6 Energy Balance

Learning Goals

After studying this chapter, students should be able to:

1. explain the concept of effective radiating temperature as it applies to a planet (pp. 123–125);
2. describe and account for the flows of energy that make up the planetary energy balance (pp. 126–132);
3. discuss the formation and significance of latitudinal radiative imbalances (pp. 132–133); and
4. explain how flows of energy influence microclimates through the energy balance concept (pp. 133–144).

Summary

1. The **effective radiating temperature** of a planet is the temperature at which that planet radiates away as much energy as it receives from the sun. We can derive an equation for calculating this temperature based on the radiation balance at the top of the atmosphere. This equation shows that the effective radiating temperature of a planet depends on the planet's **solar constant** and the planet's **albedo**. The *actual* temperature of a planet is also affected by the planet's **greenhouse effect**.
2. Of the solar radiation that reaches the top of the atmosphere, just under half of it is absorbed by Earth's surface. The rest is mostly reflected, scattered, or absorbed by clouds, gases, and aerosols in the atmosphere, while a small amount is reflected by Earth's surface. On an annual average, 30 per cent of the solar radiation that reaches the top of the atmosphere is reflected back to space, and the remaining 70 per cent is absorbed in the Earth-atmosphere system.
3. Earth's surface emits **longwave radiation**; almost 90 per cent of this radiation is absorbed in the atmosphere. The atmosphere also emits longwave radiation; just over 60 per cent of this radiation is absorbed at Earth's surface, while the rest escapes to space.
4. The **planetary energy balance** is an accounting system for flows of energy, by both radiation and convection, within the Earth-atmosphere system. It applies on an average annual basis. As a result of increases in greenhouse gases due to human activity, there is currently a small imbalance, at the top of the atmosphere, between absorbed solar radiation and outgoing longwave radiation.
5. Low thick clouds tend to have a cooling effect on Earth, while high thin clouds tend to have a warming effect. At present, and on an average annual basis, information from satellites indicates that the net effect of clouds is to cool Earth. That is, without clouds, Earth would be warmer.
6. Large radiative imbalances occur at individual latitudes. Between roughly 40° N and 40° S, absorbed solar radiation is greater than outgoing longwave radiation. Beyond these latitudes, absorbed solar radiation is less than outgoing longwave radiation. Heat flow from the equator to the poles prevents tropical regions from getting continually warmer, and it prevents polar regions from getting continually colder; it also reduces, but does not eliminate, the meridional temperature gradient.
7. We can apply the energy balance concept to a surface. A radiative surplus during the day drives a flow of sensible heat into the ground by conduction, and it drives flows of sensible and latent heat into the air by convection. These flows typically carry heat and water vapour away from the surface during the day. At night, a radiative deficit normally causes heat flow to operate in the reverse, carrying heat and water vapour toward the surface. Certain characteristics of the surface determine the relative magnitude of these flows. These characteristics are **albedo**, **emissivity**, **conductivity**, **specific heat**, **moisture content**, and **surface roughness**. The last characteristic influences winds.

Key Terms

Advection Horizontal transfer across a fluid, caused by movement within the fluid (p. 133).

Climate sensitivity The relationship between an energy imbalance and the resulting temperature change once the system has regained balance (p. 130).

Conductive sensible heat flux The transfer of sensible heat by conduction between Earth's surface and the ground below (p. 138).

Convective latent heat flux The transfer of latent heat by convection between Earth's surface and the atmosphere (p. 138).

Convective sensible heat flux The transfer of sensible heat by convection between Earth's surface and the atmosphere (p. 138).

Dew Atmospheric water vapour that has condensed onto a cool surface during the night (p. 140).

Effective radiating temperature The temperature at which a system radiates away as much energy as it receives (p. 123).

Energy balance An accounting system for the flows of energy in a climate system (p. 123).

Evapotranspiration The process by which water vapour enters the atmosphere either directly from water bodies or other moisture sources, or from the openings in the leaves of plants (p. 140).

Flux convergence The result when the input of energy to a volume exceeds the output of energy from that volume (p. 138).

Flux divergence The result when the input of energy to a volume is less than the output of energy from that volume (p. 138).

Frost Atmospheric water vapour that has collected on a surface as ice crystals (p. 140).

Meridional Relating to or varying along a meridian, or in the north–south direction (p. 133).

Planetary circulation The average patterns of pressure and wind over Earth's surface (p. 133).

Radiative forcing A measure of how much a change in Earth's atmosphere, or at Earth's surface, alters the flows of radiation in the energy balance and, thus, forces the climate to change (p. 123).

Sky-view factor A measure of the amount of sky that can be "seen" from a point on the ground (p. 136).

Transpiration The process by which water vapour is released through a plant's stomata (p. 140).

Urban heat island A microclimate created by a city, in which temperatures are higher than they are in the surrounding region (p. 133).

Key Equations

Effective radiating temperature

$$T_E = \left[\left(\frac{S}{4\sigma}\right)(1-\alpha)\right]^{0.25}$$

Net shortwave radiation

$$K^* = K\downarrow - K\uparrow$$

Net longwave radiation

$$L^* = L\downarrow - L\uparrow$$

Net longwave radiation

$$L^* = L\downarrow - L\uparrow = \varepsilon_a \sigma T_a^4 - [\varepsilon_s \sigma T_s^4 + (1 - \varepsilon_s)L\downarrow]$$

Net radiation at the surface (day)

$$Q^* = K^* + L^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow)$$

Net radiation at the surface (night)

$$Q^* = L^* = L\downarrow - L\uparrow$$

Surface energy balance

$$Q^* = Q_H + Q_E + Q_G$$

Answers to Selected Review Questions (p. 145)

1. **Since Earth is continually receiving radiation from the sun, why doesn't it keep getting hotter? What causes Earth to re-establish a balance when the energy balance is disturbed?**

   Earth does not keep getting hotter because a warmer Earth will respond by emitting more radiation, thus preventing further warming. A negative feedback mechanism works to stabilize the system such that the Earth will emit more or less radiation when the energy balance is disturbed.

3. **How can we use Equation 6.3 as a model to help us understand a planet's temperature?**

   The equation can be used to predict how changes in the planetary albedo or the output of the sun might influence a planet's temperature. If the planet's actual temperature is known, the equation can be used to estimate the size of that planet's greenhouse effect.

5. **Over the course of a year, why is there a net transfer of heat by convection from the surface to the atmosphere?**

   Earth's surface has a radiative surplus and the atmosphere has a radiative deficit.

7. **What role do clouds play in the planetary energy balance? What is the net effect of clouds on Earth's temperature?**

   Clouds both reflect solar radiation and absorb and emit longwave radiation. Clouds have a net cooling effect on Earth's temperature.

9. **What factors influence the net radiation, Q^*, at a surface? How does each of these factors influence net radiation?**

   The net shortwave radiation and the net longwave radiation influence the net radiation, Q^*, at a surface. Incoming shortwave radiation and longwave radiation from the atmosphere cause Q^* to increase. Reflected shortwave radiation and longwave radiation leaving the surface cause Q^* to decrease.

11. **Why can deserts get very hot during the day and very cold at night?**

Deserts get very hot during the day due to little or no evaporation, poor conductivity, and low specific heat. At night, the clear skies, along with the low water vapour content of the air allow for strong radiative cooling.

Answers to Selected Problems (p. 146)

1. **Given the following information for a planet in another solar system, calculate the planet's radiative equilibrium temperature. In this solar system, the sun has a radius of 500,000 km, and it emits 25,000,000 W/m^2. The planet has an albedo of 21 per cent and it is 76,000,000 km from its sun.**

Calculate the solar constant for the planet.

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

$$E_2 = 25{,}000{,}000\,\mathrm{W\,m^{-2}}\left(\frac{500{,}000\,\mathrm{km}}{76{,}000{,}000\,\mathrm{km}}\right)^2$$

$$= 1082\ \mathrm{W/m^2}$$

The solar constant is 1082 W/m^2.

$$T_E = \left[\left(\frac{S}{4\sigma}\right)(1-\alpha)\right]^{0.25}$$

$$T_E = \left[\left(\frac{1082\,\mathrm{W\,m^{-2}}}{4(5.67\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}}\right)(1-0.21)\right]^{0.25}$$

$$= 247.8\ \mathrm{K}$$

$$= -25.2^\circ\mathrm{C}$$

3. a) **In Section 2.10, you learned that the sun was producing about 30 per cent less energy when the solar system first formed than it is today. Given these conditions, what would have been Earth's effective radiating temperature? (Assume that Earth's albedo was the same as it is today.)**

b) The temperature you calculated in a) should fall below the freezing point of water, yet there is evidence that liquid water existed on Earth as early as 3.8 billion years ago. This apparent contradiction has been called the *faint young sun paradox*. Provide two solutions to this paradox, given the following

- **your understanding of the factors affecting the temperature of a planet;**
- **the greater amount of both carbon dioxide and methane in Earth's early atmosphere (Section 2.10); and**
- **the greater area of ocean surface compared to the area of land surface on the young Earth.**

The solar constant for Earth is 1365 W/m$^{2.}$

Reduce the solar constant by 30 per cent:

(0.3)(1365 W/m^2) = 955.5 W/m^2

$$T_E = \left[\left(\frac{S}{4\sigma}\right)(1-\alpha)\right]^{0.25}$$

$$T_E = \left[\left(\frac{955.5\,\mathrm{W\,m^{-2}}}{4(5.67\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}}\right)(1-0.3)\right]^{0.25}$$

= 233 K

= –40°C

Two solutions to the paradox:

- There may have been more greenhouse gases at that time leading to a larger greenhouse effect.
- The greater area of ocean surface may have resulted in a lower planetary albedo.

Study Questions

For suggested answers, see below.

1. What are the noticeable effects of the increase in stored energy on a global scale that has resulted from the current small radiative imbalance in the Earth system?
2. What are several examples of microclimates that can develop in a city?
3. How does the sky-view factor influence longwave exchange?
4. How can plants affect latent heat flux?

5. What are the three surface heat flows that will exist as a result of a daytime radiative surplus? Briefly describe each.

Additional Problems

For answers, see below.

1. Calculate the effective radiating temperature for Mars. Use a solar constant of 588 W/m^2 and an albedo of 17 per cent.

2. Calculate the total amount of solar radiation received at the top of Mars's atmosphere, averaged over the surface of Mars.

3. Calculate the albedo at noon for a surface when incoming shortwave radiation is 720 W/m^2 and the reflected shortwave radiation is 186 W/m^2.

4. Calculate the amount of longwave radiation emitted from a surface with an emissivity of 0.96 and a temperature of –5°C.

5. Given the following information, determine the net radiation. Incoming solar radiation is 583 W/m^2, incoming longwave radiation is 319 W/m^2, the surface temperature is 8°C, the surface albedo is 22 per cent, and the surface emissivity is 0.92. The reflection of longwave radiation can be ignored.

Answers to Study Questions

1. Some of the energy is being used as latent heat to melt ice and evaporate water. The rest of it is being stored in the oceans, resulting in thermal expansion of the water and a rise in sea level. (p. 123)

2. Parks can create cool, moist escapes from the often hot, dry conditions of downtown cores. Fountains in vast concrete plazas can significantly chill the air. A courtyard can produce warmth on an otherwise cool day. Canyons between tall buildings can lead to cool, windy conditions. (pp. 133–134)

3. Open spaces have much higher sky-view factors than do more urban or enclosed spaces. A lower sky-view factor results in a smaller longwave loss. (p. 136)

4. Plants can affect latent heat flux through transpiration. When the air is warm and dry, and it is windy, transpiration will be high. However, plants need to replace the moisture they lose by drawing up more water through their roots; if there is too little water in the soil, the plant's stomata will close, transpiration will cease, and the latent heat flux will decrease. (p. 140)

5. Sensible heat will flow from the surface to the ground by conduction. Sensible heat will flow from the surface to the atmosphere by convection. Latent heat will flow to the atmosphere by convection as water evaporates at the surface and condenses in the air. (p. 140)

Answers to Additional Problems

1.

$$T_E = \left[\left(\frac{S}{4\sigma}\right)(1-\alpha)\right]^{0.25}$$

$$T_E = \left[\left(\frac{588\,\mathrm{W\,m^{-2}}}{4(5.67\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}}\right)(1-0.17)\right]^{0.25}$$

$$= 215.4\ \mathrm{K}$$

$$= -57.6^\circ\mathrm{C}$$

2. The total amount of solar radiation intercepted by Mars is

$$S\pi r_M^{\ 2}$$

Averaged over Mars's spherical surface, this becomes

$$\frac{S\pi r_M^{\ 2}}{4\pi r_M^{\ 2}} = \frac{S}{4}$$

$$\frac{588\,\mathrm{W\,m^{-2}}}{4} = 147\,\mathrm{W\,m^{-2}}$$

3. $$\alpha = \frac{K\uparrow}{K\downarrow}$$

$$= \frac{186\,\mathrm{W\,m^{-2}}}{720\,\mathrm{W\,m^{-2}}}$$

$$= 0.26$$

4. $L\uparrow = \varepsilon\sigma T^4$

$L\uparrow = (0.96)\ (5.67\times10^{-8}\ \mathrm{W{\cdot}m^{-2}{\cdot}K^{-4}})\ (268\ \mathrm{K})^4$

$= 280.8\ \mathrm{W/m^2}$

5. $Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$

$K\uparrow = \alpha K\downarrow$

$K\uparrow = (0.22)\ (583\ \mathrm{W/m^2})$

$K\uparrow = 128\ \mathrm{W/m^2}$

$L\uparrow = \varepsilon\sigma T^4$

$L\uparrow = (0.92)\ (5.67\times10^{-8}{\cdot}\mathrm{W\,m^{-2}{\cdot}K^{-4}})\ (281\ \mathrm{K})^4$

$L\uparrow = 325\ \mathrm{W/m^2}$

$Q^* = 583\ \mathrm{W/m^2} - 128\ \mathrm{W/m^2} + 319\ \mathrm{W/m^2} - 325\ \mathrm{W/m^2}$

$= 449\ \mathrm{W/m^2}$