Barcelona Supercomputing Center
Centro Nacional de Supercomputación

EXCELENCIA SEVERO OCHOA

Dust prediction models

Sara Basart (sara.basart@bsc.es)

inDust

inDust Training School on Dust Products, Aveiro, Portugal, 4-6 February 2019

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.

Outlook

1. **Dust cycle and associated processes**

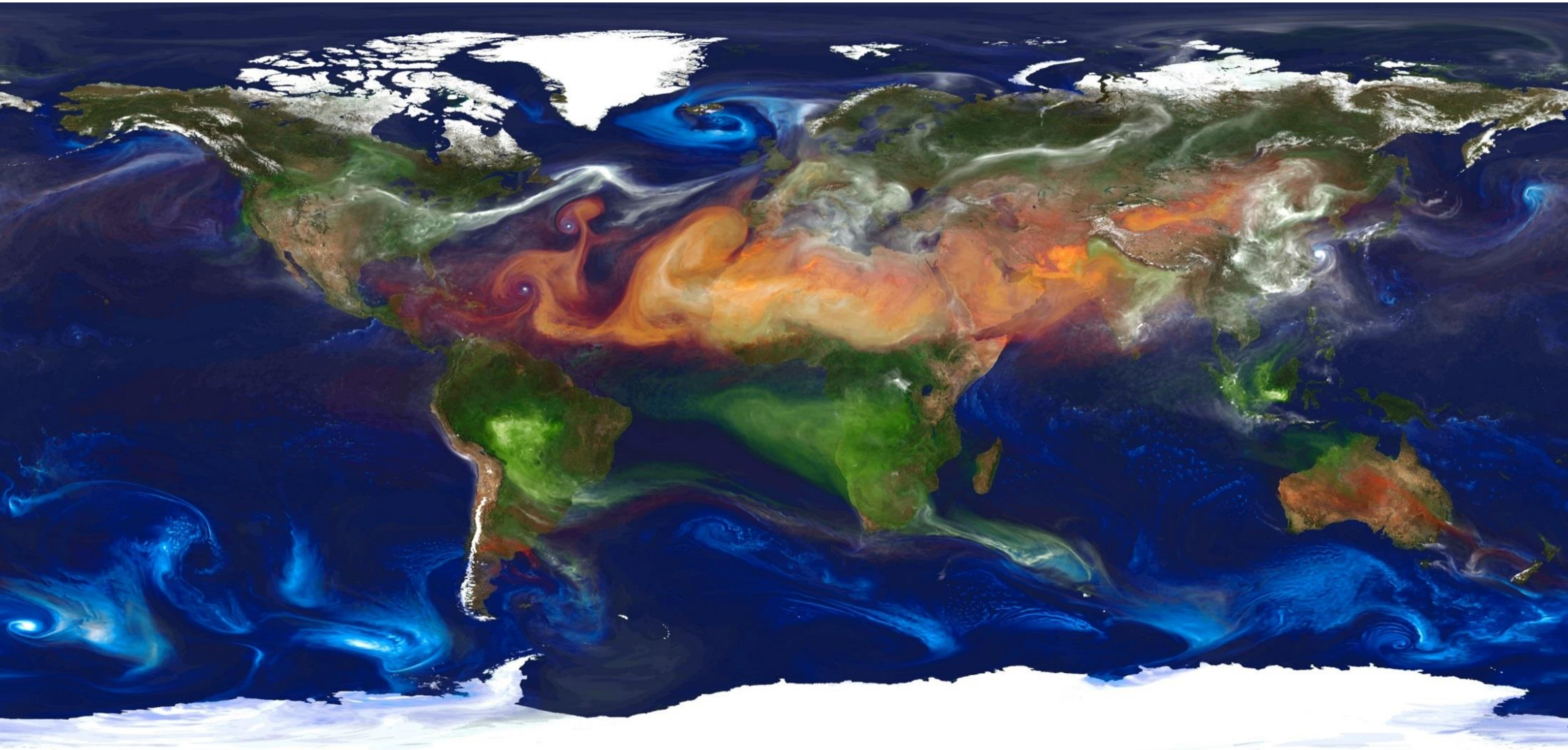
    - *The atmospheric dust cycle*
    - *Dust global climatology*
    - *Types of dust storms and model forecasting skills*

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 impacts and its extension

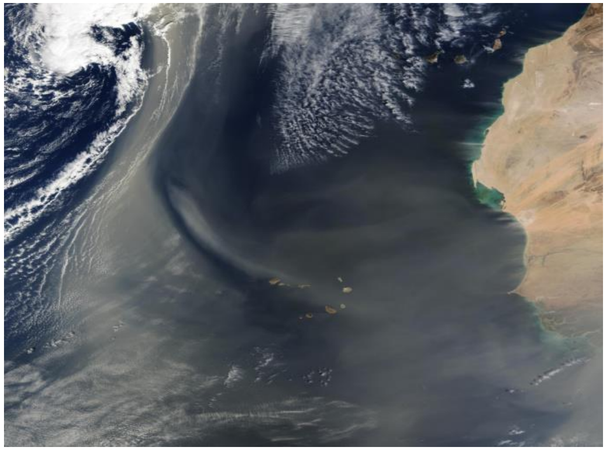


Organic Carbon + Elemental carbon
Dust
Sulfate
Sea salt

NASA | GEOS-5 Aerosols

Dust cycle and associated processes

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

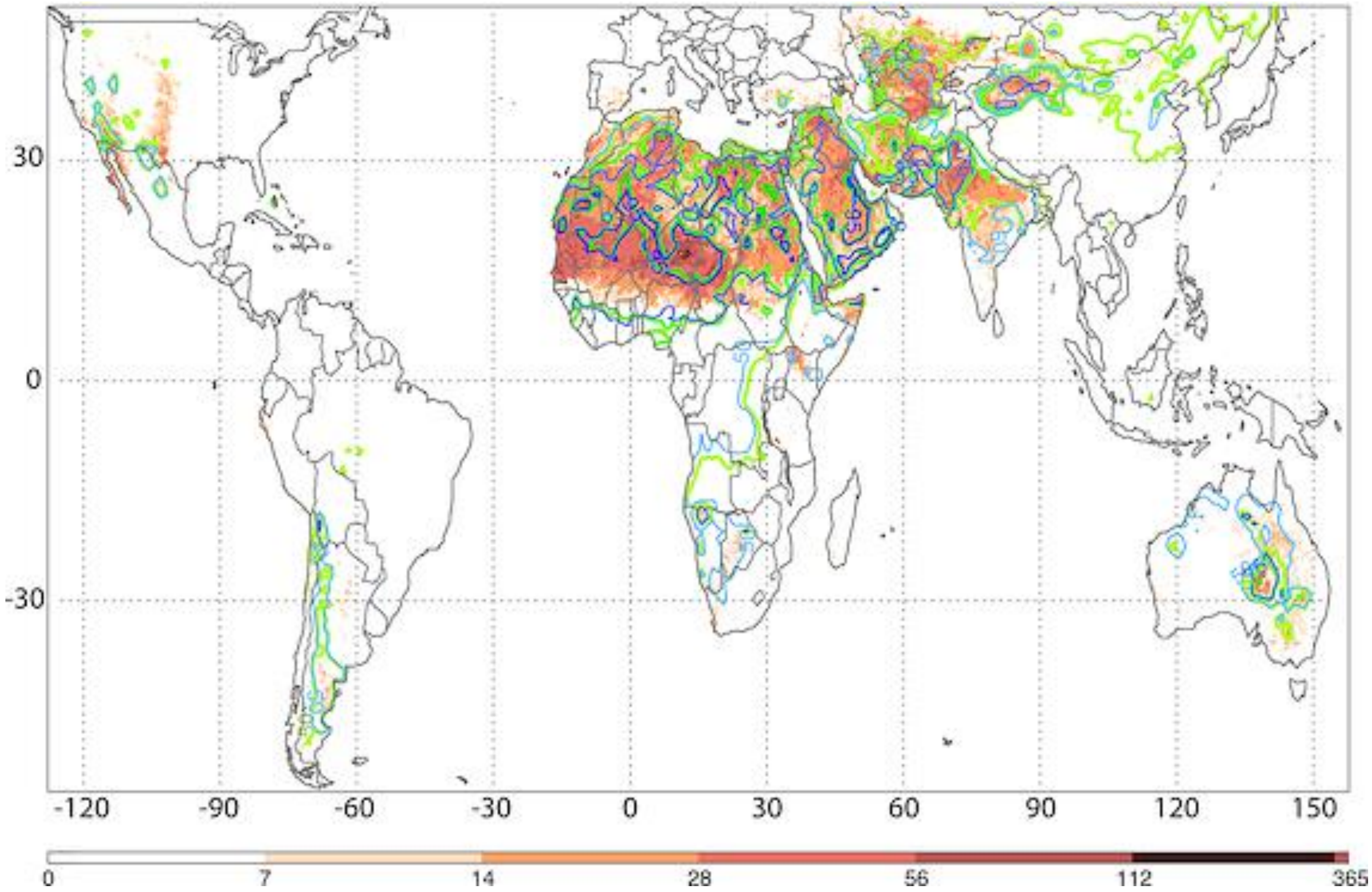


MODIS True color Western Africa – Altantic Ocean

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 cycle and associated processes

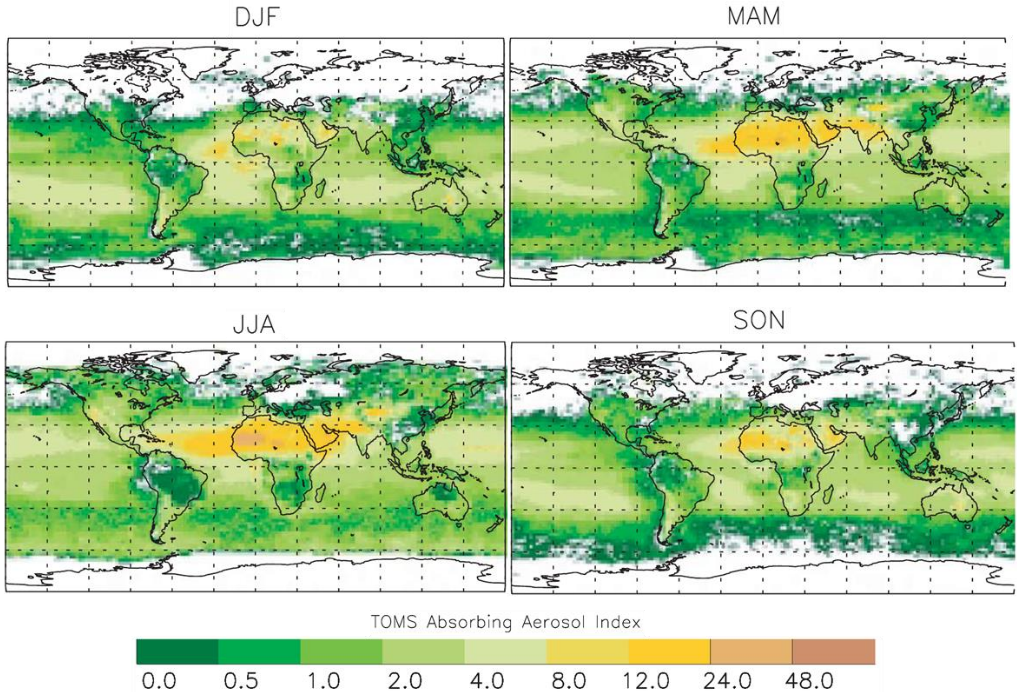
Dust global distribution



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



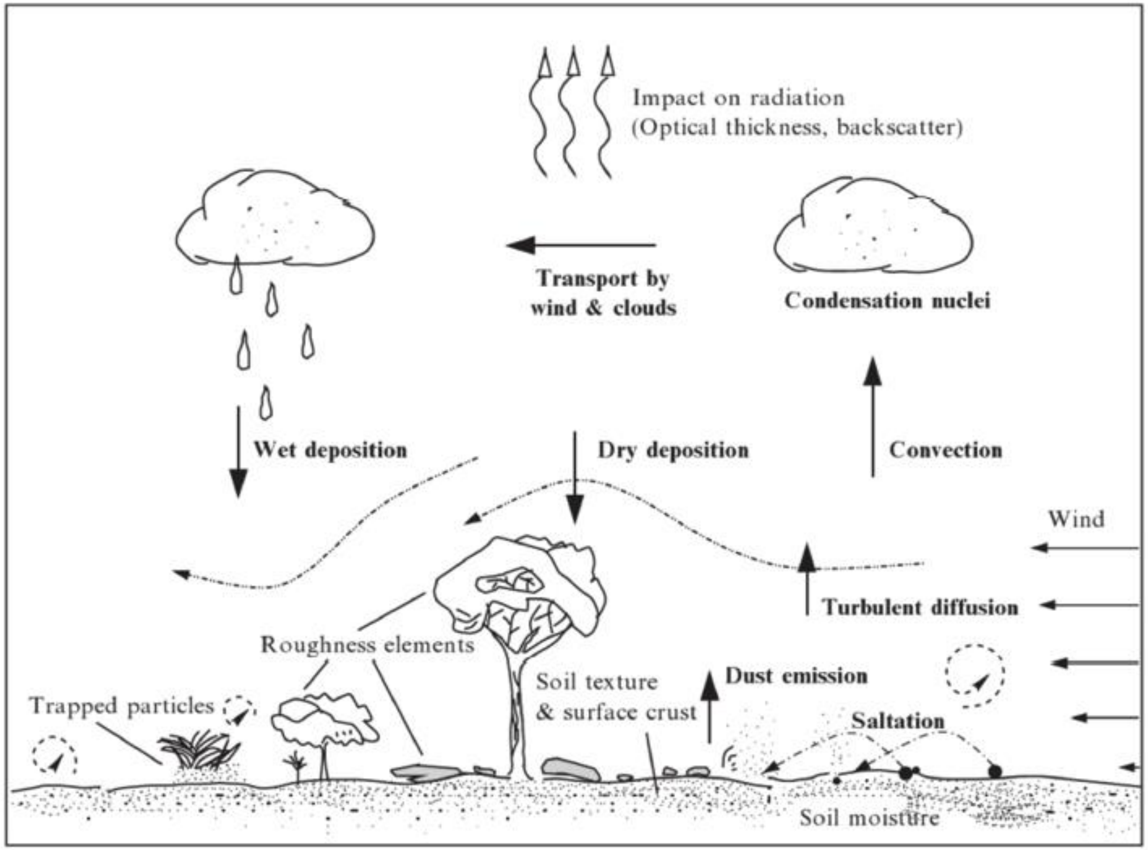
• Seasonal dust distribution changes well characterized. Follows seasonal changing weather regimes (mainly) and vegetation changes (in semi-arid areas)

• 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

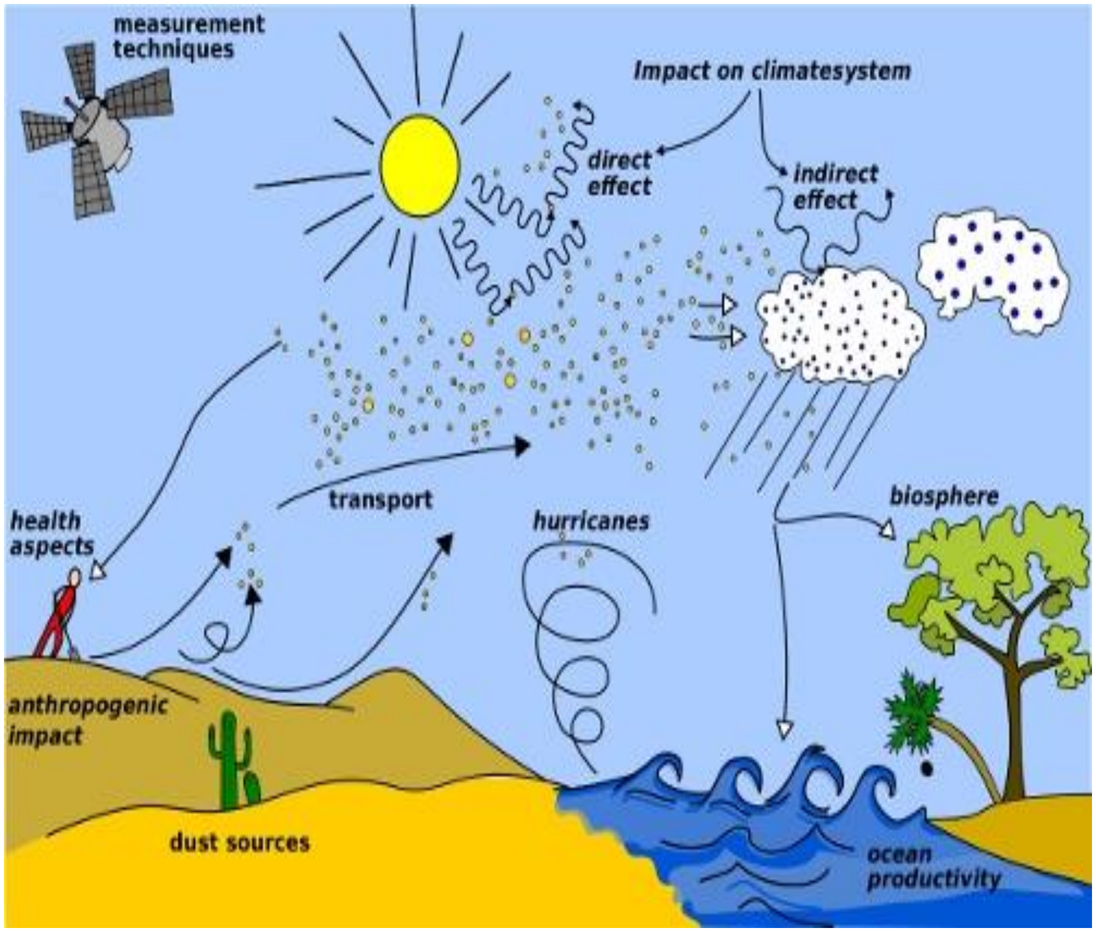


Image from WMO website (http://www.wmo.int/pages/prog/arep/wwrp/new/hurricanes.html)

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

Types of dust storms:

Synoptic dust storms (large scale weather systems)

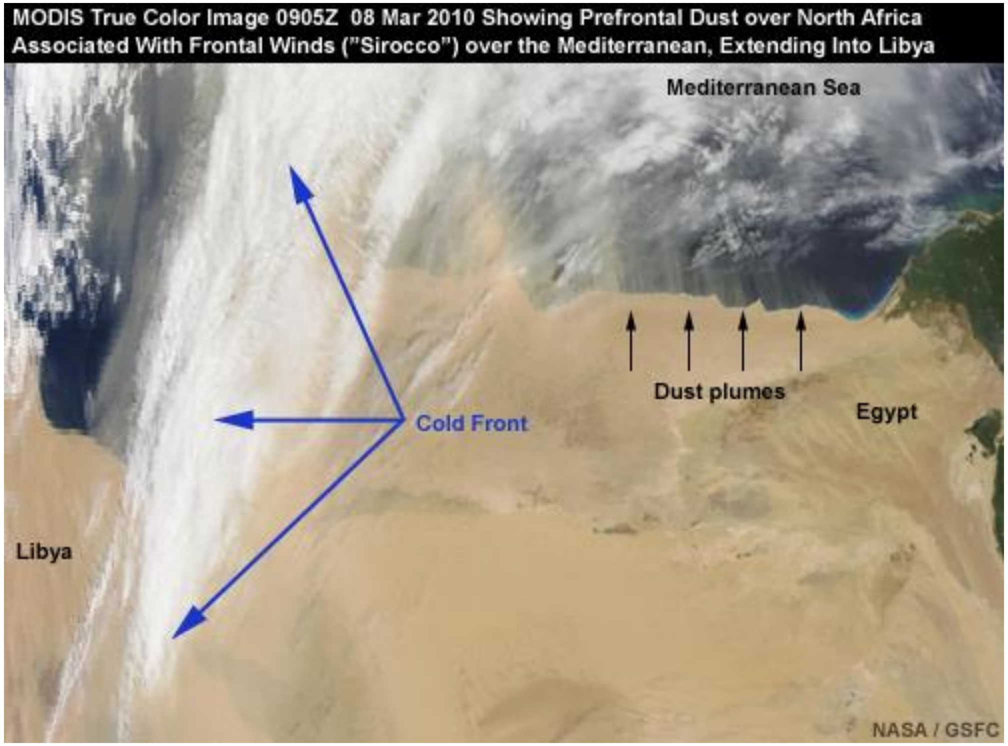
- Prefrontal winds
- Postprontal winds
- Large-scale Trade winds
- …

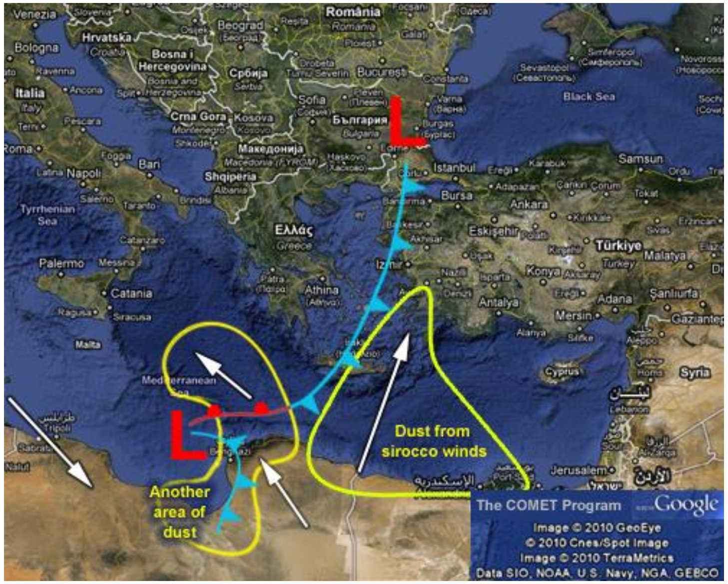
Mesoscale dust storms

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

Dust cycle and associated processes

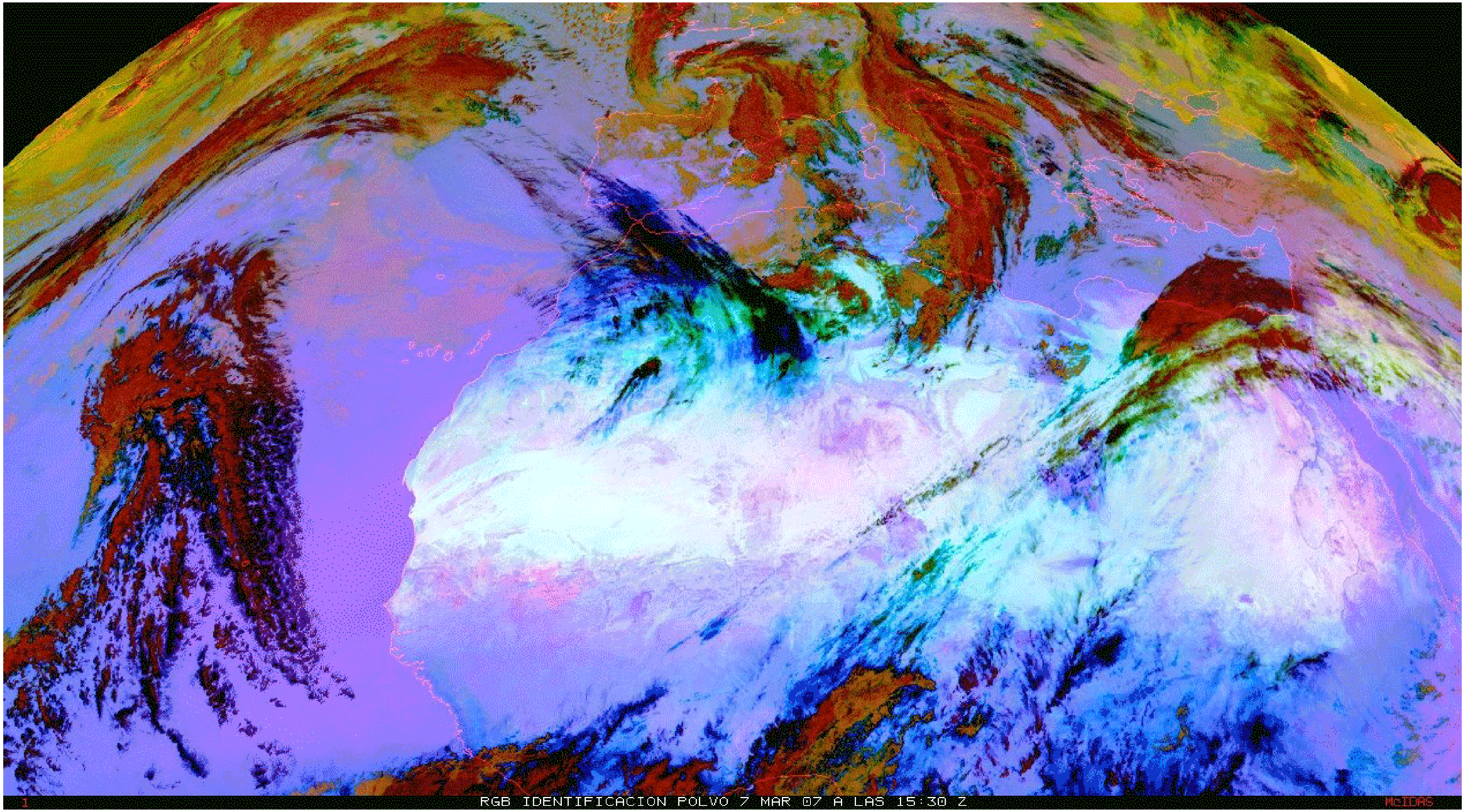
Synoptic dust storms: Pre-frontal





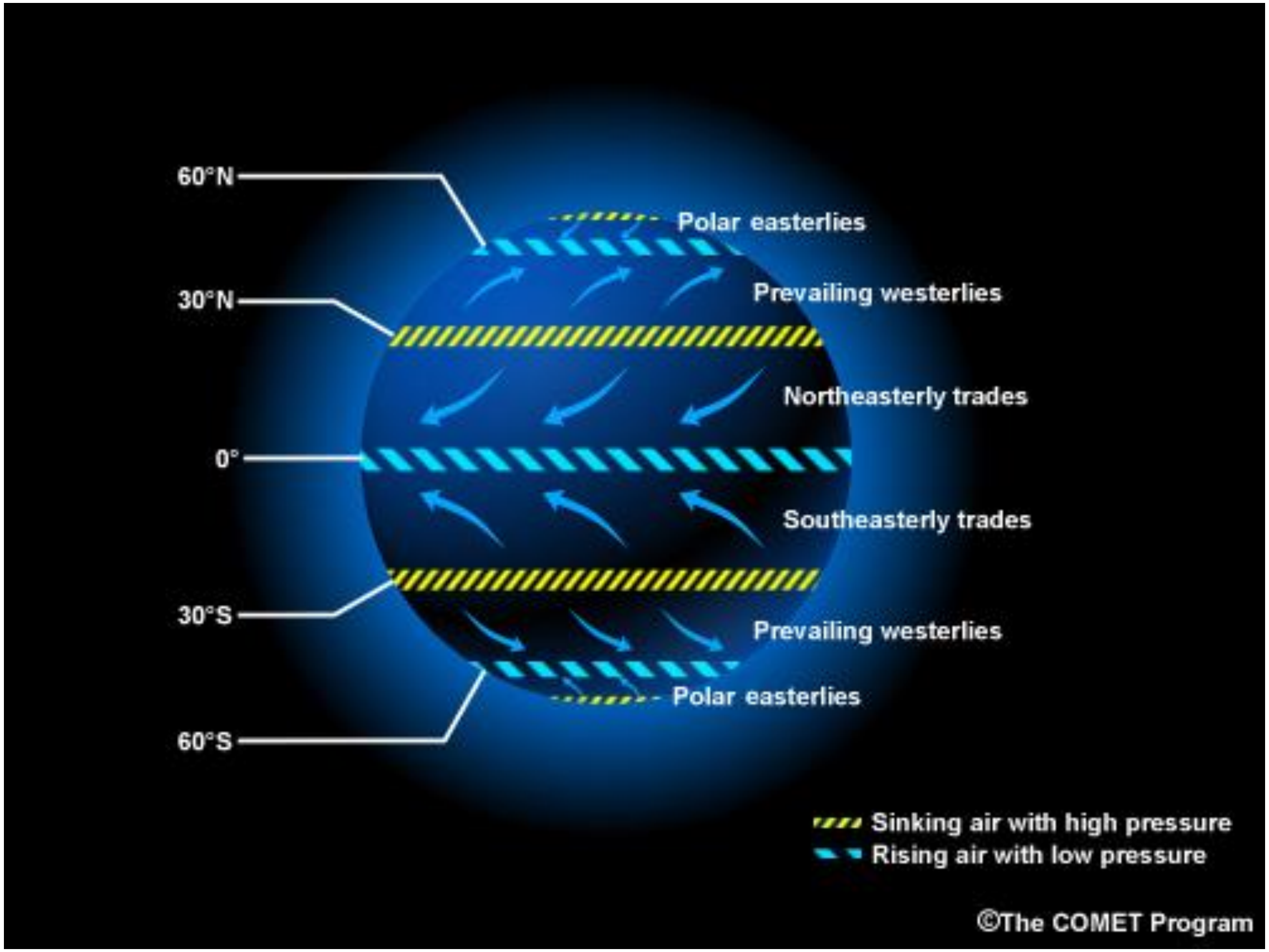
Dust cycle and associated processes

Synoptic dust storms: Post-frontal



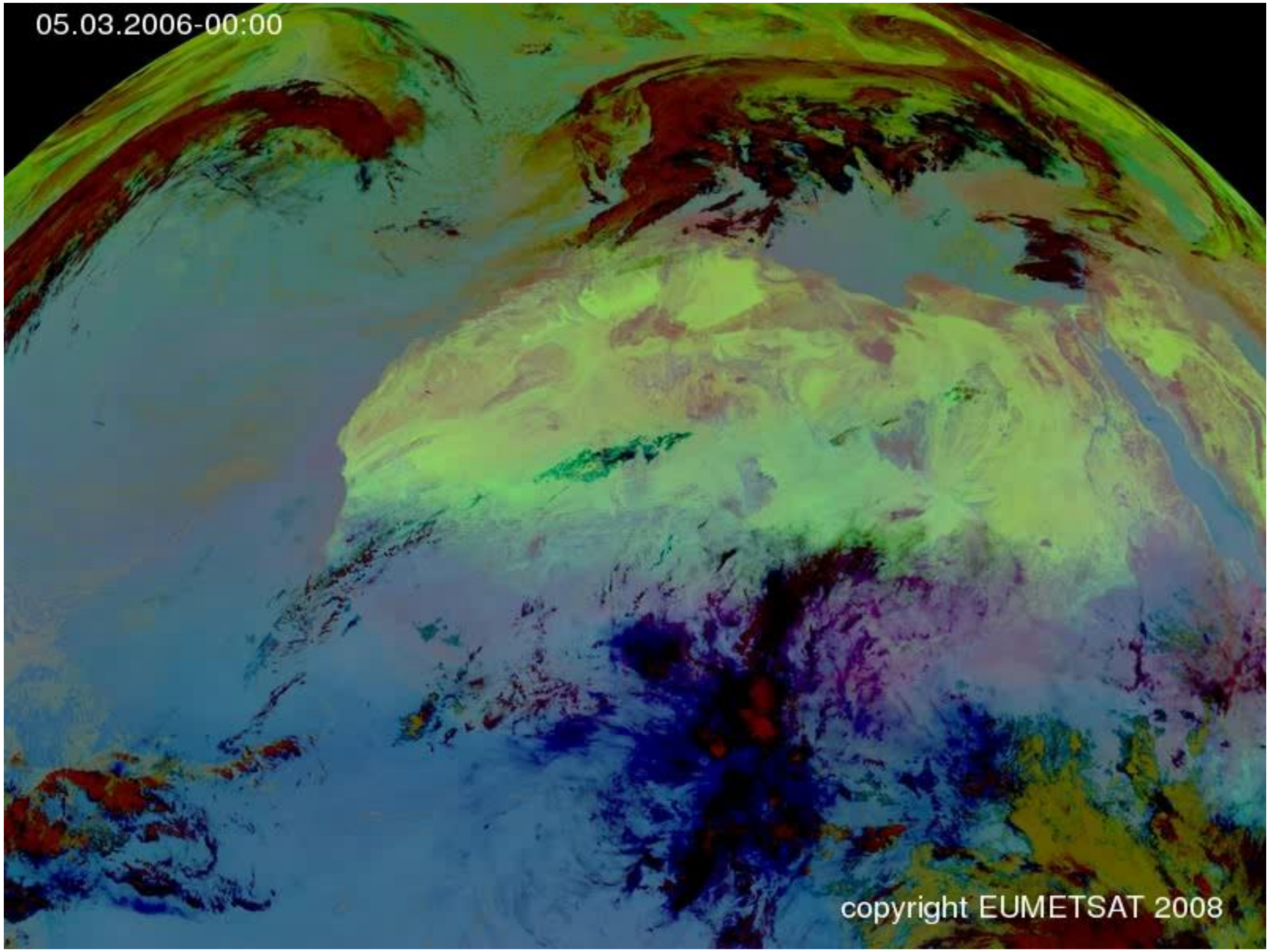
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



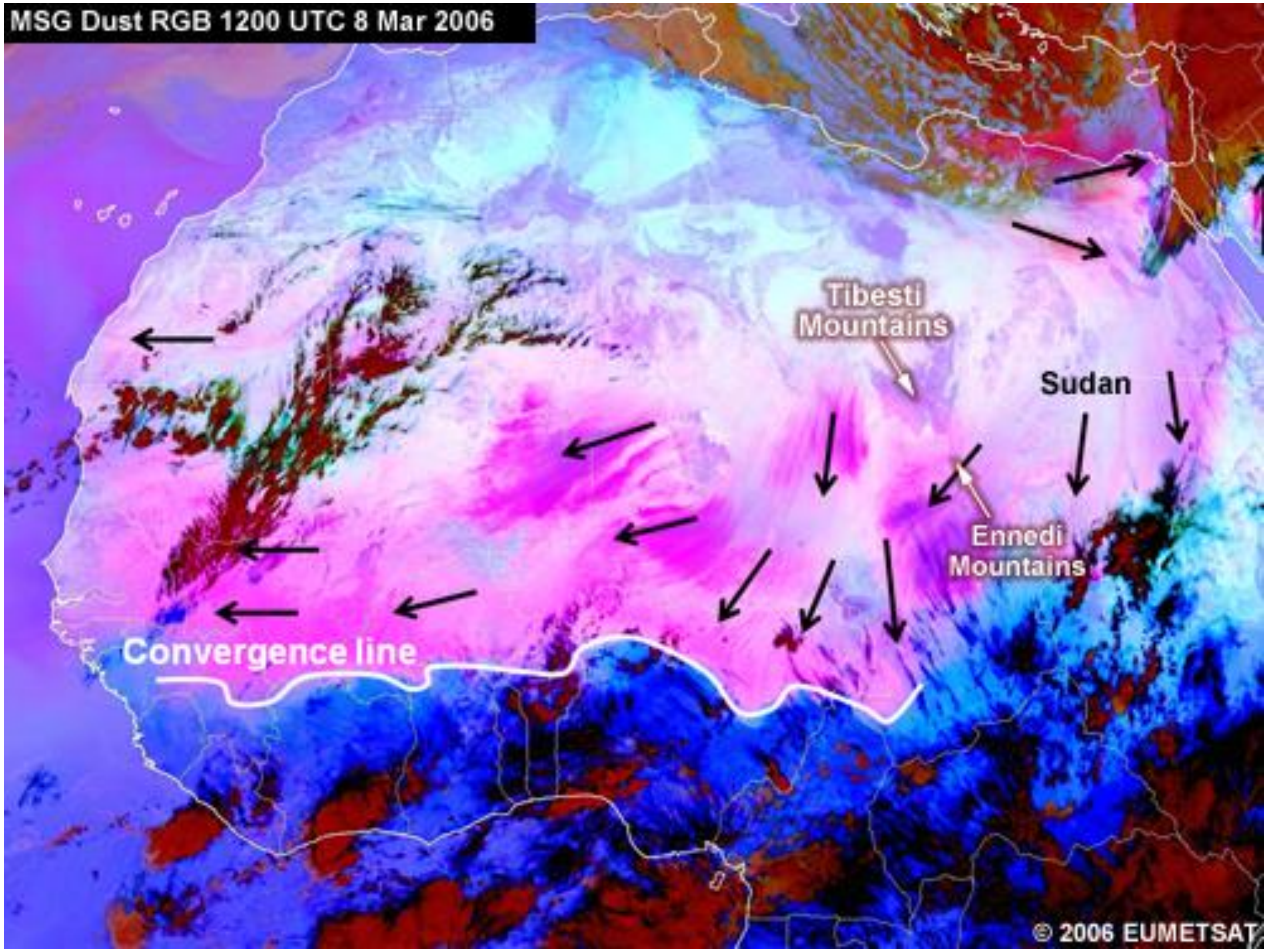
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



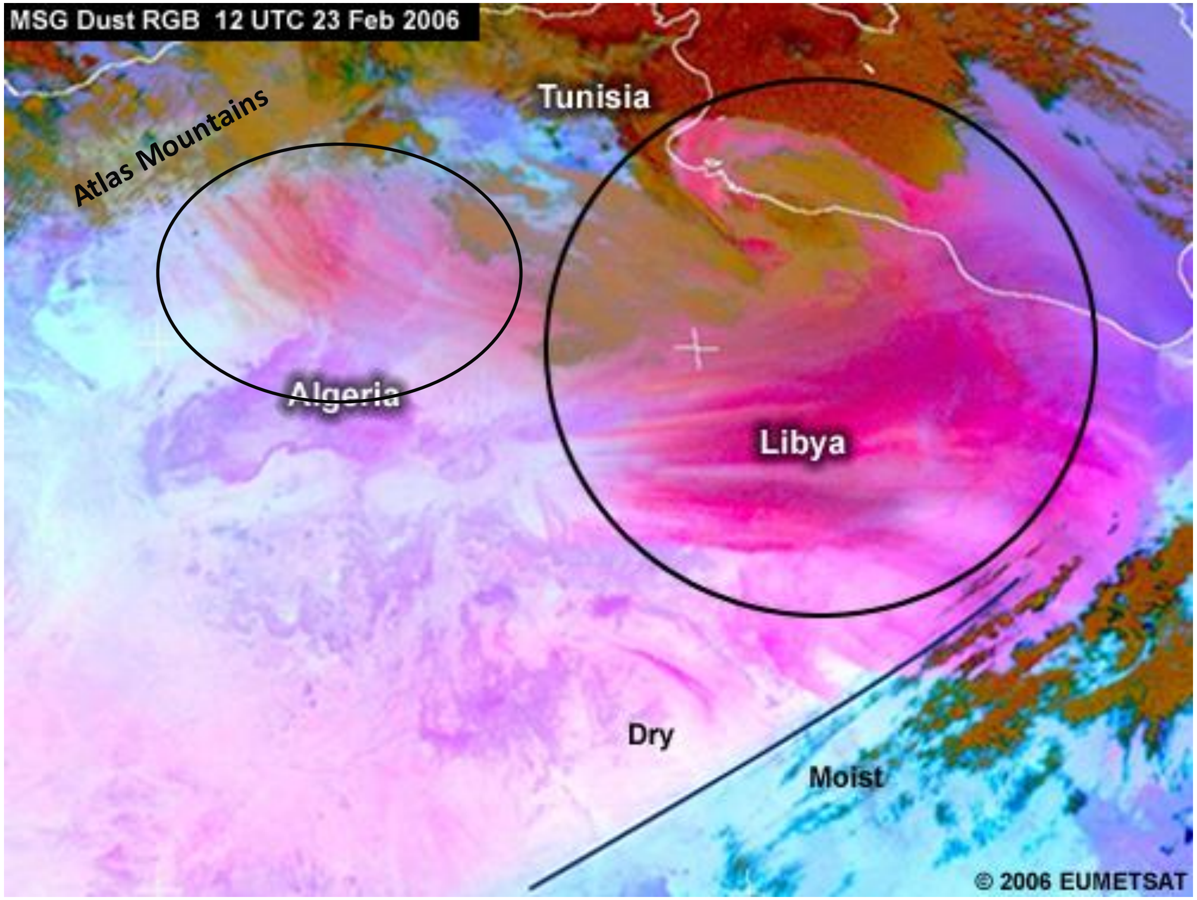
Dust cycle and associated processes

Synoptic dust storms: Large-scale trade winds



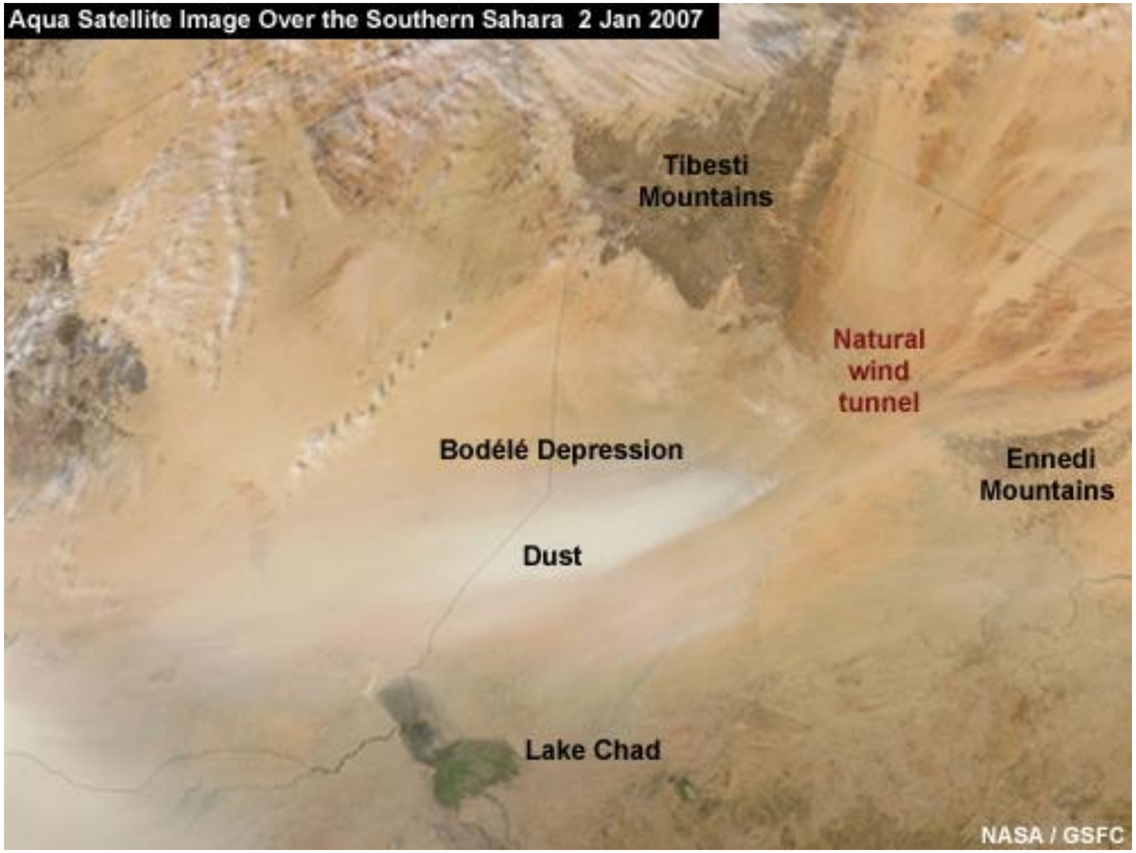
Dust cycle and associated processes

Mesoscale dust storms: Downslope winds



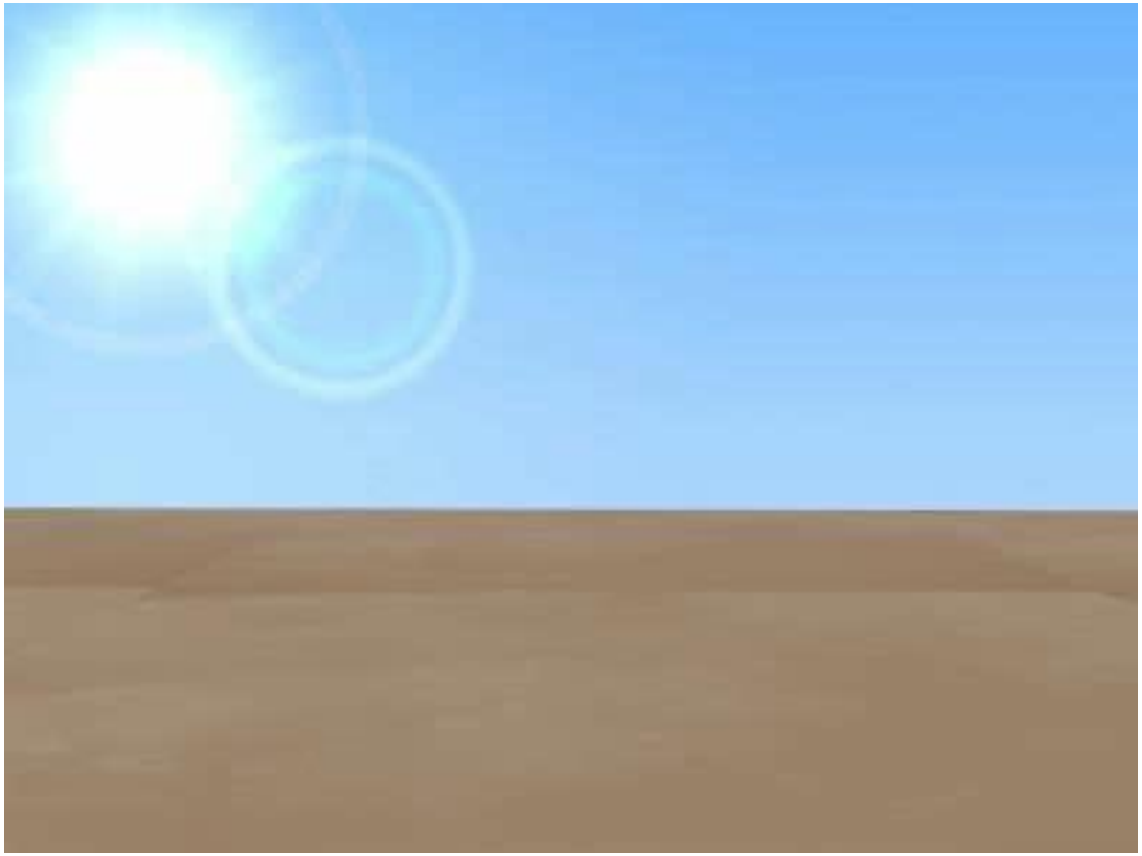
Dust cycle and associated processes

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

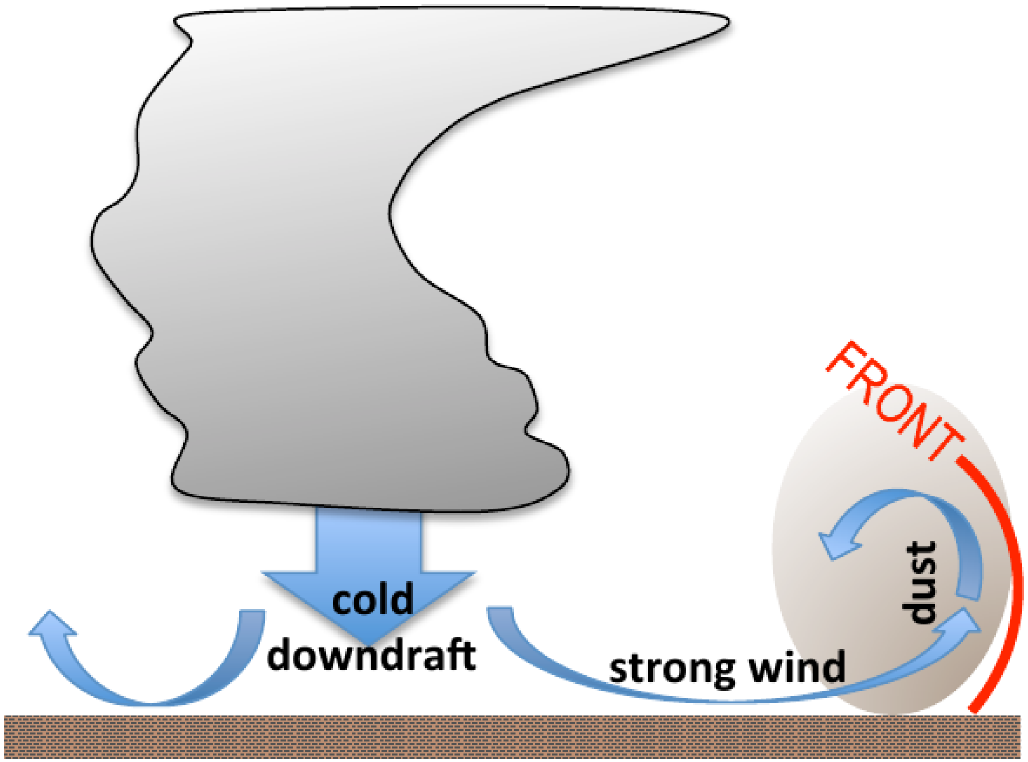
Mesoscale dust storms: Haboobs

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: Haboobs

Intensive cold downbursts from convective cells produced high velocity surface wind, creating cold front which was lifting, mixing and pushing dust

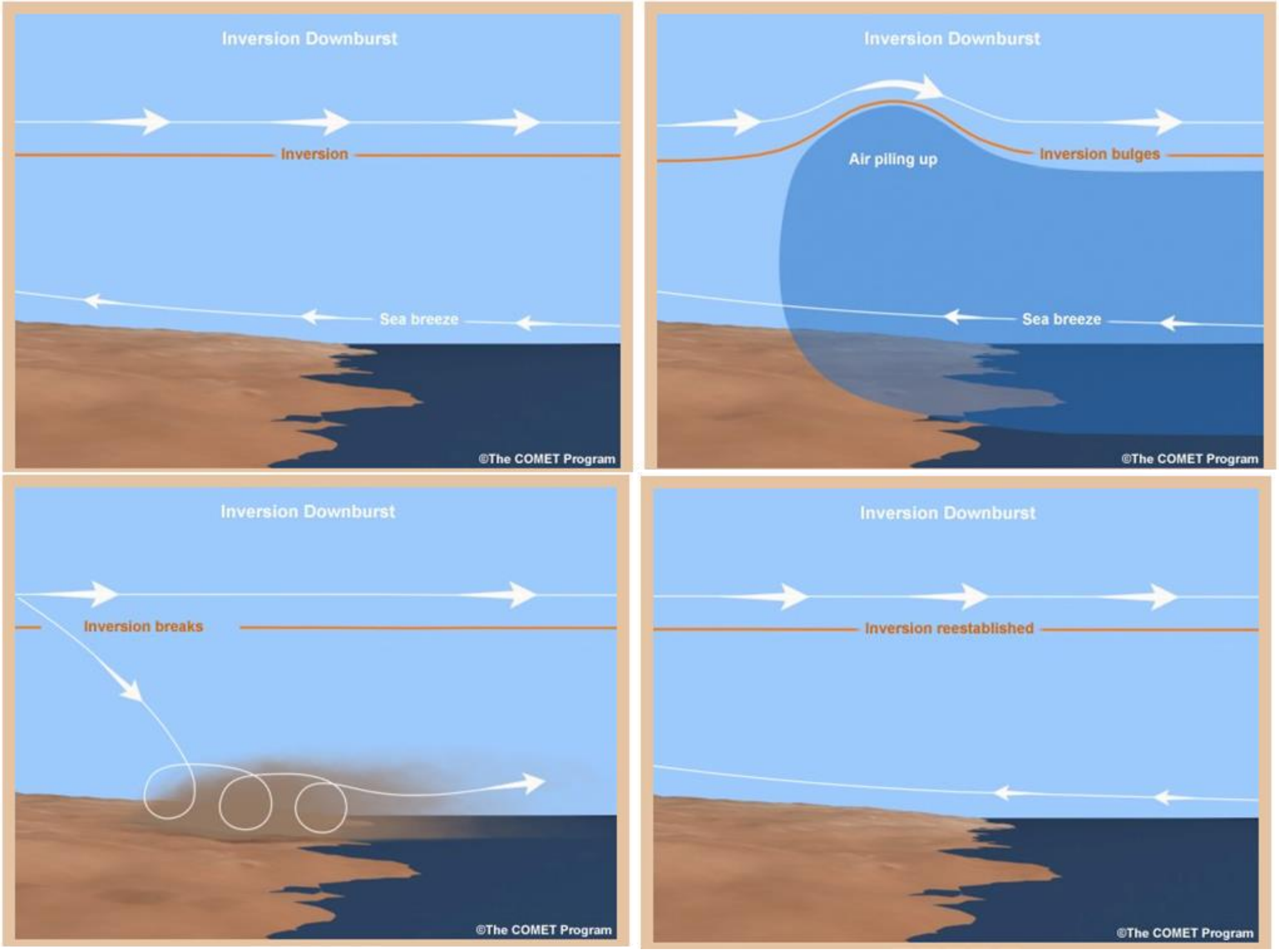


Expected: high wind speed, drop in temperature, rise in humidity, rise in pressure, reduction of visibility.

(Vukovic et al., in preparation)

Dust cycle and associated processes

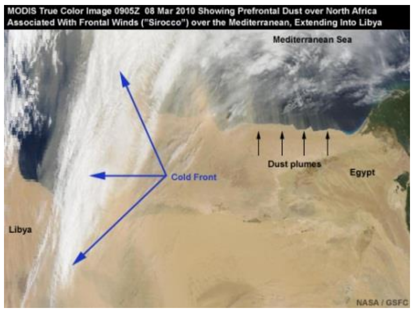
Mesoscale dust storms: Inversion downbursts



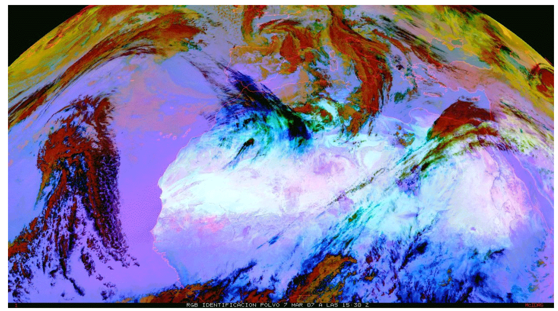
Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dust cycle and associated processes

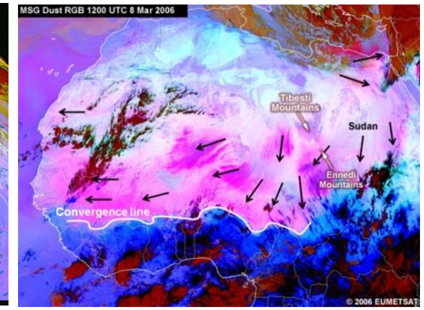
Synoptic dust storms (large scale weather systems) **Well captured by models.**



Pre-frontal winds

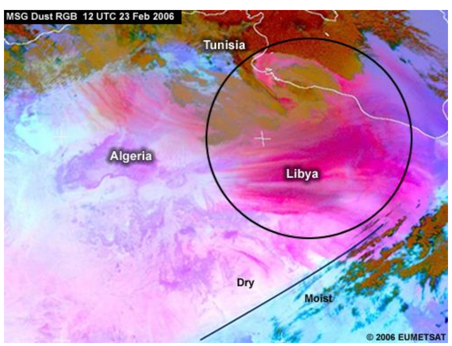


Post-frontal winds

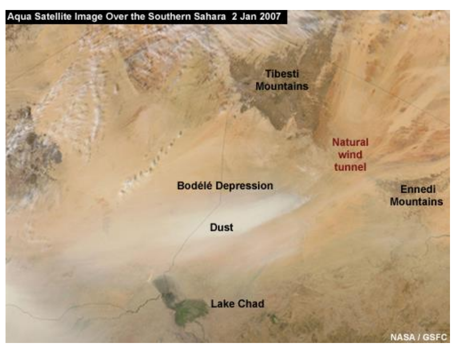


Large-scale trade winds

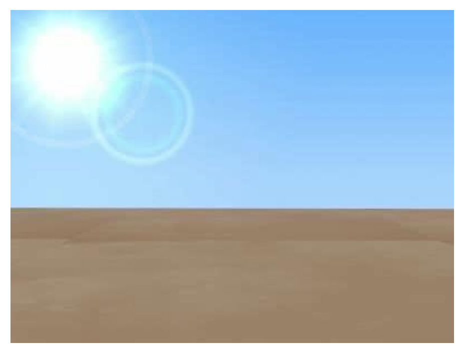
Mesoscale dust storms **Poorly captured by models.**
Some types improve in regional models.



Downslope winds



Gap flow

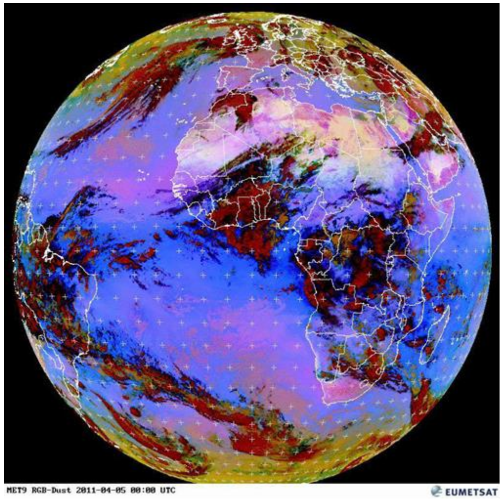


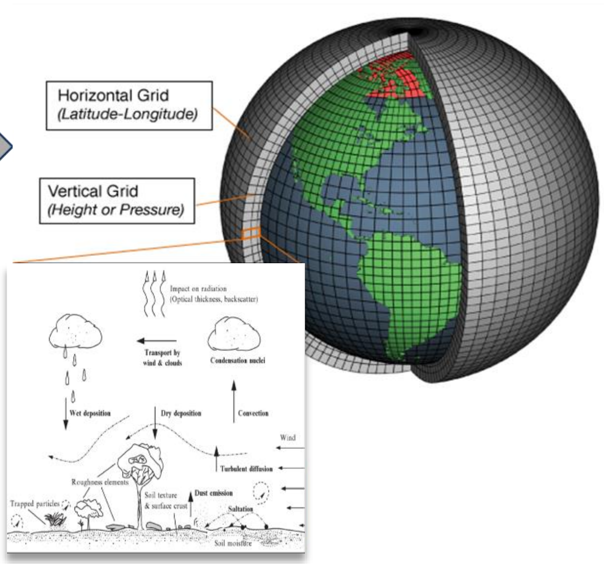
Dust devils

Haboobs

Dust forecasting models

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 forecasting models

Dust forecasting models do **not** take account dust **resuspension**

Kathmandu, Nepal, March 2017

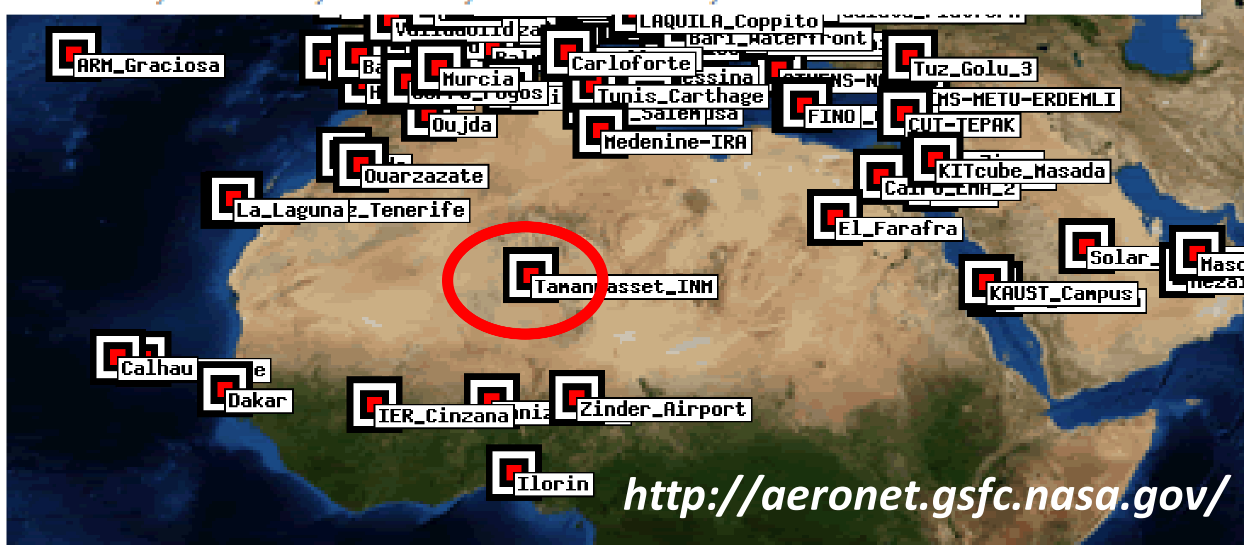
Dust forecasting models

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

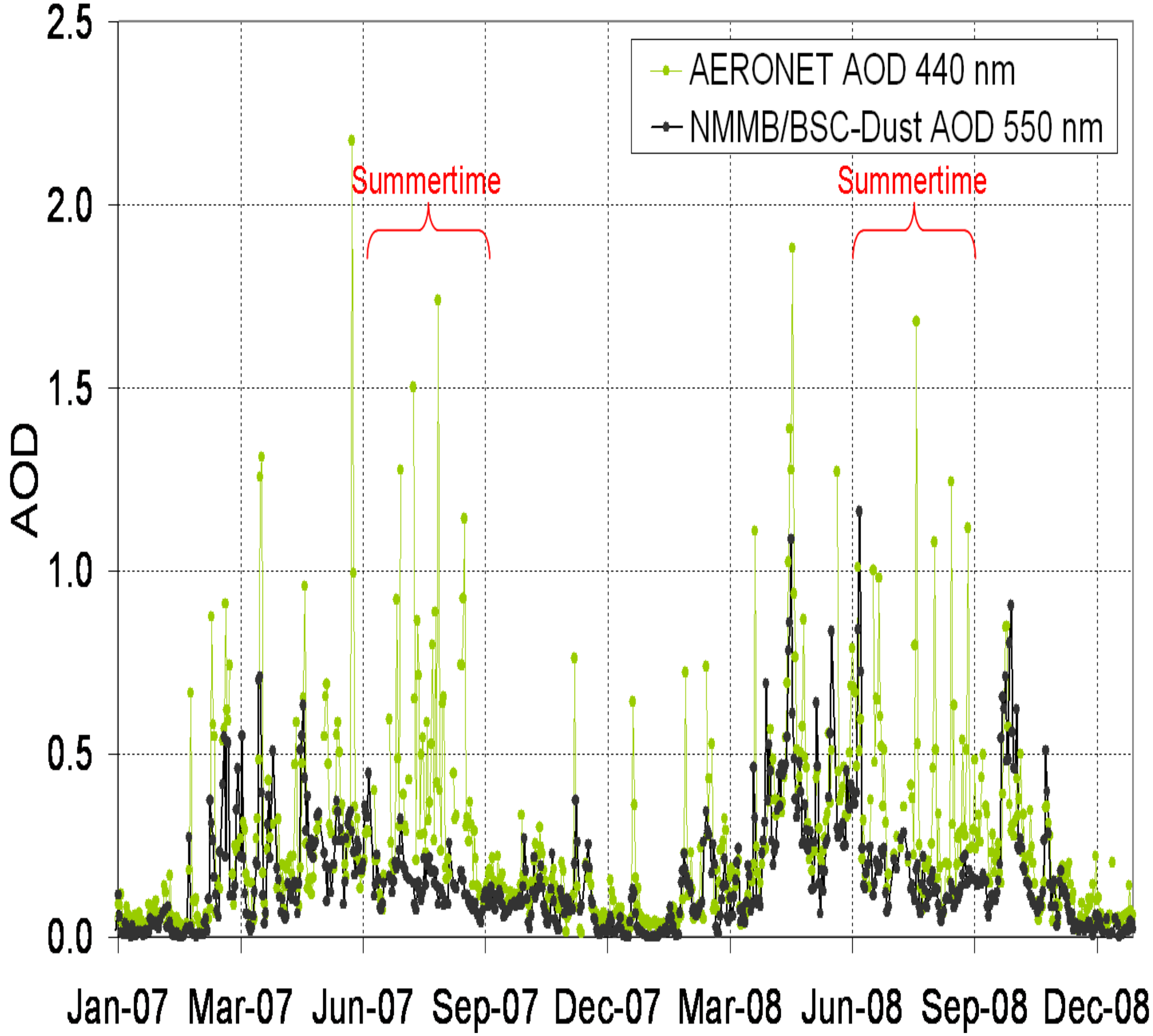
Atmospheric Chemistry and Physics
Open Access

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]

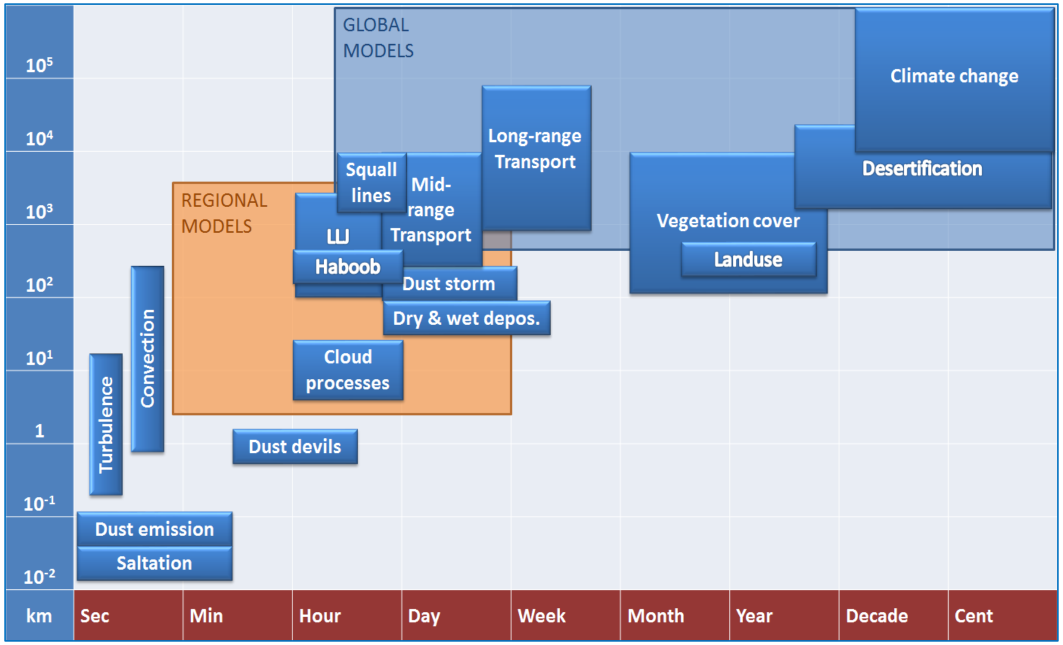


Dust forecasting models



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)

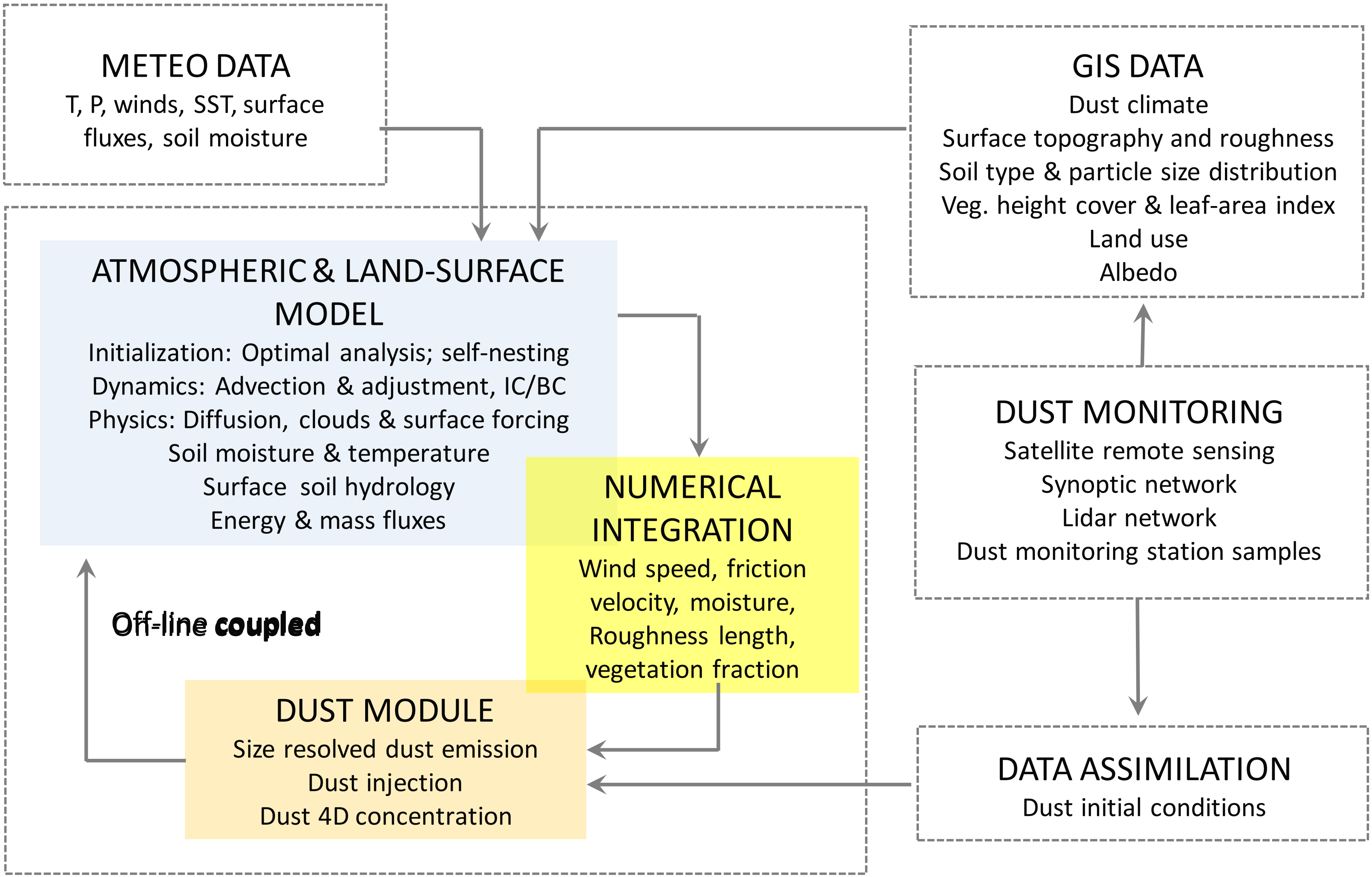
Dust forecasting models

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

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

$-u\frac{\partial C_k}{\partial x} - v\frac{\partial C_k}{\partial y}$	*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



Desert dust soil types

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;

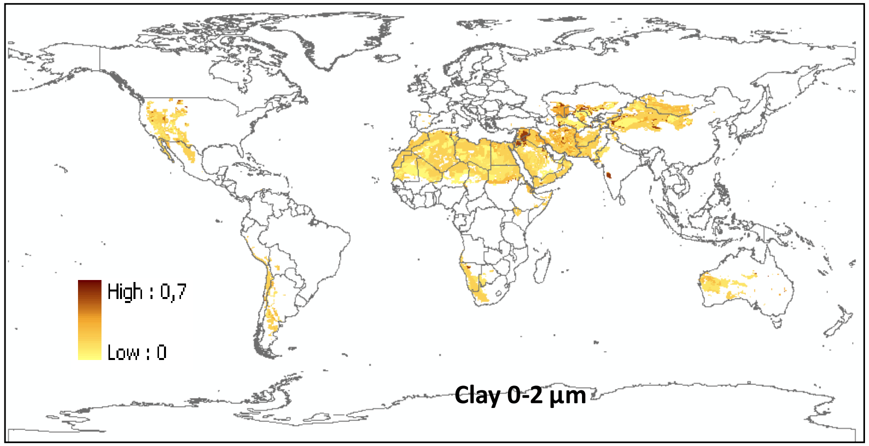
C) The Great Hamada south-west of El-Abiodh-Sidi-Cheikh;

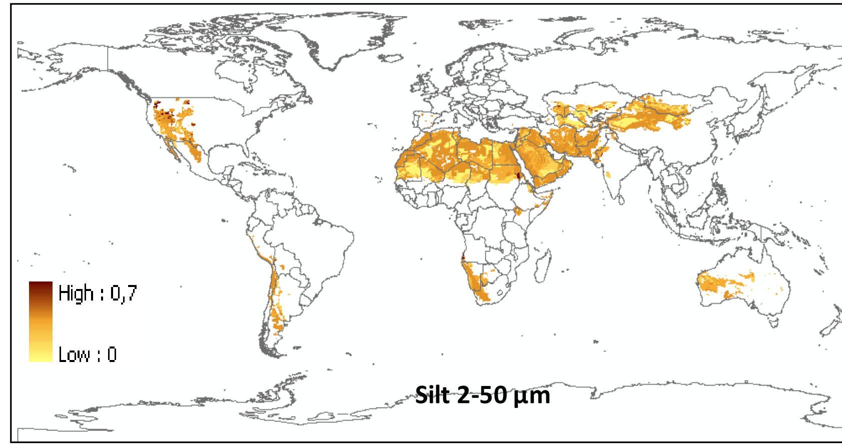
D) Daïa in the Mechfar, at Hassi Cheikh well;

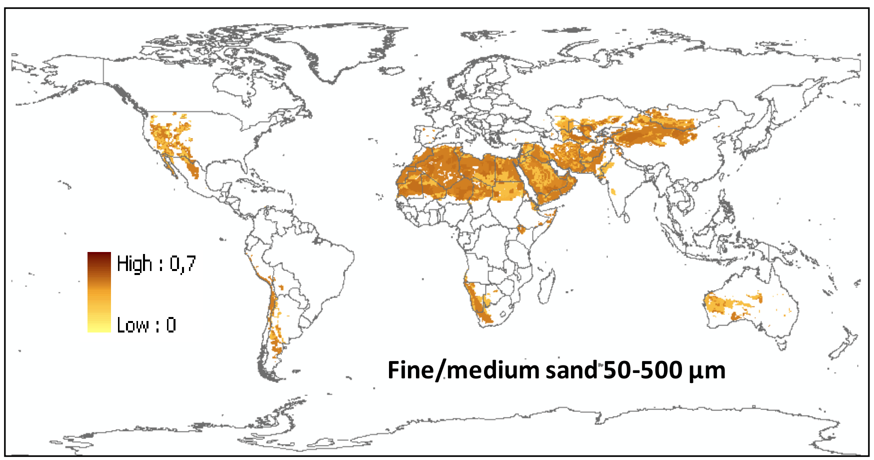
E) North-east of the Great Western Erg: coarse sand interdune corridor with deflation cauldron and palaeolake deposits;

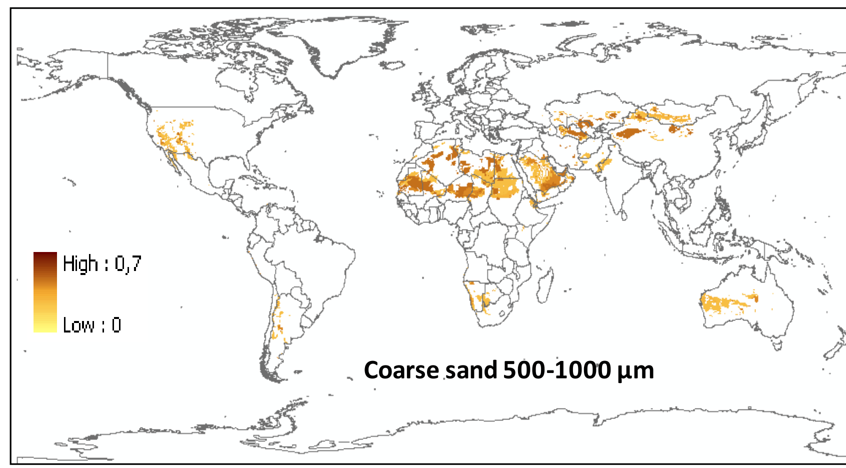
F) North-east of the Great Western Erg: great coarse sand dome dunes, covered by fine sand active dunes.

Soil size distribution derived from soil texture





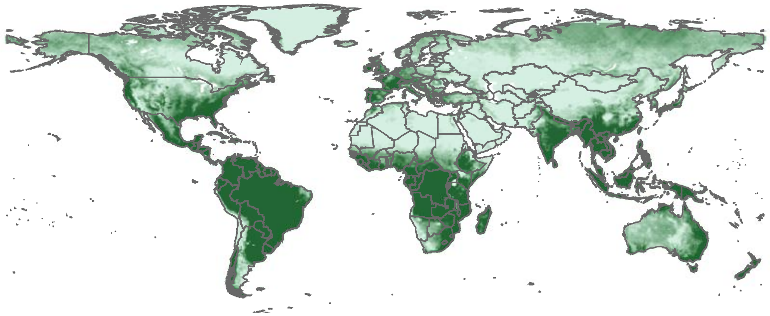




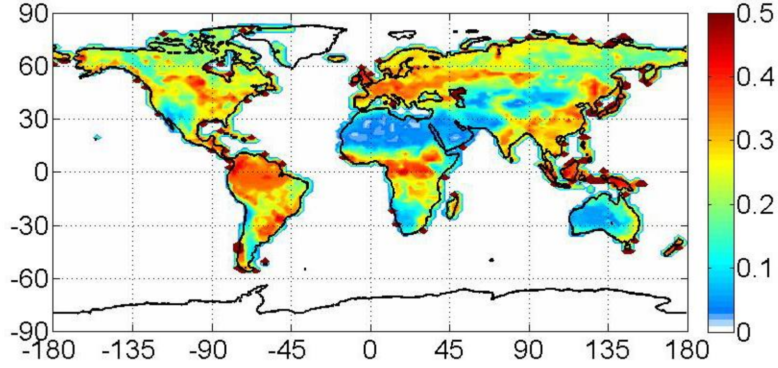
Four top soil texture classes according STASGO-FAO 1km database are converted to 4 parent soil size categories following Tegen et al. [2002].

Vegetation, roughness, soil moisture

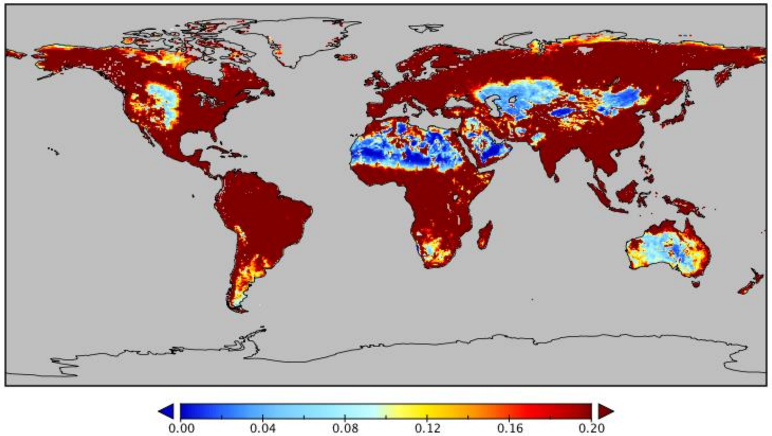
Vegetation fraction
(MODIS)



Soil moisture
(model based)



Roughness length
(ASCAT + PARASOL)



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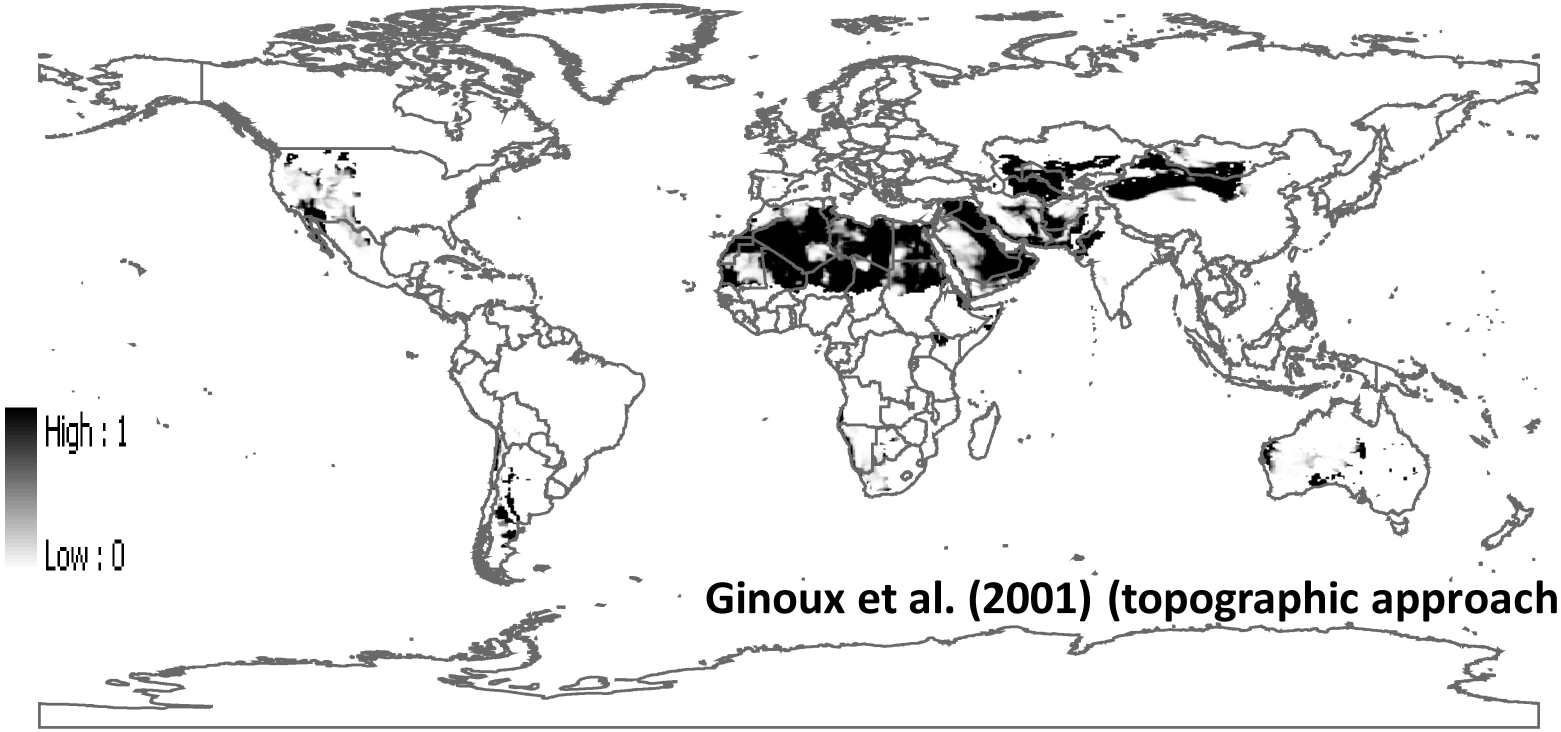
Source mapping: why?



Ginoux et al. (2001) (topographic approach)

$$S = \left(\frac{z_{max} - z_i}{z_{max} - z_{min}} \right)^5$$

S: probability to have accumulated sediments in the grid cell i of altitude zi

best fit with the sources identified by Prospero et al. 2000

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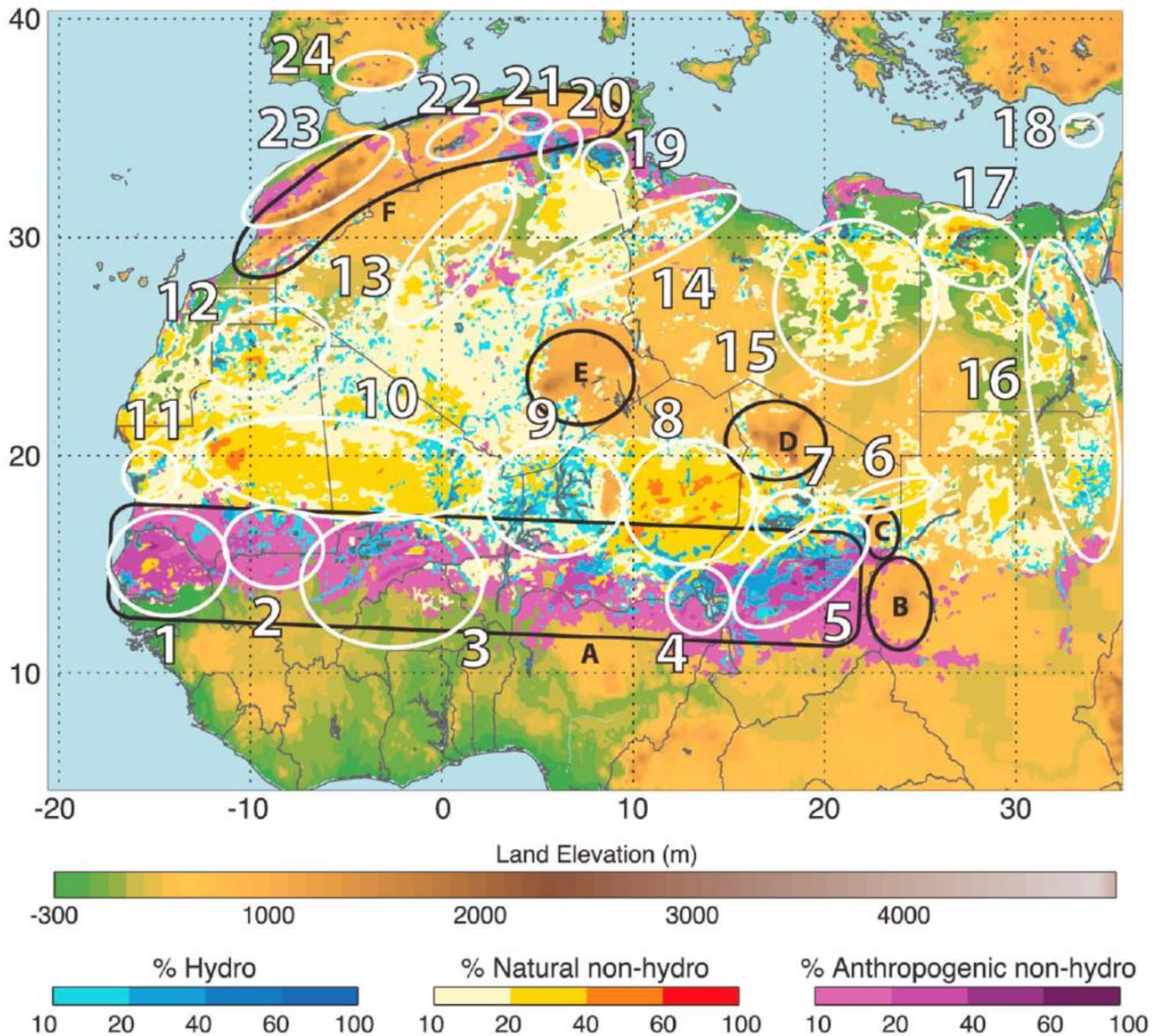
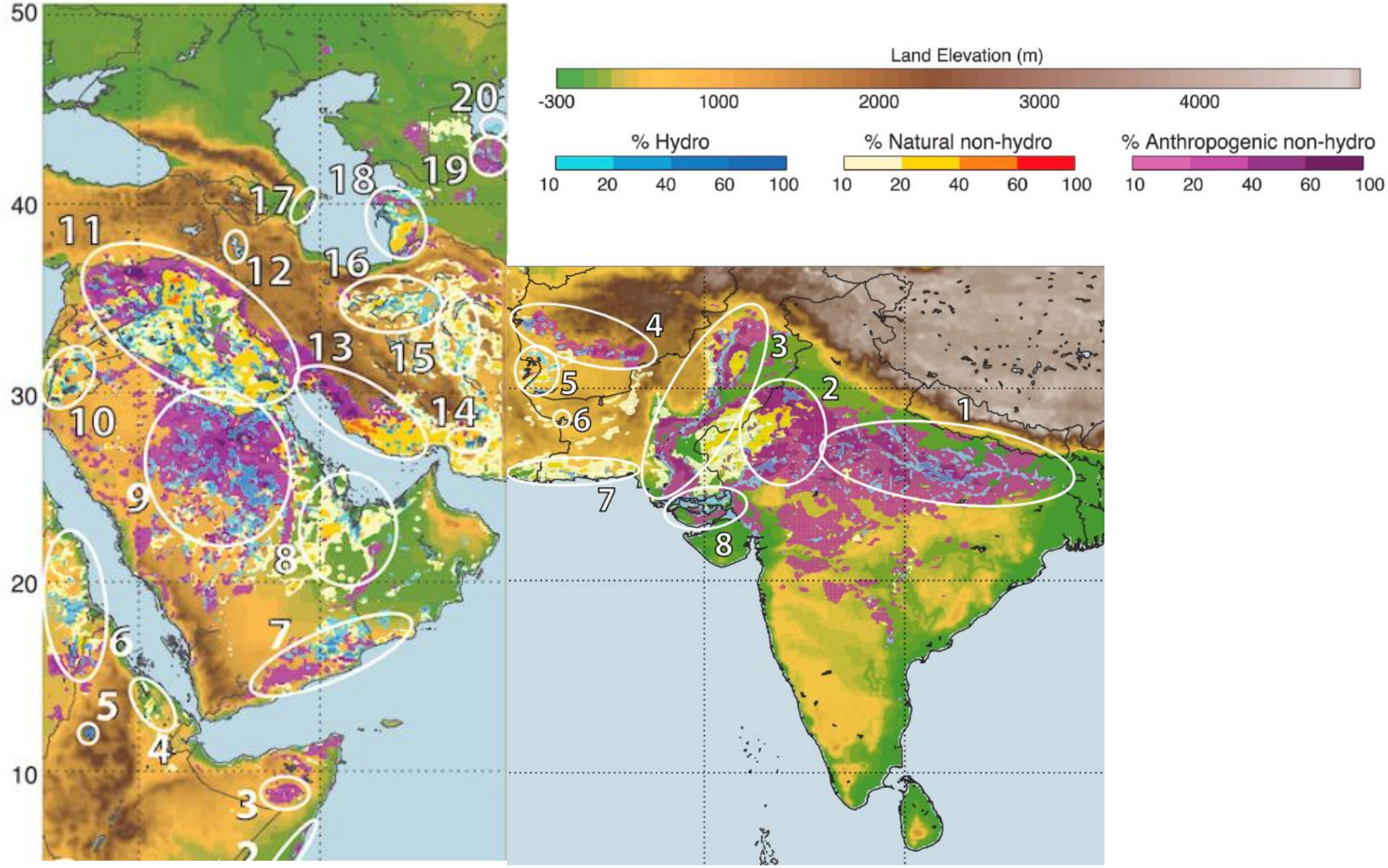
Natural and anthropogenic dust sources



(Ginoux et al. 2012)

Natural and anthropogenic dust sources



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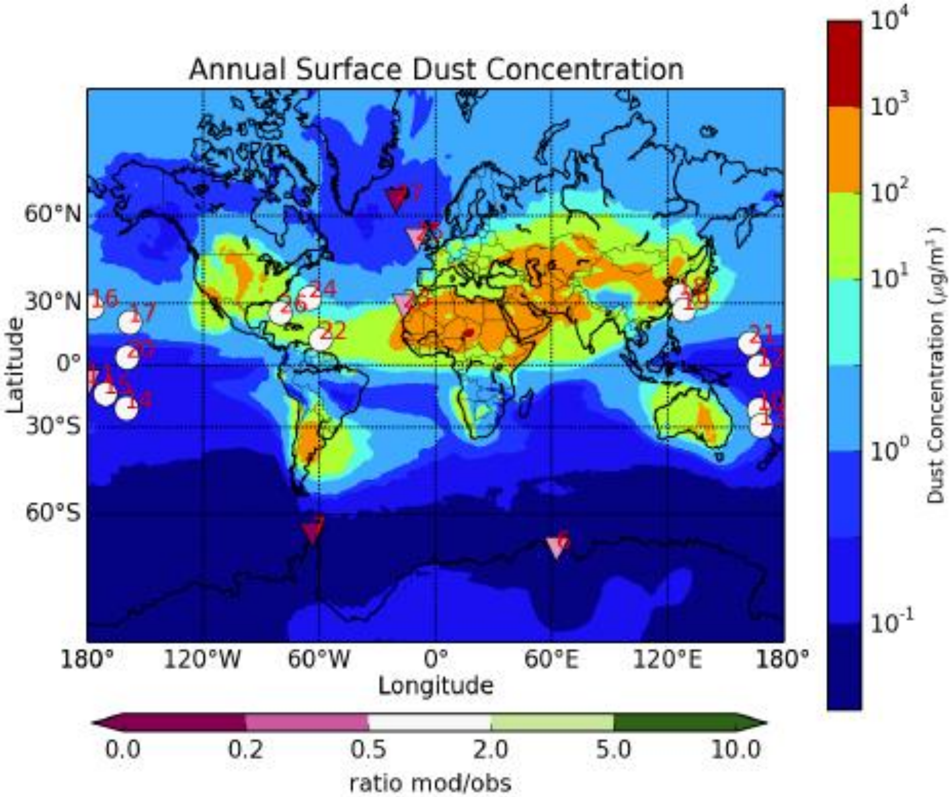
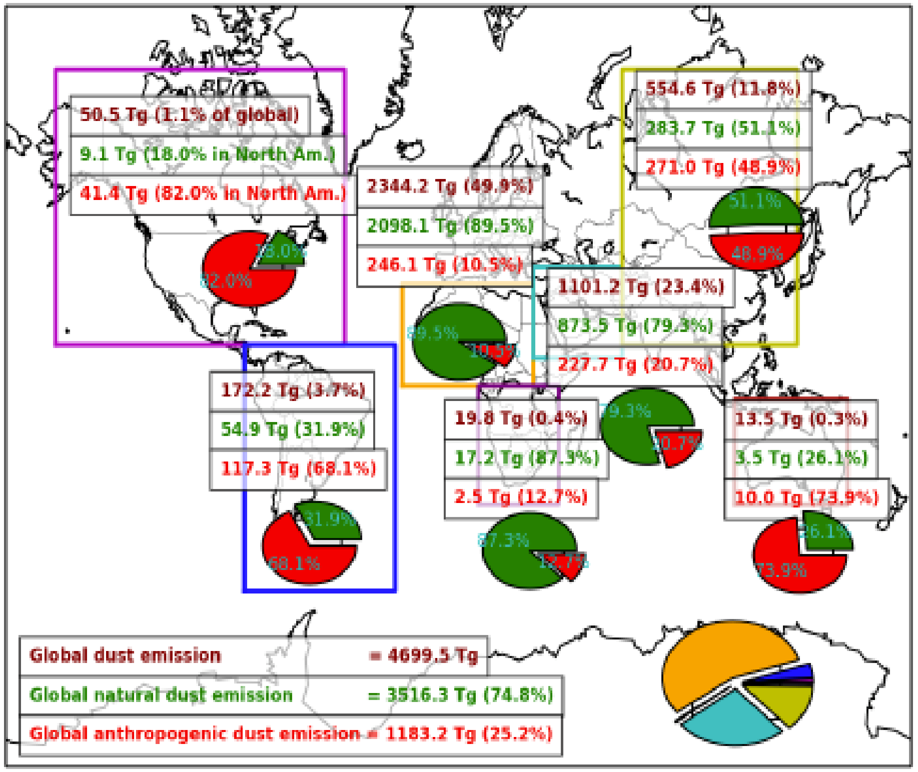
(Ginoux et al. 2012)

Current quantification natural vs. anthropogenic





Perez García-Pando et al., in prep

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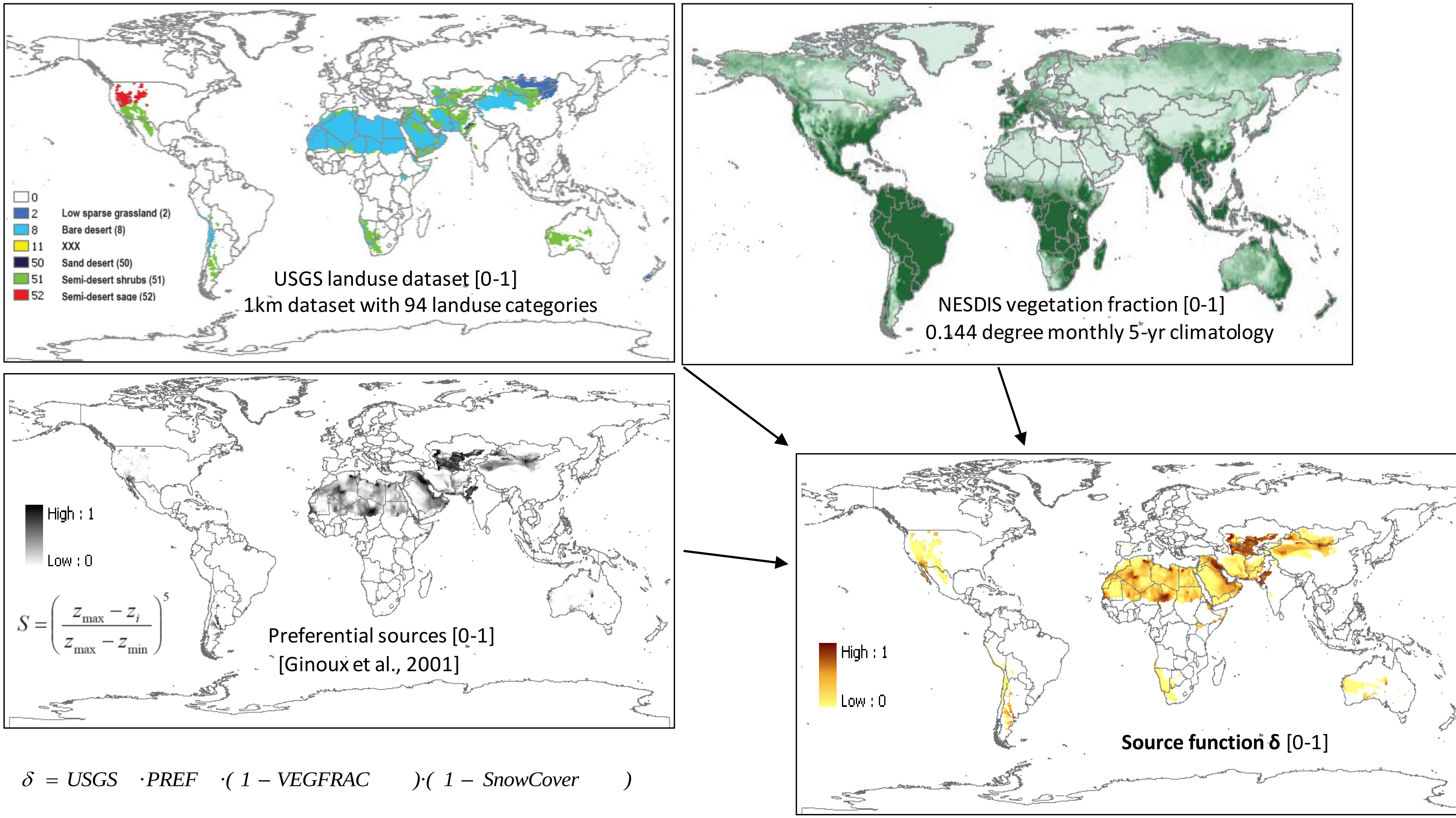
Major challenge for modeling

Dust sources functions

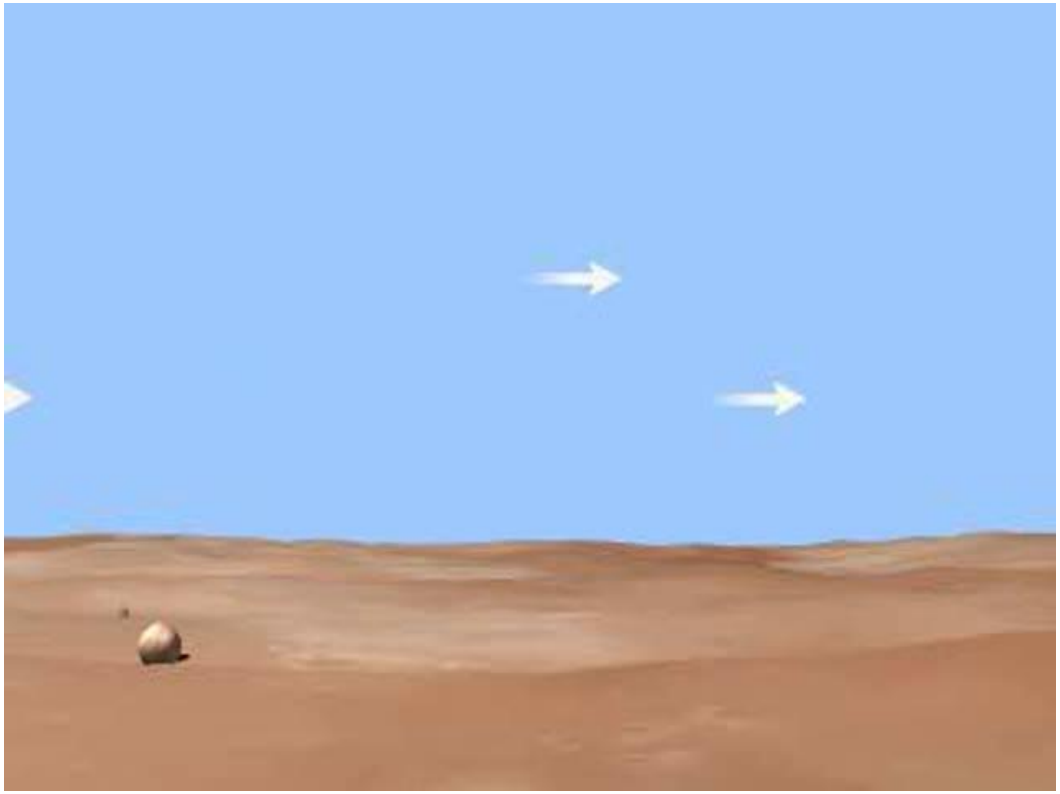
Dust source function: the NMMb/BSC-Dust model



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

Dust emission mechanisms

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



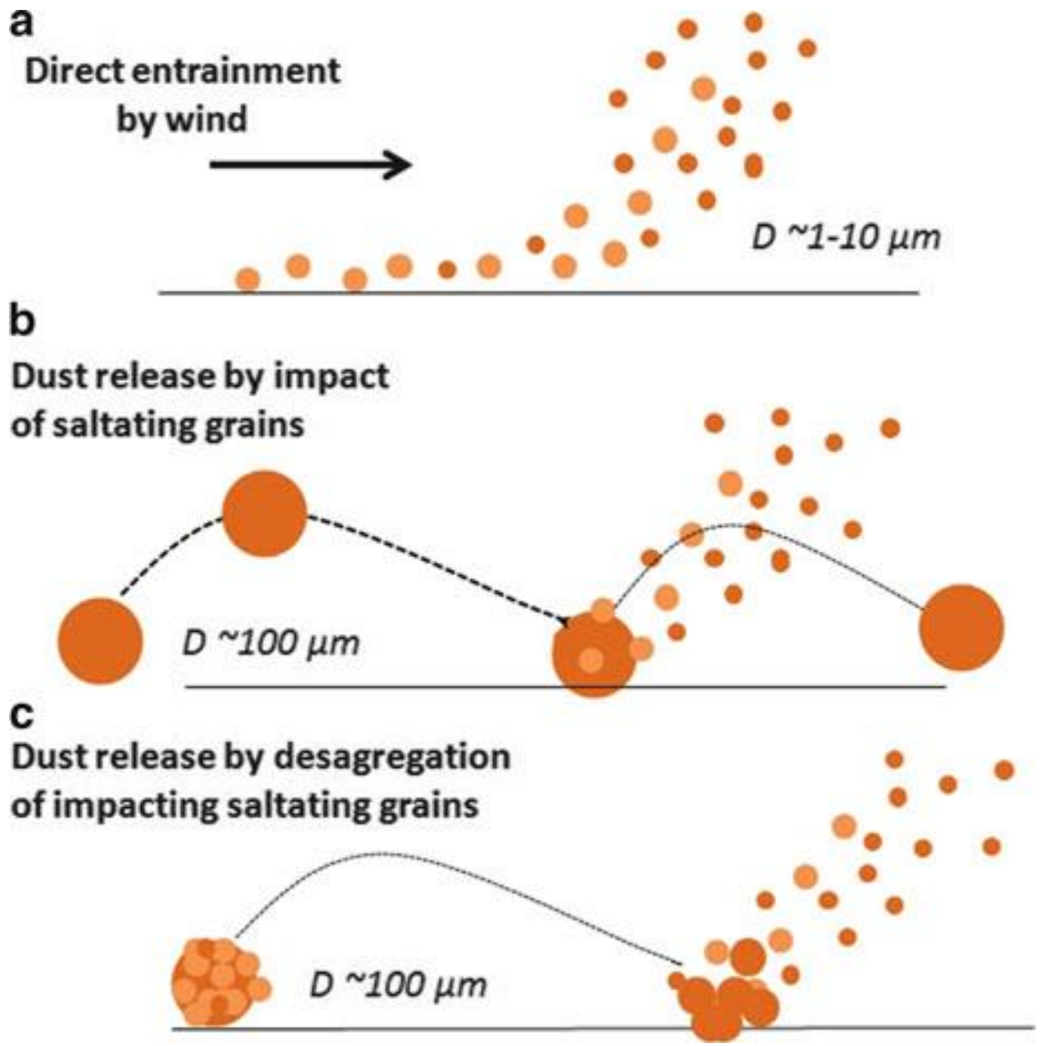
- Creep or rolling motion of the largest particles (> 500 um)

- 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 emission mechanisms



Emitted dust mass

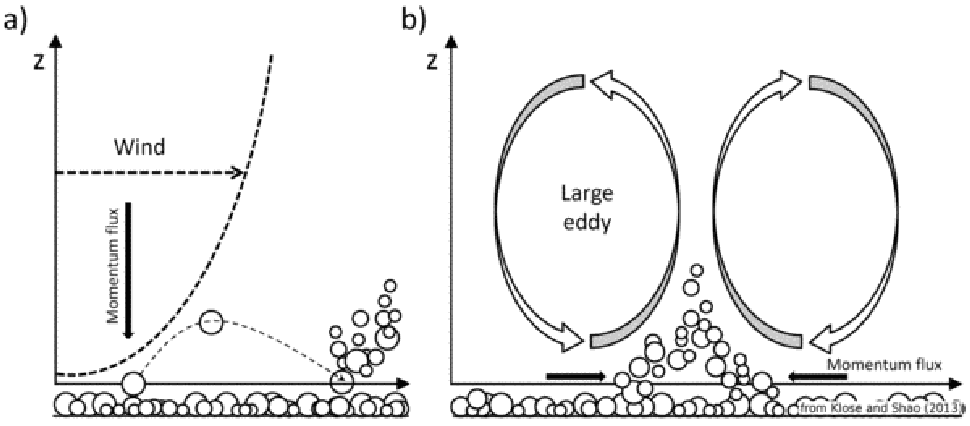
&

Size distribution

Dust emission schemes

Dust storm generation requires:

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

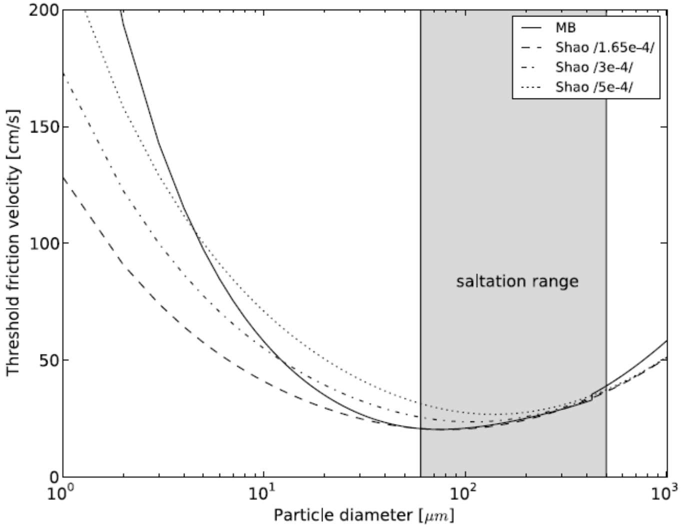


(a) Conventional view of dust emission via saltation bombardment; (b) Illustration of convective turbulent dust emission.
Extracted from Shao (2008)

Friction velocity is 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 vs particle radius →



Darmenova et al., 2009

Dust emission schemes

Simple schemes

Formulation of vertical dust flux (F)

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

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= $cu_{10}{}^2(u_{10} - u_{10t})$
Liu and Westphal (2001) COAMPS	F= $fu_{10}{}^2(u_{10} - u_{10t})$
Liu and Westphal (2001) COAMPS	F= $fcu_*{}^4$

Dust emission schemes

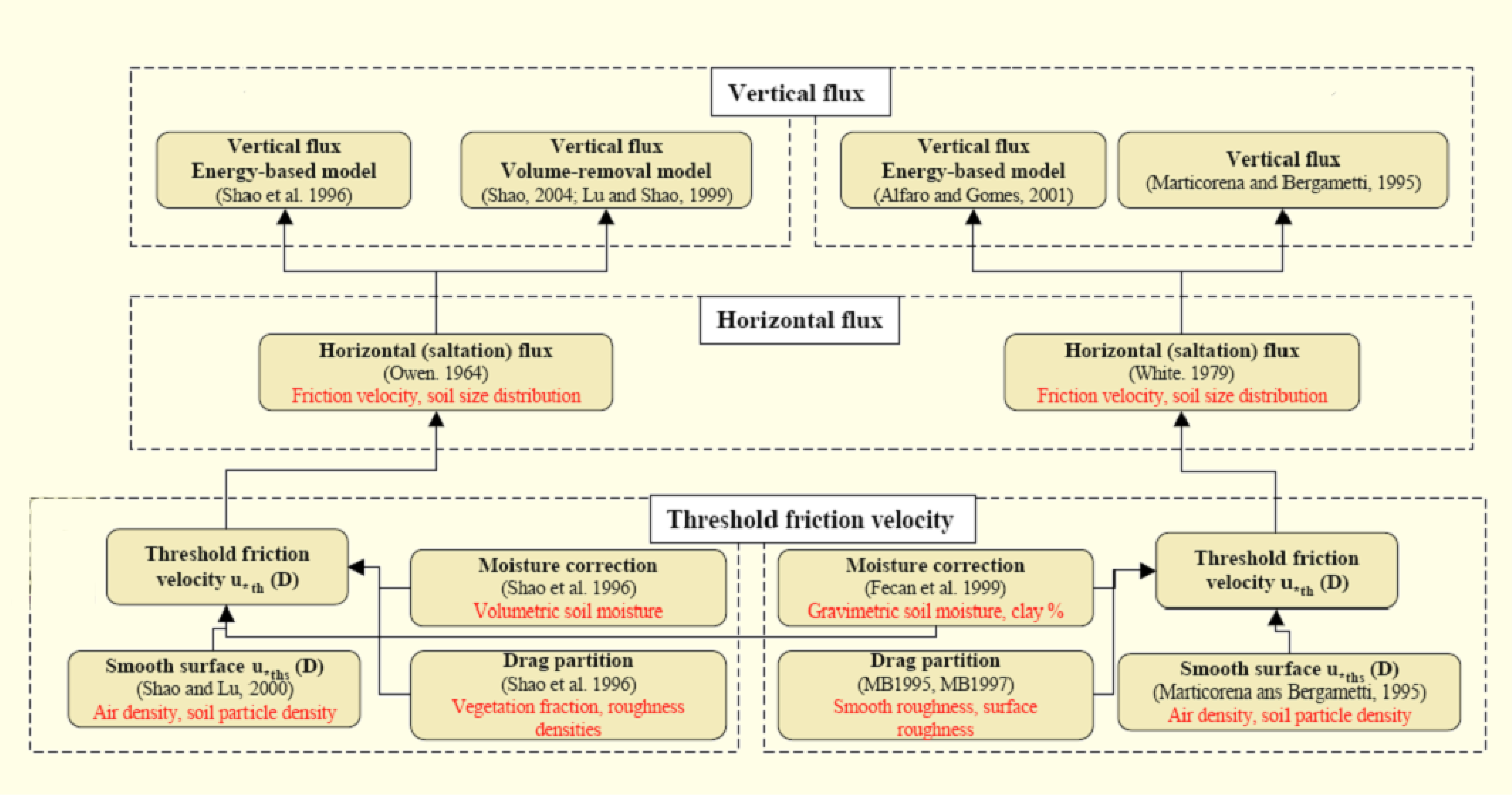
Simple schemes

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 emission schemes

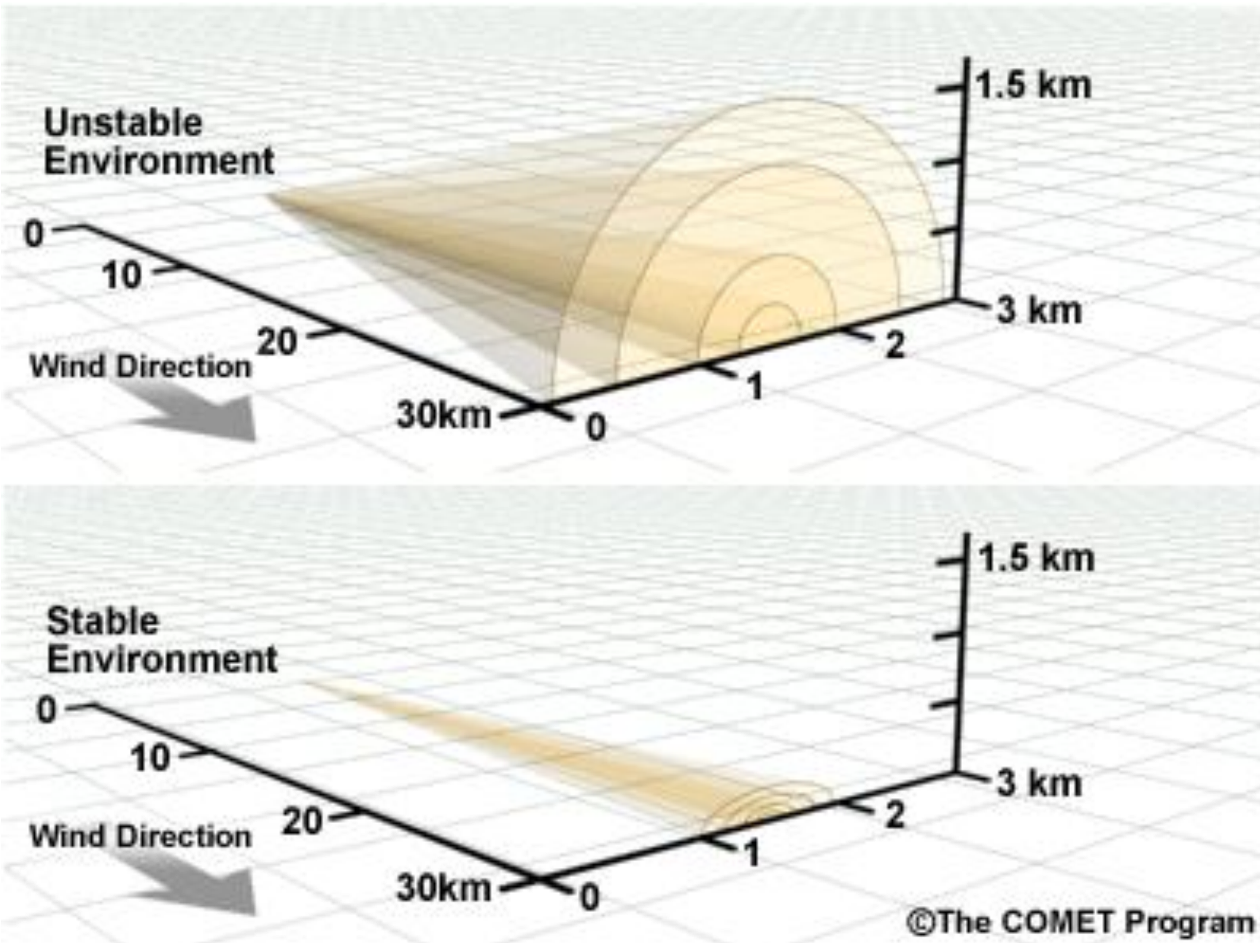


Physically-based **dust emission schemes** employ different parameterizations of the related physical processes, as well as require different input data.

Dispersion

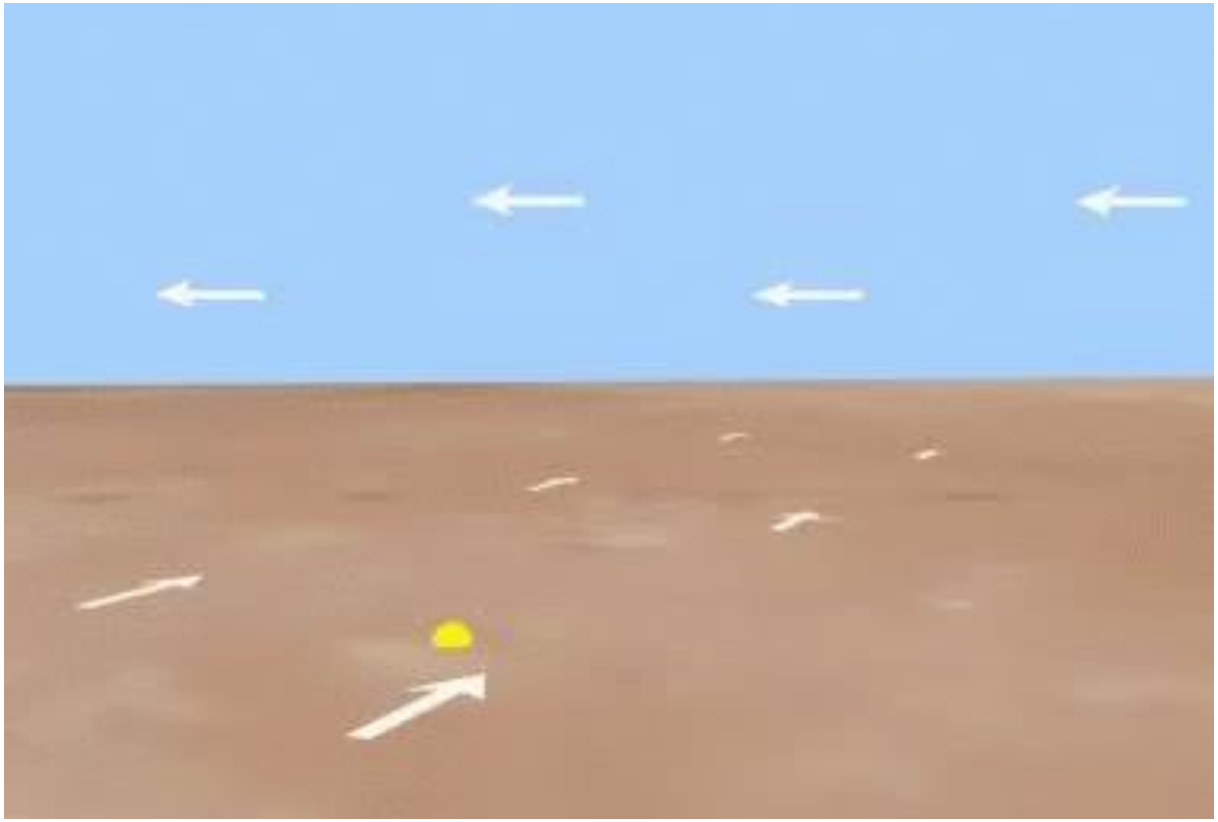
Movie from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Dispersion



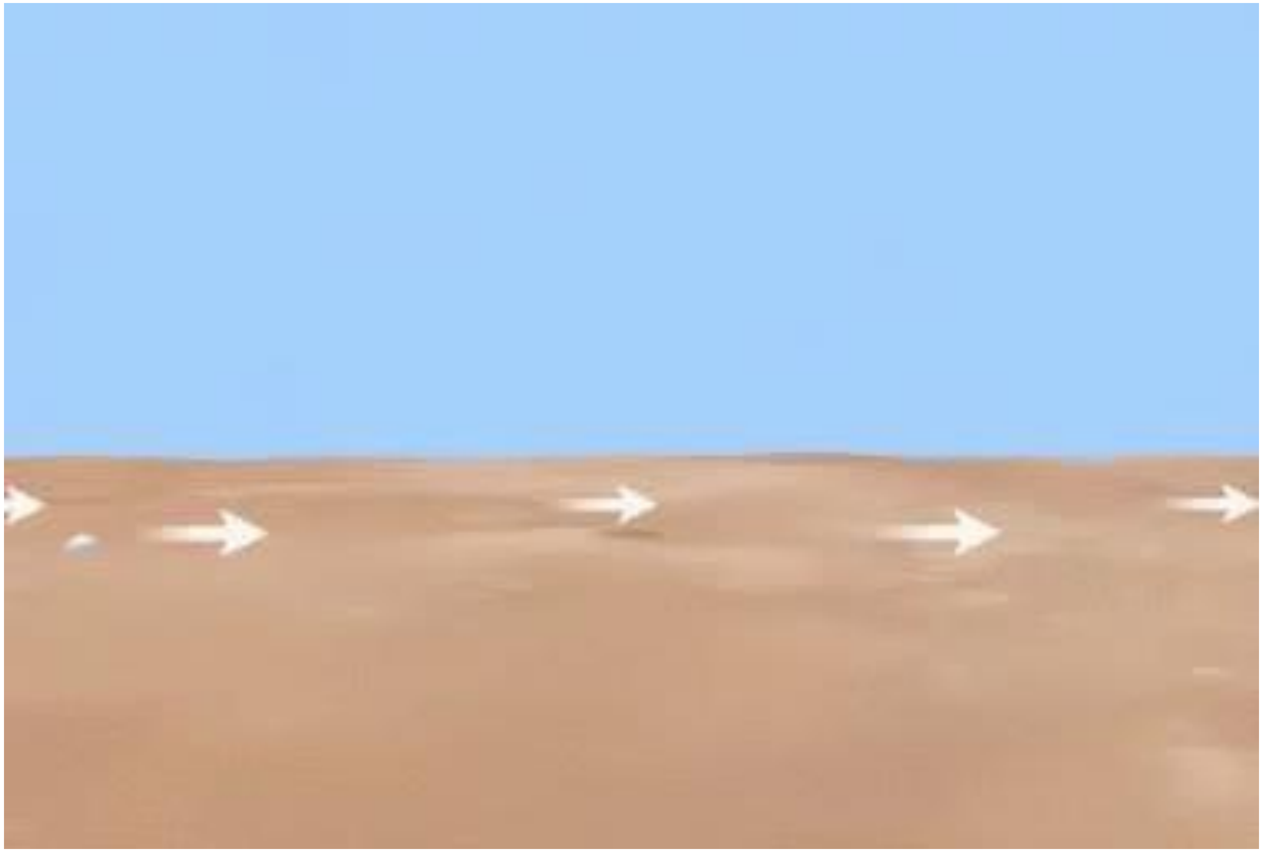
Unstable Environment
1.5 km
0
10
20
30km
Wind Direction
0
1
2
3 km
Stable Environment
1.5 km
0
10
20
30km
Wind Direction
0
1
2
3 km
©The COMET Program

Advection and diffusion



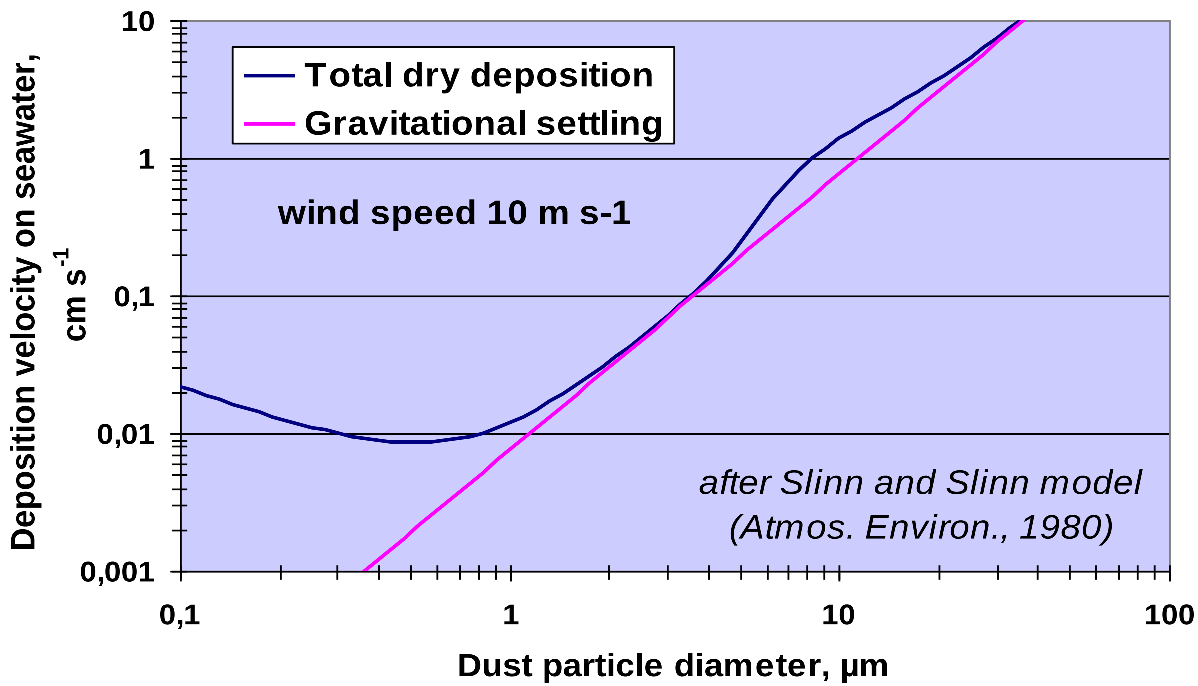
Movie from the COMET program at http://meted.ucar.edu/ of the
University Corporation for Atmospheric Research (UCAR)

Sedimentation and dry deposition



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

Sedimentation and dry deposition



- **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.

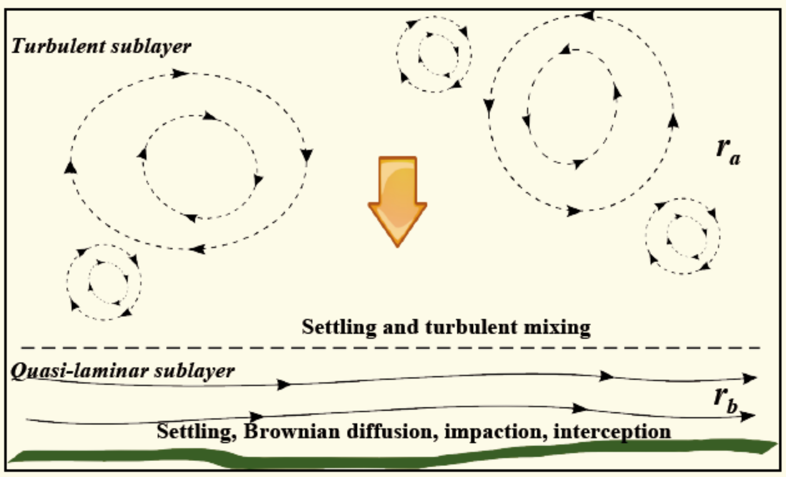
- **Sedimentation** (or gravitational settling) is the settling of particles fall down due to gravity → Very large particles will settle out quickly

Dry deposition

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

Wet deposition

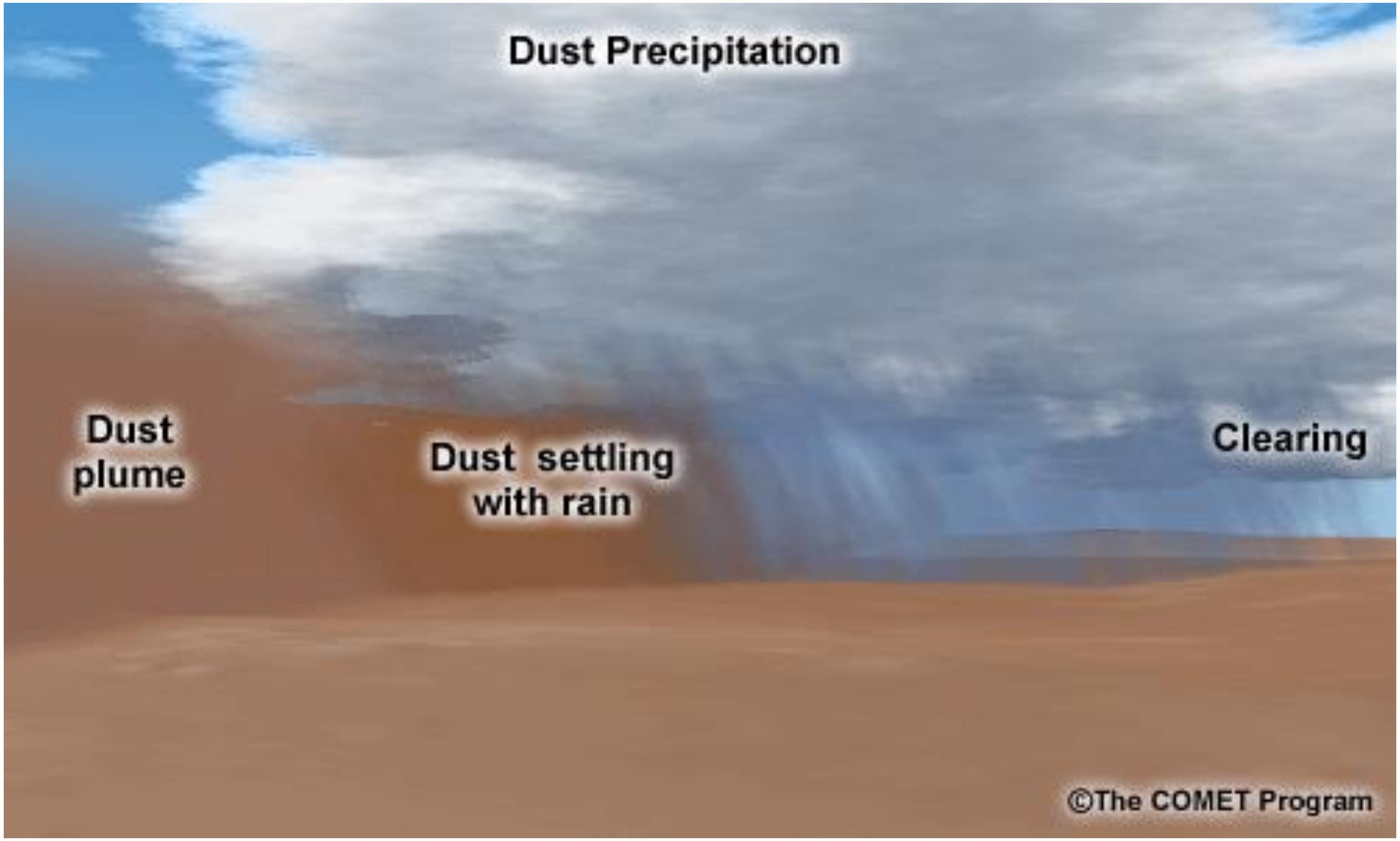
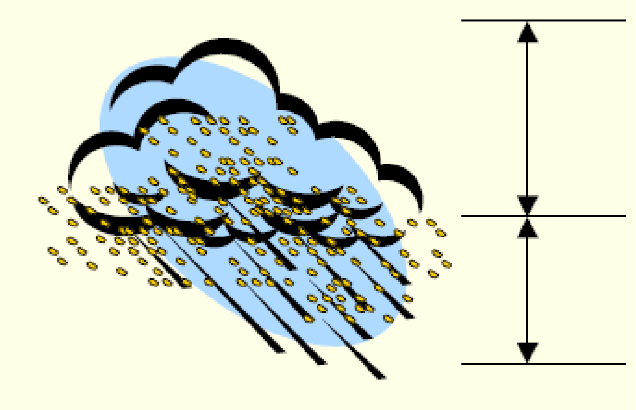


Image from the COMET program at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research (UCAR)

Wet deposition



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.

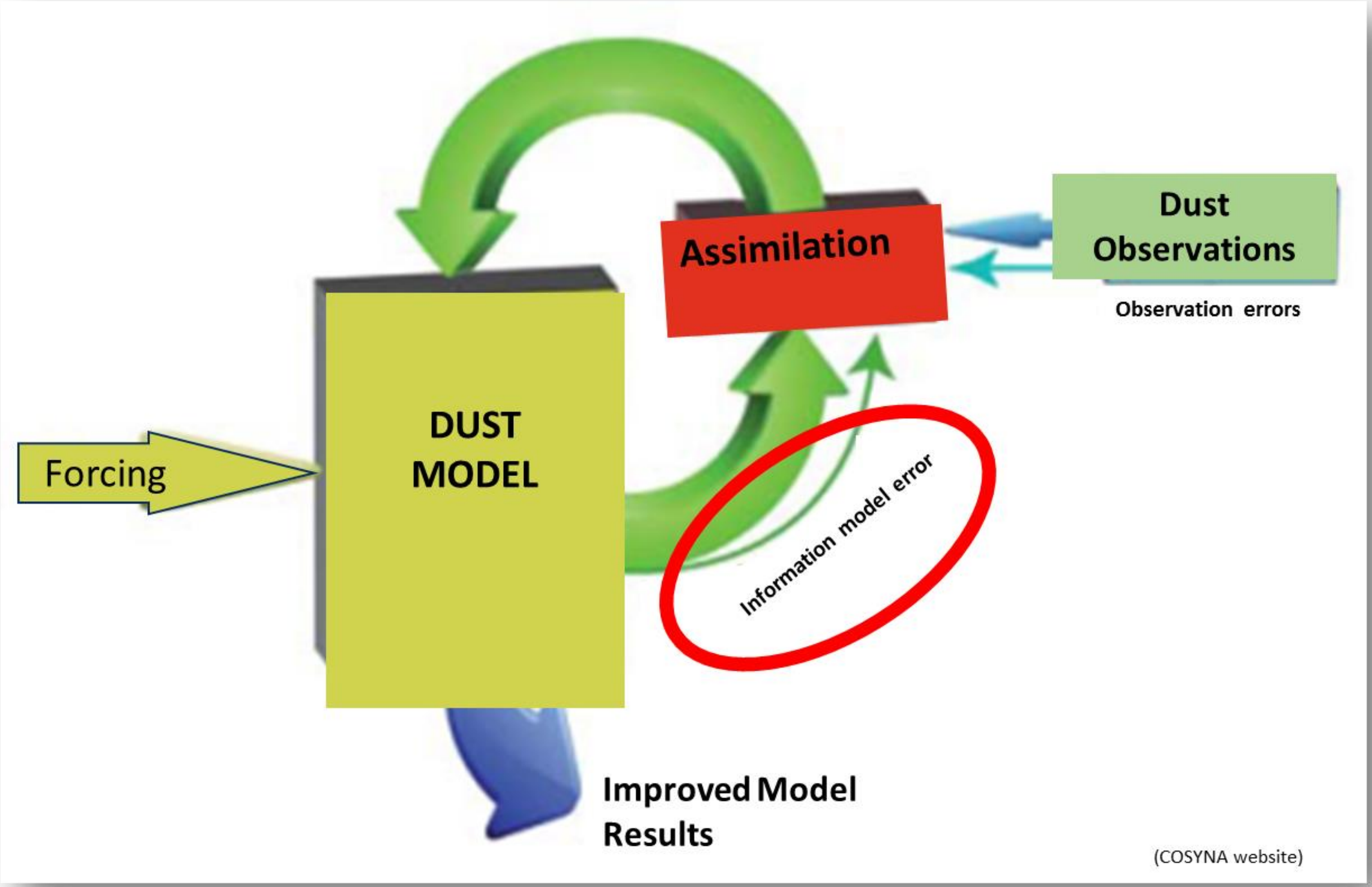
Decrease rate of the aerosol concentration due to **wet scavenging** in a layer with uniform concentration can be described by a first-order equation:

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

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).

Data Assimilation



Obtaining the 'best' estimate of current atmospheric dust conditions **(analysis)**
Creating datasets describing the recent history of dust in the atmosphere **(reanalysis)**

Dust forecasting models

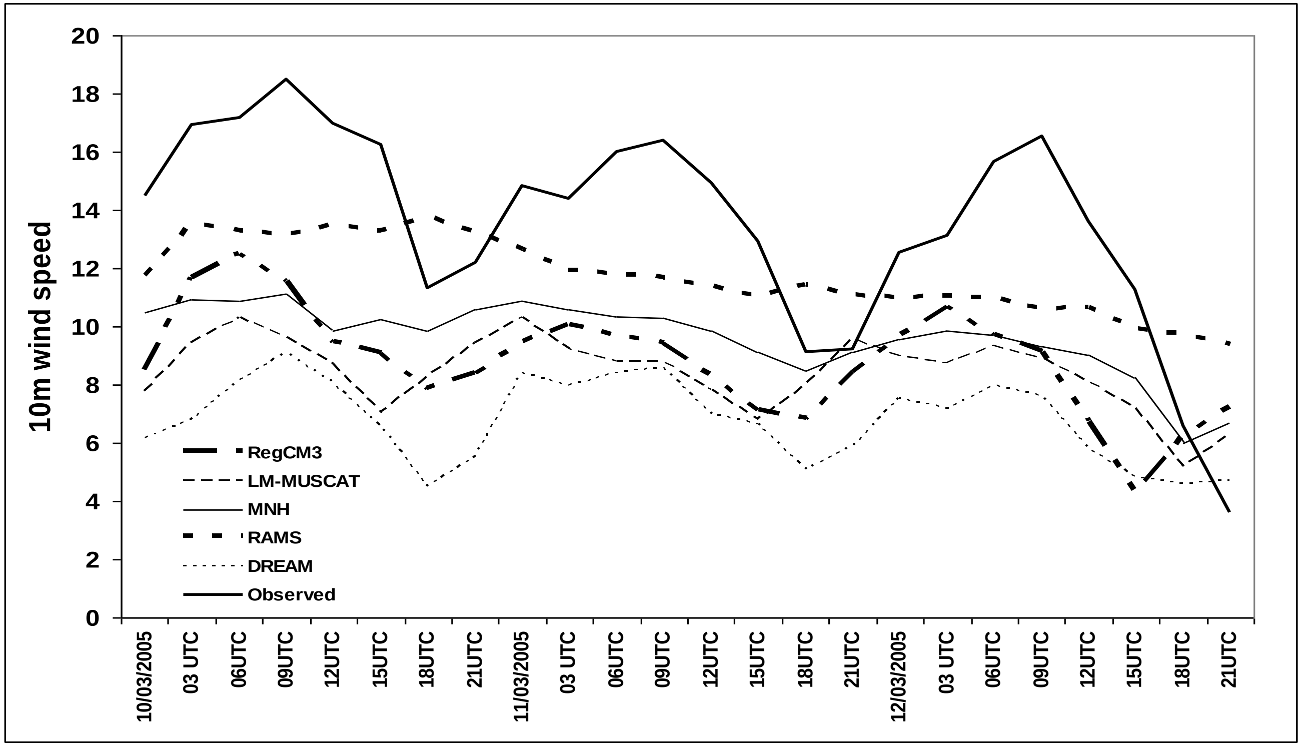
Main differences between dust models

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**

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