Atmospheric processes: from cloud to global scales

Download the coursebook (PDF)

ENV-407 / **5 credits**

Teacher(s): Berne Alexis, Gehring Josué Etienne, Nenes Athanasios

Language: English

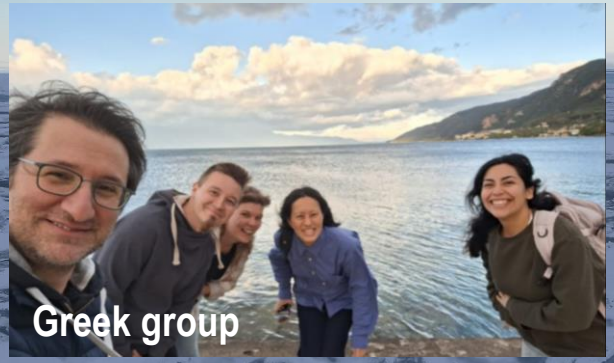
Alexis Berne

Athanasios Nenes

Josué Gehring

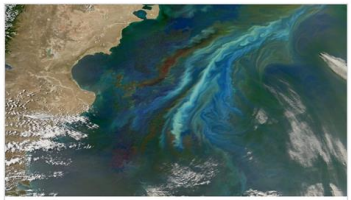
LAPI – Athanasios (Thanos) Nenes

Laboratory of atmospheric processes and their impacts

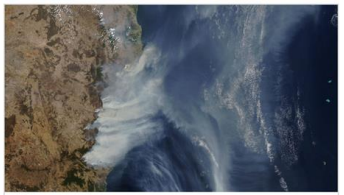


http://lapi.epfl.ch

http://cstacc.iceht.forth.gr



Biogeochemical Cycles



Aerosol – Cloud – Climate Interactions

LAPI

Air Quality and Health

Aerosol Chemistry and Impacts

iMIRACLI

CleanCloud

FORCeS

ReCLEAN

GREEN FJORD

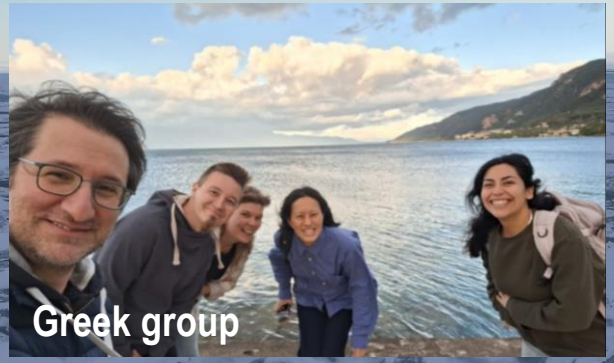
IPIC Air

erc European Research Council Established by the European Commission

EASVOLEE

LAPI – Athanasios (Thanos) Nenes

Laboratory of atmospheric processes and their impacts

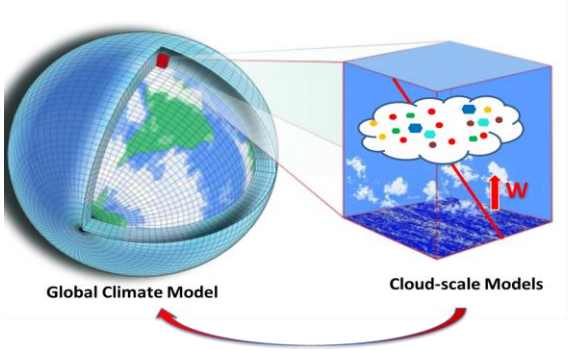


http://lapi.epfl.ch

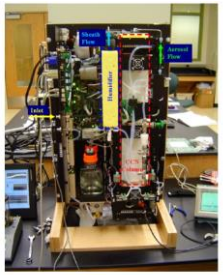
http://cstacc.iceht.forth.gr

Field and Laboratory Observations

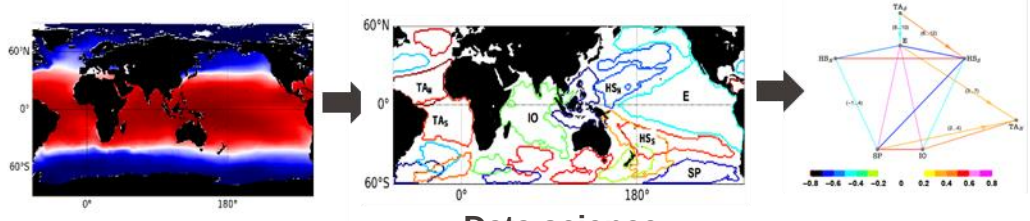
Modeling



Instrumentation

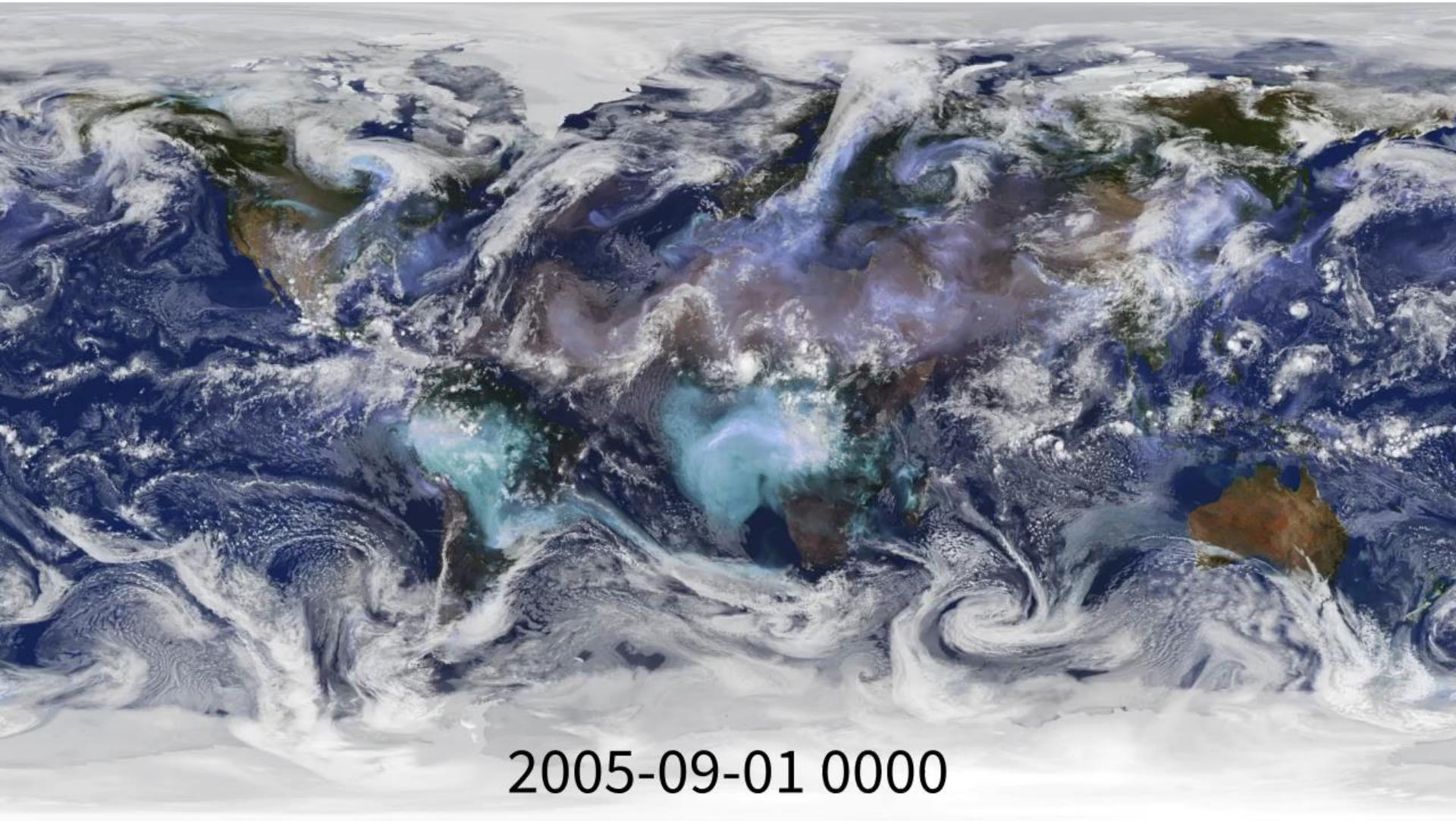


Cloud Condensation Nuclei Counter, US Patent 7,656,510

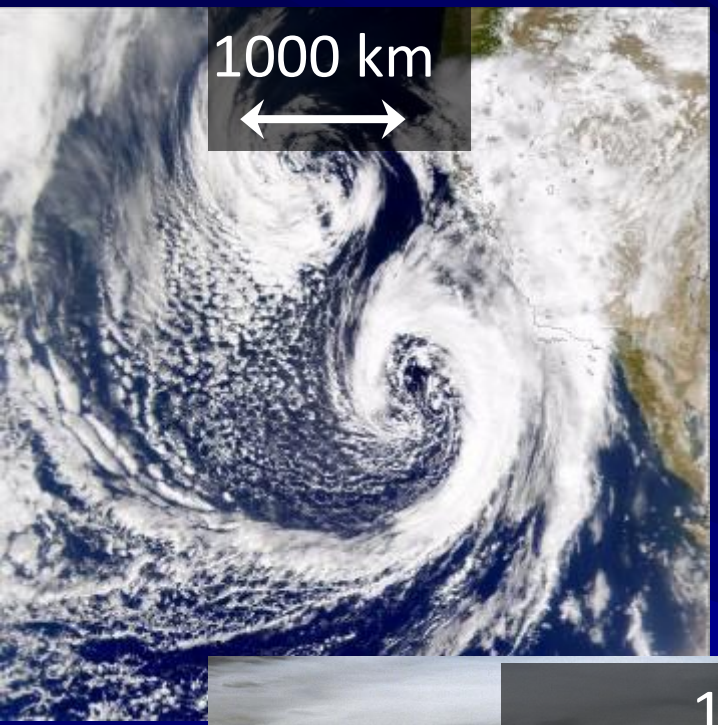


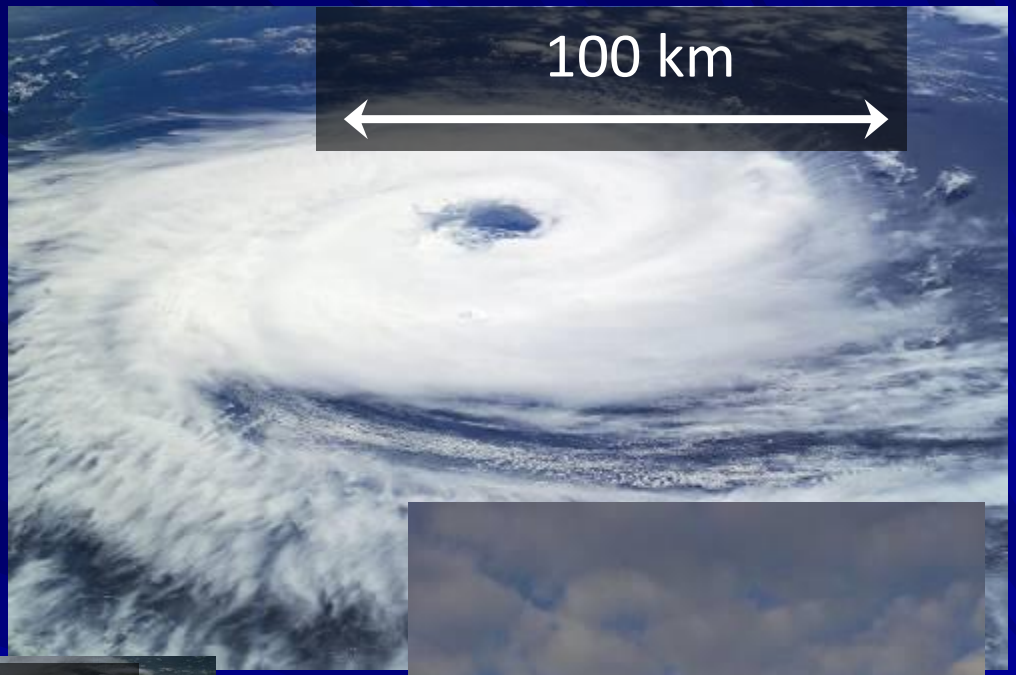
Data science

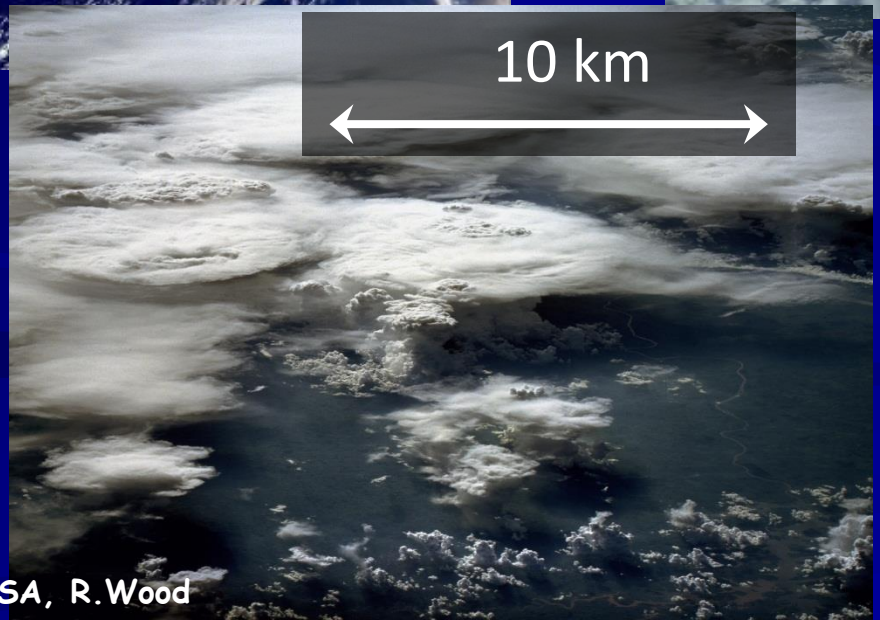
Clouds are everywhere and at all scales…



Clouds are everywhere and at all scales…







Photos: NASA, R.Wood

Clouds have an important radiative impact.

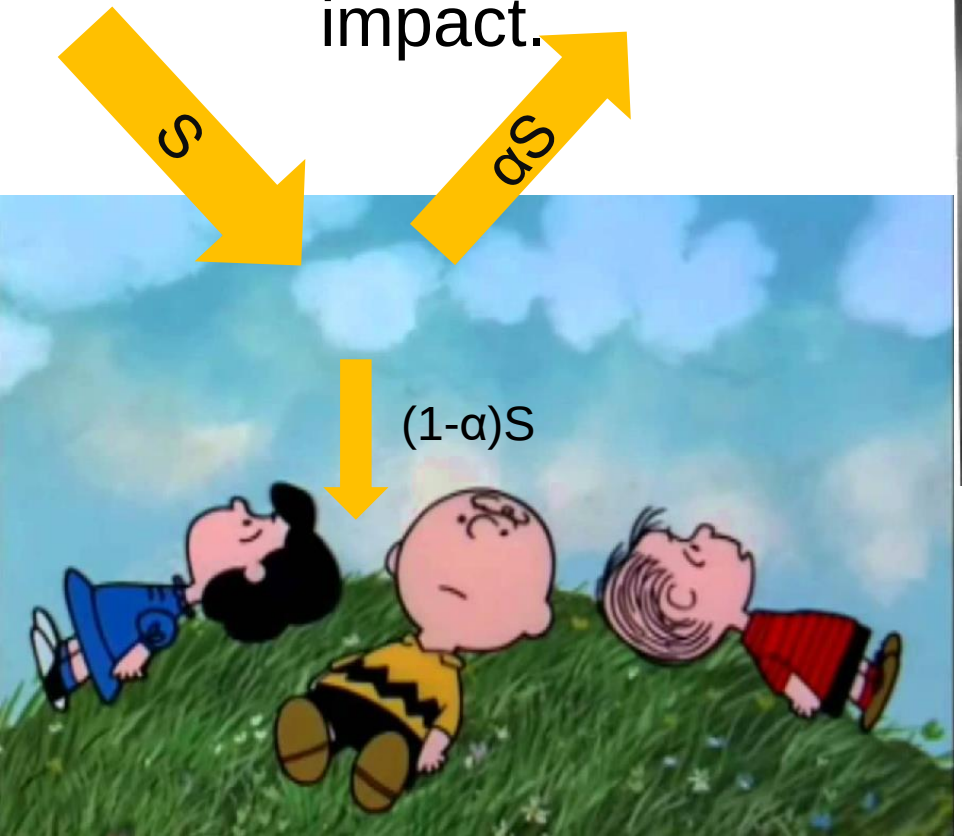


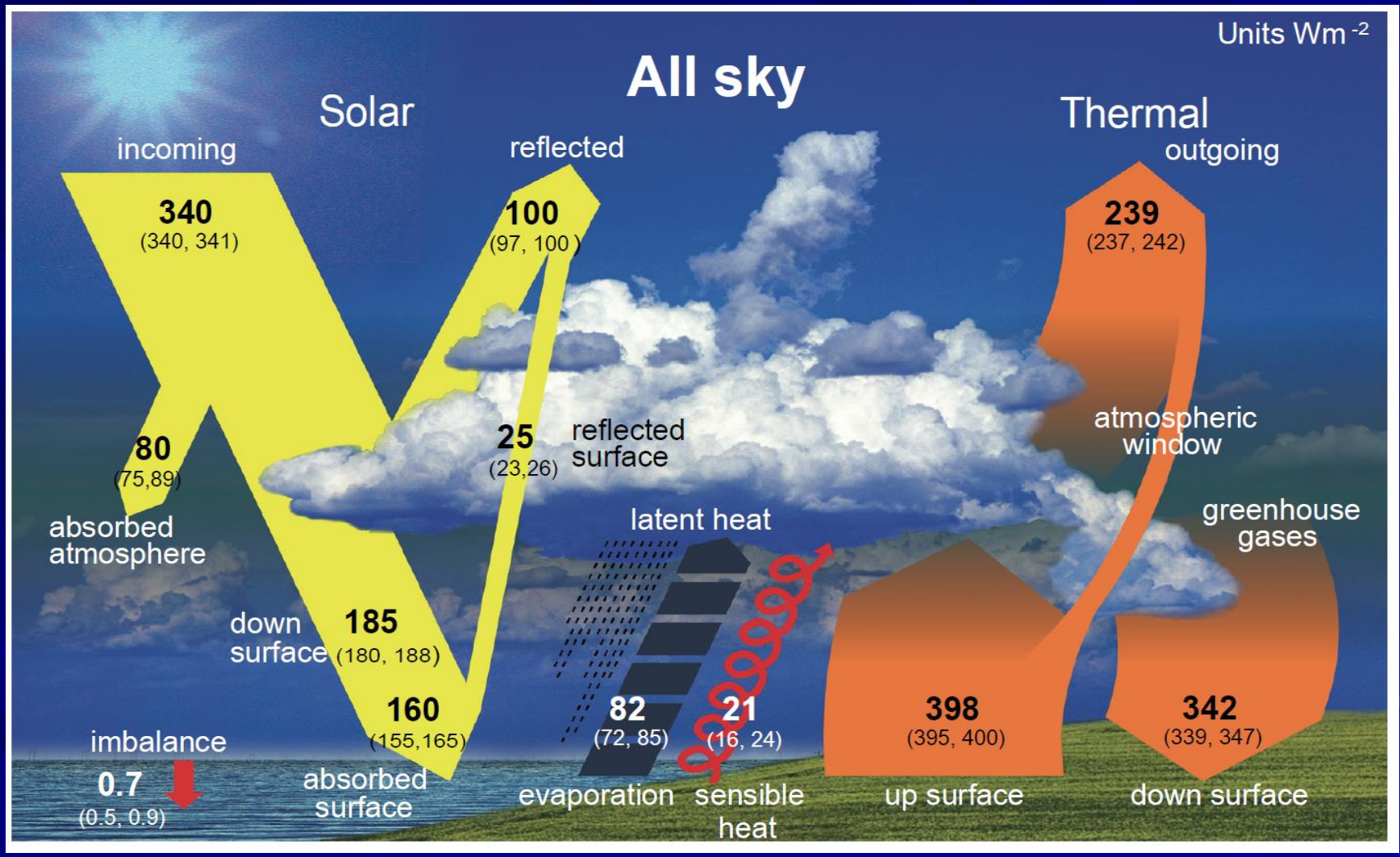
Photo from Wynn Bullock

Clouds also have an important hydrological impact.

Both critically important for regional and global climate

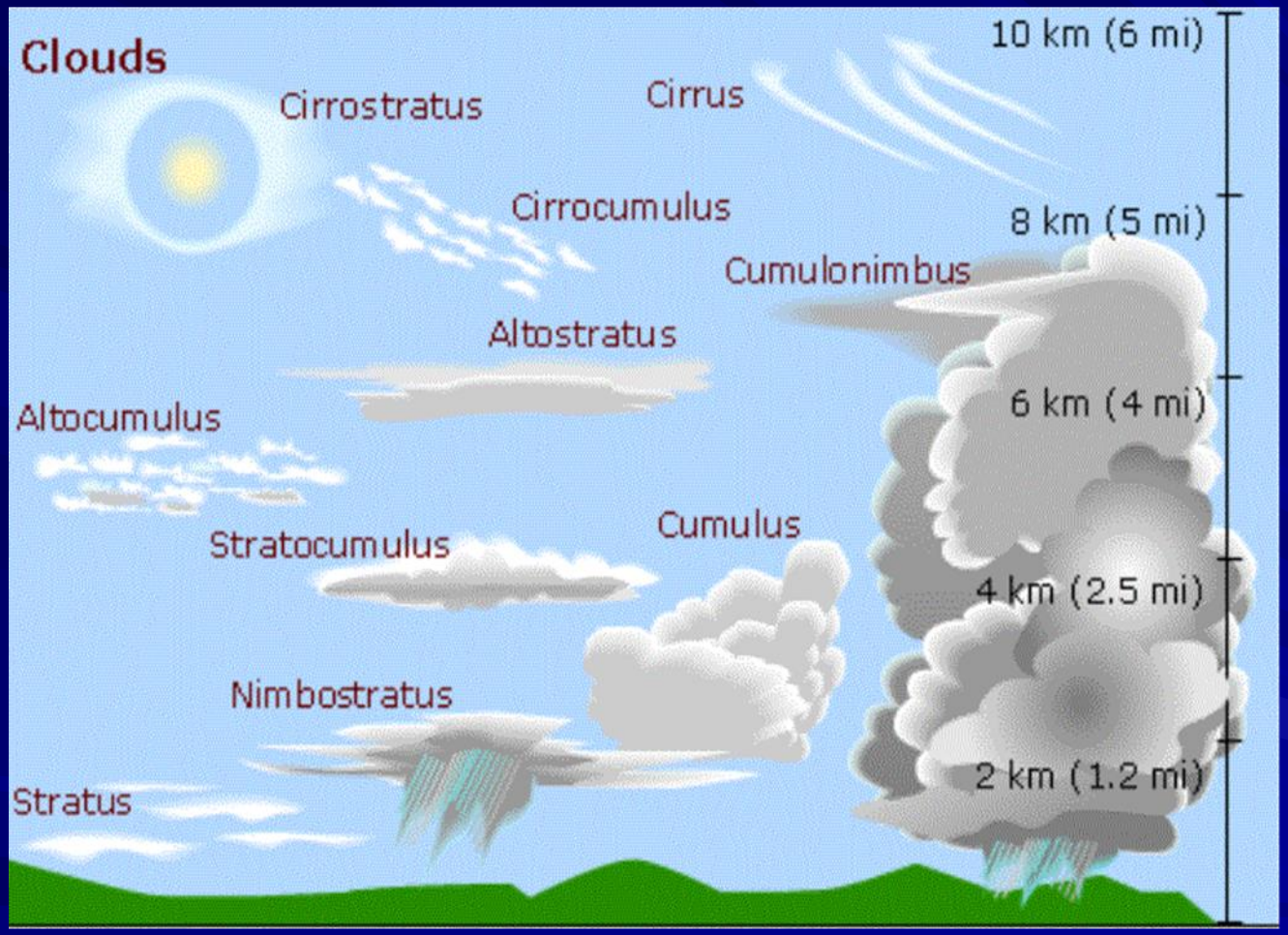
Courtesy: S.Sullivan

Clouds play a central role in the climate system



Based on J.T. Houghton: "The science of climate change"

Cloud impacts vary alot



High clouds (ice crystals): *warm* climate

Mid-level: Warm/cool

Low clouds (liquid drops): *cool* climate

http://www.ucar.edu/news

Types of clouds

Base height

- decrease in tropopause height with latitude
- decrease in cloud elevation

Structure

- reflects instability and nuclei

Phase

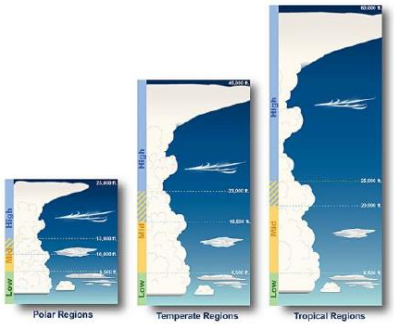
- *warm clouds*: liquid water
- *cold clouds*: ice crystals or mix

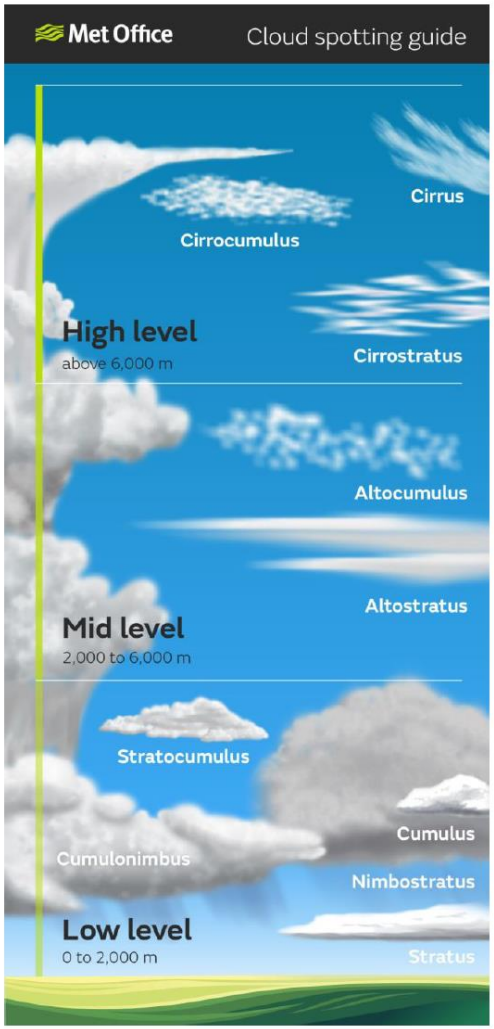
Cirro-form
Ice crystals
"Wispy" appearance

Cumulo-form
Vertical instability
Fluffy appearance

Strato-form
Vertical stability
Broad, layered

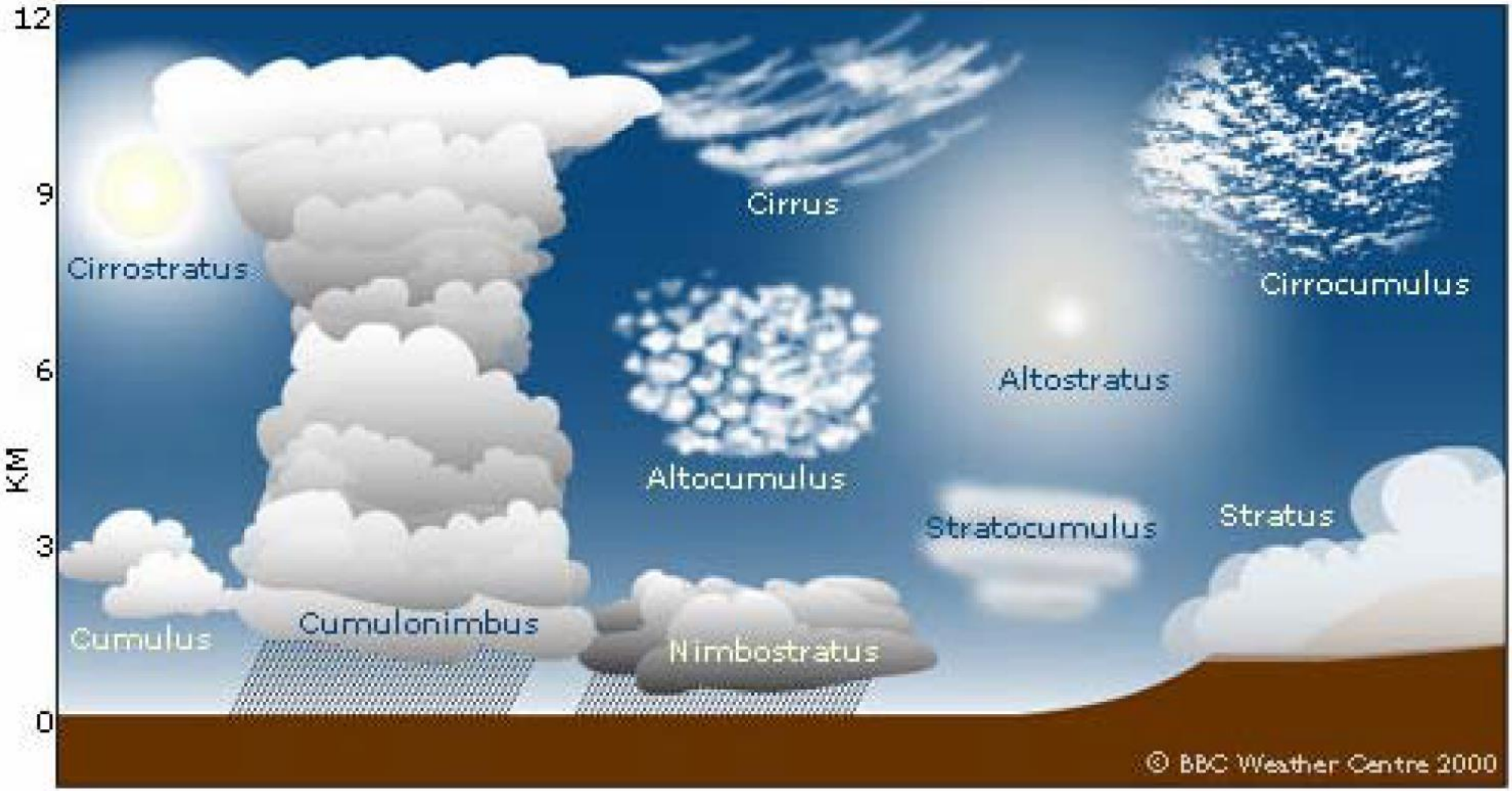
Nimbo-form
Great vertical height
Rain clouds



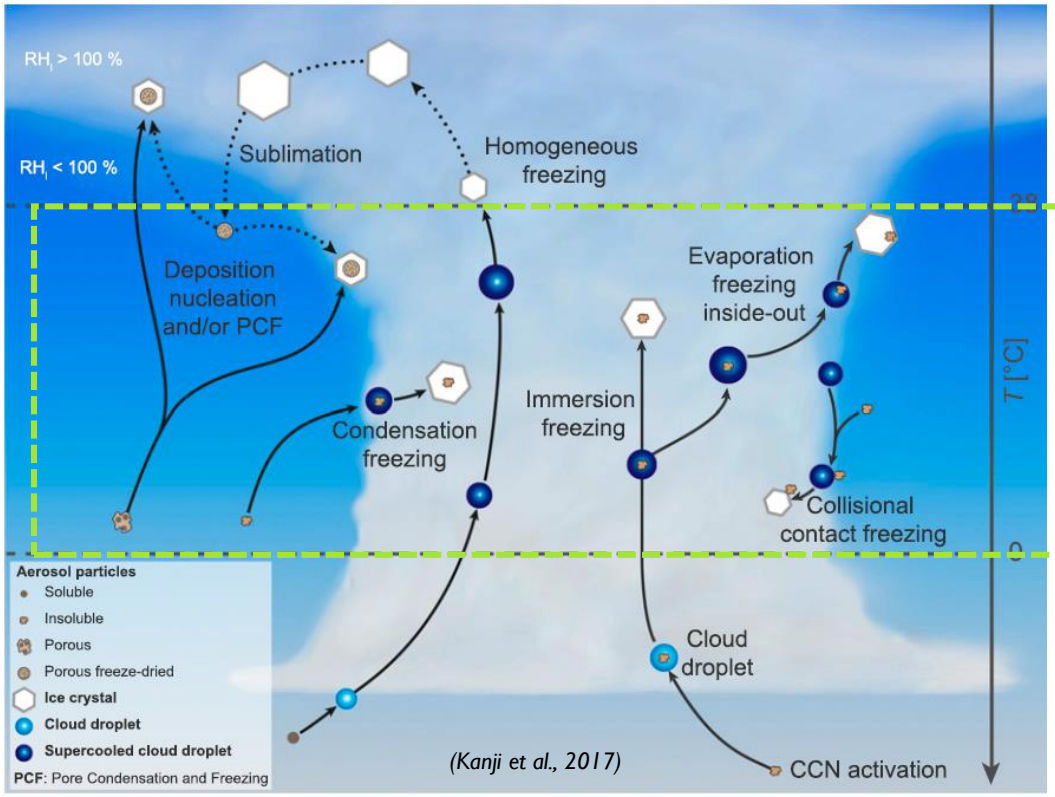


weather.gov and *World Met Organization*

Common Cloud Names, Shapes, and Altitudes:



Clouds types in the atmosphere



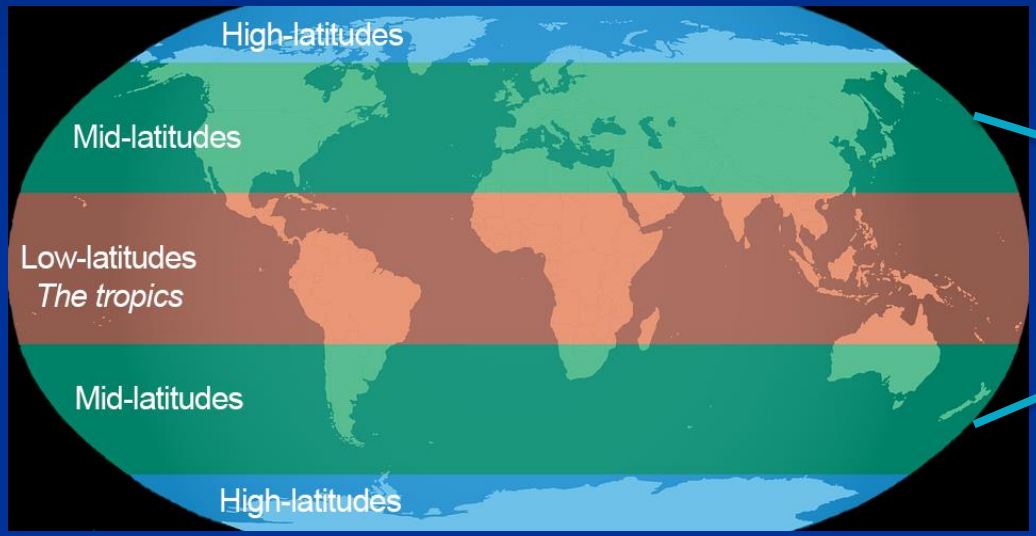
Pure ice clouds (glaciated)

Mixed-phase clouds

Liquid-phase clouds

Atmospheric Particles ("aerosol") are the seeds for cloud formation
Aerosol/Cloud/Climate interactions are a major source of uncertainty in climate projections

Liquid+ice ("mixed-phase") clouds Are very important for climate

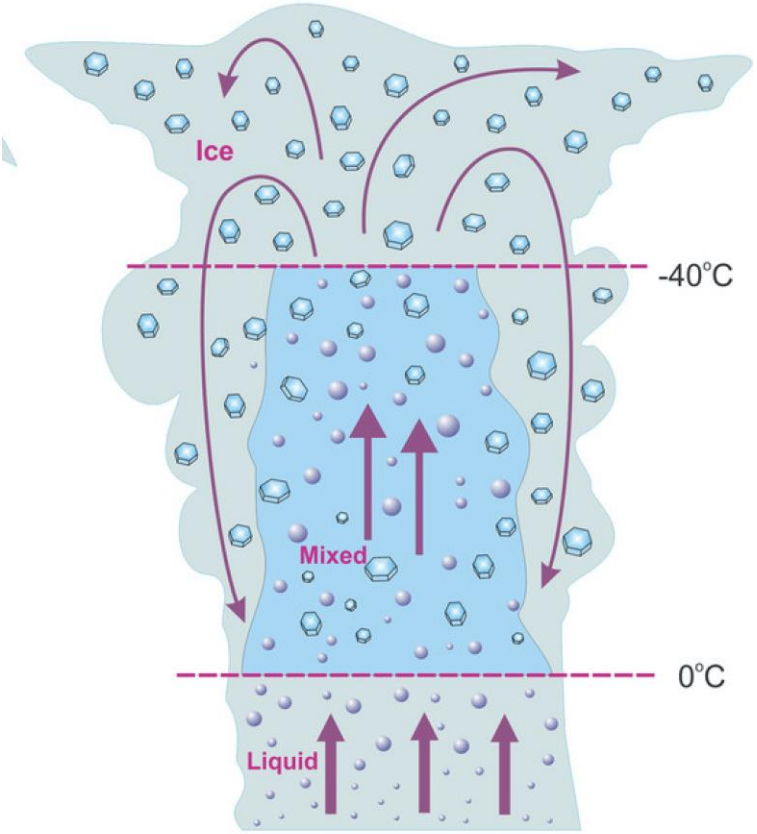


30-50% of precipitation occurs from the ice phase

Field and Heymsfield, 2015
Mülmenstädt et al. 2015

"…much of what is rain, when it arrives at the surface of the Earth, might have been snow, when it began its descent . . ."

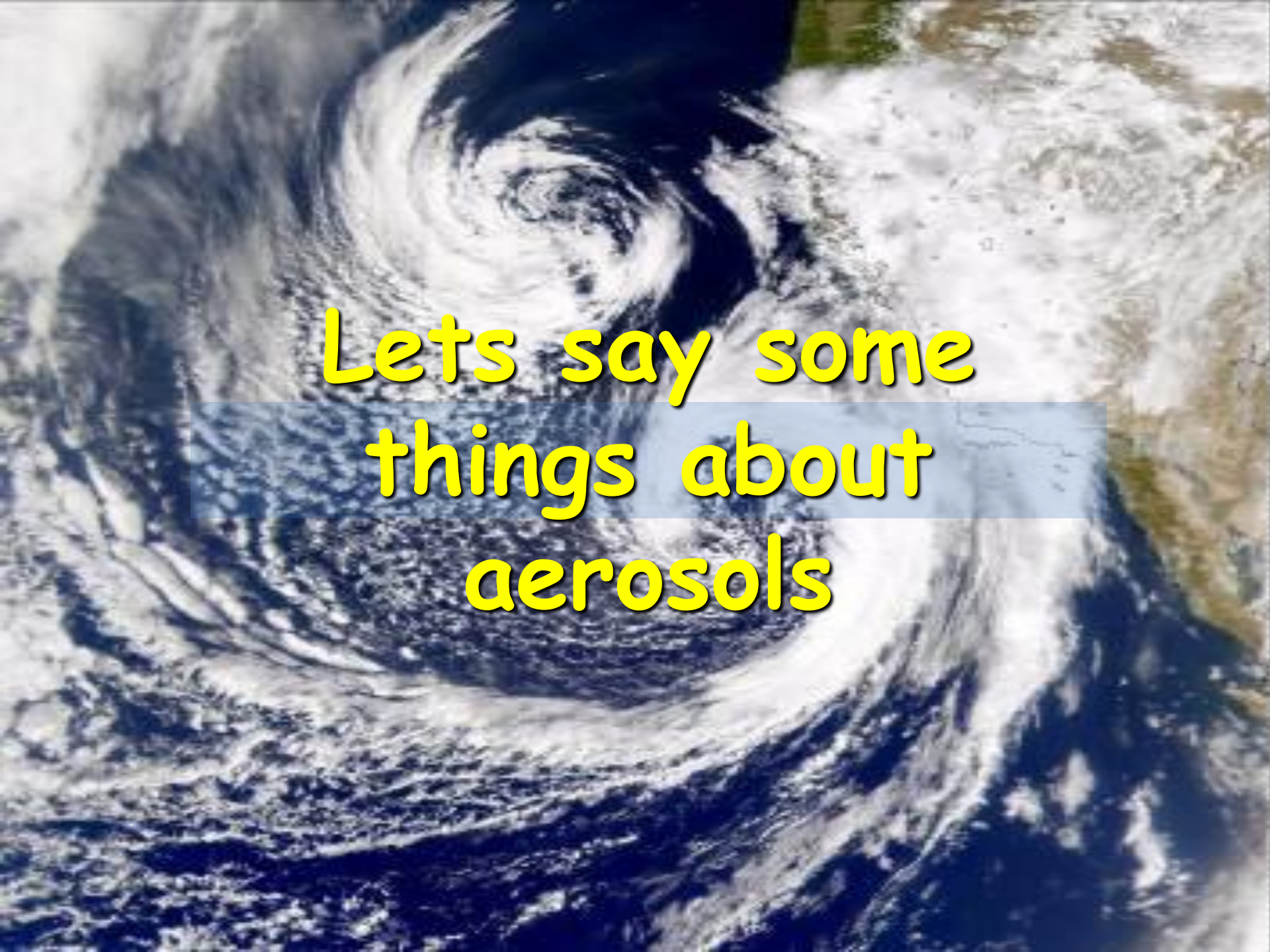
Mixed-Phase clouds are important for extremes and control precipitation on a regional and global scale



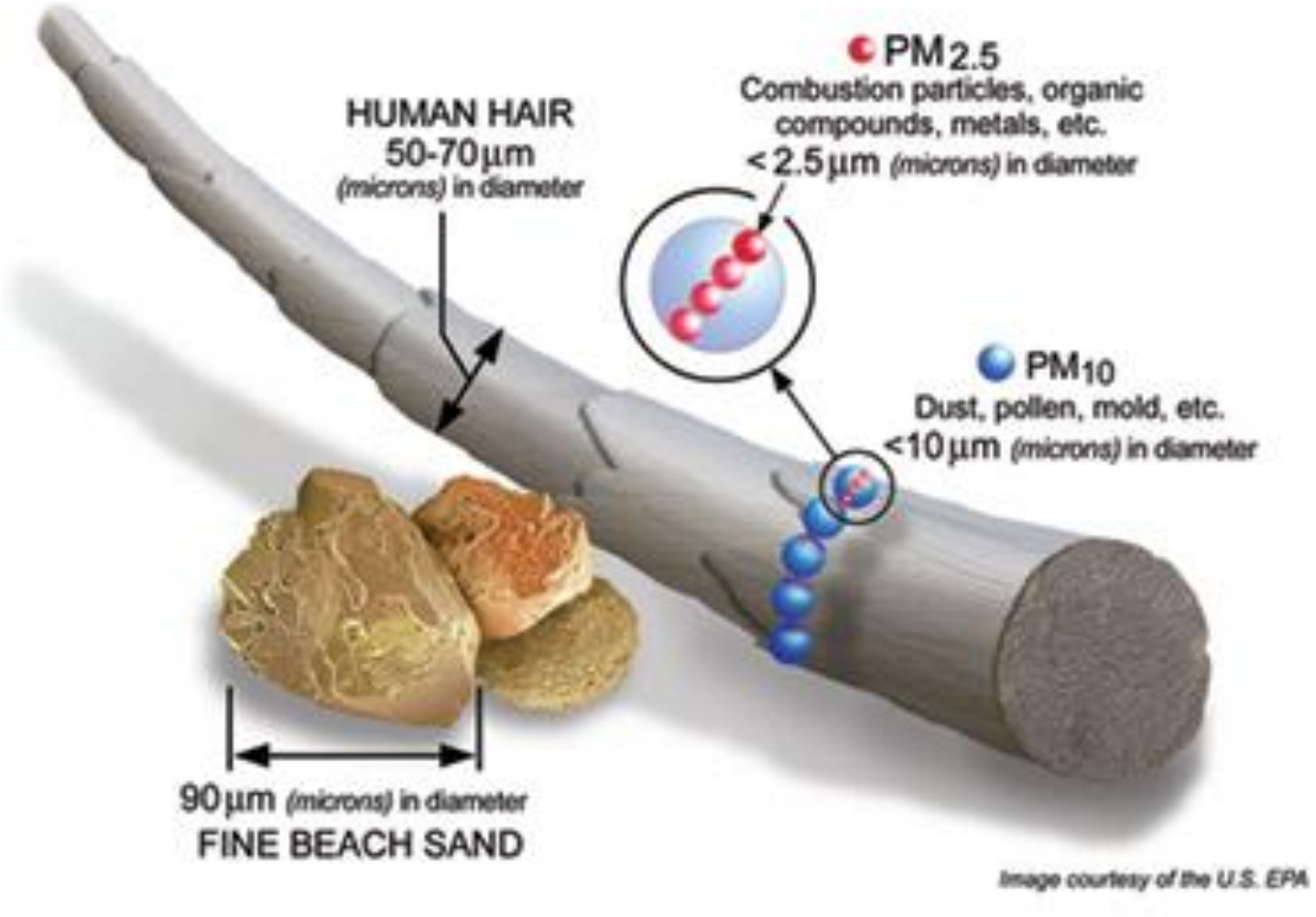
Precipitation at mid- and high-latitudes mostly generated from the mixed- and ice- cloud phase

Mulmenstadt et al . 2015

Precipitation extremes have huge impacts on economy and society at large.


Lets say some
things about
aerosols

Aerosol sizes and “names”



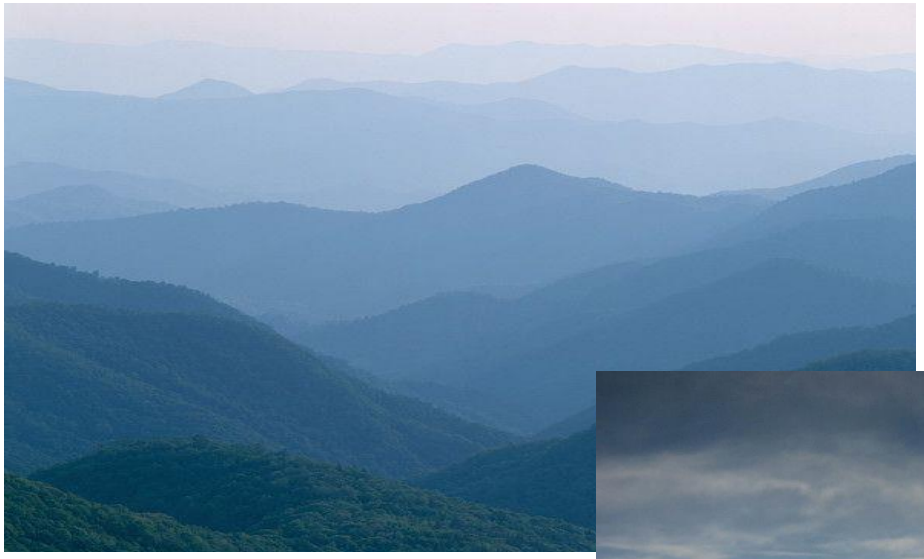
Aerosols: Significance

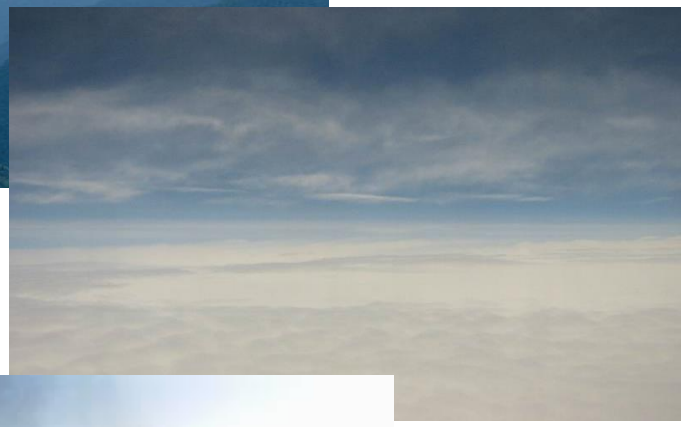
Health Effects

Visibility

Atmospheric Optics

Cloud Formation





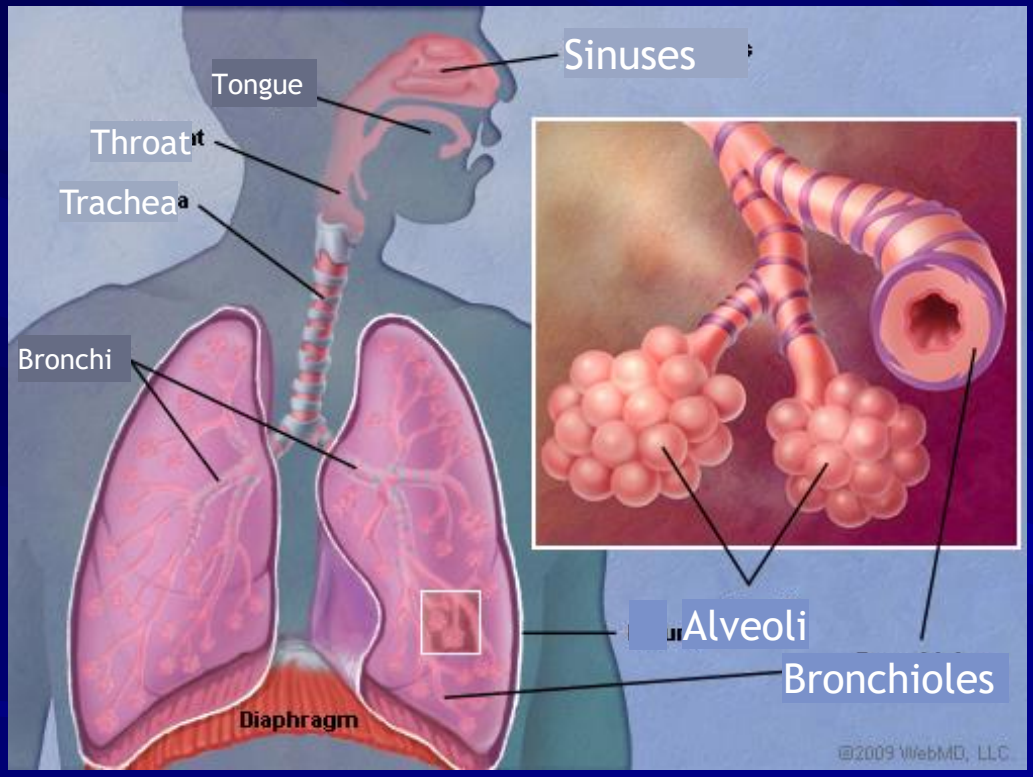
Aerosols directly scatter/absorb light

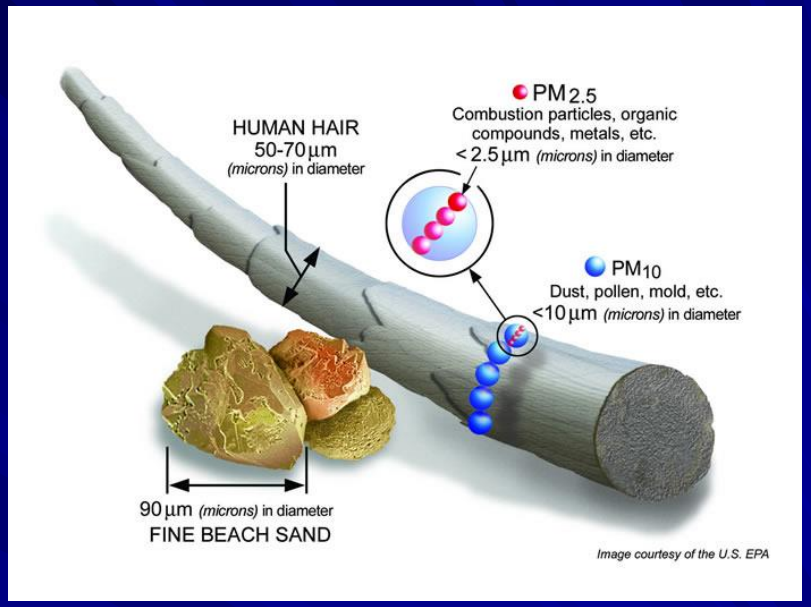
"direct radiative forcing" of aerosol.

Dust and smoke over East Mediterranean

Soot from Kuwaiti oil fires

Effects of $PM_{2.5}$ on Human Health





- Irritation of the airways
- Reduced lung function
- Aggravated asthma
- Chronic bronchitis
- Irregular heartbeat
- Nonfatal heart attacks
- Some cancers

http://www.epa.gov/ord/ca/quick-finder/particulate-matter-image.htm

http://www.webmd.com/lung/picture-of-the-lungs

Aerosols: other effects

- Snow/Ice albedo modification
  - ✓ Black carbon («soot») on snow and ice causes them to darken.
  - ✓ May have high regional importance for melting glaciers and ice pack.
- Nutrient deposition to ocean
  - ✓ Some oceanic ecosystems limited by various micronutrients (e.g. Iron, P).
  - ✓ Deposition of nutrient containing aerosol (dust, geoengineering) can stimulate ocean biota, and affect the carbon cycle.

Origins of Aerosol

Primary emissions

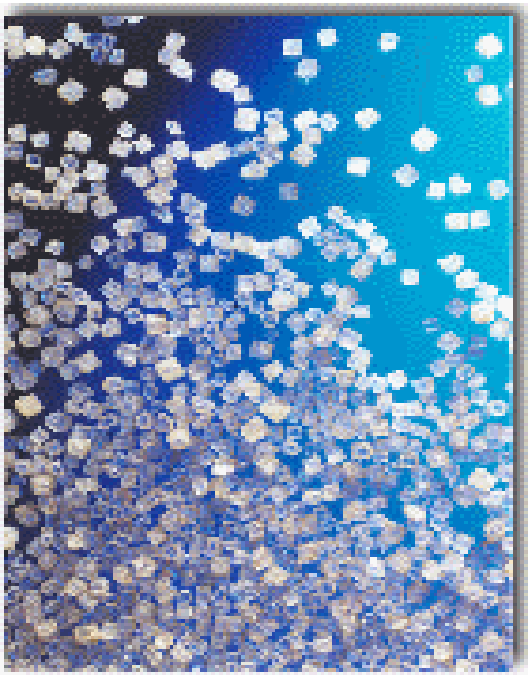
automobiles, industry, domestic, vegetation, forest fires..

Secondary compounds

Oxidation of precursors (by O_3, H_2O_2, OH, NO_3, etc.)

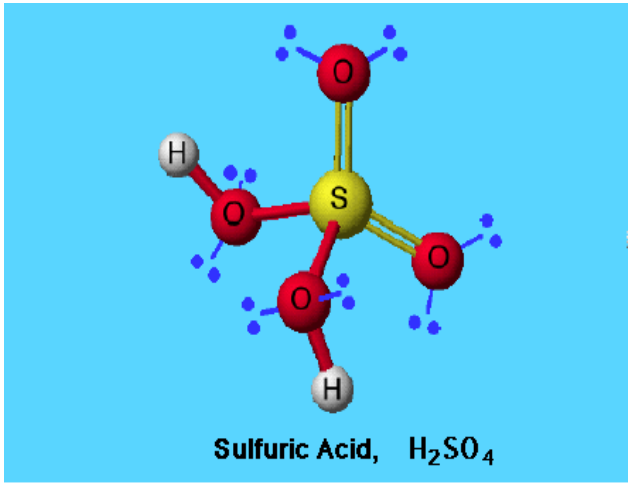
Reaction of volatile bases (NH_3) with acids to form NH_4NO_3, $(NH_4)_2SO_4$, etc…

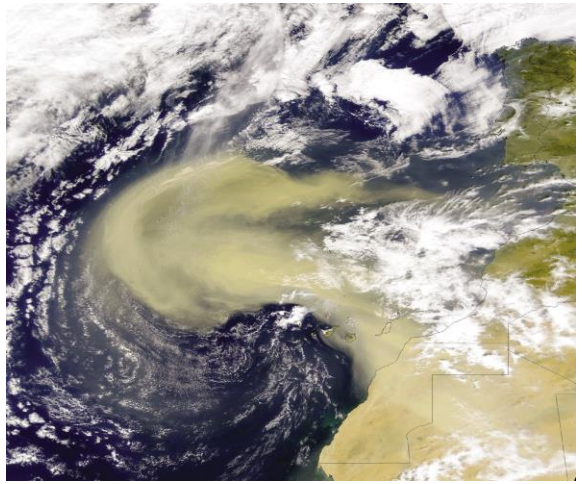
Aerosol constituents



Some inorganic components:

- Ammonium sulfate & bisulfate
- Sulfuric acid
- Seasalt (NaCl)
- Crustal material ($CaCO_3$, Mg & K salts)
- Nitrate salts (NH_4NO_3, $NaNO_3$)
- Chloride salts (KCl, NH_4Cl)



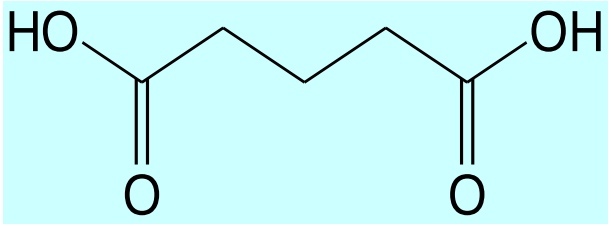


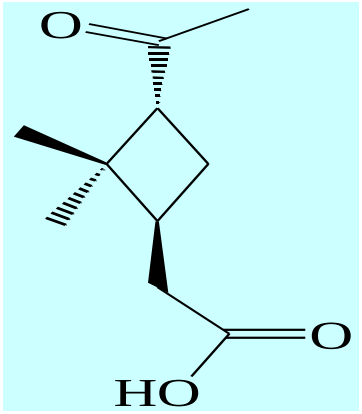
Aerosol constituents

Some (of many) organic compounds:

Glutaric Acid

Both primary (biomass combustion) and secondary (cyclohexene oxidation) species

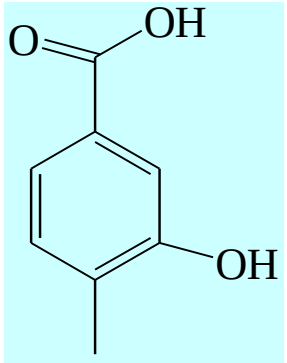




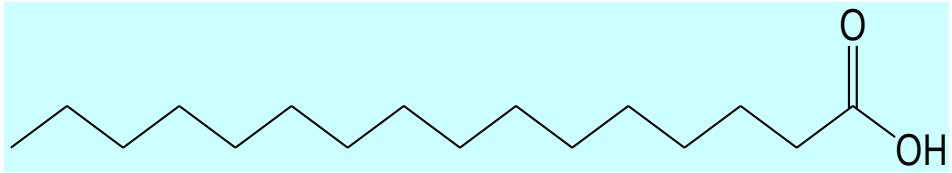
Pinonic Acid

From oxidation of terpenes

HydroxyMethyl Benzoic Acid



Both primary (gasoline combustion) and secondary (aromatic oxidation) aerosol species



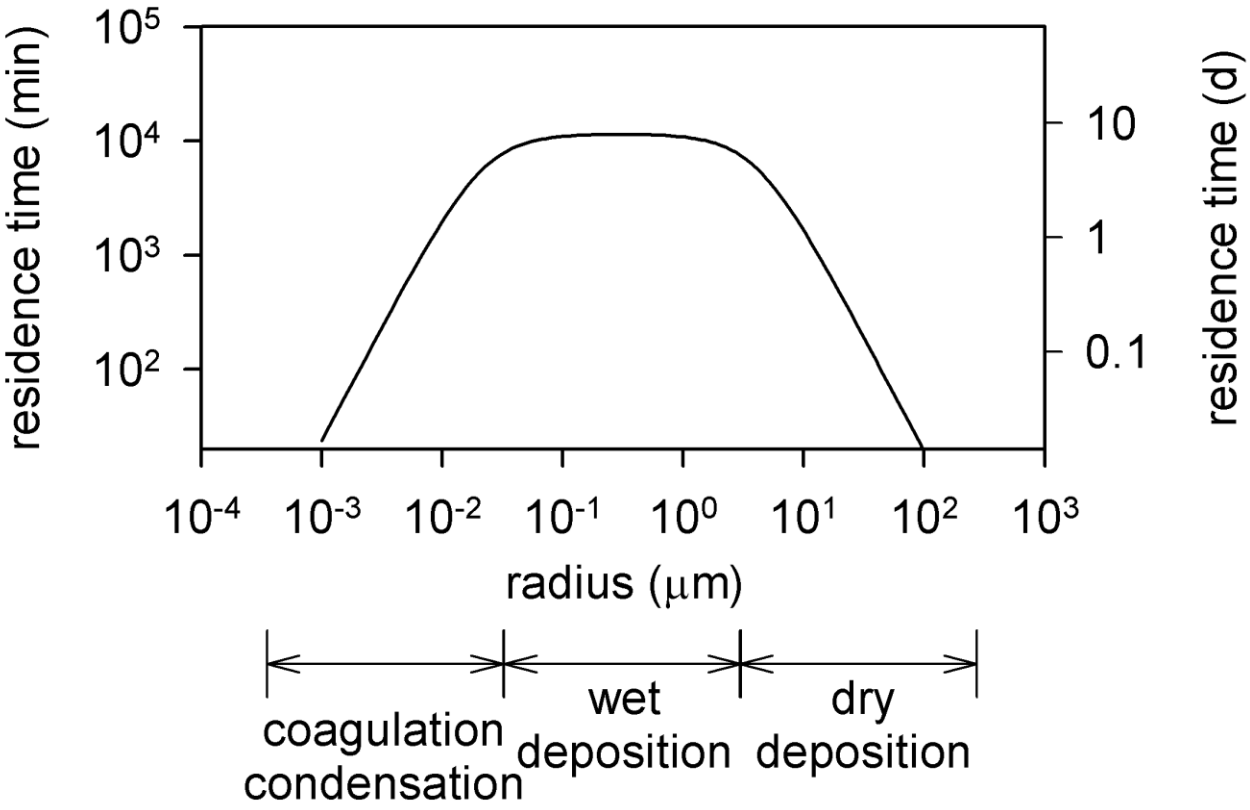
Palmitic Acid

Common plant wax, primary aerosol constituent

And many thousands more…

Size Is a Key Aerosol Property

- Properties and lifetime of Aerosol Particles Depend on Their Size



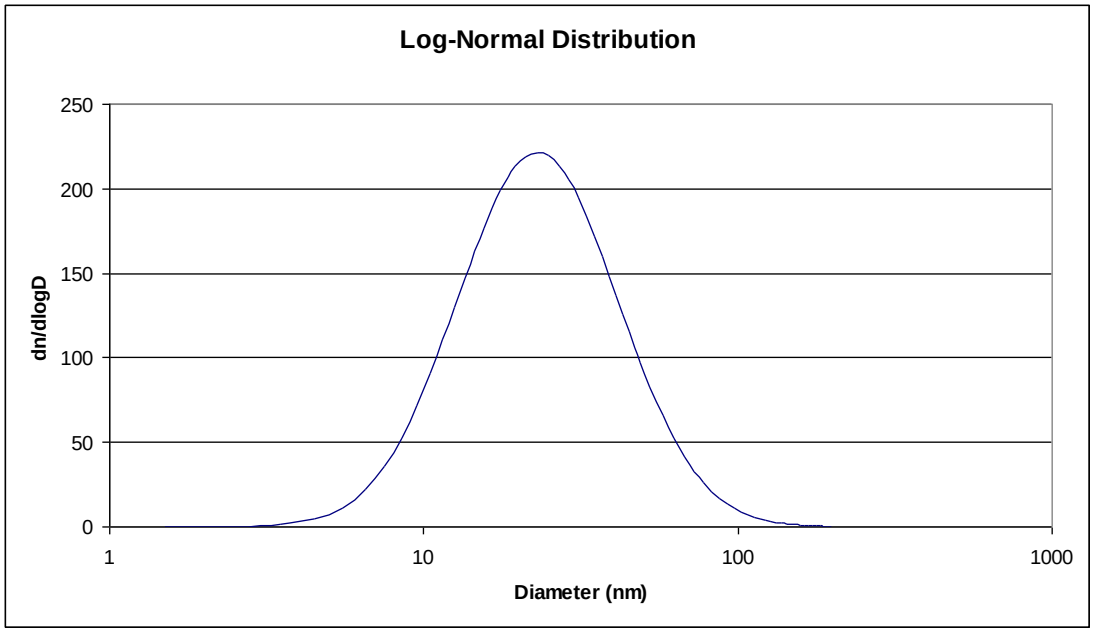
Size Is important

- Many Properties of Aerosol Particles Depend on Their Size
- Most Aerosols have Log-Normal Size Distributions
- Common Types of Size Distributions
  - Number (number of particles of given size)
  - Mass (or Volume)
  - Surface Area

Lognormal distributions

- Appears as a normal distribution when x-axis is plotted on log scale

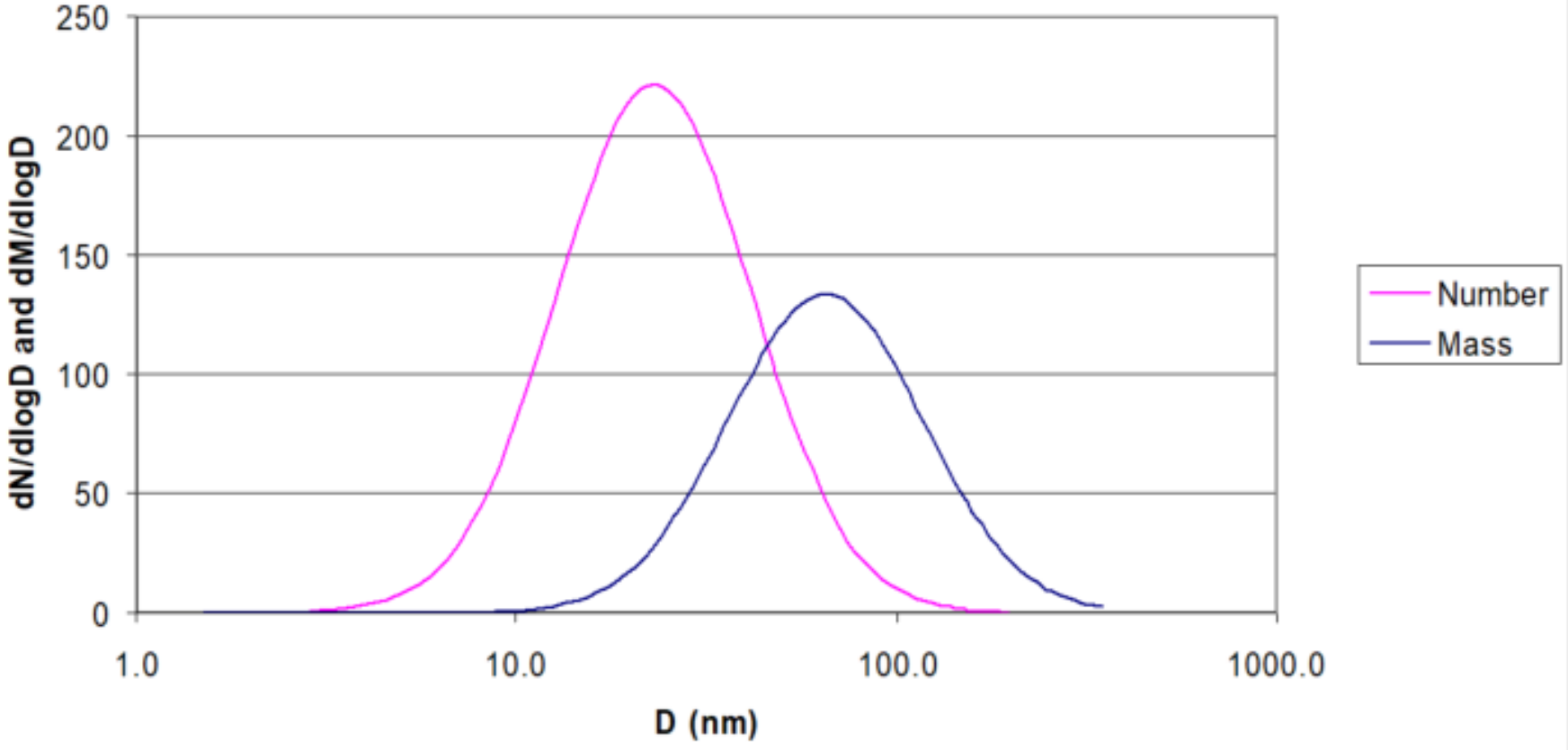
$$n(D) = \frac{N}{(2\pi)^{1/2} \ln \sigma_D} \exp\left[- \frac{(\ln D - \ln D_g)^2}{2 \ln^2 \sigma_D} \right]$$



Geometric Mean Diameter = 23 nm; Geometric Standard Deviation (σ) = 1.8

Number vs. Mass Distributions

Mass distribution is "shifted" with respect to the number distribution because of the large difference in volume between small and large particles.



Calculation Example

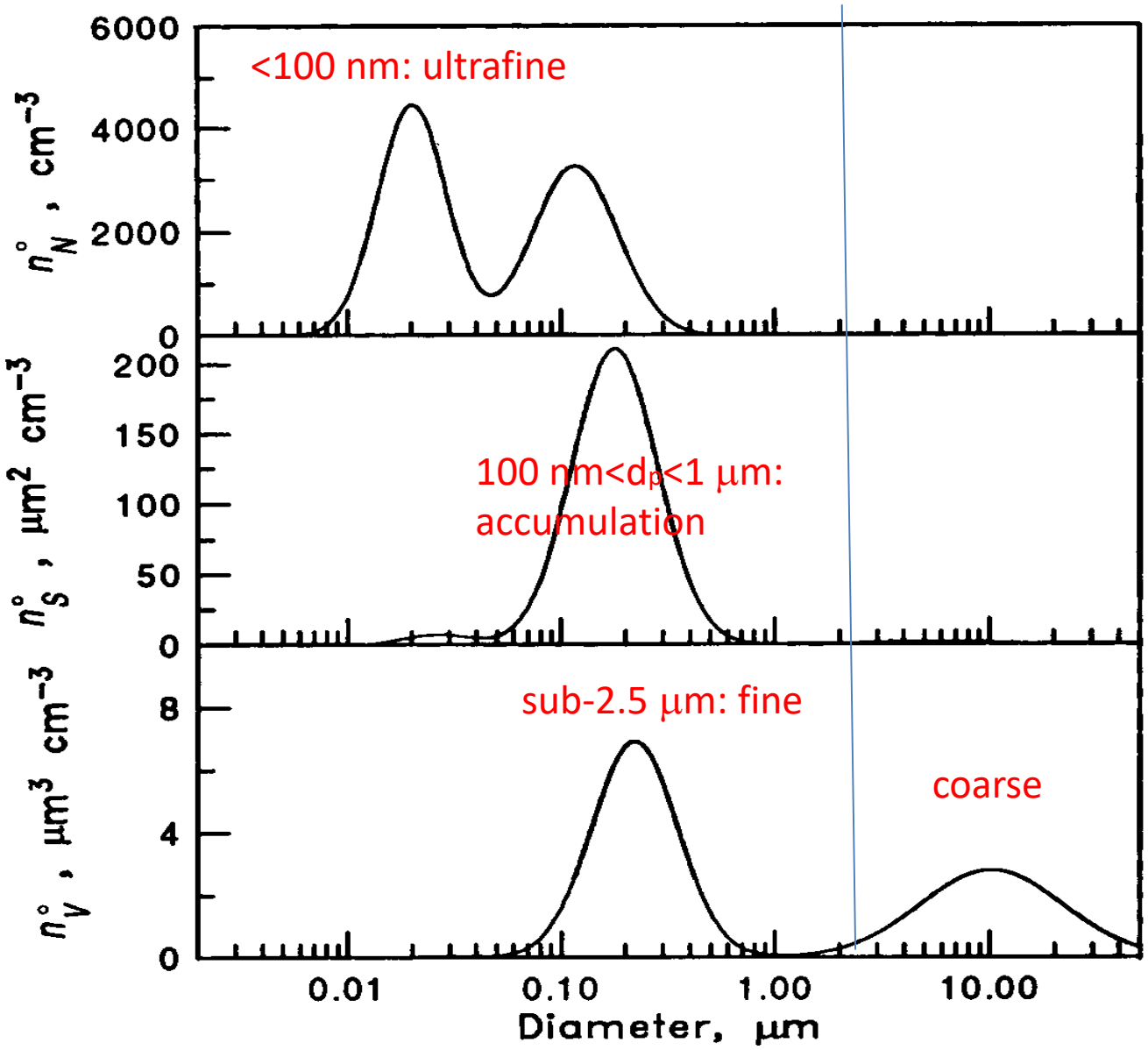
- How many 10 nm particles would have the same volume as one 100 nm particle?

- How many 10 nm particles would have the same surface area as one 100 nm particle?

Calculation Example

- How many 10 nm particles would have the same volume as one 100 nm particle?
  - $N*[\pi(10\ nm)^3/6] = 1*[\pi(100\ nm)^3/6]$
  - $N = (100/10)^3 = 1000$
- How many 10 nm particles would have the same surface area as one 100 nm particle?
  - $N*[\pi(10\ nm)^2] = 1*[\pi(100\ nm)^2]$
  - $N = 100$

Size Distribution: Remote continental air



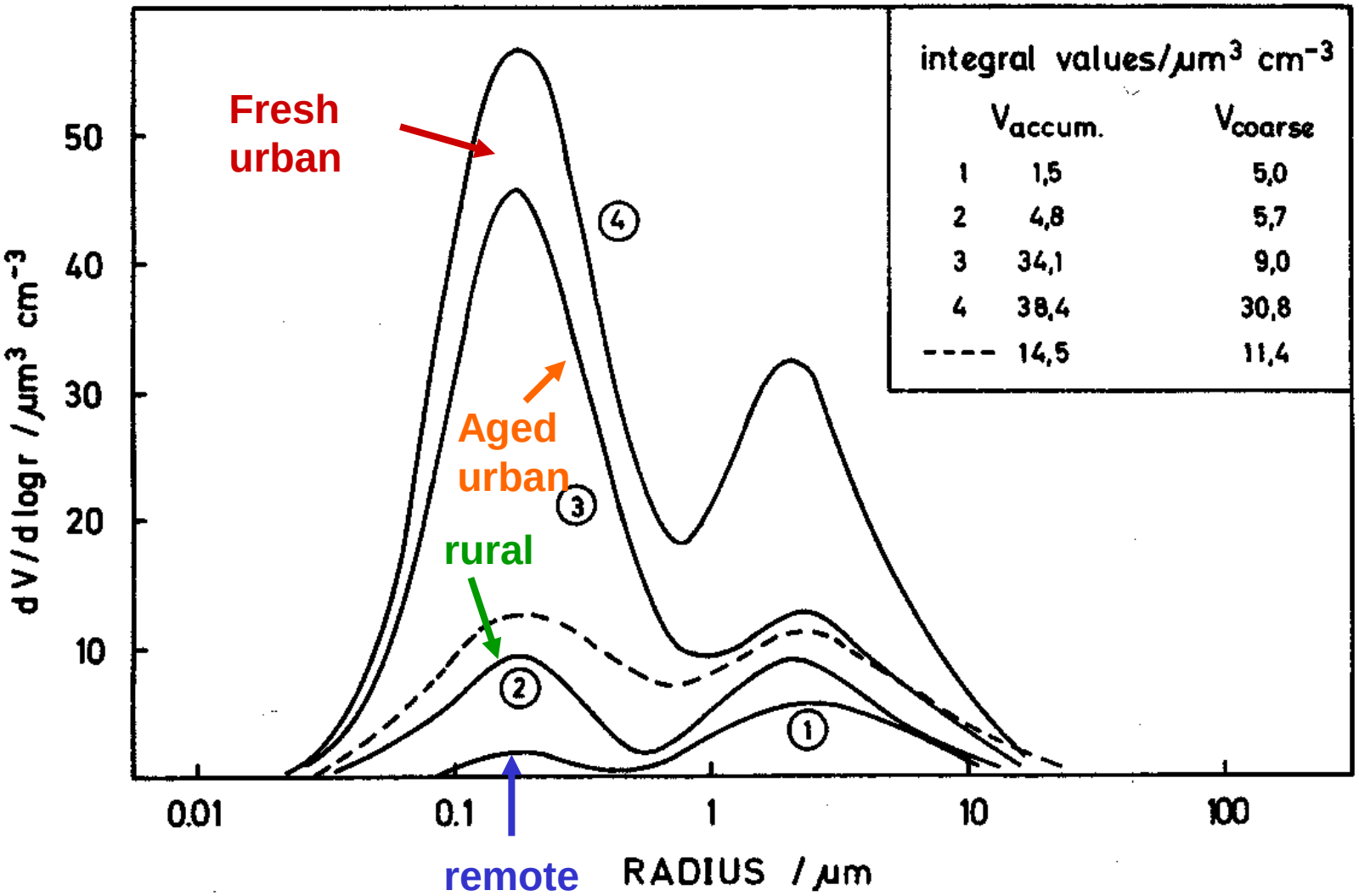
Number

Surface

Volume

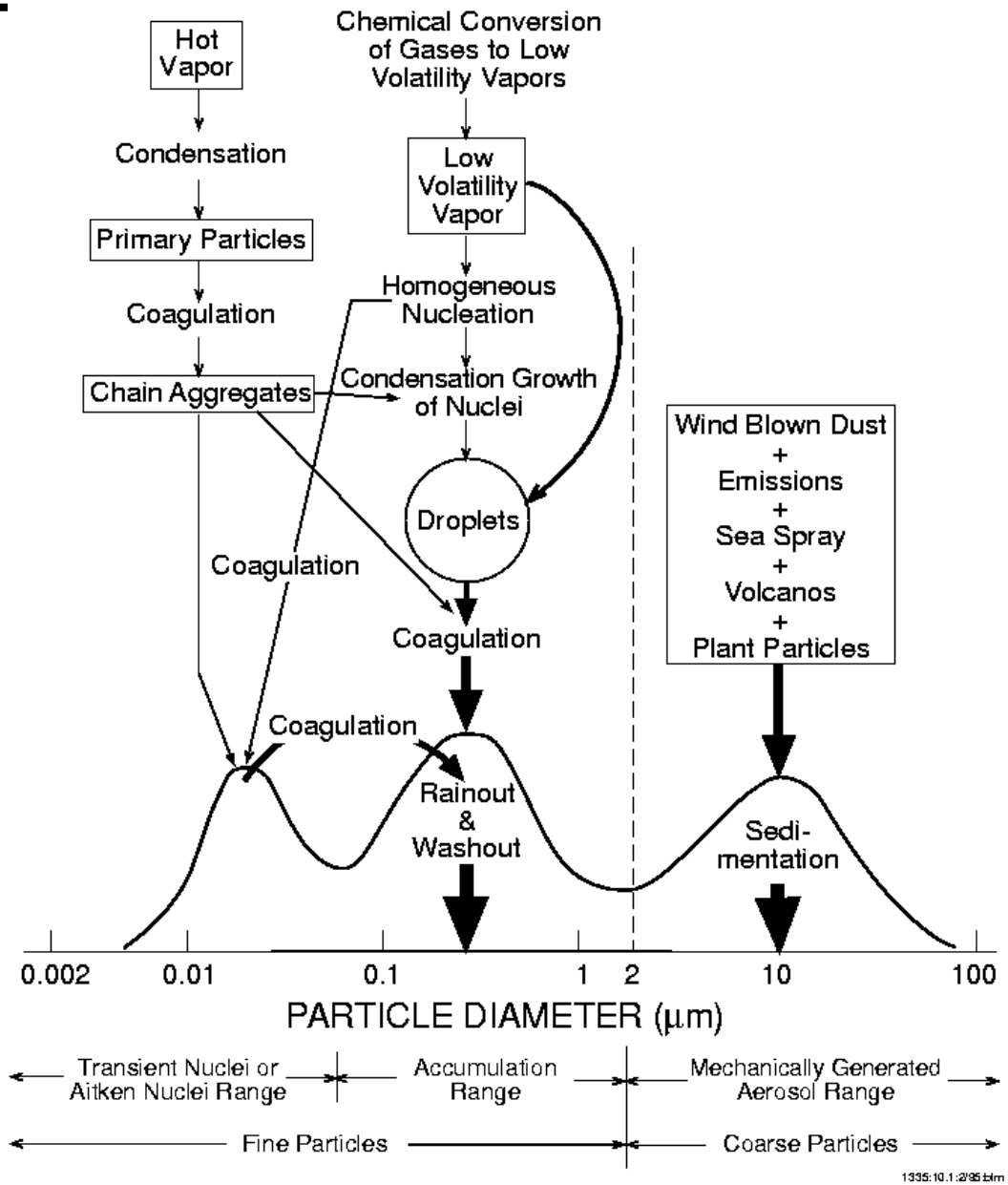
Seinfeld and Pandis

Size distributions vary a lot



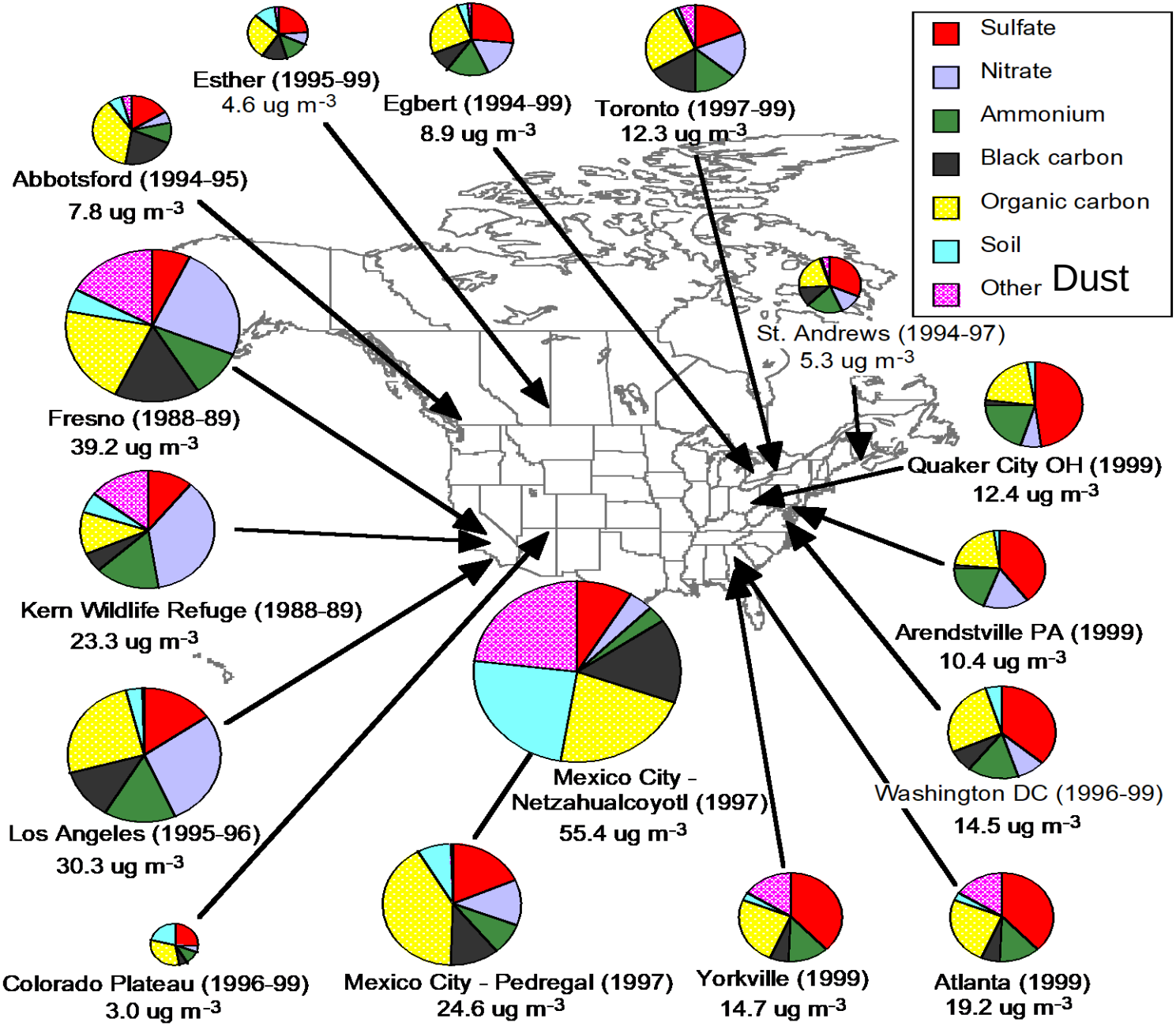
Warneck [1999]

Size distribution is shaped by the processes present



Seinfeld and Pandis

Aerosol composition is complex and highly variable




Now let's switch
to clouds

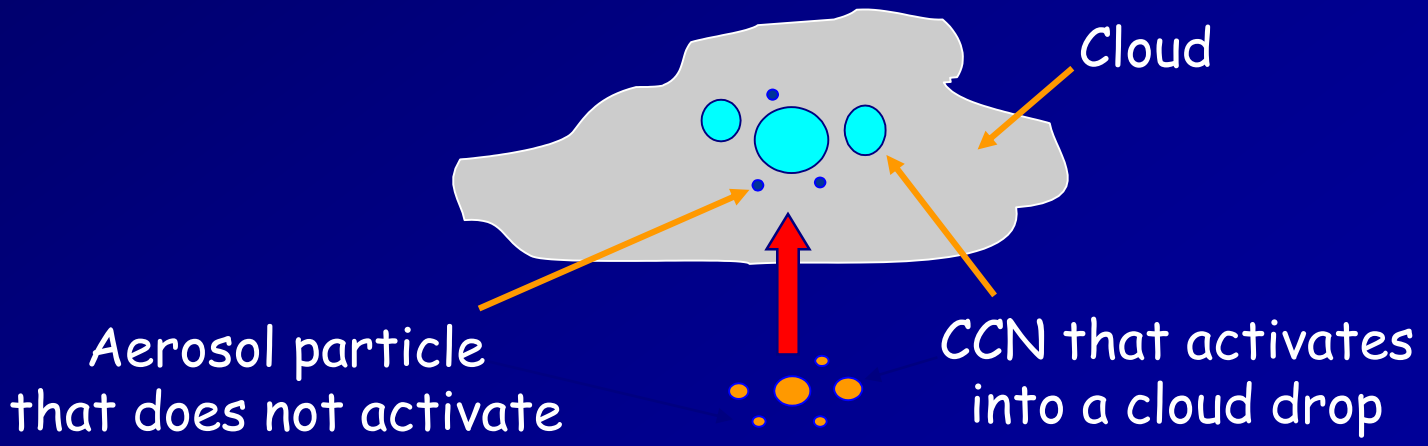
How do (liquid water) clouds form?

Clouds form in regions of the atmosphere where there is too much water vapor (it is "supersaturated").

This happens when air is cooled (primarily through expansion in updraft regions and radiative cooling).

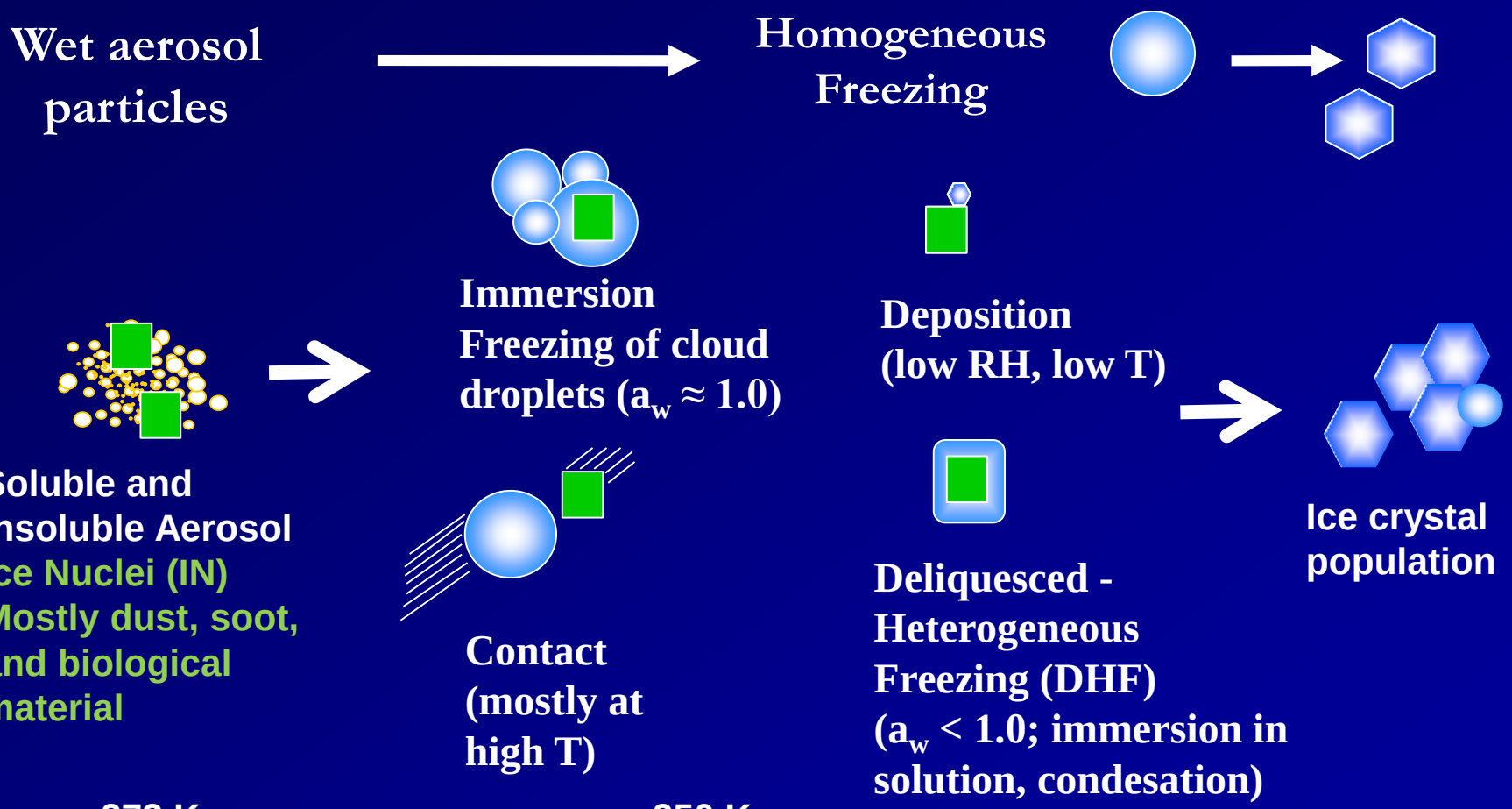
Cloud droplets nucleate on pre-existing particles found in the atmosphere (aerosols) with ~ 0.1μm diameter.

Aerosols that can become droplets are called cloud condensation nuclei (CCN).



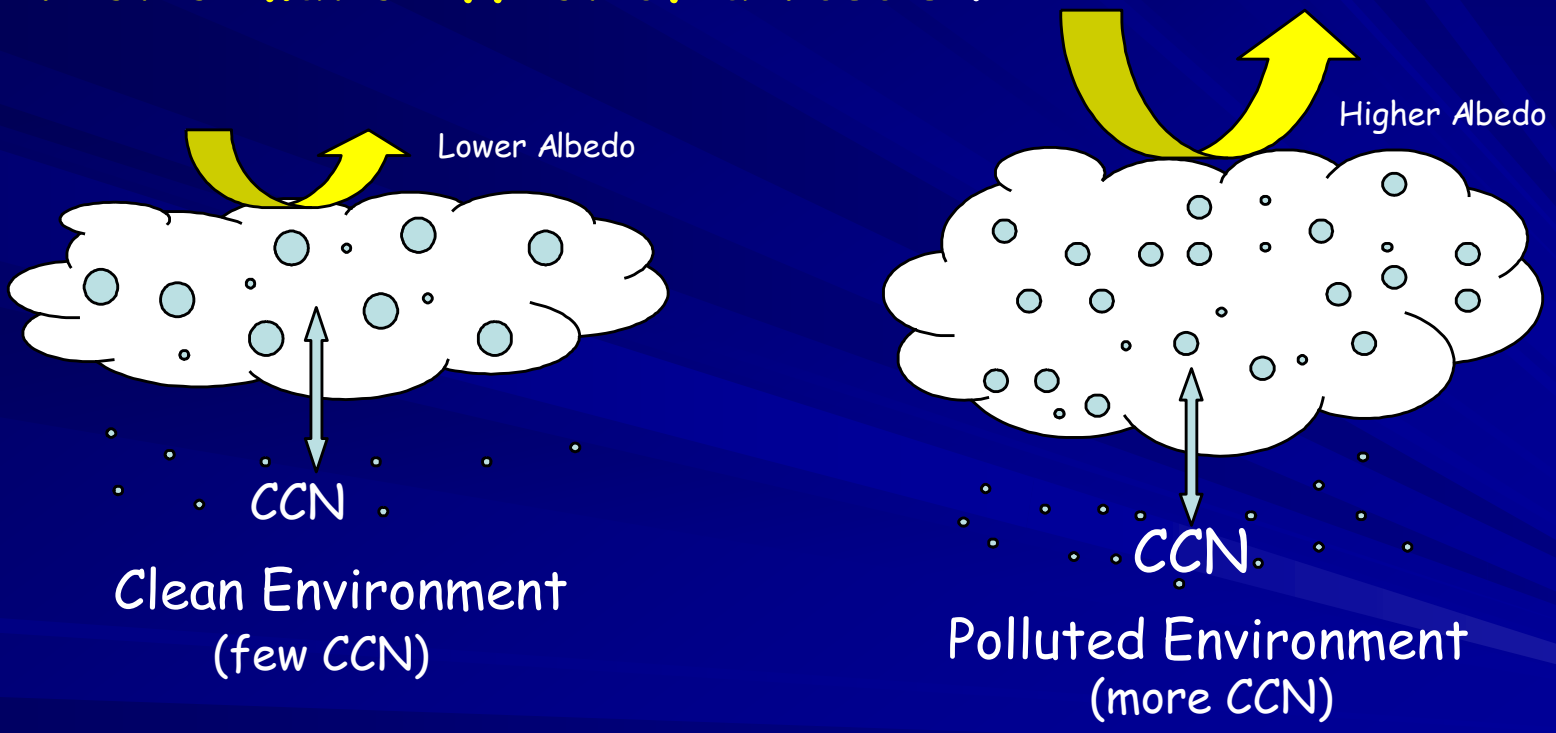
Ice formation mechanisms

Multiple mechanisms for ice formation can be active.



Increases in aerosol affects warm clouds

You make clouds that are "whiter", precipitate less (persist longer) and potentially cover larger areas of the globe. This is thought to yield a net cooling on climate and is termed as the "**indirect climatic effect of aerosols**".

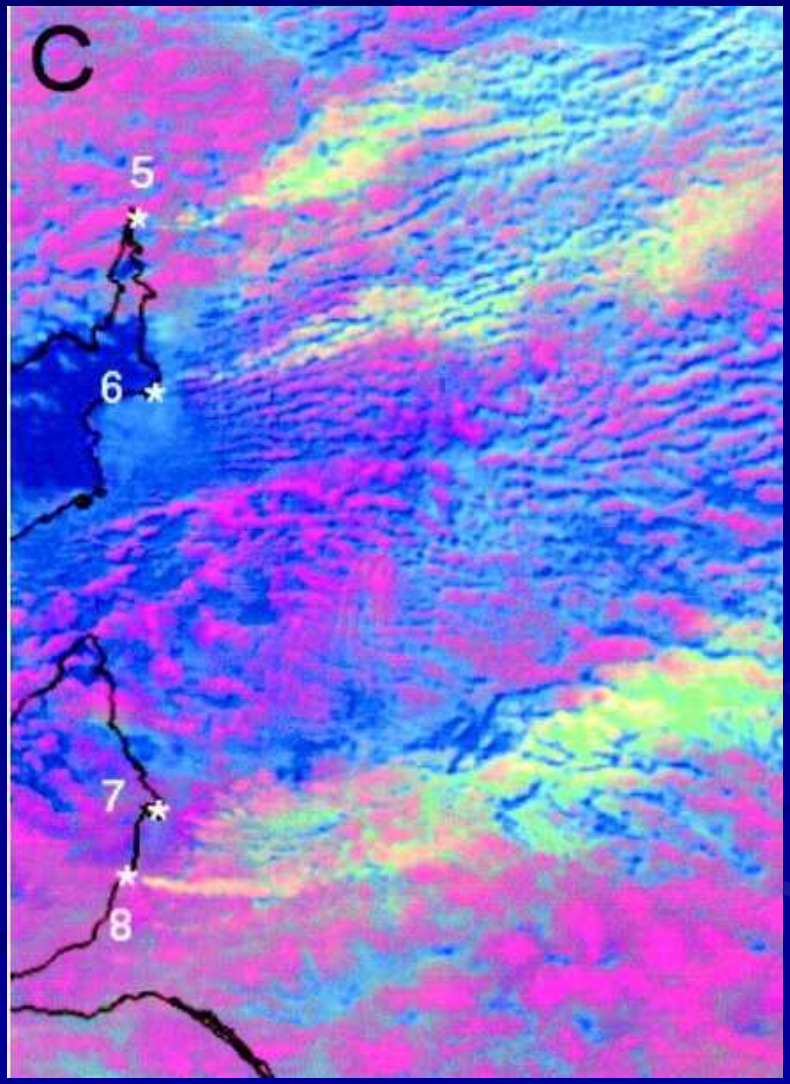


Increasing particles tends to cool climate (potentially alot).

Quantitative assessments done with climate models.

Observational evidence of indirect effect

Satellite observations of clouds off W. Australia.



Red: Clouds with low reflectivity.

White: Clouds that reflect alot.

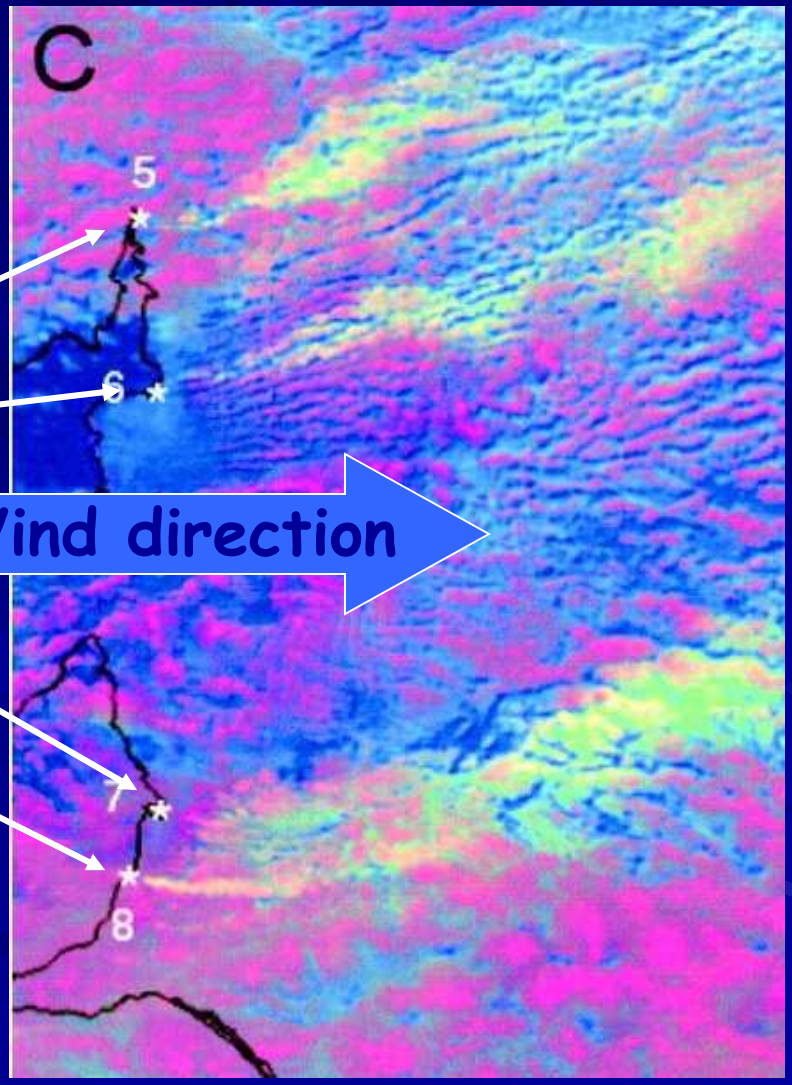
Blue: Clear sky.

Rosenfeld et al., Science

Observational evidence of indirect effect

Air pollution can affect cloud properties

Satellite observations of clouds off W. Australia.



Red: Clouds with low reflectivity.

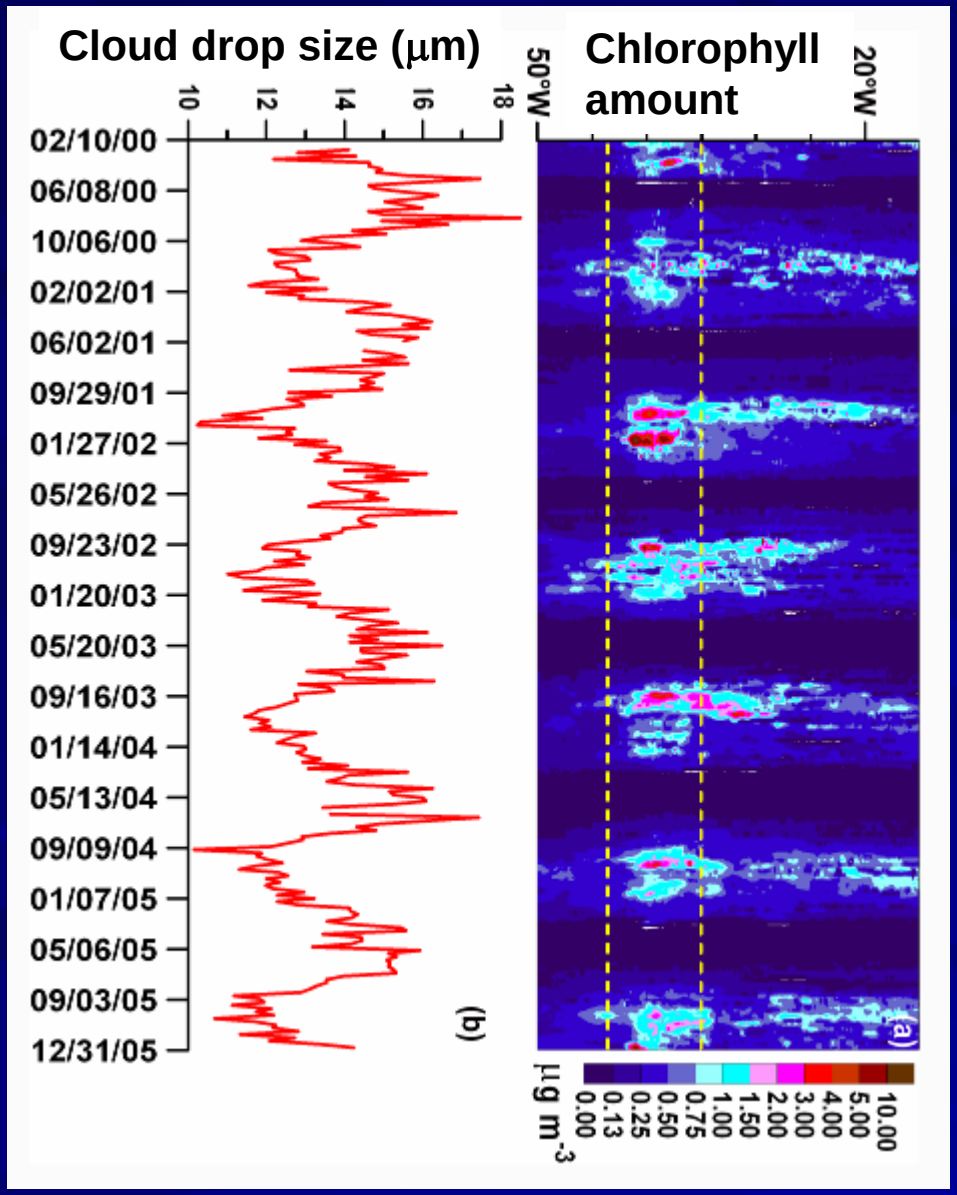
White: Clouds that reflect alot.

Blue: Clear sky.

Rosenfeld et al., Science

Phytoplankton affect clouds too…

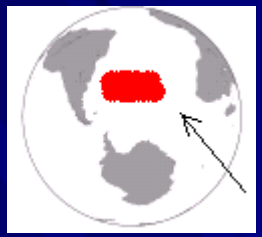
Location: East of Patagonia (South America)

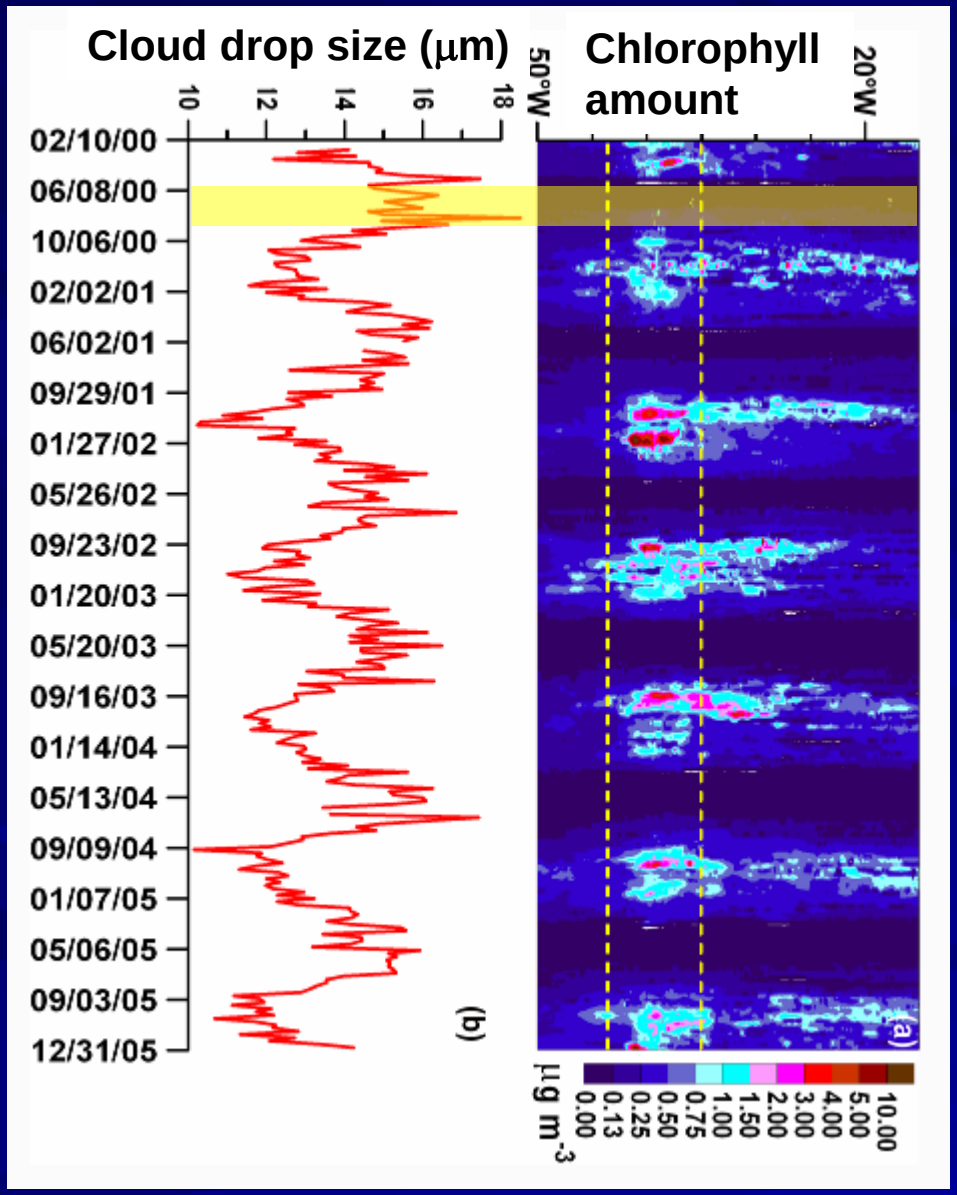


Meskhidze and Nenes, Science, 2006

Phytoplankton affect clouds too…

Location: East of Patagonia (South America)



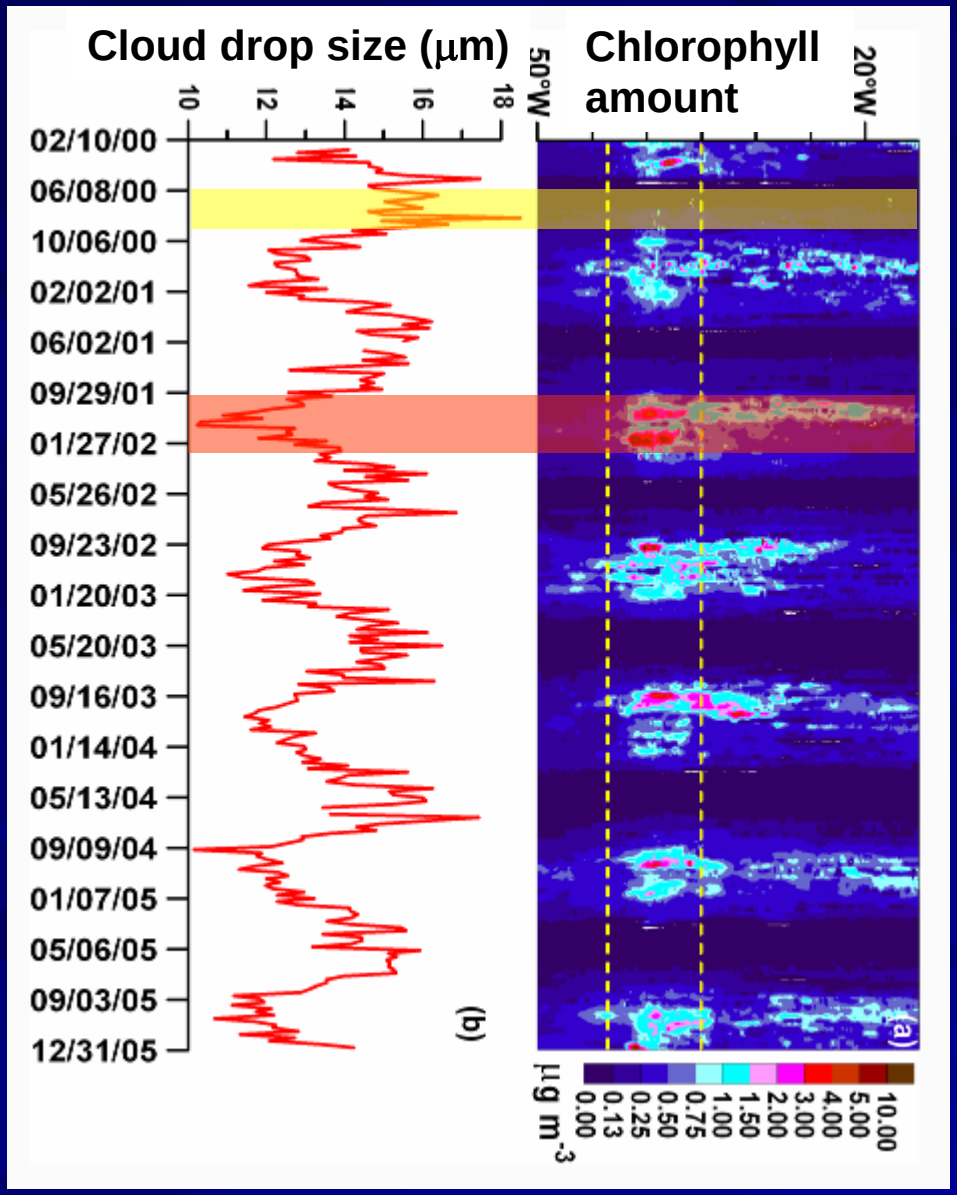


Low chlorophyll period, clouds have large drops (not very reflective)

Meskhidze and Nenes, Science, 2006

Phytoplankton affect clouds too…

Location: East of Patagonia (South America)



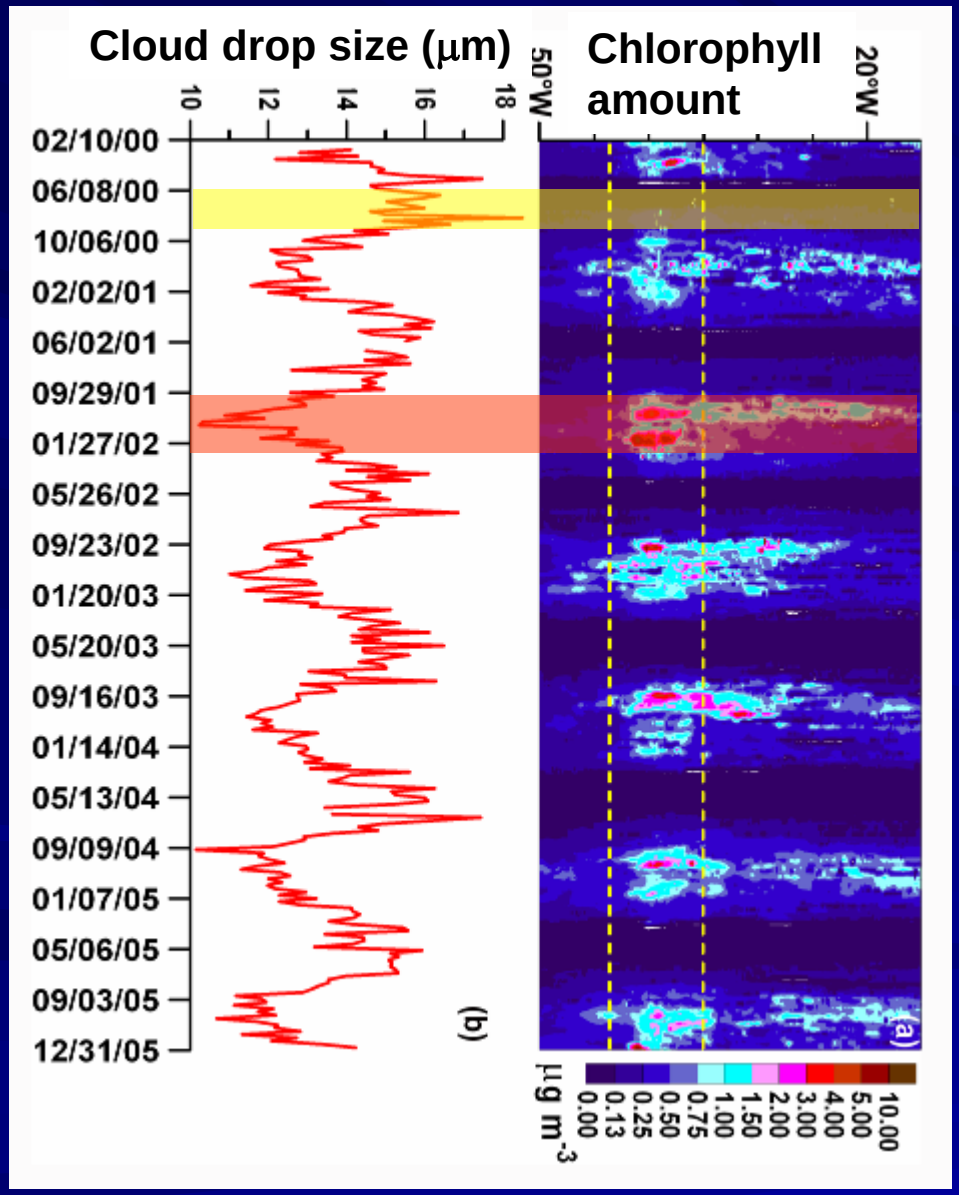
Low chlorophyll period, clouds have large drops (not very reflective)

High Chlorophyll period, Clouds have small drops (very reflective)

Meskhidze and Nenes, Science, 2006

Phytoplankton affect clouds too…

Location: East of Patagonia (South America)



Low chlorophyll period, clouds have large drops (not very reflective)

High Chlorophyll period, Clouds have small drops (very reflective)

Phytoplankton emissions increase particle loads, and strongly impact clouds.

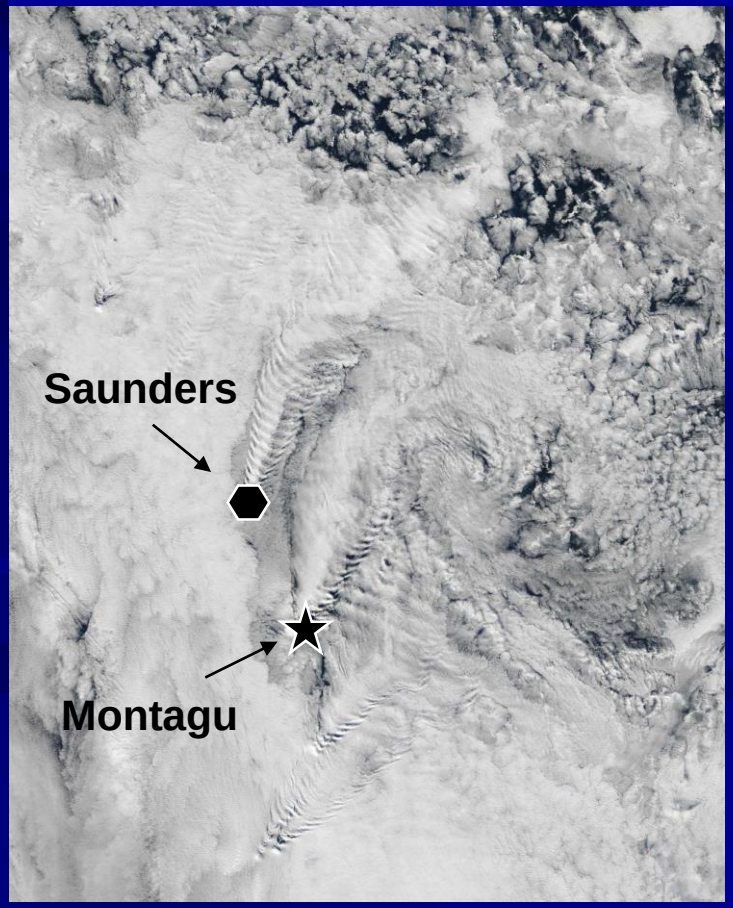
Biology-cloud interactions affect radiation in the region.

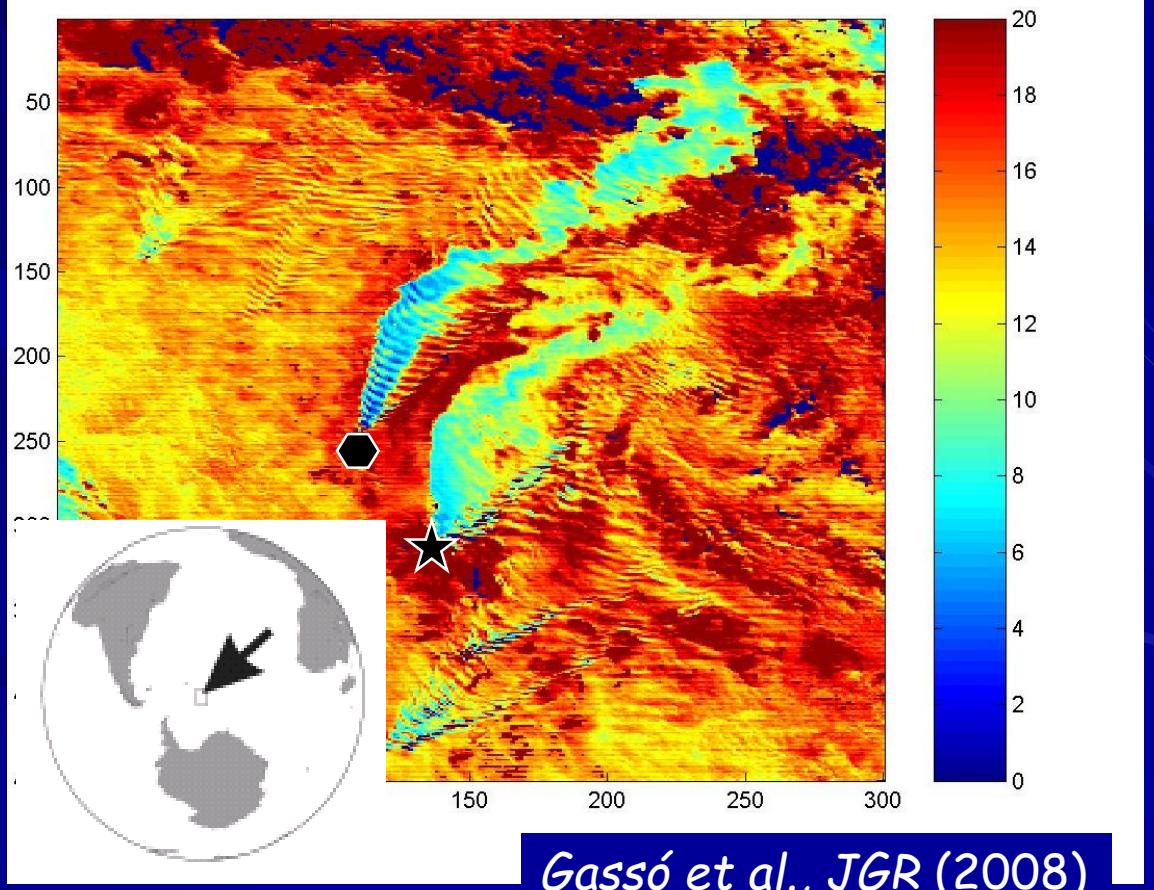
Meskhidze and Nenes, Science, 2006

So do volcanoes (even when "sleeping") …

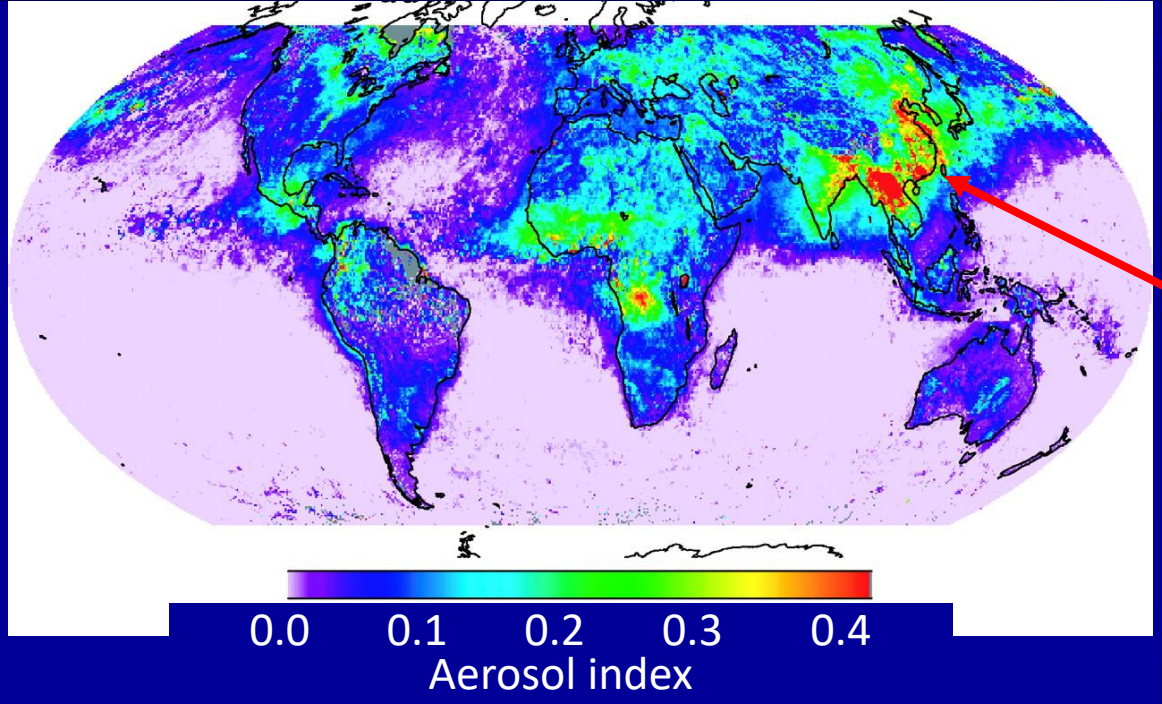
Volcanoes continuously emit SO_2 which becomes sulfate aerosol.
The aerosol can substantially increase CCN in volcanic plumes.
Clouds in the plume are much more reflective than outside.

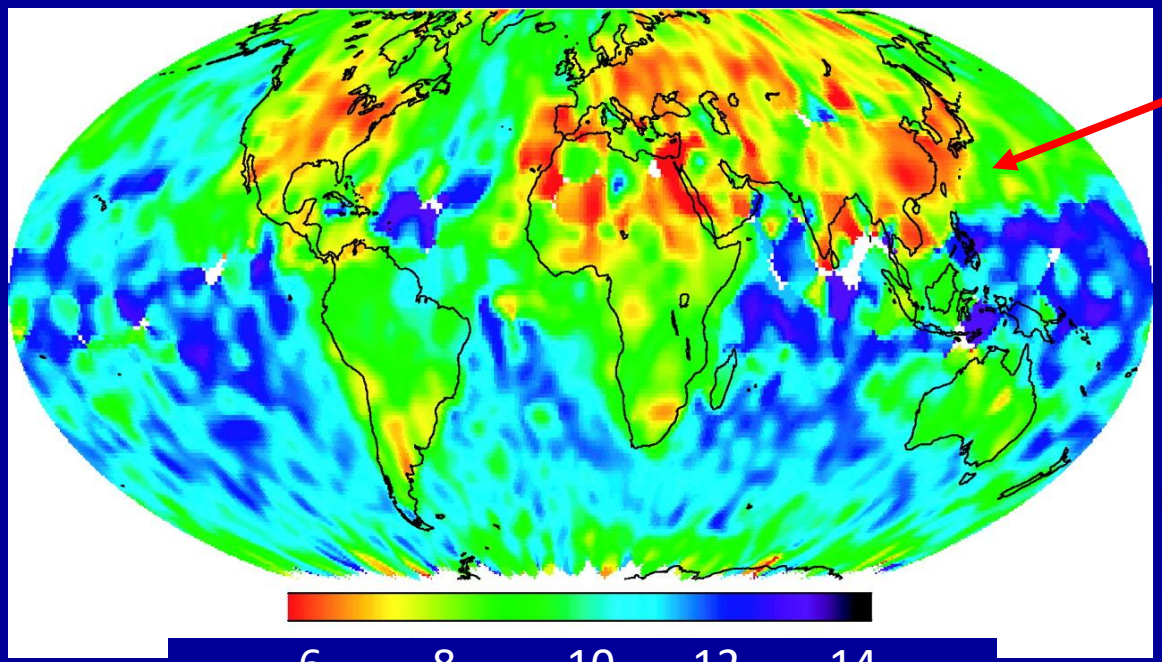
Location: Sandwich Islands , ~55S,~30W





Gassó et al., JGR (2008)





A remote sensing global picture…

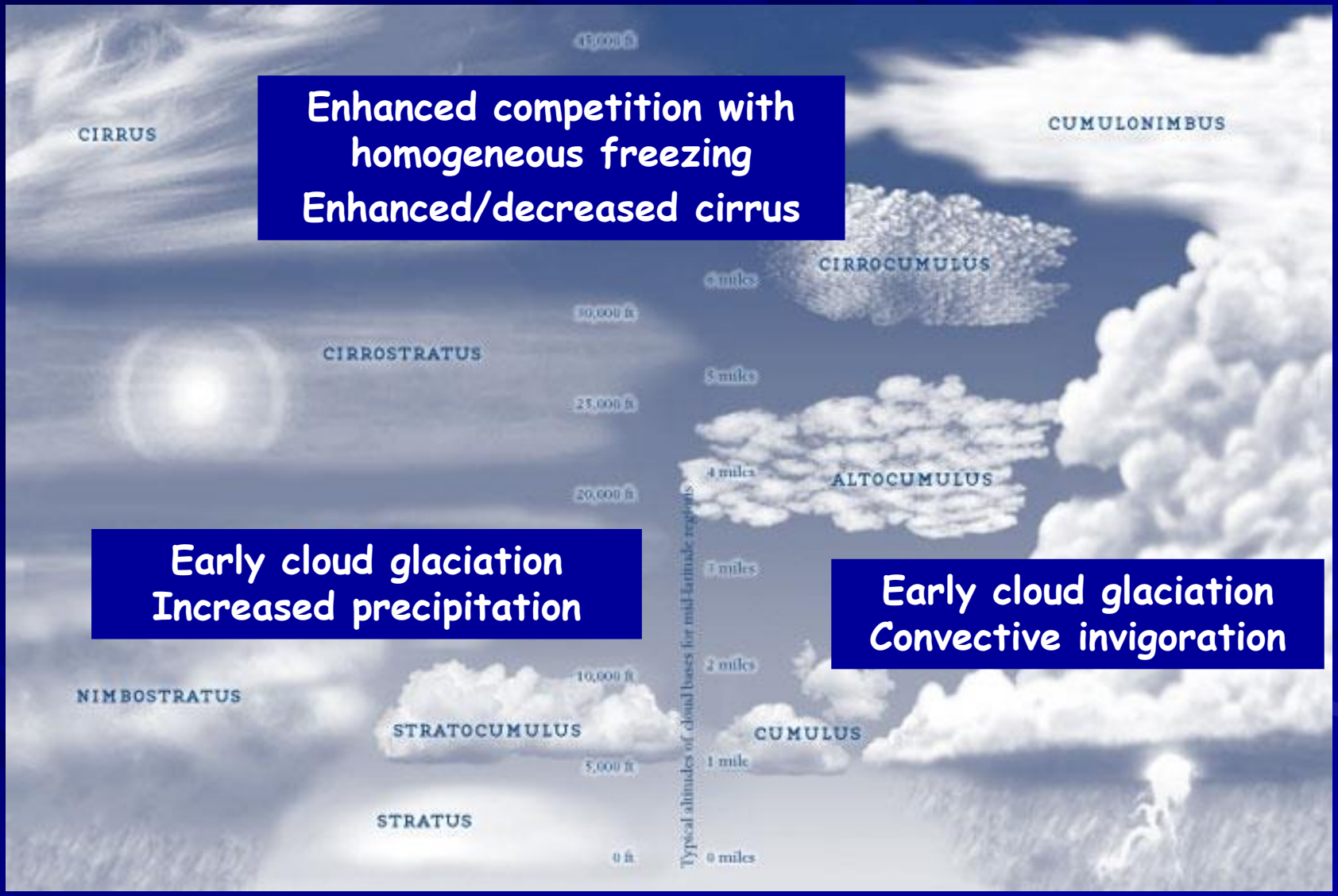
A lot of aerosol…

…gives smallest cloud droplets

We see the same on all satellite platforms…

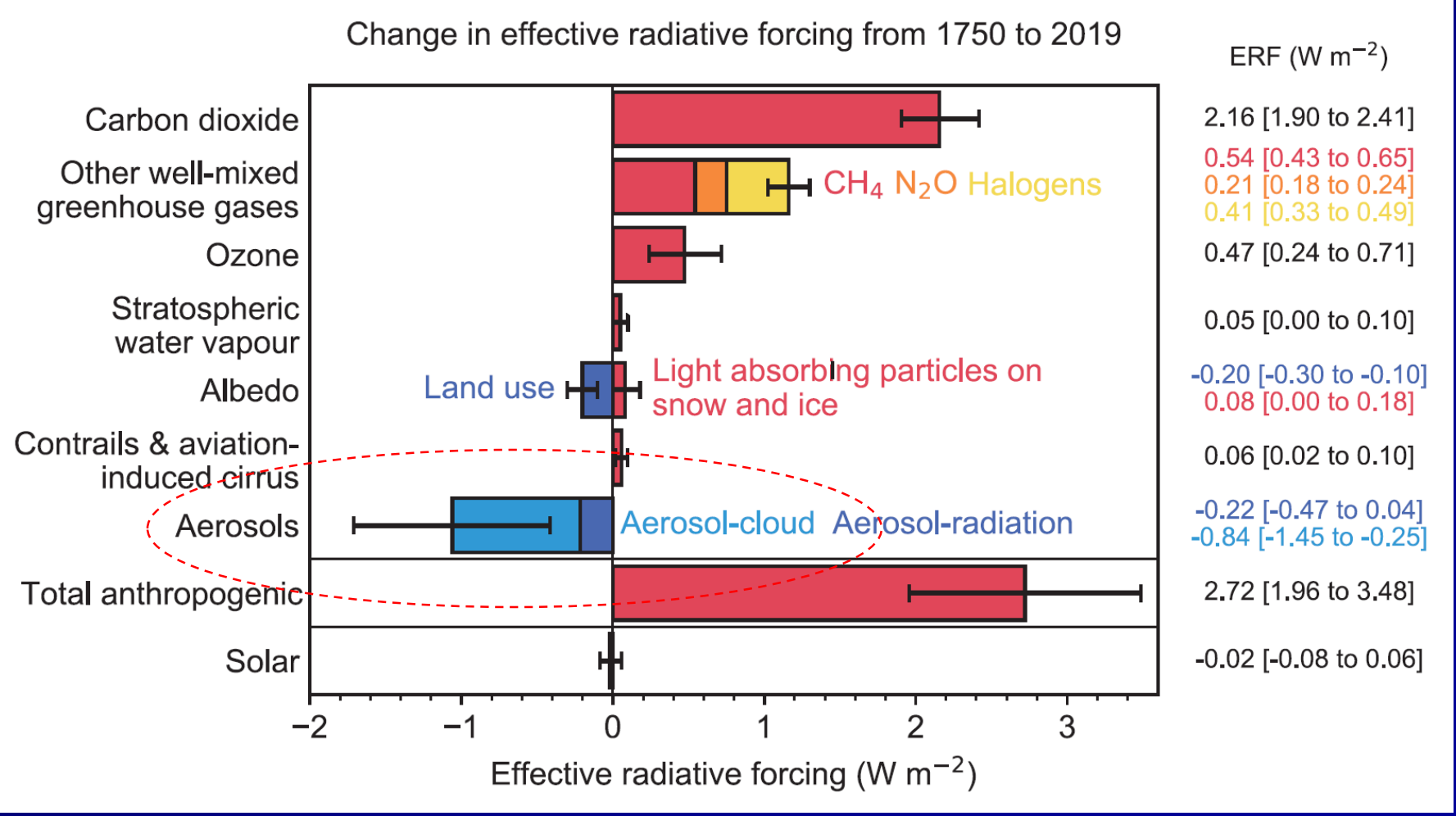
Breón et al. (2002)

Aerosol effects on ice clouds and climate



Courtesy: D.Barahona

Aerosol-cloud interactions are important for climate - but highly uncertain



Forster et al. (2021), IPCC AR6