The Atmosphere 2

COMPOSITION

Earth's atmosphere is composed of seven primary compounds:

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 the 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%

Carbon dioxide is produced during cellular respiration, the combustion of fossil fuels, and the decay of organic matter. It is required for photosynthesis. CO_2 is a major greenhouse gas that has increased about 40% since the time of the Industrial Revolution. The average time that a CO_2 molecule exists 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, grazing animals, 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. The average cycle of a methane molecule in the atmosphere is approximately 10 years.

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. N_2O is a contributor to the greenhouse effect and is the single most important contributing substance reducing stratospheric ozone. The ozone depleting potential of nitrous oxide is comparable to several currently controlled substances such as CFCs.

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. The two most important layers to be familiar with for the AP Environmental Science exam are the troposphere and the stratosphere (the layer that contains stratospheric ozone that serves to absorb harmful UV radiation).

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 the absorption of UV radiation by ozone. The stratosphere contains the ozone layer. Ozone is produced by UV radiation and lightning.

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.

WEATHER AND CLIMATE

Weather is caused by the movement or transfer of heat energy, which results from the unequal heating of Earth's surface by the sun, and 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.

Weather describes whatever is *currently* happening outdoors. Climate describes weather patterns in a place *over a period of years.*

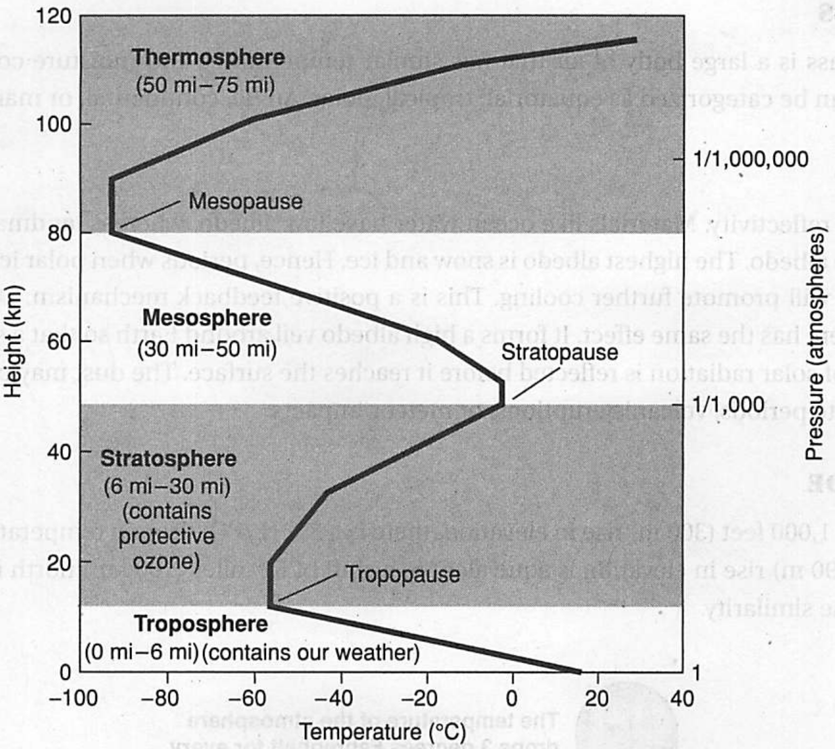


Figure 2.1 Changes in temperature in the atmosphere

Conduction involves the transfer of heat through solid substances and results from a difference in temperature between different parts of the substance.

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 to the equator receive much more solar energy than regions nearer to 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 comes 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, as listed beginning on page 44.

TIP

Several different factors influence climate:

- **Air mass**
- **Albedo**
- **Altitude**
- **Angle of sunlight**
- **Carbon cycle**
- **Clouds**
- **Distance to oceans**
- **Fronts**
- **Greenhouse effect**
- **Heat**
- **Human activity**
- **Land changes**
- **Landmass distribution**
- **Latitude**
- **Location**
- **Moisture content of air**
- **Mountain ranges**
- **Pollution**
- **Precession**
- **Rotation**
- **Solar output**
- **Volcanoes**
- **Wind patterns**

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.

ALBEDO

Albedo is reflectivity. Materials like ocean water have low albedo, whereas landmasses 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, or meteor impacts.

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.

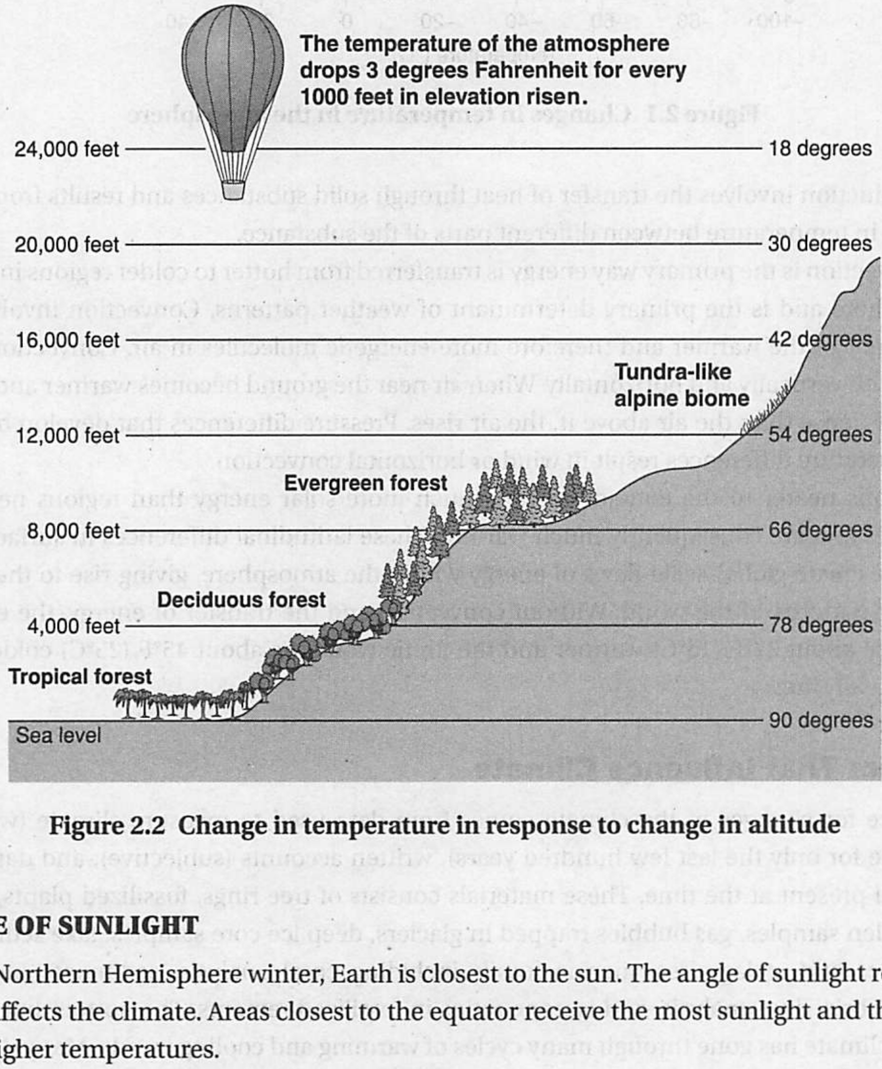


Figure 2.2 Change in temperature in response to change in altitude

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 have 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.

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

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

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.

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

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

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. Mid-level 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 (the temperature below which water droplets begin to condense), 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 vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). 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.

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.

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 and, as a consequence, 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 (e.g., 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 the water vapor in the air (at constant barometric pressure) condenses into liquid water at the same rate at which it evaporates. At temperatures below the dew point, water will leave the air.

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 the most 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.

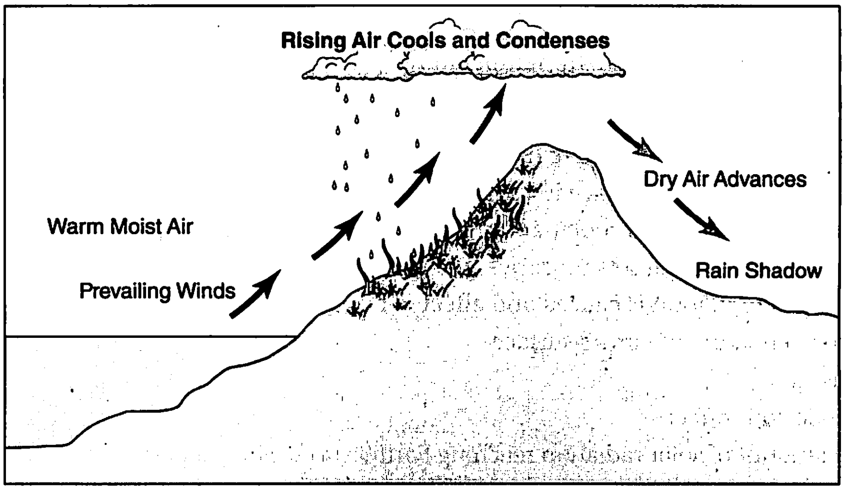


Figure 2.3 Rain shadow effect

POLLUTION

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

PRECESSION

The wobble of Earth on its axis changes the amount of energy received by the sun. Changes in the orientation (tilt) of Earth in space 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. 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 the 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, pressure differences (gradients), and the Coriolis effect.

- 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 Earth's surface
  - seasons
  - the Coriolis effect
  - the amount of solar radiation reaching 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 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 toward the coast.

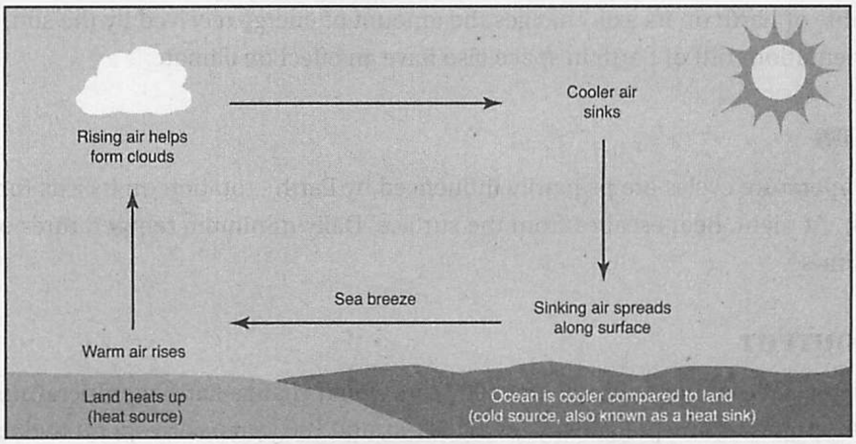


Figure 2.4 Sea breeze

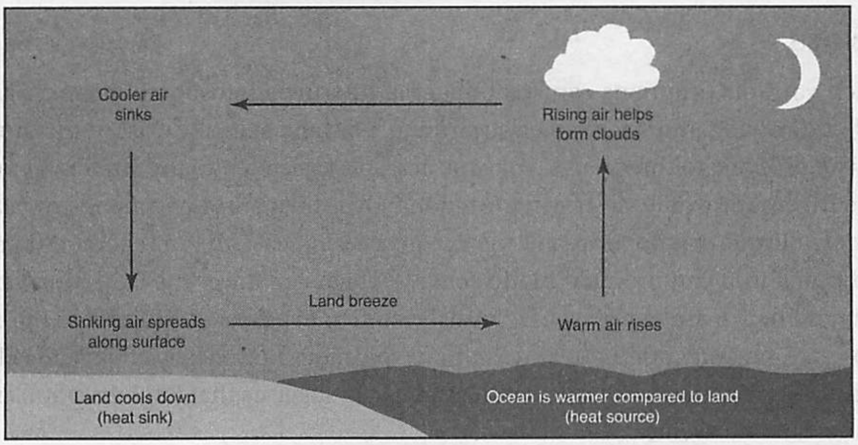


Figure 2.5 Land breeze

ATMOSPHERIC CIRCULATION—PRESSURE

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 Earth over long periods of time, convection cells created by warm ocean waters that commonly lead to hurricanes, and ocean currents, which are caused by differences in water density, winds, and Earth's rotation.

A low-pressure system has lower pressure at its center than the areas around it. Winds blow towards the low pressure, and the air rises in the atmosphere where they meet. As the air rises, the water vapor within it condenses, forming clouds and often precipitation. As a result of Earth's spin and the Coriolis effect, winds of a low-pressure system swirl counterclockwise north of the equator and clockwise south of the equator. Low pressure usually produces cloudy and stormy weather.

A high-pressure system has higher pressure at its center than the areas around it. Wind blows away from high pressure. Winds of a high-pressure system swirl in the opposite direction as a low-pressure system—clockwise north of the equator and counterclockwise south of the equator with air from higher in the atmosphere sinking down to fill the spaces left as air blows outward. High-pressure masses contain cool, dense air that descends toward Earth's surface and becomes warmer. High pressure is usually associated with fair weather.

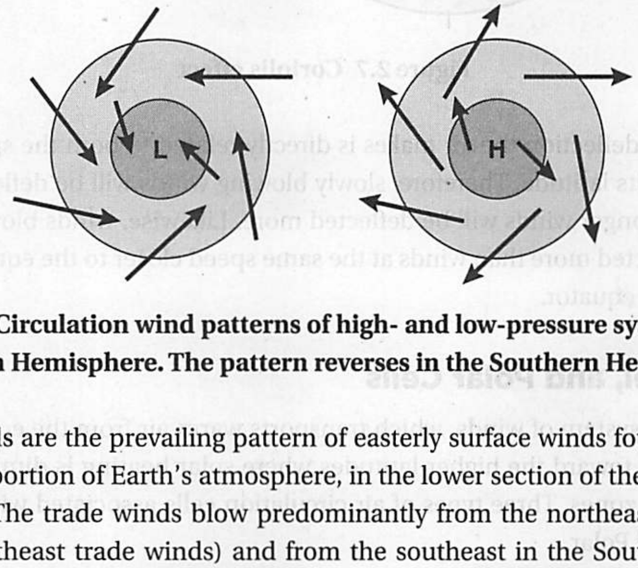


Figure 2.6 Circulation wind patterns of high- and low-pressure systems in the Northern Hemisphere. The pattern reverses in the Southern Hemisphere

The trade winds are the prevailing pattern of easterly surface winds found in the tropics, within the lower portion of Earth's atmosphere, in the lower section of the troposphere near 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.

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.

Coriolis Effect

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

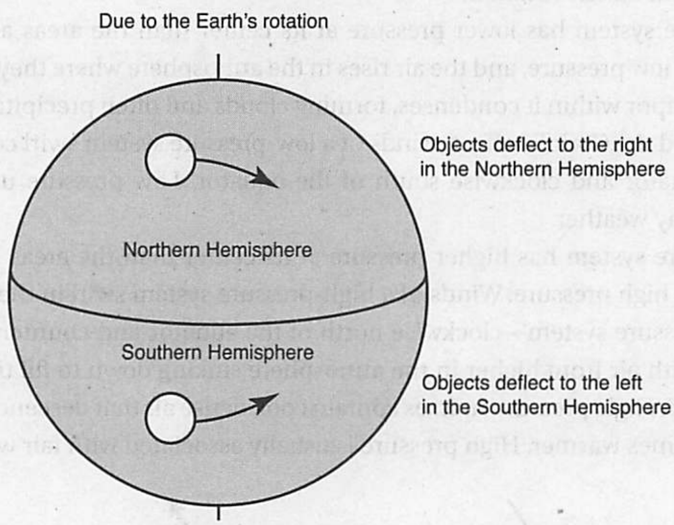


Figure 2.7 Coriolis effect

The amount of deflection the air makes is directly related to both the speed at which the air is moving and its latitude. Therefore, slowly blowing winds will be deflected only a small amount, while stronger winds will be deflected more. Likewise, winds blowing closer to the poles will be deflected more than winds at the same speed closer to the equator. The Coriolis force is zero at the equator.

Hadley, Ferrel, and Polar Cells

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.

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 rainforest. Temperature variation from day to night (diurnal) is greater than from season to season.

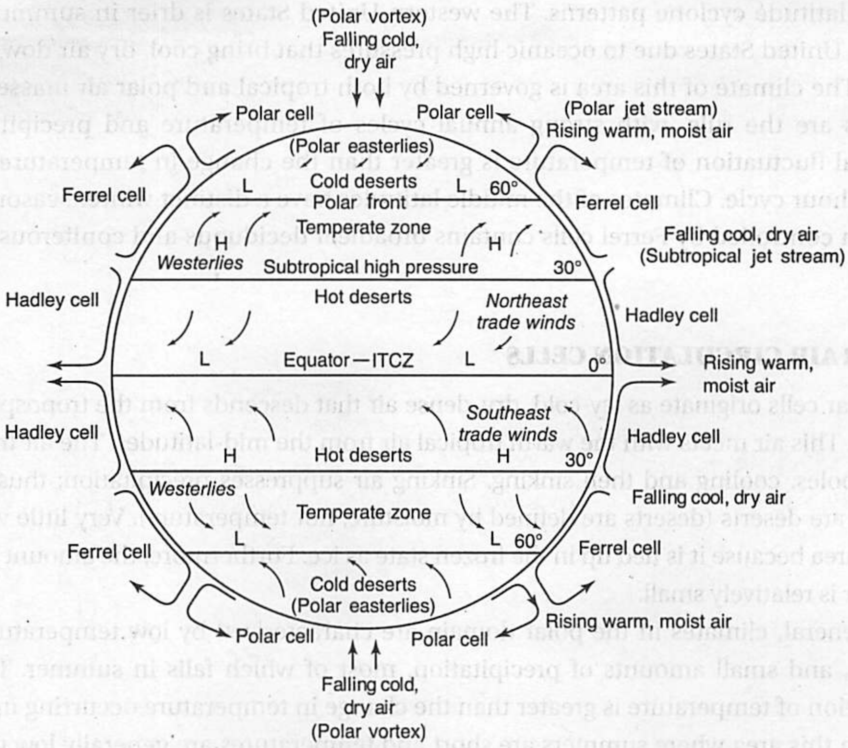


Figure 2.8 The Hadley, Ferrel, and Polar cells

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.

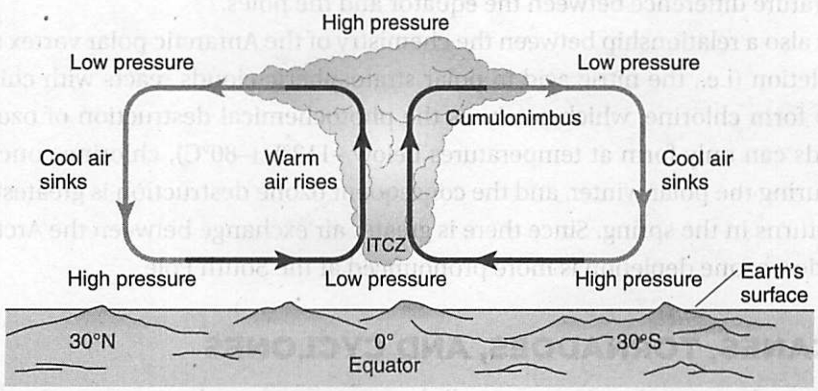


Figure 2.9 Hadley cell

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. Mid-latitude climates can have severe winters and cool summers due to mid-latitude cyclone patterns. The western United States is drier in summer than the eastern United States due to oceanic high pressures that bring 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 mid-latitudes. 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.

POLAR VORTEX

A polar vortex is a low-pressure zone embedded in a large mass of very cold air that lies atop both poles. The bases of the two polar vortices are located in the middle and upper troposphere and extend into the stratosphere. These cold, low-pressure areas strengthen in their respective winters and weaken in their respective summers due to their dependence upon the temperature difference between the equator and the poles.

There is also a relationship between the chemistry of the Antarctic polar vortex and severe ozone depletion (i.e., the nitric acid in polar stratospheric clouds reacts with chlorofluorocarbons to form chlorine, which catalyzes the photochemical destruction of ozone). Since these clouds can only form at temperatures below –112°F (–80°C), chlorine concentrations build up during the polar winter, and the consequent ozone destruction is greatest when the sunlight returns in the spring. Since there is greater air exchange between the Arctic and the mid-latitudes, ozone depletion is more pronounced at the South Pole.

HURRICANES, TORNADOES, AND CYCLONES

Hurricanes, cyclones, and typhoons are all the same weather phenomenon. In the Atlantic and Northeast Pacific, the term "hurricane" is used. The same type of disturbance in the Northwest Pacific is called a "typhoon," and "cyclones" occur in the South Pacific and Indian Ocean. The ingredients for these storms include a pre-existing weather disturbance, warm tropical oceans, atmospheric moisture, and relatively light winds in the upper troposphere. If the right conditions persist long enough, they can combine to produce violent winds, very large waves, torrential rains, and floods.

Hurricanes

Hurricanes are the most severe weather phenomenon on the planet. Hurricane Katrina, which hit New Orleans, Louisiana, in 2005, was responsible for about $81 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.

CASE STUDIES

HURRICANE KATRINA: Hurricane Katrina, which occurred in 2005, was one of the deadliest and most destructive hurricanes in the history of the United States. Nearly 2,000 people died in the actual hurricane and in the subsequent floods. Total property damage was estimated at $81 billion. Katrina caused severe destruction along the Gulf coast from central Florida to Texas, much of it due to the storm surge. The largest number of deaths occurred in New Orleans, Louisiana, which flooded as the levee system failed and 80% of the city and the surrounding areas became flooded. The worst property damage occurred in coastal areas, such as Mississippi beachfront towns with storm surge waters reaching 6–12 miles (10–19 km) inland.

HURRICANE SANDY: Hurricane Sandy occurred in 2012 and was the second-costliest hurricane in United States history. It also became the largest Atlantic hurricane on record (as measured by diameter, with winds spanning 1,100 miles (1,800 km)). Damages have been estimated to cost about $75 billion, a total surpassed only by Hurricane Katrina. At least 233 people were killed along the path of the storm in eight countries.

In the United States, Hurricane Sandy affected 24 states, including the entire eastern seaboard from Florida to Maine and west across the Appalachian Mountains to Michigan and Wisconsin, with particularly severe damage in New Jersey and New York. Its storm surge hit New York City, flooding streets, tunnels, and subway lines and cutting power in and around the city.

Tornadoes

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.

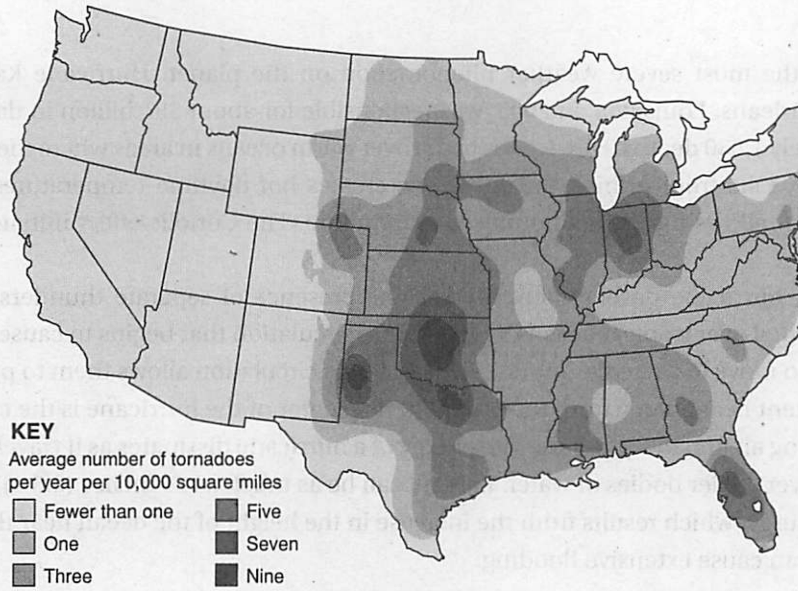


Figure 2.10 Average number of tornadoes per year

Tornadoes vs. Cyclones

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 to 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.

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.

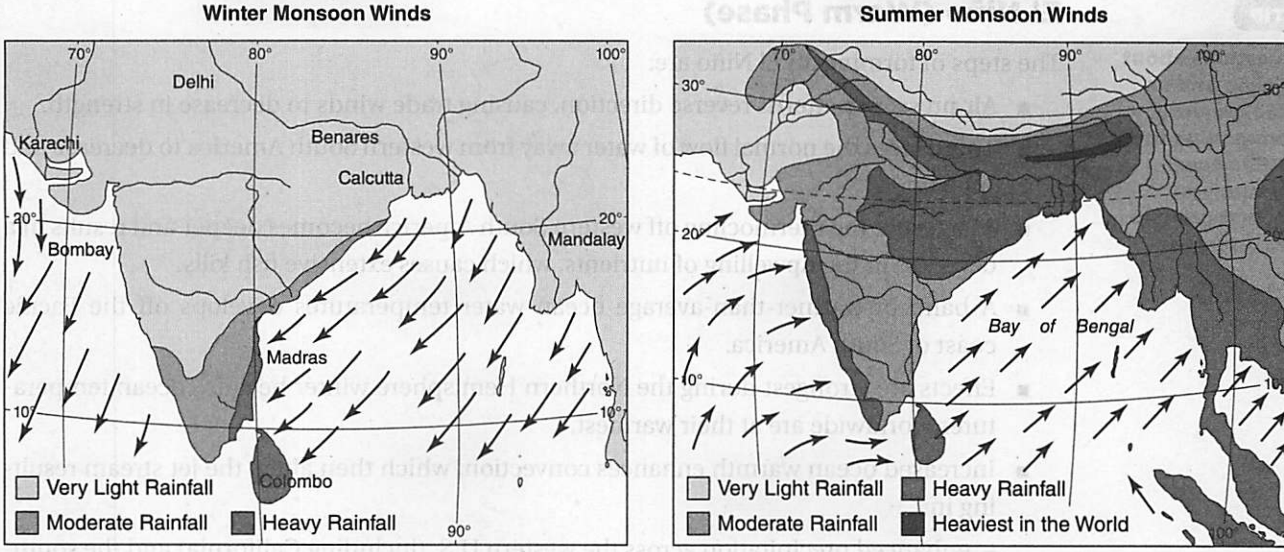


Figure 2.11 Winter and summer monsoon wind patterns

EL NIÑO—SOUTHERN OSCILLATION (ENSO)

La Nada (Normal Conditions)

During normal 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 is 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.

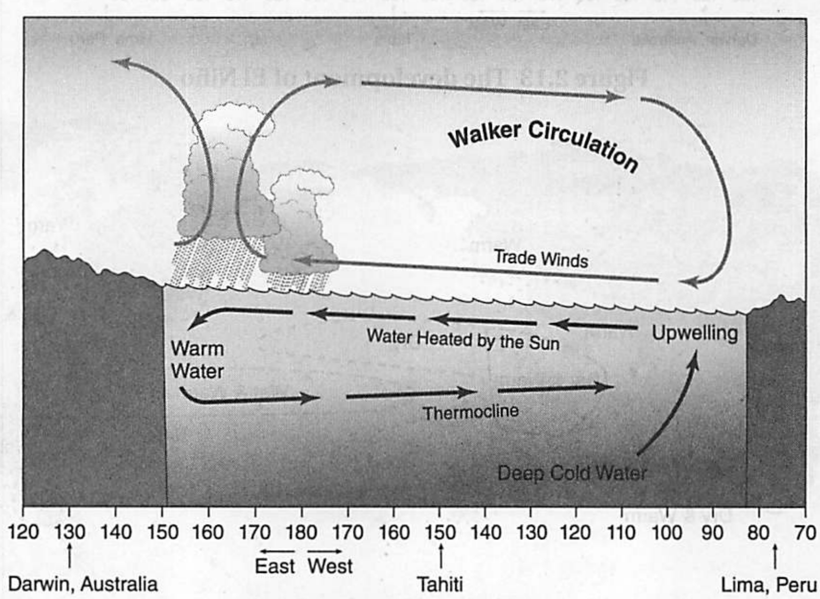


Figure 2.12 Normal conditions

TIP

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

El Niño (Warm Phase)

The steps of forming an El Niño are:

- Air pressure patterns reverse direction, causing trade winds to decrease in strength.
- This causes the normal flow of water away from western South America to decrease and "pile up."
- As a result, the thermocline off western South America becomes deeper and results in a decrease in the upwelling of nutrients, which causes extensive fish kills.
- A band of warmer-than-average ocean water temperatures develops off the Pacific coast of South America.
- Effects are strongest during the Northern Hemisphere winter because ocean temperatures worldwide are at their warmest.
- Increased ocean warmth enhances convection, which then alters the jet stream resulting in:
  - enhanced precipitation across the western U.S. (including California) and the southern U.S.
  - winter temperatures that are often cooler than normal in the southeast U.S.

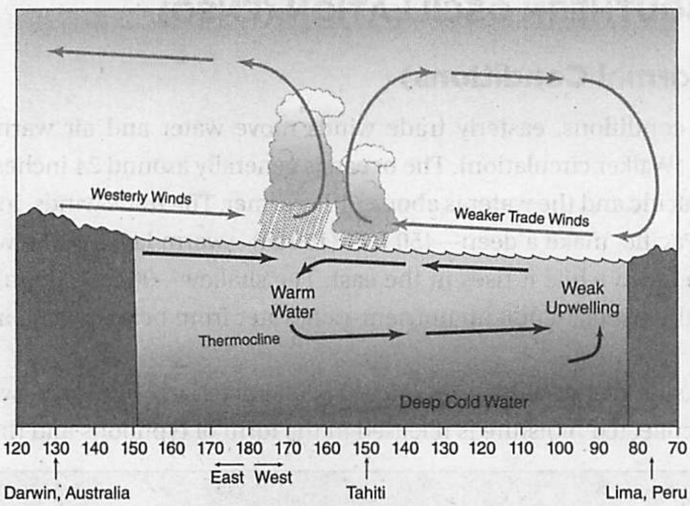
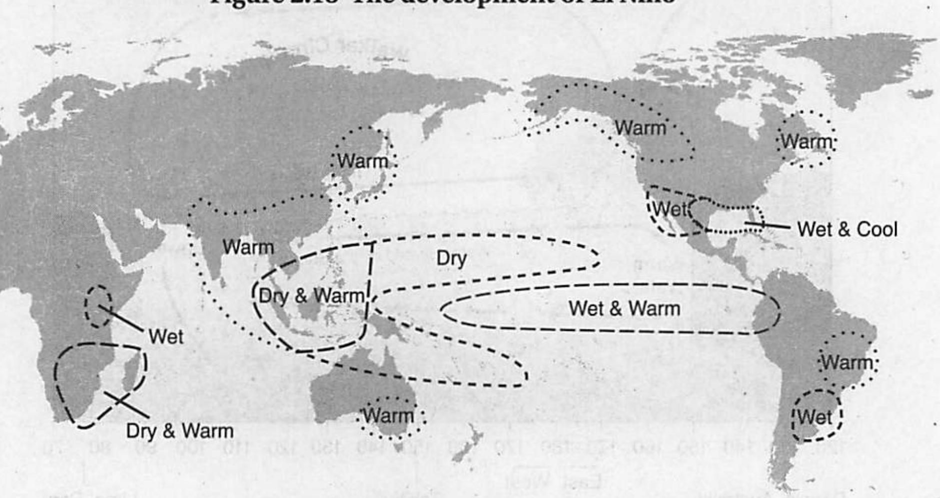


Figure 2.13 The development of El Niño



Source: National Weather Service

Figure 2.14 El Niño effects (December–February)

Upwellings

Upwellings occur when prevailing winds, produced through the Coriolis effect and moving clockwise in the Northern Hemisphere, push warmer, nutrient-poor surface waters away from the coastline. This surface water is then replaced by cooler, nutrient-rich deeper waters. The deeper waters contain high levels of nitrates and phosphates, which result from the decomposition and sinking of surface water plankton. When these nutrients are brought to the surface through upwelling, they supply necessary nutrients for phytoplankton, which form the base of the oceanic food chain.

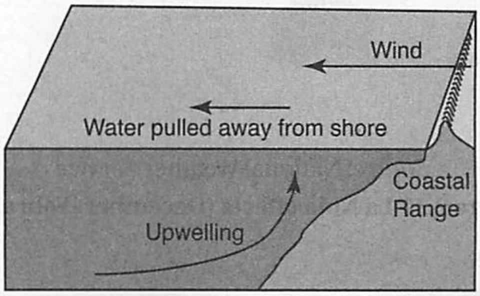


Figure 2.15 Upwelling

La Niña (Cool Phase)

The steps of forming a La Niña are:

- Trade winds that blow west across the tropical Pacific are stronger than normal.
- This results in an increase in the upwelling off of South America.
- This then results in cooler-than-normal sea surface temperatures off of South America.
- This leads to wetter-than-normal conditions across the Pacific Northwest, and both drier- and warmer-than-normal conditions in the southern United States, which results in an increase in the number of hurricanes.
- Winter temperatures are warmer than normal in the southeastern United States and cooler than normal in the northwest.
- This also causes heavier-than-normal monsoons in India and Southeast Asia.

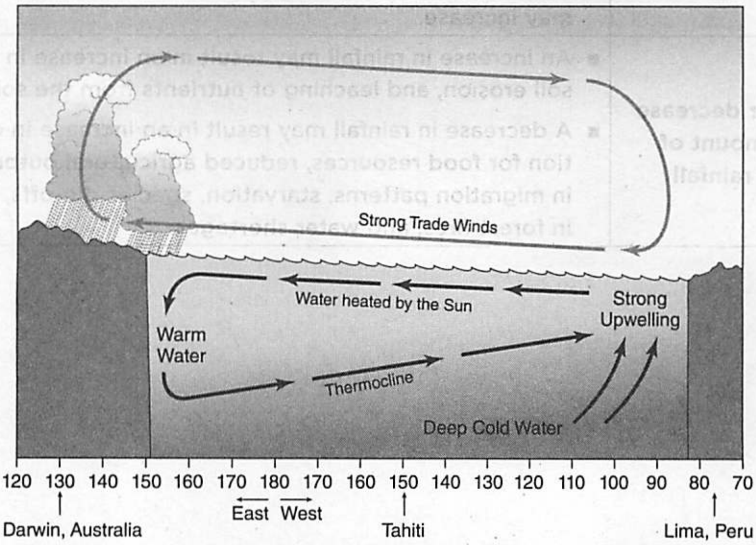
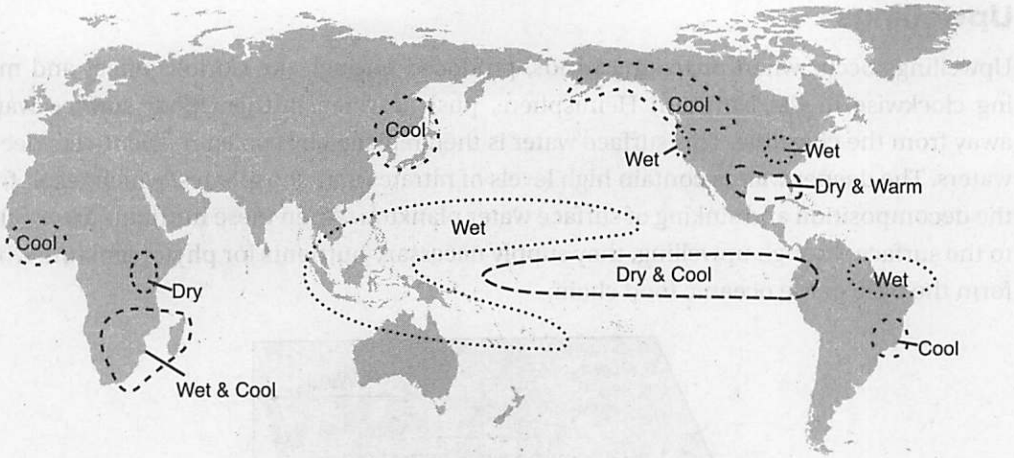


Figure 2.16 La Niña



Source: National Weather Service

Figure 2.17 La Niña effects (December–February)

Environmental Effects of ENSO Weather Patterns

Cause	Environmental Effect(s)
Warmer or cooler ocean temperatures	■ Some marine species may not be able to tolerate warmer or cooler water temperatures, resulting in a disruption in marine food webs and biodiversity. ■ Animal migration patterns may become disrupted. ■ Shifts in traditional weather patterns (e.g., an increase in insect-borne diseases). ■ A negative impact on coral reefs (e.g., bleaching). ■ A decrease in upwelling, resulting in die-offs. ■ The amount of CO_2 that warmer ocean water can hold decreases, which directly affects global warming. ■ Warmer ocean temperatures may change the ocean current flows and affect glacial melting. ■ The strength and frequency of hurricanes and/or tornadoes may increase.
Increase or decrease in the amount of normal rainfall	■ An increase in rainfall may result in an increase in flooding, soil erosion, and leaching of nutrients from the soil. ■ A decrease in rainfall may result in an increase in competition for food resources, reduced agricultural output, changes in migration patterns, starvation, species die-offs, an increase in forest fires, and water shortages.

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) CO_2, H_2O, O_2, N_2
   (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

7. The ozone layer exists primarily in what section of the atmosphere?

(A) Troposphere
(B) Stratosphere
(C) Mesosphere
(D) Thermosphere
(E) Ionosphere

8. Along the equator,

(A) warm, moist air rises
(B) warm, moist air descends
(C) warm, dry air descends
(D) cool, dry air descends
(E) cool, moist air descends

9. Most of Earth's deserts are at approximately 30° north and south latitudes because these latitudes are characterized by

(A) generally warm ocean currents
(B) predominately low atmospheric pressure
(C) descending dry air currents
(D) a slow-moving jet stream
(E) enhanced solar radiation

10. Characteristics or requirements of a monsoon include all of the following EXCEPT

(A) a seasonal reversal of wind patterns
(B) large land areas cut off from continental air masses by mountain ranges and surrounded by large bodies of water
(C) different heating and cooling rates between the ocean and the continent
(D) extremely heavy rainfall
(E) heating and cooling rates between the oceans and the continents that are equal

11. An atmospheric condition in which the air temperature rises with increasing altitude, holding surface air down and preventing dispersion of pollutants, is known as (a)

(A) temperature inversion
(B) cold front
(C) warm front
(D) global warming
(E) upwelling

12. The surface with the lowest albedo is

(A) snow
(B) ocean water
(C) forest
(D) desert
(E) black topsoil

13. Jet streams over the U.S. travel primarily

(A) north to south
(B) south to north
(C) east to west
(D) west to east
(E) in many directions

14. The correct arrangement of atmospheric layers, arranged in order from the most distant from Earth's surface to the one closest to Earth's surface, is

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

TIP

Be careful that, when answering questions that involve placing items in order, you have the order going in the proper direction. A common trick is to have the correct choices in the opposite direction.

15. Areas of low pressure are typically characterized by _________ air and move toward regions where the pressure is ________ with time.

(A) sinking, falling
(B) rising, falling
(C) sinking, rising
(D) rising, rising
(E) non-moving, changing

16. The global circulation pattern that dominates the tropics is called the

(A) Ferrel cell
(B) Polar cell
(C) Bradley cell
(D) Hadley cell
(E) Tropical cell

17. Which of the following statements about sea and land breezes is FALSE?

(A) Sea breezes can sometimes result in rain showers and thunderstorms near the shore.
(B) Smaller versions of sea/land breezes often form in the vicinity of large lakes.
(C) Land breezes form mostly during the daytime hours.
(D) Sea and land breezes are examples of thermal circulations.
(E) All of these statements are false.

18. Jet streams follow the sun in that as the sun's elevation __________ (increases, decreases) each day in the spring, the jet stream shifts by moving __________ (north, south) during the Northern Hemisphere spring.

(A) increases, north
(B) increases, south
(C) decreases, north
(D) decreases, south
(E) None of the above

19. Usually, fair and dry/hot weather is associated with high pressure around __________ latitude with rainy and stormy weather associated with low pressure around __________ latitude.

(A) 0 degrees N/S, 90 degrees E/W
(B) 90 degrees E/W, 90 degrees N/S
(C) 30 degrees N/S, 50–60 degrees N/S
(D) 50–60 degrees N/S, 30 degrees N/S
(E) 45 degrees N/S, 45 degrees E/W

20. The three necessary ingredients for thunderstorm formation are

(A) moisture, lifting mechanism, instability
(B) lifting mechanism, mountains, oceans
(C) stability, moisture, heat
(D) lifting mechanism, fronts, moisture
(E) deserts, mountains, clouds

FREE-RESPONSE QUESTION

TIP

Before writing your responses, be sure to map out or brainstorm what you are going to write about. A few minutes planning and organizing your responses will get you a much higher score.

(a) Choose ONE of the following: Hadley cell, Ferrel cell, or Polar cell. In your description, include the following:

(i) A description of the type of cell
(ii) An explanation of how that cell develops
(iii) The cell's location with respect to the equator

(b) Describe the characteristics of that cell in terms of climatic conditions. In your description, include temperature, relative humidity, and prevailing winds.

(i) Identify and describe ONE biome that would exist at sea level within the specific latitudes of that cell. In your description, give examples of both plants and animals that would be found within that biome.

MULTIPLE-CHOICE ANSWERS AND EXPLANATIONS

1. **(C)** The troposphere is the atmospheric layer closest to Earth and extends for about 11 miles (18 km) above Earth at the equator and about 5 miles (8 km) above Earth at the poles. Temperature declines as altitude increases.
2. **(E)** Nitrogen (78%), oxygen (21%), water vapor (about 0–4%), and the rest below 1%.
3. **(A)** Latitude expresses how far north or south of the equator a location is. The equator is 0° latitude, and the poles are at 90°. For every 1,000 feet (300 m) in altitude, there is a 3°F (1.5°C) drop in temperature.
4. **(D)** A low-pressure air mass (low) occurs when warm air, which is less dense than cooler air, spirals inward toward the center of a low-pressure area. Since the center of the low-pressure area is of even less density and pressure, the air in this section rises and the warm air cools as it expands. The temperature begins to fall and may go below the dew point—the point at which air condenses into water droplets. These water droplets make up clouds. If the droplets begin to coalesce on condensation nuclei, rain follows.
5. **(C)** During La Niña, large portions of central North America experience increased storminess, increased precipitation, and an increased frequency of significant cold-air outbreaks, while the southern states experience less storminess and precipitation. Also, there tends to be considerable month-to-month variations in temperature, rainfall, and storminess across central North America during the winter and spring seasons.
6. **(D)** The rain shadow effect occurs on the leeward side of a mountain, the side away from the ocean. Moist air from the ocean rises when it hits mountains, cools, and loses its moisture on the windward side. On the leeward side, air is much drier. For example, the western side of the Sierra Nevada Mountain Range in California is much wetter than the eastern side.
7. **(B)** 97% of ozone (O_3) is found in the lower stratosphere, which is 9 to 35 miles (15–55 km) above Earth's surface. Temperature increases with altitude in the stratosphere due to absorption of heat energy by ozone molecules.
8. **(A)** Hadley cells occur between 0° and 25° north and south latitudes (equatorial region). In this area, there is upward air motion, cooling of the air due to uplift, high humidity, high clouds, and heavy rains.
9. **(C)** Deserts are arid regions defined by the amount of rainfall an area receives in a year (less than 10 inches [approximately 25 cm]), *not* by temperature. Deserts are often hot, but dry; cold places, such as Antarctica, qualify as deserts too.

   Since there is more direct sunlight at the equator, warm air rises and begins to cool. Since the rising cooler air holds less water than warmer air, precipitation is common at the equator (e.g., tropical rainforests). This drier air mass then moves both north and south. At around ±30 degrees north and south latitudes, the dry air begins to sink and warm. The warmer air can now hold more water, resulting in the evaporation of water and the formation of deserts.
10. **(E)** During monsoon season, winds blow from cooler ocean areas (higher pressure) to warmer landmasses (lower pressure). As the air rises over the landmasses, it cools and is unable to retain water, producing great amounts of precipitation. In winter, the

ocean is now warmer and the cycle reverses. Drier air travels from the land out to the ocean. Monsoons exist in Australia, Africa, and North and South America.

11. **(A)** Temperature inversions are atmospheric conditions in which the air temperature rises with increasing altitude, holding surface air down and preventing the dispersion of pollutants.

12. **(E)** Albedo is a measure of reflection of sunlight from a surface. Of the choices, dark topsoil absorbs the most energy and therefore reflects the least amount of energy, resulting in the lowest albedo.

13. **(D)** Jet streams are large-scale upper air flows that travel from west to east and are produced by differences in temperature. They can travel as fast as 250 miles per hour (400 kph) and travel between 3 and 8 miles (5–13 km) above Earth's surface.

14. **(B)** Remember, the question required you to place the layers in order from the most distant to the closest.

15. **(B)** In a high-pressure system, air pressure is greater than the surrounding areas. This difference in air pressure results in wind. In a high-pressure area, air is denser than in areas of lower pressure. The result is that air will move from the high-pressure area to an area of lower pressure. Clear skies and fair weather usually occur in these regions. On the other hand, winds tend to blow into a low-pressure system because air moves from areas of higher pressure into areas of lower pressure. As winds blow into a low-pressure system, the air moves up. This upward-flow of air can cause clouds, strong winds, and precipitation to form.

16. **(D)** Hadley cells dominate the tropics.

17. **(C)** A sea breeze, or onshore breeze, is a gentle wind that develops over bodies of water near land due to differences in air pressure created by their differences in heat capacity and associated rates of heating and cooling. It is a common occurrence along coasts during the morning as solar radiation heats the land more quickly than the water. A land breeze, or offshore breeze, is the reverse effect, caused by land cooling more quickly than water in the evening. The sea breeze dissipates and the wind flows from the land toward the sea. Both are important factors in coastal regions' prevailing winds and more moderate temperature profile.

18. **(A)** The position of the jet stream also determines where the storm track is. As the jet stream moves north during spring, the storm track moves north, leaving the southern plains of Texas and Oklahoma and moving into the northern plains near the Dakotas.

19. **(C)** Except for a few locations, most of the world's deserts are located along 30 degrees N/S latitude with lush forests from abundant rains located around 50–60 degrees N/S latitude.

20. **(A)** Moisture, a lifting mechanism, and instability are all needed for thunderstorms to form. The moisture is needed for rain. The lifting mechanism is needed to get the air moving initially in an upward direction, and the unstable atmosphere ensures the upward-moving air continues to do so.

FREE-RESPONSE ANSWER

Let's do this response together, using it as a teaching tool rather than just providing an answer and rubric. Let's choose the Hadley cell for this example.

The first step is to brainstorm. Write a list of key words that would apply to the question. Remember that the order of the key words is not important; we will put them into the correct order later. Here is a sample of key words: Hadley, Ferrel, Polar, temperature, solar insolation, humidity, biomes, plants, and animals.

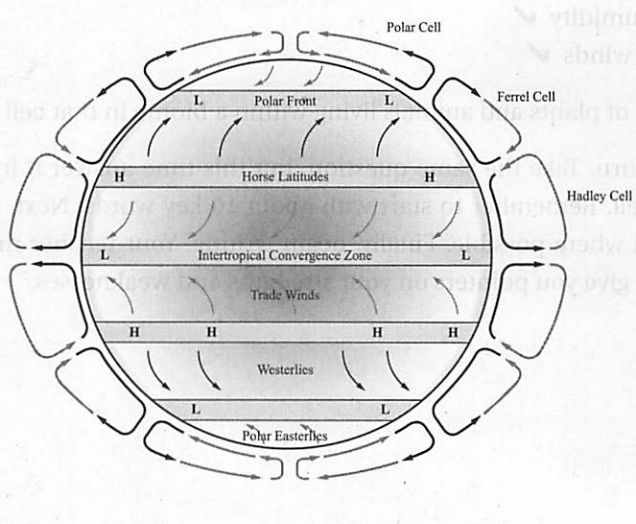
Now that we have around 10 key words, let's expand the list by adding details—items that we will discuss in our response. We can also begin to map out the order in which we will discuss the items.

- Hadley: 0° to 30°, deserts, equatorial regions, tropical rainforests, subtropical areas, savannas
- Location
- Temperature (heat moves from the equator to colder areas)
- Relative humidity
- Prevailing winds
- Solar insolation
- Biomes
- Animals
- Plants

Remember, you have 23 minutes to spend on this response, so do not spend more than 5 minutes organizing. Now look over the list and add anything that you have missed. Now it is time to begin writing.

The first step is to write a thesis statement: **"The world's biomes are primarily determined by climatic conditions. Deserts are characterized as areas of low precipitation, while tropical rainforests are characterized by areas of high precipitation."**

The next step is to begin describing what determines climatic conditions that, in turn, affect the type of life present within that zone. **"Solar insolation, that is the amount of sunlight received on Earth, is greatest at the equator and diminishes toward the poles. Since heat flows from warmer regions to cooler regions, the warmer air produced at the equator moves through major worldwide wind patterns that distribute this energy worldwide. As one moves from the equator to the poles, there are three major air circulation cells—Hadley, Ferrel, and Polar."** At this point, a labeled sketch would be helpful.



TIP

When writing your FRQ responses, a picture is worth a thousand words! If you can sketch out a labeled diagram of what you are describing, it will go a long way in improving your score.

Now, for the remaining time, we can refer to the detailed outline and complete the response, adding details and examples where necessary.

From the equator to 30° north and south latitudes, Hadley cells exist. Since this area of Earth receives the greatest solar radiation due to Earth's axis tilt, this area of Earth is the warmest. Near the equator, this warm, moist air rises. As the warm air rises, it begins to cool and become denser. Since cooler air cannot hold as much water vapor as warmer air, the humidity of the air increases to the point where clouds are produced. This, in turn, causes great amounts of rainfall. Monthly average temperatures are quite high at sea level, and there is no winter. Vegetation near sea level is tropical rainforest. In these tropical systems, temperature variations from day to night are greater than from season to season. Tropical rainforests, which extend about 1,500 miles (2,400 km) north and south of the equator, are found in South and Central America, Africa, and southeast Asia. Climatic conditions can include rain throughout the year, monsoons—a short, dry season followed by a heavy, rainy period, and tropical savanna with characteristic wet and dry seasons.

Tropical rainforests have characteristically high-species plant and animal diversity. Vegetation is dense. Bromeliads, orchids, ferns, and palms are present. Leaves are large in an effort to absorb sunlight, and there is little need to conserve water lost through transpiration. Soils are characteristically low in nutrients with the nutrients being stored in vegetation. Soil is characteristically acidic. Decomposition of organic material is high due to temperature and moisture. Leaching of soil nutrients is high; therefore, soil quality is very low. Abundant insects and animal biodiversity are characteristic. Examples of animals that one might find in a tropical rainforest biome might include numerous species of butterflies, ants, mosquitoes, millipedes, bats, monkeys, sloths, tarsiers, hippopotamuses, macaws, toucans, parrots, anacondas, alligators, and numerous species of frogs.

At this point, we think we are done. Our last job is to be sure that we have answered all questions. Let's put a check beside each topic that we answered and that we were required to address:

- Describe the cell ✔
- How it develops ✔
- Location of the cell ✔
- Characteristics of the cell
    1. Temperature ✔
    2. Relative humidity ✔
    3. Prevailing winds ✔
- List examples of plants and animals living within a biome in that cell ✔

Now it is your turn. Take the same question, but this time answer it in terms of either a Ferrel or a Polar cell. Remember to start with about 10 key words. Next, organize your key words and expand where possible. Finally, begin writing. Your teacher may wish to collect your response and give you pointers on your strengths and weaknesses.