Solutions for Essentials of Meteorology 8th Edition by Ahrens

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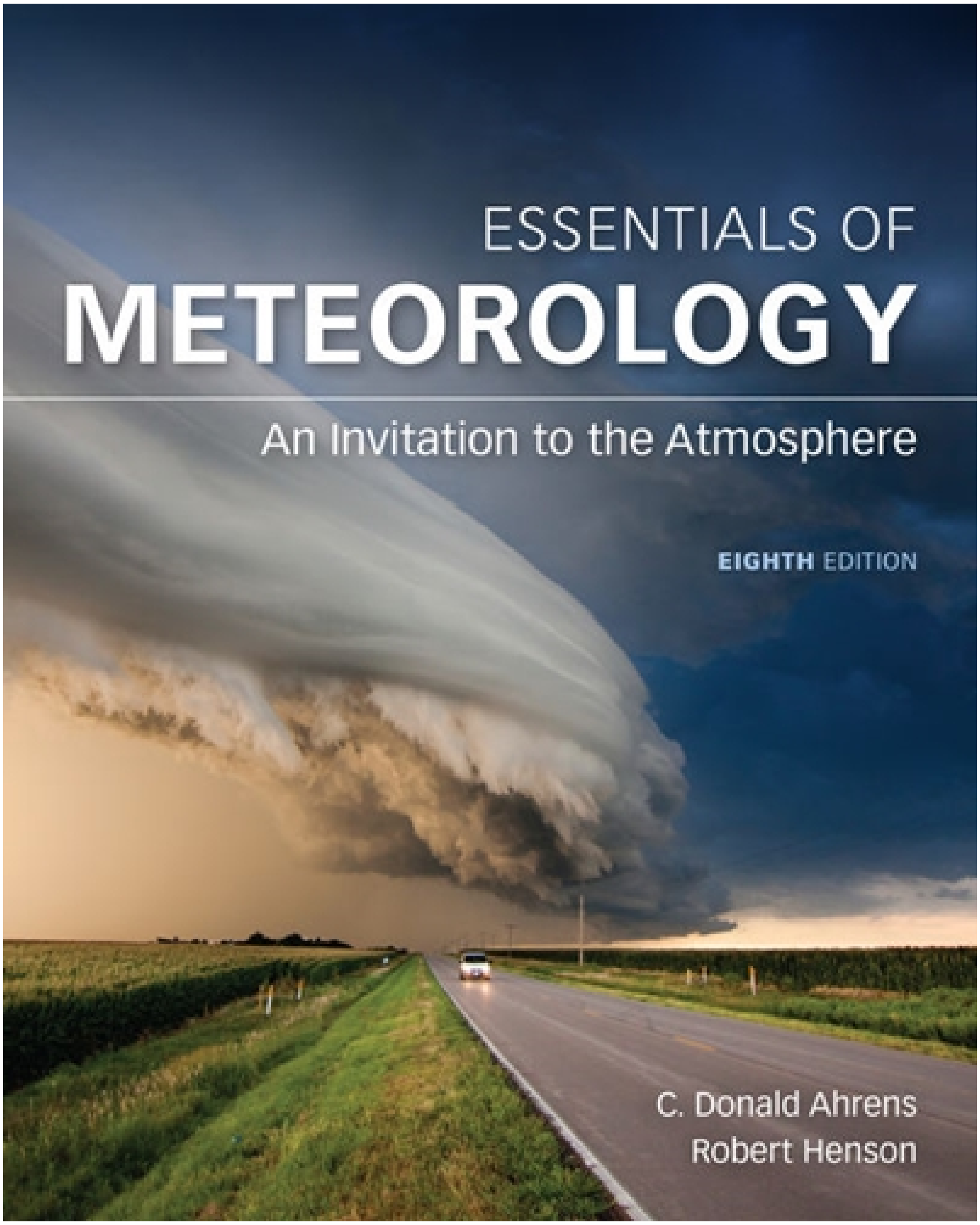

Solutions

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Chapter 2
Warming and Cooling the Earth and Its Atmosphere

Chapter Outline

Temperature and Heat Transfer
- Temperature Scales
- Latent Heat—The Hidden Warmth
- Conduction
- Convection
- ***Focus on a Special Topic***

Radiant Energy
- ***Focus on an Environmental Issue***

Radiation—Absorption, Emission, and Equilibrium
- Selective Absorbers and the Atmospheric Greenhouse Effect
- Enhancement of the Greenhouse Effect
- Warming the Air from Below
- Shortwave Radiation Streaming from the Sun
- Earth's Annual Energy Balance
- ***Focus on a Special Topic***

Why Earth Has Seasons
- Seasons in the Northern Hemisphere
- ***Focus on a Special Topic***
- Seasons in the Southern Hemisphere
- Local Seasonal Variations

Summary

Key Terms

Questions for Review

Questions for Thought and Exploration

Learning Objectives

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.

2.4 Describe the principles of conduction, convection, and advection and summarize their roles in Earth's atmosphere.

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.

2.7 Define the terms *blackbody*, *radiative equilibrium temperature*, *selective absorber*, *atmospheric window*, and describe their relationship to the atmospheric greenhouse effect.

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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.
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.
2.13 Illustrate how Earth's seasons are affected by Earth's proximity to the Sun, the Sun's angle to Earth, and the number of daylight hours on Earth.
2.14 Compare and contrast the cycle of seasons observed in the Northern Hemisphere with those in the Southern Hemisphere.
2.15 Explain the reasons for local seasonal variations, and demonstrate how these variations can be most effectively utilized.

Summary

In this chapter, we look at the concepts of temperature and heat. Heat transfer via the processes of conduction, convection, latent heat, and radiation are described. We learn, for example, that air is a relatively poor conductor of heat but can transport energy efficiently over large distances by convection. The latent heat energy associated with changes of phase of water is shown to be a very important energy transport mechanism in the atmosphere. A physical explanation of why rising air cools and sinking air warms is given.

We then look at the electromagnetic spectrum and the physical laws, which govern the emission of electromagnetic radiation, are reviewed next. This provides sufficient background for a detailed study of the atmospheric greenhouse effect and the exchange of energy between Earth's surface, the atmosphere, and space. We see that, because the amounts of energy absorbed and emitted by Earth are in balance, Earth's average radiative equilibrium temperature varies little from year to year. We should understand that the energy the Earth absorbs from the sun consists primarily of short-wave radiation. A focus section describes the sun's ultraviolet energy, and its damaging effects on living cells. Essentially all of the energy emitted by Earth is 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 then radiate a portion of it back to the surface. Because of this effect, Earth's average surface temperature is appreciably higher than would otherwise be the case. 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.

Finally, we will learn that variations in the intensity of sunlight reaching the ground and the length of the day caused by the changing tilt of Earth relative to the plane of its orbit around the sun are the main causes of seasonal variations on Earth. We follow seasonal changes for a full year in the Northern Hemisphere. By comparison, seasons in the Southern Hemisphere are six months out of phase and moderated by the larger surface coverage by oceans.

Teaching Suggestions, Demonstrations, and Visual Aids

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.

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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 uncovered pot is used to evaporate water, not to increase the water's temperature.

3. The concept of equilibria is sometimes difficult for students to grasp. Place a glass of water on a tabletop 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. Blindfold 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 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 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 as 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 that way 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).

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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. Begin the lecture by drawing an ellipse on the blackboard with the sun positioned much closer to one end of the ellipse. On the other end of the ellipse, closest to the sun, make a dot for Earth and label it, "January and winter." Then label the other end "July and summer." Act confused and ask, "Wait a minute, is that correct?" Usually this is enough to start an interesting discussion on what causes the seasons.

9. Explain the seasons by shining a fairly broad, collimated beam of light onto a globe in a darkened room. Begin by showing Earth with no tilt, then increase the tilt to 23.5°. Finally, increase the tilt to 45°. Explain how the change in tilt would influence the average temperature measured in July and January in the Northern Hemisphere.

   Using the globe or drawings, the students should understand whether they would need to look to the south or north of overhead to see the sun at noon from different locations on Earth at different times of year. They should also understand whether it is necessary to look east, northeast, or southeast to see the sun rise.

10. The attenuation of light as it passes through a scattering medium can be demonstrated by placing a photodetector at one end of an aquarium full of water and a light source at the other end. Then begin to add milk in small but measurable amounts. The signal at the detector will decay exponentially with the amount of milk added. The decay will depart from the exponential law when enough milk is added that appreciable multiple scattering begins to occur. The effect of an absorbing medium can be demonstrated if India ink (diluted with water if necessary) is used in place of milk.

Student Projects

1. Items #2, 3, 9, and 10 above could form the basis of student projects or experiments.

2. There are several interesting experiments in Chapter 4 (Heat) in Hands-On Meteorology.

3. 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 flushed 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:

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$$S = \frac{\text{mass } \times \text{specific heat}}{\text{area}} \times \frac{\Delta T}{\Delta t}$$

4. Use Weather Underground to examine the current weather at locations in both the northern and southern hemispheres. Discuss the relationship between the observed weather conditions and the current season.

5. Use NASA's Interactive Global Geostationary Weather Satellite Images to observe current visible and infrared satellite images. Comment on the differences between the images, and suggest reasons for these differences.

Answers to Questions for Review

1. Temperature is the quantity that tells us how hot or cold something is relative to some set standard value. Heat, on the other hand, is energy in the process of being transferred from one object to another because of the temperature difference between them.

2. The temperature of air or any other substance is a measure of the average speed of atoms and molecules, where higher temperatures correspond to faster average speeds.

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

4. The heat energy required to change a substance, such as water, from one state to another is called latent heat. 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.

5. 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. Converting from °C to K can be done by simply adding 273 to the Celsius temperature.

6. Earth emits a lot less radiation than the sun because it is cooler than the sun.

7. An object's temperature has a direct effect on the wavelengths of radiation that an object emits, and the higher the object's temperature, the shorter are the wavelengths of emitted radiation. Similarly, as an object's temperature increases, its peak emission of radiation shifts toward shorter wavelengths. This relationship between temperature and wavelength is called Wien's law* (or Wien's displacement law) after the German physicist Wilhelm Wien (1864–1928). In addition, objects that have a high temperature emit radiation at a greater rate or intensity than objects with a lower temperature. Thus, as the temperature of an object increases, more total radiation is emitted each second. This relationship between temperature and emitted radiation is known as the Stefan–Boltzmann law* after Josef Stefan (1835–1893) and Ludwig Boltzmann (1844–1906).

8. Earth is cooler than the sun; therefore, it emits radiation at longer wavelengths.

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9. A radiative equilibrium temperature is reached when the amount of radiation entering the surface of the body equals the amount exiting the surface of the body.
10. Carbon dioxide and water vapor are called selective absorbing greenhouse gases because they absorb radiation at certain wavelengths and not others.

11. Water vapor, carbon dioxide, nitrous oxide, methane, chlorofluorocarbons.

12. The atmosphere allows visible radiation to pass through, but inhibits to some degree the passage of infrared radiation leaving Earth's surface resulting in the gradual warming of our atmosphere.

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

14. Averaged for an entire year, Earth and its atmosphere (including its clouds), will redirect about 30% of the sun's incoming radiation back to space, which gives Earth and its atmosphere a combined albedo of 30%.

15. Solar energy is able to warm the surface air, and as it warms, it actually becomes less dense than the air directly above it. The warmer air rises and the cooler air sinks, setting up thermals, or free convection cells that transfer heat upward and distribute it through a deeper layer of air. The rising air expands and cools, and, if sufficiently moist, the water vapor condenses into cloud droplets, releasing latent heat that warms the air. Meanwhile, Earth constantly emits infrared energy. Greenhouse gases that emit infrared energy upward, and downward back to the surface absorb some of this energy. Since the concentration of water vapor decreases rapidly above Earth, most of the absorption occurs in a layer near the surface. Hence, the lower atmosphere is mainly heated from the ground upward.

16. The outpouring of solar energy constantly bathes Earth with radiation, while Earth in turn constantly emits infrared radiation. The rate of absorption of solar radiation equals the rate of emission of infrared Earth radiation.

17. There is more insolation during the summer (longer days, larger sun angles) in the Northern Hemisphere.

18. Our seasons are regulated by the amount of solar energy received at Earth's surface. This amount is determined primarily by the angle at which sunlight strikes the surface, and by how long the sun shines on any latitude (daylight hours).

19. Summer and January.

20. The sun's elevation is lower over the horizon and the albedo is larger.

21. During the summer in far northern latitudes, the sun is never very high above the horizon, so its radiant energy must pass through a thick portion of atmosphere before it reaches Earth's surface. Some of the solar energy that does reach the surface melts frozen soil or is reflected by snow or ice. And, that which is absorbed is spread over a large area.

22. Hills that face south receive more sunshine and become warmer than north-facing hills, thus providing a different environment for plants.

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Answers to Questions for Thought and Exploration

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 warmer ground below.

2. Heat energy is released into the air during freezing.

3. The warm air coming out of the heat registers will rise.

4. By infrared radiation.

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

6. Summers would be hotter, winters would be colder.

7. 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, the clouds might absorb more infrared Earth radiation and, thus, tend to strengthen the atmospheric greenhouse effect.

8. 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.

9. No, because water vapor is a greater contributor to the atmospheric greenhouse effect than CO_2.

10. In the northern hemisphere, the sun crosses the sky from east to west at a lower elevation in December than it does in June.

11. This is due to the lag in seasonal temperature. Although incoming solar energy is the same on both days, in February outgoing energy still exceeds incoming energy.

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