Aerosol, Cloud and Climate

Today:

- Interaction aerosol – atmospheric water
- Cloud formation
- Climate effects of aerosols and clouds
- Human impact

Literature connected with today's lecture (see "Reading instructions"):

These slides – Aerosol, Cloud and Climate

Jacob, chapter 8

Martinsson – Aerosol, Water and Clouds

Exercises:

8:1 – 8:6

Aerosols and Aerosol Particles

An aerosol is a suspension of fine solid or liquid **particles in air** (or another gas).

The suspended particles are called **aerosol particles.**

- Sizes of 0.001 – 100 µm
- Air close to the Earth's surface: ~1 kg/m^3
  ⇒ Aerosol Particles are trace constituent

Particle number concentrations

Over the oceans: ~100 cm^{-3}

Urban environment: up to 1 million cm^{-3}

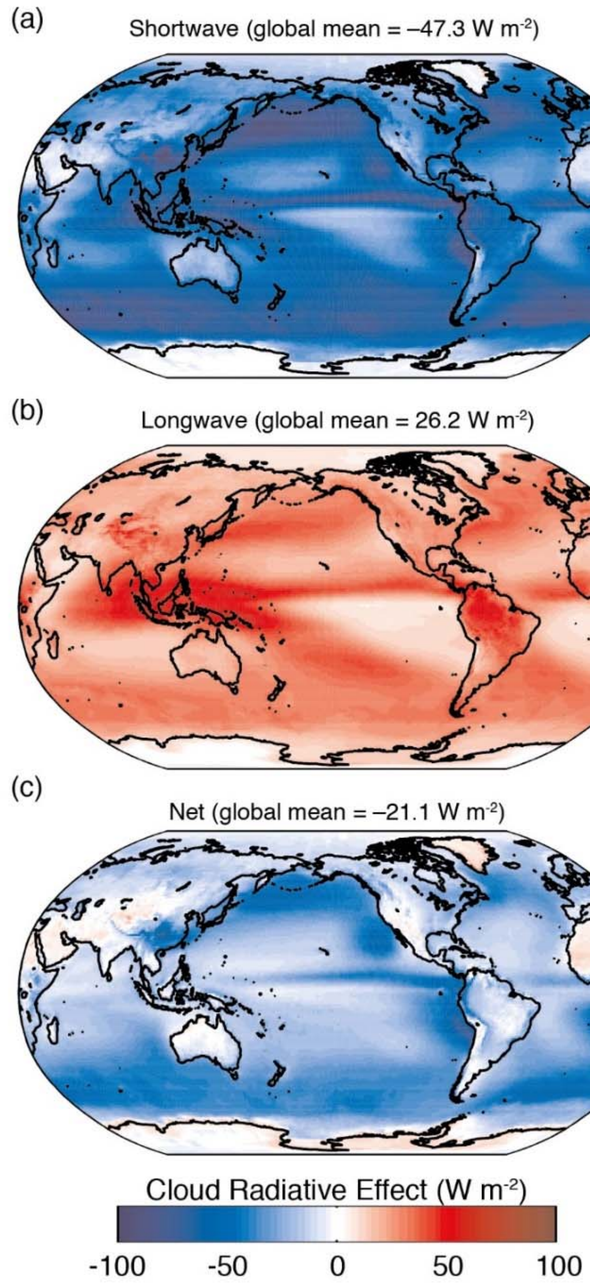
Mass concentrations

Over the oceans: ~10 µg/m^3

Urban environment: 10 – 1000 µg/m^3

Clouds

- Radiative impact on climate
  - shortwave: $-47 Wm^{-2}$ (albedo)
  - longwave: $+26 Wm^{-2}$
  - Total cooling $\sim 21 Wm^{-2}$



IPCC states that:

The RF of the total aerosol effect in the atmosphere, which includes cloud adjustments due to aerosols, is –0.9 [–1.9 to −0.1] W m−2 (medium confidence), and results from a negative forcing from most aerosols and a positive contribution from black carbon absorption of solar radiation.

There is high confidence that aerosols and their interactions with clouds have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. They continue to contribute the largest uncertainty to the total RF estimate.

Aerosol particles and clouds impact climate

…understanding of microphysics is needed to estimate climate impact

Aerosol – Water Interaction

Water in the atmosphere

- Global average relative humidity (RH): 80%
- Global average cloud cover: 50%

Aerosol-water interaction

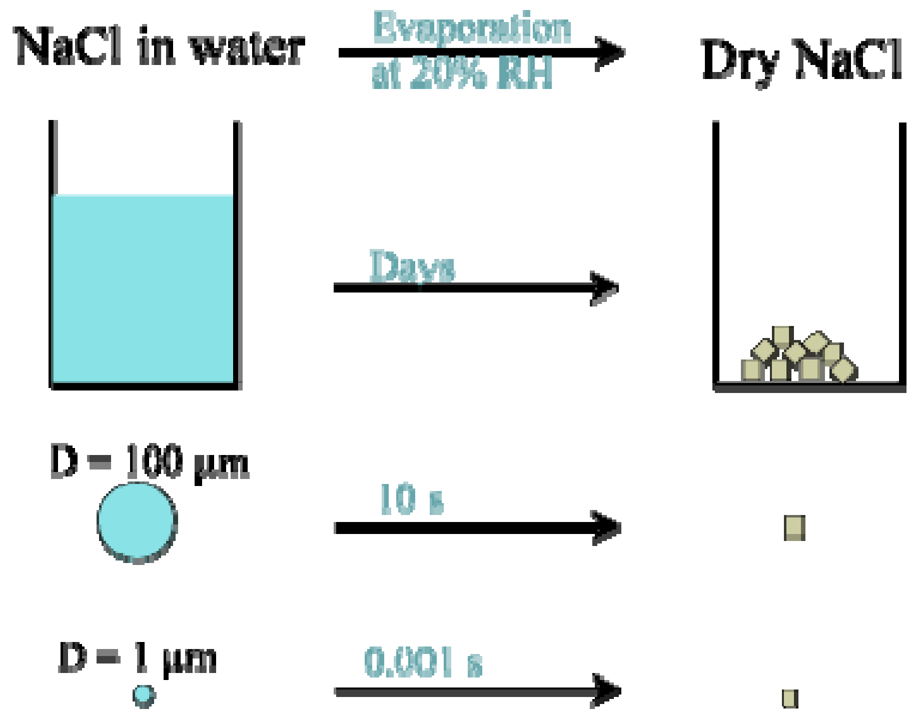
- Relative humidity increase ⇒ Most aerosol particles grow
- Cloud droplets form on pre-existing aerosol particles

  http://www.youtube.com/watch?v=EneDwu0HrVg

Typical concentrations

- Aerosol mass ~ $\mu g/m^3$
- 10° C and 80% RH ⇒ 7 g H_20/m^3

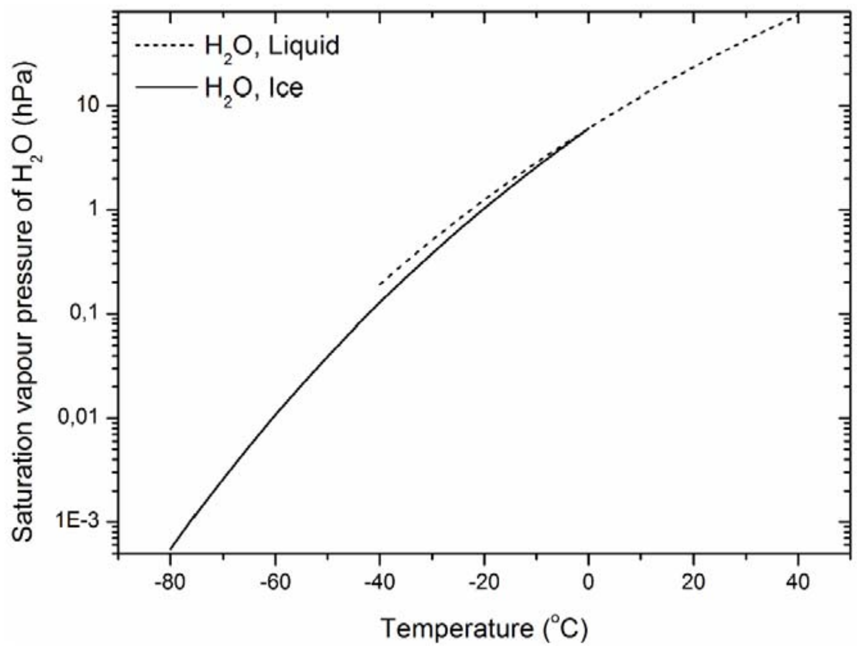
Aerosol – Water Interaction



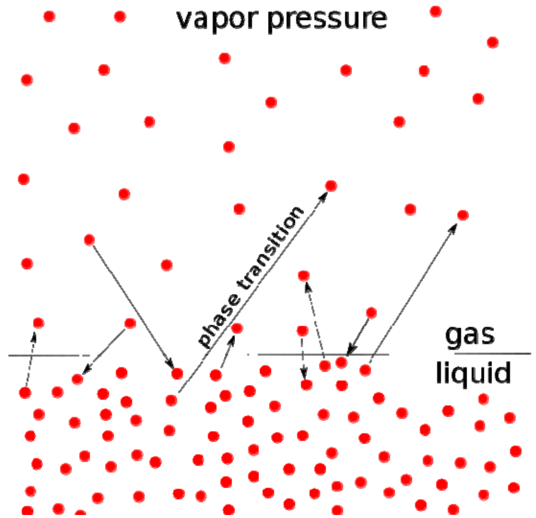
Condensation/evaporation fast in small systems

Vapor pressure

- Vapor pressure
  - the partial pressure of water vapor in the air
- Saturation vapor pressure
  - the equilibrium vapor pressure of water over a flat surface



- Condensation on aerosol particles depends on
  1. Particle size
  2. Particle composition



The impact of particle size

RH and vapour pressure:

- p_0 = Saturation vapour pressure (strongly dependent on the temperature)
- p = partial pressure
- Saturation ratio: p/p_0;   RH = $100 \cdot p/p_0$

Plane (macroscopic) surface:

- RH > 100%: condensation
- RH < 100%: evaporation
- RH = 100%: limit, vapour flows to and from the surface with equal probabilities

Small drops:

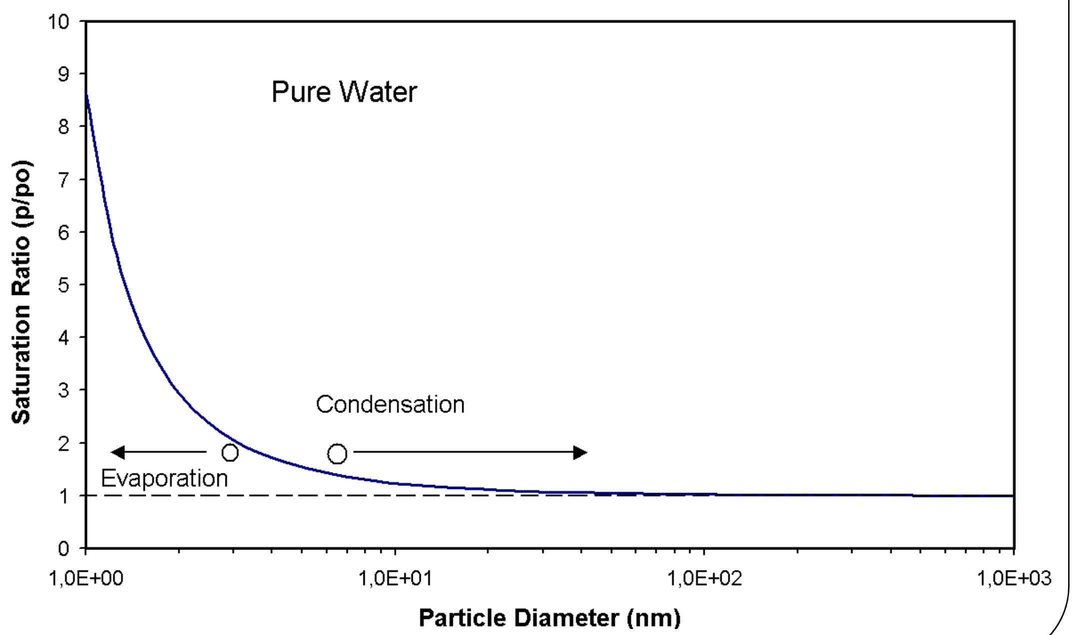
- Have significant curvature of their surface ⇒
- ⇒ Modification of the attractive forces between surface molecules ⇒
- ⇒ Increase in the vapour pressure over the droplet (**The Kelvin Effect**)

The Kelvin Effect:

$$\frac{p^*}{p_0} = e^{4\sigma M/\rho RTD}$$

$p > p^*$: Condensation
$p < p^*$: Evaporation
$p = p^*$: Limit

σ = surface tension (H_2O)
D = droplet diameter
T = temperature
ρ = density (H_2O)
M = molar mass (H_2O)
R = gas constant



Exercise 8:2a

The Kelvin equation: $$\frac{p^*}{p_0} = e^{4\sigma M/\rho RTD}$$

A pure water droplet of diameter D = 0.01 µm is situated in air with relative humidity of 103% (RH = 100 p/p_0). The temperature is 20ºC.

We know all parameters:
(σ, M_{H2O}= 18 kg/kmole, ρ = 1000 kg/m^3, R, T, D)

Calculate: $$100\frac{p^*}{p_0} = 124\% > 103\%$$

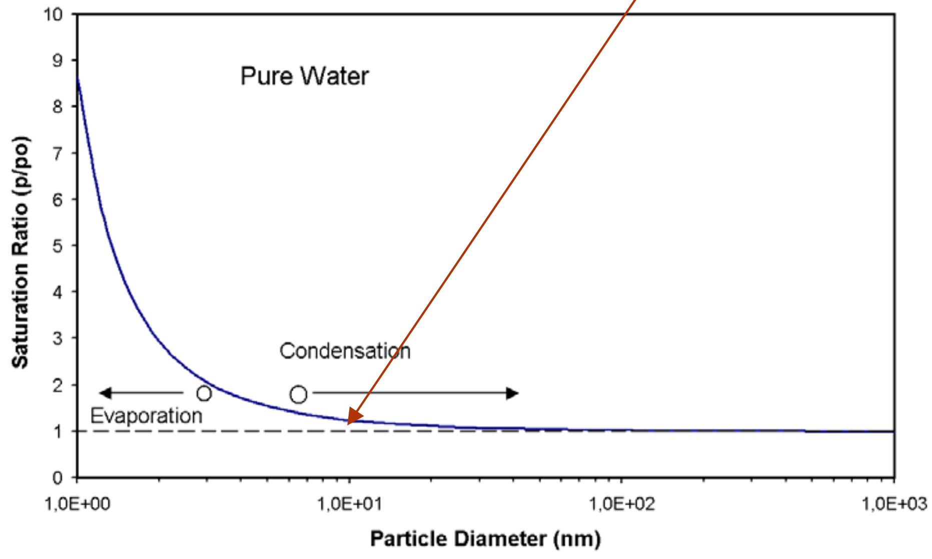
Will the droplet:

a. grow

b. remain unchanged

c. evaporate

Vapor pressure over particle surface too large
$\Rightarrow$ Droplet evaporates



Hint: The fate of pure droplets is determined by the Kelvin effect.

(The surface tension (σ) of water is 0.073 N/m)

Now we know the impact of particle size.

But…cloud drops form on pre-existing particles

How does aerosol composition (dissolved material) impact the vapor pressure…? (of the droplet)

Salt causes vapour pressure depression

Salt droplet at RH < 100%:

- The lowering of the vapour pressure increases with salt concentration
- The droplet will assume the size that gives the same vapour pressure at the droplet surface as the surrounding air:
- Cloud drop formation at low RH requires low vapour pressure at droplet surface
  - $\Rightarrow$ Large vapour pressure lowering
  - $\Rightarrow$ High ion concentration
  - $\Rightarrow$ Smaller amount of water in the droplet (for the given amount of salt)
  - $\Rightarrow$ Gives small droplets
- Similarly: High RH
  - $\Rightarrow$ Low ion concentration
  - $\Rightarrow$ Large droplet

Lowering of vapour pressure for diluted (ideal) solutions (**Raoult's law**)

$$\frac{p}{p_0} = \frac{n_w}{n_w + n_s}$$

n_s = moles ions
n_w = moles water

The vapour pressure is lowered in proportion to the number of ions substituting water molecules

Raoult's law with more common parameters:

$$\frac{p}{p_0} = \left[1 + \frac{6imM_w}{M_s \rho_w \pi D^3}\right]^{-1}$$

M_w = molar mass water
M_s = molar mass salt
m = salt mass;
ρ_w = density water
i = ions per salt molecule;
D = droplet diameter

Raoult's law valid for RH close to 100%.

More concentrated solutions are described based on empirical data.

Now we know about the effects of both

size and compostion

Droplet Size Dependence on RH

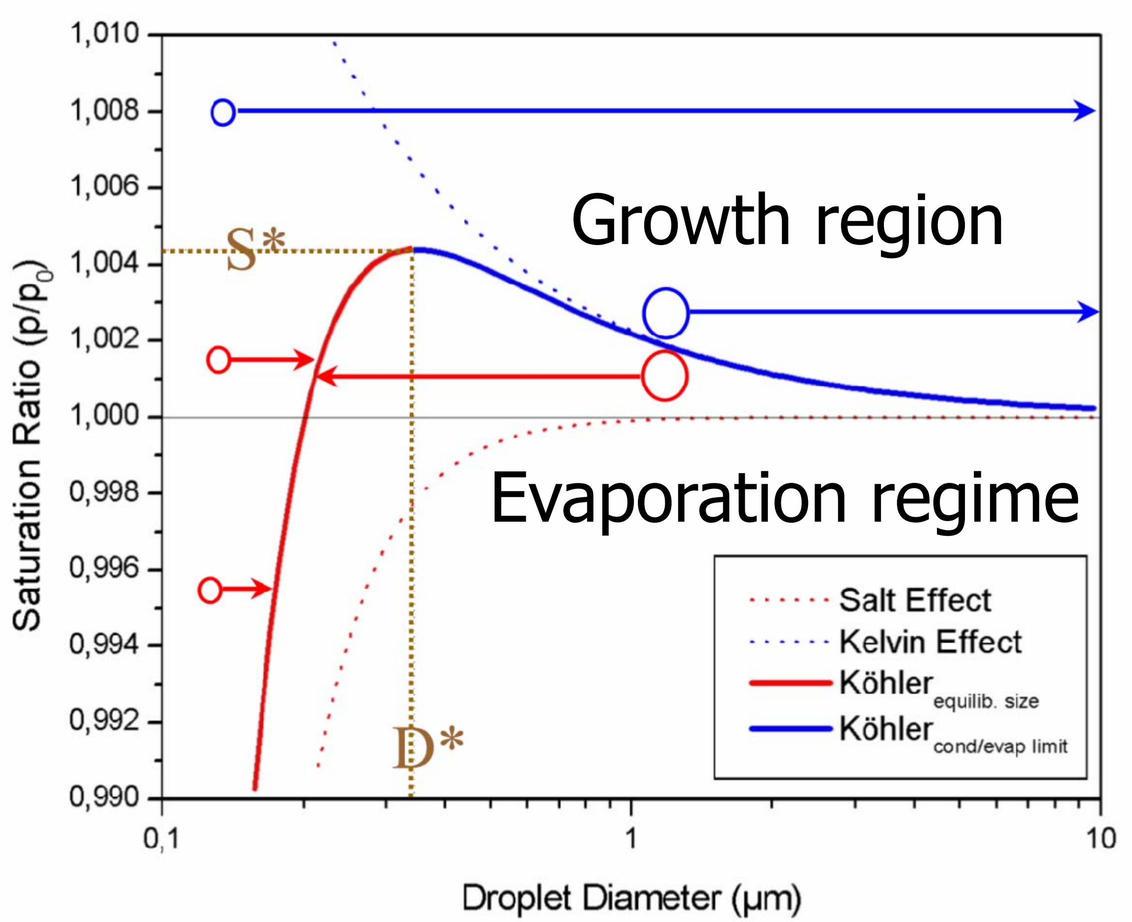
The droplet size as a function of RH depends on:

- The Kelvin effect
- Vapour pressure lowering

These effects combine to the Köhler equation:

- p/p_0 = "salt effect" × Kelvin effect

$$\frac{p}{p_0} = \left[1 + \frac{6imM_w}{M_s \rho_w \pi D^3}\right]^{-1} \times e^{4\sigma M/\rho RTD}$$



D* = critical diameter of activation
S* = critical saturation ratio of activation

Exercise 8:2b

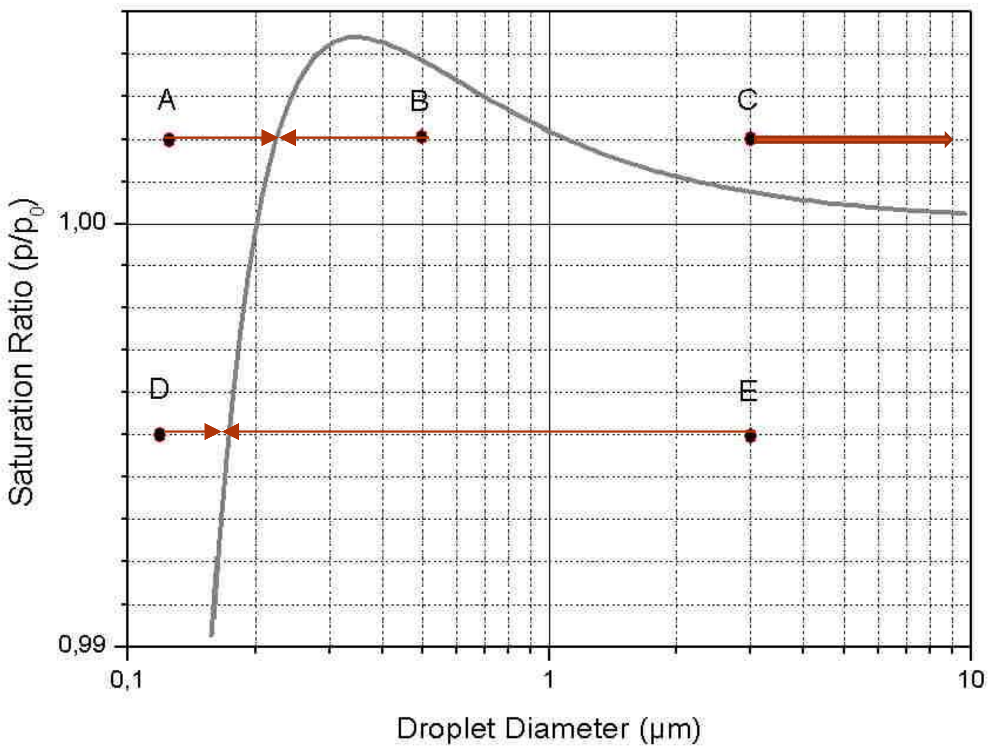
Water uptake by aerosol particles

The figure shows the saturation ration as a function of droplet diameter for droplets that have formed on a particle of given size and chemical composition.

The Figure includes five points (A, B, C, D, E) indicating droplets formed on the same kind of particle.

Assume that the saturation ratio remains constant for a long time.

How large are droplets A, B, C, D and E after this time has passed?



A: 0.23 µm
B: 0.23 µm
C: free growth (activated)
D: 0.18 µm
E: 0.18 µm

Droplet Size Dependence on RH (at high RH)

Critical saturation ratio:

- Strongly dependent on the amount of salt available
  - Small particle
    - ⇒ small amount of salt available
    - ⇒ small droplet
    - ⇒ strong Kelvin effect
    - ⇒ high critical saturation ratio
  - Cloud droplets form more easily on large particles

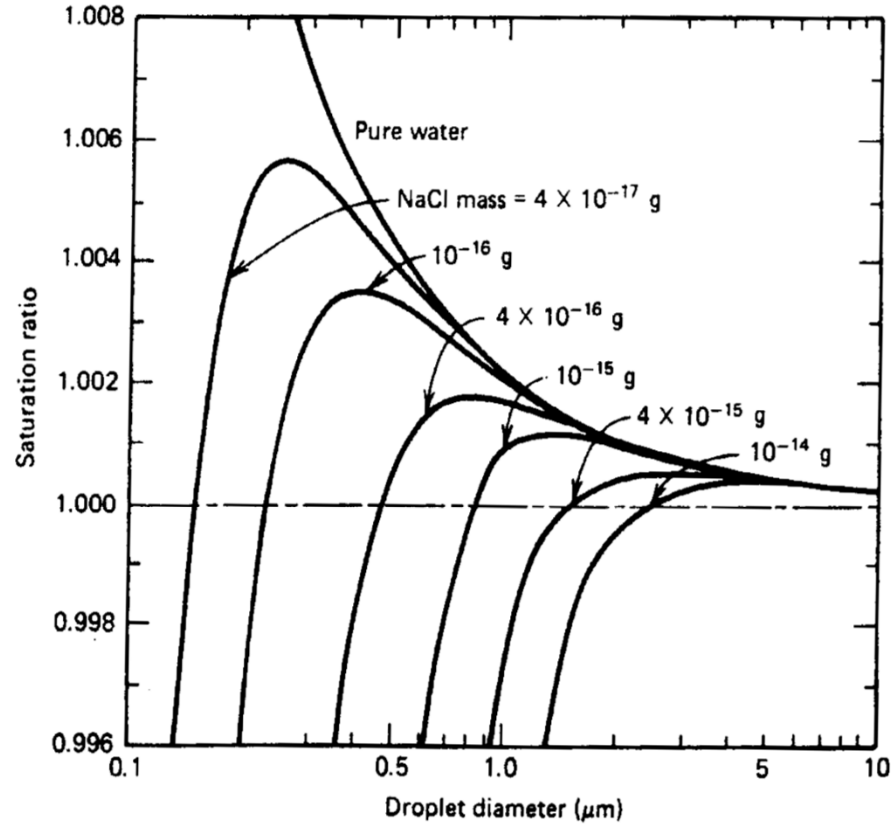
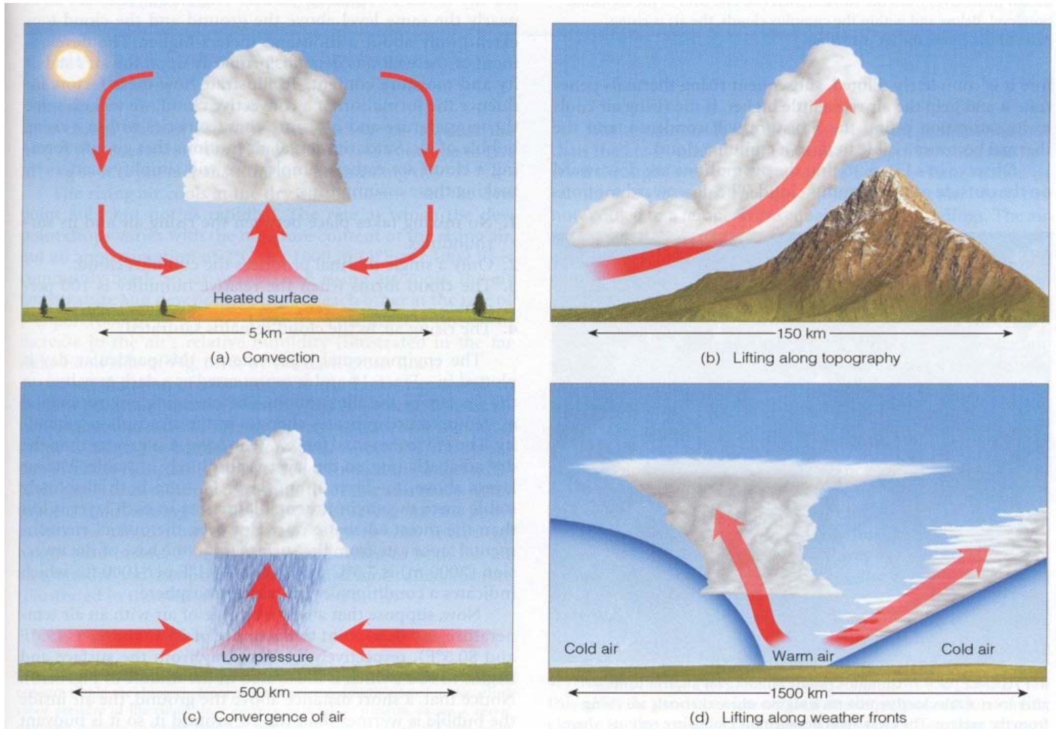
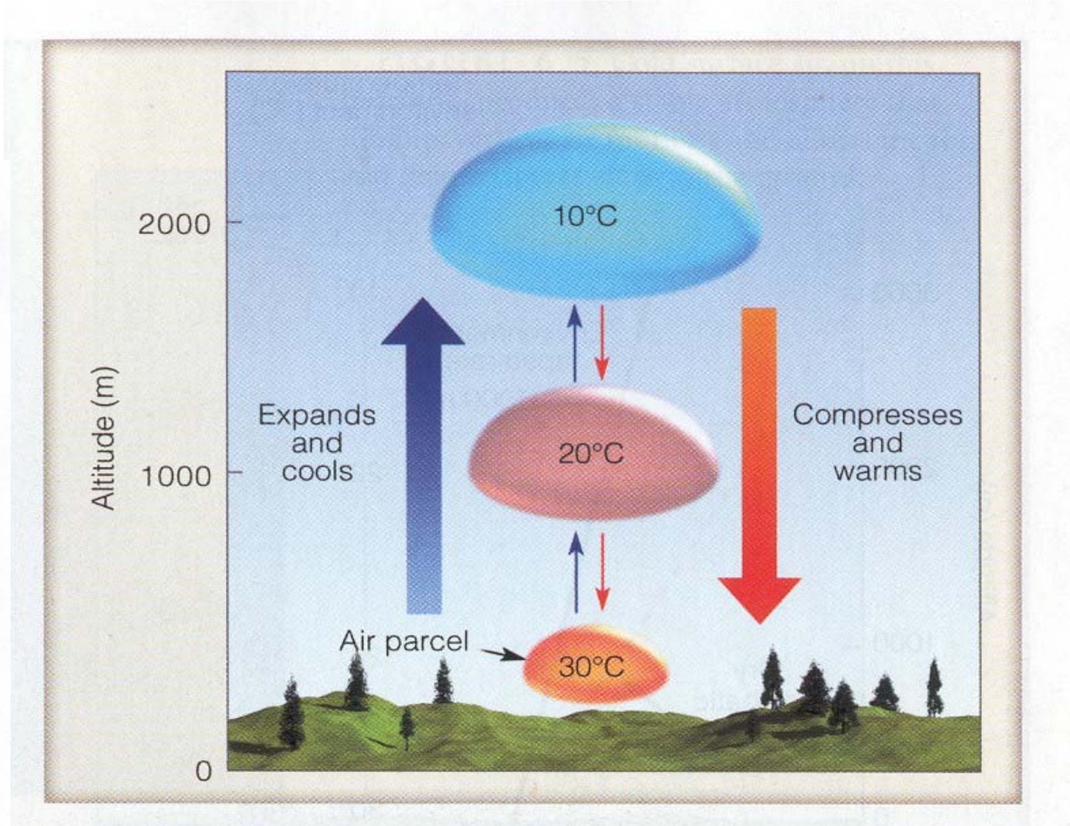


FIGURE 13.4 Saturation ratio versus droplet size for pure water and droplets containing the indicated mass of sodium chloride at 293 K [20°C]. The region above each curve is a growth region and that below, an evaporation region.

Cloud formation





Clouds form in H_2O supersaturation:

- Usually by upward air motion due to
  - Ground absorbs solar radiation ⇒ decreases air density
  - Convergence of air
  - Topography and fronts

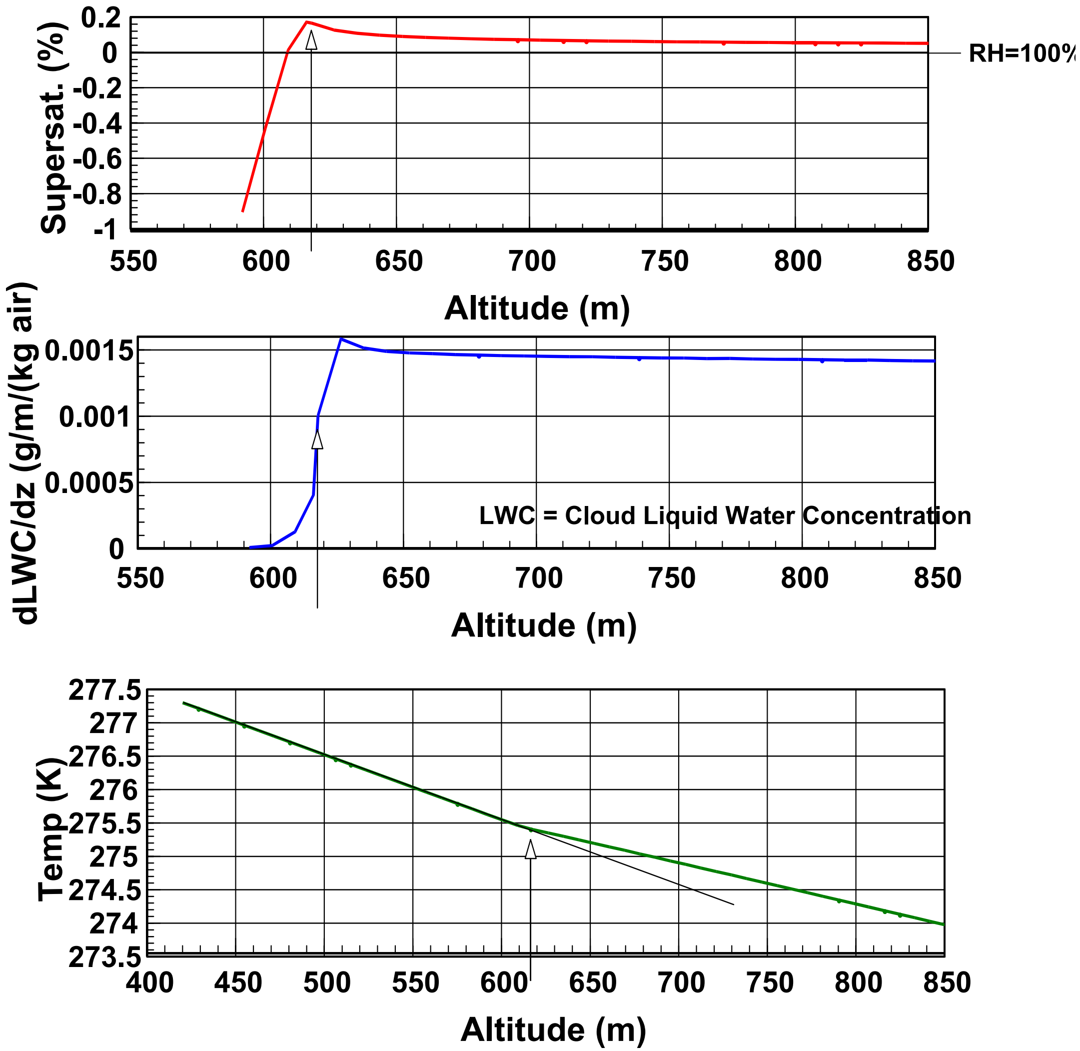
H_2O in vertical air motion:

- Upward motion causes expansion and therefore cooling
- Cooling reduces the saturation vapour pressure faster than expansion ⇒ RH increases
- Particle growth
- Eventually supersaturation – Droplet activation – Cloud formation

Cloud Formation – example from a cloud model

Water – mass balance:

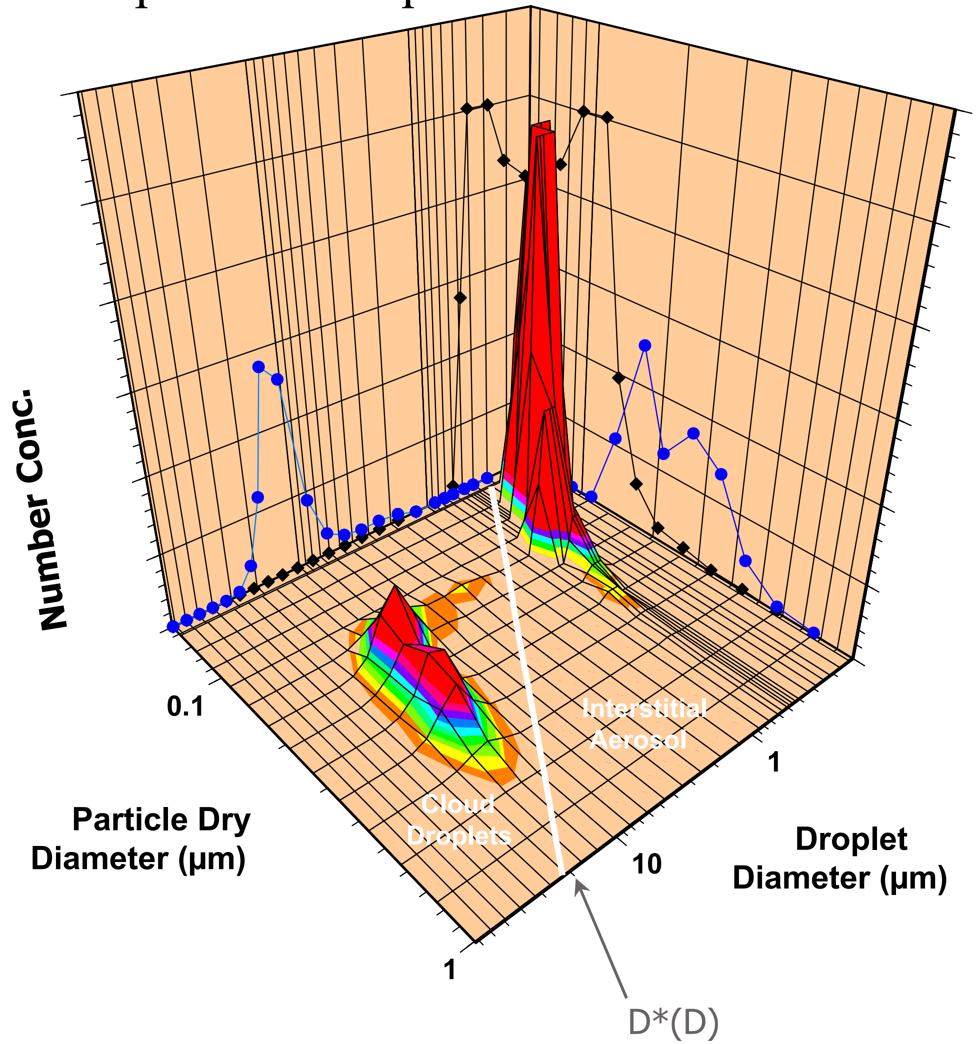
- Water mass conserved in the rising air
- At supersaturation:
  - Formation of condensable water at a given rate
  - Droplet growth is a growing sink of vapour
  - Causes a maximum supersaturation in the cloud
  - Higher up – Decreasing RH due to growing sink



Cloud Microstructure

- Large particles
  - act as CCN (Cloud Condensation Nuclei)
  - grow by condensation to about 30 µm diameter
- Small particles
  - are found as small interstitial droplets within the cloud

Example from experiment:



Precipitation

- Cloud droplets up to approx. 30 µm
- Rain drops ~ 1 mm
- How to form such large drops? (Diffusional growth would require days!)

Cold clouds (Below zero degr.):

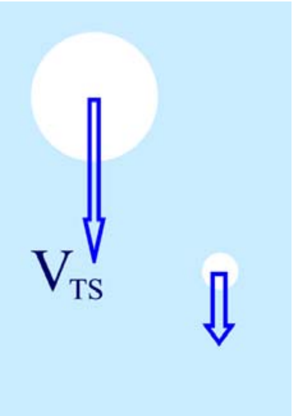
- Most particles form super-cooled droplets
- A small fraction form ice particles – Dependent on particle composition
  - The fraction of ice particles increases at lower temperature
  - Below -40°C liquid droplets are not formed
- The saturation vapour pressure over ice is lower than over water for a given temperature
  - The ice particles grow at the expense of the super-cooled droplets

Warm clouds

- Clouds without ice particles
- Form precipitation if drop size distribution broad

Precipitation forming:

- Colliding droplets/ice particles may merge to form a lager drop - Coalescence
- Cloud droplets have fairly high sedimentation velocity
- Large droplet – High sedimentation velocity ⇒
- Threshold effect
  - Once started, the coalescences accelerates due to the presence of large droplets



Precipitation only from 1 of 10 clouds

The other clouds dissipates by evaporation of the droplets

Light Scattering of Aerosols

- Atmospheric light scattering
  - Reduced visibility – difficult to see distant objects
- Gas molecules scatter light inefficiently
- Aerosol particles scatter light efficiently
  - Efficiency dependent on particle size
  - Strongest scattering when particle diameter ≥ wavelength
    - Anthropogenic particles mainly affects solar radiation
    - Small effect on terrestrial radiation (long wave)
- Influence from relative humidity:
  - Water vapour scatters light inefficiently
  - Water uptake by aerosol particles increases scattering at high humidity
  - Fog: Extremely strong light scattering

Questions

1. Does the efficient light scattering by particles affect the climate?

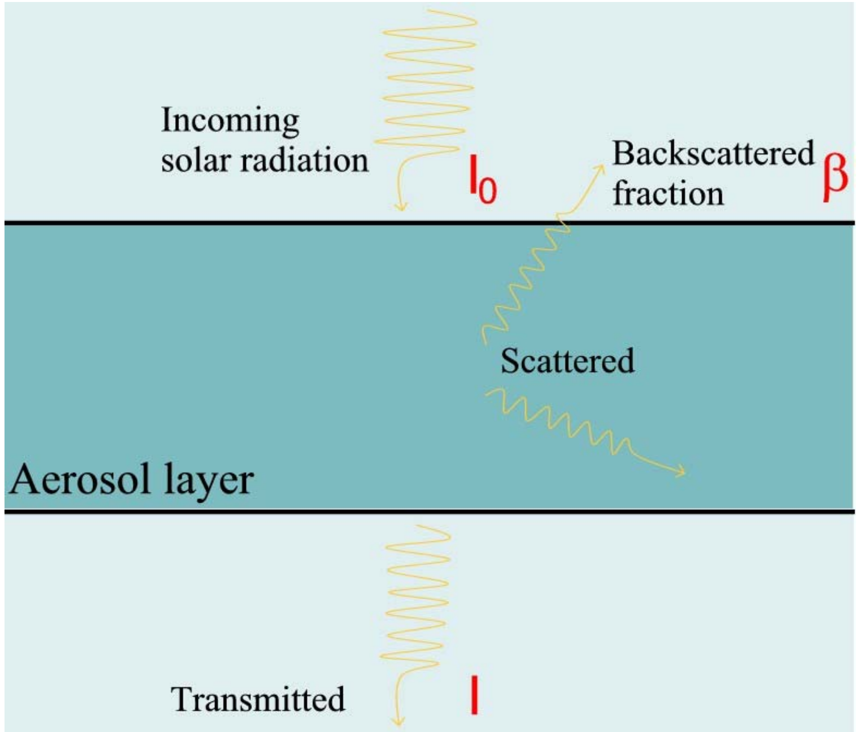
2. How large is the climate effect from particles compared to that of GHGs?

Climate Effects

- **Greenhouse gases**
  - Increase atmospheric absorption of terrestrial radiation
  - Cause increased long wave radiation from the atmosphere to the Earth's surface
- **Aerosols**
  - Affects the Earth's albedo, i.e. direct reflection of solar radiation to space
  - Two aerosol effects
    - **Direct** – radiative properties of the aerosol particles
    - **Indirect** – aerosol affects the microstructure of clouds and therefore cloud radiative properties

Light Scattering and Climate

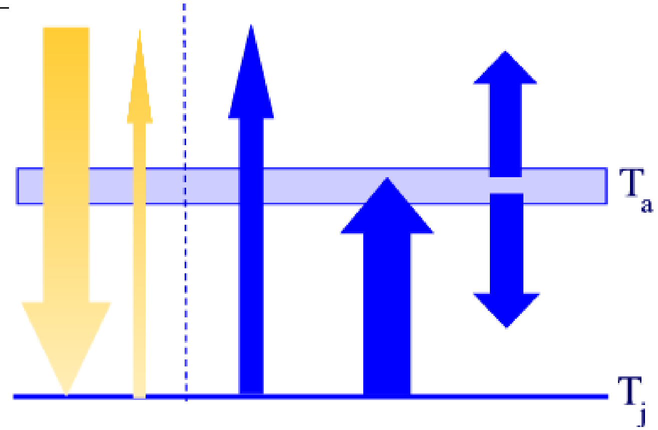
- Attenuation of light by an aerosol layer:



- Optical depth (δ): $I = I_0 e^{-\delta}; \quad \delta = \ln\left(\frac{I_0}{I}\right)$

- Layer albedo: $A_a = \left(1 - \frac{I}{I_0}\right)\beta = \left(1 - e^{-\delta}\right)\beta \approx \left(1 - (1 - \delta)\right)\beta = \delta\beta \quad (\text{small}\ \delta)$

Aerosols – Direct Climate Effect



Influence of aerosol on total albedo:

- Total albedo

  $A_T \approx A_0 + A_a(1\text{-}A_0)^2$

- Change of the earth's albedo (ΔA) due to aerosol layer (albedo A_a):

  $\Delta A \approx A_T - A_0 = A_a(1\text{-}A_0)^2 = \delta\beta(1\text{-}A_0)^2$

- Radiative forcing due to aerosols

  $\Delta F = F_{in} - F_{out}$ (in the changed system)

  $\Delta F = F_S A_0/4 + (1\text{-}f/2)\sigma T_j^4 - F_S A_T/4 -$

  $- (1\text{-}f/2)\sigma T_j^4 = -\Delta A F_S/4$

Typical values: $A_0 = 0.28$, $\beta = 0.2$, $\delta = 0.1$

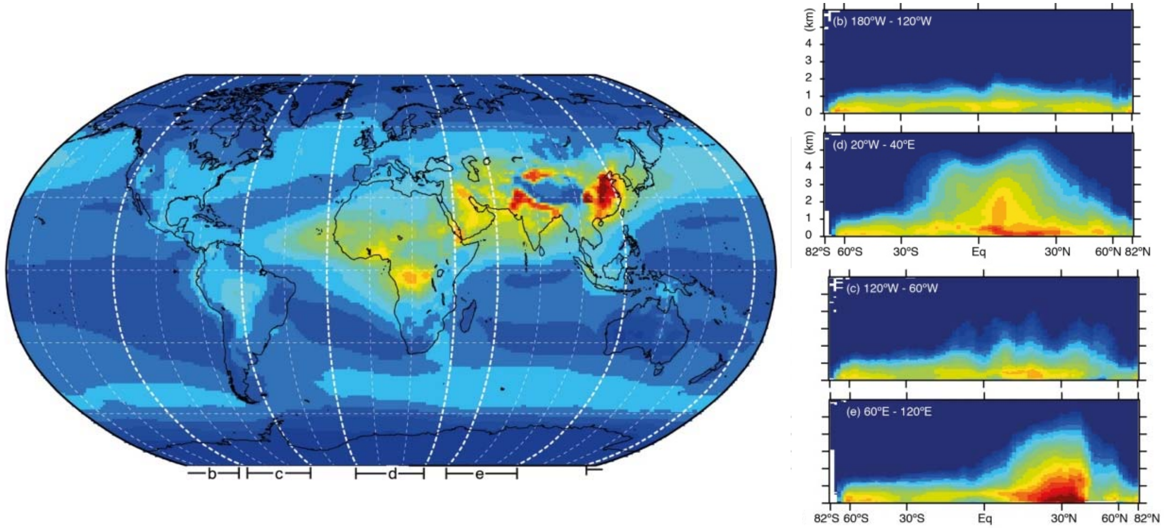
$\Rightarrow \Delta F = -3.6\ W/m^2$ (Total effect, incl both natural and anthropogenic aerosol sources)

Estimated direct effect of aerosols caused by human activities (IPCC 2013):

- Sulphate + Nitrate + Mineral dust — $-0.9\ W/m^2$
- Black carbon — $+0.6\ W/m^2$
- **Net RF** — **$-0.3\ W/m^2$**

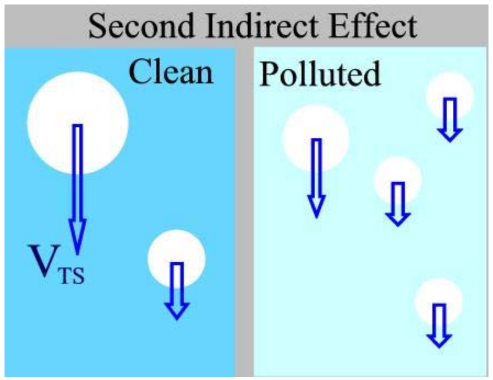
Differences compared with greenhouse gases:

- Short residence time $\Rightarrow$ Large regional variation



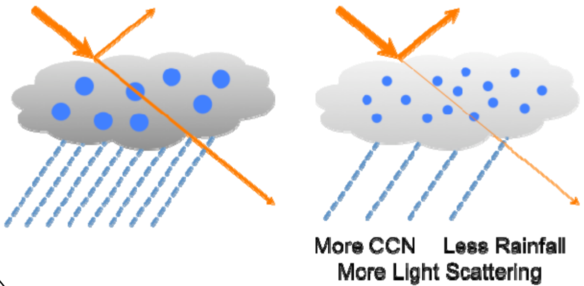
Cloud – Aerosol Interaction

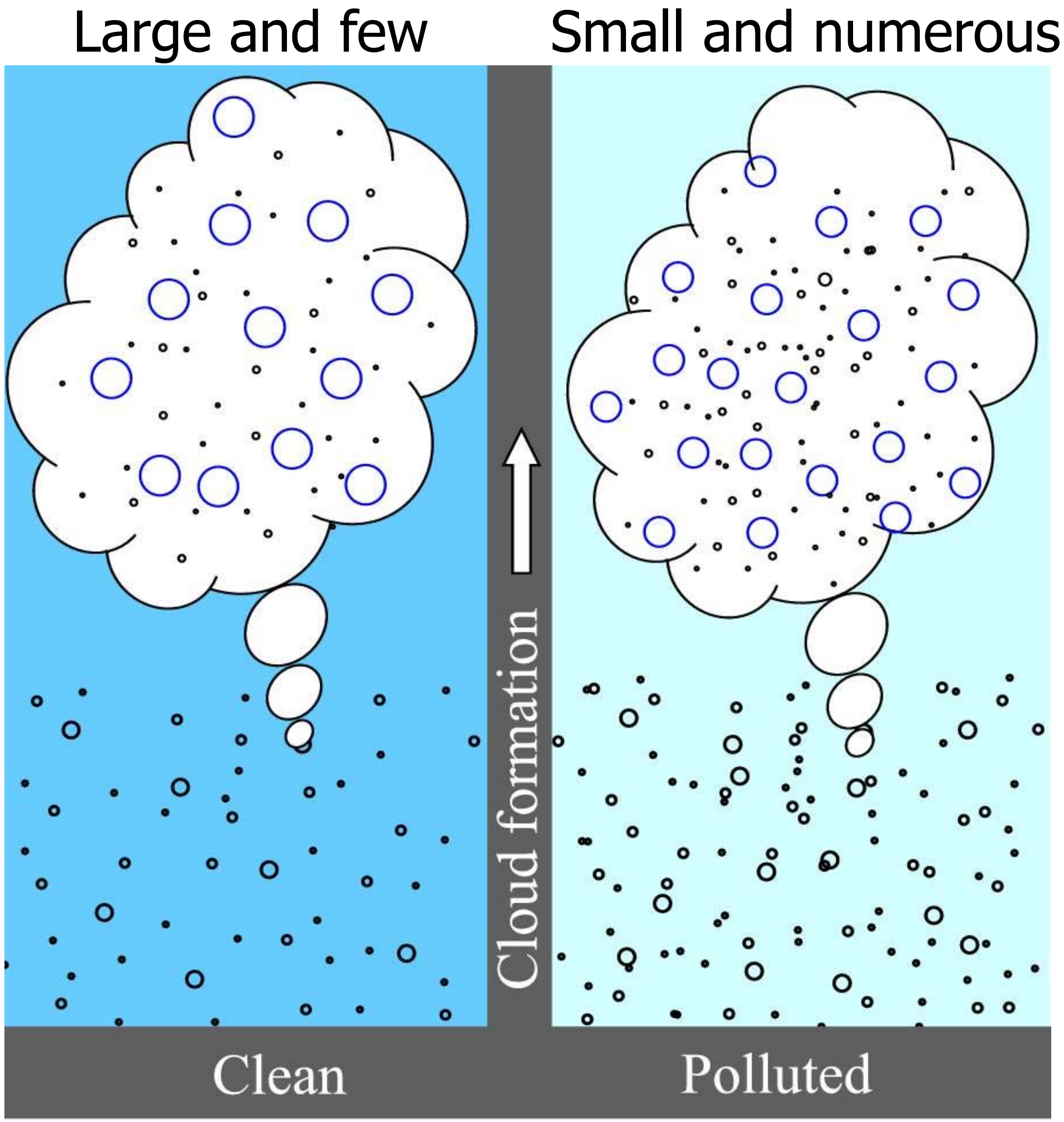
- The Earth's albedo: 28%
  - 19% from clouds
- Pollution ⇒ Increased particle number concentration — Aerosol indirect effects!
  - higher cloud droplet number concentration
    - higher cloud albedo – **1st ind effect**
    - prolonged cloud life-time – **2nd ind effect**



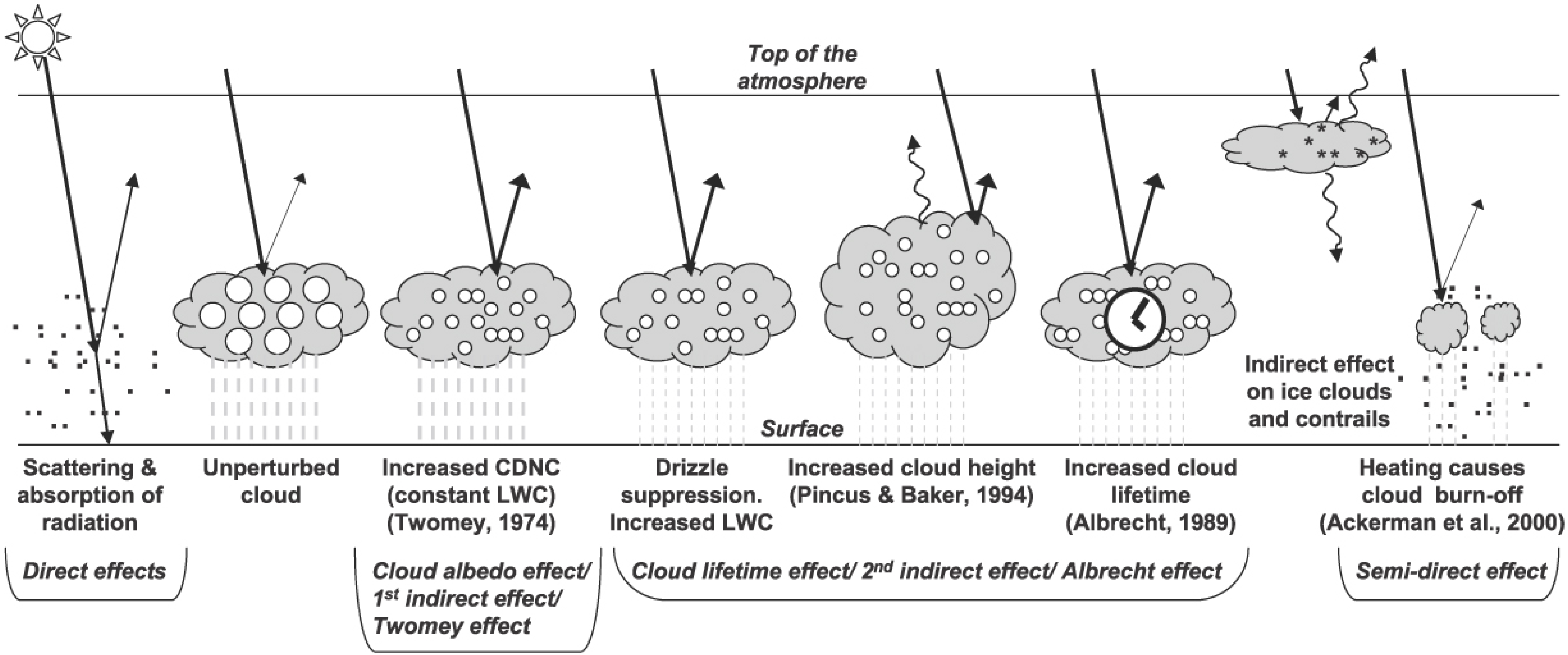
Smaller rel. velocities for coalescence

⇒ Lower probability of precipitation





Aerosol effects on clouds



Cloud Albedo – 1st Indirect Effect

Optical thickness of a cloud (τ):

$$\tau = \int_0^\infty hQ_e 2\pi r n(r) dr \approx 2\pi \bar{r}^2 hN \qquad (1)$$

$Q_e \approx 2$ for cloud droplets; h = geom. thickness
Droplet distribution assumed to be narrow

$$w \approx \frac{4}{3}\pi\rho_L \bar{r}^3 N \quad \text{(water mass / air volume)} \qquad (2)$$

(1) och (2) $\Rightarrow$

$$\tau = 2.4\left(\frac{w}{\rho_L}\right)^{2/3} hN^{1/3}; \quad \Rightarrow \quad \frac{\Delta\tau}{\tau} = \frac{1}{3}\frac{\Delta N}{N}; \text{ (h, w const.)}$$

It can be shown that:

$$A \approx \frac{\tau}{\tau + 6.7} \quad \Rightarrow \quad \frac{\Delta\tau}{\tau} = \frac{\Delta A}{A(1-A)} \Rightarrow$$

$$\boxed{\Delta A = \frac{A(1-A)}{3}\frac{\Delta N}{N}}$$

- The cloud albedo most sensitive around 0.3 – 0.7
- Assume an average cloud: coverage 30% and albedo 0.6
- An increase by 20% of the cloud droplets:
  - Increase by 1.6 %-units in cloud albedo
  - Increase by 0.4 %-units in planetary albedo
  - Causing a radiative forcing of $-1.4\ W/m^2$ ($\Delta F = -\Delta A F_S/4$)
- Compare with the GHGs: $+3\ W/m^2$
- Anthropogenic sulphur emissions larger than the natural sulphur flux (> 100% increase)
- Aerosols have large potential to disturb the climate by the indirect effect
- More research needed to quantify the indirect effect(s)

Climate effects of Aerosols

UN Climate panel (IPCC)

Direct and **Indirect** effect:

The largest uncertainties in RF

⇒

Large uncertainty in total RF during the industrial era

⇒

Induces uncertainty in the climate sensitivity due to greenhouse gases