Solar Radiation and the Seasons

Energy

- **Energy**: “The ability to do work”
- **Energy**: Force applied over a distance
  - Force = mass x acceleration; force unit: Newton: \( N = kg \cdot m/s^2 \)
  - Expressed using the unit Joule: \( J = N \cdot m = kg \cdot m^2/s^2 \)
  - 1 Joule = 0.239 calories
- **Power** – Energy per unit time; power unit: Watt: \( W = \frac{J}{s} \)
- Energy is transferred from the sun to the earth in the form of electromagnetic energy. This radiation provides energy for the movement of the atmosphere, the growth of plants, the evaporation of water and an infinite variety of other processes

Kinetic and Potential Energy

- **Kinetic energy** – the energy of motion
- **Potential energy** – energy due to position in the gravitational field

Kinetic Energy

Kinetic energy can occur as the motion associated with moving objects, such as a falling raindrop, or the random motion of atoms and molecules.

The greater the amount of internal kinetic energy, the higher the temperature; i.e. temperature is a measure of the average internal kinetic energy of a substance.
Kinds of Energy

- Fuel: chemical energy
- Electrical
- Sound
- Sensible energy, thermal energy, heat
- Latent energy
- Radiation

Conservation of Energy

- Energy can not be created or destroyed
- Energy can be transferred from one form to another
- Energy cascade
- Source of energy on earth
- What is the source of the light energy providing this image?

Energy Transfer Mechanisms

**Conduction** – The transfer of heat energy from one molecule to another. Within material, a particle can gain (lose) kinetic energy through collisions with faster (slower) nearby particles.

- Boiling water
- Ocean currents
- Wind

**Convection** – The vertical movement of energy within a fluid (liquid or gas).
- Boiling water
- Ocean currents
- Wind

**Advection** – Horizontal movement of heat energy.

**Radiation** – The transfer of energy by electromagnetic (EM) waves.
- All objects with temperature greater than 0 K emit EM radiation.
Radia%on

• Radiation is emitted by all matter
• EM radiation was “wave-like” characteristics
  – EM waves are oscillating electrical and magnetic fields
  – Oscillating electrical field produces an oscillating magnetic field and vice-versa
  – Frequency of oscillation has wide range
  – Speed of propagation (v), frequency (f) and wavelength (λ) are related as:
    \[ v = f \lambda \]
  – Wavelength is measured from crest to crest.

  • Intensity associated with wave amplitude
  • Quality associated with frequency or wavelength
  • All forms of electromagnetic radiation travel at the speed of light 300,000 km per second in a vacuum
  • Takes 8 minutes for energy from the Sun to reach the Earth.
  • Energy reaches us from other stars. Proxima Centauri 4.3 years. Astronomical distances given in light-years.
The amount of radiation emitted and its wavelengths are not the result of mere chance; they obey some fundamental physical laws.

### Radiation Laws

- **Blackbodies** – perfect emitters of radiation – emit the maximum possible radiation at every wavelength – and perfect absorbers – absorb all incident radiation.
- Blackbodies are hypothetical, ideal radiators
- Everything else is considered a grey body
- However, the Sun is nearly a blackbody

### Table 2-1 Wavelength Categorizations

<table>
<thead>
<tr>
<th>Type of Energy</th>
<th>Wavelength (micrometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>X-ray</td>
<td>0.0001 to 0.01</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>0.01 to 0.4</td>
</tr>
<tr>
<td>Visible</td>
<td>0.4 to 0.7</td>
</tr>
<tr>
<td>Near Infrared</td>
<td>0.7 to 4.0</td>
</tr>
<tr>
<td>Thermal Infrared</td>
<td>4 to 100</td>
</tr>
<tr>
<td>Microwave</td>
<td>100 to 1,000,000 (1 meter)</td>
</tr>
<tr>
<td>Radio</td>
<td>&gt;1,000,000 (1 meter)</td>
</tr>
</tbody>
</table>

### Stefan-Boltzmann Law

\[ I = \sigma T^4 \]

- $I$ = intensity of radiation in W m\(^{-2}\)
- $\sigma$ = Stefan-Boltzmann constant (5.67 \times 10\(^{-8}\) W m\(^{-2}\) K\(^{-4}\))
- $T$ = temperature of the body in Kelvin

### Planck’s Radiation Law

\[ I(\nu, T) = \frac{2\pi\nu^3}{c^2} \left(\frac{1}{e^{\frac{h
u}{kT}} - 1}\right) \]

- $I(\nu, T)$ = intensity of radiation in W m\(^{-2}\) nm\(^{-1}\)
- $\nu$ = frequency of the radiation
- $c$ = speed of light in m s\(^{-1}\)
- $h$ = Planck’s constant (6.626 \times 10\(^{-34}\) J s)
- $k$ = Boltzmann’s constant (1.381 \times 10\(^{-23}\) J K\(^{-1}\))
- $T$ = temperature of the body in Kelvin

### Diagrams

- Planck’s Radiation Law graph showing intensity vs. wavelength for different temperatures.
- Stefan-Boltzmann Law graph illustrating the fourth power relationship between intensity and temperature.
Stefan-Boltzmann Law: Examples

Example 1:
• How much radiation is emitted by a blackbody at a temperature of 25°C
  First step: Convert Celsius to Kelvin
  \[ T \text{ (K)} = 25 \text{ (°C)} + 273.15 = 298.15 \text{ K} \]
  Second Step: Plug values into equation
  \[ I = \sigma T^4 \]
  \[ I = 5.67 \times 10^{-8} \times 298.15^4 \]
  \[ I = 448 \text{ W m}^{-2} \]

Grey Bodies

• True black bodies do not exist in nature
• Most liquids and solids must be treated as grey bodies which means they emit some percentage of the maximum amount of radiation possible at a given temperature.
• The percentage of energy radiated by a substance relative to that of a blackbody is referred to as its emissivity (\(\varepsilon\)).

Example 2:
• For a greybody at the same temperature (25°C), what is the radiation emitted if the emissivity is 0.7?
  \[ I = 0.7 \times 5.67 \times 10^{-8} \times 298.15^4 \]
  \[ I = 0.7 \times 448 \]
  \[ I = 314 \text{ W m}^{-2} \]

If we know the intensity, we can then solve for temperature

Example 3:
• What is the temperature (°C) of a blackbody that is emitting 1000 W m²?
  Rearranging \( I = \sigma T^4 \) we get:
  \[ T = (I/\sigma)^{0.25} \]
  \[ T = (1000/ 5.67 \times 10^{-8})^{0.25} \]
  \[ = 364.42 \text{ K} \]
  \[ = 91.27 \text{ °C} \]

• By incorporating the emissivity of any body, we derive the general version of the Stefan-Boltzman Law: \( I = \varepsilon \sigma T^4 \)
Wien’s Displacement Law:

- Tells us that hotter objects radiate energy at shorter wavelengths.
- Peak solar radiation intensity has a wavelength of 0.5 µm (micrometers).
- Peak Earth radiation intensity has a wavelength of 10 µm.
- For any radiating body, the wavelength of peak emission is given by Wiens Law.
- Short wave radiation < 0.4 µm
- Longwave radiation > 0.4 µm

\[ \lambda_{\text{max}} = \frac{2897}{T} \]

- \( \lambda_{\text{max}} \) = wavelength of maximum radiation emission (µm)
- \( T \) = temperature of the emitting surface (K)
- 2897 = Constant

Example 1:
What is the wavelength of maximum radiation for a blackbody at a temperature of 25°C?

\[ \lambda_{\text{max}} = \frac{2897}{T} = \frac{2897}{25 + 273.15} = 9.72 \mu m \]

Invert the equation to solve for temperature

What is the temperature of a surface whose wavelength of maximum radiation is 1 µm? 15 µm?

\[ \lambda_{\text{max}} = \frac{2897}{T} \quad \rightarrow \quad T = \frac{2897}{\lambda_{\text{max}}} \]

\[ T = \frac{2897}{1} = 2897 \, K = 2624 \, ^\circ C \]

\[ T = \frac{2897}{15} = 193 \, K = -80 \, ^\circ C \]

Emission Spectrum:

- Energy radiated by a substance occurs over a wide range (spectrum) of wavelengths.
- Hotter objects radiate more energy than do cooler bodies.
- Hotter objects also radiate energy at shorter wavelengths than cooler bodies.
- Compare the emission spectra of the Earth and the Sun.

Because of the emission spectra of the Earth and the Sun are almost entirely separate, we refer to Earth radiation as LONGWAVE RADIATION, and Solar radiation as SHORTWAVE RADIATION.
More Sample Problems

Here are some problems to do at home if you want some more practice. We will go over the answers later.

1. How much radiation is emitted by a black body at a temperature of 15°C?
2. What is the temperature of a blackbody emitting 500 Wm\(^{-2}\)?
3. What is the radiative emission of a greybody (real object) with an emissivity of 0.95 and a temperature of 24°C?
4. Assuming a portion of the sun emits a maximum wavelength of 0.477 µm (i.e. peak solar irradiance is in the green portion of the EM spectrum, use Wein’s Law to estimate the temperature of the surface of the sun.

Radiation Laws

Lambert’s Law:

\[ I = I_0 \cos \gamma \]

or

\[ I = I_0 \sin \beta \]

\( I \) = radiation on a horizontal surface
\( I_0 \) = radiation on a surface perpendicular to the source
\( \gamma \) = angle between beam of radiation and line normal to surface (zenith angle)
\( \beta \) = angle between beam of radiation and the surface (elevation angle)
Radiation Laws

**Some Examples**

If the radiation measured normal to the beam is 500 W m\(^{-2}\), what would the incident radiation be if the zenith angle were 30°?

\[
I = I_0 \cos \gamma \\
I = 500 \cos 30° = 500 \times 0.866 = 433 \text{ W m}^{-2}
\]

Radiation Laws

**Some Examples**

If the zenith angle is 30° and the incident radiation is 500 W m\(^{-2}\), what would the radiation measured normal to the beam be?

\[
I = I_0 \cos \gamma \\
I_0 = \frac{500}{0.866} = 577 \text{ W m}^{-2}
\]

Radiation Laws

**Inverse Square Law:**

\[
\frac{I_1}{I_2} = \left( \frac{r_2}{r_1} \right)^2 \\
\text{or} \\
\frac{I_1}{I_2} = \left[ \frac{r_2}{r_1} \right]^2
\]

\(I_1\) = flux density at distance \(r_1\)

\(I_2\) = flux density at distance \(r_2\)

Radiation Laws

**An Example**

\[
\frac{I_1}{I_2} = \left( \frac{r_2}{r_1} \right)^2 \\
I_1 = 40 \text{ W m}^{-2} \\
I_2 = 10 \text{ W m}^{-2} \\
r_1 = 0.5 \text{ m} \\
r_2 = 1.0 \text{ m}
\]
Radiation Laws

Problem
If the temperature of the sun is 5770K, calculate the radiation reaching the outside of the earth’s atmosphere.

Sun’s radius: 7 x 10^8 m
Mean earth-sun distance: 1.5 x 10^11 m

Solution
If the temperature of the sun is 5770K, calculate the radiation reaching the outside of the earth’s atmosphere.

1. Compute radiative emission at the sun’s outer surface:
   \[ E = \sigma T^4 = 5.67 \times 10^{-8} \times 5770^4 = 62,847,255 \text{ W m}^{-2} \]

2. Use inverse square law to get radiation at earth-sun distance
   \[ I_s = I_i \left( \frac{r_i}{r_s} \right)^2 = 62,847,255 \left( \frac{1.5 \times 10^{11}}{7 \times 10^8} \right)^2 = 1369 \text{ W m}^{-2} \]

Solar Constant

- Only constant when averaged
- Variations due to
  - Long-term increase in solar output
  - Earth’s elliptical orbit
  - Sun spots
Solar Radiation Basics

- Earth Motion: Revolution and Rotation

- Revolution: once a year; elliptical orbit
  - Aphelion: 152.1 x 10^6 km; July 4
  - Perihelion: 147.3 x 10^6 km; January 3
Solar Radiation

- **Earth Motion**: Revolution and Rotation
  - **Revolution**: once a year; elliptical orbit
    - Aphelion: $152.1 \times 10^6$ km; July 4
    - Perihelion: $147.3 \times 10^6$ km; January 3
  - **Rotation**: once a day; axis tilt: $66.5^\circ$ from plane of the ecliptic
    - Diurnal sun angle variation due to rotation
    - Annual sun angle variation due to axis tilt and revolution
    - Daylength variation due to axis tilt and revolution
Solar Radiation Annual Cycle

Daily total of the undepleted solar radiation received in the northern hemisphere on a horizontal surface as a function of latitude and time of year. (after Gates 1962).

How to Calculate the Solar Noon Sun Angle

- Similar Angles
- Complementary Angles
- Zenith Angle
- Elevation Angle

How to Calculate the Solar Noon Sun Angle

- Latitude Angle

How to Calculate the Solar Noon Sun Angle

- Declination Angle
- Subsolar Point
- Analemma
SOLAR ZENITH ANGLE = |LATITUDE - DECLINATION|
Southern Hemisphere Latitudes and Declinations are NEGATIVE in the above equation.

SOLAR ELEVATION ANGLE = 90° - SOLAR ZENITH ANGLE
(complementary angles)
EXAMPLES:

- What is the Declination today?
- What is the Declination on October 15?
- What is the Elevation Angle of the Sun in Honolulu at Solar Noon on October 15?
  
  Declination on Oct. 15: 8°S
  Latitude of Honolulu: 21°N
  Zenith Angle = |21 minus -8| = 29°
  Elevation Angle = 90° - 29° = 61°

EXAMPLES:

- What is the Elevation Angle of the Sun at 55°S on May 1?
  
  Declination on May 1 = 15°N
  Zenith Angle = |55 minus 15| = 70°
  Elevation Angle = 90° - 70° = 20°

EXAMPLES:

- What is the Elevation Angle of the Sun at 0°S on June 21?
  
  Declination on June 21 = 23.5°N
  Zenith Angle = |0 minus 23.5| = 23.5°
  Elevation Angle = 90° - 23.5° = 66.5

WHAT FACTORS AFFECT THE AMOUNT OF SOLAR RADIATION REACHING THE OUTSIDE OF THE EARTH’S ATMOSPHERE?

- Output of the Sun
- Earth Sun Distance
- Material between Earth and Sun
Causes of variation in solar radiation incident on earth’s surface

• Variation in solar radiation reaching atmosphere
  – Output of the Sun
  – Earth Sun Distance
  – Material between Earth and Sun
• Seasonal, diurnal, and spatial variations at the earth’s surface:
  – Sun angle: latitude, time of year, time of day
  – Daylength: latitude, time of year
  – Atmospheric effects:
    • Atmospheric absorption: gases and aerosols
    • Atmospheric reflection: scattering
    • Reflection and absorption by clouds

Scattering

• Mie scattering: by aerosols
• Rayleigh scattering by gas molecules
• Scattering creates diffuse light and reduces direct light
• Global Radiation = Direct + Diffuse

Atmospheric Transmission

Roughly half of solar radiation at the top of the atmosphere reaches the earth’s surface.
Atmospheric Absorption