Lecture 2.

Fundamentals of aerosols and clouds.

1. Clouds: types; phase, size distribution, ice morphology

2. Aerosols: classification, size distribution

Suggested reading:

Chapters 2 and 3 in *Aerosol Pollution Impact on Precipitation: A Scientific Review*. WMO/IUGG INTERNATIONAL AEROSOL PRECIPITATION SCIENCE ASSESSMENT GROUP (IAPSAG) REPORT.

Clouds.

Major characteristics are *cloud type, cloud coverage and distribution, liquid water content of cloud, cloud droplet concentration, and cloud droplet size*.

- ✓ Cloud droplet sizes vary from a few micrometers to 100 micrometers with average diameter in 10 to 20 μm range.
- ✓ Cloud droplet concentration varies from about 10 cm^{-3} to 1000 cm^{-3} with average droplet concentration of a few hundred cm^{-3}.
- ✓ The liquid water content of typical clouds, often abbreviated LWC, varies from approximately 0.05 to 3 g(water) m^{-3}, with most of the observed values in the 0.1 to 0.3 g(water) m^{-3} region.

NOTE: Clouds cover approximately 60% of the Earth's surface. Average global coverage over the oceans is about 65% and over the land is about 52%.

Table 2.1 Cloud classification

Type	Height	Height of cloud base: Polar regions	Temperate regions	Tropical regions	Precipitation
Cumulus Cumulonimbus Stratus	Low	Below 2km	Below 2km	Below 2km	Light showers are possible Always reported when showers /thunderstorms/hail occurs Near costs/hills
Nimbostratus Altostratus Altocumulus	Middle	2-4 km	2-7 km	2-8 km	Normally continuous Often continuous Occasionally
Cirrus Cirrostratus Cirrocumulus	High	3-8 km	5-13 km	6-18 km	No

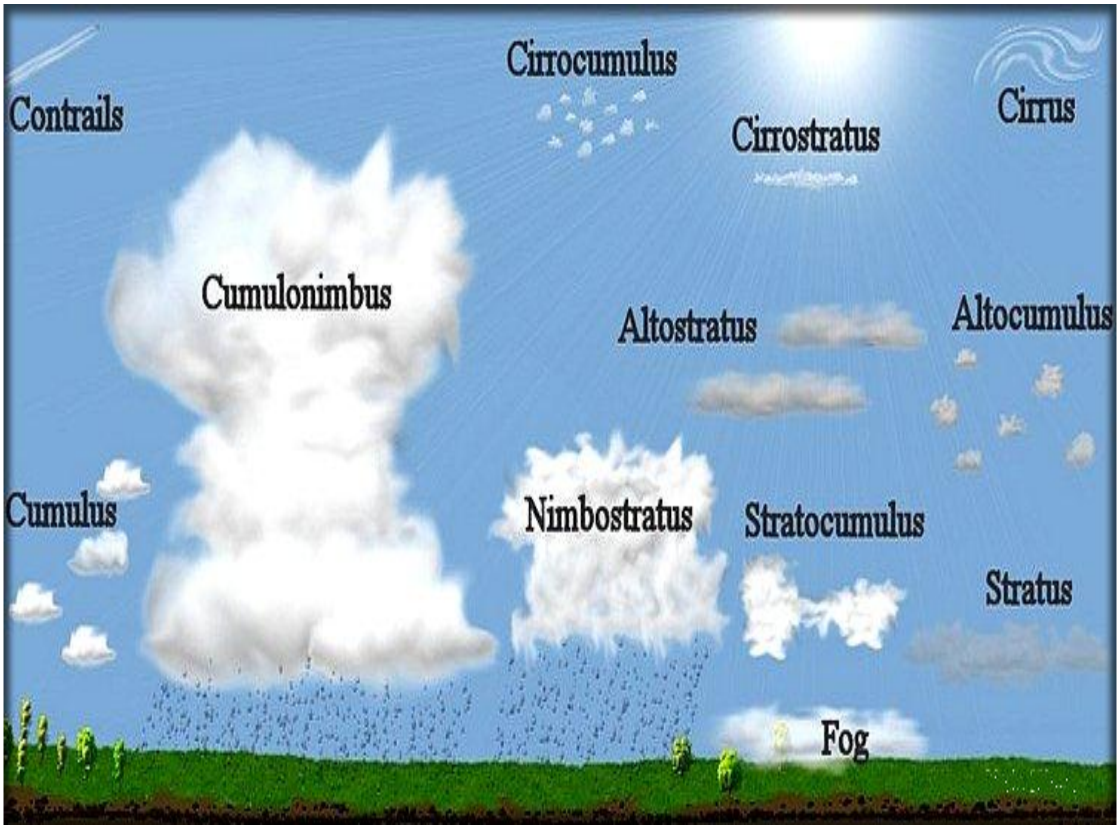


Figure 2.1 Types of clouds. Fog is often considered as a cloud whose base starts at the ground.

Different types of clouds (based on cloud phase): liquid, mixed phase and ice

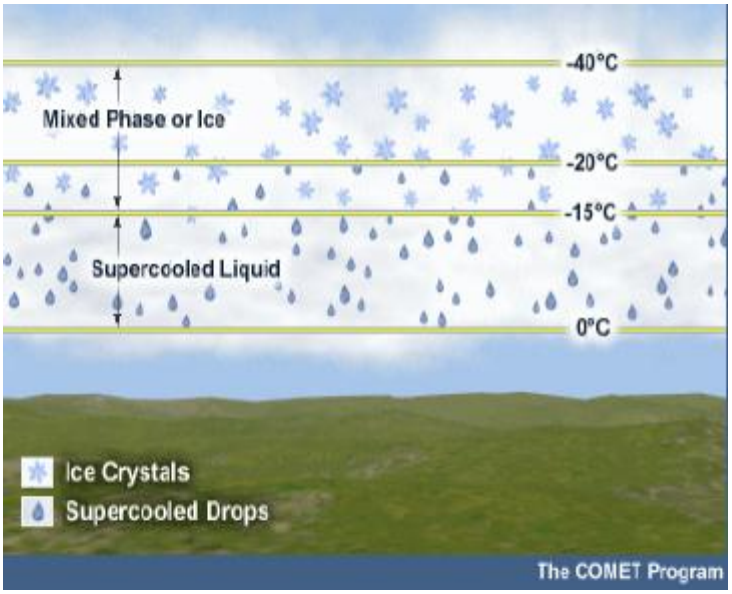
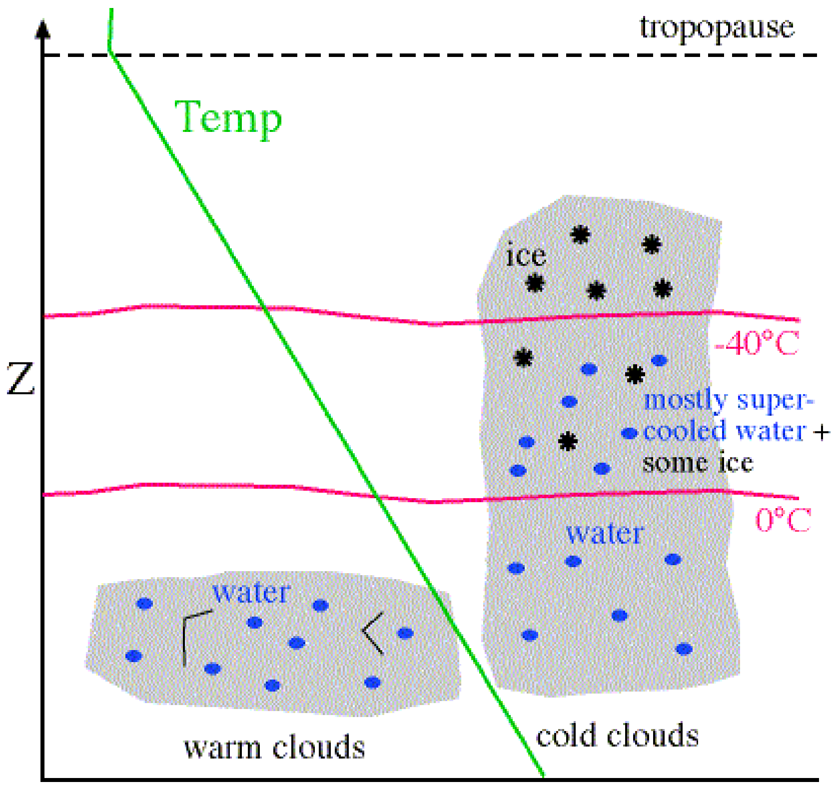


Figure 2.2 Idealized cloud phase vs T

Warm vs. cold clouds



Cloud droplets size distribution is often approximated by a modified gamma distribution

$$N(r) = \frac{N_0}{\Gamma(\alpha) r_n} \left(\frac{r}{r_n} \right)^{\alpha - 1} \exp(-r / r_n) \qquad [2.1]$$

where $\mathbf{N_0}$ is the total number of droplets (cm^{-3}); $\mathbf{r_n}$ in the radius that characterizes the distribution ; $\boldsymbol{\alpha}$ in the variance of the distribution, and $\boldsymbol{\Gamma}$ is the gamma function.

Table 2.2 Characteristics of representative size distributions of some clouds (for α =2)

Cloud type	N_o (cm^{-3})	r_m (μm)	r_{max} (μm)	r_e (μm)	l ($g\ m^{-3}$)
Stratus:					
over ocean	50	10	15	17	0.1-0.5
over land	300-400	6	15	10	0.1-0.5
Fair weather cumulus	300-400	4	15	6.7	0.3
Maritime cumulus	50	15	20	25	0.5
Cumulonimbus	70	20	100	33	2.5
Altostratus	200-400	5	15	8	0.6

Mean radius: $\mathbf{r_m = (\alpha + 1)\, r_n}$ **;** Effective radius: $\mathbf{r_e = (\alpha + 3)\, r_n}$

- ✓ For many practical applications, the optical properties of water clouds are parameterized as a function of the **effective radius** and **liquid water content** (LWC).

The **effective radius** is defined as

$$r_e = \frac{\int \pi r^3 N(r) dr}{\int \pi r^2 N(r) dr} \qquad [2.2]$$

where N(r) is the droplet size distribution.

The **liquid water content** (LWC) is defined as

$$LWC = \rho_w V = \frac{4}{3} \rho_w \int \pi r^3 N(r) dr \qquad [2.3]$$

The **liquid water path** (LWP) is defined as LWC times the cloud height.

Table 2.3 Representative cloud properties ($N_{hydrometeors}$ is the number of cloud particles per volume of air). From Heintzenberg and Charlson (2009)

Location	Height (km)	Type	Temperature (°C)	LWC/IWC (mg m^{-3})	$N_{hydrometeors}$ (cm^{-3})
Surface	0	Fog	≈ 0	10–100	1–100
Lower troposphere	1–5	Cumulus	10 to ≈ –35	100–1000	10–1000
Lower troposphere	1–3	Stratus	10 to ≈ –35	100–500	10–1000
Troposphere	1–15	Cumulo-nimbus	0 to –60	1000–10,000	100–1000
Upper troposphere	7–15	Cirrus	–40 to –90	1–10	0.01–10
Stratosphere	15–25	Polar strato-spheric clouds	< –80	0.001–0.01	1–10
Mesosphere	80–85	Noctilucent clouds	≈ –120	0.00001–0.0001	25–500

Cloud Ice Crystals

- ✓ Ice crystals present in clouds found in the atmosphere are often six-sided. However, there are variations in shape: plates - nearly flat hexagon; columns - elongated, flat bottoms; needles - elongated, pointed bottoms; dendrites - elongated arms (six), snowflake shape.
- ✓ Ice crystal shapes depend on temperature and relative humidity. Also, crystal shapes can be changed due to collision and coalescence processes in clouds.
- ✓ Ice crystal shape depends on the type of ice nuclei (IN) present => Pollution/different aerosols may influence ice crystal shape
- ✓ Size distributions may have two modes

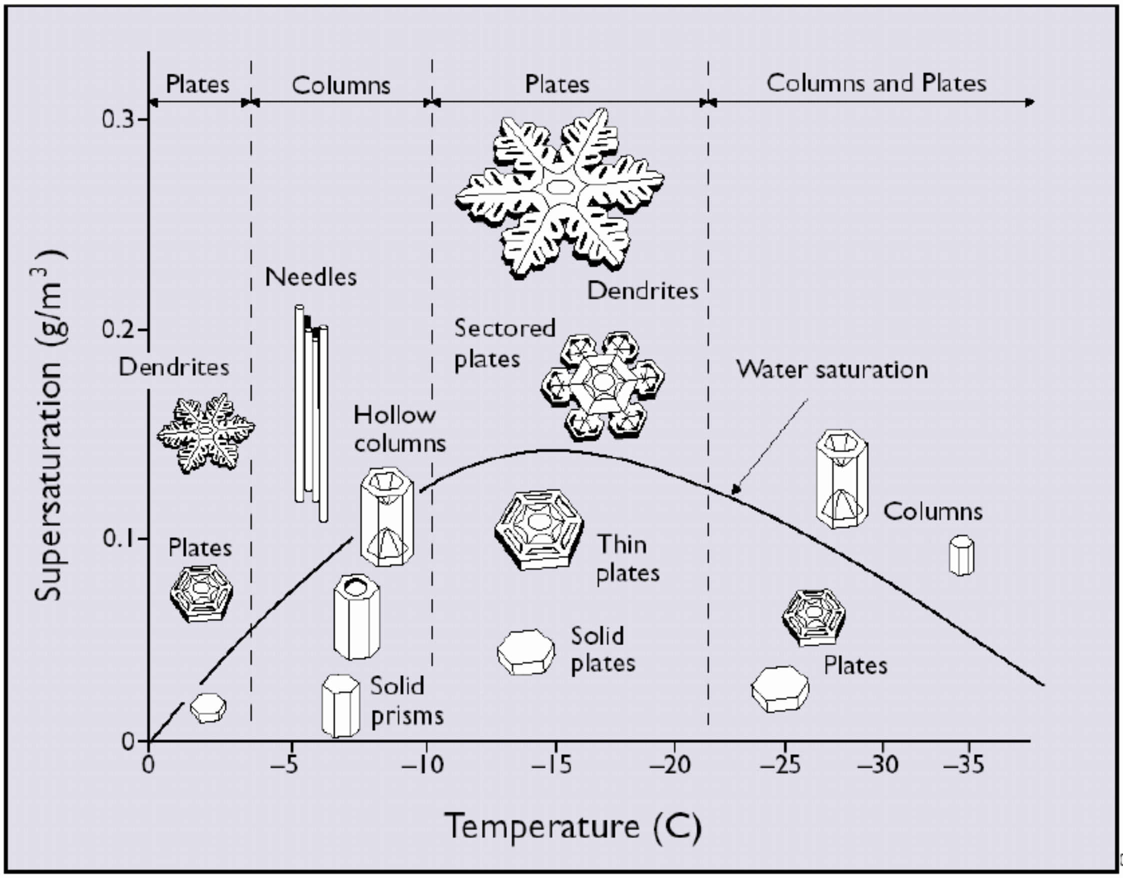


Figure 2.3 Ice crystal's shape as a function of supersaturation and temperature – a "classical" view

<u>What determines the structure of clouds</u>:

- Macro-physics of clouds:
    - Air motion that controls cloud formation
    - Mixing
    - Adiabatic cooling (lifting)
    - Diabatic cooling (removal of heat)
- Micro-physics of clouds:
    - Nucleation of droplets and ice crystals
    - Aggregation, growth
    - Evaporation, entrainment
    - Feedbacks

Aerosols.

Atmospheric aerosols are solid or liquid particles or both suspended in air with diameters between about 0.002 μm to about 100 μm.

- Interaction of the particulate matter (aerosols and clouds particles) with electromagnetic radiation is controlled by the particle size, composition, mixing state, shape and amount.
- Atmospheric particles vary greatly in sources, production mechanisms, sizes, shapes, chemical composition, amount, distribution in space and time, and how long they survive in the atmosphere (i.e., lifetime).

Primary and secondary aerosols:

Primary atmospheric aerosols are particulates that emitted directly into the atmosphere (for instance, sea-salt, mineral aerosols (or dust), volcanic dust, smoke and soot, some organics).

Secondary atmospheric aerosols are particulates that formed in the atmosphere by gas-to-particles conversion processes (for instance, sulfates, nitrates, some organics).

Location in the atmosphere: **stratospheric and tropospheric** aerosols;

Geographical location**: marine, continental, rural, industrial, polar, desert** aerosols, etc.

Spatial distribution**:**

Atmospheric aerosols exhibit complex, heterogeneous distributions, both spatially and temporally.

Anthropogenic (man-made) and natural aerosols**:**

Anthropogenic sources: various (biomass burning, gas to particle conversion; industrial processes; agriculture's activities)

Natural sources: various (sea-salt, dust storm, biomass burning, volcanic debris, gas to particle conversion).

Chemical composition*:*

Individual chemical species: **sulfate** (SO_4^{2-}), **nitrate** (NO_3^-), **soot** (elemental carbon), **sea-salt** (NaCl); minerals (e.g., quartz, SiO_4, clays, feldspar).

Multi-component (MC) aerosols: complex make-up of many chemical species (called internally mixed particles)

Shapes of aerosol particles: many are spherical but not all!

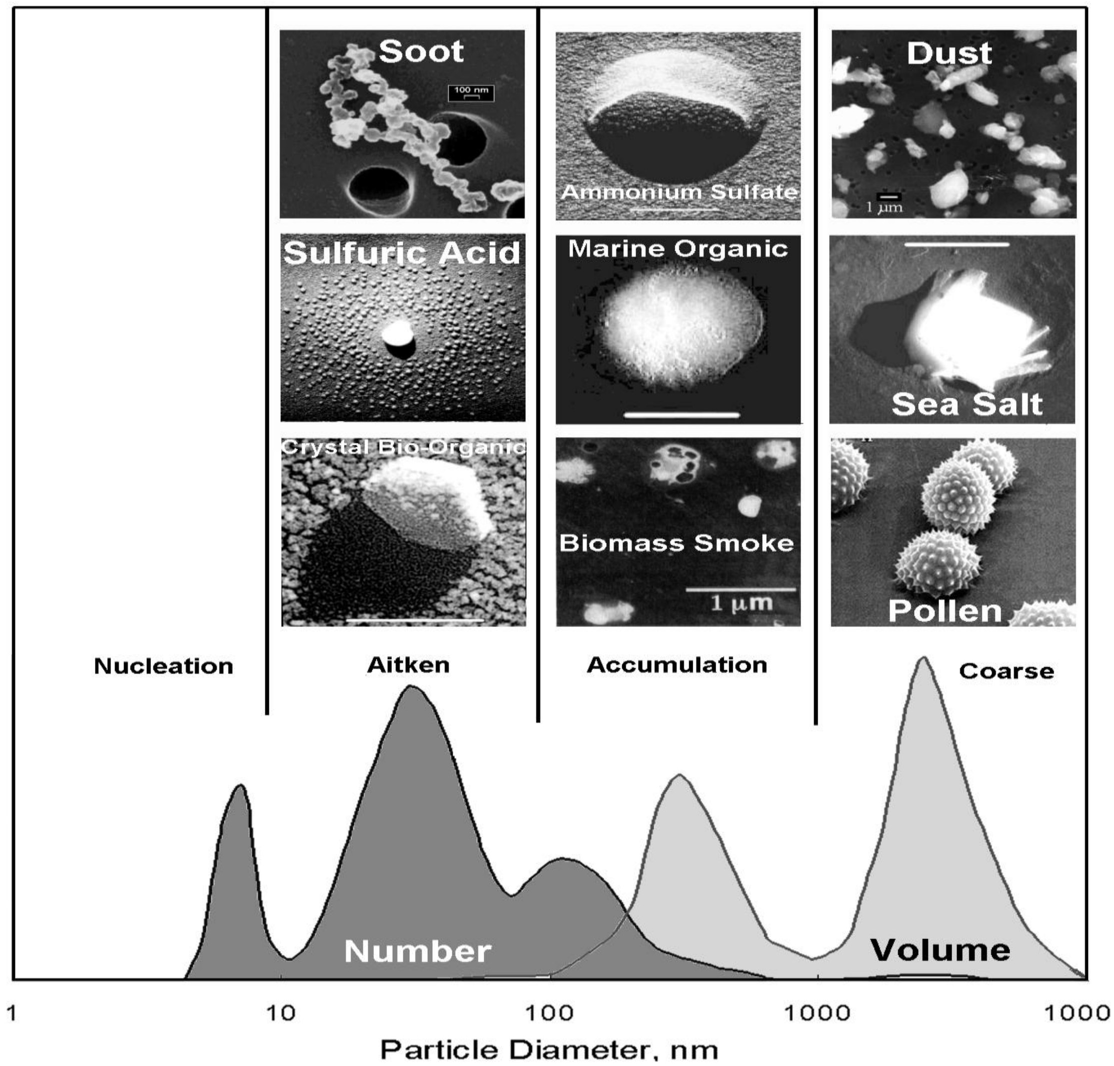


Figure 2.4 Representative shapes of aerosol particles

Particle size:

The particle size distribution of aerosols are commonly approximated by a certain analytical function (such as log-normal, power law, or gamma function)

Log-normal function:

$$\boldsymbol{N}(\boldsymbol{r}) = \frac{\boldsymbol{No}}{\sqrt{2\boldsymbol{\pi}}\ \ln(\boldsymbol{\sigma})\ \boldsymbol{r}} \exp\left(-\frac{\ln(\boldsymbol{r}/\boldsymbol{r_o})^2}{2\ln(\boldsymbol{\sigma})^2}\right) \qquad [2.4]$$

Normalization:

$$\int \boldsymbol{N}(\boldsymbol{r})\boldsymbol{dr} = \boldsymbol{N}_0 \qquad [2.5]$$

If three size modes are present (e.g., see Figs. 2.4 and 2.5), then one takes a sum of three log-normal functions

$$N(r) = \sum_i \frac{N_i}{\sqrt{2\pi}\ \ln(\sigma_i)\ r} \exp\left(-\frac{\ln(r/r_{0,i})^2}{2\ln(\sigma_i)^2}\right) \qquad [2.6]$$

where **N(r)** is the particle number concentration, $\mathbf{N_i}$ is the total particle number concentration of i-th size mode with its median radius $\mathbf{r_{0,i}}$ and geometric standard deviation $\boldsymbol{\sigma_i}$.

NOTE*:* Surface area or volume (mass) size distributions can be found using the k-moment of the lognormal distribution (k=2 or k=3, respectively):

$$\int r^k N(r)dr = N_0 r_0^k \exp(k^2 (\ln\sigma)^2/2) \qquad [2.7]$$

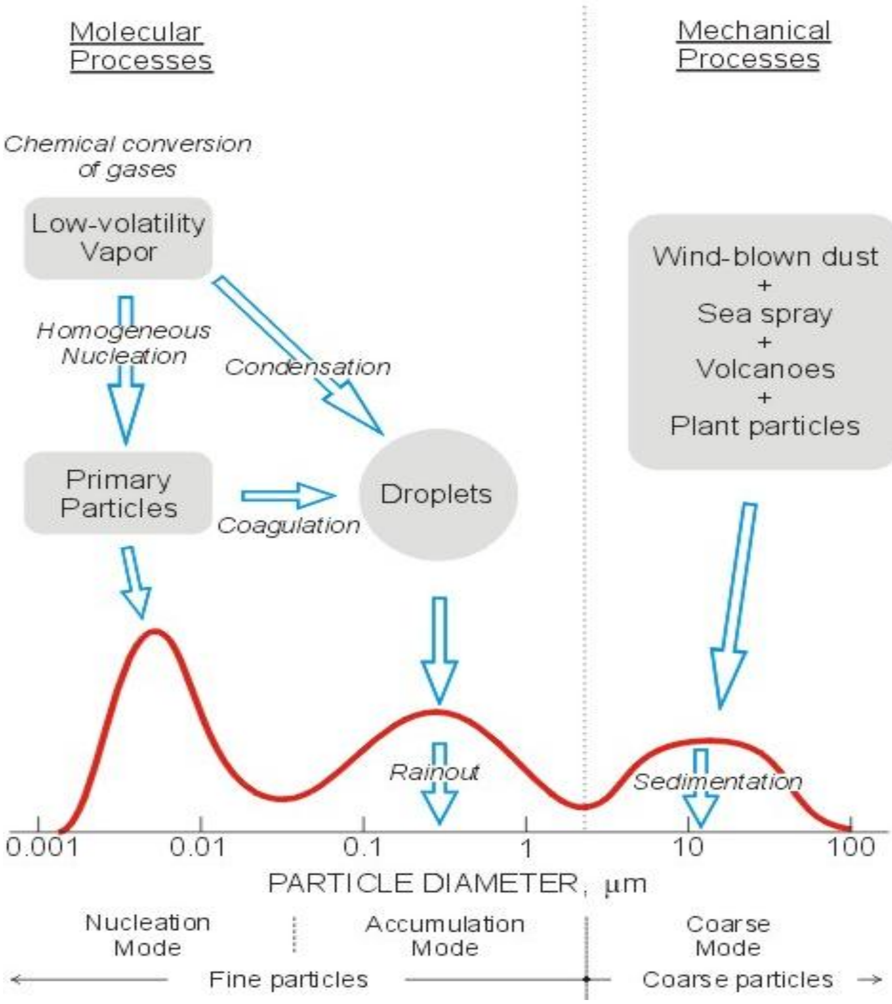


Figure 2.5 A "classical view" of the distribution of particle mass of atmospheric aerosols (from Whitby and Cantrell, 1976).

NOTE: Fine mode (d < ~ 2.5 μm) and coarse mode (d > ~ 2.5 μm); fine mode is divided on the nuclei mode (about 0.005 μm < d < 0.1 μm) and accumulation mode (0.1μm < d < 2.5 μm).

Aerosol as CCN

The number and type of CCNs can affect the lifetimes, amount and radiative properties of clouds and hence have an influence on climate (called indirect effect)

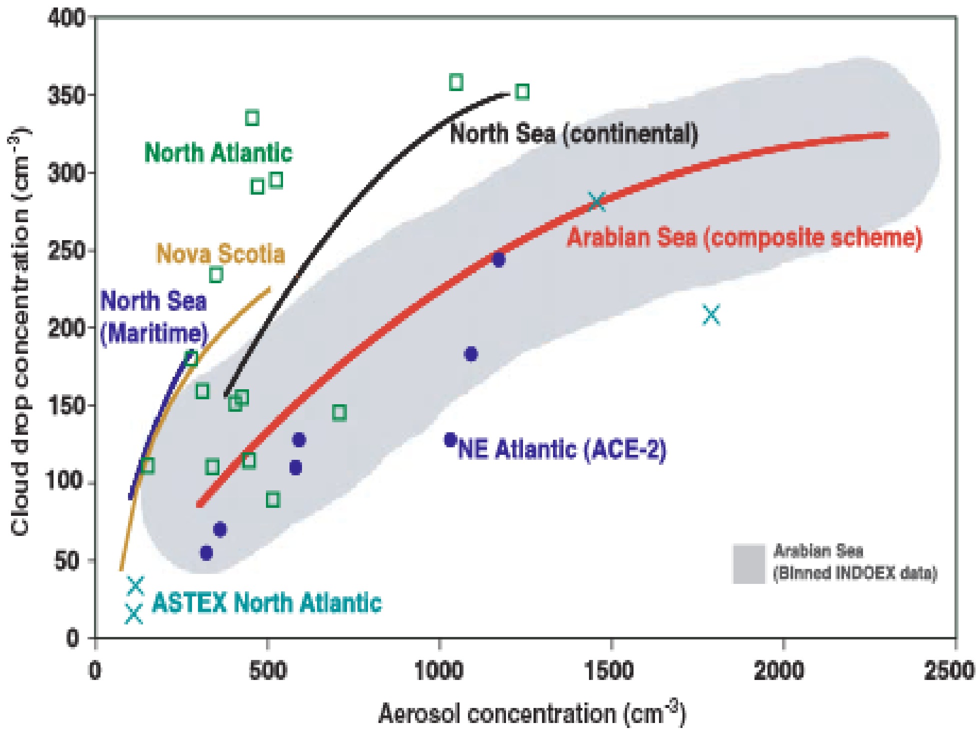


Figure 2.6 Summary of observations (Ramanathan et al., 2001).

Note that the increase in cloud drops tapers off as the CCN concentrations increase.

In stronger updrafts (convective clouds), the increase in drops with increase in pollution is steeper.

Aerosol as IN

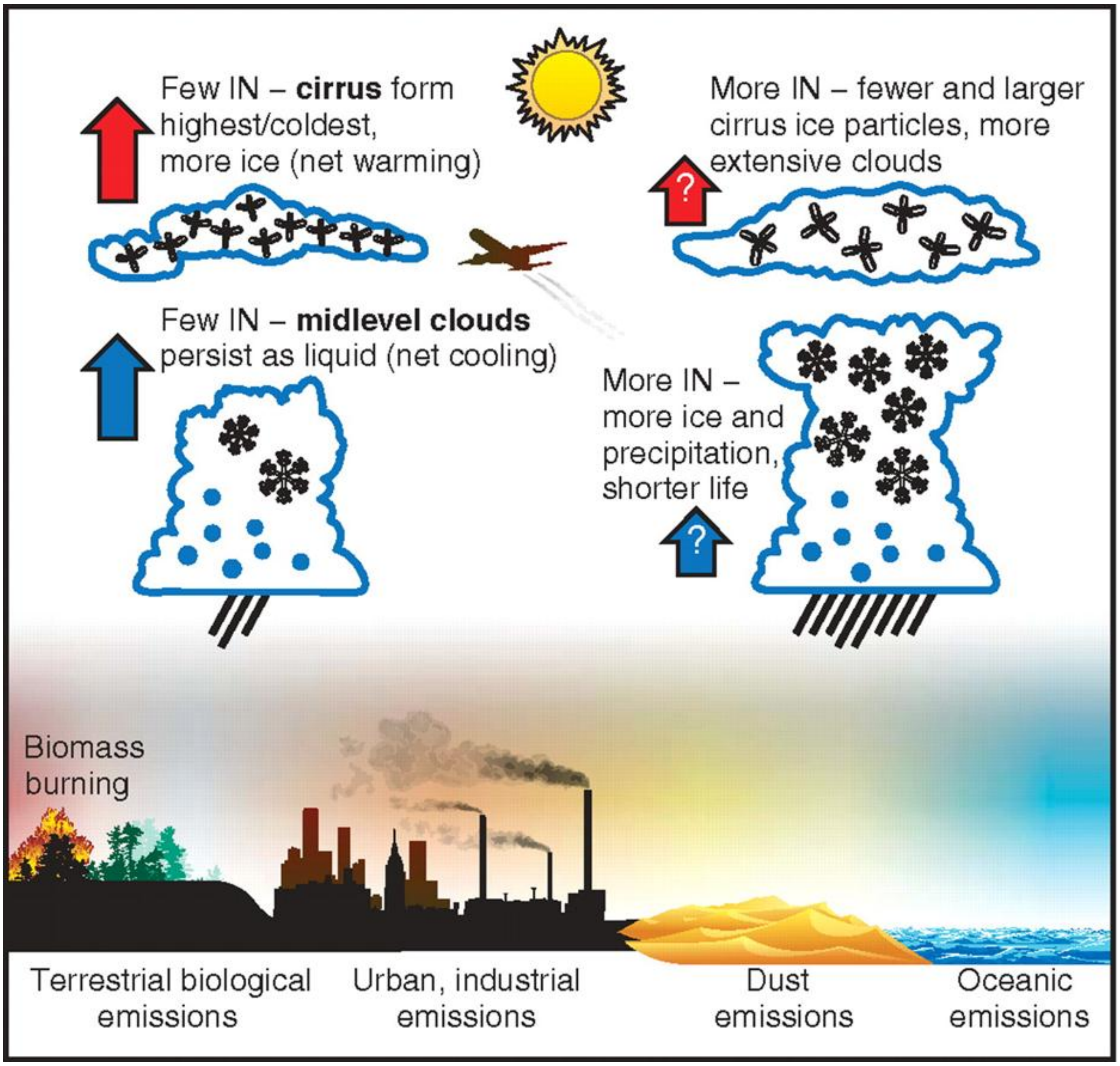


Figure 2.7 Schematic diagram of the effect of ice nuclei from various possible aerosol sources on midlevel precipitating clouds and cirrus ice clouds. The likely but uncertain change in the magnitude of the general cooling impact (blue arrows) of midlevel clouds and warming impact (red arrows) of high cirrus clouds in response to increases in the relative number concentrations of IN is indicated (From DeMott et al., PNAS, 2010;107:11217-11222)