Lecture 2.

Fundamentals of aerosols and clouds.

1. Clouds: types; phase, size distribution, ice morphology
2. Precipitation.
3. Aerosols.

Required reading:

Chapters 2, 3 and 4 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

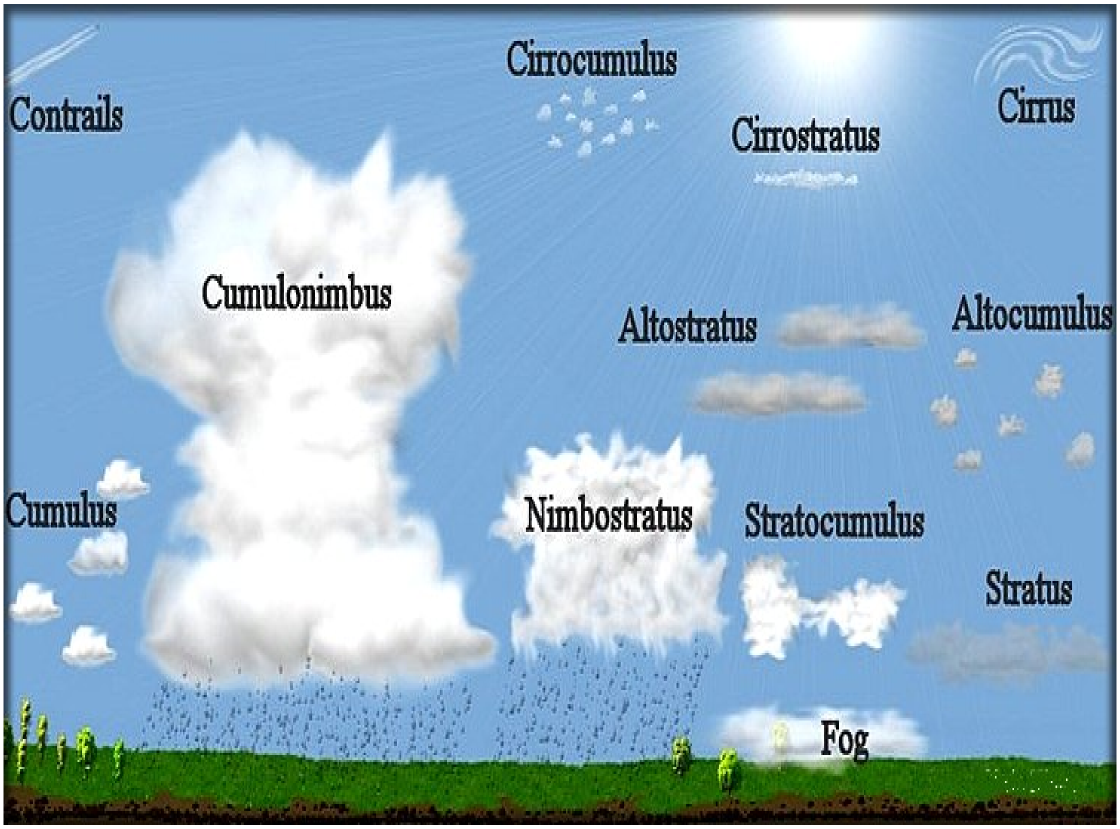


Figure 2.1 Types of clouds. Fog is often considered as a cloud whose base starts at the ground.

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

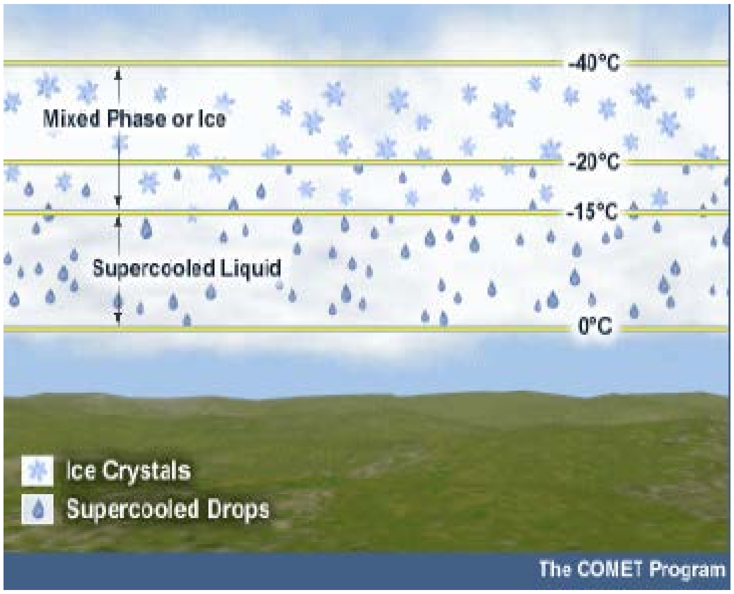
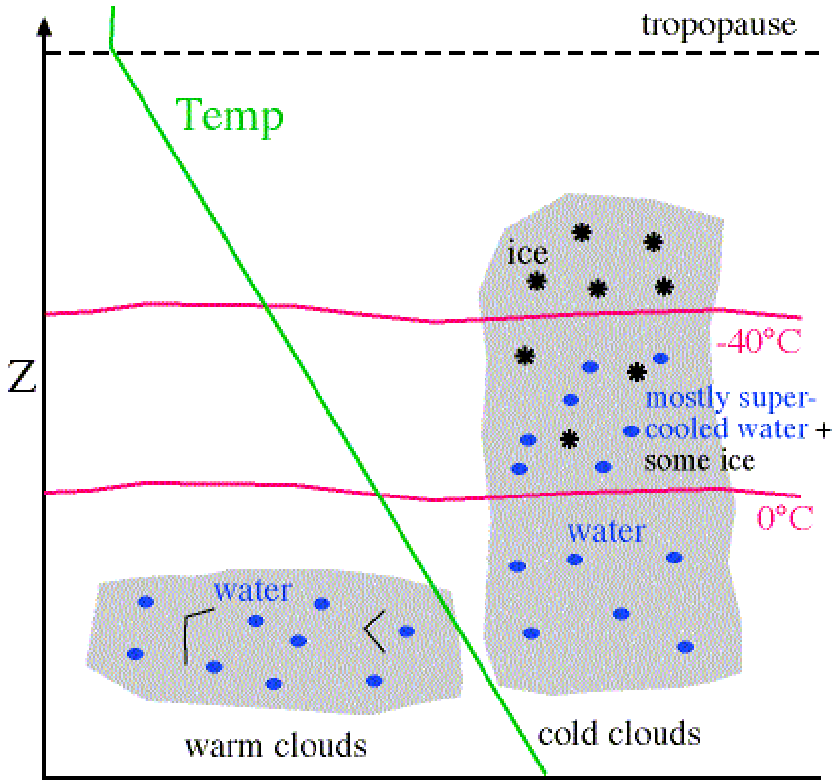


Figure 2.2 Idealized cloud phase vs T

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 $\boldsymbol{\alpha}$ =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

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

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.

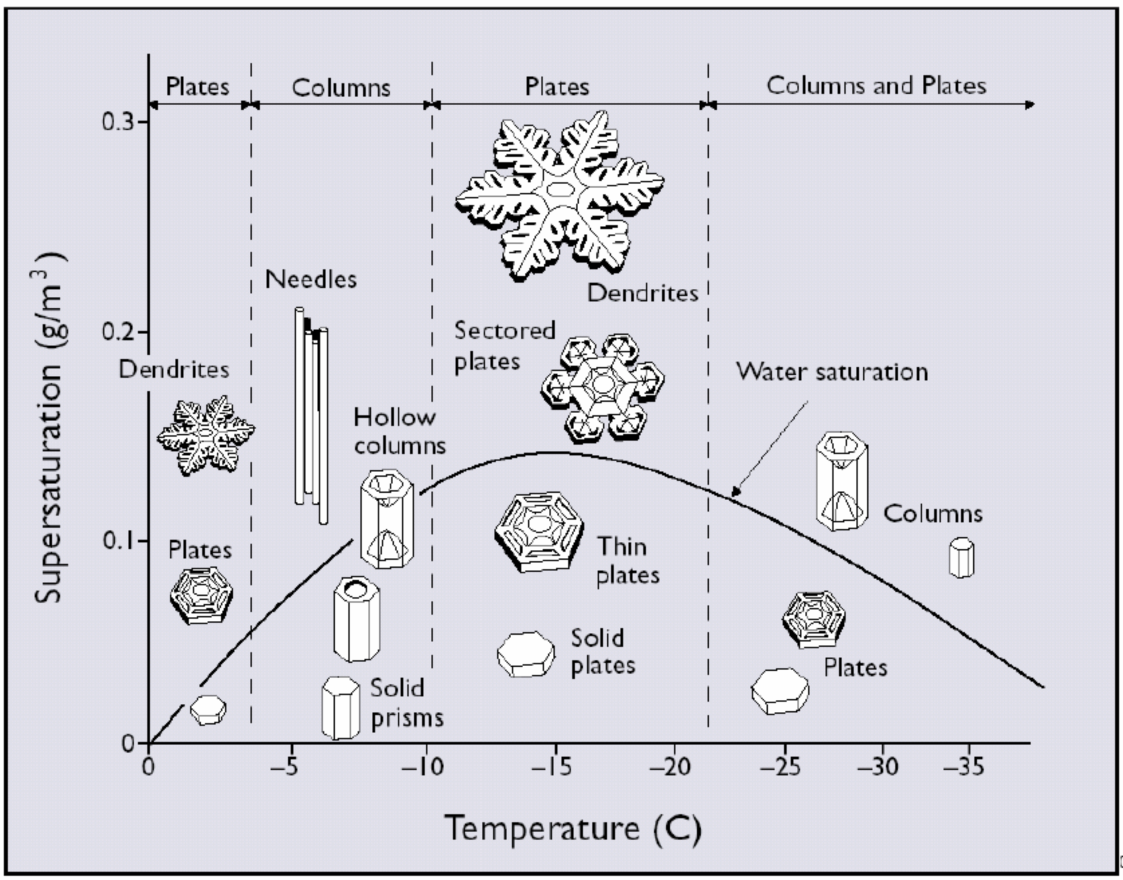


Figure 2.3 Ice crystal's shape as a function of supersaturation and temperature – a "classical" view

- ✓ 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

What determines the structure of clouds:

- 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

Precipitation.

Two mechanisms of the formation of precipitation: ice crystal process and collision-coalescence process:

- ✓ Ice crystal process (mainly in cold clouds): When ice crystals and supercooled water droplets coexist in a cloud, ice crystals collect the available water vapor at a much faster rate than liquid water. Thus, ice crystals grow larger at the expense of water droplets. Eventually, this process generates ice crystals large enough to fall as snowflakes.
- ✓ Collision-coalescence process (mainly in warm clouds): The bigger droplets fall faster, they collide and join with smaller water droplets. After many collisions the droplets are large enough to fall to the grounds as rain.

IN << CCN

- ✓ IN are far less abundant in the atmosphere that cloud condensation nuclei (CCN): Typical CCN and IN concentrations: 100 cm^{-3} and 0.01 cm^{-3}
- ✓ In ice clouds, cloud water is typically distributed on fewer cloud particles than in a liquid cloud => ice crystals are larger than cloud droplets and therefore more likely to form precipitation.

Table 2.3 Properties of rain and snow.

Type	Phase	Size (mm)*	Fall Speed (m/s)*	Notes
Drizzle	Liquid	0.05-0.5	3-5	Very light rain from stratus
Rain	Liquid	0.5-3	5-10	Light to moderate intensity
Rain (heavy)	Liquid	3-6	10+	From *Tcu, Cb*
Pristine Ice	Solid	0.5-2	0.5	Disc or needle shape
Aggregates	Solid	3-15	0.5-1	Classic snowflake
Graupel	Solid	2-5	1-3	Spherical structure, rimed
Hail	Solid-Liquid	10-100	>10	Can have a sponge structure

* data taken from Rogers & Yau (1989)

Types of precipitation and common abbreviations used by meteorologists:

1. ***Rain*** (R, RA)- Rain is liquid precipitation that reaches the surface in the form of drops that are greater than 0.5 millimeters in diameter. The intensity of rain is determined by the accumulation over a given time. Categories of rain are light, moderate and heavy.
2. ***Snow*** (SN, SNW, S)- Snow is an aggregate of ice crystals that form into flakes. Snow forms at temperatures below freezing. For snow to reach the earth's surface the entire temperature profile in the troposphere needs to be at or below freezing. It can be slightly above freezing in some layers if the layer is not warm or deep enough the melt the snow flakes much. The intensity of snow is determined by the accumulation over a given time. Categories of snow are light, moderate and heavy.
3. ***Snow Pellets*** (GS)- A snow pellet is precipitation that grows by supercooled water accreting on ice crystals or snow flakes. Snow pellets can also occur when a snowflake melts about half way then refreezes as it falls. Snow pellets have characteristics of hail, sleet and snow. With sleet (ice pellets), the snowflake almost completely melts before refreezing thus sleet has a hard ice appearance. Soft hail grows in the same way snow pellets can grow and that is ice crystals and supercooled water accreting on the surface. Snow pellets will crush and break apart when pressed. They can bounce off objects like sleet does. Snow pellets have a whiter appearance than sleet. Snow pellets have small air pockets embedded within their structure and have visual remnants of ice crystals unlike sleet. Snow pellets are typically a couple to several millimeters in size.
4. ***Snow Grains*** (SG)- Snow grains are small grains of ice. They do not produce much accumulation and are the solid equivalent to drizzle.
5. ***Ice Crystals*** (IC)- Also called diamond dust. They are small ice crystals that float with the wind.
6. ***Sleet / Ice Pellets*** (PE, PL, IP, SLT)- Sleet (Ice Pellets) are frozen raindrops that strike the earth's surface. In a sleet situation the precipitation aloft when it is first generated will be snow. The snow falls through a layer that is a little above freezing and the snow partially melts. If the snow completely melts it will be more likely to reach the earth's surface as supercooled water instead of sleet. If the snow partially melts there will still be ice within the falling drop for water to freeze on when the drop falls into a subfreezing

layer. The lowest layer of the troposphere will be below freezing in a sleet situation and deep enough to freeze drops completely. The lower boundary layer can be above freezing and sleet occur if the sleet does not have time to melt before reaching the surface.
7. ***Hail*** (GR, A)- Hail is dense precipitation ice that is that least 5 millimeters in diameter. It forms due to ice crystals and supercooled water that freeze or stick to the embryo hail stone. Soft hail is more white and less dense since it has air bubbles. Soft hail occurs when hail grows at a temperature below freezing by ice crystals and small supercooled water and cloud droplets merging onto the hail. Hard hail occurs when liquid water drops freeze on the outer edges of the hailstone after the outer edge is above freezing. The freezing of supercooled water releases latent heat and this can result in the outer edge of the hail stone warming above freezing. Then the water refreezes creating solid ice. Hail will commonly have soft ice and hard ice layers when it is sliced open.
8. ***Graupel*** (GS)- Graupel forms in the same way as hail except the diameter is less than 5 millimeters. It usually grows by soft hail processes.
9. ***Drizzle*** (DZ, L)- Drizzle is liquid precipitation that reaches the surface in the form of drops that are less than 0.5 millimeters in diameter.
10. ***Freezing Drizzle*** (FZDZ, ZL)- Freezing Drizzle is liquid precipitation that reaches the surface in the form of drops that are less than 0.5 millimeters in diameter. The drops then freeze on the earth's surface.
11. ***Freezing Rain*** (FZRA, ZR)- Freezing Rain is liquid precipitation that reaches the surface in the form of drops that are greater than 0.5 millimeters in diameter. The drops then freeze on the earth's surface.
12***. Freezing Fog*** (FZFG)- Freezing fog is a fog composed of supercooled water drops. These drops freeze just after they wet the earth's surface.
13. ***Mixed Precipitation*** (MXD PCPN)- The combination of two or more winter precipitation types occurring at the same time or over a period of time at the same place.

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)

Particle size:

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

Log-normal function:

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

Normalization:

$$\int N(r)dr = N_0 \qquad [2.5]$$

If three size modes are present (e.g., see Figure 5.4), then one takes a sum of three log-normal functions

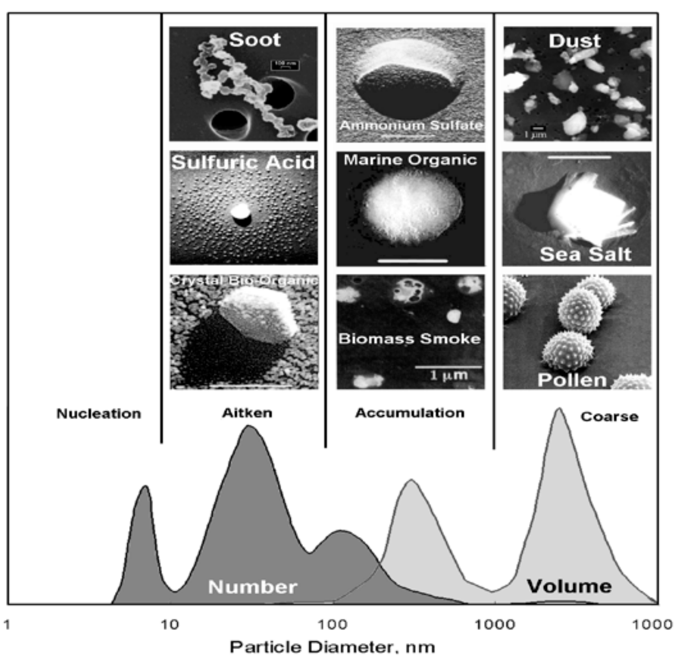
$$N(r) = \sum_i \frac{N_i}{\sqrt{2\pi}\ \ln(\sigma_i)\ r} \exp\left(-\frac{\ln(r/r_{0,i})^2}{2\ln(\sigma_i)^2}\right) \qquad [2.6]$$

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):

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

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



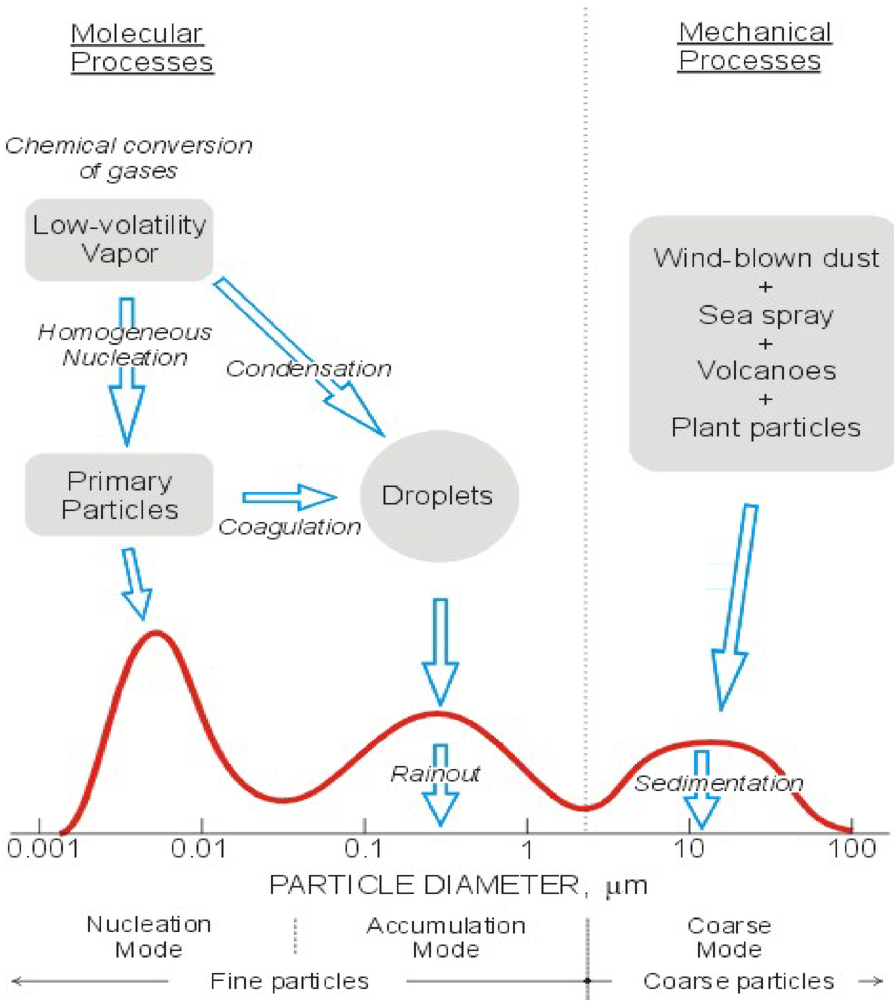


Figure 2.4 A "classical view" of the distribution of particle mass of atmospheric aerosols (from Whitby and Cantrell, 1976).

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).

Aerosols as CCN

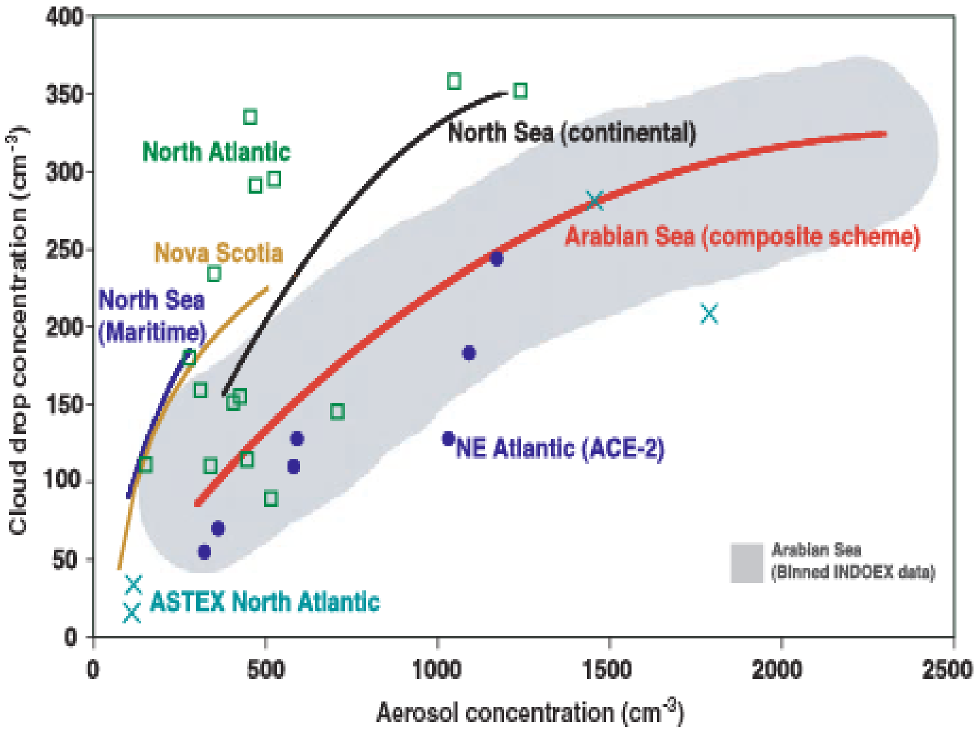


Figure 2.5 Summary of observations (Ramanathan et al., 2001).

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.