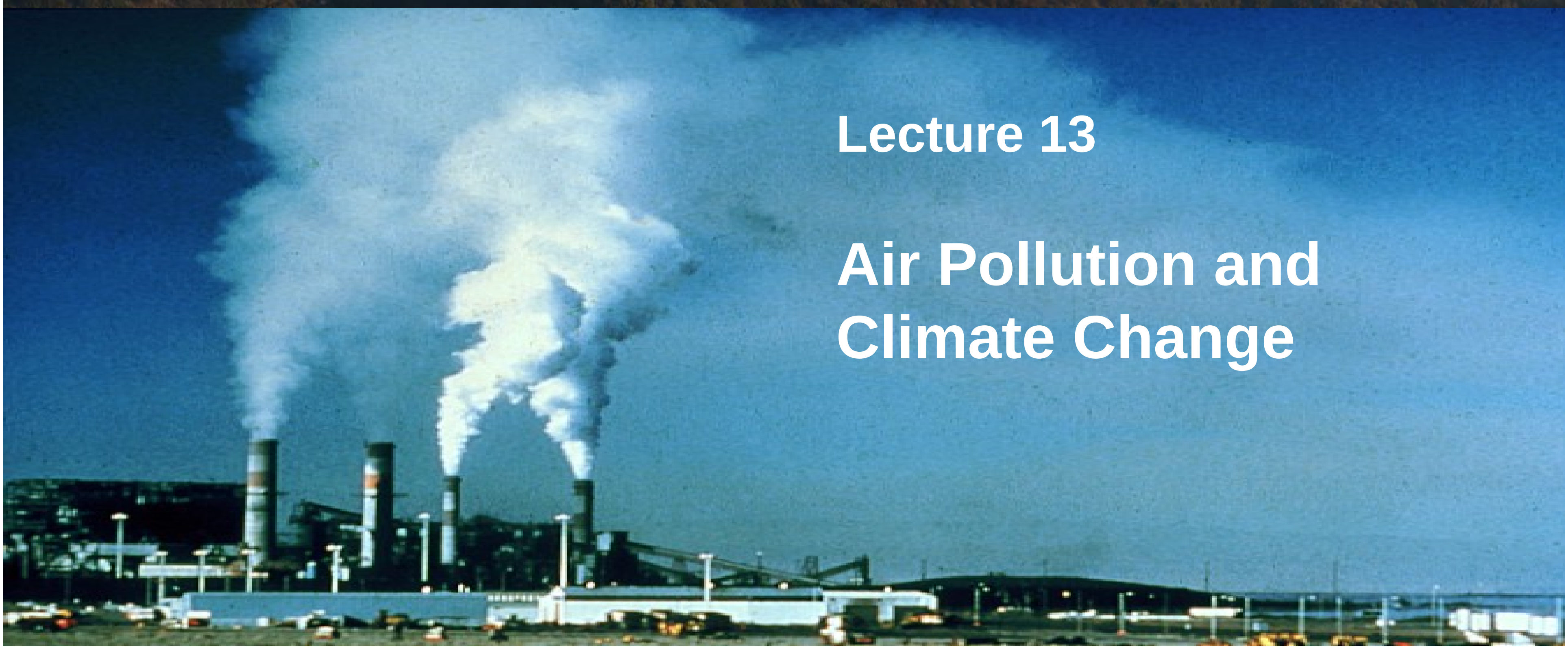
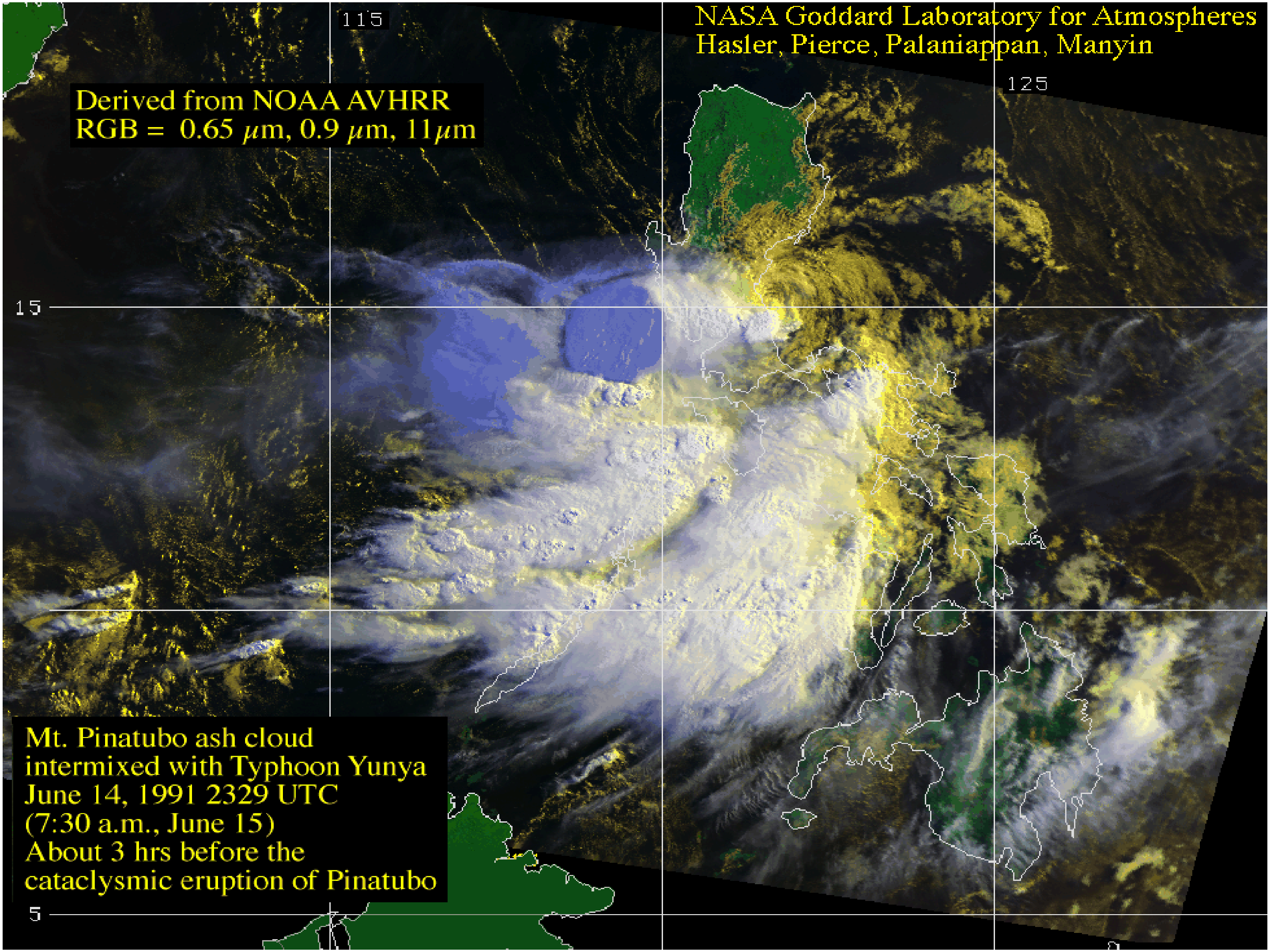


Lecture 13

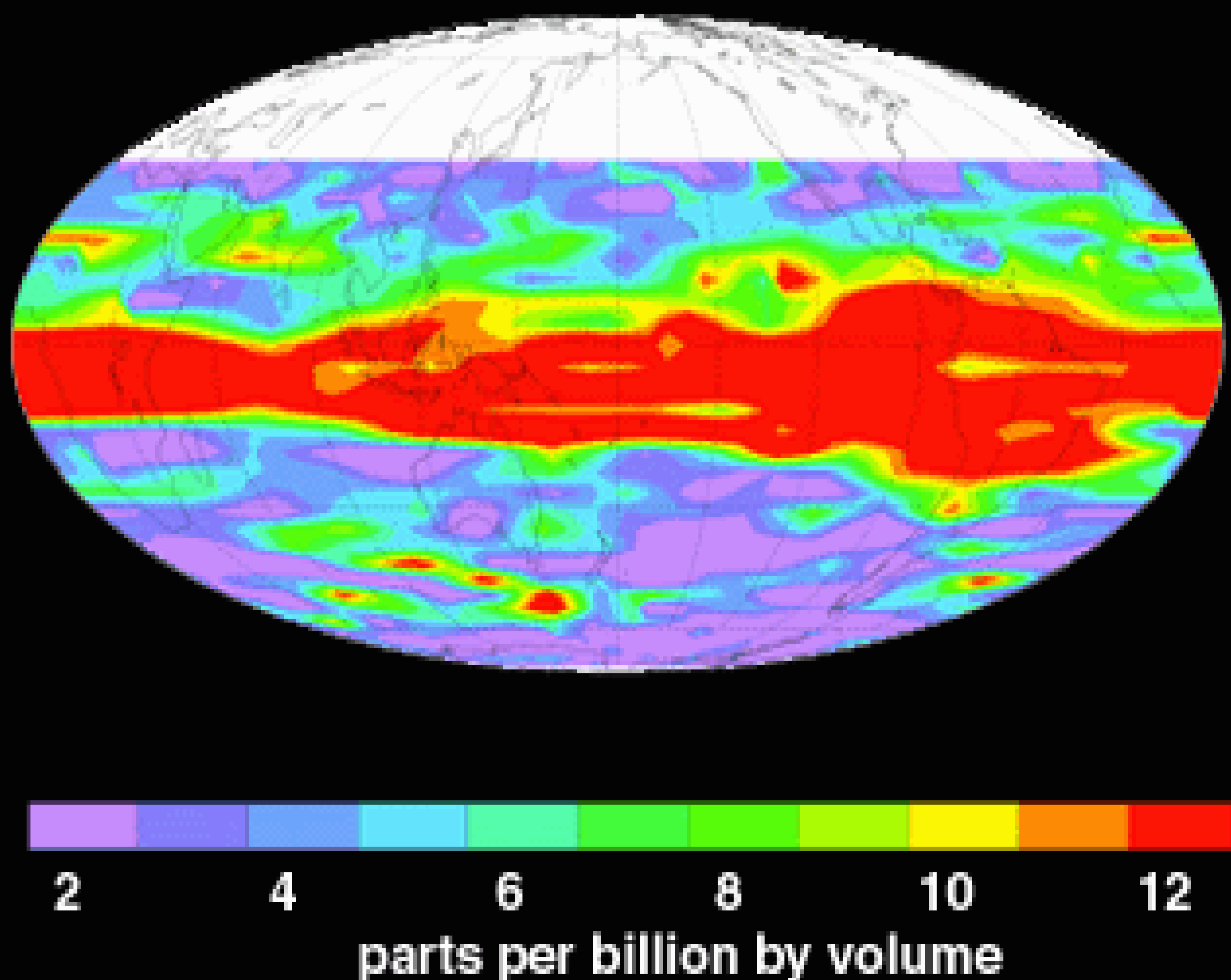
Air Pollution and Climate Change


Volcanoes spew enormous amounts of material into the atmosphere, including sulfur dioxide, which is transformed in the atmosphere into sulfate aerosols. These aerosols reflect sunshine.


NASA Goddard Laboratory for Atmospheres
Hasler, Pierce, Palaniappan, Manyin
Derived from NOAA AVHRR
RGB = 0.65 μm, 0.9 μm, 11μm
115
125
15
5
Mt. Pinatubo ash cloud
intermixed with Typhoon Yunya
June 14, 1991 2329 UTC
(7:30 a.m., June 15)
About 3 hrs before the
cataclysmic eruption of Pinatubo

SO_2 injected into the statosphere by Pinatubo Volcano

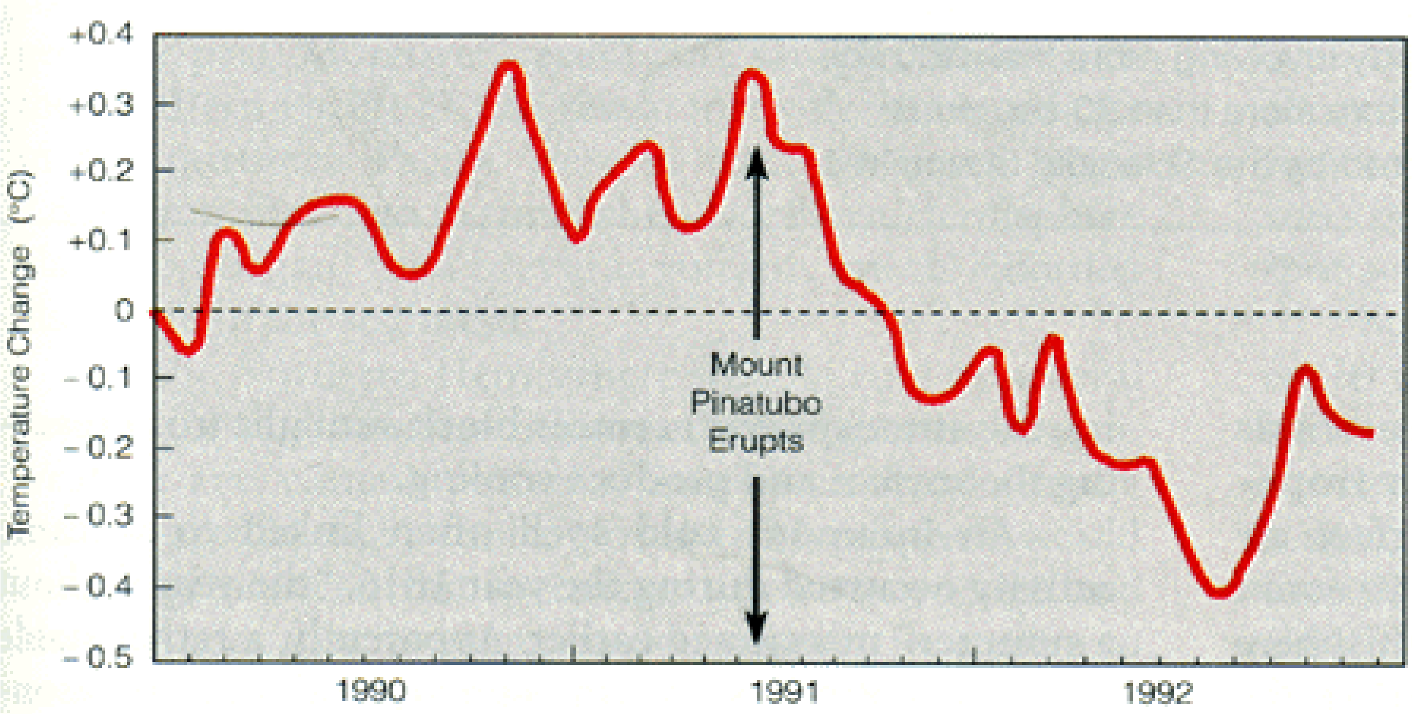
Measured by MLS on 21 Sep 1991, for layer at 26 km; from *Read et al., GRL 20, 1299* (1993)



In the case of the 1991 Mt. Pinatubo eruption, the reflection of sulfate aerosol cloud resulted in a radiative forcing of about -0.5 W/m^2, which lasted for a few months. This coincided with a global cooling on the order of a few tenths of degree C, which lasted a year or so.

Other historical volcanic eruptions are also associated with anomalies in the climate record. The most noteworthy is the enormous 1815 eruption of the Tambora volcano. This is referred to as the “year without a summer” in Europe and North America. The cooling effect was probably on the order of 5ºC.

However, the global cooling effects of the volcanic eruptions we are familiar with last at most a few years.



Observed global air temperature anomaly associated with the Mt. Pinatubo eruption in 1991. (from Ahrens, Meteorology Today)

Atmospheric Aerosols

Sources

- Natural Origin: sea spray, dust from arid/semi-arid areas, volcanic eruption, forest fire, interplanetary meteors, gas-phase chemistry

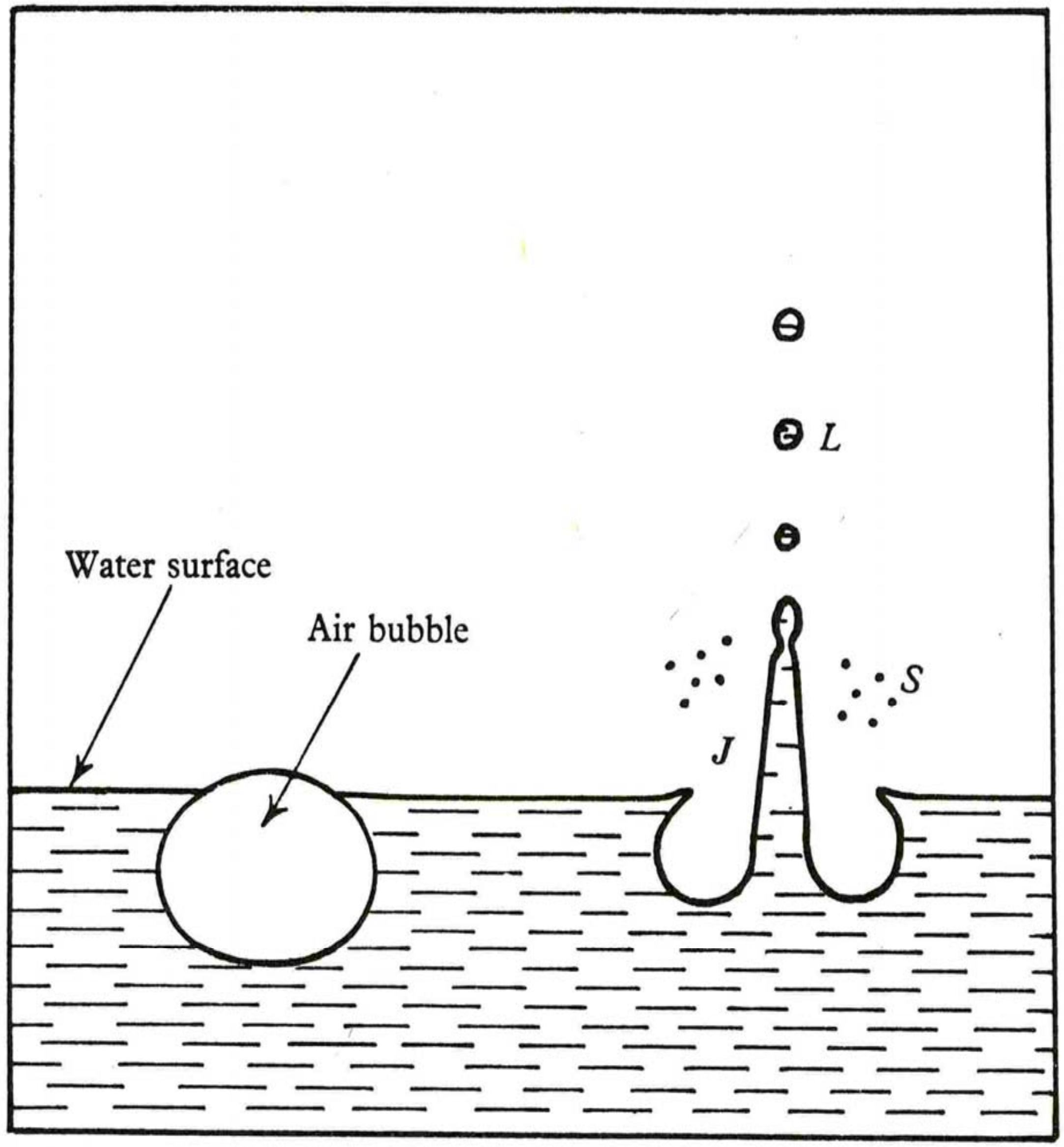
- Man-made: combustion, gas-phase chemistry

Sinks

- Coalescence of tiny aerosols due to air motions

- Cloud formation; aerosols as nuclei

- Precipitation scavenging



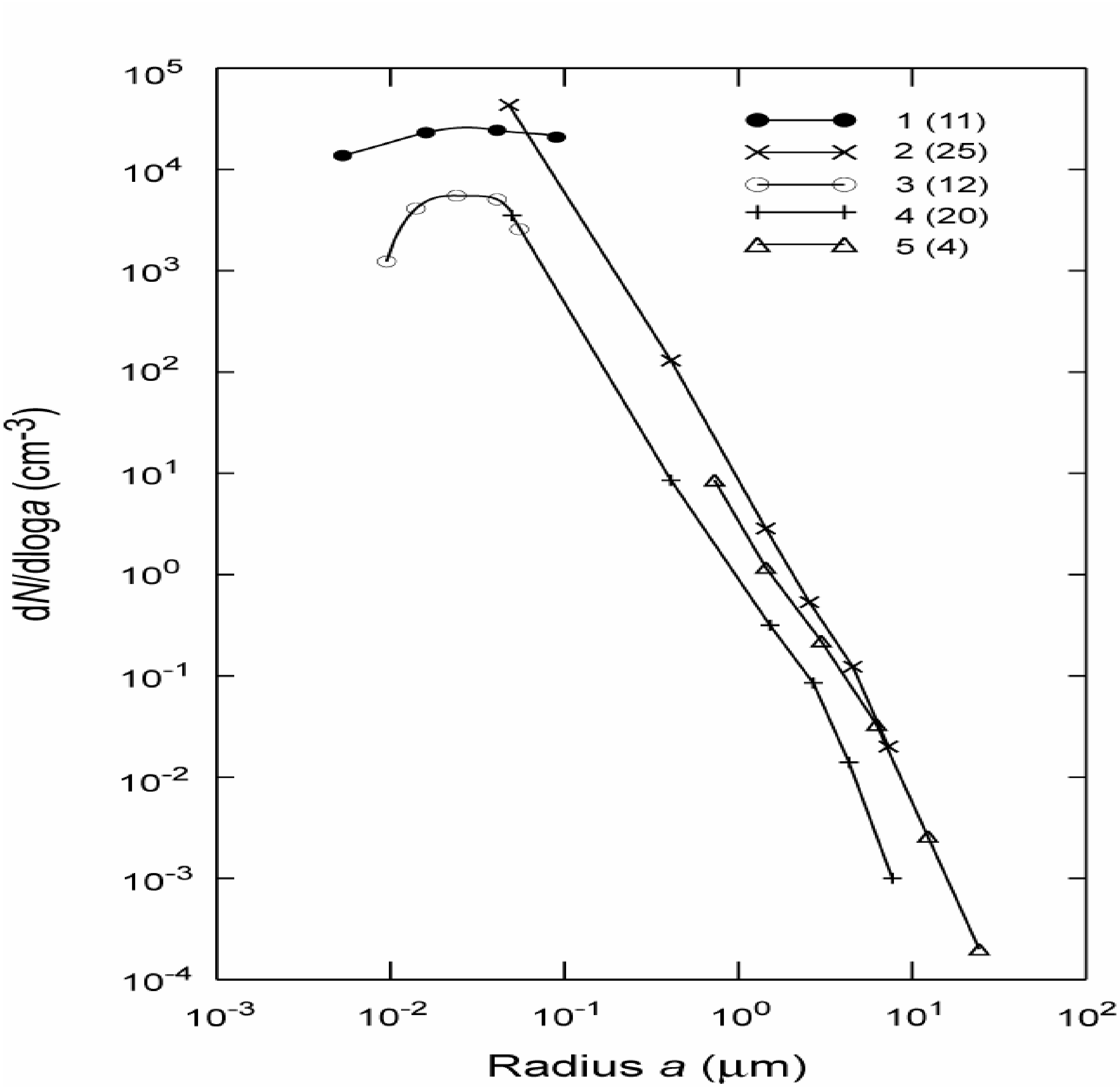
The formation of sea-salt particles from the bursting of bubbles. The large drops *L* are formed by disintegration of the jet *J*. More numerous smaller particles S are formed by bursting of the bubble film. Sea-salt aerosols primarily reflect sunlight.

Difficulty of Aerosols in Climate Research

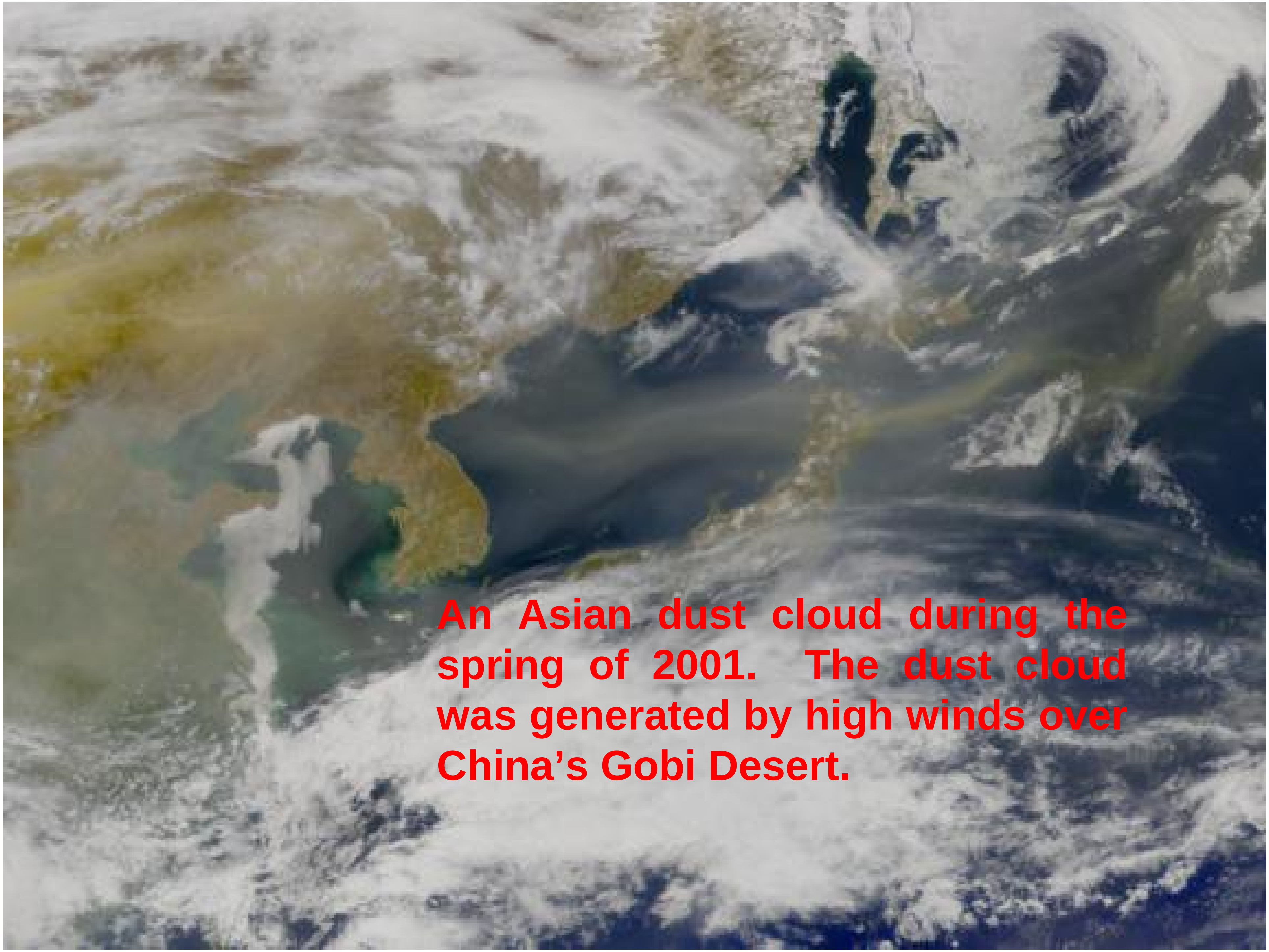
- Regional in character (dust storm, pollution sources)
- Transport by circulation and modification of composition
- Interaction with clouds and precipitation preventing clear-cut observations from space
- Composition determined by chemistry

Aerosol Composition

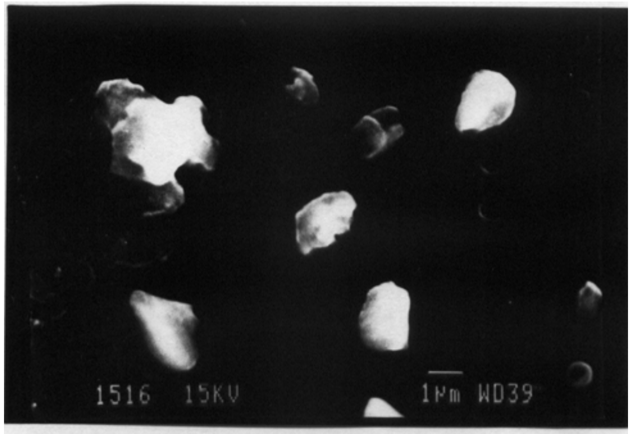
- Water-soluble: sea salt, sulfate, nitrate, organic carbon (optical properties are largely unknown)
- Sulfate Particles (natural and anthropogenic): mainly reflect sunlight
- Soot, carbonaceous materials (black carbon): mainly absorb sunlight
- Dust-like substance (mineral): reflect and absorb sunlight

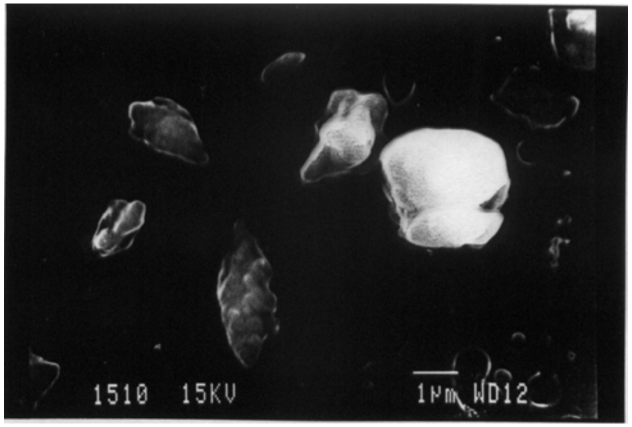


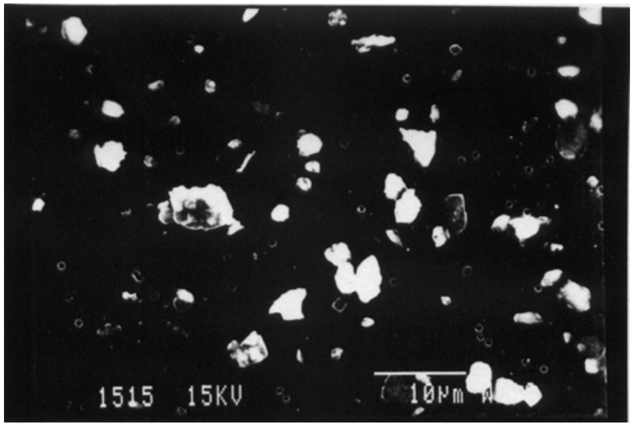
Size distribution of natural aerosols measured at a number of locations in Germany (data taken from Junge, 1963). Aerosols with radii smaller than 0.1 μm is collectively referred to as Aitken nuclei. For radii between 0.1 to 1 μm, the aerosols are referred to as large nuclei. Aerosols with radii larger than 1 μm are called giant nuclei. The majority of atmospheric aerosols have sizes on the order of 0.1 μm. Some of them are effective condensation and ice nuclei for cloud formation

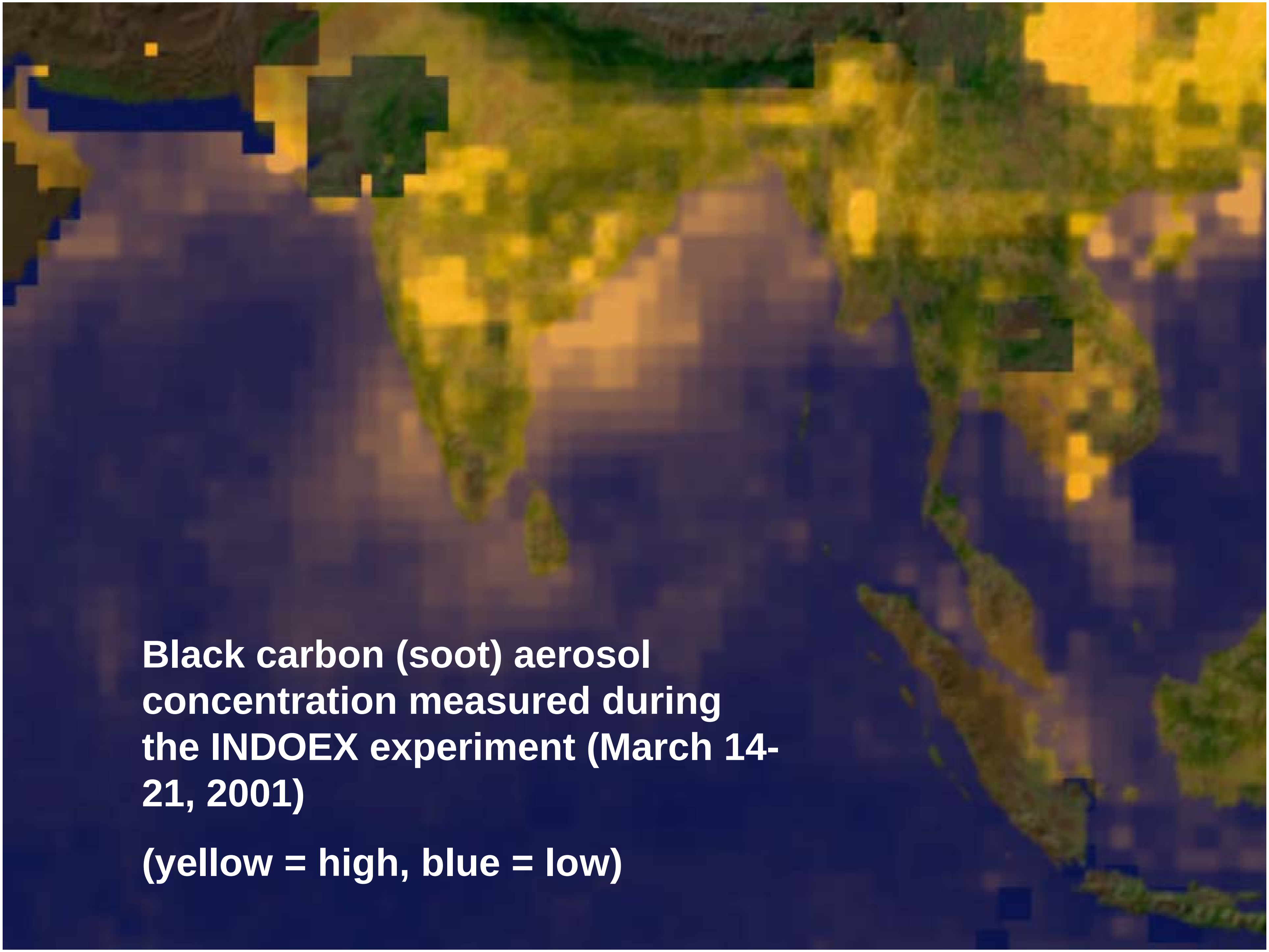

An Asian dust cloud during the spring of 2001. The dust cloud was generated by high winds over China's Gobi Desert.

Typical shapes of dust particles

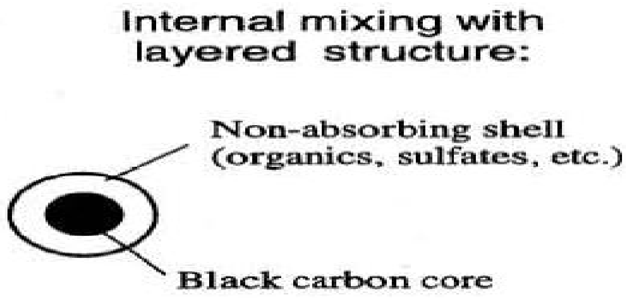


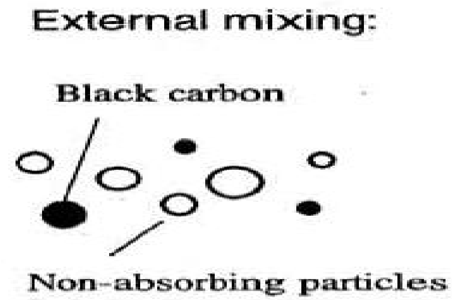


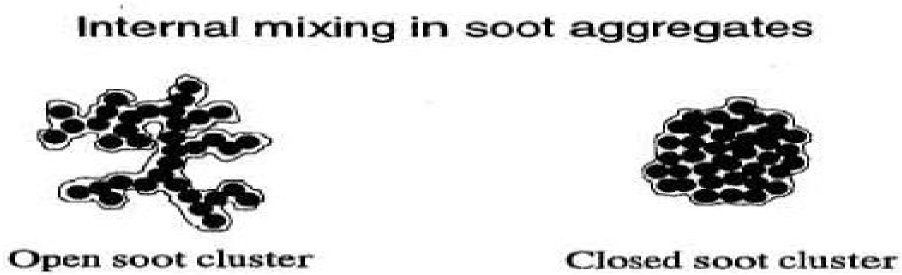


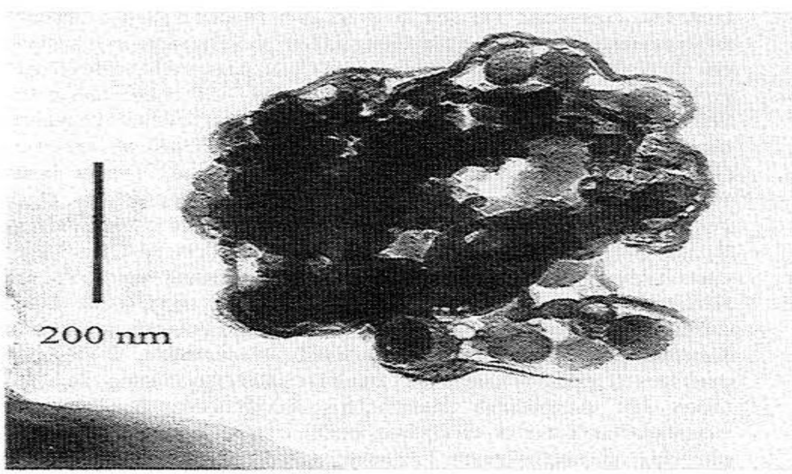

Black carbon (soot) aerosol concentration measured during the INDOEX experiment (March 14-21, 2001)
(yellow = high, blue = low)

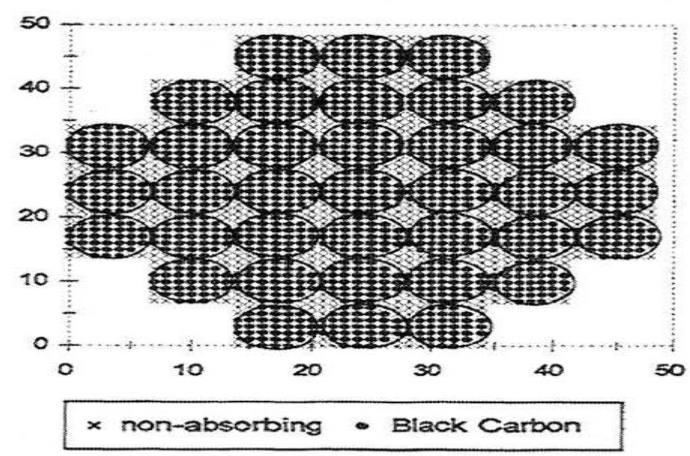
Composition and shape of soot









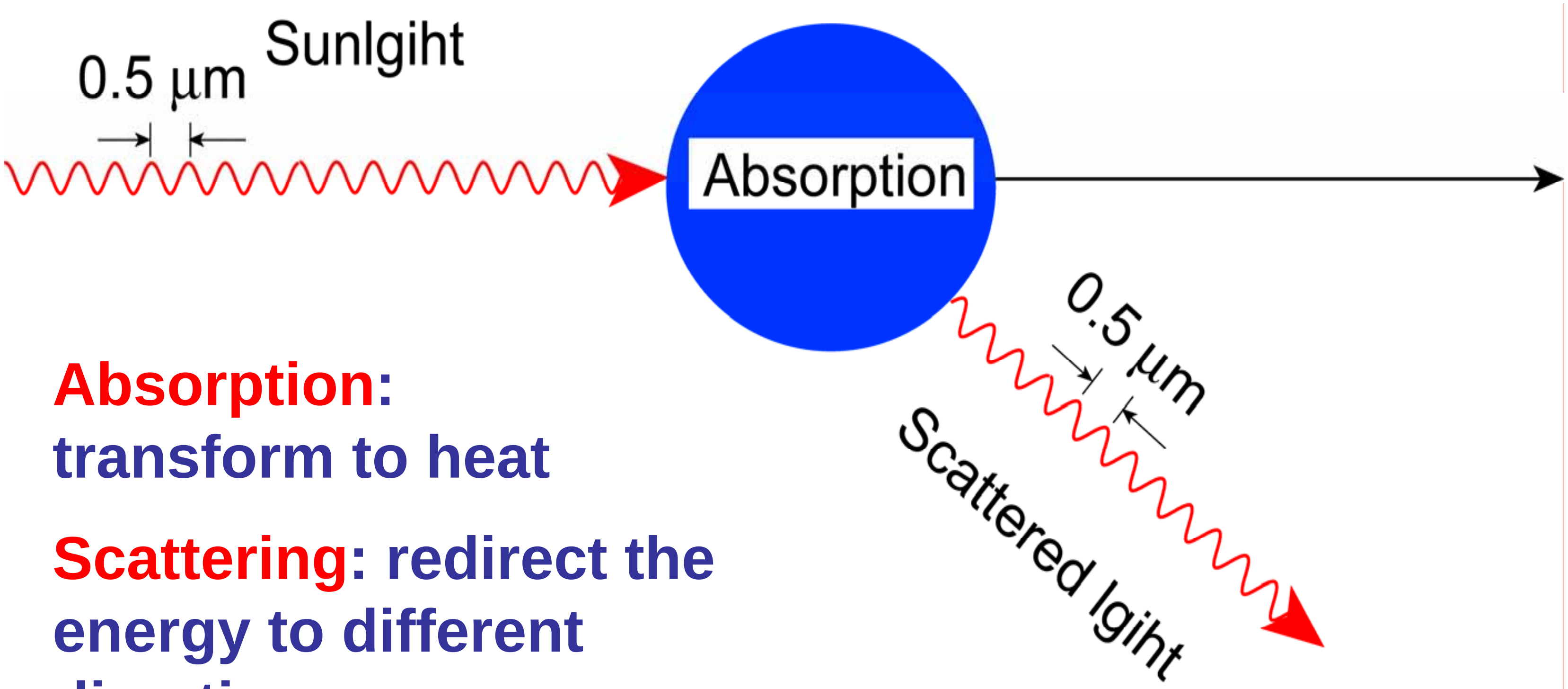


Climate Effects of Black Carbon Aerosols in China and India

Surabi Menon, James Hansen, Larissa Nazarenko, Yunfeng Luo

In recent decades, there has been a tendency toward increased summer floods in south China, increased drought in north China, and moderate cooling in China and India while most of the world has been warming. We used a global climate model to investigate possible aerosol contributions to these trends. We found precipitation and temperature changes in the model that were comparable to those observed if the aerosols included a large proportion of absorbing black carbon ("soot"), similar to observed amounts. Absorbing aerosols heat the air, alter regional atmospheric stability and vertical motions, and affect the large scale circulation and hydrologic cycle with significant regional climate effects (Science, 27 September 2002).

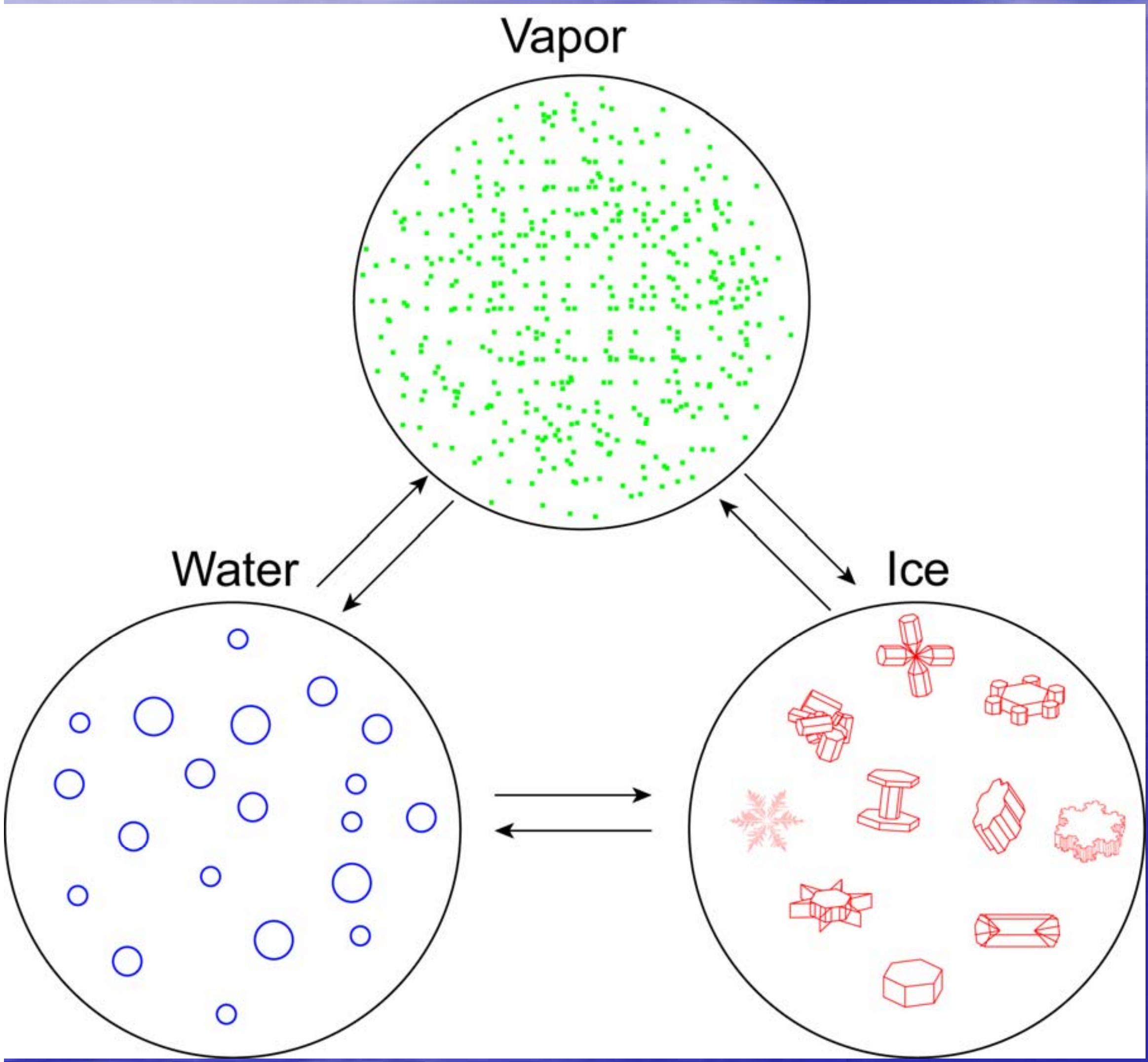
Light Scattering and Absorption by Aerosols: Direct Radiative Forcing



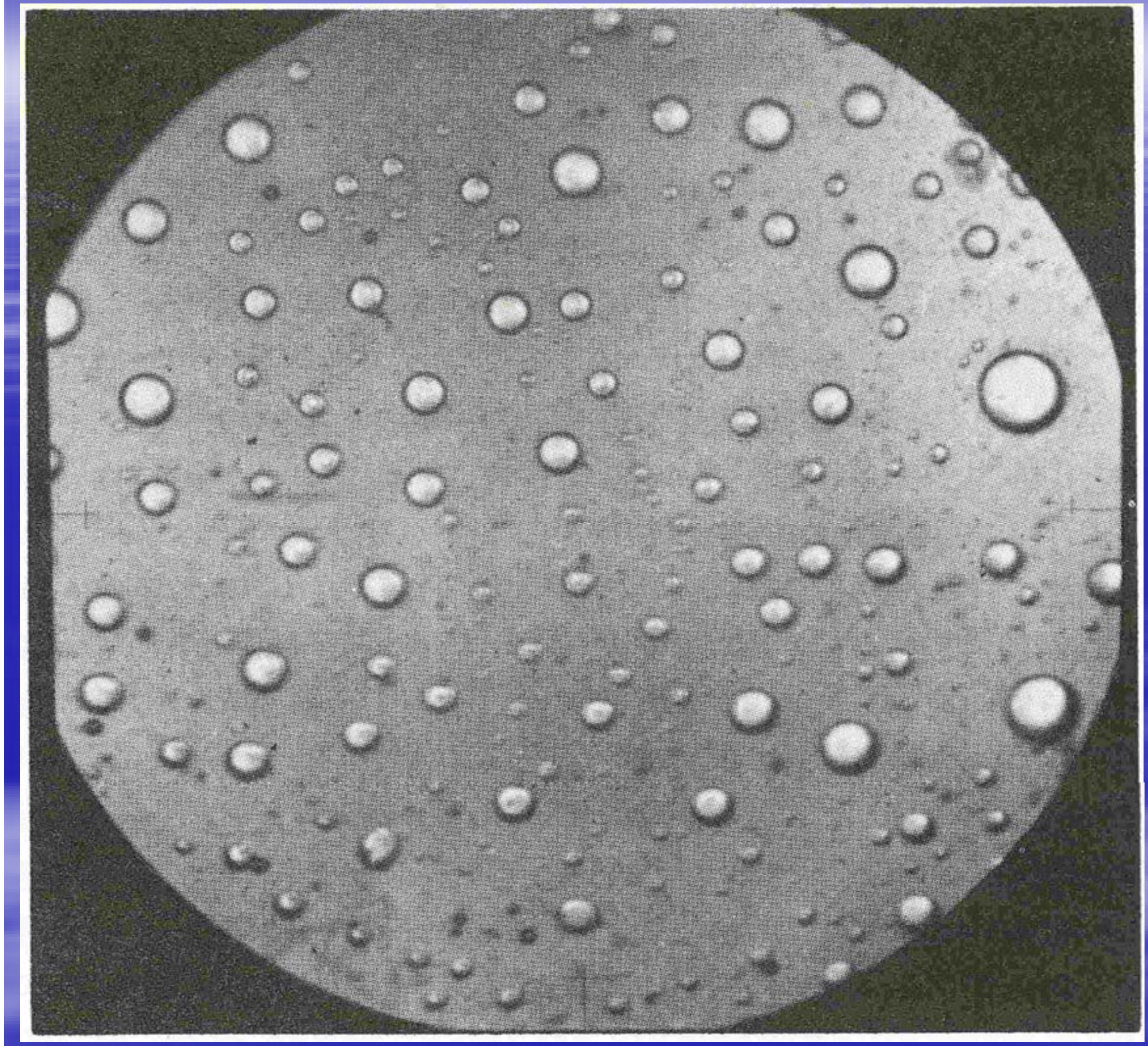
Absorption:
transform to heat

Scattering: redirect the energy to different directions

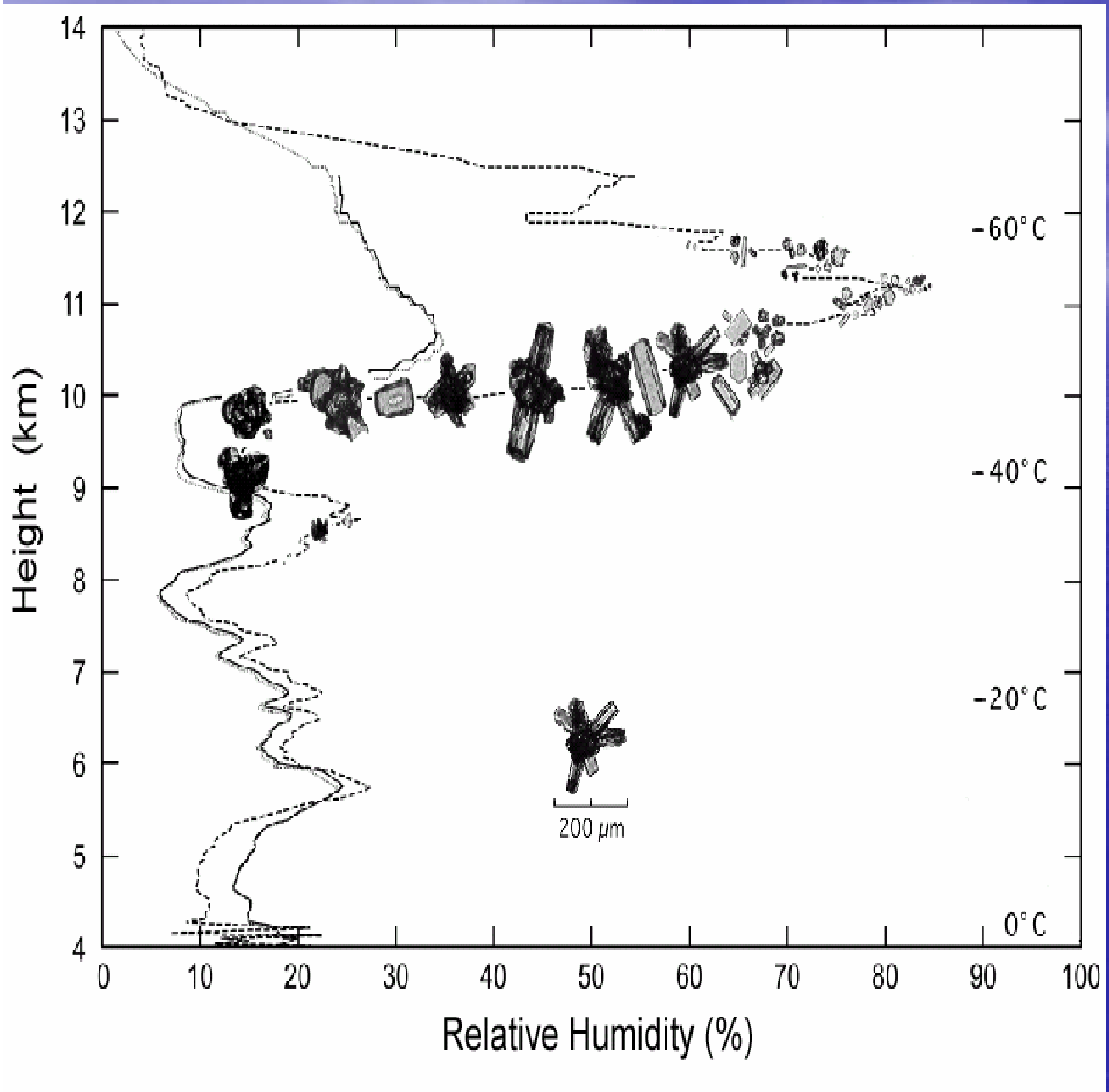
Clouds and Aerosols



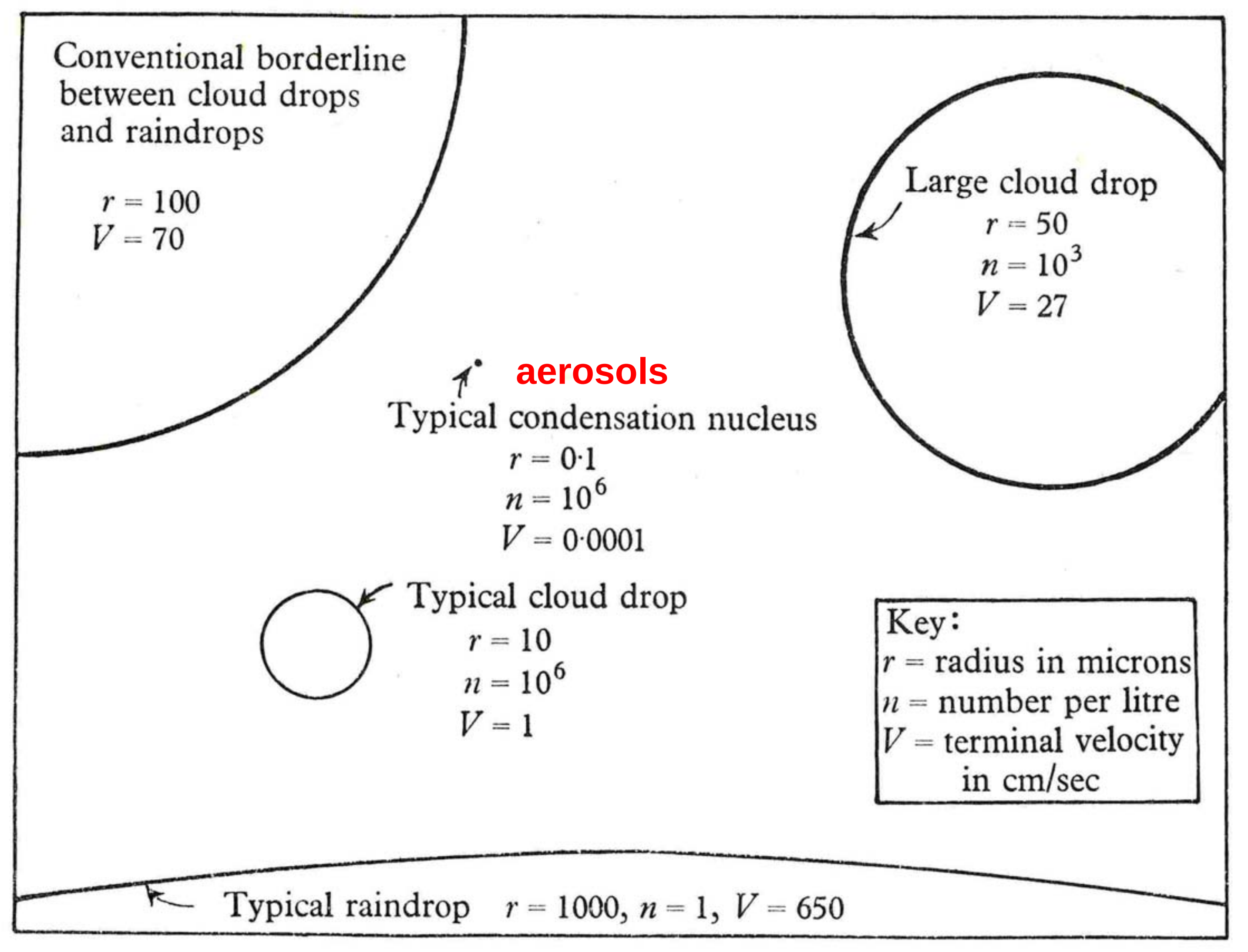
Atmospheric water (H_2O) has three thermodynamic phases: water vapor in molecular form (~ 10^{-4} μm); liquid water droplets in spherical shape (~ 1-20 μm); ice crystals in various shapes (~ 10-1000 μm). Formation of water droplets and ice crystals requires the presence of aerosols as nuclei.



A typical sample of cloud droplets caught on an oiled slide and photographed under the microscope in an aircraft. The largest drop has a diameter of about 30 μm. (By courtesy of the Director-General, Meteorological Office, Bracknell.)



Ice crystal size and shape as a function of height and relative humidity captured by a replicator balloon sounding system in Marshall, Colorado on November 10, 1994. The relative humidity was measured by cryogenic hygrometer (dashed line) and Vaisala RS80 instruments (solid line and dots). Also shown is temperature as a function of height (courtesy of Andrew Heymsfield of the National Center for Atmospheric Research).



Comparative sizes, concentrations, and terminal falling velocities of some particles involved in condensation and precipitation processes. (From McDonald, *Advances in Geophysics*, 1958)

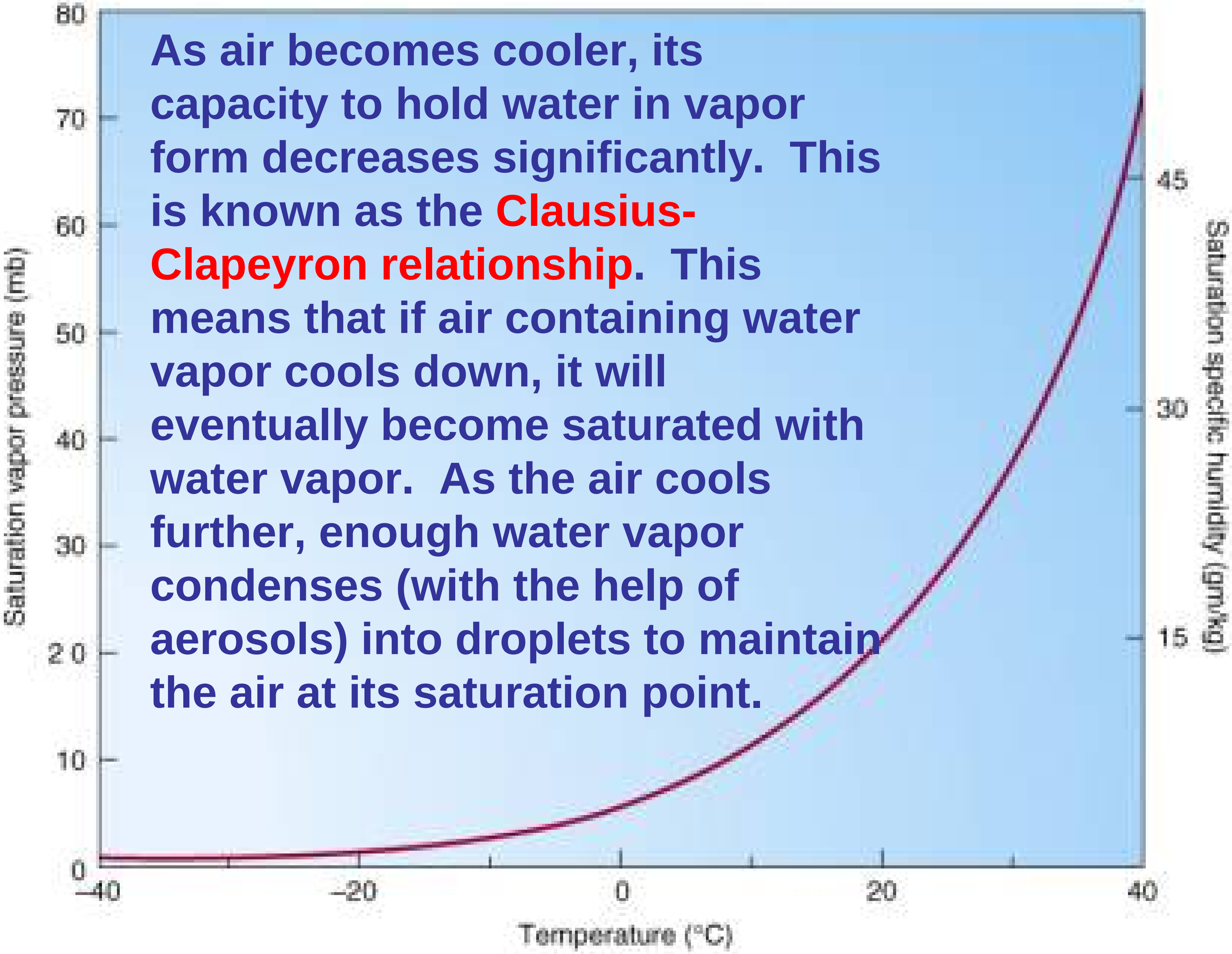
Relative Humidity (RH)

- Relative humidity is defined as the ratio of the amount of water vapor in the air to the amount of water vapor that air would hold if it were saturated. So completely saturated air has a RH of 100%. If the air has half as much water vapor as it can hold, the RH is 50%.

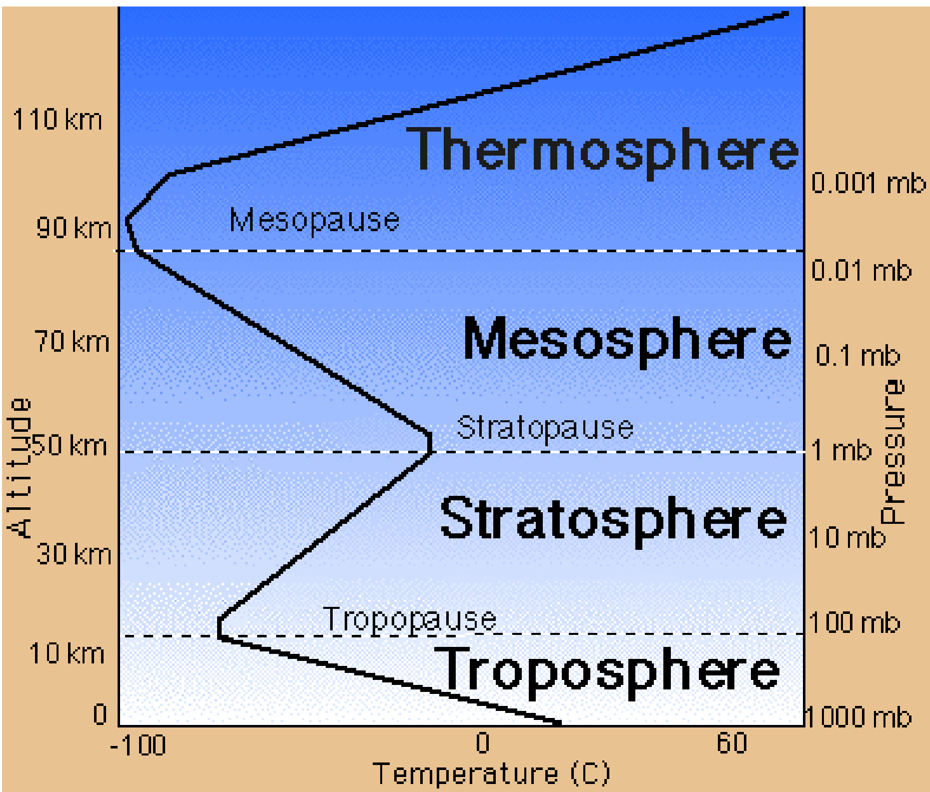
- Without the presence of aerosols (condensation and ice nuclei), formation of clouds cannot occur at a RH less than about 400%, a condition that is impossible for the Earth's atmosphere.

- With the assistance of aerosols, clouds can form and produce precipitation in an atmosphere with a RH less than 100%.

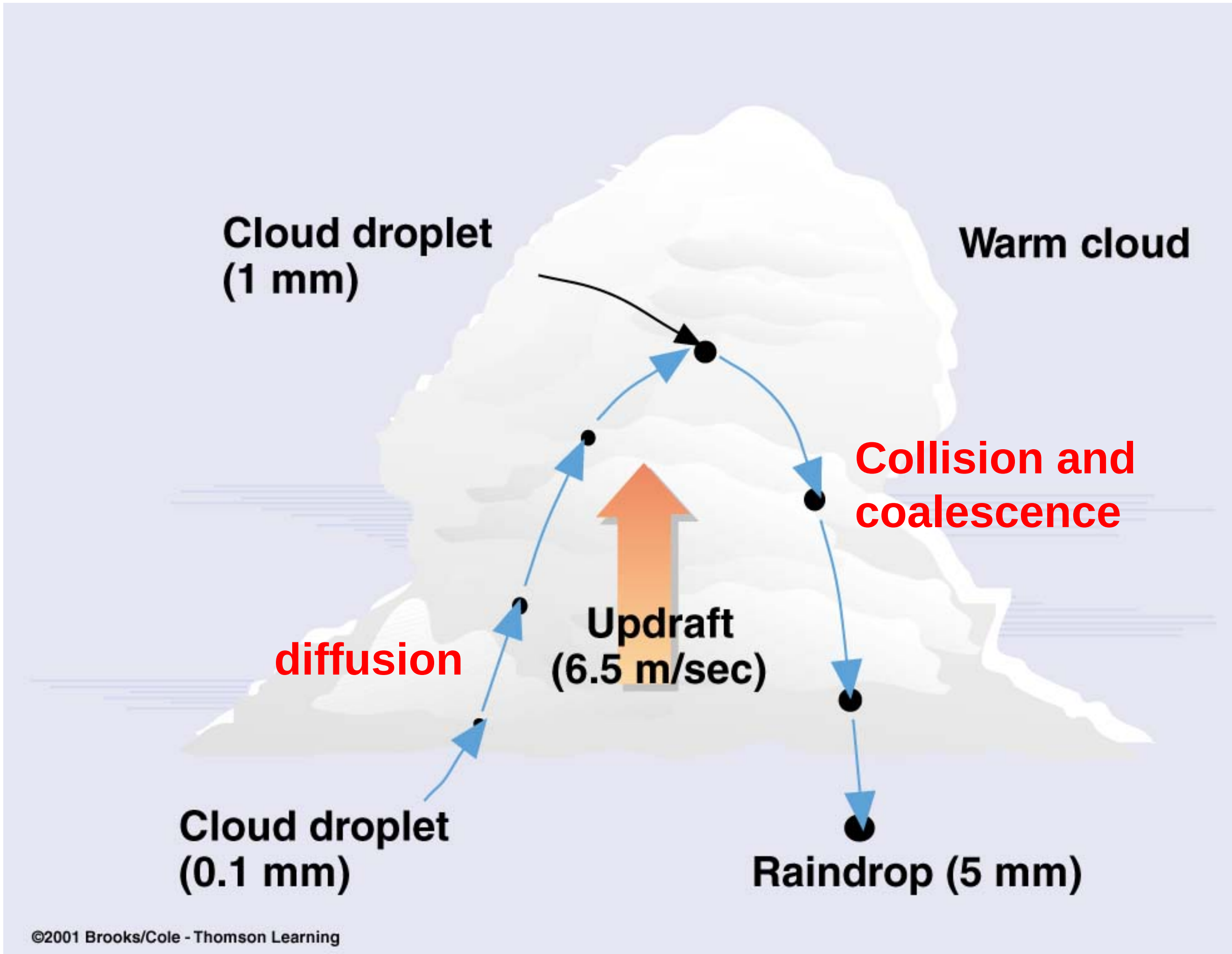
As air becomes cooler, its capacity to hold water in vapor form decreases significantly. This is known as the **Clausius-Clapeyron relationship**. This means that if air containing water vapor cools down, it will eventually become saturated with water vapor. As the air cools further, enough water vapor condenses (with the help of aerosols) into droplets to maintain the air at its saturation point.



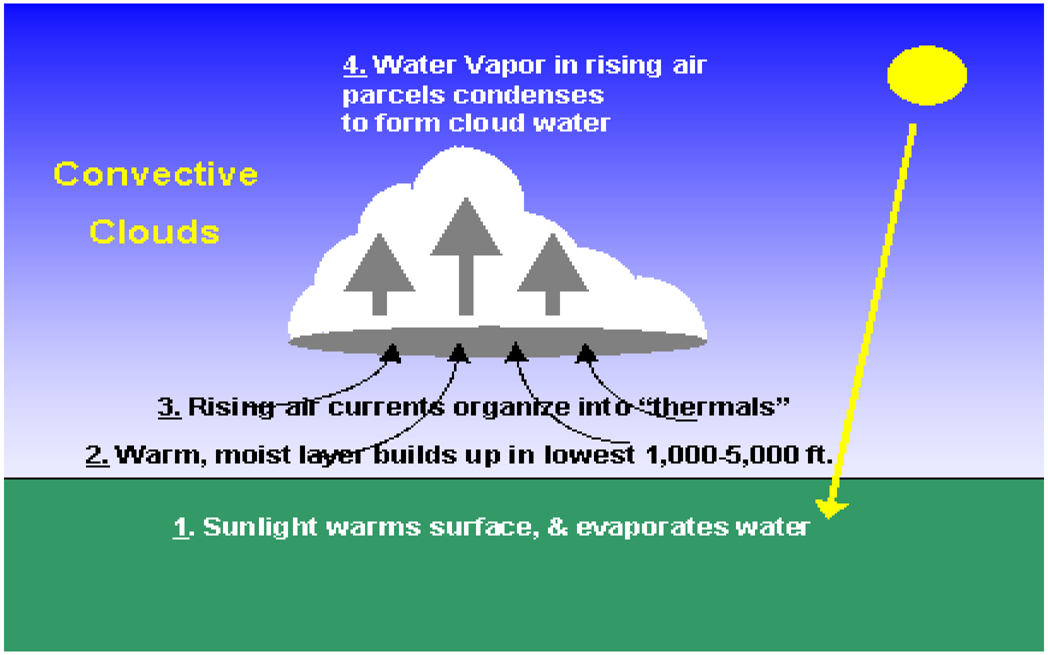
In the lowest 10 km of the atmosphere, temperature decreases with height. So when warm air rises from the surface, it cools. Because of the Clausius-Clapeyron relationship, this often means that the air is quickly brought to saturation. Condensation begins, and clouds form.



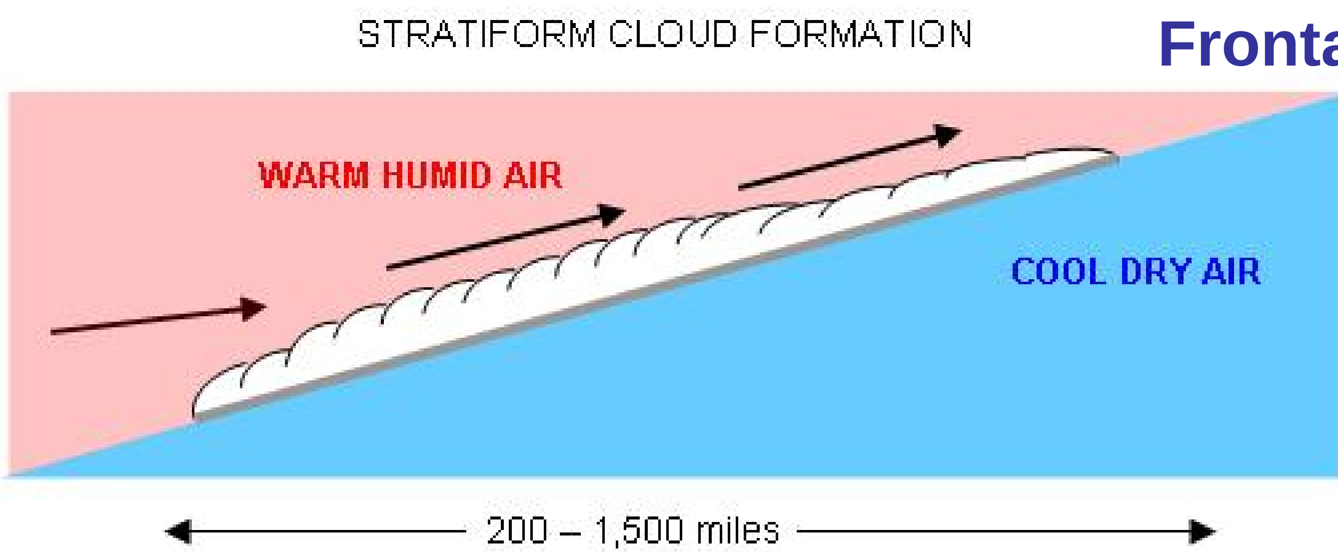
If the air is especially buoyant, condensation continues, causing the water droplets to increase in size. Eventually the water droplets are so large they begin to coalesce and fall as precipitation. For this reason, rising motion is often associated with precipitation.


Cloud droplet
(1 mm)
Warm cloud
Collision and
coalescence
diffusion
Updraft
(6.5 m/sec)
Cloud droplet
(0.1 mm)
Raindrop (5 mm)
©2001 Brooks/Cole - Thomson Learning

How do clouds form?

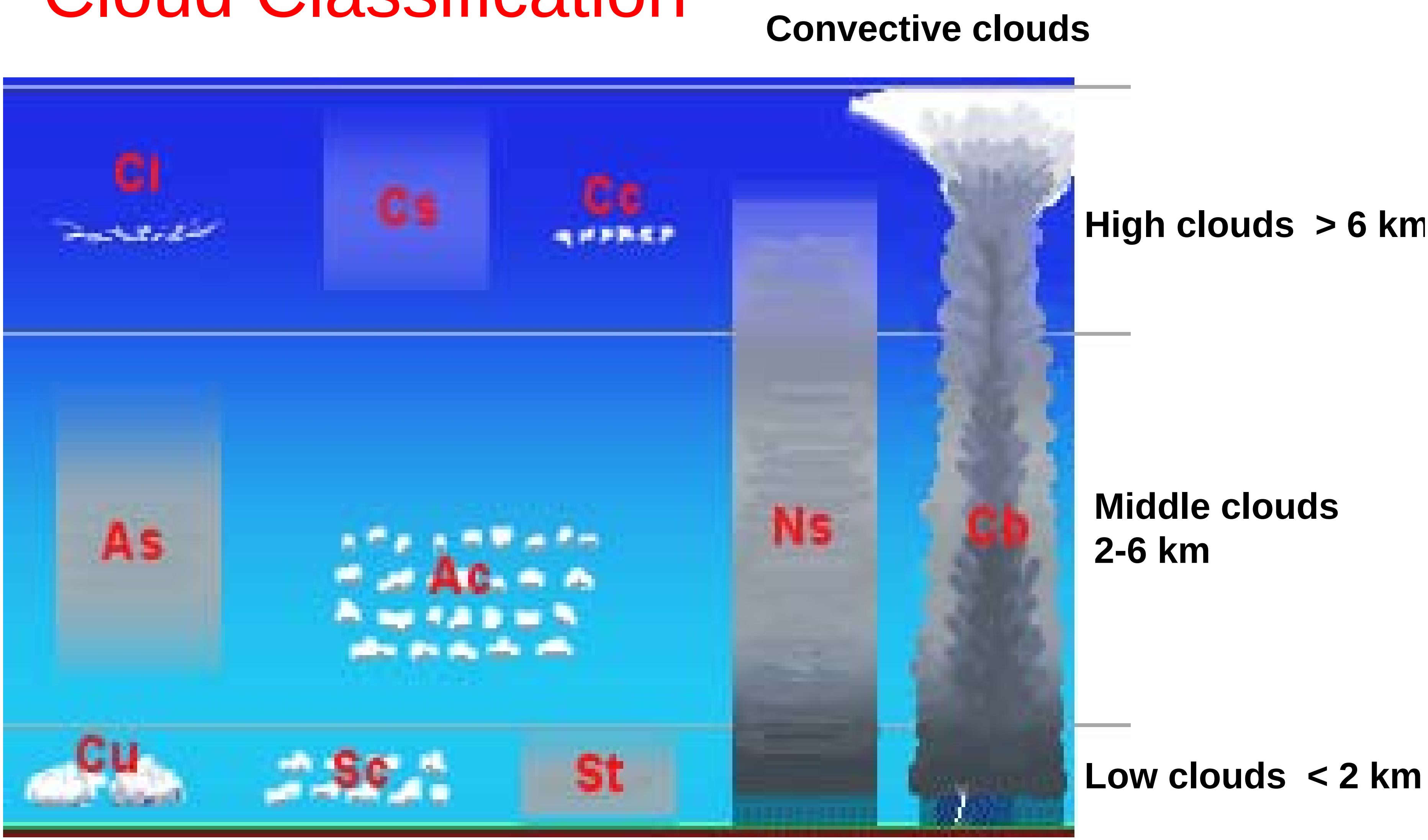


Convection (tropics, midlatitude-summer)



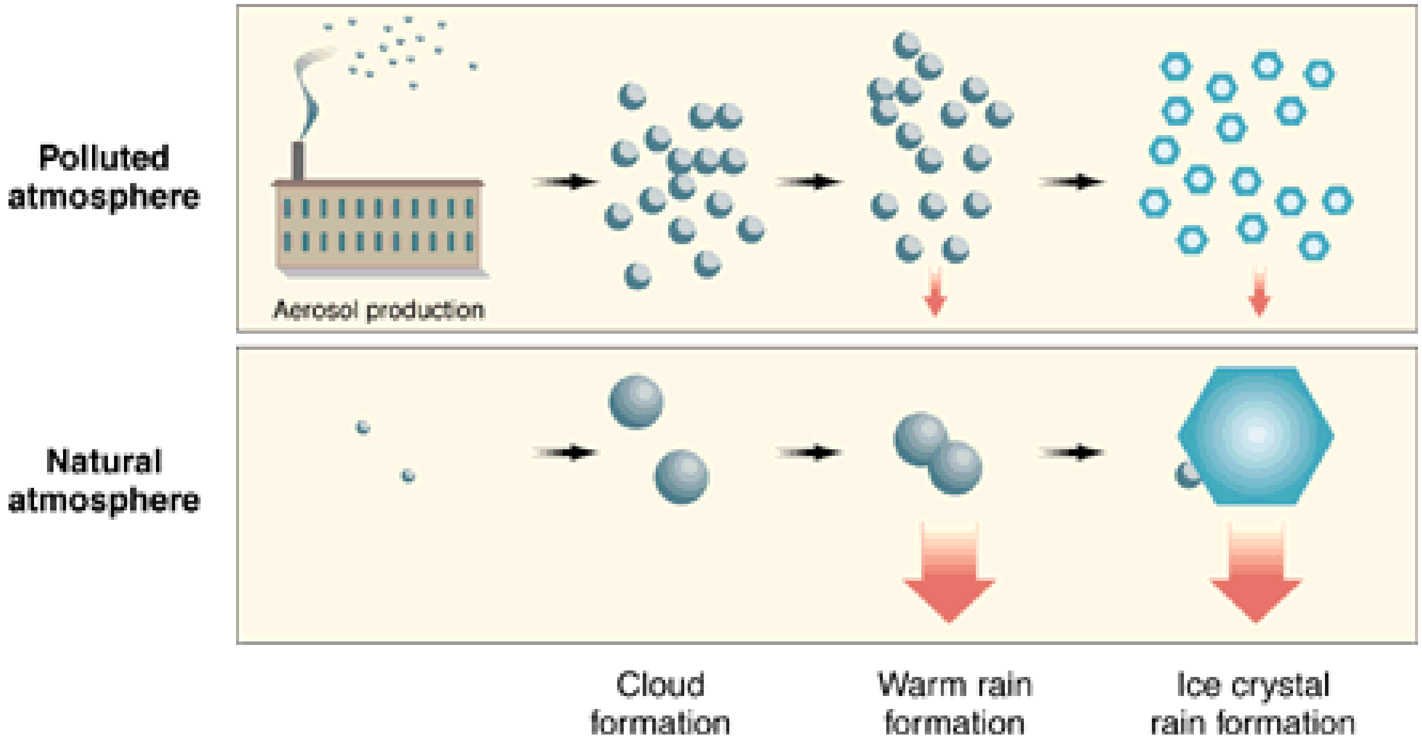
Frontal system

Cloud Classification



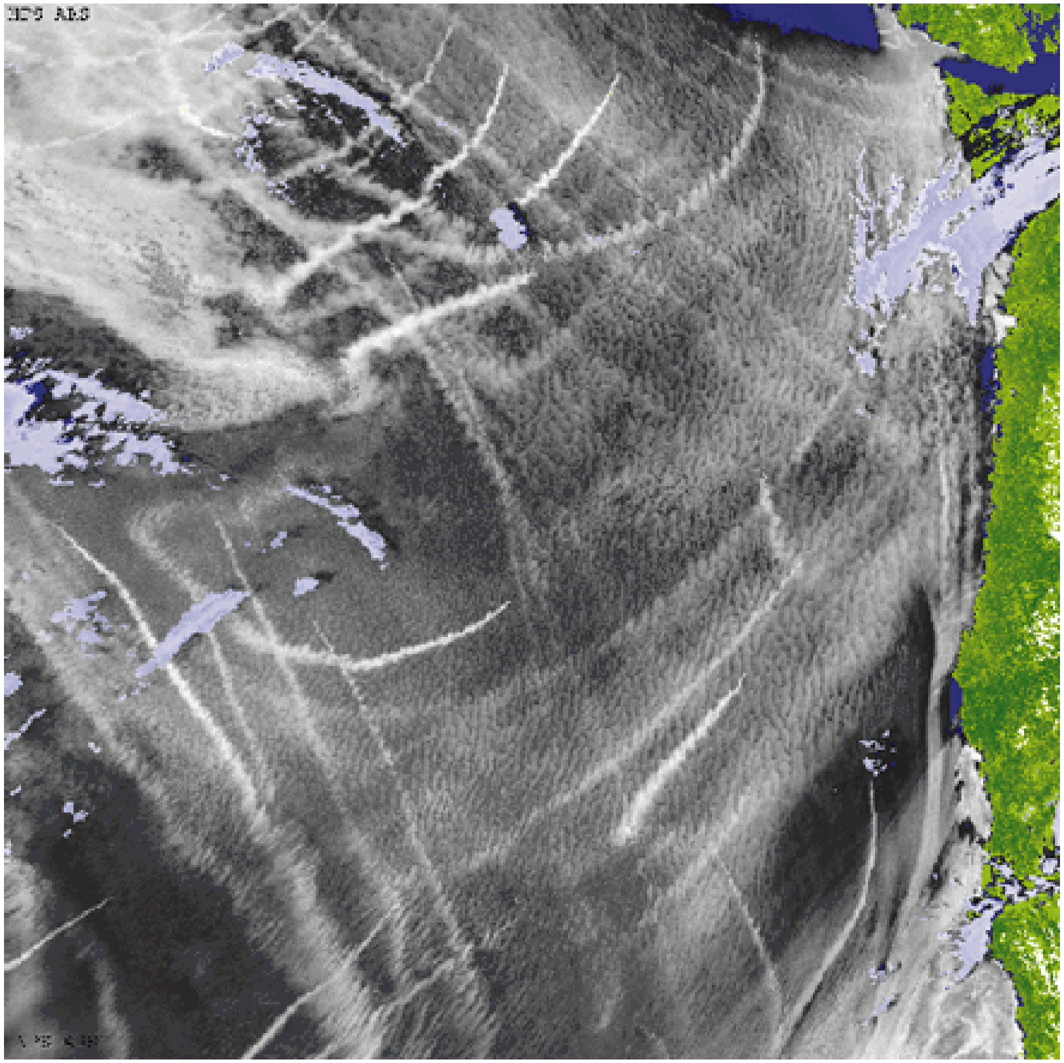
Aerosol-Cloud Interaction (Indirect Effect, Counter Greenhouse warming)

- **Solar albedo effect** (first indirect effect): air pollution → more condensation nuclei (aerosols) → competing for water vapor → more smaller droplets formed and clouds last longer → reflect more sunlight → cooling
- **Precipitation reduction** (second indirect effect) (because of smaller droplets): Adding air pollution could alter atmospheric water cycle.

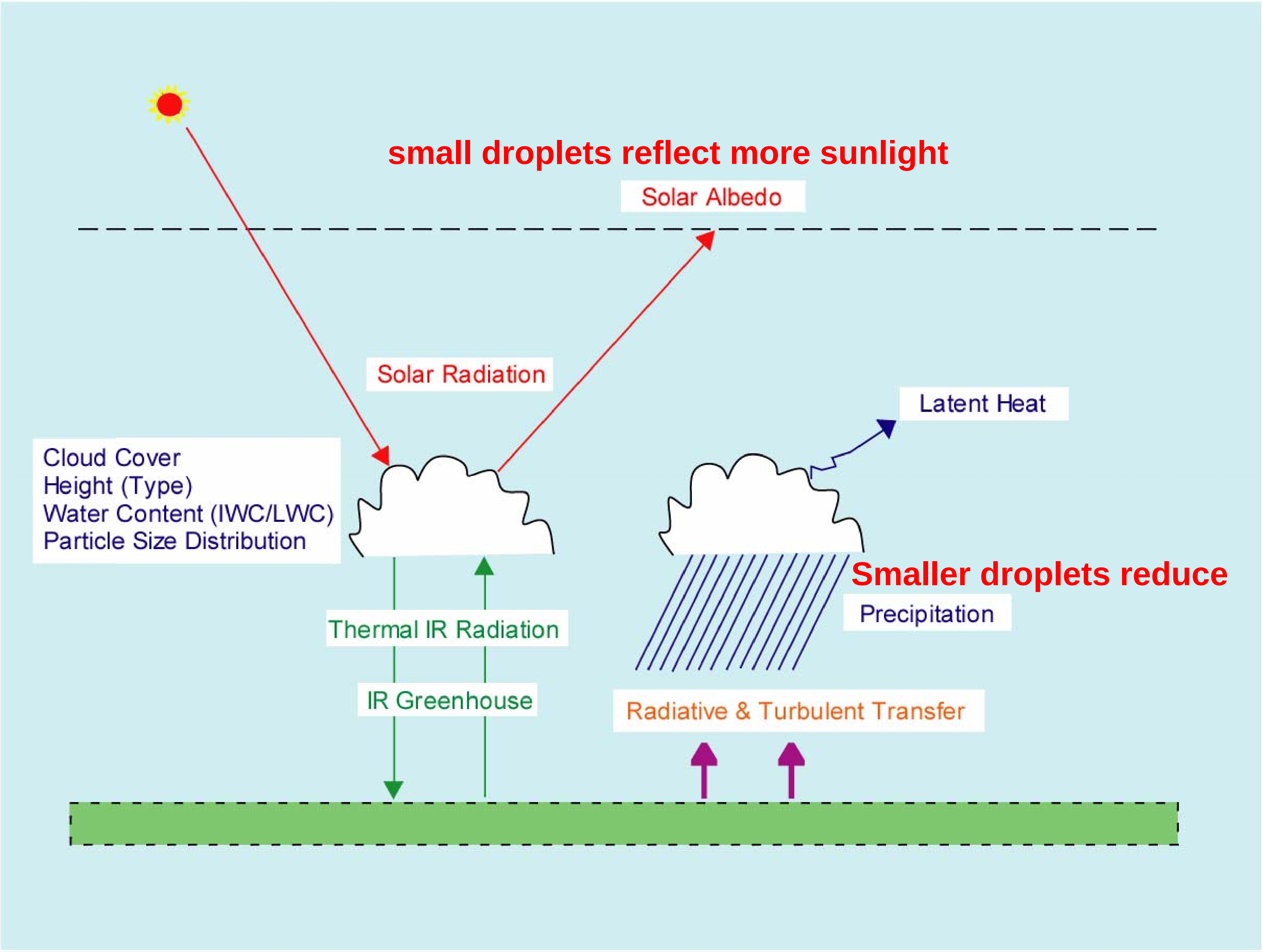


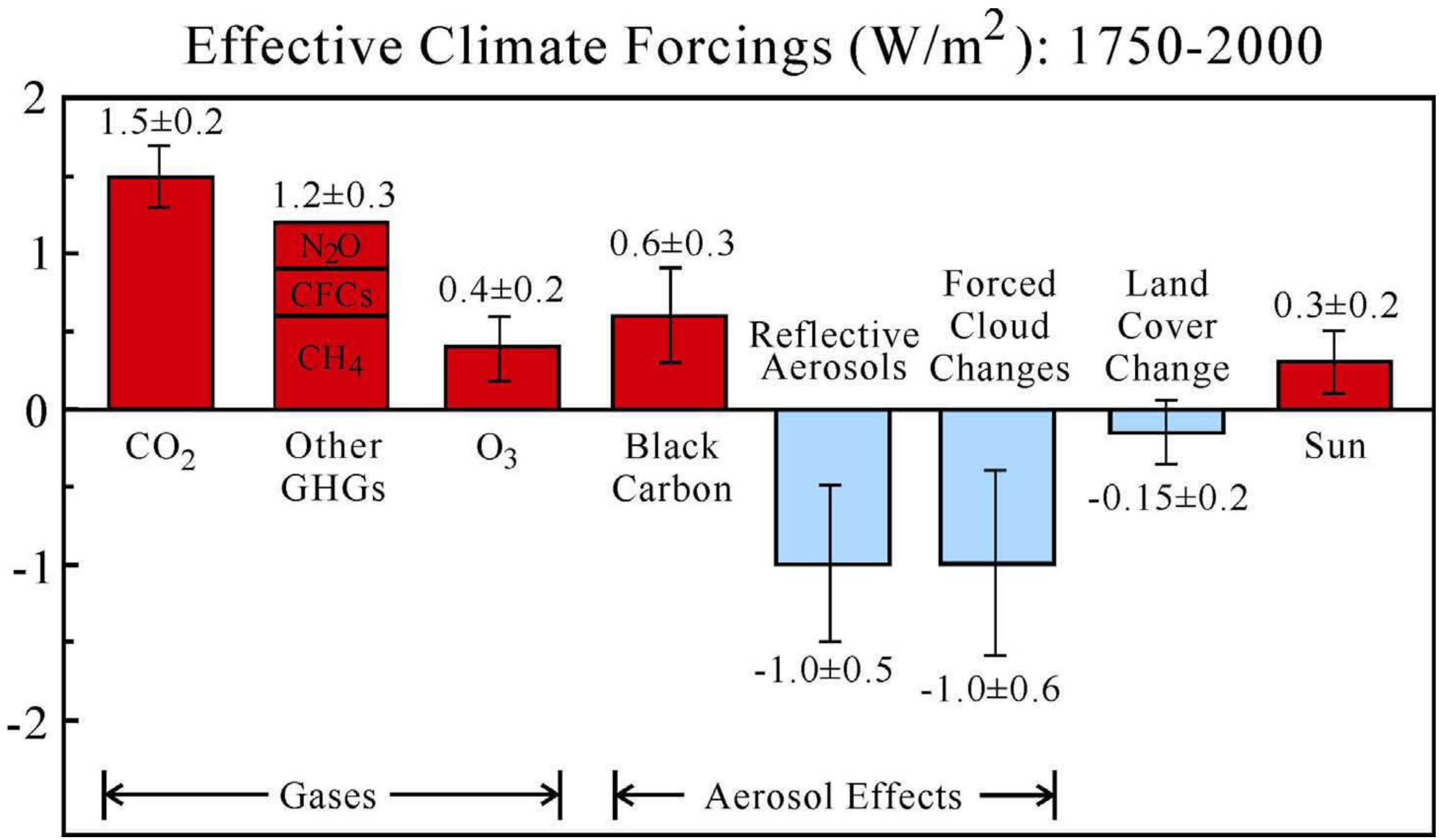
Processes by which aerosols affect clouds. The polluted cloud contains eight times as many droplets of half the size, twice the surface area, twice the optical depth, and higher reflectivity than the natural cloud.


Some observation reveals that air pollution modifies clouds downwind, becomes brighter, and reduces precipitation



Aerosol modification of marine stratus clouds. A false color image of ship tracks (white streaks, brighter) in a boundary layer cloud deck (mottled white) offshore from the northwestern United States (green). Cloud-free ocean is dark blue, high-altitude clouds are light blue. CREDIT: PHIL DURKEE/NAVAL POSTGRADUATE SCHOOL (SATELLITE IMAGE)


small droplets reflect more sunlight
Solar Albedo
Solar Radiation
Latent Heat
Cloud Cover
Height (Type)
Water Content (IWC/LWC)
Particle Size Distribution
Smaller droplets reduce
Precipitation
Thermal IR Radiation
IR Greenhouse
Radiative & Turbulent Transfer



Climate forcing agents in the industrial era. “Effective” forcing accounts for “efficacy” of the forcing mechanism

Source: Hansen et al., JGR, **110**, D18104, 2005.

Climate Radiative Forcing

(1) Net Flux at TOP* (pristine atmosphere)

(2) Net Flux at TOP* (polluted atmosphere)

Radiative Forcing (W/m^2) = (2) – (1) = Gain of Radiative Flux in Earth-Atmosphere

* generally refer to tropopause

Summary

1. Aerosol Direct Radiative Forcing
   - Sulfuric aerosols primarily reflect sunlight → cooling
   - Black carbon aerosols primarily absorb sunlight → atmospheric warming
   - Dust aerosols: depend on size, shape, and chemical composition.
   - Organic carbon aerosols: chemical composition and their climatic effect are largely unknown at this point.

2. Aerosol Indirect Climate Forcing-cloud interaction: large uncertainties exist in observation and computer model

3. Significant research is currently underway to understand the role of aerosols (air pollution) on climate and climate change