The Carbon Cycle

Carbon, just like all other elements, cycles through the environment and is constantly in the process of changing forms and locations. In this section, as in many other pieces of scientific literature, we will periodically refer to carbon by its chemical symbol, C. There is no new carbon in the world, rather, all carbon is continuously recycled from one form to another. All plants, animals (including humans!), fungi, bacteria, and archaea are made of mostly carbon-based molecules such as lipids, carbohydrates, proteins, and nucleic acids. Carbon is also prevalent in soils, rocks and sediments, water bodies (dissolved), and the atmosphere. These locations where carbon resides are known as pools or reservoirs, and the processes that move carbon from one location to another are called fluxes. Figure 7.1 shows a simplified version of the global carbon cycle.

Figure 7.1: A simplified carbon cycle. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System.
Some reservoirs hold on to carbon for only a short time. Aerobic (oxygen-using) organisms convert carbohydrates created by other organisms into carbon dioxide (CO₂) almost instantaneously, which they exhale into the atmosphere. When considering the flux of respiration, living organisms are the source of carbon, and the atmosphere is the sink. The carbon stays in the reservoir of living organisms for a relatively short time, depending on their life span, from hours and days to years and decades. In contrast, the residence time of carbon in the fossil pool is dramatically different. Fossil fuels form over a course of 300-400 million years, forming from ancient plants and animals that decomposed slowly under very specific, anaerobic (without oxygen) conditions in wetland environments. Their bodies were gradually transformed by the heat and pressure of the Earth’s crust into the fossil fuels that we mine today to provide petroleum oil, natural gas, and coal (see more on this in chapter 4).

Reservoirs and fluxes of importance
The two largest reservoirs of carbon on Earth are the oceans, which cover the majority of Earth’s surface, and the lithosphere (the mineral fraction of Earth: soils, rocks, and sediments). Each of these reservoirs holds more carbon than all of the other reservoirs combined. Much of the carbon stored in these reservoirs, especially deep in the lithosphere or in deep ocean environments, has an extremely long residence time, and does not actively participate in rapid fluxes. The notable exceptions here, of course, are fossil fuels, which are mined by humans and converted into gaseous forms of carbon through combustion.

Biomass, which is biological material derived from living, or recently living organisms, is a much smaller reservoir of carbon. The amount of carbon stored in all of the terrestrial vegetation (550 Gt C) (Gt = gigatonne = 10⁹ metric tons = 10¹⁵ g) is just a fraction of that stored in the oceans (38,000 Gt C) and lithosphere (18,000 Gt C). All of the carbon that is currently stored in all of the vegetation on Earth got there through the process of photosynthesis. Plants and other photosynthetic organisms are called primary producers, because they “fix” atmospheric CO₂ into organic carbon, such as sugar, a form that is usable by animals and other organisms that need to consume their carbon molecules.

Photosynthetic organisms, such as plants, algae, and cyanobacteria, bring in CO₂ from the atmosphere and, using energy from the sun, convert CO₂ and water into glucose molecules (organic carbon). The products of photosynthesis are oxygen and glucose (Equation 7.1). These glucose molecules are simple sugars that autotrophs (“self-feeders”) can “burn” for energy, or transform into other usable carbon molecules through the process of cellular respiration (described in the next paragraph), or to build plant biomass. Photosynthesis takes place in organelles called chloroplasts, shown in Figure 7.2. Photosynthesis accounts for 123 Gt of C per year that is removed from the atmosphere and stored in plant biomass. Such a massive amount of
photosynthesis occurs on Earth that no other single flux moves as much carbon in the same timeframe.

\[
6\text{CO}_2 + 6\text{H}_2\text{O} + \text{solar energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \quad \text{Eq. 7.1}
\]

**Figure 7.2:** Chloroplasts visible in freshwater algae. Chloroplasts are green in color due to the chlorophyll \(a\) they contain, and are the site of photosynthesis. Chlorophyll \(a\) is the green pigment that allows plants, algae, and cyanobacteria to absorb the energy they need for photosynthesis from sunlight. a) *Closterium moniliferum* Ralfs, (Chlorophyta) green coccoid algae; b) *Botryococcus braunii* Kützing, (Chlorophyta) green coccoid algae with discoid chloroplasts. Image credit: K. Manoylov, Lake Sinclair, GA

Biomass in the carbon cycle, including plants and animals, is the reservoir of carbon that we are most likely most familiar with, and also the reservoir that is most readily available to us. We all participate in the flux of **consumption** of carbon when we eat food. All of our food is simply plant and/or animal biomass. Our body takes the carbon molecules contained in this biomass, and uses them, along with the oxygen we breathe in, for **cellular respiration** to create the adenosine triphosphate (ATP) we need for energy. The products of cellular respiration include the \(\text{CO}_2\) we exhale, water, and energy that is stored in ATP (Equation 7.2). Our bodies also builds additional biomass out of the carbon molecules in this food, allowing us to create new cells for growth or replenishment. This is the only way we, and all other **heterotrophs** (“other-eaters”), can bring in the carbon we need to build and maintain our bodies. Remember, you are what you eat!

\[
\text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{energy} \quad \text{Eq. 7.2}
\]
Cellular respiration is an important flux in the carbon cycle, and one that contributes carbon to the atmosphere. Remember that animals and other heterotrophs complete cellular respiration using the carbon molecules that they bring in through their food. Plants and other photosynthetic autotrophs complete cellular respiration using the carbon molecules they formed from CO₂ through photosynthesis. Any carbon molecules that are left over after the organism has acquired sufficient energy through cellular respiration make up the biomass of the plant. As plants and animals die and decompose, their bodies are consumed by decomposer organisms such as fungi and bacteria. Through the flux of decomposition, some decaying biomass is converted into atmospheric carbon by the decomposers, while most of the biomass is buried into the soil, contributing to soil carbon. In oxygen-rich environments, decomposers rapidly consume dead and decaying biomass using the same process of aerobic cellular respiration described above. In oxygen-deficient environments, decomposers complete other metabolic pathways, and very slowly consume the organic matter. Some of the gases produced from anaerobic decomposition include methane (CH₄), nitrous oxide (N₂O), and the foul-smelling hydrogen sulfide (H₂S).

The biomass reservoir of the carbon cycle is also important to us as a source of energy. Through the flux of combustion, we convert the potential energy held in biomass into heat energy that we can use, and release carbon dioxide in the process. If you have ever burned logs on a campfire, or even burned food on the stove, you have completed this flux of biomass combustion. Of course, this happens naturally as well, the best example being natural forest fires caused by lightning strikes. The chemical reaction for combustion is identical to the chemical reaction for cellular respiration. The difference is that in cellular respiration, energy is released in a controlled fashion, and captured in ATP molecules. In combustion, all of this energy is released rapidly in the form of light and heat.

As all of the fluxes we’ve discussed so far involve the atmosphere, we have not yet discussed the flux that connects the atmosphere to the oceans. Carbon can enter the oceans through two primary fluxes: first through photosynthesis by algae or cyanobacteria (also called phytoplankton in Figure 7.1), and second through the chemical reaction of ocean-atmosphere exchange. The ocean, as with all surface water bodies, always contains some dissolved CO₂. This CO₂ is in equilibrium with the CO₂ in the air. Some atmospheric CO₂ is constantly dissolving into the ocean, while some dissolved CO₂ is constantly diffusing into the atmosphere. Under normal conditions, these two fluxes will be happening at equal rates. As you can see in Figure 7.1, however, this is no longer the case. In the section Human impacts on the carbon cycle, we will discuss why this is the case.

*Activity: Better understanding the carbon cycle*

To further review the carbon cycle, and better understand the human impacts on it, use this interactive graphic from Woods Hole laboratories: [http://www.whoi.edu/feature/carboncycle/](http://www.whoi.edu/feature/carboncycle/). As you will see, the information described in this text is only a small portion of the total carbon
cycle on Earth. Finally, complete Table 7.1 as a way to review the sink/source relationship within this cycle. See if you can correctly identify the source and sink of carbon for each of these important fluxes in the carbon cycle.

### Table 7.1. Practice understanding the sink/source relationship with cycles

<table>
<thead>
<tr>
<th>Carbon flux</th>
<th>Carbon source</th>
<th>Carbon sink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular respiration</td>
<td>Carbohydrates in living organisms</td>
<td>CO₂ in the atmosphere</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumption</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decomposition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean/atmosphere exchange</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil fuel formation</td>
<td></td>
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</tr>
</tbody>
</table>

**Human impacts on the carbon cycle**

Humans, just like all other living organisms, have impacted the global carbon cycle since the dawn of our species. However, the magnitude of our impacts has changed dramatically throughout history. The **Industrial Revolution**, which occurred around the turn of the 19th century, began to make major changes in the use of resources around the world. Beginning in Britain, industrialization eventually affected the whole world. The development of coal-fueled steam power, and later transportation following the discovery of large oil deposits, had enormous influence on the economic and social structure of the world. As the world accelerated in the production and transportation of manufactured goods, the production and consumption of fossil fuels grew. As economic growth continued to increase, so did the production of carbon dioxide
through fossil fuel combustion. See Figure 7.4 later in this text.

Some of the human impacts on the carbon cycle have been quantified for you in Figure 7.1. Changes to fluxes in the carbon cycle that humans are responsible for include: increased contribution of CO$_2$ and other greenhouse gases to the atmosphere through the combustion of fossil fuels and biomass; increased contribution of CO$_2$ to the atmosphere due to land-use changes; increased CO$_2$ dissolving into the ocean through ocean-atmosphere exchange; and increased terrestrial photosynthesis. The first two impacts, both contributing excess CO$_2$ to the atmosphere at a rate of 4 Gt of carbon per year have, by far, the largest impact on our planet. For this reason, this is the change that we will most often focus on throughout this section. The excess CO$_2$ in the atmosphere is responsible for the increased CO$_2$ dissolving into the ocean, which we will discuss later in this section. This is also, in part, responsible for the increased terrestrial photosynthesis that can be observed, as additional CO$_2$ is available to plants for photosynthesis. However, intensive agricultural and forestry practices also contribute to the change in this flux.

One characteristic example of a human impact on the carbon cycle is illustrated in Figure 7.3. Throughout most of our recent human history, people have been physically altering the landscape around them in order to have more control over their surroundings and increase their odds of survival. One way that people have done this is through agriculture. In order for most forms of agriculture to be successful, native vegetation is eliminated or minimized. Resources from this native vegetation, such as wood, may be used for combustion to provide heat, sanitation, or fuel for cooking. Combustion may also be used as an efficient way to clear the land and make way for crops or grazing lands for livestock. Often, settlements are formed around these newly fashioned agricultural fields, and the land is used in a similar fashion for many years in the future.

Let’s identify the ways in which humans are impacting the carbon cycle in this scenario of agricultural establishment. You should be able to identify from the above paragraph that the flux of combustion will release CO$_2$ previously held in vegetation into the atmosphere. In addition, remember that the land that used to house native vegetation is now home to agricultural lands. In most controlled agricultural environments, there is less total vegetative biomass than there would be under natural conditions. This decreased biomass leads to lower total photosynthesis rates, thereby decreasing the amount of CO$_2$ that is removed from the atmosphere and turned into plant biomass. Also, open soil on the fields between crops, during the winter months, or as a result of overgrazing allows for the air to penetrate deep into the soil structure. This provides the environment necessary for enhanced aerobic respiration by soil microorganisms. This decreases soil carbon, which can lead to erosion and soil degradation, and also releases additional CO$_2$ to the atmosphere.
As you learned in Chapter 5, biomass is an important form of energy to human civilization. Prior to the Industrial Revolution, this was essentially the only form of fuel to which most people on Earth had access. In many less-industrialized countries, combustion of biomass such as wood or animal dung is still the primary energy source that many citizens, particularly in rural areas, depend on for domestic use (heating, sanitation, and cooking) as it is inexpensive, relatively efficient, and readily available. Figure 7.3c shows the global distribution of biomass fires in the world. While the burning of biomass for domestic use contributes to some of these fires, it is the so-called slash-and-burn agriculture that makes up a larger contribution. Take a minute to compare the areas highlighted in Figure 7.3c to the countries of the world that are currently experiencing rapid population growth (Chapter 3). If you need a refresher, use the CIA World Factbook website to view current global population growth values by country: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2002rank.html.

While biomass burning still has a significant impact on the global carbon cycle, human impacts on fluxes such as fossil fuel extraction and combustion continue to grow. For a review of the impacts of non-renewable energy sources such as fossil fuels, see Chapter 4. Burning of any fossil fuel (coal, natural gas, crude oil) moves carbon from a previously-sequestered state deep within the Earth’s crust into carbon dioxide in the atmosphere. As countries become more industrialized, their reliance on and combustion of fossil fuels tends to increase. Look at the graph in Figure 7.4, which compares CO₂ emissions from fossil fuels of regions across the globe.

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How has the use and distribution of fossil fuels changed throughout the past 250 years?

Figure 7.4. Total annual CO\textsubscript{2} emissions from fossil fuel combustion 1850-2011 by global region. Data from the Carbon Dioxide Information Analysis Center (CDIAC) [http://cdiac.esd.ornl.gov/](http://cdiac.esd.ornl.gov/)

The data shown in Figure 7.4 reveals much about the regions of the world it depicts. The effects of historic events such as the Great Depression of 1929-1939, World Wars, the fall of the Soviet Union in 1991, and the Kuwait oil fires of 1991 can be seen. Furthermore, between 1850 and 2011, different regions have gone in and out of the lead position as top producer of CO\textsubscript{2} from fossil fuel emissions. Population is one reason why fossil fuel use has changed throughout time. This is particularly apparent when comparing the data for Western Europe to that of India and Southeast Asia.
As countries industrialize, their relationship with agriculture also changes. **More-industrialized countries** rely very little on slash-and-burn agriculture. Their agricultural practices, however, are no less impactful on the environment. The growing population (Chapter 3) in many countries has required agriculture to become industrialized in order to meet demand. As a person living in the United States, **industrialized agriculture** probably produces the vast majority of the food you eat, including grains, fruits and vegetables, dairy and eggs, meats, and even fish. Industrialized agriculture can refer to a variety of practices, but has several main components: the use of motorized machinery; the use of chemicals such as fertilizers, pesticides, hormones, and/or antibiotics; and the intense and efficient production of one product across a large area of land.

One example of the impacts of industrialized agriculture is the production of methane (CH\(_4\)), a potent greenhouse gas. You will learn more about methane later in this section. As you saw earlier, methane is a common product of anaerobic metabolisms. The gut of **ruminant animals** (such as sheep, cattle, and goats) has evolved to allow the animals to digest the very tough carbon molecules, such as cellulose, in grass. They do this through symbiosis, or cooperation, with anaerobic bacteria who live in the gut tract. These anaerobic bacteria produce methane and other gases as a result of their metabolism when they break down molecules like cellulose. This is sometimes called enteric fermentation. The methane gas is excreted from the animal, and this contributes significantly to total methane emissions (Figure 7.5). A similar type of bacteria live in the fecal matter, or manure, of livestock. As the manure is handled or stored for future use, methane is also released to the environment.

The methane excretions of one cow or a few sheep would be miniscule and insignificant. If you were a small farmer with only enough livestock to feed your family, your contribution to total methane emissions would be close to zero. However, the demand for animal protein from meat, dairy, and eggs is very large in the United States. As of January 2015, the United States had a

![Figure 7.5. US methane emissions by source.](image-url)

36% of the US methane production comes from agriculture: enteric fermentation (production of methane by anaerobic bacteria within the ruminant gut) and manure management. All emissions estimates from the Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2013. US EPA.
total cattle inventory of 89.9 million animals, and in 2014, 25.5 billion pounds of beef was consumed in the United States (statistics: National Cattlemen’s Beef Association). The impacts of enteric fermentation and manure management for almost 90 million animals are very significant, as seen in Figure 7.5. In both cases, carbon that was previously stored in biomass (cattle feed) is moved into the atmosphere, this time in the form of CH\(_4\). This is another example of how humans have impacted the carbon cycle.

Previously in this chapter, you identified other ways the carbon cycle is impacted by human agriculture. Through industrialized agriculture, we must also account for the fossil fuels that are used. In order to deliver agricultural products to consumers, fossil fuels are used numerous times: deliveries of fertilizer, feed, and/or seed to farms; farm machinery; delivery of products to processors; food processing; delivery of foods to super markets; etc.

As animal products, especially meat, are expensive, the demand is typically greater in more-industrialized countries than it is in less-industrialized countries. This makes industrialized agriculture, and especially industrialized animal agriculture, one of the major contributors to greenhouse gas emissions in more-industrialized countries.

Knowledge check – answer these questions on your own to further explore the impacts of biomass and fossil fuel burning on the global carbon cycle.

1. Why is there a correlation between population growth rate and global distribution of biomass fires?
2. Do you think this correlation is more likely due to personal biomass fires for activities such as cooking, or due to slash-and-burn agriculture? Why?
3. Given any other knowledge you might have about the areas highlighted in in Figure 7.3c, what other environmental impacts may be occurring here besides carbon cycle alterations?
4. Compare the production of CO\(_2\) emissions from fossil fuel combustion across world regions in 1900, 1950, and 2011 in Figure 7.4. What has accounted for these differences?
5. Has the total worldwide production of CO\(_2\) from fossil fuels increased evenly relative to human population growth during the time period displayed in Figure 7.4? Why or why not?
6. What are the differences in contributions of greenhouse gas emissions from more-industrialized countries and less-industrialized countries? What are the similarities?

Resources
Carbon Dioxide Information Analysis Center [http://cdiac.esd.orl.gov/](http://cdiac.esd.orl.gov/)
Sass, Ronald. *Q2: What are the Causes of Global Climate Change?* OpenStax CNX. Sep 22, 2009 [http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3](http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3)


**Terms list**

- Aerobic
- Anaerobic
- Autotroph
- Biomass
- Carbon
- Carbon dioxide
- Cellular respiration
- Chloroplast
- Combustion
- Consumption
- Decomposition
- Equilibrium
- Flux
- Greenhouse gas
- Heterotroph
- Industrial Revolution
- Industrialized agriculture
- Less-industrialized country
- Lithosphere
- Methane
- More-industrialized country
- Nitrous oxide
- Ocean-atmosphere exchange
- Photosynthesis
- Potential energy
- Primary producer
- Reservoir
- Residence time
- Ruminant animal
- Sink
- Slash-and-burn agriculture
- Source
The Science of Climate Change

What is causing global climate change?
Scientists have identified the source of our current global climate change as being the increased human-caused emissions of greenhouse gases such as carbon dioxide (CO$_2$), methane (CH$_4$), and nitrous oxide (N$_2$O), since the industrial revolution. Greenhouse gases are defined as large (at least three atoms) gas molecules that participate in the greenhouse effect. While you already know about the “big three” greenhouse gases (CO$_2$, CH$_4$, and N$_2$O), it’s important to realize that water vapor (H$_2$O) is also a greenhouse gas. While humans have little direct impact on water vapor concentrations in the atmosphere, is it still an essential component of the natural greenhouse effect that occurs in our atmosphere.

The Earth receives energy from the sun and in turn radiates energy back into space. When these two energies are equal, a stable temperature of the Earth is achieved. This temperature can be calculated from basic physics and is equal to about 18°C (0°F). This thermal equilibrium temperature is obviously much colder than that of the surface of the Earth. The actual average value of the Earth’s surface temperature is about 15°C (59°F). The difference between these temperatures is due primarily to the natural greenhouse gas concentrations in the atmosphere, causing the greenhouse effect. If the Earth had no naturally occurring atmospheric greenhouse gases, the temperature at the surface of the Earth would equal the thermal equilibrium temperature. The influence of these greenhouse gases, mainly water and some CO$_2$, moderates the Earth’s climate and makes life possible (Figure 7.6).

As solar radiation reaches the Earth’s atmosphere, there are a variety of possibilities for its fate. Some solar radiation is reflected by the Earth and its atmosphere, and does not contribute to warming. Some passes through the atmosphere and reaches the surface of the Earth. When this solar radiation is absorbed by objects on Earth’s surface, it is re-emitted as infrared radiation (heat) that escapes to space. However, some of this heat is intercepted in the atmosphere by greenhouse gases. These gases absorb and re-emit the radiation in all directions. This creates a warming impact on the Earth’s surface. Radiation can be bounced around from one greenhouse gas molecule to another, becoming trapped, and increasing its warming potential. For this reason, an increased greenhouse gas concentration causes an increase in the overall warming potential of the Earth’s atmosphere.

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Figure 7.6. This diagram shows the Earth's greenhouse effect. The Earth absorbs some of the energy it receives from the sun and radiates the rest back toward space. However, certain gases in the atmosphere, called greenhouse gases, absorb some of the energy radiated from the Earth and trap it in the atmosphere. These gases essentially act as a blanket, making the Earth’s surface warmer than it otherwise would be. While this greenhouse effect occurs naturally, making life as we know it possible, human activities in the past century have substantially increased the amount of greenhouse gases in the atmosphere, causing the atmosphere to trap more heat and leading to changes in the Earth’s temperature. Credit: US EPA
On a geological time scale, the climate has changed many times in the past, even before the presence of humans. These changes occurred naturally because man had not yet evolved. A well-known example of past climate change is the occurrence of ice ages. Ice ages have occurred repeatedly throughout Earth’s history, the most severe ice age of which scientists have reliable data occurred around 650,000 years ago. During this time, solid, glacial ice covered much of Canada, the northern United States, and northern Europe; the level of the ocean decreased 120 m, and the global average temperature decreased by 5°C.

A geologic history of ice events is preserved in the ice sheets covering Antarctica and Greenland. This history has been uncovered over the past decades by scientists who have cored deeply into the ice and deciphered the temperature and atmospheric composition records stored in the ice. This process of obtaining ice cores is shown in Figure 7.7. The temperature at which the ice originally formed can be obtained from an interpretation of the measured ratio of the stable isotopes (see Chapter 1 supplement for a description of isotopes) of oxygen in the molecules of water forming the ice. The atmospheric gas composition is taken from air bubbles trapped in the ice at the time of formation. From these data, scientists have gathered a set of reliable data that track atmospheric temperature and gas concentrations that dates back 800,000 years. These data helped scientists come to the conclusion that the Earth’s temperature and greenhouse gas concentrations are directly correlated to one another (Figure 7.8). During the ice age 650,000 years ago, the Earth was experiencing depressed temperature and atmospheric CO₂ concentrations below 200 parts per million (ppm). We can also see from these data, that CO₂ concentrations can be naturally elevated to as high as 300 ppm, correlating with increased temperatures.
Figure 7.8. Estimates of the Earth’s changing CO\textsubscript{2} concentration (top) and Antarctic temperature (bottom), based on analysis of ice core data extending back 800,000 years. Until the past century, natural factors caused atmospheric CO\textsubscript{2} concentrations to vary within a range of about 180 to 300 ppm. Warmer periods coincide with periods of relatively high CO\textsubscript{2} concentrations. NOTE: The past century’s temperature changes and rapid CO\textsubscript{2} rise (to 400 ppm in 2015) are not shown here. Source: Based on data appearing in NRC (2010).

The 100,000 year major cycle of the ice ages and some variations within the cycles agree very well with predicted periodic relationships between the Earth’s orbit around the sun, generally referred to as the **Milankovitch cycles**. Milankovitch cycles describe the very slight “wobbles” that occur in the Earth’s tilt and path as it moves around the sun. The Earth is always slightly tilted on its axis with respect to the sun. The angle of this tilt, however, changes periodically, varying from about 22° to about 25°. A less severe tilt will cause milder summers and winters close to the poles, preventing full summer ice melt in the northern- and southernmost regions, and allowing for a buildup of ice from year to year.
The path through which the Earth travels on its journey around the sun also changes from a more circular to a more elongated shape. Again, a round orbit will cause milder summers and winters close to the poles. These are very long term changes, and the results of the Milankovitch cycles can be observed in the changes in temperature and atmospheric CO₂ concentration shown in Figure 7.8. The climate change event that scientists are currently documenting is occurring much more rapidly than could be explained by Milankovitch cycles. Therefore, scientists agree that the cause of our currently changing climate is due to human impacts and not natural forces.

Greenhouse gases
We will be covering the four major categories of greenhouse gases that have been impacted by humans the most. See Table 7.2 for a numeric comparison of these greenhouse gases.

- Carbon dioxide, CO₂
- Methane, CH₄
- Nitrous oxide, N₂O
- Synthetic **fluorinated gases**, including **hydrofluorocarbons** (HFCs), **perfluorocarbons** (PFCs), and **sulfur hexafluoride** (SF₆)

Carbon dioxide (CO₂) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere of any of the greenhouse gases that we’ll discuss here. Remember that CO₂ is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically. Any time biomass or fossil fuels are burned, CO₂ is released. Major anthropogenic sources include: electricity production from coal-fired and natural gas power plants, transportation, and industry (Chapter 4). To get an idea of how CO₂ concentration has changed over time, watch this video compiled by the National Oceanic and Atmospheric Administration (NOAA): [http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html](http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html). This video contains atmospheric CO₂ concentrations measured directly, dating back to 1958, as well as atmospheric CO₂ concentrations measured indirectly from ice core data, dating back to 800,000 BCE. By 1990, a quantity of over seven billion tons of carbon (equivalent to 26 billion tons of carbon dioxide when the weight of the oxygen atoms are also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. Similar to the action of the naturally existing greenhouse gases, any additional greenhouse gases leads to an increase in the surface temperature of the Earth.

While CO₂ is produced by aerobic cellular respiration, gases such as CH₄ and N₂O are often the products of anaerobic metabolisms. Agriculture is a major contributor to CH₄ emissions, as you saw in section 7.1. In addition to anaerobic bacteria, methane is also a significant component of
natural gas, and is commonly emitted through the mining and use of natural gas and petroleum, in addition to coal mining. For a review of how fossil fuels are mined, see Chapter 4. Finally, **landfills** contribute significantly to CH\textsubscript{4} emissions, as the waste put into the landfill largely undergoes anaerobic decomposition as it is buried under many layers of trash and soil. Natural sources of CH\textsubscript{4} include swamps and wetlands, and volcanoes.

The vast majority of N\textsubscript{2}O production by humans comes from agricultural land management. While some N\textsubscript{2}O is naturally emitted to the atmosphere from soil as part of the nitrogen cycle, human changes in land management, largely due to agricultural practices, have greatly increased N\textsubscript{2}O emissions. Some N\textsubscript{2}O is also emitted from transportation and industry.

Due to their relatively high concentrations in the atmosphere compared to synthetic gases, CO\textsubscript{2}, CH\textsubscript{4}, and N\textsubscript{2}O, are responsible for most of the human-caused global climate change over the past century. Figure 7.9 shows the increases in all three gases following the industrial revolution. Ice core data (Figure 7.8) shows us that the atmospheric CO\textsubscript{2} concentration never exceeded 300 ppm before the industrial revolution. As of early 2015, the current atmospheric CO\textsubscript{2} concentration is 400 ppm. Comparing Figure 7.9 to Figure 7.8, above, what is likely to happen to global temperature following this unprecedented rise in greenhouse gas levels?

**Figure 7.9.** Increase in greenhouse gas concentrations in the atmosphere over the last 2,000 years. Increases in concentrations of these gases since 1750 are due to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. Source: USGCRP (2009)
One class of greenhouse gas chemicals that has no natural sources is the fluorinated gases. These include HFCs, PFCs, and SF$_6$, among others. Because these are synthetic chemicals that are only created by humans, these gases were essentially non-existent before the industrial revolution. These synthetic gases are used for a wide variety of applications, from refrigerants to semiconductor manufacturing, and propellants to fire retardants. They tend to have a long lifetime in the atmosphere, as seen in Table 7.2. Some of these chemicals, as well as the older chlorofluorocarbons (CFCs), have been phased out by international environmental legislation under the Montreal Protocol (see Chapter 6). Due to their long lifespan, many of these now-banned CFCs remain in the atmosphere. Newer chemical replacements, such as HFCs, provide many of the same industrial applications, but unfortunately have their own environmental consequences.

Just as greenhouse gases differ in their sources and their residence time in the atmosphere, they also differ in their ability to produce the greenhouse effect. This is measured by the global warming potential, or GWP, of each greenhouse gas. The GWP of a greenhouse gas is based on its ability to absorb and scatter energy, as well as its lifetime in the atmosphere. Since CO$_2$ is the most prevalent greenhouse gas, all other greenhouse gases are measured relative to it. As the reference point, CO$_2$ always has a GWP of 1. Note the very high GWP values of the synthetic fluorinated gases in Table 7.2. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH$_4$ and N$_2$O compared to CO$_2$. How does this impact the comparison of the environmental effects of agricultural practices in less-industrialized and more-industrialized countries that we completed in section 7.1?

Table 7.2. Comparison of common greenhouse gases in the atmosphere. Data from US EPA. For more information: [http://epa.gov/climatechange/ghgemissions/gases.html](http://epa.gov/climatechange/ghgemissions/gases.html)

<table>
<thead>
<tr>
<th>Greenhouse gas</th>
<th>Chemical formula or abbreviation</th>
<th>Lifetime in atmosphere</th>
<th>Global warming potential (100-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>CO$_2$</td>
<td>Variable</td>
<td>1</td>
</tr>
<tr>
<td>Methane</td>
<td>CH$_4$</td>
<td>12 years</td>
<td>28-36</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>N$_2$O</td>
<td>114 years</td>
<td>298</td>
</tr>
<tr>
<td>Hydrofluorocarbons</td>
<td>Abbreviation: HFCs</td>
<td>1-270 years</td>
<td>12-14,800</td>
</tr>
<tr>
<td>Perfluorocarbons</td>
<td>Abbreviation: PFCs</td>
<td>2,600-50,000 years</td>
<td>7,390</td>
</tr>
<tr>
<td>Sulfur hexafluoride</td>
<td>SF$_6$</td>
<td>3,200 years</td>
<td>22,800</td>
</tr>
</tbody>
</table>

Other climate influencers

In addition to greenhouse gases, other manmade changes may be forcing climate change. Increases in near surface ozone from internal combustion engines, aerosols such as carbon black, mineral dust and aviation-induced exhaust are acting to raise the surface temperature. This
primarily occurs due to a decrease in the **albedo** of light-colored surfaces by the darker-colored carbon black, soot, dust, or particulate matter. As you know, it is more comfortable to wear a white shirt on a hot summer day than a black shirt. Why is this? Because the lighter-colored material bounces more solar radiation back toward space than the darker-colored material does, allowing it to stay cooler. The darker-colored material absorbs more solar radiation, increasing its temperature. Just as the white shirt has a higher albedo than the black shirt, light-colored objects in nature (such as snow) have a higher albedo than dark-colored objects (such as soot or dust). As humans increase the amount of carbon black, soot, dust, and particulates in the atmosphere, we decrease the albedo of light-colored surfaces, causing them to absorb more solar radiation and become warmer than they would without human influence. An example of this can be seen in the snow on Figure 7.10.

![Figure 7.10](image)

**Figure 7.10.** A photograph of the extreme dust deposition from the deserts of the Colorado Plateau onto the Colorado Rockies snowpack in 2009. Taken from the high point of the Senator Beck Basin in the San Juan Mountains, it captures the extent of the impact of darkening in which the snow albedo dropped to about 30%, more than doubling the absorption of sunlight. Credit: S. McKenzie Skiles, Snow Optics Laboratory, NASA/JPL

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Tools scientists use to study climate change

Scientists must gather together all data that is available to them in order to make meaningful conclusions and predictions regarding climate change. When they bring these data together, the prediction they make is in the form of a scientific model. A model is a projection of what might happen in the future based on knowledge of current and past events. The models that are published to predict climate change must pass a rigorous scientific peer-review process, and often require the combination of findings of hundreds of experiments. These large-scale models are typically beyond the capacity of a standard desktop computer, and must be run by large super-computers housed at research universities or government laboratories. For more information on how scientists build and test models, follow the link below and click on the slideshow animation, paying special attention to the sections “Model Overview” and “Testing Models.” [http://www.epa.gov/climatechange/science/future.html](http://www.epa.gov/climatechange/science/future.html)

Figure 7.11. Observed and projected changes in global average temperature under three no-policy emissions scenarios. The shaded areas show the likely ranges while the lines show the central projections from a set of climate models. A wider range of model types shows outcomes from 2 to 11.5°F. Changes are relative to the 1960-1979 average. Source: USGCRP 2009
Figure 7.11 is one example of a scientific model of the impacts of climate change. Within this figure, we see the directly-measured observations of global average temperature (black line). We also see models of four different scenarios: 1900 to 2000 simulation using actual greenhouse emissions (green line), and 2000 to 2100 simulation using very high (purple line), high (red line), and low (blue line) greenhouse gas emissions scenarios.

Why did scientists make a model of the data from 1900 to 2000 in Figure 7.11 when they could just look up the data in published literature? This is an important component of model testing. In order to ensure accuracy of the model, you should not only be able to predict future events, but past events as well. Scientists use this as a way to “calibrate” their model. Since this model reliably predicts past events, chances are good that it will reliably predict future events as well.

Another example of a climate model is shown in Figure 7.12, this time comparing climate projections with and without the influences of humans on greenhouse gas emissions. This large model is a combination of the work of many different models, in order to achieve the most accurate outcome.

Figure 7.12. Comparison between observed average global temperatures and corresponding modeled temperatures with and without anthropogenic climate forces (IPCC, Working group 1, 2007).
In Figure 7.12, the decadal averages of observations are shown for the period 1906 to 2005 (black line). All temperatures are plotted relative to zero being defined as the corresponding average for the period from 1901 to 1950. The blue shaded band shows the 5% to 95% confidence interval for 19 simulations from 5 climate models using only the natural forcing effects due to solar activity and volcanoes. The red shaded band shows the 5% to 95% confidence interval for 58 different simulations from 14 climate models using both natural and anthropogenic forces. These different simulations and the different models are used by different scientific groups and represent different treatments of the Earth’s systems. It is thus quite encouraging that model calculations are in major agreement with the assumption that global temperature change from 1900 to 2000 is due to both natural and anthropogenic effects, with anthropogenic effects being the major causes in its recent dramatic increase.

You will see more examples of climate models as you make your way into the final section of the climate change chapter: consequences of climate change.

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Resources
NASA Global Climate Change: Vital Signs of the Planet http://climate.nasa.gov/


Sass, Ronald. Q2: What are the Causes of Global Climate Change? OpenStax CNX. Sep 22, 2009 http://cnx.org/contents/5d263a29-7bd6-47bf-ad70-c233619bca33@3

University of San Diego Virtual Museum: Climate Change http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml


Terms list
Albedo
Chlorofluorocarbon
Confidence interval
Fluorinated gases
Global warming potential
Greenhouse effect
Hydrofluorocarbon
Ice age
Ice core
Landfill
Milankovitch cycles
Model
Parts per million
Perfluorocarbon
Solar radiation
Stable isotopes
Sulfur hexafluoride
Thermal equilibrium
temperature
Water vapor
Consequences of Climate Change

As part of your assigned reading for this section, read the article “The Coming Storm” by Don Belt published in National Geographic:
http://ngm.nationalgeographic.com/print/2011/05/bangladesh/belt-text

In this section, we will discuss the effects of climate change, both those that have already been observed, as well as future predictions based on scientific climate models (see section 7.2 for a discussion of scientific models). Here, the differences between the terms global warming and climate change become apparent. Global warming refers to the increase in the average temperature of the Earth’s atmosphere due to elevated greenhouse gas concentrations, heightening the greenhouse effect. We have already observed this increase occurring, as you saw in Figure 7.12 from section 7.2. We have also seen, and expect to continue to see, other changes occurring in the climate of the Earth. Furthermore, changes have been observed, and we expect to continue to observe, changes in other chemical, physical, and biological aspects of the Earth’s environment. We will only discuss some of the consequences of climate change in this section, including changes in temperature, precipitation, ocean level, and ocean acidity. There are many more changes that have been seen, and are projected to continue in the future. These include: changes in the amount and distribution of ice and snow, changes in seasonality, ecosystem shift, and habitat changes of plant and animal populations, in addition to others. For more information about these consequence of climate change, visit this site:

Temperature and precipitation

Temperature and precipitation are the two most direct impacts on the Earth’s climate due to climate change. By now, you should already understand why an increase in greenhouse gas levels in the atmosphere causes an increase in temperature. But why does it also impact precipitation patterns? As you already know, water vapor is an important component of the Earth’s atmosphere (see Chapter 6). As the air in the troposphere warms and cools, the amount of water vapor that it holds changes dramatically. Here in Georgia, we have very hot and humid summers. The high summer humidity in this region is possible due to the increased capability warm air has to hold water vapor. Simply put, warmer air can hold more water than cooler air. As air cools, its ability to hold water vapor decreases, and any excess water will leave the air as liquid water. A great example of this is the formation of dew on surfaces overnight. During the day, the temperature is warmer than it is at night, and the air has a relatively high holding capacity for water vapor. When the sun sets, the air cools, decreasing its capacity to hold water vapor. That extra water must go somewhere, and it does that by accumulating on surfaces. Similarly, when warm and cool air fronts collide, the chances for rain and thunderstorms increase. Furthermore, an increase in temperature enhances evaporation occurring at the Earth’s
surface. This increased evaporation leads to greater concentrations of water vapor in the atmosphere which can lead to increased precipitation.

The change in temperature that we have already seen in the Earth’s average atmospheric temperature is relatively small (about 0.6 °C, according to Figure 7.12 from section 7.2). However, as with many of the aspects of climate change, the potential for greater changes increases dramatically as time progresses in the future. This can be seen in Figure 7.13, which displays a model of the predicted temperature increase. Notice that these changes occur relatively rapidly, and are not uniform across the globe. What might be some of the reasons for this?

![Figure 7.13](image)

**Figure 7.13.** Projected changes in global average temperatures under three emissions scenarios (rows) for three different time periods (columns). Changes in temperatures are relative to 1961-1990 averages. The scenarios come from the IPCC Special Report on Emissions Scenarios: B1 is a low emissions scenario, A1B is a medium-high emissions scenario, and A2 is a high emissions scenario. Source: IPCC Working Group I: The Physical Science Basis, 2007.

Changes in precipitation occur due to a variety of factors, including changes in atmospheric water vapor content due to changing temperature, as discussed above. Also at play is the heightened **evaporation** rate of water on Earth’s surface under warmer temperatures. More evaporation leads to more precipitation. Finally, shifts in wind patterns impact the distribution of precipitation events. As you can see in Figure 7.14, there are some areas of the globe that are expected to have an increase in precipitation, while others are expected to have a dramatic
decrease. Some major population centers projected to have a moderate to severe precipitation increase include (population estimates of the metropolitan area given in parentheses): New York, United States (20.1 million); Bogotá, Colombia (12.1 m.); and Manila, Philippines (11.9 m.).

What sort of challenges might these cities face in the future as they deal with this change in their climate?

Figure 7.14. Change in annual average precipitation projected by the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) by the GFDL CM2.1 model for the 21st century based on the A1B emissions scenario (see Figure 7.13). The plotted precipitation differences were computed as the difference between the 2081 to 2100 20-year averages minus the 1951 to 2000 50-year average. Blue areas project increases in precipitation; brown areas project decreases.

In contrast, many more major metropolitan areas are projected to have a moderate to severe precipitation decrease (droughts) by the end of the 21st century. These include Delhi, India (21.8 m.); Lagos, Nigeria (21 m.); São Paulo, Brazil (20.9 m.); Kolkata, India (14.6 m.); Istanbul, Turkey (14.4 m.); Los Angeles, United States (13.3 m.); Rio de Janeiro, Brazil (12 m.); Paris, France (12 m.); and Lahore, Pakistan (11.3 m.). The largest challenge that these areas are likely to face is a dwindling water supply for drinking and agriculture. See Chapter 8 for more detail on challenges faced by societies to supply clean, reliable water to their populations and farms.

Additional challenges may be felt by all areas of the world with regard to changes in the seasonality or timing of precipitation, as well the form in which precipitation falls (e.g., mist or downpour; rain, ice, or snow). All of these factors affect the availability of soil water for plants,
the flow of rivers and streams, and the overall accessibility of water worldwide. Furthermore, scientists predict an increase in the number and severity of storms as climate change progresses. For a full discussion of the potential impacts of this, see the assigned article.

*Sea level rise*

While we know that water continuously cycles around the world (see Chapter 8 for information on the water cycle), and that the overall quantity of water on Earth will not change due to global climate change, the distribution of this water is changing. In particular, oceans are increasing in volume while land ice stores (such as glaciers) are decreasing. This contributes to an increase in sea level worldwide (Figure 7.15).

![Global Average Absolute Sea Level Change, 1880–2014](image)

**Figure 7.15.** This graph shows average absolute cumulative changes in sea level for the world’s oceans since 1880, based on a combination of tide gauge measurements and recent satellite measurements. The shaded band shows the likely range of values, based on the number of measurements collected and the precision of the methods used.

From the data in Figure 7.15, we see that sea level has increased at an average of 0.06 inches (0.15 cm) per year over the time period shown above. Most of this rise, however, has occurred within the most recent decades. The rate of increase has gone up to between 0.11 to 0.14 inches
There are two forces causing sea level to rise, both caused by climate change. First, the increased global temperature has caused increased ice melting in many regions of the globe. Melting land ice (such as the glacier shown in figure 7.16) contributes to sea level rise because water that used to be stored in ice sitting on top of land becomes running water which reaches the ocean through runoff. We also observe sea ice melting (see http://www.epa.gov/climatechange/science/indicators/index.html for data and figures). Sea ice, such as the ice that covers the arctic regions of the Northern Hemisphere, has no land underneath it. When it melts, the water stays in the same locations, and the overall sea level does not change.

The second factor that influences sea level rise is a phenomenon called thermal expansion. Due to the physical properties of water, as water warms, its density decreases. A less dense substance will have fewer molecules in a given area than a more dense substance (see Chapter 1 supplemental material). This means that as the overall temperature of the oceans increases due to global climate change, the same amount of water molecules will now occupy a slightly larger volume. This may not seem significant, but considering the 1.3 billion trillion liters (264 billion gallons) of water in the ocean, even a small change in density can have large effects on sea level as a whole.

Scientists have already documented sea level rise in some areas of the world, including one familiar to most of us: the Southeastern United States. Figure 7.17 depicts the measured land area lost due to increasing sea level since 1996. Note that the Southeast (defined here as the
Atlantic coast of North Carolina south to Florida) is particularly susceptible to land area loss due to the gently sloping nature of our coastline. Moving northward into the Mid-Atlantic States (defined here as Virginia north to Long Island, New York), coastal habitats tend to have a steeper geography, which protects against some losses.

![Figure 7.17](image)

**Figure 7.17.** This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011. The results are divided into two regions: the Southeast and the Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new land.

While the ecological effects of sea level rise remain in the United States, we don’t project any catastrophic loss of life, property, or livelihood for some time. This is, in part, due to large investments that we have made in infrastructure to protect our cities and farmlands. This is not the case in many areas of the world. For a discussion of the impacts of sea level rise on less-industrialized nations of Bangladesh, Maldives, Kiribati, and Fiji, review the required article reading.

**Ocean acidification**

Dissolved CO$_2$ is essential for many organisms, including shell-building animals and other organisms that form a hard coating on their exterior (e.g., shellfish, corals, Haptophyte algae). This hard coating is built out of aragonite, a mineral form of the molecule calcium carbonate,
CaCO₃. These organisms rely on the formation of carbonate ions (see Chapter 1 supplemental material for information on ions), CO₃²⁻, from dissolved CO₂, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where bicarbonate (HCO₃⁻) is formed as an intermediate, and hydrogen ions (H⁺) are generated (equations 7.3 and 7.4).

\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{HCO}_3^- \quad \text{Eq. 7.3}
\]

\[
\text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-} \quad \text{Eq. 7.4}
\]

To have a better visualization of this process, follow along with the interactive graphic at: http://www.whoi.edu/home/oceanus_images/reefcalcification.html.

As you can see, both equations 7.3 and 7.4 each produce one H⁺. This is significant to water chemistry because an increase in H⁺ concentration means a decrease in the pH of the water. You can see in Figure 7.18 that a lower pH means that the liquid is more acidic. As shown in the interactive graphic, an increase in CO₂ in the atmosphere causes additional CO₂ to be dissolved in the ocean. This means that more CO₂ in the atmosphere leads to more acidic ocean environments.

Unfortunately for shell-building animals, the buildup of H⁺ in the more acidic ocean environment blocks the absorption of calcium and CO₃²⁻, and makes the formation of aragonite more difficult. An aragonite deficit is already being documented in many of the world’s oceans, as shown in Figure 7.19.

The increasing acidity of the world’s oceans is resulting in habitat changes across the globe. This is only expected to worsen as atmospheric CO₂ levels continue to increase. Many organisms, including the corals that are the foundation species of the beautiful coral reefs, are very sensitive to changes in ocean pH. Scientists have documented cases of ecosystem destruction through coral bleaching, caused by the effects of climate change including ocean acidification and increased temperature. For

**Figure 7.18.** The pH scale and relative acidity. Illustration from Anatomy & Physiology, Connexions Web site. http://cnx.org/content/col11496/1.6/, Jun 19, 2013.
more information, visit the NOAA Coral Reef Conservation Program website: http://coralreef.noaa.gov/threats/climate/.

Figure 7.19. This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the most recent decade (2004–2013). Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

Looking Forward: Climate Solutions
While the situation surrounding global climate change is in serious need of our attention, it is important to realize that many scientists, leaders, and concerned citizens are making solutions to climate change part of their life’s work. The two solutions to the problems caused by climate change are mitigation and adaptation, and we will likely need a combination of both in order to prosper in the future.

Adaptation strategies
We know that climate change is already occurring, as we can see and feel the effects of it. For this reason, it is essential to also adapt to our changing environment. This means that we must
change our behaviors in response to the changing environment around us. Some adaptation strategies are discussed in the required article reading.

Adaption strategies will vary greatly by region, depending on the largest specific impacts in that area. For example, in the city of Delhi, India, a dramatic decrease in rainfall is projected over the next century (Figure 7.14). This city will likely need to implement policies and practices relating to conservation of water, for example: rainwater harvesting, water re-use, and increased irrigation efficiency. Rain-limited cities near oceans, such as Los Angeles, California may choose to use desalination to provide drinking water to their citizens. Desalination involves taking the salt out of seawater to make it potable (Chapter 8).

Cities with low elevations near oceans may need to implement adaptation strategies to rising sea levels, from seawalls and levees to relocation of citizens. One adaptations strategy gaining use is the creation or conservation of wetlands, which provide natural protection against storm surges and flooding.

**Mitigation strategies**

In general, a strategy to mitigate climate change is one that reduces the amount of greenhouse gases in the atmosphere or prevents additional emissions. Mitigations strategies attempt to “fix” the problems caused by climate change. Governmental regulations regarding fuel efficiency of vehicles is one example of an institutionalized mitigation strategy already in place in the United States and in many other countries around the world. Unlike some other countries, there are no carbon taxes or charges on burning fossil fuels in the United States. This is another governmental mitigation strategy that has been shown to be effective in many countries including India, Japan, France, Costa Rica, Canada, and the United Kingdom.

In addition to government measures and incentives, technology can also be harnessed to mitigate climate change. One strategy for this is the use of carbon capture and sequestration (CCS). Through CCS, 80-90% of the CO$_2$ that would have been emitted to the atmosphere from sources such as a coal-fired power plant is instead captured and then stored deep beneath the Earth’s surface. The CO$_2$ is often injected and sequestered hundreds of miles underground into porous rock formations sealed below an impermeable layer, where it is stored permanently (Figure 7.20).
Scientists are also looking into the use of soils and vegetation for carbon storage potential. Proper management of soil and forest ecosystems has been shown to create additional carbon sinks for atmospheric carbon, reducing the overall atmospheric CO$_2$ burden. Increasing soil carbon further benefits communities by providing better-quality soil for agriculture and cultivation.

Technologies related to alternative energy sources (Chapter 5) mitigate climate change by providing people with energy not derived from the combustion of fossil fuels. Finally, simple activities such as energy conservation, choosing to walk or bike instead of driving, and disposing of waste properly are activities that, when done by large numbers of people, actively mitigate climate change by preventing carbon emissions.

Take a moment to identify ways that you personally can be involved in the mitigation of or adaptation to climate change. What changes can you make in your own life to prevent excess carbon emissions? Similar to your ecological footprint, which you should have already calculated in lab, you can also calculate your **carbon footprint**. Use the EPA’s carbon footprint
calculator to do so, and investigate the Reduce Your Emissions section to find ways to decrease your carbon footprint.

Resources


NOAA Coral Reef Conservation Program: Climate Change http://coralreef.noaa.gov/threats/climate/

NOAA Geophysical Fluid Dynamics Laboratory: Will the wet get wetter and the dry drier? http://www.gfdl.noaa.gov/will-the-wet-get-wetter-and-the-dry-drier


US EPA Carbon Dioxide Capture and Sequestration http://www.epa.gov/climatechange/ccs/


Terms list
Acidity          Climate          pH
Adaptation      Climate change  Precipitation
Aragonite       Coral bleaching Runoff
Bicarbonate     Desalination    Sea ice
Calcium carbonate Evaporation   Thermal expansion
Carbon capture and sequestration Glacier Wetland
Carbon footprint Hydrogen ions
Carbon tax      Land ice
Carbonate       Mitigation