Chapter 6: Climate Change and the Carbon Cycle

Image depicting stark contrast between two landscapes, a lush green area representing thriving ecosystems, and a cracked barren soil representing ecosystem collapse, symbolizing the impacts of climate change.

Learning Outcomes

By the end of this chapter, students will be able to:

1. List the major carbon reservoirs on Earth, and identify how carbon flows from one reservoir to another.
2. Describe ways in which humans are impacting multiple portions of the carbon cycle.
3. Describe the causes and consequences of global climate change.
    a. List the major greenhouse gases and identify their sources and impacts.
    b. Describe the effects of climate change on ecosystems.
    c. Evaluate the impacts of climate change from the viewpoint of diverse groups of people across the world.
4. Describe how scientists use models to study climate change.
5. Identify methods of climate remediation, including carbon sequestration.

Contents

6.1 The Carbon Cycle

The carbon cycle is governed by the law of conservation of matter, which states that matter cannot be created or destroyed. Carbon is, therefore, continually exchanged among Earth's systems in a process called the **carbon cycle (Figure 1)**. The locations where carbon resides are known as carbon pools or **reservoirs**, and the physical, chemical, and biological processes that move carbon from one pool to another are called **fluxes**. As carbon is continuously recycled between reservoirs, it changes form, for example as carbon dioxide gas (CO_2) in the air, organic molecules (carbohydrates, proteins, lipids) in living things, or carbonate minerals in geologic materials. In any flux, the **source** is the reservoir losing carbon, and the **sink** is the reservoir gaining carbon. In the sections below we explore the primary fluxes responsible for transferring carbon among Earth's reservoirs.

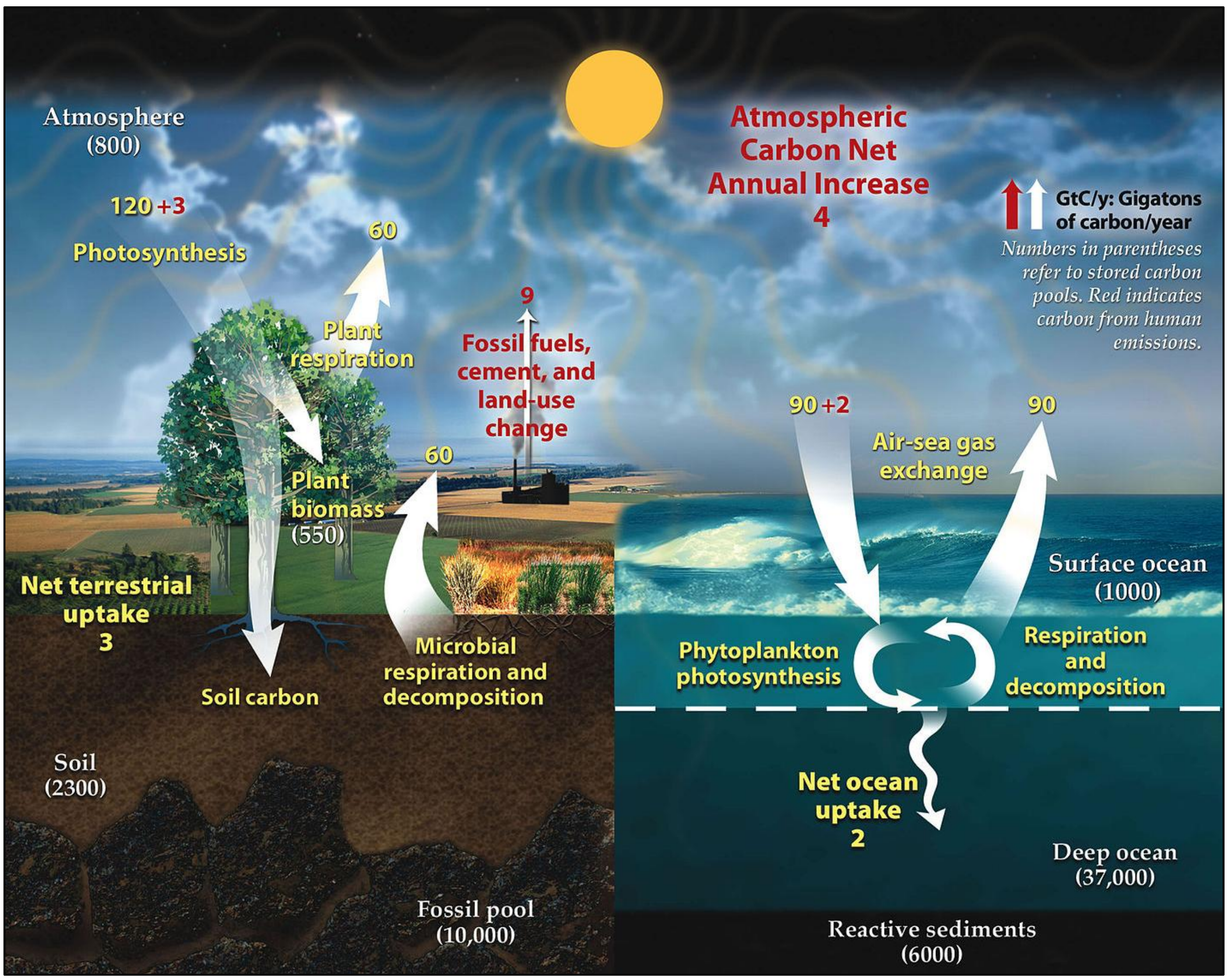


Figure 6.1: A simplified carbon cycle. Diagram adapted from U.S. DOE, Biological and Environmental Research Information System, public domain, https://scied.ucar.edu/image/carbon-cycle-diagram-doe-numbers

6.1.1 Major Carbon Reservoirs

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 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**, meaning it remains in place for thousands to millions of years and does not participate in rapid fluxes. A notable exception is **fossil fuels**, which formed over 300–400 million years under anaerobic conditions in wetlands. Heat and pressure transformed ancient plant and animal remains into coal, petroleum, and natural gas. Today, humans extract and burn these fuels, releasing carbon back into the atmosphere as CO_2 (See Chapter 3).

All living things on Earth [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 gas and solid particulate matter), and the atmosphere. Some reservoirs hold on to carbon for only a short time. **Aerobic** (oxygen-using) organisms convert carbohydrates created by other organisms into CO_2 almost instantaneously, which they exhale into the atmosphere. 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.

6.1.2 Photosynthesis and Terrestrial Uptake

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 = 10^9 metric tons = 10^{15} g) is just a fraction of that stored in the oceans and lithosphere. All of the carbon that is currently stored in all of the vegetation on Earth got there through the flux of **photosynthesis**. Plants and other photosynthetic organisms are called **primary producers**, because they make the food that is usable by animals and other organisms that need to consume their carbon molecules.

In photosynthesis, organisms such as plants, algae, and cyanobacteria, bring in CO_2 from the atmosphere and, using energy from the sun, convert CO_2 and water into glucose molecules (organic carbon). The products of photosynthesis are oxygen and glucose (**Equation 6.1**). 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 section), or to build plant biomass. Photosynthesis takes place in organelles called **chloroplasts**, shown in **Figure 6.2**. 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 that much carbon in the same timeframe.

$$6CO_2 + 6H_2O + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2 \qquad \textbf{Equation 6.1}$$

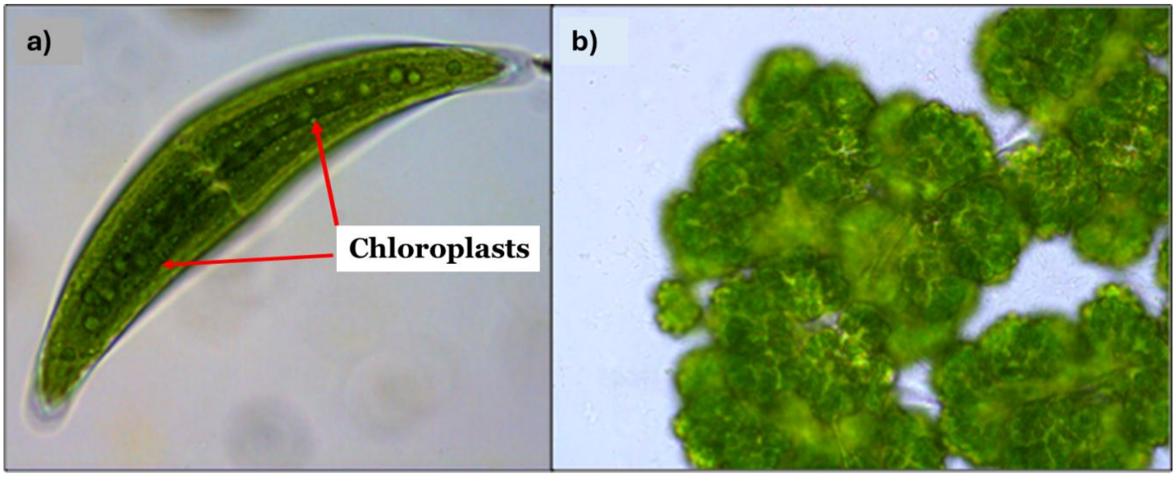


Figure 6.2: Chloroplasts visible in freshwater algae. Chloroplasts are green in color due to the chlorophyll *a* they contain and are the site of photosynthesis. Chlorophyll *a* is the green pigment that allows plants, algae, and cyanobacteria to absorb the energy they need for photosynthesis from sunlight. a) *Closterium moniliferum* Ralfs, (Chlorophyta) green coccoid algae; b) *Botryococcus braunii* Kutzing, (Chlorophyta) green coccoid algae with discoid chloroplasts. Image credit: K. Manoylov, Lake Sinclair, GA

6.1.3 Consumption, Respiration, and Decomposition

Biomass (plants, animals, and other living organisms) is a familiar carbon reservoir and the one most accessible to us. When we eat food, we participate in the **consumption** flux: transferring carbon from plant or animal biomass into our own bodies. All food is essentially carbon-based organic matter, and the process of consumption is only a physical process that transfers carbon from one living organism to another.

Once consumed, our bodies use these carbon molecules in two ways: First is **building biomass** - carbon from food becomes part of our tissues, allowing growth and repair. 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*! Second is **energy production** - carbon molecules are broken down during **cellular respiration**, a biochemical process that occurs inside cells. In cellular respiration, carbon compounds (such as glucose) react with oxygen to produce **ATP** (adenosine triphosphate), the energy currency of the cell. The byproducts are carbon dioxide (CO_2), which we exhale, and water (**Equation 6.2**).

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \qquad \textbf{Equation 6.2}$$

It's important to distinguish between *cellular respiration* and *respiration*. **Cellular respiration** refers to the chemical reactions inside cells that convert food molecules into ATP, releasing CO_2 and water as waste. Animals and other heterotrophs complete cellular respiration using the carbon molecules that they bring in through the food they consume. Plants and other photosynthetic autotrophs complete cellular respiration using the carbon molecules they formed from CO_2 through photosynthesis. **Respiration** refers to the act of breathing, taking in oxygen from the air and releasing CO_2 back into the atmosphere.

When living things die, their biomass is 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 (anaerobic = without oxygen), and very slowly consume the organic matter. Some of the gases produced from anaerobic decomposition include **methane** (CH_4), **nitrous oxide** (N_2O), and the foul-smelling hydrogen sulfide (H_2S).

6.1.4 Combustion

Combustion is a chemical reaction in which a substance, such as fossil fuel or biomass, reacts rapidly with oxygen to release energy in the form of heat and light, producing carbon dioxide and water as primary products. Through combustion, we convert the **potential energy** held in biomass and in fossil fuels into heat energy that we can use. When you burn logs on a campfire, burn food on the stove, or drive a gasoline vehicle, you have completed this flux of combustion. Combustion also happens naturally, for example, forest fires caused by lightning strikes. The chemical reaction for combustion is identical to the chemical reaction for cellular respiration (**Equation 6.2**). 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.

6.1.5 Ocean-Atmosphere Exchange

Carbon can enter the oceans through two primary fluxes: first through photosynthesis by algae (also called phytoplankton in **Figure 6.2**), and second through the physical process of **ocean-atmosphere exchange** driven by differences in partial pressure between the atmosphere and the ocean surface. The ocean, as with all surface water bodies, always contains some dissolved CO_2. This CO_2 is in **equilibrium** with the CO_2 in the air. Some atmospheric CO_2 is constantly dissolving into the ocean, while some dissolved CO_2 is constantly diffusing into the atmosphere. Under normal conditions, these two fluxes will be happening at equal rates. As you can see in **Figure 6.1**, however, this is no longer the case. In the next section *Human impacts on the carbon cycle*, we will discuss why this is the case.

6.1.6 The Carbon Cycle and Climate Change

The carbon cycle is central to Earth's climate system because it regulates the amount of carbon dioxide (CO_2) in the atmosphere, a key greenhouse gas. Greenhouse gases trap heat in the atmosphere, contributing to warming. When carbon moves naturally among reservoirs like the atmosphere, oceans, soils, and living organisms, the cycle maintains a balance that keeps Earth's climate relatively stable. Human activities, however, disrupt this balance by transferring large amounts of carbon from long-term storage in fossil fuels into the atmosphere through combustion. This rapid increase in atmospheric CO_2 traps more heat, driving global warming and altering weather patterns, ocean chemistry, and ecosystems. By understanding the carbon cycle, we can see how everyday actions such as burning fuel or clearing forests affect global climate, and why managing carbon flows is essential for reducing climate change impacts.

Key points: Carbon cycle basics

1. Carbon moves between the atmosphere, oceans, soil, and living organisms.
2. Main processes that transform and move carbon are: **photosynthesis**, **cellular respiration**, **decomposition**, **ocean absorption**.
3. Plants absorb CO_2 from the atmosphere; animals and microbes release CO_2 to the atmosphere.

6.1.7 Activity: Better Understanding of 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/. As you will see, the information described above is only a small portion of the total carbon cycle on Earth. Finally, complete **Table 6.1** 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 6.1. Practice understanding the sink/source relationship with cycles

Cabon flux	Carbon source	Carbon sink
Photosynthesis		
Cellular respiration		
Consumption		
Combustion		
Decomposition		
Ocean-atmosphere exchange		
Fossil fuel formation		

Test your knowledge…

1. *Explain how photosynthesis, cellular respiration, combustion, and decomposition move carbon (what's the source and what's the sink?).*
2. *Which process(es) remove CO_2 from the atmosphere?*
3. *Which two reservoirs store the largest amount of carbon?*
4. *Thinking of the atmosphere, which of the components listed here are **sinks** and which are **sources**? Forests, the ocean, animals, factories, forest fires, fungi*

6.2 Humanity's Impact on the Carbon Cycle

Human activities have become one of the most significant forces shaping the global carbon cycle. While natural processes have always moved carbon among Earth's reservoirs, the scale and speed of human-driven changes are unprecedented. From the clearing of forests for agriculture to the burning of fossil fuels for energy, these actions have altered carbon fluxes in ways that impact climate, ecosystems, and even ocean chemistry. Some of the human impacts on the carbon cycle have been quantified for you in **Figure 6.1** shown in red. 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.

6.2.1 Historical Shifts

Humans have influenced the carbon cycle for thousands of years, but the scale of our impact has grown dramatically over time. Human activities such as burning fossil fuels and deforestation have significantly increased atmospheric CO_2 levels (**Figure 6.3**). Methane emissions from agriculture and nitrous oxide from fertilizers further amplify the greenhouse effect. 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. 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. These changes accelerated fossil fuel combustion, moving carbon from deep within Earth's crust into the atmosphere as CO_2. Beginning in Britain, industrialization eventually affected the whole 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.

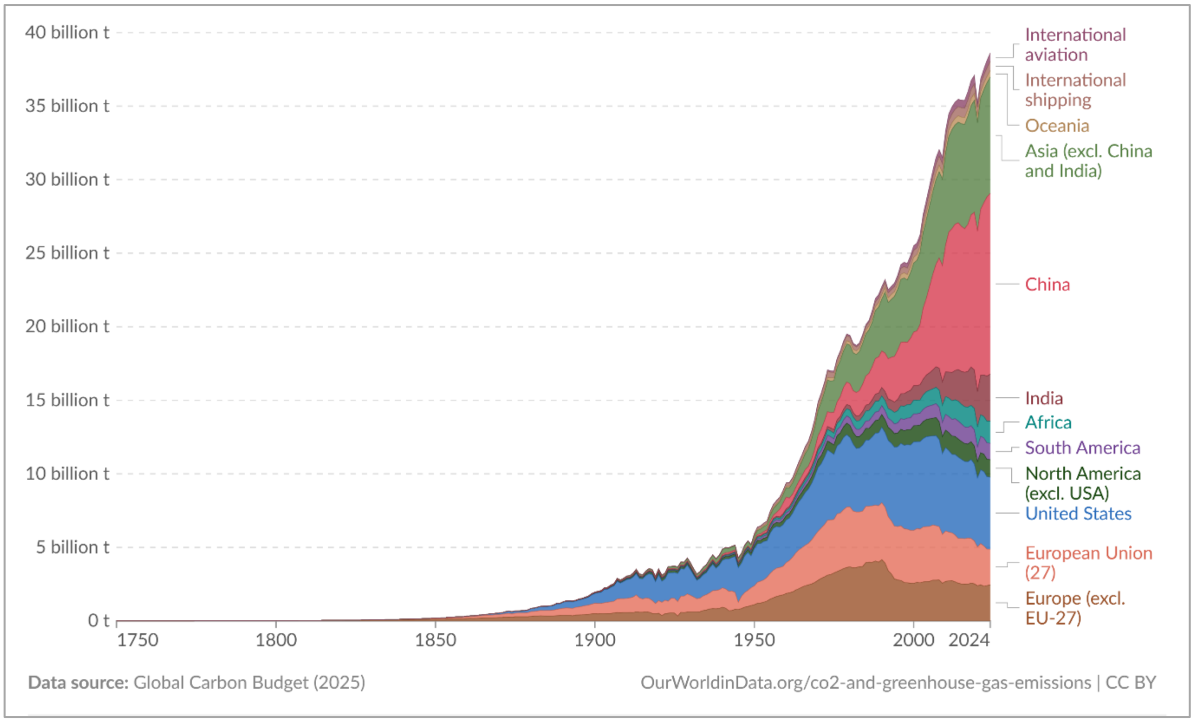


Figure 6.3. Annual CO_2 emissions by world regions. Published online at OurWorldinData.org. (Source: CO2 emissions Our World in Data)

The data shown in **Figure 6.3** 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 producers of CO_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.

6.2.2 Agricultural Practices and Land-Use Changes

When agricultural land is established, several changes affect the carbon cycle. First, burning vegetation during land clearing releases carbon dioxide (CO_2) that was previously stored in plants into the atmosphere. Second, replacing native vegetation with crops reduces overall plant biomass compared to natural ecosystems. This lower biomass means less photosynthesis occurs, reducing the amount of CO_2 removed from the atmosphere and stored in plants. Additionally, exposed soil, like between crop cycles, during winter, or due to overgrazing, allows air to penetrate deeper into the soil. This promotes aerobic respiration by soil microorganisms, which breaks down soil organic matter. As a result, soil carbon decreases, increasing the risk of erosion and degradation, while releasing more CO_2 into the atmosphere.

One characteristic example of a human impact on the carbon cycle is illustrated in **Figure 6.4**. 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.

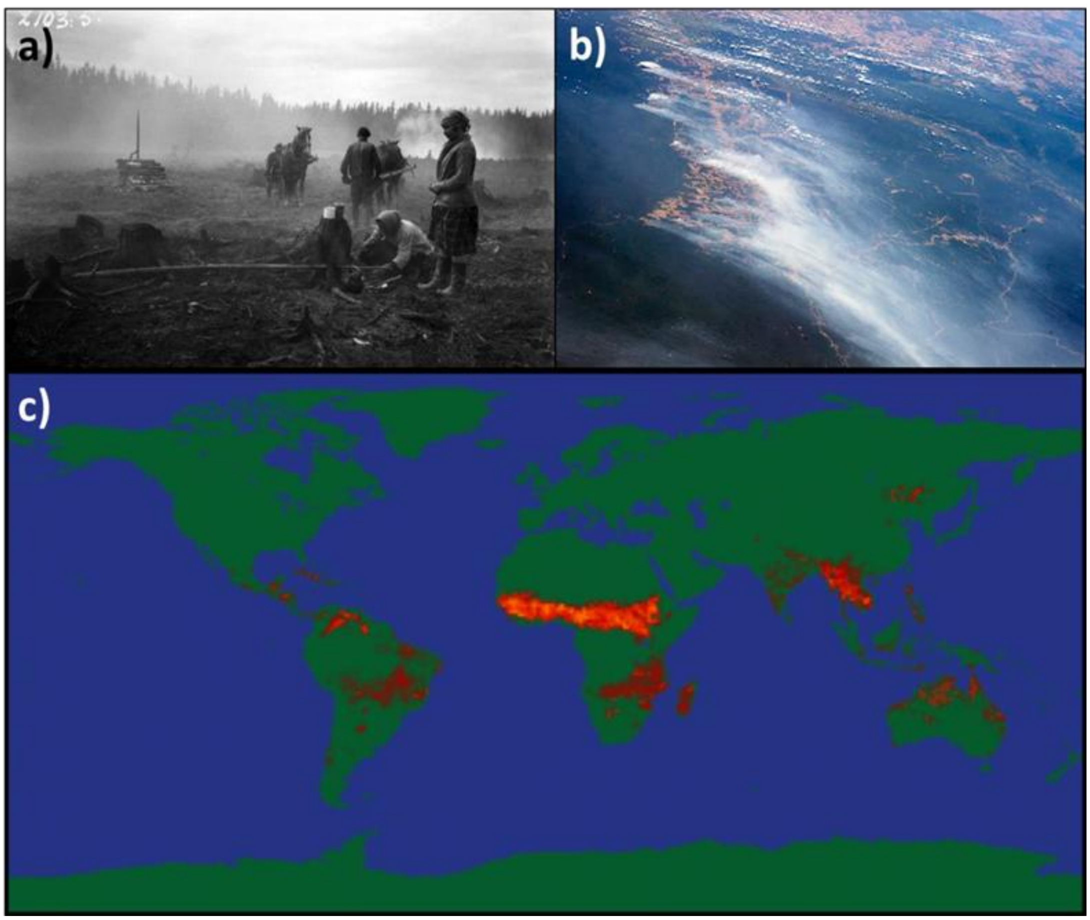


Figure 6.4. Impacts of slash and burn agriculture and biomass burning. a) Slash and burn agriculture in Maaninka, Finland. This kind of agriculture was still in use in Finland at the end of the 1920s. b) Slash and burn agriculture at the margins of the Amazon Rainforest in South America captured by astronauts on the International Space Station in August, 2014 Credit: astronaut photograph ISS040-E-103496. c) Global distribution of biomass fires, represented by red orange, and yellow dots (lighter colors indicate more fires), based on nighttime measurements obtained by the DMSP Operational Linescan System. Credit: Julia Cole, NASA Earth Observatory

As discussed in Chapter 4, biomass has long been an essential energy source for human societies. Before the Industrial Revolution, it was the primary fuel available to most people worldwide. Even today, in many **less-industrialized countries**, biomass such as wood and animal dung remains a major energy source for rural households. It is commonly used for heating, cooking, and sanitation because it is inexpensive, relatively efficient, and widely available. **Figure 6.4c** illustrates the global distribution of biomass fires. While some of these fires result from domestic biomass use, a larger share is linked to **slash-and-burn agriculture**, which clears land for farming. Take a minute to compare the areas highlighted in **Figure 6.4c** to the countries of the world that are currently experiencing rapid population growth (Chapter 2). If you need a refresher, use the World Meter website: Population by Country (2025) - Worldometer

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 3. Burning of any fossil fuel (coal, natural gas, 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 6.3**, which compares CO_2 emissions from fossil fuels of regions across the globe.

6.2.3 Industrialized Agriculture

As countries industrialize, their relationship with agriculture also changes. **Industrialized countries** rely very little on slash-and-burn agriculture but their agricultural practices still impact the environment. The growing population (Chapter 2) in many countries has required agriculture to become industrialized in order to meet demand. If you live in an industrialized country like the United States, **industrialized agriculture** probably produces much 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: 1) the use of motorized machinery; 2) the use of chemicals such as fertilizers, pesticides, hormones, and/or antibiotics; 3) and the intense and efficient production of one product across a large area of land.

Industrialized agriculture significantly contributes to methane (CH_4) emissions, a powerful greenhouse gas. You'll learn more about methane later in this chapter. Methane is commonly produced during anaerobic metabolism. In **ruminant animals** (such as sheep, cattle, and goats) the gut is specially adapted to digest tough carbon compounds like cellulose found in grass. This process relies on a symbiotic (cooperative) relationship with anaerobic bacteria living in the digestive tract. These bacteria break down cellulose and, as a byproduct of their metabolism, release methane and other gases. This process is known as **enteric fermentation**. The methane is then expelled by the animal, making ruminants a major source of global methane emissions (see **Figure 6.5**). Similar bacteria are also present in livestock manure. When manure is stored or processed for later use, these microbes continue producing methane, which escapes into 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 and most other industrialized countries. As of July 2025, the United States had a total cattle inventory of 94.2 million animals, and in 2024, 28.7 billion pounds of beef was consumed in the United States (United States Cattle Inventory Report). The impacts of enteric fermentation and manure management for over 90 million animals are very significant, as shown in **Figure 6.5**. In both cases, carbon that was previously stored in biomass (cattle feed) is moved into the atmosphere in the form of CH_4. This is another example of how humans have impacted the carbon cycle.

Earlier in this section, other forms of impact on the carbon cycle by human agriculture were discussed. Through industrialized agriculture, we must also account for the fossil fuels used. 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 processers; food processing; delivery of foods to supermarkets; 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.

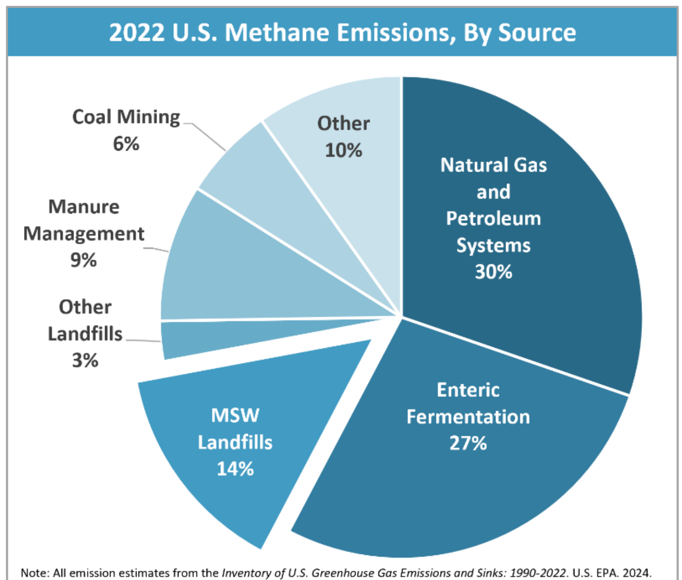


Figure 6.5. United States' methane emissions by source. 36% of the US methane production comes from agriculture: enteric fermentation (production of methane by anaerobic bacteria within the ruminant gut) and manure management. All emissions estimates from the Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2022. US EPA Basic Information about Landfill Gas | US EPA

Key points from: Humanity's impact on the carbon cycle

1. Fossil fuel combustion and deforestation increase CO_2 concentration in the atmosphere.
2. Higher CO_2 in the air results in more CO_2 entering the oceans
3. Animal production releases methane (CH_4); fertilizers release nitrous oxide (N_2O).
4. CH_4 and N_2O are greenhouse gases with higher **Global Warming Potential (GWP)** than CO_2.

Test your knowledge…

1. *Summarize three major ways humans alter the carbon cycle, based on the examples provided in this section.*
2. *How did the Industrial Revolution change human impacts on the global carbon cycle?*
3. *Identify the two human-driven fluxes that add the largest amounts of CO_2 to the atmosphere.*
4. *Why is ocean acidification linked to the carbon cycle?*
5. *Describe how fossil fuel combustion alters the distribution of carbon among major reservoirs in the carbon cycle.*
6. *How do industrialized agricultural practices increase CO_2 emissions through fossil fuel use?*
7. *What is enteric fermentation, and why does it matter for methane emissions?*

6.3 The Science of Climate Change

Understanding the science behind climate change is essential before exploring its impacts and solutions. By examining how greenhouse gases interact with Earth's systems, we can better appreciate the urgency of mitigation and adaptation strategies discussed in the next section.

6.3.1 The Cause of Global Climate Change

Scientists have determined that the primary driver of current global climate change is the increase in human-caused emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), since the Industrial Revolution. **Greenhouse gases** are molecules with at least three atoms that trap heat in the atmosphere through the greenhouse effect. While the "big three" gases (CO_2, CH_4, and N_2O) are most discussed, water vapor (H_2O) is also a greenhouse gas. Humans have little direct influence on atmospheric water vapor, but it remains a critical component of the natural greenhouse effect (**Figure 6.6**).

Earth receives energy from the Sun and radiates energy back into space. If these energy flows were equal without greenhouse gases, Earth's surface temperature would be about -18°C (0°F). This is known as **thermal equilibrium temperature** and is much colder than Earth's average surface temperature which is about 15°C (59°F). This difference is due to naturally occurring greenhouse gases, mainly water vapor and some CO_2, which trap heat and make life possible. Without them, Earth would be far too cold to sustain life.

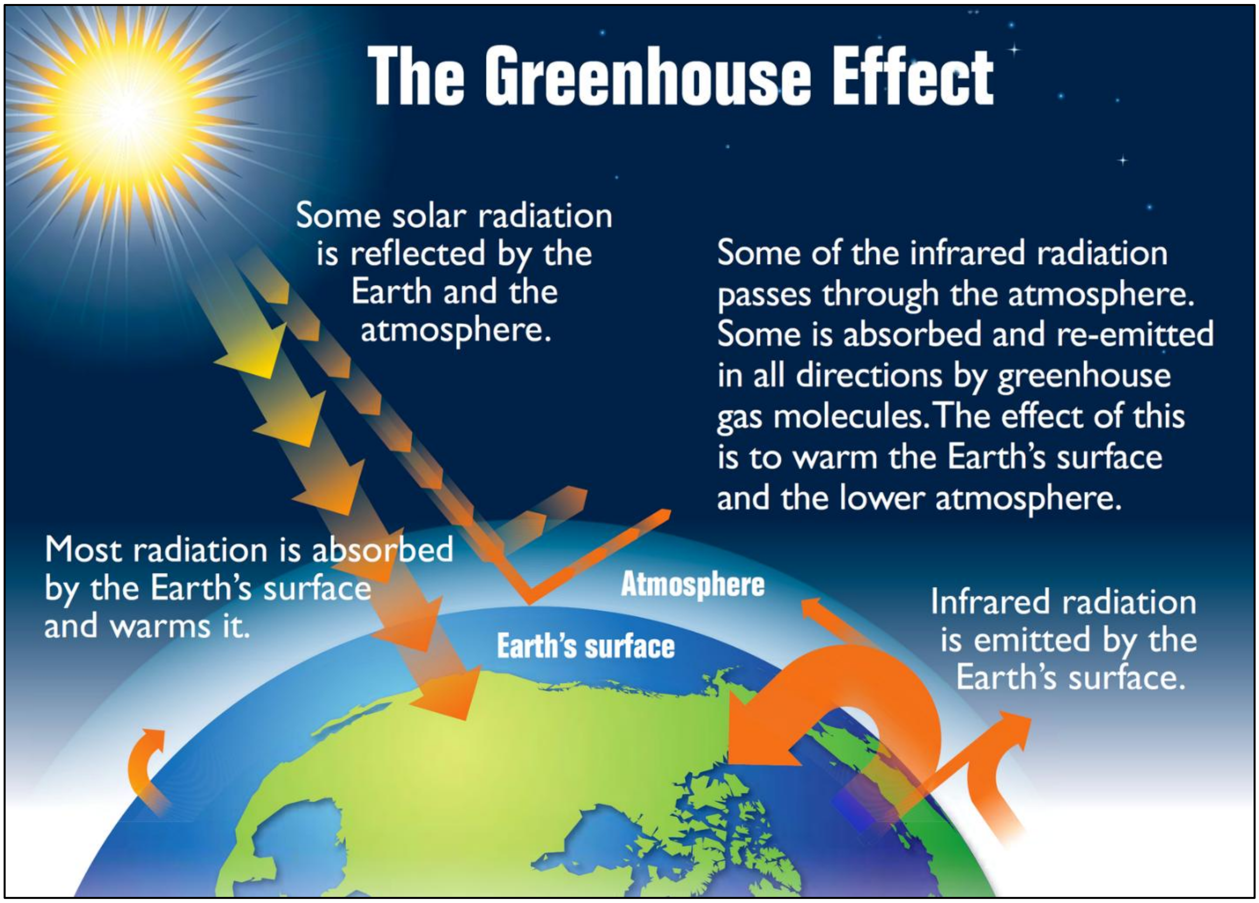


Figure 6.6. This diagram shows the Earth's greenhouse effect. The Earth absorbs some of the energy it receives from the sun and radiates the rest back toward space. However, greenhouse gases absorb some of the energy radiated from the Earth and trap it in the atmosphere. These gases essentially act as a blanket, making the Earth's surface warmer than it otherwise would be. The greenhouse effect occurs naturally but 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

When solar radiation enters Earth's atmosphere, it can follow several paths. Some radiation is reflected by the atmosphere or Earth's surface and does not contribute to warming. Some passes through the atmosphere and reaches the surface, where it is absorbed and then re-emitted as infrared radiation (heat). While some of this heat escapes into space, greenhouse gases in the atmosphere absorb and re-emit part of it in all directions. This process traps heat and warms Earth's surface. Infrared radiation can be absorbed multiple times by different greenhouse gas molecules, increasing its warming effect. Therefore, higher concentrations of greenhouse gases amplify Earth's overall warming potential.

6.3.2 Natural Climate Variability

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 6.7**. 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 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 date back 800,000 years. These data helped scientists conclude that the Earth's temperature and greenhouse gas concentrations are directly correlated to one another (**Figure 6.8**). During the ice age 650,000 years ago, the Earth was experiencing depressed temperature and atmospheric CO_2 concentrations below 200 parts per million (ppm). We can also see from these data that CO_2 concentrations can be naturally elevated to as high as 300 ppm, correlating with increased temperatures.

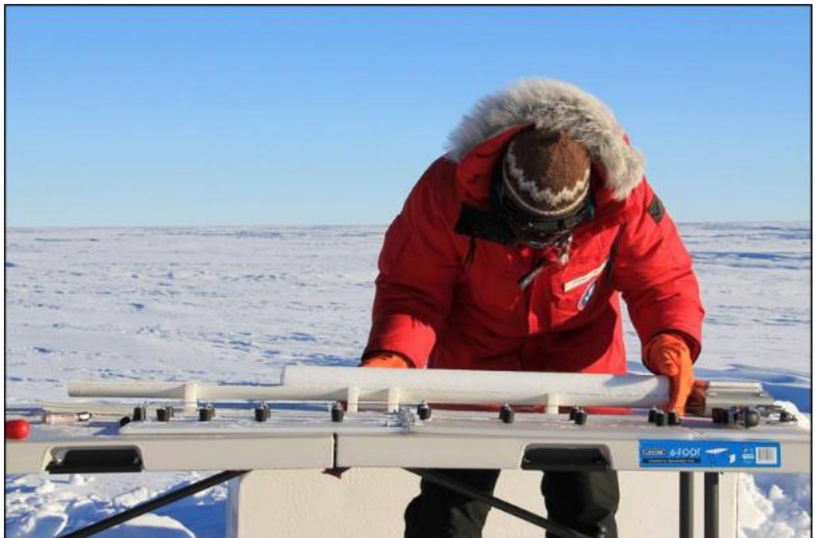


Figure 6.7. On Dec. 8, 2010, Michelle Koutnik, of the University of Copenhagen's Center for Ice and Climate, prepared a core of Antarctic ice to be wrapped and put into core tubes for transport back to labs at Brigham Young University in Utah. But first, Koutnik measured the core's length, diameter and weight. The traverse was the first of two field campaigns to study snow accumulation on the West Antarctic Ice Sheet and tie the information back to larger-scale data collected from satellites. Credit: NASA/Lora Koenig.

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.

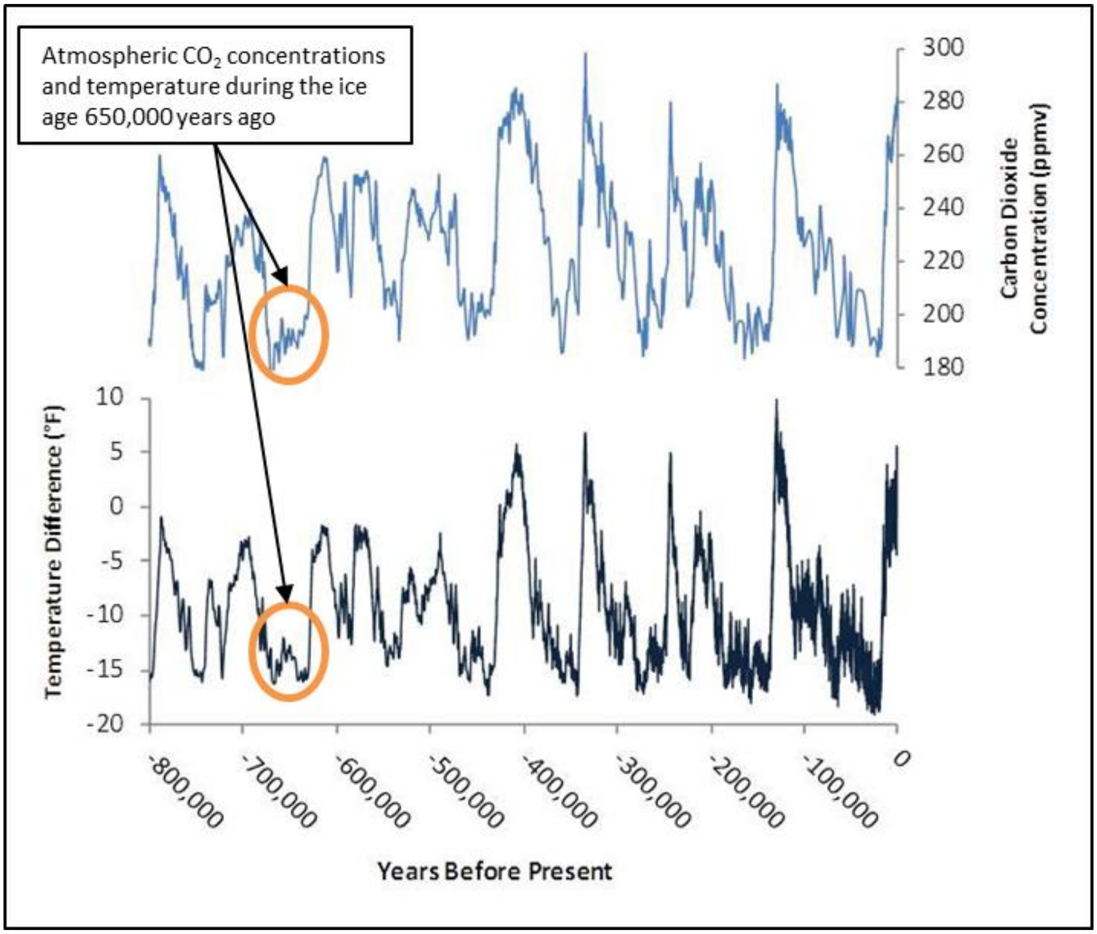


Figure 6.8. Estimates of the Earth's changing CO2 concentration (top) and Antarctic temperature (bottom), based on analysis of ice core data extending back 800,000 years. Until the past century, natural factors caused atmospheric CO2 concentrations to vary within a range of about 180 to 300 ppm. Warmer periods coincide with periods of relatively high CO2 concentrations. NOTE: The past century's temperature changes and rapid CO2 rise (to 423 ppm in 2024) are not shown here. Source: Based on data appearing in NRC (2010).

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 CO_2 concentration shown in **Figure 6.8**. 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.

6.3.3 Greenhouse Gases

Greenhouse gases differ in their concentration in the atmosphere, their sources, and in their warming potential (ability to trap heat and contribute to the greenhouse effect). Four major greenhouse gases have been impacted by humans the most and will be the focus of this section. See **Table 6.2** for a comparison of their influence on climate. They include

- Carbon dioxide, CO_2
- Methane, CH_4
- Nitrous oxide, N_2O
- Synthetic fluorinated gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)

6.3.3.1 Natural Greenhouse Gases

Carbon dioxide (CO_2) is the greenhouse gas responsible for most of the human-caused climate change in our atmosphere. It has the highest concentration in the atmosphere among the greenhouse gases influenced by human activities. CO_2 is a direct product of both combustion and cellular respiration, causing it to be produced in great quantities both naturally and anthropogenically (human activities). Any time biomass or fossil fuels are burned, CO_2 is released. Major anthropogenic sources include electricity production from coal-fired and natural gas power plants, transportation, and industry (Chapter 3). To get an idea of how CO_2 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. This video contains atmospheric CO_2 concentrations measured directly, dating back to 1958, as well as atmospheric CO_2 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 is also considered) was being emitted into the atmosphere every year, much of it from industrialized nations. Like the action of the naturally existing greenhouse gases, any additional greenhouse gases lead to an increase in the surface temperature of the Earth.

While CO_2 is produced by aerobic cellular respiration, CH_4 and N_2O are often the products of anaerobic processes (reactions occurring without oxygen gas). Agriculture is a major contributor to CH_4 emissions, as you saw in section 6.2. In addition to **anaerobic bacteria**, methane is also a significant component of natural gas and is commonly emitted during mining of all fossil fuels and during use of natural gas and petroleum. For a review of how fossil fuels are mined, see Chapter 3. Finally, **landfills** contribute significantly to CH_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_4 include swamps and other wetlands, and volcanoes.

The vast majority of N_2O production by humans comes from agricultural land management. While some N_2O 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_2O emissions. Some N_2O is also emitted from transportation and industry.

Due to their relatively high atmospheric concentrations compared with many synthetic gases, CO_2, CH_4, and N_2O are responsible for most of the human-caused global climate change over the past century. **Figure 6.9** shows the rise in these three gases since the Industrial Revolution. Paleoclimate data (**Figure 6.8**) demonstrate that atmospheric CO_2 concentrations remained below about 300 ppm until industrialization. Comparing **Figure 6.9** to **Figure 6.8**, above, what is likely to happen to global temperature following this unprecedented rise in greenhouse gas levels? Use this our world in data link for a real-time update, for instance, the global average atmospheric CO2 concentration reached a new high near 423 ppm in 2024.

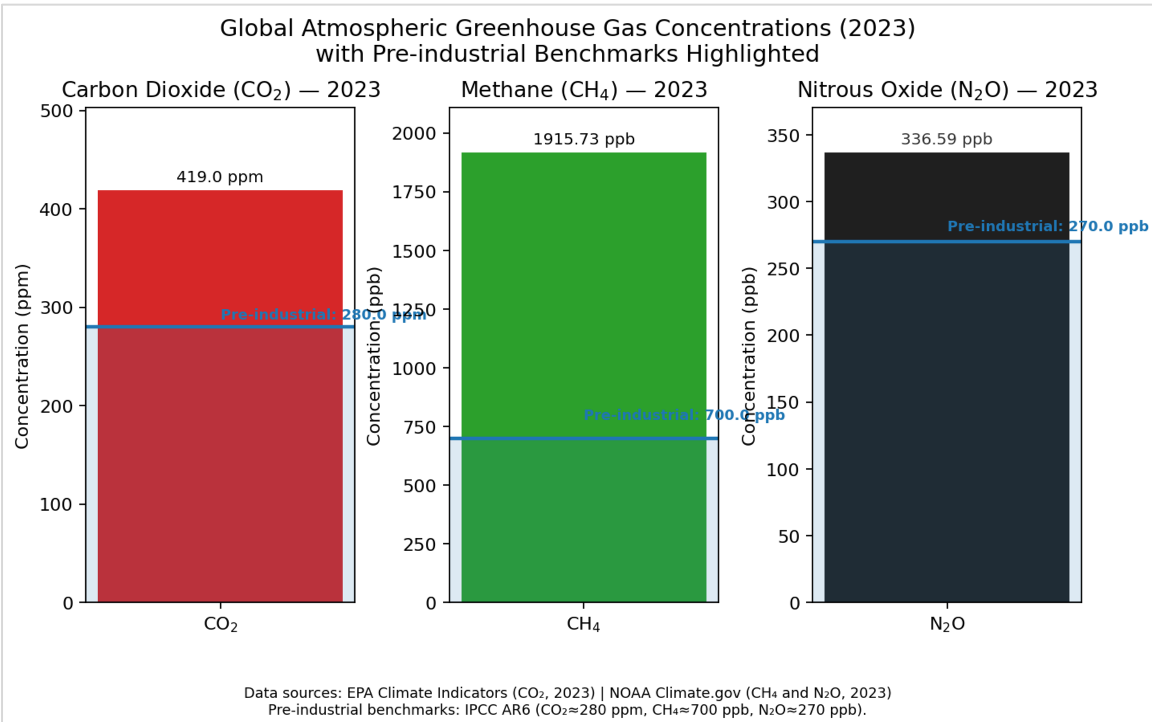


Figure 6.9. Current greenhouse gas concentrations in the atmosphere with the pre-industrial revolution concentrations highlighted. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the greenhouse gas per million or billion molecules of air. (Source: AI generated using EPA, NOAA & IPCC data))

6.3.3.2 Synthetic Greenhouse Gases

One class of greenhouse gas chemicals that has no natural sources is fluorinated gas. 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 6.2**. 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 5). 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.

6.3.3.3 Global Warming Potential

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 6.2**. This is largely due to their very long residence time in the atmosphere. Also note the higher GWP values for CH_4 and N_2O 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 6.1**?

Table 6.2. Comparison of common greenhouse gases in the atmosphere. Table based on data from US EPA. For more information Overview of Greenhouse Gases | US EPA

Greenhouse gas	Chemical formula or abbreviation	Lifetime in atmosphere	Global warming potential (100-year)
Carbon dioxide	CO_2	Variable	1
Methane	CH_4	12 years	28-36
Nitrous oxide	N_2O	114 years	298
Hydrofluorocarbons	Abbreviation: HFCs	1-270 years	12-14,800
Perfluorocarbons	Abbreviation: PFCs	2,600-50,000 years	7,390
Sulfur hexafluoride	SF_6	3,200 years	22,800

6.3.4 Other Climate Influencers

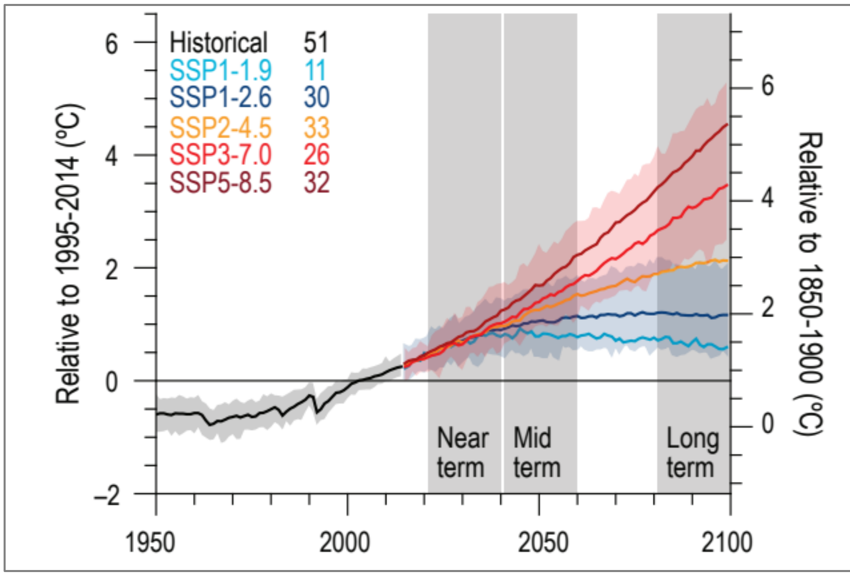
In addition to greenhouse gases, other manmade changes may be forcing climate change. Increases in near surface ozone from internal combustion engines, aerosols such as carbon black, mineral dust and aviation-induced exhaust are acting to raise the surface temperature. This primarily occurs due to a 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 6.10**.

Figure 6.10. 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

6.3.5 Using Models to Study Climate Change

Scientists combine data from many sources to draw meaningful conclusions about climate change and to make informed predictions. When these data are integrated, they are used to develop scientific models. A **scientific model** is a representation of how a system works and a projection of how it may change in the future, based on our understanding of current conditions 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: How Do We Predict Climate Change? Climate Models Explained - Caltech Science Exchange

Figure 6.11 shows observed global average temperature changes (black line) from 1950 to the present, along with projections for the future under five different greenhouse gas emission scenarios (colored lines). These scenarios, called SSPs (Shared Socioeconomic Pathways), range from very low emissions (SSP1-1.9, light blue) to very high emissions (SSP5-8.5, dark red). The shaded areas around each line represent uncertainty ranges. Why do scientists include historical data in models when actual measurements exist? This is part of model testing and calibration. A reliable model should accurately reproduce past trends before being used to predict future conditions. Since these models match historical observations well, scientists have greater confidence in their projections for near-term, mid-term, and long-term climate changes.



SSP1-1.9 (blue): Very low emissions, consistent with limiting warming to around 1.5°C.

SSP1-2.6 (light blue): Low emissions scenario.

SSP2-4.5 (orange): Intermediate emissions scenario.

SSP3-7.0 (red): High emissions scenario.

SSP5-8.5 (dark red): Very high emissions scenario.

Figure 6.11. Projected global surface temperature change relative to 1995–2014 (left axis) and 1850–1900 (right axis) under five Shared Socioeconomic Pathway (SSP) scenarios from the IPCC Sixth Assessment Report (AR6). The black line shows historical observations, while colored lines represent future projections based on different emissions pathways.

Another example of a climate model is shown in **Figure 6.12**, 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, to achieve the most accurate outcome. In **Figure 6.12**, observed global surface temperature changes are shown for the period 1850 to 2020 (black line), expressed as anomalies relative to the 1850–1900 average. The shaded bands represent the 5% to 95% confidence intervals from climate model simulations. The blue band shows results from models using only natural forcings (such as solar variability and volcanic activity), while the brown band shows results from models using both natural and anthropogenic forcings (including greenhouse gases and aerosols). The strong agreement between observed warming and simulations that include human influence demonstrates with very high confidence that the observed increase in global temperature since the mid-20th century is primarily due to anthropogenic greenhouse gas emissions. Natural forcings alone cannot explain the observed trend, highlighting the dominant role of human activities in recent climate change. You will see more examples of climate models as you make your way into the next section: *Consequences of Climate Change*.

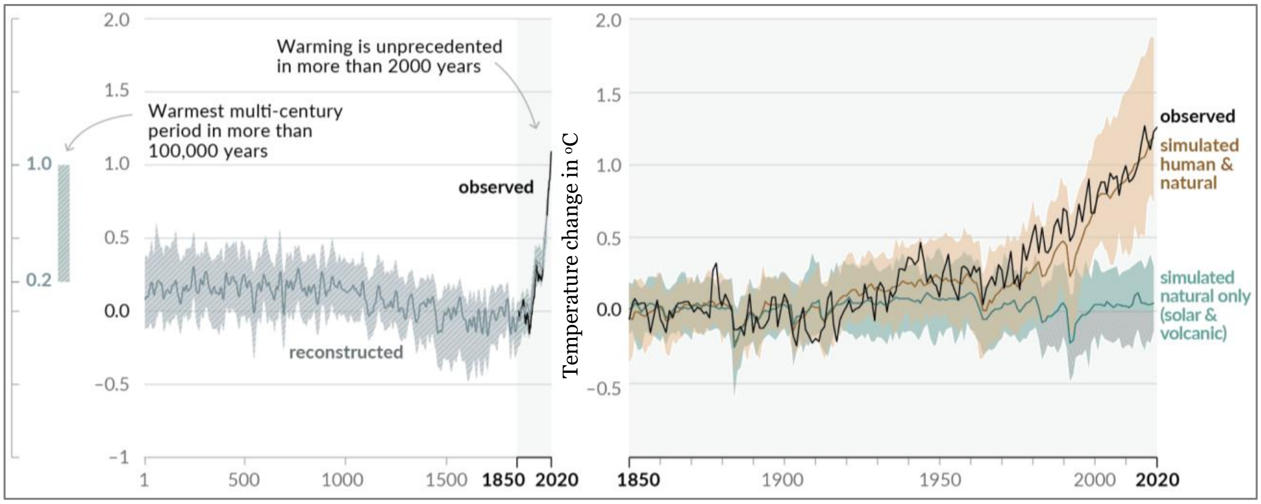


Figure 6.12. Left panel shows change in global observed (1850-2020) and reconstructed (1-2000). Right panel shows change in global surface temperature as observed and simulated using human and natural and only natural factors (1850-2020). (Source: IPCC, AR6).

Key points from the Science of Climate Change

- Key greenhouse gases: **CO_2**, **CH_4**, **N_2O**, and fluorinated gases.
- Human activities amplify natural greenhouse effect, leading to global warming.
- Main evidence is rising global temperatures.
- Global warming is driven by the ***enhanced*** greenhouse effect - added greenhouse gases trap more heat in Earth's atmosphere.
- Scientific consensus: Climate change is real and primarily human induced.

Test your knowledge…

1. *What is the primary cause of the current increase in global temperatures, and how does it differ from natural drivers of climate change?*
2. *Which gas is the most abundant greenhouse gas in Earth's atmosphere?*
3. *What is the nature of and primary role of greenhouse gases?*
4. *Why is the greenhouse effect essential for life on Earth?*
5. *Why is the current climate change not considered part of the natural climate variability?*
6. *What is "global warming potential," and how does it compare among the four major greenhouse gases?*
7. *What are climate models?*

6.4 Consequences of Climate Change

Climate change leads to rising temperatures, melting ice caps, and ocean acidification. Increased CO_2 dissolves in seawater, forming carbonic acid and lowering pH, which harms marine life. 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 6.3** for a discussion of scientific models). Here, the differences between **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 (**Figure 6.12** from section 6.3). We have also seen, and expect to continue to see, other changes occurring in the **climate** of the Earth. Changes have been observed and will continue in other chemical, physical, and biological aspects of the Earth's environment. In this section we will discuss a few of the consequences of climate 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 among others. For more information about these consequences of climate change, visit this site: View the Indicators | US EPA

6.4.1 Temperature Changes

The change in temperature that we have already seen in the Earth's average atmospheric temperature is about 1.1°C above pre-industrial level according to World Meteorological Organization, primarily due to human-induced greenhouse gas emissions. While it may seem relatively small, it has led to widespread changes in climate systems, including more frequent heatwaves, altered precipitation patterns, and melting ice sheets. Future temperature changes will depend on the trajectory of emissions and socio-economic development. **Figure 6.13**, based on the IPCC Sixth Assessment Report (AR6), illustrates projected seasonal mean temperature changes for the near-term period (2021–2040) under two contrasting scenarios: 1) a low emissions scenario (SSP1- 2.6) that assumes strong mitigation efforts and sustainable development, and 2) a high emission (SSP3-7.) that assumes continued high emissions and limited climate policy. Across all scenarios, warming is evident in every region and season, with the most pronounced increases occurring in high-latitude regions, particularly during boreal winter (Dec, Jan, Feb). Under low emissions, most land areas experience warming of 0.5°C to 1.5°C, while high emissions show widespread warming exceeding 2°C, and even greater warming in the Arctic. Seasonal differences are clear: winter warming in northern latitudes is stronger than summer warming, amplifying risks such as permafrost thaw and ecosystem disruption. What might be some of the reasons for the differences in warming across different parts of the globe?

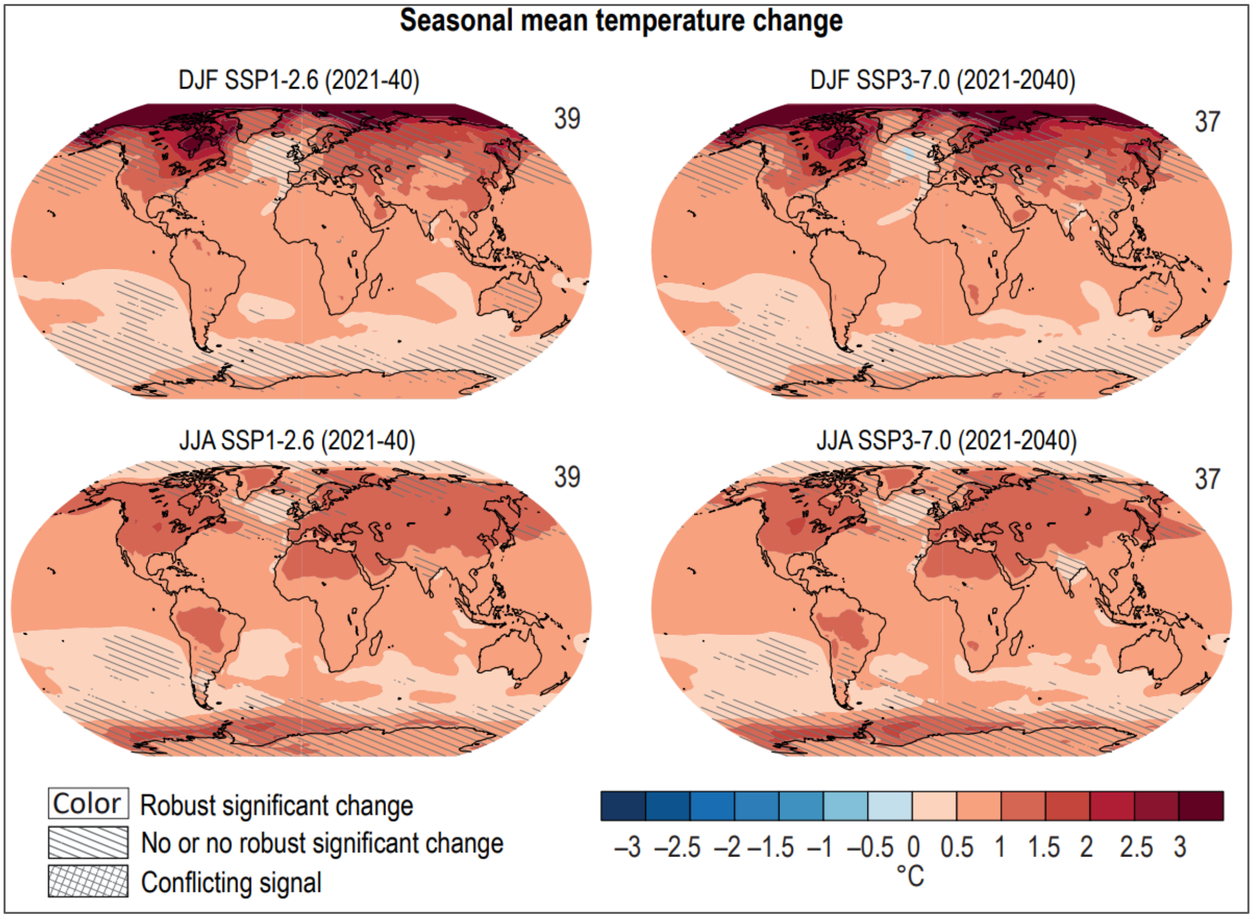


Figure 6.13. Projected seasonal mean temperature change for the near-term period (2021–2040) under two emissions scenarios (low -SSP1-2.6 and high -SSP3-7.0) from the [IPCC Sixth Assessment Report (AR6)](). Maps show changes for December–February (DJF) and June–August (JJA) relative to 1995–2014.

These projections underscore that climate change will continue to intensify global and regional temperature extremes, even under low-emission pathways. Limiting warming requires rapid and sustained reductions in greenhouse gas emissions to avoid the severe impacts associated with high-emission scenarios.

6.4.2 Precipitation Changes

By now, you 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 5). As the air in the troposphere warms and cools, the amount of water vapor that it holds changes dramatically. For example, the high summer humidity in this region (Georgia, USA) is 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.

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 6.14**, 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?

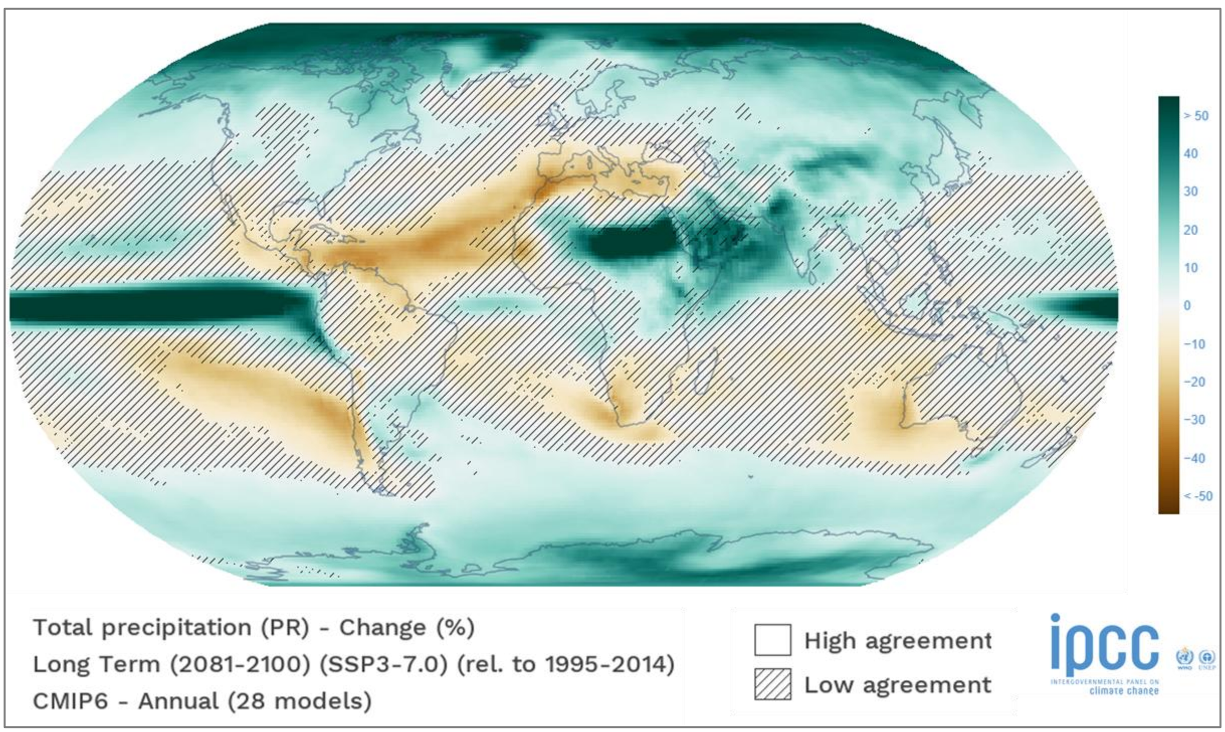


Figure 6.14. Percent change in annual average precipitation projected by the Coupled Model Intercomparison Project Phase 6 (CMIP6) by IPCC for the 21st century for Shared Socioeconomic Pathway 3 (SSP3) (see Figure 6.11 for other pathways). Blue areas project increases in precipitation; brown areas project decreases. Data: multi-model CMIP6 ensemble from IPCC AR6 Interactive Atlas, IPCC

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 Chapters 7 and 8 for more detail on challenges faced by societies to supply clean, reliable water to their populations.

Additional challenges may be felt by all areas of the world regarding changes in the seasonality or timing of precipitation, as well as the form in which precipitation falls (e.g., mist or downpour; rain, ice, or snow). All 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 in the next section.

6.4.3 Sea Level Rise

Although the total amount of water on Earth remains constant (see Chapter 7 for the water cycle), global climate change is altering its distribution. Oceans are gaining volume while land-based ice stores (glaciers and ice sheets) are shrinking. This shift contributes to **sea level rise**, which is the long-term increase in the average height of the ocean's surface (**Figure 6.15**). It is caused by two main processes: melting land ice and thermal expansion.

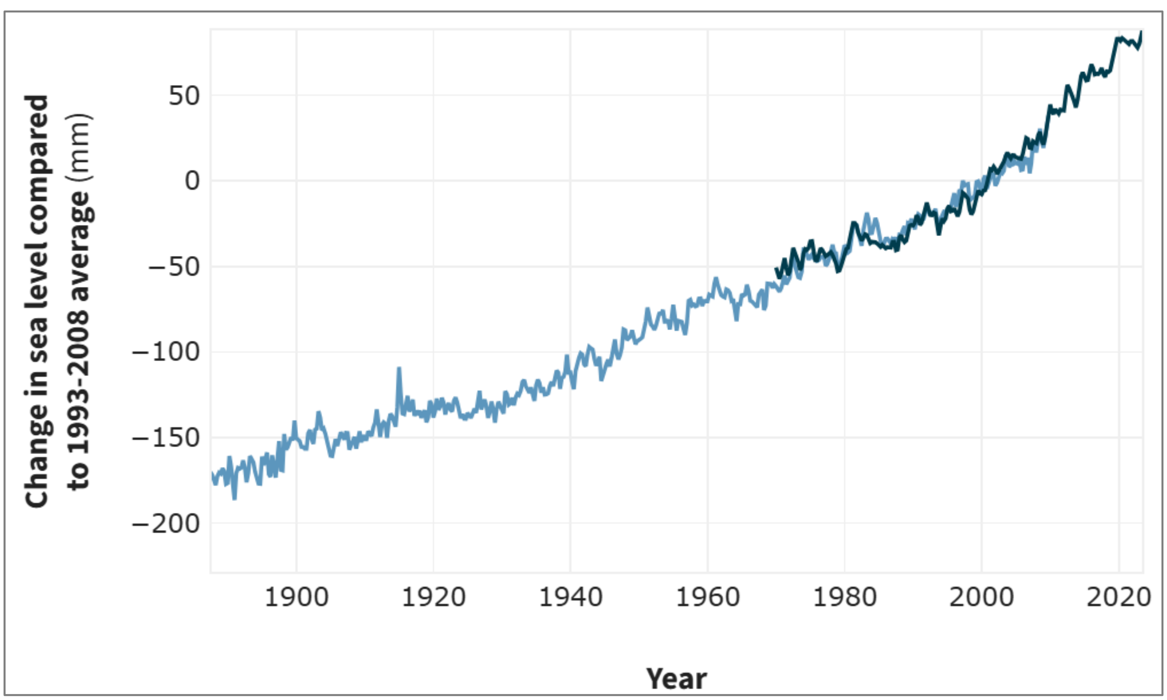


Figure 6.15. Change in sea level. Estimates from Church and White (2011) (light blue line) and University of Hawaii Fast Delivery sea level data (dark blue). Source: NOAA

Figure 6.15 shows changes in global sea level from 1900 to 2020, measured in millimeters relative to the 1993–2008 average. The data reveal a steady upward trend over the past century, with sea level rising by about 200 mm (20 cm) since 1900. Most of this increase has occurred in recent decades, reflecting an acceleration in the rate of rise. The increase in average global temperature has caused increased ice melting in many regions of the globe. Melting **land ice** (such as the glacier shown in **Figure 6.16**) 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 View the Indicators | US EPA 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 location, and the overall sea level does not change.

Figure 6.16. Photographs of Muir Glacier, Alaska. (Source: National Ice and Snow Data Center Collection)

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 denser substance. 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 documented accelerating sea level rise globally and regionally. Along the U.S. Atlantic Coast, sea level has risen by about 8–9 inches since 1880, with the rate increasing in recent decades. Projections from the IPCC indicate that, without major reductions in greenhouse gas emissions, global sea level could rise by up to 1 meter (about 3 feet) by 2100. The Southeast, with its gently sloping coastal plain, remains particularly vulnerable to inundation, while the Mid-Atlantic's steeper coastal profile offers some protection but does not eliminate risk. **Figure 6.17** depicts the measured land area lost due to increasing sea level since 1996. These changes threaten coastal ecosystems, infrastructure, and communities.

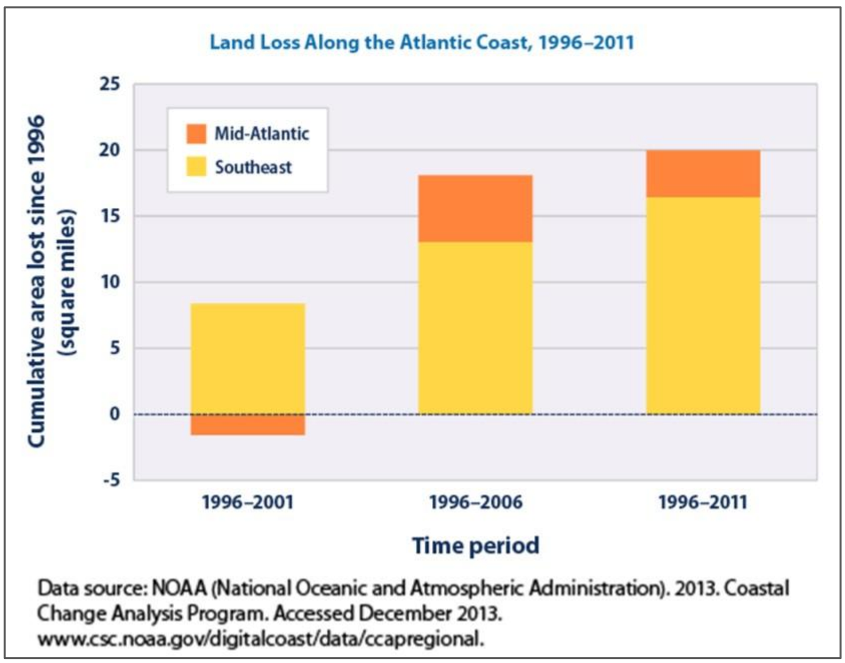


Figure 6.17. This graph shows the net amount of land converted to open water along the Atlantic coast during three time periods: 1996–2001, 1996–2006, and 1996–2011, and separated into two regions: Southeast and Mid-Atlantic. Negative numbers show where land loss is outpaced by the accumulation of new 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 have been made in infrastructure to protect cities and farmland. 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 review the following article titled "Adaptation as a Water Resource Policy Challenge-Institutions and Science (https://www.scirp.org/html/30566.html).

6.4.4 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**, $CaCO_3$. These organisms rely on the formation of **carbonate** ions (see Chapter 1 for information on ions), CO_3^{2-}, from dissolved CO_2, through a natural, chemical reaction that occurs. This takes place through a chain-reaction equation, where **bicarbonate** (HCO_3^-) is formed as an intermediate, and **hydrogen ions** (H^+) are generated (**Equations 6.3** and **6.4**).

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \qquad \textbf{Equation 6.3}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \qquad \textbf{Equation 6.4}$$

To have a visualization of this process, follow along with the interactive graphic at: https://www.whoi.edu/ocean-learning-hub/multimedia/carbon-dioxide-shell-building-and-ocean-acidification/

As you can see, both Equations 6.3 and 6.4 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 6.18** that a lower pH means that the liquid is more **acidic**. As shown in the interactive graphic, an increase in CO_2 in the atmosphere causes additional CO_2 to be dissolved in the ocean. This means that more CO_2 in the atmosphere leads to more acidic ocean environments.

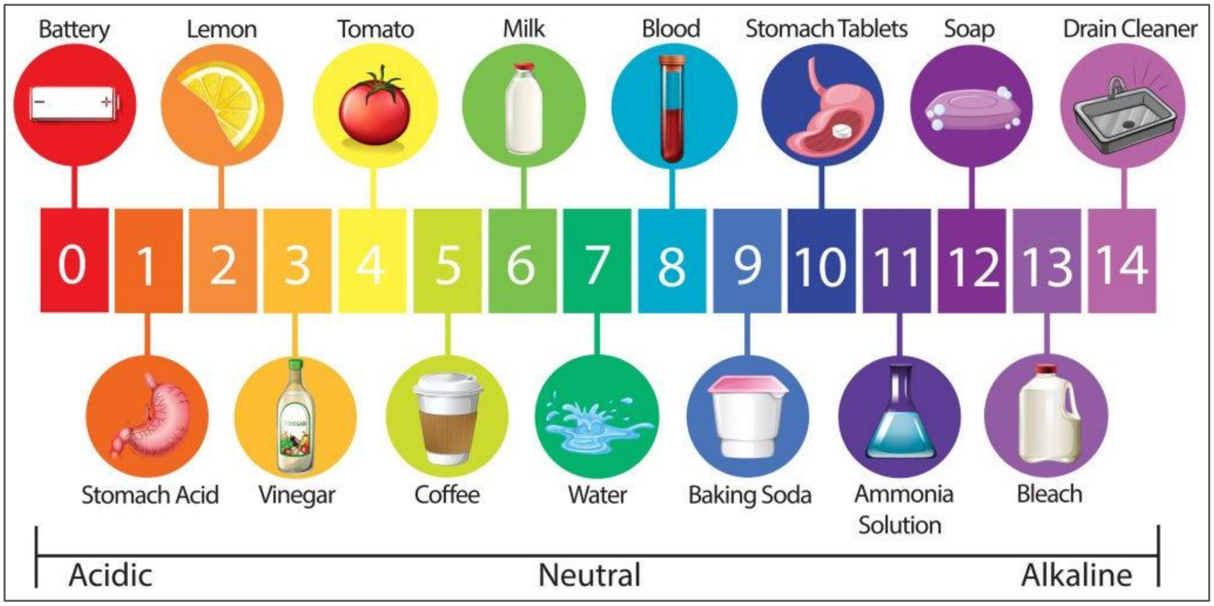


Figure 6.18. The pH scale and relative acidity. (Source: Australian Environmental Education)

Unfortunately for shell-building animals, the buildup of H^+ in the more acidic ocean environment blocks the absorption of calcium and CO_3^{2-} 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 6.19**. The increasing acidity of the world's oceans is resulting in habitat changes across the globe.

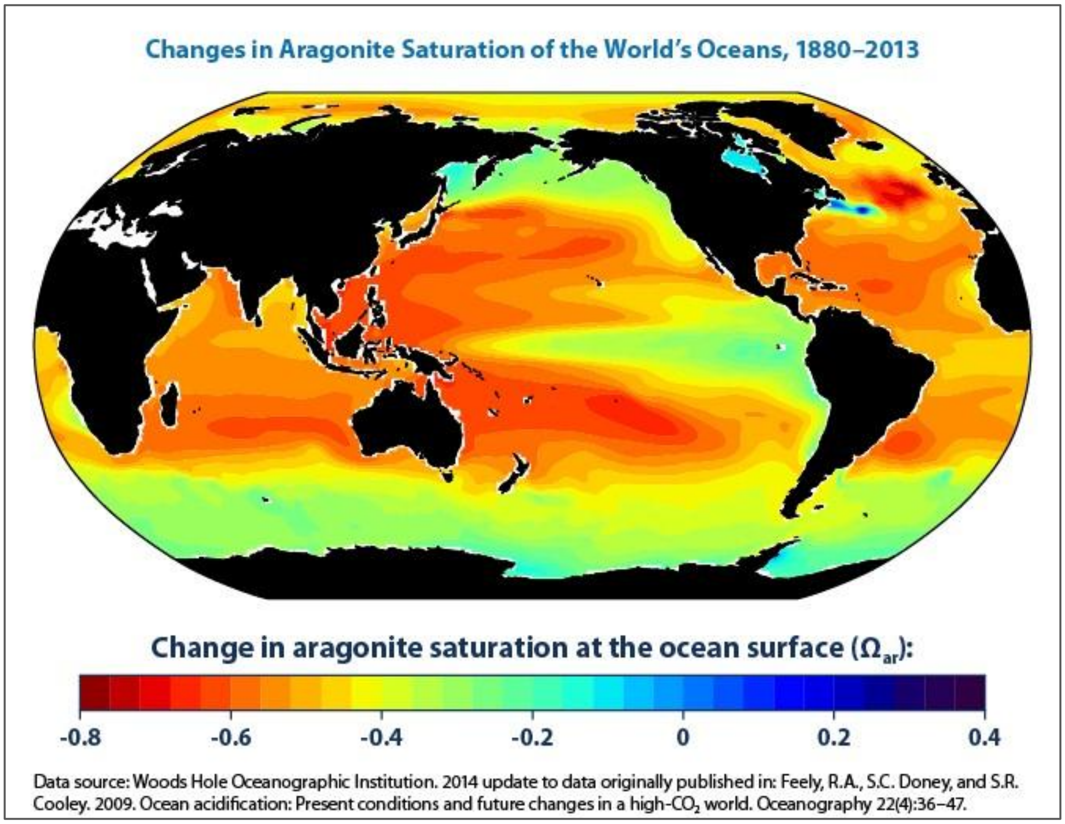


Figure 6.19. This map shows changes in the aragonite saturation level of ocean surface waters between the 1880s and the 2004–2013 decade. Aragonite is a form of calcium carbonate that many marine animals use to build their skeletons and shells. A negative change represents a decrease in saturation.

This is only expected to worsen as atmospheric CO2 levels continue to increase. Many organisms, including 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 more information, visit the NOAA Coral Reef Conservation Program website: NOAA's Coral Reef Conservation Program (CRCP) - Coral Reef Threats

Key Points from Consequences of Climate Change

1. Changes include rising temperatures, melting ice caps and changes in precipitation.
2. Ocean acidification from dissolved CO2 harms marine life.
3. Extreme weather events are linked to greenhouse gas buildup

Test your knowledge…

1. *How are temperatures projected to change across the globe (increase equally everywhere or not)?*
2. *Does melting sea ice cause sea level rise, why or why not?*
3. *What two things cause sea level to rise?*
4. *How are precipitation patterns expected to change across the globe?*
5. *Why does global warming affect precipitation?*
6. *Why is ocean acidification linked to the carbon cycle?*

6.5 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 working on solutions to climate change as 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 to prosper in the future. **Mitigation** refers to efforts aimed at limiting the magnitude of climate change by reducing greenhouse gas emissions or enhancing carbon sinks. **Adaptation** refers to efforts aimed at coping with the effects of climate change that are already occurring or expected in the future.

6.5.1 Adaptation Strategies

Adaptation refers to actions taken to adjust natural or human systems in response to actual or expected climate impacts, aiming to reduce harm or exploit beneficial opportunities. Unlike mitigation, which addresses the causes of climate change by reducing greenhouse gas emissions, adaptation focuses on managing the consequences mainly through change in behaviors. Effective adaptation strategies need to be **flexible** and evolve as climate projections and conditions change. They need to be **equitable**, ensuring that vulnerable populations have access to adaptation resources. Below is a summary of some adaptation strategies

1. *Infrastructure and coastal protection:* Examples include 1) Building sea walls and levees to protect low-lying coastal areas from sea-level rise and storm surges. 2) Managed retreat involving relocating infrastructure and communities away from high-risk zones. 3) Flood-resilient design such as elevating buildings, improving drainage systems, and using permeable surfaces.
2. *Agriculture and food security:* 1) Developing crop varieties that tolerate heat and water stress. 2) Efficient water use through drip irrigation and rainwater harvesting. 3) Diversification**:** shifting planting schedules and crop types to match changing climate patterns.

3. *Ecosystem-based adaptation:* 1) Wetland and mangrove restoration. These provide natural buffers against flooding and storm surges. 2) Forest conservation - stabilizes soil, regulates water cycles, and supports biodiversity. 3) Urban green spaces to reduce heat island effects and improve air quality.
4. *Water resource management:* 1) Reservoirs and storage - Increase water availability during droughts. 2) Desalination and recycling as alternative sources for freshwater. 3) Integrated watershed management that balances ecological health with human needs.
5. *Health and Social Systems:* 1) Early warning systems that include alerts for extreme weather events, heatwaves, and disease outbreaks. 2) Climate-sensitive healthcare that includes preparedness for vector-borne diseases and heat stress. 3) Community education to build awareness and capacity for local adaptation.
6. *Policy and Governance*: 1) Climate-resilient planning - incorporating climate risk into urban development and zoning. 2) Insurance and risk sharing - financial tools to buffer economic losses. 3) International cooperation to share technology, knowledge, and resources for adaptation.

6.5.2 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 into 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 6.20**).

Scientists are also looking into the use of soil 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.

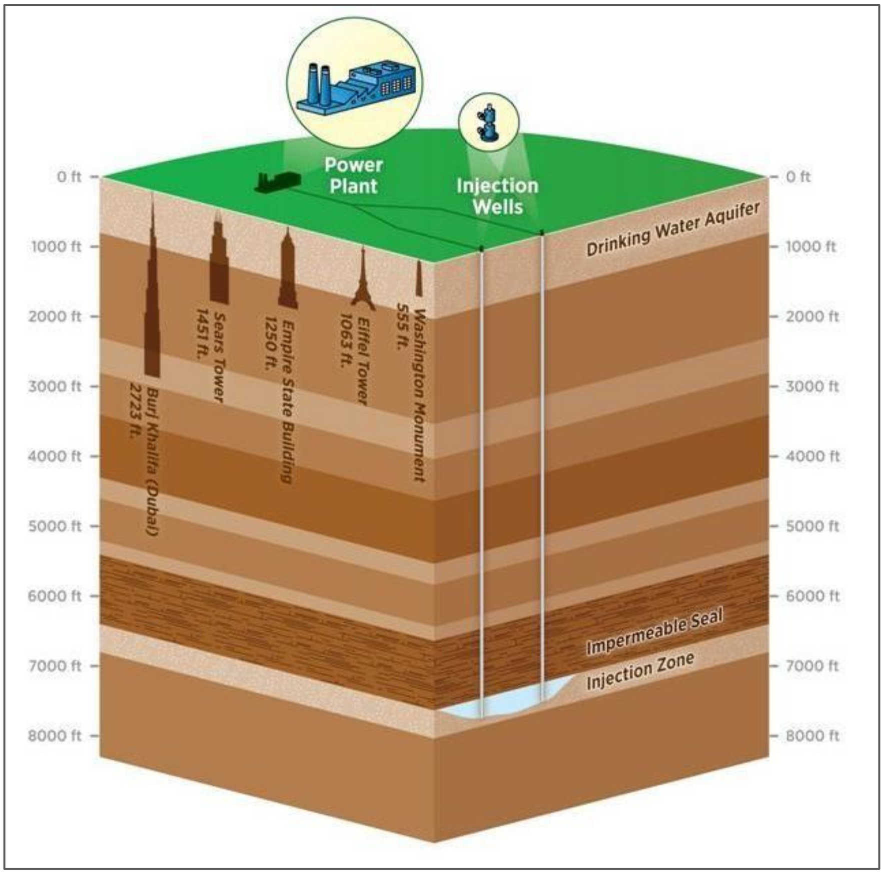


Figure 6.20. Carbon capture and sequestration schematic with landmarks shown to scale for depth reference. Source: US EPA.

Technologies related to alternative energy sources (**Chapter 4**) 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 may have already calculated in lab, you can also calculate your **carbon footprint**. Use the carbon footprint calculator to do so, and investigate the Reduce Your Emissions section to find ways to decrease your carbon footprint: https://www3.epa.gov/carbon-footprint-calculator/

Test your knowledge…

1. *What is the primary goal of climate mitigation strategies?*
   (Hint: Think about reducing greenhouse gas emissions and limiting global temperature rise.)
2. *Give one example of a renewable energy source that contributes to climate mitigation and explain how it helps.*
3. *Why is reforestation considered an effective climate mitigation measure?*
   (Hint: Consider its role in carbon sequestration.)

6.6 Climate Change Resilience

Climate resilience refers to the ability of communities, ecosystems, and economies to anticipate, absorb, adapt to, and recover from climate-related shocks and stresses. It is a cornerstone of sustainable development and climate adaptation strategies. Climate resilience strategies look different in different places based (among other things) on what the threats (risks) are, the likelihood of disaster occurring, and resource availability. Strategies include coastal defenses against sea-level rise, surge walls, warning systems, evacuation plans and infrastructure, diversified agriculture for drought resilience, and urban green spaces to reduce heat islands to maintain healthy ecosystems. Healthy ecosystems also store carbon and buffer climate impacts, linking resilience to the carbon cycle.

6.6.1 Why Climate Resilience Matters

Climate resilience is essential for safeguarding communities and ecosystems against the growing risks of climate change. It reduces vulnerability to extreme weather events, protects livelihoods, and ensures long-term sustainability. By strengthening resilience, societies can adapt to changing conditions rather than simply reacting to disasters.

For example, coastal cities implementing flood defenses can prevent storm surge damage. In short, climate resilience is not just about survival; it is about enabling communities to thrive despite uncertainty. It supports economic stability, reduces disaster recovery costs, and preserves natural resources for future generations. **Table 6.3** summarizes some strategies, their benefits and specific examples of each.

Table 6.3 Key Strategies for Climate Resilience

Strategy	Benefits	Examples
Coastal protection	Reduces erosion and flood risk	Sea walls, levees, mangrove restoration
Drought-resistant crops	Ensures food security in dry conditions	Heat-tolerant crop varieties, drip irrigation
Urban green spaces	Cools cities, improves air quality	Parks, green roofs, tree planting
Early warning systems	Saves lives, reduces disaster costs	SMS alerts, weather forecasting tech
Ecosystem restoration	Enhances biodiversity and carbon storage	Wetland restoration, reforestation

6.6.2 Projected Benefits of Climate Resilience Investments

Figure 6.21 below is bar chart illustrates the economic rationale for investing in climate resilience. Each strategy, such as early warning systems, infrastructure upgrades, and agricultural adaptation, shows benefits that significantly outweigh initial costs. For example, agriculture-related resilience measures yield the highest return, with benefits nearly five times greater than investment costs. This visual emphasizes that proactive resilience planning is not only environmentally sound but also economically advantageous.

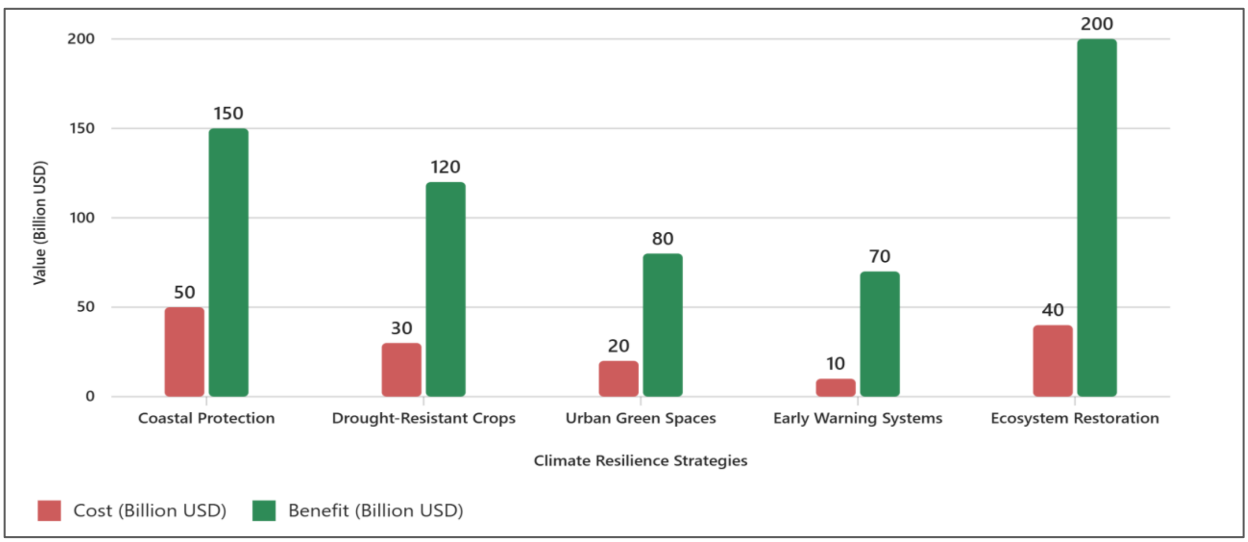


Figure 6.21. Comparison of estimated costs and benefits for key climate resilience strategies.

The diagram highlights three core strategies: coastal protection, drought-resistant crops, and urban green spaces. Coastal protection measures, such as sea walls and levees, reduce erosion and flood risk. Drought-resistant crops ensure food security under dry conditions, while urban green spaces help cool cities and improve air quality. These strategies demonstrate how infrastructure, agriculture, and urban planning can work together to reduce climate vulnerability.

6.6.3 Case Studies for Each Strategy

To learn more about the application of these strategies, explore the following case studies:

1. Coastal Protection: Case Study: Netherlands Delta Works – A system of dams and storm surge barriers protecting low-lying areas from flooding: Exploring the Delta Works Project in the Netherlands: Achieving Flood Control While Preserving Ecosystem Health
2. Drought-Resistant Crops: Case Study: India's adoption of drought-tolerant millet varieties to ensure food security during dry seasons. (PDF) Climate Change, Food Security and Farming Millets in India: The Need to Change Cropping Pattern
3. Urban Green Spaces: Case Study: Singapore's Green Roof Initiative – Incorporating vegetation on rooftops to reduce heat and improve air quality. Sky High Harvest: How Singapore Is Growing Farms on Skyscraper Roofs
4. Early Warning Systems: Case Study: Bangladesh Cyclone Preparedness Program – Community-based early warning systems reducing cyclone fatalities. Cyclone Preparedness Programme (CPP) - BDRCS and National_EAP_Cyclone_Bangladesh.pdf
5. Ecosystem Restoration: Case Study: Louisiana Wetland Restoration – Projects to restore wetlands and buffer against hurricanes. Conducting Large-Scale Wetland Restoration in Louisiana | NOAA Fisheries and Restoring Coastal Wetlands of Southeast Louisiana on NWRs

6.6.4 Interactive Activities

- **Activity 1**: Investment Decision Simulation - Allocate a hypothetical $100 billion budget across five resilience strategies to maximize benefits.
- **Activity 2**: Local Resilience Mapping - Identify climate risks in your region and propose at least two resilience strategies.
- **Activity 3**: Debate - "Should governments prioritize climate resilience over mitigation?" Two teams present arguments supported by data.

Test your knowledge…

1. *What is climate resilience, and why is it important?*
2. *Name two strategies for climate resilience and their benefits.*
3. *How do ecosystems contribute to climate resilience?*
4. *Why is early investment in resilience cost-effective?*

End of Chapter Review

1. Which fluxes in the carbon cycle are physical processes and which ones are chemical (or biochemical) processes?
2. What's the difference between photosynthesis and cellular respiration. Do these processes take place in plants only, in animals only, or in both plants and animals?
3. Why is there a correlation between population growth rate and global distribution of biomass fires?
4. 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?
5. Given any other knowledge you might have about the areas highlighted in Figure 6.4c, what other environmental impacts may be occurring here besides carbon cycle alterations?
6. Compare the production of CO_2 emissions from fossil fuel combustion across world regions in 1900, 1950, and 2024 in Figure 6.3. What accounts for these differences?
7. Has the total worldwide production of CO_2 from fossil fuels increased evenly relative to human population growth during the period displayed in Figure 6.3? Why/why not?
8. What are the differences in contributions of greenhouse gas emissions from more industrialized countries and less-industrialized countries? What are the similarities?
9. What's the difference between enteric fermentation and manure management? What's similar between the two?
10. How does fossil fuel combustion alter the carbon cycle?
11. List three major greenhouse gases and their sources.
12. Define global warming potential (GWP). How do CO_2, CH_4 and N_2O compare in their GWP?
13. Explain the role of oceans in carbon sequestration.
14. Explain how greenhouse gases trap heat in the atmosphere.
15. Why would Earth be much colder without the greenhouse effect?
16. Which of the following is a consequence of climate change?
    a. Increased biodiversity everywhere
    b. Rising sea levels
    c. Decreased greenhouse gas concentrations
    d. More stable weather patterns
17. Which region is most vulnerable to sea-level rise?
    a. Mountainous regions
    b. Coastal areas
    c. Deserts
    d. Polar ice sheets
18. Which of the following is an economic impact of climate change?
    a. Increased crop yields globally
    b. Damage to infrastructure from extreme weather
    c. Lower energy costs
    d. Reduced insurance premiums
19. Which health effect is linked to climate change?

a. Reduced respiratory illnesses
b. Increased heat-related illnesses
c. Lower incidence of vector-borne diseases
d. Decreased allergy cases

20. What is the difference between mitigation and adaptation?
21. Describe one strategy for climate resilience.
22. Compare the short-term and long-term carbon impacts of burning biomass versus burning fossil fuels.
23. What is the difference between "carbon sequestration" and "carbon storage," and how do they relate to human climate mitigation strategies?
24. How do feedback loops (e.g., permafrost thaw or increased wildfires) amplify humanity's initial impacts on the carbon cycle?
25. What policy or technological approaches are currently used to reduce human-driven carbon emissions? Give one example from each category.
26. A forest ecosystem is clear-cut and later allowed to regrow. Describe how carbon fluxes change immediately after harvesting, and how they change during regrowth.

Resources

- Carbon Dioxide Information Analysis Center http://cdiac.esd.ornl.gov/
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- Earth Institute 2017 State of the Planet – In a Warmer World Expect the Wet to Get Wetter and the Dryer, Dryer: In a Warmer World, Expect the Wet to Get Wetter, and the Dry, Drier – State of the Planet
- Feldman David 2013, Adaptation as a Water Resource Policy Challenge-Institutions and Science https://www.scirp.org/html/30566.html
- How Do We Predict Climate Change? Climate Models Explained - Caltech Science Exchange https://scienceexchange.caltech.edu/topics/sustainability/climate-change-predictions
- IPCC FAQ on Climate Resilience: https://www.ipcc.ch/report/ar6/wg2/about/frequently-asked-questions/keyfaq5/
- IPCC Sixth Assessment Report: Climate Change 2021 Synthesis Report AR6 Climate Change 2021: Synthesis Report — IPCC
- NASA Global Climate Change: Vital Signs of the Planet http://climate.nasa.gov/
- NOAA Coral Reef Conservation Program: Climate Change https://coralreef.noaa.gov/
- NOAA Earth System Research Laboratory: Carbon Cycle Science: Carbon Cycle Greenhouse Gases - NOAA Global Monitoring Laboratory
- NOAA Earth System Research Laboratory: NOAA CSL: Research
- 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
- NOAA Paleoclimatology: Astronomical Theory of Climate Change http://www.ncdc.noaa.gov/paleo/milankovitch.html

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- Sass, Ronald. *Q2: What are the Causes of Global Climate Change?* OpenStax CNX. Sep 22, 2009 Global Climate Change: Ronald Sass : Free Download, Borrow, and Streaming : Internet Archive
- UN Climate Adaptation Strategies: https://www.un.org/en/climatechange/climate-adaptation
- UN Sustainable Development Goal 13: https://www.un.org/sustainabledevelopment/climate-change/
- University of San Diego Virtual Museum: Climate Change http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml
- USDA Climate Change and Agriculture in the United States: Effects and Adaptation Climate Change and Agriculture in the United States: Effects and Adaptation | U.S. Climate Resilience Toolkit
- Woods Hole Oceanographic Institution: Carbon Around the Earth http://www.whoi.edu/feature/carboncycle/
- Xiong, Jinghua, et al. "Global evaluation of the “dry gets drier, and wet gets wetter” paradigm from a terrestrial water storage change perspective." *Hydrology and Earth system sciences* 26.24 (2022): 6457-6476. https://doi.org/10.5194/hess-26-6457-2022

Terms

Acidity
Adaptation
Aerobic
Albedo
Anaerobic
Aragonite
Autotroph
Bicarbonate
Biomass
Calcium carbonate
Carbon
Carbon capture and sequestration
Carbon dioxide
Carbon footprint
Carbon tax
Carbonate
Cellular respiration
Chlorofluorocarbon
Chloroplast
Climate
Climate change
Combustion
Confidence interval
Consumption
Coral bleaching
Decomposition
Desalination
Equilibrium
Evaporation
Fluorinated gases
Flux
Glacier
Global warming
Global warming potential
Greenhouse effect
Greenhouse gas
Heterotroph
Hydrofluorocarbon
Hydrogen ions
Ice age
Ice core
Industrial Revolution
Industrialized agriculture
Land ice
Landfill
Less-industrialized country
Lithosphere
Methane

Milankovitch cycles
Mitigation
Model
More-industrialized country
Nitrous oxide
Ocean-atmosphere exchange
Parts per billion (ppb)
Parts per million (ppm)
Perfluorocarbon
pH
Photosynthesis
Potential energy
Precipitation
Primary producer
Reservoir
Residence time
Resilience
Ruminant animal
Runoff
Sea ice
Sink reservoir
Slash-and-burn agriculture
Solar radiation
Source reservoir
Stable isotopes
Sulfur hexafluoride
Thermal equilibrium temperature
Thermal expansion
Water vapor
Wetland