Física da Atmosfera
Aula introdutória
Parte 2

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A bit of history

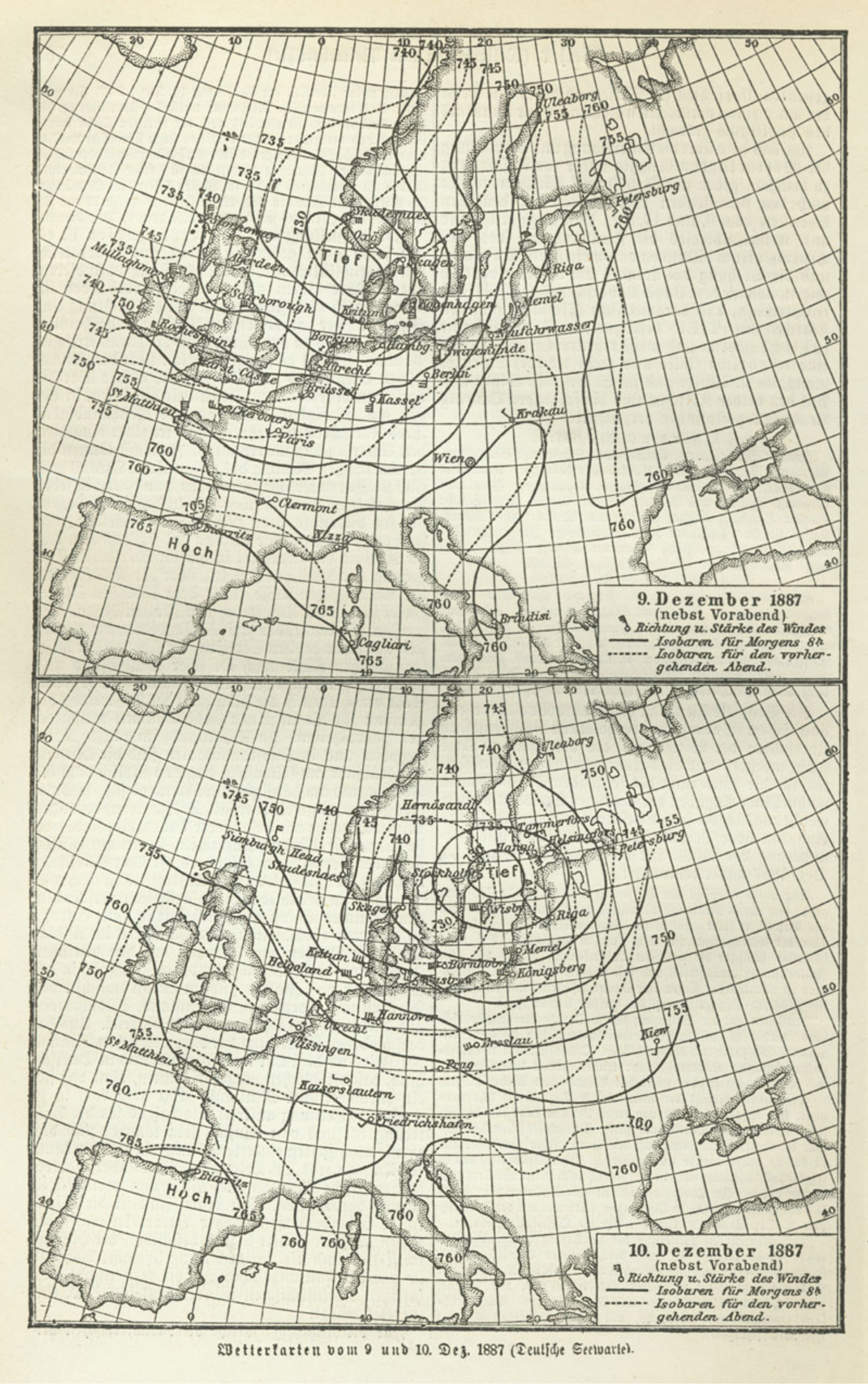
Weather forecasts began as observation of repetitive patterns

- 650 AC Babylonians made forecasts from cloud formations and position of the start
- 340 AC, Aristotle described a series of meteorological situations in a book called *Meteorológica*
- Since 300 AC Chinese made some sort of weather forecast

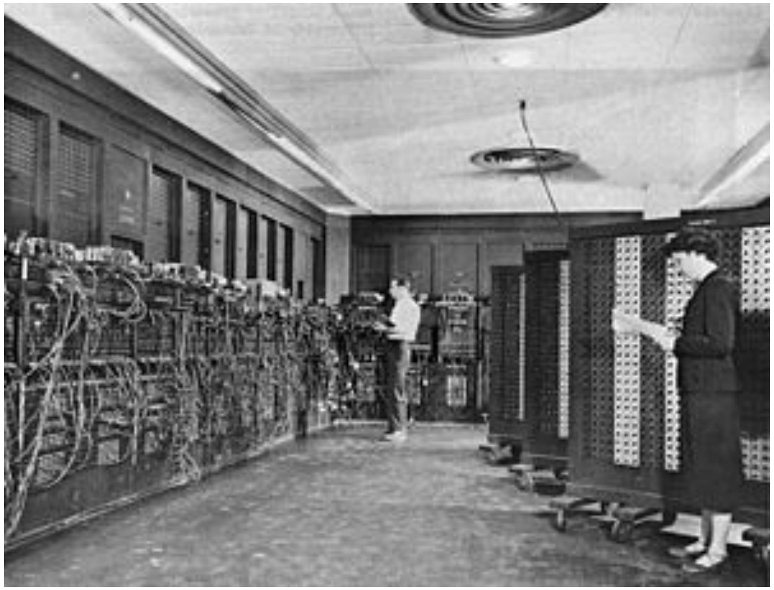
> Lets explain the thunder (…). There are two kinds of exhalations: dry and humid. (...). The humid condenses and forms a cloud (…). The radiated heats disperses on the top of the cloud, cooling it. A dry exhalation, that gets trapped in the process, will be eject from the cloud with high speed. When it collides with the neighboring clouds it makes a noise. We call this noise: thunder.
> – **Aristoteles Meteorologica**

Modern History

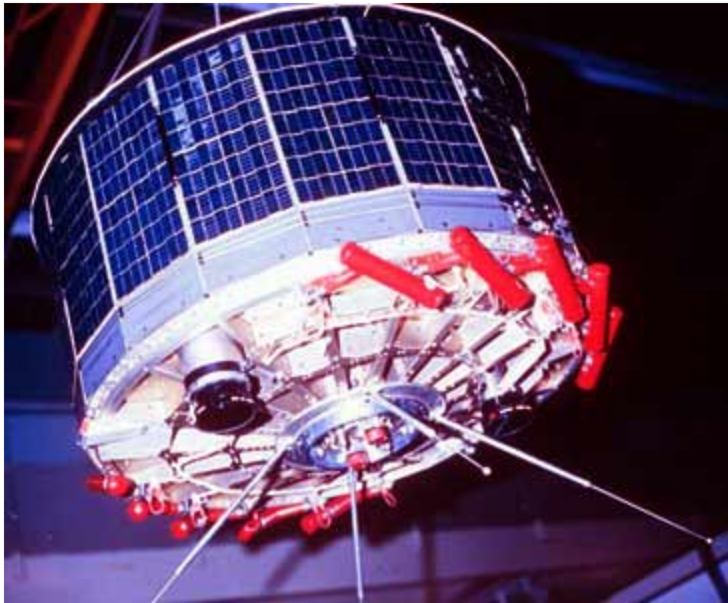
- 1400's
  - Hygrometer - Cryfts (1450)
  - Anemometer - Alberti (1450)
- 1500's
  - Thermoscope - Galileo
- 1600's
  - Barometer - Torricelli (1643)
  - Les Meteores - Descarte (1637)
- 1700's
  - Trade winds - Hadley (1730)
- 1800's
  - Three-cell model - Ferrel (1855)
  - Weather maps of surface pressure
- 1900's
  - Weather prediction - Bjerknes (1903)
  - Polar front theory - Bjerknes (1921)



Modern Technology



- 1900's
  - Numerical weather prediction
    - Richardson (1922)
  - Daily balloon observations (1940's)
  - First computer – ENIAC (1946)
  - First weather forecast
    - Von Neumann and Charney (1950)
  - Weather satellites (Tiros I, 1960)
  - First global model
    - Smagorinsky (1963)



Fluid dynamics

- The most important equation is Navier-Stokes. Derived from Newton's second law, states the conservation of momentum

$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla\mathbf{v} + \upsilon\nabla^2\mathbf{v} - \frac{\nabla P}{\rho} + \mathbf{g}$$

- Partial
- 2nd order
- 1st degree
- Homogeneous
- **Non-Linear**

$$\sum_j v_j \frac{\partial v_j}{\partial x_j}$$

→ CAOS

1^{st} law of thermodynamics

- By defining a virtual potential temperature

$$\theta_v = T_v \left(\frac{1000\,\text{hPa}}{p_a} \right)^{\kappa}$$

- That already includes pressure variation, conservation of energy gives

$$\frac{d\theta_v}{dt} = \frac{1}{c_p^d} \frac{\theta_v}{T_v} \frac{dQ}{dt}$$

Mass Conservation

- If mass is conserved, then **dρ/dt=0**, where

$$\frac{d\rho}{dt} = \frac{\partial\rho}{\partial t} + \mathbf{v}\cdot\nabla\rho$$

- ... Similar to conservation of momentum:

$$\frac{\partial q}{\partial t} = -\mathbf{v}\cdot\nabla q + D_q\nabla^2 q + F_q - S_q$$

Sources and sinks of water vapor

Molecular diffusion

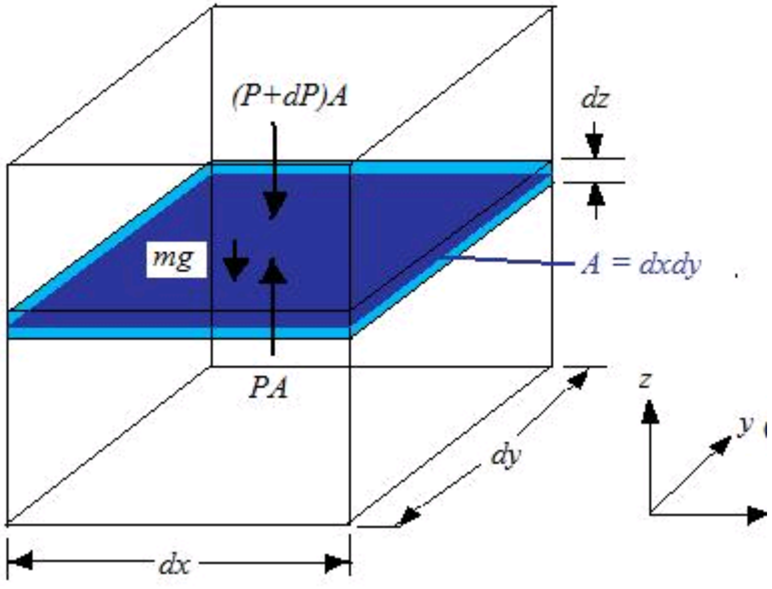
$$\frac{\partial \mathbf{v}}{\partial t} = -\mathbf{v}\cdot\nabla\mathbf{v} + \nu\nabla^2\mathbf{v} - \frac{\nabla P}{\rho} + \mathbf{g}$$

Sources and sinks of momentum

Equação Hidrostática

- É a equação de movimento na ausência de aceleração verticais. É dada pelo equilíbrio entre a força gradiente de pressão e a gravidade

$$dp_a = -\rho_a g dz$$



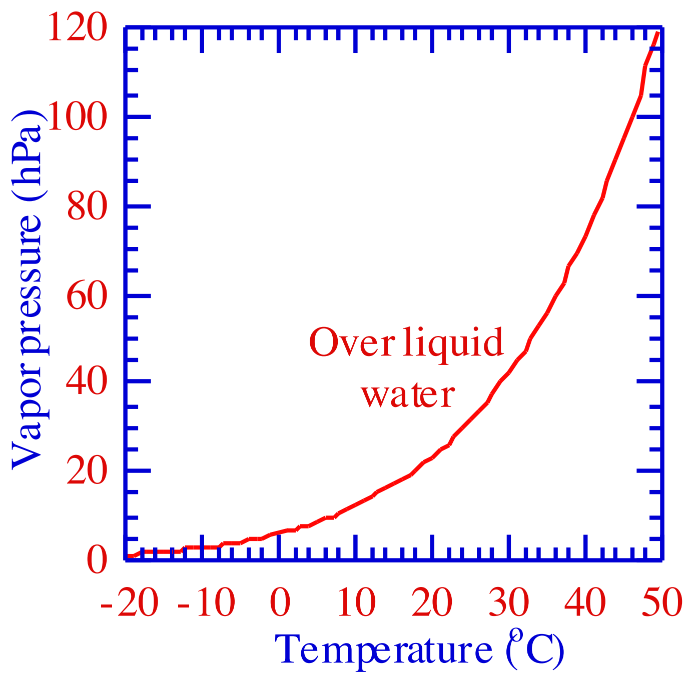
Equação de Clausius-Clapeyron

- A pressão de vapor de saturação varia com a temperatura:

$$\frac{\mathrm{d}p_{v,s}}{\mathrm{d}T} = \frac{\rho_{v,s}}{T} L_e$$

- E podemos encontrar uma expressão para ela:

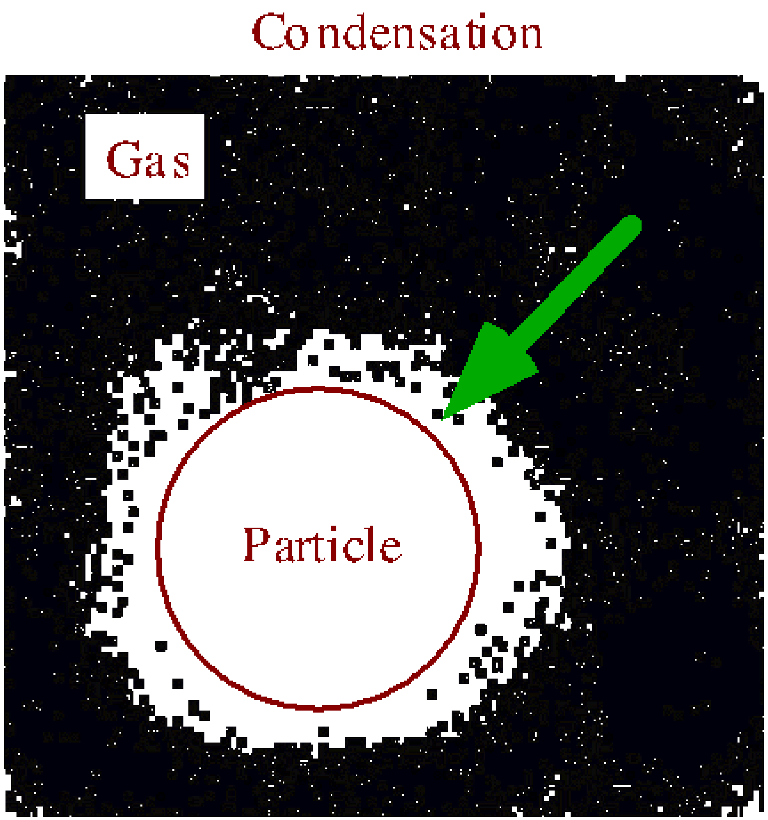
$$p_{v,s} = 6.112 \exp\left(\frac{17.67 T_c}{T_c + 243.5} \right)$$

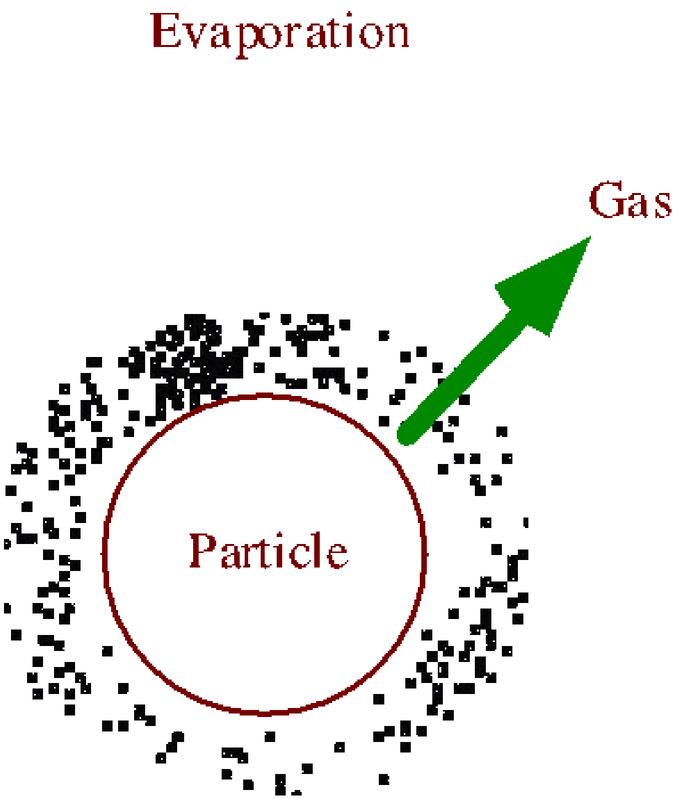


Condensação/Evaporação

Condensação para $p_v > p_{v,s}$

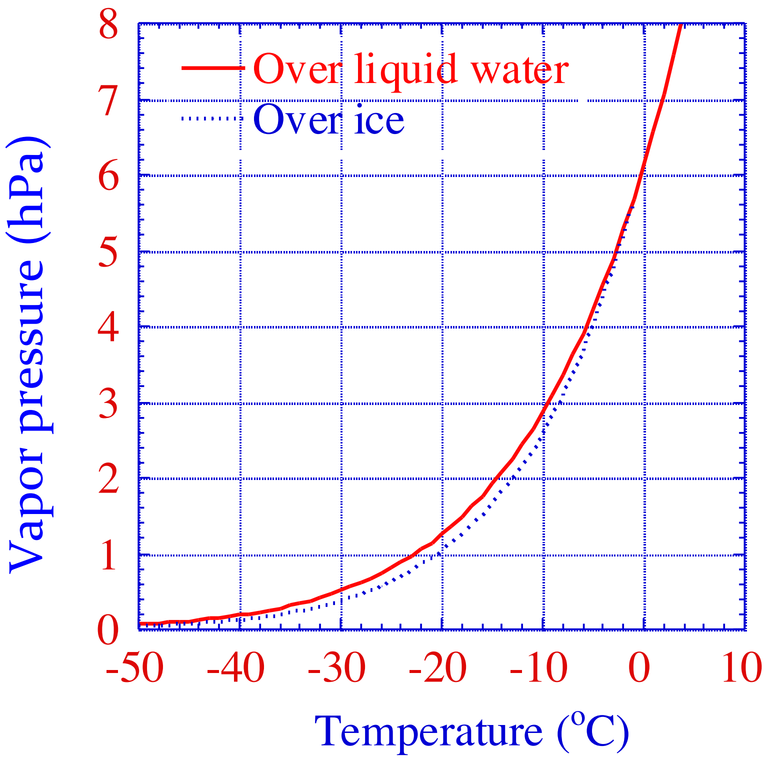
Evaporação para $p_v < p_{v,s}$

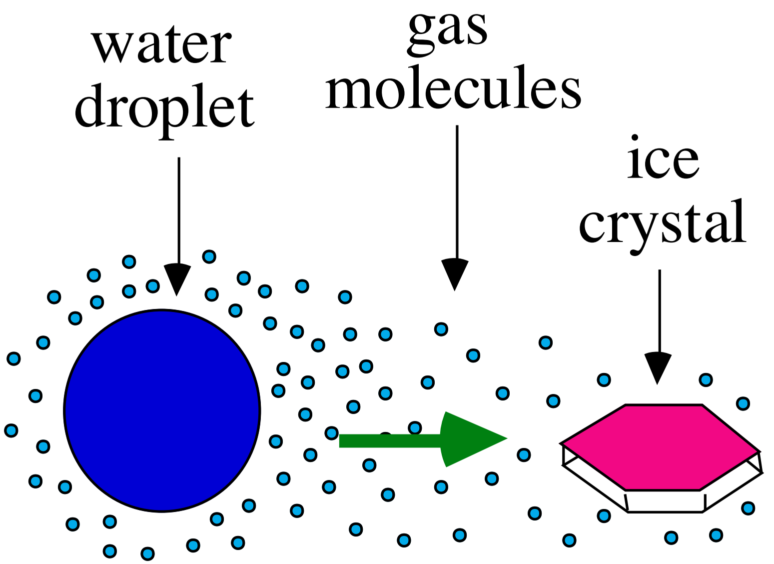




Formation of Rain in Cold Clouds

Ice Crystal (Bergeron) Process





- $p_{v,s}$ sobre gelo é menor que sobre água
- As gotas evaporam e o vapor flui para os cristais

Equations of motion

$$p_a = \rho_a R' T_v \qquad \mathrm{d}p_a = -\rho_a g \mathrm{d}z \qquad T_v = T\left(1 + 0.608\mathrm{q}_v\right)$$

$$\frac{d\theta_v}{dt} = \frac{1}{c_p^d}\frac{\theta_v}{T_v}\frac{dQ}{dt} \qquad \theta_v = T_v\left(\frac{1000\,\mathrm{hPa}}{p_a}\right)^{\kappa}$$

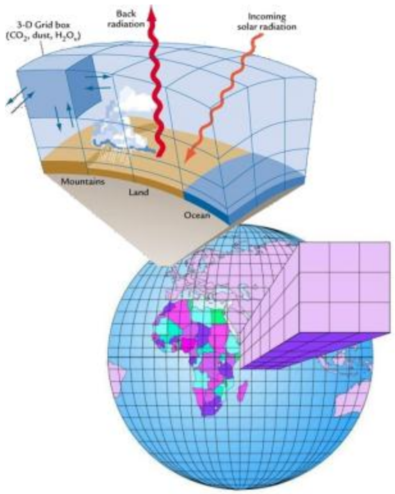
$$\frac{\partial \mathbf{V}}{\partial t} = -\mathbf{V}\cdot\nabla\mathbf{V} + \nu\nabla^2\mathbf{V} - \frac{\nabla P}{\rho} + \mathbf{g} \qquad \frac{\mathrm{d}\rho}{\mathrm{d}t} = \frac{\partial\rho}{\partial t} + \mathbf{v}\cdot\nabla\rho$$

+ chemistry (about 200 prognostic variables)
+ aerosols (about 30 prognostic variables)

Equações de Din. dos Fluídos

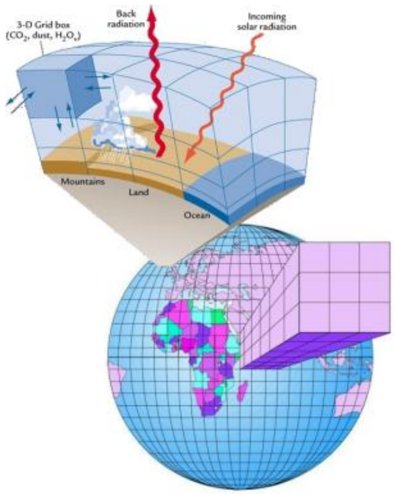
- Estas equações juntas podem descrever o movimento
  - da atmosfera,
  - das correntes oceânicas,
  - da água em um cano,
  - do ar passando sobre uma asa
  - das estrelas em uma galáxia

Do these equations solve it all?



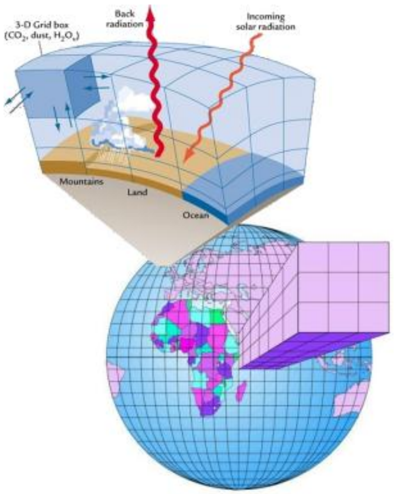
How to include subgrid processes?

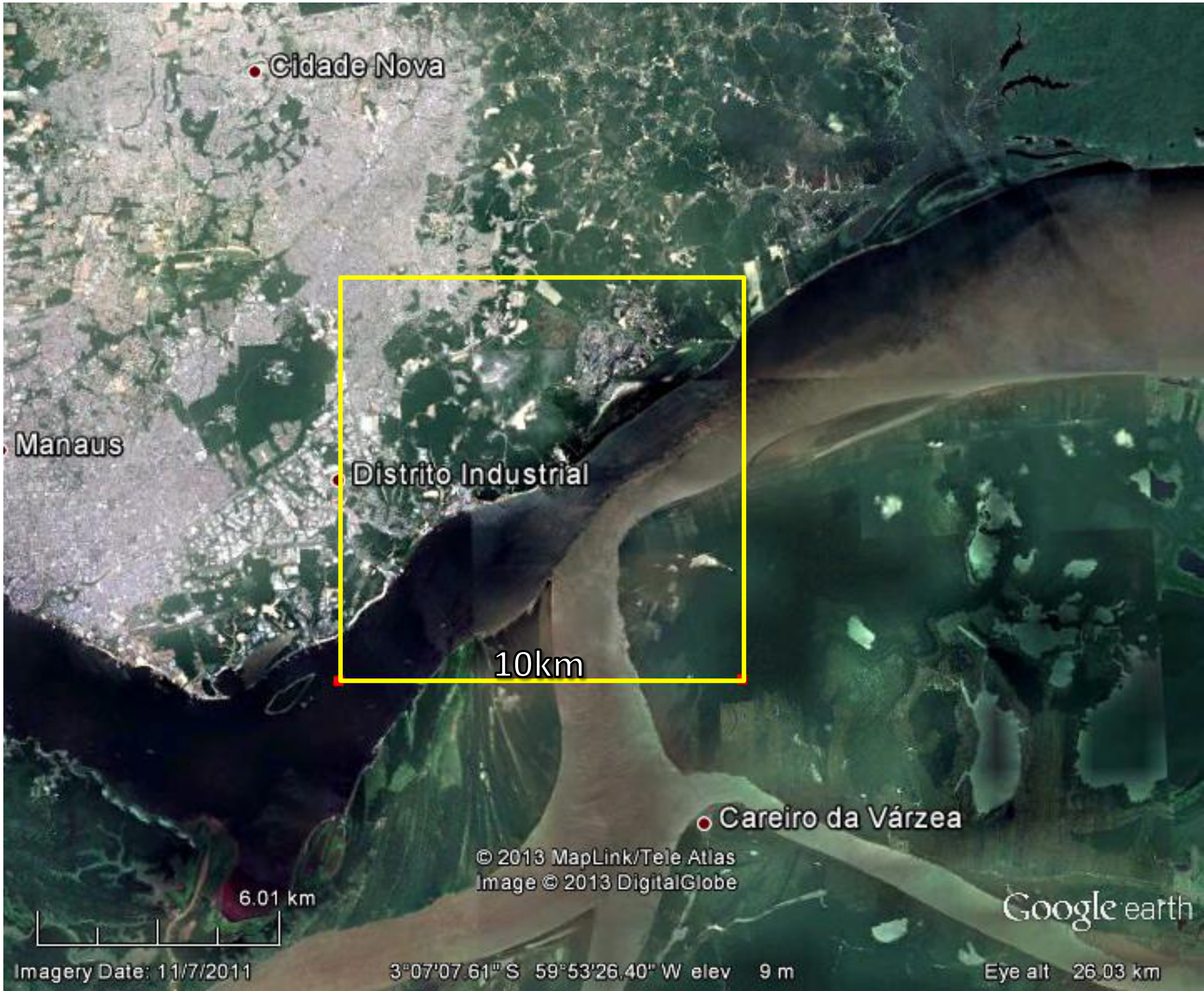
How to include the subgrid scale?



Clouds, rain, vegetation, cities, rivers, etc, etc, etc…

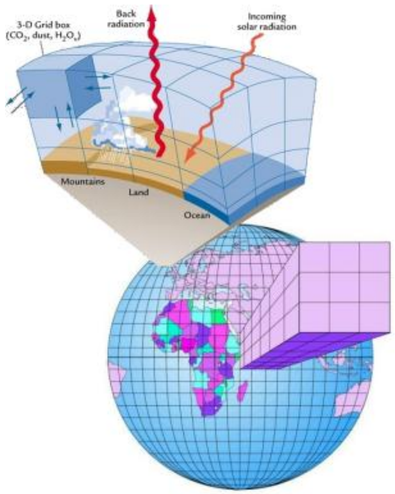
How to include the subgrid scale?





Pollution, aerosols, turbulence, etc, etc, etc...

How to include the subgrid scale?

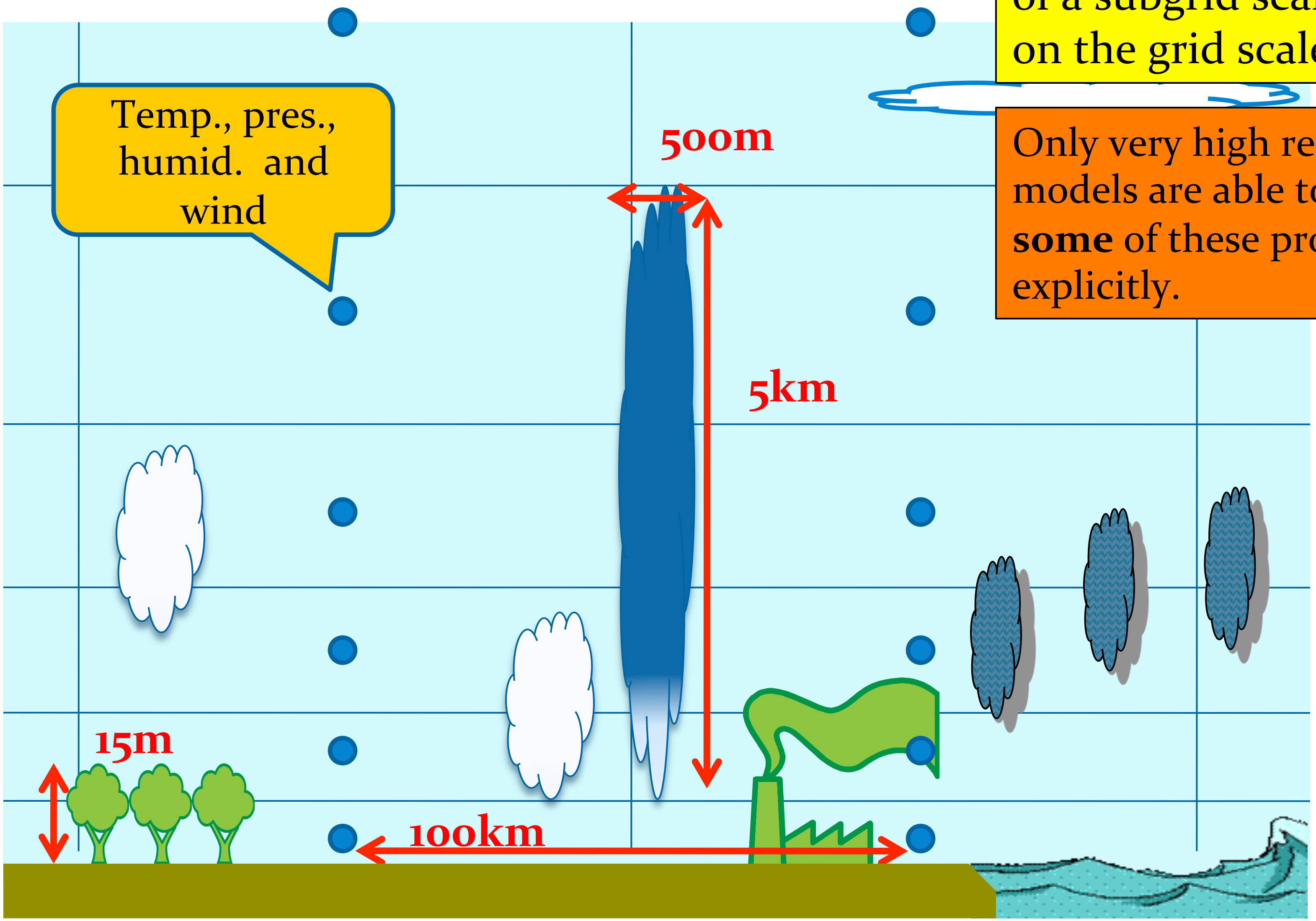


Phisiology, human activities, etc, etc, etc...

Parametrizations

a set of **empirical** equations used to estimate the **mean effect** of a subgrid scale process on the grid scale.

Only very high resolution models are able to solve **some** of these processes explicitly.



Numerical model of the atmosphere

- Differential equations at the grid scale
- Parameterizations for representing the sub-grid scale

Source code:
Readable text written in some programming language

Binary program:
Machine language

Numerical model of the atmosphere

- Differential equations at the grid scale
- Parameterizations for representing the sub-grid scale

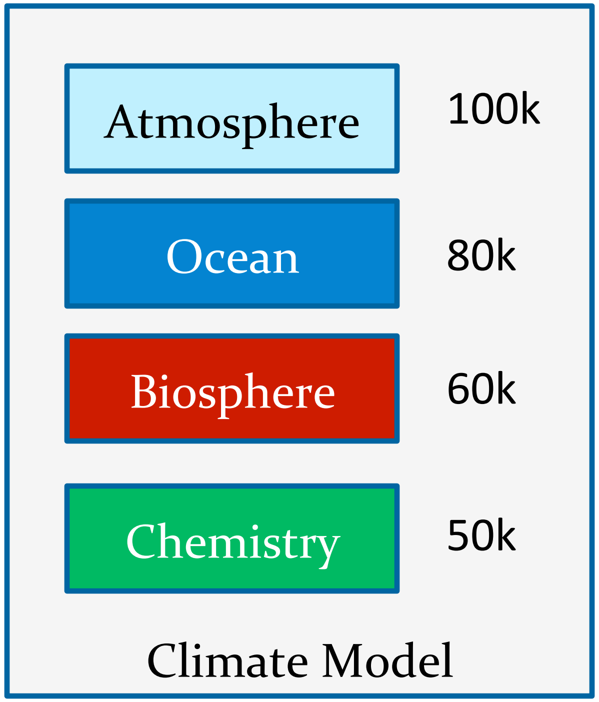
Computacional Complexity

- Many researcher, during many years.

```
PROGRAM PARES
  DO I=1,5
    PRINT I*2
  ENDDO
END PROGRAM
```

```
2
4
6
8
10
```

Are there bugs?



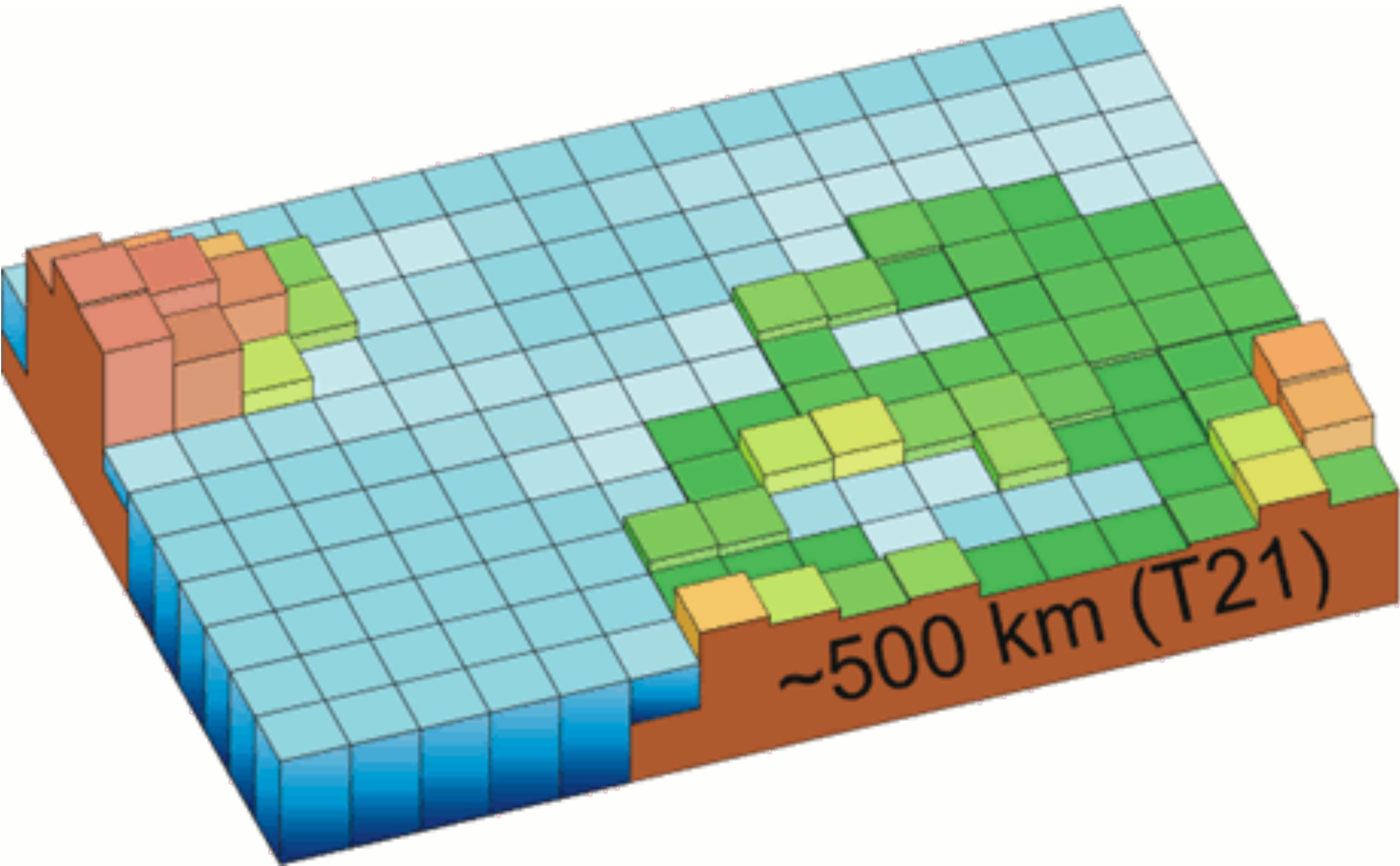
100-300 K lines of code

Is the weather forecast good?

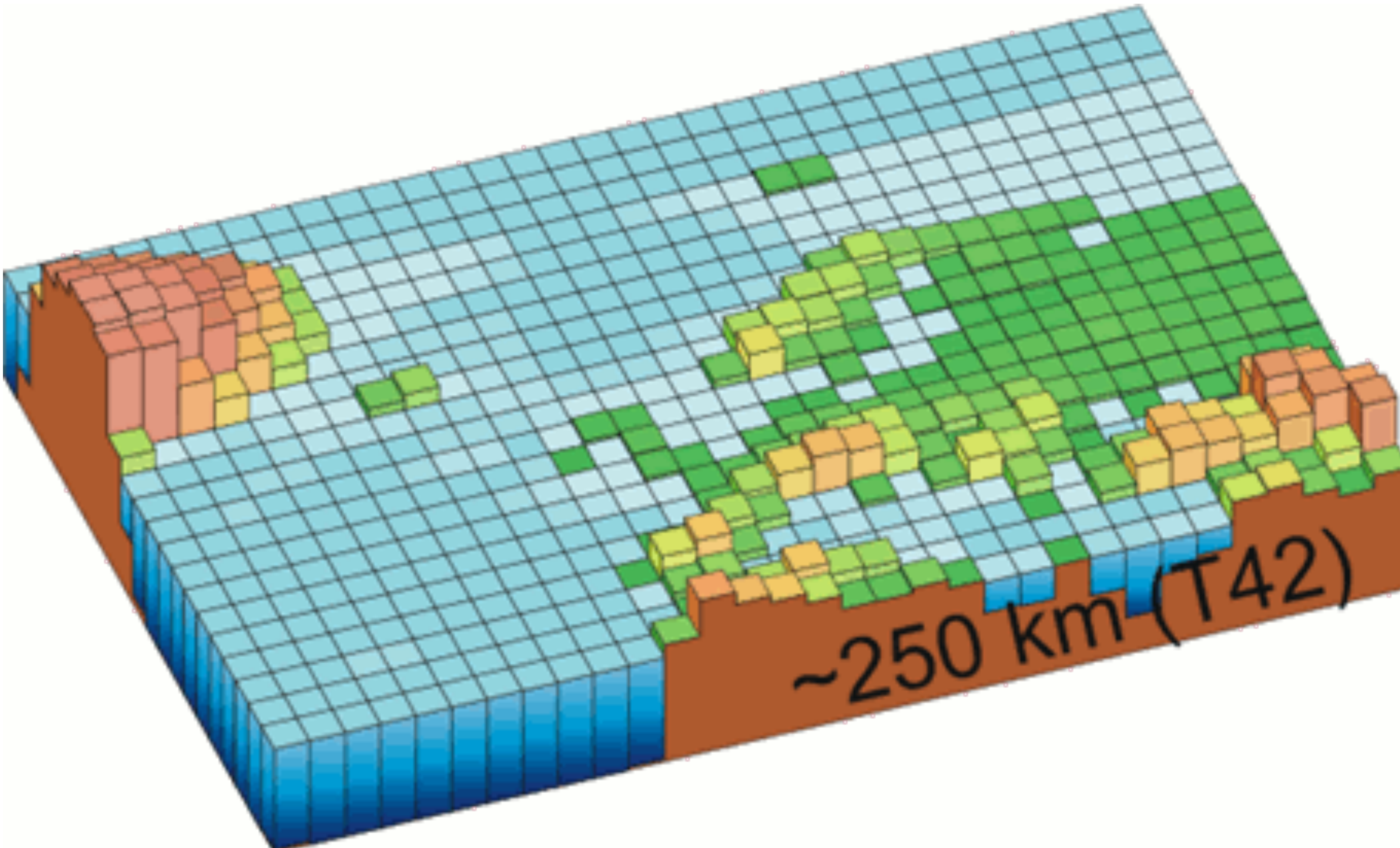
The quality of our solution (**weather forecast**) will depend on many factors:

- Adequate spatial and temporal resolutions

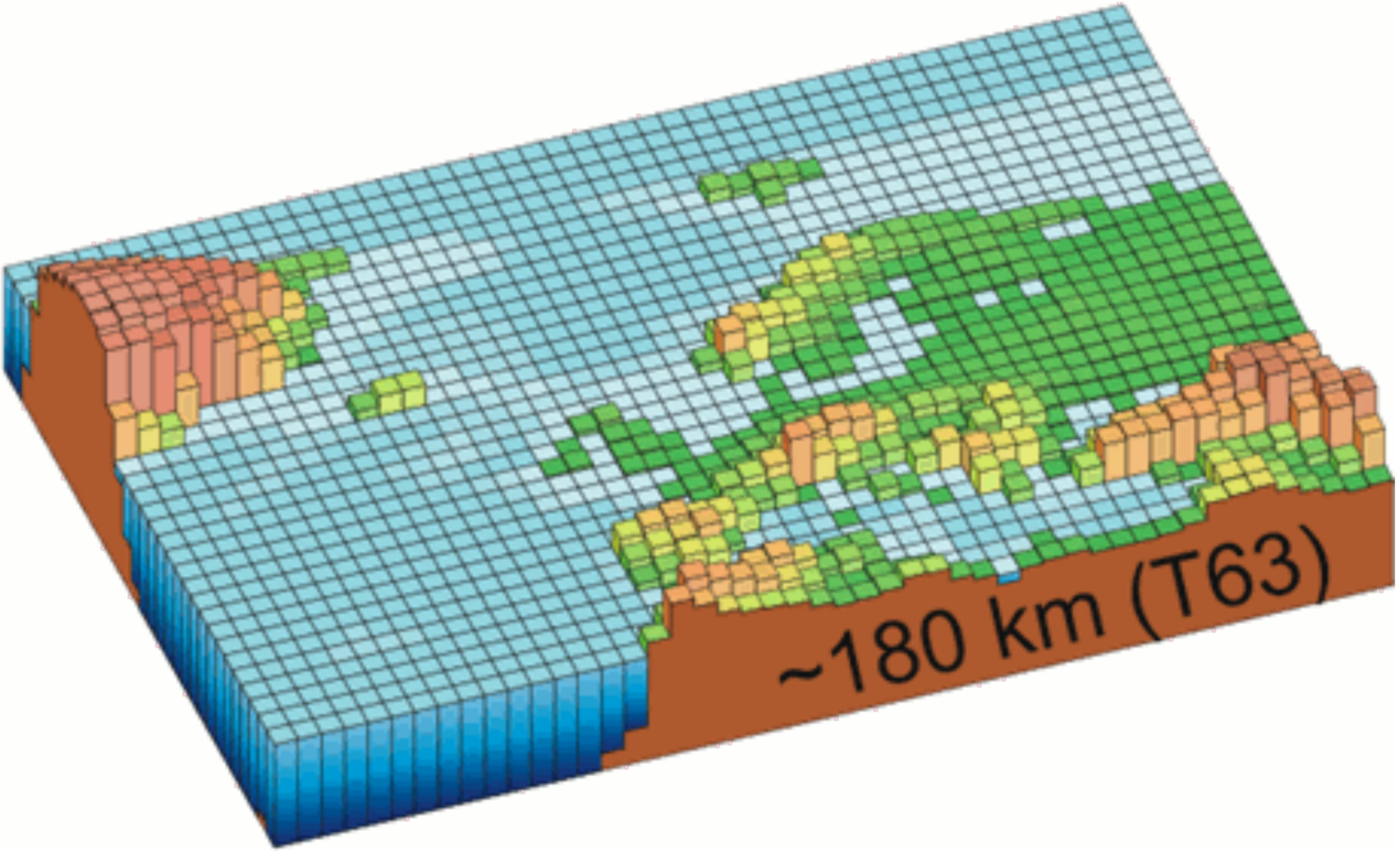
Resolution



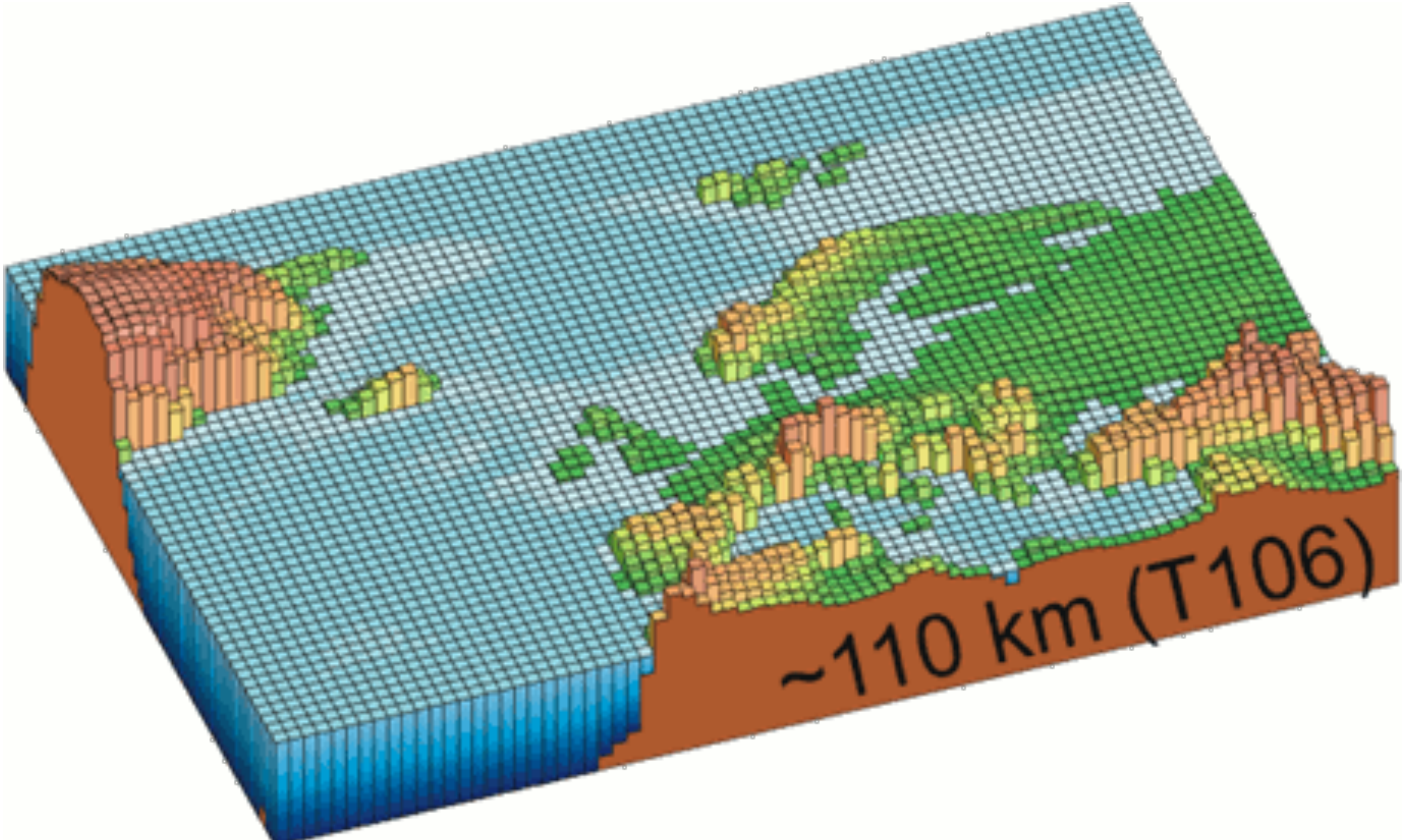
Resolution



Resolution



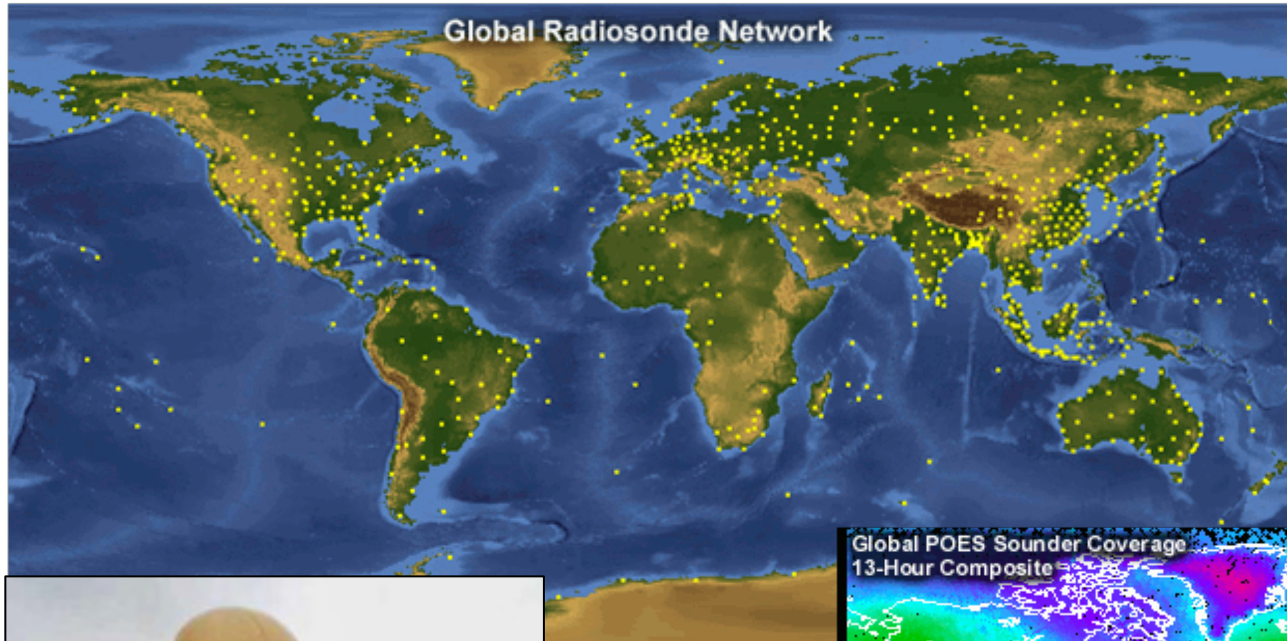
Resolution



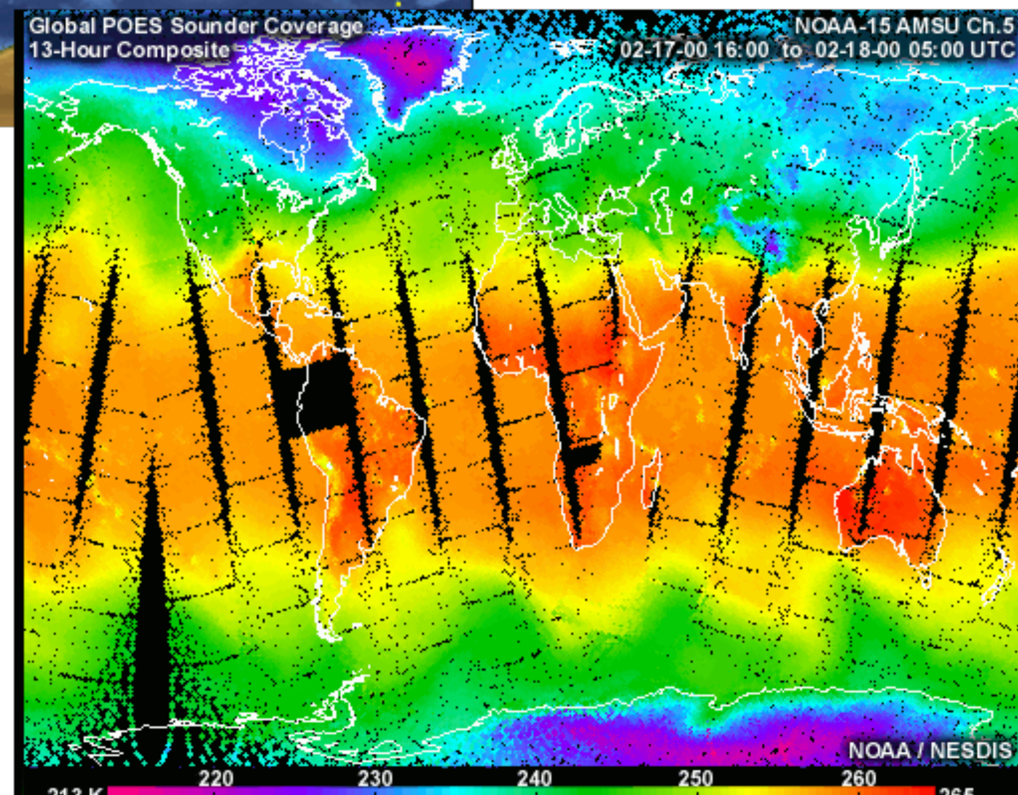
Is the weather forecast good?

The quality of our solution (**weather forecast**) will depend on many factors:

- Adequate spatial and temporal resolutions
- Quality of initial condition
  - Great improvement with satellites in the 1970
  - Still the limiting factor today!



Radiosondes, large effort of lots of people, every day



Just 1 satellite

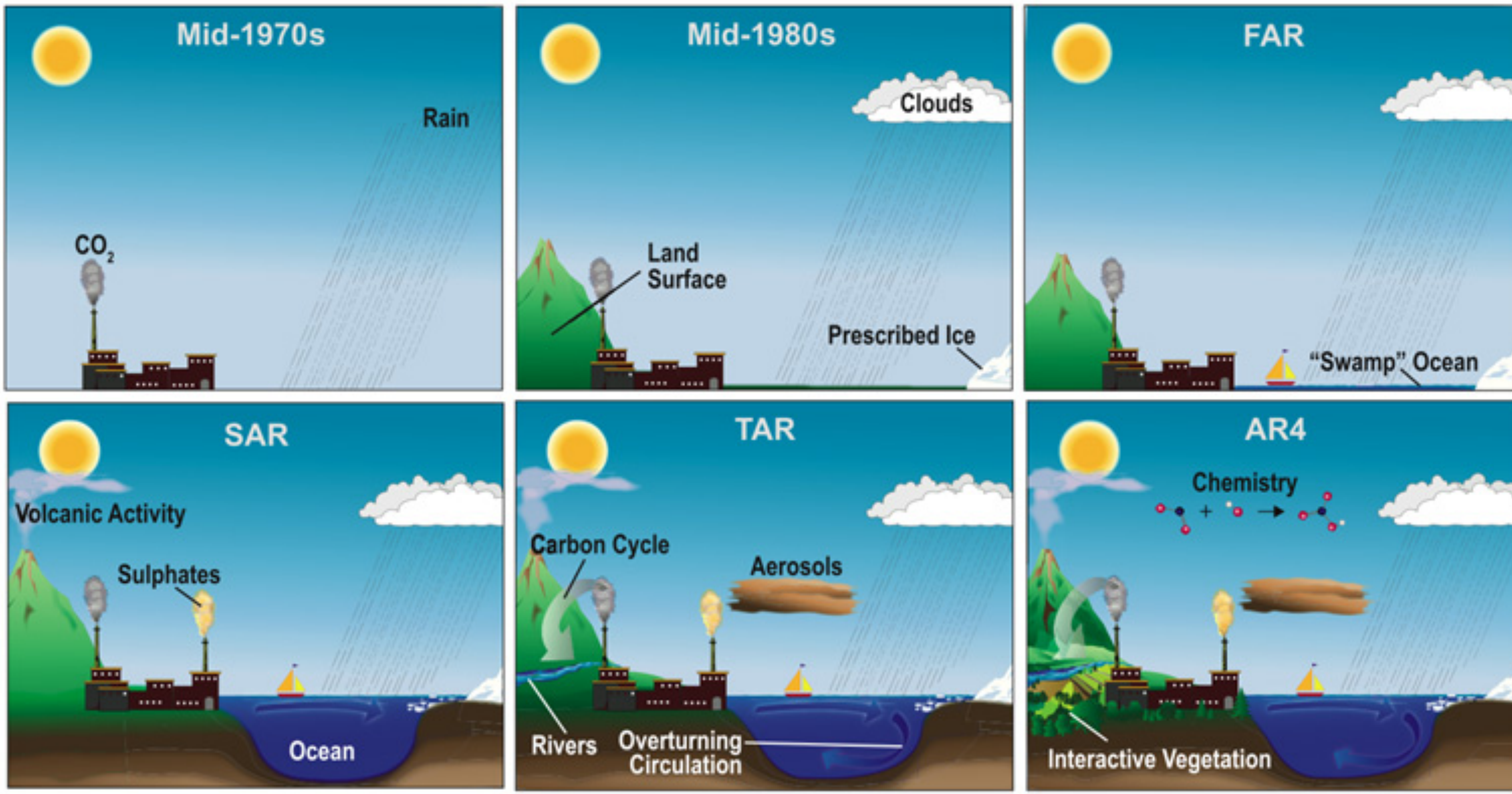
Is the weather forecast good?

The quality of our solution (**weather forecast**) will depend on many factors:

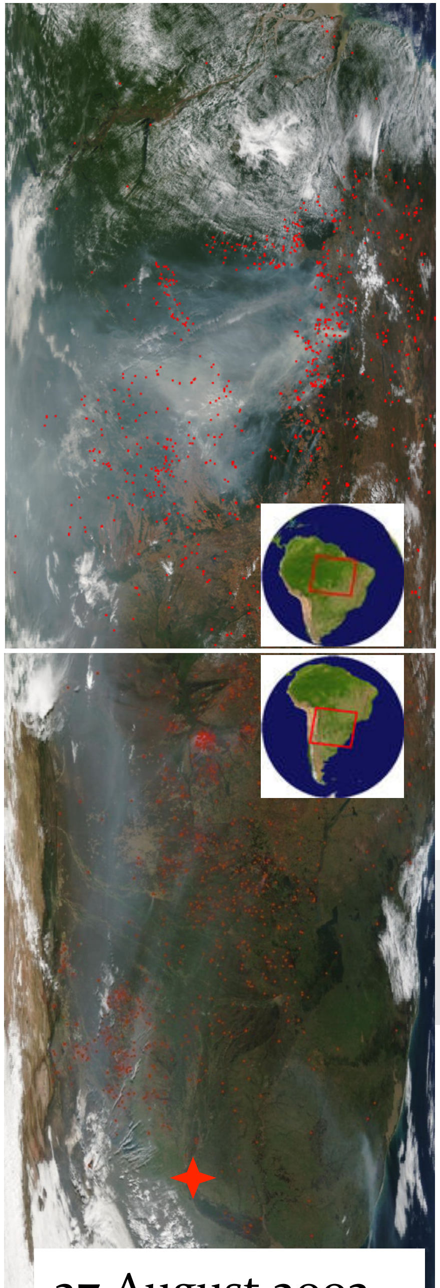
- Adequate spatial and temporal resolutions
- Quality of initial condition
  - Great improvement with satellites in the 1970
  - Still the limiting factor today (**weather**)!
- Physical processes (**limiting factor for climate**)
  - Radiation
  - Biosphere-atmosphere
  - Chemistry
  - ....

Which processes to include depend on the problem we want to takle!

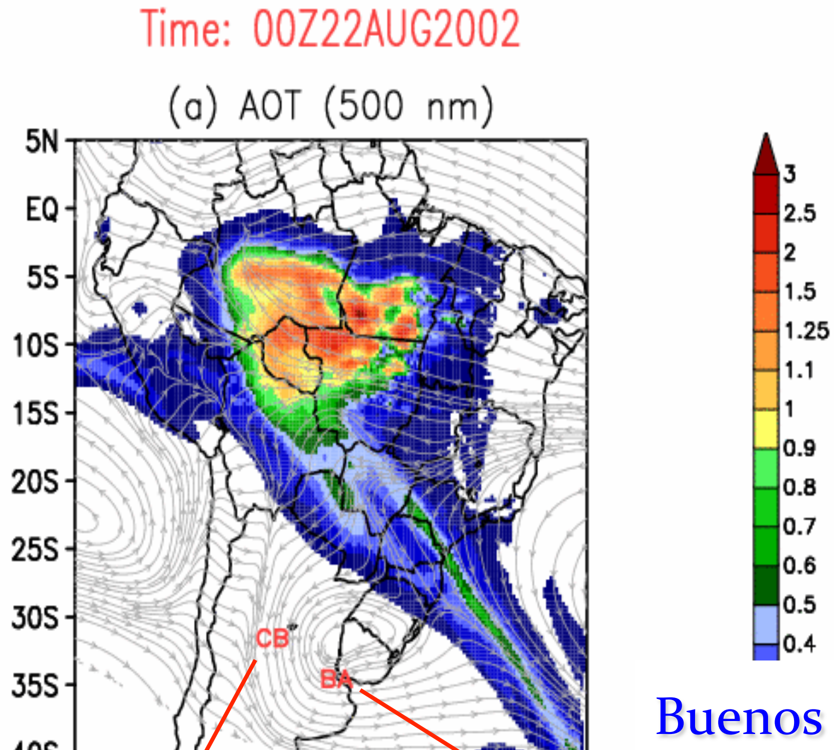
Evolution of climate models



An example of long range transport (advection) of smoke



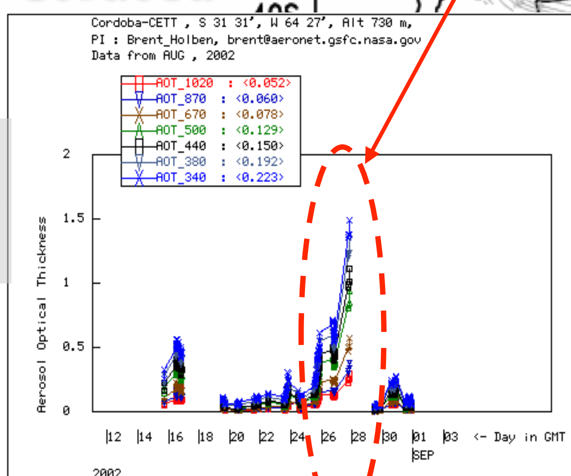
27 August 2002



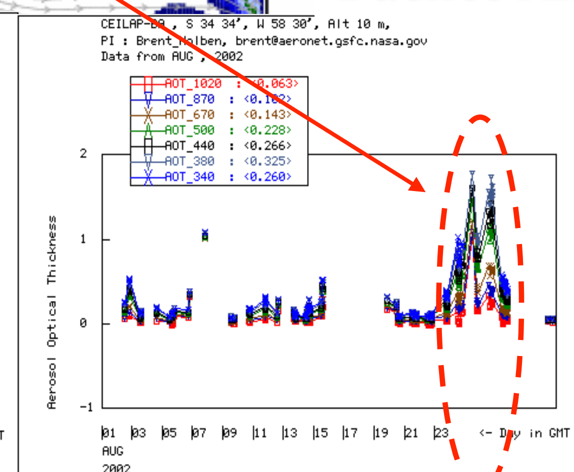
Córdoba

Buenos Aires

AOT

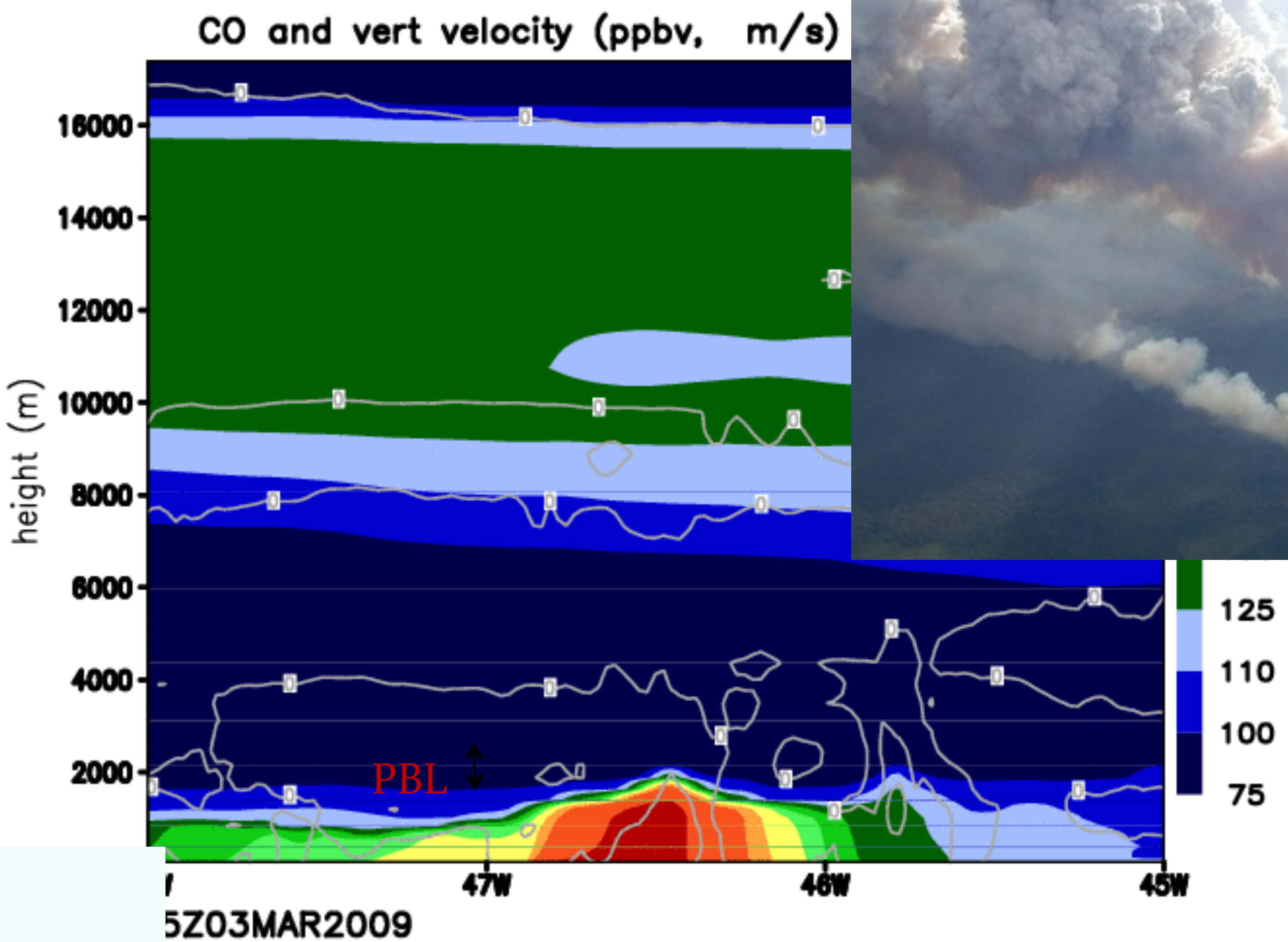


26–29 Aug 2002



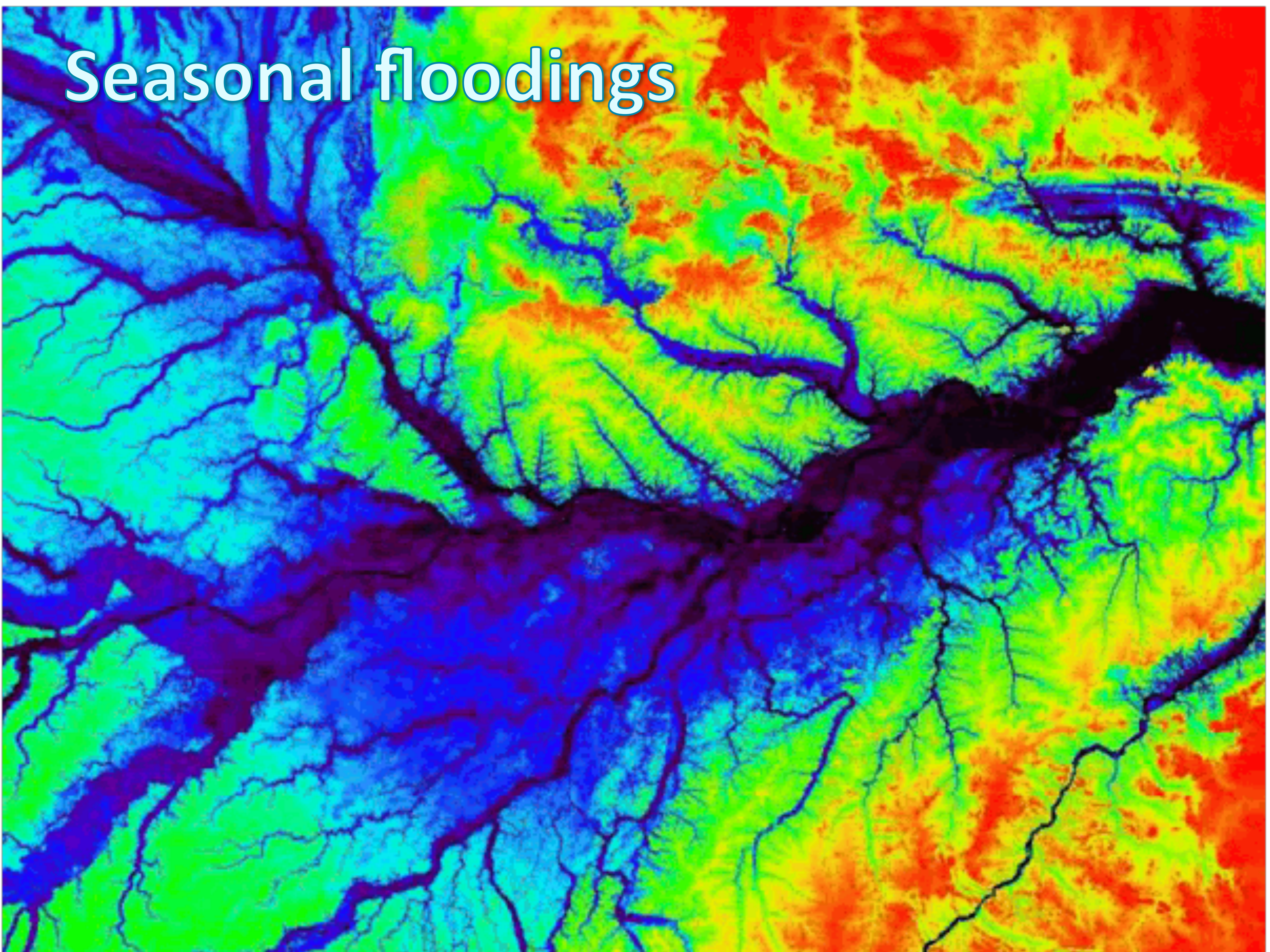
26–29 Aug 2002

Vertical cross section showing vertical velocity and the transport of CO from the PBL to the high troposphere



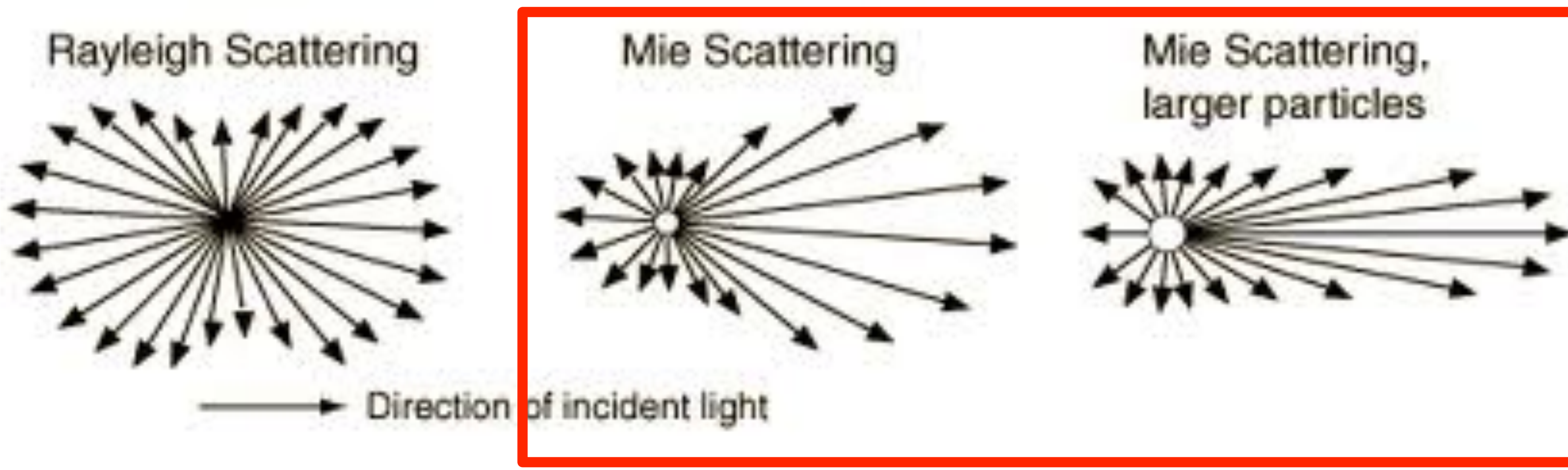
S. Freitas - INPE

Seasonal floodings



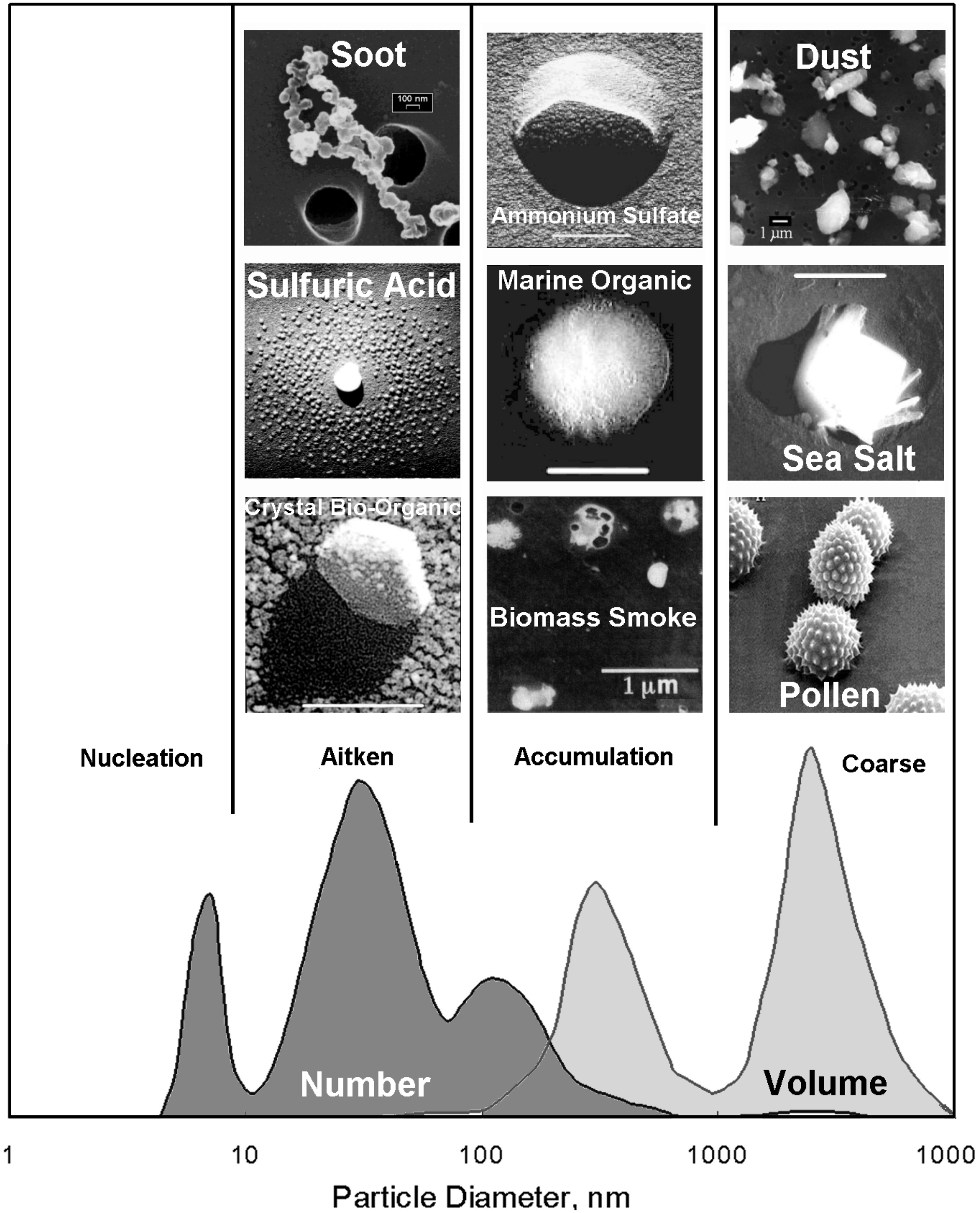
Aerosols are very complicated

- Classical electromagnetism
  - Rayleigh scattering - molecules
  - Mie scattering – aerosol and droplets

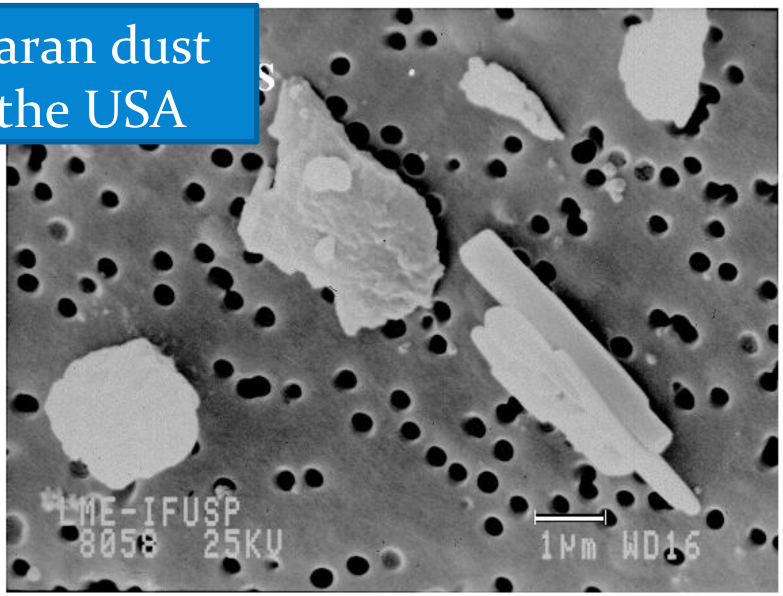


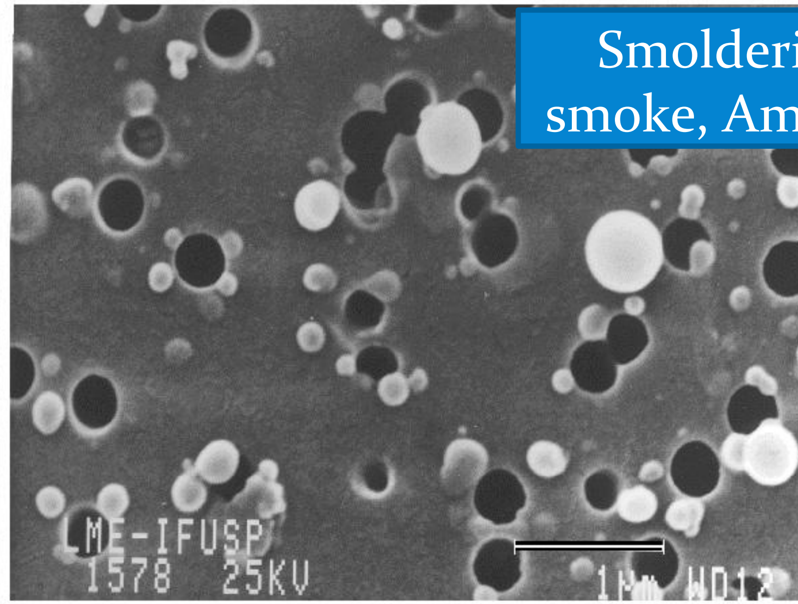
Size << λ **Size ≈ λ** **Size > λ**

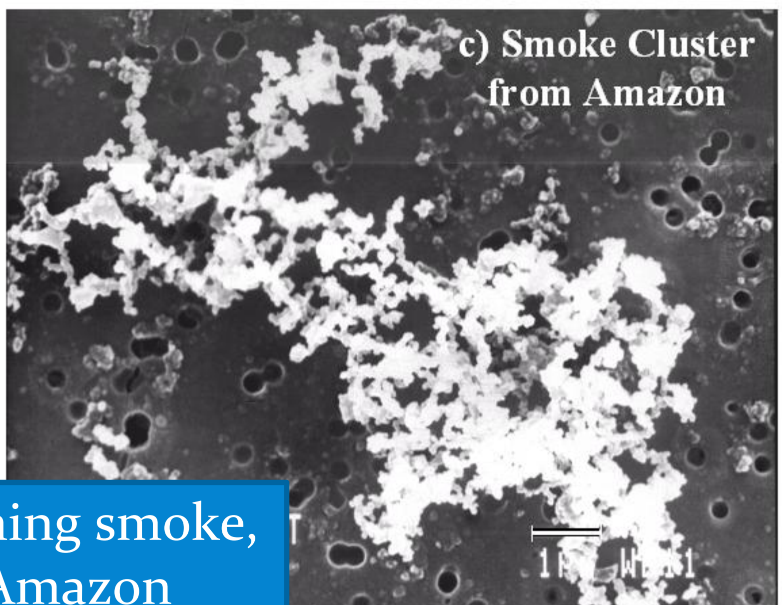
- Interaction of the aerosol with the radiation field depends:
  - Size
  - Shape
  - Surface properties

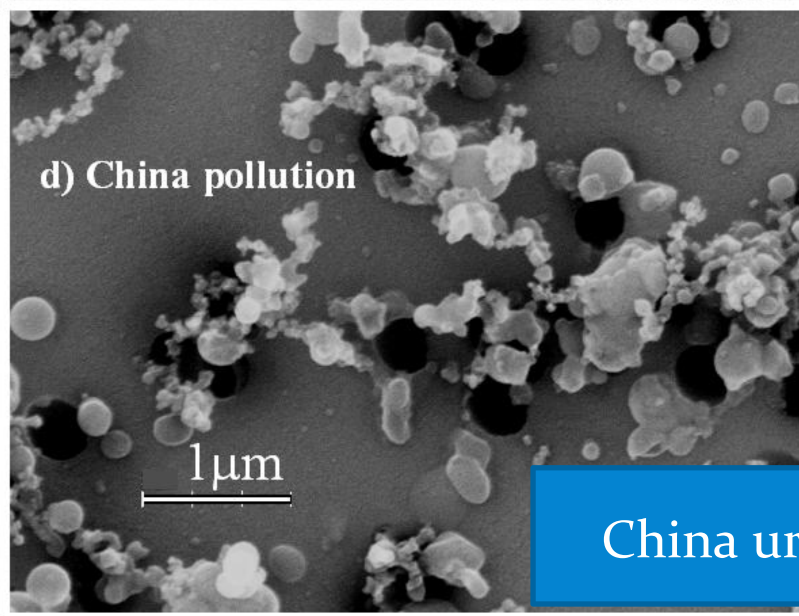


… Aerosols can be very different

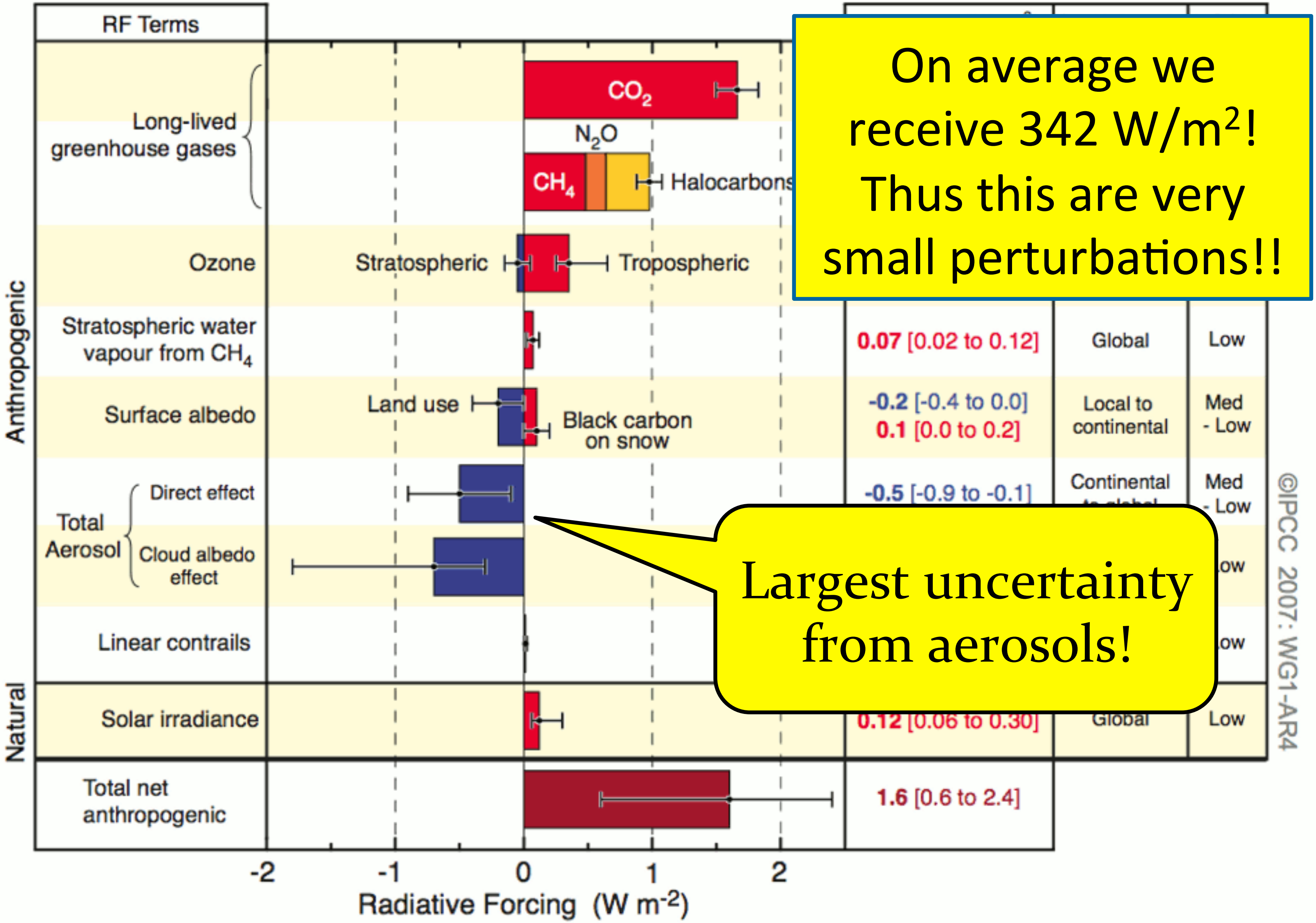




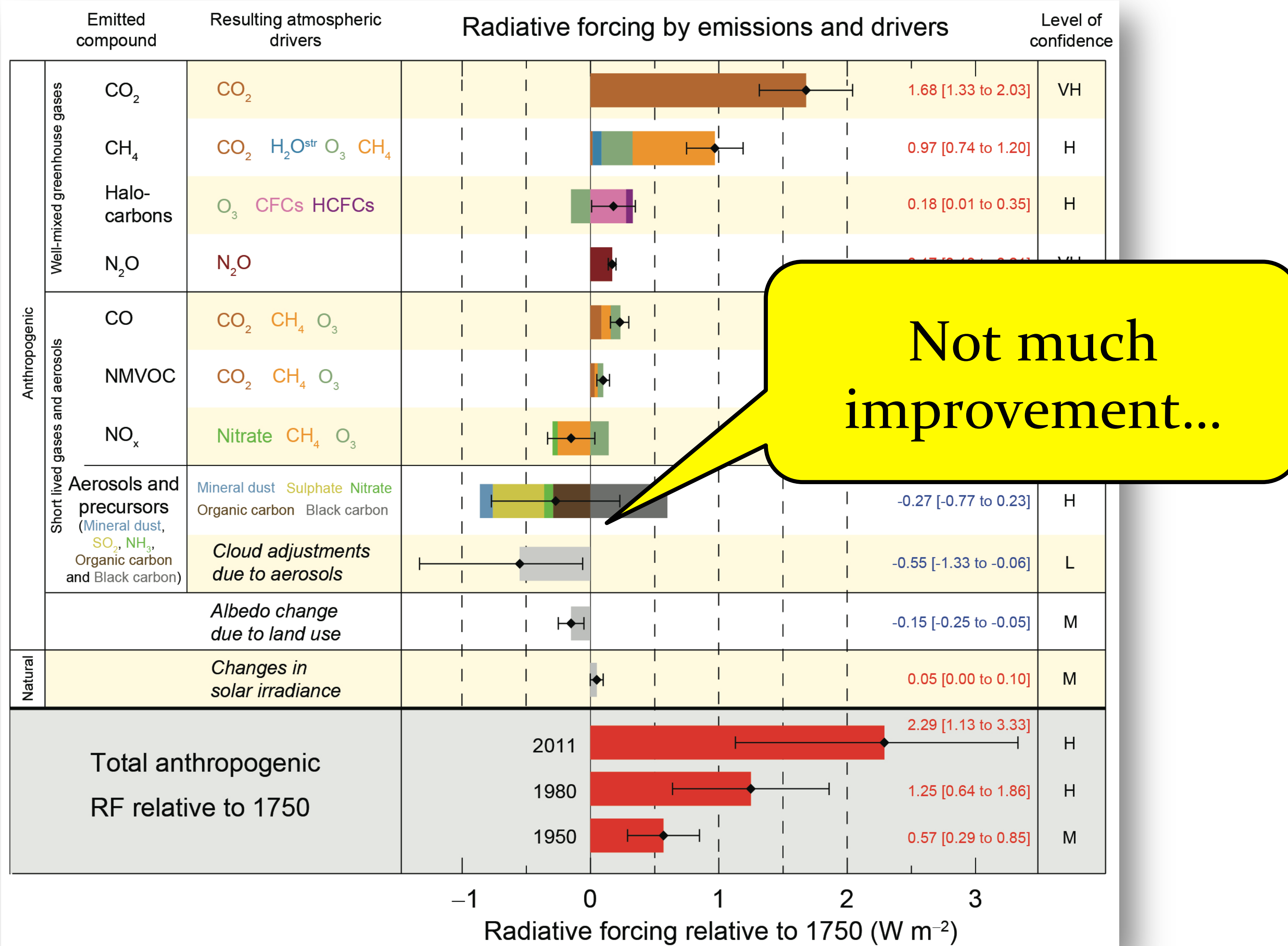




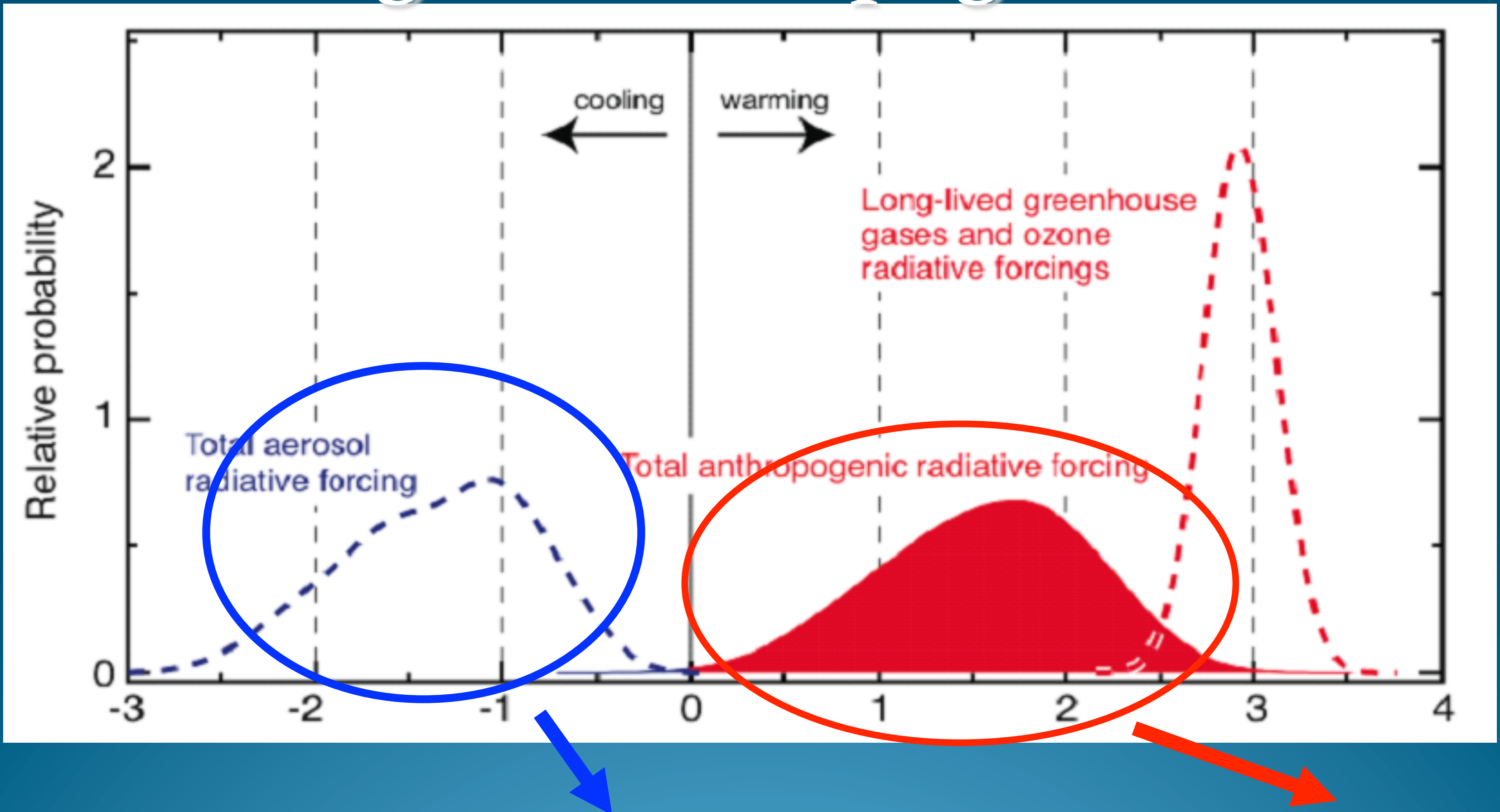
Radiative forcings of the global climate system IPCC 2007



Forçante radiativa do sistema climático global (IPCC 2013)



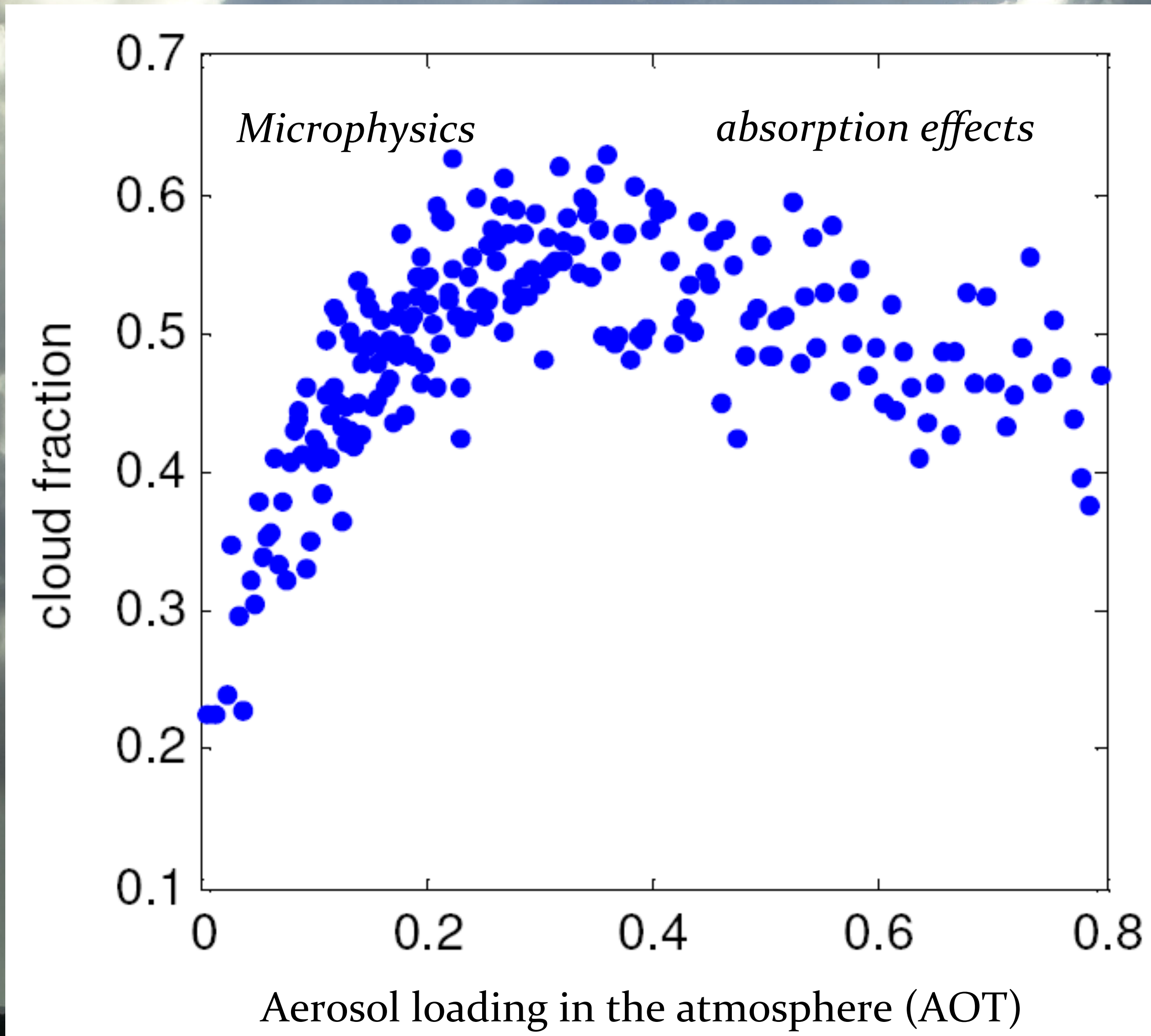
Combining all anthropogenic effects



What is being doing to this component is critical to the final forcing

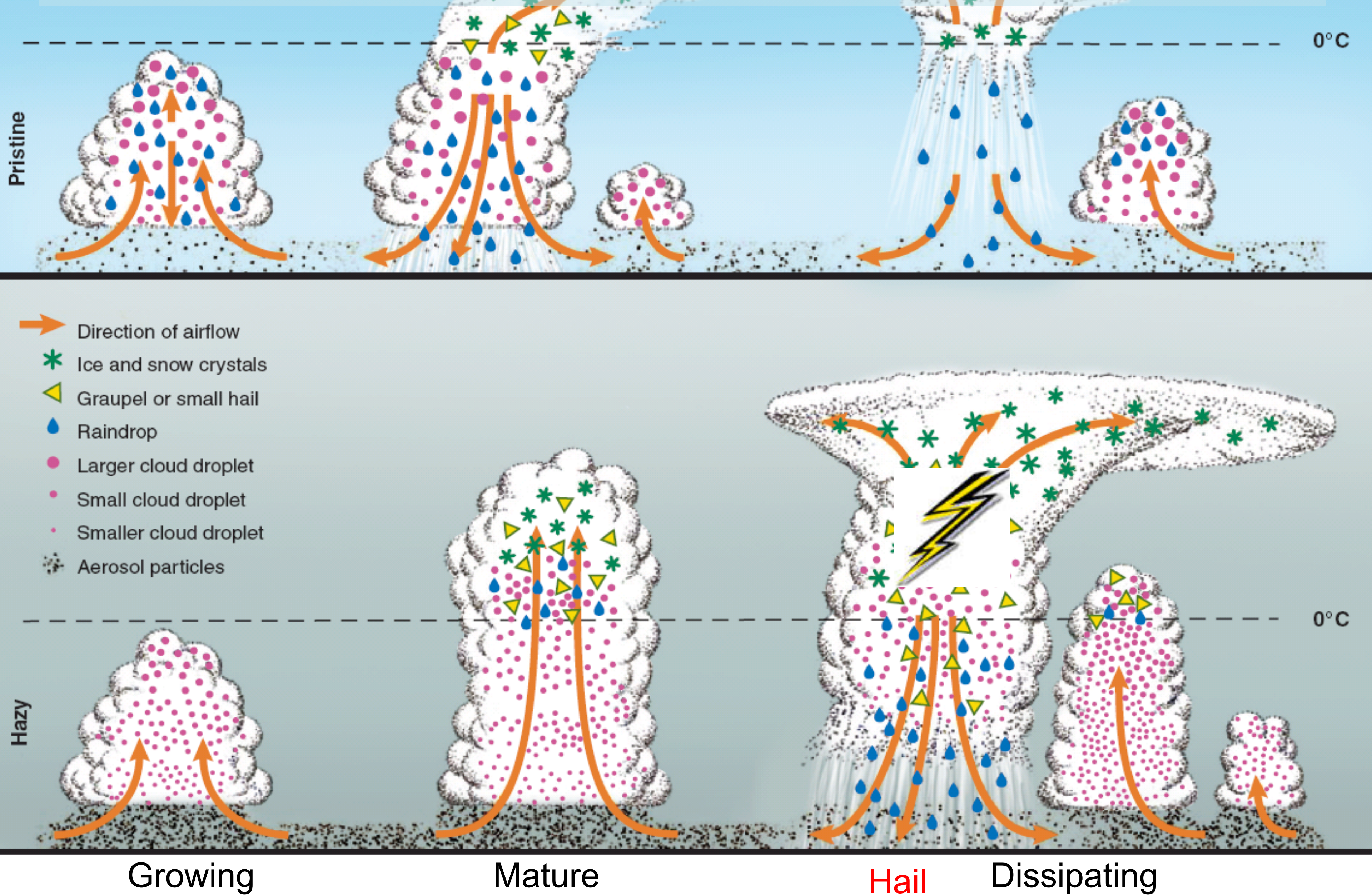
- *Combined anthropogenic forcing* is not straight sum of individual terms.
- Tropospheric ozone, cloud-albedo, contrails → asymmetric range about the central estimate
- Uncertainties for the agents represented by normal distributions except: contrail (lognormal); discrete values → trop. ozone, direct aerosol, cloud albedo
- Monte Carlo calculations to derive probability density functions for the combined effect

Relationships between cloud properties and aerosol loading in Amazonia



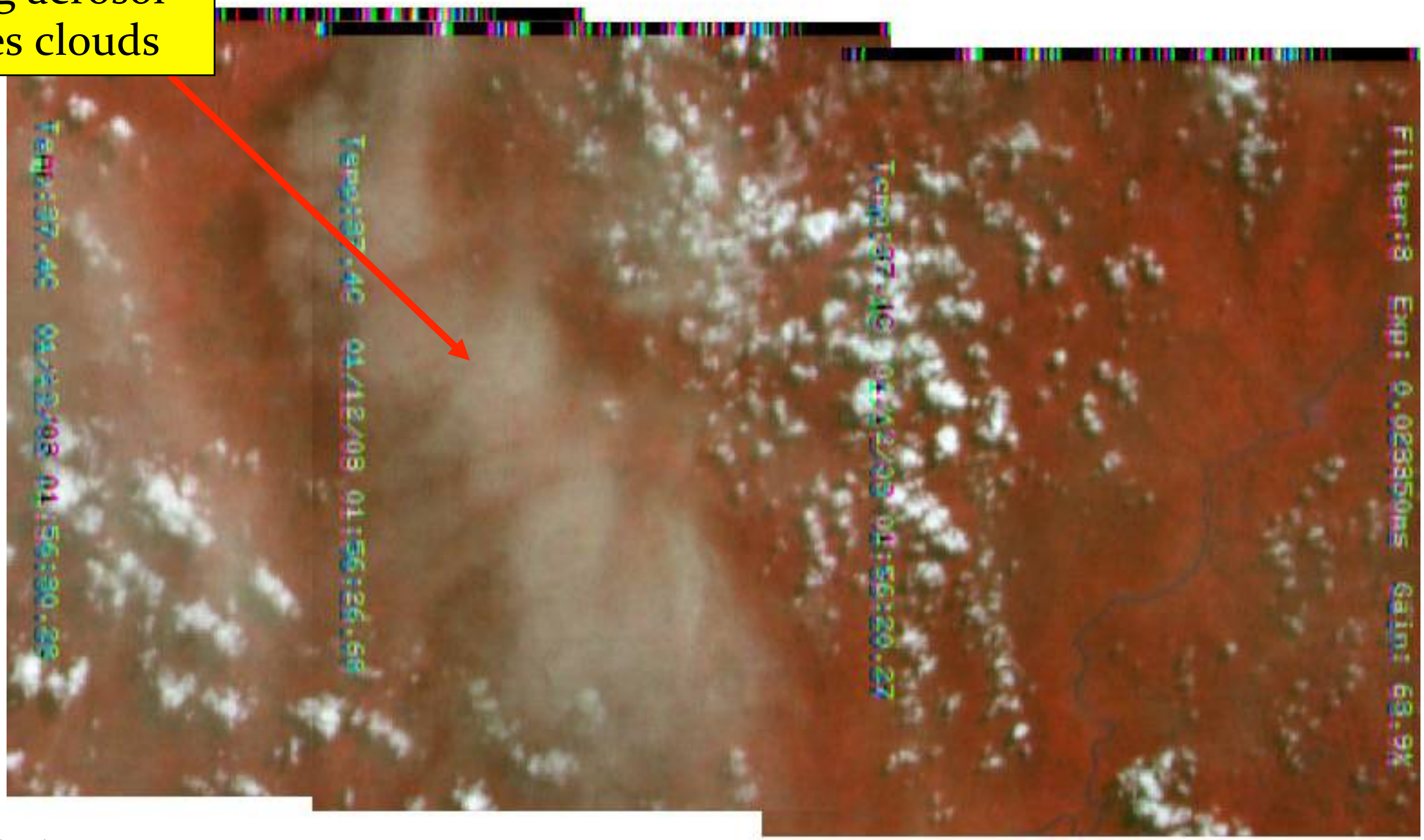
Koren et al., Science 2008

Rosenfeld D., U. Lohmann, G.B. Raga, C.D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, M.O. Andreae, 2008: Flood or Drought: How Do Aerosols Affect Precipitation? ***Science***, 321, 1309-1313.



With too much aerosols: Cloud supression

Absorbing aerosol suppresses clouds

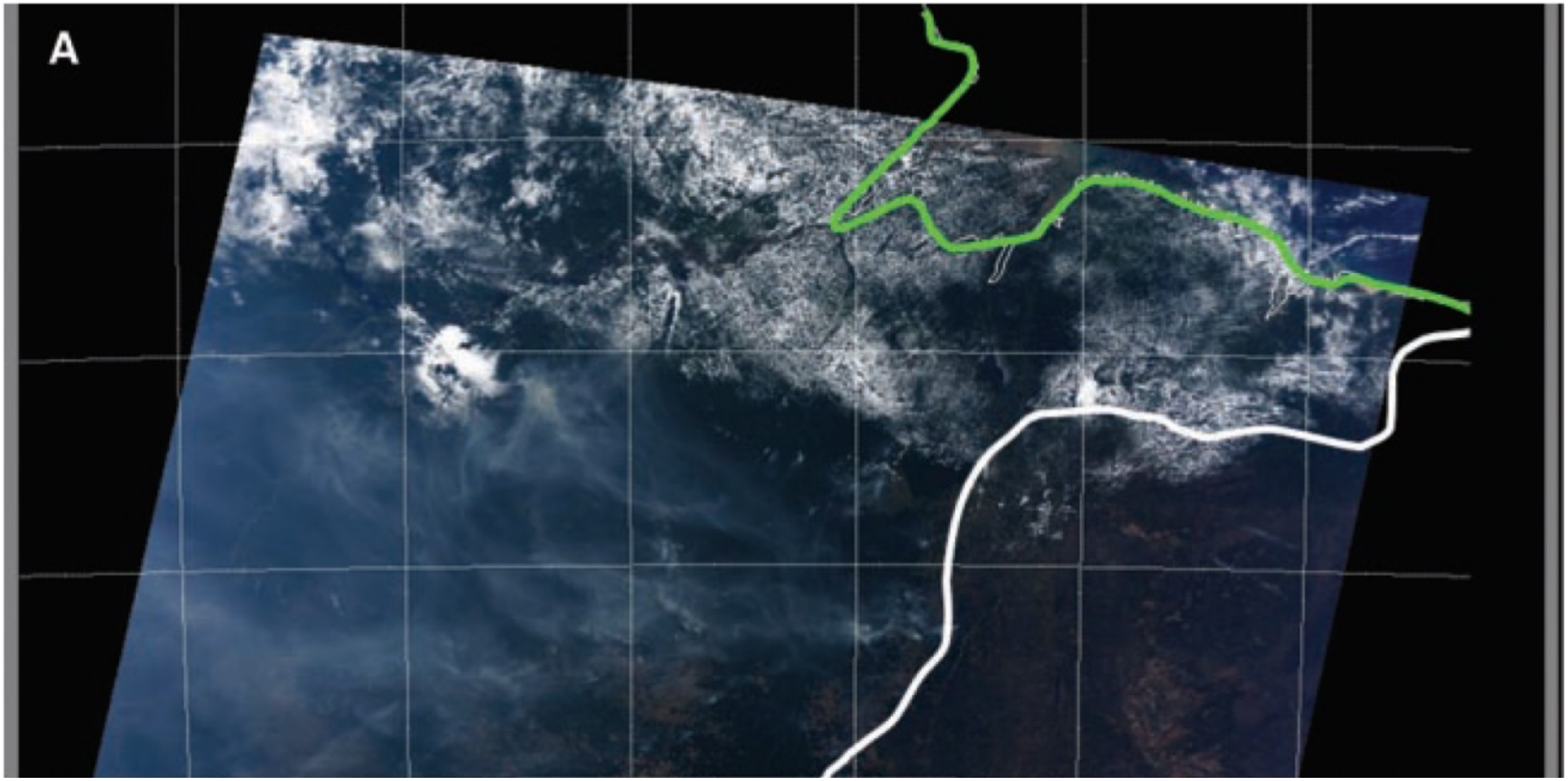


- Stabilization
- Suppression of surface fluxes
- Microphysical influences on droplets

Columbia Shuttle January 2003

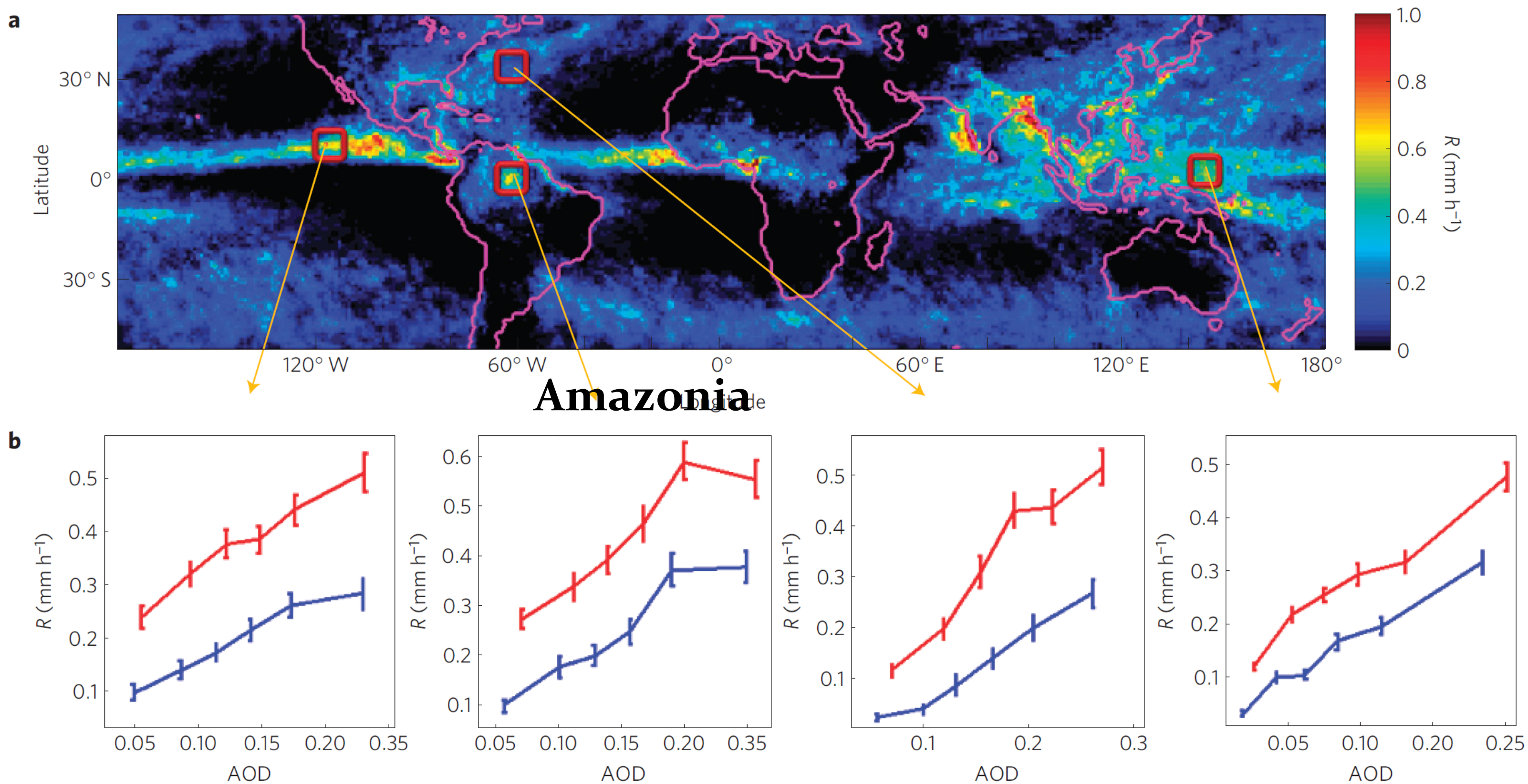
Large scale low cloud suppression

Terra and Aqua satellite images of the east Amazon basin, 11 August 2002. *(From Koren et al., 2004)*



Rain rate (TRMM) versus Optical Depth (MODIS)

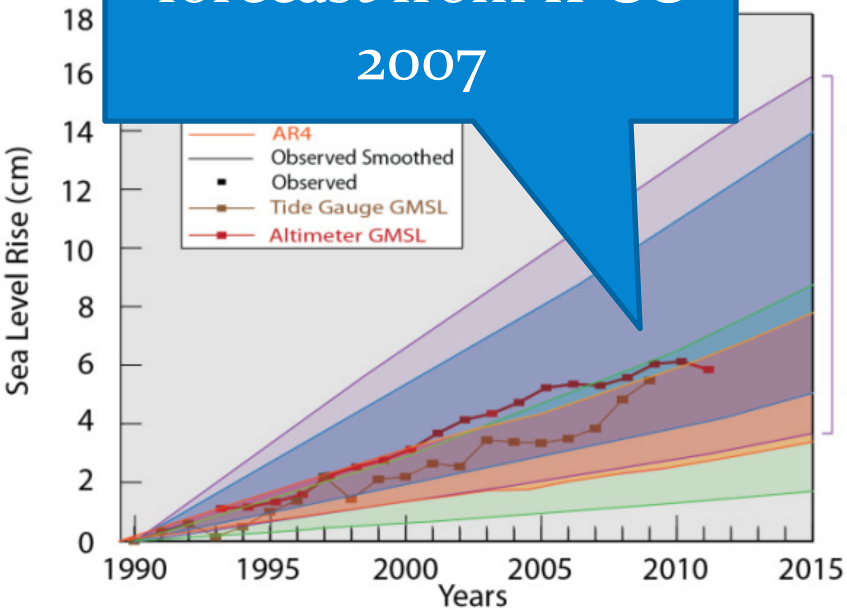
NATURE GEOSCIENCE DOI: 10.1038/NGEO1364 LETTERS

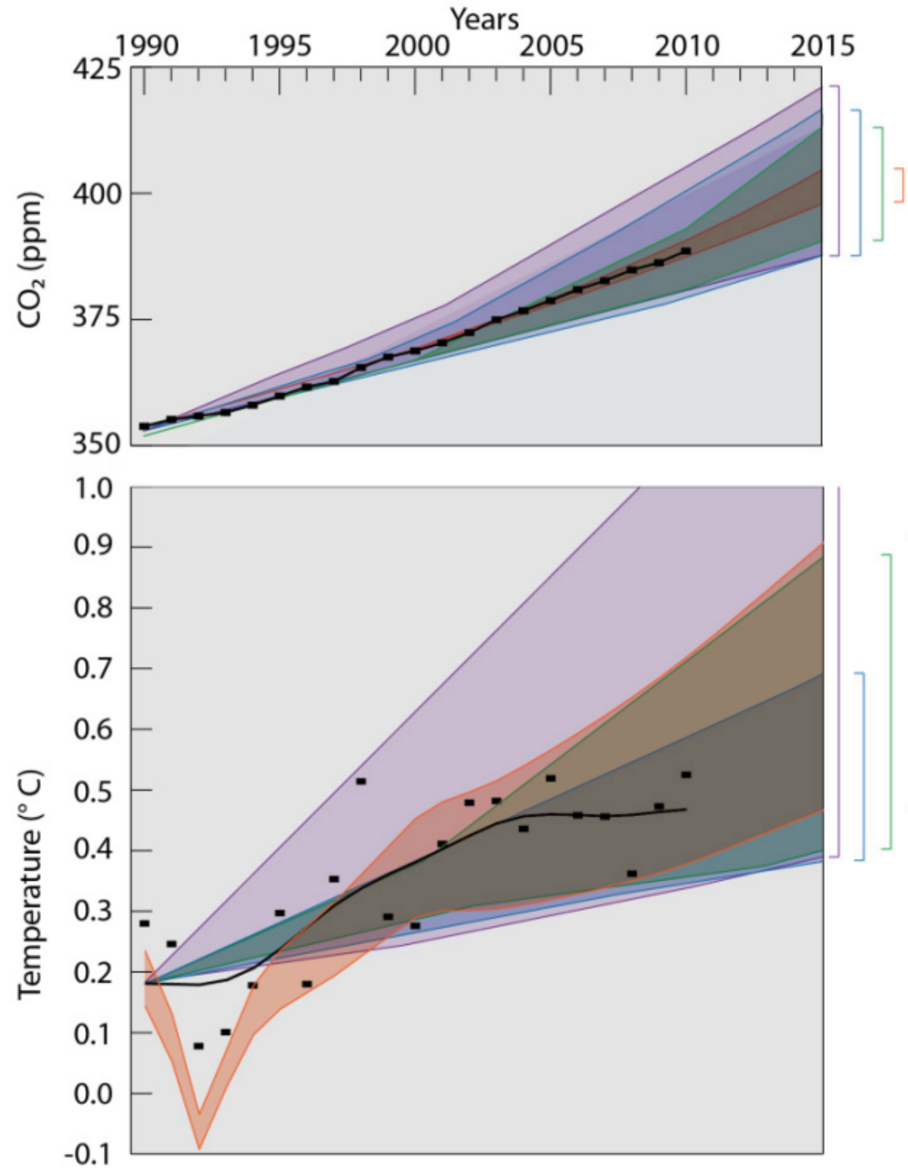


13:30 local-time map of rain rate (*R*) and the observed trend with aerosol loading in four selected regions. Period: July and August 2007. **b**, The average *R* values are plotted for six aerosol-loading sets (blue, including zero *R* grid squares; red, without zero *R* grid squares). Note the *R* intensification as a function of AOD in all cases. (Koren et al., Nature 2012)

Despite it all…

Current increase larger than worse forecast from IPCC 2007

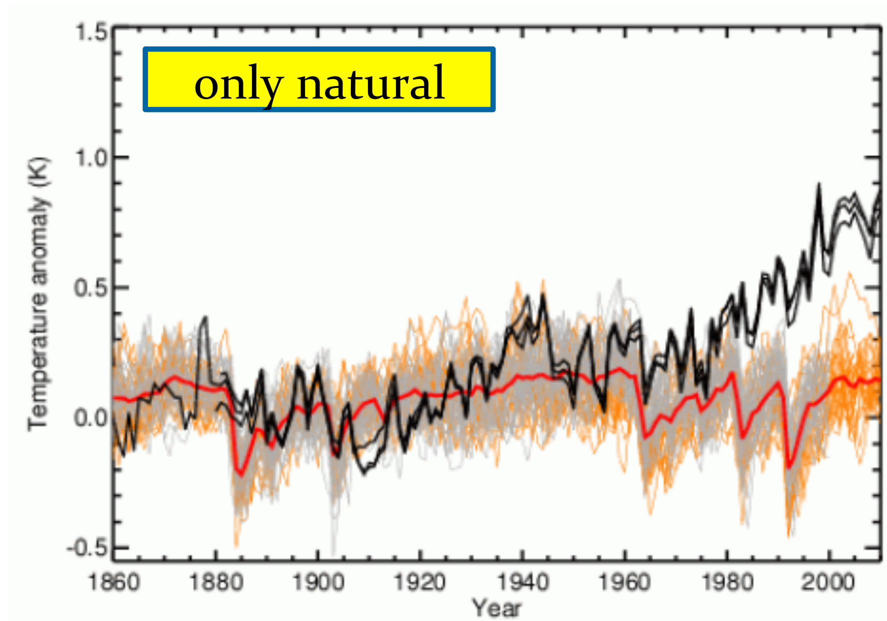


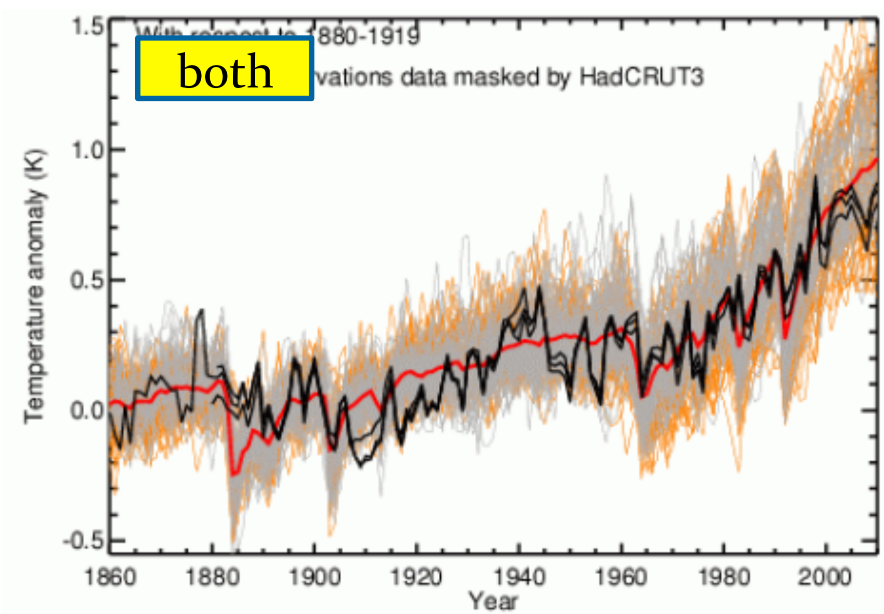


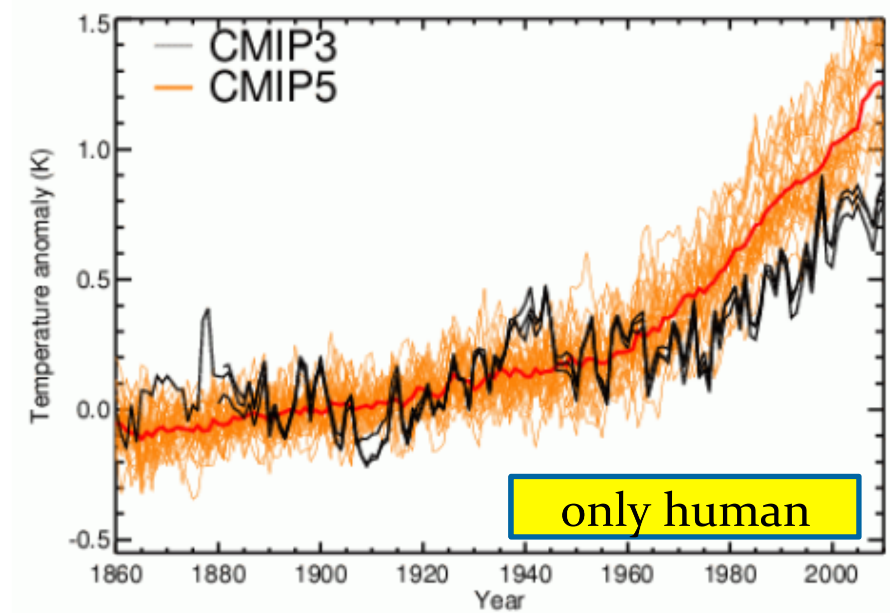
IPCC, AR5, Unpublished

Only explained by

- natural+antropogenic



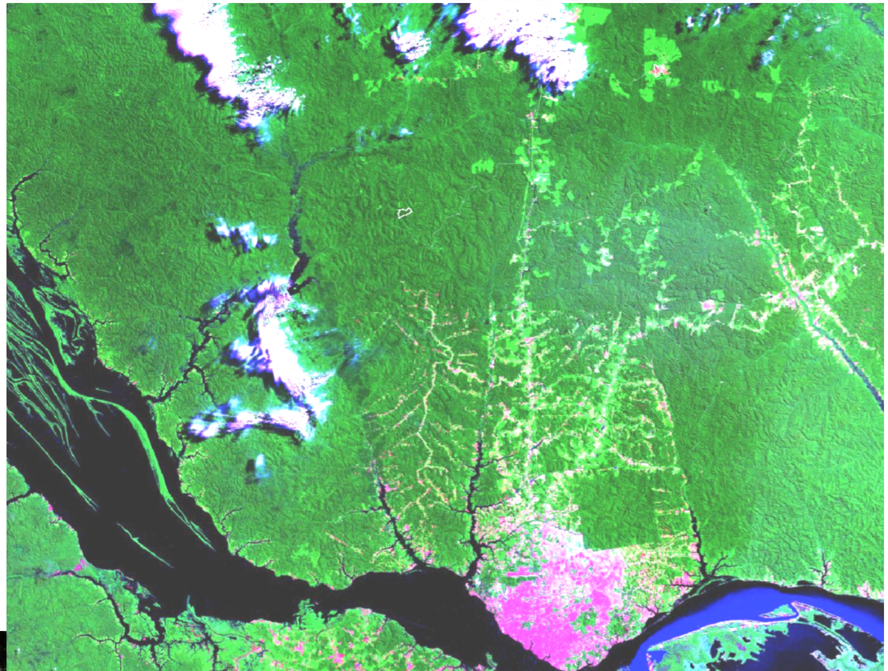


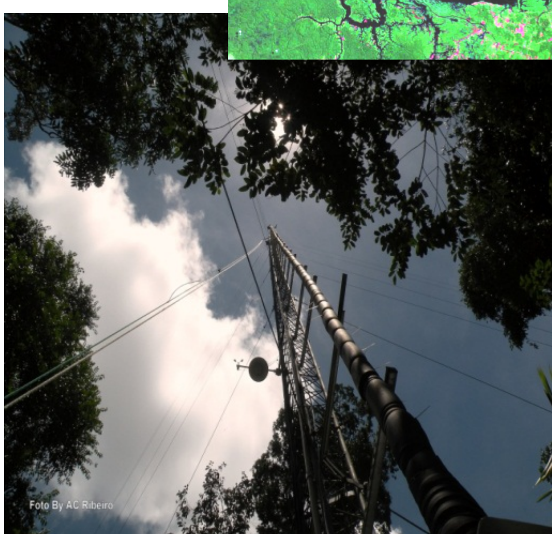


IPCC, AR5


Manaus

The ZF2 measurement site in Central Amazonia



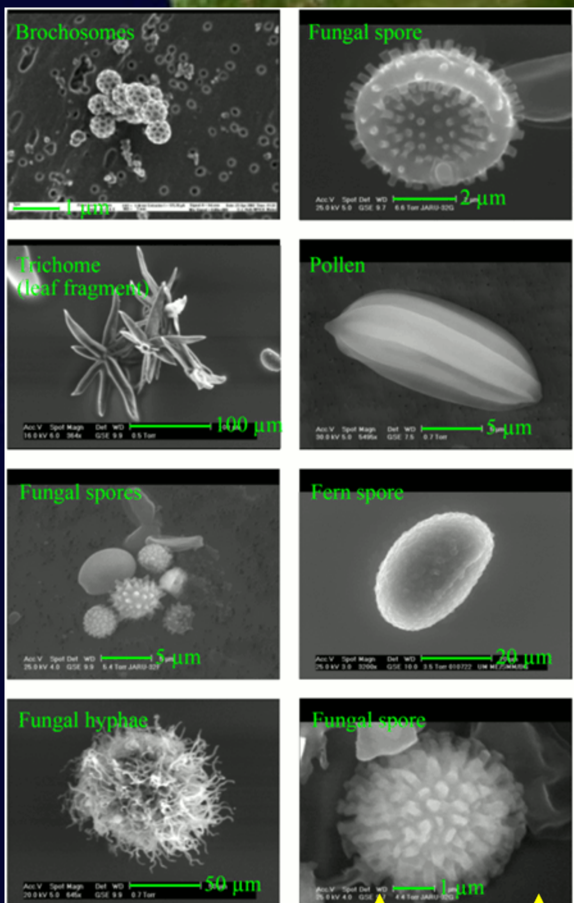


Dry aerosol (RH<40%)
Site continuously operational since Feb 2008.

Manaus ZF2 site: Instruments, dryer and ACSM

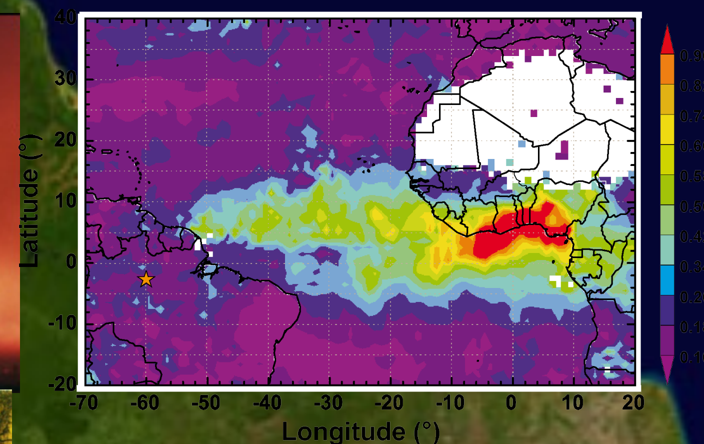
Amazonia: 3 different types of aerosols

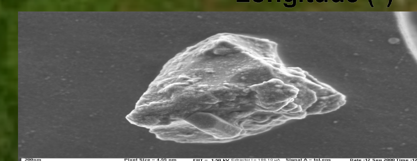
Biogenic (primary and SOA)

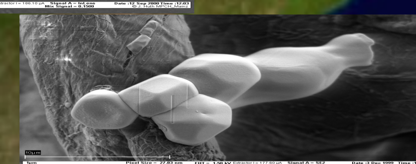


Biomass Burning

Dust from Sahara



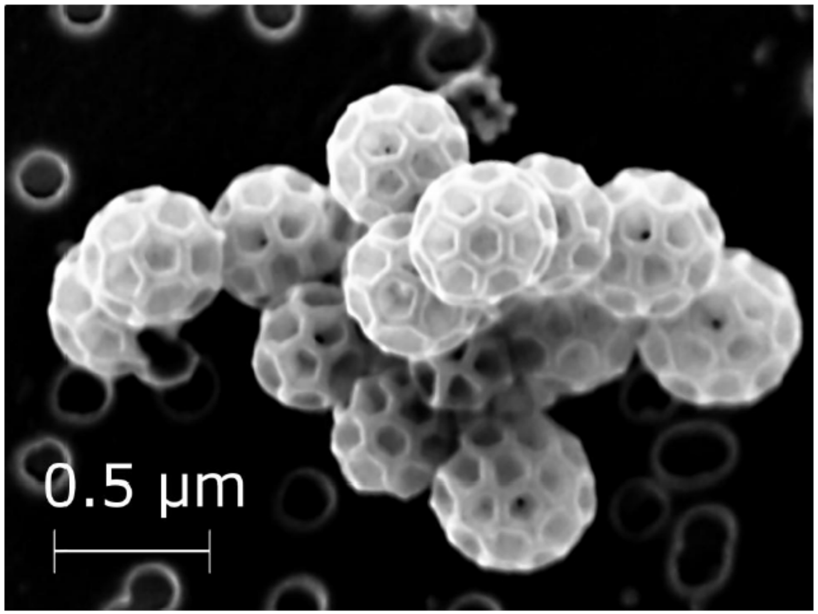




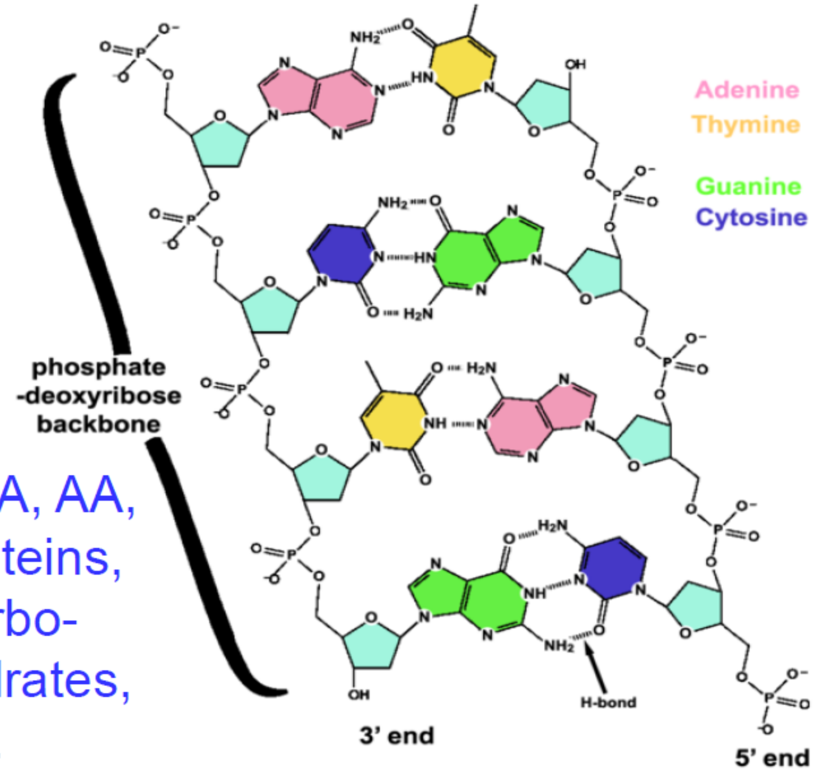
Each with VERY different properties and impacts

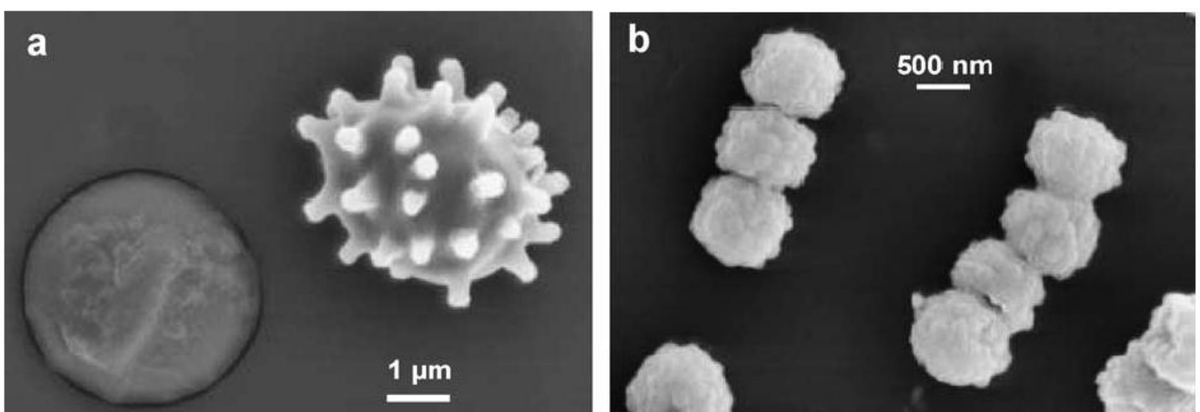
Biological Particles & Molecules

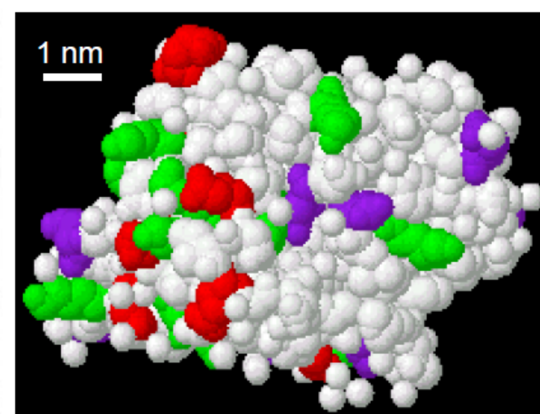
Bacteria, Brochosomes, Spores, Pollen, Plant Debris, etc.

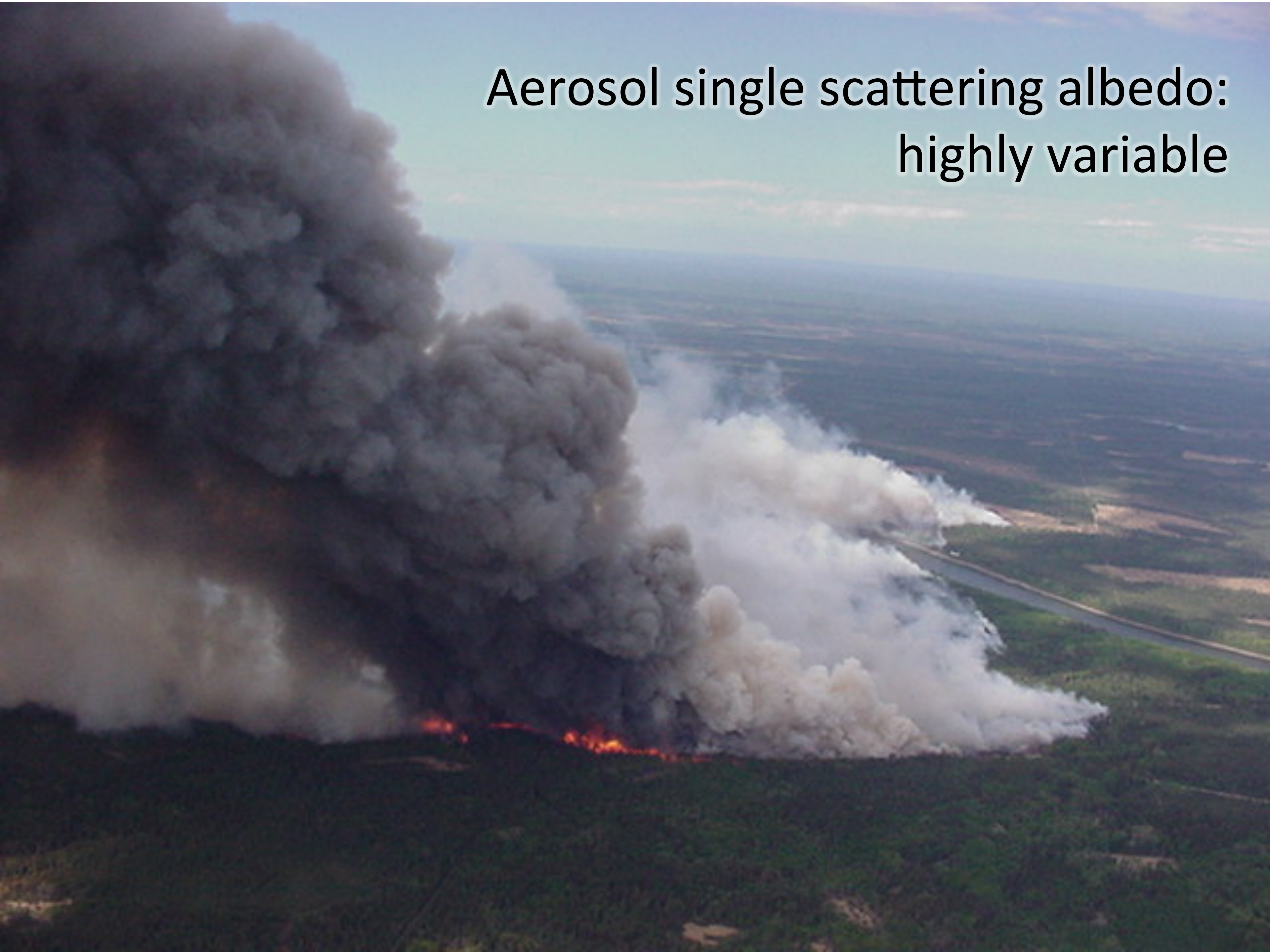


DNA, AA, Proteins, Carbo-hydrates, etc.



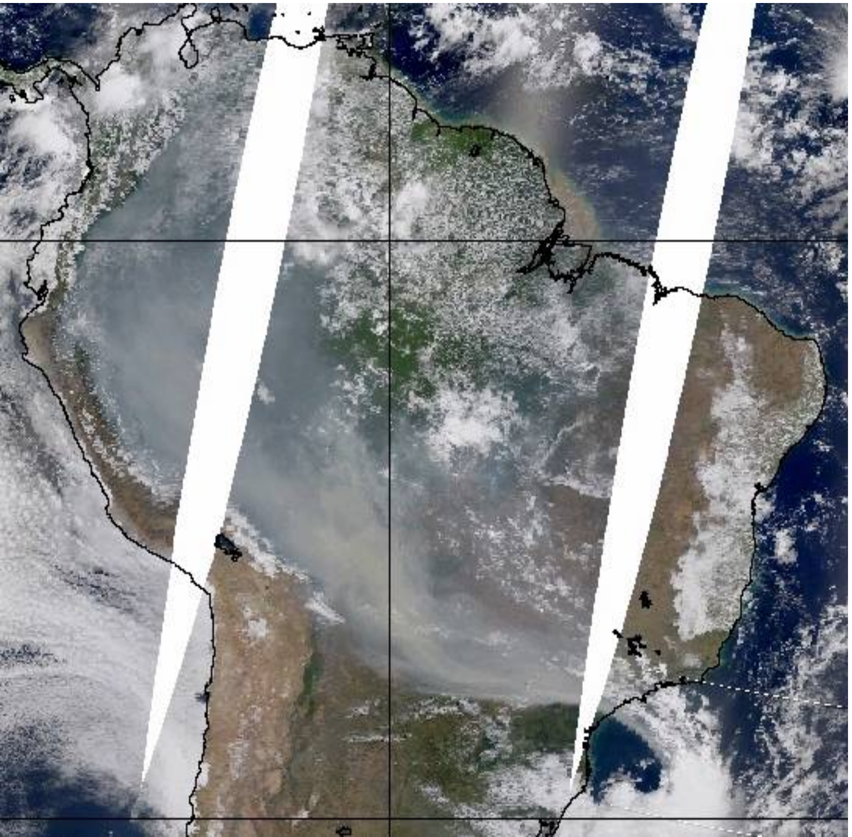


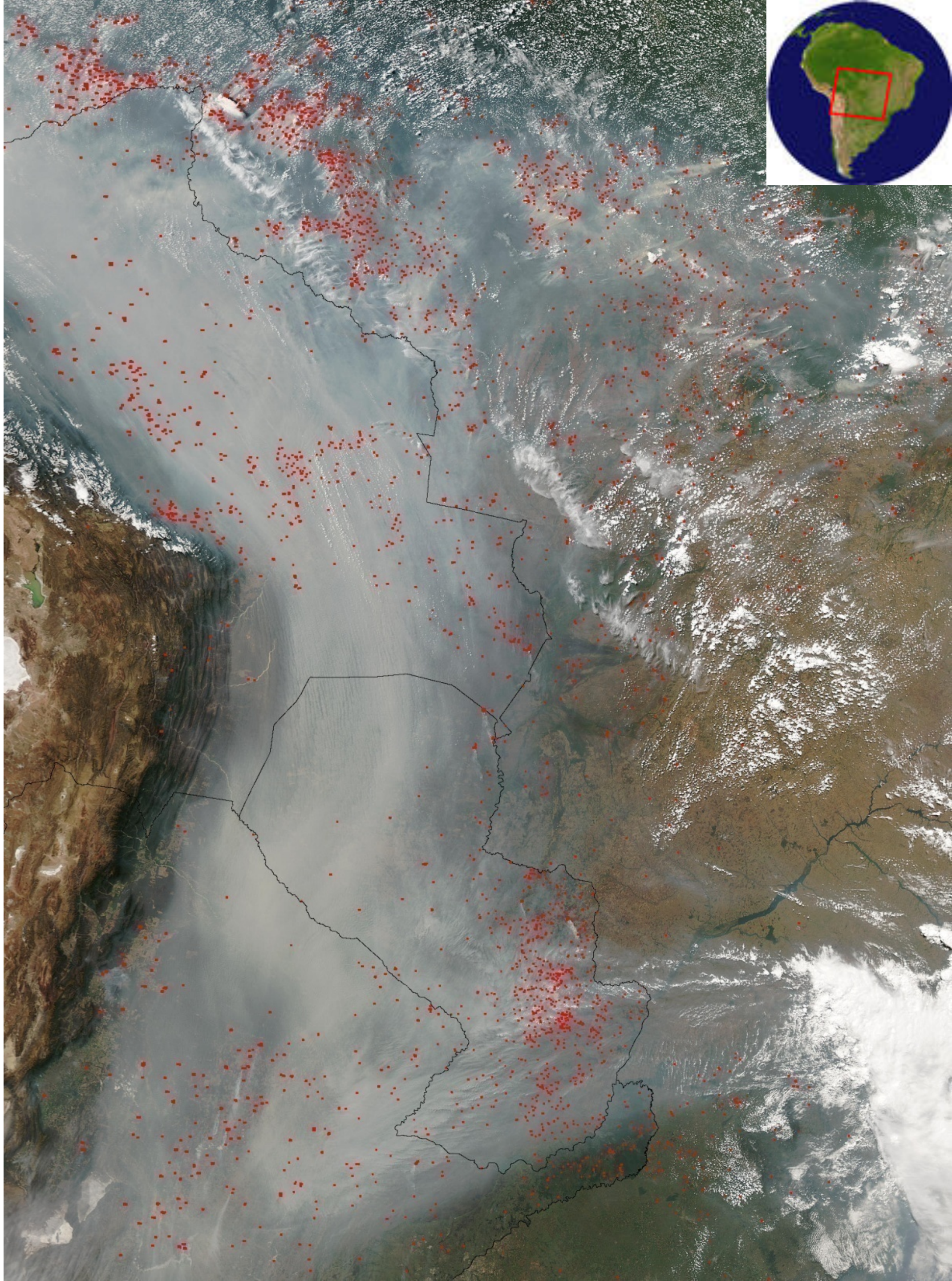



Aerosol single scattering albedo:
highly variable

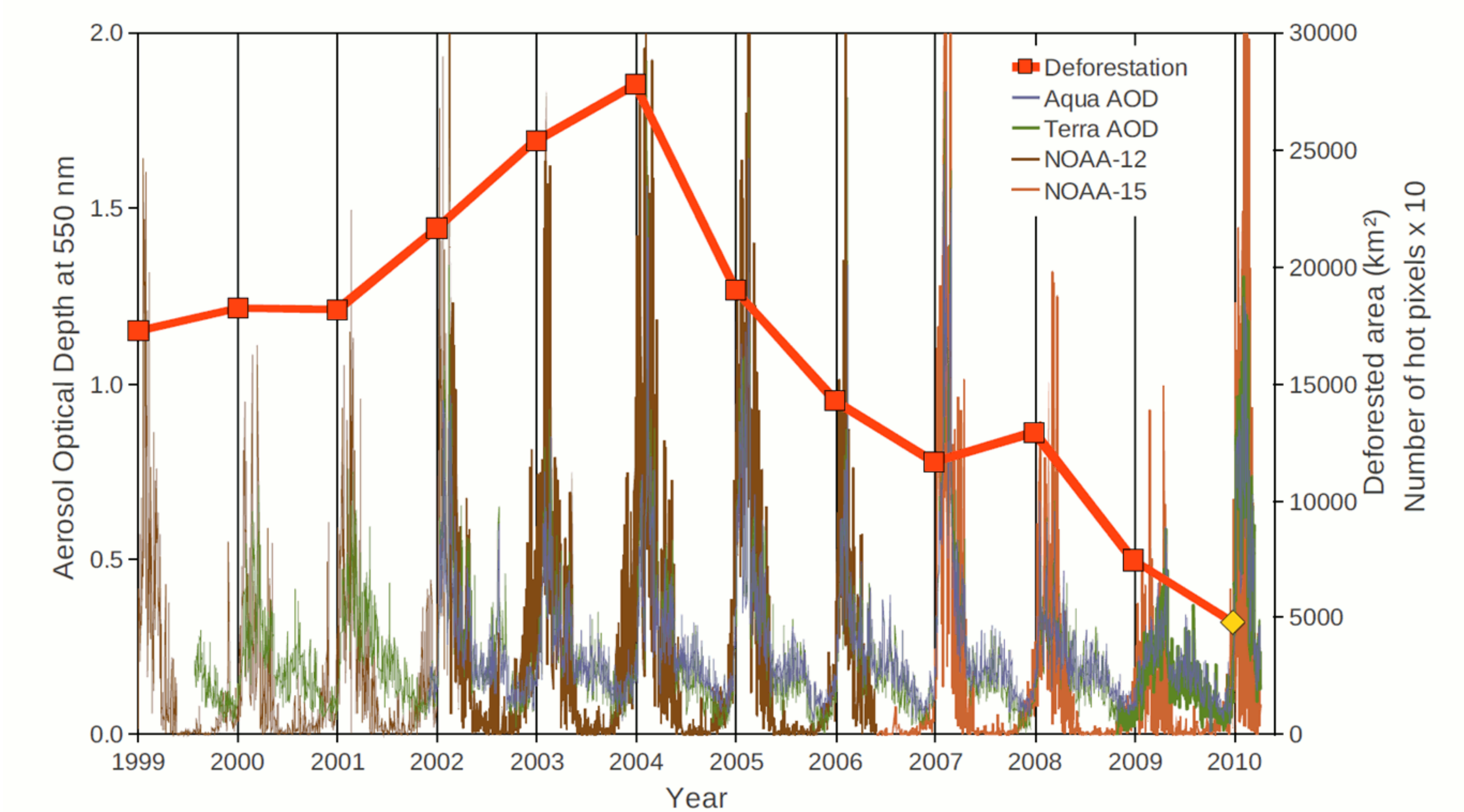
Large scale aerosol distribution in Amazonia

- Severe health effects on the Amazonian population (about 20 million people)
- Climatic effects, with strong effects on cloud physics and radiation balance.
- Changes in carbon uptake and ecosystem functioning





Yearly deforestation with MODIS AOD and hot pixels from NOAA



Yearly deforestation over the Brazilian Amazon region (INPE, 2010) compared to MODIS daily smoke optical depth and the daily number of hot pixels from NOAA-12 and NOAA-15.

Amazonia

Average aerosol forcing clear sky

Top: - 10 w/m^2

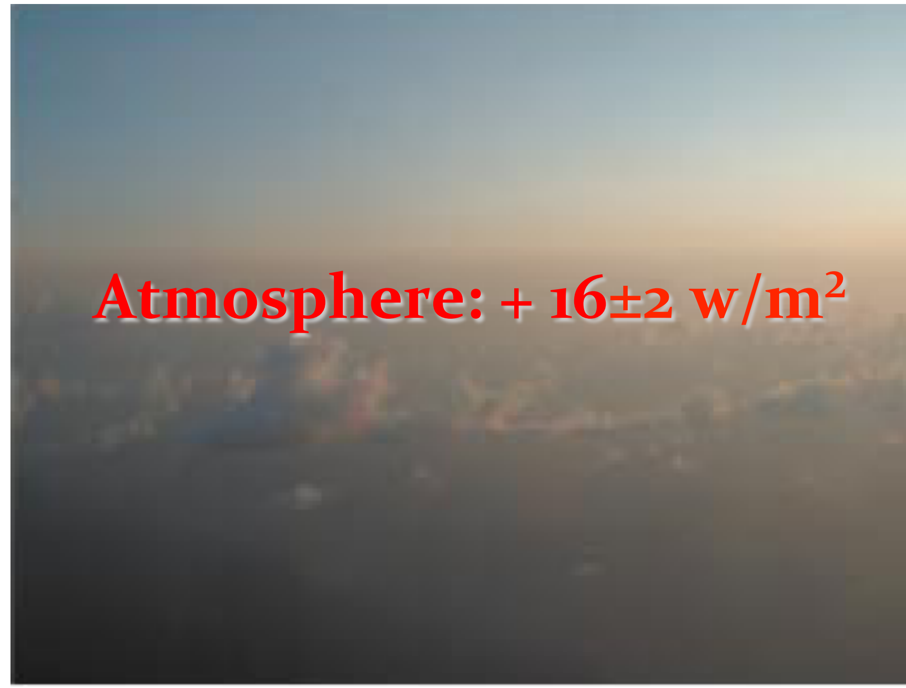
Surface: - 38 w/m^2

Conditions: surface: forest vegetation
AOT (τ=0.95 at 500nm); 24 hour average
7 years (93-95, 99-02 dry season Aug-Oct)

INDOEX

average aerosol forcing clear sky

Top: - 7±1 w/m^2



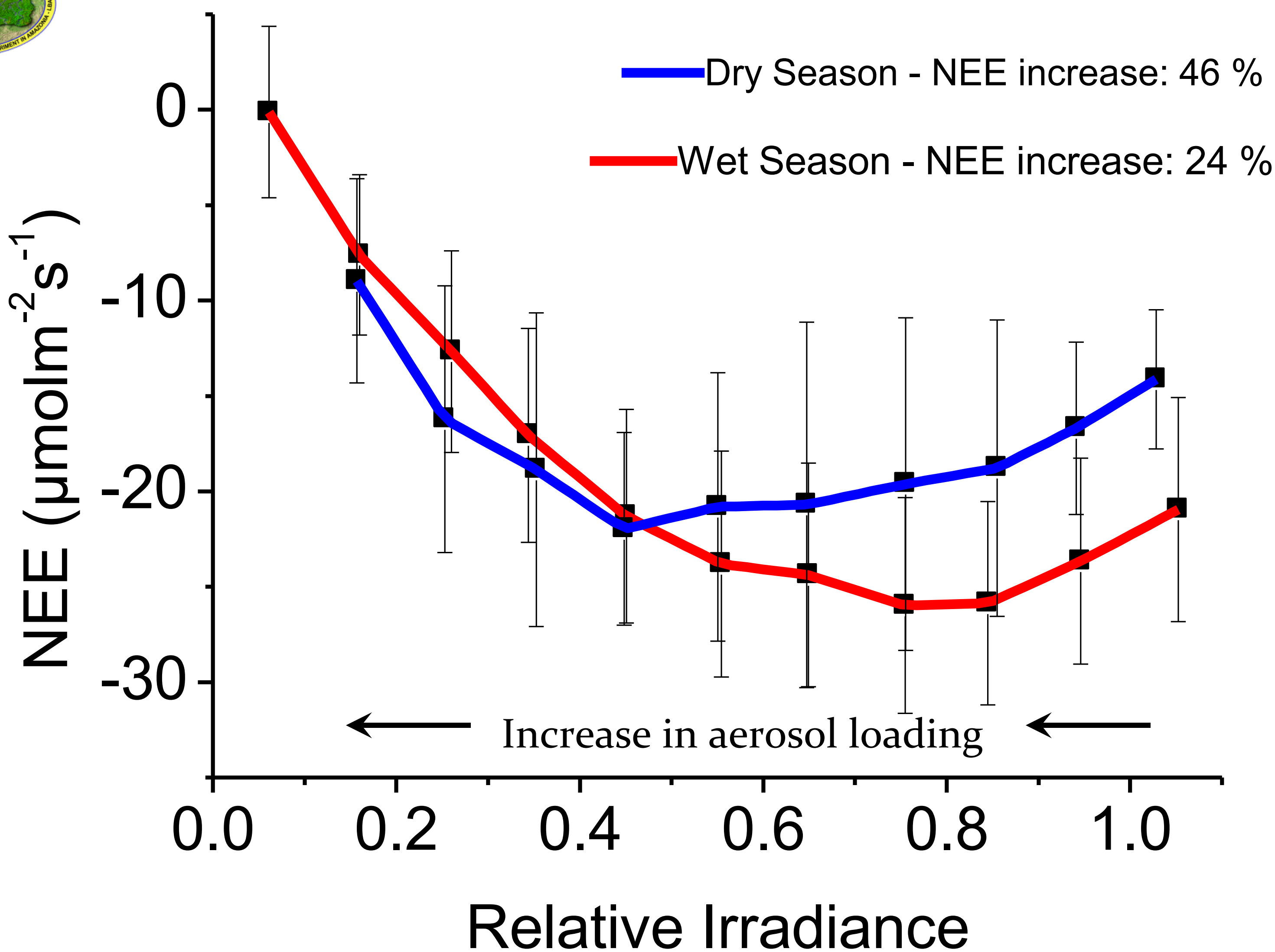
Surface: - 23±2 w/m^2

Conditions: surface: ocean
AOT (τ=0.3 at 630 nm); 24 hour average
Jan-Mar 99

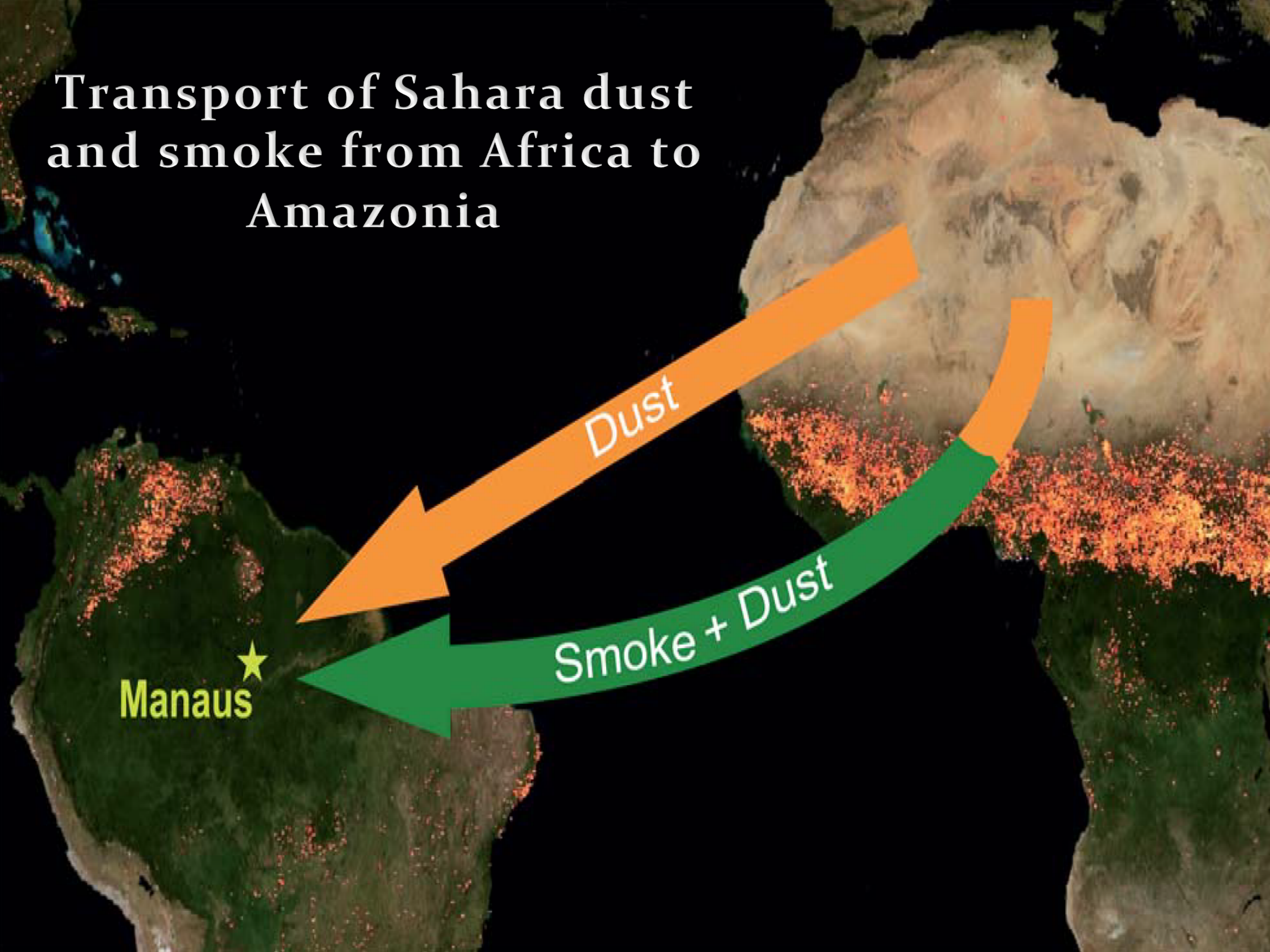
Procópio et al. (2004)

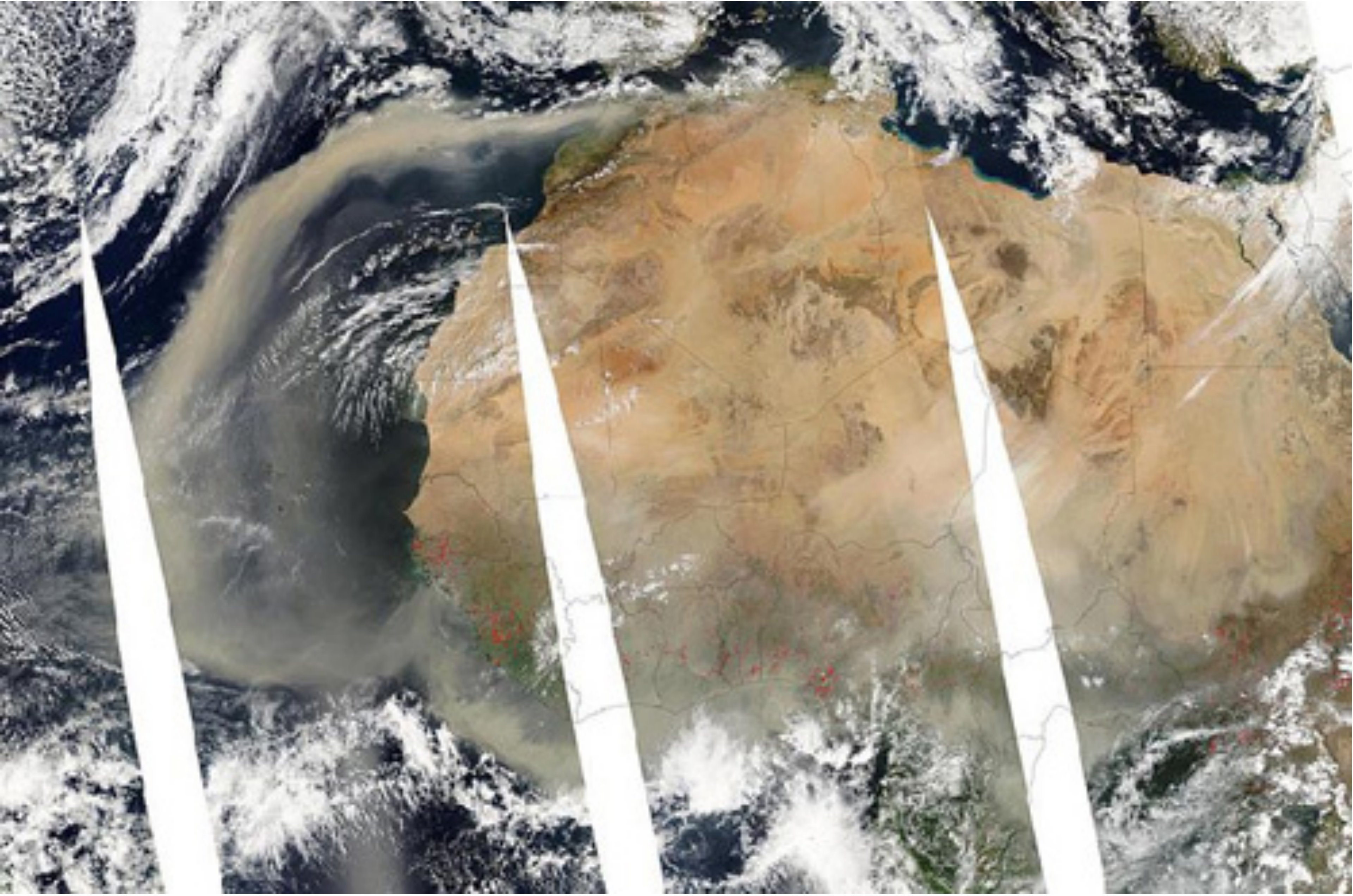
Strong aerosol effect on forest photosynthesis diffuse radiation have a large effect on CO_2 fluxes

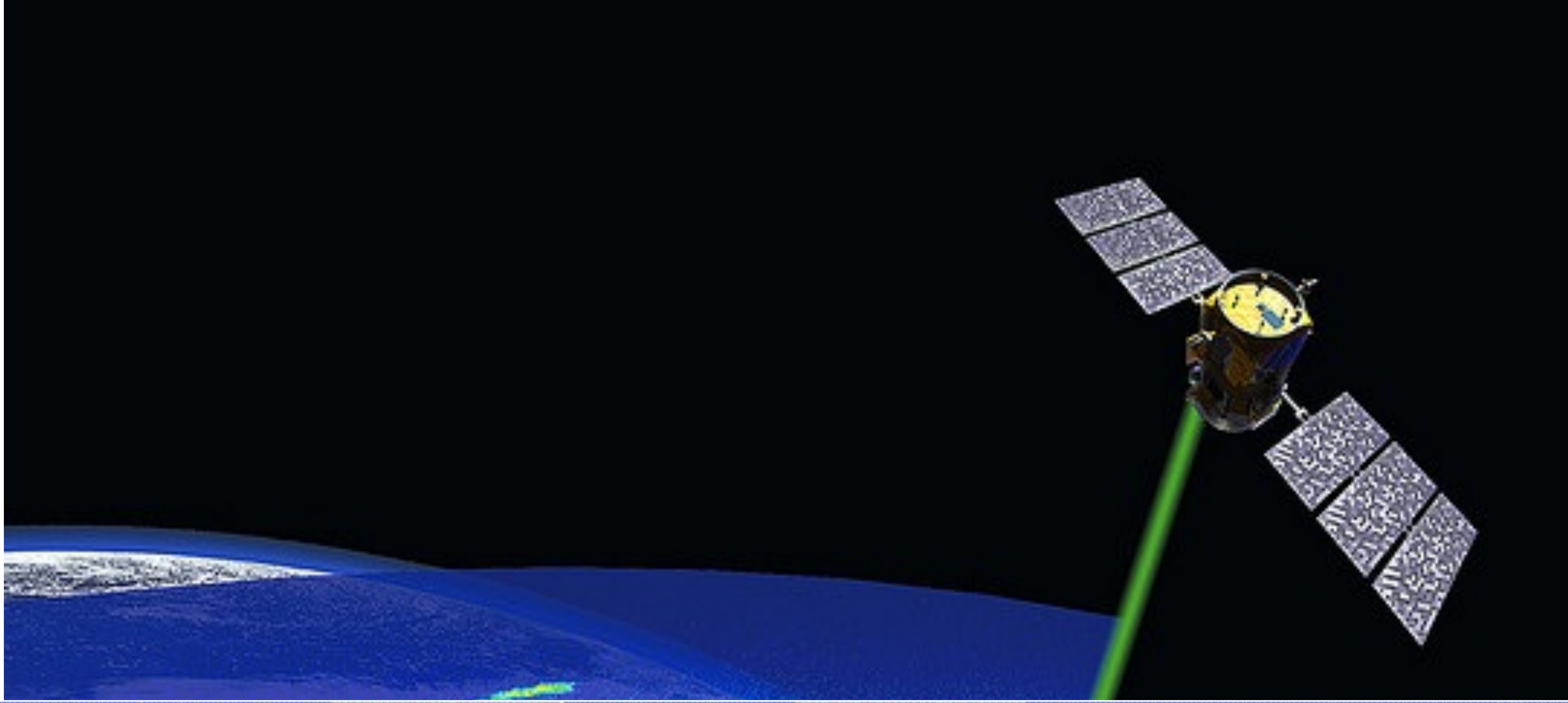
Amazonia Rondonia Forest site 2000-2001

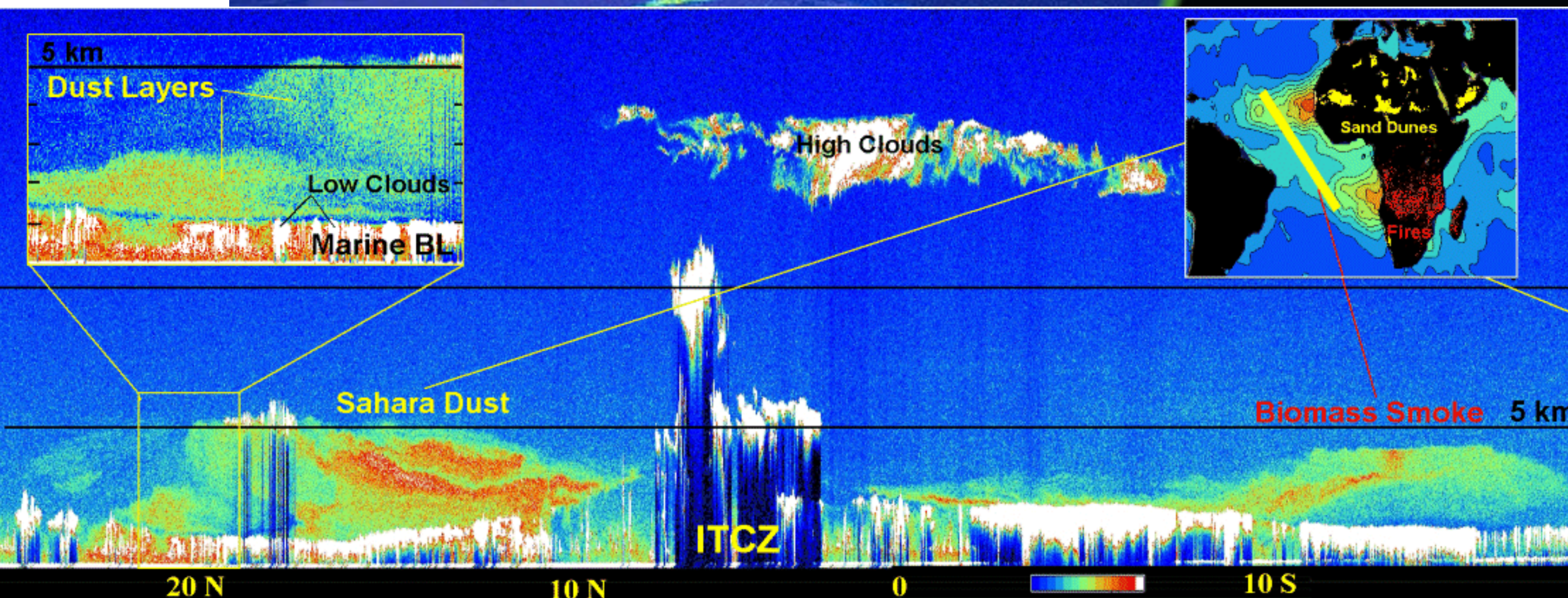


Transport of Sahara dust and smoke from Africa to Amazonia

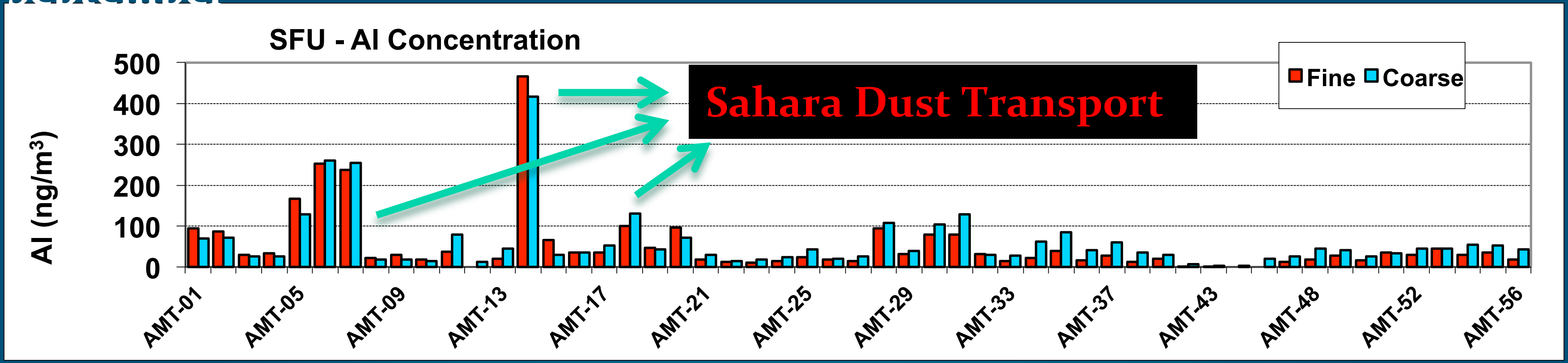


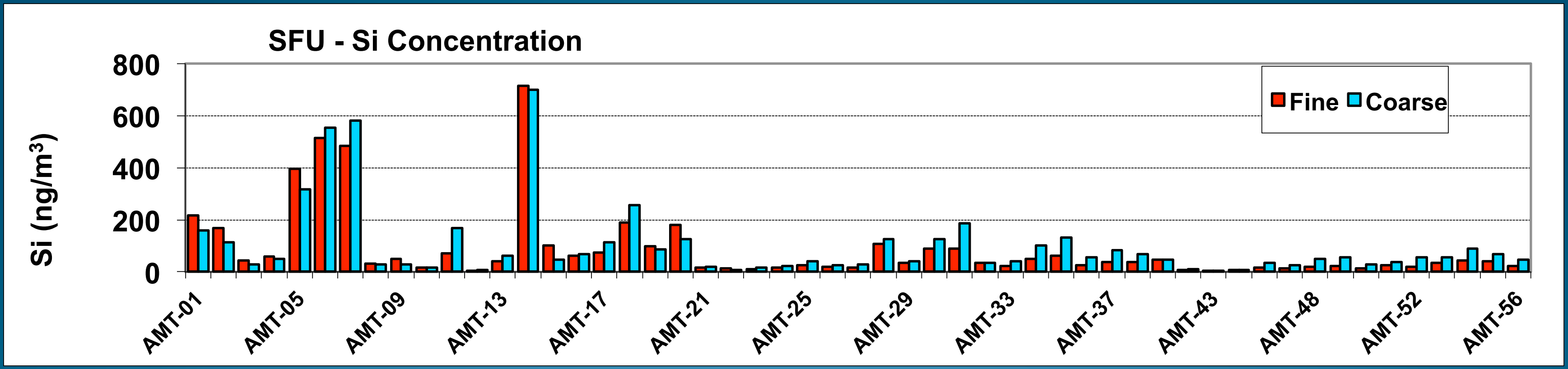


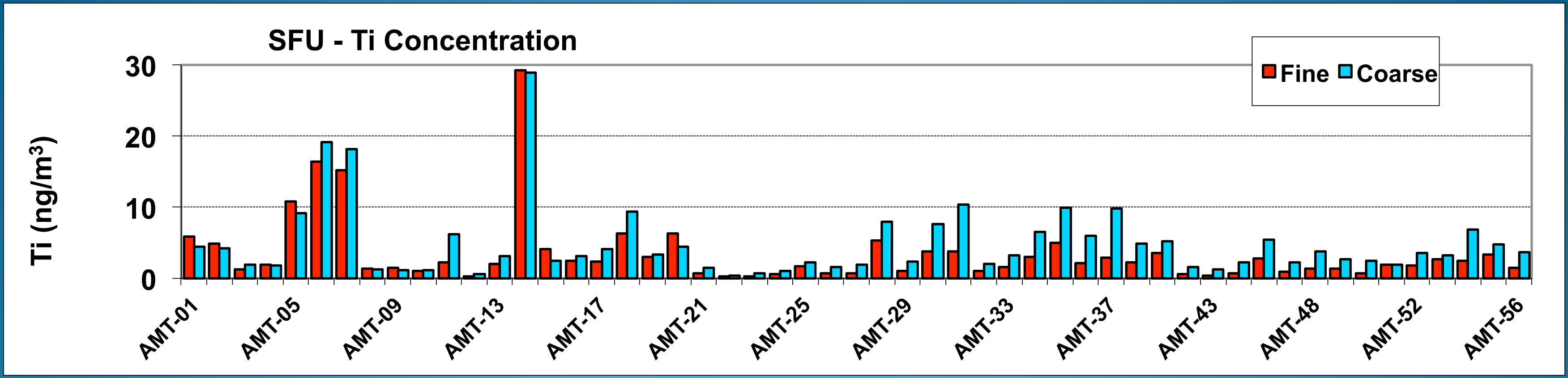


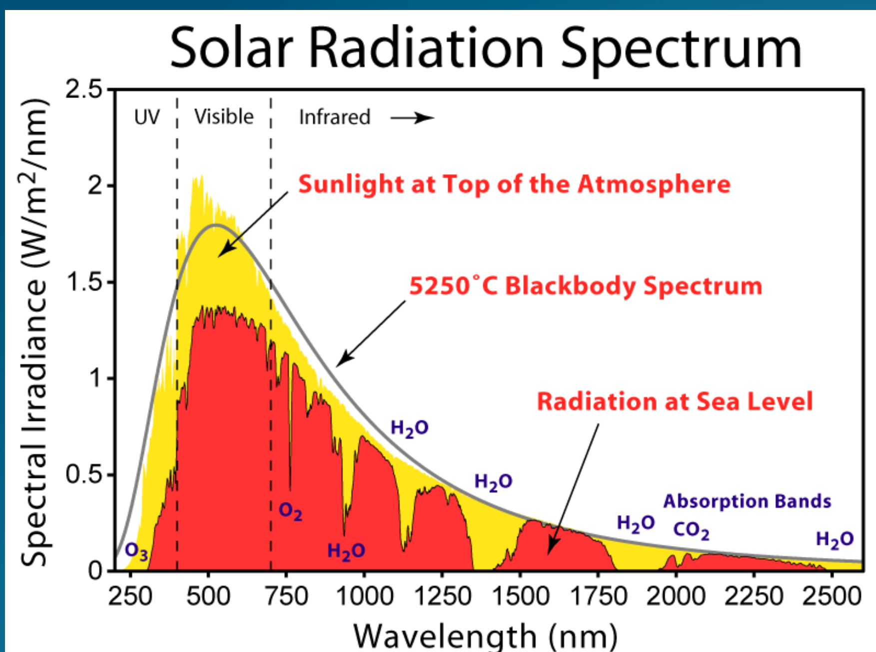

5 km
Dust Layers
Low Clouds
Marine BL
High Clouds
Sand Dunes
Fires
Sahara Dust
Biomass Smoke
5 km
ITCZ
20 N
10 N
0
10 S

Al, Si and Ti elemental Concentration for fine and coarse mode aerosols Feb. to September









Thanks!

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