The Atmosphere

CHAPTER 2

A frozen Continent . . . beat with perpetual storms . . . the parching Air Burns frore, and cold performs th' effect of Fire.

—Milton, *Book II—Paradise Lost*

COMPOSITION

Earth's atmosphere is composed of seven primary compounds:

Component

NITROGEN (N_2) 78%

Fundamental nutrient for living organisms. Deposits on Earth through nitrogen fixation and reactions involving lightning and subsequent precipitation. Returns to the atmosphere through combustion of biomass and denitrification.

OXYGEN (O_2) 21%

Oxygen molecules are produced through photosynthesis and are utilized in cellular respiration.

WATER VAPOR (H_2O) 0–4%

Largest amounts occur near equator, over oceans, and in tropical regions. Areas where atmospheric water vapor can be low are polar areas and deserts.

CARBON DIOXIDE (CO_2) $<<1\%$

Volume of CO_2 has increased about 25% in the last 300 years due to the burning of fossil fuels and deforestation. CO_2 is produced during cellular respiration and the decay of organic matter. It is a reactant in photosynthesis. CO_2 is also a major greenhouse gas. Humans are responsible for about 5,500 million tons of CO_2 per year. The average time of a CO_2 molecule in the atmosphere is approximately 100 years.

METHANE (CH_4) <<<1%

Methane contributes to the greenhouse effect. Since 1750, methane has increased about 150% due to the use of fossil fuels, coal mining, landfills, grazers, and flooding of rice fields. Human activity is responsible for about 400 million tons per year as compared with approximately 200 million tons per year produced naturally. Average cycle of a methane molecule in the atmosphere is approximately 10 years.

TIP

Don't confuse weather and climate. Weather describes whatever is happening outdoors in a given place at a given time. Weather is what happens from minute to minute. Climate describes the total of all weather occurring over a period of years in a given place. This includes average weather conditions, regular weather sequences (like winter, spring, summer, and fall), and special weather events (like tornadoes and floods.)

NITROUS OXIDE (N_2O) <<<1%

Concentration increasing about 0.3% per year. Sources include burning of fossil fuels, use of fertilizers, burning biomass, deforestation, and conversion to agricultural land. Humans are responsible for about 6 million tons per year. N_2O is a contributor to the greenhouse effect. Average time of a N_2O molecule in the atmosphere is approximately 170 years.

OZONE (O_3) <<<1%

97% of ozone is found in the stratosphere (ozone layer) 9–35 miles (15–55 km) above Earth's surface. Ozone absorbs UV radiation. Ozone is produced in the production of photochemical smog. A "hole" in the ozone layer occurs over Antarctica. Chlorofluorocarbons (CFCs) are the primary cause of the breakdown of ozone.

STRUCTURE

The atmosphere consists of several different layers:

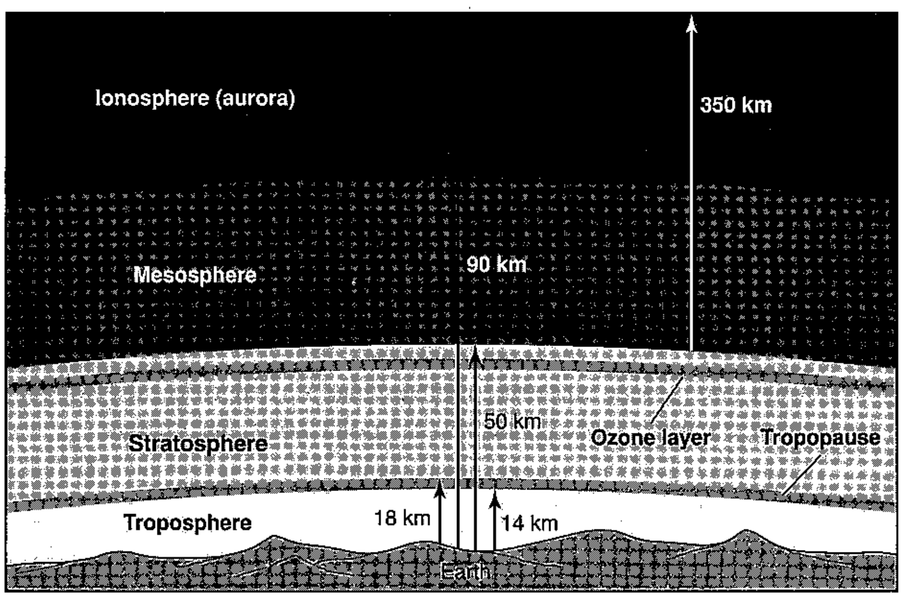

Figure 2.1 Layers of the atmosphere

Layers

TROPOSPHERE

0–7 miles (0–11 km) above surface. 75% of atmosphere's mass is in the troposphere. Temperature decreases with altitude, reaching –76°F (–60°C) near the top. Weather occurs in this zone.

STRATOSPHERE

Temperature increases with altitude due to absorption of heat by ozone. Ozone is produced by UV radiation and lightning. Contains the ozone layer.

MESOSPHERE

Temperature decreases with altitude. Coldest layer. Ice clouds occur here. Meteors (shooting stars) burn up in this layer.

THERMOSPHERE (IONOSPHERE)

Temperature increases with height due to gamma rays, X-rays, and UV radiation. Molecules are converted into ions which results in the aurora borealis (northern lights) in the northern hemisphere and the aurora australis (southern lights) in the southern hemisphere. The aurora borealis most often occurs from September to October and from March to April.

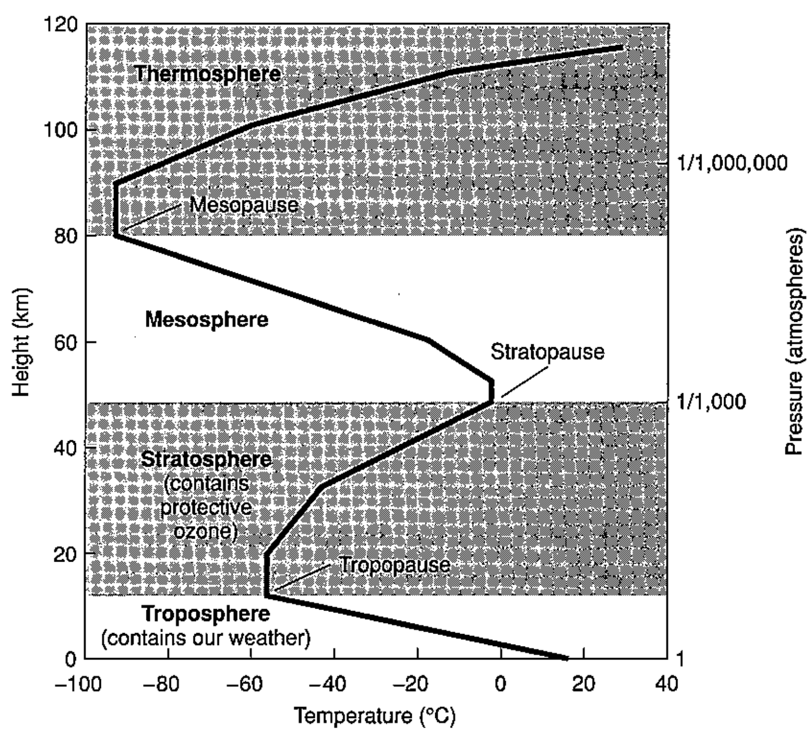

Figure 2.2 Changes in temperature in the atmosphere

TIP

Several different factors influence climate:

- Air mass
- Air pressure
- Albedo
- Altitude
- Angle of sunlight
- Clouds
- Distance to oceans
- Fronts
- Heat
- Land changes
- Latitude
- Location
- Humidity or moisture content of air
- Mountain ranges
- Pollution
- Rotation
- Wind patterns
- Human activity

WEATHER AND CLIMATE

Weather is caused by the movement or transfer of heat energy, which influences the following physical properties: temperature, air pressure, humidity, precipitation, available sunshine determined by cloud cover, wind speed, and wind direction. Climate describes the total of all weather occurring over a period of years in a given place. Energy can be transferred wherever there is a temperature difference between two objects. Energy can be transferred through radiation, conduction, and convection.

Radiation is the flow of electromagnetic radiation. It is the method by which Earth receives solar energy.

Conduction is energy. It is transferred by the collisions that take place between heat-carrying molecules.

Convection is the primary way energy is transferred from hotter to colder regions in Earth's atmosphere and is the primary determinant of weather patterns. Convection involves the movement of the warmer and therefore more energetic molecules in air. Convection takes place both vertically and horizontally. When air near the ground becomes warmer and therefore less dense than the air above it, the air rises. Pressure differences that develop because of temperature differences result in wind or horizontal convection.

Regions nearer the equator receive much more solar energy than regions nearer the poles and are consequently much warmer. These latitudinal differences in surface temperature create global-scale flows of energy within the atmosphere, giving rise to the major weather patterns of the world. Without convection and the transfer of energy, the equator would be about 27°F (15°C) warmer and the Arctic would be about 45°F (25°C) colder than they actually are.

FACTORS THAT INFLUENCE CLIMATE

Evidence for changes in the climate come from data used to measure climate (which is available for only the last few hundred years), written accounts (subjective), and data from material present at the time. These materials consists of tree rings, fossilized plants, insect and pollen samples, gas bubbles trapped in glaciers, deep ice core samples, lake sediments, stalactites and stalagmites, marine fossils including coral analysis, sediments including rafted debris, dust analysis, and isotope ratios in fossilized remains. The bottom line is that Earth's climate has gone through many cycles of warming and cooling trends. Many different factors influence the climate.

AIR MASS

An air mass is a large body of air that has similar temperatures and moisture content. Air masses can be categorized as equatorial, tropical, polar, arctic, continental, or maritime.

AIR PRESSURE

Most of the total mass of the atmosphere—99%—is within 20 miles (32 km) of Earth's surface. Gravity on an air mass results in air pressure and is measured in millibars, inches of mercury, or hectopascals (hPa). Air pressure decreases with altitude. Low pressure usually produces cloudy and stormy weather. High pressure masses contain cool, dense air that descend toward Earth's surface and becomes warmer. High pressure is usually associated with fair weather.

ALBEDO

Albedo is reflectivity. Materials like ocean water have low albedo, whereas land masses have moderate albedo. The highest albedo is snow and ice. Hence, periods when polar ice is highly extended will promote further cooling. This is a positive-feedback mechanism. Dust in the atmosphere has the same effect. It forms a high albedo veil around Earth so that a significant amount of solar radiation is reflected before it reaches the surface. The dust may come from dry climate periods, volcanic eruptions, meteor impacts, and so on.

ALTITUDE

For every 1,000 feet (300 m) rise in elevation, there is a 3°F (1.5°C) drop in temperature. Every 300 feet (90 m) rise in elevation is equivalent to a shift of 62 miles (100 km) north in latitude and biome similarity.

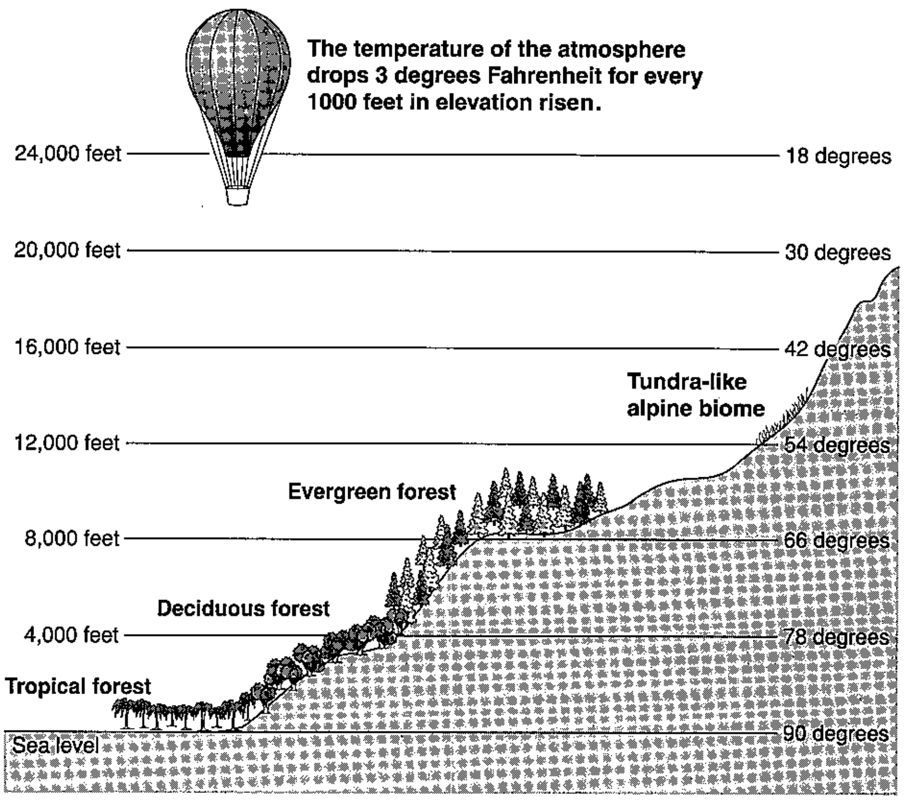

Figure 2.3 Change in temperature in response to change in altitude

ANGLE OF SUNLIGHT

In the Northern Hemisphere winter, Earth is closest to the sun. The angle of sunlight reaching Earth affects the climate. Areas closest to the equator receive the most sunlight and therefore higher temperatures.

CARBON CYCLE

The consumption of carbon in the form of carbon dioxide (CO_2) results in cooling. Two different processes consume carbon dioxide: carbonate rock weathering and silicate rock weathering.

Carbonate rock weathering: $\mathbf{CO_2} + H_2O + CaCO_3 \rightarrow Ca^{2+} + 2HCO_3^-$

Silicate rock weathering: $2\mathbf{CO_2} + H_2O + CaSiO_3 \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2$

The production of carbon in the form of carbon dioxide results in warming. Both carbonate formation in the oceans and metamorphic breakdown of carbonate yield carbon dioxide.

Carbonate formation in the oceans: $Ca^{2+} + 2HCO_3^- \rightarrow \mathbf{CO_2} + H_2O + CaCO_3$

Metamorphic breakdown of carbonate: $SiO_2 + CaCO_3 \rightarrow \mathbf{CO_2} + CaSiO_3$

CLOUDS

Clouds are collections of water droplets or ice crystals suspended in the atmosphere. As warmer air rises, it expands due to decreasing air pressure and thus drops in temperature; therefore, it cannot hold as much water vapor. The vapor begins to condense forming tiny water particles or ice crystals. High-level clouds (prefix *cirr*) are primarily ice crystals. Midlevel clouds (prefix *alto*) and low-level clouds (prefix *strat*) are composed primarily of water droplets but may also contain ice particles or snow.

DISTANCE TO OCEANS

Oceans are thermally more stable than landmasses; the specific heat (heat-holding capacity) of water is five times greater than air. Because of this, changes in temperature are more extreme in the middle of the continents than on the coasts.

FRONTS

When two different air masses meet, the boundary between them forms a front. The air masses can vary in temperature, dew point, or wind direction. A warm front is the boundary between an advancing warm air mass and the cooler one it is replacing. Since warm air is less dense, it rises and cools, and the moisture it contains is released as rain. A cold front is the leading edge of an advancing mass of cold air. Cold fronts are associated with thunderhead clouds, high surface winds, and thunderstorms. After a cold front passes, the weather is usually cool with clear skies.

GREENHOUSE EFFECT

The most important greenhouse gases are water (H_2O), carbon dioxide (CO_2), and methanae (CH_4). Without this effect, Earth would be cold and inhospitable. If taken too far, Earth could evolve into a hothouse.

HEAT (CONVECTION)

Climate is influenced by how heat energy is exchanged between air over the oceans and the air over land.

LAND CHANGES

Climate is influenced by urbanization and deforestation.

LANDMASS DISTRIBUTION

Materials absorb and reflect solar radiation to different extents. Ocean water is much more absorbent than landmasses so that continents reflect a lot more solar energy back into space than the oceans. Earth receives more solar radiation at low latitudes (near the equator) than near the poles. An Earth with landmasses clustered at low latitudes would reflect more solar energy into space, resulting in a cooler planet than one with more equatorial ocean area. Approximately 600–800 million years ago, there were significant glacial deposits in North America, Australia, and Africa. At this time, paleomagnetism of rocks suggests that these continents were near the south pole and that the equatorial Earth was largely ocean.

LATITUDE

The higher the latitudes, the less solar radiation. This affects the climate.

LOCATION

Climate is influenced by the location of high and low air pressure zones and where landmasses are distributed.

MOISTURE CONTENT OF AIR (HUMIDITY)

The moisture content of air is a primary determinant of plant growth and distribution and is a major determinant of biome type (desert vs. tropical forest). Atmospheric water vapor supplies moisture for clouds and rainfall, and it plays a role in energy exchanges within the atmosphere. Water vapor is also a greenhouse gas as it traps heat energy leaving Earth's surface. The dew point is the temperature at which condensation takes place.

MOUNTAIN RANGES

The presence or absence of mountain ranges affects the climate. Mountains influence whether one side of the mountain will receive rain or not (rain shadow effect). The side facing the ocean is the windward side and receives rain; the side of the mountain opposite the ocean is the leeward side and receives little rain. Temperatures decrease as the altitude increases. Orographic lifting occurs when an air mass is forced from a low elevation to a higher elevation as it moves over rising terrain. As the air mass gains altitude, it expands and cools, which can raise the relative humidity and create clouds and, under the right conditions, precipitation.

PLATE TECTONICS AND VOLCANOES

Plate tectonics affect atmospheric carbon dioxide, which factors into climate changes through the greenhouse effect. Volcanoes produce carbon dioxide. If global volcanism slows, as would be the case when supercontinents stabilize, less atmospheric carbon dioxide would trigger global cooling. Increased volcanism puts more carbon dioxide in the atmosphere and results in more greenhouse warming.

POLLUTION

Greenhouse gases are emitted from both natural sources (e.g., volcanoes) and industry.

PRECESSION

The wobble of Earth on its axis changes the amount of energy received by the sun. Changes in the orientation of Earth in space (tilt and obliquity) also have an effect on climate.

ROTATION

Daily temperature cycles are primarily influenced by Earth's rotation on its axis (once every 24 hours). At night, heat escapes from the surface. Daily minimum temperatures occur just before sunrise.

SOLAR OUTPUT

Changes in solar output of only 1% per 100 years would change Earth's temperature by up to 1°F (0.5°C). Times of sunspot activity (every 11, 90, and 180 years) correspond to decreases in solar radiation reaching Earth. The sun's magnetic field reverses every 22 years.

VOLCANOES

Sulfur-rich volcanic eruptions can eject material into the stratosphere, potentially causing tropospheric cooling and stratospheric warming. Volcanic aerosols exist in the atmosphere for an average of one to three years, and may result in tropospheric cooling. Volcanic aerosols injected into the stratosphere can also provide surfaces for ozone-destroying reactions. Over the course of millions of years, large volumes of volcanic ash deposited in the oceans can increase the iron content in seawater. This additional iron can promote biotic activity, which can lower the CO_2 concentration of seawater, and hence atmospheric CO_2 levels, resulting in global cooling. Over the course of weeks to years, ongoing production of ash from volcanoes may locally change climate by modifying the local atmosphere. Recent research also suggests that large eruptions may trigger El Niño climatic events.

WIND PATTERNS

Wind patterns are influenced by temperature and pressure differences (gradients).

- The Sun heats the atmosphere unevenly.
- The air closest to the surface is warmer and rises.
- Air at high elevations is cooler and sinks.
- This rising and falling sets up convection processes and is the primary cause of winds.
- Global air circulation is caused and affected by:
  - uneven heating of the Earth's surface.
  - seasons.
  - the Coriolis effect.

- the amount of solar radiation reaching the Earth's surface over a period of time.
- convection cells created by areas of warm ocean water which in turn are caused by differences in water density, winds, and the Earth's rotation.

During relatively calm, sunny days, the land warms up faster than the sea. This causes the air above it to become less dense than the air over the sea, which results in a sea breeze. A land breeze occurs during relatively calm, clear nights when the land cools down faster than the sea. This results in the air above the land becoming denser than the air over the sea. As a result, air moves from the land towards the coast.

Anabatic winds tend to develop in hilly or mountainous areas during the daytime, especially if the weather is relatively calm with at least some sunshine. In situations like this, the air around the hilltops becomes warmer than the air at the same altitude over adjacent valleys. This is because it conducts heat from the nearby land surface.

Katabatic winds occur on otherwise clear, still nights when the air that is in contact with the ground loses heat rapidly by radiation back to space. The result is that air near the ground over hill and mountain summits becomes colder than air at the same altitude over adjacent valleys.

HUMAN ACTIVITY

Climate can also be influenced by human activity. Deforestation, urbanization, heat island effects, release of pollutants including greenhouse gases and the burning of fossil fuels, and the production of acid rain are examples of how humans have altered climatic patterns. Increased pollution alone, combined with an increase in convectional uplift in urban areas, tends to increase the amount of rainfall in urban areas as much as 10% when compared with undeveloped areas.

Major Climatic Periods

Several major climatic periods have occurred. They are described below.

2,000,000 B.C.E. TO 12,000 B.C.E. (PLEISTOCENE ICE AGE)

Large glacial ice sheets covered much of North America, Europe, and Asia. The Pleistocene had periods when the glaciers retreated (interglacial) because of warmer temperatures and advanced because of colder temperatures (glacial). During the coldest periods of the Pleistocene Ice Age, average global temperatures were probably 7°F–9°F (4–5°C) colder than they are today.

12,000 B.C.E. TO 3000 B.C.E.

This warming of Earth and subsequent glacial retreat began about 14,000 years ago. The warming was shortly interrupted by a sudden cooling period between 10,000–8500 B.C.E. Scientists speculate that this cooling may have been caused by the release of fresh water trapped behind ice on North America draining into the North Atlantic Ocean. The release altered vertical currents in the ocean, which exchange heat energy with the atmosphere. The warming resumed by 8500 B.C.E. By 5000 to 3000 B.C.E., average global temperatures reached their maximum level and were 2°F–4°F (1–2°C) warmer than they are today, a period known as the

Climatic Optimum. During the Climatic Optimum, many of Earth's great ancient civilizations began and flourished. In Africa, the Nile River had three times its present volume, indicating a much larger tropical region.

3000 B.C.E. TO 750 B.C.E.

From 3000 to 2000 B.C.E., a cooling trend occurred. This cooling caused large drops in sea levels and the emergence of many islands (Bahamas) and coastal areas that are still above sea level today. A short warming trend took place from 2000 to 1500 B.C.E., followed once again by colder conditions. Colder temperatures from 1500 to 750 B.C.E. caused renewed ice growth in continental glaciers and alpine glaciers and a sea level drop of between 6 to 10 feet (2–3 m) below present-day levels.

750 B.C.E. TO 900 C.E.

The period from 750 B.C.E. to 900 C.E. saw warming up to 150 B.C.E. During the time of the Roman Empire (150 B.C.E. to 300 C.E.) a cooling began that lasted until about 900 C.E. At its height, the cooling caused the Nile River and the Black Sea to freeze.

900 C.E. TO 1200 C.E. (LITTLE CLIMATIC OPTIMUM)

During this warm period, the Vikings established settlements on Greenland and Iceland. The snow line in the Rocky Mountains was about 400 yards (370 m) above current levels. A period of cool and more extreme weather followed the Little Climatic Optimum. There are records of floods, great droughts, and extreme seasonal climate fluctuations up to the 1400s.

1550 C.E. TO 1850 C.E. (LITTLE ICE AGE)

From 1550 to 1850 C.E., global temperatures were at their coldest since the beginning of the Holocene. During the Little Ice Age, the average annual temperature of the Northern Hemisphere was about 2°F (1.0°C) lower than today.

1850 C.E. TO PRESENT

The period from1850 to the present is one of general warming.

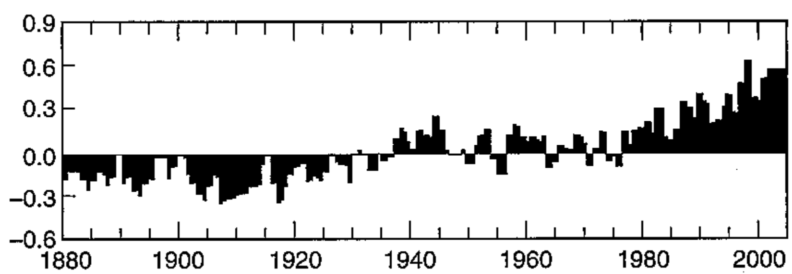

Figure 2.4 Average changes in ocean and land temperatures (°C) from 1880 to 2000

ATMOSPHERIC CIRCULATION AND THE CORIOLIS EFFECT

Due to the rotation of Earth on its axis, rotation around the sun, and the tilt of Earth's axis, the sun heats the atmosphere unevenly. Air closer to Earth's surface is the warmest and rises. Air at higher elevations is cooler and, as such, more dense and sinks. This sets up convection processes and is the primary cause for winds. Global air circulation is also affected by uneven heating of Earth's surface, seasons, the Coriolis effect, the amount of solar radiation reaching the Earth over long periods of time, convection cells created by warm ocean waters that commonly leads to hurricanes, and ocean currents, which are caused by differences in water density, winds, and Earth's rotation.

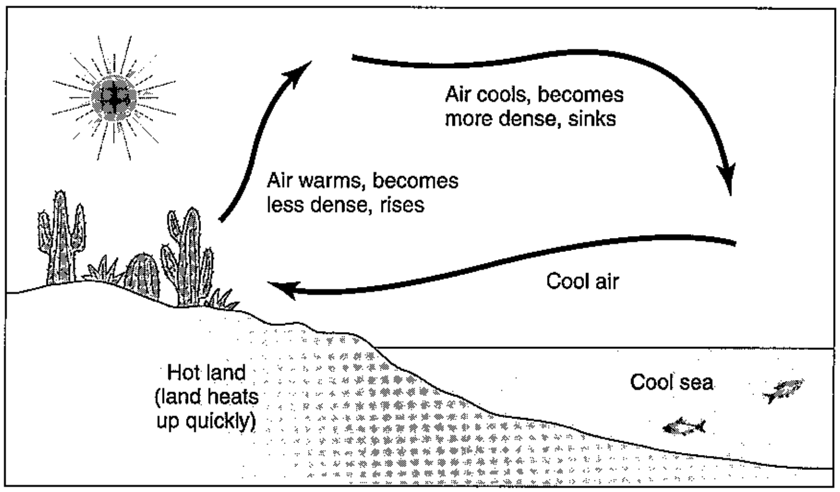

Figure 2.5 Convection cell

The trade winds are the prevailing pattern of easterly surface winds found in the tropics, within the lower portion of the Earth's atmosphere, in the lower section of the troposphere near the Earth's equator. The trade winds blow predominantly from the northeast in the Northern Hemisphere (northeast trade winds) and from the southeast in the Southern Hemisphere (southeast trade winds), strengthening during the winter. Historically, the trade winds have been used by captains of sailing ships to cross the world's oceans for centuries; they also enabled European empire expansion into the Americas and helped trade routes to become established across the Atlantic and Pacific oceans. The trade winds act as the steering flow for tropical storms that form over the Atlantic, Pacific, and south Indian oceans and make landfall in North America, Southeast Asia, and India, respectively. Trade winds also steer African dust westward across the Atlantic Ocean into the Caribbean Sea, as well as portions of southeast North America.

Horizontal winds move from areas of high pressures to areas of low pressures. Wind speed is determined by pressure differences between air masses. The greater the pressure difference is, the greater the wind speed. Wind direction is based upon from where the wind is coming. A wind coming from the east is called an easterly.

Wind speed is measured with an anemometer, and wind direction is measured with a wind vane.

Earth's rotation on its axis causes winds not to travel straight. This is called the Coriolis effect. It causes prevailing winds in the Northern Hemisphere to spiral clockwise out from high-pressure areas and spiral counterclockwise in toward low-pressure areas.

The worldwide system of winds, which transports warm air from the equator where solar heating is greatest toward the higher latitudes where solar heating is diminished, gives rise to Earth's climatic zones. Three types of air circulation cells associated with latitude exist—Hadley, Ferrel, and polar.

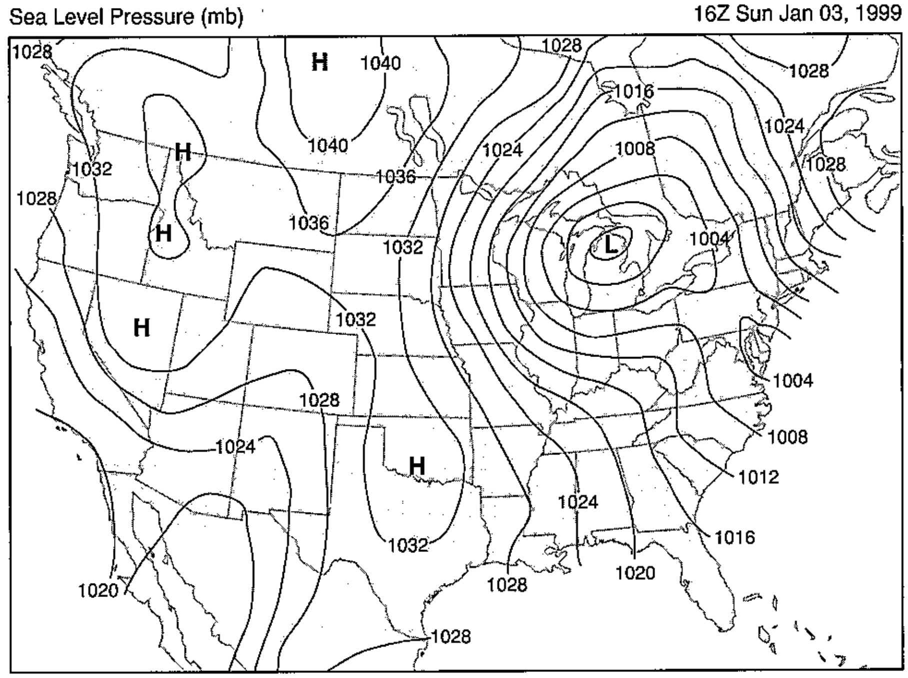

Figure 2.6 The solid contours represent pressure contours (isobars) in millibars. The isobars have an interval of 4 mb. Wind speed is directly related to the distance between the isobars. The closer together they are, the stronger the wind

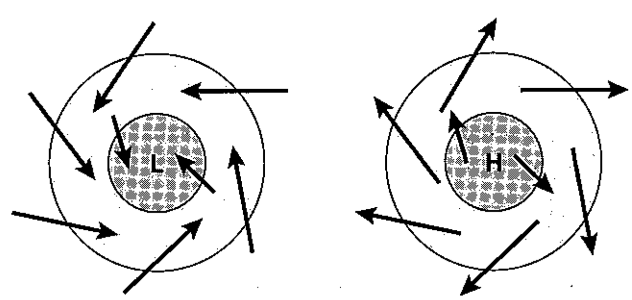

Figure 2.7 Circulation wind patterns of high- and low-pressure systems in the Northern Hemisphere. The pattern reverses in the Southern Hemisphere

Hadley Air Circulation Cells

Air heated near the equator rises and spreads out north and south. After cooling in the upper atmosphere, the air sinks back to Earth's surface within the subtropical climate zone (between 25° and 49° north and south latitudes). Surface air from subtropical regions returns toward the equator to replace the rising air. The equatorial regions of the Hadley cells are characterized by high humidity, high clouds, and heavy rains. The monthly average temperatures are around 90°F (32°C) at sea level, and there is no winter. The vegetation is tropical rain forest. Temperature variation from day to night (diurnal) is greater than from season to season.

Subtropical regions of the Hadley cell are characterized by low relative humidity, little cloud formation, high ocean evaporation due to low humidity, and many of the world's deserts. The climate is characterized by warm to hot summers and mild winters.

The tropical wet and dry (or savanna) climate has a dry season more than two months long. Annual losses of water through evaporation in this region exceed annual water gains from precipitation.

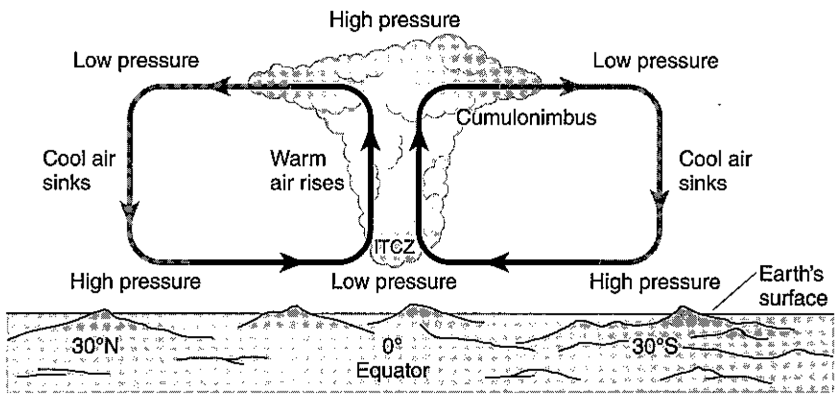

Figure 2.8 Hadley Cell

Ferrel Air Circulation Cells

Ferrel cells develop between 30° and 60° north and south latitudes. The descending winds of the Hadley cells diverge as moist tropical air moves toward the poles in winds known as the westerlies. Midlatitude climates can have severe winters and cool summers due to midlatitude cyclone patterns. The western United States is drier in summer than the eastern United States due to oceanic high pressures that brings cool, dry air down from the north. The climate of this area is governed by both tropical and polar air masses. Defined seasons are the rule, with strong annual cycles of temperature and precipitation. The seasonal fluctuation of temperature is greater than the change in temperature occurring in a 24-hour cycle. Climates of the middle latitudes have a distinct winter season. The area of Earth controlled by Ferrel cells contains broadleaf deciduous and coniferous evergreen forests.

Polar Air Circulation Cells

The polar cells originate as icy-cold, dry, dense air that descends from the troposphere to the ground. This air meets with the warm tropical air from the midlatitudes. The air then returns to the poles, cooling and then sinking. Sinking air suppresses precipitation; thus, the polar regions are deserts (deserts are defined by moisture, not temperature). Very little water exists in this area because it is tied up in the frozen state as ice. Furthermore, the amount of snowfall per year is relatively small.

In general, climates in the polar domain are characterized by low temperatures, severe winters, and small amounts of precipitation, most of which falls in summer. The annual fluctuation of temperature is greater than the change in temperature occurring in a 24-hour cycle. In this area where summers are short and temperatures are generally low throughout the year, temperature rather than precipitation is the critical factor in plant distribution and soil development. Two major biomes exist—the tundra and the taiga.

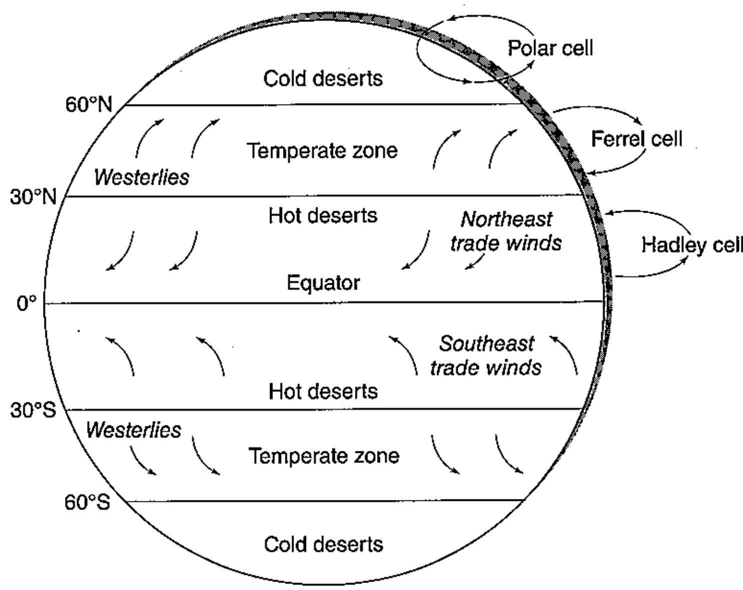

Figure 2.9 The Hadley, Ferrel, and polar cells

Hurricanes, Cyclones, and Tornadoes

Hurricanes are the most severe weather phenomenon on the planet. Hurricane Katrina that hit New Orleans, Louisiana, in 2005 was responsible for $75 billion in damage and approximately 1,830 deaths. Hurricanes begin over warm oceans in areas where the trade winds converge. A subtropical high-pressure zone creates hot daytime temperatures with low humidity that allows for large amounts of evaporation. The Coriolis effect initiates the cyclonic flow.

The stages of hurricane development include the presence of separate thunderstorms that have developed over tropical oceans, and cyclonic circulation that begins to cause these thunderstorms to move in a circular motion. This cyclonic circulation allows them to pick up moisture and latent heat energy from the ocean. In the center of the hurricane is the eye, an area of descending air and low pressure. The energy of a hurricane dissipates as it travels over land or moves over cooler bodies of water. Rainfall can be as much as 24 inches (0.6 m) in 24 hours. A storm surge, which results from the increase in the height of the ocean near the eye of a hurricane, can cause extensive flooding.

Tornadoes are swirling masses of air with wind speeds close to 300 miles per hour (485 kph). Like hurricanes, the center of the tornado is an area of low pressure. In the United States, tornadoes are frequent from April through July and occur in the center of the United States in an area known as "Tornado Alley." Due to advances in weather forecasting, modeling, and warning systems, the death rate due to tornadoes has decreased significantly.

While both tornadoes and tropical cyclones are spinning, turbulent vortices of wind, they have little in common. Tornadoes have diameters on the scale of hundreds of meters and are produced from a single convective storm, such as a thunderstorm. Tropical cyclones, on the other hand, have diameters of hundreds of kilometers and are comprised of many convective storms. Tornadoes occur primarily over land, as solar heating of the land surface usually contributes the development of the thunderstorm that spawns the vortex. In contrast, tropical cyclones are an oceanic phenomenon and die out over land due to the loss of a moisture source. Additionally, while tornadoes require substantial vertical shear of the horizontal winds (i.e., change of wind speed and/or direction with height) to form, tropical cyclones require very low values of vertical shear in order to form and grow. Finally, tropical cyclones have lifetimes that are measured in days, while tornadoes typically last for less than an hour.

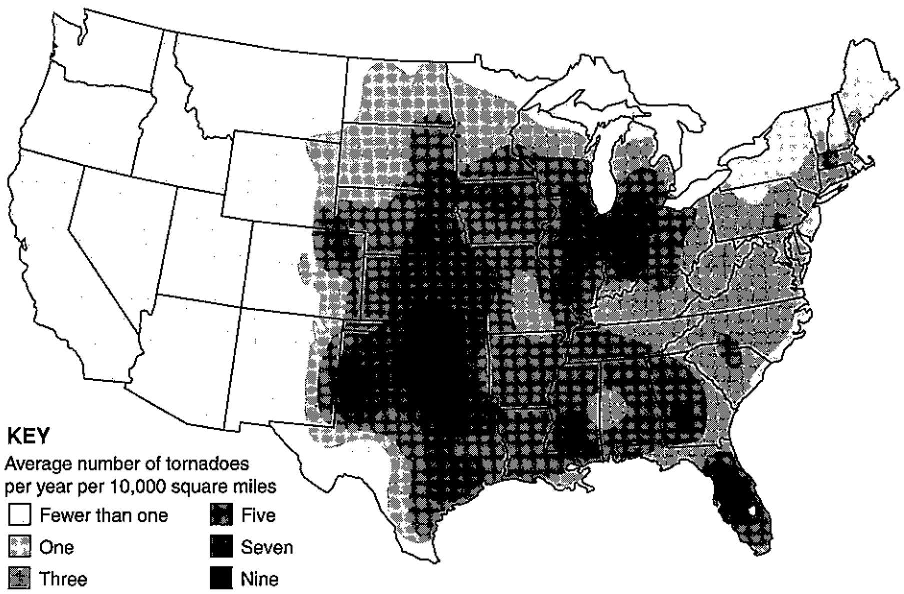

Figure 2.10 Average number of tornadoes per year

Monsoons

Monsoons are strong, often violent winds that change direction with the season. Monsoon winds blow from cold to warm regions because cold air takes up more space than warm air. Monsoons blow from the land toward the sea in winter and from the sea toward land in the summer. India's climate is dominated by monsoons. During the Indian winter, which is hot and dry, the monsoon winds blow from the northeast and carry little moisture. The temperature is high because the Himalayas form a barrier that prevents cold air from passing onto the subcontinent. Furthermore, most of India lies between the Tropic of Cancer and the equator, so the sun's rays shine directly on the land. During the summer the monsoons move onto the subcontinent from the southwest. The winds carry moisture from the Indian Ocean and bring heavy rains from June to September. Farmers in India rely on these torrential summer rainstorms to irrigate their land. Additionally, a large amount of India's electricity is generated by water power provided by the monsoon rains.

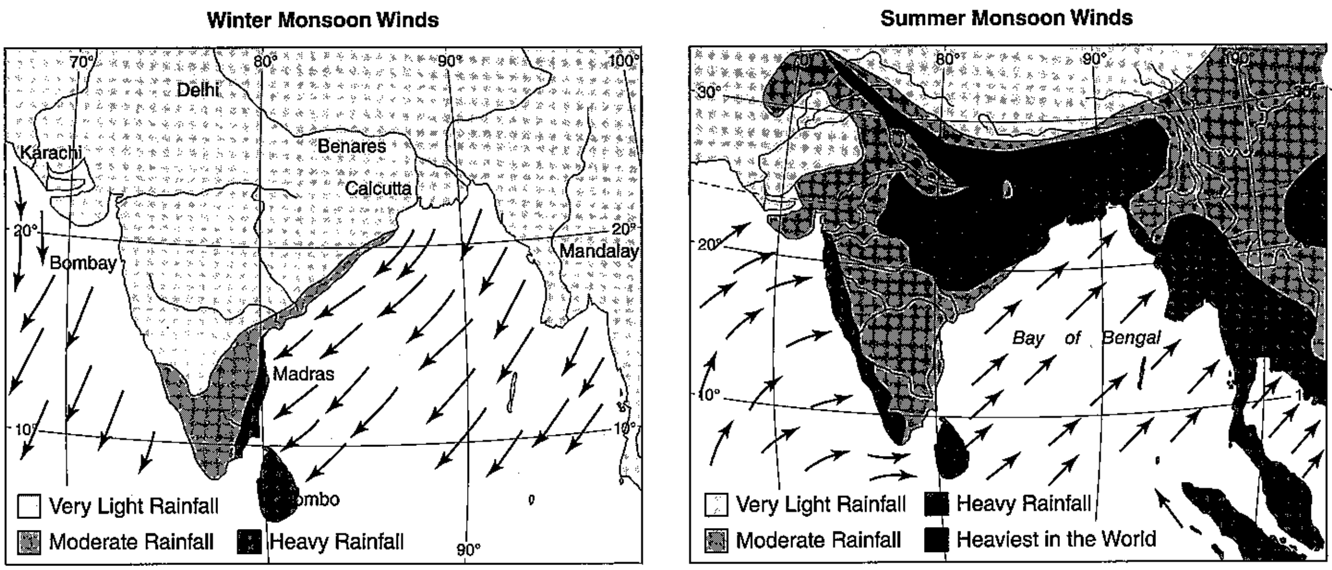

Figure 2.11 Winter and summer monsoon wind patterns

Rain Shadow Effect

A rain shadow is a dry area on the mountainside facing away from the direction of the wind. The mountains block the passage of rain-producing weather systems, casting a "shadow" of dryness behind them. Warm, moist air rises through orographic lifting to the top of a mountain range or large mountain, where, due to decreasing atmospheric pressure with increasing altitude, it expands and adiabatically cools to reach its dew point. At the dew point, moisture condenses onto the mountain, and it precipitates on the top and windward sides of the mountain. The air descends on the leeward side, but due to the process of precipitation, it has lost much of its initial moisture. Typically, descending air also gets warmer down the leeward side of the mountain, creating an arid region.

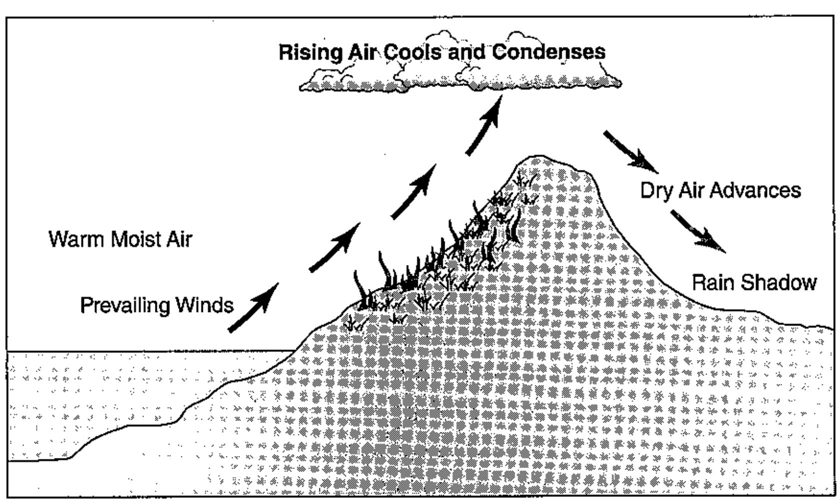

Figure 2.12 Rain shadow effect

EL NIÑO AND LA NIÑA

Normal State

During normal (non-El Niño or "La Nada") conditions, easterly trade winds move water and air warmed by the sun toward the west (Walker circulation). The ocean is generally around 24 inches (60 cm) higher in the western Pacific and the water about 14°F warmer. The trade winds, in piling up water in the western Pacific, make a deep—450 feet (150 m)—warm layer in the west that pushes the thermocline down while it rises in the east. The shallow—90 feet (30 m)—eastern thermocline allows the winds to pull up nutrient-rich water from below, which increases fishing stocks. The western side of the equatorial Pacific is characterized by warm, wet low-pressure weather, as the collected moisture is released in the form of typhoons and thunderstorms.

TIP

Questions about El Niño and La Niña are very common on the APES exam. Be sure you know these two processes!

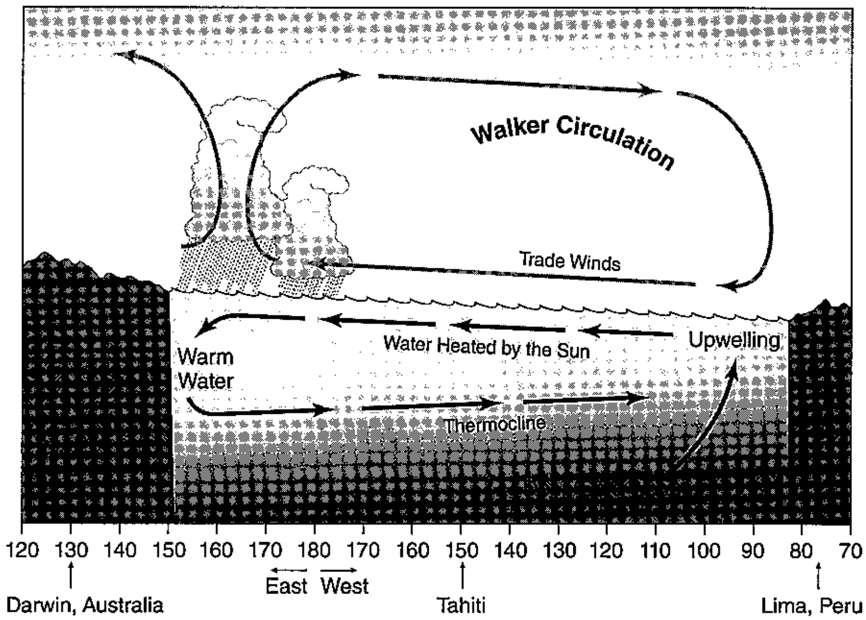

Figure 2.13 Normal conditions

El Niño

When the air pressure patterns in the South Pacific reverse direction (the air pressure at Australia is higher than at Tahiti), the trade winds decrease in strength (and can reverse direction). The result is that the normal flow of water away from South America decreases and ocean water piles up off South America. This pushes the thermocline deeper and decreases the upwelling of nutrient-rich deep water, which results in extensive fish kills off the South American coast. With a deeper thermocline and decreased westward transport of water, the sea surface temperature increases in the eastern Pacific. This is the warm phase of El Niño-Southern Oscillation (ENSO) called El Niño. The net result is a shift of the prevailing rain pattern from the normal western Pacific to the central Pacific; rainfall is more common in the central Pacific while the western Pacific becomes relatively dry.

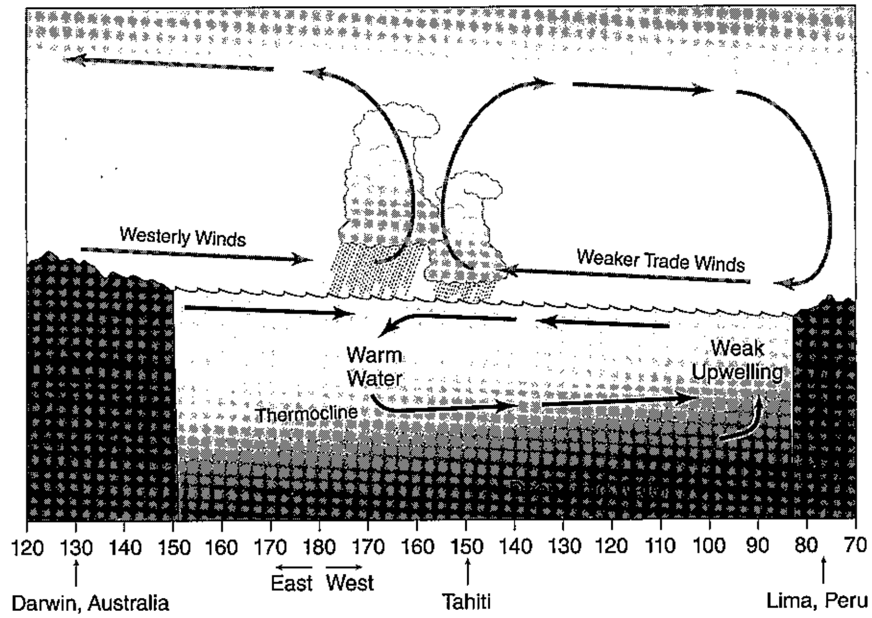

Figure 2.14 The development of El Niño

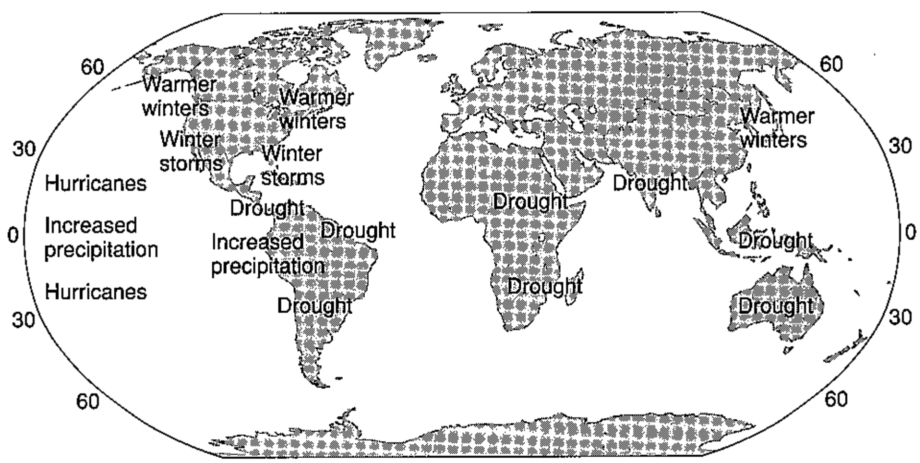

Figure 2.15 Climatological effects of El Niño

La Niña

There are occasions when the trade winds that blow west across the tropical Pacific are stronger than normal, leading to increased upwelling off South America and hence *cooler-than-normal* sea surface temperatures. The prevailing rain pattern also shifts farther west than normal. These winds pile up warm surface water in the western Pacific. This is the cool phase of ENSO called La Niña. La Niña is characterized by unusually cold ocean temperatures in the eastern equatorial Pacific. La Niña tends to bring nearly the opposite effects of El Niño to the United States, with wetter-than-normal conditions across the Pacific Northwest and both dryer and warmer-than-normal conditions in the southern states. Winter temperatures are warmer than normal in the southeastern United States and cooler than normal in the northwest. The increased temperatures in the southeast during La Niña years correlate with the substantial increase in hurricanes that occurs during the same time period. La Niña is also responsible for heavier-than-normal monsoons in India and Southeast Asia.

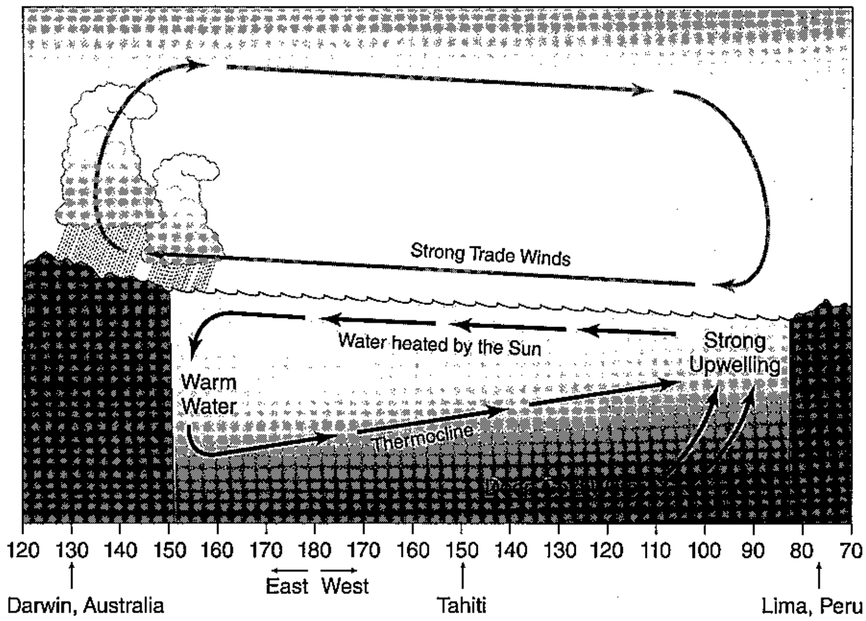

Figure 2.16 La Niña

QUICK REVIEW CHECKLIST

- ☐ **Atmosphere Composition**
  - ☐ Nitrogen, oxygen, water vapor, carbon dioxide, methane, nitrous oxide, ozone
- ☐ **Structure of the Atmosphere**
  - ☐ Ionosphere, mesosphere, stratosphere, troposphere
- ☐ **Weather and Climate**
  - ☐ Differences between weather and climate
  - ☐ Factors that affect climate: air mass, air pressure, albedo, altitude, angle of sunlight, clouds, distance to oceans, fronts, heat, land changes, latitude, location, humidity, mountain ranges, pollution, rotation, wind patterns
  - ☐ Human activity and influence on climate
- ☐ **Atmospheric Circulation**
  - ☐ Coriolis effect
  - ☐ Types of winds (breezes): sea breeze, land breeze, anabatic winds, katabatic winds
  - ☐ Hadley, Ferrel, and polar cells
  - ☐ Hurricanes and Tornadoes: what causes them, mitigation, case studies (Katrina)
- ☐ **El Niño and La Niña**
  - ☐ How they develop
  - ☐ Environmental effects

MULTIPLE-CHOICE QUESTIONS

1. The zone of the atmosphere in which weather occurs is known as the

    (A) ionosphere
    (B) mesosphere
    (C) troposphere
    (D) thermosphere
    (E) stratosphere

2. 99% of the volume of gases in the lower atmosphere, listed in descending order of volume, are

    (A) O_2, N_2, CO_2, H_2O
    (B) H_2O, N_2, O_2, CO_2
    (C) O_2, CO_2, N_2, H_2O
    (D) O_2, CO_2, N_2, H_2O
    (E) N_2, O_2, H_2O, CO_2

3. Regional climates are most influenced by

    (A) latitude and altitude
    (B) prevailing winds and latitude
    (C) altitude and longitude
    (D) latitude and longitude
    (E) Coriolis effect and trade winds

4. A low-pressure air mass is generally associated with

    (A) hot, humid weather
    (B) fair weather
    (C) tornadoes
    (D) cloudy or stormy weather
    (E) hurricanes

5. La Niña would produce all the following effects EXCEPT

    (A) more rain in southeast Asia
    (B) wetter winters in the Pacific Northwest region of the United States
    (C) warmer winters in Canada and northeast United States
    (D) warmer and drier winters in the southwest and southeast United States
    (E) more Atlantic hurricanes

6. On the leeward side of a mountain range, one would expect

    (A) more clouds and rain than on the windward side
    (B) more clouds but less rain than on the windward side
    (C) colder temperatures
    (D) less clouds and less rain than on the windward side
    (E) no significant difference in climate compared with the windward side