Air Pollution Meteorology

Major Sources of Air Pollution

- The number of different types of pollution sources in modern society is almost endless.
- We look at only the most significant sources of air pollutants.
- Mobile (50 - 70%), and stationary sources.
- 15-25% from heavy industrial stationary sources and as much as 25% from other stationary sources.

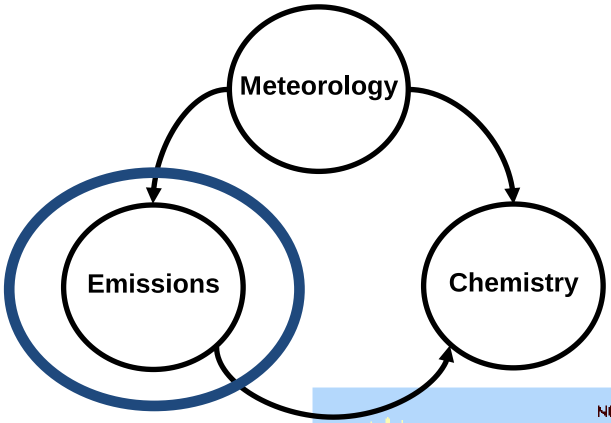
Emissions – What Are They?

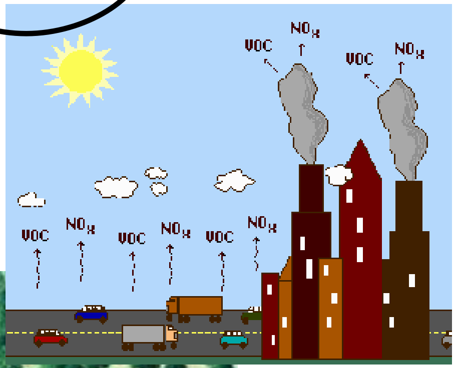
– Man-made sources (anthropogenic)

- NO_x through combustion
- VOCs and particulate carbon through combustion and numerous other sources
- SO_2 through combustion of coal and oil that contains sulfur
- Metals through industrial processes
- PM through combustion, mechanical processes (e.g., wind blown dust through human activity)

– Natural sources (biogenic)

- VOCs from trees/vegetation
- NO_x from soils (fertilizer)





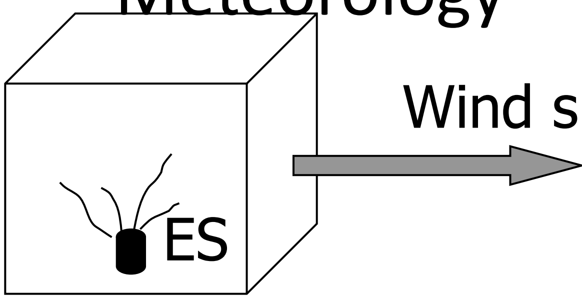
Impacts of Meteorology on Atmospheric Pollution and

Variable or Process	Impact on air pollution and chemistry
Temperature	1. Modulates chemical reactions and photolytic rates 2. Modulates biogenic emissions (isoprene, terpenes, dimethyl sulfide, etc.) 3. Influences the volatility of chemical species 4. Determines aerosol dynamics (coagulation, condensation, nucleation)
Temperature vertical gradients	Determines vertical diffusion intensity (or turbulent mixing)
Temperature and humidity	Affects aerosol thermodynamics (e.g., gas-particle partitioning, secondary aerosol formation)
Water vapor	Modulates hydroxyl radical (OH) concentrations, size of hydrophilic aerosol
Cloud liquid water	Determines wet scavenging and atmospheric composition
Cloud processes	Affects mixing, transformation and scavenging of chemical compounds
Precipitation	Determines the wet removal of trace gases and aerosol
Land surface parameterization (soil type and vegetation cover, soil moisture, leaf area)	Affects natural emissions (e.g., dust, BVOCs) and dry deposition
Lightning	Determines free troposphere nitrogen oxides (NOx) emissions
Radiation	Determines photolysis rates and influences many chemical reaction rates; Determines isoprene emissions
Wind speed and direction	Determines horizontal transport and vertical mixing of chemical species; Influences dust and sea-salt emissions
ABL height	Influences mixing in the boundary layer and concentrations

	$PM_{2.5}$	Ozone
Sunlight	↑ Photochemistry	↑ Photochemistry
Clouds	↑ Aqueous Chemistry ↓ Reduce Photochemistry	↓ Reduce Photochemistry
Precipitation	↔ Minor direct impact	↔ Minor direct impact

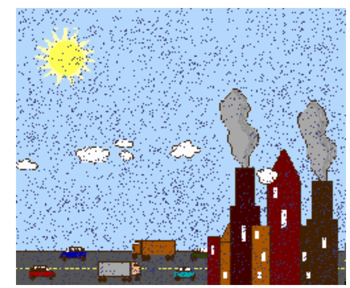
Emissions Impact

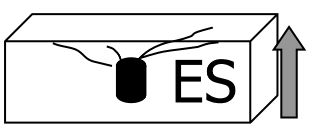
- Pollutant concentration depends on
  - Emissions source (ES) location, source density, and source strength
  - Meteorology



Wind speed (WS)

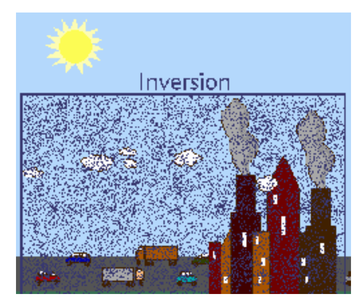
Concentration $\propto$ ES/WS





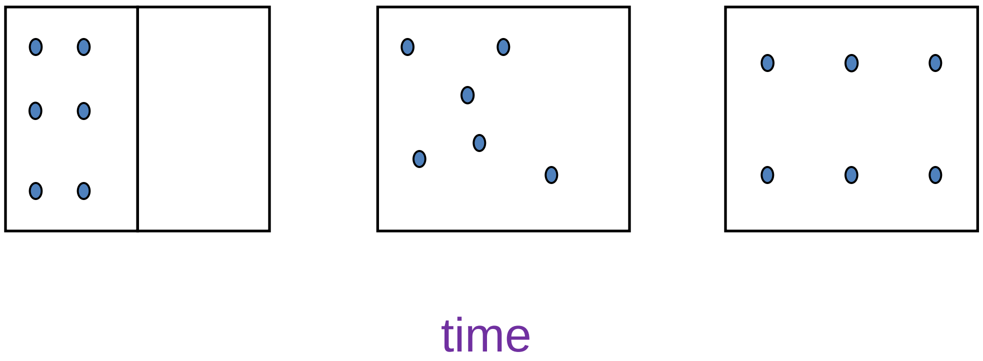
Vertical mixing (VM)

Concentration $\propto$ ES/VM



Diffusion and Dispersion

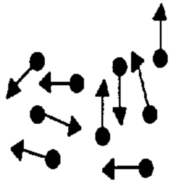
- Diffusion: process where a constituent moves from a higher concentration to a lower concentration



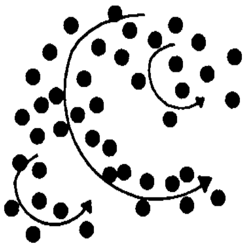
- Dispersion: mixing caused by physical processes

Diffusion and Dispersion

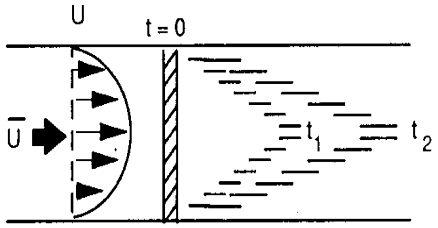
- Molecular Diffusion: Random motion of particles



- Eddy Diffusion: Turbulent mixing of particles

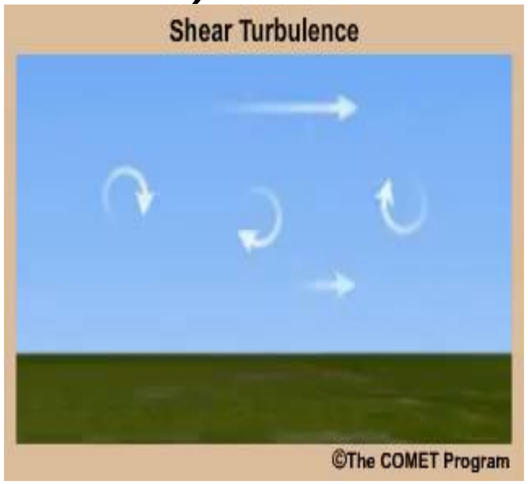


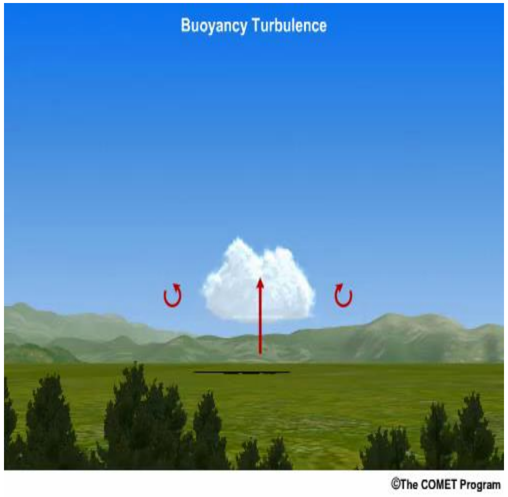
- Mechanical Dispersion: mixing caused by variations in velocities



How do winds affect pollution?

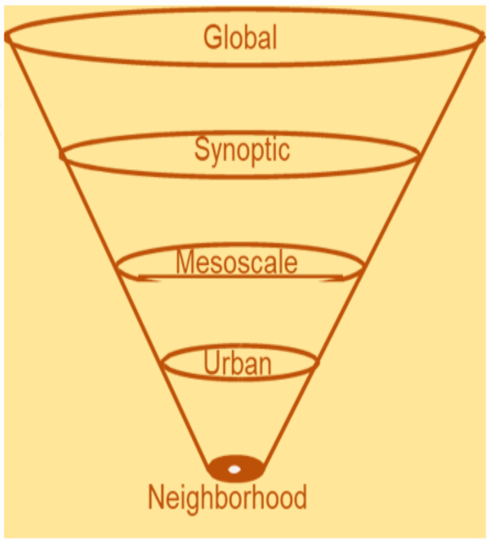
- **Disperse pollutants** – the spreading of atmospheric constituents
- Dispersion is a dilution process
  - Molecular diffusion (not efficient)
  - Atmospheric turbulence - Three kinds of turbulence act to disperse a plume:
    - Mechanical
    - Shear
    - Buoyancy (convective)





How do winds affect pollution?

- Disperse pollutants – the spreading of atmospheric constituents
  - Dispersion is a dilution process
  - Atmospheric turbulence
- **Pollutant transport** – movement of pollutants from one area to another by the wind
- Types
  - Neighborhood scale: monitor to monitor
  - Regional scale: city to city and state to stat
  - National scale: country to country.
  - Global scale: continent to continent



How do winds affect pollution?

Wind-blown dust

Two requirements

- Dusty land/soil
- Winds 7 m/s can loft dust

Land Environment	Threshold Wind Speed
Fine to medium sand in dune-covered areas	4.5-7 m/s
Sandy areas with poorly developed desert pavement	8 m/s
Fine material, desert flats	9-11 m/s
Alluvial fans and crusted salt flats (dry lake beds)	12-16 m/s
Well-developed desert pavement	17+ m/s

Settling of Dust

- Particle size plays an important role in both lifting and settling thresholds. Longer suspension times for smaller particles result in long periods of dust haze in arid areas.

- Particles between 10 and 50 micrometers fall at ~300 meters per hour. Using that rate, if dust is lifted to 1500 meters and the wind ceases, the dust will settle in about 5 hours.
- Heavier particles will settle near the source area, with the smaller ones settling farther away.

- Most dust particles are hygroscopic, or water-attracting. In fact, they usually form the nucleus of precipitation. Because of this affinity to moisture, precipitation very effectively removes dust from the troposphere.

Cyclonic conditions

- Areas of Low pressure are generally
  - fast moving,
  - associated with strong winds and
  - upward motion, clouds and precipitation

→ all result in low pollutant concentrations

Anticyclonic conditions

- High pressure areas have the opposite conditions:
  - Often slow moving and stagnant
  - Associated with weak pressure gradients and light winds
  - Downward motion – clear skies and no precip
  - Formation of a subsidence inversion that stabilizes the atmosphere and limits vertical mixing

  → Conditions that lead to stagnation and high pollutant concentrations

Pollutant removal

- Gravitational settling removes particulates > 1 μm, with those > 10 μm settling quickly.
- Gaseous pollutants can be absorbed onto particles and removed with them.

Dry Deposition

- Deposition (surface absorption) is a turbulent transfer (flux) of pollution to the ground, analogous to heat, water vapour, etc., fluxes.
- $F_p = - K_P \, \partial C/\partial z$
- Where F_p is the pollutant flux that depends on the eddy diffusivity of the matter (K_p) and on the pollutant (C) concentration gradient.

Wet Deposition

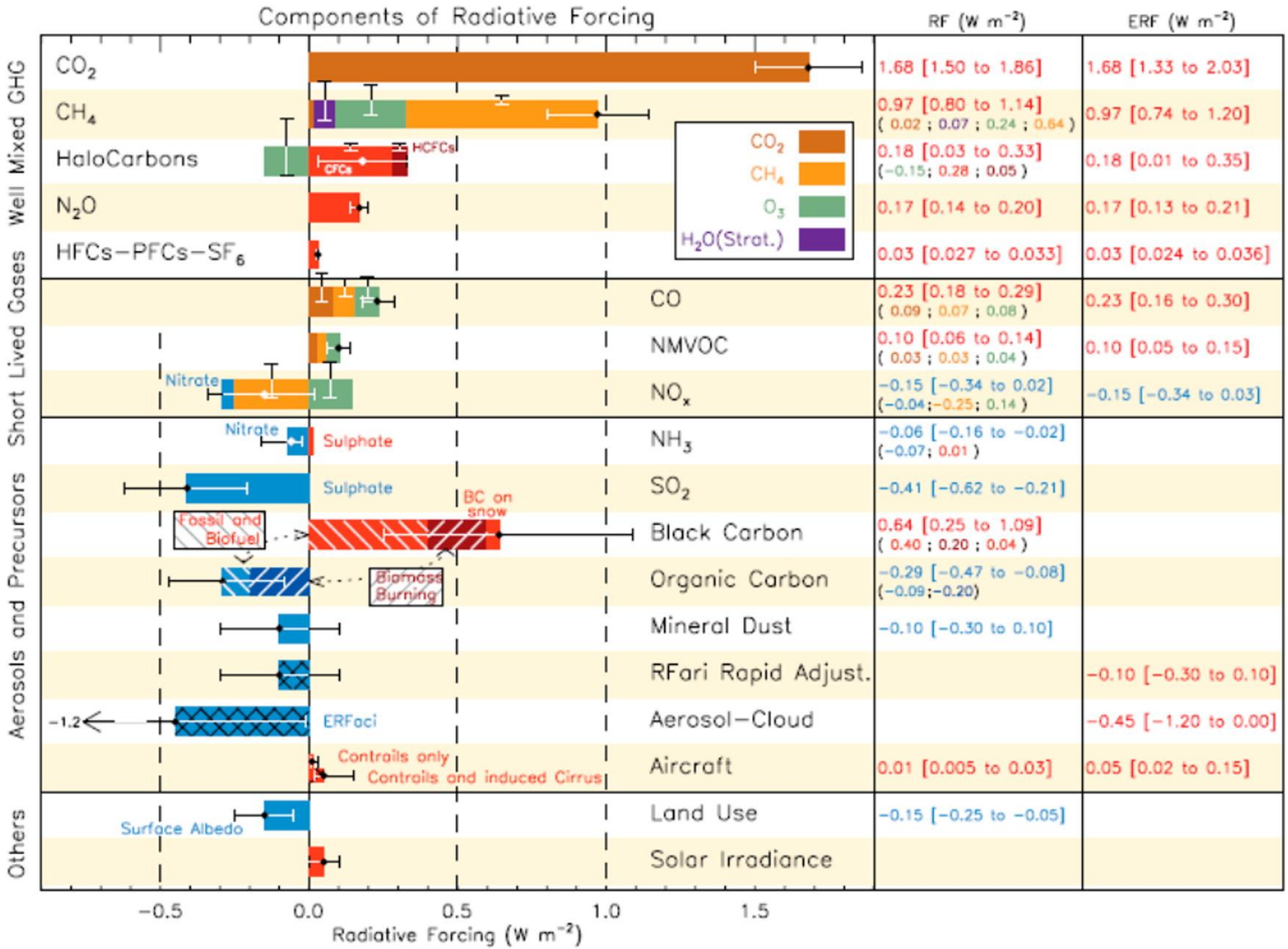
- Another mechanism for pollutant removal is through precipitation that scavenges pollutants from the air.
- Scavenging of particles or gases
  - in clouds (rainout), or
  - below clouds (washout)
- This effectively cleanses the air of gases and small particulates, some of which may become condensation nuclei for raindrops or snowflakes. Falling precipitation can also collect material (“washout”).
- considered as an exponential decay process:

$$\chi(t) = \chi(0) \exp(-\Lambda t)$$

where Λ is the scavenging or washout coefficient

- GHGs:
  - O_3, CO2, CH_4, N_2O, HFC, PFC, SF_6
- Air pollutants with direct radiative forcing:
  - SO_2, aerosols (black and organic carbon, PM2.5)
- Air pollutants with indirect effects on radiative forcing:
  - All gases that influence OH (NO_x, CO, VOC, H_2O, etc.),
  - O_3 precursors (NO_x, VOC, CO),
  - Aerosol precursors (primary and secondary, including NH_3)

The dominant sources of air pollution and GHGs are the same:
fossil fuels combustion
Biomass burning, including forest fires
agriculture emissions



Source: IPCC AR5

NO_x and climate change

Increase in NO_x leads to

- decreased lifetime of CH_4 and HFCs (via OH):
  $\downarrow$ radiative forcing
- increase in O_3:
  $\uparrow$ radiative forcing
- increased N deposition $\rightarrow$ fertilization $\rightarrow$ CO_2 uptake:
  $\downarrow$ radiative forcing

Net effect not yet clear, but significant impacts on radiative forcing expected for 2100.

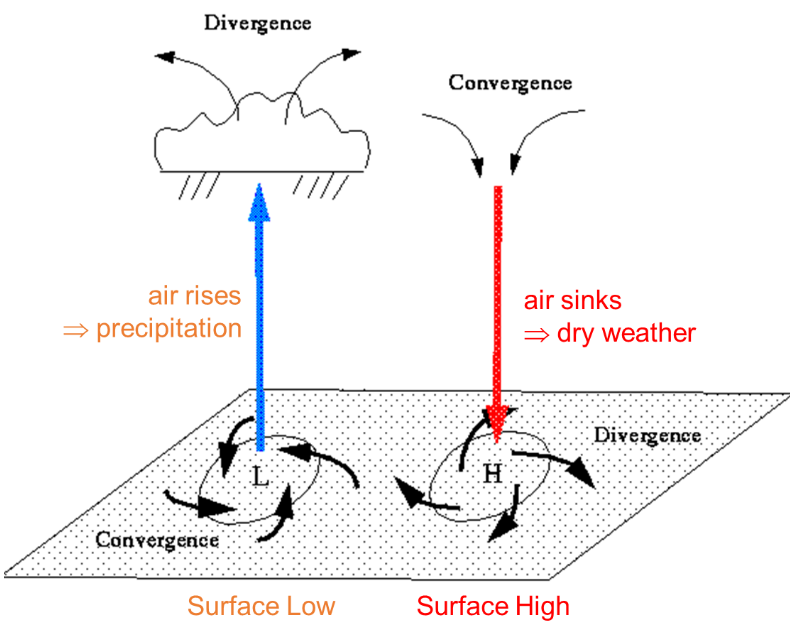
- Sulfates, Nitrate:
  - Cooling effect
  - Changes in precipitation observed in many countries related to increase in SO_2
- Black carbon:
  - Warming effect
- Organic carbon:
  - Cooling effect
  - Net effect of PM from different sources?

Global Dimming and Drying

Aerosols intercept sunlight and reduce the amount of sunlight at the surface, which is commonly known as *Global Dimming*.

The dimming leads to a decrease in evaporation.

How Highs and Lows affect surface weather



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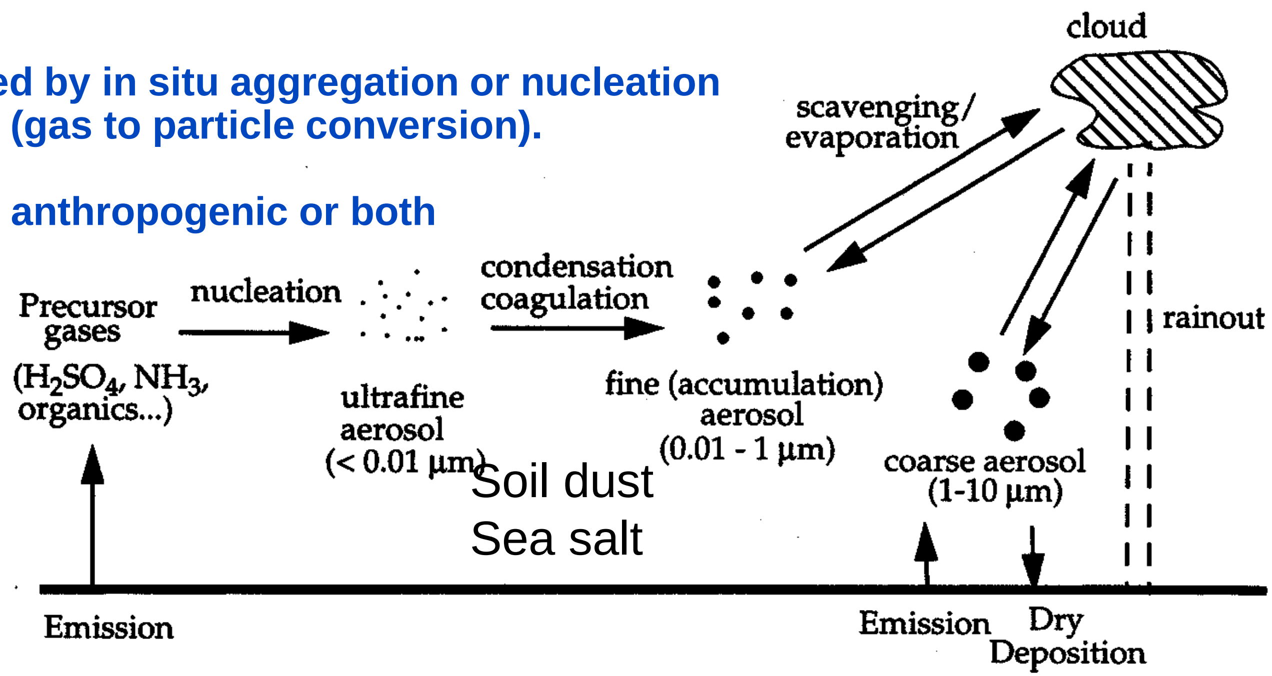
ATMOSPHERIC AEROSOL

Aerosol: Solid, liquid or combination of thereof suspen

Size range: 0.001 μm (molecular cluster) to 100 μm (s

- **Primary aerosol – emitted or injected directly into the atmosphere.**
- **Secondary aerosol - created by in situ aggregation or nucleation from gas phase molecules (gas to particle conversion).**

Either type may be natural or anthropogenic or both



Soil dust
Sea salt

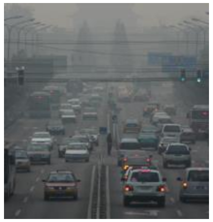
Environmental importance: health (respiration), visibility, radiative balance, cloud formation, heterogeneous reactions, delivery of nutrients…

Types and Sources of Aerosols

Type	Sources
Dust	Desert, bare soil
Sulfuric aerosol	Fossil fuel burning, ocean phytoplankton
Sea salt	Ocean spray
Smoke	Forest fires
Organic carbon	Fossil fuel burning, forest fires

Natural Sources

Anthropogenic
Sources



Lifetimes are ….

Distribution of aerosols around the globe is heterogeneous and they have a short residence time

- Aitken nuclei – hours to days (diffusion/coagulation)

- Accumulation mode – weeks

- Coarse mode – hours to days (deposition)

Direct Aerosol Effect

There are three processes causing the direct aerosol effect:

(i) the absorption of the longwave radiation and incoming solar radiation.

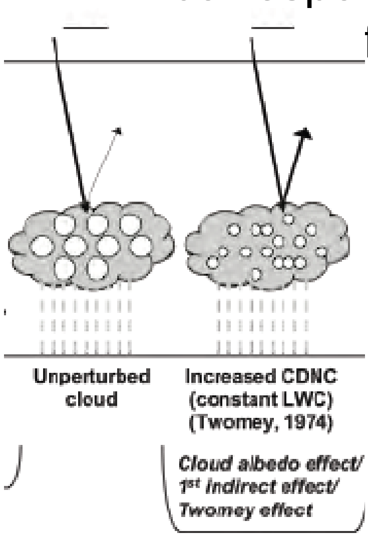
(ii) the longwave radiation emitted by the Earth surface is backscattered by the mineral dust particles.

(iii) incoming shortwave radiation is backscattered as well (global dimming).

All three processes result in reductions of the surface temperature (surface cooling), which leads to a decrease of the net surface radiation forcing of about 1 Wm^{-2}, at the same time with a increase in lower atmospheric heating of about 1 K day^{-1} due to absorption.

Cloud Albedo and Life Time Effect

The indirect effect corresponding to radiative forcing is called cloud albedo effect or Twomey effect, the one corresponding to the hydrological cycle is called cloud ffect.

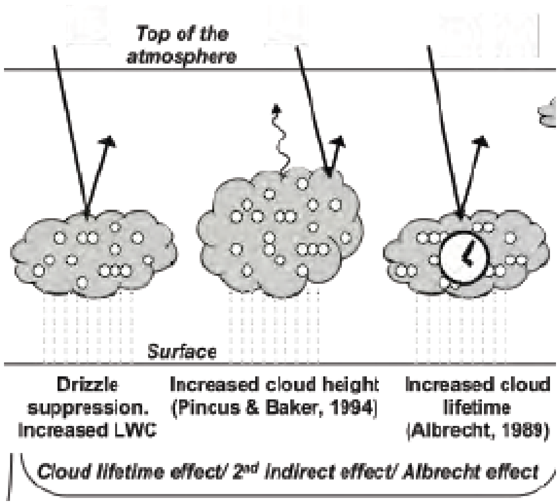


A "contaminated" cloud has more numerous but smaller cloud droplets as a "clean" cloud, which leads to different properties.

Cloud Albedo Effect: the reflectivity/the optical depth of the contaminated cloud is enhanced- the cloud is brighter, which causes an increased albedo.

This means that more radiation is backscattered into the space, so that the net solar radiation at the top-of-the atmosphere is reduced and it gets cooler.

Cloud Albedo and Life Time Effect

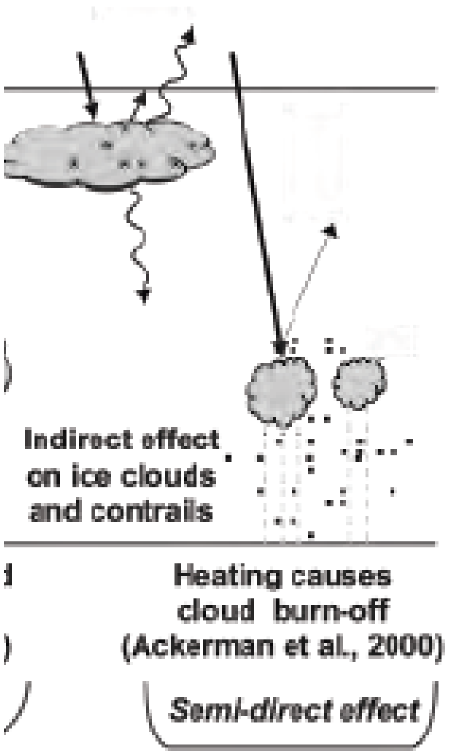


Cloud Life Time Effect

Small droplets are growing less probable by coalescence than bigger ones, so that precipitation could be diminished or suppressed depending on environmental conditions, cloud types and the stage in the storm's lifecycle. **By diminishing or suppressing rainfall the lifetime of the cloud changes, it takes longer until the cloud rains and disappears.** A longer lifetime of contaminated clouds leads to an overall increased cloud cover, which reduces the net solar radiation at the surface, it gets cooler again.

Additionally the total amount of precipitation is reduced, so that aerosols reduce vital water resources in semi-arid regions. This can cause drier soil, which in turn raises more dust (feedback loop).

Aerosol Semi-direct Effect



The absorption of solar radiation in clouds leads to another effect- the so called semi-direct effect. Due to this absorption the evaporation of cloud droplets within the clouds is increased, which may lead to a decrease in cloud cover.

Secondary, followed by the temperature increase the relative humidity is reduced. These affect the thermal atmospheric structure and dynamics and in contrast to the other aerosol effects amplify warming of the Earth-atmosphere system