Lecture 5.
Composition and structure of the Earth’s atmosphere.

Basic properties of gases, aerosols, and clouds that are important for radiative transfer modeling.

Objectives:
1. Structure of the Earth’s atmosphere and radiative transfer modeling.
2. Basic properties of atmospheric gases.
3. Basic properties of aerosols.
4. Basic properties of clouds.
5. Refractive indices of common atmospheric particulates.

Required reading:
L02: 3.1, 5.1, pp.169-176

1. Basic properties of planetary atmospheres, Structure of the Earth’s atmosphere and radiative transfer modeling.
   ✓ Propagation of the electromagnetic radiation in an atmosphere is affected by the state of the atmosphere (temperature, pressure, air density) and atmospheric composition (gases and particulates)

Interactions of atmospheric constituents with radiation:
   ✓ Gases – all scatter radiation, and some can absorb (and emit) radiation depending on their molecular structure
   ✓ Particulates (aerosol and clouds) – all scatter radiation, and some can absorb (and emit) radiation depending on their refractive indices (determined by composition)
**Dimensionality of radiation transfer**

- Radiative transfer in models (NWPs, CTMs, GCMs, etc.) is commonly solved in one dimension (1-D) based on the concept of the plane parallel atmosphere (see Fig. 3.4 in Lec 3).

**EXAMPLE:** In global and regional climate models, radiative transfer is solved in each column defined by model grid size. The vertical resolution is the same as the number of vertical layers in the model.

- Three-dimensional (3-D) radiative transfer codes are mainly used in cloud studies (e.g., LES models) and vegetation studies.

Schematic of 3-D radiative field in vegetation (left) and 3-D ice water content of a cirrus cloud.
Planets 101

Basic properties and composition of terrestrial planet atmospheres:

Temperature profile

Atmospheric composition
Atmospheric structure of giant planets:

NOTE: “Surface” and “atmosphere” are not always clearly defined (unlike for the Earth) – see example for Jupiter below.
Practically any 1-D RT code includes a set of standard atmospheric models. Each model consists of profiles of T, P, and concentrations of main atmospheric gases.

**Figure 5.1** Temperature profiles (top), water and ozone density (bottom) of the standard atmospheric models often used in radiative transfer calculations. “Standard U.S. 1976 atmosphere” is representative of the global mean atmospheric conditions; “Tropical
“Subtropical atmosphere” is for latitudes between 30° and 45°; “Subarctic atmosphere” is for latitudes between 45° and 60°; and “Arctic atmosphere” is for latitudes > 60°.

2. Atmospheric gases.

Table 5.1 Gaseous composition of the Earth’s atmosphere

<table>
<thead>
<tr>
<th>Gases</th>
<th>% by volume</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constant gases</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen, N₂</td>
<td>78.084%</td>
<td>Photochemical dissociation high in the ionosphere; mixed at lower levels</td>
</tr>
<tr>
<td>Oxygen, O₂</td>
<td>20.948%</td>
<td>Photochemical dissociation above 95 km; mixed at lower levels</td>
</tr>
<tr>
<td>Argon, Ar</td>
<td>0.934%</td>
<td>Mixed up to 110 km</td>
</tr>
<tr>
<td>Neon, Ne</td>
<td>0.001818%</td>
<td>Mixed in most of the middle atmosphere</td>
</tr>
<tr>
<td>Helium, He</td>
<td>0.000524%</td>
<td></td>
</tr>
<tr>
<td>Krypton, Kr</td>
<td>0.00011%</td>
<td></td>
</tr>
<tr>
<td>Xenon, Xe</td>
<td>0.000009%</td>
<td></td>
</tr>
<tr>
<td><strong>Variable gases</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water vapor, H₂O</td>
<td>4.0% (maximum, in the tropics) 0.00001% (minimum, at the South Pole)</td>
<td>Highly variable; photodissociates above km dissociation</td>
</tr>
<tr>
<td>Carbon dioxide, CO₂</td>
<td>0.0365% (~0.4% per year)</td>
<td>Slightly variable; mixed up to 100 km; photodissociates above</td>
</tr>
<tr>
<td>Methane, CH₄</td>
<td>~0.00018% (increases due to agriculture)</td>
<td>Mixed in troposphere; dissociates in mesosphere</td>
</tr>
<tr>
<td>Hydrogen, H₂</td>
<td>~0.00006%</td>
<td>Variable photochemical product; decreases slightly with height in the middle atmosphere</td>
</tr>
<tr>
<td>Nitrous oxide, N₂O</td>
<td>~0.00003%</td>
<td>Slightly variable at surface; dissociates in stratosphere and mesosphere</td>
</tr>
<tr>
<td>Carbon monoxide, CO</td>
<td>~0.000009%</td>
<td>Variable</td>
</tr>
<tr>
<td>Ozone, O₃</td>
<td>~0.000001% - 0.0004%</td>
<td>Highly variable; photochemical origin</td>
</tr>
<tr>
<td>Fluorocarbon 12, CF₂Cl₂</td>
<td>~0.00000005%</td>
<td>Mixed in troposphere; dissociates in stratosphere</td>
</tr>
</tbody>
</table>
The amount of the gas can be expressed in several ways:

i) Molecular number density = molecular number concentration = molecules per unit volume of air;

ii) Density = molecular mass concentration = mass of gas molecules per unit volume of air;

iii) Mixing ratios:

Volume mixing ratio is the number of gas molecules in a given volume to the total number of all gases in that volume (when multiplied by $10^6$, in ppmv (parts per million by volume))

Mass mixing ratio is the mass of gas molecules in a given volume to the total mass of all gases in that volume (when multiplied by $10^6$, in ppmm (parts per million by mass))

**NOTE:** Commonly used mixing fraction: one part per million 1 ppm ($1 \times 10^{-6}$);
one part per billion 1 ppb ($1 \times 10^{-9}$); one part per trillion 1 ppt ($1 \times 10^{-12}$).

iv) Mole fraction is the ratio of the number of moles of a given component in a mixture to the total number of moles in the mixture.
The structure of molecules is important for an understanding of their energy forms and their ability to absorb/emit radiation:

✓ Linear molecules (CO2, N2O; C2H2, all diatomic molecules):
✓ Symmetric top molecules (NH3, CH3CL, CF3CL)
✓ Spherical symmetric top molecules (CH4)
✓ Asymmetric top molecules (H2O, O3)
✓ The structure of a molecule determines whether the molecule has a permanent dipole or may acquire the dipole. The presence of the dipole is required for absorption/emission processes by the molecules (see Lecture 6).

Figure 5.3 Molecular structures of key atmospheric gases and their dipole moment.
3. Basic properties of 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, 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$_4$).

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

✓ 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:**

\[ N(r) = \frac{N_0}{\sqrt{2\pi} \ln(\sigma)} \exp\left(-\frac{\ln(r / r_0)^2}{2 \ln(\sigma)^2}\right) \] \[ [5.1] \]

Normalization:

\[ \int N(r) dr = N_0 \] \[ [5.2] \]

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

\[ N(r) = \sum_i \frac{N_i}{\sqrt{2\pi} \ln(\sigma_i)} \exp\left(-\frac{\ln(r / r_{0,i})^2}{2 \ln(\sigma_i)^2}\right) \] \[ [5.3] \]

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 \( \sigma_i \).

**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):

\[ \int r^k N(r) dr = N_0 r_0^k \exp(k^2 (\ln \sigma)^2 / 2) \] \[ [5.4] \]
Figure 5.4 A “classical view” of the distribution of particle mass of atmospheric aerosols (from Whitby and Cantrell, 1976).

**NOTE:** Fine mode \((d < \sim 2.5 \, \mu m)\) and coarse mode \((d > \sim 2.5 \, \mu m)\); fine mode is divided on the nuclei mode \((0.005 \, \mu m < d < 0.1 \, \mu m)\) and accumulation mode \((0.1 \mu m < d < 2.5 \, \mu m)\).
Shapes of aerosol particles: many are spherical but not all!
Along with size and composition, particle shape (spherical vs. non-spherical) is an important factor that affects how particle scatter and absorb radiation.

Figure 5.5 Schematic representation of the aerosol size distribution and electronic images of representative aerosol types.
4. Basic properties of 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 5.2 Types and properties of clouds.

<table>
<thead>
<tr>
<th>Type</th>
<th>Height of base (km)</th>
<th>Freq. over oceans (%)</th>
<th>Coverage over oceans (%)</th>
<th>Freq. over land (%)</th>
<th>Coverage over land (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratocumulus(Sc)</td>
<td>0-2</td>
<td>45 (Sc+St)</td>
<td>34 (Sc+St)</td>
<td>27 (Sc+St)</td>
<td>18 (Sc+St)</td>
</tr>
<tr>
<td>Stratus (St)</td>
<td>0-2</td>
<td>6 (Sc+St)</td>
<td>6 (Sc+St)</td>
<td>6 (Sc+St)</td>
<td>5 (Sc+St)</td>
</tr>
<tr>
<td>Nimbostratus (Ns)</td>
<td>0-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altocumulus (Ac)</td>
<td>2-7</td>
<td>46 (Ac+As)</td>
<td>22 (Ac+As)</td>
<td>35 (Ac+As)</td>
<td>21 (Ac+As)</td>
</tr>
<tr>
<td>Altostratus (As)</td>
<td>2-7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nimbostratus (Ns)</td>
<td>0-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cirrus (Ci)</td>
<td>7-18</td>
<td>37 Ci+Cs+Cc</td>
<td>13 Ci+Cs+Cc</td>
<td>47 Ci+Cs+Cc</td>
<td>23 Ci+Cs+Cc</td>
</tr>
<tr>
<td>Cirrostratus (Cs)</td>
<td>7-18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cirrocumulus (Cc)</td>
<td>7-18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cumulus (Cu)</td>
<td>0-3</td>
<td>33</td>
<td>12</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Cumulonimbus(Cb)</td>
<td>0-3</td>
<td>10</td>
<td>6</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

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

\[
N(r) = \frac{N_0}{\Gamma(\alpha) r_n} \left( \frac{r}{r_n} \right)^{\alpha-1} \exp(-r / r_n) \tag{5.5}
\]

where \(N_0\) is the total number of droplets (cm\(^{-3}\)); \(r_n\) in the radius that characterizes the distribution; \(\alpha\) in the variance of the distribution, and \(\Gamma\) is the gamma function.
Table 5.3 Characteristics of representative size distributions of some clouds (for $\alpha = 2$)

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

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

- 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

$$r_e = \frac{\int r^3 N(r) dr}{\int r^2 N(r) dr} \quad [5.6]$$

where $N(r)$ is the droplet size distribution.

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

$$LWC = \rho_w V = \frac{4}{3} \rho_w \int r^3 N(r) dr \quad [5.7]$$

**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 the clouds.
5. Refractive indices of common atmospheric particulates.

Refractive index (or optical constants), \( m = n - ik \), is the material properties of dielectric that determines its radiative properties. In general, each material has its own spectral refractive index. The imaginary part \( k \) of the refractive index determines the absorption of the EM wave as it propagates through the medium; the real part \( n \) of the refractive index gives the phase velocity of propagation.
✓ It is believed that the refractive indices of the (bulk material apply down to the smallest atmospheric aerosol particles.
✓ The refractive index is a function of wavelength. Each substance has a specific spectrum of the refractive index.
✓ Particles of different sizes, shapes and indices of refraction will have different scattering and absorbing properties.

**Examples of refractive indices:**

![Figure 5.7](image-url) The complex refractive index of water and ice.
Figure 5.7 A “classical plot” showing the imaginary part of the refractive indexes of some aerosol materials (Bohren and Huffman, 1983, Fig.5.16).

NOTE: Main absorbing species in the SW are black carbon (soot) and hematite (dust), but in the LW various species have high imaginary parts of the refractive index. But overall absorption (i.e., absorption coefficient) is also controlled by particle size.
• Aerosol particles often consist of several chemical species (called the internal mixture).

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:**

$$m_e = \sum_j m_j f_j$$  \[5.8\]

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:

$$f_1 \frac{\varepsilon_1 - \varepsilon_e}{\varepsilon_1 + 2\varepsilon_e} + f_2 \frac{\varepsilon_2 - \varepsilon_e}{\varepsilon_2 + 2\varepsilon_e} = 0$$  \[5.9\]

where $\varepsilon_i$ are the dielectric constants of two materials and $f_i$ are their volume fractions.

The refractive index is $m = \sqrt{\varepsilon}$

C) **Maxwell-Garnett approximation** for two specious when one is a matrix (host material) with the dielectric constant $\varepsilon_2$ and another is an inclusion with $\varepsilon_1$:

$$f_1 \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 + 2\varepsilon_2} = \frac{\varepsilon_e - \varepsilon_2}{\varepsilon_e + 2\varepsilon_2}$$  \[5.10\]

$$f_2 \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1} = \frac{\varepsilon_e - \varepsilon_1}{\varepsilon_e + 2\varepsilon_1}$$

**NOTE:** B) and C) approaches can be extended for the n-component mixtures.