

Lecture 8

Properties of atmospheric aerosols and clouds

Objectives:

1. Properties of atmospheric aerosols
2. Properties of clouds and precipitation.
3. Refractive indices of water, ice, and aerosol species.

Required reading:

G: 1.6; 4.3

Additional/advanced reading

G: 4.2

1. Properties of atmospheric aerosols

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

- Aerosol particles vary greatly in sources, production mechanisms, sizes, chemical composition, amount, distribution in space and time, and how long they survive in the atmosphere (i.e. lifetime).

Important properties of atmospheric aerosols:

1) **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).

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

Aerosol vertical distribution: exponential decrease or/and multi-layered structure

3) **Particle sizes: fine mode** ($d < 2.5 \mu\text{m}$) and **coarse mode** ($d > 2.5 \mu\text{m}$);

fine mode is divided on the **nuclei mode** (about $0.005 \mu\text{m} < d < 0.1 \mu\text{m}$) and **accumulation mode** ($0.1 \mu\text{m} < d < 2.5 \mu\text{m}$).

NOTE: The distinction between fine and coarse particles is a fundamental because, in general, the fine and coarse particles mode originate separately, are transformed separately, are removed from the atmosphere by different mechanisms, have different chemical composition, have different optical properties, etc.

4) **Chemical composition: sulfate** (SO_4^{2-}), **nitrate** (NO_3^-), **soot** (elemental carbon), **sea-salt** (NaCl); **multi-component (MC)** aerosols, etc.;

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

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

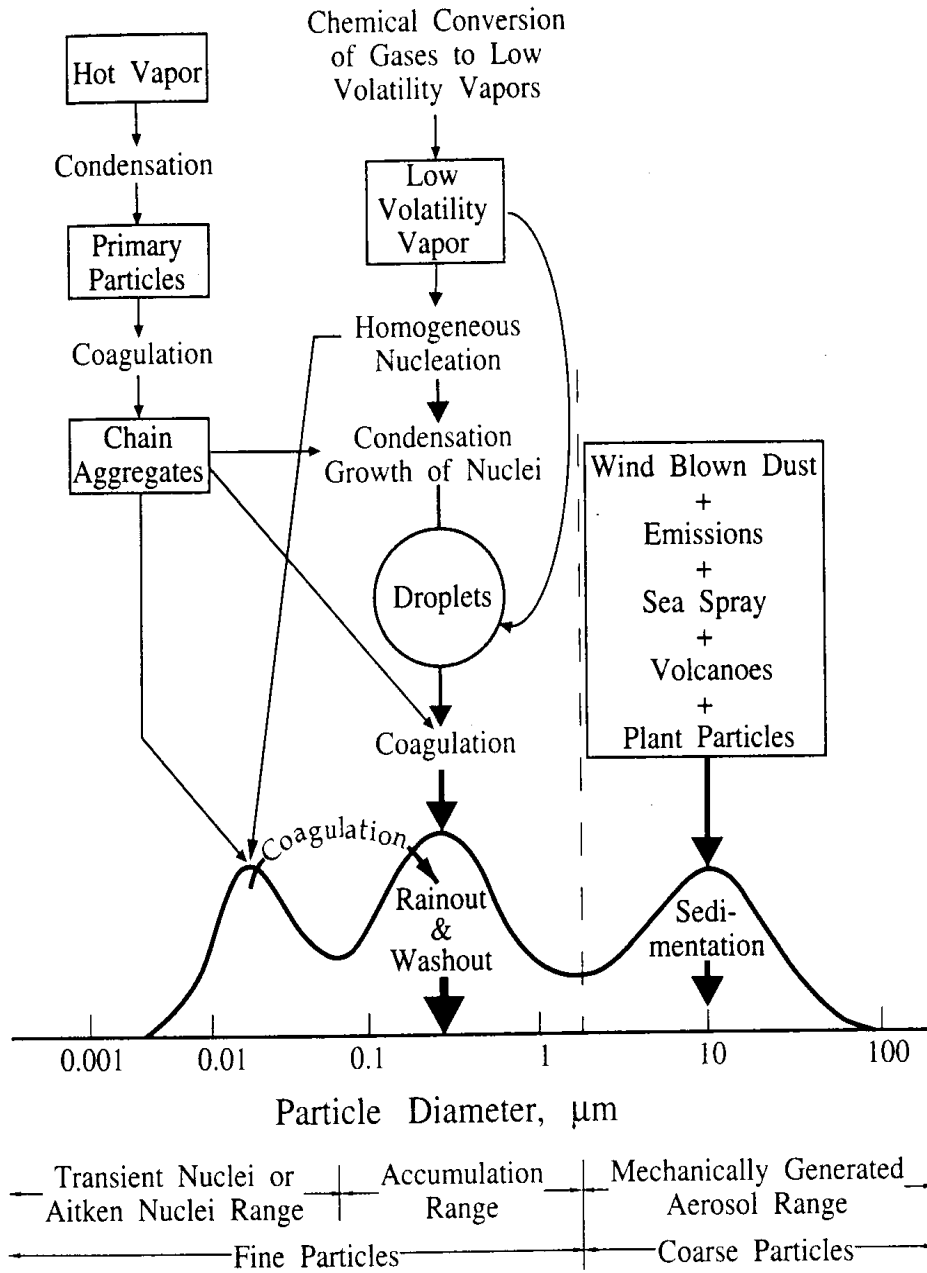
Anthropogenic sources: various (biomass burning, gas to particle conversion; industrial processes; agriculture's activities)

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

Aerosol concentration (number of aerosol particles/unit volume of air):

from 10^{-6} cm^{-3} to 10^7 cm^{-3}

Figure 8.1 Idealized schematic of the distribution of particle surface area of an atmospheric aerosols (from Whitby and Cantrell, 1976).



- **The particle size distribution** of aerosols are often approximated by a sun of three log-normal functions as

$$N(r) = \sum_i \frac{N_i}{\sqrt{2\pi} \ln(\sigma_i) r} \exp\left(-\frac{\ln(r / r_{0,i})^2}{2 \ln(\sigma_i)^2}\right) \quad [8.1]$$

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

Table 8.1 Aerosol components used in the MISR retrieval algorithm.

Aerosol type	r_0	r_{\min}	r_{\max}	σ	RH (%)	Vary with RH	H_b (km)	H_t (km)	H_s (km)	Shape	ρ g cm ⁻³
Sulfate/nitrate(1) (Accum. Mode)	0.07	0.007	0.7	1.86	0	yes	0	15	2	spheres	1.7
Sulfate/nitrate(2) (Accum. Mode)	0.45	0.05	2.0	1.3	0.3	no	15	30	10	spheres	1.7
Mineral dust (1) (Accum. mode)	0.47	0.05	2.0	1.0	0	no	0	5	2	Prolate/ Oblate spheroids	2.6
Mineral dust (2) (Accum. mode)							5	10	10		
Mineral dust (Coarse mode)							0	2	10		
Sea salt (Accum. mode)	0.35	0.05	1.0	2.51	0	yes	0	5	2	spheres	2.2
Sea salt (Coarse mode)	3.3	1.0	20.0	2.03	0	0	2	10			
Black carbon (or soot)	0.012	0.001	0.5	2.0	0	no	0	8	10	spheres	2.3
Carbonaceous	0.13	0.007	2.0	1.8	97	no	0	5	2	spheres	1.8

Here H_b is the base height of the aerosol layer; H_t is the top height of the aerosol layer, and H_s is the scale height of the aerosol layer; ρ is the density of an aerosol particle

NOTE: Similar models were proposed to characterize the regional aerosols (e.g., urban, maritime, continental, rural, industrial, polar, desert)

Table 8.2 IPCC global emission estimates for major aerosol types (**estimated flux Tg yr⁻¹**)

<i>Source</i>	<i>Low</i>	<i>High</i>	<i>Best</i>
NATURAL			
<u>Primary:</u>			
soil dust	1000	3000	1500
sea salt	1000	10000	1300
volcanic dust	4	10000	30
biological debris	26	80	50
<u>Secondary:</u>			
sulfates from biogenic gases	80	150	130
sulfates from volcanic SO ₂	5	60	20
organic matter from biogenic VOC	40	200	60
nitrates	15	50	30
<u>Total natural</u>	2200	23500	3100
ANTHROPOGENIC			
<u>Primary:</u>			
industrial particulates	40	130	100
dust	300	1000	600
soot	5	20	10
<u>Secondary:</u>			
sulfates from SO ₂	170	250	190
biomass burning	60	150	90
nitrates from NO _x	25	65	50
organics from anthropogenic VOC	5	25	10
<u>Total anthropogenic</u>	600	1640	1050
Total	2800	26780	4150

2. Properties of clouds and precipitation

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

Important properties of clouds:

- 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 $0.3\text{ g(water) m}^{-3}$ 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 8.3 Types and properties of clouds.

<i>Type</i>	<i>Height of base (km)</i>	<i>Freq. over oceans (%)</i>	<i>Coverage over oceans (%)</i>	<i>Freq. over land (%)</i>	<i>Coverage over land (%)</i>
Low level:					
Stratocumulus (Sc)	0-2	45	34	27	18
Stratus (St)	0-2	(Sc+St)	(Sc+St)	(Sc+St)	(Sc+St)
Nimbostratus (Ns)	0-4	6	6	6	5
Mid level:					
Altostratus (As)	2-7	46	22	35	21
Altostratus (As)	2-7	(Ac+As)	(Ac+As)	(Ac+As)	(Ac+As)
High level:					
Cirrus (Ci)	7-18	37	13	47	23
Cirrostratus (Cs)	7-18	Ci+Cs+Cc	Ci+Cs+Cc	Ci+Cs+Cc	Ci+Cs+Cc
Cirrocumulus (Cc)	7-18				
Clouds with vertical development					
Cumulus (Cu)	0-3	33	12	14	5
Cumulonimbus (Cb)	0-3	10	6	7	4

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

$$N(r) = \frac{N_0}{\Gamma(\alpha)r_n} \left(\frac{r}{r_n}\right)^{\alpha-1} \exp(-r/r_n) \quad [8.2]$$

where N_0 is the total number of droplets (cm^{-3}); r_n in the radius that characterizes the distribution ; α in the variance of the distribution, and Γ is the gamma function.

Table 8.4 Characteristics of representative size distributions of some clouds
(for $\alpha=2$)

Cloud type	N_0 (cm^{-3})	r_m (μm)	r_{\max} (μm)	r_e (μm)	LWC (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

- 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

$$r_e = \frac{\int \pi r^3 N(r) dr}{\int \pi r^2 N(r) dr} \quad [8.3]$$

where $N(r)$ is the droplet size distribution (e.g., in units $\text{m}^{-3}\mu\text{m}^{-1}$).

NOTE: **Mean** radius: $r_m = (\alpha + 1) r_n$ **Effective** radius: $r_e = (\alpha + 3) r_n$

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

$$LWC = \rho_w V = \frac{4}{3} \rho_w \int \pi r^3 N(r) dr \quad [8.4]$$

➤ **Raindrops**



Nonspherical particles: shape depends of size of a rain drop

- Raindrop size distribution is often represented by the **Marshall-Palmer distribution**:

$$N(r) = N_0 \exp(-2\Lambda r) \quad [8.5]$$

where $N_0 = 8 \times 10^3 \text{ m}^{-3} \text{ mm}^{-1}$, but, in general, N_0 depends on rain type;

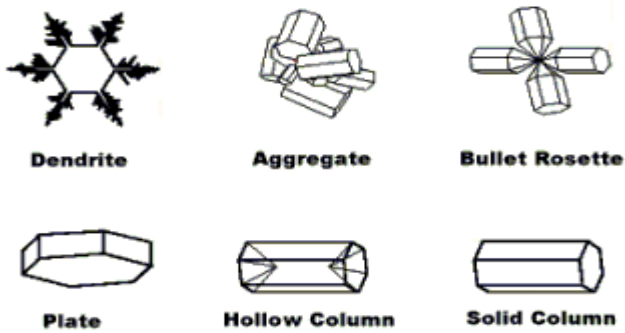
Λ is related to the rainfall rate, Rr , as $\Lambda = 4.1 Rr^{-0.21} \text{ mm}^{-1}$

➤ **Ice crystals**

- Depending on the atmospheric conditions, clouds may consist of ice crystals (e.g., cirrus clouds) or ice crystal/water droplet mixtures.
- Ice crystals often have the hexagonal structure with sizes on the order of several hundred micrometers. However, a large variety of shapes (called habits) and sizes of ice crystals have been reported.

NOTE: Growth of ice crystal habits is controlled by T and supersaturation with respect to ice (see figure 1.12 in the textbook)

Figure 8.2 Examples of ice habits.



3. Refractive indices of water, ice, and aerosol species.

- It is believed that the refractive indices of the medium (bulk material) (see Lecture 5) apply down to the smallest atmospheric aerosol particles.

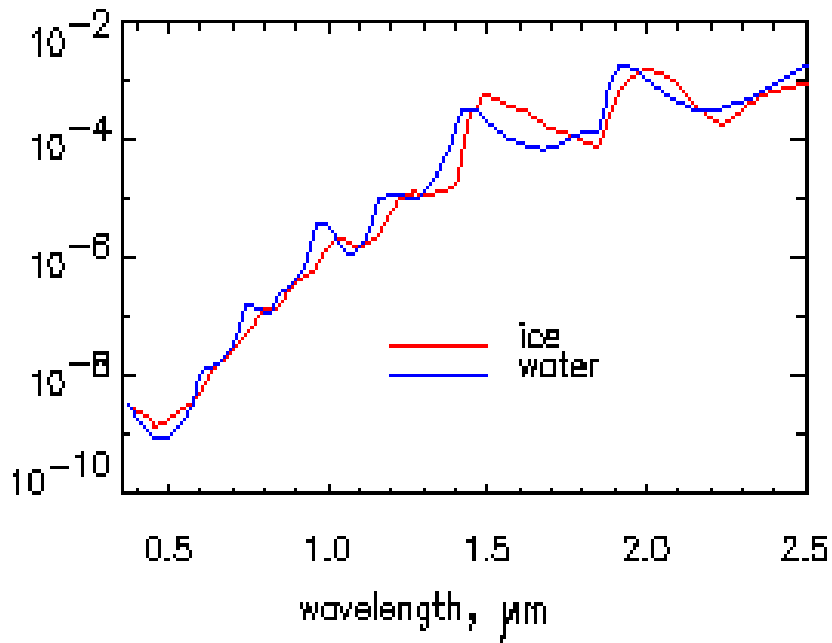


Figure 8.3 The imaginary part of the refractive index of water and ice.

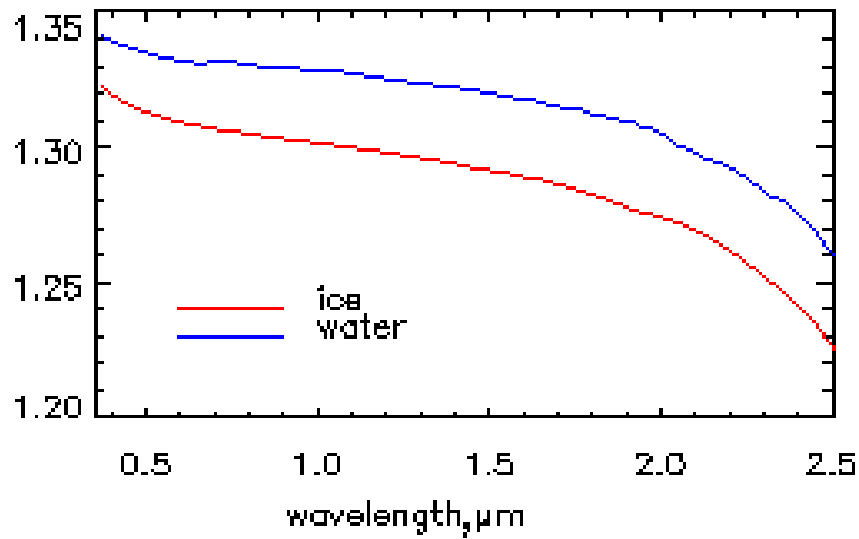


Figure 8.4 The real part of the refractive index of water and ice.

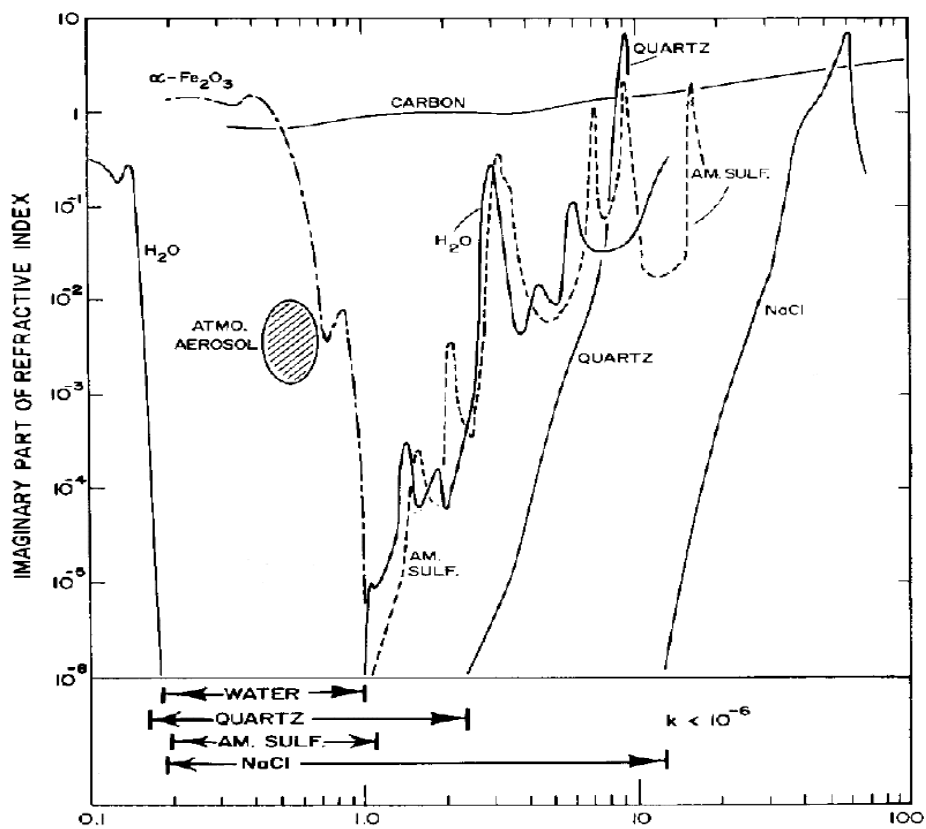


Figure 8.5 The imaginary part of the refractive indices of some aerosol species