Instructor's Manual and Test Bank to accompany Meteorology Today, 11th Edition

Chapter 2
Energy: Warming Earth and the Atmosphere

Learning Objectives

Energy, Temperature, and Heat
2-1: Define the terms energy, potential energy, kinetic energy, radiant energy, temperature and heat, and describe their relationships in the context of Earth’s atmosphere.
2-2: Compare the Fahrenheit, Celsius, and Kelvin temperature scales and outline their scientific backgrounds and uses today.
2-3: Differentiate heat capacity, specific heat, latent heat and sensible heat, and explain how they relate to evaporation–transportation–condensation cycles in Earth’s atmosphere.
Heat Transfer in the Atmosphere
2-4: Describe the principles of conduction, convection, and advection and summarize their roles in Earth’s atmosphere.
Radiant Energy
2-5: Define electromagnetic and radiant energy, and illustrate the relationship between radiation and temperature.
2-6: Apply the principles of radiant energy to the Sun and Earth.
Radiation—Absorption, Emission, and Equilibrium
2-7: Define the terms blackbody, radiative equilibrium temperature, selective absorber, atmospheric window, and describe their relationship to the atmospheric greenhouse effect.
2-8: Discuss the atmospheric greenhouse effect, and assess its impact on climate and life on Earth.
2-9: Examine the effect that conduction, convection, scattering, and reflection have on Earth’s radiant energy budget.
2-10: Investigate the roles of energy absorption and emission with regard to Earth’s energy balance, and in this context, explain latitudinal temperature fluctuations observed on Earth.
Solar Particles, the Aurora, and Space Weather
2-11: Describe the solar wind and its interaction with Earth’s magnetic field.
2-12: Identify the differences between solar winds and storms and their respective phenomena as observed in Earth’s atmosphere.

Summary

This chapter begins with a definition of temperature and a comparison of the absolute (Kelvin), Celsius, and Fahrenheit temperature scales. Heat, the flow of energy between objects having different temperatures, occurs in the atmosphere by the processes of conduction, convection, and radiation. Air is a relatively poor conductor of heat but can transport heat efficiently over large distances by the process of convection. The latent heat energy associated with the phase changes of water is shown to also be a very important energy transport mechanism in the atmosphere. A physical explanation of why rising air cools and sinking air warms is given.

The nature of and rules which govern the emission of electromagnetic radiation are reviewed next. Students should find the discussion of Sunburning and UVB radiation in this section interesting and relevant. The atmospheric greenhouse effect and the exchange of energy between the earth's surface, the atmosphere, and space are examined in detail. As the role of greenhouse gases in climate change is undergoing vigorous investigation, the latest research results are presented. Students will see that, because the amounts of energy absorbed and emitted by Earth are in balance, the Earth's average radiative equilibrium temperature varies little from year to year. Students should understand that the energy Earth absorbs from the Sun consists primarily of short-wave radiation. The energy emitted by Earth is almost entirely in the form of infrared radiation. Selective absorbers in the atmosphere, such as water vapor and carbon dioxide, absorb some of Earth's infrared radiation and re-radiate a portion of it back to the surface. Because of this effect, Earth's average surface temperature is much higher than it would be otherwise. A useful focus section describes this effect in the context of radiative equilibrium. Results from recent research relating to the effect of increasing concentrations of carbon dioxide and other greenhouse gases and the effects of clouds on Earth's energy balance are reviewed.

The final portion of the chapter describes the physical characteristics of the Sun and the causes of the aurora.

The chapter includes focus sections on “The Fate of a Sunbeam”; “Rising Air Cools and Sinking Air Warms”; “Wave Energy, Sunburning, and UV Rays”; “Blue Skies, Red Suns, and White Clouds”; and “Characteristics of the Sun”.

Key Terms

energy
potential energy
kinetic energy
temperature
heat
absolute zero
Kelvin scale
Fahrenheit scale
Celsius scale
heat capacity
specific heat
latent heat
sensible heat
conduction
convection
thermals
advection
radiant energy (radiation)
electromagnetic waves
wavelength
micrometer
photons
Stefan-Boltzmann law
Wien’s law
longwave radiation
shortwave radiation
visible region
ultraviolet (UV) radiation
infrared (IR) radiation
blackbody
radiative equilibrium temperature
selective absorbers
Kirchhoff’s law
greenhouse effect
greenhouse gases
atmospheric window
solar constant
scattering
reflected (sunlight)
albedo
solar wind
space weather
aurora borealis
aurora australis
airglow

Teaching Suggestions

1. Heat a thin iron bar in a flame (from a Bunsen burner or a propane torch). Begin by holding the bar fairly close to the end of the bar. Students will see that heat is quickly conducted through the metal when the instructor is forced to move his or her grip down the bar. Repeat the demonstration with a piece of glass tubing or glass rod. Glass is a poor conductor and the instructor will be able to comfortably hold the glass just 2 or 3 inches from the tip. Ask the students if they believe energy is being transported away from the hot glass and if so, how? Without heat loss by conduction, the glass will get hotter than the iron bar and the tip should begin to glow red - a good demonstration of energy transport by radiation. Faint convection currents in the air can be made visible if the hot piece of glass is held between an overhead projector and the projection screen. Ask the students what they would do to quickly cool a hot object. Many will suggest blowing on it, an example of forced convection. Someone might suggest plunging the hot object into water. This makes for a satisfying end to the demonstration. Evaporating water can be seen and heard when the hot iron rod is put into the water (the glass will shatter if placed in the water). The speed with which the rod is cooled is proof of the large amount of latent heat energy associated with changes of phase.

2. Ask the students whether they believe water could be brought to a boil most rapidly in a covered or an uncovered pot. The question can be answered experimentally by filling two beakers with equal amounts of water and placing them on a single hot plate (to insure that energy is supplied to both at equal rates). It is a good idea to place boiling stones in the beakers to insure gentle boiling. Cover one of the beakers with a piece of foil. The covered pot will boil first. Explanation: a portion of the energy added to the uncovered pot is used to evaporate water, not to increase the water's temperature.

3. The concept of equilibrium is sometimes difficult for students to grasp. Place a glass of water on a table top and ask the students whether they think the temperature of the water in the glass is warmer, cooler, or the same as the surroundings. Many will say it is the same. Ask the students whether they think there is any energy flowing into or out of the glass. With some encouragement, they will recognize that the water is slowly evaporating and that this represents energy flow out of the glass. Energy flowing out of the glass will cause the water's temperature to decrease. Will the water just continue to get colder and colder until it freezes? No, as soon as the water's temperature drops below the temperature of the surroundings, heat will begin to flow into the water. The rate at which heat flows into the glass will depend on the temperature difference between the glass and the surroundings. The water temperature will decrease until energy flowing into the glass balances the loss due to evaporation.

4. Use a lamp with a 150 Watt reflector bulb to help explain the concept of radiation intensity. Blind-fold a student and hold the lamp at various distances from the student's back. Ask the student to judge the distance of the bulb. Use the same lamp to illustrate the concepts of reflection, albedo, and absorption by measuring the amount of reflected light from various colored surfaces with a sensitive light meter. The reflectivity of natural surfaces outdoors could be measured or could form the basis for a student or group project.

5. A 200 Watt clear light bulb connected to a dimmer switch can be used to illustrate how the temperature of an object affects the amount and type of radiation that the object will emit. Explain that the passage of electricity through the resistive filament heats the filament. The filament's temperature will increase until it is able to emit energy at the same rate it gains energy from the electric current. With the dimmer switch set low, the bulb can be made to glow a dull red. At low temperatures, the bulb emits low-intensity, longwave radiation. As the setting on the dimmer switch is increased, the color of the filament will turn orange, yellow, and then white as increasing amounts of shortwave radiation are emitted. The intensity of the radiation will increase dramatically.

6. Many students don't understand that a colored object appears colored because it reflects or scatters light of that color. The object isn't emitting visible light (ask the student whether they would see the object if all the lights in the room were turned off). Some students have the misconception that a green object reflects all colors but green. Similarly it is important that students understand that a red or green filter transmits red or green light. Put a red and a green (or blue) filter on an overhead projector and draw a hypothetical filter transmission curve. Put the two filters together and show that no light is transmitted. Ask the students what happens to the light that is not transmitted by the filter.

7. Thought experiment to illustrate the magnitude of latent heat of evaporation/condensation: Ask students to think about taking a hot shower. Their body temperature is ~ 100°F; the water temperature is > 100°F; the air temperature in the room is ~75°F. Why, then, do you feel cold when you step, dripping wet, out of the shower?

8. Discuss the concept of a *scale*, such as the Celsius scale for temperature. A scale must have a meaningful zero point and a meaningful increment. Discuss the meaning of the zero point for the Celsius scale. Discuss the meaning of a 1° increment of temperature within the Celsius scale. Invite students to comment on the relative merits of the Kelvin, Celsius and Fahrenheit temperature scales.

9. A mnemonic trick for converting between Celsius and Fahrenheit: 20°C = 68°F; 30°C = 86°F. Note that the digits “68” are reversed to “86”.

10. Have students give specific examples of each of the phase changes shown in Figure 2.3.

Student Projects

1. Solar irradiance (energy per unit time per unit area) at the ground can be measured relatively easily. Begin with a rectangular piece of aluminum a few inches on a side and 3/8 or 1/2 inch thick. Drill a hole in one side so that a thermometer can be inserted into the middle of the block. Paint one of the two surfaces with flat black paint. Position the block in a piece of styrofoam insulation so that the painted surface faces outward and is flush with the styrofoam surface. Insert the thermometer into the side of the block. Orient the block so that the black surface is perpendicular to incident radiation from the Sun. Note the time and measure the block temperature every 30 seconds for 10 to 15 minutes. When plotted on a graph, students should find that temperature, T, increases linearly with time, t. The slope of this portion of the graph can be used to infer the solar irradiance, S, using the following equation:

$$S = \frac{mass \times specificheat}{area} \times \frac{\Delta\ T}{\Delta\ t}$$

2. Describe the difference between *energy* and *power*. How is energy related to power? The strength of light bulbs is usually given in watts. Is this energy or power?

3. Explain, using concepts presented in the chapter, why windshield sun shades used in cars are more effective if they are brightly colored.

4. Using the concept of convection, explain why wall heat vents are more effective when they are located close to the floor rather than to the ceiling.

5. Explain why humid nights are generally warmer than nights with low humidity.

Answers to Questions for Review

1. Temperature is a measure of the average speed of atoms and molecules.

2. Heat is energy in the process of being transferred from one object to another because of the temperature difference between them.

3. (a) Each degree on the Kelvin scale is exactly the same size as a degree Celsius, and a temperature of 0 K is equal to -273°C.
   (b) Because there are no negative values.
   (c) Cold, because 250 K = -23°C = -9°F.

4. Conduction: The transfer of heat from molecule to molecule within a substance. Convection: The transfer of heat by the mass movement in liquids and gases. Radiation: Heat transfer from one object to another without the space between them necessarily being heated.

5. When water vapor condenses into clouds, latent heat is released into the atmosphere. This provides a tremendous amount of heat in storms, such as thunderstorms and hurricanes.
6. Advection is horizontal; convection is vertical.

7. A small increase in temperature results in a large increase in the amount of radiation emitted because doubling the absolute temperature of an object increases the maximum energy output by a factor of 16, which is 24.

8. Because Earth is cooler than the Sun, it emits a lot less radiation than the Sun.

9. Because Earth is cooler, its radiation is at longer wavelengths than that of the Sun.

10. Ultraviolet.

11. The amount of radiation entering the surface of the body equals the amount exiting the surface of the body.

12. Because it is also continually receiving energy from the Sun and the atmosphere.

13. Because they absorb radiation at certain wavelengths and not others.

14. The atmosphere allows visible radiation to pass through, but inhibits to some degree the passage of infrared radiation leaving Earth's surface.

15. CO_2, methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs).

16. An enhancement of Earth's greenhouse effect.

17. Reflection and the scattering of solar radiation by the atmosphere, clouds, and Earth's surface.

18. Longwave radiation from Earth, conduction, and convection.

19. On a sunny day, Earth’s surface warms by absorbing more energy from the Sun and the atmosphere than it radiates, while at night Earth cools by radiating more energy than it absorbs from its surroundings.

20. Because they absorb and radiate with nearly 100 percent efficiency for their respective temperatures.

21. Charged particles (ions and electrons), or plasma, travelling through space.

22. The aurora is produced by the solar wind disturbing the magnetosphere. The disturbance involves high-energy particles within the magnetosphere being ejected into Earth’s upper atmosphere, where they excite atoms and molecules. The excited atmospheric gases emit visible radiation, which causes the sky to glow like a neon light.

Answers to Questions for Thought

1. The bridge will become icy first because it is able to lose heat energy over its entire surface; it cools on top, on the sides, and on the underside. The road, on the other hand, loses heat energy quickly, but only at its upper surface. Also, when the road begins to cool, heat may flow up from the warmer ground below.

2. The branches cool rapidly by emitting infrared energy. The bare ground cools also, but it gains heat from the warmer soil below. Thus, the temperature of the bare ground may not drop below freezing and the freshly fallen snow will melt.

3. These objects must be good emitters of radiation. Good emitters of radiation will cool to temperature less than that of the surrounding air. Energy lost by radiation is not quickly replaced by conduction. Air is a selective emitter of radiation and does not cool as rapidly as the ground.

4. The ice can form when the air is dry and a strong wind blows over the water, causing rapid evaporation and cooling to the freezing point.

5. Winter. Even though the oceans are cooler in winter than in summer, there is a greater temperature contrast between the oceans and the atmosphere in winter.

6. In the form of electromagnetic radiation only.

7. Ultraviolet radiation carries more energy per photon than visible radiation.

8. At a given distance from the large fire the energy received per unit area and per unit time is greater than the energy received at the same distance from the small fire.

9. Without water vapor to absorb Earth's emitted infrared radiation, Earth would lose more heat.

10. A plowed field. A plowed field is dark and has a low albedo - it is a poor reflector and a good absorber of sunlight. The snow surface has a high albedo and is a good reflector and poor absorber of sunlight.

11. The low cloud absorbs energy emitted by Earth's surface and re-radiates infrared radiation back to the surface. A portion of the energy lost by Earth is returned.

12. Removing the water vapor, because water vapor is a strong absorber of infrared radiation and because atmospheric concentrations of H_2O are much higher than the concentrations of CO_2.

13. An increase in cloud cover would increase Earth-atmosphere albedo and, thus, less sunlight would reach Earth's surface. Depending on the height and thickness of the cloud cover, clouds may absorb more infrared Earth radiation and, thus, strengthen the atmospheric greenhouse effect.

14. If the Sun was cooled to a temperature of 2000°C it would emit less energy at short and more energetic wavelengths (those corresponding to ultraviolet and blue light). The Sun’s energy would be shifted to red and less energetic wavelengths of light. .

15. The energized particles from a large solar flare, that may produce auroral displays at lower latitudes, usually take a day or so to reach Earth's outer atmosphere.

16. In Fig. 2.23, note that the aurora belt extends closer to Maine than to Washington state. The aurora belt circles the magnetic north pole, not the geographic North Pole.

Answers to Critical Thinking Questions

Figure 2.16. A global increase in cloudiness would increase the albedo and decrease the amount of solar energy reaching the surface. The increased cloudiness would likely be accompanied by an increase in water vapor, which is a greenhouse gas.

Figure 2.18. The deficit could decrease, thus reducing the rate of poleward heat transfer.