MET 200 Lecture 3
Radiation & Earth’s Radiation Balance

Outline of Previous Lecture
Weather Maps and Satellites
Temperature and Pressure
Heat and energy transfer

Lecture 3
Outline

• Laws of Radiation
• Earth’s Radiation Balance
• Greenhouse Effect

Radiation

• Radiation - energy leaving a body in the form of electromagnetic waves.
• Light is a form of electromagnetic radiation.
• The speed of light is 299,792,458 m/s or ~ 3x10^8 m/s through a vacuum (slightly slower through air).
Radiation Quality and Quantity

- The amplitude corresponds to the energy carried
- The wavelength corresponds to the type

Radiation – Types

Radiation Concepts

Blackbody - is a theoretical object that absorbs all incident radiation and emits the maximum possible radiation for its temperature – according to Planck’s Law.

Planck’s Law

The amount of radiation emitted by a blackbody is described by Planck’s Law

\[ E_\lambda = \frac{2\pi c^2}{\lambda^5 \left[ e^{(h \omega / kT)} - 1 \right]} \]

- k is the Boltzmann constant, and is 1.38x10^{-23} J/K
- h is Planck’s constant and is 6.626x10^{-34} Js
- c is the speed of light in a vacuum and is 2.9979x10^8 m s^{-1}
- Blackbody radiation is isotropic, homogeneous, unpolarized and incoherent.
- Planck’s Law means that the sun isn’t special, all objects radiate
Planck’s Law

Planck’s Law describes the radiant energy at all wavelengths emitted from a black body.

Radiant Energy $u(\lambda) \sim \frac{2\pi \hbar c}{\lambda^5} \frac{1}{e^{\frac{\hbar c}{\lambda kT}} - 1}$

where
- $\hbar$ is the reduced Planck constant
- $c$ is the speed of light
- $k$ is the Boltzmann constant
- $T$ is the temperature

Black body curve for the sun.

Planck’s Law and Black Body Radiation

Planck’s Law describes the radiant energy at all wavelengths emitted from a black body.

Radiant Energy

Stefan-Boltzman Law

Stefan-Boltzman law is obtained by integrating Planck’s Law across all wavelengths. As the temperature of a black body increases, the irradiance $(E)$ emitted by that object per unit time and unit area increases by a power of 4.

$E = \sigma T^4$

where $\sigma$ is a constant $= 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$

If $T$ doubles, $E$ increases by 16 times!

$E$ is in Watts/m$^2$
Wein’s Law*

The wavelength \( \lambda_{\text{max}} \) of peak radiation emitted by an object is inversely related to temperature \( T \).

\[
\lambda_{\text{max}} \sim \frac{b}{T} = \frac{2897}{T}, \quad b = \text{Wien’s displacement constant}
\]

\( \lambda_{\text{max}} \) is in \( \mu \text{m} \) and \( T \) is in Kelvin

*Wein’s Law is obtained by taking the derivative of Planck’s Law

Kirchhoff’s law of thermal radiation

For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the absorptivity is equal to the emissivity for each wavelength.

\[
a_\lambda = \varepsilon_\lambda
\]

A good absorber is a good emitter, and a poor absorber is a poor emitter. Naturally, a good reflector must be a poor absorber. This is why, for example, lightweight emergency thermal blankets are based on reflective metallic coatings: they lose little heat by radiation.

Summary of Laws of Radiation

1. All objects emit radiation (except at 0°K).
2. Hotter objects emit more energy per unit area than colder objects.
3. The hotter the object the shorter the wavelength of maximum radiation.
4. Objects that are good absorbers of radiation are good emitters of radiation.

Radiation Concepts

Solar constant - Amount of solar radiation passing through a unit area at the top of the earth’s atmosphere perpendicular to the direction of the radiation at the mean Earth-sun distance.

\[
S = E_s \times \left( \frac{R_s}{R_{SE}} \right)^2
\]

At the sun’s surface:

\[
E_s = \sigma T^4 = 5.67 \times 10^{-8} \text{ W/(m}^2\text{*K}^4\text{)} \times (5800 \text{K})^4 = 6.416 \times 10^7 \text{ W/m}^2
\]

The radius of the sun \( R_s = 6.955 \times 10^8 \text{ m} \)

Distance of sun to Earth \( R_{SE} = 1.5 \times 10^{11} \text{ m} \)

\[
S = E_s \times \left( \frac{R_s}{R_{SE}} \right)^2 = 1379 \text{ W/m}^2
\]
Radiation Concepts
What happens to sunlight once it reaches the Earth?
Transmission  45%+5%=50% reaches surface
Scattering (reflection)  19%+6%+5%=30%=Albedo
Absorption  45% by surface and 25% by atm.

Reflection and Scattering of Incoming Sunlight
- Albedo: the ratio of reflected radiation to incident radiation
- Surface albedo varies geographically and in time.

Earth Radiation Balance
Without an atmosphere: radiative equilibrium temperature = -18°C

Incoming Energy (visible) = Outgoing Energy (IR)
\[ S(1-a) \pi r^2 = \sigma T_E^4 \quad (4 \pi r^2) \]
\[ T_E = \left[ \frac{S (1-a)}{4\sigma} \right]^{1/4} = 255K = -18°C \]
Where \( S \) = solar constant, \( a \) = albedo, and \( \sigma \) = constant.

Without an Atmosphere
Radiative Equilibrium Temperature = -18°C and we would have a frozen planet.
Atmospheric Windows

Transmission vs Absorption

The Atmosphere is nearly transparent for shortwave or visible radiation, but strongly absorbs longwave radiation.

Atmosphere Absorbs Radiation

The Atmosphere is nearly transparent for shortwave but absorbs strongly longwave radiation.

Atmospheric Absorption of Solar Radiation

A Simple Greenhouse Model

- Incoming solar radiation = \(0.7 \times 1379\)/4 W m\(^{-2}\) = 241 W m\(^{-2}\)
- IR flux from surface = \(\sigma T_o^4\)
- Assume atmospheric layer has an absorption efficiency = \(f \sim 0.77\)
- Kirchhoff’s law: absorptivity = emissivity
- IR flux from atmospheric layer = \(f \sigma T_i^4\) (up and down)
A Simple Greenhouse Model

Balance at top of atmosphere
\[ f \sigma T_1^4 + (1-f) \sigma T_0^4 = 241 \]

Balance for atmospheric layer
\[ f \sigma T_1^4 + f \sigma T_1^4 = f \sigma T_0^4 \]

Balance at the surface
\[ \sigma T_0^4 = 241 + f \sigma T_1^4 \]

We have two equations and two unknowns, can solve.
\[ T_0 = 288 \text{ K} ; \ T_1 = 241 \text{ K} \]

Greenhouse gases affect \( f \); as \( f \) increases, \( T_0 \) and \( T_1 \) increase

Increasing the Greenhouse Effect

Water vapor feedback

Adding CO2

Increased greenhouse effect

Increased temperature and water vapor

Questions?