AOSC 621
Physics and Chemistry of
the Atmosphere II:
Radiative Transfer

LESSON 1
AOSC 621 - PHYSICS AND CHEMISTRY OF THE ATMOSPHERE II

- *Chemistry of Atmospheres*, Richard P. Wayne, Oxford University Press

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Lessons
- Tuesday 9.00 am to 10.15 am
- Thursday 9.00 am to 10.15 am

Office hours
- No set office hours will be posted. Students may come by my office at any time.
- If you wish to make a formal appointment - send me an e-mail, or call me ahead.

The textbooks listed above cover most of the material given in this course. However, some contents may be extracted from other books. PowerPoint presentations will be prepared for each class, these will contain any material not covered by either book. The .ppt files will be distributed after each class.

In addition to the homework, projects will be assigned. There will be two exams, a mid-term exam and a final exam. 60% of the final grade will be based on these two exams, 20% on the project, and the remaining 20% on the homework assignments. Mid exam: March 15
The purpose of this course is twofold:

1. To examine how solar radiation is transferred through the atmosphere, absorbed by the Earth, and re-emitted by the Earth and atmosphere.

2. To examine how this radiation drives the dynamics and chemistry of the atmosphere.
Earth’s (long-term) energy balance

solar incident = solar reflected + Earth emitted
Atmospheric composition

Table 1.1 The composition of the atmosphere

<table>
<thead>
<tr>
<th>Permanent constituents</th>
<th>Variable constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constituent</strong></td>
<td><strong>% by volume</strong></td>
</tr>
<tr>
<td>Nitrogen (N\textsubscript{2})</td>
<td>78.084</td>
</tr>
<tr>
<td>Oxygen (O\textsubscript{2})</td>
<td>20.948</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.934</td>
</tr>
<tr>
<td>Carbon dioxide (CO\textsubscript{2})</td>
<td>0.034</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>18.18 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>5.24 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
<td>1.14 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Xenon (Xe)</td>
<td>0.089 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Hydrogen (H\textsubscript{2})</td>
<td>0.5 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Methane (CH\textsubscript{4})</td>
<td>1.7 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Nitrous oxide (N\textsubscript{2}O)\textsuperscript{b}</td>
<td>0.3 \times 10\textsuperscript{-4}</td>
</tr>
<tr>
<td>Carbon monoxide (CO)\textsuperscript{b}</td>
<td>0.08 \times 10\textsuperscript{-4}</td>
</tr>
</tbody>
</table>

\textsuperscript{a} After the U.S. Standard Atmosphere (1976) with modifications.

\textsuperscript{b} Concentration near the earth’s surface.
Composition of the Earth’s Troposphere

- **N₂**
- **O₂**
- **H₂**
- **CH₄**
- **N₂O**
- **CO₂**
- **PM**
- **CO**
- **O₃**
- **SO₂, NO₂, CFC’s, etc**
- **Ar**
- Inert gases
Height profiles for minor species

- **Species:**
  - Chlorofluorocarbons, $\text{CCl}_3\text{F}$ and $\text{CCL}_2\text{F}_2$
  - Nitrous oxide, $\text{N}_2\text{O}$
  - Methane, $\text{CH}_4$
  - Nitric acid, $\text{HNO}_3$
  - Carbon monoxide, $\text{CO}$
  - Carbon dioxide, $\text{CO}_2$.

- Note that the $\text{CO}_2$ line is vertical. This signifies that $\text{CO}_2$ is well mixed in the atmosphere and has no significant chemical loss or production.

- The lines for the chlorofluorocarbons and nitrous oxide are vertical in the troposphere (well mixed) but suffer chemical loss in the stratosphere.
Height profiles for minor species
HYDROSTATIC EQUATION

\[
d p = -g \rho \, dz. \tag{1.1}
\]

For planetary atmospheres of moderate and low density, and specifically the Earth’s atmosphere, the equation of state is closely approximated by the *ideal gas law*,

\[
\rho = \frac{\tilde{M} \, p}{RT} = \tilde{M} \, n, \tag{1.2}
\]

where \( \tilde{M} \) is the *mean molecular mass*, \( R \) is the *gas constant per mole*, and \( n \) is the total *concentration* of molecules (number of molecules per unit volume). More detailed descriptions of each of the above quantities are given below. Substituting Eq. 1.2 into Eq. 1.1, we find

\[
\frac{d p}{p} = -\frac{d z}{H}, \quad \text{where} \quad H = \frac{RT}{\tilde{M} \, g}. \tag{1.3}
\]

Where \( H \) is called the atmospheric scale height
Three forms of the hydrostatic equation

\[ p(z) = p(z_0) \exp \left[ - \int_{z_0}^{z} \frac{dz'}{H(z')} \right], \quad (1.4a) \]

\[ n(z) = n(z_0) \frac{T(z_0)}{T(z)} \exp \left[ - \int_{z_0}^{z} \frac{dz'}{H(z')} \right], \quad (1.4b) \]

\[ \rho(z) = \rho(z_0) \frac{T(z_0)}{T(z)} \exp \left[ - \int_{z_0}^{z} \frac{dz'}{H(z')} \right]. \quad (1.4c) \]
Pressure and Atmospheric Mass

- The hydrostatic relationship tells us that the pressure decreases exponentially with height.

- A hydrostatically balanced atmosphere does not mean that there is no vertical motion. There still can be vertical motion (topographically forced vertical motion), but no acceleration or deceleration.

- But a non-hydrostatic balance atmosphere column would have severe up/down draft (gravity waves) => typically in thunderstorm (very short time over a small area).
Global Energy Flows \( W \text{ m}^{-2} \)

- Reflected Solar Radiation: 101.9 \( W \text{ m}^{-2} \)
- Incoming Solar Radiation: 341.3 \( W \text{ m}^{-2} \)
- Outgoing Longwave Radiation: 238.5 \( W \text{ m}^{-2} \)

Trenberth et al., 2009, BAMS
Radiation

- Primary Energy transfer mechanisms in the atmosphere and oceans

- Phase Change (ice <-> water <-> water vapor)
- Vertical convection (including turbulent heat and momentum fluxes at the (land and ocean) surface.
- Meridional mass circulation driven by equator-pole heating contrast.
- West-east mass circulation driven by west-east thermal and mechanic contrasts (land-ocean, sea surface temperature variation, and orography).
Radiation - quantity and quality

- To describe electromagnetic radiation, we need to provide information about the amount of energy transferred (quantity), and the type, or quality, of the energy.

- In the case of radiation, quantity is associated with the height of the wave, or its amplitude. Everything else being equal, the amount of energy carried is directly proportional to wave amplitude.

- The quality, or “type,” of radiation is related to another property of the wave, the distance between wave crests (wavelength).

- The radiation emitted by an object obey some fundamental physical laws => the amount of radiation (quantity) emitted and its wavelength (quality) is related.
Electromagnetic Radiation

• By analogy a stream of particles can be considered as a wave.
• The chemistry of the atmosphere is dominated by radicals derived from the dissociation of atmospheric species.
• It is much easier to picture this dissociation as the interaction of a photon with a molecule than as an interaction of a wave with the molecular field.
• Dissociation requires a threshold of energy, i.e. a certain frequency. Only photons with an energy (frequency) above this threshold will cause dissociation.
Electromagnetic spectrum
Electromagnetic spectrum

- Most of the energy that drives the dynamics comes from a narrow band of frequencies known as the visible spectrum - heats the ground
- Most of the energy that drives the chemistry of the atmosphere comes from the ultraviolet part of the spectrum - high energy photons.
- Most of the energy that heats the atmosphere is thermal radiation from the ground
Schematic of a wave
WAVELENGTH

• DISTANCE BETWEEN SUCCESSIVE PEAKS
• GIVEN THE SYMBOL $\lambda$
• MANY UNITS USED:
  • (A) MICRON, $10^{-6}$ METERS
  • (B) NANOMETER, $10^{-9}$ METERS
  • (C) ANGSTROM, $10^{-10}$ METERS
FREQUENCY

Defined as the number of maxima that pass an observer per second
Given the symbol $\nu$

\[ c = \lambda \nu \]

Wave number is also used. It is the reciprocal of the wavelength
In the textbook it is given the symbol $\bar{\nu}$

Caution - the use of $\nu$ and $\bar{\nu}$ are reversed in many textbooks
VELOCITY

• WAVE VELOCITY IS DEFINED AS THE DISTANCE A PEAK MOVES IN ONE SECOND.

• IN VACUO THE WAVE VELOCITY OF AN ELECTROMAGNETIC WAVE IS $2.997925 \times 10^8$ METERS PER SECOND

• THE WAVE VELOCITY IS GIVEN THE SYMBOL $c$. 
SOLAR ENERGY

• Solar constant – energy from the sun that falls on unit surface normal to the line from the sun, per unit time, at the outside of the atmosphere at the mean solar distance

\[ S = 1.368 \text{ Kw per meter}^2 \]

• S is integrated over all wavelengths

• S varies with the sunspot cycle
Measurements of total solar irradiance 1979-2000

Total Solar Irradiance: Original Data (top) and Composite (bottom)
Days (Epoch Jan. 0, 1980)
SOLAR SPECTRUM

• A blackbody curve for a temperature of 6000K matches the observed solar spectrum.
• The difference between the 6000K spectrum below about 400 nm is due to absorption in the photosphere.
• The structures shown below 400 nm are known as Fraunhoffer lines.
UV-VISIBLE SOLAR SPECTRUM
OBSERVED FROM THE GROUND
Absorption spectra of atmospheric gases

- CH$_4$
- N$_2$O
- O$_2$ & O$_3$
- CO$_2$
- H$_2$O

*WAVELENGTH (micrometers)*

- H$_2$O dominates >15 µm

*IR Windows*
UV-VISIBLE SOLAR SPECTRUM OBSERVED FROM THE GROUND

• Slide shows the absorption of the solar radiation by the atmosphere.
• Major absorbers are molecular oxygen ($O_2$), ozone ($O_3$), water vapor ($H_2O$) and carbon dioxide ($CO_2$).
• The wavelength is in nm. 1000nm is equal to one micron.
INFRARED FLUX FROM EARTH
SAHARA
INFRARED FROM EARTH
ANTARCTIC
SOLAR GEOMETRY
EFFECTIVE AREA

• If the solar zenith angle (SZA) of the sun is \( \theta \), then the effective area is given by \( \frac{1}{\cos \theta} \).
• Hence the energy on unit area at the surface is \( S \) divided by the effective area, i.e. \( S \cdot \cos \theta \).
• College Park is at a latitude of 39 degrees.
• At summer solstice the SZA is 17 degrees, and at the winter solstice 61 degrees.
• The ratio of the effective areas is 1.97, i.e. twice as much energy per unit area is incident on College Park at summer solstice than at winter solstice.
Optical line-of-sight paths

Figure 1.5 Geometry of the slant-column number. The right-circular cylinder of unit geometrical cross section contains $N$ molecules (number per m$^2$).

Note that the angle defined here is the polar angle.
Slant column mass

\[ \mathcal{M}_i(1, 2) = \int_1^2 ds \rho_i(s) \approx \rho_i(z_0) \int_1^1 ds e^{-[z_2(s) - z_1(s)]/H_i}. \]  

Referring to Fig. 1.5, we transform from the variable \( ds \) to \( dz \); \( ds = dz \sec \theta \), where \( \theta \) is the polar angle \((0 \leq \theta < \pi/2)\) made by the vector \( \hat{\mathbf{\Omega}} \) with the vertical, \( \cos \theta = |\hat{z} \cdot \hat{\mathbf{\Omega}}| \). \( \hat{z} \) is a unit vector in the positive \( z \) direction. Integration of the above equation yields

\[ \mathcal{M}_i(1, 2) = \rho_i(z_0) H_i \sec \theta \left( e^{-z_1/H_i} - e^{-z_2/H_i} \right) \]
\[ = [\rho_i(z_1) - \rho_i(z_2)] H_i \sec \theta. \]