Lecture 15

Scattering. Part 3: Scattering and absorption by water and ice cloud particles. Optics of non-spherical particles.

Objectives:

1. Scattering and absorption by cloud water droplets.
2. Scattering and absorption by cloud ice particles.
3. Optics of inhomogeneous and/or non-spherical or particles.

Required Reading:

L80: 5.6-5.7

Advanced Reading:

G&Y:7.7

1. Optics of cloud particles.

Recall Lecture 4 where we discussed the basic properties of clouds.

- In contrast to atmospheric aerosols, the cloud droplets consist of a single species – water. Thus, to calculate the absorption and scattering cross sections of cloud droplets, one needs to know the size of droplets and the refractive index of water versus wavelength.

NOTE: Cloud droplet sizes vary from a few micrometers to 100 micrometers with average diameter in 10 to 20 μm range (see Lecture 4).

Differences in optics of water drops and ice particles are due to

i) Particle shapes;

ii) Differences between the refractive indices of water and ice.

Figure 15.1 The imaginary part of the refractive index of water and ice.

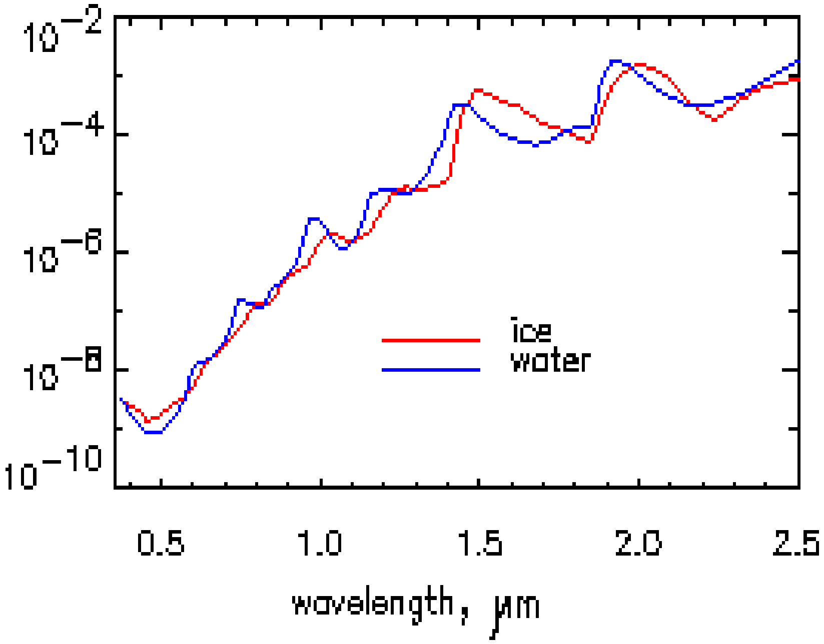
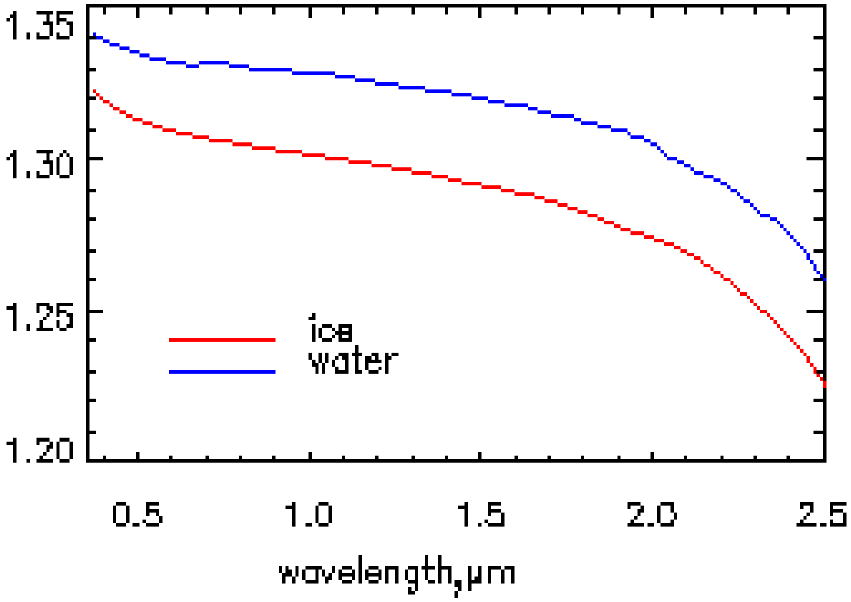
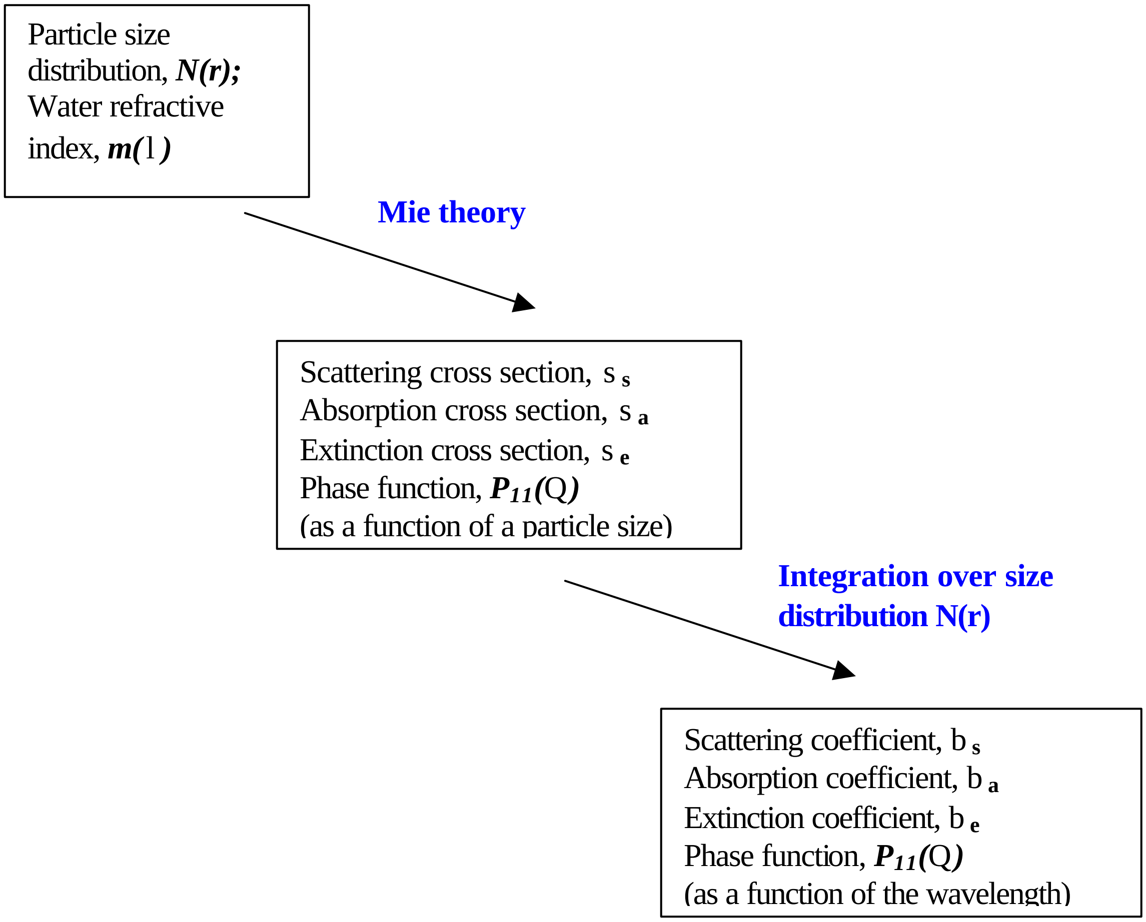


Figure 15.2 The real part of the refractive index of water and ice.



Strategy to compute optics of cloud water particles:



NOTE: The above strategy is the same as for the aerosol particles made of a single species.

- 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

$$r_e = \frac{\int p r^3 N(r) dr}{\int p r^2 N(r) dr} \qquad [15.1]$$

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

The **liquid water content** (LWC) was defined in Lecture 4:

$$LWC = r_w V = \frac{4}{3} r_w \int p r^3 N(r) dr \qquad [15.2]$$

Using that the extinction coefficient of cloud droplets is

$$b_e = \int s_e(r) N(r) dr = \int Q_e p r^2 N(r) dr$$

and that $Q_e \approx 2$ for water droplets at solar wavelengths, we have

$$b_e \approx \frac{3}{2} \frac{LWC}{r_e} \qquad [15.3]$$

The parameterizations of the optical properties of clouds vs LWC and r_e:

$$\begin{aligned} b_e &= LWC(a_1 r_e^{a_2} + a_3) \\ 1 - v_0 &= a_4 r_e^{a_5} + a_6 \qquad [15.4] \\ g &= a_7 r_e^{a_8} + a_9 \end{aligned}$$

where $\boldsymbol{a_i}$ are the coefficients determined by fitting these expressions to exact computations using Mie theory; w_0 is the single scattering albedo and ***g*** is the **asymmetry factor.**

The ***asymmetry factor g*** is defined as

$$\boxed{g = \frac{1}{2} \int_{-1}^{1} P(\cos \Theta) \cos \Theta \, d(\cos \Theta)} \qquad [15.5]$$

NOTE: A set of optical characteristics b_e, w_0 and ***g*** is required to perform the radiative transfer calculation in a two-stream approximation which often used in the climate models (will be discussed later in Lecture 18).

g=0 for isotropic scattering

g>0 scattering in the forward direction

g<0 scattering in the backward direction

2. Scattering and absorption by cloud ice particles.

- 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 and sizes of ice crystals have been reported.

Optical properties of ice crystals depend on

i) Sizes and shapes;
ii) Orientations
iii) Ice refractive index

Approaches to predict ice crystal optics:

i) Ray-optics approach (also called ray tracing approach) based on geometrical optics for the size parameters of 15-20 and larger;
ii) Finite differences time domain (FDTD) method for the size parameters smaller than about 20;
iii) Laboratory measurements of optical properties (e.g., phase function) of the ice crystals of known shapes and sizes.

NOTE: Improved ray tracing techniques use the Monte Carlo method to trace photons in complex ice crystals, accounting for absorption and polarization. For the recent review of various techniques, see Liou K.N., Y. Takano and P.Yang, Light scattering and radiative transfer in ice crystal clouds: applications to climate research in Light Scattering by Nonspherical Particles, Academic Press, 2000.

3. Optics of inhomogeneous and/or non-spherical particles.

- In climate and remote sensing applications, it is often assumed that aerosol particles are spherical and homogeneous. However, aerosol particles often consist of several chemical species (called the internal mixture) and can have various shapes.

Strategy to characterize aerosol optics:

Consider a collection of aerosol particles as the external mixture of particles made of a single species and/or internally mixed particles.

There are several approaches (called **mixing rules**) to calculate the **effective refractive index** m_e of the internally mixed particles using the refractive indices of the individual species:

a) **Volume (or mass) weighted mixing**:

$$m_e = \sum_j m_j f_j$$

where m_j is the refractive index of j-species and f_j is its volume fraction.

b) **Bruggeman approximation** for two randomly mixed species:

$$f_1 \frac{e_1 - e_e}{e_1 + 2e_e} + f_2 \frac{e_2 - e_e}{e_2 + 2e_e} = 0$$

where e_i are the dielectric constants of two materials and f_i are their volume fractions.

Recall that the refractive index is $m = \sqrt{e}$

c) **Maxwell-Garnett approximation** for two specious when one is a matrix (host material) with the dielectric constant e_2 and another is an inclusion with e_1:

$$f_1 \frac{e_1 - e_2}{e_1 + 2e_2} = \frac{e_e - e_2}{e_e + 2e_2}$$

$$f_2 \frac{e_2 - e_1}{e_2 + 2e_1} = \frac{e_e - e_1}{e_e + 2e_1}$$

NOTE: b) and c) approaches can be extended for the n-component mixtures.

Optical properties of the external mixture of i-species are

$$b_e = \sum_i b_e^i \qquad b_s = \sum_i b_s^i \qquad b_a = \sum_i b_a^i$$

where b_e^i , b_s^i and b_a^i are calculated for each particle type characterized by the particle size distribution $N_i(r)$ and a refractive index (or effective refractive index) m_i, using Mie theory or other approaches depending on the particle shape.

NOTE: If an atmospheric layer has molecules, aerosols and/or cloud particles, one calculates the **effective properties** of this layer as an external mixture of the optical properties of these constituents.

Approaches to calculate optical properties of non-spherical particles:

i) Extension of Mie theory: calculates the optical properties of two concentric spheres; cylinders, disks

ii) Geometrical optics approximation (for sizes much larger than the wavelength);

iii) T-matrix technique: calculates the optical properties of axisymmetric particles (i.e., bodies-of-revolution, for instance, spheroids);

iv) Discrete dipole approximation (DDA) (also called the coupled dipole approximation): calculates the optical properties of the particles of any shapes with sizes smaller than about 5λ.