4. SOLAR & TERRESTRIAL RADIATION

PART I: RADIATION


Reading Assignment:
- A&B: Ch. 2 (p. 34-42)
- LM: Lab. 5

1. Introduction

- **Radiation** = Mode of **Energy** transfer
  - by **electromagnetic waves**
  - **only mode** to transfer energy **without the presence of a substance** (fluid or solid)
  - works **best in a vacuum** (empty space)

  ➔ **Radiation** = the **only way** for Earth to receive **energy from the Sun**

- **Weather** systems are **powered by radiation**

- From **Earth-Sun geometry** we know:
  - spatial and temporal **variations** of receipt of radiation at the top of the atmosphere
- From **Atmospheric Composition**: important for radiation at the surface
  - **O₃** → UV radiation, **shortwave**
• \( \text{H}_2\text{O} \ & \ \text{CO}_2 \rightarrow \) IR radiation, greenhouse, longwave

\[ \Rightarrow \text{need to consider different types of radiation} \]

2. Electromagnetic Radiation

• radiation waves exhibit characteristics of both electric fields and magnetic fields

(from A&B, Figure 2-5 a)

• Electromagnetic radiation moves at “speed of light”

• radiation spreads in all directions and moves in straight lines
Electromagnetic radiation is described by three interdependent variables:

- **wavelength** \( \lambda \) “lambda” [m, \( \mu \)m]
- **frequency** \( \nu \) “nu” [s\(^{-1}\), Hz]
- **velocity** \( c \) [m s\(^{-1}\)]

\( \lambda \cdot \nu = c \)

(c = “speed of light” \( \sim 3 \times 10^8 \) m s\(^{-1}\))

### 3. Radiation Spectrum -

**Definition:**

The *Radiation Spectrum* is the distribution of radiative energy over different *wavelengths*, or frequencies.
In meteorology: only small part of EM-spectrum of interest.

- three important ranges:
  - **ultraviolet** radiation (UV)
  - **visible** radiation
  - **infrared** radiation (IR)
### Radiation in the Earth-Atmosphere System

<table>
<thead>
<tr>
<th>UV (Ultraviolet Radiation)</th>
<th>Visible Radiation</th>
<th>Infrared Radiation (IR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>10^{-2} – 0.4 μm</td>
<td>0.4 – 0.7 μm</td>
</tr>
<tr>
<td><strong>Effect</strong></td>
<td>Sunburn</td>
<td>“sunlight”</td>
</tr>
<tr>
<td><strong>Effect</strong></td>
<td>0.4 μm violet</td>
<td>0.5 μm blue</td>
</tr>
<tr>
<td></td>
<td>0.6 μm green</td>
<td>0.7 μm yellow</td>
</tr>
<tr>
<td><strong>Class</strong></td>
<td>Shortwave radiation</td>
<td></td>
</tr>
<tr>
<td><strong>sun output</strong></td>
<td>7 %</td>
<td>43 %</td>
</tr>
<tr>
<td><strong>Earth output</strong></td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

- **shortwave radiation**: only solar radiation
- **longwave radiation**: IR radiation emitted by the E/A-system
4. Radiation Laws

(i) General Principles

- **all things emit radiation**
  - the amount and wavelengths depend primarily on the **emission temperature**
  - higher the °T ⇒ faster the electrons vibrate ⇒
    - shorter wavelength \( \lambda \)
    - more total radiation emitted

- when any radiation is **absorbed** by an object:
  - increase in molecular motion
  - increase in temperature

(ii) Black Bodies and Gray Bodies

- an object or body that absorbs all radiation incident on it is termed a **black body**
  - **idealization**: perfect black bodies do not exist
  - often a **good approximation for absorption** in a given range of wavelengths
  - many natural substances behave nearly like black bodies
a **black body** is also an ideal emitter
→ emission spectrum follows a general law (Planck’s curve) describing the **maximum possible emission** for a given temperature
→ is often used as comparison standard for emission spectrum
→ **a black body** has an ideal emission efficiency, termed **emissivity**: \( \varepsilon = 1 \)

an object or body with a **less than ideal emission** efficiency (same at all wavelengths) is termed a **gray body**:
→ **a gray body** has a non-ideal emission efficiency: **emissivity** \( \varepsilon < 1 \)
→ is often a good approximation for emission spectra of real objects or bodies

(iii) **Reflection – Absorption – Transmission**

only **three things** can happen, when radiation with a wavelength, \( \lambda \), hits an object or substance:

1. part or all can be **reflected**:
   → fraction reflected: **reflectivity**, \( \alpha_\lambda \)
   → this part does **not interact** with the object, it is rejected

2. part or all can be **absorbed**:
   → fraction absorbed: **absorptivity**, \( a_\lambda \)
   → this part raises the temperature of the object
→ **radiative energy** is converted to heat

3. part or all can be transmitted:
   → fraction transmitted: **transmissivity**, \( t_\lambda \)
   → this part does **not interact** with the object, it just goes through it.

Since these are the only possibilities, it follows from the principle of conservation:

\[
\alpha_\lambda + a_\lambda + t_\lambda = 1
\]

(iv) **Stefan-Boltzmann Law:**
the total emitted energy flux

All objects or substances emit radiation at a rate proportional to the 4th power of their absolute temperature

Total energy flux emitted: \( F_{tot} \) [W m\(^{-2}\)]:

\[
F_{tot} = \varepsilon \sigma T^4
\]

- \( \varepsilon \) emissivity \((0 \sim 1)\); depends on quality of material
  (see Lab Manual #5 for list of values)
- \( \sigma \) Stefan-Boltzmann constant \( = 5.67 \times 10^{-8} \) [W m\(^{-2}\) K\(^{-4}\)]
- \( T \) **absolute** temperature of emitting object [K]
- \( T^4 \) fourth power: faster than linear increase with temperature.
Example Problem
(see web under this topic for more exercise problems)

If a cloud bottom has a temperature of $-10 \, ^\circ C$, how much energy would it be emitting if the emissivity were 1.0?

**Solution**

- convert temperature to SI-unit: $[^\circ C] \rightarrow [K]$
  \[ T = (-10 \, ^\circ C) + 273.15 = 263.15 \, K \]
- use Stefan-Boltzmann law for $\varepsilon = 1$ (black body):
  \[ F_{\text{cloud}} = \varepsilon \cdot \sigma \cdot T^4 = 1 \times 5.67 \cdot 10^{-8} \times (263.15)^4 \]
  \[ = 271.9 \, W \, m^{-2} \]
- **Check units**: units okay – physics okay.
  \[[\varepsilon \cdot \sigma \cdot T^4] = [1] \times [W \, m^{-2} \, K^4] \times [K^4] = [W \, m^{-2}] \checkmark\]
**Wien’s Displacement Law:**

*the wavelength of maximum emittance*

A rise of temperature increases the total radiation, and shifts this energy output to shorter wavelengths, in inversely proportional to the absolute temperature. Hotter Body – Shorter Wavelength of maximum emittance: $\lambda_{\text{max}} [m] :$

\[
\lambda_{\text{max}} = \frac{a}{T} = a \cdot T^{-1}
\]

- $\lambda_{\text{max}}$ wavelength [μm]
- $a$ constant: 2898 [μm K]
- $T$ absolute temperature [K]

![Graph showing Blackbody Irradiance vs Wavelength for different temperatures](image)
Example Problem
(see web under this topic for more exercise problems)

If a cloud bottom has a temperature of -10°C what is the wavelength of the peak energy emission? What part of the electromagnetic spectrum is this in?

Solution

• convert temperature to SI-unit: \([\°C] \rightarrow [K]\)
  \[ T = (-10 \°C) + 273.15 = 263.15 K \]

• use Wien’s law:
  \[ \lambda_{\text{max}} = a \cdot T^{-1} = 2898 \div 263.15 = 11.0 \, \mu m \]

• Check units: units okay – physics okay.
  \([a \cdot T^{-1}] = [\mu m \cdot K] \times [K^{-1}] = [\mu m]\)
PART II: ATMOSPHERIC INFLUENCES ON RADIATION

Reading Assignment:
- A&B: Ch. 3 (p. 56-68)
- LM: Lab. 5

1. Introduction

Global Shortwave Radiation Balance (overview)
- ~ 30 % of solar radiation is reflected by clouds, atmospheric gases and the surface
- ~ 25 % of solar radiation is absorbed by the atmosphere (clouds, atmospheric gases, aerosol)
- ~ 45 % of solar radiation is absorbed by the surface (oceans, land surface) (transmission)

Influence of Clouds on Shortwave Radiation Balance
- Clear conditions (no clouds):
  - ~ 70 % of solar radiation is absorbed by the surface (55% direct, 15% diffuse sky radiation)
  - only ~ 13 % of solar radiation is reflected
- Cloudy conditions (overcast):
  - ~ 25 % of solar radiation is absorbed by the surface (4% direct, 21% diffuse sky radiation)
  - 51 % of solar radiation is reflected
2. Reflection and Scattering of Radiation

- **Reflection**
  - Specular Reflection (Mirror)
  - Diffuse Reflection or Scattering

- **Scattering**

(from A&B, Figures 3-2, and (Phys.Princ. 2-2) 1)
Blue Sky and White Clouds: Rayleigh and Mie Scattering

- Air Molecules tend to scatter Short Wavelengths more, and in all directions
- Particles (droplets, aerosol) tend to scatter All Wavelengths equally, and more forwards than backwards
- short-wave reflectance: the albedo (~ whiteness)
3. **Transmission** of Radiation through the Atmosphere

- **Transmission:**

  ![Diagram of radiation transmission](image)

  (from A&B, Figure (Spec. Int. 3-1) 3)

  a) At the top of the atmosphere white (sun-) light is started to be scattered: mostly the blue portion

  b) As radiation proceeds through the atmosphere, more of the blue portion is scattered away from the direct beam (further transmitted as diffuse radiation)

  c) At the surface mostly the **red light is left** in the direct beam →
4. Absorption of Radiation in the Atmosphere

- **Absorption:**

  - **Kirchhoff’s law:** if a substance is an efficient emitter in a given wavelength range, it is also an efficient absorber at the same wavelength range:
    \[ \varepsilon_{\lambda} = a_{\lambda} \]

- **Selective absorption:** the absorptivities of atmospheric gases are highly specific to certain spectral bands or wavelength ranges
  
  - **solar radiation** (shortwave) absorbers:
    - UV-absorbers: ozone (O₃), oxygen (O₂)
    - visible range (0.4 - 0.7 \( \mu \)m): almost none (\( \rightarrow \)window)
  
  - **terrestrial radiation** (longwave) absorbers:
    - IR absorbers: H₂O, CO₂, N₂O, O₃, O₂
    - peak terrestrial radiation (8 - 12 \( \mu \)m): almost none (\( \rightarrow \)window)

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**greenhouse radiation trap**

**Atmospheric Windows for Radiation**

- **Window:** something that lets light (radiation) through
Atmospheric Window:

There are two atmospheric windows:

- **visible range window** (0.4 - 0.7 μm):
  - lets most solar radiation through to the surface
  - enables solar radiation to “deliver” the bulk of its energy to the surface (for use in climate processes)

- **longwave window** (8 - 12 μm):
  - lets some terrestrial radiation through to space
  - enables Earth to “vent off” some of its energy back to space

What happens if the windows are closed?

- **visible range window** (0.4 - 0.7 μm)
  -
- **longwave window** (8 - 12 μm):
  
  *(more accurately: the *enhanced* Greenhouse Effect)*

source:
http://www.fe.doe.gov/issues/climatechange/globalclimate_whatis.html
(Jan. 22, 2001)