5 Radiation

Learning Goals

After studying this chapter, students should be able to:

- describe the relationships given by the four radiation laws (pp. 89–93);
- distinguish between the radiation emitted by the sun and the radiation emitted by Earth (pp. 93–95);
- define the term albedo, and explain how albedo is important in the climate system (pp. 95–98);
- explain how the radiative properties of atmospheric gases and aerosols influence the climate system (pp. 98–104);
- explain why we have seasons (pp. 111–117); and
- account for all the factors that influence the amount of solar radiation absorbed at Earth's surface (pp. 117–119).

Summary

1. **Radiation** is energy that travels in the form of electromagnetic waves; it can transfer heat and travel in a vacuum. Electromagnetic radiation is grouped and named according to **wavelength**. In atmospheric science, only ultraviolet, visible, and infrared wavelengths are significant.
2. Radiation is emitted according to the radiation laws. As temperature increases, the rate of radiation emission increases, and the wavelengths of the emitted radiation decrease. Most of the radiation emitted by the sun is at wavelengths between 0.15 and 3.0 μm; we call this **shortwave radiation**. Most of the radiation emitted by Earth is at wavelengths between 3.0 and 100.0 μm; we call this **longwave radiation**.
3. All radiation that is incident on a substance is accounted for through some combination of absorption, reflection, and transmission.
4. **Albedo** is the reflectivity of surfaces to the sun's radiation. Surfaces with high albedos—such as snow or deserts—will reflect much of the sun's radiation; surfaces with low albedos—such as wet soil and vegetative coverings—will absorb much of the sun's radiation.
5. The sun's radiation is scattered by gas molecules and aerosols in the atmosphere. Selective—or **Rayleigh**—scattering by gas molecules makes the sky blue. Non-selective—or **Mie**—scattering by aerosols, including cloud droplets, makes clouds and fog white.
6. The gases of the atmosphere selectively absorb radiation. The atmosphere is much more effective at absorbing longwave radiation than it is at absorbing shortwave radiation. The gases most responsible for absorbing longwave radiation are water vapour, carbon dioxide, methane, nitrous oxide, and ozone. These are greenhouse gases. The gases most responsible for absorbing shortwave radiation are oxygen and ozone. Atmospheric gases do not effectively absorb visible radiation (0.4 to 0.7μm) or wavelengths within the atmospheric window (8 to 11 μm). Clouds, however, absorb all longwave radiation.
7. The **greenhouse effect** occurs because the atmosphere allows the transmission of shortwave radiation, but greenhouse gases and clouds absorb longwave radiation. Earth is currently 33°C warmer than it would be without this greenhouse effect.
8. We can use the selective absorption of radiation by gases to explain the temperature structure of the atmosphere. There are three points at which temperature reaches a maximum due to strong absorption of solar radiation: at the "top" of the atmosphere, in the upper stratosphere, and at Earth's surface.
9. The recent melting and thinning of sea ice has caused temperatures in the Arctic to increase about twice as much as they have elsewhere. This phenomenon is known as Arctic amplification and occurs mostly due to certain radiative and thermal properties of ice and water.
10. The maximum amount of solar radiation that can be received anywhere in the Earth-atmosphere system is the **solar constant**. Solar radiation received at Earth's surface will be less than the solar constant due to the effects of sun angle and atmospheric attenuation. Sun angle varies with latitude, time of year, and time of day. Atmospheric attenuation varies with the content of the atmosphere, combined with sun angle. Once solar radiation reaches Earth's surface, the amount absorbed largely depends on surface shadiness, slope, and albedo.

Key Terms

Absorptivity A measure of a substance's ability to absorb incident radiation (p. 90).

Albedo The proportion of the sun's incident radiation that is reflected by a surface (p. 95).

Altitude angle The angle of the sun above the horizon (p. 108).

Analemma A graph giving the latitude at which the sun is directly overhead for any day of the year (p. 114).

Aphelion The position in Earth's orbit when Earth is farthest from the sun (p. 111).

Atmospheric window The band of wavelengths of radiation, from 8 to 11 μm, that is not absorbed by gases in the atmosphere (p. 101).

Beam depletion The increasing depletion of the solar beam by atmospheric constituents as the sun's path length through the atmosphere increases (p. 108).

Beam spreading The spreading of the solar beam over an increasing surface area as the sun's angle decreases (p. 108).

Black body A hypothetical substance that does not reflect or transmit radiation but instead absorbs all of the radiation incident on it (p. 90).

Circle of illumination A circular boundary between Earth's light half and its dark half (p. 113).

Continentality The degree to which a climate is affected by its distance from a body of water (p. 117).

December solstice The date on which the sun is directly overhead at the Tropic of Capricorn. This is the first day of winter in the northern hemisphere and the first day of summer in the southern hemisphere (p. 112).

Diffuse radiation The sun's radiation that reaches Earth's surface after being scattered (p. 98).

Direct beam radiation The sun's radiation that reaches Earth's surface without first being scattered (p. 98).

Electromagnetic spectrum The continuous spectrum of wavelengths of electromagnetic radiation (p. 88).

Emissivity The ratio of radiation emitted by a real substance to the amount emitted by a black body at the same temperature (p. 90).

Inverse square law A general mathematical law used to determine the amount of any physical quantity propagating from a point source at a given distance from that source (p. 106).

June solstice The date on which the sun is directly overhead at the Tropic of Cancer. This is the first day of summer in the northern hemisphere and the first day of winter in the southern hemisphere (p. 112).

Kirchhoff's law A radiation law stating that the emissivity of a substance at a given wavelength is equal to the absorptivity of that substance at the same wavelength (p. 94).

Longwave radiation The radiation emitted by Earth, which includes only infrared radiation (p. 94).

March equinox A date on which the sun is directly overhead at the equator. This is the first day of spring in the northern hemisphere and the first day of fall in the southern hemisphere (p. 112).

Mie scattering Scattering of radiation by particles bigger than the wavelengths they scatter (p. 98).

Path length The distance that the sun's rays must travel through the atmosphere to reach Earth's surface (p. 109).

Perihelion The position in Earth's orbit when Earth is closest to the sun (p. 111).

Planck's curve The graphical representation of Planck's law; it shows that the rate of emission of radiation per wavelength rises rapidly with increasing wavelength, reaches a peak (λ_{max}), and then decreases gradually with further increases in wavelength (p. 90).

Planck's law A radiation law stating that, for any substance, the rate of emission per wavelength increases with temperature, and the lengths of the waves emitted decrease with temperature (p. 90).

Rayleigh scattering Scattering of radiation by particles smaller than the wavelengths they scatter (p. 98).

Reflectivity A measure of a substance's ability to reflect incident radiation (p. 95).

Scattering The process by which atmospheric gases and aerosols reflect radiation in multiple directions (p. 98).

September equinox A date on which the sun is directly overhead at the equator. This is the first day of fall in the northern hemisphere and the first day of spring in the southern hemisphere (p. 112).

Shortwave radiation The radiation emitted by the sun, which includes ultraviolet, visible, and infrared radiation (p. 94).

Sine law of illumination An equation used to calculate the amount of radiation incident on a surface, based on altitude angle (p. 108).

Solar constant The amount of energy that strikes the top of the atmosphere, on a surface perpendicular to the solar beam, when Earth is at an average distance from the sun (p. 106).

Stefan–Boltzmann law A radiation law stating that the rate of emission of radiation by a substance will increase with the temperature of the substance (p. 90).

Subsolar point The latitude at which the sun is directly overhead at noon (p. 113).

Transmissivity A measure of a substance's ability to transmit incident radiation (p. 95).

Wavelength The distance between any two like points on a wave (p. 87).

Wavelength of maximum emission The wavelength at which the rate of emission of radiation is highest (p. 90).

Wien's law A radiation law stating that the wavelength at which a substance emits the most energy will decrease as the temperature of the substance increases (p. 90).

Zenith angle The angle of the sun from the zenith (p. 108).

Key Equations

Stefan–Boltzmann law

$$E = \varepsilon \sigma T^4$$

Wein's law

$$\lambda_{max} = \frac{2897}{T}$$

Kirchhoff's law

$$\varepsilon_{\lambda} = a_{\lambda}$$

Sine law of illumination

$$S = S_i \sin\theta$$

Answers to Selected Review Questions (p. 120)

1. **What do the radiation laws tell us about the emission of radiation? How and why is the radiation emitted by Earth different from that emitted by the sun?**

   The radiation laws tell us that temperature determines both the rate of emission and the wavelengths that will be emitted. The radiation emitted by Earth is different than that emitted by the sun because Earth is much cooler. Earth emits radiation in the infrared portion of the spectrum and the sun emits ultraviolet, visible, and infrared radiation.

3. **How is Rayleigh scattering similar to and different from Mie scattering?**

   They each scatter radiation off in many directions. Rayleigh scattering is selective scattering because it scatters some wavelengths more than others. It is caused by gas molecules. Mie scattering is non-selective scattering because it scatters all wavelengths nearly equally. It is caused by aerosols and water droplets, which are bigger than the wavelengths of light.

5. **How do the radiative properties of gases (Figure 5.15) help explain a) the greenhouse effect and b) the temperature structure of the atmosphere?**

   a) The atmosphere is almost transparent to the sun's radiation but it is almost opaque to Earth's longwave radiation. b) Temperature maximums occur where solar radiation is most strongly absorbed—by nitrogen and oxygen in the upper thermosphere, and by oxygen and ozone in the stratosphere.

7. **What causes seasons?**

   Seasons occur because Earth revolves around the sun, Earth's axis is tilted, and the north end of the axis always points to the North Star. Together, these conditions cause sun angle and day length to vary throughout the year, at a given latitude.

9. **What factors influence the amount of solar radiation received at the top of the atmosphere?**

   The factors are latitude, time of year, and time of day.

11. **What determines the distribution of shortwave radiation received at Earth's surface?**

    The solar constant, sun angle, depletion of the sun's rays in the atmosphere, shadiness, and slope angle

Answers to Selected Problems (p. 121)

1. **Determine roughly how much more blue light than red light is scattered in the atmosphere. Use Expression 5.9, and make the simplification that the wavelength of blue light is 0.4μm and the wavelength of red light is 0.7μm.**

    Rayleigh Scattering ~ λ^{-4}

    Blue: $0.4^{-4} = 39.1$ μm

    Red: $0.7^{-4} = 4.2$ μm

    $$\frac{39.1\ \mu\text{m}}{4.2\ \mu\text{m}} = 9.3$$

    Approximately 9.3 times more blue light than red light is scattered in the atmosphere.

3. **Compare the annual variation in noon sun angle at 55º N to that at 15º N.**

    Noon sun angle at 55°N:

    For the June solstice, the subsolar point is 23.5°N.
    Step 1: 55° – 23.5° = 31.5°
    Step 2: noon sun angle = 90° – 31.5° = 58.5°

    For the December solstice, the subsolar point is 23.5°S.
    Step 1: 55° + 23.5° = 78.5°
    Step 2: noon sun angle = 90° – 78.5° = 11.5°

    At 55°N the noon sun angle varies from 58.5° to 11.5°.

    Noon sun angle at 15°N:

    The sun is directly overhead twice per year (4 May and 12 August).

    For the December solstice, the subsolar point is 23.5°S.
    Step 1: 15° + 23.5° = 38.5°
    Step 2: noon sun angle = 90° – 38.5° = 51.5°

At 15°N the noon sun angle varies from 90° to 51.5°.

5. **Calculate the noon sun angle for each of the following.**
a) 57º S on 9 January
b) 12 º N on 30 April
c) 39 º N on 15 November

a) The subsolar point on 9 January is 22.3°S.
Step 1: 57° + 22.3° = 34.7°
Step 2: noon sun angle = 90° – 34.7° = 55.3°

b) The subsolar point on 30 April is 14.1°N.
Step 1: 14.1° – 12° = 2.1°
Step 2: noon sun angle = 90° – 2.1° = 87.9°

c) The subsolar point on 15 November is 18.4°S.
Step 1: 39° + 18.4° = 57.4°
Step 2: noon sun angle = 90° – 57.4° = 32.6°

7. **a) Calculate the noon sun angles on the June solstice for each of the following latitudes: 0º, 50º N, and 90º N. Why are the noon sun angles at the equator and at 50º N so similar?**
b) For the same three latitudes, calculate the amount of solar radiation received at noon at the top of the atmosphere on the June solstice. Use a solar constant of 1365W/m^2.

a) For the June solstice the subsolar point is 23.5°N. Noon sun angle at 0°:
Step 1: 23.5° – 0° = 23.5°
Step 2: noon sun angle = 90° – 23.5° = 66.5°
Noon sun angle at 50°N:
Step 1: 50° – 23.5° = 26.5°
Step 2: noon sun angle = 90° – 26.5° = 63.5°

Noon sun angle at 90°:
Step 1: 90° – 23.5° = 66.5°
Step 2: noon sun angle = 90° – 66.5° = 23.5°

The noon sun angles at the equator and at 50°N are so similar because the number of degrees of latitude between the subsolar point and those latitudes is similar on the June solstice.

b) Solar radiation received at noon at the top of the atmosphere on the June solstice at 0°:
S = (1365 W/m^2) sin 66.5°
= 1251.8 W/m^2

Solar radiation received at noon at the top of the atmosphere on the June solstice at 50°:

$S = (1365\ W/m^2) \sin 63.5°$
$= 1221.6\ W/m^2$

Solar radiation received at noon at the top of the atmosphere on the June solstice at 90°:
$S = (1365\ W/m^2) \sin 23.5°$
$= 544.3\ W/m^2$

Study Questions

For suggested answers, see below.

1. What is albedo? What factors determine the albedo of a surface? Give examples of surfaces with high albedos and low albedos.

2. Why is the solar constant higher on planets located farther away from the sun?

3. What are two reasons why the amount of solar radiation striking a surface will decrease as sun angle decreases?

4. Which areas of Earth will experience 24 hours of day light and 24 hours of darkness?

5. Why is the temperature gradient between the equator and the poles much less in summer than it is in winter?

Additional Problems

For answers, see below.

1. Determine how much more blue light than green light is scattered in the atmosphere. Assume the wavelength of blue light is 0.40 μm and the wavelength of green light is 0.51 μm.

2. Calculate the amount of radiation emitted by a glass surface with a temperature of 26°C.

3. If the amount of radiation emitted by wet soil is 382 W/m^2, what is the temperature of the soil?

4. a) What is the wavelength of maximum emission of a surface with a temperature of 12°C? b) What types of waves are most commonly emitted from this object at this temperature?

5. Calculate the solar constant for Saturn. The average distance between the sun and Saturn is 1.43×10^9 km. The radius of the sun is 6.96×10^5 km. The radiation emitted by the sun is 6.4×10^7 W/m^2.

6. If 828 W/m^2 of radiation is received on a horizontal surface when the sun is directly overhead, how much radiation will be received when the altitude angle is 37°?

7. How much greater is the sun's path length when the sun's altitude angle is 6° compared to when the sun's angle is 45°?

8. Calculate the noon sun angle at 20°S for the two equinoxes, the June solstice, and the December solstice.

9. Calculate the noon sun angle for each of the following.
   a) 42°N on 2 August
   b) 10°S on 4 October

10. Compare the annual variation in noon sun angle at 48°N to that at 3°S.

Answers to Study Questions

1. Albedo is the proportion of the sun's incident radiation that is reflected by a surface. It is dependent on the colour and roughness of the surface and somewhat dependent on the angle of the sun. Snow and thick clouds have high albedos. Asphalt, forests, and water (at high sun angles) have low albedos. (pp. 95–97)

2. The radiation leaving the sun spreads out more and more the farther it travels from its starting point. The same amount of radiation is spread over a larger area and the radiation received per unit of surface area decreases. (pp. 106–108)

3. Radiation will be spread over an increasingly larger area and the solar beam will experience greater depletion due to a longer path length. (p. 109)

4. All latitudes from 66½° N to the North Pole and all latitudes from 66½° S to the South Pole will experience 24 hours of day light and 24 hours of darkness. (p. 113)

5. In the northern hemisphere summer, the amount of solar radiation received at the North Pole is greater than the amount received at the equator due to the increased day length at the North Pole. However, at Earth's surface, beam depletion causes more solar radiation to be received at the equator than at the North Pole during that time. There is much less difference between the amounts of radiation received at these two locations in the summer than there is in winter. (p. 116)

Answers to Additional Problems

1. Rayleigh Scattering $\sim \lambda^{-4}$

   Blue: $0.40^{-4} = 39.1\ \mu\text{m}$

   Green: $0.51^{-4} = 14.8\ \mu\text{m}$

   $$\frac{39.1\ \mu\text{m}}{14.8\ \mu\text{m}} = 2.6$$

   Approximately 2.6 times more blue light than green light is scattered in the atmosphere.

2. $$\begin{aligned} E &= \varepsilon\sigma T^4 \\ &= (0.92)\ (5.67 \times 10^{-8}\,\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4})\ (299\ \text{K})^4 \\ &= 416.9\ \text{W/m}^2 \end{aligned}$$

3. $E = \varepsilon\sigma T^4$

$$T = \left(\frac{E}{\varepsilon\sigma}\right)^{0.25}$$

$$= \left(\frac{382\ \text{Wm}^{-2}}{(0.95)(5.67\times10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4})}\right)^{0.25}$$

$= 290.2$ K

$= 17.2$°C

4. $$\lambda_{max} = \frac{2897\ \mu\text{m K}}{285\ \text{K}}$$

$= 10.2\ \mu$m

Infrared waves are most commonly emitted from this object at this temperature.

5. $$E_2 = E_1\left(\frac{R_1}{R_2}\right)^2$$

$$E_2 = 6.4\times10^7\ \text{Wm}^{-2}\left(\frac{6.96\times10^5\ \text{km}}{1.43\times10^9\ \text{km}}\right)^2$$

$= 15.2$ W/m^2

6. S = (828 W/m^2) sin 37°

$= 498.3$ W/m^2

7. $$PL = 1\times\frac{1}{\sin 6°}$$

$$= \frac{1}{0.105}$$

$= 9.57$

$$PL = 1\times\frac{1}{\sin 45°}$$

$$= \frac{1}{0.707}$$

$$= 1.41$$

$$\frac{9.57}{1.41} = 6.8$$

Therefore, the sun's path length is 6.8 times longer when the sun angle is 6° compared to when it is 45°.

8. Noon sun angle at 20°S:

For the March equinox, the subsolar point is 0°.
Step 1: 20° – 0° = 20°
Step 2: noon sun angle = 90° – 20° = 70°

For the June solstice, the subsolar point is 23.5°N.
Step 1: 23.5° + 20° = 43.5°
Step 2: noon sun angle = 90° – 43.5° = 46.5°

For the September equinox, the subsolar point is 0°.
Step 1: 20° – 0° = 20°
Step 2: noon sun angle = 90° – 20° = 70°

For the December solstice, the subsolar point is 23.5°S.
Step 1: 23.5° – 20° = 3.5°
Step 2: noon sun angle = 90° – 3.5° = 86.5°

9. a) The subsolar point on 2 August is 18°N.
Step 1: 42° – 18° = 24°
Step 2: noon sun angle = 90° – 24° = 66°

b) The subsolar point on 4 October is 4°S.
Step 1: 10° – 4° = 6°
Step 2: noon sun angle = 90° – 6° = 84°

10. Noon sun angle at 48°N:

For the June solstice, the subsolar point is 23.5°N.
Step 1: 48° – 23.5° = 24.5°
Step 2: noon sun angle = 90° – 24.5° = 65.5°

For the December solstice, the subsolar point is 23.5°S.
Step 1: 48° + 23.5° = 71.5°
Step 2: noon sun angle = 90° – 71.5° = 18.5°

At 48°N the noon sun angle varies from 65.5° to 18.5°.

Noon sun angle at 3°S:

The sun is directly overhead twice per year (30 September and 15 March).

For the June solstice, the subsolar point is 23.5°N.
Step 1: 3° + 23.5° = 26.5°
Step 2: noon sun angle = 90° – 26.5° = 63.5°

At 3°S the noon sun angle varies from 90° to 63.5°.