Causes of Climate Change

Module Overview

For the past 8,000 years, the ice cores of Antarctica and Greenland indicate that Earth's climate has been unusually stable. Yet global climate has changed several times in Earth's geological history, sometimes at a relatively abrupt rate, as shown by the Greenland ice core data. In the module, *Temperature Over Time*, you compared temperature patterns and trends over different time scales and regions. You identified several glacial and interglacial periods throughout Earth's history and the recent warming trend.

In this module, you will learn what causes climate to change. You will compare both the natural and anthropogenic (human) causes of climate change, which are referred to as forcings by climate scientists. In the module, *Energy: The Driver of Climate*, you balanced Earth's annual energy budget by adding or subtracting the processes that cause the average amount of energy gained by Earth to equal the average amount of energy lost by Earth. Climate forcings are any factors that cause a change in Earth's energy balance, which will ultimately lead to a change in global mean temperature (GMT) and global climate.

When you complete this module, you will be able to

- Explain natural causes of global climate change.
- Trace the flow of carbon through the carbon cycle.
- Explain the natural and human-related processes that cause increases and decreases in the concentration of greenhouse gases in the atmosphere.
- Explain the trends in atmospheric carbon dioxide concentration over different time scales.
- Compare the changes in atmospheric carbon dioxide and temperature over different time scales.
- Explain how patterns (or fingerprints) can be used to identify the source of recent climate change.
- Compare climate models of observed temperature changes due to natural causes to those that include both natural and anthropogenic (human) causes.
- Describe the types of feedbacks (or processes) that amplify and reduce changes in climate.

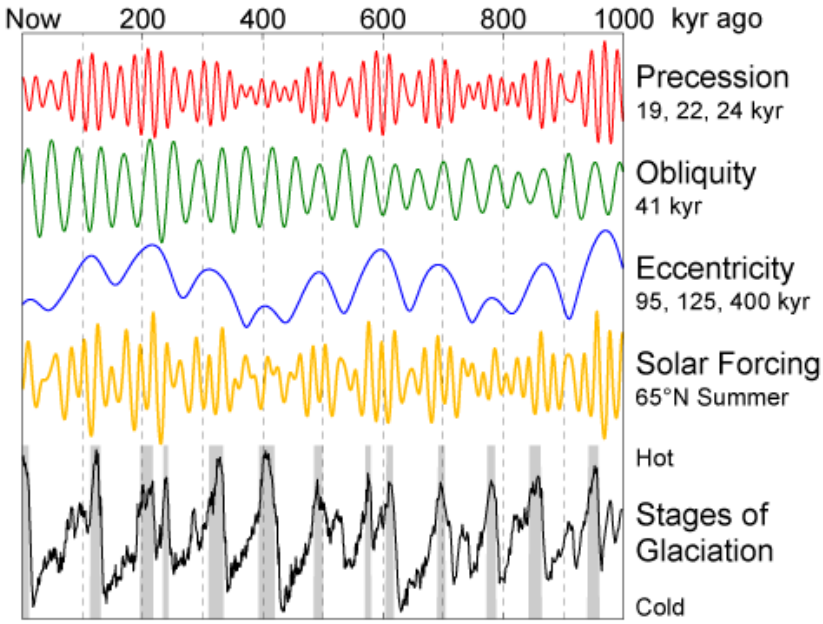
Radiative Forcings

The planet's global average temperature is determined by the balance of incoming and outgoing energy from Earth. This energy balance may be altered in three ways. The sun's intensity may increase or decrease. The reflection of solar radiation by clouds or ice may increase or decrease, causing either more or less radiation to be reflected to space rather than to Earth's surface. Or the amount of infrared radiation from Earth's atmosphere to space may increase or decrease.

Any factor that causes a change to Earth's energy balance is known as a **radiative forcing** or a forcing. A radiative forcing is expressed in W/m^2 (watts per square meter). A *positive forcing*, such as that produced by increasing concentrations of greenhouse gases, *tends to warm* the Earth's surface. A *negative forcing*, such as that produced by airborne particulates that reflect solar energy, *tends to cool* the Earth's surface. Forcings may also be either natural- or human-caused (also known as anthropogenic).

Climate has changed throughout Earth's geologic history, mostly due to natural causes. Natural phenomena that cause shifts in global climate are changes in Earth's orbital cycles, volcanic eruptions, variations in solar activity, movement of tectonic plates, and the atmospheric-ocean pattern in the tropical Pacific Ocean, known as El Niño-Southern Oscillation (ENSO). Climate also changes in response to the concentration of greenhouse gases in the atmosphere. The concentration of atmospheric greenhouse gases can increase or decrease due to both natural phenomena and human activity.

Natural Causes of Climate Change



Milankovitch cycles over the past 1,000,000 years.
Image Source: Global Warming Art

Orbital Changes

The Milankovitch Theory explains the 3 cyclical changes in Earth's orbit and tilt that cause the climate fluctuations that occur over tens of thousands of years to hundreds of thousands of years. You learned about these orbital changes, known as the Milankovitch cycles, in the *Temperature over Time* module. These fluctuations include changes in the shape (eccentricity) of Earth's orbit every ~100,000 years, the tilt (obliquity) of Earth's axis every ~41,000 years, and the

wobbling (precession) of Earth's axis about ~23,000 years. Milankovitch proposed that glacial periods began when the three cycles align to favor an extended period of more solar radiation in the winter and less solar radiation in the summer at a latitude of 65°N. These conditions for the northern latitudes favor somewhat higher temperatures, but also more water vapor in the air – causing more snowfall. A relatively cool summer for the northern latitudes favors less melting of winter snow and glacier formation.

The figure above shows the alignment of each of the orbital changes to the glacial and interglacial periods. The interplay of the three orbital cycles affects the amount of solar radiation received at different latitudes over the year. The amount of solar radiation reaching the Northern Hemisphere (sat 65°N seems to control the advance and retreat of glaciers and ice sheets.

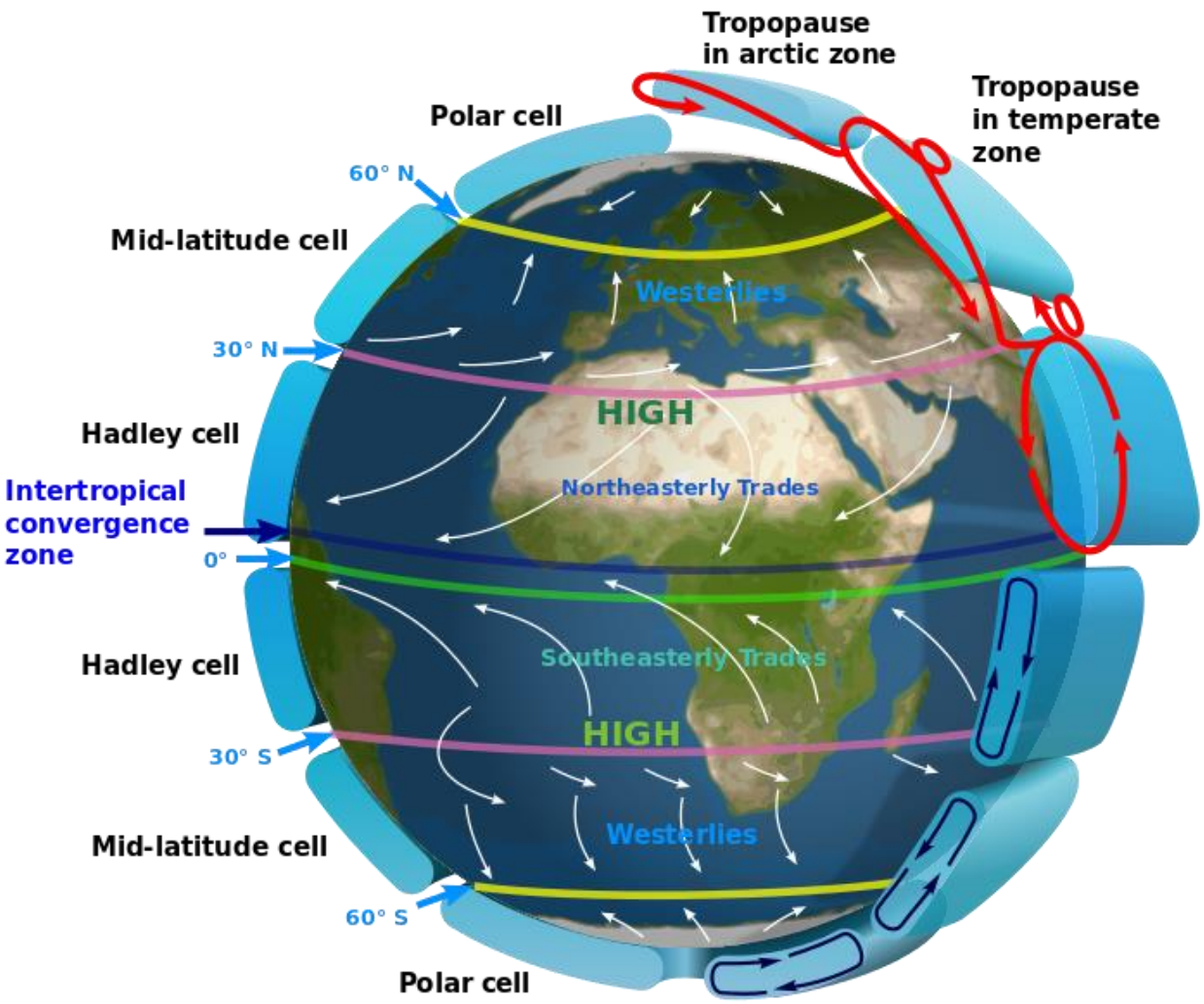
Volcanic Eruptions

Volcanic eruptions discharge carbon dioxide, but they may also emit aerosols, such as volcanic ash or dust, and sulfur dioxide. **Aerosols** are liquids and solids that float around in the air. They may also include soot, dust, salt crystals, bacteria, and viruses. Aerosols scatter incoming solar radiation, causing a slight cooling effect. Volcanic aerosols can block a percentage of sunlight and cause a cooling that may last for 1-2 years.

Karymsky Volcano in Russia. ***Image Source: Microsoft Clip Art***

The year 1816, often referred to as the "year without a summer, occurred after the violent eruption of Indonesia's Mount Tambora. This was possibly the largest known eruption in the history of human civilization. Snow fell in the northeastern United States and Canada in June, causing regional losses of crops, food shortages, and increased mortality. Relatively cold years also followed other famous volcanic eruptions (such as the 1883 eruption of Krakatau also in Indonesia and 1991 eruption of Mount Pinatubo in the Philippines).

In violent eruptions, volcanoes release ash particles and sulfur dioxide (SO_2) into the stratosphere. The larger particles settle after a few days while the sulfur dioxide combines with water vapor to from sulfuric acid (H_2SO_4) and sulfate particles, known together as sulfurous aerosols. Winds transport these sulfurous aerosols around the planet in easterly or westerly directions. For this reason, volcanoes that erupt at lower latitudes (closer to the equator) are more likely to cause hemispheric or global cooling. Volcanoes that erupt at higher latitudes (closer to the poles) are less likely to cause cooling because the sulfurous aerosols are confined to wind patterns surrounding the poles.



Credit: NASA

Global Wind Patterns

Large global wind systems are created by the uneven heating of the Earth's surface. These global wind systems, in turn, drive the oceans' surface currents. To understand how global winds form and drive the major ocean currents, you need to know that **wind** is the basically the movement of air from an area of high pressure to an area of low pressure. **Pressure** is force per unit area, and **air pressure** is simply the weight (force) of the column of air above a particular location, per unit area. Air pressure therefore depends on elevation or altitude (higher up means less air above), the average temperature of the air above the particular location (hot air is lighter than cold air), and what the air's composition is. For example, air with a large amount of water vapor is less dense than dry air because the water molecule has less mass than either an individual nitrogen or oxygen molecule. Also as elevation or altitude increases, air becomes less dense.

How does unequal heating of the Earth's surface form large global wind patterns? In area near the equator, the sun is almost directly overhead for most of the year. Warm air rises at the equator and moves toward the poles. At the poles, the cooler air sinks and moves back toward the equator. However, it is not this simple. Global winds do not move directly from south to north or north to south because the Earth rotates. All winds in the Northern Hemisphere appear to curve to right as they move. In the southern hemisphere, winds appear to curve to the left. This is known as the **Coriolis effect**, which is the apparent shift in the path of any fluid or object moving about the surface of the Earth due to the rotation of the Earth.

At the equator, warmer, moist air rises and produces a low-pressure area extending many kilometers north and south of the equator. Also near the equator, the trade winds converge into a broad east to west area of light winds. The area is known as the doldrums because there are light winds. This belt of air around the equator receives much of the sun's radiant energy. The latitude where Earth's mean annual surface temperature is highest is presently located at 10°N, and is known as the Intertropical Convergence Zone (ITCZ). As you learned, the Northern Hemisphere has more landmass and is therefore relatively warmer than the Southern Hemisphere and the reason that the ITCZ is located just north of the equator.

Trade Winds – About 30° north and south of the equator, the warm, moist air that rose vertically from the equatorial region and moved toward the poles cools and begins to sink. Here the sky is clear. There are few clouds and little rainfall. Winds are calm. These are called the horse latitudes, because when food ran out, sailors had to throw horses overboard. Deserts, such as the Sahara in Africa, are also common at 30˚N and 30˚S. At the horse latitudes some of the sinking air travels back toward the equator. The air moving back toward the equator forms warm, steady winds, known as the trade winds.

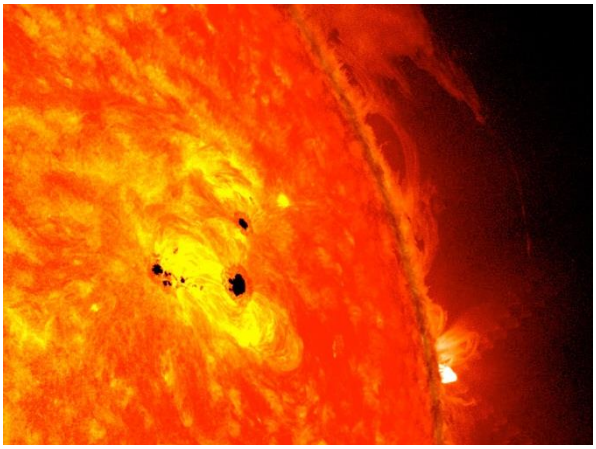
The rising air at the equatorial regions and the sinking air at about 30˚N and 30˚S form huge convection currents, known as **Hadley cells** for the English meteorologist who first proposed their existence to explain the trade winds.

Prevailing Westerlies – Some of the cool, sinking air at 30° north and south of the equator continues to move toward the north and south poles. These winds are called the westerlies. In both hemispheres, the air rises vertically at about 50˚ to 60˚ of latitude, creating an area of lower pressure. As the air rises, it cools and moves toward the poles.

Polar Easterlies – As this cold air approaches the north and south poles, it begins to sink forming an area of higher pressure. This sinking air flows back toward the equator from the poles. These winds are called the polar easterlies.

Variation in Solar Radiation

The total amount of solar radiation varies by very small amounts. The energy emitted by the sun only varies by 1.3 W/ m^2. This change in solar radiation is related to the number of sunspots. **Sunspots** are darker areas on the sun's surface. A sunspot develops where an intense magnetic field weakens the flow of gases that transport heat energy from the sun's interior. Sunspots appear dark because their temperature is lower than the surrounding area.

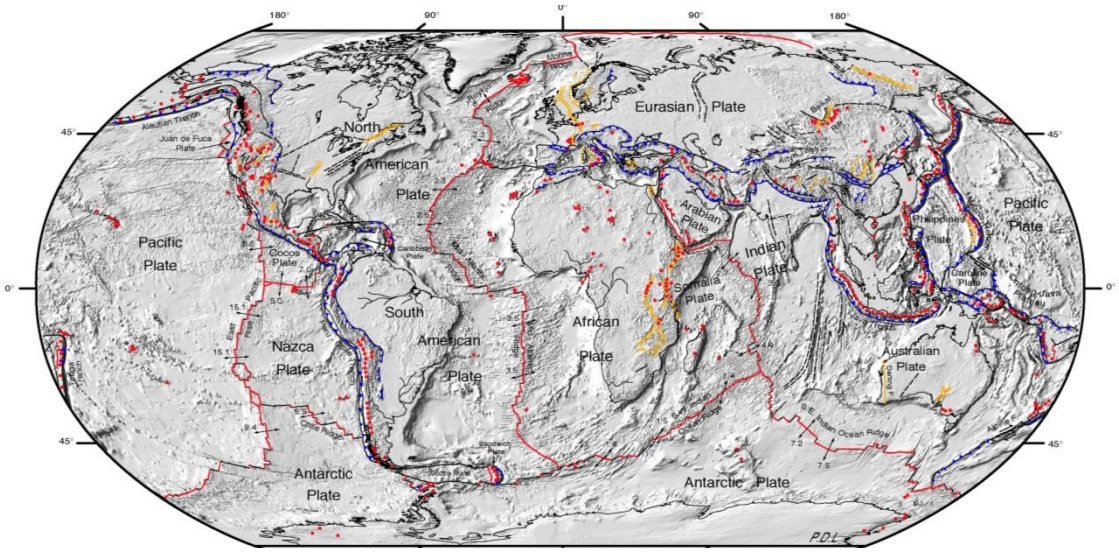


Sunspots. Image taken Feb. 2013
Credit: NASA/SDO/AIA/HMI/Goddard Space Flight Center

Sunspot activity increases and decreases over an approximate 11-year cycle. The sun emits slightly more radiation during active periods of sunspots. Because the sunspots are suppressing heat, the heat flows to surrounding areas causing these regions to radiate more heat and appear brighter than normal. More sunspots are associated with a warmer global climate, and less sunspots appear to be associated with a cooler global climate. About 300 years ago, there was a period of reduced solar activity. This was called the Little Ice Age.

Movement of Crustal Plates

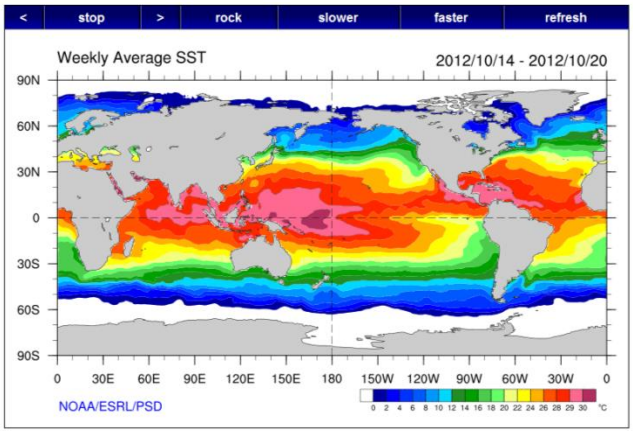
As tectonic plates move over geological timescales, landmasses are carried to different positions and latitudes. These changes affect global circulation patterns of air and ocean water and the climate of the continents. One form of evidence for plate tectonics and an example of how plate tectonics affects climate is the location of coal mines. Coal mines were formed over millions of years ago in tropical areas, yet are found at higher latitudes today. You also learned in the *Temperature Over Time* module that, since the industrial revolution, the Northern Hemisphere has warmed more than the Southern Hemisphere. This is because the Northern Hemisphere has a larger percentage of Earth's landmass compared to ocean than the Southern Hemisphere. Remember that landmasses warm faster than oceans due to the high heat capacity of the oceans.



The Digital Tectonic Activity Map. Image Source: NASA

El Niño-Southern Oscillation (ENSO)

El Niño-Southern Oscillation (ENSO) is an oscillation of the ocean and atmosphere system in the tropical area of the Pacific Ocean that affects global weather. Normally the southeast trade winds blow across the tropical Pacific Ocean toward the west moving warmer surface water toward the western Pacific around Indonesia and northeastern Australia. Every 5 to 7 years, the southeast trade winds weaken for about 8 or 9 months, allowing the warm surface water to flow eastward toward South America. This warmer current of water typically reaches the western coast of South America near Christmas and has become known to the Peruvian fishermen as El Niño (for the Christ child).



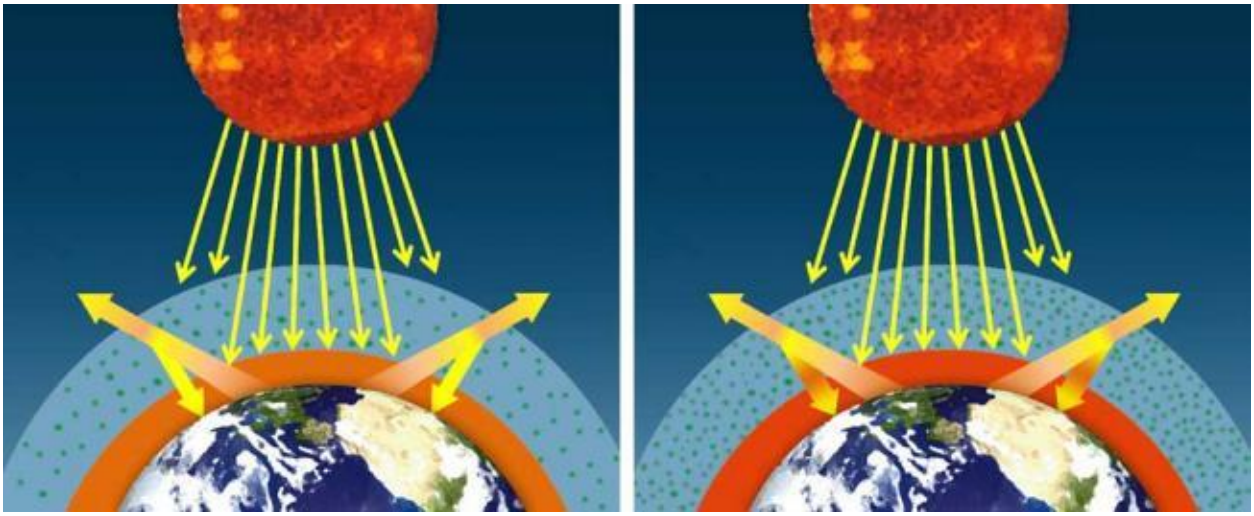
Weekly Sea Surface Temperature Totals. Image Source: NOAA

El Niño is also known as the warm-water phase of the ENSO. El Niño causes the water temperature off of South America to be warmer. An El Niño warm-water phase changes global weather patterns. South America experiences wetter than average weather, while North America experiences mild but stormier winter weather. During an El Niño warm water phase, there are fewer and less intense hurricanes in the Atlantic Ocean because the rising warmer air over the eastern Pacific Ocean causes more wind shear and hurricanes are not able to form in the Caribbean Sea. Sometimes, after an El Niño phase subsides, a colder-than-normal water phase, known as La Niña, results.

Changes in Greenhouse Gases

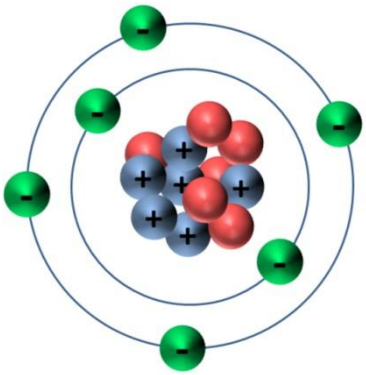
In the *Energy: The Driver of Climate* module, you learned that greenhouse gases are effective absorbers of infrared radiation and have kept Earth at approximately 15°C (59°F). You also learned that relatively small changes in the amounts of greenhouse gases in Earth's atmosphere can alter the balance between incoming and outgoing radiation, ultimately determining Earth's climate.

Natural Vs. Amplified Greenhouse Effect



The Carbon Dioxide Story

The carbon cycle is important to understand because it explains the both the ways that carbon dioxide is produced and consumed through natural processes and the ways that humans are able to rapidly alter the cycle in very short spans of time. Carbon dioxide (CO_2), the major greenhouse gas of concern, provides the predominant way that carbon is cycled throughout natural reservoirs.



Carbon Atom with 6 electrons, 6 protons and 6 neutrons

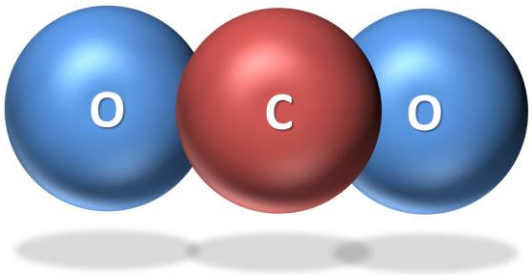
Carbon

Pure carbon is very rare. It is found in nature only as the minerals, graphite and diamond. Most carbon is bonded to other elements to form compounds. Carbon, "the building block of life," combines with hydrogen and oxygen to form the basic compounds that make up living things. We (as well as all of the other plants and animals on earth) are made of carbon, as much as 50% of our dry weight. It is the element that all organic substances contain – from fossil fuels to DNA. Hydrocarbons—such as coal, oil (also known as petroleum), and natural gas)—are compounds made of hydrogen and carbon. Carbon is also found in calcite ($CaCO_3$), a mineral in limestone, a sedimentary rock, and marble, a metamorphic rock.

Carbon is found on Earth in three large reservoirs—in the atmosphere, as CO_2; in the oceans, as dissolved CO_2; and underground, as coal, oil, natural gas, and calcium carbonate rock. Carbon cycles through all four of Earth's spheres—the atmosphere, hydrosphere, geosphere, and biosphere—on different time scales. The cycle is known as the carbon cycle. Carbon is primarily cycled in the form of CO_2 between the natural carbon reservoirs.

The Carbon Cycle

Carbon dioxide only makes up 0.040% of the total atmosphere. However, it is the major greenhouse gas that contributes to global warming for the following two reasons. Carbon dioxide spends a relatively long time in the atmosphere (approximately 100 years). Carbon dioxide is also is a strong absorber of infrared radiation.



Carbon dioxide consists of one atom of carbon and two atoms of oxygen, which are held together by covalent bonds (or the sharing of electrons). When agitated by infrared radiation, the CO_2 molecule vibrates in all three directions and absorbs heat. The molecule is then able to re-radiate or emit heat in all directions, including back toward Earth. Thus, CO_2 absorbs infrared radiation emitted from Earth's surface and then emits the same infrared radiation as was absorbed.

Watch Episode 1: Global Warming, It's All About Carbon.
NPR's Robert Krulwich and Odd Todd, in partnership with Wild Chronicles, present an animated cartoon series on the atom at the heart of global warming: carbon.

Carbon dioxide constantly moves into and out of the atmosphere through several major pathways. Over *short time scales*, the processes of photosynthesis, respiration, organic decomposition (decay), and combustion (burning of organic material) increase or decrease the concentration of atmospheric CO_2. Carbon dioxide is also exchanged between the atmosphere and oceans by gas exchange over short time scales. Each year, approximately one-fifth of the carbon (in the form of CO_2) in the atmosphere is cycled in and out.

Over *longer time scales*, the concentration of atmospheric CO_2 is changed by the formation of fossil fuels, weathering of rocks, and volcanic eruptions. The following sections describe these short- and long-term processes.

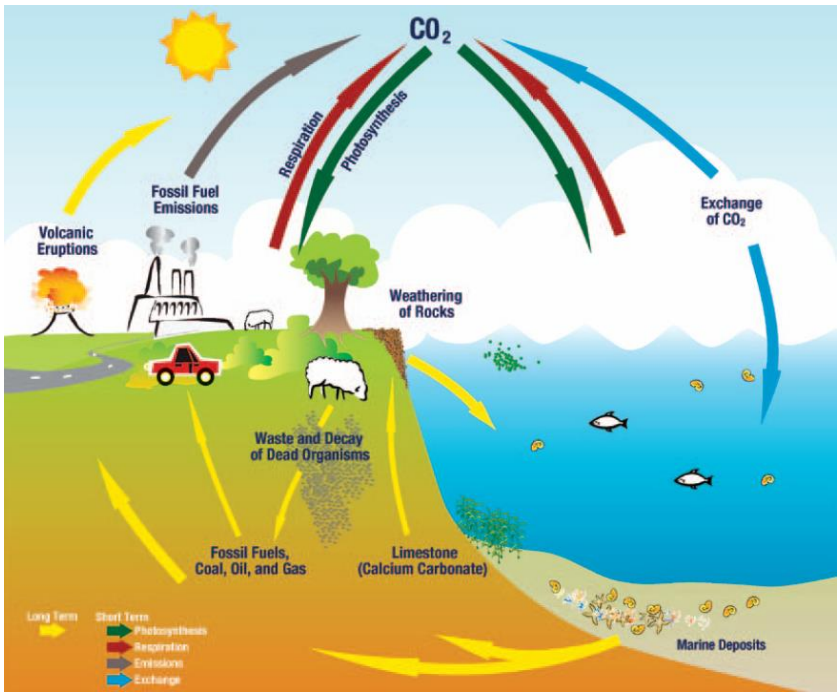


Image Source: [Climate Change: Evidence, Impacts and Sources]

Sinks of Carbon Dioxide

Processes or regions that predominately absorb atmospheric carbon dioxide are referred to as sinks. Carbon dioxide may be removed from the atmosphere when it is used by plants and algae for photosynthesis, dissolved in water, or deposited in the sediments on land or in the ocean.

Image Source: Microsoft Clip Art

Photosynthesis

Green plants use water from the soil and CO_2 from the atmosphere to make carbohydrates (glucose) and oxygen in the process of photosynthesis. In the ocean, algae carry on the same process. During photosynthesis, plants and algae convert the radiant energy of the sun into chemical energy to make the carbohydrates (glucose) and produce oxygen as a byproduct. Plants and algae make more glucose in photosynthesis than they consume in respiration. The excess glucose produced by these photosynthetic organisms becomes the food consumed by animals.

$$6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

carbon dioxide + water + energy → glucose + oxygen

Oxygen is then used by the animals and plants to oxidize food. This provides the animals and plants with energy. So when animals consume plants or they consume other animals that eat plants, they use the carbohydrates (glucose) as a source of energy.

Dissolution in Water

Carbon dioxide can also be absorbed in the surface water of the ocean. As the concentration of carbon dioxide in the atmosphere increases, some of this CO_2 will be dissolved in the oceans. When the water is cooler than the atmosphere, more CO_2 can be dissolved. Gases are more soluble in cooler water than in warmer water due to the Second Law of Thermodynamics. Gases are exchanged through the ocean surface until equilibrium is reached.

When CO_2 combines with water, it forms carbonic acid.

$$CO_2 + H_2O \rightarrow H_2CO_3$$

dissolved CO_2 + water → carbonic acid

The oceans provide a huge reservoir of carbon. Scientists estimate that the oceans hold more than 50 times the total atmospheric carbon dioxide content. However, as the ocean temperatures rise over the next centuries, surface waters will begin to release carbon dioxide and the oceans will become a source instead of a sink.

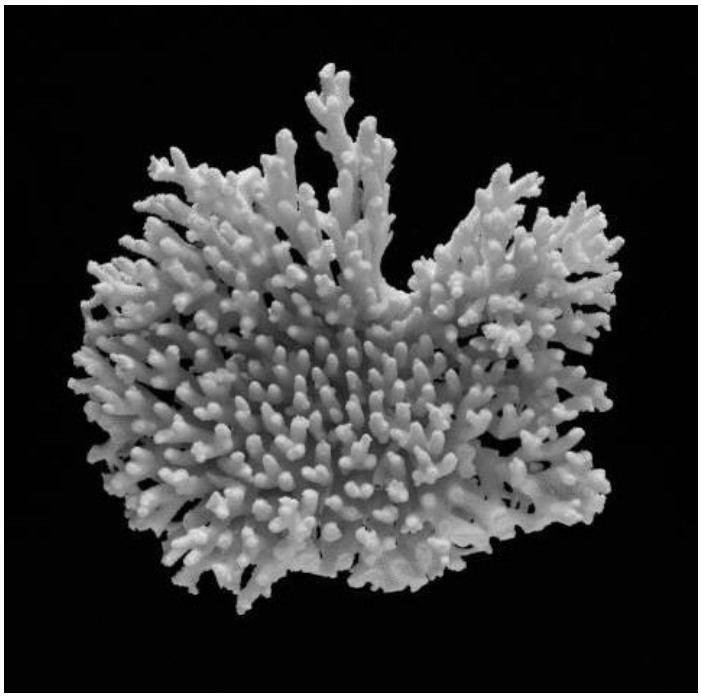
Ocean Acidification

Ocean acidification is a very alarming problem for Earth's oceans, and ultimately, life on Earth. As more carbon dioxide gas is absorbed in the ocean, the pH of the ocean decreases (becomes more acidic), which lowers the availability of the carbonate ions needed by organisms that build shells. This impact on organisms that build skeletons and shells out of calcium carbonate will profoundly affect ocean ecosystems and food webs. You will learn more about ocean acidification in the module on impacts of climate change.

Image Source: Microsoft Clip Art

Deposition as Carbonate Sediments

Rainwater dissolves atmospheric CO_2 producing carbonic acid. Carbonic acid also reacts with rock through chemical weathering to form bicarbonate ions (HCO_3^-) that are carried by groundwater and streams to the ocean. Marine organisms use bicarbonate and the calcium (Ca^{2+}) in seawater to produce the calcium carbonate ($CaCO_3$) that they need to make their shells, skeletons, and spines. A coral reef is one example—a coral reef is a huge colony of organisms that use calcium carbonate to build a hard outer skeleton.



Coral Skeleton – Image Source: Microsoft Clip Art

When marine organisms die, their remains slowly sink and reach the ocean floor. Over time, these organic materials are compressed by their own weight and other sediments, gradually changing into carbonate rock, such as limestone.

Formation of Fossil Fuels

Some carbon from organic matter is deposited as sediments. This carbon-rich sediment eventually is buried and can be changed into **fossil fuels** (coal, oil, or natural gas) over very long periods of time. Fossil fuels formed hundreds of millions of years ago during the Carboniferous Period (about 300 million years ago) before the dinosaurs roamed the planet.

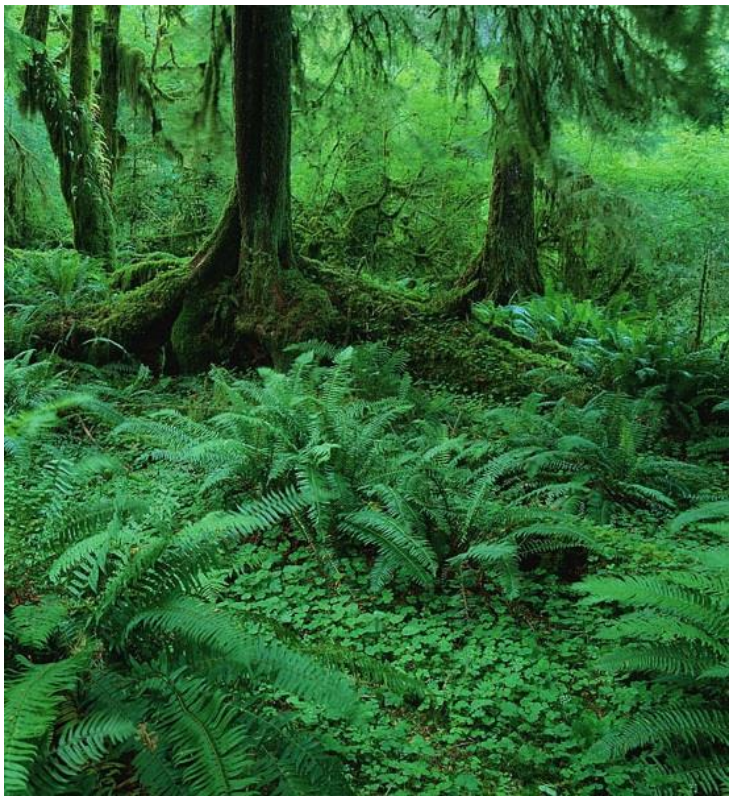


Image Source: Microsoft Clip Art

During this time, Earth was a much warmer and swampier place. When ancient marine organisms died, they decomposed and became buried under layers of mud, rock, sand, and shallow seas. Over the millions of years, these ancient plants and animals slowly decomposed and formed fossil fuels. **Coal** formed from the remains of trees, ferns, and plants in swampy areas. **Oil** and **natural gas** were created from organisms that lived in rivers or shallow seas. Heat, pressure, and bacteria acted to compress and change the organic material first into oil, and later into natural gas, which formed deeper underground.

Today, we are basically tapping energy that was originally stored hundreds of millions of years ago.

Watch Episode 2: Global Warming, It's All About Carbon.

NPR's Robert Krulwich and Odd Todd, in partnership with Wild Chronicles, present an animated cartoon series on the atom at the heart of global warming: carbon. Episode 2: Carbon's special knack for bonding.

Sources of Carbon Dioxide

Processes or regions that predominately produce atmospheric carbon dioxide (CO_2) are referred to as sources. Carbon dioxide is added to the atmosphere naturally when organisms respire or decompose (decay), carbonate rocks are weathered, forest fires occur, and volcanoes erupt. Carbon dioxide is also added to the atmosphere through human activities, such as the burning of fossil fuels and forests and the production of cement.

Image Source: Microsoft Clip Art

Respiration and Decomposition

You are probably familiar with respiration and the respiratory system. One definition of **respiration** is the exchange of oxygen and carbon dioxide between the blood of an animal and the environment. Carbon dioxide is released when organisms respire or breathe.

Respiration also takes place at the cellular level and often called **cellular respiration**. Every cell needs to respire to produce the energy it needs, and all plants and animals return both carbon dioxide and water vapor to the atmosphere through this process. The process of respiration produces energy for organisms by combining glucose with oxygen from the air. During cellular respiration, glucose and oxygen are changed into energy and CO_2. Therefore, CO_2 is released into the atmosphere during the process of cellular respiration.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + H_2O + \text{energy}$$

glucose + oxygen → carbon dioxide + water + energy

Respiration is also the process by which once-living (organic) organisms are decomposed. When organisms die, they are decomposed by bacteria. Carbon dioxide is released into the atmosphere or water during the decomposition process.

Limestone
Image Source: SFMWD

Weathering of Carbonate Rocks

Over geologic time, limestone may become exposed (due to tectonic processes or changes in sea level) to the atmosphere and to the weathering of rain. The carbonic acid that forms when carbon dioxide dissolves in water, in turn, dissolves carbonate rocks and releases carbon dioxide.

Burning of Fossil Fuels and Forests

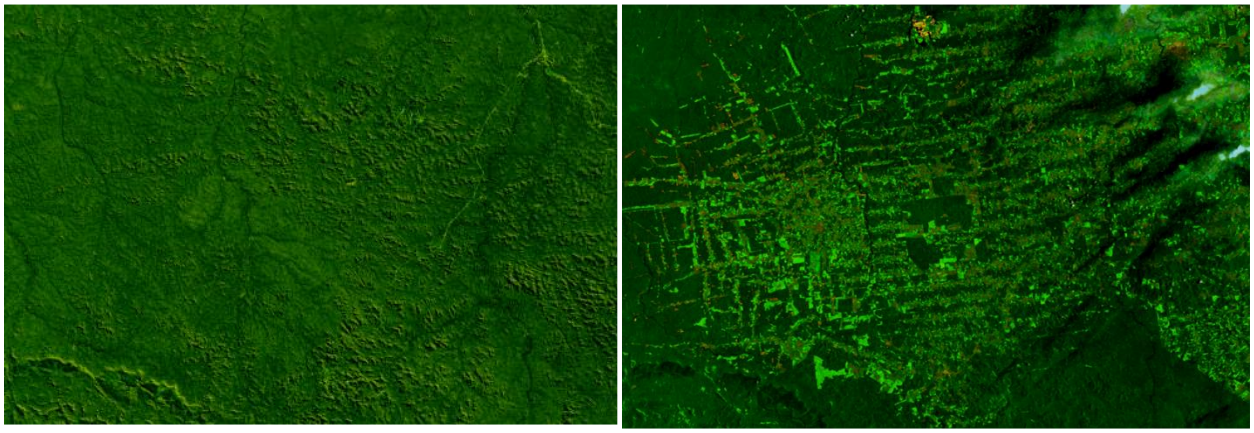
Carbon dioxide is added to the atmosphere by human activities. When hydrocarbon fuels (i.e. wood, coal, natural gas, and oil) are burned, CO_2 is released. During combustion or burning, carbon from fossil fuels combine with oxygen in the air to form CO_2 and water vapor.

Drilling for Oil – Image Source: Microsoft Clip Art

These natural hydrocarbon fuels come from once-living organisms and are made from carbon and hydrogen, which release CO_2 and water when they burn.

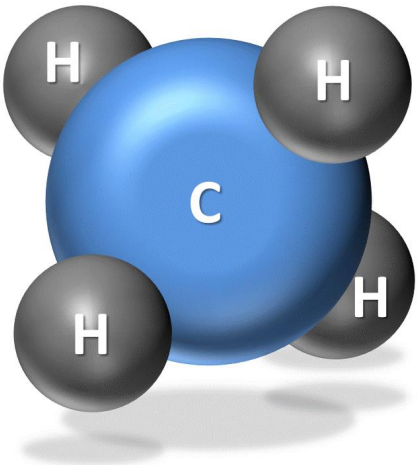
The burning of fossil fuels is occurring at a much higher rate than that of their production.

Not only does the burning of forests release carbon dioxide, but deforestation can also affect the concentration of CO_2 in the atmosphere. Because CO_2 is used by plants for photosynthesis, fewer trees result in more CO_2 being left in the atmosphere.



These two satellite images show changes in the topography due to deforestation in the Amazonian forest in Rondônia, Brazil. Image Source: NASA

Watch Episode 3: Global Warming, It's All About Carbon.
NPR's Robert Krulwich and Odd Todd, in partnership with Wild Chronicles, present an animated cartoon series on the atom at the heart of global warming: carbon. In episode 3: If you break a carbon bond -- presto! -- civilization.



Methane and the Carbon Cycle
Methane (CH_4) is also composed of one atom of carbon surrounded by four atoms of hydrogen. It is the principal component of natural gas and the second most important greenhouse gas of concern. You learned that a methane molecule is 30 times stronger than a molecule of carbon dioxide (CO_2), but methane is present in smaller concentrations and has a shorter lifetime than CO_2. Methane is the main component of natural gas. Methane enters the atmosphere and eventually combines with oxygen (oxidizes) to form more CO_2. Methane converts to CO_2 by this simple chemical reaction.

$$\mathbf{CH_4 + O_2 \rightarrow CO_2 + H_4}$$

methane + oxygen → carbon dioxide + hydrogen


Image Source: Microsoft Clip Art

Landfills, rice farming and cattle farming release methane into Earth's atmosphere. Methane is produced and emitted into the atmosphere when bacteria decompose organic plant and animal matter in such places at wetlands (e.g., marshes, mudflats, flooded rice fields), sewage treatment plants, landfills, and the guts of cattle and termites. Methane is also released into the atmosphere when natural gas pipelines and oil wells leak.

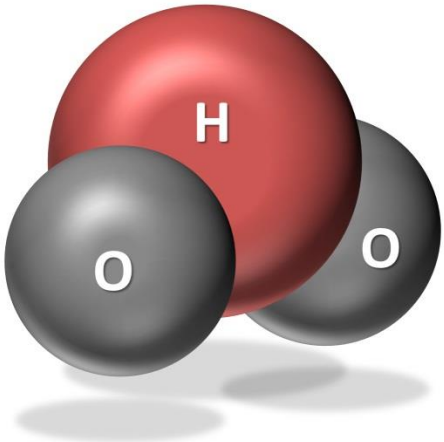
Permafrost

Permafrost is permanently frozen ground that traps moisture, heat, and trillions of tons of methane deep beneath the surface. Permafrost may be a thin as a few meters or as thick as more than 1,000 meters (3,281 feet). Vast regions of permafrost in Canada, Alaska, Siberia, and the Tibetan Plateau are starting to thaw. As permafrost melts, carbon dioxide or methane is released, further increasing the concentration of atmospheric greenhouse gases.

Watch NASA's The "Sleeping Giant" in Arctic Permafrost

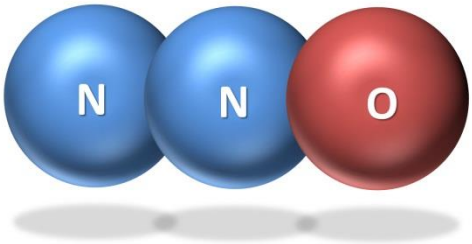
Other Greenhouse Gases

Other greenhouse gases include water vapor, halocarbons, nitrous oxides, and ozone. Water vapor is the strongest greenhouse gas. The amount of water vapor (H_2O) in the atmosphere is largely controlled by the temperature of the air and therefore varies from region to region. Warmer air can hold more moisture or water vapor. When the air becomes saturated (or holds as much water vapor as the air can at that temperature), the excess water vapor will condense into cloud droplets. If these droplets are large enough, they will fall as precipitation.

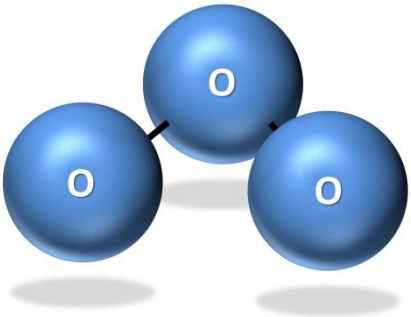


Water vapor plays an important role in the climate system. As air warms, it can hold more water vapor. In turn, more water vapor can absorb and re-emit more infrared radiation. Any process that acts to amplify (**positive feedback**) or lessen (**negative feedback**) the initial cause of the change in climate is known as a **climate feedback**. The water vapor feedback is known as a positive climate feedback because increased amounts of water vapor amplify the warming trend.

Halocarbons, which are composed of carbon, chlorine, fluorine, and hydrogen, include chlorofluorocarbons (CFCs). CFCs are synthetic gases that were used in cleaning solvents, refrigerants, and plastic foam.



Nitrous oxide (N_2O), a relatively long-lived gas, has increased in atmospheric concentration due mainly to agriculture. Nitrate (NO_3^-) and ammonia (NH_4^+) are used as fertilizers.



Bacteria convert a small amount of this nitrate and ammonia into the form of nitrous oxide. Internal combustion engines also produce nitrous oxide.

Ozone (O_3) is also a relatively minor greenhouse gas because it is found in relatively low concentrations in the troposphere (the lowest layer of the atmosphere). In the troposphere, it is produced by a combination of pollutants—mostly hydrocarbons and nitrogen oxide compounds.

Humans have been altering the land for at least 8,000 years. They extract and use fossil fuels for energy and clear forests for agricultural production and grazing land. They use shallow swampy areas to grow rice. Humans also build roads and buildings. It is estimated that 46% of Earth's land remains unmodified and most of this land is located in inhospitable regions of the planet. But how do we know if humans are causing climate change? In the following investigations, you will analyze several types of data to answer this question.

To learn more, proceed to the Investigations.