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
  $\Rightarrow$ Aerosol Particles are trace constituent

Particle number concentrations

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

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

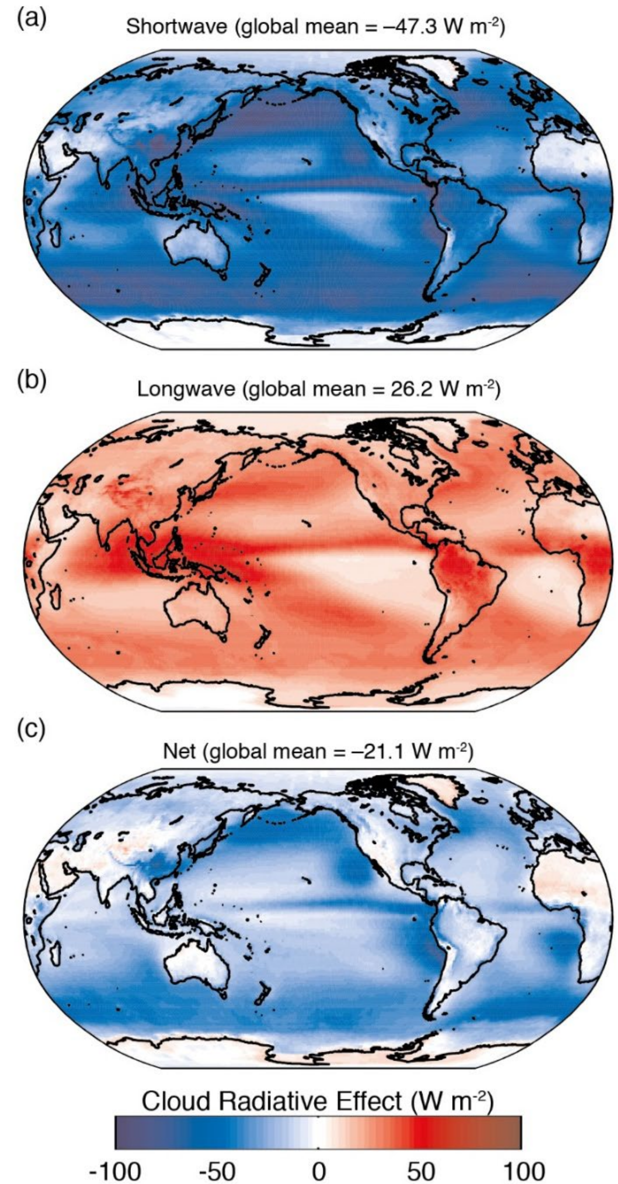
Mass concentrations

Over the oceans: ~10 µg/m^3

Urban environment: 10 – 1000 µg/m^3

Clouds

- Radiative impact on climate
  - shortwave: $-47\,\mathrm{Wm}^{-2}$ (albedo)
  - longwave: $+26\,\mathrm{Wm}^{-2}$
  - Total cooling $\sim 21\,\mathrm{Wm}^{-2}$
  - Total human impact $\sim 2.5\,\mathrm{Wm}^{-2}$



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

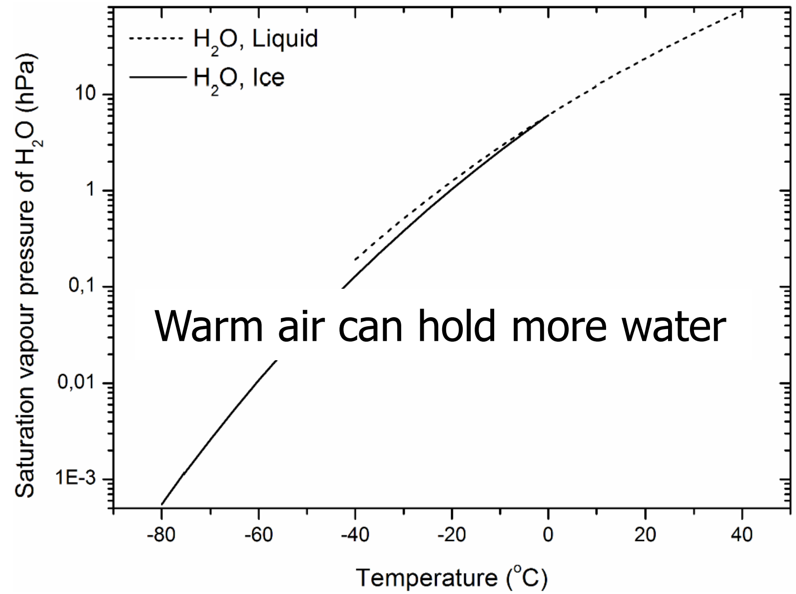
  http://www.youtube.com/watch?v=EneDwu0HrVg

Typical concentrations

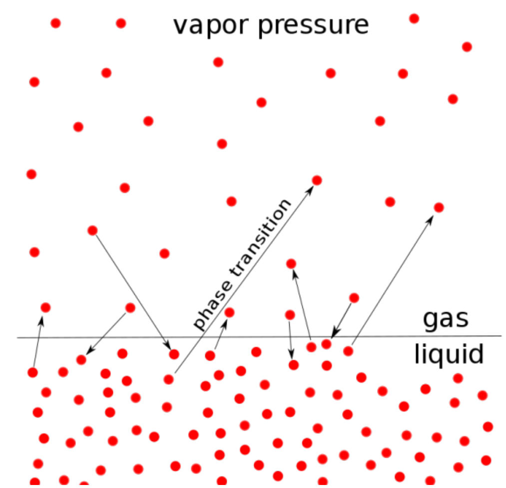
- Aerosol mass ~ $\mu g/m^3$
- 10° C and 80% RH ⇒ 7 g H_2O/m^3
- ⇒ Clouds can have much larger impact than the particles alone

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

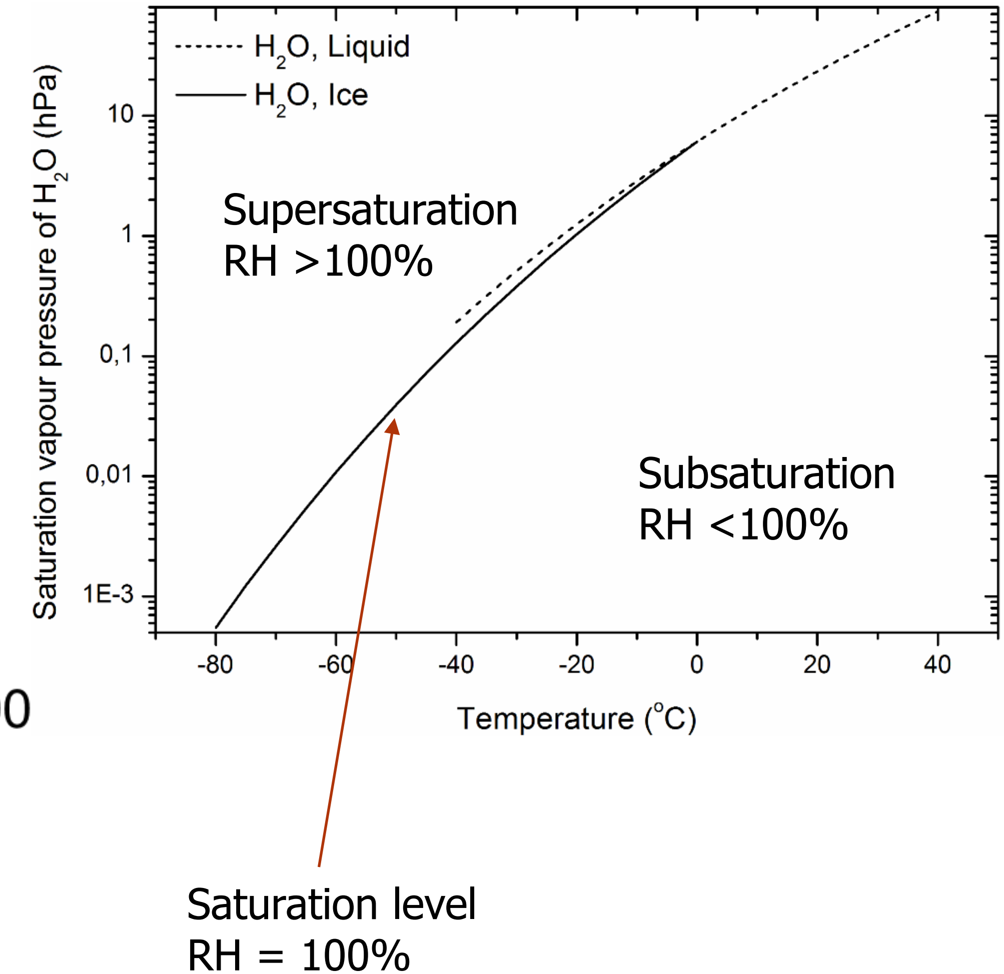


- Condensation on aerosol particles depends on
  1. Particle size
  2. Particle composition



Saturation – for flat surfaces

- Saturation ratio (s) $s = \dfrac{p}{p_0}$
  - p=partial pressure of H_2O
  - p_0=saturation vapour pressure (strongly dependent on temperature)
- Relative humidity (RH)
  - RH = 100 * s (%)
- Supersaturation (S) S = RH-100



Curved surfaces

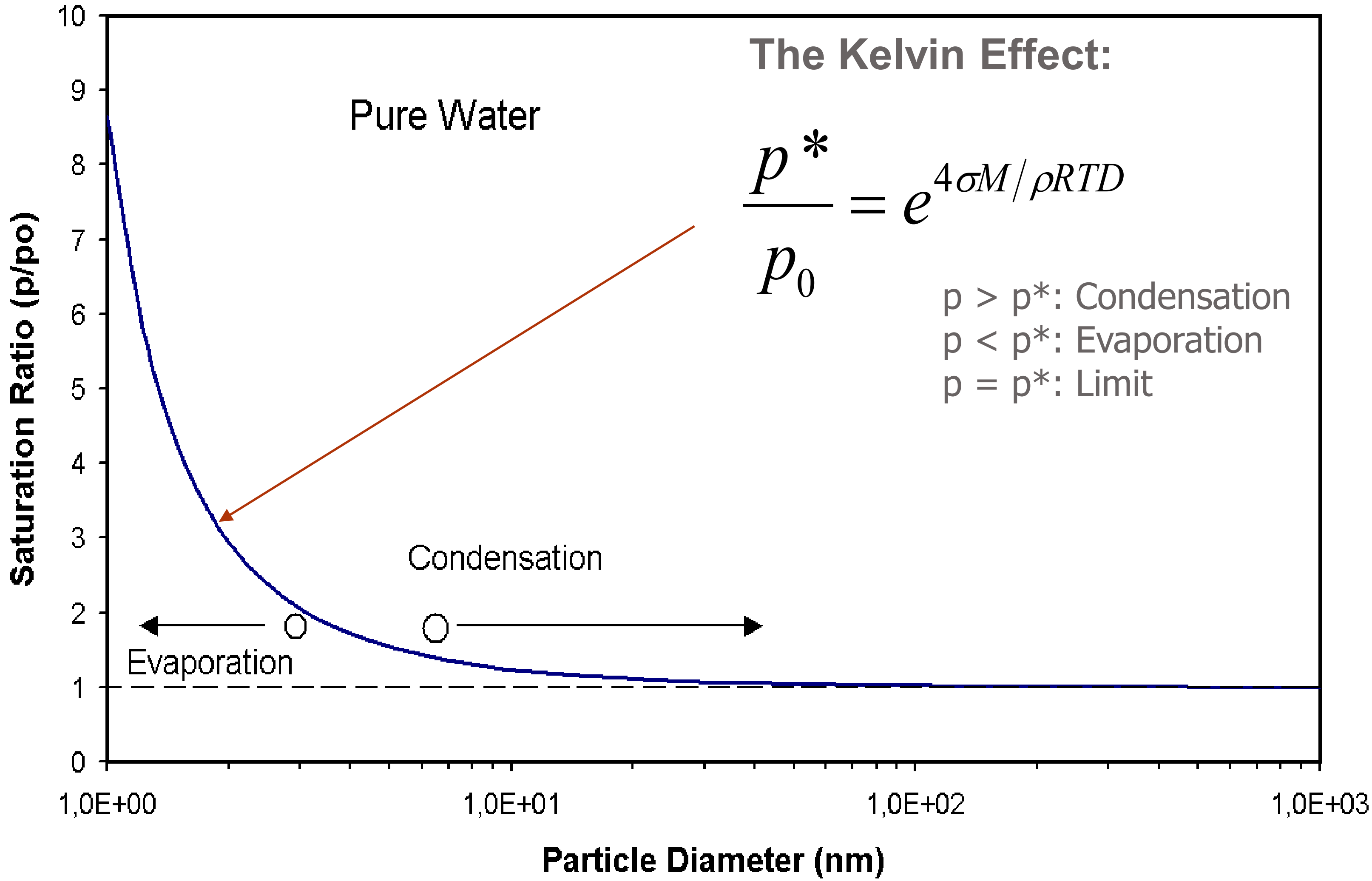
- Aerosol particles
  - no flat surface
  - Not pure water

- Two effects combine to describe water uptake:
  - Kelvin
  - Raoult

Curved surfaces

- No flat surface
  - Kelvin effect
  - Forces between molecules at the surface change with curvature
  - Small droplets – less forces – harder to keep water molecules

Condensation on Particles



The Kelvin Effect:

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

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

p0: saturation vapor pressure over flat surface
p*: saturation vapor pressure over curved surface

σ = surface tension, D = droplet diameter, T = temp.
ρ = density, M = molar weight, R = gas constant

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)

Depression of Vapour Pressure Solute effect / salt effect (Rault effect)

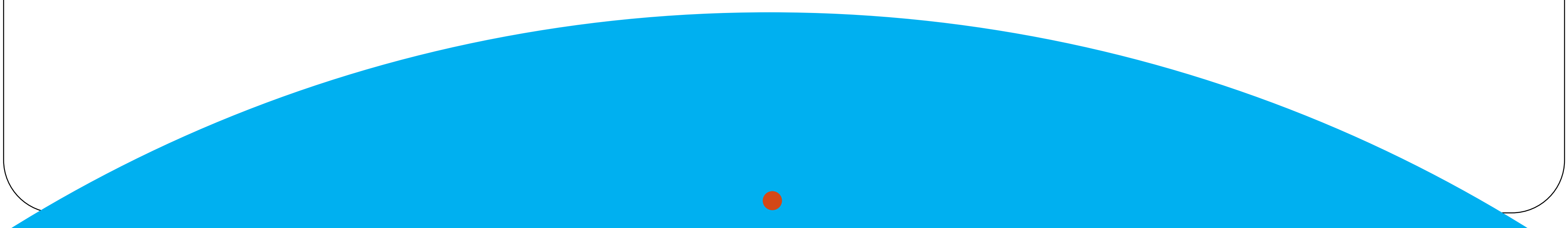
- When a material is dissolved in water, a reduction of the vapour pressure occurs, i.e. the equilibrium is lowered
- The higher the concentration – the higher the vapor pressure is lowered
- $p_i = x_i \, p_{0,I}$

  $x_i = 1$ for water, decreases when other molecules are added

Rault effect

- The Rault effect is bigger for a smaller droplets

…(assuming the same amount of material dissolved in the droplets)



Depression of Vapour Pressure

Depression 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, M_s = molar weight water, 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.

Relation RH - Droplet Size

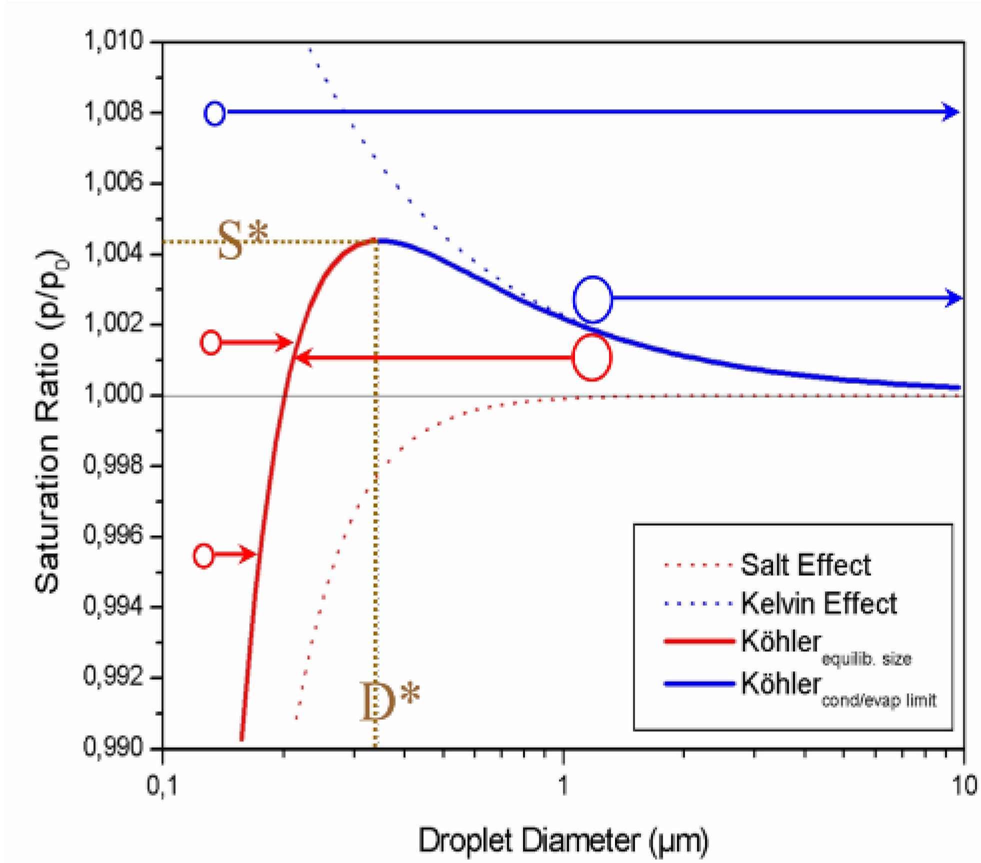
The droplet size as a function of RH depends on:

- The Kelvin effect
- Vapour pressure depression

These effects combine to the Köhler equation:

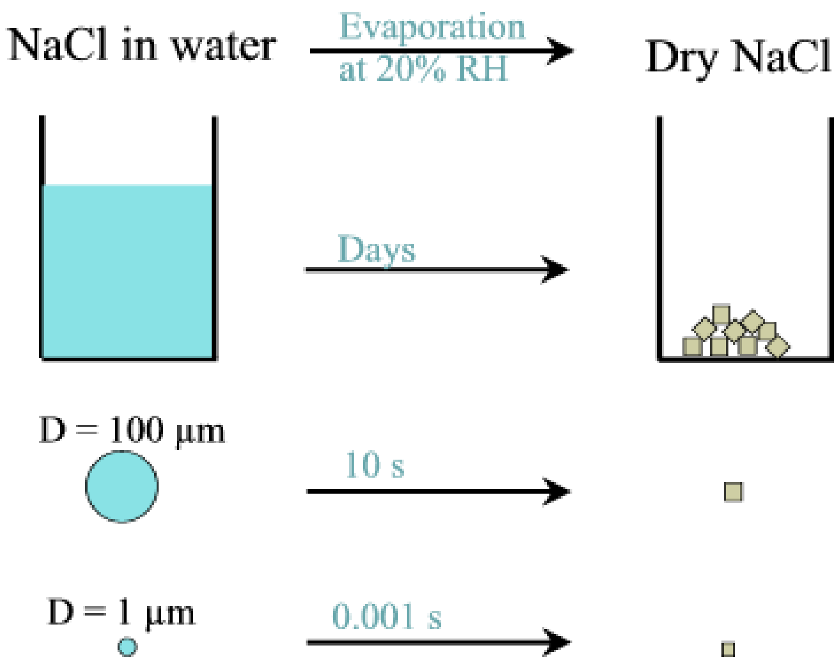
- p/p_0 = ”Salt effect” * Kelvin effect

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



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

Aerosol – Water Interaction



Condensation/evaporation fast in small systems

Now we know about the effects of both

size and composition

…and can combine the two

Exercise 8:2b

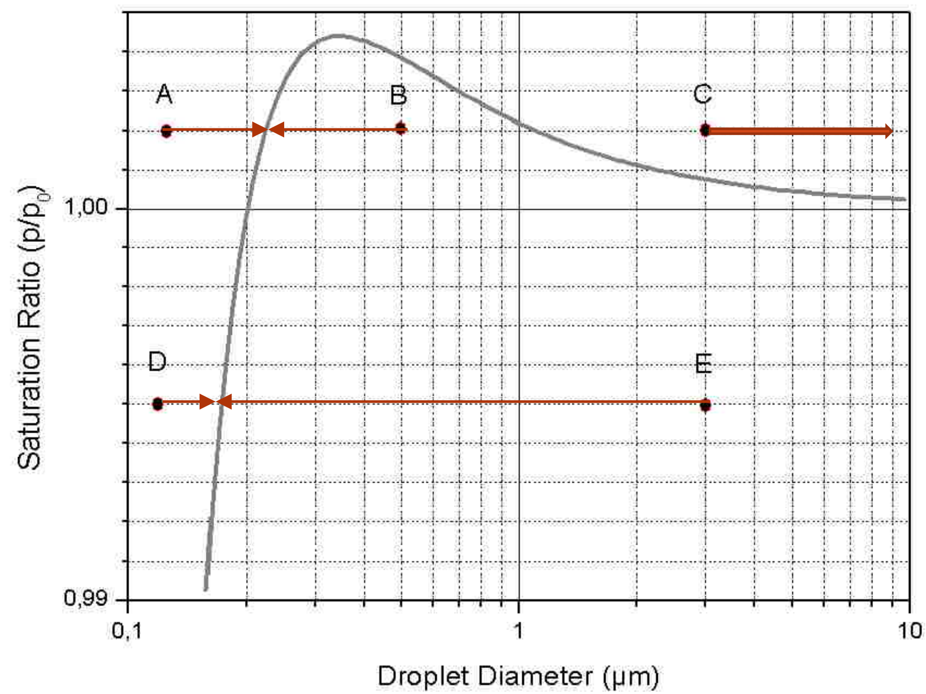
Water uptake by aerosol particles

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.

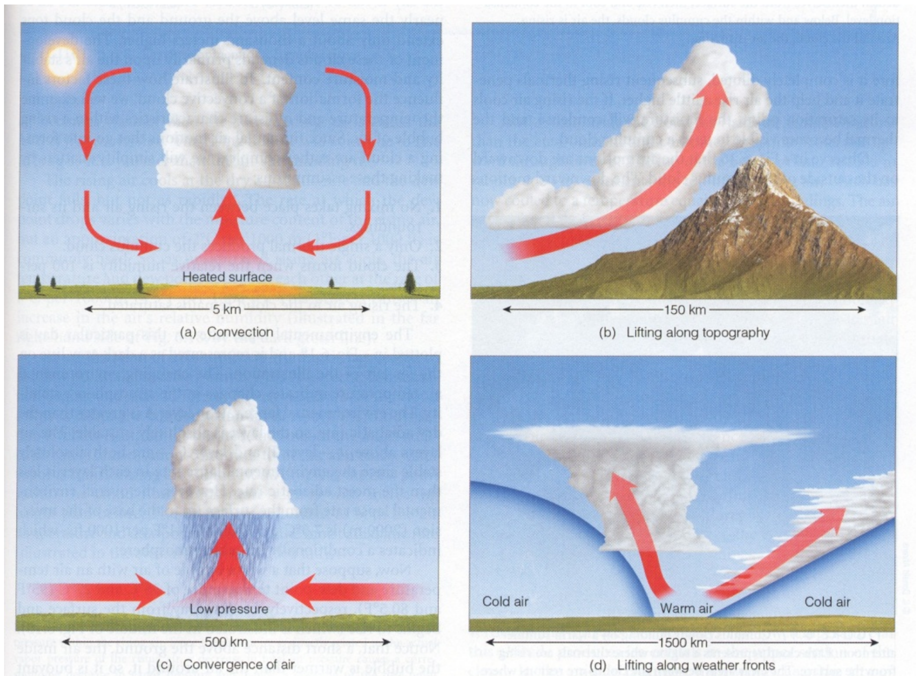
Assume that the saturation ratio remains constant for a long time.

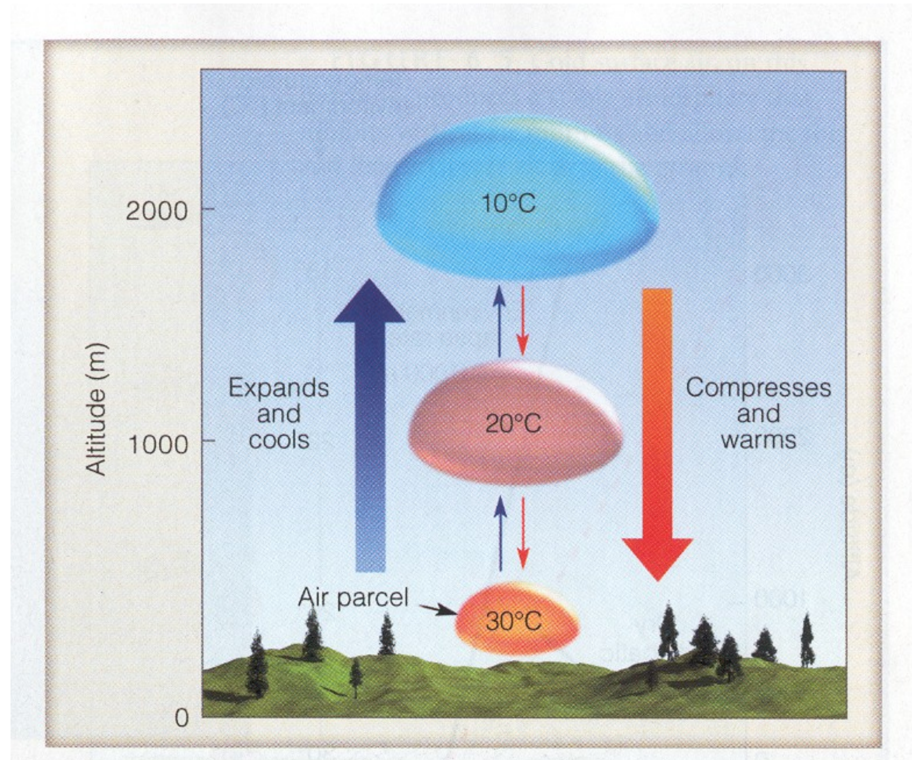
How large are droplets A, B, C, D and E after this time has passed?



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

Cloud Formation





Cloud Formation

Clouds form in H_2O supersaturation:

- Usually by upward air motion due to
  - Topography and fronts
  - Absorption of solar radiation by ground, changing the air density
- Cooling reduces the saturation vapour pressure faster than expansion $\Rightarrow$ RH up
- Particle grows by condensation of H2O
- Eventually supersaturation – Droplet activation – Cloud formation

Water – mass balance:

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

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.):

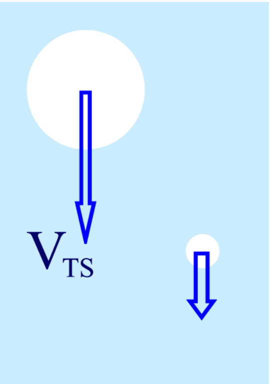
- Most particles form super-cooled droplets
- A small fraction form ice particles – Dependent on particle composition
  - The fraction of ice particles increases at lower temperature
  - Below -40°C liquid droplets are not formed
- The saturation vapour pressure over ice is lower than over water for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

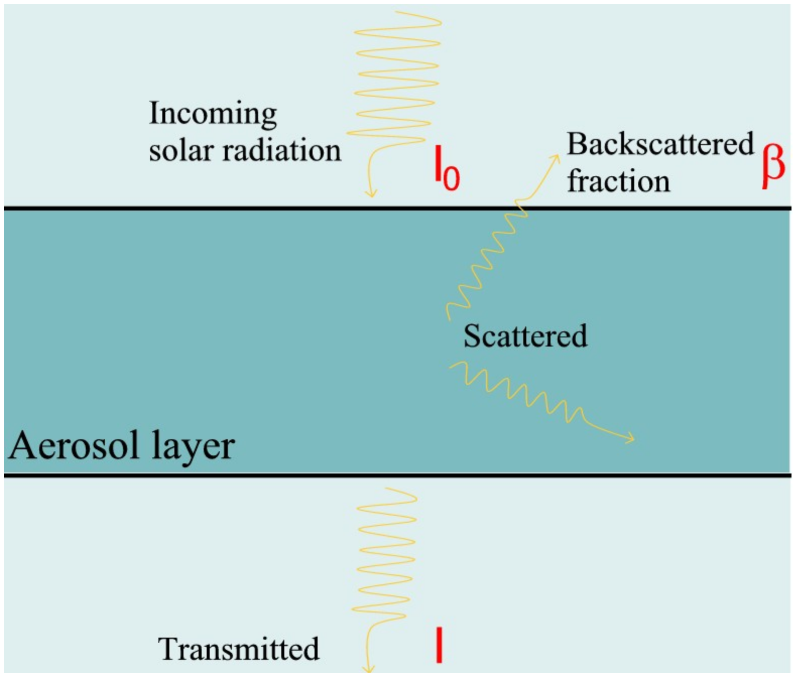
2. How large is the climate effect from particles compared to that of GHGs?

Climate Effects

- **Greenhouse gases**
  - Increase atmospheric absorption of terrestrial radiation
  - Cause increased long wave radiation from the atmosphere to the Earth's surface
- **Aerosols**
  - Affect 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

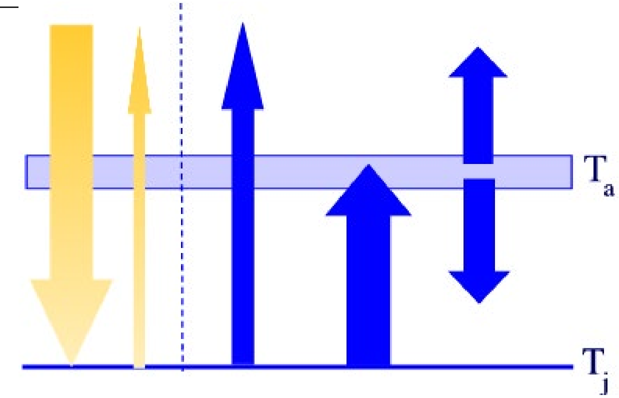
- Attenuation of light by an aerosol layer:



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

- Aerosol 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: $A_0 = 0.28$, $\beta = 0.2$, $\delta = 0.1$

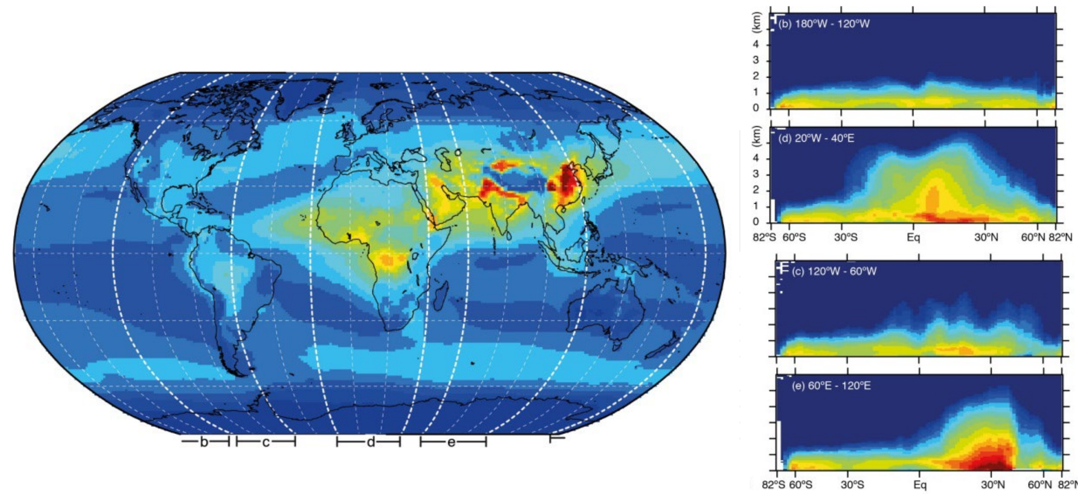
$\Rightarrow \Delta F = -\ 3.6\ W/m^2$ (Total effect, incl both natural and anthropogenic aerosol sources)

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

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

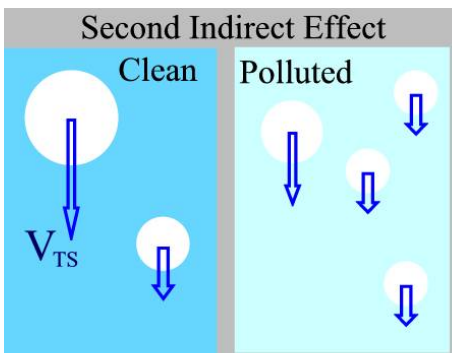
Differences compared with greenhouse gases:

- Short residence time $\Rightarrow$ Large regional variation



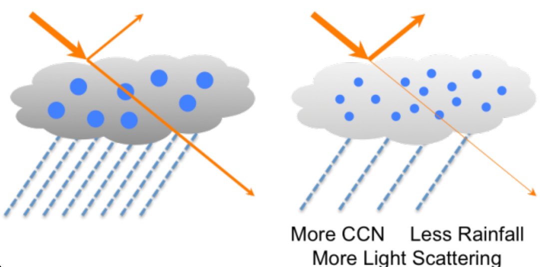
Cloud – Aerosol Interaction

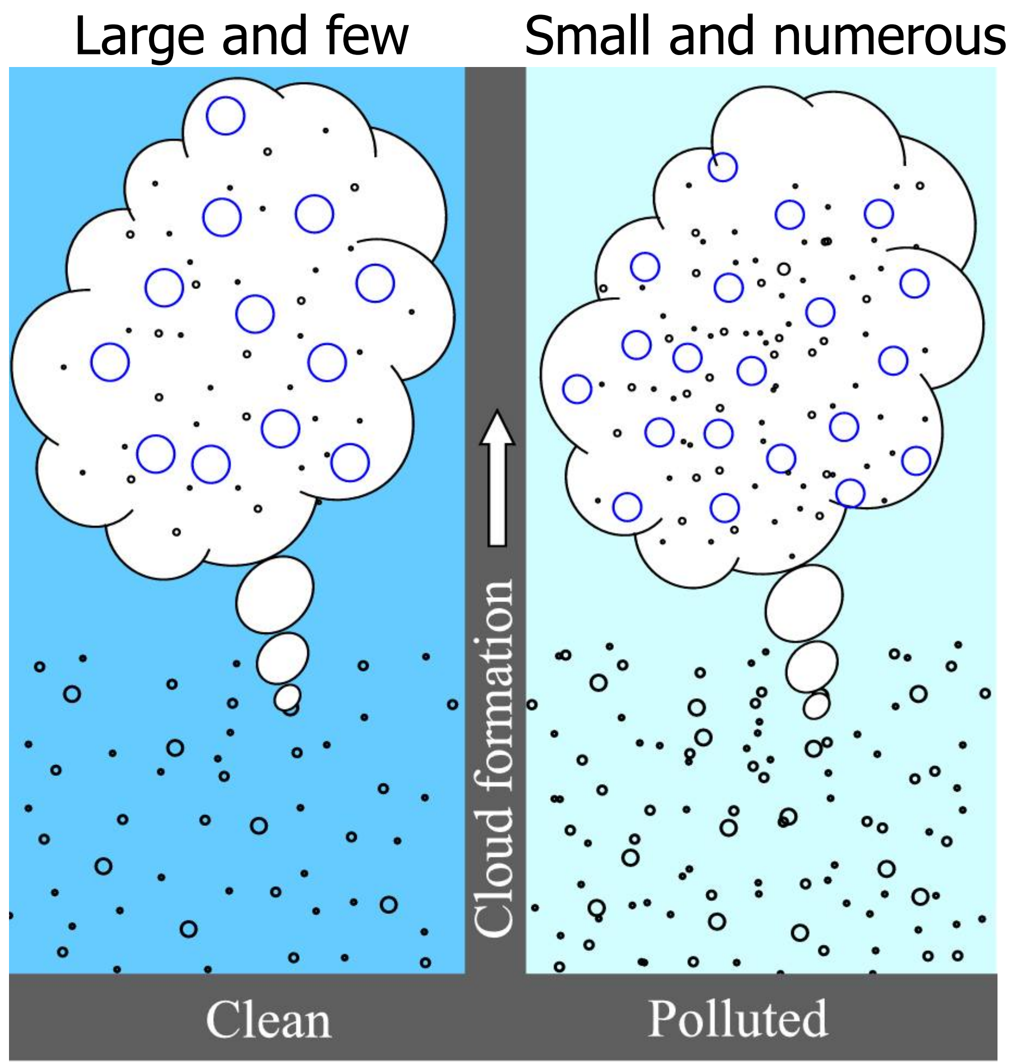
- The Earth's albedo: 28%
  - 19% from clouds
- Pollution ⇒ Increased particle number concentration – Aerosol indirect effects!
  - higher cloud droplet number concentration
    - higher cloud albedo – **1st ind effect**
    - prolonged cloud life-time – **2nd ind effect**



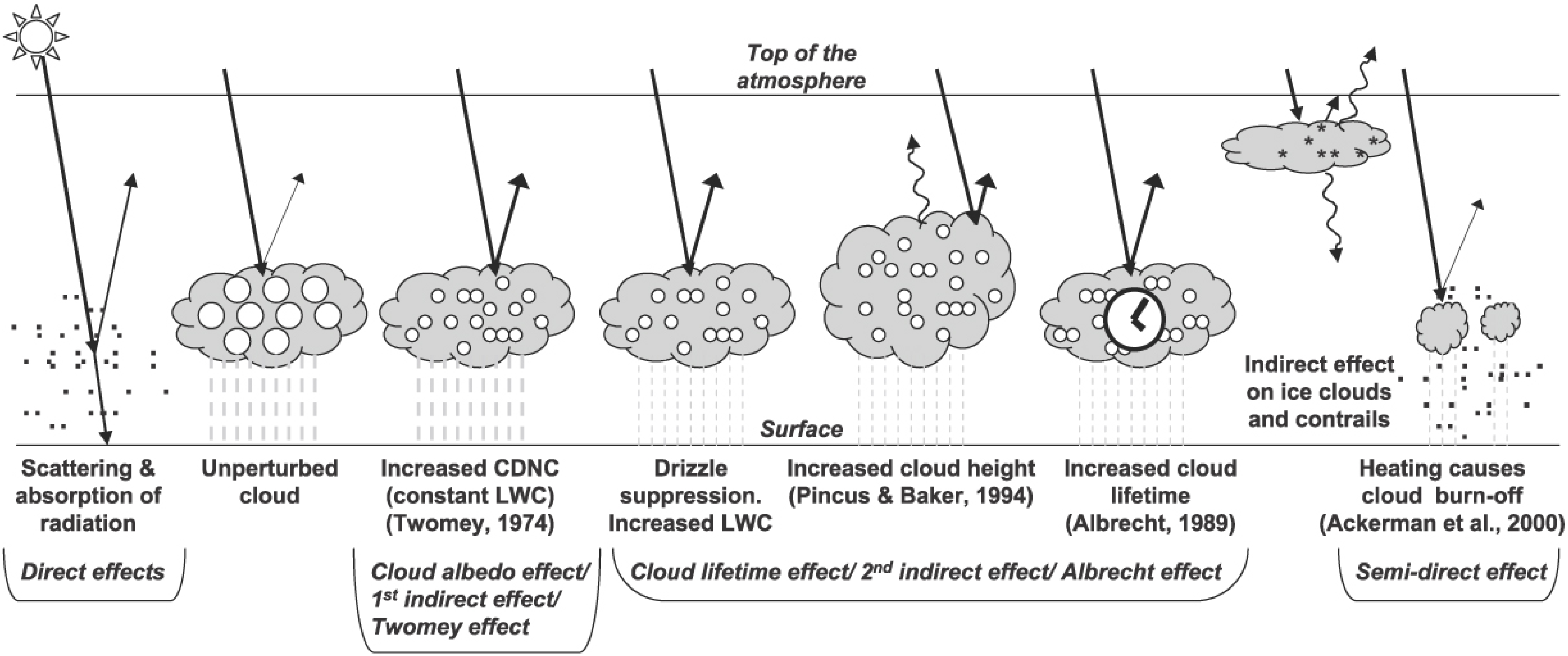
Smaller rel. velocities for coalescence

⇒ 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

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

(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

<u>UN Climate panel (IPCC)</u>

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