The Fundamentals of Solar and Terrestrial Radiation

The Energy Source that “drives” the earth’s atmosphere, oceans and our weather
Heat transfer processes-how energy moves around

• Conduction - Where molecules transfer energy between them by coming into contact with one another.

• Convection - Where a fluid moves from one place to another carrying its heat energy with it.
  – In atmospheric science, convection is usually associated with vertical movement of the fluid (air or water).
  – Advection is the horizontal component of the classical meaning of convection.

• Radiation - The transfer of heat by radiation does not require contact between the bodies exchanging heat, nor does it require a fluid between them. This is electromagnetic radiation. Feeling heat from the sun!
ElectroMagnetic Radiation

\[ \lambda \cdot \nu = c \]
(wavelength x frequency = speed of light, \( c = 3 \times 10^8 \) m/s). Therefore can use either wavelength (e.g. 1 micron) or frequency (e.g. 1 GHz)

All bodies emit electromagnetic radiation at all frequencies. Both the **Intensity** at each frequency as well as the total **Power** depend only on the temperature.

\[
I_{\text{Intensity}} = \frac{2h\nu^3c^2}{\exp(hc\nu/KT) - 1}
\]
\[
P_{\text{Power}} = \sigma T^4 \quad [\text{Watts/area}]
\]
where \( \sigma = 5.67 \times 10^{-8} \) W/m\(^2\)K\(^4\), and \( h = 6.63 \times 10^{-34} \) J s

Energy = Power x time  [J or W\( \cdot \)s]

Electromagnetic radiation interacts with matter when the frequency of the radiation resonates with specific atoms or molecules. Otherwise nothing happens.
Ways to label radiation

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

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

• By its wavelength, $\lambda$ (or frequency)
1600’s - Light is a “wave”.

.. and we know its speed

Roemer experiment (1675) was "simple". Earth's orbit is small compared with Jupiter's one, and while the first one makes half of it orbit around the sun, Jupiter has only moved once around its own axis (similar to Earth's Rotation movement). Let's call S to the sun's orbit, E to Earth's orbit, J to Jupiter and L to one of Jupiter's satellites. When Earth is between the Sun and Jupiter, we observe the time that L uses for making a round on J, so the time between two eclipses of L. So, since this time, we know that the eclipses will be in half a year till Earth goes to the other side of the Sun. L's eclipses were retarded during half a year in 986 seconds, and we attribute that to the time that the light uses in cover the diameter of the Earth's orbit, 296.000.000 kilometers, and if we divide this by 986 we get 300.000 km/sec approximately.
The luminiferous aether: it was hypothesized that the Earth moves through a "medium" of aether that carries light. The hypothesis survives for nearly 200 until 1878.

James Clerk Maxwell (1831-1909)

Electricity/Magnetism and E-M waves: no more aether
A Satellite Sees a Hurricane

GOES stays high up in the sky. It has two main parts that tell forecasters on the ground about the weather.

One part is called a Sounder. It sends waves of sound into the air. The sound waves bump into drops of water in the air. The waves bounce back to the satellite.

Another part is a special camera. It takes pictures of clouds. The pictures show how big the clouds are. They show how the clouds are moving.

This picture of a hurricane shows a very big cloud. The cloud moves in circles.

Facts About Hurricanes

- Hurricanes form over oceans. Hurricanes die out quickly over land.
- The center of a hurricane is called the eye.
- Hurricane winds can blow faster than most cars can go.
- Hurricanes happen from June to November. Most happen in September.

Heavy rain and strong winds in hurricanes can harm plants, animals, buildings, and people.

What Are Storms?

Storms are kinds of dangerous weather.

- Thunderstorms can form during very hot weather. They have rain, strong winds, thunder, and lightning.
- Tornadoes form during thunderstorms. The winds in tornadoes spin very fast.
- Hurricanes have strong winds and heavy rain. Hurricanes cause big waves and floods.

Dear Boys and Girls,

Quacker and I were playing in the park. The sky got dark. A storm was on the way!

I wanted to stand under a tree until the storm passed. Quacker said we should go home right away. What do you think we should have done?

Your friend,

Whiskers
1. **Blackbody radiation**— Classically, e-m waves are emitted any time charges are accelerated. How can one describe theoretically the intensity vs. wavelength of hot bodies? (The tungsten filament in an incandescent light is a good approximation to such a hot body, although the perfect radiating source is a “black” body, or a small hole leading to a hot cavity.) It is a fundamental idea that any solid body at non-zero temperature has charges in motion and therefore produces radiation. The hotter the body, the more agitated the motions of the charges, the more intense the radiation and the shorter the wavelengths emitted. This fully explained the behavior of radiation at longer wavelengths. Planck explained the short wavelength behavior by invoking quantum mechanics.
The Electromagnetic Spectrum (Sun) 
5780°K

1 micrometer (µm) = 10^{-6} meters = 10^{-4} centimeters
All matter emits radiation if it is above absolute zero!

• The higher the temperature of matter, the more radiation it emits
  – Planck’s law
    • Specifies emitted energy as a function of wavelength
  – Stefan Boltzman law \((E = \sigma T^4)\) \(T\) is in degrees Kelvin
    • If \(T\) doubles, \(E\) increases by 16 times! \(E\) is amount of radiation emitted by the body.
  – Wavelength of peak radiation emitted by an object is related to temperature by Wien’s law
    • \(\lambda_{\text{max}} \sim 3000/T\)
      \(\lambda_{\text{max}}\) is in \(\mu\text{m}\) and \(T\) is in Kelvin
Stefan Boltzmann Law

\[ E = \sigma \, T^4 \quad \text{[Watts per square meter per } K^4]\]

Where \( \sigma = 5.67 \times 10^{-8} \, \text{Wm}^{-2} \, \text{K}^{-4} \)

<table>
<thead>
<tr>
<th>( T ) (K)</th>
<th>( E ) (Wm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>91</td>
</tr>
<tr>
<td>300</td>
<td>459</td>
</tr>
<tr>
<td>400</td>
<td>1452</td>
</tr>
</tbody>
</table>
The temperature determines the amount of radiation emitted and the wavelength of maximum emission.

The temperature of Earth is at equilibrium when solar energy into Earth/Atmosphere system = terrestrial radiation out of Earth/Atmosphere system.
What determines the amount of solar radiation transmitted through the earth-atmosphere system?

- **Astronomical Effects**
  - Earth’s Orbit
  - Solar Output
- **Geometric Effects**
  - Axis tilt
  - Rotation
  - Orientation
- **Atmospheric Effects**
  - Clouds, gases, dust
- **Surface Effects**
  - Albedo
Earth’s Solar Constant

The Solar Constant is defined as the average annual power per unit area of radiant energy arriving at the top of the earth’s atmosphere on a plane perpendicular to the incoming sun’s rays.

Average annual power per unit area arriving at the top of the earth’s atmosphere \( SC = 1365-1372 \) W m\(^{-2}\)
A Statement of Conservation of Energy

• What can happen to radiation that is incident upon a medium
  – It can be absorbed
  – It can be reflected
  – It can be transmitted

• $E_i = E_a + E_r + E_t$
From the conservation of energy statement ...

\[ E_i = E_a + E_r + E_t \]

We will call the reflected energy the *Albedo*

*Albedo can be surface or planetary (sfc + atmosphere)*
Albedo of various surfaces

- Albedo is ratio of reflected radiation to incident radiation
- Surface albedo varies
  - Spatially
  - Temporally

### Table 2.3: Typical Albedo of Various Surfaces

<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.
Atmospheric Absorption

The Electromagnetic Spectrum and Absorbing Gases
Major short wave absorbers:

- $\text{H}_2\text{O}$ (near infra-red) nir
- $\text{CO}_2$ nir
- $\text{O}_3$ uv, vis
- Clouds nir
- Aerosol vis, nir

Minor short wave absorbers:

- $\text{O}_2$ (near UV) nuv
- $\text{N}_2$ nuv
The energy of radiation

- \( E = \frac{hc}{\lambda} = h\nu \)
  - \( E = \) Energy
  - \( h = \) Planck’s constant
  - \( c = \) Speed of light (a constant)
  - \( \lambda = \) Wavelength of radiation

- The smaller the wavelength, the larger the energy
  - From smaller to larger wavelength (from larger to smaller energy)
    - gamma rays, X-rays, uv, visible, near infrared, infrared, microwave
How do molecules absorb/emit radiation?

- Atoms and molecules have the ability to change their energy levels.
  - They do this by modifying one of the following properties:
    - Composition - through photo dissociation
    - Electronic energy state
    - Vibrational energy state
    - Rotational energy state
  - Changing from one energy state to another is called a “transition”
Photo-dissociation  A high energy transaction

\[ 2 \text{H}_2\text{O} + \text{ultra violet radiation} \rightarrow 2 \text{H}_2 + \text{O}_2 \]

Energy required to break a chemical bond depends on the strength of that bond.
A model of an atom

Components: nucleus composed of protons and neutrons, electrons “orbiting” the nucleus
VIBRATIONAL TRANSITIONS
Medium Energy - visible/near infrared

Carbon Dioxide $\text{CO}_2$
Molecule

Action at the molecular level
More action at the molecular level
What happens to long wave (terrestrial) radiation?

- The earth's surface emits LW radiation at relatively warm temperatures.
  - 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.
- The 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.
MAJOR LW ABSORBERS

$\text{H}_2\text{O} \quad 6.7\mu\text{m}$

$\lambda > 18\mu\text{m}$ (rotational)

$\text{CO}_2 \quad 2.7, 4.3, 14.7\mu\text{m}$

$\text{O}_3 \quad 9.6\mu\text{m}, 14\mu\text{m}$ (weak)

Clouds $\quad 0.7\mu\text{m} - 500\mu\text{m}$
The Electromagnetic Spectrum and Absorbing Gases
Atmospheric Windows

• Portions of the electromagnetic spectrum where atmospheric gases absorb relatively little energy
  – Visible Wavelengths
    • Vision has evolved to use these wavelengths
  – 8-12 micrometers in the terrestrial band
Annual Radiation Budget - Short Wave Detail

Earth's albedo: 30% reflected and scattered

Incoming solar radiation: 100%

-4% 
20%
6%

Atmosphere

Clouds

Top of atmosphere
19% absorbed by atmosphere and clouds

Earth's surface

Direct and diffuse

51% absorbed at surface
Annual Radiation Budget

-100 - 30 = +70

117

130

+19

+111

-64

-6

-70

-96

-64

160

+51

+96

+147

Energy lost to space

Energy gained by atmosphere

Energy lost by atmosphere

Energy gained at earth surface

Energy lost at earth surface
Radiative balance?

Do the LW and SW gains and losses balance:

At the top of the atmosphere?

For the atmosphere itself?

At the earth's surface?
Radiation Budget Top of the Atmosphere (TOA)

- Solar
  - 100 units incident
  - 19 units absorbed by atmosphere (delete!)
  - 4 units reflected by earth’s surface
  - 20 units reflected by clouds
  - 6 units reflected by atmosphere (gases)
- Net gain 70 units

- Terrestrial
  - 64 units from atmos
  - 6 units from surface
- Net loss 70 units

There is a balance at the TOA Gain = Loss

RADIATIVE EQUILIBRIUM
Radiation Budget - Atmosphere

- **Solar**
  - absorbs 19 units

- **Terrestrial**
  - absorbs 111 units from surface emission
  - emits 64 units upward to space
  - emits 96 units down to the surface

\[
+ 19 + 111 - 64 - 96 = -30
\]
The atmosphere loses 30 units of energy by radiative processes. What would happen if this continued without any compensation?
Radiation Budget Surface

- **Solar**
  - 51 units absorbed at the surface

- **Terrestrial**
  - +96 units from atmos
  - -117 units emitted by the surface

\[ +51 +96 -117 = +30 \] units gain from radiation at the surface

An Imbalance?????
Radiative imbalance

If the surface gains 30 units of radiation, and the atmosphere loses 30 units of radiation, what would this mean?

The earth’s surface would heat indefinitely and the atmosphere would cool. Does this happen?

Why or why not?

What other heat transfer processes are there?
  Conduction
  Convection
  Evaporation/condensation (Latent Heat)
Annual Energy Budget

100 - 30 = 70
Origin of Atmospheric Transport
the radiation budget at the top of the atmosphere

Red arrows are incoming Solar Radiation
Blue arrows are outgoing Long wave Radiation

White arrows are transport by the atmosphere and oceans

LATITUDE
80°N 38°N 0°
Atmospheric greenhouse effect

- Radiative equilibrium predicts surface temperature of ~ -18 degrees C
- Earth’s observed average surface temperature is ~ 15 C
- Why?
  - Our atmosphere contains selective absorbers (greenhouse gases)
    - Carbon dioxide, water vapor, methane, ozone, nitrous oxide
  - These compounds slow release of outgoing infrared radiation and warm earth’s surface
The Greenhouse Effect

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

Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the earth's surface and the lower atmosphere.

Solar radiation passes through the clear atmosphere.

Most radiation is absorbed by the earth's surface and warms it.

Infrared radiation is emitted from the earth's surface.
Atmospheric greenhouse effect

• The greenhouse effect is one of the best understood phenomena in atmospheric science

• Enhancements of the greenhouse effect due to increasing greenhouse gas concentrations are not easily predicted
Greenhouse gas emissions

- Human activities have caused dramatic increases in greenhouse gas concentrations
The U.S. is a major contributor to greenhouse gas emissions.
Greenhouse gas emissions are increasing

- U.S. emissions are increasing
- Emissions from developing countries are likely to increase dramatically in the future
The effect on future climate is difficult to predict

• Direct radiative effects of greenhouse gases are easily predicted

• Positive and negative feedbacks complicate climate change predictions. For example,
  – A warmer climate means greater water evaporation
    • Water vapor is a potent greenhouse gas (positive feedback)
    • More water vapor may increase cloud formation and thereby cool the earth (negative feedback)

• This topic will be addressed in more detail later this semester