Chapter 2: HEATING EARTH'S SURFACE AND ATMOSPHERE

Outline

I. Earth–Sun Relationships
- A. Earth's Motions
  - 1. Rotation
  - 2. Revolution
    - a. Perihelion
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- B. The Seasons
- C. Earth's Orientation
  - 1. Plane of the ecliptic
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- D. Solstices and Equinoxes
  - 1. Summer solstice; Tropic of Cancer
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II. Energy, Heat, and Temperature
- A. Forms of Energy
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III. Mechanisms of Energy Transfer
- A. Conduction
- B. Convection
- C. Radiation
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IV. What Happens to Incoming Solar Radiation?
- A. Reflection and Scattering
  - 1. Reflection and Earth's albedo
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- B. Absorption by Earth's Surface and Atmosphere

V. Radiation Emitted by Earth
- A. Heating the Atmosphere
  - 1. Atmospheric window
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- B. The "Greenhouse Effect"

VI. Heat Budget

VII. Latitudinal Heat Balance

Key Learning Outcomes

- **The ultimate cause behind all weather phenomena involves the *differential* or unequal heating of the Earth's surface. Many factors are responsible for this unequal heating and will be explored in upcoming chapters. However, a vital first step is to understand the *Earth-Sun relationship,* or how the tilt of the Earth in its yearly revolution around the Sun creates the seasons.**

Possible challenges: Although most students have been exposed to the concept of the Earth-Sun relationship since grade school, a surprisingly large number enter college with very little understanding of *why* seasons occur, the role of the *tilt* of the Earth in influencing weather, or even the knowledge that different areas of the globe may be experiencing different seasons during the same time period.

In particular, they may understand the concept of a tilted Earth (with respect to the plane of the ecliptic), but fail to grasp that the tilt remains *fixed* as the Earth circles the Sun during the course of the year. A common misconception of students is that the Earth tilts one way, say, during winter solstice but "flops over" and tilts in the opposite direction by the summer solstice. When attempting to visually explain the Earth-Sun relationship, students may create some rather interesting (and erroneous) diagrams along the ecliptic! The first Strategy for Teaching below should help to address this misconception.

- **From this starting point, the concept of *energy*, specifically heat energy, will be introduced as we examine how this energy is transmitted from the Sun to the Earth's surface and ultimately into the atmospheric circulation through the heat transfer processes of *conduction*, *convection*, and *radiation*.**

Possible challenges: Most students will have a familiarity with the concept of *energy* and its various forms and even at least a passing acquaintance with the laws of thermodynamics. Conduction and convection, important concepts in this chapter, are usually easily grasped with some examples, but *radiation* may prove to be more of a challenge and just the phrase "electromagnetic spectrum" can evoke some trepidation. The previous section laid the basis for transferring solar energy to Earth, and an understanding of how radiation accomplishes this is vital for completing the picture.

Keep it simple! Explaining radiation as simply another method of heat transference that acts to move energy from the Sun to the Earth through the vacuum of space should be sufficient. There are a few suggestions in the Strategies for Teaching below and several intriguing examples of how the electromagnetic spectrum provides us with color in our everyday life.

- **Radiant energy reaches the Earth's surface but many factors may affect its path along the way and these factors can have a significant influence on the amount of heating that may occur at any location on our planet's surface.**

Possible challenges: Reflection, absorption, and scattering can all occur as radiant energy passes through our Earth's atmosphere on its journey toward our surface. The concept of *reflection* and what this means in the heat transference process often creates some confusion. Having just spent the first part of the chapter stressing the transfer of heat energy from the Sun to the Earth's surface and then encountering a scenario where the process suddenly seems to "quit working" can be frustrating for students. However, approaching this as a "balance" issue can help; reflection plays an important role in moderating the Earth's temperature and knowing *where* and *why* this occurs aids the student in understanding the key concept of unequal heating of the Earth's surface.

- **The previous sections can now be united into a comprehensive picture of the "infamous" (or not so infamous) *greenhouse effect*—and what role human activities might play in global warming.**

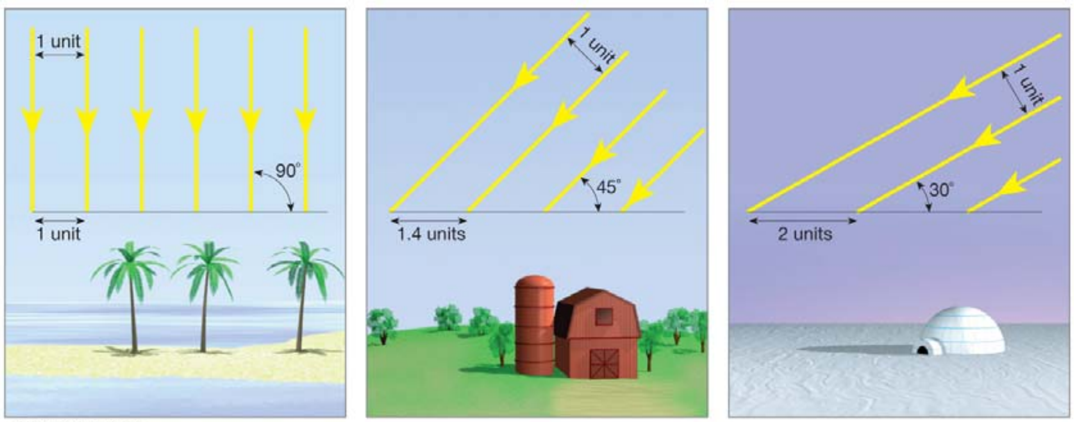
Possible challenges: There is such a wealth of material on global warming that many instructors may feel reluctant to even attempt to introduce this subject. In addition, global warming can be a contentious subject to tackle. However, the difference between the greenhouse effect and global warming should be emphasized and, depending on the instructor's timetable, an interesting (and lively) discussion is possible. The instructor has an opportunity to explain the role of the scientist in this highly political debate (and how much of the debate is not centered on the science at all). The scientific method learned in Chapter 1 can be reintroduced here. The global scientific community overwhelmingly supports the concept of global warming; why, then, is there so much dispute?

As science instructors, one of our key roles is introducing students to the importance of critical analysis in making informed, rational decisions. Teaching science involves not just the passing on of the vast library of facts that mankind has accumulated over the millennia; it is instructing students on how to evaluate these facts and fashion them into the greater truths about our natural world.

Strategies for Teaching *Heating Earth's Surface and Atmosphere*

A. Understanding the Earth-Sun Relationship

1. Introducing this topic requires vivid visual aids. The instructional DVD that accompanies the text contains all the photographs and diagrams found in the text, as well as animations that can be very useful in bringing the Earth's yearly revolution to life. An examination of how differing Sun angles can heat the Earth in different ways is a good place to start.



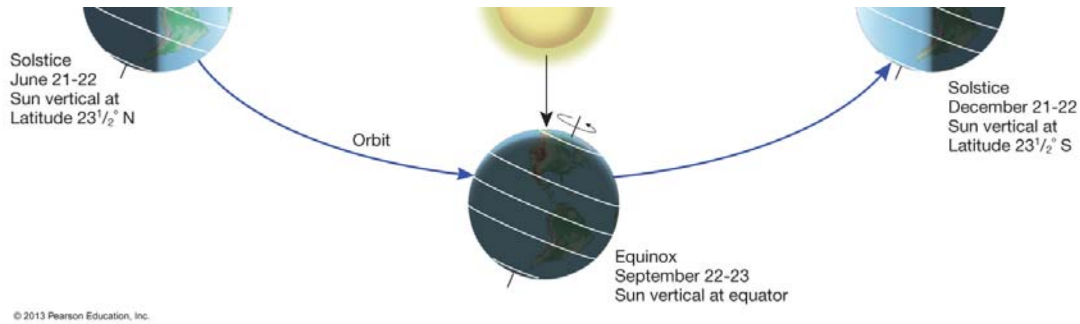


Figure 2–5

The animation in the instructional DVD should be utilized here; putting the above picture into motion is much more effective in helping students to create a mental picture. The animation is particularly effective in demonstrating the changing daylight hours; it can be stopped at the different equinox and solstice points for students to see how not only do the daylight hours change at a given location over the course of the year, but the change—or lack of —at different latitudes is striking. After observing this animation, students should be challenged: what is (are) the major factor(s) in determining the amount of solar energy reaching any point on Earth?

At this point, the instructor may also want to offer a few illustrations of the "land of the midnight sun." There is an attractive one of the 24-hour sun that is accessible from the instructional DVD, but there are many more available on the Internet as well.

Note: If the classroom has a celestial globe, this can also be employed to show how the Earth's North Pole is (currently) "locked" onto the North Star, Polaris, and therefore doesn't "flop" back and forth as it revolves around the Sun (a common misunderstanding). Instructors can find many spectacular time-lapse videos online demonstrating this concept.

3. A final exercise can be introduced utilizing the analemma. Many students find the analemma challenging and it can be useful to point out an analemma on a globe. The instructor can emphasize the value of knowing one's noon Sun angle for any day of

the year or, correspondingly, being able to calculate one's latitude by the noonday Sun. Students should be encouraged to think of examples as well. One example: this knowledge can have definite value in areas such as solar energy. Box 2–3 goes into this area in further detail.

B. Energy, Heat, and Temperature

1. Most students will be familiar (hopefully!) with the concept of "energy," but a brief review is usually a good idea. Explaining the first law of thermodynamics helps set the stage for explaining all the energy transferences that will be covered later. Numerous examples of energy transfers can be given in order to contrast "energy" with "temperature," along with the explanation that the students will be exposed to temperature in much more detail in the following chapter. However, now the three important methods of heat transfer—conduction, convection, and radiation—can be introduced.

2. Each heat transfer process should be quickly demonstrated. Conduction can be easily illustrated by simply grasping a cold metal object (such as a metal faucet, available in most classrooms). Convection can either be shown through the animation on the instructional DVD or, if the instructor has the time, by setting up a quick convection experiment in front of the classroom (or having the students do their own). This may involve something as simple as a glass beaker of boiling water to which food coloring or glitter has been added to something as elaborate as a convection model available through science catalogs. An effective technique is to show how convection also is prevalent throughout many natural systems, from currents in the Earth's mantle affecting plate tectonics to the roiling surface of the Sun. For the purposes of this course, however, the concentration will be on convection as a means of transferring heat energy from the surface of the Earth aloft.

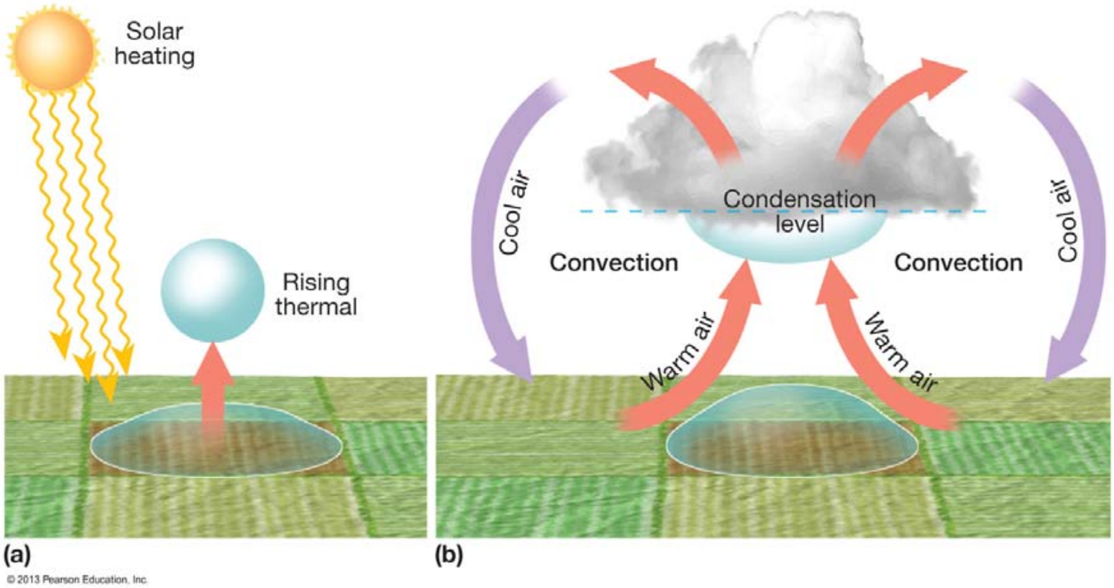
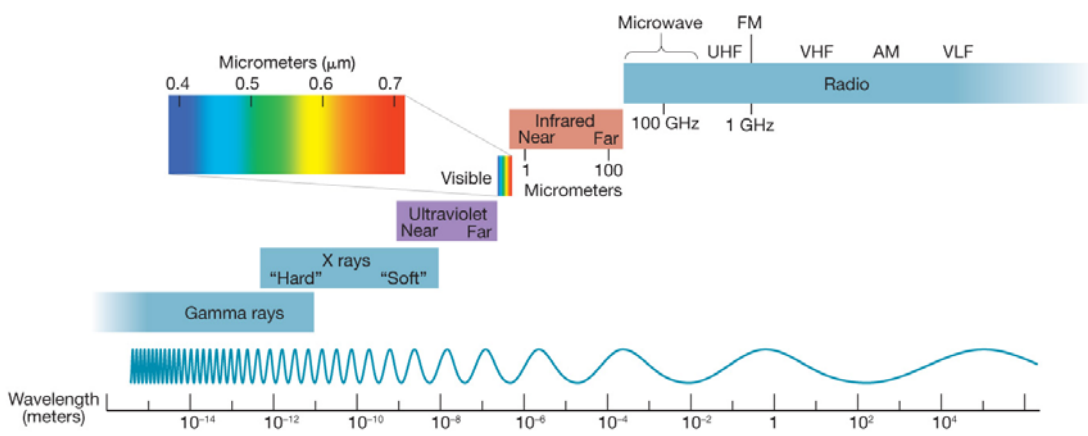


Figure 2–11

Radiation can be the most challenging to demonstrate. Using a prop to demonstrate wave motion—a piece of flexible rubber hose with the instructor at one end and a student at another works well—the instructor or student (not both) can show how slow, languid movements produce long waves and quick, energetic movements produce short waves. Then the appropriate illustration from the text can be displayed to explain the various divisions in the electromagnetic spectrum.



Many interesting examples can be given by both the instructor and students to illustrate the differences between light being "reflected" or "absorbed" and how that affects the colors that we see (the yellow color of the Sun versus a yellow shirt a student may be wearing). An instructor may also wish to show one of the many excellent pictures to be found online of the phenomenon called the "Green Flash." This can naturally lead up to upcoming concepts such as the distribution of incoming solar radiation and the greenhouse effect.

C. Distribution of Solar Radiation

The emphasis is on "unequal heating of the Earth's surface"; therefore, students need to have some understanding of the many factors that can affect the distribution of incoming solar radiation.

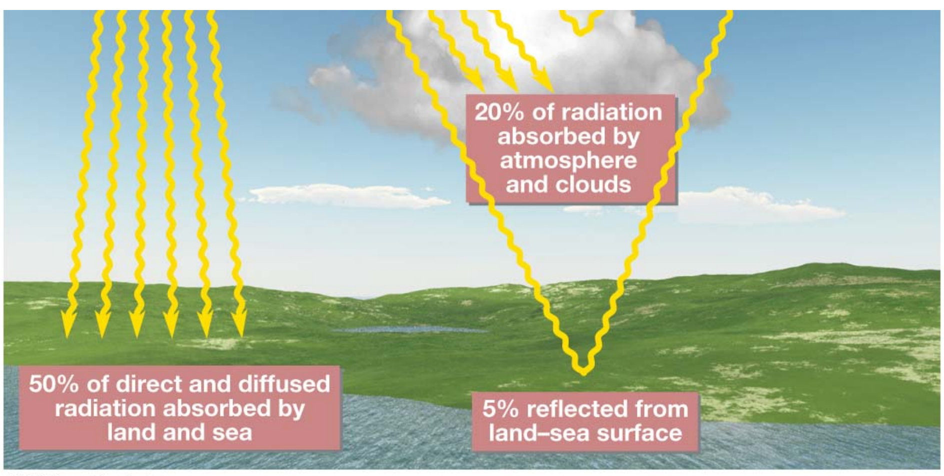


Figure 2–15

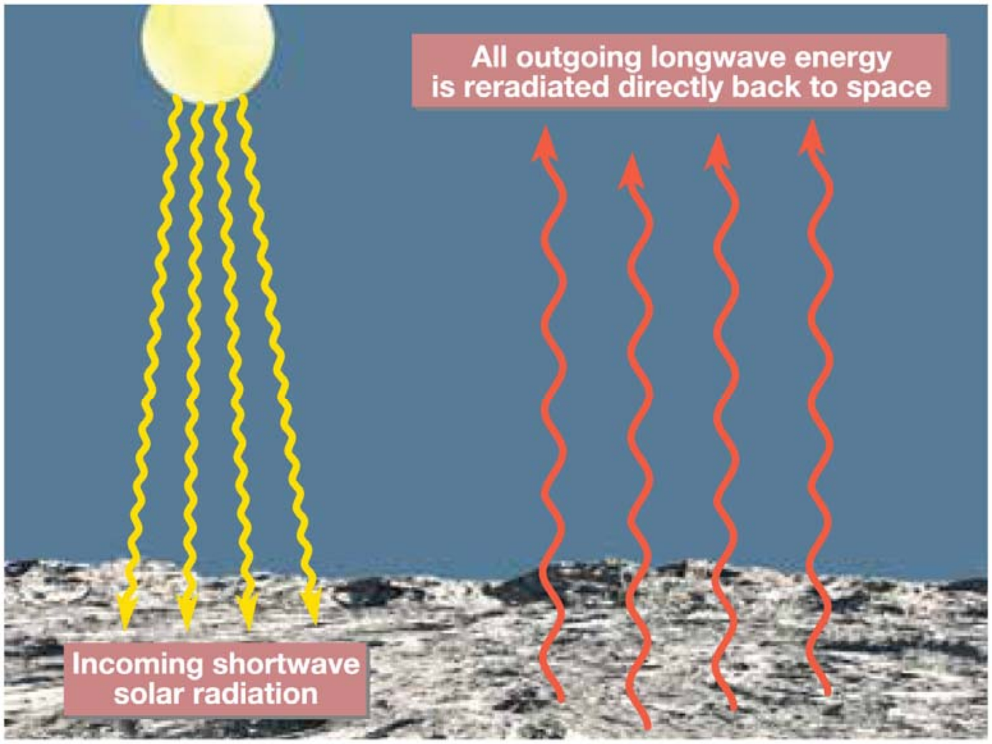
1. Reflection has already been addressed and can now be illustrated with an appropriate picture, easily available online, of the brilliant Earth as taken by the *Apollo* astronauts.

   Albedo is an important concept and students should be encouraged to give examples of substances with both high and low albedos. By understanding the nature of reflection, how does its albedo affect the temperature of any object?
   Extra: If the instructor has sufficient time, an experiment utilizing dark and light (reflective) containers can be set up either as a demonstration at the front of the classroom or by the students themselves. Using heat lamps and thermometers suspended in the containers allows the students to see firsthand how different materials absorb heat at different rates.

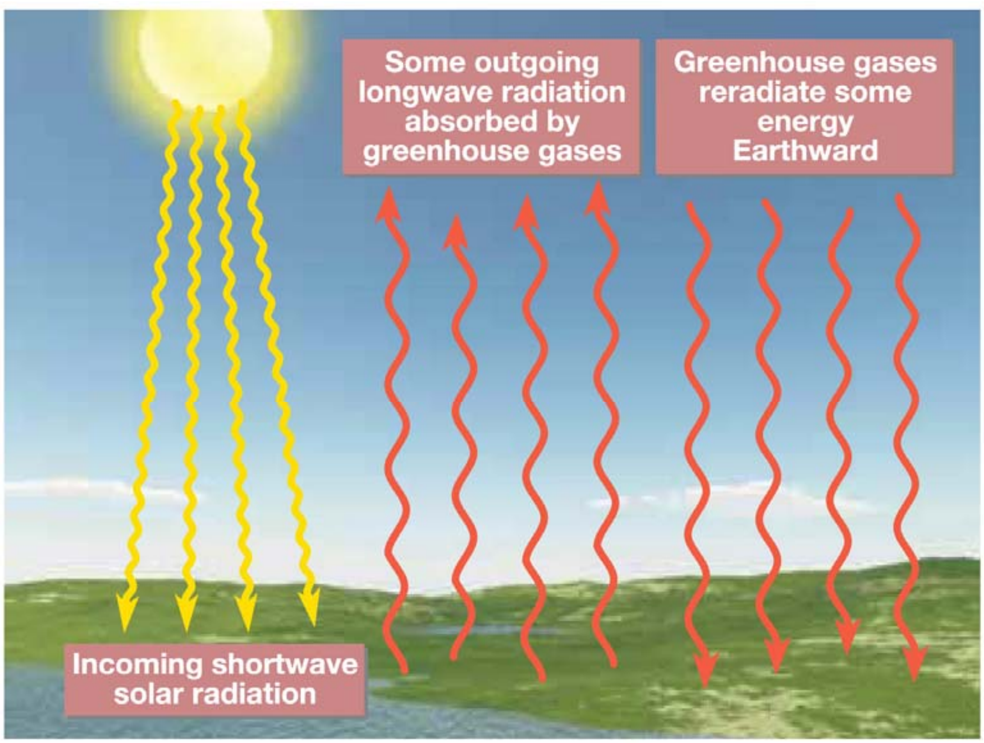
   Scattering is most useful in explaining the blue of the sky. How can it also explain sunsets? How can the presence of pollutants in the atmosphere affect sky color?

   The Geoscience Animation Library has an excellent animation entitled "Atmospheric Energy Balance" that runs through each of these steps.

2. The *greenhouse effect* should be given ample time not only for its importance in illustrating the distribution of solar radiation but also because of its relevance. Again, the animation on the instructional DVD should be accessed and each step in the model carefully explained. The soundness of this model should be emphasized; many students may be surprised to learn that there is little scientific disagreement regarding the validity of the greenhouse effect model.



(a) Airless bodies like the Moon



(b) Bodies with modest amounts of greenhouse gases like Earth

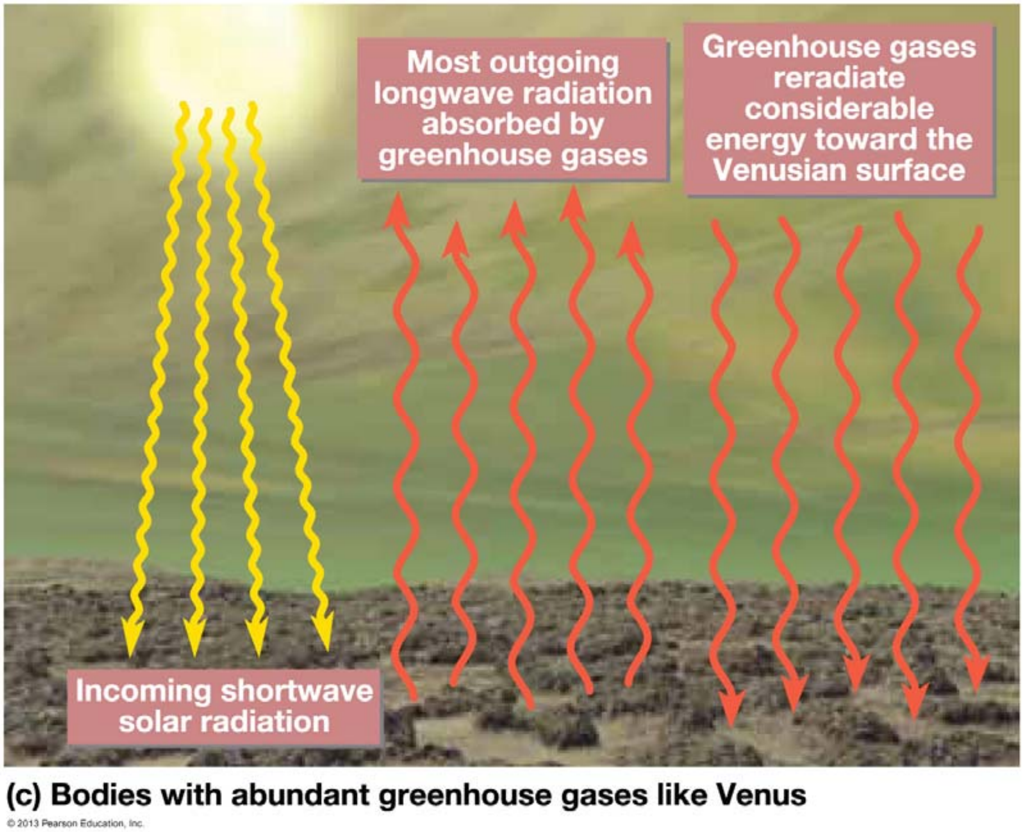


Figure 2-22

Finally, this is an opportunity to encourage students to connect the science they learn in the classroom with real-world events. This can be an excellent time to assign readings and papers outside traditional meteorology curriculum. A good place to start would be the website of the Intergovernmental Panel on Climate Change (IPCC): http://ipcc.ch.

Answers to Concept Checks 2.1

1. No. For example, Earth is closest to the Sun in January (winter in the Northern Hemisphere) and is farthest from the Sun in July (the warmest month of the year in the Northern Hemisphere). The angle of solar energy encountering Earth explains seasonal temperature changes much more than Earth–Sun distance.

2.

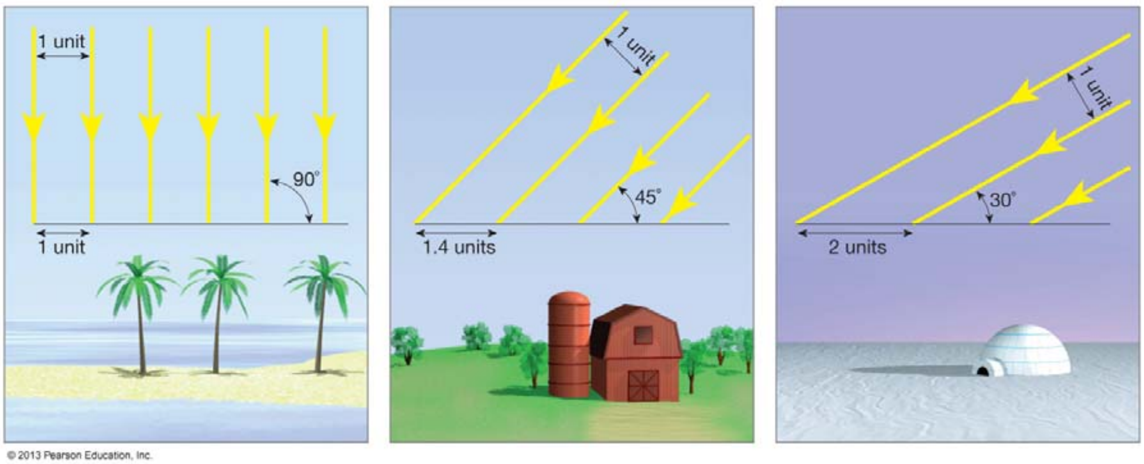


Figure 2–3

3. The primary cause of the seasons at any location on Earth involves both the changing angle of the solar rays over the course of the year and the changing length of the daylight hours.

4. The "tropics" stretches from 23.5° N to 23.5° S and experiences the noon Sun directly overhead (90°) at least one day a year. The northernmost boundary of this region (23.5°N) is the Tropic of Cancer, where the noon sun reaches 90° around June 21–22. The southern boundary is set by the Tropic of Capricorn, and there the vertical rays of the noon Sun will be found around December 21–22.

5. Tropical regions experience little variation between seasons due to the high noon Sun angle throughout the year and uniform length of daylight/darkness hours, but the further one moves from the equator, the more extreme the variation between seasonal noon Sun angles and seasonal length of daylight hours.

Answers to Eye on the Atmosphere (#1)

1. September 22–23

2. Roughly 12 hours

3. The sun reaches 23.5 degrees above the horizon on December 21–22.

Answers to Concept Check 2.2

1. Heat is a form of energy, while temperature indicates how hot something is. Heat generally refers to a quantity of energy, while temperature refers to intensity (degree of "hotness"). Although a cup of boiling water and a pail of boiling water have the same temperature, the pail of boiling water contains a greater quantity of heat.

2. Liquid water is evaporated from the Earth's land-sea surface. The latent heat energy stored in this water vapor is released into the atmosphere whenever the water vapor condenses.

3. Latent heat is the "hidden" heat energy stored or released when water changes from one state into another. The release of heat energy in the atmosphere when water vapor returns to its liquid state would be an example. *Sensible heat* is the heat we can *feel* and measure with a thermometer (it can be "sensed"). People living adjacent to the Gulf of Mexico can testify to this sensible heat that flows out of the Gulf into the surrounding states, giving them their "muggy" summers.

Answers to Concept Check 2.3

1. Conduction is the transfer of heat through matter by molecule-to-molecule contact, while convection refers to heat transfer by the movement of a mass or substance. Radiation, the method of heat transfer between the Sun and Earth, is the transfer of heat through space by electromagnetic waves. Meteorologically, conduction is the least important mechanism of heat transfer.

2. The term *convection* is used in two somewhat different ways. In its broadest meaning, convection refers to one of the three basic methods of heat transfer. The more limited use of the term refers to *vertical* motions in the atmosphere, while the term *advection* is reserved for *horizontal* motions such as wind.

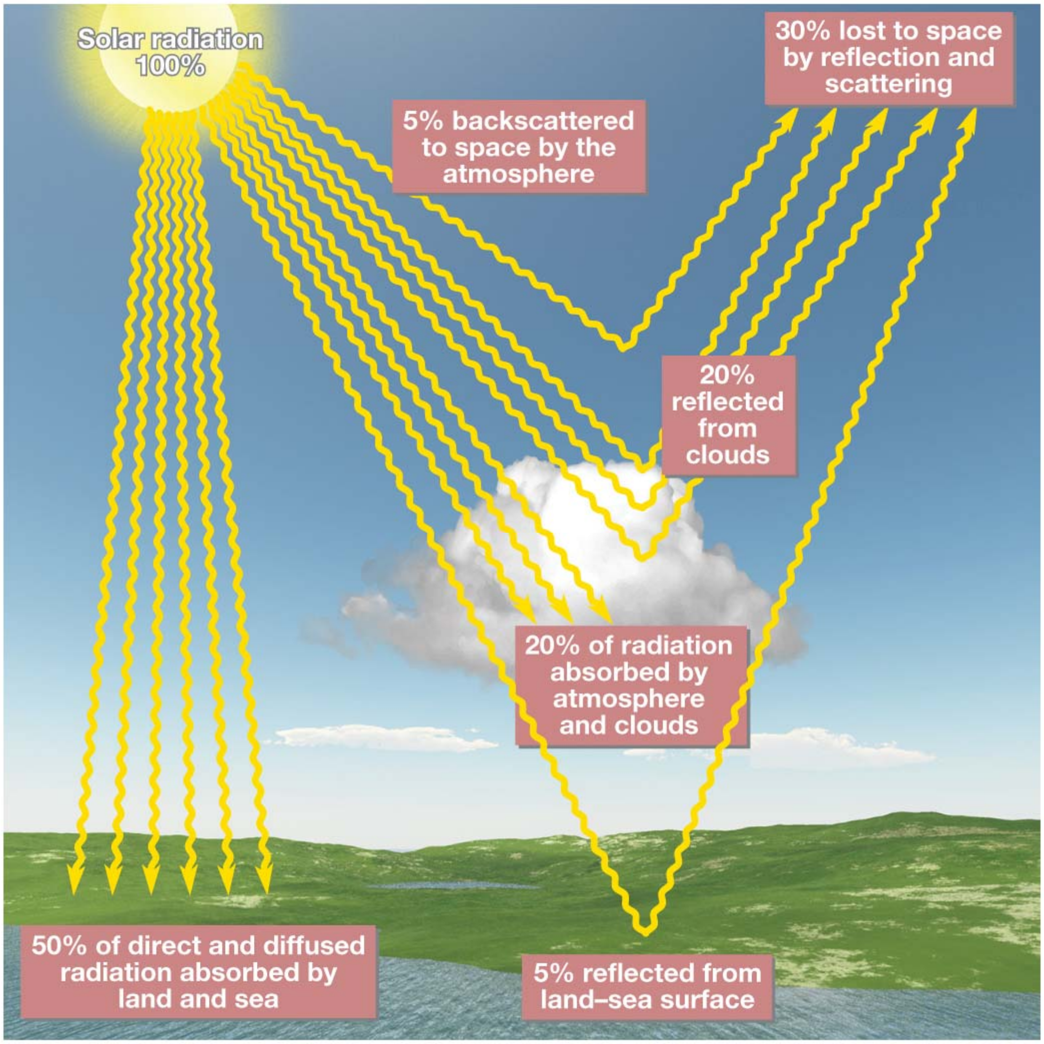
3. Each of these represents a type of electromagnetic radiation based upon a different wavelength range. Ultraviolet has the shortest wavelength range (from 0.1 to 0.4 micrometers); visible rays are intermediate (from 0.4 to 0.7 micrometers); and infrared is the longest (from 0.7 to about 1000 micrometers). The categories of ultraviolet, visible, and part of the infrared (from 0.7 to about 2.0 micrometers) are termed *shortwave radiation*. Solar radiation lies almost entirely in this region. Earth radiation is entirely in the infrared and is often described as *longwave radiation*.

4. Most of the Sun's radiant energy is provided by wavelengths in the visible (43 percent) and near infrared (49 percent). A small part is provided by ultraviolet radiation (7 percent).

5. The higher the temperature of a radiating body, the shorter the wavelength of maximum radiation. The entire spectrum of emitted wavelengths is also shifted toward shorter values as the temperature increases.

Answers to Concept Check 2.4

1. Figure 2–15



2. Air molecules more effectively scatter the shorter wavelength (blue and violet) portion of “white” sunlight; hence, when we look at the sky, we see predominantly blue light.

3. When the Sun is near the horizon, the solar beam must travel through a great deal more of the atmosphere than when the Sun angle is higher. Therefore, by the time the light reaches our eyes, most of the blue and violet have been scattered out, leaving a beam that consists mostly of red and yellow.

4. The *primary* factor causing albedos to vary during different times of the day is the angle of the Sun's rays. A lower Sun angle results in higher reflectivity (albedo), particularly over water. Locations close to water (such as coastal areas) will experience this as well. Other factor that can influence albedo include cloud cover, the amount of dust in the air, and the nature of the surface material.

Answers to Eye on the Atmosphere (#2)

1. The terminator does not appear to be a "clean line" due to the presence of air molecules, which scatter sunlight and give the terminator a "fuzzy" appearance.

2. The astronauts are looking north and the sunlight is to the west. Since the Earth rotates west to east, the coast will soon be in darkness. They are viewing a sunset.

Answers to Concept Check 2.5

1. The gases composing the atmosphere are selective absorbers. Because of this, they cannot absorb much shortwave solar energy and are not effectively heated by solar energy. The solar radiation largely passes through the atmosphere and is absorbed by Earth's surface, warming it. Earth emits longer wavelength radiation (infrared), which certain atmospheric gases absorb very strongly. Hence the atmosphere is heated primarily by re-radiation from Earth's surface.

2. Carbon dioxide and water vapor are the primary heat-absorbing gases in the lower atmosphere. Water vapor is the most influential in weather.

3. Radiation reflected and emitted from the middle and the upper levels of Earth's atmosphere (from gases and cloud tops) provides the greatest loss of radiation back to space.

4. The term *greenhouse* is used to represent the near-transparency of Earth's atmosphere to solar radiation and its strong absorption of Earth's longer wavelength infrared radiation. This combination allows Earth's surface and the lower atmosphere to be warmed by the Sun's energy, but restricts the rate of energy loss from these regions back to space. The net effect is a significant warming of Earth's surface and lower atmospheric temperatures.

5. The media frequently report the "villain" to be the greenhouse effect; in actuality, this effect is vital in providing a comfortable temperature for the survival of most species on Earth. The real problem appears to be the rising level of carbon dioxide in the atmosphere due to industrial activities.

Answers to Eye on the Atmosphere (#3)

1. Hurricane Bill is found on the western (left) side of the global picture, between the 2:00 and 3:00 positions.

2. One advantage of infrared images is their ability to show temperature differences. IR images that show bright white cloud tops, for example, indicate that these cloud tops are very cold and therefore quite high—the type of towering clouds most likely to produce severe weather.

Answers to Concept Check 2.6

1. The global wind systems and, to a lesser extent, the oceans act as giant thermal engines, transferring surplus heat from the tropics poleward.

2. Atmospheric and oceanic circulations are caused primarily by the imbalance of heating that exists between the tropics and the poles.

Give It Some Thought

1. There would be no seasons, since the length of daylight at any given location on Earth would remain the same.

2. Seasons would be more extreme if Earth's axis were inclined 40°. Both summer days and winter nights would be longer. The Tropic of Cancer would be at 40°N latitude, the Tropic of Capricorn at 40°S latitude, the Arctic Circle at 50°N latitude, and the Antarctic Circle at 50°S latitude.

3. a. Figure d
   b. Figures a and b do not show the Earth's tilt at the spring and fall equinox positions. Figures b and c show the Earth revolving clockwise, instead of a counterclockwise, around the Sun.

4. The Earth is closest to the Sun around January 3, which corresponds to the Northern Hemisphere's winter. However, it is the *tilt* of the Earth as it revolves around the Sun that really determines its seasons, not the relatively insignificant change in its distance from the Sun.

5. In the Northern Hemisphere, we look *south* to watch the Sun rise to our left (east) and set to our right (west). However, in the Southern Hemisphere, we must look *north*, so the Sun now rises to our right (east) and sets on our left (west).

6. a. conduction
   b. convection
   c. radiation

d. convection

7. The bucket is heated by radiation from the fire on the side of the bucket, which in turn will heat the water on that side of the bucket via conduction, and a convection current will be generated to heat the rest of the water. The bottom of the bucket never comes into play.

8. The Sun angle at the North Pole is very low, spreading out the solar energy and reducing its intensity. In addition, this energy has to travel through a thicker atmosphere, which increases its chances of being scattered, reflected, or absorbed by the atmosphere. Finally, the ice cover present here has a high albedo, causing much of the solar energy that does reach the surface to be reflected back into space.

9. The Stefan–Boltzman law states that the rate of radiation emitted by a body is proportional to the *fourth* power of the body's temperature. At temperatures much hotter than the Sun, the radiation would be very intense. For the planet to receive the same intensity of light as the Earth receives from the Sun, the planet would have to be much further away. However, according to Wien's displacement law, at those very high temperatures the star would be emitting mostly UV radiation which, even at this great distance, is not conducive to habitation by human life.

10. a, c, b

11. The Earth's average temperature would significantly decrease as less solar radiation was absorbed by the Earth's surface.

12. The equatorial winds and oceans act to transfer surplus heat from the tropics poleward.

13. The ash and debris emitted by Mount Pinatubo circled the planet and blocked sufficient solar energy to lower the global temperature.

Answers to End of the Chapter Problems

1. June 21
   ___________ 50°N: 16.5°; 0°: 66.5°; 20°S: 86.5°

   50°N has the greatest noon-Sun angle difference.

2. June 21 50°N: 14 h, 52 min day, 9 h, 8 min night; 0°: 12 h day, 12 h night; 20°S: 10 h, 48 min day, 13 h, 12 min night

   December 21 50°N: 9 h, 8 min day, 14 h, 52 min night; 0°: 12 h day, 12 h night; 20°S: 13 h, 12 min day, 10 h, 48 min night

50°N has the greatest season variation in length of daylight, 0° the least.

3. Answer varies with location. See Figure 2–6.