Dust modeling

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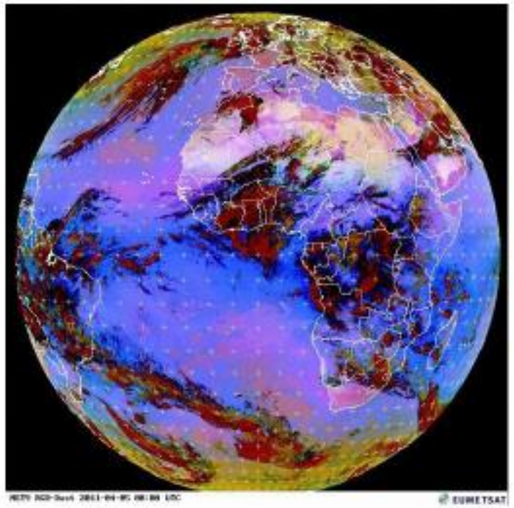
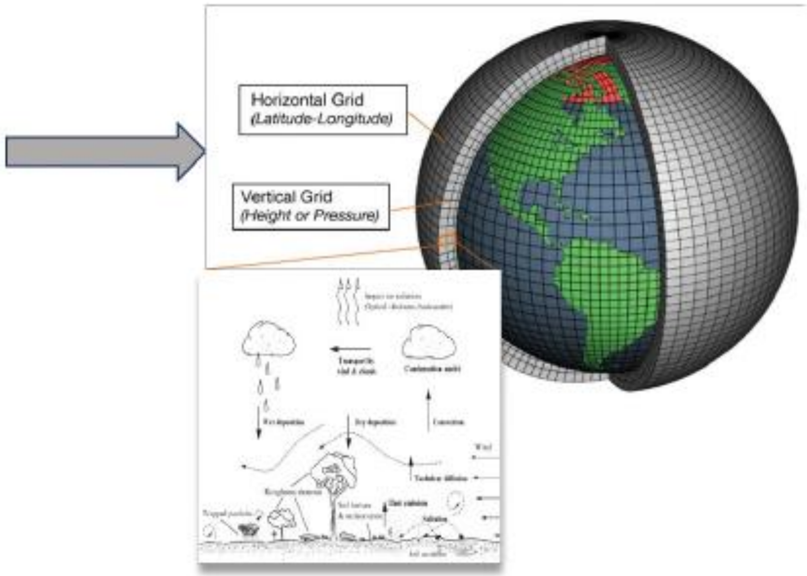
BSC and ICREA

Outline of the session

- Global and regional models
- Spatiotemporal scales
- Forecast lead times
- Dust conservation equation
- Dust emission modeling
- (advection, diffusion, deposition)

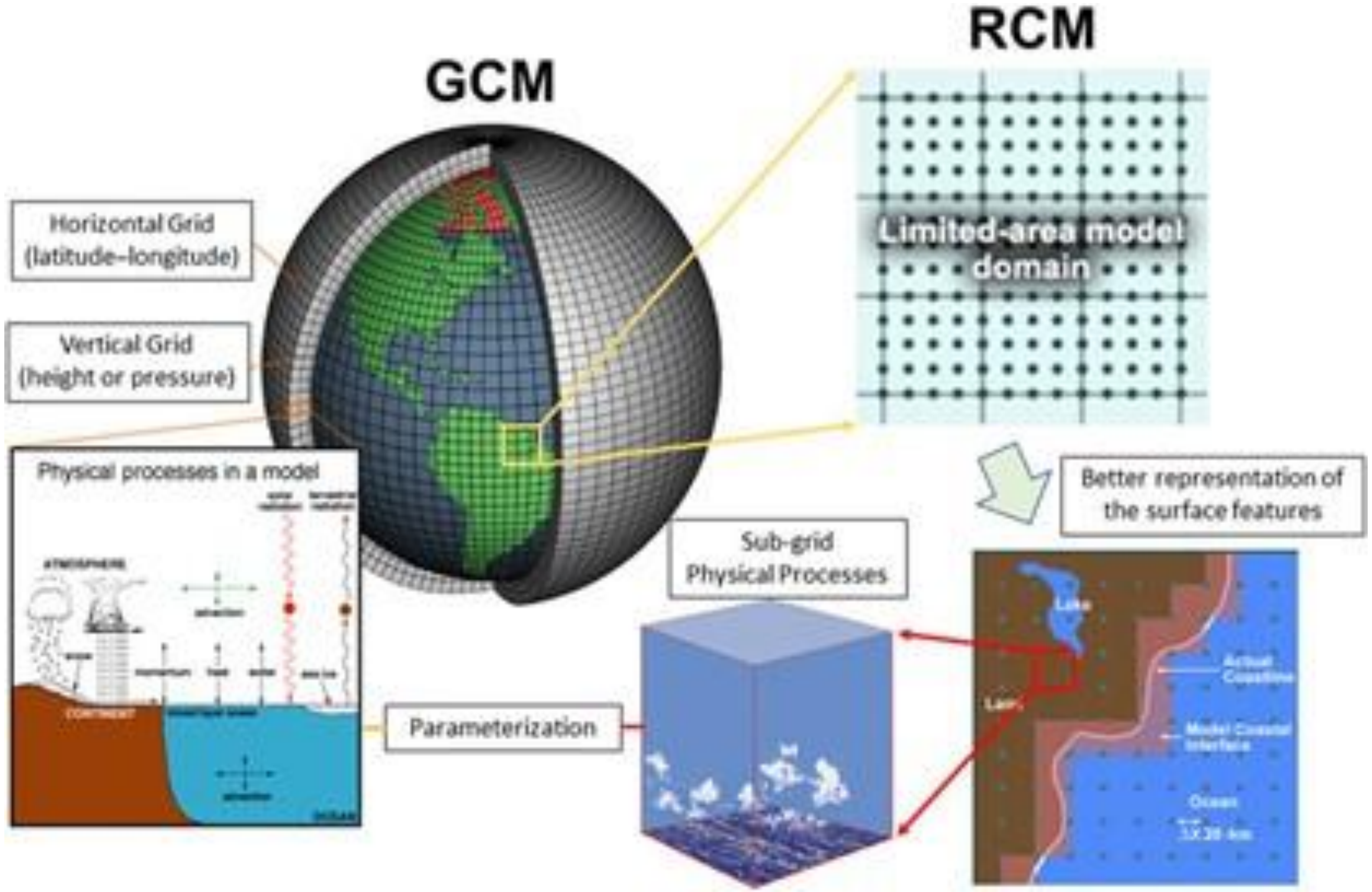
What is a dust model and why we need it?



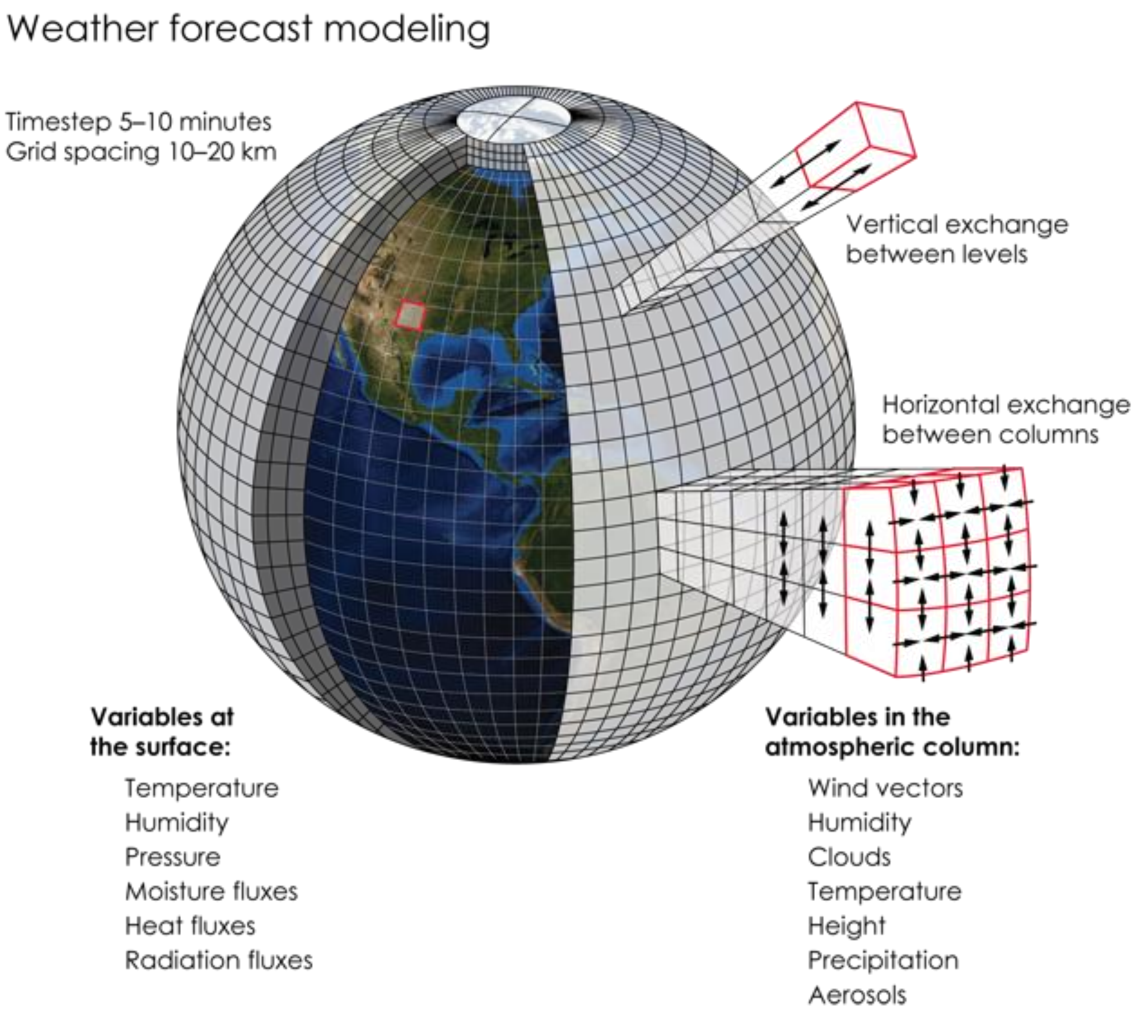


- ✔ *To complement dust-related observations, filling the temporal and spatial gaps of the measurements.*
- ✔ *To help us to understand the dust processes and their interaction with climate and ecosystems.*
- ✔ *To predict the impact of dust on surface level concentrations*

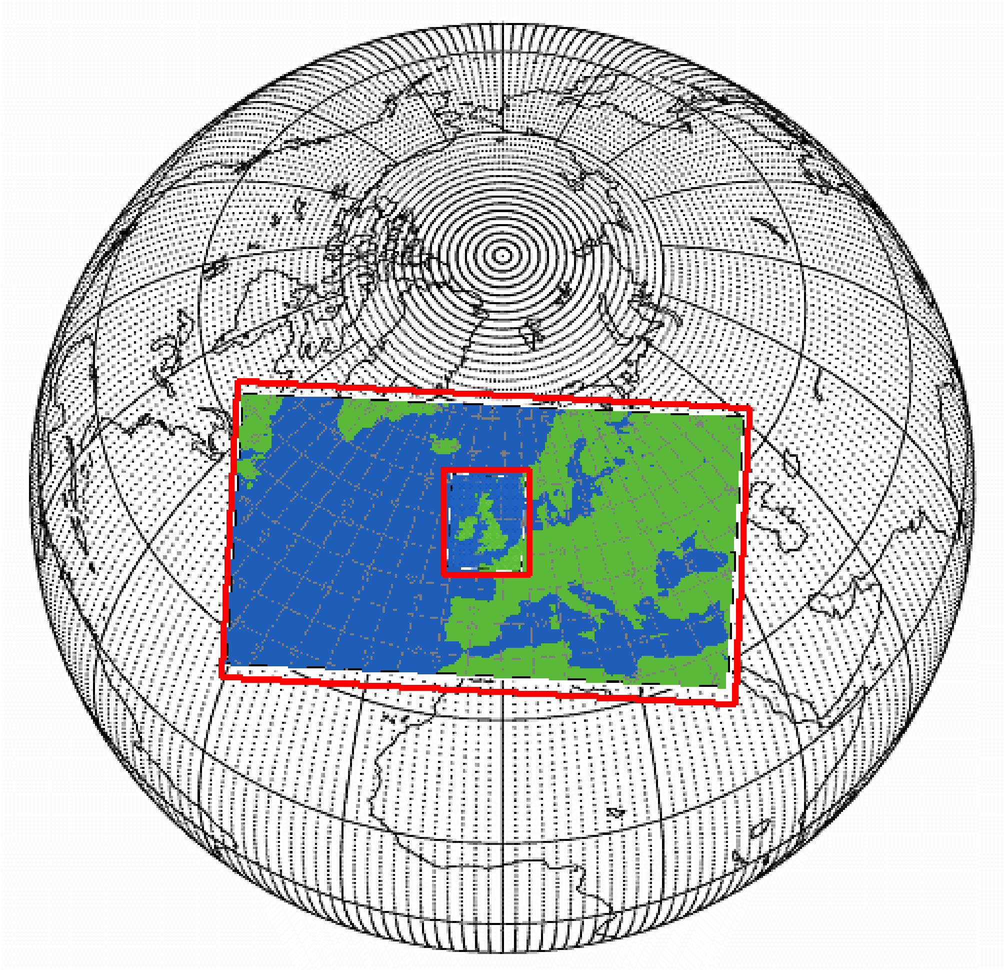
Global and regional modeling



Global model



Regional model

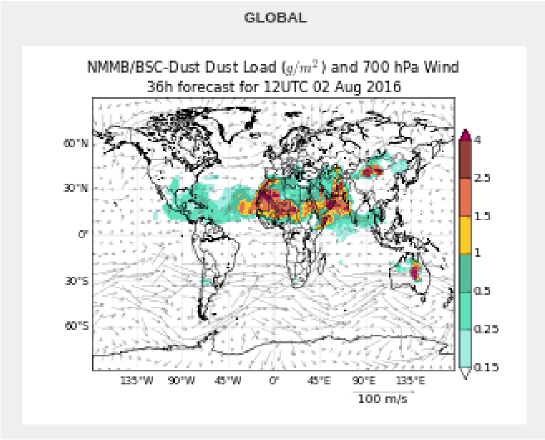


Dust models at BSC based on MONARCH

BSC dust operational forecast (global and regional domains)

Global

*Contribution to the **ICAP** multi-model ensemble (global) http://icap.atmos.und.edu*

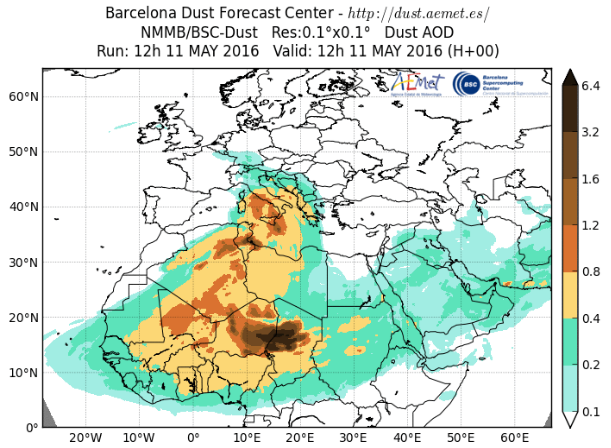


Regional

WMO Barcelona Dust Forecast Center*.*

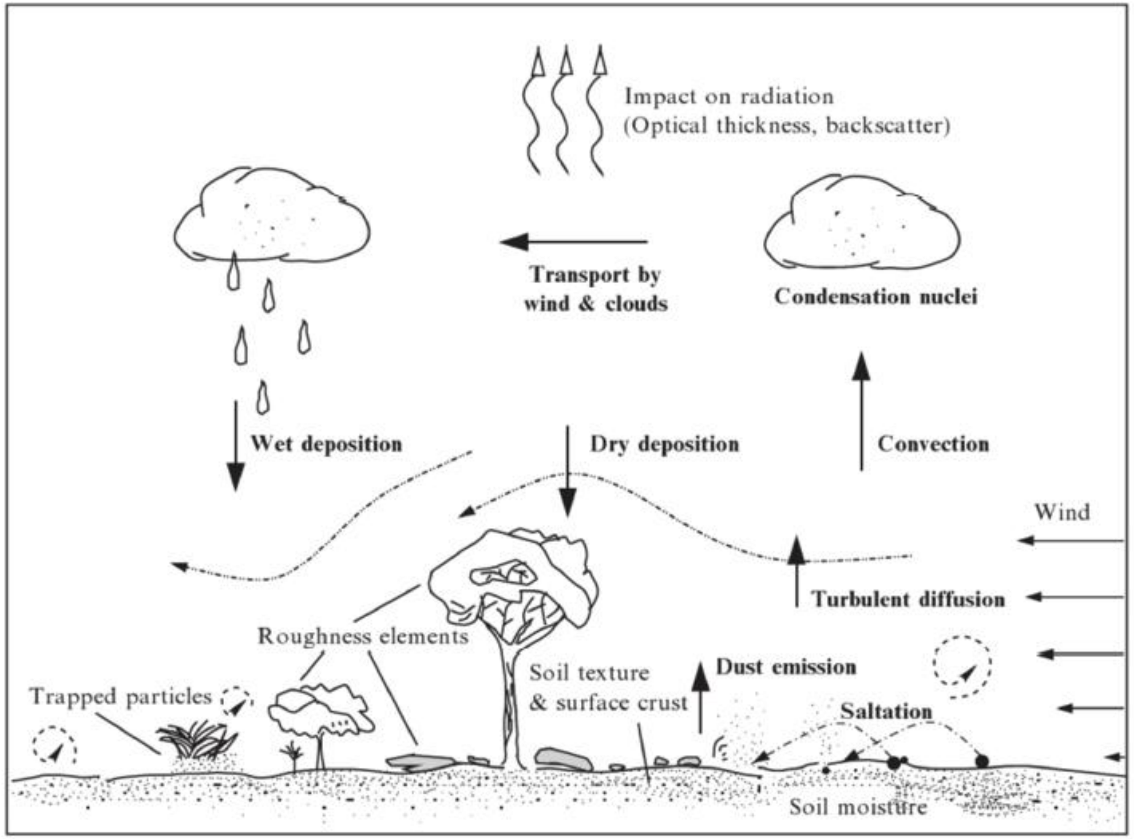
First specialized WMO Center for mineral dust prediction.

http://dust.aemet.es



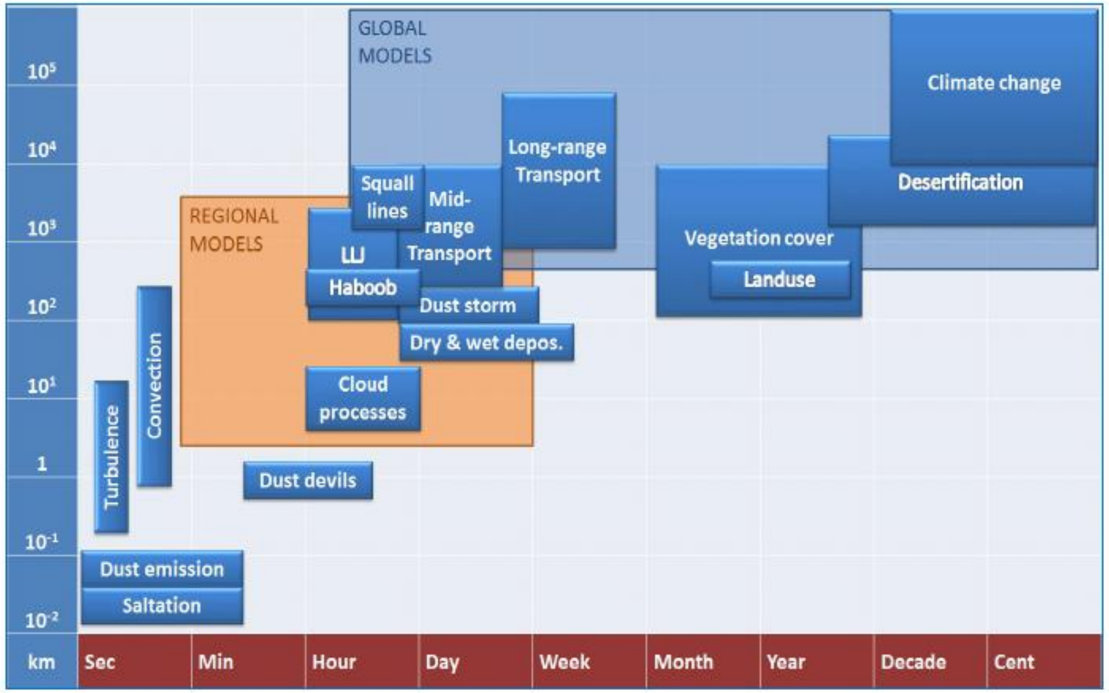
Dust models

Dust models are a mathematical representation of atmospheric dust cycle.



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

Models´spatiotemporal scales

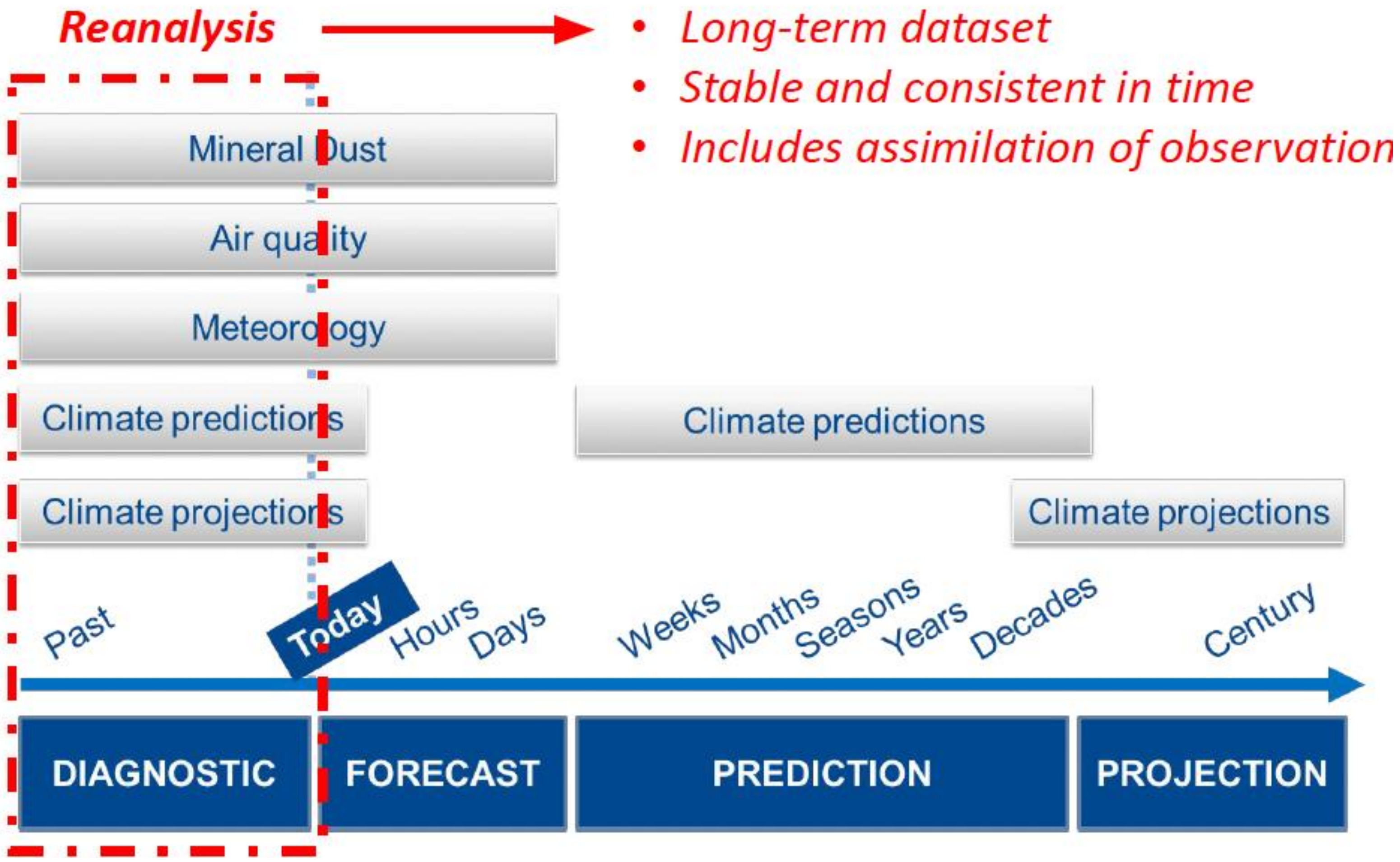


Dust processes span over five orders of magnitude in space and time. **Dust transport** is a global phenomenon. However, **dust emission** is a threshold phenomenon, sporadic and spatially heterogeneous, that is locally controlled on small spatial and temporal scales.

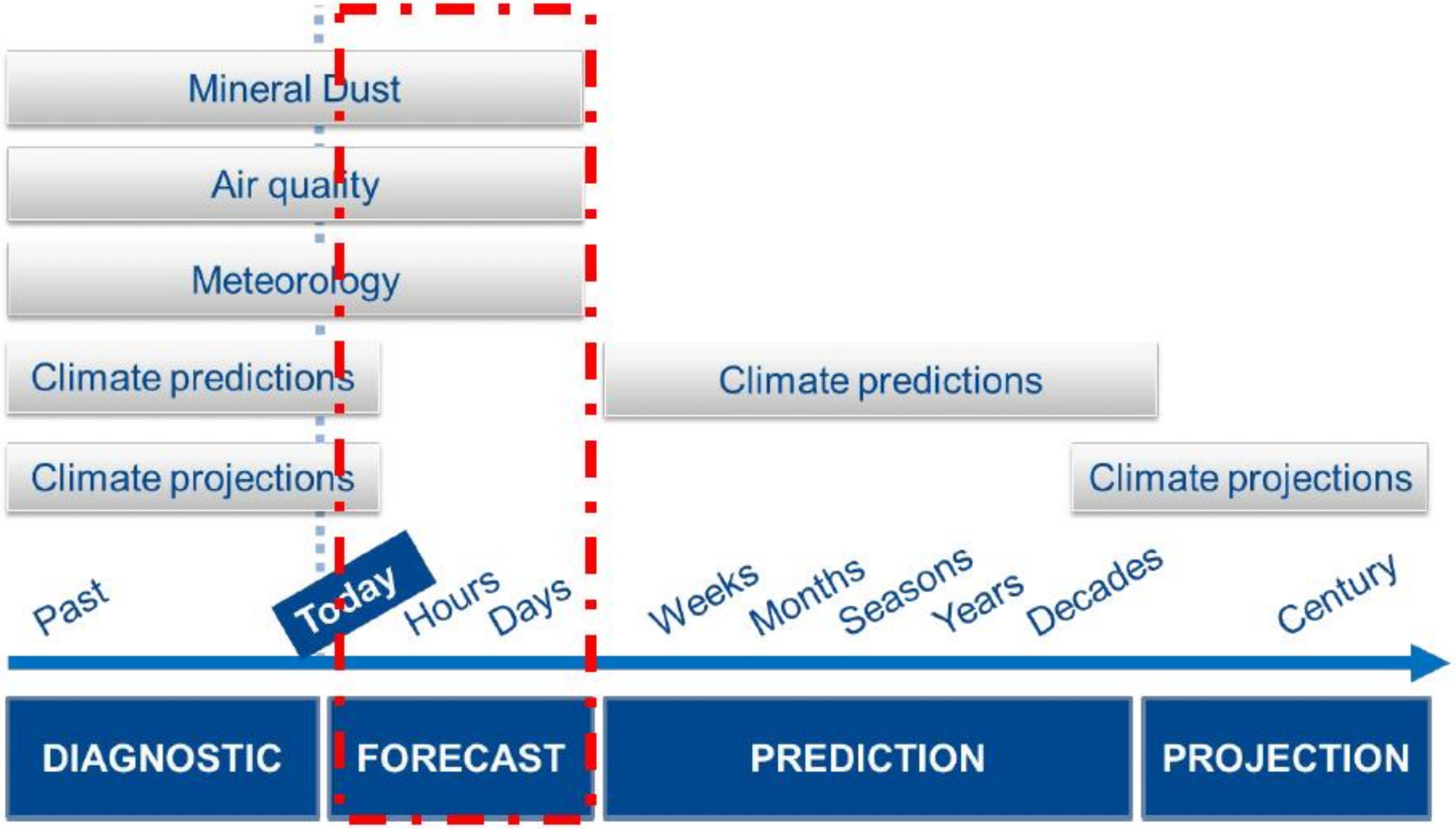
Accurate representation of dust sources and sinks is critical for providing realistic magnitudes and patterns of atmospheric dust fields.

Adapted from Shao (2011)

Forecasting lead times



Forecasting lead times

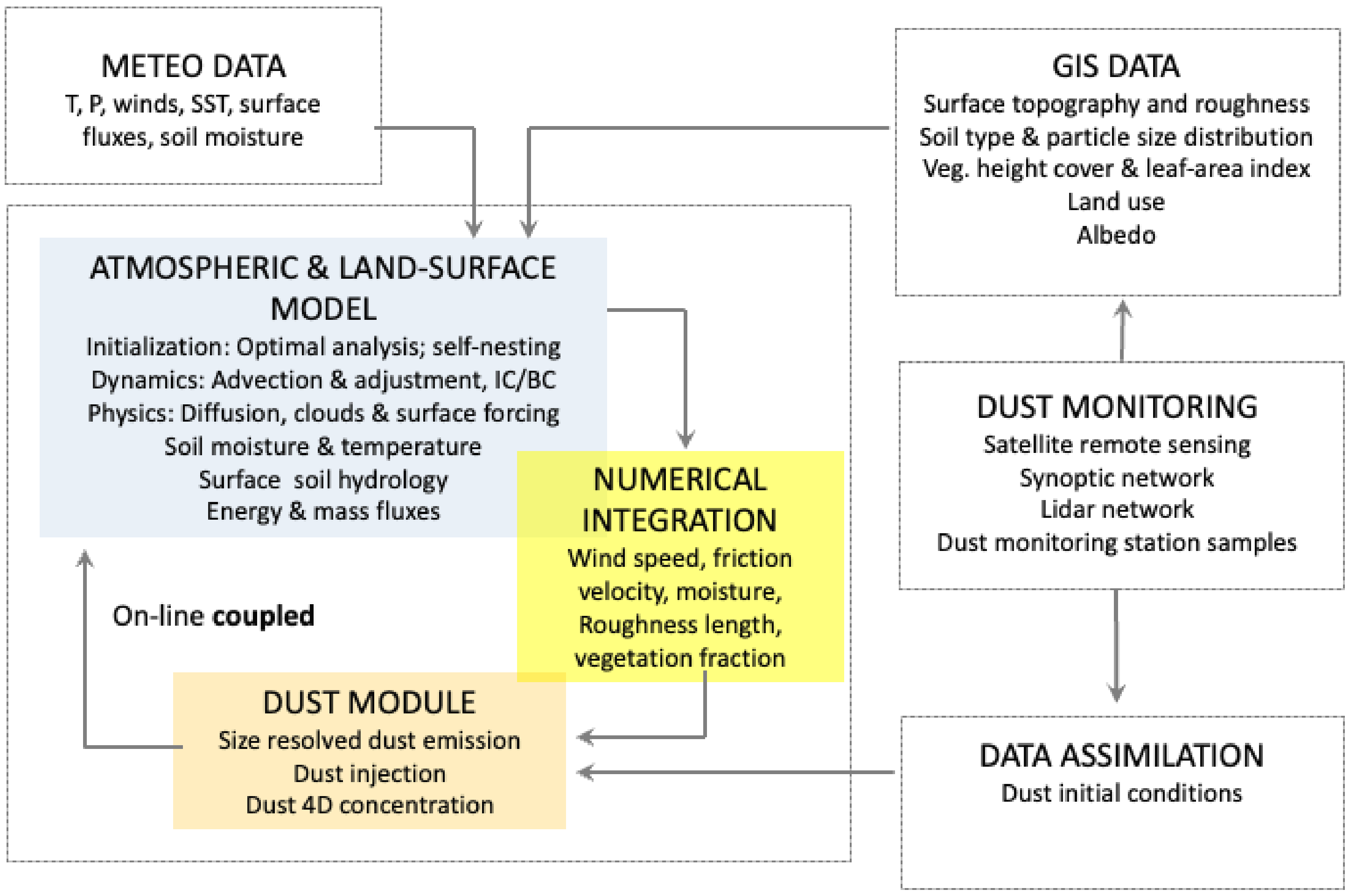


A piece of dust modeling history

- Late **80's**:
  - First demonstration that SDS dynamic simulations are possible
- **90's**:
  - First satellite products capable to detect SDS
  - First successful daily SDS forecast test
  - First long-term daily SDS forecasts
- **2000's**:
  - Fast growth in dust observations and forecasting models
- **2010's**:
  - Fast growth in user-oriented applications

WE ARE **NOW** READY TO PROVIDE ADDED-VALUE DUST **INFORMATION** !

General structure of a dust forecast model



Dust conservation (continuity) equation

In terms of mass mixing ratio of a dust bin q_d (kg of dust per kg of air)

$$\frac{\partial q_d}{\partial t} + \underbrace{\mathbf{u}\cdot\nabla q_d}_{\text{3-D advection}} + \underbrace{\frac{\partial}{\partial z}(W_s q_d)}_{\text{vertical settling}} = \underbrace{E}_{\text{emission}} - \underbrace{(D_{\text{dry}} + D_{\text{wet}})}_{\text{deposition}} + \underbrace{\nabla\cdot(K\nabla q_d)}_{\text{sub-grid diffusion}}.$$

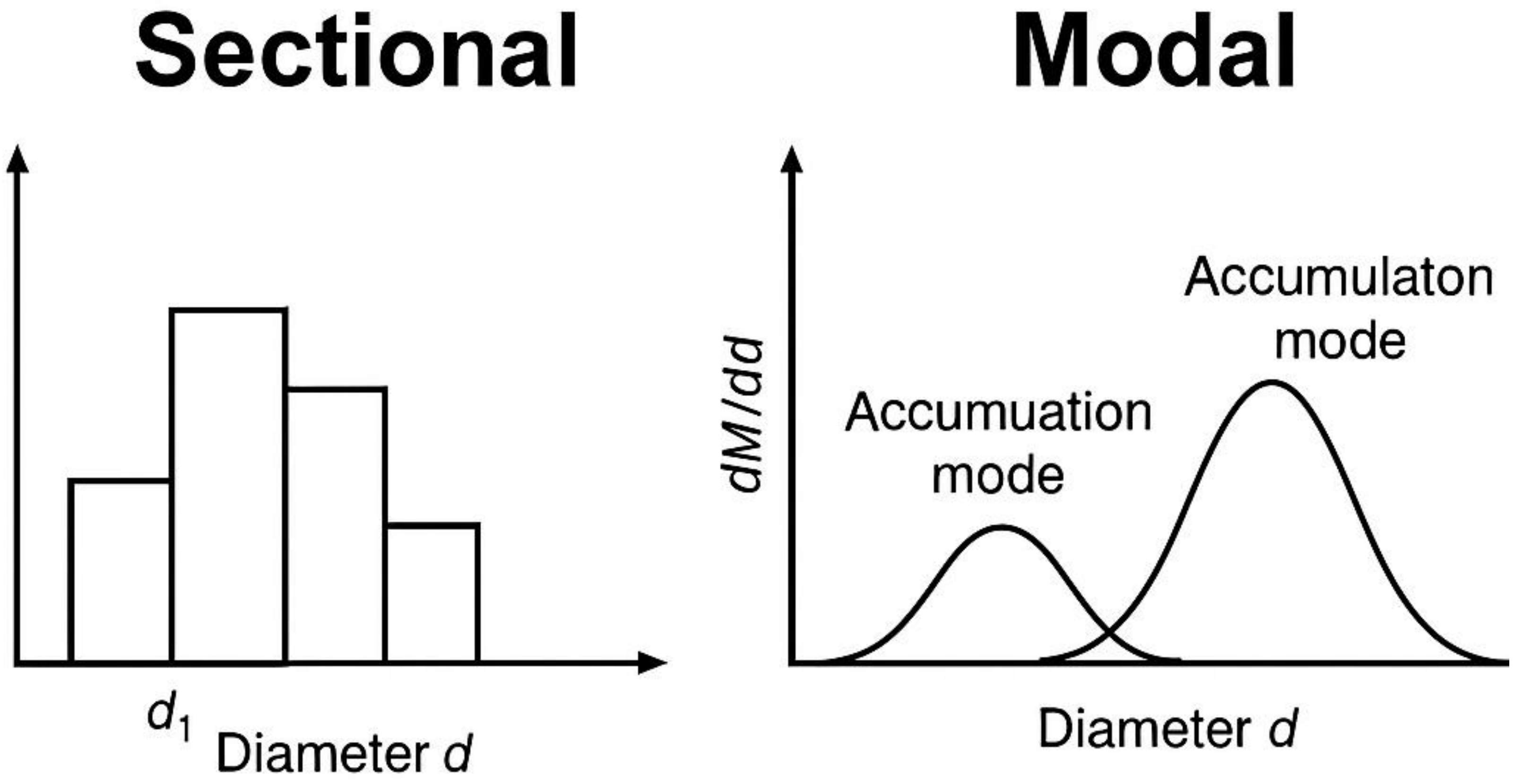
In terms of mass concentration units C_d (kg m^{-3})

$$\frac{\partial(\rho C_d)}{\partial t} + \nabla\cdot(\rho\mathbf{u}\,C_d) + \frac{\partial}{\partial z}(\rho W_s C_d) = E - (D_{\text{dry}} + D_{\text{wet}}) + \nabla\cdot(\rho K\nabla C_d).$$

- $\mathbf{u}(x, y, z, t)$ is the resolved wind.
- $W_s(d)$ is the particle's Stokes-settling velocity, a function of diameter; the term acts only in the vertical.
- E is the source flux from land-surface emission schemes (saltation burst, sandblasting, etc.), converted to mixing ratio by dividing by air density.
- $D_{\text{dry}} = V_d\, q_d$ is dry deposition, with V_d the surface deposition velocity; D_{wet} is removal by in-cloud and below-cloud scavenging.
- K is an eddy-diffusion tensor that represents unresolved turbulent mixing or numerical sub-grid tracers.

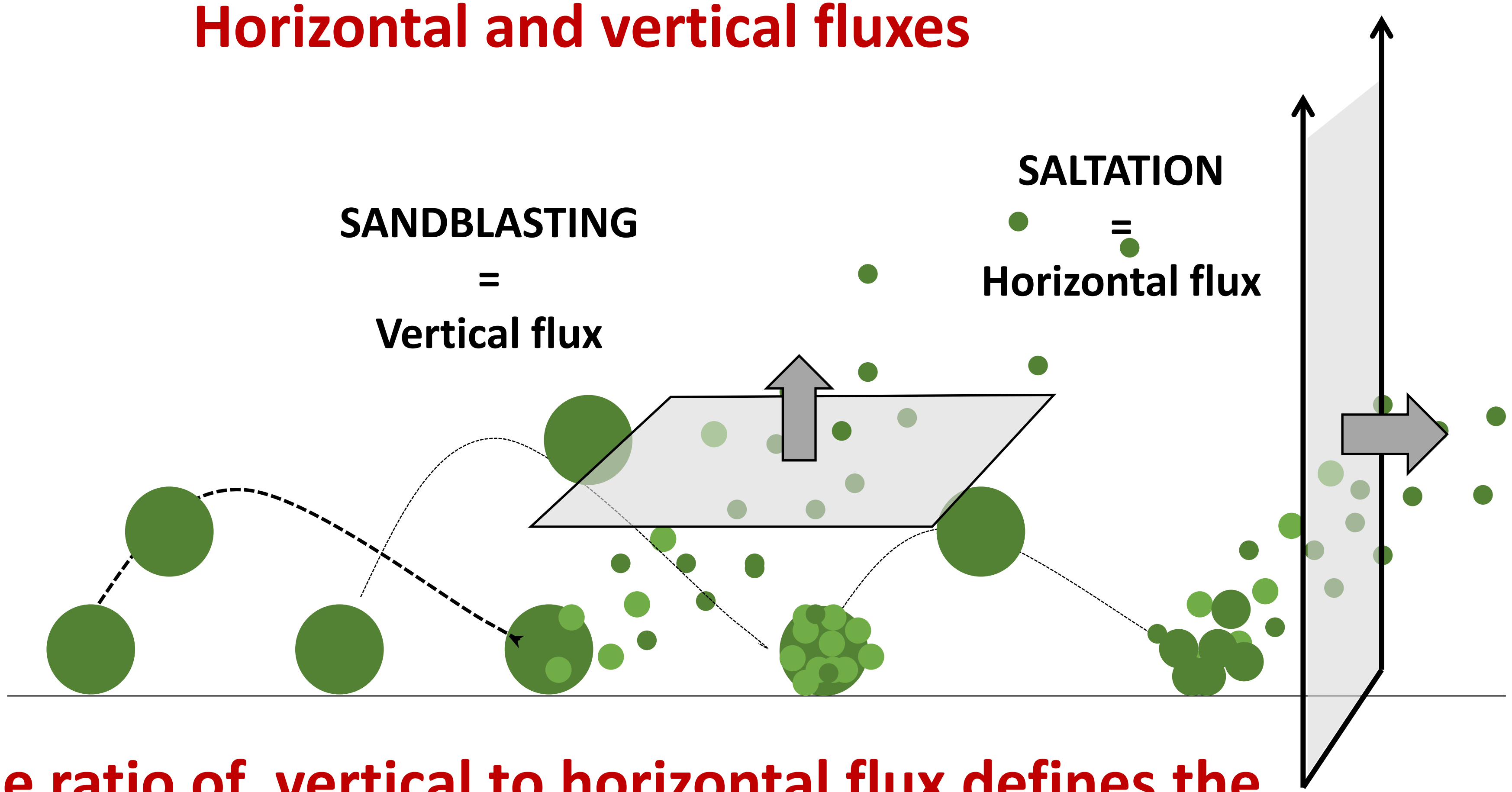
Each size bin or mode has its own continuity equation with its own W_s and optical properties;

Bin/sectional or modal representation



Dust emission

Horizontal and vertical fluxes



The ratio of vertical to horizontal flux defines the sandblasting efficiency (α=F/G)

Parameterization of saltation fluxes

General expression (i.e. White, 1979)

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

Complete expressions (Marticorena et Bergametti, 1995) including :

-the **size and roughness dependence** of the **threshold** wind friction velocity

- the **relative contribution** of the different soil grain sizes

- the fraction of erodible surface €

$$G = E\,c\,\frac{\rho}{g}U^{*3}\sum_{D_p}\left(1+\frac{U_t^*(D_p, Z_0, z_0)}{U^*}\right)\left(1-\frac{U_t^*(D_p, Z_0, z_0)^2}{U^{*2}}\right)dS_{rel}(D_p)\,dD_p$$

Different options for saltation

Table 1. List of the most commonly used saltation mass flux relations.

Mass flux equation	Comments	Study
$Q_{\text{Bagnold}} = C_B \sqrt{\frac{D_p}{D_{250}}} \frac{\rho_a}{g} u_*^3$	C_B = 1.5, 1.8 or 2.8 for uniform, naturally graded and poorly sorted sand, respectively.	Bagnold (1941)
$Q_{\text{Kawamura}} = C_K \frac{\rho_a}{g} u_*^3 \left(1 - \frac{u_{*it}^2}{u_*^2}\right)\left(1 + \frac{u_{*it}}{u_*}\right)$	C_K = 2.78 (Kawamura 1951) or 2.61 (White 1979). The origin of this relation is often confused to be White (1979); see Namikas and Sherman (1997).	Kawamura (1951)
$Q_{\text{Owen}} = \frac{\rho_a}{g} u_*^3 \left(0.25 + \frac{v_t}{3u_*}\right)\left(1 - \frac{u_{*it}^2}{u_*^2}\right)$	v_t is a particle's terminal fall speed.	Owen (1964)
$Q_{\text{Lettau}} = C_L \sqrt{\frac{D_p}{D_{250}}} \frac{\rho_a}{g} u_*^3 \left(1 - u_{*it}/u_*\right)$	C_L = 6.7	Lettau and Lettau (1978)
$Q_{\text{UH}} = C_{\text{UH}} \rho_a \sqrt{\frac{D_p}{g}} u_*^2 \left(1 - \frac{u_{*sfc}^2}{u_*^2}\right)$	Ungar and Haff (1987) did not estimate a value of C_{UH}.	Ungar and Haff (1987)
$Q_{\text{Sorensen}} = \frac{\rho_a}{g} u_*^3 (1 - u_{*it}^2/u_*^2)(\alpha + \gamma u_{*it}/u_* + \beta u_{*it}^2/u_*^2)$	α, β and γ are parameters that characterize the dimensions of a typical saltation hop.	Sorensen (2004)
$Q_{\text{DK}} = C_{\text{DK}} \frac{\rho_a}{g} u_{*it} u_*^2 \left(1 - \frac{u_{*it}^2}{u_*^2}\right)$	$C_{\text{DK}} \approx 5$	Proposed here and in Durán *et al* (2011a)

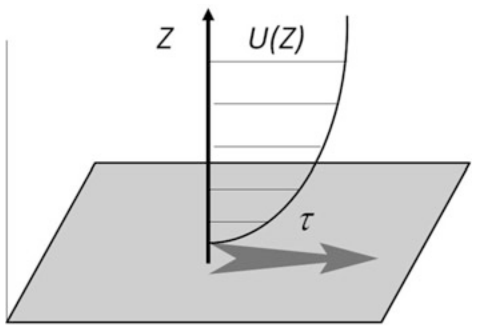
D_{250} is a reference diameter of 250 μm.

Friction velocity

Friction velocity is a *velocity scale* that packages the surface-layer momentum flux into metres per second:

$$u_* = \sqrt{\frac{\tau}{\rho}},$$

where τ is the turbulent shear stress (N m^{-2}) exerted by the air on the surface and ρ is air density. Because τ = ρ u_^{2}*, quoting the single number *u** is equivalent to giving the stress.



In neutral (well-mixed) conditions the mean wind profile over roughness z_0 follows the logarithmic law

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right),$$

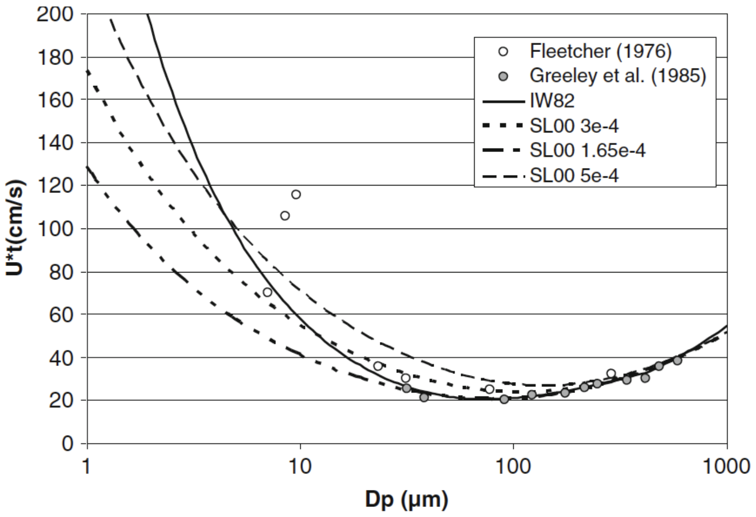
so if you know the roughness length and have an anemometer at height *z* you can rearrange

$$u_* = \kappa\, u(z) \Big/ \ln(z/z_0),$$

Stability correction:

$$u_* = \frac{\kappa\, u(z)}{\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right)}.$$

Threshold friction velocity: influence of particle size



$$U_t^* (D_p) = \left[A_N \left(\frac{\rho_p g D_p}{\rho_a} + \frac{\gamma}{\rho_a D_p} \right) \right]^{0.5} \quad (5.3)$$

with $A_N = \sqrt{f(\mathrm{Re}_{*t})} \approx 0.0123$.

Re_t is the Reynolds number at the erosion threshold, that is, $\mathrm{Re}_t = (U_t^* . D_p)/\nu$,, where ν is the kinematic viscosity of the air. The term $\gamma/_{\rho_a D_p}$ accounts for the interparticle forces, γ being adjusted to wind-tunnel measurements (from 1.65

Threshold friction velocity: influence of soil moisture

$$\text{for } w < w' : \quad U^*_{tw} / U^*_{td} = 1 \qquad (5.4a)$$

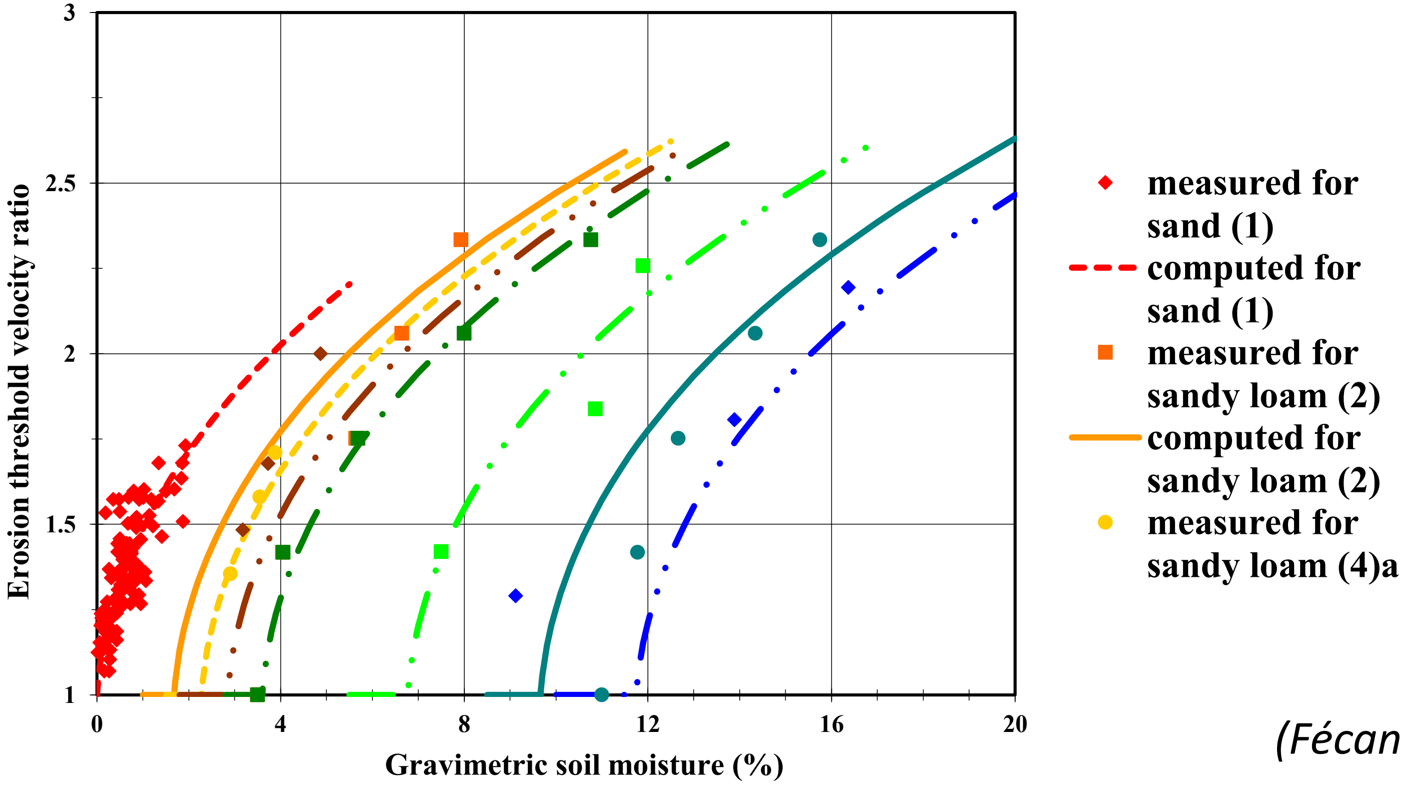
$$\text{for } w > w' : \quad U^*_{tw} / U^*_{td} = \left[1 + 1.21 (w - w')^{0.68}\right]^{0.5} \qquad (5.4b)$$

with U^*_{tw} the threshold wind friction in wet conditions, U^*_{td}, the threshold wind friction in dry conditions, w the gravimetric soil moisture content and w' the minimal soil moisture for which the erosion threshold increases, which depends on soil texture and more specifically on soil clay content:

$$w' = 0.0014(\%\text{Clay})^2 + 0.17\,(\%\text{Clay}) \qquad (5.5)$$

(Fecan et al. 1999)

Threshold friction velocity: influence of soil moisture



(Fécan et al., 1999)

⇨A parameterisation that perfoms well in the field

(Ishisuka et al. 2005)

Threshold friction velocity: influence of roughness

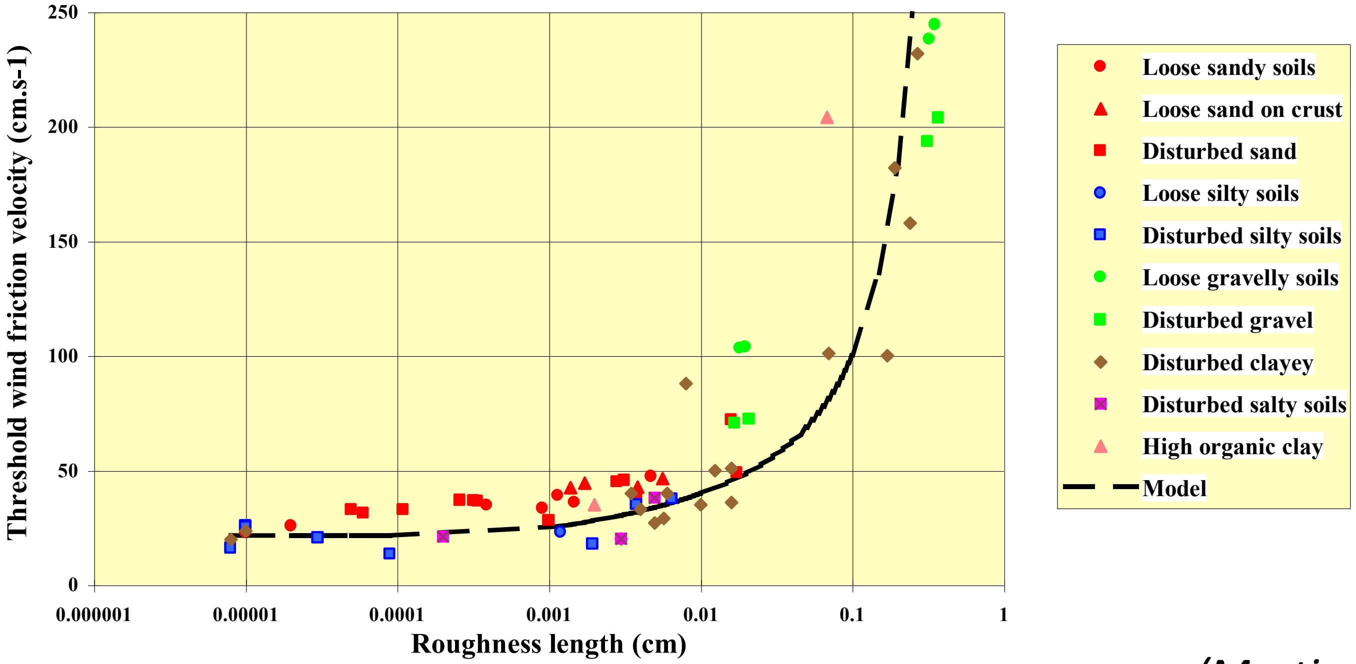
$$f_R(Z_0, z_{0s}) = 1 - \left(\ln(Z_0/z_{0s}) / \ln\left(a(X/z_{0s})^b\right)\right) \quad (5.7)$$

where z_{0s} is the aerodynamic roughness length of the erodible surface, and a and b are empirical coefficient describing the evolution of the IBL as a function of the distance (X) estimated, respectively, to be $a = 0.35$, $b = 0.8$ and $X = 10$ (with Z, Z_0 and z_{0s} in cm).

Marticorena et al. 1997

Threshold friction velocity: influence of roughness

Roughness dependent threshold wind friction velocities

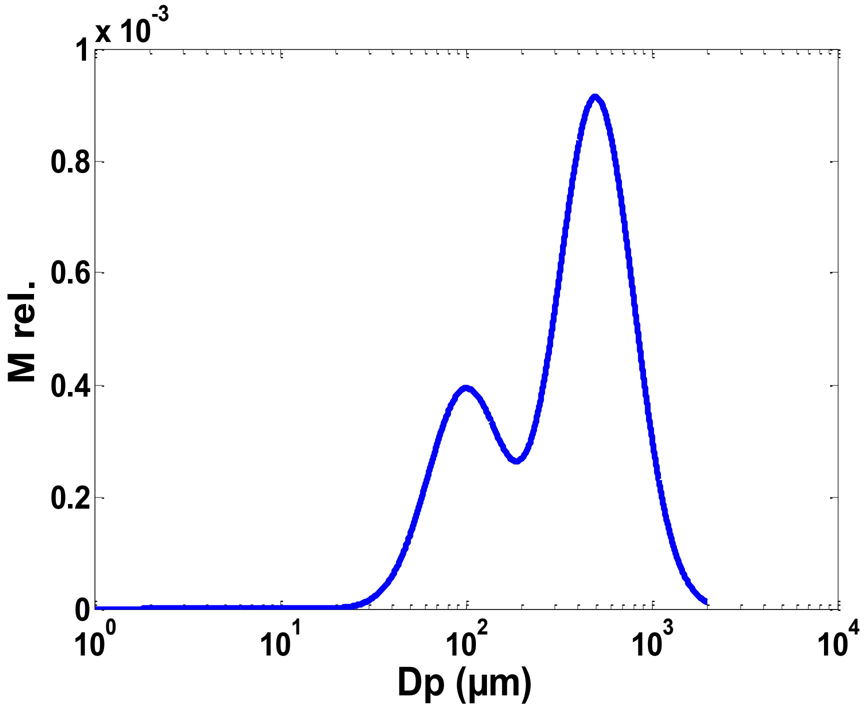


(Marticorena et al., 1997)

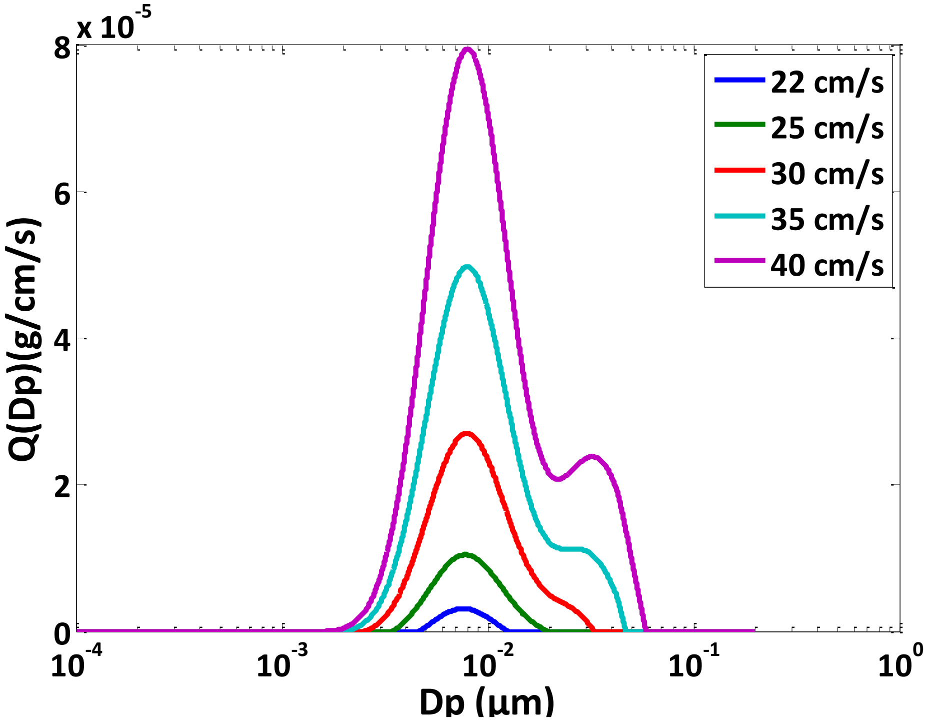
⇨ **Good agreement for relatively low roughness density and solid obstacle**

Saltation as a size-segregating process

Soil mass size distribution

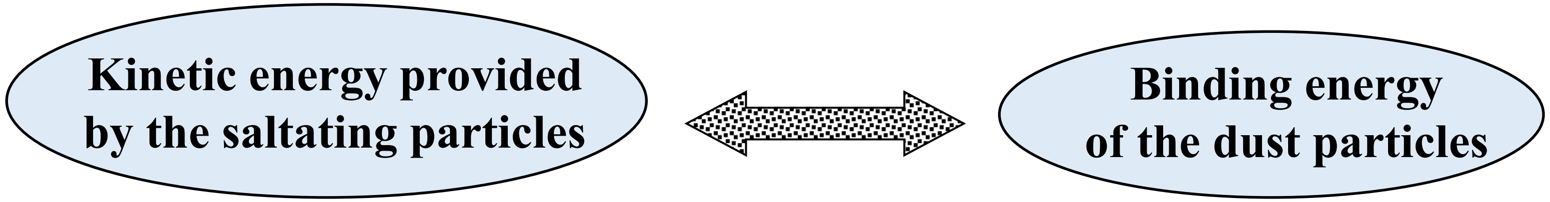


Saltation flux size distribution



Sandblasting and vertical fluxes

➪ Conceptual understanding of sandblasting



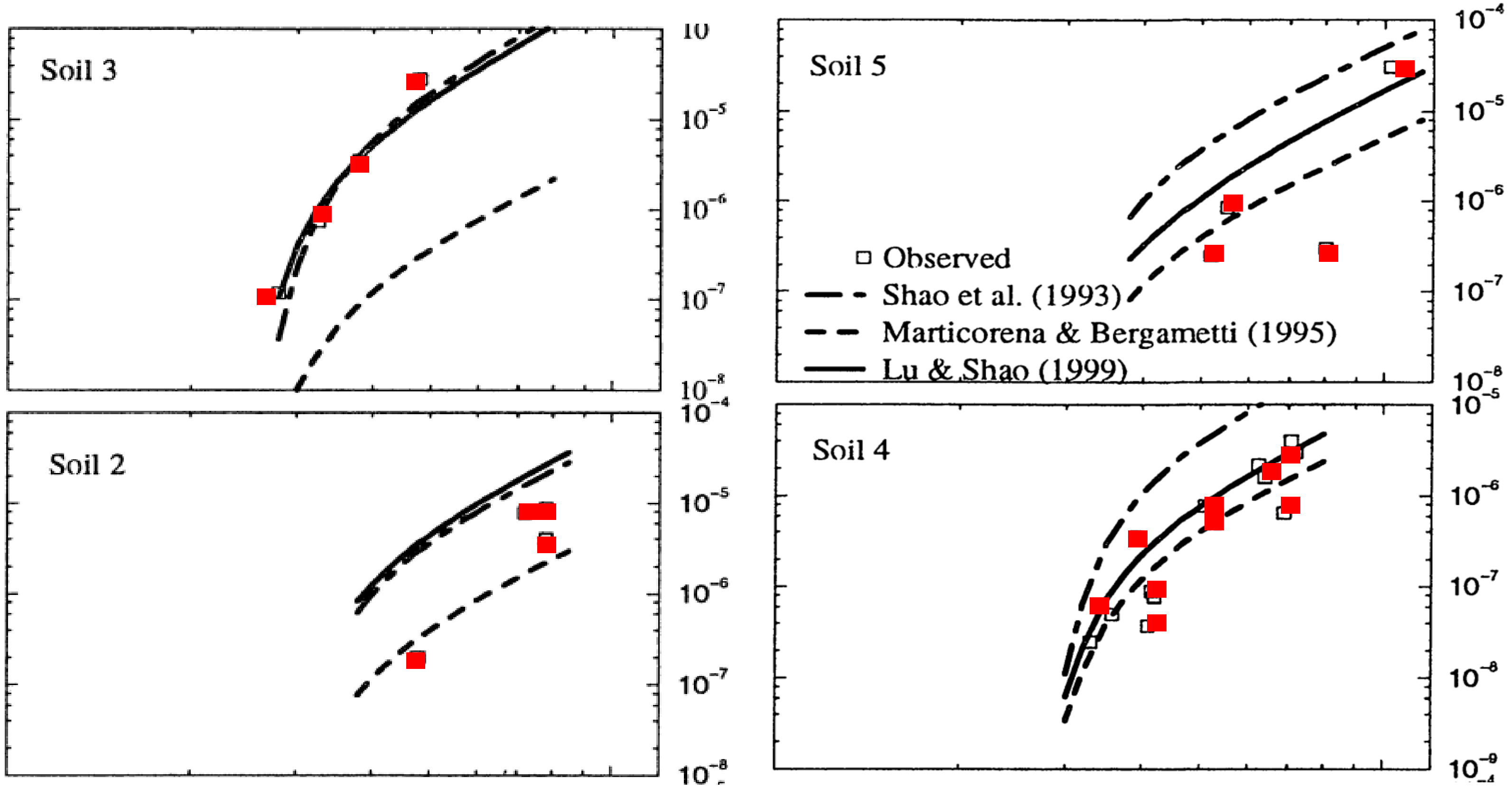
➪ Empirical parameterization

- *Marticorena and Bergametti (1995)* : $\alpha = f(\%clay)$

➪ Physical parameterizations

- *Lu and Shao (2001)*
  $\alpha = f(p)$; p: plastic flow pressure = soil hardness
- *Alfaro et al. (1996;1998)*
  $\alpha = f(e_d)$; Cohesion energy of the particles
- *Shao et al. (2004)*
  $\alpha = f(p; \text{soil pdf})$; undisturbed and fully disturbed pdf
- *Kok (2011a, 2011b)*
  $\alpha = f(\text{soil texture})$; fragmentation theory

Simulated vertical mass fluxes



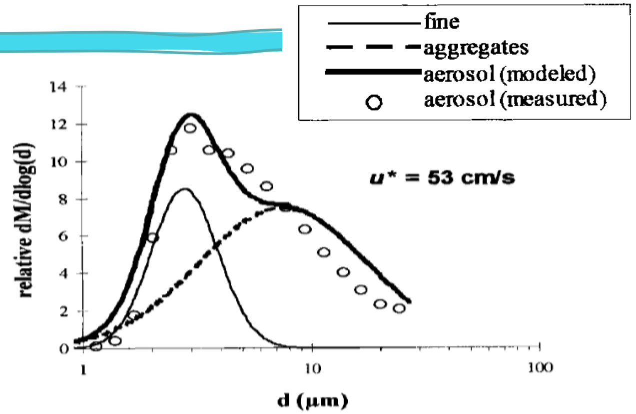
(Shao, 2001; data from Gillette, 1979)

⇨**The orders of magnitude of the dust mass fluxes are reasonably well reproduced**

Emitted dust PSD

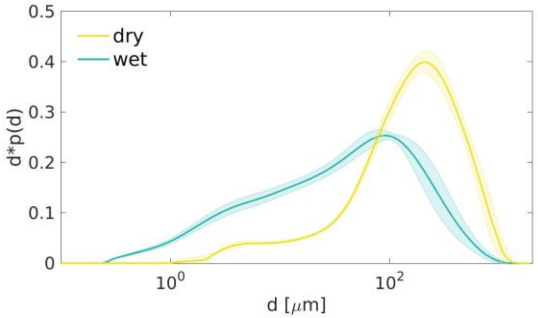
Alfaro et al. – Dust Production Model

- Three lognormal modes
- Bonding energy of aggregates
- Kinetic energy of saltators
- PSD depend on wind (based on wind tunnel)



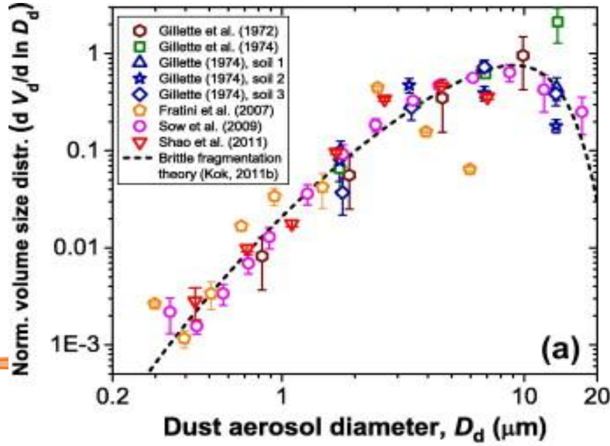
Shao model

- Weighted average between disturbed and undisturbed PSD
- Weighting factor ~ 2 empirical coeffs and wind
- PSD depends on wind (based on wind tunnel
- Revised version in 2011 based on measurements



Kok model (brittle fragmentation theory - BFT)

- Following the physics of brittle materials
- Emitted PSD up to ~ 12 µm independent of both the undisturbed soil PSD and the wind speed
- Dispersed soil PSD and the side crack propagation length (λ) assumed constant



Regional dust emission modeling

PROCESS

EROSION THRESHOLD

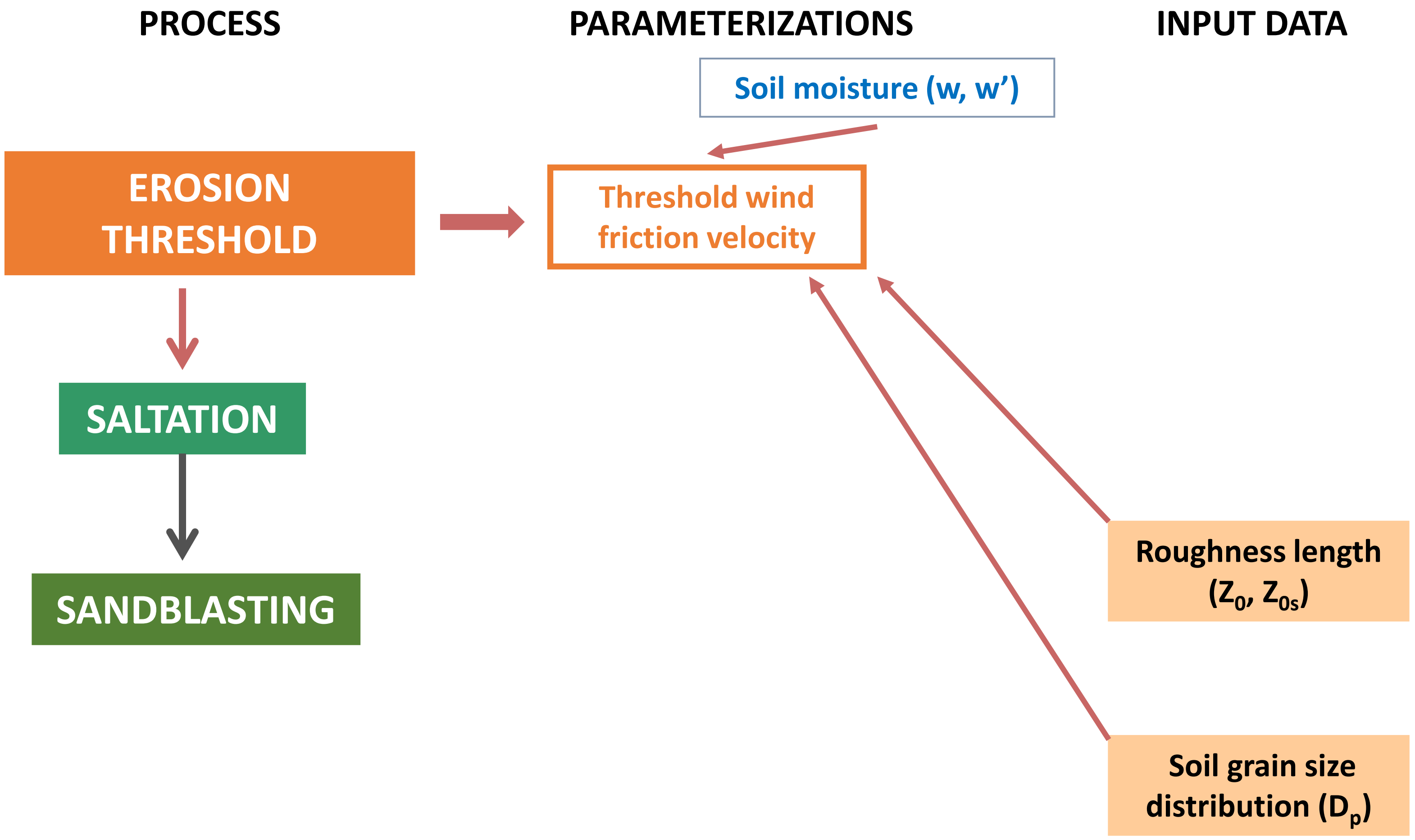
↓

SALTATION

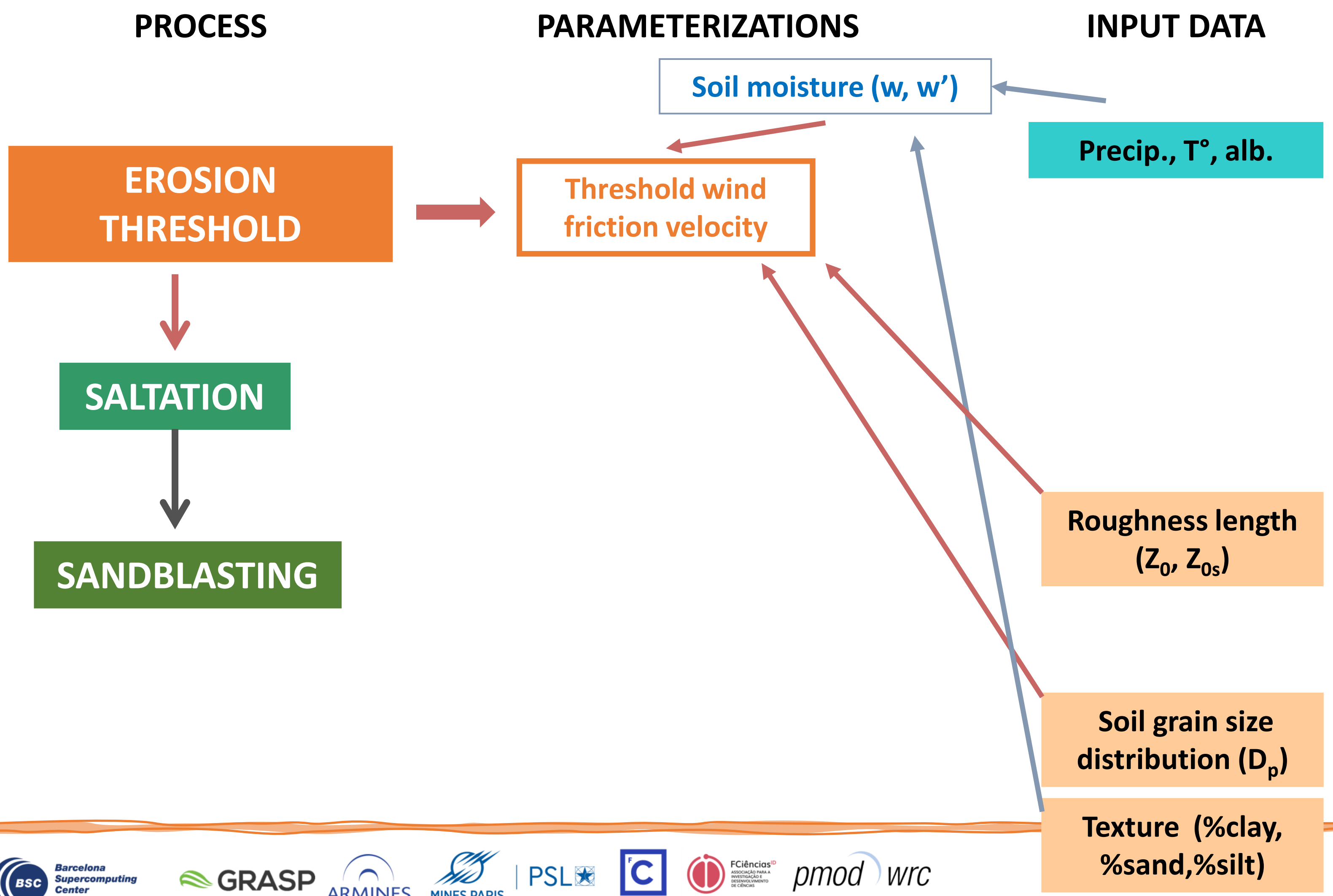
↓

SANDBLASTING

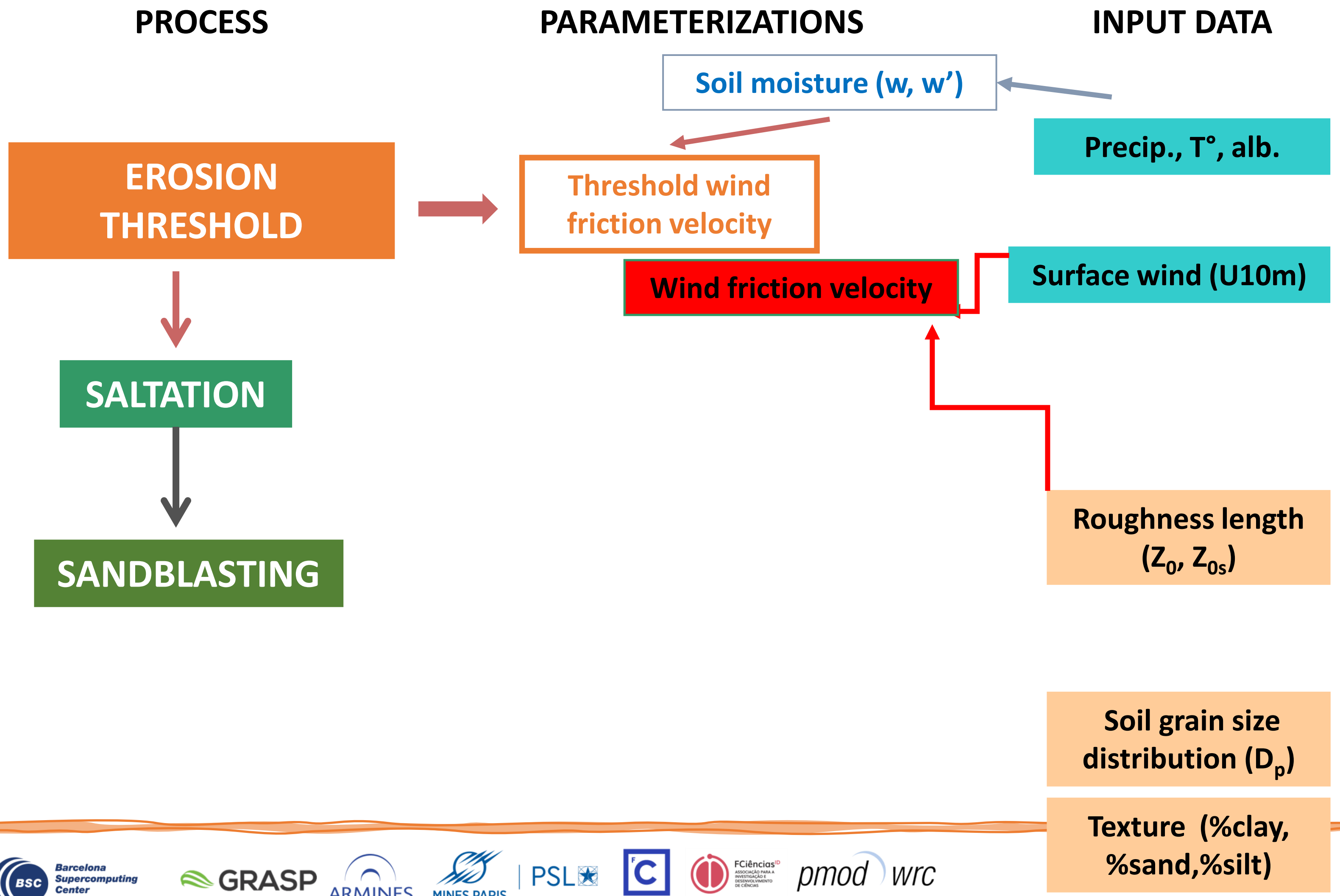
Regional dust emission modeling



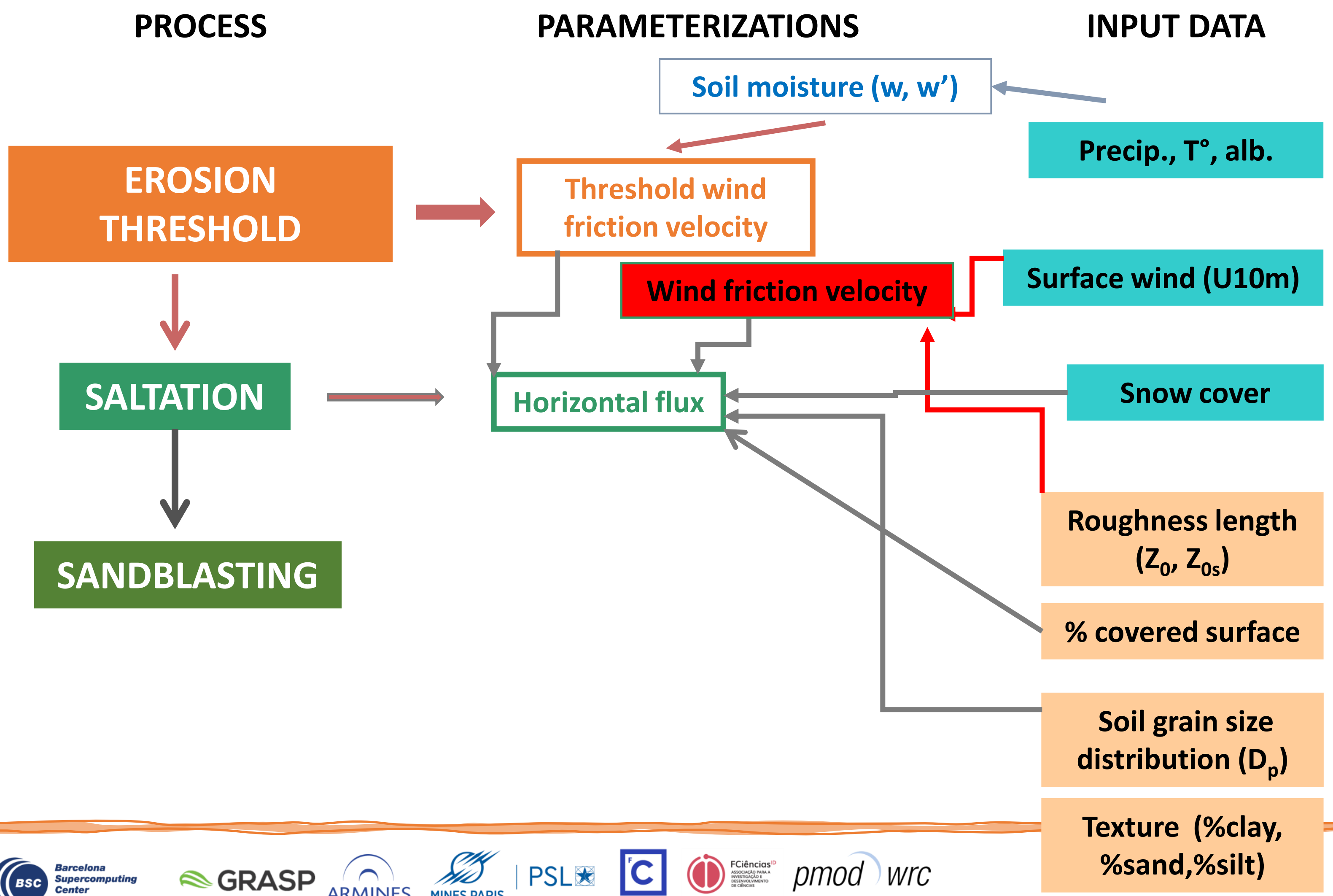
Regional dust emission modeling



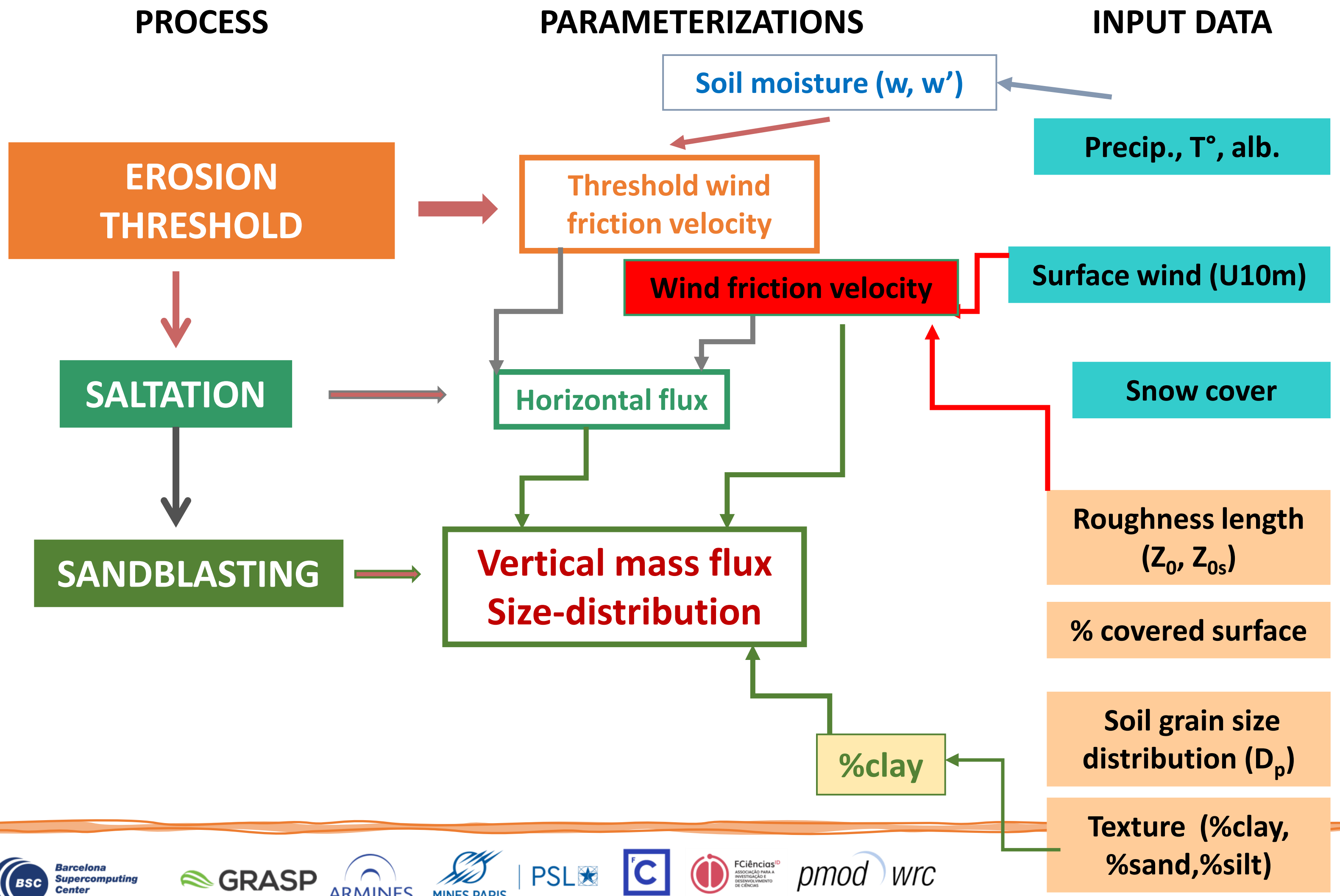
Regional dust emission modeling



Regional dust emission modeling



Regional dust emission modeling



Regional dust emission modeling

INPUT DATA

Provided by global or regional meteorological and/or climate models

METEOROLOGICAL DATA

- Precip., T°, alb.
- Surface wind (U10m)
- Snow cover

Specific parameters not available in distributed data sets : soil maps, land-use maps, atmospheric model inputs ..

SURFACE PROPERTIES

- Roughness length (Z_0, Z_{0s})
- % covered surface (E)
- Soil grain size distribution (D_p)
- Texture (%clay, %sand,%silt)

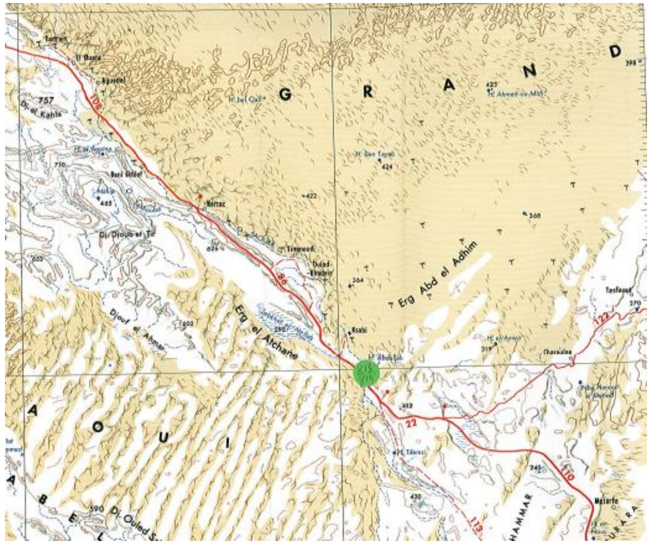
ATARRI

Regional dust emission modeling

Surface roughness and soil mapping

A geomorphologic approach

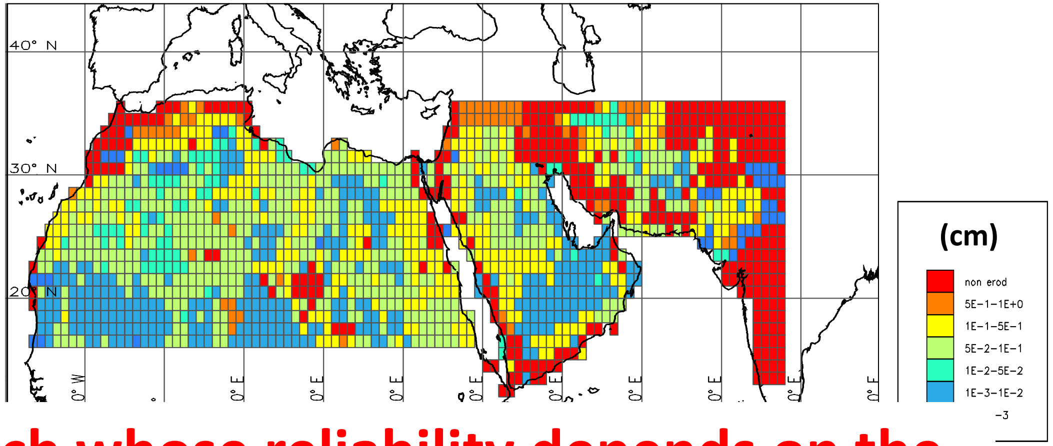
IGN topographic map



(Callot et al, 2000)

Manual file production

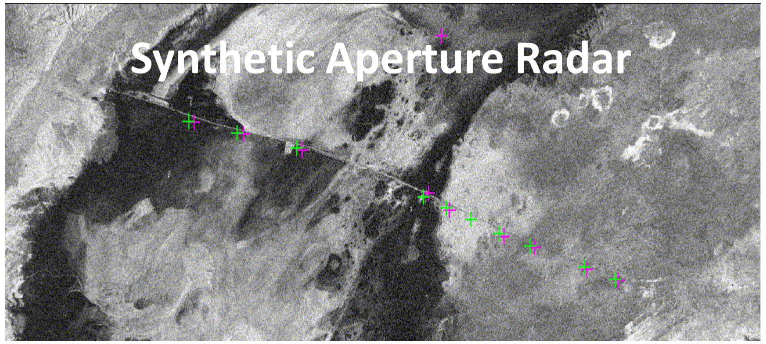
Aerodynamic roughness map

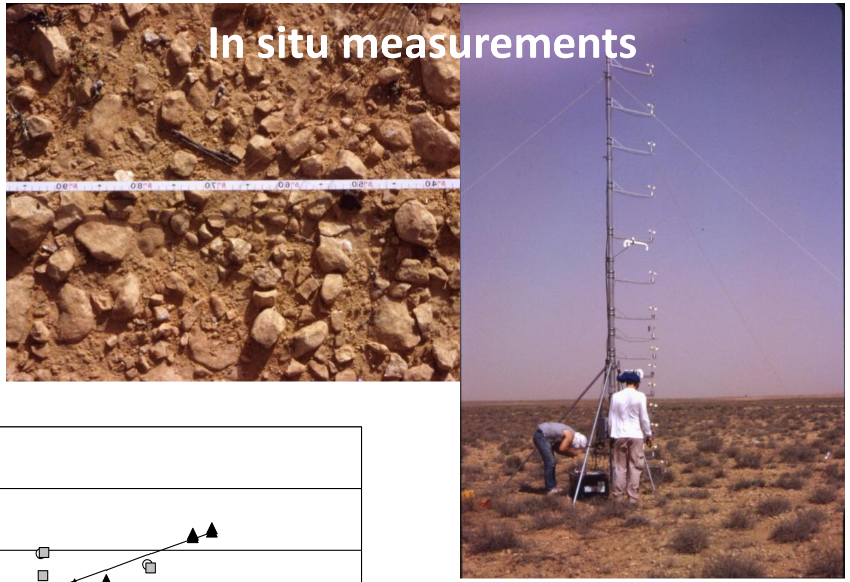


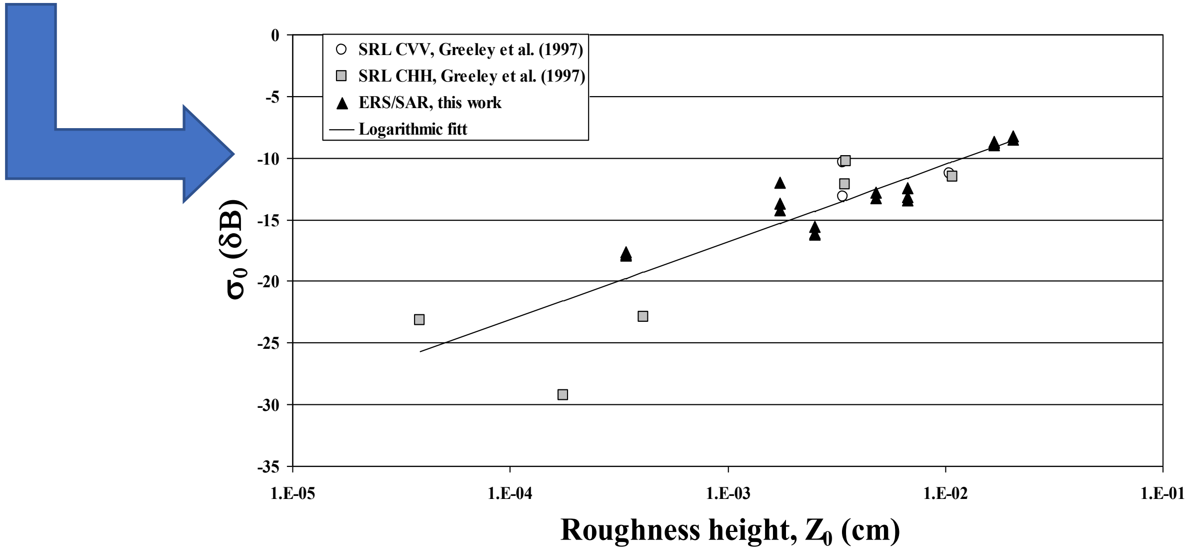
⇨A time consuming approach whose reliability depends on the quantity and quality of available initial maps/information

Regional dust emission modeling

Roughness mapping by radar measurements







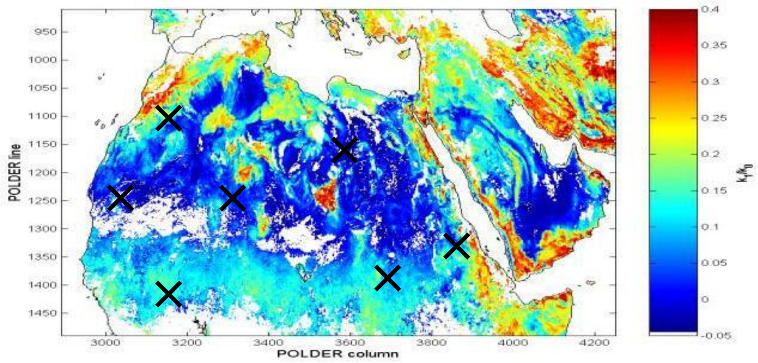
(Marticorena al., 2006)

⇨ **High resolution (~10m) mapping for local applications**

Regional dust emission modeling

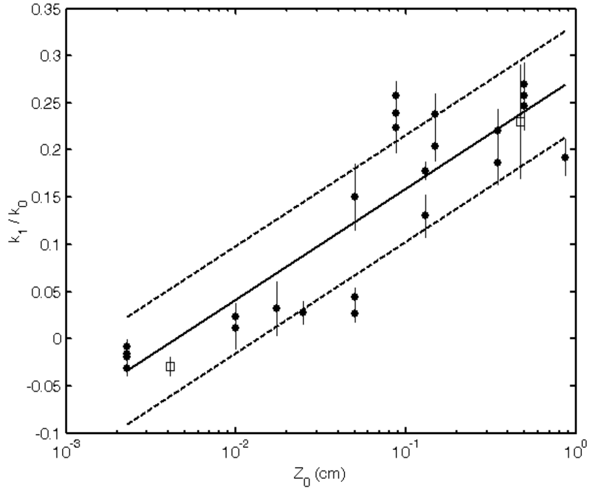
Roughness mapping with POLDER BRDF

Protrusion coefficient (*) from POLDER-1



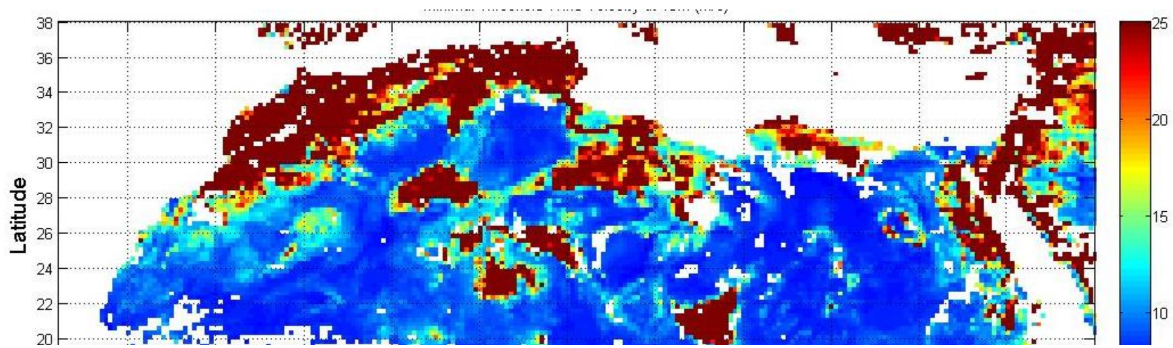
*(*Roujean et al.*, 1992]

Empirical relationship



(Marticorena et al., 2004; 2006)

Threshold wind velocities (at 10m)



⇨ **Medium resolution mapping for regional applications**

Regional dust emission modeling

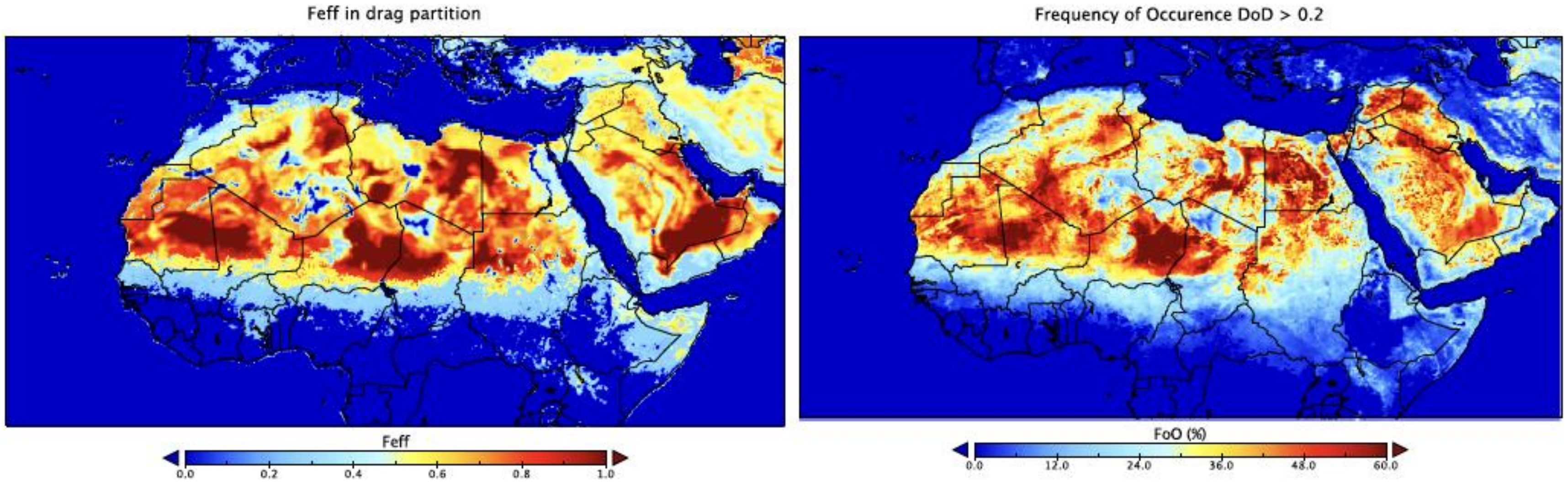


Figure 7. f_{eff} (left) strongly resembles the FoO from MODIS (right, in %).

Regional dust emission modeling

INPUT DATA

Provided by global or regional meteorological and/or climate models

- Precip., T°, alb.
- Surface wind (U10m)
- Snow cover

METEOROLOGICAL DATA

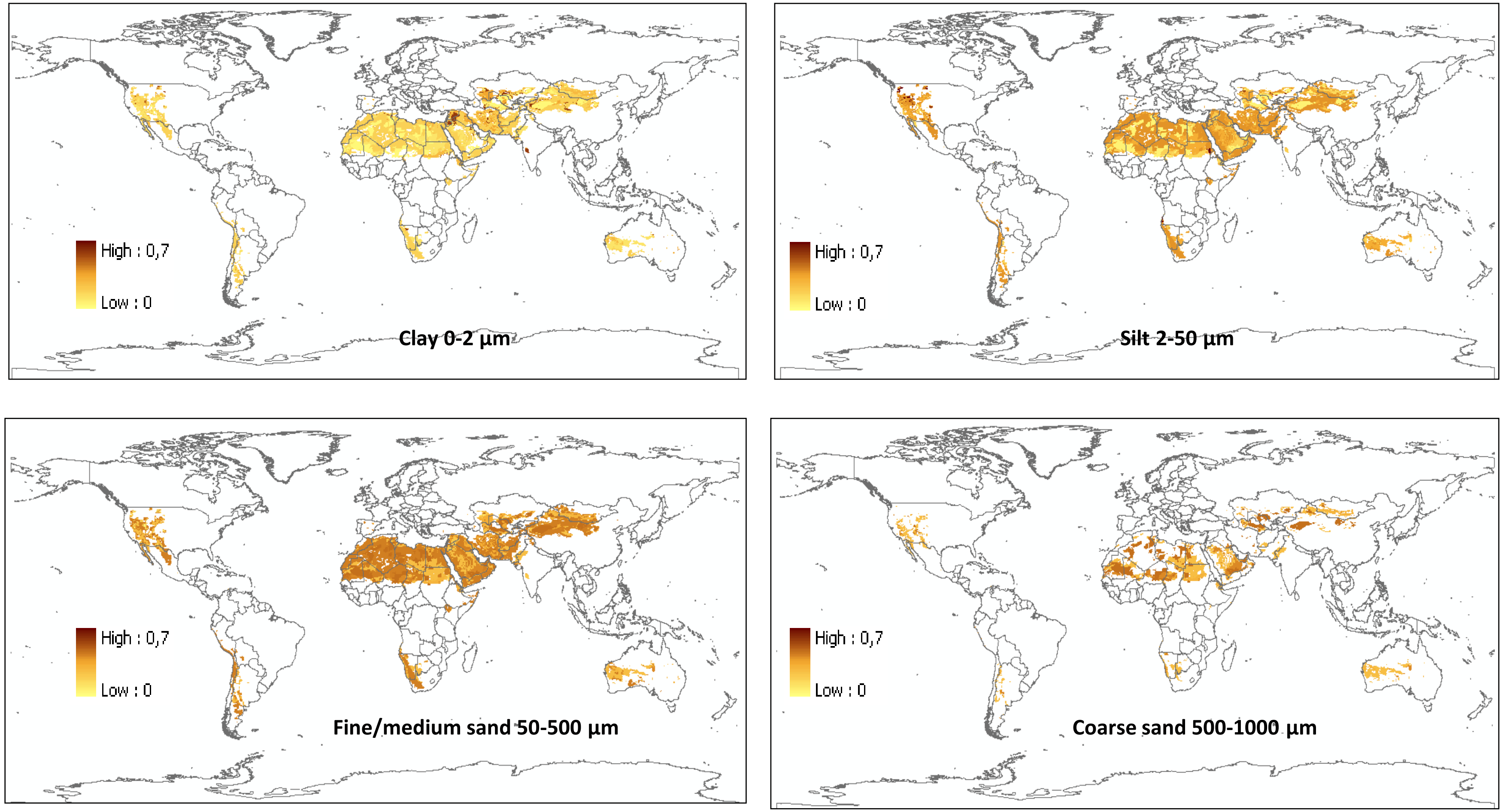
- Roughness maps derived from remote sensing
- Soil characteristics derived from geomorphological interpretations and/or in-situ sampling

- Roughness length (Z_0, Z_{0s})
- % covered surface (E)
- Soil grain size distribution (D_p)
- Texture (%clay, %sand,%silt)

SURFACE PROPERTIES

Soil texture

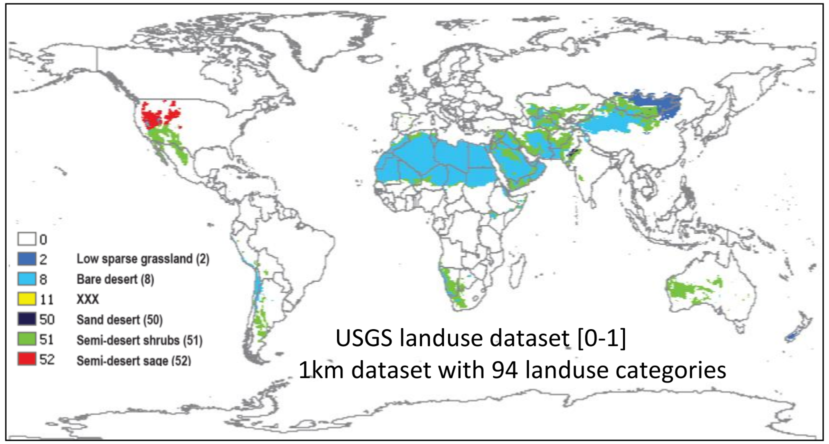
Parent soil size distribution



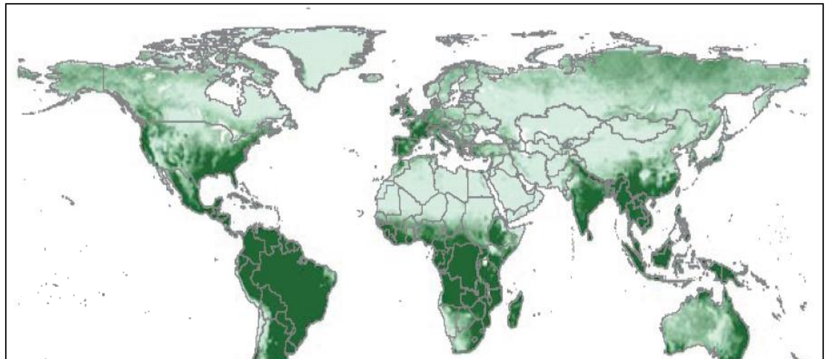
Four top soil texture classes according STASGO-FAO 1km database are converted to 4 parent soil size categories following Tegen et al. [2002]

Erodible fraction

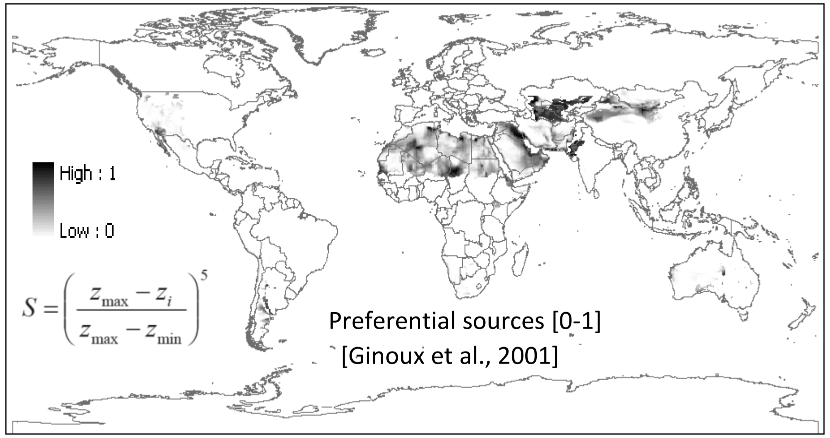
Dust source function: the NMMb/BSC-Dust model



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

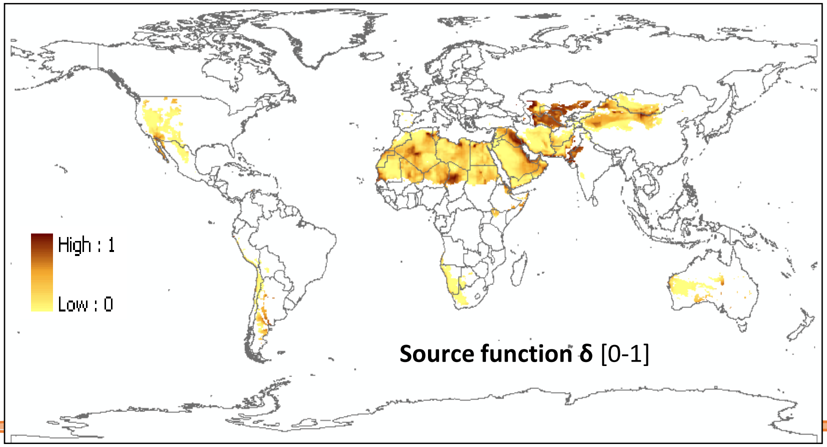


NESDIS vegetation fraction [0-1]
0.144 degree monthly 5-yr climatology



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

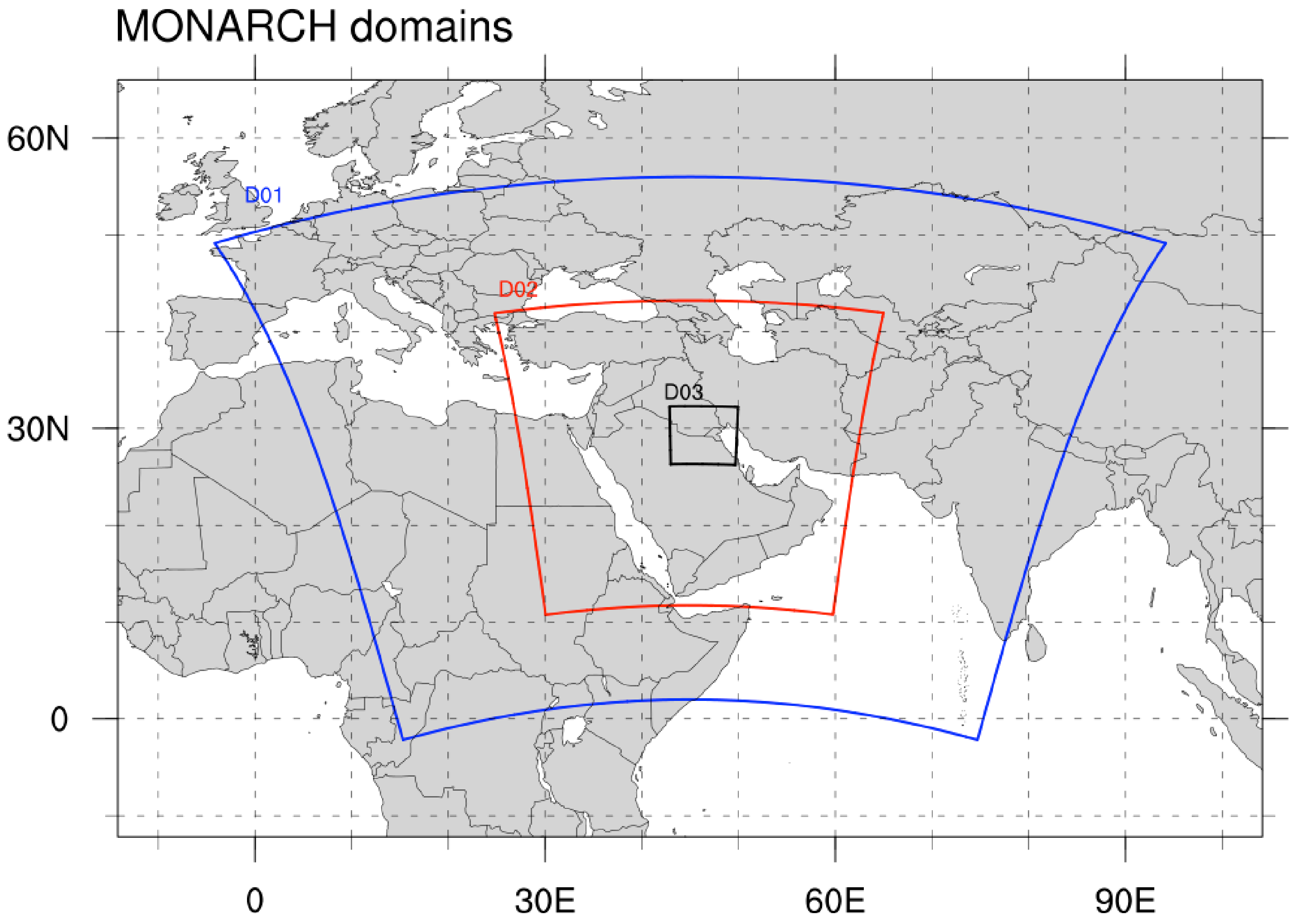
Preferential sources [0-1]
[Ginoux et al., 2001]



Source function δ [0-1]

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

Effects of erodible fraction on results



Effects of erodible fraction on results

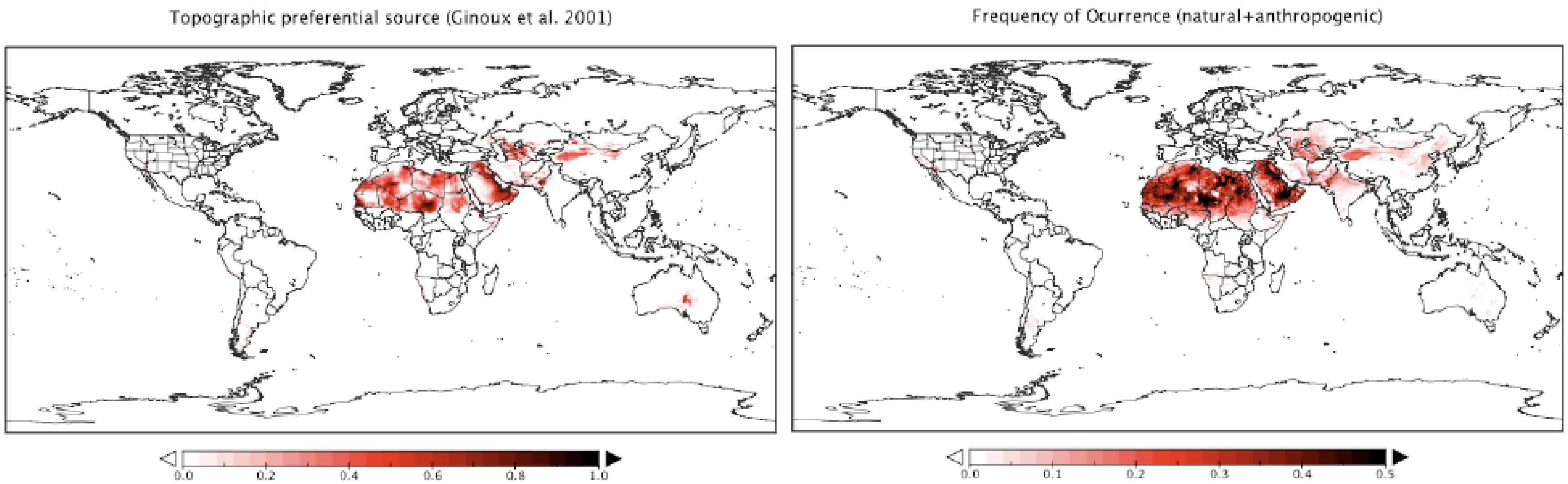


***Figure 6**. Topographic preferential source (Ginoux et et al. 2001) (left). Frequency of Occurrence (FoO) of DOD > 0.2 based on MODIS Deep Blue colletion 6 (Ginoux et al., 2012) (right).*

Effects of erodible fraction on results

AERONET stations map with DOD time series

Effects of erodible fraction on results

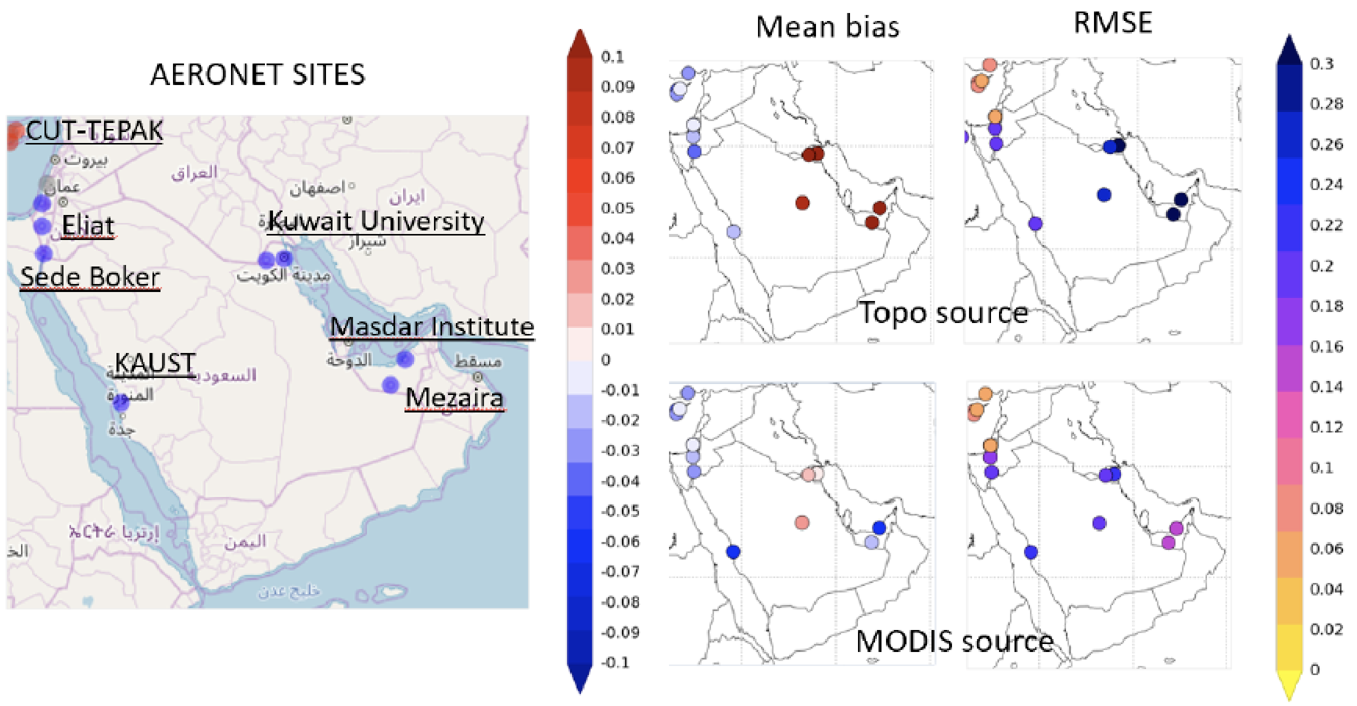
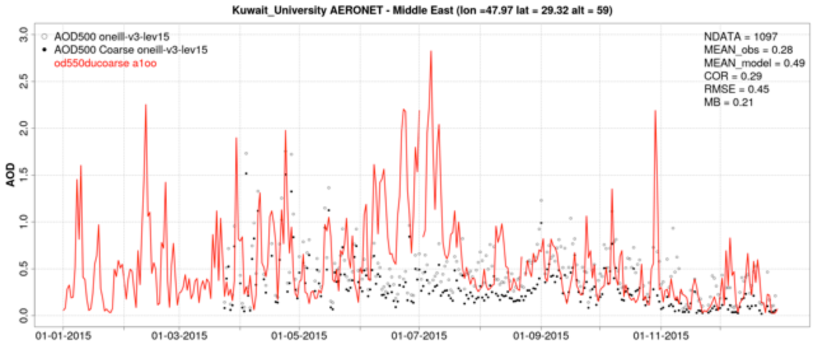
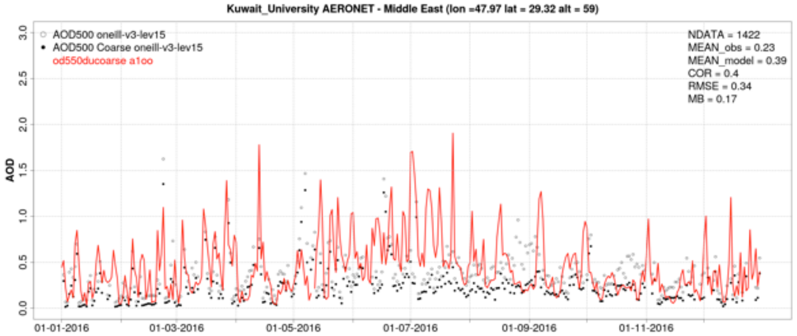


Figure 11. On the left: Map showing the location of AERONET stations and their names used in the evaluation. On the right: the Mean Bias and Root Mean Square Error (RMSE) for the two simulations, using the topo source or the MODIS source.

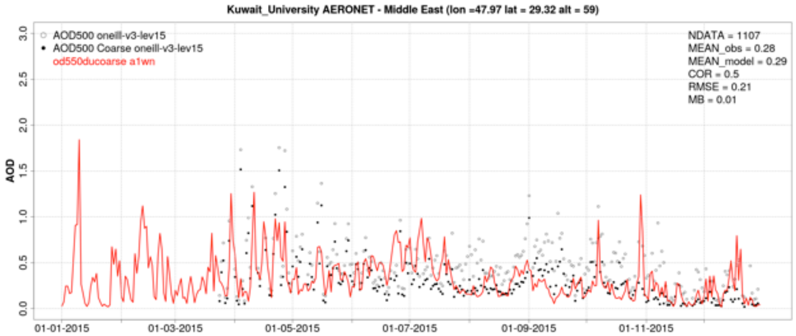
Effects of erodible fraction on results

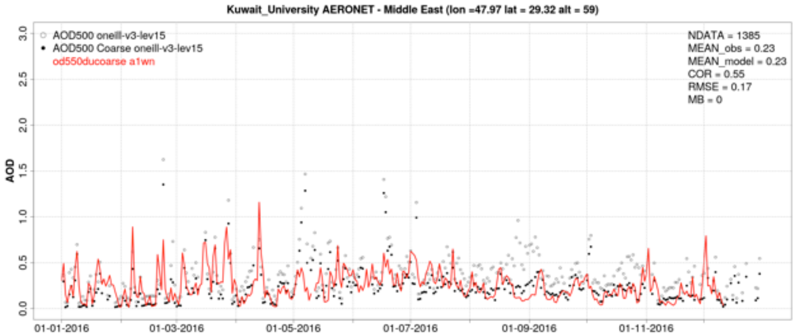
2015 | 2016





Topo Source



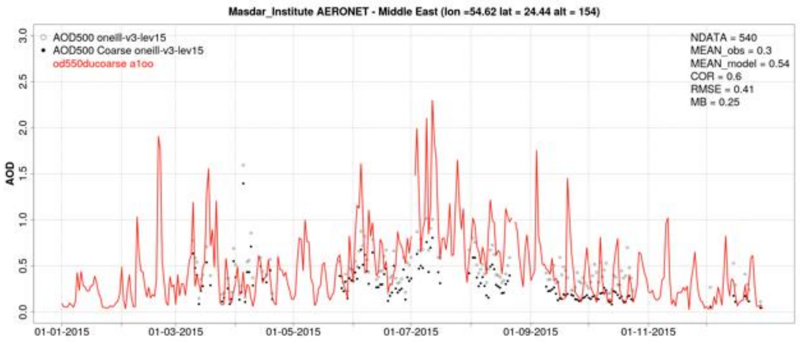


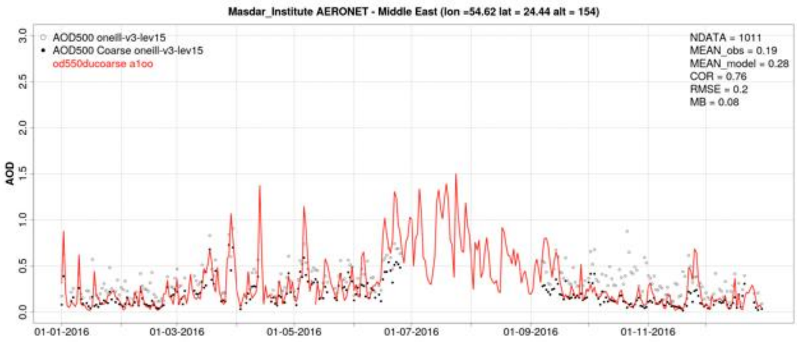
MODIS Source

Effects of erodible fraction on results

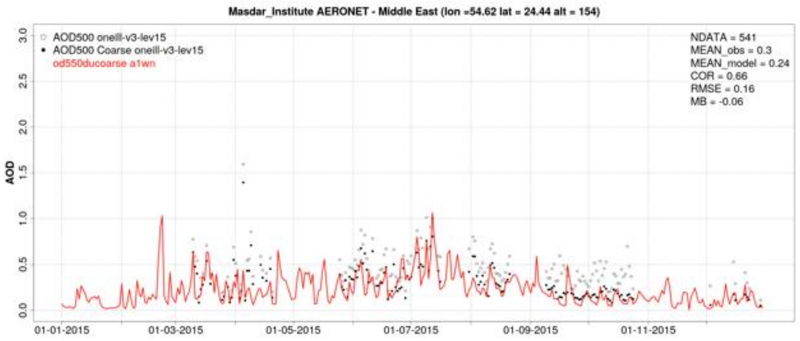
2015

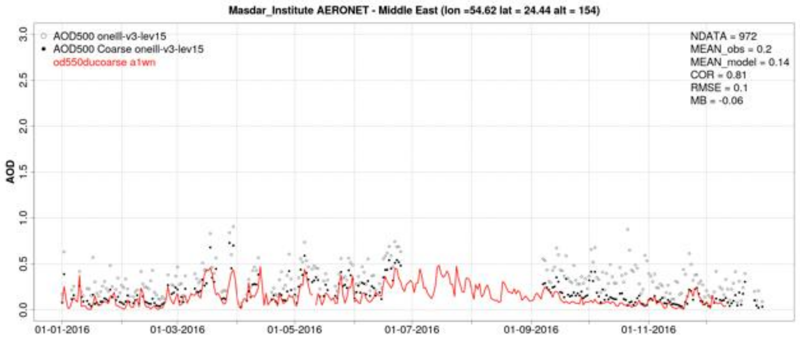
2016





Topo Source

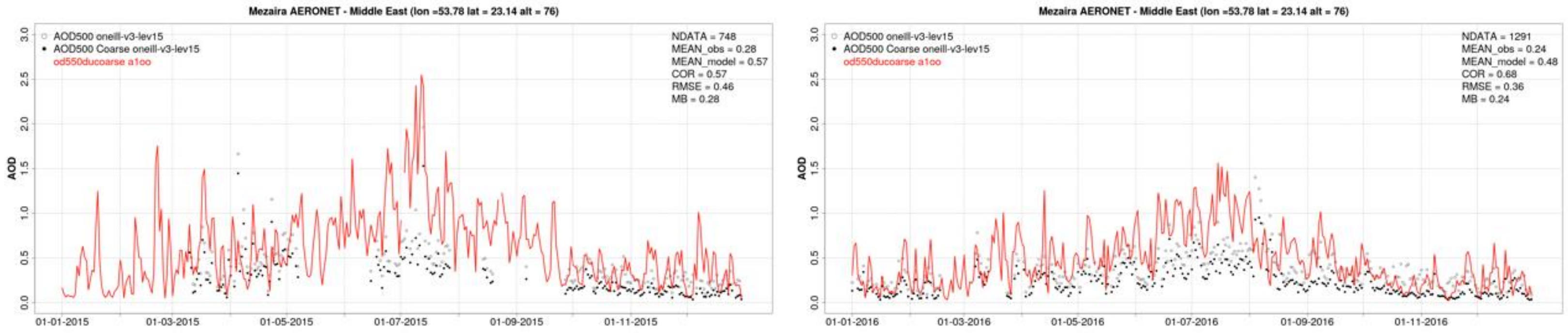




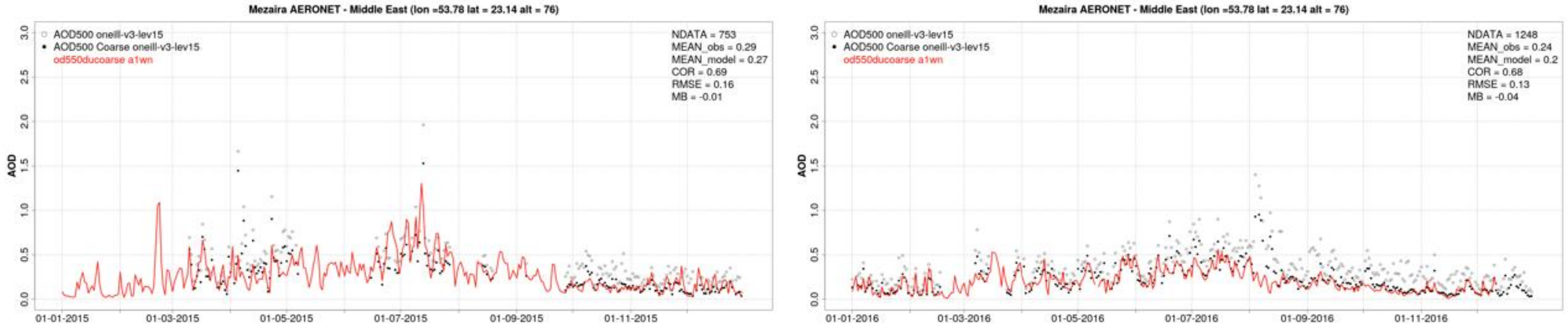
MODIS Source

Effects of erodible fraction on results

2015 | 2016



Topo Source

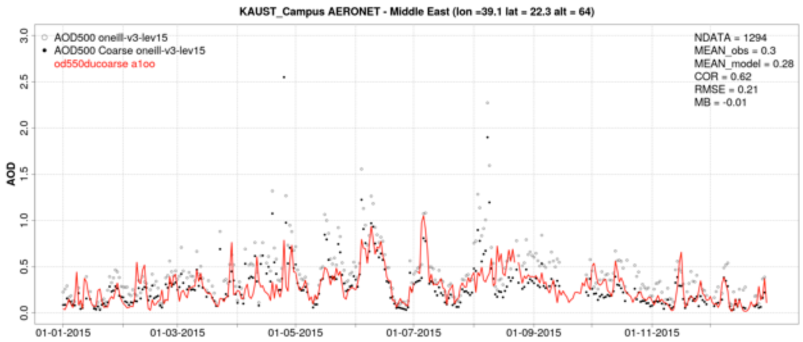


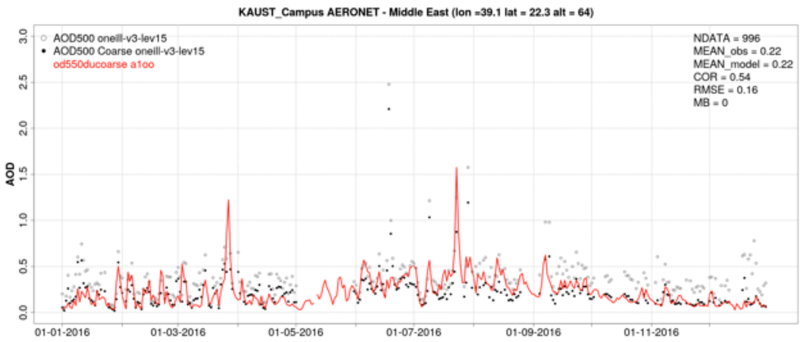
MODIS Source

Effects of erodible fraction on results

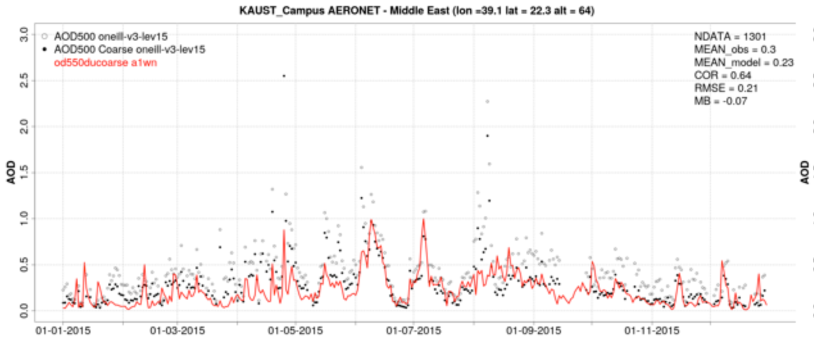
2015

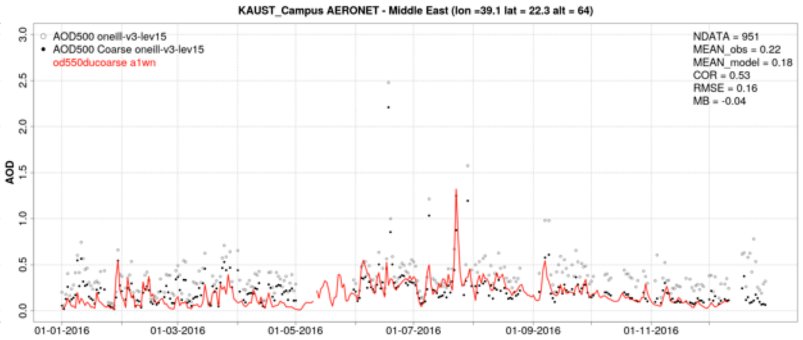
2016





Topo Source





MODIS Source

Advection

3D Advection Equation

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = 0$$

1D example

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = 0$$

With:

- Constant velocity $u > 0$
- Initial dust distribution: a bump in the center
- Boundary: periodic (dust leaving the right comes back on the left)

🔢 Upwind Scheme (Forward Time, Backward Space)

Discretize the domain:

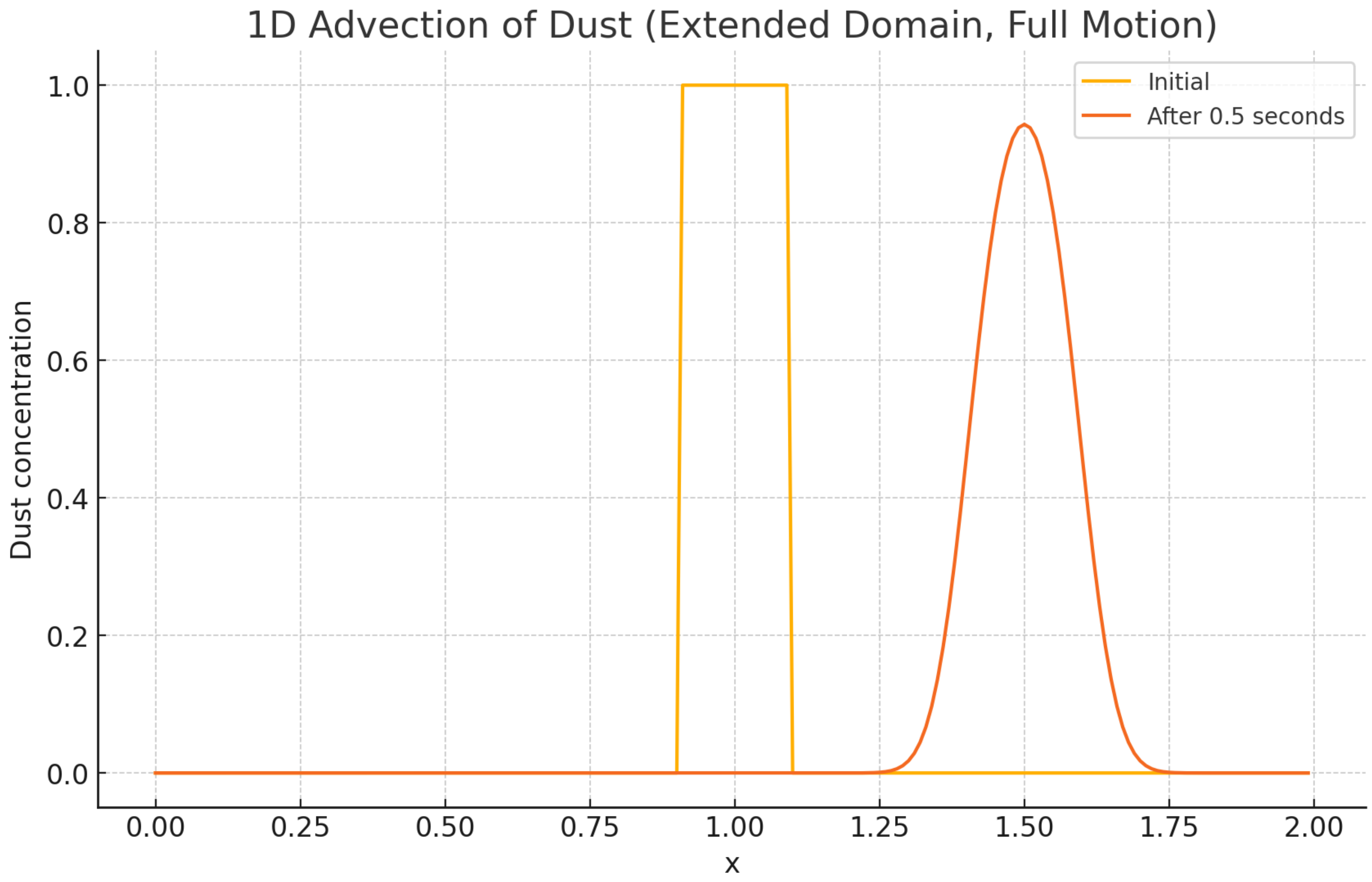
- Time step: Δt
- Space step: Δx
- Grid point: C_i^n is dust at space x_i and time t_n

The **upwind method** is:

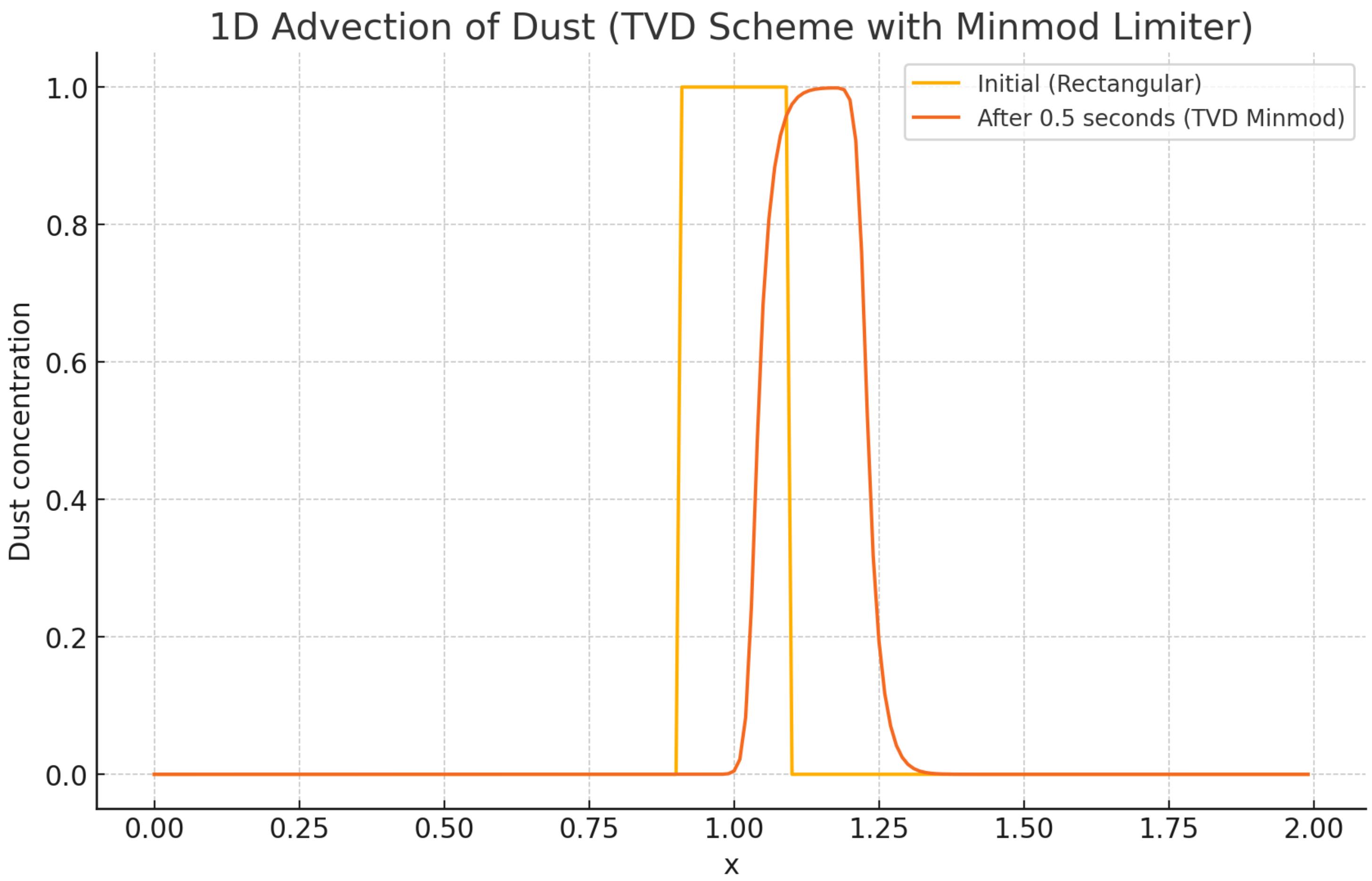
$$C_i^{n+1} = C_i^n - \frac{u\Delta t}{\Delta x}\left(C_i^n - C_{i-1}^n\right)$$

Advection

Upwind scheme (with numerical diffusion)



Advection



1D Advection of Dust (TVD Scheme with Minmod Limiter)
Initial (Rectangular)
After 0.5 seconds (TVD Minmod)
Dust concentration
x
0.0
0.2
0.4
0.6
0.8
1.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

Diffusion

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

📘 1D Diffusion Equation (Continuous Form)

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

Where:

- $C(x,t)$ is the dust concentration,
- D is the diffusion coefficient,
- x is the spatial coordinate,
- t is time.

Diffusion

🔢 Discrete Approximation:

1. **Time derivative (Forward Euler):**

$$\frac{\partial C}{\partial t} \approx \frac{C_i^{n+1} - C_i^n}{\Delta t}$$

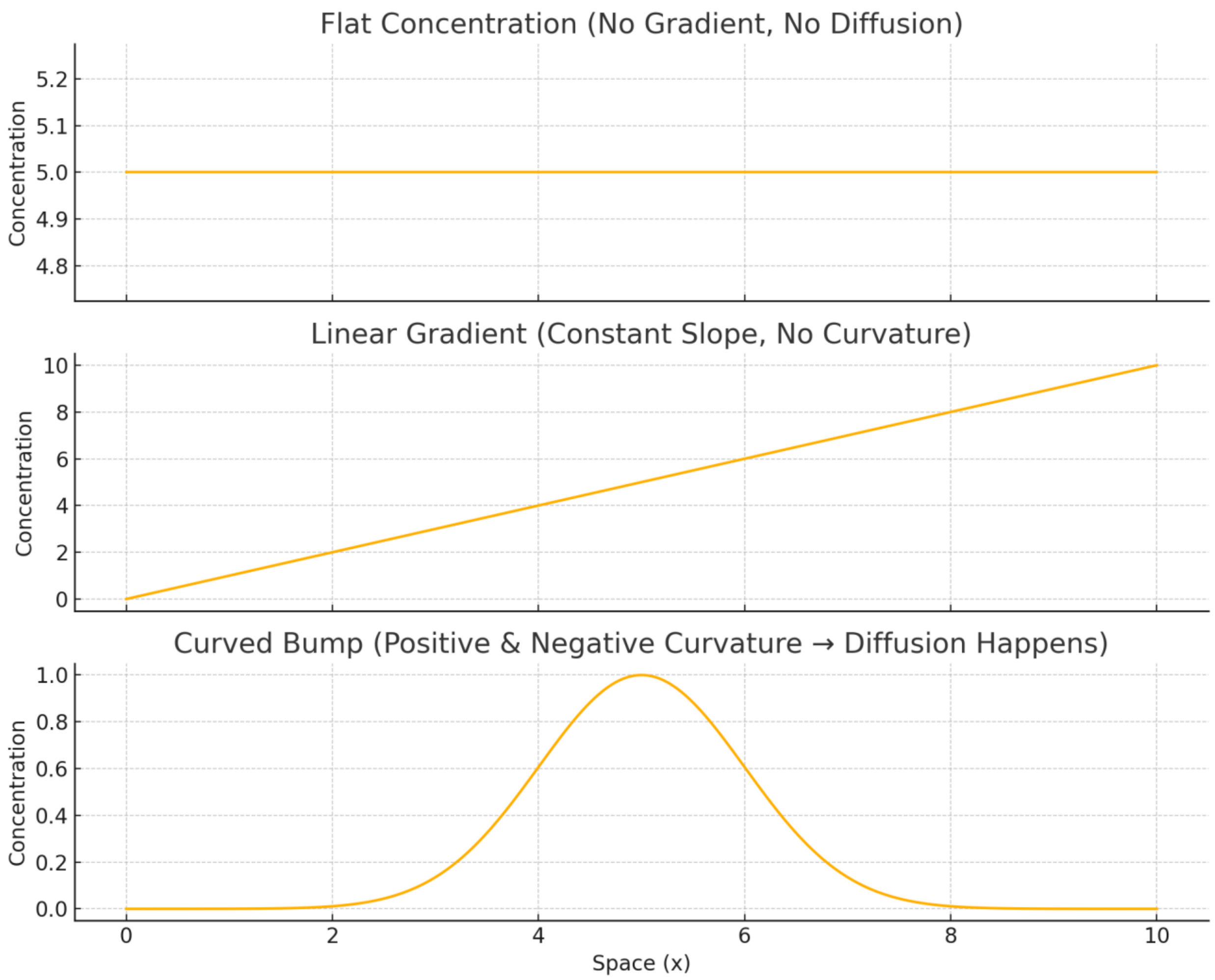
2. **Second spatial derivative (Central Difference):**

$$\frac{\partial^2 C}{\partial x^2} \approx \frac{C_{i+1}^n - 2C_i^n + C_{i-1}^n}{\Delta x^2}$$

✅ Final Discretized Formula (Explicit Scheme):

$$C_i^{n+1} = C_i^n + \frac{D\Delta t}{\Delta x^2}\left(C_{i+1}^n - 2C_i^n + C_{i-1}^n\right)$$

Diffusion

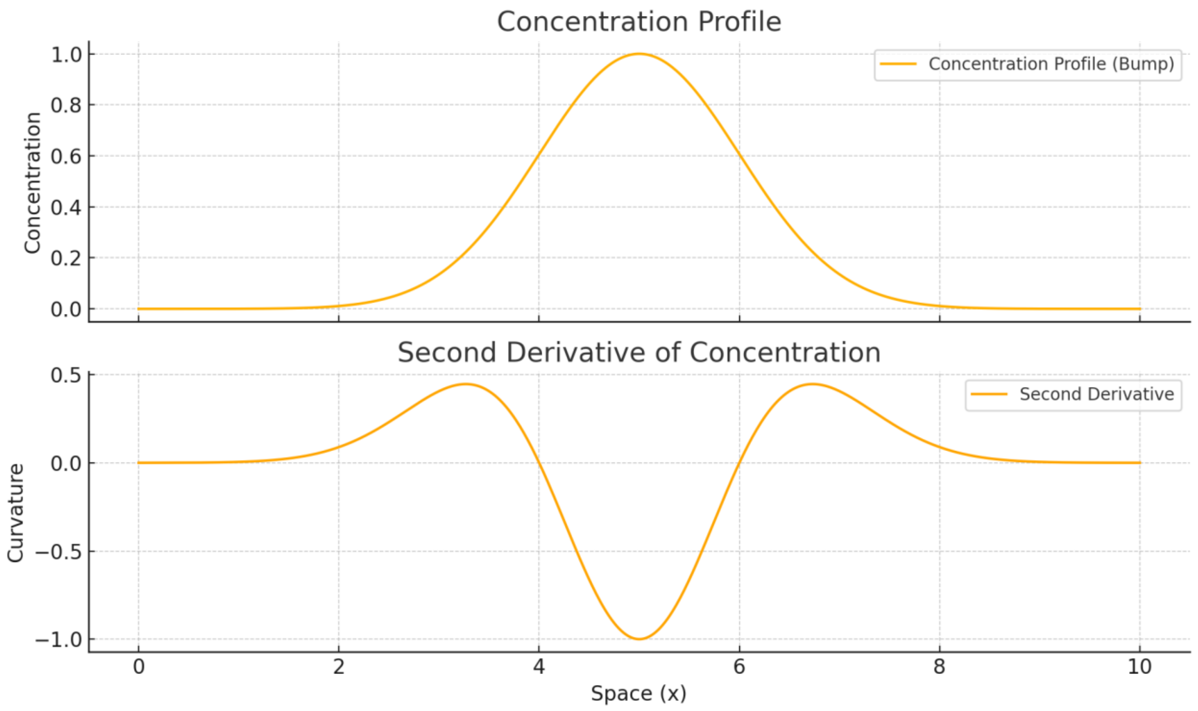


Here's a visual showing how the shape of the concentration profile affects diffusion:

1. **Flat Line**:
   1. No slope, no curvature → **no movement**. Everything is in balance.
2. **Linear Gradient**:
   1. Constant slope, but no curvature → **still no diffusion**. The rate of change is the same everywhere.
3. **Curved Bump**:
   1. Here's where it gets interesting:
      1. In the middle (the bump), dust is **high** → it **spreads outward**.
      2. On the sides (the dips), dust is **low** → dust **flows in**.
   2. This movement is caused by the **second derivative** (curvature).

So: **Diffusion occurs when the curvature isn't zero**, and that's why the second derivative drives the process!

Diffusion

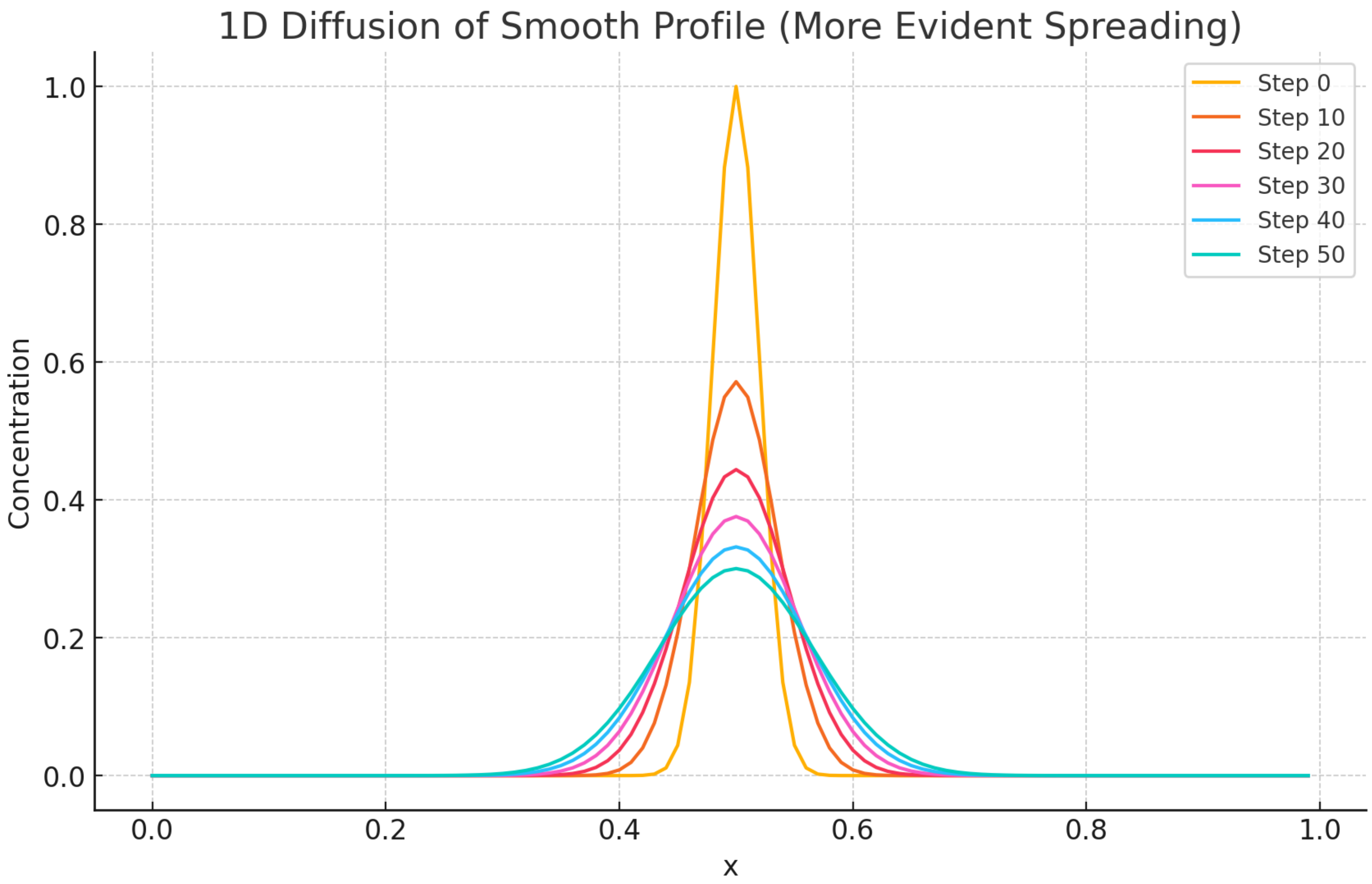


Here's the visual showing both the **concentration profile** (the bump) and its **second derivative**:

- The **bump** is highest in the middle and tapers off to the sides.
- The **second derivative**:
  - Is **negative** at the top of the bump → this means concentration is curving downward → **dust flows outward**.
  - Is **positive** in the dips → the curve is curving upward → **dust flows inward**.

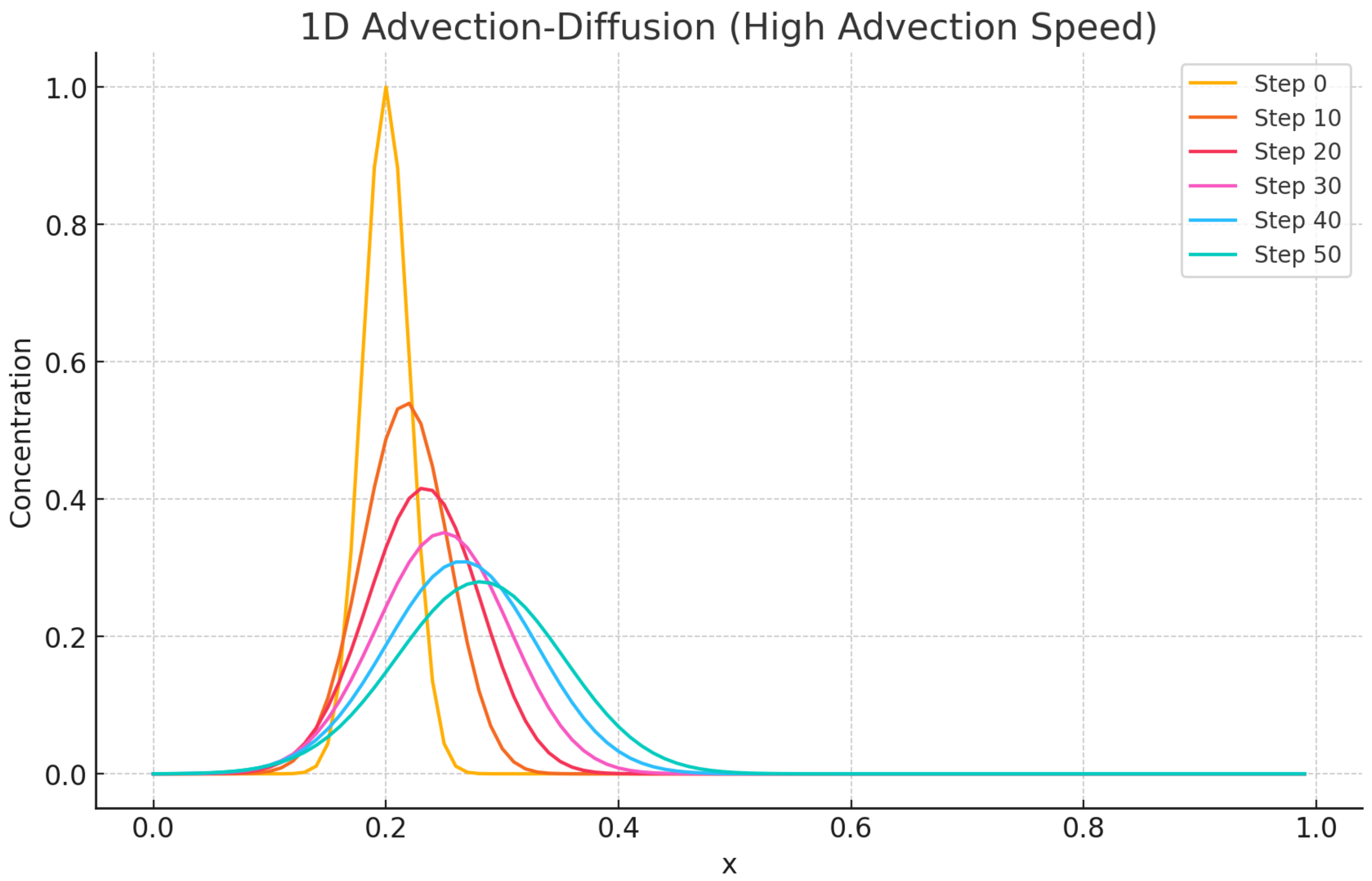
This second derivative determines where and how fast dust will **diffuse** — it's the mathematical way to measure the **"push" or "pull"** caused by local shape.

Diffusion

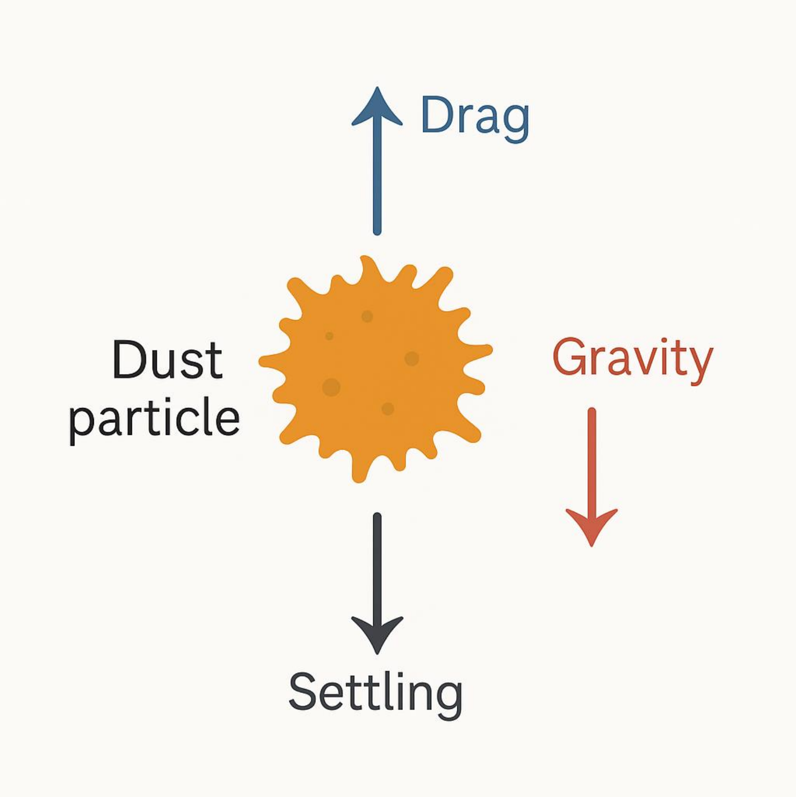


1D Diffusion of Smooth Profile (More Evident Spreading)
Step 0
Step 10
Step 20
Step 30
Step 40
Step 50
Concentration
x
0.0
0.2
0.4
0.6
0.8
1.0

Diffusion and advection



Dust settling (sedimentation)



What Controls How Fast Dust Settles?

1. Gravity

The main force pulling dust downward.

2. Air Resistance

As dust falls, it **pushes through air**.

The air pushes back → this is **drag**.

The result is a **terminal (settling) velocity** — the constant speed a particle falls at when gravity and drag are balanced.

3. Particle Size

Large particles fall quickly (seconds to minutes).

Small particles can stay **suspended for days or even weeks**, especially in the upper atmosphere.

4. Air Turbulence

Wind gusts and turbulence can **keep particles suspended** longer.

In calm air, dust settles faster.

Dust settling (sedimentation)

⏱️ Settling Velocity: The Key Quantity

For a small spherical particle in still air, the **Stokes' Law** gives its settling velocity:

$$v_s = \frac{2}{9} \cdot \frac{r^2(\rho_p - \rho_a)g}{\mu}$$

Where:

- v_s: settling velocity
- r: particle radius
- ρ_p: particle density
- ρ_a: air density
- g: gravity
- μ: dynamic viscosity of air

🔎 Takeaway:

- Settling speed increases with **bigger, heavier particles**.
- Smaller particles settle much more slowly.

Note that the effect of
Turbulence is solved separately in the vertical diffusion term

Dry deposition

Dry deposition is how dust (and other aerosols or gases) **settles onto the ground** in the absence of rain. It's driven by:

Gravity

Turbulence

Surface interaction (sticking, bouncing, etc.)

📉 Deposition Flux

Once you know v_d, you get the **deposition flux**:

$$F = v_d \cdot C$$

Where:

- F: flux of deposited dust (mass per area per time)
- C: near-surface concentration of dust

Dry deposition

⚙️ The Resistance Approach

This approach models the **deposition velocity** v_d — the effective speed at which dust is removed from the air — using a chain of resistances:

$$v_d = \left(\frac{1}{r_a + r_b + r_c}\right) + v_s$$

or sometimes:

$$v_d = \left(\frac{1}{r_a + r_b + r_c}\right) \quad \text{(for gases or very small particles)}$$

Where:

Term	Name	What It Represents
r_a	Aerodynamic resistance	Transport through the turbulent atmosphere above the surface
r_b	Quasi-laminar boundary layer resistance	Passage through the thin, low-turbulence air just above the ground
r_c	Surface resistance	How well the surface captures or holds the particle once it reaches the ground
v_s	Gravitational settling velocity	Rate at which particles fall under gravity (important for larger particles)

1. r_a — Aerodynamic Resistance

- Depends on **wind speed**, **turbulence**, **surface roughness**
- Lower over forests or cities (rough)
- Higher over ice or deserts (smooth)

2. r_b — Quasi-Laminar Layer Resistance

- Important for **fine particles**
- Thin layer of air right above the ground where turbulence drops off
- Acts like a "last filter" before particles hit the ground

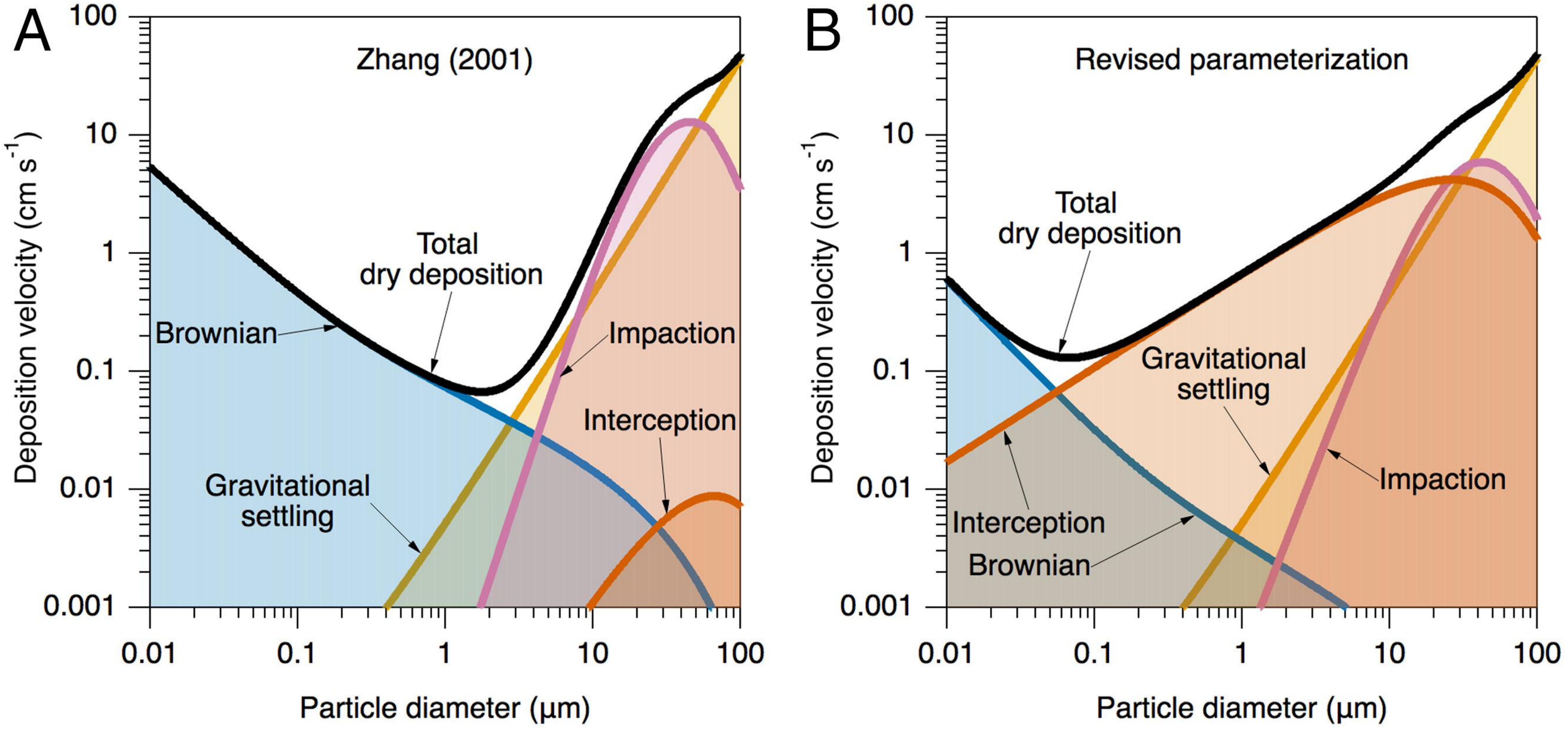
3. r_c — Surface Resistance

- Tells you how easily particles **stick to** or **bounce off** the surface
- Very **low** over wet or sticky surfaces (like leaves or water)
- **High** over hard, dry surfaces (like concrete or ice)

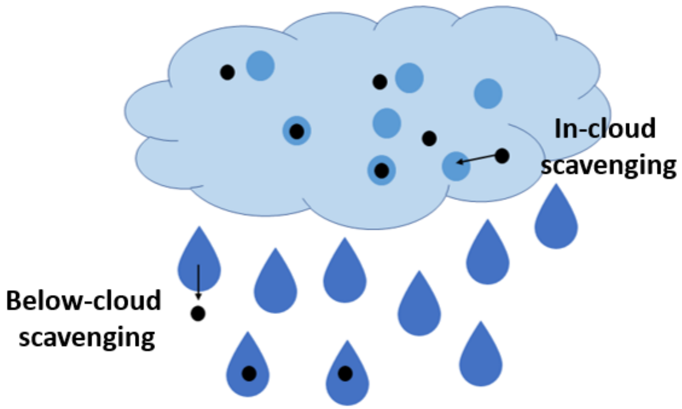
4. v_s — Settling Velocity

- Adds a **direct gravitational component** to deposition
- Dominant for **coarse particles** (> 10 µm)

Dry deposition



Wet scavenging (deposition)



1. In-Cloud Scavenging ("Rainout")

What it is:

- Occurs **inside clouds**, before the precipitation reaches the ground.
- Dust and aerosols become **incorporated into cloud droplets** (or ice crystals) during cloud formation.
- When these droplets grow and fall, they **carry the particles down** with them.

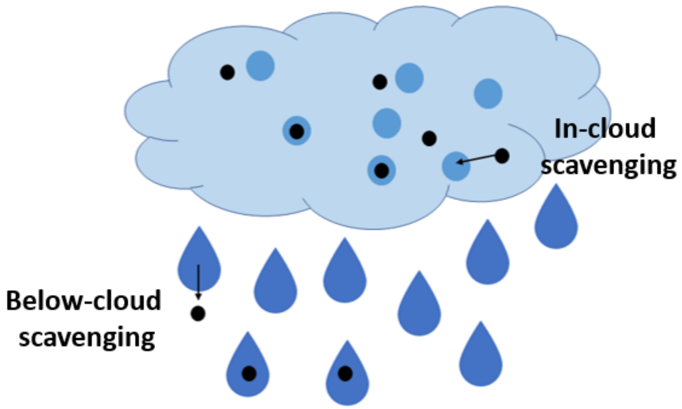
Mechanisms:

- **Nucleation**: particles act as **cloud condensation nuclei (CCN)** or **ice nuclei (IN)**
- **Diffusion or collision** with existing cloud droplets

Key features:

- Important for **fine particles** that don't settle easily
- Affects **higher altitudes**
- Highly dependent on **cloud microphysics** (temperature, droplet size, supersaturation)

Wet scavenging (deposition)



🌨️ 2. Below-Cloud Scavenging ("Washout")

🔍 What it is:

- Occurs **below the cloud**, as falling rain or snow **collides with and captures** particles in the air.

🧪 Mechanisms:

- **Interception**: raindrops collect particles in their path
- **Impaction**: larger particles hit falling drops due to inertia
- **Brownian diffusion**: small particles zigzag into droplets

📌 Key features:

- Affects **low-altitude or near-surface dust**
- More effective for **larger precipitation rates** and **larger particles**
- Dominates removal of dust **already in the lower atmosphere**

In-cloud scavenging

1. In-Cloud Scavenging (Rainout)

General Removal Rate Equation:

$$\frac{dC}{dt} = -\Lambda C$$

Where:

- C: concentration of aerosol particles in the cloud
- Λ: in-cloud scavenging coefficient (s^{-1})

Solution:

$$C(t) = C_0 e^{-\Lambda t}$$

Where C_0 is the initial concentration.

Scavenging Coefficient (empirical form):

$$\Lambda = \alpha R$$

Where:

- α: empirical parameter (depends on aerosol and cloud type)
- R: precipitation rate (mm/hr)

Solving the Equation

Let's solve:

$$\frac{dC}{dt} = -\Lambda C$$

Step 1: Separate variables

$$\frac{dC}{C} = -\Lambda \, dt$$

Step 2: Integrate both sides

$$\ln C = -\Lambda t + \text{const}$$

Step 3: Exponentiate

$$C(t) = C_0 e^{-\Lambda t}$$

Where C_0 is the initial concentration at time $t = 0$.

Below cloud scavenging

🌧️ 2. Below-Cloud Scavenging (Washout)

✅ General Washout Equation:

$$\frac{dC}{dt} = -\Lambda C \quad \Rightarrow \quad C(t) = C_0 e^{-\Lambda t}$$

Same form as in-cloud, but Λ is defined differently here.

✅ Scavenging Coefficient (Below-Cloud):

$$\Lambda = \int_{D_{\min}}^{D_{\max}} \pi D^2 V(D) N(D) E(D)\, dD$$

Where:

- D: raindrop diameter
- $V(D)$: terminal velocity of raindrop
- $N(D)$: raindrop size distribution (e.g., Marshall-Palmer)
- $E(D)$: **collection efficiency** (depends on dust particle size and mechanism)

In practice, people often use:

$$\Lambda = A \cdot R^B$$

Where:

- A and B are empirical constants
- R is rain rate (mm/hr)

💧 Collection Efficiency $E(D_p, D_r)$

The efficiency depends on the **interaction between particle size** D_p and **raindrop size** D_r. It's the sum of contributions from:

$$E = E_B + E_I + E_S$$

Where:

- E_B: Brownian diffusion efficiency (small particles)
- E_I: Inertial impaction efficiency (large particles)
- E_S: Interception efficiency (intermediate sizes)

Each term has its own empirical or theoretical expression.

📦 Wet Deposition Flux

Finally, the **wet deposition flux** (mass per area per time) is:

$$F = \Lambda C \quad (\text{or}) \quad F = v_d \cdot C$$

Where:

- v_d: effective wet deposition velocity (m/s)
- C: particle concentration (kg/m³ or µg/m³)

THANK YOU

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European Union

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