Atmospheric Radiation

Last time: pressure, temperature, density, basic thermodynamics

Today: The Fundamentals of Solar and Terrestrial Radiation

Please read Chapter 2 in Ahrens and Henson
Conduction - Heat Transfer

Conduction of heat occurs as warmer molecules conduct heat to adjacent cooler molecules.

Heat conduction is by “hot” molecules bumping into “cold” molecules, transferring kinetic energy from hot to cold.

Warm ground surfaces heat overlying air by conduction.

Figure 2.5
Convection is heat energy moving as a fluid from hotter to cooler areas.

Warm air at the ground surface rises as a thermal bubble, expends energy to expand, and hence cools. This process constantly goes on around us, especially on a clear, sunny day.
Electromagnetic Radiation

Radiation travels as waves or “photons”

Waves do not require molecules to propagate

Electromagnetic waves come in all forms, short to long

The shorter the wavelength, or higher the frequency, the more energy the wave carries

<table>
<thead>
<tr>
<th>TYPE OF RADIATION</th>
<th>RELATIVE WAVELENGTH</th>
<th>TYPICAL WAVELENGTH (meters)</th>
<th>ENERGY CARRIED PER WAVE OR PHOTON</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM radio waves</td>
<td></td>
<td>100</td>
<td>Increasing</td>
</tr>
<tr>
<td>Television waves</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Microwaves</td>
<td></td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Infrared waves</td>
<td></td>
<td>$10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Visible light</td>
<td></td>
<td>$5 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>Ultraviolet waves</td>
<td></td>
<td>$10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>X rays</td>
<td></td>
<td>$10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>
Ways to label radiation

• By its source
  - Solar radiation - originating from the sun
  - Terrestrial radiation - originating from the earth

• By its name
  - ultra violet, visible, near infrared, infrared, microwave, etc....

• By its wavelength
  - short wave radiation $\lambda \leq 3$ micrometers
  - long wave radiation $\lambda > 3$ micrometers
  - One micron is one millionth of a meter
Black Body Radiators

• Hypothetical objects that absorb all of the radiation that strikes them. They also emit radiation at a maximum rate for its given temperature.
  - Does not have to be black to do so.
• The energy emission rate is given by
  - Stefan Boltzmann law (total energy)
  - Wien’s law (peak emission wavelength)
  - Planck’s law (wavelength dependent emission)
Basic Radiation Laws

• Stefan-Boltzmann law:
  - \( E = \sigma T^4 \) (energy flux in Watts/m\(^2\))
  - As \( T \) increases, \( E \) increases by a power of 4.
    If \( T \) doubles, \( E \) increases by 16 times!

• Wien’s law:
  - \( \lambda_{\text{max}} \sim 3000/T \) (\( \lambda_{\text{max}} \) is in µm and \( T \) is in Kelvin)
  - Wavelength of peak radiation emitted by an object
    is inversely related to temperature

• Planck’s law:
  - Describes the emission of radiation in each
    wavelength, as a function of temperature
Solar radiation has peak intensities in the shorter wavelengths, dominant in the region we know as visible, but extends at low intensity into longwave regions.
Shortwave and Longwave Radiation

The hot sun radiates at shorter wavelengths that carry more energy. Sun is a shortwave emitter.

Energy absorbed by the cooler earth is then re-radiated at longer wavelengths, as predicted by Wein's law. Earth is a long wave emitter.
Earth Radiation Balance

Incoming Energy = Outgoing Energy

\[(\text{absorbed sunshine})(\text{area}) = (\text{thermal loss})(\text{area})\]

\[S(1-\alpha)\pi r^2 = \sigma T^4 (4 \pi r^2)\]

- **S** = solar insolation at top of atmosphere. 1380 Wm\(^{-2}\). This is the “power” density from the Sun at 1 AU from the Sun.
- **\(\alpha\)** is the mean albedo of Earth, 0.3.
- **\(\sigma\)** is the Stefan-Boltzmann constant, \(5.67 \times 10^{-8}\) Wm\(^{-2}\)K\(^{-4}\).
If the earth always radiates energy, why doesn’t it cool?

*It is in a state of radiative equilibrium.*

Incoming radiation is balanced by outgoing radiation.

- Radiative equilibrium predicts surface temperature of about 255 K (or about -18° C)

- But, the earth’s observed average surface temperature is ~15° C, or 288 K.

Why? The answer lies in an understanding of absorption, reflection, and transmission of radiation in the atmosphere.
Conservation of Energy

• Radiation incident upon a medium can be:
  - Absorbed
  - Reflected
  - Transmitted

• $E_i = E_a + E_r + E_t$
Short Wave (Solar) Radiation

- **Absorbed** by the atmosphere
- **Reflected** by clouds, particles and air molecules back to space
- **Transmitted** to the surface
  - where it is
    - absorbed
    - reflected back upward into the atmosphere
      - some of this may be absorbed by the atmosphere
      - some may be transmitted through the atmosphere back to space
Reflection

- **Albedo**: the ratio of reflected radiation to incident radiation
- **Surface albedo varies**
  - Spatially
  - Temporally

<table>
<thead>
<tr>
<th>SURFACE</th>
<th>ALBEDO (PERCENT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh snow</td>
<td>75 to 95</td>
</tr>
<tr>
<td>Clouds (thick)</td>
<td>60 to 90</td>
</tr>
<tr>
<td>Clouds (thin)</td>
<td>30 to 50</td>
</tr>
<tr>
<td>Venus</td>
<td>78</td>
</tr>
<tr>
<td>Ice</td>
<td>30 to 40</td>
</tr>
<tr>
<td>Sand</td>
<td>15 to 45</td>
</tr>
<tr>
<td>Earth and atmosphere</td>
<td>30</td>
</tr>
<tr>
<td>Mars</td>
<td>17</td>
</tr>
<tr>
<td>Grassy field</td>
<td>10 to 30</td>
</tr>
<tr>
<td>Dry, plowed field</td>
<td>5 to 20</td>
</tr>
<tr>
<td>Water</td>
<td>10*</td>
</tr>
<tr>
<td>Forest</td>
<td>3 to 10</td>
</tr>
<tr>
<td>Moon</td>
<td>7</td>
</tr>
</tbody>
</table>

*Daily average.*
Solar radiation is scattered and reflected by the atmosphere, clouds, and earth's surface, creating an average albedo of 30%. Atmospheric gases and clouds absorb another 19 units, leaving 51 units of shortwave absorbed by the earth's surface.
Scattering: Why is the sky blue?

- Sunlight is scattered by air molecules
- Air molecules are much smaller than the light’s \( \lambda \)
- Shorter wavelengths (green, blue, violet) scattered more efficiently
- Unless we are looking directly at the sun, we are viewing light scattered by the atmosphere, so the color we see is dominated by short visible wavelengths
  - blue dominates over violet because our eyes are more sensitive to blue light
Why are Sunsets Red?

- The sun appears fairly white when it’s high in the sky.
- Near the horizon, sunlight must penetrate a much greater atmospheric path.
  - More scattering.
- In a clean atmosphere, scattering by gases removes short visible λ’s from the line-of-sight.
  - Sun appears orange/yellow because only longer wavelengths make it through.
- When particle concentrations are high, the slightly longer yellow λ’s are also scattered.
  - Sun appears red/orange.
Solar radiation passes first through the upper atmosphere, but only after absorption by earth's surface does it generate sensible heat to warm the ground and generate longwave energy. This heat and energy at the surface then warms the atmosphere from below.
Long Wave (Terrestrial) Radiation

- The earth's surface emits LW radiation at temperatures warm relative to the top of the atmosphere.
  - Some of this radiation escapes directly through the atmosphere to space, thus cooling the planet.
  - Some is absorbed by gases and clouds in the atmosphere.

- Atmospheric gases and clouds emit LW radiation in all directions.
  - The atmosphere's LW emission downward "warms" the surface.
  - The atmosphere's LW emission upward joins that from the surface escaping to space, thus cooling the planet.
Absorption: Kirchoff’s Law

• Objects that are good absorbers are also good emitters
  - Consider an asphalt road
    • During the day the asphalt absorbs solar radiation and warms
    • At night the asphalt emits infrared radiation and cools relative to its surroundings
Atmospheric Absorption

Solar radiation passes rather freely through Earth's atmosphere.

Earth's re-emitted longwave energy either fits through a narrow "window" or is absorbed by greenhouse gases and re-radiated toward earth.

Major LW absorbers:
- Water vapor
- CO$_2$
- O$_3$
- Clouds
Molecular Absorbers/Emitters

- Molecules of gas in the atmosphere interact with photons of electromagnetic radiation
- Different kinds of molecular transitions can absorb/emit very different wavelengths of radiation
- Some molecules are able to interact much more with photons than others
- Different molecular structures produce wavelength-dependent absorptivity/emissivity

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Arrangement</th>
<th>Permanent Dipole Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>N N</td>
<td>No</td>
</tr>
<tr>
<td>O₂</td>
<td>O O</td>
<td>No</td>
</tr>
<tr>
<td>CO</td>
<td>O C O</td>
<td>Yes</td>
</tr>
<tr>
<td>CO₂</td>
<td>O O O O</td>
<td>No</td>
</tr>
<tr>
<td>N₂O</td>
<td>N N O</td>
<td>Yes</td>
</tr>
<tr>
<td>H₂O</td>
<td>H H H</td>
<td>Yes</td>
</tr>
<tr>
<td>O₃</td>
<td>O O O</td>
<td>Yes</td>
</tr>
<tr>
<td>CH₄</td>
<td>H C H H</td>
<td>No</td>
</tr>
</tbody>
</table>

Diatomic Structures
N₂, O₂, CO

Triatomic Structures
CO₂, N₂O

H₂O, O₃
Solar radiation powers the climate system.

Some solar radiation is reflected by the Earth and the atmosphere.

About half the solar radiation is absorbed by the Earth’s surface and warms it.

Infrared radiation is emitted from the Earth’s surface.

The Greenhouse Effect

Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth’s surface and the lower atmosphere.
Earth's surface absorbs the 51 units of shortwave and 96 more of longwave energy units from atmospheric gases and clouds. These 147 units gained by earth are due to shortwave and longwave greenhouse gas absorption and emittance.

Earth's surface loses these 147 units through convection, evaporation, and radiation.
The Job of the Atmosphere
is to let the energy out!

The movement of the air (and oceans) allows energy to be transported to its “escape zones!”