

CHAPTER 7 THE STRUCTURE AND MOTION OF THE ATMOSPHERE

Objectives

1. To learn about the structure of the atmosphere and its composition.
2. To learn about the causes and patterns of air movement in the atmosphere.
3. To understand the Coriolis effect.
4. To examine specific atmospheric gases of particular importance.

Key Concepts

Major Concept (I) *Earth receives solar radiation unequally over its surface; with the intensity per unit area of surface greatest at the equator, intermediate in the middle latitudes, and the lowest intensity is at the polar regions.*

Related or supporting concepts:

- If Earth had no atmosphere, and sunlight struck its surface at exactly 90° , radiation would bombard the surface at a theoretical value (input rate) of 2 calories per square centimeter per minute ($\text{cal}/\text{cm}^2/\text{min}$). This value is called the solar constant.
- The Sun is so far away, its rays of light can be considered nearly parallel when they reach Earth.
- On the real Earth, the sun's rays can strike Earth's surface at right angles only between 23.5°N (Tropic of Cancer) and 23.5°S (Tropic of Capricorn).
- Other areas of Earth's surface receive much less solar energy per unit area per unit time since Earth's surface is curved.
- Earth's atmosphere reduces the maximum theoretical amount of solar radiation that can reach Earth's surface from $2 \text{ cal}/\text{cm}^2/\text{min}$ to approximately $1.6 \text{ cal}/\text{cm}^2/\text{min}$. This is because the atmosphere both absorbs and reflects solar radiation.
- Therefore, Earth's surface is heated unequally.

Major Concept (II) *Earth must lose an amount of heat back to space that is equal to the amount it gains from the sun or else Earth's average temperature, about 16°C , would increase or decrease with time.*

Related or supporting concepts:

- Earth's heat budget is illustrated in figure 7.2.
- If assume 100 units of incoming solar energy reach Earth's outer atmosphere, 35 units will be reflected to space immediately (31 from the upper atmosphere and 4 from Earth's surface). The remaining 65 units are absorbed by Earth's surface and atmosphere.
- Of the 65 units of heat absorbed, 47.5 are absorbed by Earth's surface and the atmosphere absorbs the remaining 17.5.
- To maintain a heat balance, Earth must reradiate 65 units of heat back to space. The loss of 59.5 units of heat from the atmosphere and 5.5 units from the Earth's surface accomplish this.
- Notice that in the above calculations Earth's surface has absorbed 47.5 units of heat and lost only 5.5 units for a net gain of 42 units of heat. At the same time the atmosphere absorbs 17.5 units of heat while losing 59.5 units of heat for a net loss of 42 units of heat.
- The lost 42 units of heat from the atmosphere are replaced by the 42 units of heat gained by Earth's surface. This transfer is accomplished by evaporation, conduction, and re-radiation.
- To understand the heat budget of a portion of the ocean, we need to know the following:

- a. the total energy absorbed,
- b. the loss of energy due to evaporation,
- c. the transfer of heat (advectively) through currents (input and outflow of energy),
- d. warming or cooling of the overlying atmosphere due to energy at the sea surface, and
- e. heat re-radiated to space from the sea surface.

Major Concept (III) *The intensity of solar radiation available at Earth's surface varies with latitude and the time of year (see fig. 7.5).*

Related or supporting concepts:

- The intensity of solar radiation at middle latitudes between about 40° and 60°N & S is highly variable annually. This is because the angle of the Sun's rays reaching the surface is highly variable at these latitudes.
- The intensity of solar radiation is fairly constant through the year in the tropics.
- Polar latitudes are subject to severe changes in length of daylight.
- Land and ocean respond very differently to the annual changes in solar radiation.
- Land has low heat capacity, it gains or loses heat over a short period of time (such as overnight!), while the oceans have a very high heat capacity, absorbing or releasing heat with very small changes in temperature. (Think about maritime vs. continental climates.)
- The average annual range in sea surface temperatures is quite small because of water's high heat capacity and the transfer of heat through the water by mixing. Sea surface temperature variations range from:
 - a. 0° to 2°C in the tropics,
 - b. 5° to 8°C at middle latitudes, to
 - c. 2° to 4°C at polar latitudes.

Major Concept (IV) *Two fluid bodies blanket the solid Earth, the atmosphere surrounding the globe and the oceans covering most of its surface.*

Related or supporting concepts:

- The oceans and the atmosphere are in contact with one another over 71% of the globe's surface. This direct physical contact leads to constant interaction between the two.
- The planet's weather and climate are strongly influenced by air-sea interactions.
- A few examples of products of the interaction of the atmosphere, the oceans, and the sun include:
 - a. clouds,
 - b. winds,
 - c. storms,
 - d. rain, and
 - e. fog.

Major Concept (V) *The atmosphere is a reasonably well-mixed envelope of gases roughly 90 km (54 mi) thick. We can identify four layers in the atmosphere that have distinct characteristics.*

Related or supporting concepts:

- The four layers of the atmosphere, in order from lowest to highest elevation, are:
 - a. the troposphere,
 - b. the stratosphere,
 - c. the mesosphere, and
 - d. the thermosphere.

- The density of the atmosphere decreases rapidly with increasing height. Roughly 90% of the mass of the atmosphere is found in the first 15 km (9 mi) and 99% of the mass in the first 30 km (18 mi).
- The troposphere has the following characteristics:
 - a. it is about 12 km (7 mi) thick,
 - b. the temperature decreases rapidly with altitude,
 - c. the mean temperatures at the bottom and top are 16°C and -60°C,
 - d. it is heated from below by conduction and from condensation of water vapor,
 - e. it is the region where you find precipitation, evaporation, rapid convection, the major wind systems, and clouds, and
 - f. it is the densest layer of the atmosphere.
- Just above the troposphere is a region of relatively constant temperature, -60°C, about 10 km (6 mi) thick called the tropopause. This is where high velocity winds called jet streams occur.
- The stratosphere has the following characteristics:
 - a. it is about 28 km (17 mi) thick,
 - b. the temperature increases with altitude from about -60°C to 0°C,
 - c. this is where ozone, an unstable form of oxygen, appears, and
 - d. it is heated as the ozone absorbs incoming ultraviolet radiation.
- The stratopause is a region of relatively constant temperature, about 0°C, at an elevation of 50 km (30 mi) capping the top of the stratosphere. It extends upward to an elevation of about 60 km (36 mi).
- The mesosphere has the following characteristics:
 - a. it is about 20 km (12 mi) thick,
 - b. the temperature decreases rapidly with elevation from about 0°C to -80°C,
 - c. the pressure is only about 1/1000 what it is at Earth's surface, and
 - d. it extends upwards to about 90 km (54 mi).
- At the top of the mesosphere there is another region of fairly constant temperature called the mesopause. The mesopause is about 10 km (6 mi) thick.
- The top layer of the atmosphere is the thermosphere.

Major Concept (VI) *The atmosphere is composed of a mixture of a number of different gases. It has pressure variations that produce regions of low and high pressure with ascending and descending air.*

Related or supporting concepts:

- You can see from table 7.1 that while there are a number of different gases in the atmosphere, nitrogen and oxygen account for roughly 99 percent of the gas (nitrogen 78%, oxygen 21%). Interestingly, there is very little hydrogen. Remember when we talked about the hydrologic cycle and water reservoirs, we learned that there is relatively little water stored in the atmosphere, given its enormous size.
- Water vapor makes up between 0 and 4 percent of the atmospheric gases.
- Motion in the atmosphere is the result of density differences from one location to another.
- The density of air will increase with:
 - a. decreasing temperature,
 - b. increasing atmospheric pressure or altitude, and
 - c. decreasing water vapor content.
- The density of air will decrease with:
 - a. increasing temperature,
 - b. decreasing atmospheric pressure or altitude, and
 - c. increasing water vapor content.
- The overlying air presses down on the surface of the planet. The weight of a column of air at the surface pushes down with a force called the atmospheric pressure.
- Atmospheric pressure can be measured using different units. The average atmospheric pressure at sea level is:
 - a. 1013.25 millibars, or
 - b. 14.7 lbs/in².

This is equivalent to the pressure exerted by a column of mercury 760 mm high. A column of mercury 1 cm high exerts a pressure of 1 torr.

- High pressure zones have pressures greater than average and low pressure zones have pressures below this average value.
- Lines of constant pressure, called isobars, are shown on maps such as the one illustrated in figure 7.9.

Major Concept (VII) *As Earth has aged the composition of the atmosphere has changed naturally. There is clear evidence now, however, that human activities have produced marked changes in atmospheric chemistry over a very short period of time.*

Related or supporting concepts:

- Two gases of particular concern are carbon dioxide (CO₂) and ozone.
- Ozone molecules consist of three oxygen atoms rather than the usual two.
- CO₂ is stored in four reservoirs: three that are active including the atmosphere, the oceans, and the terrestrial system; and one inactive reservoir, Earth's crust (see fig. 7.10). Most CO₂ is stored in the oceans while the smallest amount is found in the atmosphere.
- Short-wavelength incoming radiation is not blocked by CO₂, but re-radiated long-wavelength energy is, and this warms the atmosphere causing the greenhouse effect.
- Changing atmospheric chemistry can be monitored for past years by analyzing bubbles trapped in polar ice. It can be demonstrated that following the Industrial Revolution, the concentration of CO₂ has risen dramatically and continues to rise at an increasing rate. The concentration of CO₂ in the atmosphere has increased from 280 ppm to 360 ppm since 1850. Currently, the average increase in concentration is about 1.5–2 ppm per year. Take a look at figure 7.11 to see a graph of the increase with time.
- There is a clear seasonal variation in CO₂ related to increasing uptake by plants for photosynthesis in the spring and summer, and increasing release through decay in the fall and winter.
- Scientists have estimated that the greenhouse effect may produce a global warming of 2–4°C over the next hundred years. This could melt high latitude ice and raise sea level by as much as 1 m by the year 2100.
- Careful measurements of short term increases in global temperatures have shown a twenty year warming period which began in 1920 and another period of warming that began in 1977 and continued through the 1980s.
- There is considerable debate over the actual cause or causes of the observed global warming and different mechanisms have been proposed to explain it including:
 - a. increasing levels of CO₂,
 - b. variations in sun spot cycles, and
 - c. changing concentrations of dust particles in the air.
- Some natural processes actually lead to global cooling. Massive volcanic eruptions can release enough ash to the air to block incoming solar radiation and cool the planet for a period of time.
- The use of fossil fuels and the burning of tropical forests produces about 7 billion tons of CO₂ annually. Roughly 3 billion tons are stored in the atmosphere, another 2 billion tons enters the oceans and ocean sediments. At least 1 billion tons are taken up by plants in the regrowth of logged forests.
- An international conference on greenhouse gas emissions was held in Kyoto, Japan in 1997. The Kyoto pact calls for 38 industrial nations to cut their emissions of greenhouse gases by an average of 5.2% from 1990 levels by the year 2012. Specific reductions include:
 - a. United States: reduction of 7%
 - b. European Union: reduction of 8%
 - c. Japan: reduction of 6%
- The United States has not signed the Kyoto treaty because of concerns about its effect on the economy.
- The United States currently is responsible for the greatest emission of greenhouse gases at 25% of the world total.
- If the Kyoto pact is followed it should reduce projected global greenhouse gas emissions in 2012 by 66%.

- Greenhouse gases are likely to continue to increase even with the Kyoto pact because a number of nations such as China, India, and Russia are not bound by the pact and are expected to account for 58% of the world's emissions of greenhouse gases by 2012.

Major Concept (VIII) *The depletion of the ozone layer was first reported in 1985 by British scientists who said the amount of ozone had been decreasing over Antarctica since the late 1970s.*

Related or supporting concepts:

- Depletion of the ozone layer over the poles is most severe in the winter months. The greatest loss is over Antarctica because Antarctic winters are colder than Arctic winters.
- The ozone hole grew to its largest recorded size in 2000, expanding to an area roughly three times the size of the United States.
- The ozone hole shrank somewhat in 2001 and in September 2002 was about 40 times smaller than in 2001 and was split into two regions (fig. 7.12).
- The dramatic change in the size of the hole in 2002 is thought to be due to changes in weather patterns that led to warmer temperatures in the upper atmosphere (stratospheric warmings).
- Ozone breaks down more rapidly at colder temperatures so stratospheric warmings reduce ozone depletion.
- Satellites carrying total ozone mapping spectrometers (TOMS) have been used to map the zone since 1978.
- The United States is currently monitoring both the Arctic and Antarctic ozone holes with NASA's *Earth Probe* (EP) satellite.
- The Arctic winter of 1996–97 was the fifth consecutive winter of unusually cold temperatures in the stratosphere.
- There are three possible explanations for the unusually cold temperatures in the Arctic between 1992 and 1997:
 - a. under conditions of decreasing ozone the atmosphere is unable to absorb as much solar radiation to warm itself,
 - b. increasing levels of greenhouse gases trap increasing amounts of heat lower in the atmosphere and less heat reaches the stratosphere, and
 - c. there may be some other natural variations in climate that we do not know about yet.
- Measurements taken early in 2000 found cumulative ozone losses of more than 60% over the Arctic.
- It is generally accepted that the loss of ozone is related to the release of chlorine into the atmosphere. Most of the chlorine release results from the use of chlorofluorocarbons (CFCs). CFCs are used as coolants for refrigeration and air conditioners, and as solvents in making insulating foams.
- CFCs are spread throughout the troposphere by winds and gradually make their way into the stratosphere where ultraviolet radiation breaks them down and allows the chlorine gas to be trapped in inert molecules.
- The concentrations of CFC's appears to have reached a maximum in the troposphere and they are expected to decline gradually in response to efforts to limit their production.
- Stratospheric clouds, which commonly are more abundant in the winter, free the chlorine gas and it then attacks the ozone.
- Methyl bromide has recently been recognized as an even more efficient agent in breaking down ozone. It is thought to be responsible for as much as 20% of the decrease in ozone over Antarctica and 5–10% of the decrease globally.
- Sources of methyl bromide include:
 - a. microscopic single-celled organisms living at the sea surface,
 - b. pesticides,
 - c. industrial activities, and
 - d. slow-smoldering burning of vegetation.
- Decreased levels of ozone in the atmosphere will allow more ultraviolet radiation to reach the surface. A 50% decrease in ozone is estimated to cause a 350% increase in ultraviolet radiation reaching the surface.

- Ultraviolet radiation is known to adversely affect growth and reproduction in organisms and is thought to increase the risk of skin cancer and cataracts.
- Research also indicates that increased ultraviolet light may decrease rates of photosynthesis and growth in marine plants, phytoplankton, by about 2–4% under the Antarctic ozone hole.

Major Concept (IX) *Sulfur plays an important role in atmospheric chemistry over the oceans. It may act as a feedback mechanism in helping to control the surface temperature of the water.*

Related or supporting concepts:

- Plants near the ocean's surface produce a gas called dimethyl sulfide (DMS). Roughly 20–40 million tons of DMS are added to the atmosphere annually.
- The smell of DMS contributes to the characteristic aroma of the sea.
- In the atmosphere DMS is altered to sulfate and the sulfur combines with water vapor to form sulfuric acid (see fig. 7.13). The amount of sulfuric acid falling to Earth's surface from this source is much less than the amounts associated with the problem of "acid rain."
- An increase in DMS in the atmosphere results in the following:
 - a. an increase in the density of the clouds,
 - b. greater reflection of solar radiation from the tops of the clouds,
 - c. a reduction in the heating of the surface of the ocean,
 - d. reduced photosynthesis, and
 - e. ultimately a reduction in the production of DMS that will start the cycle over again.
- This cyclical fluctuation of DMS has the effect of minimizing variations in sea surface temperature.
- Natural mechanisms have been identified that may decrease the greenhouse effect. These include:
 - a. the release of sulfur into the atmosphere from the oceans, and
 - b. large volcanic eruptions.

Major Concept (X) *Density differences in the atmosphere result in pressure differences at the surface.*

Related or supporting concepts:

- Atmospheric pressure is a measure of the force pressing down on the Earth's surface from the overlying air.
- Pressure is often measured in different units including:
 - a. atmospheres (1 atmosphere is the average atmospheric pressure at sea level),
 - b. millibars (1 atmosphere = 1013.25 millibars),
 - c. pounds per square inch or psi (1 atmosphere = 14.7 pounds per square inch),
 - d. mm or inches of mercury (1 atmosphere = 760 mm or 29.92 inches of mercury), and
 - e. torrs (1 torr = the pressure exerted by 1 cm of mercury).
- Low air density results in rising air and low surface pressure.
- High air density results in descending air and high surface pressure.

Major Concept (XI) *On a non-rotating Earth that is uniformly covered with water, the pattern of solar radiation with maximum heating at the equator will produce a single large convection cell extending from the equator to the pole in each hemisphere.*

Related or supporting concepts:

- Incoming solar radiation is not uniformly distributed as a function of latitude. The majority of the planet's surface heating occurs at the equator and tapers off towards the poles.
- Solar radiation at the equator will result in the heating of equatorial air that will lower its density and cause it to rise in a broad equatorial band of low pressure.
- The rising air will cool as it ascends, making the water vapor in it condense to form clouds and fall as rain.
- Surface winds will blow towards the equator to replace the air that has ascended.

- Air at high altitudes will move away from the equator toward the poles, losing heat along the way.
- Cold, dry air over the poles will descend back to the surface in a large high pressure area completing the convection cell.
- This type of circulation is illustrated in figure 7.15.
- Winds are named for the direction from which they blow. Therefore, the Northern Hemisphere would experience north winds at the surface and the Southern Hemisphere would experience south winds at the surface.

Major Concept (XII) *The rotation of Earth coupled with negligible friction between the atmosphere and Earth's surface results in an apparent deflection in the path of moving parcels of air when they are viewed from the surface of the globe.*

Related or supporting concepts:

- Points on the surface of Earth rotate eastward at a speed that depends on latitude. This speed is about 1674 km/hr at the equator, 1450 km/hr at 30°N and S, 837 km/hr at 60°N and S, and zero at the poles (see fig. 7.16).
- An air mass that appears stationary at one latitude will be moving eastward with the rotating Earth at a velocity equal to the rotational velocity of Earth's surface at that latitude.
- If the air mass then moves closer to the equator, it will move over points on the surface that have a higher eastward velocity than it does. Consequently, to an observer on the surface, the air mass will appear to lag behind the eastward rotation of the planet, or it will appear to be moving westward.
- If the air mass moves farther away from the equator, it will travel over points on the surface that have a slower eastward velocity than it does. Consequently, to an observer on Earth's surface, the air mass will appear to speed ahead of the planet, or it will appear to be deflected to the east (see fig. 7.17).
- An air mass that moves eastward will be rotating in the direction of Earth's rotation at a faster rate of speed than Earth is. This will cause it to be subjected to a greater centrifugal, or outward, force and hence it will move towards the equator and further away from the axis of rotation (see fig. 7.18).
- An air mass that moves westward will be rotating in the direction of Earth's rotation at a slower rate of speed than Earth is. This will cause it to be subjected to a smaller centrifugal force and hence it will move away from the equator and closer to the axis of rotation (see fig. 7.18).
- The movements discussed in the previous four related concepts can be summarized by saying that objects in frictionless motion will appear to be deflected to the right of their direction of movement in the Northern Hemisphere and to the left in the Southern Hemisphere. Take some time to go over these concepts and convince yourself of this.
- This apparent deflection is called the Coriolis effect after Gaspard Gustave de Coriolis (1792–1843), who solved the problem of deflection in frictionless motion when the motion is referred to a rotating body and its coordinate system.
- The magnitude of the Coriolis effect increases with increasing latitude because the rate of change in the rotation of Earth increases with increasing latitude as well. This is easily seen in the following table:

Band of Latitude	Approx. Change in rotational velocity	Change per degree of Lat.
0–30 degrees	250 km/hr	8.3 km/hr/deg
0–60 degrees	600 km/hr	20.0 km/hr/deg
60–90 degrees	850 km/hr	28.3 km/hr/deg

- The Coriolis effect reaches a maximum at the poles and decreases to zero at the equator when the direction of the apparent deflection reverses itself from one hemisphere to the other.

Major Concept (XIII) *With Earth's rotation and subsequent action of the Coriolis effect, atmospheric circulation is more complex and consists of three convection cells in each hemisphere rather than just one (see fig. 7.19).*

Related or supporting concepts:

- The three circulation cells in each hemisphere occur between bands of latitude 30 degrees wide from 0–30, 30–60, and 60–90 degrees N and S.
- Between these cells air moves primarily in a vertical direction and, as a result, the surface winds are weak and unpredictable. The equatorial region is referred to as the doldrums and the regions at 30° latitude are often called the horse latitudes.
- At the equator and 60°N and S latitudes, rising air creates belts of low pressure with cloud cover and frequent precipitation.
- At 30° and 90°N and S latitudes, descending air creates belts of high pressure with generally clear skies and little precipitation.
- Within these 30° wide belts of latitude air mostly moves horizontally in opposite directions at the surface and at high latitude.
- From the equator to 30°N and S, surface winds move towards the equator, creating the northeast and southeast trade winds in the Northern and Southern Hemispheres, respectively. Think about the meaning of the names of these winds and the Coriolis effect to understand more about them.
- From 30° to 60°N and S, surface winds move towards the poles to produce the westerlies. These winds blow from the southwest in the Northern Hemisphere and the northwest in the Southern Hemisphere.
- From 60° to 90°N and S, the surface winds blow away from the poles to create the polar easterlies. These come from the northeast in the Northern Hemisphere and the southeast in the Southern Hemisphere.

Major Concept (XIV) *To approximate the real Earth even more closely, we need to consider the effects of seasonal changes in Earth's surface temperature and the presence of large landmasses interrupting a water-covered planet (see fig. 7.21).*

Related or supporting concepts:

- Middle latitudes experience large seasonal changes in surface temperature, particularly over land that has a relatively low heat capacity and will gain or lose heat rapidly.
- Water's high heat capacity and its great mobility combine to minimize the variation of temperature in the oceans.
- In the Northern Hemisphere there is a nearly equal area of land and water on the surface. This produces distinct patterns of high and low atmospheric pressure that change with the seasons.
- During summer months at temperate latitudes, the warm continents heat the overlying air, causing it to rise by lowering its density. This produces low-pressure areas over the continents. The relatively cool sea surface causes sinking air and high-pressure cells over the water.
- During winter months at temperate latitudes, the land loses heat much more rapidly than the water and the pattern of high- and low-pressure cells reverses.
- Atmospheric circulation in the Northern Hemisphere is clockwise around high pressure cells and counterclockwise around low pressure cells. In the Southern Hemisphere this is reversed (see fig. 7.22).
- The wind pattern in the Southern Hemisphere exhibits little seasonal variation because there is relatively little land area. Consequently, the atmospheric circulation is quite similar to that predicted by the model of a water-covered planet discussed in the previous major concept.

Major Concept (XV) *Large seasonal temperature variations over land can produce major climatic changes in coastal regions. One example of this is the monsoon effect (see fig. 7.23).*

Related or supporting concepts:

- During summer months, a large low-pressure system forms over India and Southeast Asia in response to the heating of the land. Counterclockwise airflow around this system carries warm, moist air from the Indian Ocean over the continent where the moisture condenses as the air rises and cools. This results in a steady, heavy rain over the land that is referred to as the wet or summer monsoon.

- During winter months, the loss of heat from the land will cool the overlying air, producing a high-pressure system over the continent. Clockwise circulation around this system carries cool, dry air from the interior of the continent over the coastal regions. This is the dry, or winter, monsoon.

Major Concept (XVI) *Daily temperature variations over land can produce small scale weather changes in coastal regions (see fig. 7.24).*

Related or supporting concepts:

- The land will heat up faster during the day than the adjacent water. This will cause rising air over the land that will be replaced by air blowing onshore from the ocean. This is the onshore or sea breeze. It is usually strongest in the afternoon when the temperature difference between the land and the water is greatest.
- At night the land will cool off more rapidly and air will sink over the land and blow offshore out to sea. This is the offshore or land breeze. It is usually strongest in the late night and early morning hours.

Major Concept (XVII) *Areas of high and low precipitation can be caused by large, rapid changes in elevation that deflect surface winds upward (see fig. 7.25).*

Related or supporting concepts:

- When surface winds moving at sea level over the oceans encounter continents or islands, they will be deflected upwards to follow the contour of the land.
- As the wind moves higher above sea level, it will cool and water vapor will begin to condense out of the air.
- Precipitation will often fall on the windward side of mountains or islands, while on the opposite, or leeward side, it will remain dry creating a rain shadow.
- Precipitation patterns caused by changes in topography, or elevation, are called the orographic effect.

Major Concept (XVIII) *Weather patterns at the surface are strongly influenced by upper air currents. One of the best examples of this is the jet streams high in the atmosphere.*

Related or supporting concepts:

- High in the atmosphere above the sinking air near 30°N and S are the subtropical jet streams. These jets are easterlies. Above the rising air near 50–60°N and S are the polar jet streams. These jets are westerlies.
- The remaining comments in this section relate specifically to the Northern Hemisphere polar jet stream for the purposes of example.
- The jet stream blows at speeds as high as 250 km/hr (150 mi/hr) from west to east around the globe.
- The path the jet stream takes can be highly sinuous. It may curve drastically and move as much as 2000 km north and south in response to the location and motion of major low- and high-pressure systems. This oscillation is greatest in the winter and decreases in the summer.
- These low- and high-pressure systems move slowly eastward, along with the waveform of the jet stream, as the westerlies drive them.
- Circulation of air around pressure systems transports moist subtropical air to higher latitudes where condensation releases heat. At the same time, dry polar air moves to lower latitudes where it can easily pick up moisture through evaporation.

Major Concept (XIX) *Large amounts of energy are transferred from the ocean to the atmosphere in the formation of severe storms that are produced in the tropics and move to higher latitudes.*

Related or supporting concepts:

- As the trade winds move over areas of the oceans with varying surface temperatures, they may develop changes in speed and direction. This can result in convergence and divergence in the air that produces a pressure disturbance called an easterly wave.
- If the surface water temperature is warm, above 27°C, the easterly wave can strengthen into an intense low-pressure system called a tropical depression.
- Tropical depressions can intensify to become severe storms.
- Severe storms generated in tropical regions go by a variety of names, including:
 - a. tropical storm,
 - b. cyclone,
 - c. hurricane, and
 - d. typhoon.
- Warm, humid air rises quickly, causing condensation and the release of heat into the atmosphere.
- The heat that is released contributes to the velocity of the winds in these storms.
- Heavy precipitation commonly accompanies the high winds.
- Major hurricanes may have more energy than large nuclear explosions but they release the energy gradually over a larger area.
- These storms usually move to the west and away from the equator along curved paths due to the Coriolis effect. The paths curve to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.
- When these storms move over cold water or land they decrease in intensity because they can no longer draw heat into the atmosphere.
- Forecasting the strength and path of these storms is extremely important. These storms can be monitored with geostationary operational environmental satellites (GOES) and, when they approach land, land-based Doppler radar that can measure wind speed and wind distribution in great detail.

Major Concept (XX) *An El Niño is a period of anomalous climatic conditions centered in the tropical Pacific. It is characterized by abnormally high sea surface temperatures in the eastern Pacific. An El Niño is often followed by abnormally cold periods called La Niña.*

Related or supporting concepts:

- Along the western coast of South America off Ecuador and Peru, the southeast trade winds drive water away from the land, creating a nearly constant region of divergence with upwelling water rich in nutrients. These cold waters are extremely productive with dense populations of plankton that support a large and valuable food chain.
- Periodically, roughly every three to seven years, the trade winds will break down and the divergence will stop.
- The exact cause of this breakdown is still a matter of research but it has been linked to a reversal in the pattern of high- and low-pressure centers located over the eastern and western sides of the ocean basin, respectively. Normally, the trade winds are fueled by a high-pressure system over Easter Island in the eastern Pacific and a low-pressure system over Indonesia in the western Pacific.
- When this pattern of high- and low-pressure systems reverses in a process known as the Southern Ocean Oscillation, warm water from the western Pacific will flow eastward and stop the upwelling along the coast of South America.
- These conditions are known as El Niño or the El Niño-Southern Oscillation (ENSO).
- The increase in surface temperature of the water along the coasts of Ecuador and Peru can be as great as 7°C and may last for a period of months, or in extreme cases, for over a year. The temperature increase during the 1997–98 El Niño was even higher than this.
- The 1997–98 El Niño began in March, 1997. Severe storms came out of the Pacific and brought heavier-than-normal rainfall to California.
- El Niño tends to reduce rainfall in the wet monsoon areas of Asia but during the 1997–98 event India’s rainfall was 2% above normal. In addition, Indonesia experienced prolonged drought and severe fires.
- By the spring of 1998 sea-surface temperatures in the Pacific were returning to normal as El Niño faded.

- The 1997–98 El Niño was predicted 6 months in advance. This advanced warning is estimated to have saved as much as 1 to 2 billion dollars in property damage in the United States. This was the strongest El Niño on record.
- Two research programs monitor sea-surface temperature in the tropical Pacific:
 - a. the Coupled Ocean Atmosphere Response Experiment (COARE), and
 - b. the Tropical Ocean Global Atmosphere (TOGA) experiment.
- TOGA ended in 1994 but the drifting buoys that were deployed for it still operate and collect data.
- Colder years often follow these periods of abnormally warm temperatures. These cold periods have been called La Niña, or “the girl.”
- The La Niña will cause a strengthening of the trade winds with a decrease in precipitation on the eastern side of the basin and a corresponding increase on the western side.

Major Concept (XXI) *The ocean-atmosphere system in the Pacific Ocean also appear to have a natural cycle with a period of roughly 17 to 26 years.*

Related or supporting concepts:

- This cycle is known as the Pacific Decadal Oscillation (PDO).
- The PDO has a direct influence on sea surface temperature.
- The Pacific Ocean was in a warm phase of the PDO from 1977–99.
- The Pacific is currently in a cool phase of the PDO.
- El Niño events seem to occur more frequently during the warm phase of the PDO and are suppressed during the cool phase.

Major Concept (XXII) *Periods of excessively high water levels along the coast can be caused by intense low pressure and strong onshore winds associated with major storms. These are called storm surges or storm tides.*

Related or supporting concepts:

- Severe storms are associated with low atmospheric pressure. This low pressure does not exert as much force on the ocean’s surface. Consequently, the water level can rise appreciably beneath intense storms.
- Strong onshore winds associated with the storm can drive this elevated water toward the coast and cause flooding. This phenomena is a storm surge or storm tide.
- The pressure difference associated with major hurricanes and typhoons can be as great as 7.5 cm (3 in) of mercury. Since mercury is 13.6 times more dense than water this will result in an elevation of the sea surface of 97 cm (38 in).
- Surface winds blowing toward the center of the storm also increase the height of the sea surface beneath the storm.
- A storm surge can maintain high water and flooding conditions along the coast for many hours.
- “The great Galveston flood” of 1900 covered the island of Galveston, Texas with as much as 4 m (13 ft) of water, destroying the city and killing 5000 people.
- Flooding from hurricane Camille in 1969 killed several hundred people along the Gulf Coast.
- Hurricane Hugo produced a storm tide of 5 m (16.5 ft) in 1989 in South Carolina. Fortunately, early warnings led to mass evacuation of low-lying coastal regions thus saving many lives (see fig. 7.32).
- Hurricane Andrew struck Florida in 1992 with the same intensity as Hurricane Hugo but the storm surge was much smaller. It traveled very rapidly so there wasn’t as much time for water to build up. In addition, some of the wave energy was absorbed by offshore reefs and coastal mangrove swamps. On shore however, the wind damage was extreme and Hurricane Andrew was the costliest storm in U.S. history.
- Severe storms in the Bay of Bengal created storm surges that took an estimated 300,000 lives in 1970
- Indian Ocean storm surges killed and additional 10,000 people in 1985 and an estimated 139,000 people in Bangladesh in 1991.

Matching Key Terms with Major Concepts

At the end of the chapter in the textbook is a list of key terms. You should be able to match each of these with one of the previously listed major concepts. To test your ability, try to match the following key terms with the number (I–XXII) of the appropriate major concept identified in this section:

troposphere	stratosphere	ozone
mesosphere	thermosphere	atmospheric pressure
isobar	low-pressure zone	high-pressure zone
greenhouse effect	dimethyl sulfide	Coriolis effect
trade winds	westerlies	polar easterlies
doldrums	horse latitudes	monsoon
onshore	offshore	jet stream
rain shadow	orographic effect	climate
weather	easterly wave	tropical depression
hurricane	typhoon	El Niño
La Niña	storm surge	storm tide
solar constant	heat budget	

Test Your Recall

Answer the following questions to test your understanding

FILL IN THE BLANK

1. The area of rising air at the equator is known as the _____.
2. The prevailing winds between the equator and 30° N and S are called the _____.
3. Topography can influence precipitation patterns in what is called the _____ effect.
4. Dry regions on the leeward side of islands and mountains are sometimes said to be in a _____.
5. The lowest layer of the atmosphere is called the _____.
6. The molecule that consists of three oxygen atoms is called _____.
7. High velocity winds at great altitude are called _____.
8. Warming of the climate because of the effect of carbon dioxide in the atmosphere is called the _____.
9. The magnitude of the Coriolis effect _____ with increasing latitude.
10. Lines of constant atmospheric pressure are called _____.
11. Air moves in the atmosphere in large circular paths from the surface to great height and back again in six _____ that are restricted to bands of latitude.
12. During winter months, the _____ is warmer than the _____.
13. In the Southern Hemisphere, winds blow _____ around low-pressure centers.
14. The highest layer of the atmosphere is called the _____.

15. A _____ cell is formed when air is warmed at one location and cooled at another.
16. Air becomes less _____ when it is warmed.
17. Dry air is made up mostly of the gas _____.
18. The pressure of a column of mercury 1 cm high is equal to a _____.
19. Between the trade winds and the westerlies are the _____ latitudes.
20. When the land heats up faster than the adjacent water, an _____ breeze forms.

TRUE - FALSE

1. Ultimately, winds are the result of unequal heating of Earth's atmosphere.
2. The density of a parcel of air will increase if the water vapor content increases.
3. The largest component by volume of dry air is oxygen.
4. Atmospheric pressure is a measure of the force per unit area exerted at some location by the overlying air.
5. The name of a wind indicates the direction it is blowing.
6. Points on Earth's surface at high latitudes rotate eastward faster than points at low latitudes because they are closer to Earth's axis of rotation.
7. The Coriolis effect results in a deflection of moving objects to the left in the Southern Hemisphere.
8. The direction of atmospheric circulation at 60° of latitude is primarily vertically upwards.
9. There are two major atmospheric circulation cells in each hemisphere.
10. The atmosphere is heated from below.
11. The term monsoon refers to unusually wet and rainy seasons in tropical regions.
12. Strong onshore winds typically develop at night to cool coastal regions.
13. The pattern of large scale oceanic surface currents remains nearly constant.
14. There are four major layers in the atmosphere.
15. Temperature increases with altitude in the stratosphere.
16. The average atmospheric pressure at sea level is about 1013 millibars.
17. Offshore winds generally form during the day.
18. Increase levels of carbon dioxide in the atmosphere contribute to global cooling.
19. Ozone high in the atmosphere blocks incoming ultraviolet light.
20. Dimethyl sulfide helps to regulate ocean salinity.

MULTIPLE CHOICE

1. The temperature increases with increasing altitude in the
 - a. mesosphere.
 - b. stratosphere.
 - c. troposphere.
 - d. altosphere.
 - e. endosphere.
2. The highest ozone concentration is in the
 - a. mesosphere.
 - b. thermosphere.
 - c. stratopause.
 - d. stratosphere.
 - e. mesopause.
3. Air masses move because
 - a. of density variations in the atmosphere.
 - b. of unequal heating of the atmosphere.
 - c. of frictional drag with ocean currents.
 - d. a and b above.
 - e. all of the above.
4. The density of air decreases with

- a. increasing temperature.
 - b. decreasing pressure.
 - c. increasing water vapor content.
 - d. all of the above.
 - e. none of the above.
5. The average atmospheric pressure at sea level is _____ lbs/in².
- a. 12.4
 - b. 14.7
 - c. 2.9
 - d. 5.3
 - e. 26.7
6. A wind blowing from the southeast is called a _____ wind.
- a. northwest
 - b. northeast
 - c. southeast
 - d. southwest
 - e. westerly
7. A point on the equator rotates eastward at _____ km/hr.
- a. 1700
 - b. 1250
 - c. 1050
 - d. 850
 - e. 600
8. Between 30° and 60° latitude, the winds
- a. are known as the westerlies in both hemispheres.
 - b. blow out of the southwest in the Northern Hemisphere.
 - c. blow out of the northwest in the Southern Hemisphere.
 - d. help to drive surface currents in the oceans.
 - e. all of the above.
9. The horse latitudes are found at _____ degrees north and south.
- a. 30
 - b. 0
 - c. 60
 - d. 40
 - e. 90
10. During the warm summer months
- a. the air over the sea cools and sinks.
 - b. the air over the land warms and rises.
 - c. high-pressure zones form over the continents.
 - d. a and b above.
 - e. a and c above.
11. In the Northern Hemisphere
- a. winds blow clockwise around high-pressure cells.
 - b. winds blow counterclockwise around high-pressure cells.
 - c. winds blow clockwise around low-pressure cells.
 - d. a and c above.
 - e. b and c above.
12. During the day, the land warms faster than the water and a _____ is created.
- a. offshore breeze
 - b. summer monsoon
 - c. onshore breeze
 - d. dry monsoon
 - e. marine breeze
13. Roughly 99% of the mass of the atmosphere is in the first _____ km above the surface.
- a. 10

- b. 30
 - c. 100
 - d. 45
 - e. 60
14. The temperature at the top of the troposphere is about _____ degrees C.
- a. 30
 - b. 0
 - c. 50
 - d. -120
 - e. -60
15. Air usually contains about _____ percent water vapor.
- a. 10–12
 - b. 5–10
 - c. 0–4
 - d. 0.1–0.5
 - e. 0.03–0.08
16. El Niño seems to occur on a _____ year cycle.
- a. 1 to 2
 - b. 10 to 12
 - c. 5 to 10
 - d. 4 to 7
 - e. 20 to 30
17. La Niña is associated with which of the following?
- a. unusually cold surface water in the eastern tropical Pacific
 - b. unusually strong trade winds
 - c. dry conditions over western South America
 - d. wet conditions in the western Pacific basin
 - e. all of the above
18. The jet stream can blow at speeds as great as _____ km/hr.
- a. 20
 - b. 130
 - c. 250
 - d. 50
 - e. 400
19. If less DMS is produced
- a. there is less cloud cover.
 - b. there is less solar radiation reflected back to space.
 - c. there is increasing photosynthesis.
 - d. there is a rise in sea surface temperature.
 - e. all of the above.
20. A hurricane will
- a. weaken over land.
 - b. strengthen over cold water.
 - c. rotate clockwise in the Northern Hemisphere.
 - d. none of the above.
 - e. all of the above.

Visual Aids: Test Your Understanding of the Figures

1. Take a close look at figure 7.21 and compare the locations of high- and low-pressure cells in the two hemispheres in the summer and in the winter. Notice that in the Southern Hemisphere there isn't much of a change with the seasons while in the Northern Hemisphere the pattern of high- and low-pressure centers reverse with the seasons. Can you explain this difference? Could you tell what season it is by seeing the pattern of atmospheric pressure in the Northern Hemisphere?

- Look at figure 7.23 and consider the direction of the winds for the dry and wet monsoons. What does this tell you about where the atmosphere picks up water vapor?
- From figure 7.31 estimate the average time interval between the appearance of El Niño and La Niña events.

Study Problem

- The circumference of a circle of latitude is approximately equal to 6371 km multiplied by the cosine(latitude). Calculate the eastward velocity of your school in km/hr and the distance you would travel during one oceanography lecture. Just for comparison, Milwaukee is at a latitude of about 43° and one lecture is usually 50 minutes long.

Answer Key for Key Terms and Test Your Recall

KEY TERMS

troposphere (V)	stratosphere (V)	ozone (V,VIII)
mesosphere (V)	thermosphere (V)	atmospheric pressure (VI,X)
isobar (VI)	low-pressure zone (VI,X)	high-pressure zone (V,X)
greenhouse effect (VII)	dimethyl sulfide (IX)	Coriolis effect (XII)
trade winds (XIII)	westerlies (XIII)	polar easterlies (XIII)
doldrums (XIII)	horse latitudes (XIII)	monsoon (XV)
onshore (XVI)	offshore (XVI)	jet stream (V,XVIII)
rain shadow (XVII)	orographic effect (XVII)	climate (IV)
weather (IV)	easterly wave (XIX)	tropical depression (XIX)
hurricane (XIX)	typhoon (XIX)	El Niño (XX)
La Niña (XX)	storm surge (XXI)	storm tide (XXII)
solar constant(I)	heat budget (I,II)	

FILL IN THE BLANK

1. doldrums	2. trade winds	3. orographic
4. rain shadow	5. troposphere	6. ozone
7. jet streams	8. greenhouse effect	9. increases
10. isobars	11. convection cells	12. water, land
13. clockwise	14. thermosphere	15. convection
16. dense	17. nitrogen	18. torr
19. horse	20. onshore	

TRUE - FALSE

1.T 2.F 3.F 4.T 5.F 6.F 7.T 8.T 9.F 10.T 11.F 12.F 13.T 14.T 15.T 16.T 17.F 18.F 19.T 20.F

MULTIPLE CHOICE

1.b 2.d 3.d 4.d 5.b 6.c 7.a 8.e 9.a 10.d 11.a 12.c 13.b 14.e 15.c 16.d 17.e 18.b 19.e 20.a

STUDY PROBLEM

- For Milwaukee the answers are: 1220 km/hr, 1017 km