Aerosol, Cloud and Climate

Today:
- Interaction aerosol – atmospheric water
- Cloud formation
- Climate effects of aerosols and clouds

Literature connected with today's lecture (see "Reading instructions"):
These overheads – Aerosol, Cloud and Climate
Jacob, chapter 8
Martinsson – Aerosol, Water and Clouds
Exercises:
8:1 – 8:6

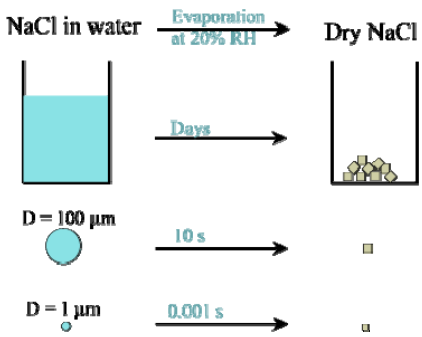
Aerosol – Water Interaction

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

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

Condensation and evaporation

RH and vapour pressure:

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

Plane (macroscopic) surface:

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

Small drops:

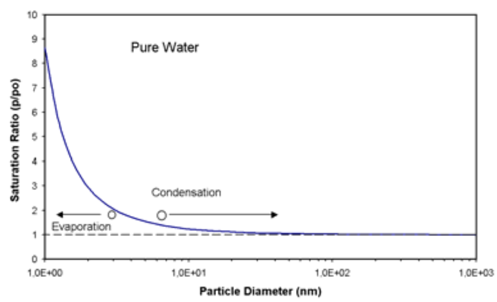
- Significant curvature of droplet surface ⇒
- Modification of the attractive forces between surface molecules ⇒
- Change (increase) of the vapour pressure over the droplet (The Kelvin Effect)

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



Exercise 8:2a

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 20º C. Will the droplet grow, remain unchanged or evaporate? Explain your answer.

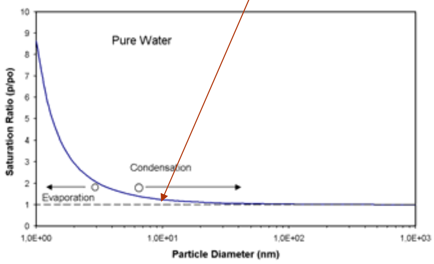
Hint: The fate of pure droplets is determined by the Kelvin effect. The surface tension (σ) of water is 0.073 N/m.

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

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

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

=> Droplet evaporate



Problem

Cloud drops form on pre-existing particles –Which will be the effect from disolved material on the vapour pressure of the drop?

Lowering of Vapour Pressure

Salt droplet at RH < 100%:

- The lowering of the vapour pressure increases with salt concentration
- The droplet assumes the size that gives the same vapour pressure at the droplet surface as the surrounding air:
  - Low RH
    - Requires low vapour pressure at droplet surface
    - ⇒ Large vapour pressure lowering
    - ⇒ High ion concentration
    - ⇒ Small amount of water in the droplet (for the given amount of salt)
    - ⇒ Small droplet
  - Similarly: High RH ⇒ Low ion concentration ⇒ 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, M_s = molar mass 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.

Droplet Size Dependence on RH

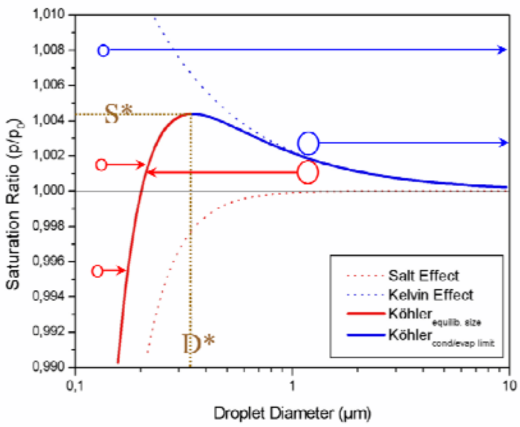
The droplet size as a function of RH depends on:

- The Kelvin effect
- Vapour pressure lowering

These effects combine to the Köhler equation:

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

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

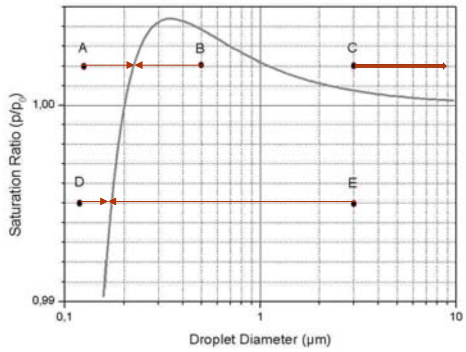


D* = critical diameter of activation
S* = critical saturation ratio of activation

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 – 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

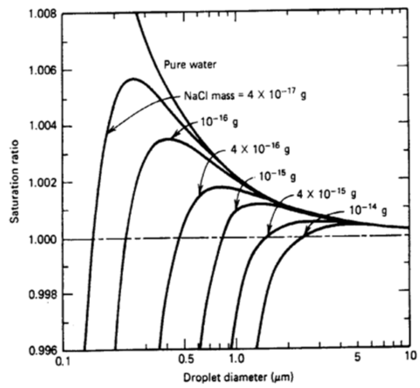
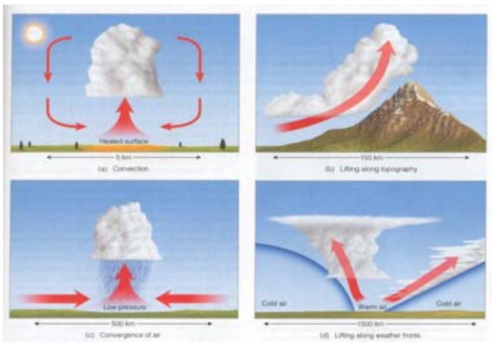
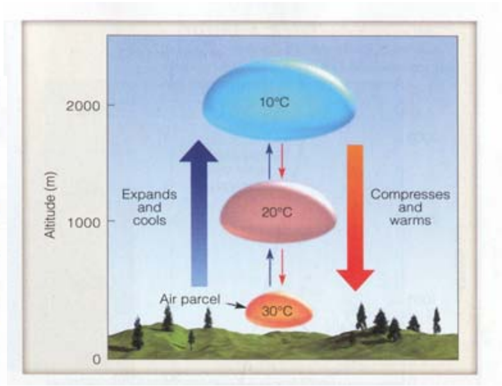


FIGURE 13.4 Saturation ratio versus droplet size for pure water and droplets containing the indicated mass of sodium chloride at 293 K [20°C]. The region above each curve is a growth region and that below, an evaporation region.

Cloud formation





Clouds form in H_2O supersaturation:

- Usually by upward air motion due to
  - Ground absorbs solar radiation => changed air density
  - Convergence of air
  - Topography and fronts

H_2O in vertical air motion:

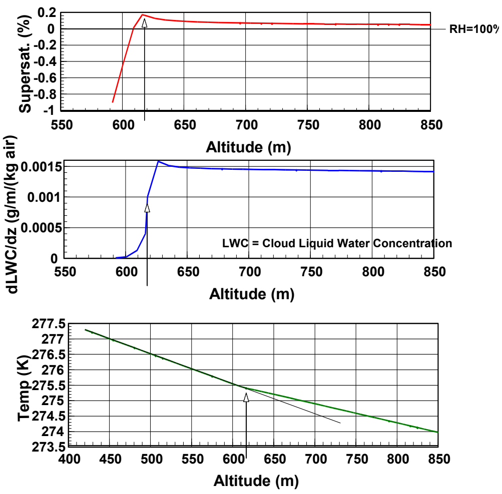
- Upward motion causes expansion and therefore cooling
- Cooling reduces the saturation vapour pressure faster than expansion => RH up
- Particle growth
- Eventually supersaturation – Droplet activation – Cloud formation

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

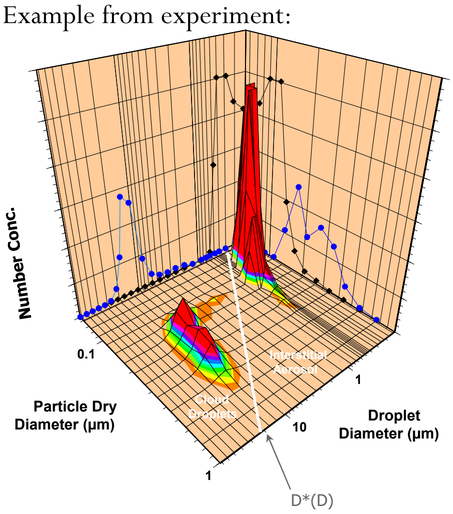
Example from a cloud model:



Cloud Microstructure

- The large particles act as CCN (Cloud Condensation Nuclei) due to low critical supersaturation
- The droplets grow by condensation to about 30 µm diameter
- The small particles are found as small, interstitial droplets in 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.):

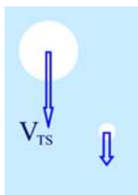
- Most particles form super-cooled droplets
- A small fraction form ice particles – Dependent on particle composition
  - The fraction of ice particles increases at lower temperature
  - Below -40°C liquid droplets are not formed
- The saturation vapour pressure over ice is lower than over water for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

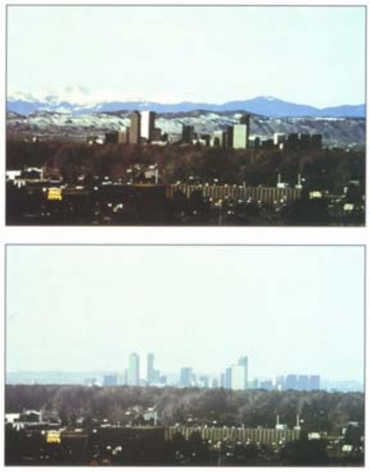


Figure 5.12 Views of Denver, Colorado, USA. (top) A computer-produced view of what Denver visibility would be like without the presence of anthropogenic aerosol particles, and (bottom) a photograph of current smoggy conditions. (Courtesy of L.L. Mauch, US National Park Service.)

Problem

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

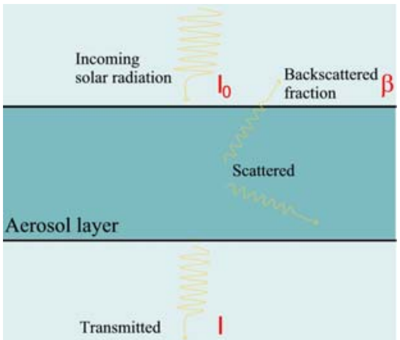
2. Compare the climate effect by particles with greenhouse gases

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 and hence the radiative properties of clouds

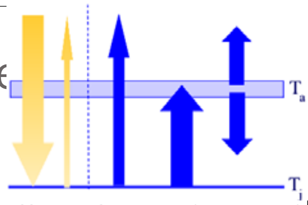
Light Scattering and Climate

- Attenuation of light by an aerosol layer:



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



Influence of aerosol on total albedo:

- Total albedo

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

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

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

- Radiative forcing due to aerosols

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

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

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

- $\Rightarrow \Delta F = -3.6\ W/m^2$ (Total effect, including 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

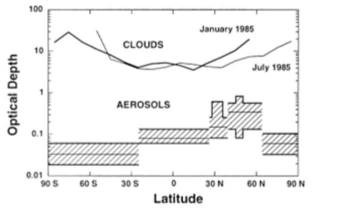
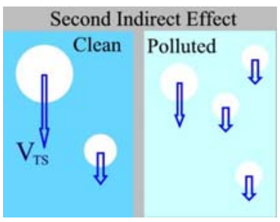


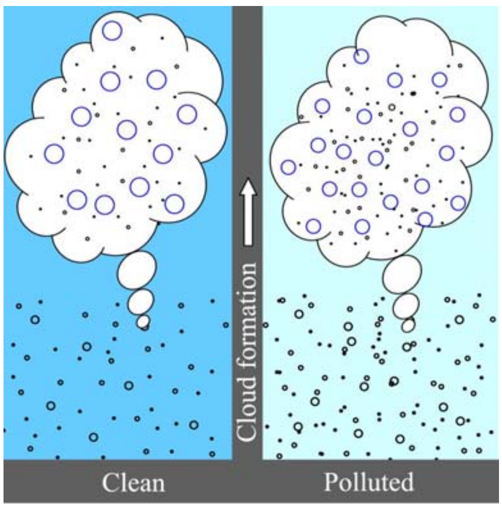
Figure 3 Zonally averaged mean of visible optical thickness of atmospheric aerosols from land-based transmission measurements (Weller and Leiterer, 1988) and mean cloud optical thickness for January and July 1985 from ISCCP C2 data.

Cloud – Aerosol Interaction

- The earth's albedo: 28%
  - 19% from clouds
- Pollution $\Rightarrow$ Increased particle number concentration
  - higher cloud droplet number concentration
    - higher cloud albedo – **First indirect effect**
    - possibly prolonged cloud life-time – **Second indirect effect**



- Smaller rel. velocities for coalescence
- Smaller probability of precipitation



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 greenhouse gases: +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

Climate effects of Aerosols

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

Direct and **Indirect** effect:

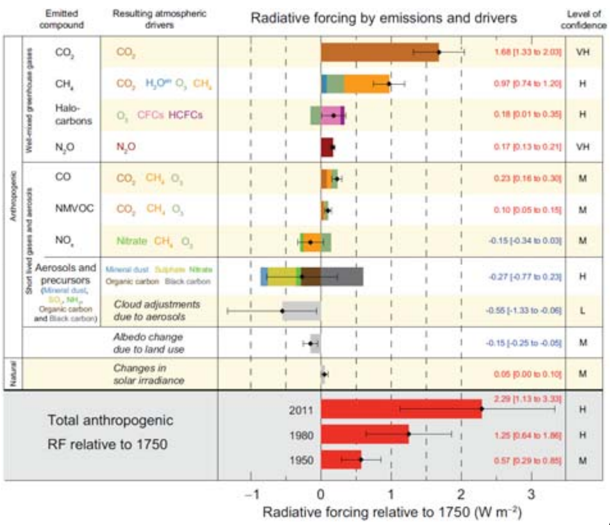
The largest uncertainties in RF

=>

Large uncertainty in total RF during the industrial era

=>

Induces uncertainty in the climate sensitivity due to greenhouse gases



Exercise 8:1 c

The optical depth, δ, is on average 0.25 between 30 to 60º latitude in the northern hemisphere. The backscattered fraction, β, is 0.2, resulting in the albedo of the aerosol layer $A_a \approx \delta \cdot \beta = 0.25 \cdot 0.2 = 0.05$.

Calculate the radiative forcing (with sign) induced by the aerosol layer in the latitude interval given. The solar constant is 1370 W/m^2 and the earth's albedo $A_0 = 0.28$.

Hint: The total albedo can be obtained from $A_T \approx A_0 + A_a(1-A_0)^2$.

Reference system without aerosol: $A = A_0 = 0.28$

Changed system with aerosol: $A = A_T \approx A_0 + A_a(1-A_0)^2$

Radiative forcing: $\Delta F = F_{in} - F_{out}$ (changed system)

$F_{in} = F_S/4$

Based on our simple climate model:

$F_{out} = A_T F_S/4 + (1-f)\sigma T_j^4 + f\sigma T_a^4$

Equilibrium in reference system:

$F_{in} = F_S/4 = A_0 F_S/4 + (1-f)\sigma T_j^4 + f\sigma T_a^4$

=> Only the albedo differs between F_{in} and F_{out}

$\Delta F = F_{in} - F_{out} = A_0 F_S/4 - A_T F_S/4 = -A_a(1-A_0)^2 F_S/4$

$= -0.05(1-0.28)^2 1370/4 = -8.9 \text{ W/m}^2$