EXERCISE 13

Atmospheric Heating

The quantity of radiation from the Sun that strikes the outer edge of Earth's atmosphere at any one place is not constant but varies with the seasons. This exercise examines, step by step, what happens to **solar radiation** as it passes through the atmosphere, is absorbed at Earth's surface, and is reradiated by land and water back to the atmosphere (Figure 13.1). Investigating the journey of solar radiation and how it is influenced and modified by air, land, and water will provide a better understanding of one of the most basic weather elements, atmospheric temperature.

Figure 13.1 Solar radiation and atmospheric heating. (Photo by E. J. Tarbuck)

Objectives

After you have completed this exercise, you should be able to:

1. Explain how Earth's atmosphere is heated.
2. Describe the effect that the atmosphere has on absorbing, scattering, and reflecting incoming solar radiation.
3. List the gases in the atmosphere that are responsible for absorbing long-wave radiation.
4. Explain how the heating of a surface is related to its albedo.
5. Discuss the differences in the heating and cooling of land and water.
6. Summarize the global pattern of surface temperatures for January and July.
7. Describe how the temperature of the atmosphere changes with increasing altitude.
8. List the cause of a surface temperature inversion.
9. Determine the effect that wind speed has on the windchill equivalent temperature.

Materials

calculator
colored pencils

Materials Supplied by Your Instructor

light source
black and silver containers
two thermometers
wood splints
beaker of sand
beaker of water

Terms

solar radiation
greenhouse effect
terrestrial radiation
albedo
environmental lapse rate
temperature inversion
isotherm
windchill equivalent temperature

Introduction

Temperature is an important element of weather and climate because it greatly influences air pressure, wind, and the amount of moisture in the air. The unequal heating that takes place over the surface of Earth is what sets the atmosphere in motion, and the movement of air is what brings changes in our weather.

The single greatest cause for temperature variations over the surface of Earth is differences in the reception of solar radiation. Secondary factors such as the differential heating of land and water, ocean currents, and altitude can modify local temperatures.

The amount of solar energy (radiation) striking Earth is not constant throughout the year at any particular place, nor is it uniform over the face of Earth at any one time. However, the total amount of radiation that the planet intercepts from the Sun equals the total radiation that it loses back to space. It is this balance between incoming and outgoing radiation that keeps Earth from becoming continuously hotter or colder.

Solar Radiation at the Outer Edge of the Atmosphere

The two factors that control the amount of solar radiation that a square meter receives at the outer edge of the atmosphere, and eventually Earth's surface, are the Sun's *intensity* and its *duration*. These variables were examined in detail in Exercise 12, "Earth–Sun Relations." Answer questions 1–3 after you have reviewed Exercise 12.

1. Briefly define solar intensity and duration.

   Intensity of solar radiation: ________________

   ____

   Duration of solar radiation: ________________

   ____

2. Complete Table 13.1 by calculating the angle that the noon Sun would strike the outer edge of the atmosphere at each of the indicated latitudes on the specified date. How many hours of daylight would each place experience on these dates? (*Hint:* You may find Tables 12.1 and 12.2 in Exercise 12 helpful.)

Table 13.1 Noon Sun Angle and Length of Day

	March 21		*June 21*	
	NOON SUN ANGLE	LENGTH OF DAY	NOON SUN ANGLE	LENGTH OF DAY
40°N:	____°	____ hrs	____°	____ hrs
0°:	____°	____ hrs	____°	____ hrs
40°S:	____°	____ hrs	____°	____ hrs

3. Explain the reason why the intensity and duration of solar radiation received at the outer edge of the atmosphere is not constant at any particular latitude throughout the year.

   ____

   ____

Atmospheric Heating

Atmospheric heating is a function of (1) the ability of atmospheric gases to absorb radiation, (2) the amount of solar radiation that reaches Earth's surface, and (3) the nature of the surface material. Of the three, selective absorption of radiation by the atmosphere provides an insight into the mechanism of atmospheric heating. The quantity of radiation that reaches Earth's surface and the ability of the surface to absorb and reradiate the radiation determine the extent of atmospheric heating.

The atmosphere is rather selective and efficiently absorbs long-wave radiation that we detect as heat while allowing the transmission of most of the short wavelengths—a process called the **greenhouse effect**. The short-wave radiation that reaches Earth's surface and is absorbed ultimately returns to the atmosphere in the form of long-wave, **terrestrial radiation**. As the radiation travels up from the surface through the atmosphere, it is absorbed by atmospheric gases, heating the atmosphere from below. Since terrestrial radiation supplies most of the long-wave radiation to the atmosphere, it is the primary source of heat. The fact that temperature typically decreases with an increase in altitude in the lower atmosphere is clear evidence supporting this mechanism of atmospheric heating.

Solar Radiation Received at Earth's Surface

As solar radiation travels through the atmosphere, it may be reflected, scattered, or absorbed. The effect of the atmosphere on incoming solar radiation and the amount of radiation that ultimately reaches the surface is primarily dependent upon the angle at which the solar beam passes through the atmosphere and strikes Earth's surface.

Figure 13.2 illustrates the atmospheric effects on incoming solar radiation for an average noon Sun angle. Answer questions 4–7 by examining the figure and supplying the correct response.

4. _______ % of the incoming solar radiation is reflected and scattered back to space.

5. _______ % of the incoming solar radiation is absorbed by gases in the atmosphere and clouds.

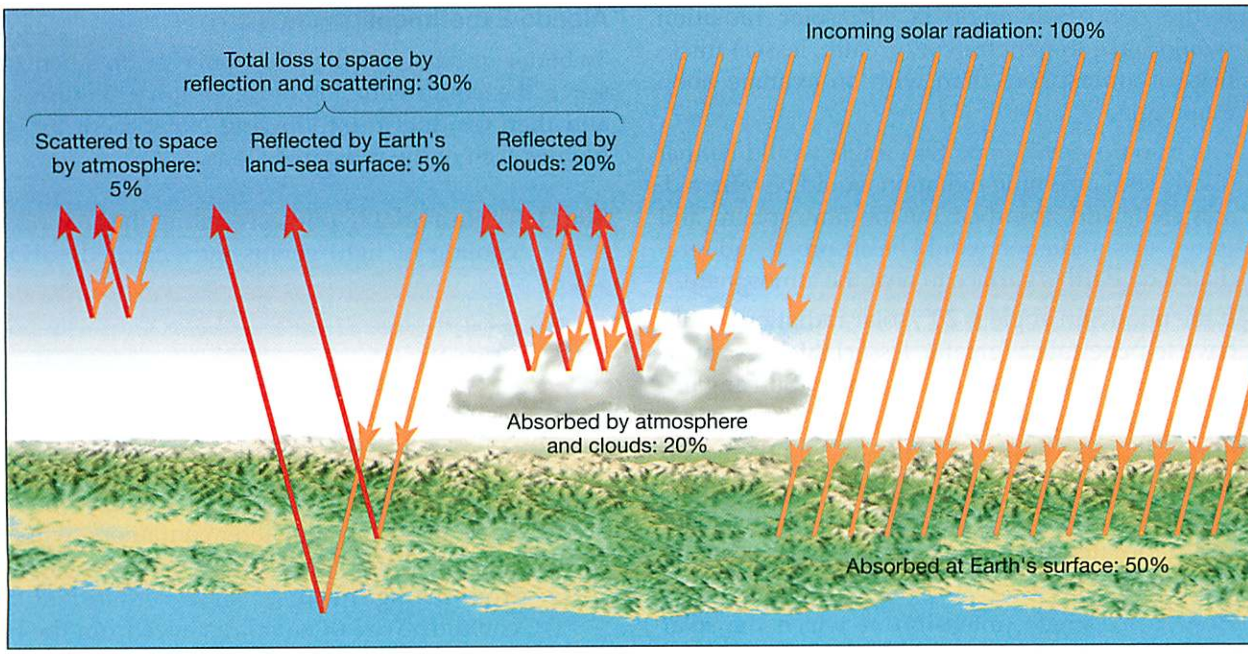


Figure 13.2 Solar radiation budget of the atmosphere and Earth.

6. _______ % of the incoming solar radiation is absorbed at Earth's surface.
7. (Two and a half, Four) times as much incoming radiation is absorbed by Earth's surface than by the atmosphere and clouds. Circle your answer.

Figure 13.3 illustrates the effects of the atmosphere on various wavelengths of radiation. Use Figure 13.3 to answer questions 8–11 by circling the correct response.

8. The incoming solar radiation that passes through the atmosphere and is absorbed at Earth's surface is primarily in the form of (ultraviolet, visible, infrared) wavelengths.
9. When the surface releases the solar radiation it has absorbed, this terrestrial radiation is primarily (ultraviolet, visible, infrared) wavelengths.
10. (Ultraviolet, Visible, Infrared) wavelengths of radiation are absorbed efficiently by oxygen and ozone in the atmosphere.
11. Oxygen and ozone are (good, poor) absorbers of infrared radiation.
12. (Nitrogen, Carbon dioxide) and (water vapor, ozone) are the two principal gases that absorb most of the terrestrial radiation in the atmosphere.

Assume Figure 13.2 represents the atmospheric effects on incoming solar radiation for an average noon Sun angle of about 50°. Answer questions 13–16 concerning other noon Sun angles by circling the appropriate responses.

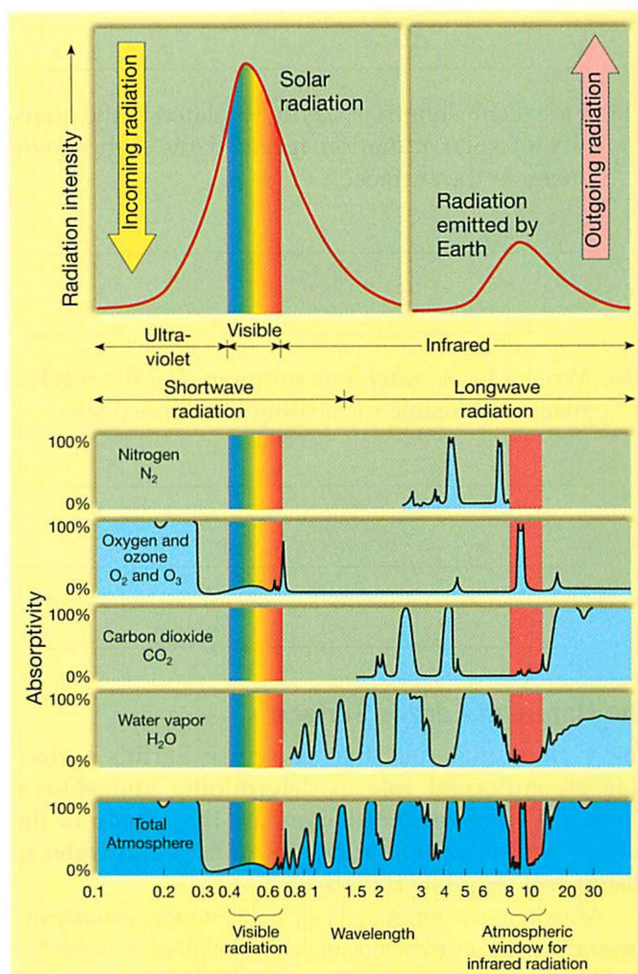


Figure 13.3 The absorptivity of selected gases of the atmosphere and the atmosphere as a whole.

13. If the noon Sun angle is 90°, solar radiation would have to penetrate a (greater, lesser) thickness of atmosphere than with an average noon Sun angle.
14. The result of a 90° noon Sun angle would be that (more, less) incoming radiation would be reflected, scattered, and absorbed by the atmosphere and (more, less) radiation would be absorbed and reradiated by Earth's surface to heat the atmosphere.
15. If the noon Sun angle is 20°, solar radiation would have to penetrate a (greater, lesser) thickness of atmosphere than with an average noon Sun angle.
16. The result of a 20° noon Sun angle would be that (more, less) incoming radiation would be reflected, scattered, and absorbed by the atmosphere and (more, less) radiation would be absorbed and reradiated by Earth's surface to heat the atmosphere.
17. How is the angle (intensity) at which the solar beam strikes Earth's surface related to the quantity of solar radiation received by each square meter?

18. How is the length of daylight related to the quantity of solar radiation received by each square meter at the surface?

19. Write a brief statement summarizing the mechanism responsible for heating the atmosphere.

The Nature of Earth's Surface

The various materials that comprise Earth's surface play an important role in determining atmospheric heating. Two significant factors are the **albedo** of the surface and the different abilities of land and water to absorb and reradiate radiation.

Albedo is the reflectivity of a substance, usually expressed as the percentage of radiation that is reflected from the surface. Since surfaces with high albedos are not efficient absorbers of radiation, they cannot return much long-wave radiation to the atmosphere for heating.

Albedo Experiment

To better understand the effect of color on albedo, observe the equipment in the laboratory (Figure 13.4) and then conduct the following experiment by completing each of the indicated steps.

Step 1: Write a brief hypothesis stating the heating and cooling of light-versus dark-colored surfaces.

Step 2: Place the black and silver containers (with lids and thermometers) about six inches away from the light source. Make certain that both containers are of equal distance from the light and are not touching one another.

Step 3: Record the starting temperature of both containers on the albedo experiment data table, Table 13.2.

Step 4: Turn on the light and record the temperature of both containers on the data table at about 30-second intervals for 5 minutes.

Step 5: Turn off the light and continue to record the temperatures at 30-second intervals for another 5 minutes.

Step 6: Plot the temperatures from the data table on the albedo experiment graph, Figure 13.5. Use a different color line to connect the points for each container.

Figure 13.4 Albedo experiment lab equipment.

Table 13.2 Albedo Experiment Data Table

	STARTING TEMPERATURE	30 SEC	1 MIN	1.5 MIN	2 MIN	2.5 MIN	3 MIN	3.5 MIN	4 MIN	4.5 MIN	5 MIN	5.5 MIN	6 MIN	6.5 MIN	7 MIN	7.5 MIN	8 MIN	8.5 MIN	9 MIN	9.5 MIN	10 MIN
Black container																					
Silver container																					

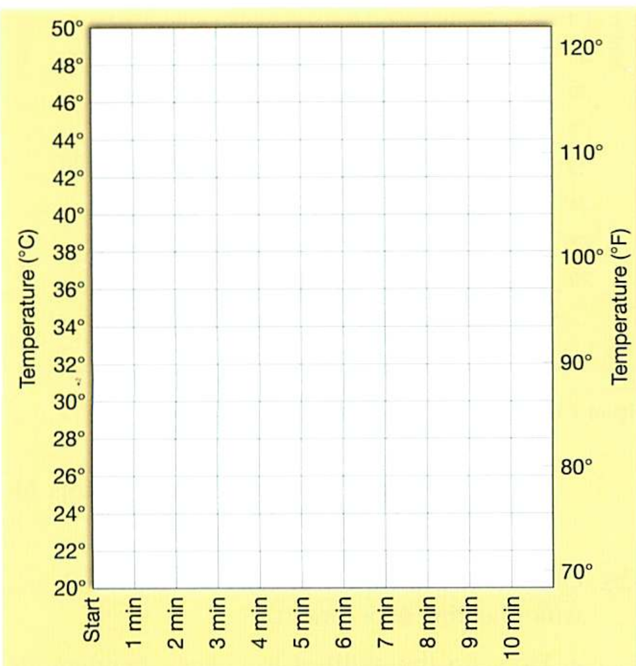


Figure 13.5 Albedo experiment graph.

20. For each container, calculate the *rate of heating* (change in temperature divided by the time the light was on) and the *rate of cooling* (change in temperature divided by the time the light was off).

	Heating Rate	Cooling Rate
Silver can:	____________	____________
Black can:	____________	____________

21. Write a statement that summarizes and explains the results of your albedo experiment.

____

____

____

____

____

22. What are some Earth surfaces that have high albedos and some that have low albedos?

High albedos: ______________________

Low albedos: ______________________

23. Given equal amounts of radiation reaching the surface, the air over a snow-covered surface will be (warmer, colder) than air above a dark-colored, barren field. Circle your answer. Then explain your choice fully in terms of what you have learned about albedo.

____

____

24. If you lived in an area with long, cold winters, a (light-, dark-) colored roof would be the best choice for your house. Circle your answer. Explain the reasons for your choice.

____

____

Land and Water Heating Experiment

Land and water influence the air temperatures above them in different manners because they do not absorb and reradiate energy equally.

Investigate the differential heating of land and water by observing the equipment in the laboratory (Figure 13.6) and conducting the following experiment by completing each of the indicated steps.

Step 1: Fill one beaker three-quarters full with dry sand and a second beaker three-quarters full with water at room temperature.

Step 2: Using a wood splint, suspend a thermometer in each beaker so that the bulbs are *just below* the surfaces of the sand and water.

Step 3: Hang a light from a stand so it is equally as close as possible to the top of the two beakers.

Step 4: Record the starting temperatures for both the dry sand and water on the land and water heating data table, Table 13.3.

Figure 13.6 Land and water heating experiment lab equipment.

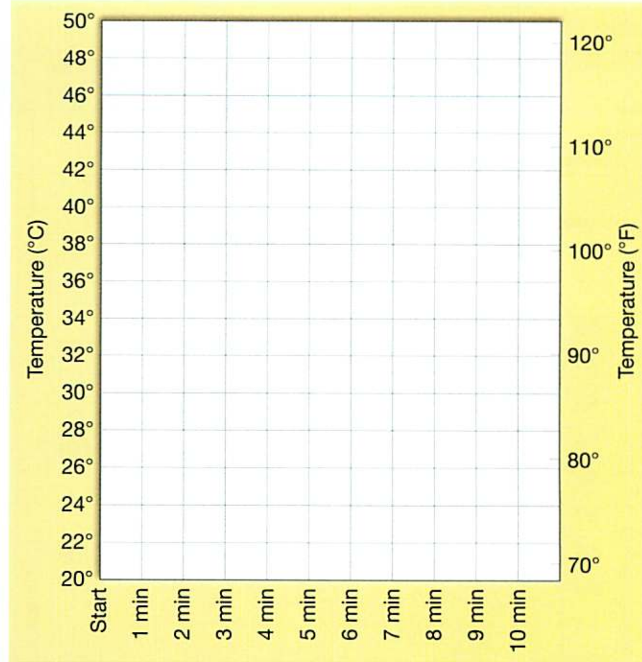


Figure 13.7 Land and water heating graph.

Step 5: Turn on the light and record the temperature on the data table at about one-minute intervals for 10 minutes.

Step 6: Turn off the light for several minutes. Dampen the sand with water and record the starting temperature of the damp sand on the data table. Turn on the light and record the temperature of the damp sand on the data table at about one-minute intervals for 10 minutes.

Step 7: Plot the temperatures for the water, dry sand, and damp sand from the data table on the land and water heating graph, Figure 13.7. Use a different color line to connect the points for each material.

25. Questions 25a and 25b refer to the land and water heating experiment.

a. How do the abilities to change temperature differ for dry sand and water when they are exposed to equal quantities of radiation?

____

____

b. How do the abilities to change temperature differ for dry sand and damp sand when they are exposed to equal quantities of radiation?

____

____

Table 13.3 Land and Water Heating Data Table

	STARTING TEMPERATURE	1 MIN	2 MIN	3 MIN	4 MIN	5 MIN	6 MIN	7 MIN	8 MIN	9 MIN	10 MIN
Water											
Dry sand											
Damp sand											

26. Suggest several reasons for the differential heating of land and water.

Figure 13.8 presents the annual temperature curves for two cities, A and B, that are located in North America at approximately 37°N latitude. On any date both cities receive the same intensity and duration of solar radiation. One city is in the center of the continent, while the other is on the west coast. Use Figure 13.8 to answer questions 27–34.

27. In Figure 13.8, city (A, B) has the highest mean monthly temperature. Circle your answer.
28. City (A, B) has the lowest mean monthly temperature.
29. The greatest *annual temperature range* (difference between highest and lowest mean monthly temperatures) occurs at city (A, B).
30. City (A, B) reaches its maximum mean monthly temperature at an earlier date.
31. City (A, B) maintains a more uniform temperature throughout the year.
32. Of the two cities, city A is most likely located (along a coast, in the center of a continent).
33. The most likely location for city B is (coastal, mid-continent).

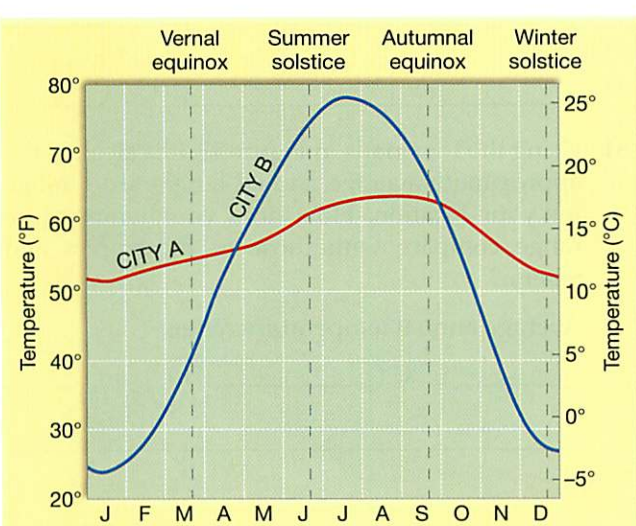


Figure 13.8 Mean monthly temperatures for two North American cities located at approximately 37°N latitude.

34. Describe the effect that the location, along the coast or in the center of a continent, has on the temperature of a city.

Atmospheric Temperatures

Air temperatures are not constant. They normally change (1) through time at any one location, (2) with latitude because of the changing sun angle and length of daylight, and (3) with increasing altitude in the lower atmosphere because the atmosphere is primarily heated from the bottom up.

Daily Temperatures

In general, the daily temperatures that occur at any particular place are the result of long-wave radiation being released at Earth's surface. However, secondary factors, such as cloud cover and cold air moving into the area, can also cause significant variations.

Questions 35–42 refer to the daily temperature graph, Figure 13.9.

35. The coolest temperature of the day occurs at ________. Fill in your answer.
36. The warmest temperature occurs at ________.
37. What is the *daily temperature range* (difference between maximum and minimum temperatures for the day)?

Daily temperature range: _____ °F (_____ °C).

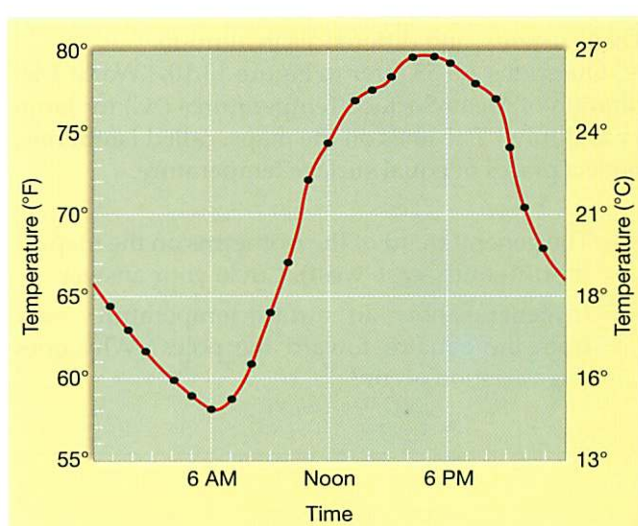


Figure 13.9 Typical daily temperature graph for a mid-latitude city during the summer.

38. What is the *daily temperature mean* (average of the maximum and minimum temperatures)?

Daily temperature mean: ______ °F (______ °C).

39. Refer to the mechanism for heating the atmosphere. Why does the warmest daily temperature occur in mid-to-late afternoon rather than at the time of the highest Sun angle?

____

____

40. Why does the coolest temperature of the day occur about sunrise?

____

____

41. How would cloud cover influence daily maximum and minimum temperatures?

____

____

42. On Figure 13.9 sketch and label a colored line that best represents a daily temperature graph for a typical cloudy day.

Global Pattern of Temperature

The primary reason for global variations in surface temperatures is the unequal distribution of radiation over the Earth. Among the most important secondary factors are differential heating of land and water, ocean currents, and differences in altitude.

Questions 43–55 refer to Figure 13.10, "World Distribution of Mean Surface Temperatures (°C) for January and July." The lines on the maps, called **isotherms**, connect places of equal surface temperature.

43. The general trend of the isotherms on the maps is (north–south, east–west). Circle your answer.

44. In general, how do surface temperatures vary from the equator toward the poles? Why does this variation occur?

____

____

____

45. The warmest and coldest temperatures occur over which countries or oceans?

Warmest global temperature: ______________________________

____

Coldest global temperature: ______________________________

____

46. The locations of the warmest and coldest temperatures are over (land, water).

47. Calculate the *annual temperature range* at each of the following locations:

Coastal Norway at 60°N: ______ °C (______ °F)

Siberia at 60°N, 120°E: ______ °C (______ °F)

On the equator over the center of the Atlantic Ocean: ______ °C (______ °F)

48. Explain the large annual range of temperature in Siberia.

____

____

49. Why is the annual temperature range smaller along the coast of Norway than at the same latitude in Siberia?

____

____

50. Why is temperature relatively uniform throughout the year in the tropics?

____

____

51. Using the two maps in Figure 13.10, calculate the approximate average annual temperature range for your location. How does your temperature range compare with those in the tropics and Siberia?

Average annual temperature range:

__________ °C (__________ °F)

____

____

52. Trace the path of the 5°C isotherm over North America in January. Explain why the isotherm de-

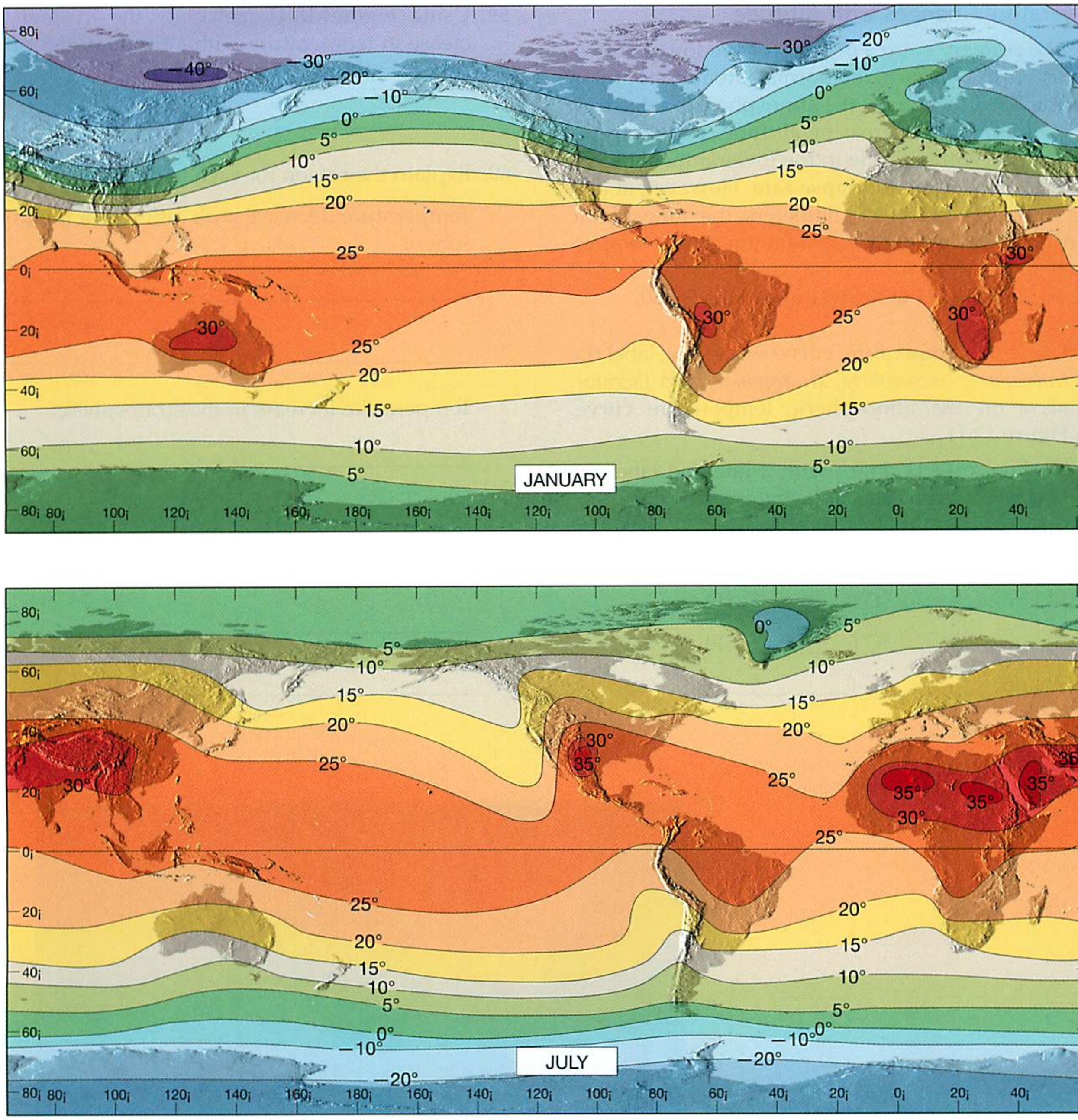


Figure 13.10 World distribution of mean surface temperatures (°C) for January and July.

viates from a true east–west trend where it crosses from the Pacific Ocean onto the continent.

____

____

53. Trace the path of the 20°C isotherm over North America in July. Explain why the isotherm deviates from a true east–west trend where it crosses from the Pacific Ocean onto the continent.

____

____

54. Why do the isotherms in the Southern Hemisphere follow a true east–west trend more closely than those in the Northern Hemisphere?

____

____

55. Why does the entire pattern of isotherms shift northward from the January map to the July map?

____

____

Temperature Changes with Altitude

Since the primary source of heat for the lower atmosphere is Earth's surface, the normal situation found in the lower 12 kilometers of the atmosphere is a decrease in temperature with increasing altitude. This temperature decrease with altitude in the lower atmosphere is called the **environmental lapse rate**. However, at altitudes from about 12 to 45 kilometers, the atmospheric absorption of incoming solar radiation causes temperature to increase.

Use Figure 13.11 to answer questions 56–60.

56. Using the temperature curve as a guide, label the *troposphere, mesosphere, stratosphere,* and *thermosphere* on the atmospheric temperature curve, Figure 13.11.

57. On Figure 13.11, mark with a line and label the *tropopause, mesopause,* and *stratopause.*

58. What is the approximate temperature of the atmosphere at each of the following altitudes?

    10 km: ________ °C (________ °F)

    50 km: ________ °C (________ °F)

    80 km: ________ °C (________ °F)

59. Using Figure 13.11, calculate the average decrease in temperature with altitude of the troposphere in both °C/km and °F/mi.

    ____

60. Explain the reason for each of the following:

    Temperature decrease with altitude in the troposphere:

    ____

    ____

    Temperature increase in the stratosphere:

    ____

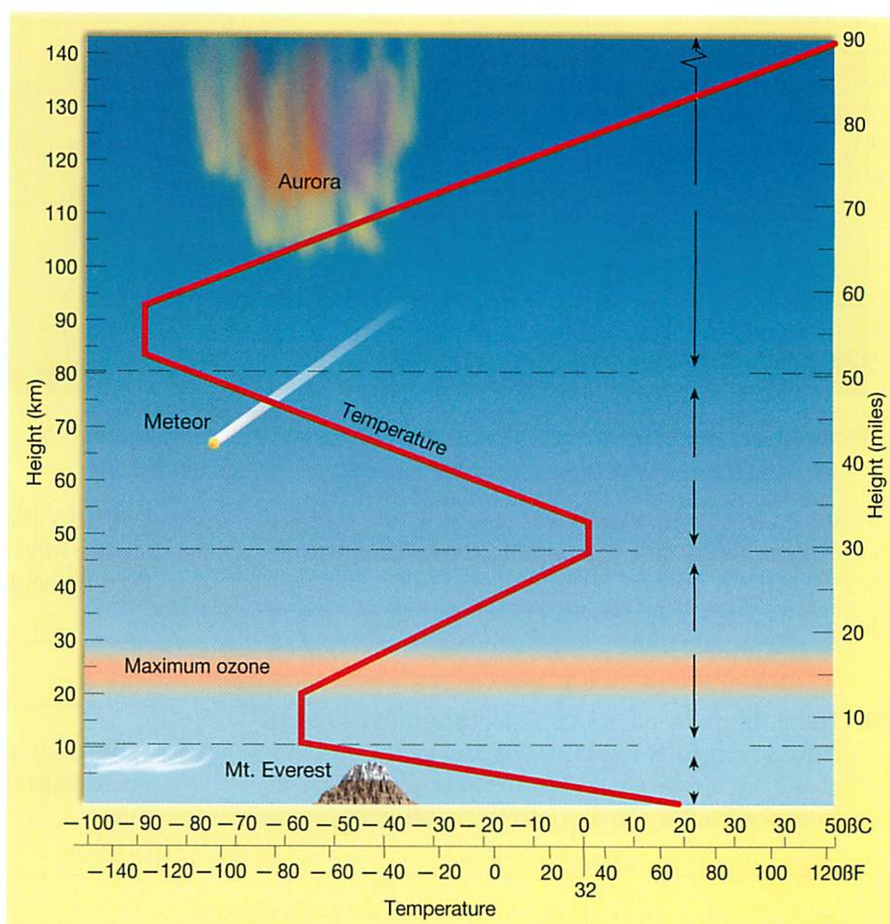
    ____

    Temperature increase in the thermosphere:

    ____

    ____

Figure 13.11 Atmospheric temperature curve.



61. Of what importance is the gas *ozone* in the stratosphere? What will be the effect on radiation received at Earth's surface of a decrease of ozone in the stratosphere?

____

____

____

Assume the average, or normal, environmental lapse rate (temperature decrease with altitude) in the troposphere is 3.5°F per 1,000 feet (6.5°C per kilometer).

62. If the surface temperature is 60°F (16°C), what would be the approximate temperature at 20,000 feet (6,000 meters)?

________ °F (________ °C)

63. If the surface temperature is 80°F (27°C), at approximately what altitude would a pilot expect to find each of the following atmospheric temperatures?

50°F: ________ feet (10°C: ________ meters)

0°C: ________ meters (32°F: ________ feet)

Periodically, the temperature near the surface of Earth increases with altitude. This situation, which is opposite from the normal condition, is called a **temperature inversion**.

64. Suggest a possible cause for a surface temperature inversion.

____

____

Windchill Equivalent Temperature

Windchill equivalent temperature is the term applied to the sensation of temperature that the human body feels, in contrast to the actual temperature of the air as recorded by a thermometer. Wind cools by evaporating perspiration and carrying heat away from the body. When temperatures are cool and the wind speed increases, the body reacts as if it were being subjected to increasingly lower temperatures—a phenomenon known as *windchill.*

65. Refer to the windchill equivalent temperature chart, Figure 13.12. What is the windchill equivalent temperature sensed by the human body in the following situations?

Air Temperature (°F)	Wind Speed (mph)	Windchill Equivalent Temperature (°F)
30°	10	________
−5°	20	________
−20°	30	________

66. Write a brief summary of the effect of wind speed on how long a person can be exposed before frostbite develops.

____

____

____

Atmospheric Heating on the Internet

Research current and historical atmospheric temperatures at your location by completing the corresponding online activity on the *Applications & Investigations in Earth Science* website at http://prenhall.com/earthsciencelab

Temperature (°F)

Wind (mph) / Calm	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
5	36	31	25	19	13	7	1	−5	−11	−16	−22	−28	−34	−40	−46	−52	−57	−63
10	34	27	21	15	9	3	−4	−10	−16	−22	−28	−35	−41	−47	−53	−59	−66	−72
15	32	25	19	13	6	0	−7	−13	−19	−26	−32	−39	−45	−51	−58	−64	−71	−77
20	30	24	17	11	4	−2	−9	−15	−22	−29	−35	−42	−48	−55	−61	−68	−74	−81
25	29	23	16	9	3	−4	−11	−17	−24	−31	−37	−44	−51	−58	−64	−71	−78	−84
30	28	22	15	8	1	−5	−12	−19	−26	−33	−39	−46	−53	−60	−67	−73	−80	−87
35	28	21	14	7	0	−7	−14	−21	−27	−34	−41	−48	−55	−62	−69	−76	−82	−89
40	27	20	13	6	−1	−8	−15	−22	−29	−36	−43	−50	−57	−64	−71	−78	−84	−91
45	26	19	12	5	−2	−9	−16	−23	−30	−37	−44	−51	−58	−65	−72	−79	−86	−93
50	26	19	12	4	−3	−10	−17	−24	−31	−38	−45	−52	−60	−67	−74	−81	−88	−95
55	25	18	11	4	−3	−11	−18	−25	−32	−39	−46	−54	−61	−68	−75	−82	−89	−97
60	25	17	10	3	−4	−11	−19	−26	−33	−40	−48	−55	−62	−69	−76	−84	−91	−98

Frostbite Times: 30 minutes | 10 minutes | 5 minutes

Figure 13.12 This windchill chart came into use in November 2001. Fahrenheit temperatures are used here because this is how the National Weather Service and the news media in the United States commonly report windchill information. The shaded areas on the chart indicate frostbite danger. Each shaded zone shows how long a person can be exposed before frostbite develops. (*After NOAA, National Weather Service*)

Notes and calculations.

Atmospheric Heating

Date Due: ____________________

Name: ____________________

Date: ____________________

Class: ____________________

After you have finished Exercise 13, complete the following questions. You may have to refer to the exercise for assistance or to locate specific answers. Be prepared to submit this summary/report to your instructor at the designated time.

1. Assume an average noon Sun angle. What percentage of the solar radiation will be absorbed by the atmosphere and what percentage will be absorbed by Earth's surface?

   Atmospheric absorption: ____________ %

   Absorption by Earth's surface: ____________ %

2. What will be the atmospheric effect of each of the following?

   Less ozone in the stratosphere:

   ____

   ____

   More carbon dioxide in the atmosphere:

   ____

   ____

   A surface with a high albedo:

   ____

   ____

3. Briefly explain how Earth's atmosphere is heated.

   ____

   ____

   ____

4. What are the primary heat-absorbing gases in the atmosphere? In general, what wavelength of radiation do they absorb?

   ____

   ____

5. What were the starting and 5-minute temperatures you obtained for the black and silver containers in the albedo experiment?

	STARTING TEMPERATURE	5-MINUTE TEMPERATURE
Black container:	________	________
Silver container:	________	________

6. Summarize the effect of color on the heating of an object.

   ____

   ____

7. What were the starting and ending temperatures you obtained for the water and dry sand in the land and water heating experiment?

	STARTING TEMPERATURE	ENDING TEMPERATURE
Water:	________	________
Dry sand:	________	________

8. Summarize the effects that equal amounts of radiation have on the heating of land and water.

9. Where are the highest and lowest average monthly temperatures located on Earth?

Highest average monthly temperature:

Lowest average monthly temperature:

10. Why does the Northern Hemisphere experience a greater annual range of temperature than the Southern Hemisphere?

11. Define each of the following:

Environmental lapse rate:

Windchill equivalent temperature:

Troposphere:

12. Referring to the average temperature graphs for Spokane and Seattle, Washington, shown in Figure 13.13, discuss the reason(s) why the two graphs are dissimilar, even though both cities are at about the same latitude.

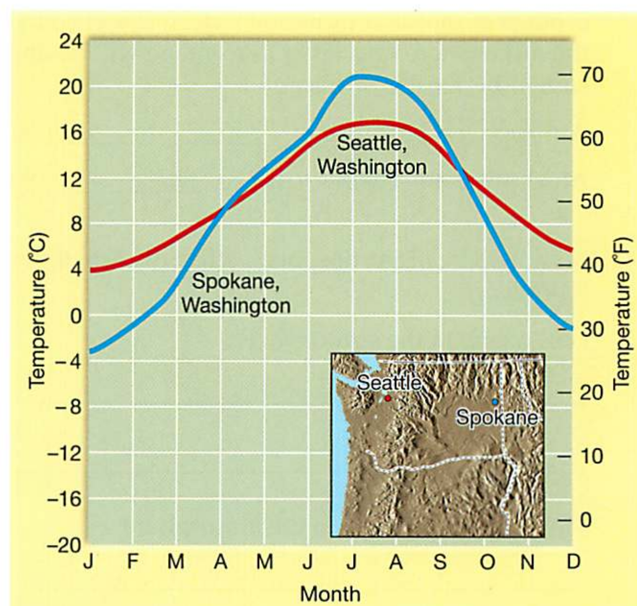


Figure 13.13 Temperature graphs for Spokane and Seattle, WA.