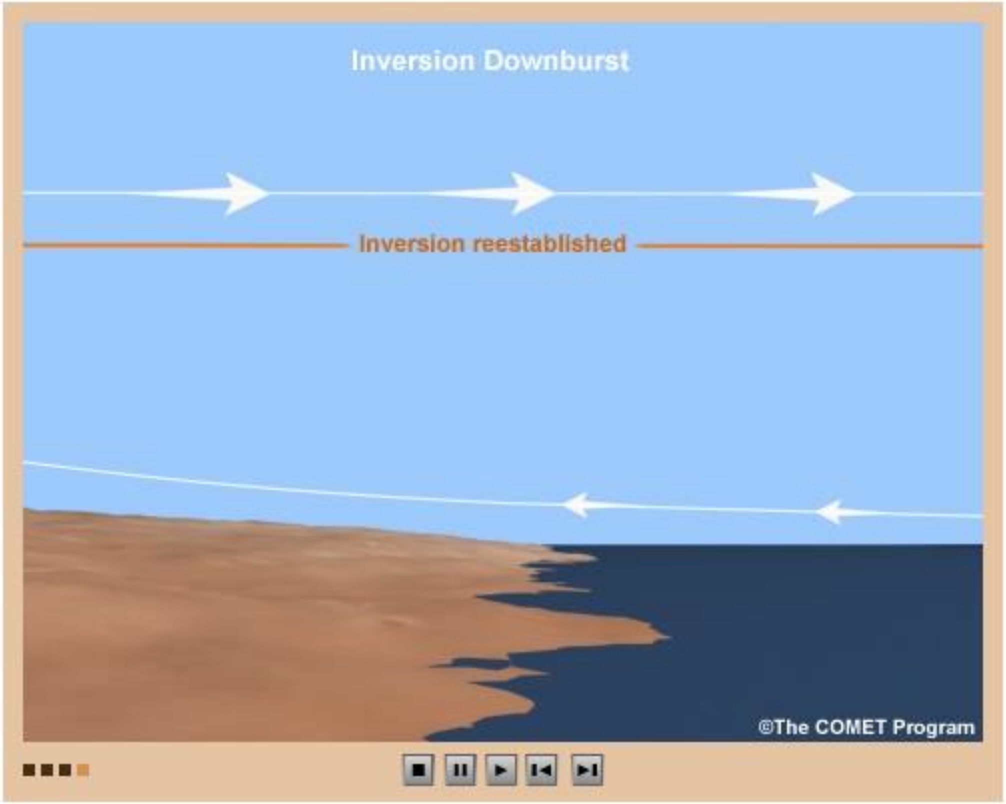
Dust cycle and associated processes

Mesoscale dust storms: Inversion downbursts



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

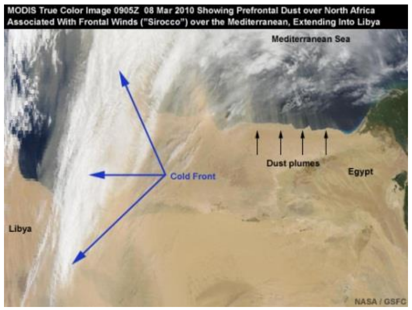
Mesoscale dust storms: Inversion downbursts



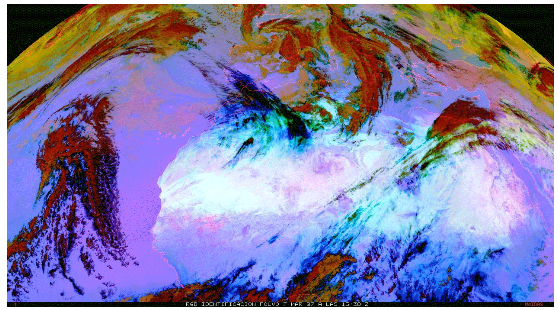
Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust cycle and associated processes: Types of dust storms

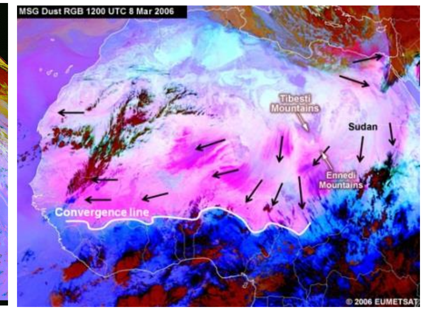
Synoptic dust storms (large scale weather systems) **Well captured by models.**



Pre-frontal winds

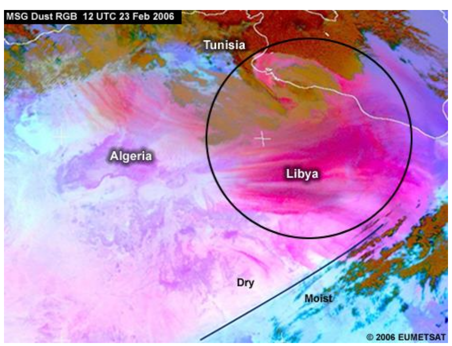


Post-frontal winds

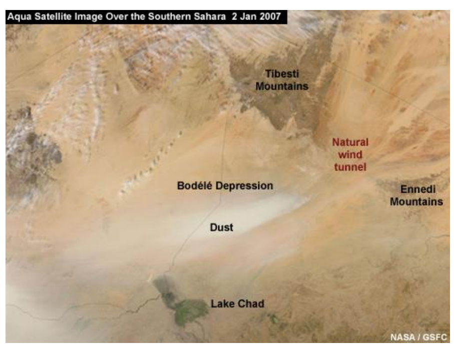


Large-scale trade winds

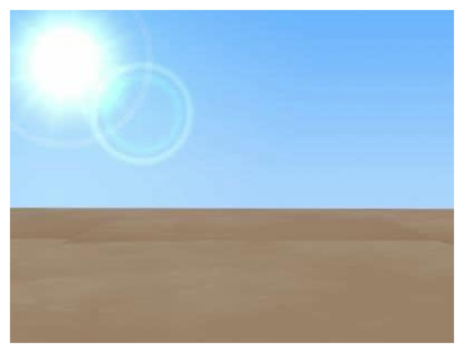
Mesoscale dust storms **Poorly captured by models.**
Some types improve in regional models.



Downslope winds



Gap flow



Dust devils

Haboobs

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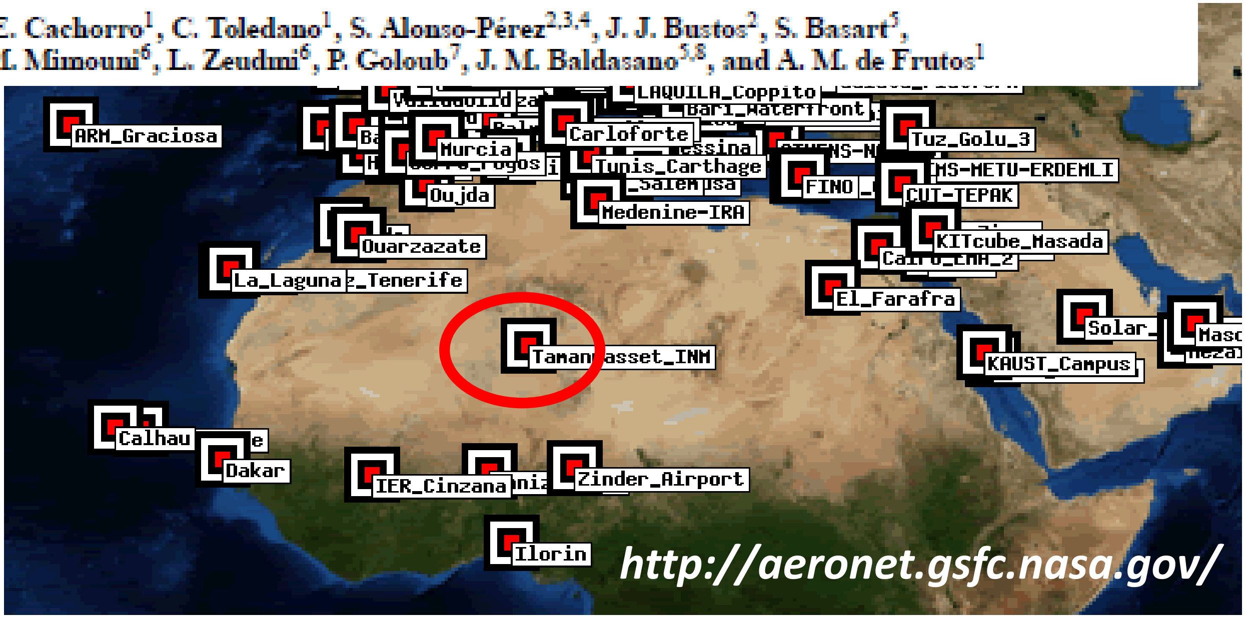
Dust cycle and associated processes: Types of dust storms

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

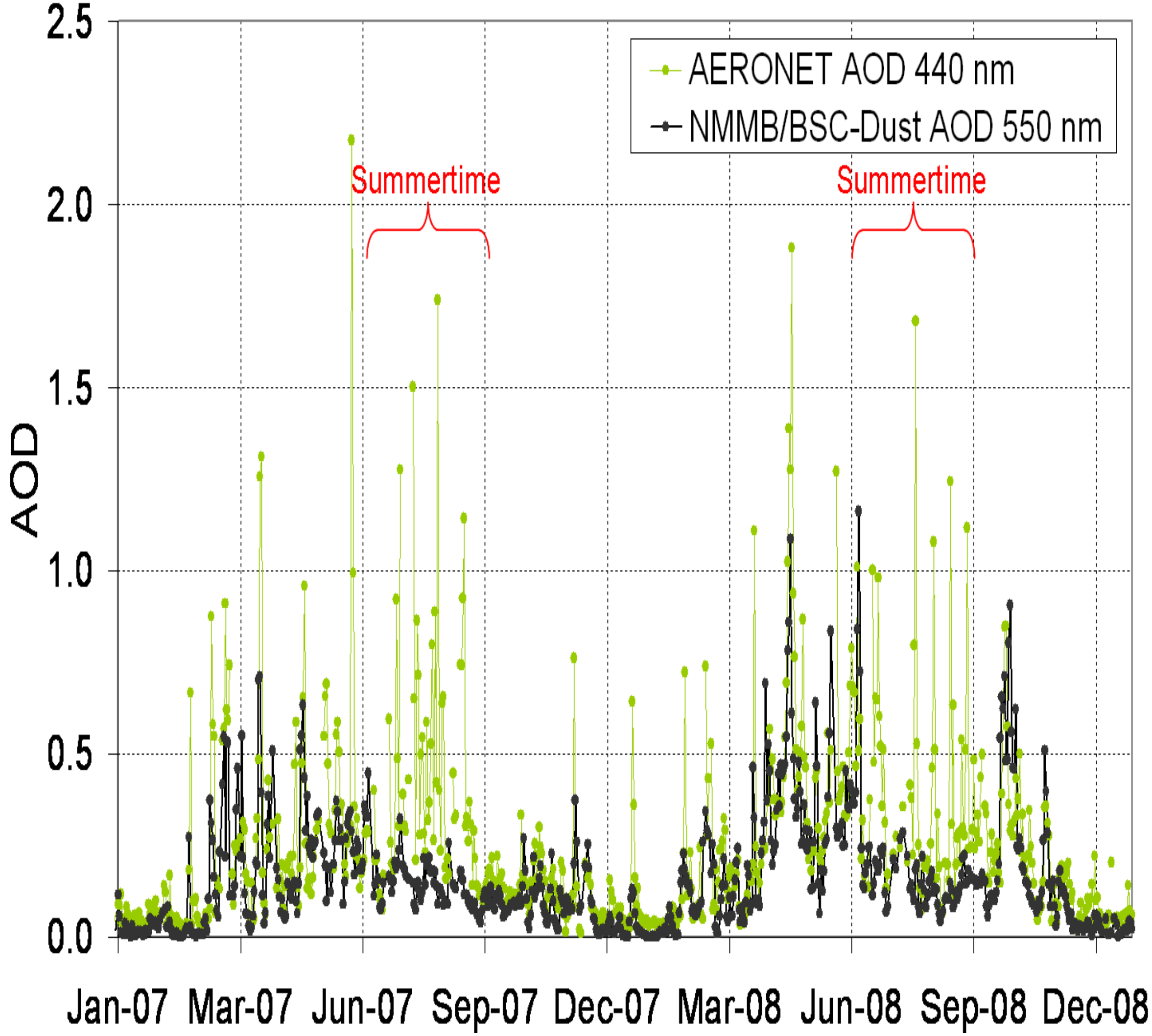
Atmospheric Chemistry and Physics
Open Access

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]

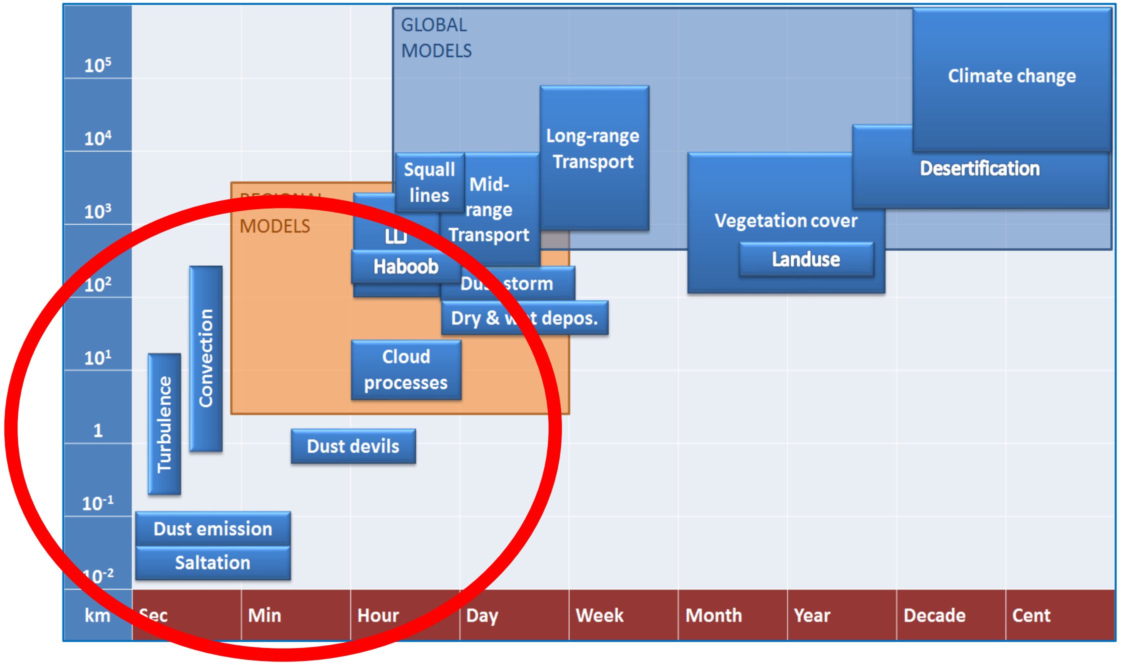


Dust cycle and associated processes: Types of dust storms



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.

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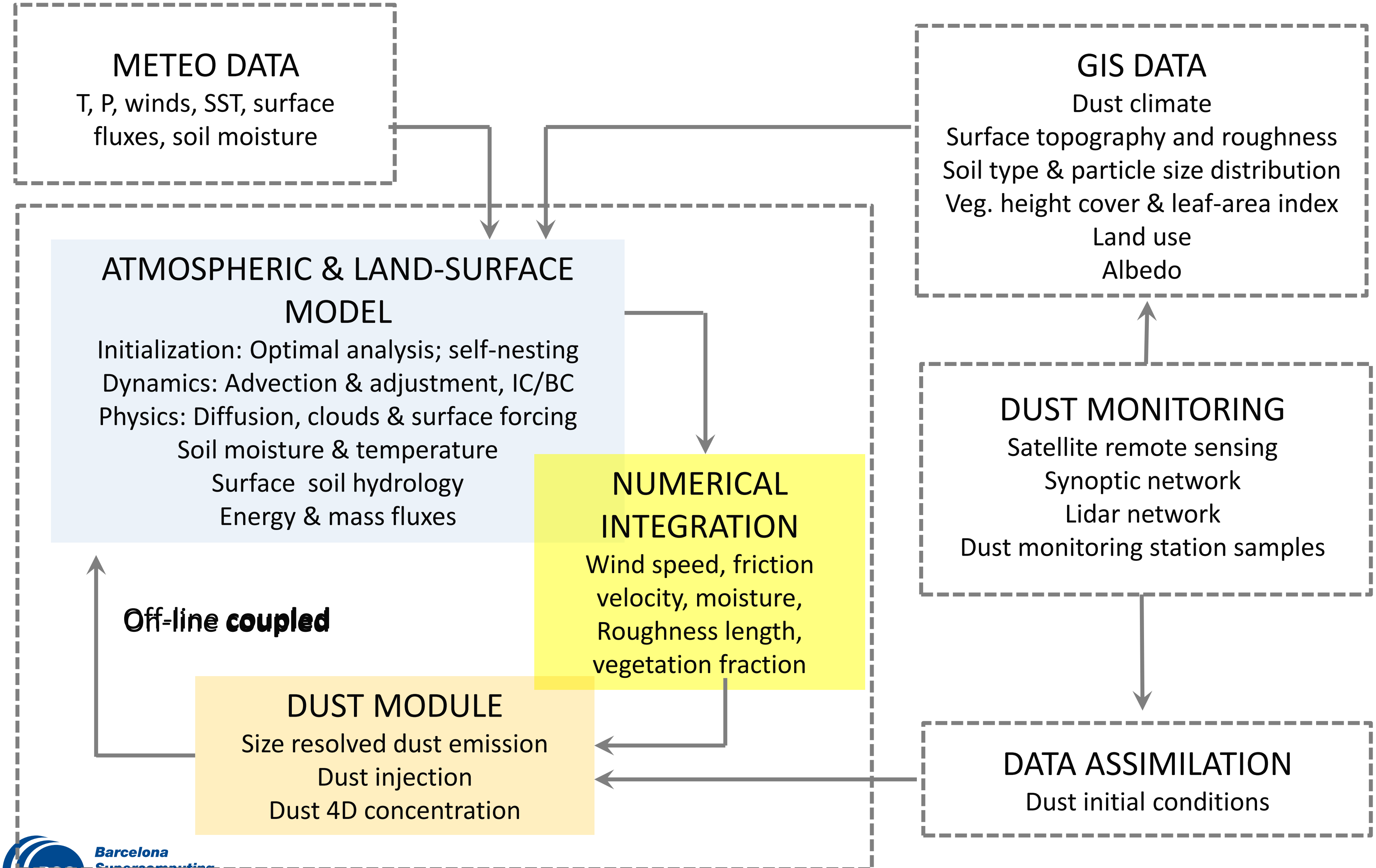
Adapted from Shao (2011)

Dust forecasting models



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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: 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* | *Horizontal diffusion* | *Vertical diffusion* | *Dust emission* | *Wet and dry deposition*

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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;

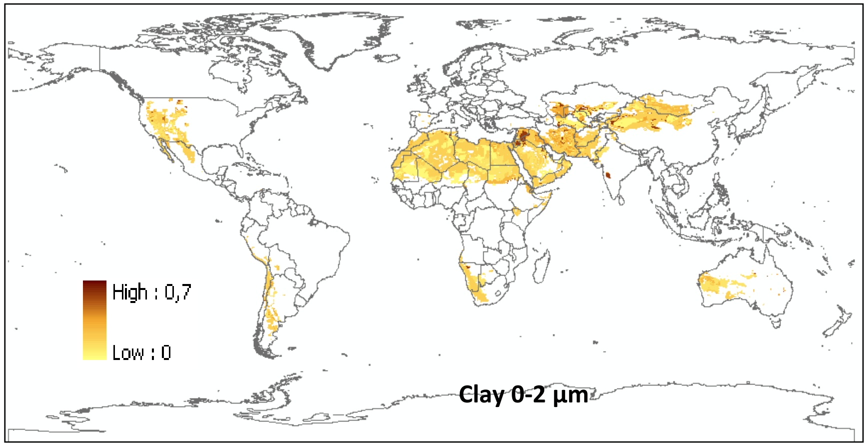
D) Daïa in the Mechfar, at Hassi Cheikh well;

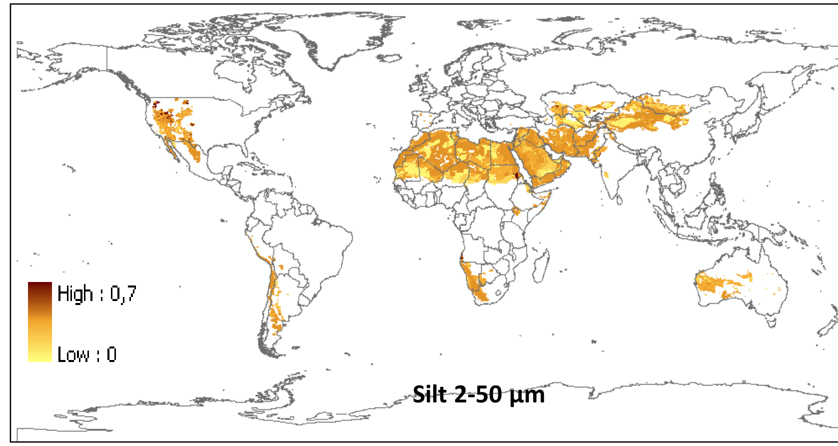
E) North-east of the Great Western Erg: coarse sand interdune corridor with deflation cauldron and palaeolake deposits;

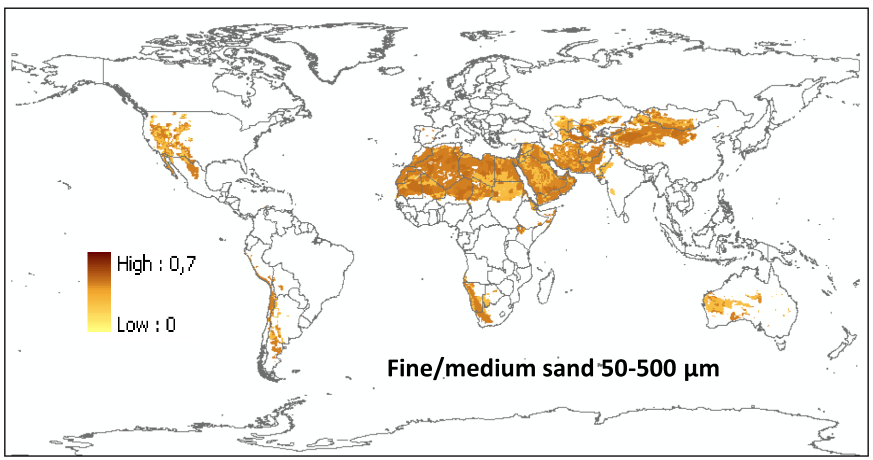
F) North-east of the Great Western Erg: great coarse sand dome dunes, covered by fine sand active dunes.

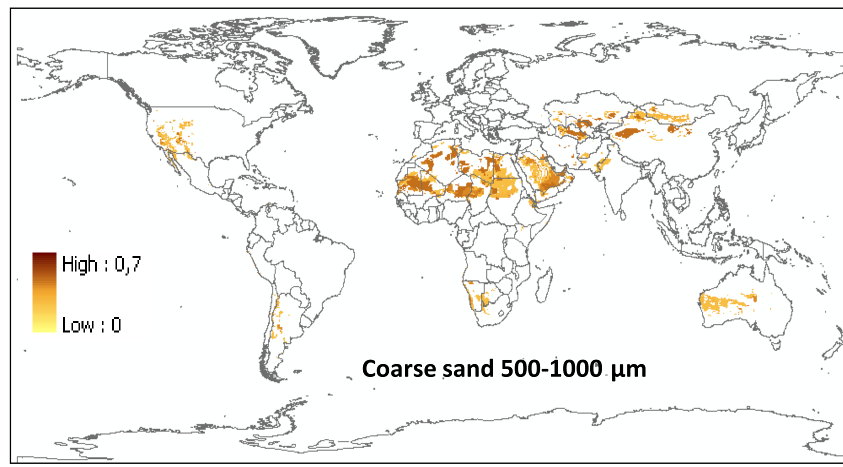
Dust forecasting models: Emission scheme

Parent soil size distribution





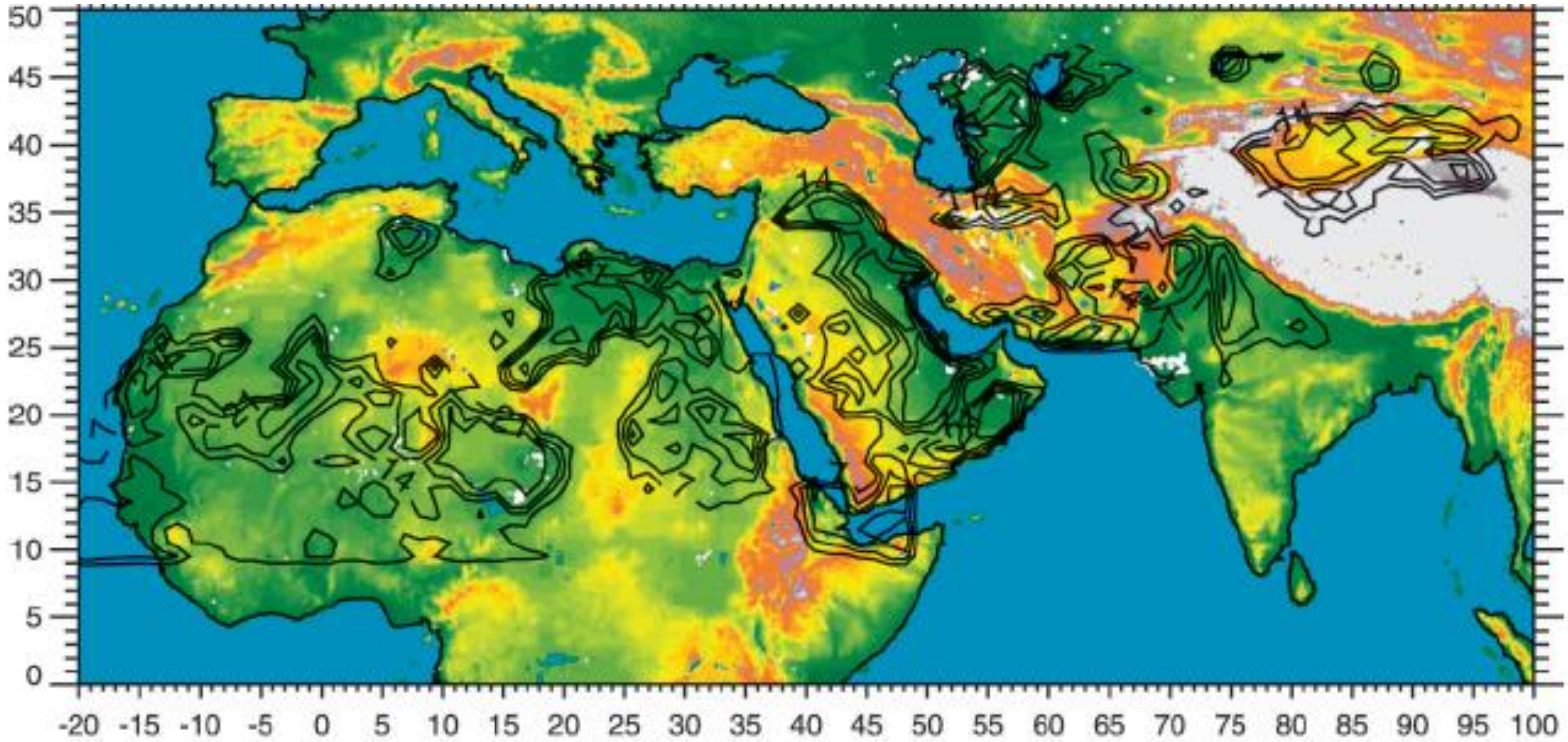




Four top soil texture classes according STASGO-FAO 1km database are converted to 4 parent soil size categories following Tegen et al. [2002]

Dust forecasting models: Emission scheme

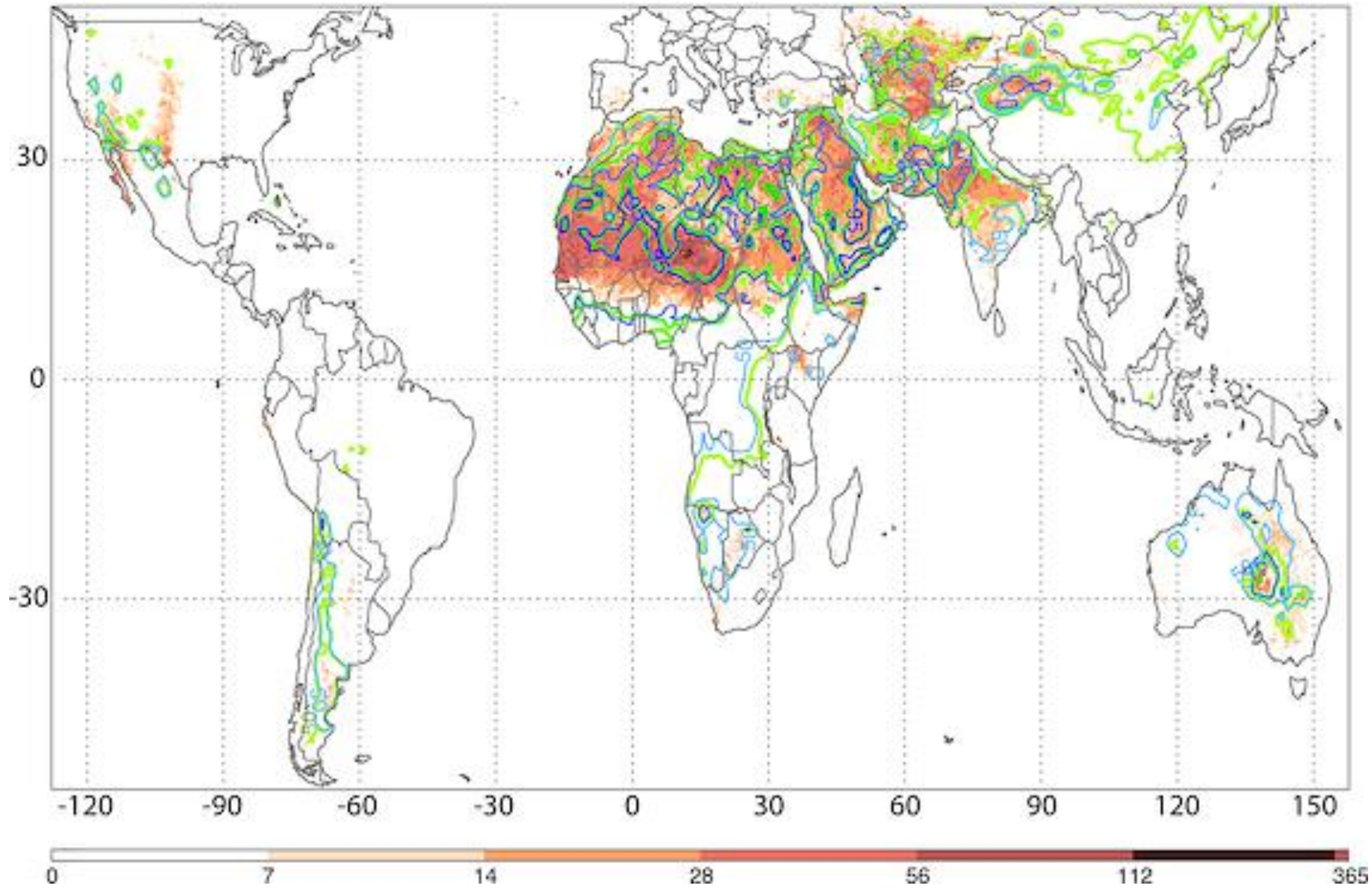
Dust source function



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



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)

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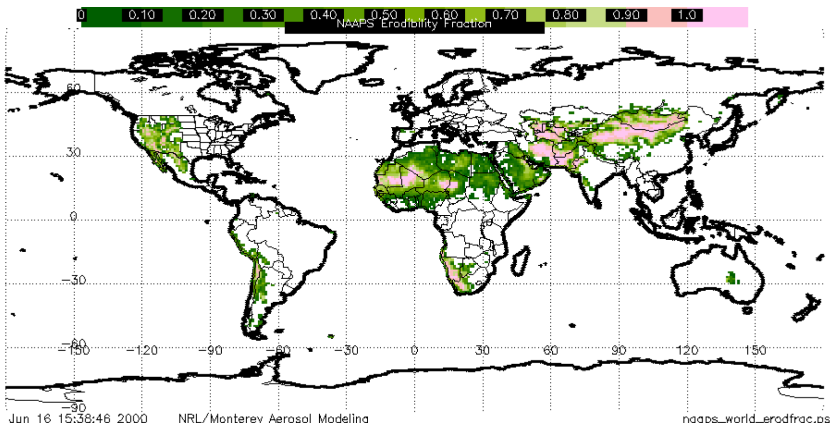
Dust forecasting models: Emission scheme

Dust source function: Other approaches

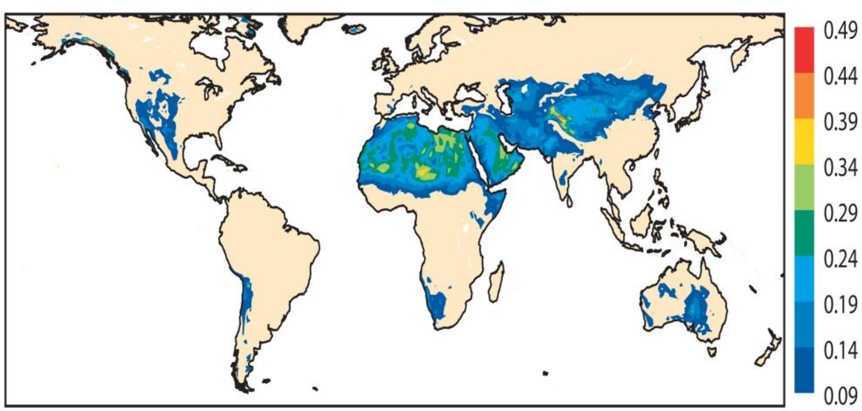


NAAPS model

Land use mask +

Erodibility map derived from TOMS

Satellite AI climatology

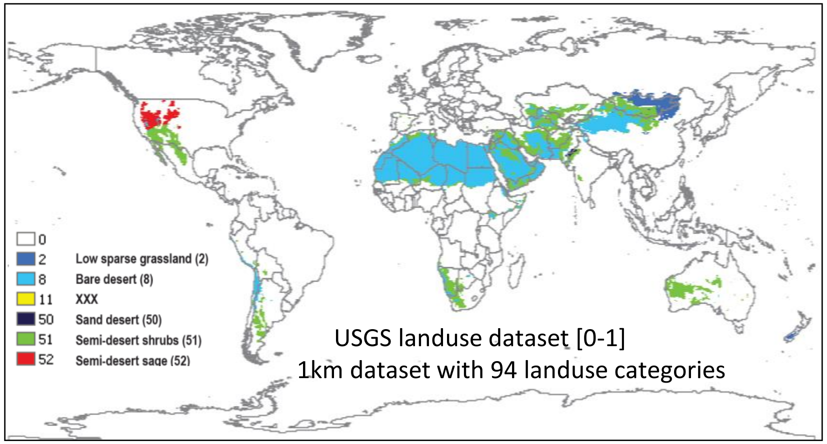


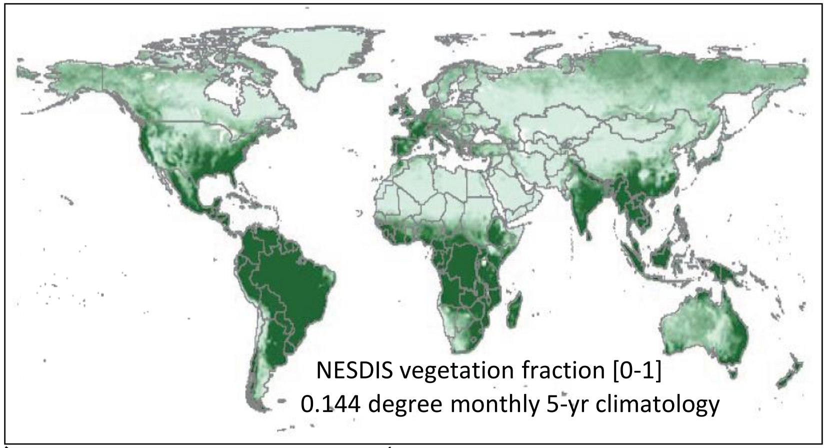
ECMWF-CAMS model

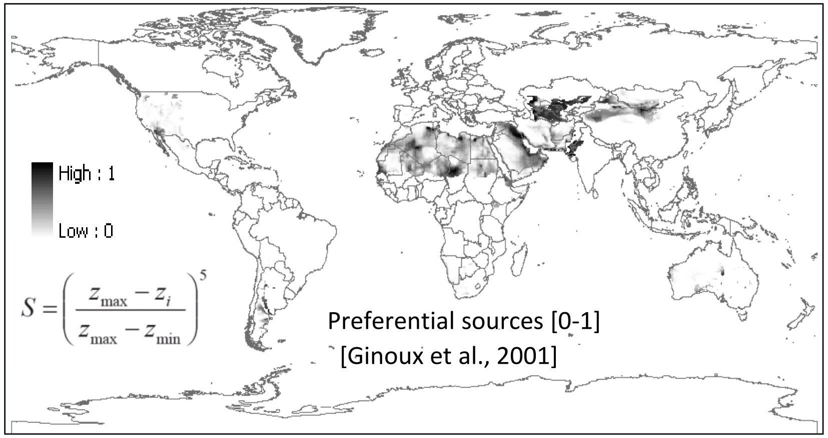
Background albedo in the ultraviolet-visible part of the shortwave spectrum. Only albedos with values between 0.09 and 0.54, assumed to be representative of light-colored soil and sparse vegetation are plotted.

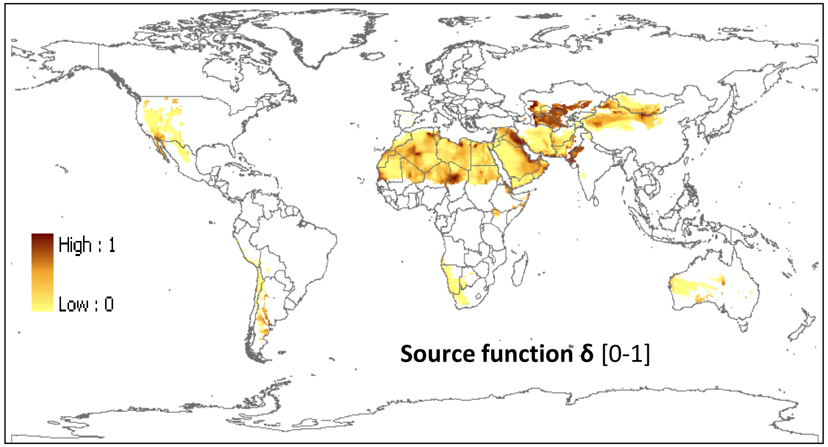
Dust forecasting models: Emission scheme

Dust source function: the NMMb/BSC-Dust model





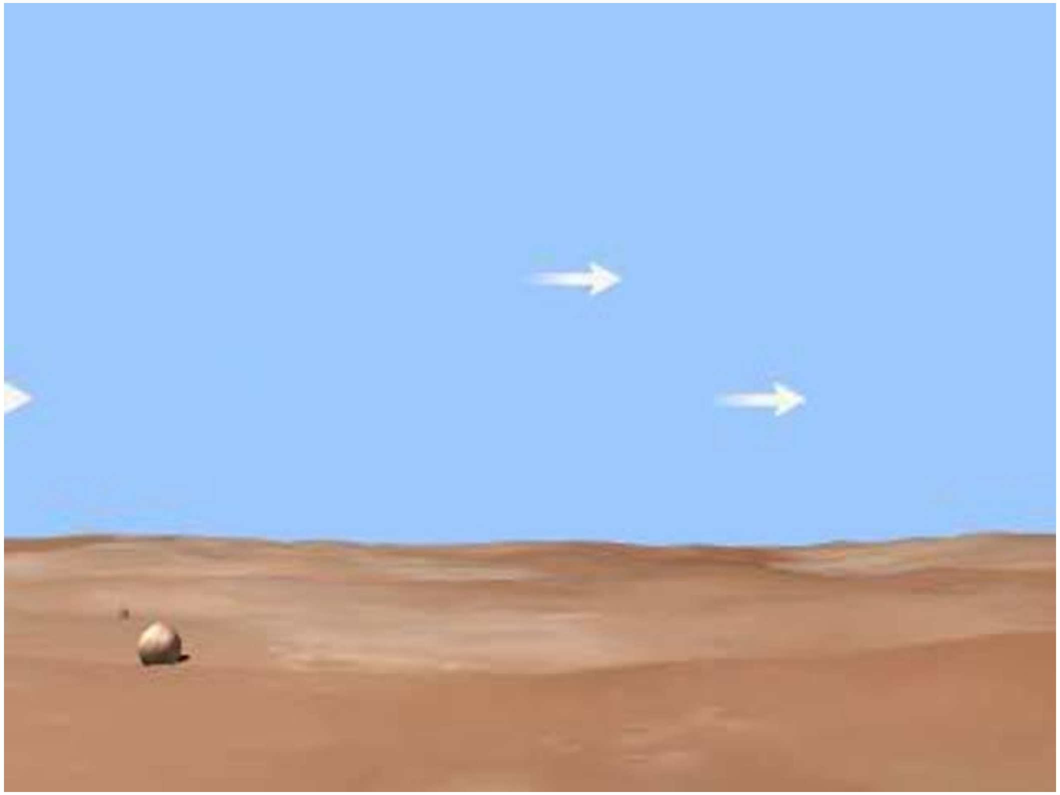




$$\delta = USGS \cdot PREF \cdot (1 - VEGFRAC) \cdot (1 - SnowCover)$$

Dust forecasting models: Emission scheme

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



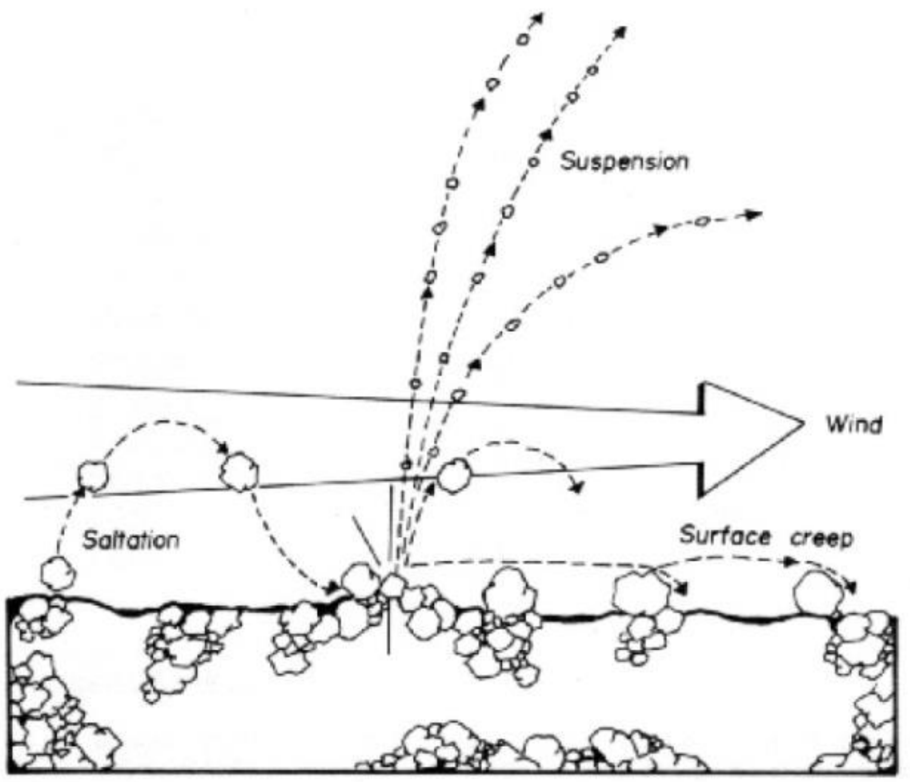
- Creep or rolling motion of the largest particles (> 500 um)

- 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)

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

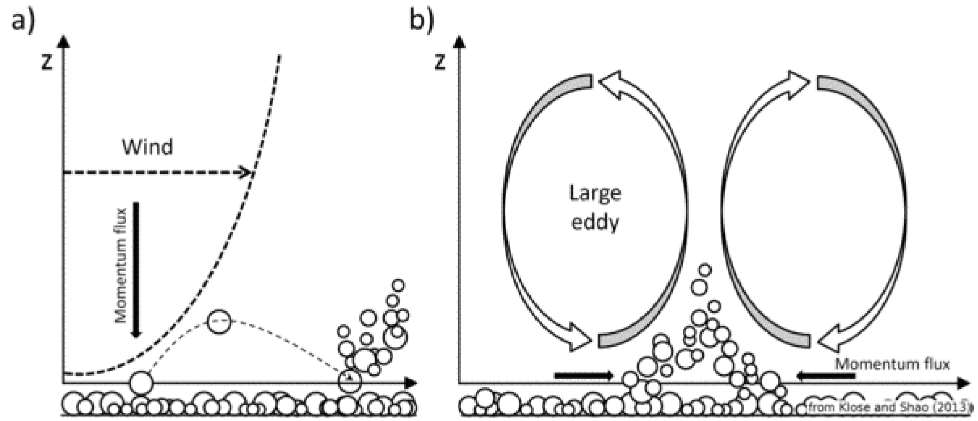
$\boldsymbol{c}$: dimensional scale dependent constant proportinality
$\boldsymbol{f}$: relative surface area of each soil particle fraction (which includes de source function, δ)
$\boldsymbol{u_*}$: friction velocity
$\boldsymbol{u_{*t}}$: threshold friction velocity
$\boldsymbol{P}$: polinomial of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

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

Dust forecasting models: Emission scheme

Dust storm generation requires:

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

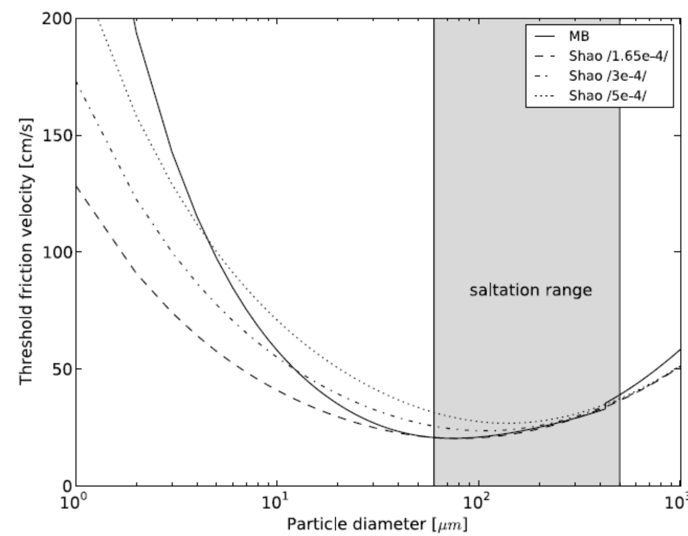


(a) Conventional view of dust emission via saltation bombardment; (b) Illustration of convective turbulent dust emission.

Extracted from Shao (2008)

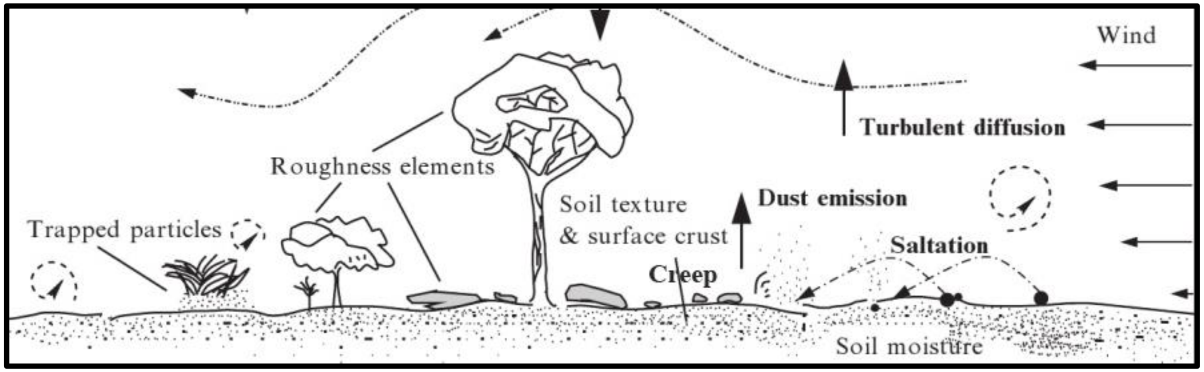
Friction velocity is the parameter used by dust models since it expresses wind speed, turbulence and stability

Threshold friction velocity vs particle radius →



Darmenova et al., 2009

Dust forecasting models: Emission scheme



Extracted from Shao (2008)

- **Threshold friction velocity u_{*thr}** is defined as the velocity above which soil particles begin to move in saltation flux
- Depends on **soil grain size, soil moisture and roughness** among others

Threshold friction velocity over smooth surface and D_p the diameter of soil particles

$$u_{*thr}(D_p, z_0, w) = \frac{u_{*dry}(D_p)}{R(z_0, z_{0s})} \cdot H(w)$$

Moisture correction is introduced to account for the supression of soil erosion in wet soils

Drag partition correction
Z_0: roughness length
Z_{0s}: roughness length over smooth surfaces

Dust forecasting models: Emission scheme

Simple schemes

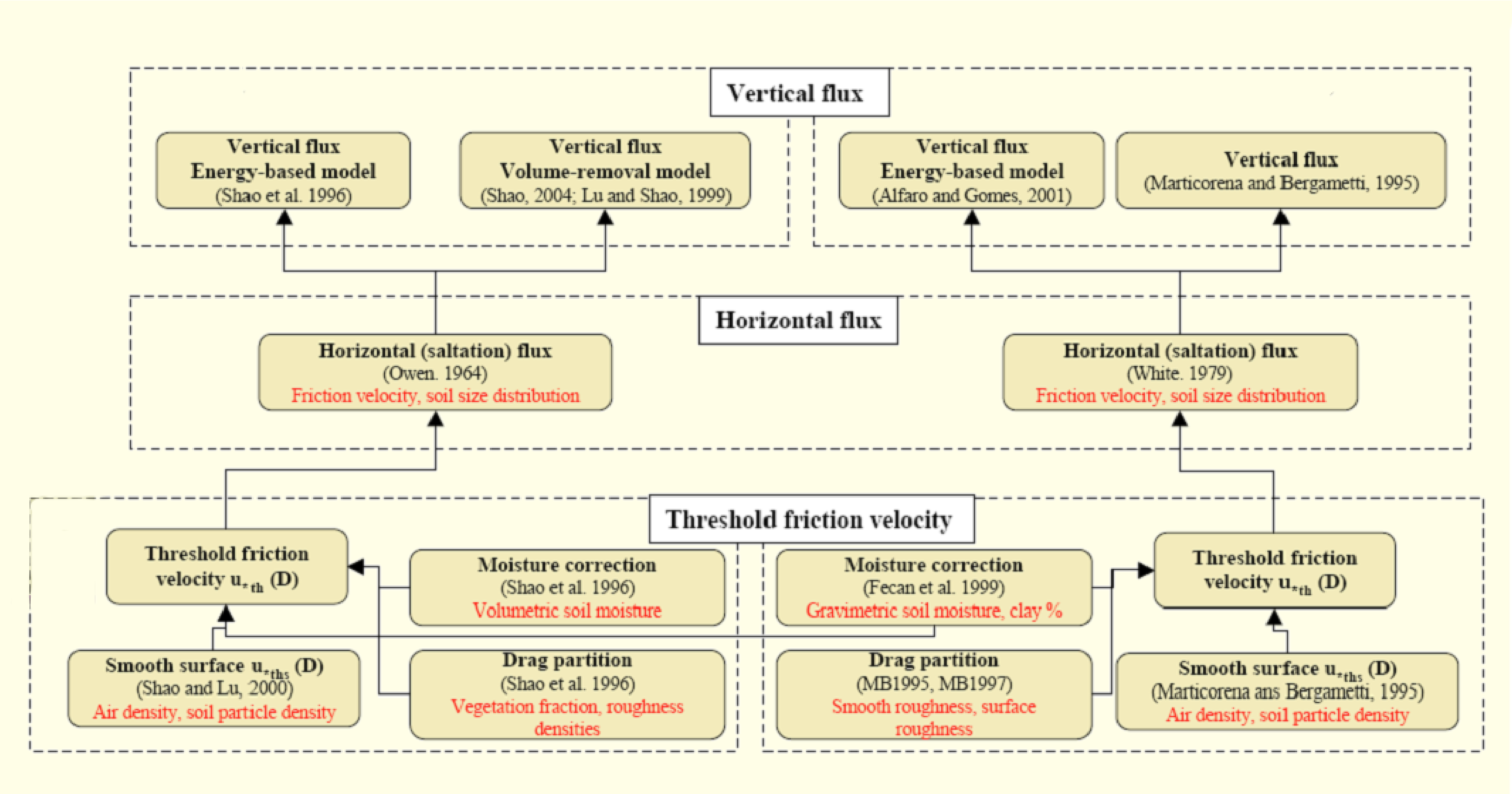
Limitations

- 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.

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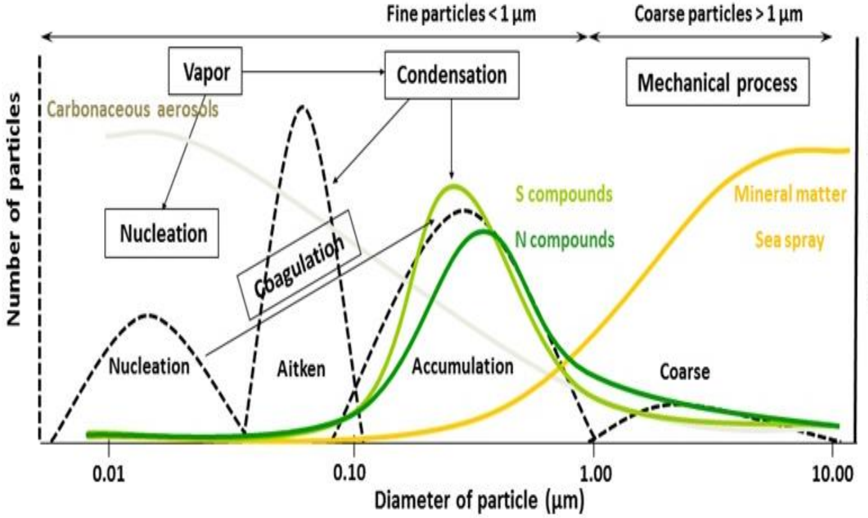
Dust forecasting models: Emission scheme

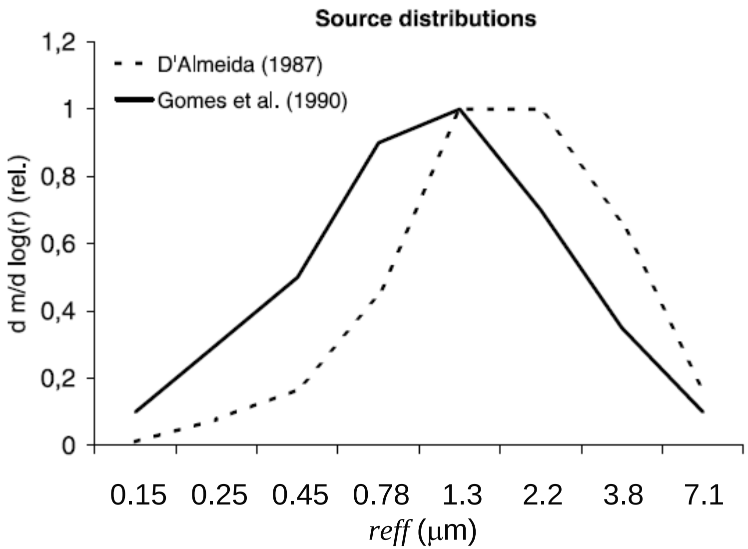
Parent soil size distribution are used to calculate **horizontal flux (H).** Dust **horizontal concentration** is calculated distributing the **vertical flux (F)** of the **first two parent soil categories** (clay and silt) over the **model particle bins.**

Parameterizations of mass size distribution of the model at sources

Modal



Sectorial



8 bin size distribution from Tegen and Lacis (1996)

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Dust forecasting models

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

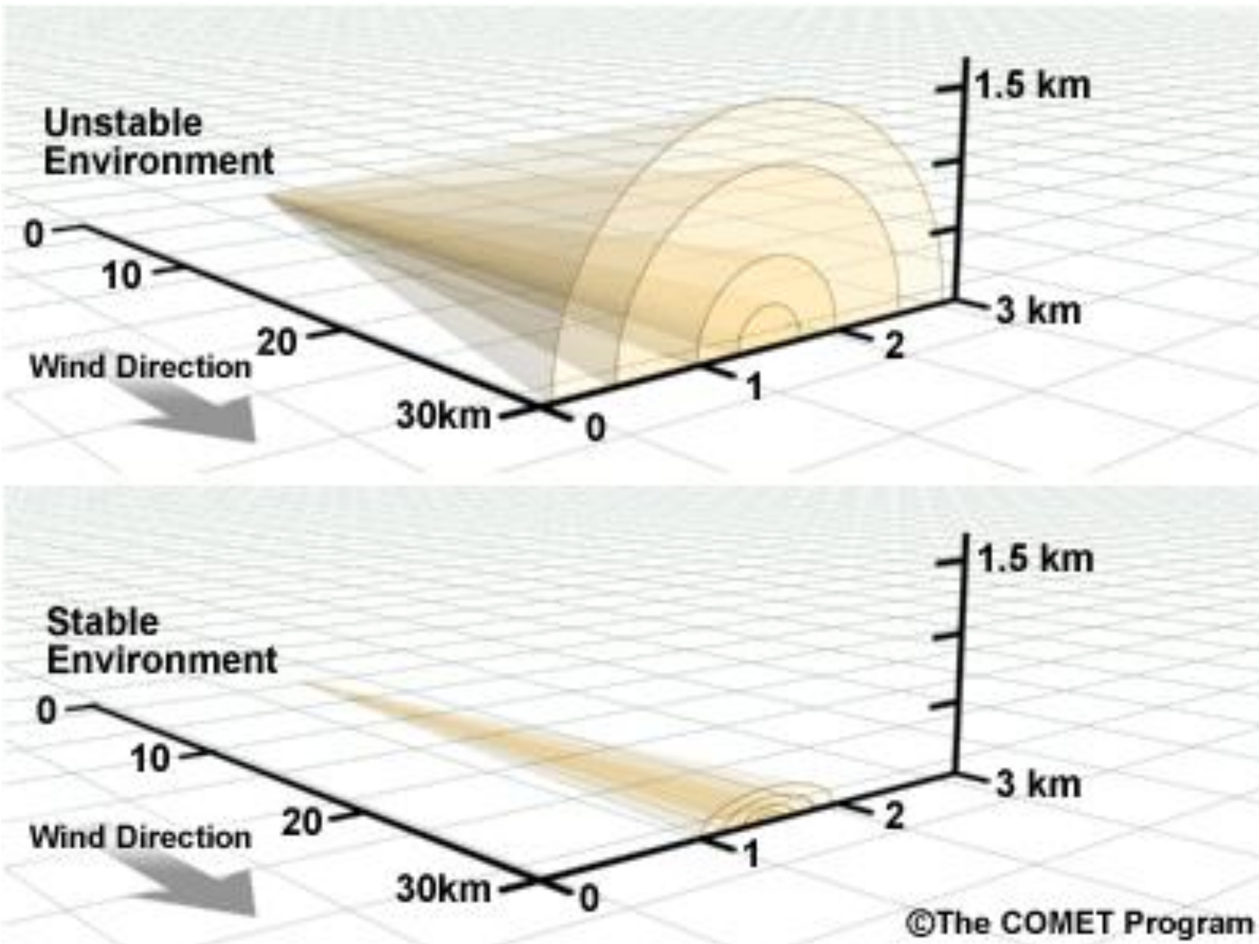
$$\frac{\partial C_k}{\partial t} = -u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y} - (w - v_{gk})\frac{\partial C_k}{\partial z} - \nabla(K_H \nabla C_k) - \frac{\partial}{\partial z}\left(K_Z \frac{\partial C_k}{\partial z}\right) + \left(\frac{\partial C_k}{\partial t}\right)_{SOURCE}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

Horizontal advection | *Vertical advection & gravitational settling* | *Horizontal diffusion* | *Vertical diffusion* | *Dust emission* | *Wet and dry deposition*

Dust forecasting models: Dispersion

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

Dust forecasting models: Dispersion



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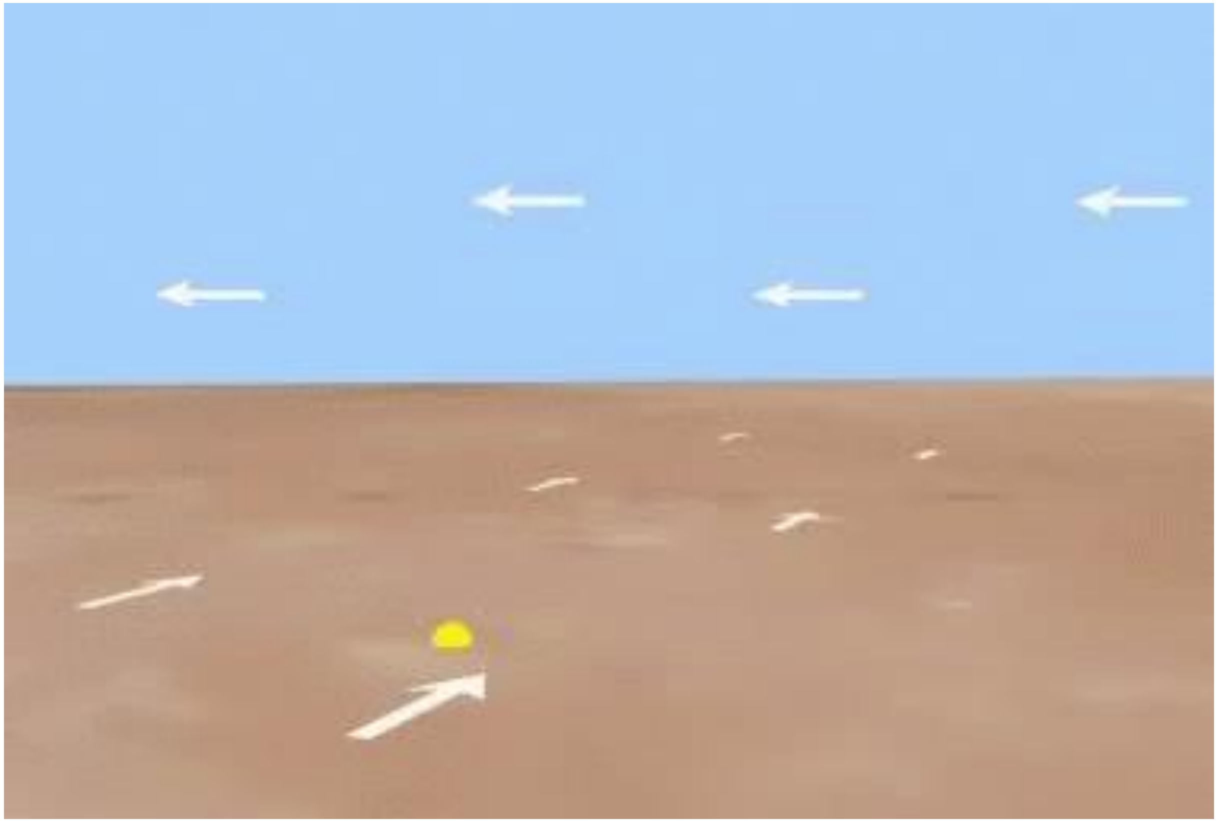
Horizontal advection	Vertical advection & gravitational settling	Horizontal diffusion	Vertical diffusion	Dust emission	Wet and dry deposition

Dust forecasting models: Advection and diffusion



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

Dust forecasting models

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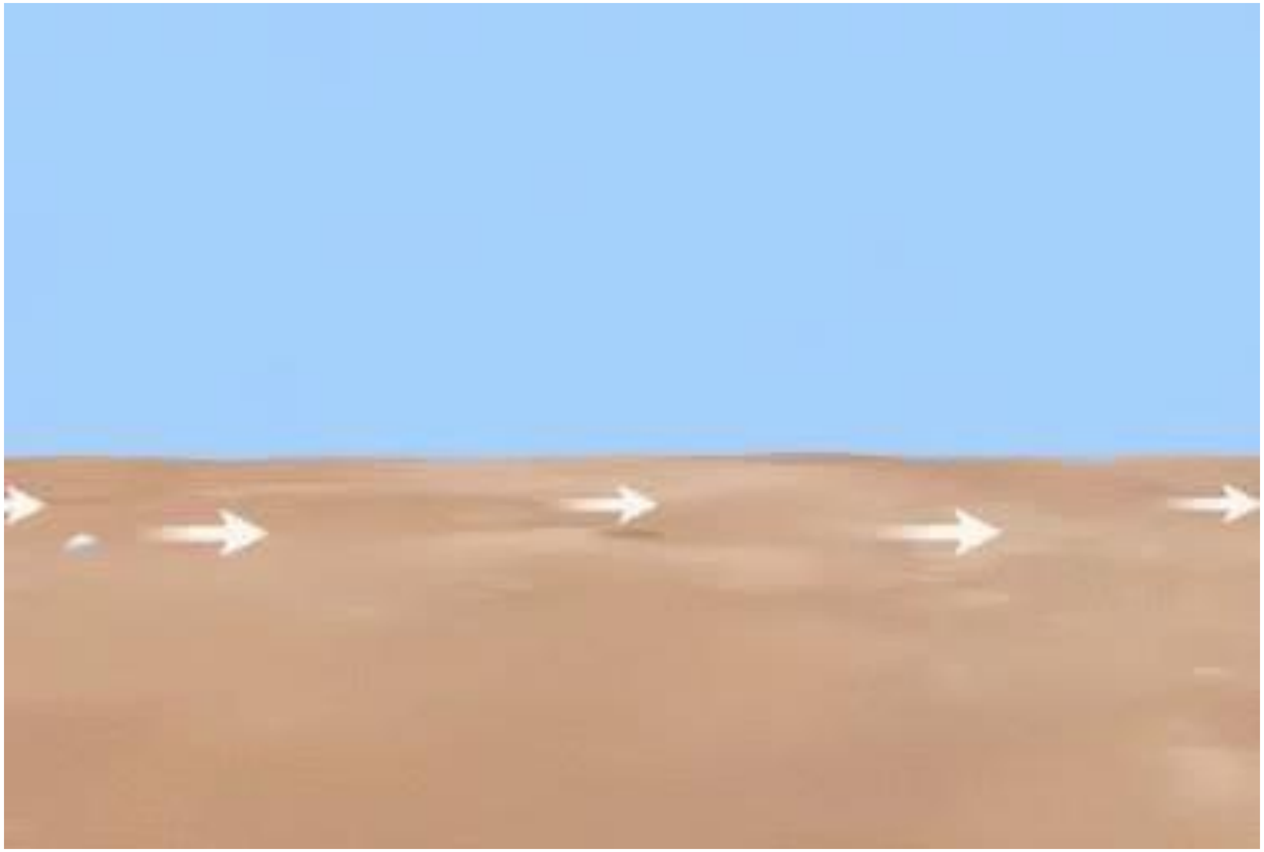
$-u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y}$	*Horizontal advection*
$(w - v_{gk})\frac{\partial C_k}{\partial z}$	*Vertical advection & gravitational settling*
$\nabla(K_H \nabla C_k)$	*Horizontal diffusion*
$\frac{\partial}{\partial z}\left(K_Z \frac{\partial C_k}{\partial z}\right)$	*Vertical diffusion*
$\left(\frac{\partial C_k}{\partial t}\right)_{SOURCE}$	*Dust emission*
$\left(\frac{\partial C_k}{\partial t}\right)_{SINK}$	*Wet and dry deposition*

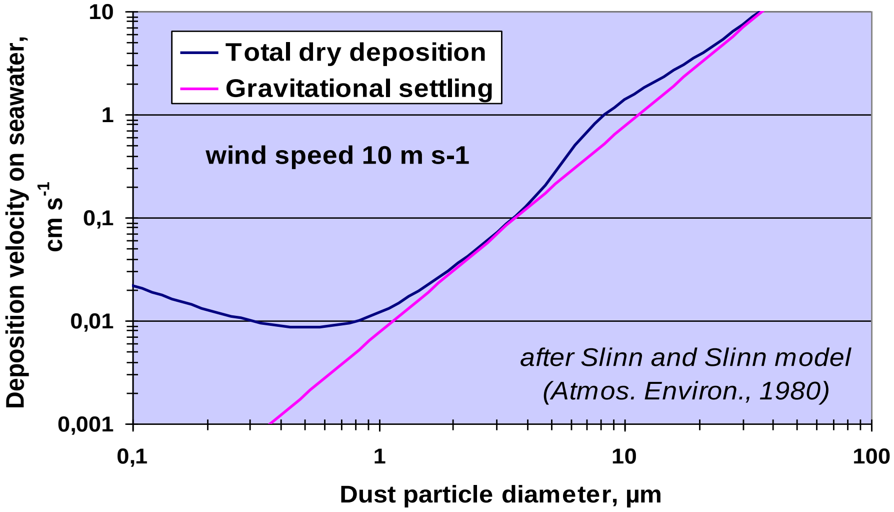
Dust forecasting models: Sedimentation and dry deposition scheme

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: Sedimentation and 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.

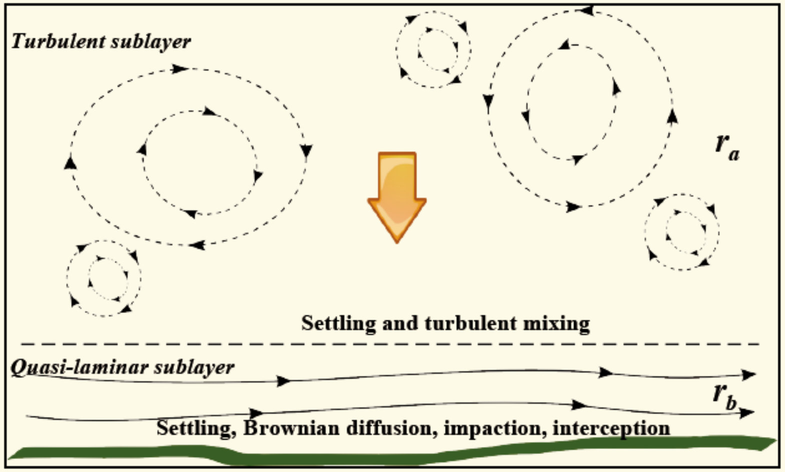
- **Sedimentation** (or gravitational settling) is the settling of particles fall down due to gravity → Very large particles will settle out quickly

Dust forecasting models: Dry deposition scheme

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

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

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



Adopted after Shao, 2000

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Dust forecasting models

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

$$\frac{\partial C_k}{\partial t} = \underbrace{-u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y}}_{\text{Horizontal advection}} - \underbrace{(w - v_{gk})\frac{\partial C_k}{\partial z}}_{\text{Vertical advection \& gravitational settling}} - \underbrace{\nabla(K_H \nabla C_k)}_{\text{Horizontal diffusion}} - \underbrace{\frac{\partial}{\partial z}\left(K_Z\frac{\partial C_k}{\partial z}\right)}_{\text{Vertical diffusion}} + \underbrace{\left(\frac{\partial C_k}{\partial t}\right)_{SOURCE}}_{\text{Dust emission}} - \underbrace{\left(\frac{\partial C_k}{\partial t}\right)_{SINK}}_{\text{Wet and dry deposition}}$$

Horizontal advection

Vertical advection & gravitational settling

Horizontal diffusion

Vertical diffusion

Dust emission

Wet and dry deposition

Dust forecasting models: Wet deposition scheme

Wet scavenging

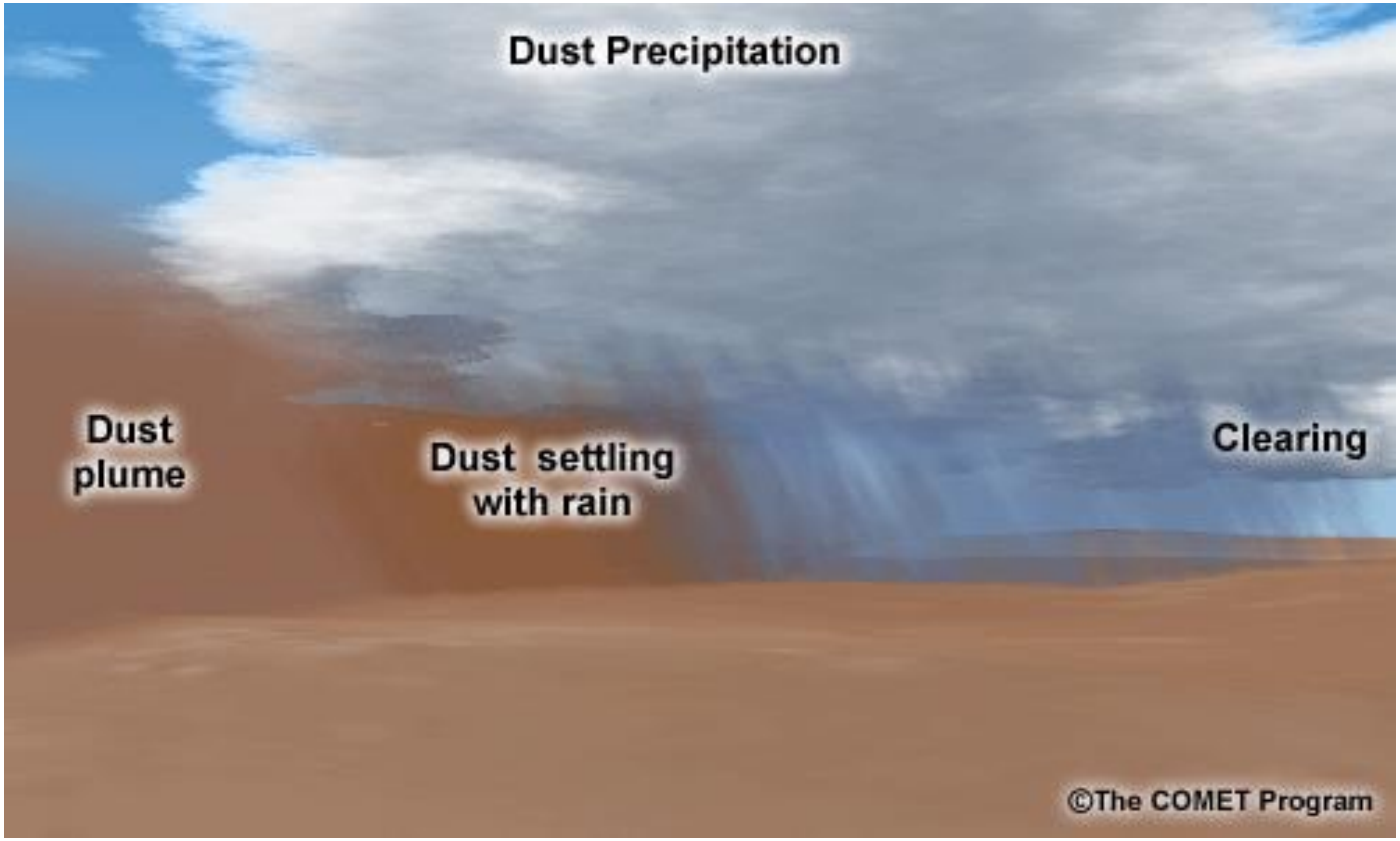
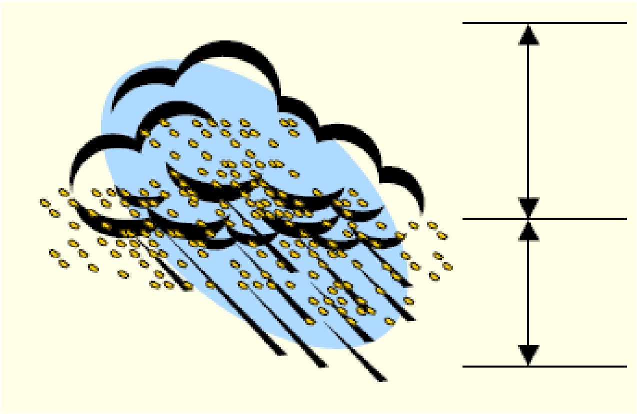


Image from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

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

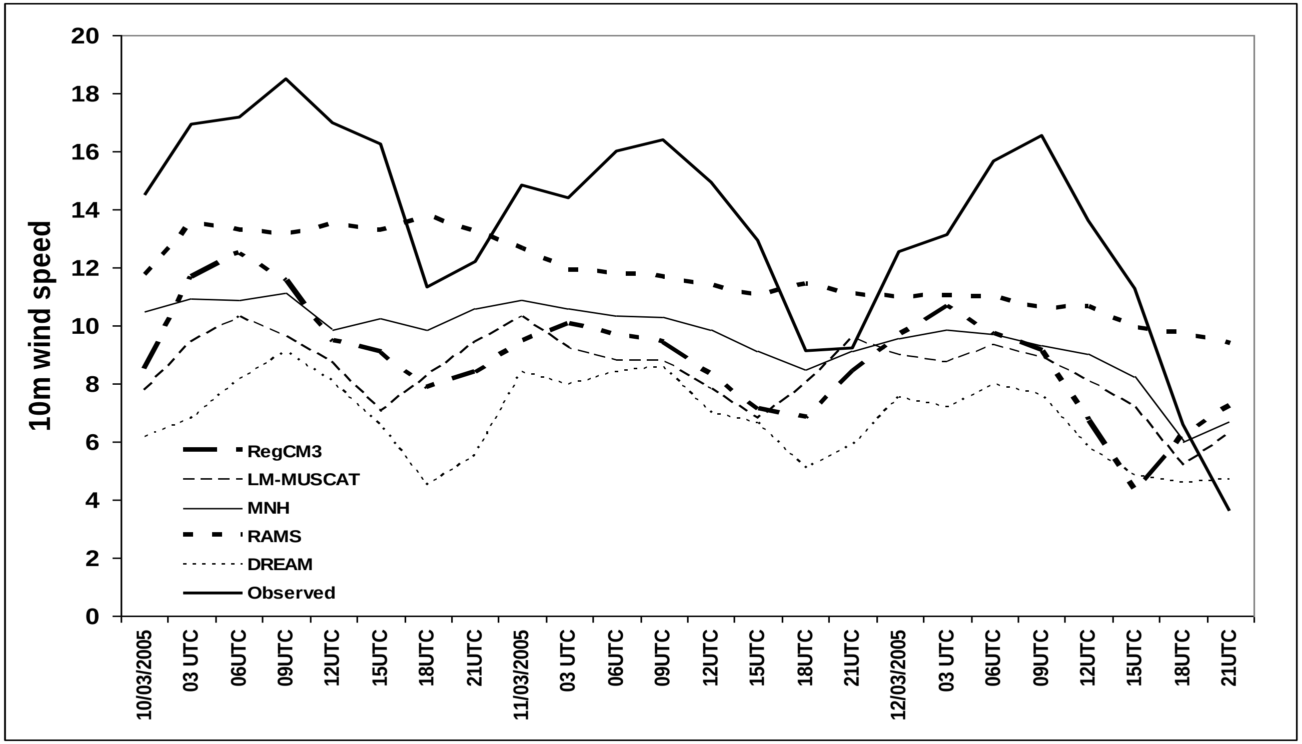
Main differences between dust models

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**

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EXCELENCIA SEVERO OCHOA

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