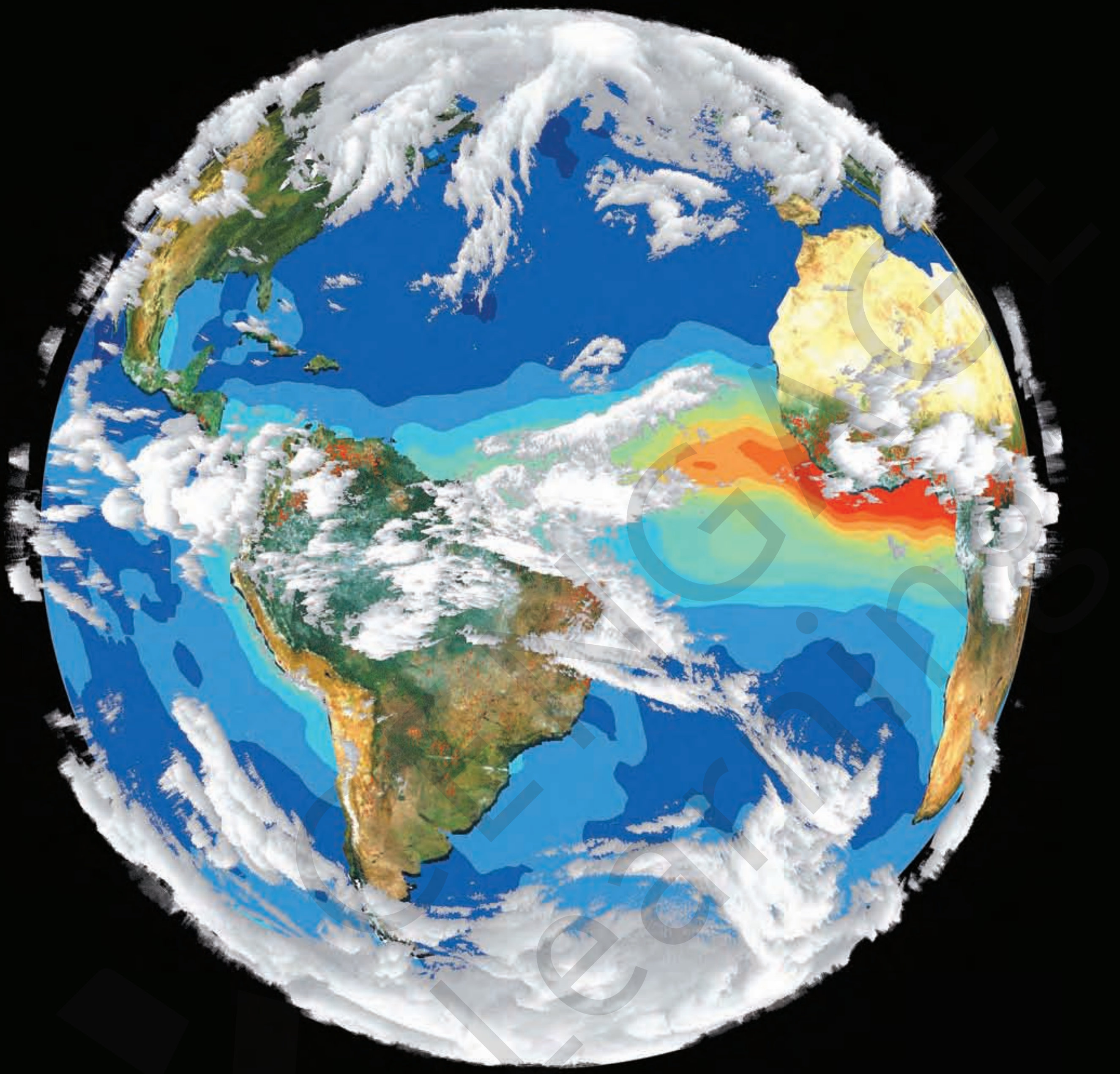

Carbon Cycle and Climate Change

The Carbon Cycle and Climate Change

J Bret Bennington

Hofstra University

Composite image of the Earth's interrelated systems and climate based on data from four different satellites. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) provided the land image layer, which is a true color composite of land vegetation for cloud-free conditions. Each red dot over South America and Africa represents a fire detected by the Advanced Very High Resolution Radiometer. The oceanic aerosol layer is based on National Oceanic and Atmospheric Administration (NOAA) data and is caused by biomass burning and windblown dust over Africa. The cloud layer is a composite of infrared images from four geostationary weather satellites.

NASA

Earth rising over the lunar surface. Photo taken by Apollo 8 astronaut Bill Anders on December 24, 1968.

"To see the earth as it truly is, small and blue and beautiful in that eternal silence where it floats, is to see ourselves as riders on the earth together, brothers on that bright loveliness in the eternal cold—brothers who know now they are truly brothers." —Archibald MacLeish (1892–1982)

"There are no passengers on spaceship Earth. We are all crew."—Herbert "Marshall" McLuhan (1911–1980)

ESSENTIAL QUESTIONS TO ASK

Carbon Cycle and Climate Change.1 Introduction

- *Where is carbon found in the major Earth systems (biosphere, atmosphere, hydrosphere, geosphere)?*
- *What is meant by the term* carbon cycle?

Carbon Cycle and Climate Change.2 Organic Carbon Cycle

- *What is the chemical process by which carbon dioxide in the atmosphere is transformed into organic carbon in the biosphere? What is the reverse chemical process?*
- *What is a fossil fuel? What is the impact on the atmosphere of the burning of fossil fuel?*

Carbon Cycle and Climate Change.3 Inorganic Carbon Cycle

- *How does the solubility pump transfer carbon dioxide from the atmosphere and store it in the oceans?*
- *How does chemical weathering transfer carbon dioxide from the atmosphere and store it in rock?*
- *What is the mechanism by which carbon dioxide is returned to the atmosphere from the geosphere?*

Carbon Cycle and Climate Change.4 Atmosphere and Climate

- *What are the important greenhouse gases and how do they function to warm the Earth's surface and atmosphere?*
- *How does the carbon cycle thermostat regulate the surface temperature of the Earth within a range suitable for living organisms?*
- *What other factors have an impact on the climate of the Earth?*

Carbon Cycle and Climate Change.5 Earth's Climate History

- *What mechanisms have maintained a stable climate through the history of the Earth, in spite of the gradually increasing energy output from the sun?*
- *Give three examples of evidence used as a proxy for reconstructing the climates and temperatures of the past.*
- *How are sediment cores and ice cores used by paleoclimatologists to reconstruct the climate history of the Earth?*

Carbon Cycle and Climate Change.6 Anthropogenic Climate Change

- *What is the evidence that recent climate warming is related to increasing levels of greenhouse gases in the atmosphere?*
- *In terms of the carbon cycle, what are the main sources of anthropogenic greenhouse gases?*

Carbon Cycle and Climate Change.7 Consequences of Climate Change

- *Why is climate change likely to be a problem for most societies, rather than a benefit?*
- *What are some of the likely impacts of climate change on the atmosphere, hydrosphere, and biosphere?*

Carbon Cycle and Climate Change.8 Preventing Climate Change

- *Why aren't the climate-regulating feedbacks inherent in the carbon cycle preventing anthropogenic climate change?*
- *What are some of the strategies for reducing the rate at which greenhouse gases are being emitted into the atmosphere?*

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Carbon Cycle and Climate Change.1

Introduction

Most people living in our age of space travel probably think of themselves as passengers on planet Earth. The more environmentally conscious of us likely share poet Archibald MacLeish's vision of being riders on a fragile, blue marble in space, utterly dependent on the life-support systems provided by our planet. But the truth, as pointed out by philosopher Marshall McLuhan, is that none of us are just passengers—we are all drivers of planet Earth. In the very simple act of breathing each of us slightly alters the composition of the Earth's atmosphere, and everything we do that consumes energy derived from fossil fuels impacts the atmosphere and ultimately the oceans, biosphere, and geosphere. The agricultural and technological activities of the rapidly expanding species *Homo sapiens* are having increasingly profound effects on Earth's systems. This is particularly true for our atmosphere and climate. There is overwhelming evidence that human activities are changing the global climate and will continue to do so well into the foreseeable future. How is this possible? What are the mechanisms by which humans interact with Earth's systems and climate? The answer can be summed up in one word: **carbon**.

Carbon, element number 6 in the periodic table (Figure Carbon Cycle.1), is the fourth most abundant element in the universe and the basic building block of organic molecules (in the human body, carbon is exceeded in mass only by oxygen, which is superabundant due to its presence in water). Carbon's electron configuration (four electrons in the outermost energy level) enables it to make four bonds with other atoms, including additional carbon atoms. This allows carbon to form a wide variety of molecules, including compounds containing chains of interconnected carbon atoms. In living systems, carbon combines with hydrogen, oxygen, and other elements to form all the functional molecules of life, including sugars, cellulose, fats, nucleic acids (DNA and RNA), and energy transfer molecules (adenosine triphosphate [ATP]). Because of carbon's versatility in bonding to itself and other atoms, there are far more carbon compounds than compounds based on any other element; millions have been described and an almost infinite variety are theoretically possible.

Carbon is an important component of all major Earth systems (Figure Carbon Cycle.2), with each system acting as a reservoir and **sink** for various forms of carbon. As has already been stated, carbon is the building block of organic compounds and is present in all organisms (living and dead) that make up the **biosphere**. In the **atmosphere**, carbon is found predominantly in molecules of carbon dioxide (CO_2) and methane (CH_4). Although less than 0.1% by volume of the Earth's atmosphere is composed of carbon dioxide and methane combined, both are important **greenhouse gases** that function to retain heat in the atmosphere. In the **hydrosphere**, carbon is found primarily in the form of bicarbonate ion (HCO_3^-), which forms from the dissolution of carbon dioxide in water. There is about 50 times more carbon in the oceans than there is in the atmosphere as CO_2 gas. In the **geosphere**, large volumes of sedimentary and metamorphic rock are composed of **carbonate minerals** making up **carbonate rock** (limestone, dolostone, and marble), most of which resides in the crust of the Earth. Also present in the crust are deposits of **hydrocarbons** derived from buried organic matter converted by heat and pressure into fossil fuels (coal, oil, and natural gas). In the Earth's mantle and in magmas, carbon is also present in the form of dissolved carbon dioxide gas.

Understanding how carbon functions in each Earth system in its various forms is important, but also important is

Figure Carbon Cycle and Climate Change.1 Carbon, the sixth element in the periodic table.

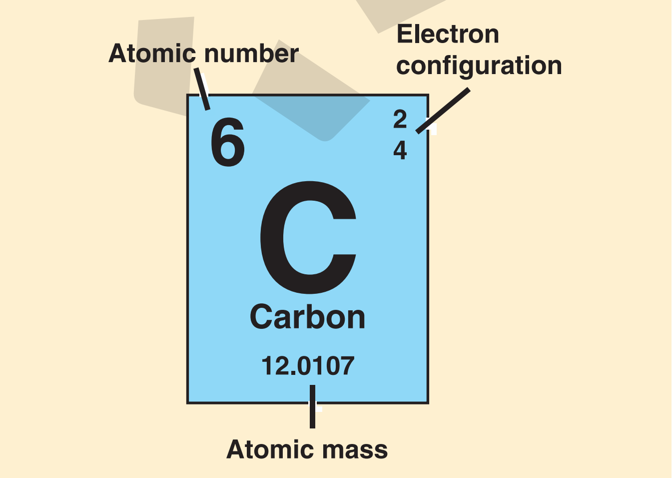
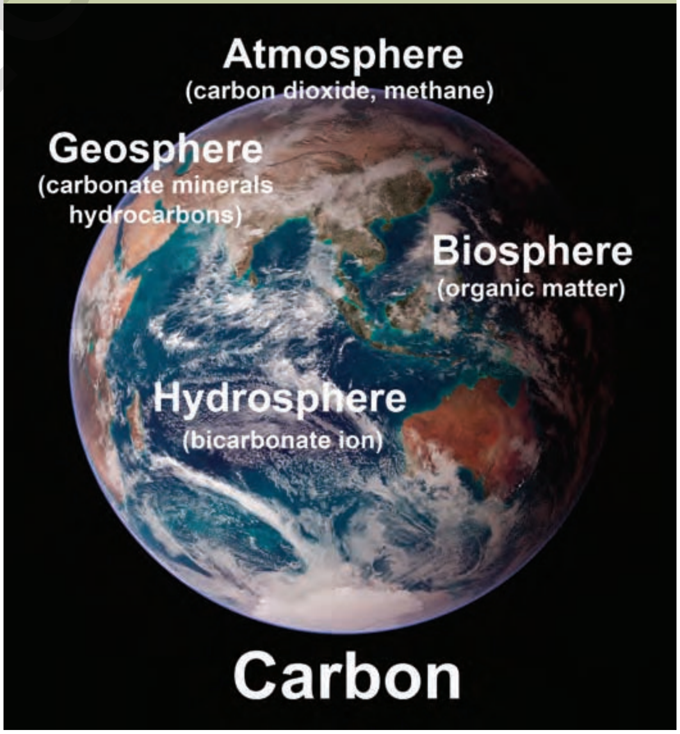


Figure Carbon Cycle and Climate Change.2 Earth's interrelated systems and their major carbon reservoirs.



understanding how carbon *moves* from one system to another as it is transferred from one reservoir to another. The collection of chemical pathways by which carbon moves between Earth systems is called the ***carbon cycle***, and it is the flow of carbon through this cycle that ties together the functioning of the Earth's atmosphere, biosphere, geosphere, and oceans to regulate the climate of our planet. This means that as drivers of planet Earth, anything we do to change the function or state of one Earth system will change the function and state of all Earth systems. If we change the composition of the atmosphere, we will also cause changes to propagate through the biosphere, hydrosphere, and geosphere, altering our planet in ways that will likely not be beneficial to human welfare. Understanding the functioning of the carbon cycle in detail so that we can predict the effects of human activities on the Earth and its climate is one of the most important scientific challenges of the twenty-first century.

Because the carbon cycle is complex, it is convenient to consider the reservoirs and pathways involving organic carbon separately from those involving inorganic carbon. The **organic carbon cycle** includes the biologically mediated movement of carbon and the transfer of organic carbon through different Earth systems and involves many processes that occur on the shorter time scales of human experience. The **inorganic carbon cycle** includes the movement of carbon mediated by nonbiological processes that mostly operate over longer, geologic spans of time.

Section Carbon Cycle and Climate Change.1 Summary

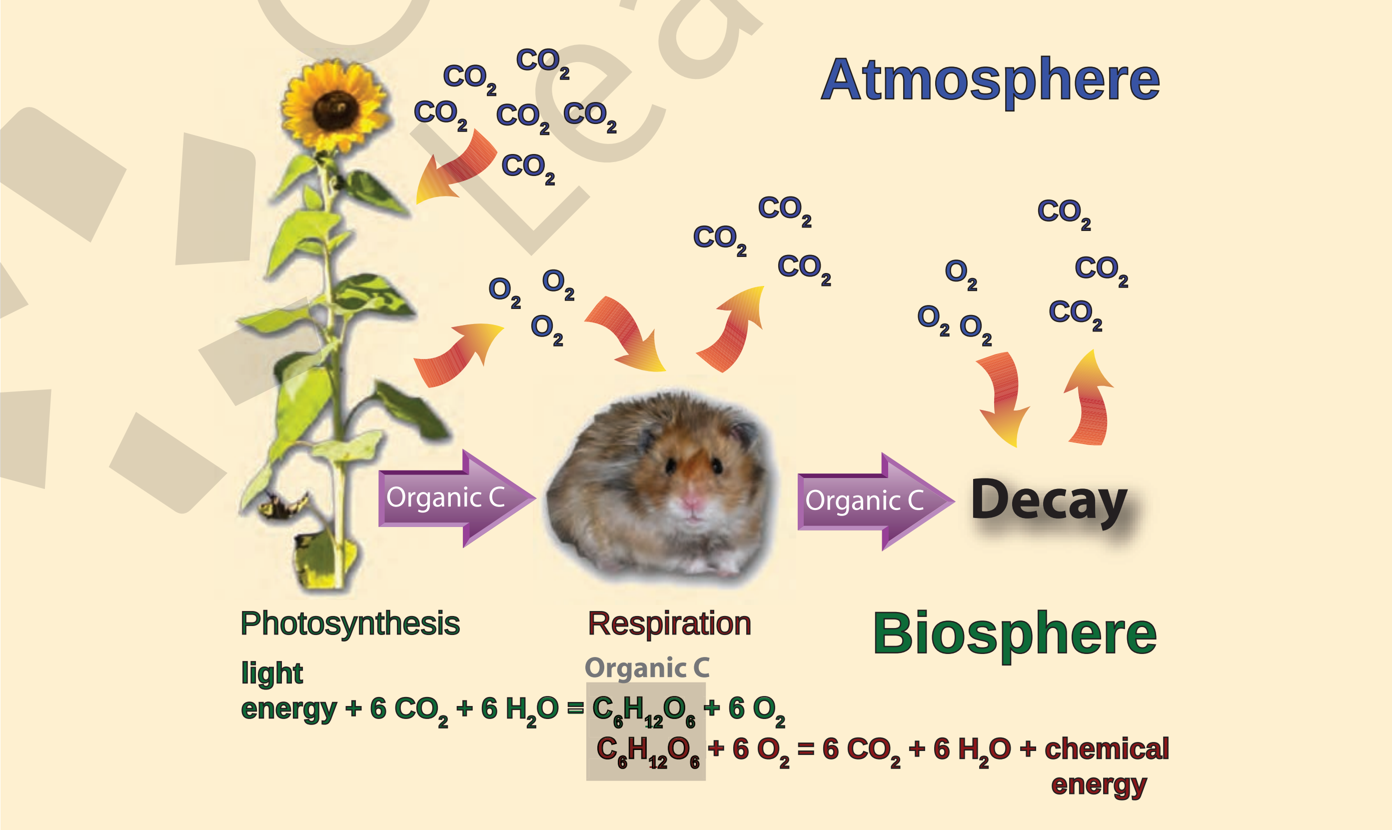
- Carbon is an abundant element that is important in the function of all major Earth systems, including the biosphere, atmosphere, hydrosphere, and geosphere.
- Carbon is transferred between Earth systems through a series of pathways called *the carbon cycle*. One important function of the carbon cycle is the regulation of Earth's climate.

Carbon Cycle and Climate Change.2

Organic Carbon Cycle

Consider two representative members of the biosphere, a sunflower and a hamster (Figure Carbon Cycle.3). Everyone knows that if you provide a sunflower with water and light it will grow and produce sunflower seeds. In other

Figure Carbon Cycle and Climate Change.3 Basic biochemical reactions of the organic carbon cycle: photosynthesis, respiration, and decay.



words, the sunflower will increase in biomass over time as it generates new organic carbon. But where is this organic carbon coming from? The simple answer is that the carbon in sunflower biomass originates as inorganic carbon dioxide gas in the atmosphere. The biochemical reactions of **photosynthesis** involving chlorophyll and a host of enzymes contained in the cells of the plant use solar energy (photons generated by the sun) and water to chemically combine carbon atoms from CO_2 into the organic molecules needed to build a sunflower (a process called **carbon fixation**). The byproduct of photosynthesis is oxygen gas (O_2) that is released into the atmosphere. The solar energy captured by photosynthesis is stored in the chemical bonds of the organic molecules produced. Green plants, algae, and certain types of bacteria are the organisms capable of photosynthesis. The reverse chemical reaction is **respiration**, whereby oxygen is used to break down organic molecules, producing chemical energy and releasing water and carbon dioxide back into the atmosphere. Both the sunflower and the hamster utilize respiration in their cells to obtain the chemical energy needed to build complex organic molecules from simple ones and to power their metabolisms. Respiration releases the solar energy trapped by photosynthesis in a chemical form (ATP) that can be used by cells.

Two important points should be noted about these chemical reactions. First, photosynthesis moves carbon from the atmosphere into the biosphere and respiration moves carbon from the biosphere back into the atmosphere. Second, the two processes are in equilibrium in living organisms; for every molecule of carbon dioxide taken out of the atmosphere by photosynthesis in the production of organic carbon, one molecule is given back by respiration in the metabolism of organic carbon. The same applies to oxygen; for each O_2 molecule released into the atmosphere by photosynthesis, respiration removes one molecule of O_2.

What happens to the organic carbon in the sunflower and the hamster after they die? Both organisms are subject to decay, a complex collection of processes that includes oxidation; aerobic **catabolism** by scavengers, fungi, and bacteria; and anaerobic catabolism by bacteria and **archaea**. In most environments, decay converts organic molecules to either carbon dioxide or methane, releasing chemical energy and heat. Methane in the atmosphere chemically reacts with oxygen (oxidation) to produce CO_2 and water. So, the end result of decay is the same as respiration—organic carbon combines with oxygen and is returned to the atmosphere as carbon dioxide (see Figure Carbon Cycle.3).

Most organic carbon is fixed from atmospheric carbon dioxide through photosynthesis, releasing oxygen (some bacteria and archaea use chemical energy to fix carbon, particularly where light is unavailable, such as in the deep ocean). In fact, photosynthesis is the source of almost all oxygen in the atmosphere of the Earth (a negligible amount of oxygen is produced by the splitting of water molecules by solar radiation). Yet, if you add up all of the organic carbon existing in the biomass of the terrestrial and marine ecosystems of the world, there is a tremendous imbalance between the carbon in organic biomass and the oxygen in the atmosphere. The Earth's atmosphere is 23% oxygen, which has a total mass of about 1×10^{15} metric tons. Estimates of the global standing biomass of organic carbon are only around 2×10^{12} metric tons, the production of which by photosynthesis would yield only 5.4×10^{12} metric tons of oxygen. The explanation for the excess of oxygen in the Earth's atmosphere is that some of the organic carbon produced by photosynthesis collects in a variety of sinks, where it is prevented from recombining with oxygen to produce carbon dioxide (Figure Carbon Cycle.4). So, where is the missing organic carbon? On land, organic carbon accumulates in soils, swamps, bogs, and lake bottoms. In fact, three to five times as much organic carbon exists in soils as is found in standing vegetation and fauna. In the oceans, organic carbon produced by photosynthesizing marine organisms sinks into the oxygen-poor waters of the deep sea, becoming dissolved in deep, cold water or buried in marine mud on the seafloor. This mechanism for moving carbon from biologically active surface waters to storage in the deep sea is called the **biological pump**.

Fossil Fuels

In regions of the Earth where sedimentary rock is in the process of forming, organic carbon in soil and ocean sinks can become trapped in deposits of accumulating sediment and sequestered in the crust of the Earth for thousands to hundreds of millions of years. On land, plant biomass growing in swamps and bogs may accumulate to form thick deposits of organic matter called peat. If peat layers become buried under younger layers of sediments, they will mature over time into coal deposits (Figure Carbon Cycle.5, *A* and *B*). Organic carbon from algae and other types of plankton accumulates in the mud deposited in lakes and oceans. If this mud becomes buried to form sedimentary rock, the trapped organic molecules will break down under heat and pressure to form deposits of hydrocarbons such as tar, oil, and natural gas (Figure Carbon Cycle.5, *C*).

We call sedimentary organic carbon deposits **fossil fuels** because they contain concentrations of energy collected from solar radiation by ancient photosynthesis and stored as chemical energy in the fossilized organic carbon. Fossil fuels contain carbon removed from the Earth's atmosphere over hundreds of millions of years of geologic time. When we burn fossil fuels in vehicles, homes, and power plants to release their energy, we also release their carbon back into the atmosphere as CO_2. In a little more than a hundred years we have extracted and burned huge quantities of fossil fuels that have accumulated over hundreds of millions of years, and we are now sending several gigatons (billions of tons) of ancient carbon back into the Earth's atmosphere every year (see Figure Carbon Cycle.4). Fossil fuels are nonrenewable resources because once they are used they cannot be replenished on a human time scale. Our civilization cannot wait millions of years for the geologic processes that bury carbon in the crust of the Earth to produce new hydrocarbon deposits.

▶ **Figure Carbon Cycle and Climate Change.4** Simplified global carbon cycle showing amounts of carbon stored in various reservoirs. Numbers in parentheses are gigatons of carbon (GtC) stored, numbers associated with transfers (*arrows*) are gigatons of carbon per year (GtC/y).

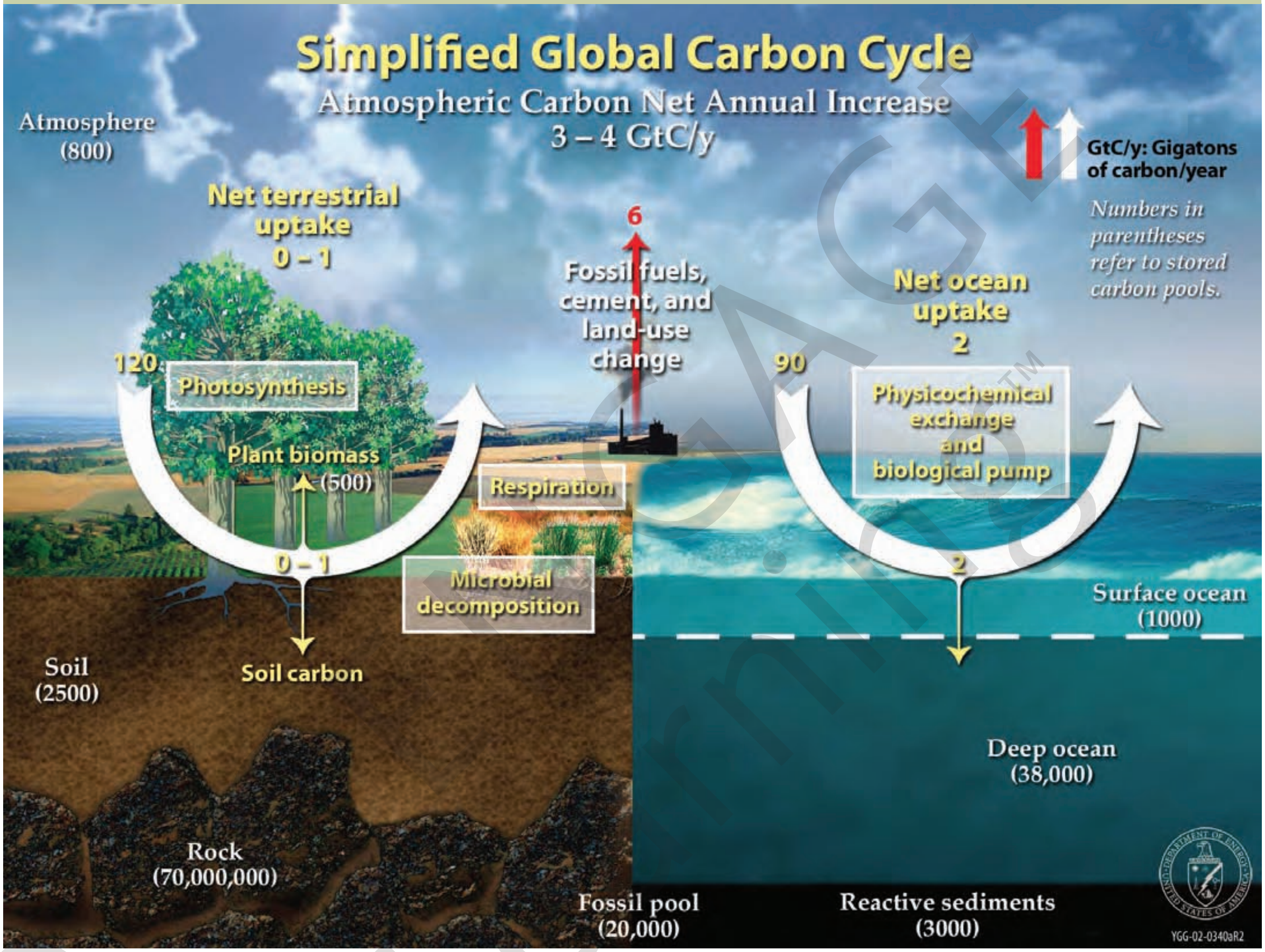


Diagram courtesy of the U.S. Department of Energy

Section Carbon Cycle and Climate Change.2 Summary

- Bacteria and plants remove carbon dioxide (CO_2) from the atmosphere by using solar energy to convert CO_2 into organic carbon compounds in the process of photosynthesis. Most organisms, including bacteria, animals, and plants, metabolize organic carbon to obtain energy, releasing carbon back into the atmosphere as CO_2.
- Some organic carbon produced by photosynthesis is stored in soils, dissolved in seawater, or buried in sediments on the sea floor, preventing the carbon from returning to the atmosphere.
- Fossil fuels are deposits of organic carbon in the form of coal, oil, and natural gas that are trapped in the crust of the Earth for thousands to hundreds of millions of years.
- Burning fossil fuels releases ancient carbon back into the atmosphere as CO_2.

Carbon Cycle and Climate Change.3

Inorganic Carbon Cycle

The inorganic carbon cycle includes the transfers and sinks for carbon in Earth systems that are not dependent on biochemical processes such as photosynthesis and respiration and do not involve organic carbon. Even if the Earth were devoid of life, carbon would still move from the atmosphere to the oceans and ultimately to the geosphere through two main pathways, the **solubility pump** and **chemical weathering** (Figure Carbon Cycle.6). When carbon dioxide in the atmosphere dissolves in water, it reacts to form a weak acid called **carbonic acid** (H_2CO_3) that dissociates into a hydrogen ion (H^+) and a bicarbonate ion (HCO_3^-) (Figure Carbon Cycle.7, *A*). In the oceans, the moderately alkaline pH and ionic composition of seawater favors this reaction so that 98% of the CO_2 that dissolves in the oceans is converted to bicarbonate ion

▶ **Figure Carbon Cycle and Climate Change.5** Fossil fuels formed from the burial of terrestrial and marine organic carbon.

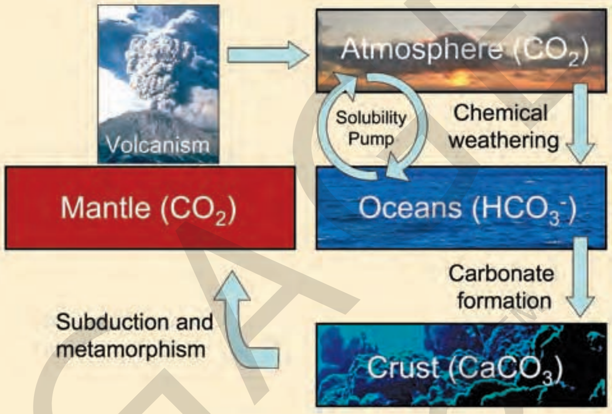
ⓐ Peat deposit forming from the accumulation of organic carbon in a bog, Killarney, Ireland.

ⓑ Coal seams exposed in shoreline cliffs near Homer, Alaska.

ⓒ Crude oil extracted from hydrocarbon-rich shale.

A, B, J Bret Bennington; C, DOE. From Wicander R, Monroe J: Essentials of Physical Geology, ed. 5. Boston: Brooks Cole, 2008

▶ **Figure Carbon Cycle and Climate Change.6** Inorganic carbon cycle. Carbon cycles through the solubility pump much faster (years to hundreds of years) than it circulates through the geologic pathways of chemical weathering, carbonate formation, metamorphism, and volcanism (tens to hundreds of millions of years).

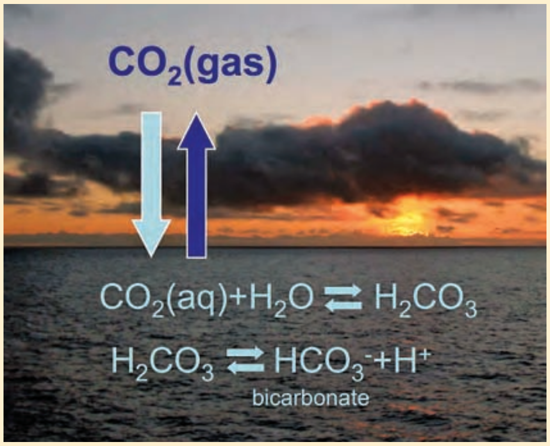


(a negligible amount of bicarbonate ion also disassociates into hydrogen ion [H^+] and carbonate ion [CO_3^{-2}]). This gives the oceans the capability of storing much more carbon dioxide than is present in the atmosphere.

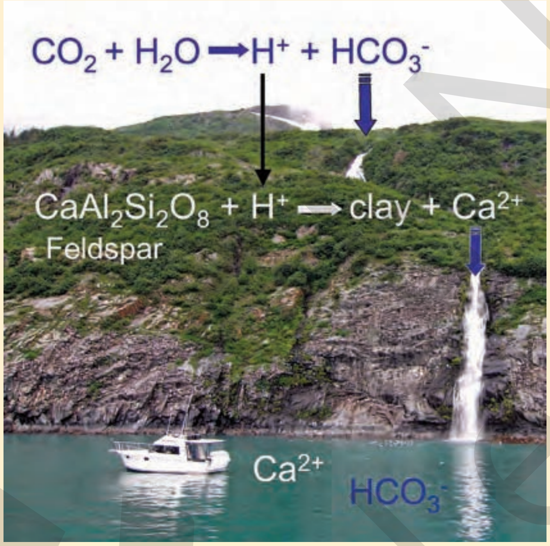
Water in the oceans is not stagnant; rather, it circulates in a global pattern driven in part by the downward movement of cold, dense water at high latitudes. Because cold water is capable of dissolving more CO_2 than warmer water, the global pattern of ocean circulation works to "pump" carbon dioxide from the atmosphere to storage in the deep, cold water of the oceans. In places where deep ocean water is upwelling, these reactions are reversed and CO_2 is returned to the atmosphere. Earlier it was mentioned that burning fossil fuels releases ancient CO_2 back into the atmosphere. Geochemists estimate that almost one third of the carbon dioxide emitted from burning fossil fuels is currently being taken up by the oceans via the solubility pump. Given sufficient time, the oceans would be capable of absorbing 80% to 90% of the CO_2 released by humans into the atmosphere; however, the solubility pump works too slowly to keep up with the high volume of CO_2 currently being liberated by our rapidly industrializing world.

Another process that removes carbon dioxide from the atmosphere and converts it to bicarbonate ion in the oceans is a chemical weathering reaction called **hydrolysis**. Carbon dioxide gas dissolves in liquid water in the atmosphere and soil, forming carbonic acid, as described earlier. The hydrogen ion produced by carbonic acid is chemically very reactive and capable of disrupting the structure of silicate minerals such as feldspars. For example, calcium feldspars (e.g., labradorite) react with carbonic acid, breaking down into clay minerals and calcium ions (Figure Carbon Cycle.7, *B*). The residual clay accumulates in soils and sedimentary deposits, while the calcium and bicarbonate ions are transported by groundwater and streams to the

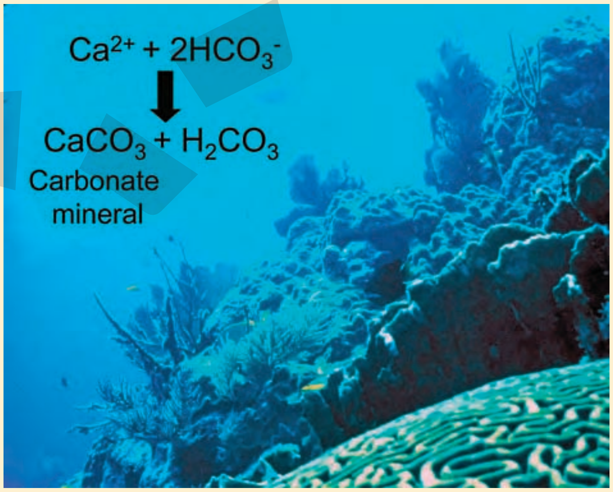
Figure Carbon Cycle and Climate Change.7 Important chemical reactions governing the inorganic transfer of carbon between the atmosphere, hydrosphere, and geosphere.



ⓐ Carbon dioxide gas dissolves in water to form carbonic acid and bicarbonate ion.



ⓑ Carbonic acid in precipitation and groundwater chemically weathers silicate minerals in rock to produce metal ions (e.g., calcium) and bicarbonate ions, which accumulate in the oceans.



ⓒ Calcium ions and bicarbonate ions combine in the oceans to produce carbonate minerals.

ocean. Note that, unlike the reactions of the solubility pump, at surface temperature and pressure the hydrolysis of silicate minerals is an irreversible chemical reaction that consumes hydrogen ions. This means that the formation of bicarbonate ion from carbon dioxide and water is also irreversible in hydrolysis, because the hydrogen ions are no longer available to recombine with the bicarbonate ions. As chemical weathering proceeds, more and more calcium and bicarbonate ion is added to the oceans. In places where conditions are warm, ocean waters are completely saturated with these ions. Under saturated conditions, calcium and bicarbonate ions combine to form carbonate minerals such as calcite, aragonite, and dolomite (Figure Carbon Cycle.7, *C*). Even when seawater is undersaturated with calcium and bicarbonate, carbonate minerals can form as a product of **biomineralization**. Many marine organisms, including algae, corals, protists, echinoderms, and mollusks, promote the precipitation of carbonate mineral in their tissues to construct shells and skeletal elements.

Marine organisms that engage in photosynthesis (e.g., algae and cyanobacteria) or that harbor photosymbionts (e.g., reef-building corals) are particularly effective at producing carbonate mineral because photosynthesis consumes CO_2 and thus raises the pH of the water around their tissues, promoting the mineralization reaction. Carbonate mineral produced both inorganically and biologically accumulates on the seafloor as sediment to form deposits of limestone rock that can persist in the crust of the Earth for hundreds of millions of years (Figure Carbon Cycle.8). If carbonate sediments and limestone are tectonically uplifted and chemically weathered (carbonic acid in rain and groundwater will dissolve carbonate minerals, producing calcium ions and bicarbonate ions in the reverse of the reaction shown in Figure Carbon Cycle.7, *C*), the liberated ions return to the ocean to eventually recombine into new carbonate mineral. The net effect of chemical weathering and the formation of limestone over geologic spans of time is to remove carbon dioxide from the atmosphere and store it in rock. Geologists estimate that the amount of CO_2 stored in carbonate rock in the crust of the Earth would be enough to increase the surface pressure of the atmosphere by a factor of 60, equivalent to the pressure experienced at a depth of 2000 feet underwater.

The processes that finally do liberate carbon from carbonate minerals and return it to the atmosphere as CO_2 occur deep in the Earth. Carbonate sediments and limestone that become caught up in tectonic plate collisions can be pushed deep into the Earth's interior or subducted into the mantle, subjecting them to metamorphism under extremely high temperatures and pressures. Under these conditions, carbonate minerals react with quartz to produce silicate minerals and carbon dioxide gas. This CO_2 remains buried in the crust and mantle of the Earth until it is liberated by outgassing during volcanic eruptions (see Figure Carbon Cycle.6). Volcanic venting of carbon dioxide is the only way that CO_2 removed from the atmosphere by chemical weathering can be replaced.

▶ **Figure Carbon Cycle and Climate Change.8** Sedimentary carbonate rock—the Middle Devonian Onondaga Limestone, near Geneseo, New York. The carbon in this rock was removed from the atmosphere more than 390 million years ago when it was precipitated as carbonate mineral by organisms in an ancient coral reef.

J Bret Bennington

Section Carbon Cycle and Climate Change.3 Summary

- Carbon dioxide dissolves in water to form carbonic acid. In the oceans, carbonic acid disassociates into hydrogen ion and bicarbonate ion. Downwelling of surface waters allows the oceans to store large quantities of bicarbonate ion in deep, cold waters. Eventually, upwelling of deep water releases carbon dioxide back into the atmosphere.

- Carbonic acid that forms in rainwater and groundwater reacts with rock to hydrolyze silicate minerals. During hydrolysis, framework silicate minerals are altered to clays, liberating silica, bicarbonate ions, and metal ions such as calcium and sodium. These ions are transported to the ocean where calcium and bicarbonate combine to form carbonate minerals. This process effectively locks up CO_2 in limestone rock, removing it from the atmosphere for immense spans of time.

- Metamorphism of limestone and silica releases CO_2 into the Earth's mantle. Volcanic eruptions pump mantle CO_2 dissolved in magma back into the atmosphere.

Carbon Cycle and Climate Change.4

Atmosphere and Climate

Now that we understand how carbon dioxide moves in and out of the atmosphere through the workings of the carbon cycle, we are ready to examine the connections between the carbon cycle, the atmosphere, and climate. Although the interior of the Earth is very hot, the escape of heat from the Earth's core and mantle has little to do with keeping the surface warm. In fact, the average geothermal heat flow is about 0.075 watts per square meter, which is one one-thousandth the energy radiated by a 75-watt light bulb! The average amount of solar energy absorbed by the Earth is about 350 watts per square meter, so the atmosphere and surface of the Earth are warmed primarily by solar radiation.

Most of the sun's energy reaching the Earth is in the form of shortwave radiation in the visible and ultraviolet spectrum. When shortwave radiation encounters something opaque, such as the surface of the Earth or clouds, some is reflected and the rest is absorbed and re-emitted as longwave or infrared (heat) radiation. The gases that make up the

Table Carbon Cycle and Climate Change.1 Gases That Compose Earth's Atmosphere

Composition of Earth's Atmosphere

Gas Name	Chemical Formula	Percent Volume
Nitrogen	N_2	78.08%
Oxygen	O_2	20.95%
Water	**H_2O**	**0 to 4%**
Argon	Ar	0.93%
Carbon dioxide	**CO_2**	**0.0360%**
Neon	Ne	0.0018%
Helium	He	0.0005%
Methane	**CH_4**	**0.00017%**
Hydrogen	H_2	0.00005%
Nitrous oxide	**N_2O**	**0.00003%**
Ozone	**O_3**	**0.000004%**

Significant greenhouse gases
Minor greenhouse gases

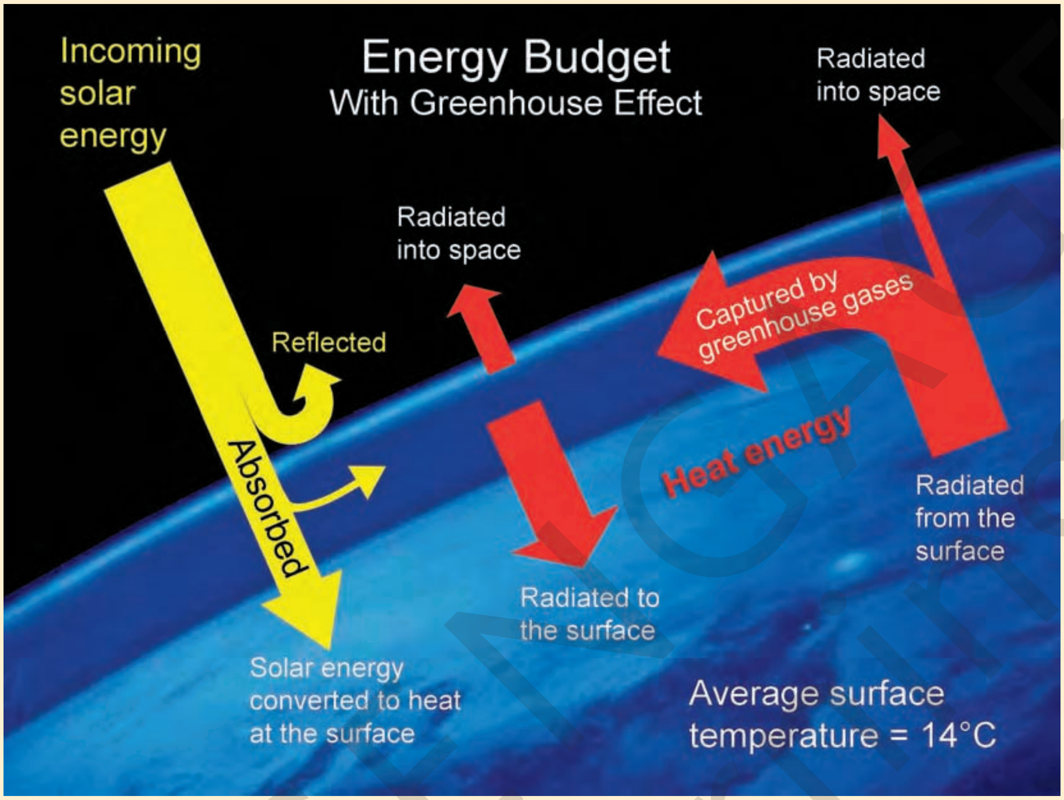
atmosphere of the Earth (Table Carbon Cycle.1) are mostly transparent to shortwave radiation. Of the total amount of solar radiation reaching the Earth, 30% is reflected back into space off of clouds and the surface. The remaining 70% is absorbed by the surface (50%) and by clouds and the atmosphere (20%) and is re-emitted as infrared radiation (Figure Carbon Cycle.9, *A*). The gases that make up the majority of the atmosphere (nitrogen, oxygen and argon—see Table Carbon Cycle.1) are also transparent to infrared radiation. However, many gases that exist in smaller amounts, such as carbon dioxide, water vapor, and methane, are opaque to infrared radiation, absorbing it and warming the atmosphere. Although some of the heat in the atmosphere is transferred to the upper layers where it can escape into space, much of it is re-radiated back toward the surface. This is the so-called **greenhouse effect** (the greenhouse gases allow light in but trap heat and warm the Earth's atmosphere in a manner loosely analogous to the glass walls of a greenhouse, which allow light to enter but prevent warm air from escaping). The greenhouse effect keeps the average surface temperature of the Earth well above freezing at a temperature hospitable to the biosphere. Because of the greenhouse effect, currently only 10% of the infrared radiation emitted from the surface escapes directly into space. If there were no greenhouse gases in the Earth's atmosphere, then most of the heat radiated from the surface of the Earth would escape back into space without warming the atmosphere (Figure Carbon Cycle.9, *B*). Such a greenhouse-free Earth would have an average surface temperature well below freezing, and we wouldn't be here to complain about the cold!

Although the greenhouse gases make up only a small fraction of the total gas in the atmosphere, they have a very disproportionate influence on the energy budget of the atmosphere. This is why human activities that increase greenhouse gas concentrations can have a significant effect—it doesn't take much to impact global climate. The relative contribution of each greenhouse gas to warming the Earth is a function of both its efficiency at absorbing heat and its abundance in the atmosphere. The most effective greenhouse gas overall is water vapor, followed by carbon dioxide, and then methane (see Table Carbon Cycle.1). Water vapor enters and exits the atmosphere very quickly via evaporation and condensation and, averaged across the globe, remains near an equilibrium concentration that is dependent on the average temperature of the atmosphere. Rather than controlling climate, water vapor responds to changes in climate through positive feedback. For example, if climate warms, then the amount of water vapor in the atmosphere increases, strengthening the greenhouse effect and adding to the warming (at the same time, more water vapor might cause more cloud formation; some clouds reflect incoming solar radiation and counteract the warming due to the water vapor greenhouse).

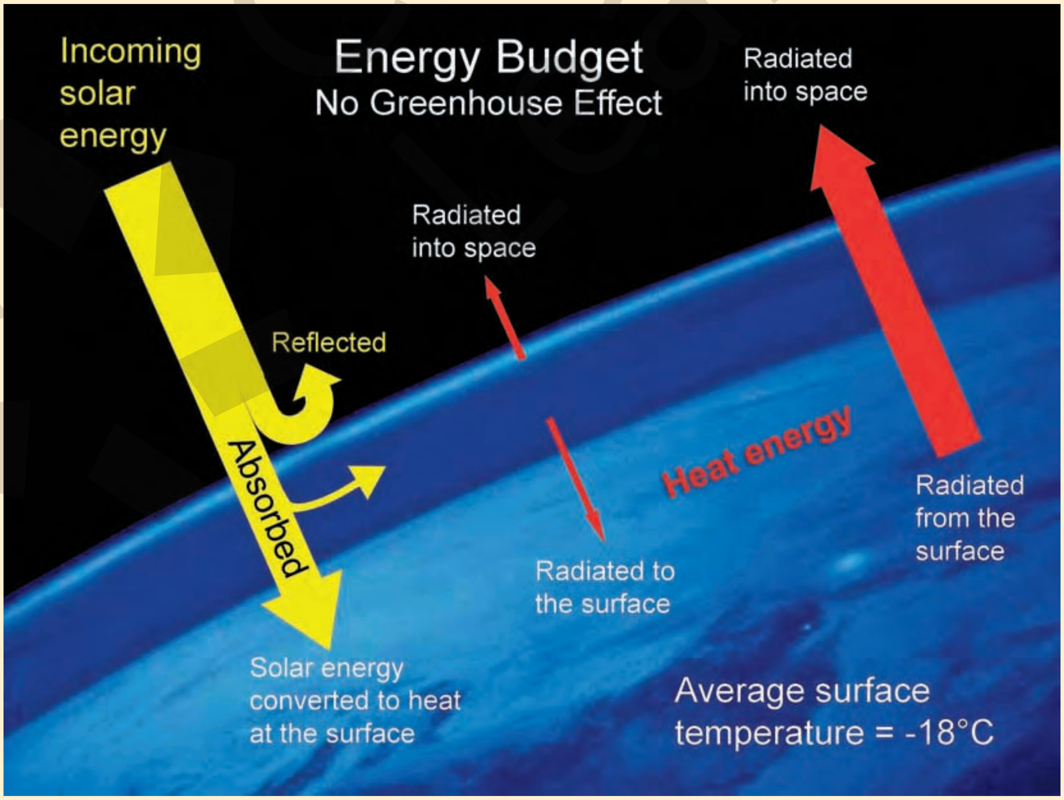
Carbon dioxide behaves very differently than water vapor because there are both organic and inorganic pathways in the carbon cycle that change CO_2 levels in the atmosphere over a broad range of time scales. A number of lines of evidence indicate that carbon dioxide concentrations have varied greatly through the history of the Earth and that major changes in global climate have been coupled with changes in the greenhouse warming of the Earth driven by variations in CO_2 levels in the atmosphere. Methane is expelled by volcanic eruptions and is produced by archaea and bacteria living in anaerobic environments (oxygen-poor localities that range from seafloor mud to the intestines of large mammals). Methane is quickly removed from the atmosphere by exposure to ultraviolet light and oxidation and only persists because it is being constantly replenished by volcanism and biological activity. Some long-term changes in global climate that have occurred in the geologic past may be related to shifts in methane levels caused by long-term changes to the abundance of methane producers in the biosphere. Other more rapid climate changes have been linked to short-term releases of methane from geologic sinks into the atmosphere.

The carbon dioxide component of the greenhouse effect is regulated over geologic time by the inorganic carbon cycle functioning as a **carbon cycle thermostat** (Figure Carbon Cycle.10). The inorganic carbon cycle is an excellent example of a negative feedback system. Negative feedback systems resist being driven to extremes and tend to return to equilibrium if they are perturbed. Imagine a world growing increasingly warm as the sun's brightness slowly increases or as volcanic eruptions emit more and more carbon dioxide into the atmosphere. On a warmer Earth, chemical weathering is promoted by more vigorous cycling of water through the atmosphere and higher temperatures. More chemical weathering removes more CO_2 from the atmosphere as carbonic acid reacts

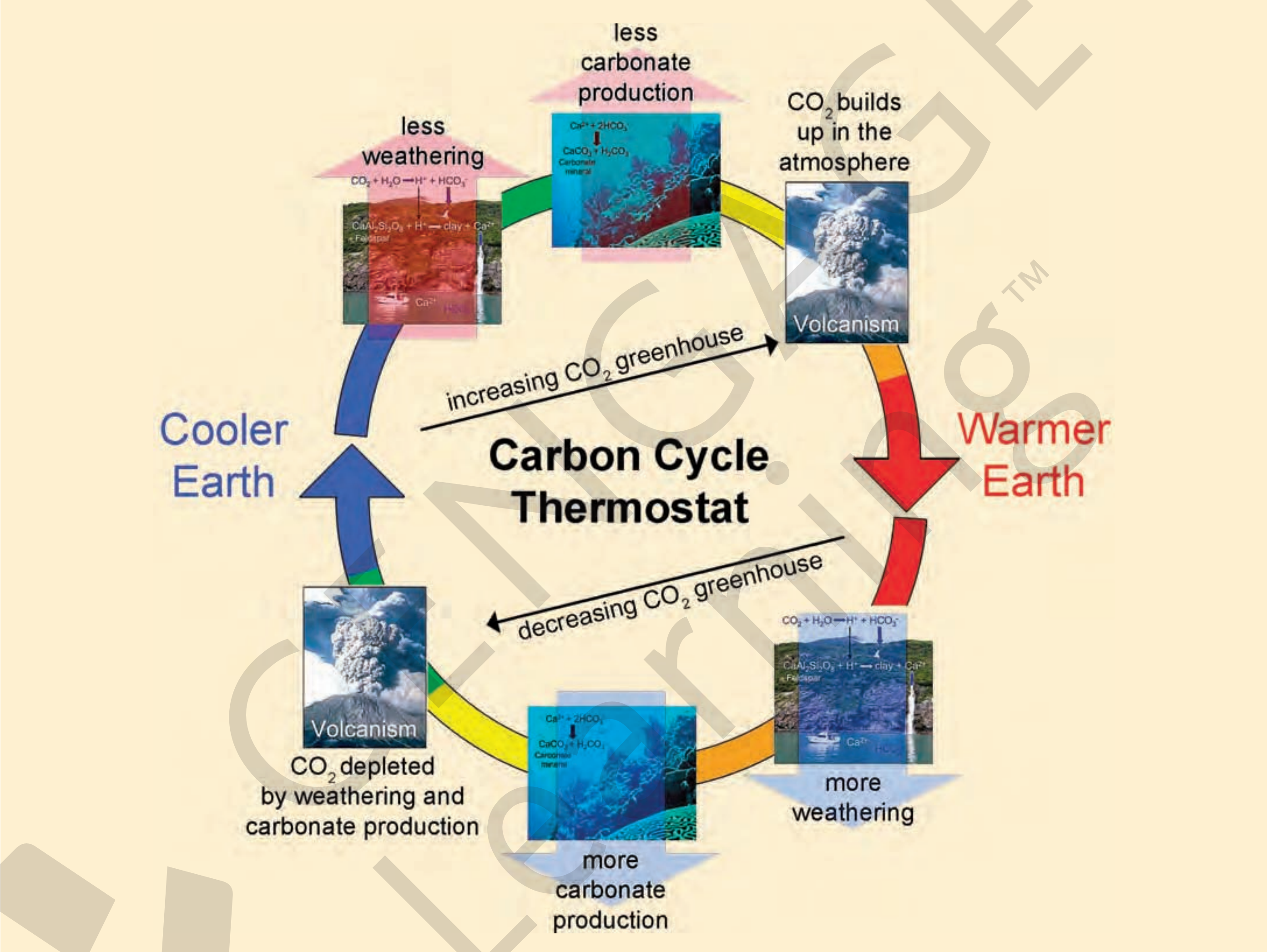
▶ **Figure Carbon Cycle and Climate Change.9** How the greenhouse effect affects the exchange of energy between the Earth and space. Width of arrows represents approximate proportion of total energy exchanged.



ⓐ Energy budget showing how greenhouse gases trap significant amounts of heat energy in the atmosphere, preventing it from radiating back into space. The heat energy in the atmosphere is a significant factor warming the surface of the Earth.



ⓑ Energy budget showing exchange of energy in the absence of greenhouse gases. Note that in this scenario, almost all the incoming solar radiation is radiated back into space and the atmosphere does little to warm the surface.



▶ **Figure Carbon Cycle and Climate Change.10** Diagram illustrating how the carbon cycle functions as a climate thermostat by regulating the carbon dioxide greenhouse in response to climate warming and cooling. When the Earth's climate is relatively cool, there is less chemical weathering and less uptake of atmospheric CO_2 into carbonate rock, which allows for volcanic emissions of CO_2 to build up in the atmosphere, warming the climate. As the Earth warms, rates of chemical weathering and carbonate production increase, drawing CO_2 from the atmosphere and transforming it into carbonate rock in the oceans. As CO_2 levels in the atmosphere drop, the climate cools. The negative feedbacks inherent in the carbon cycle maintain the climate of the Earth near a temperate equilibrium over geologic spans of time.

with silicate minerals, producing bicarbonate ion. Also, warmer oceans favor the growth of carbonate secreting organisms and the inorganic precipitation of carbonate mineral. As the Earth grows hotter, the inorganic carbon cycle removes CO_2 from the atmosphere and locks it away as limestone at an increasing rate. However, removing CO_2 from the atmosphere reduces the greenhouse effect, allowing more radiant heat to escape into space, cooling the Earth. As the Earth cools, chemical weathering slows, as does the production of limestone, decreasing the rate at which CO_2 is removed from the atmosphere. If the Earth begins to freeze over, chemical weathering and carbonate formation almost cease and little to no CO_2 is permanently removed from the atmosphere. Over time, as volcanoes continue to erupt, CO_2 levels rise and the Earth warms up again as the greenhouse strengthens. Working as a negative feedback system, the inorganic carbon cycle's control on the carbon dioxide greenhouse has likely exerted an important long-term control on the stability of Earth's climate for most of its history.

The carbon cycle is not the only factor driving climate change on the Earth. A variety of other forcing mechanisms influence the average temperature of the planet, operating over a wide range of timescales. The sun fluctuates in its luminosity over a variety of time scales, changing the amount of solar energy reaching the Earth. Recent studies have found evidence for a 1500-year solar cycle that may have contributed to historical fluctuations in climate such as the **Medieval Warm Period** and the **Little Ice Age**. Volcanic activity can have both a short-term and long-term effect on climate. Large pyroclastic eruptions associated with plate tectonic collisions (such as occurred at Krakatoa and Mount Saint Helens) inject ash and sulfur dioxide into the upper atmosphere, increasing the atmosphere's **albedo** (reflectivity) and cooling the Earth for intervals of several years. Long-term, high-volume flood basalt eruptions associated with hot spots and continental rifting can emit immense quantities of CO_2 into the atmosphere over thousands of years, causing global climate to warm for much longer periods. Because land, sea, and ice absorb and reflect solar radiation differently, the placement of the continents has an impact on climate. When plate tectonic forces move continents to low latitudes near the equator, they absorb more solar radiation than they do if located near the poles. Polar continents can host large expanses of ice that reflect sunlight back into space, cooling the Earth. Cyclical changes in the geometry of the Earth's orbit and the tilt of the Earth (**Milankovitch Cycles**) affect the distribution of sunlight across the globe, altering climate over tens of thousands to hundreds of thousands of years. Ocean circulation plays an important role in redistributing heat around the globe, influencing regional climates. Some factors interact with the inorganic carbon cycle to perturb global climate. Higher rates of seafloor spreading cause increased volcanism across the globe, putting more CO_2 into the atmosphere. Plate tectonic collisions that raise high mountain ranges can cool the Earth by causing increased rates of chemical weathering (as a general rule, the farther above sea level rock is, the faster it weathers) and by radiating more heat into space. As you can see, there are many potential controls on climate and we should not be surprised to learn that, within the boundaries of the climate extremes regulated by the carbon cycle thermostat, the Earth has had a complex climate history.

Section Carbon Cycle and Climate Change.4 Summary

- Water vapor, carbon dioxide, and methane are greenhouse gases that trap heat being radiated from the surface of the Earth.
- The inorganic carbon cycle functions as a thermostat for the long-term climate of the Earth by regulating the amount of carbon dioxide in the atmosphere.
- Other mechanisms for changing climate include plate tectonics and volcanism, variability in solar output, ocean circulation, and changes in the geometry of the Earth's orbit and tilt of the Earth.

Carbon Cycle and Climate Change.5
Earth's Climate History

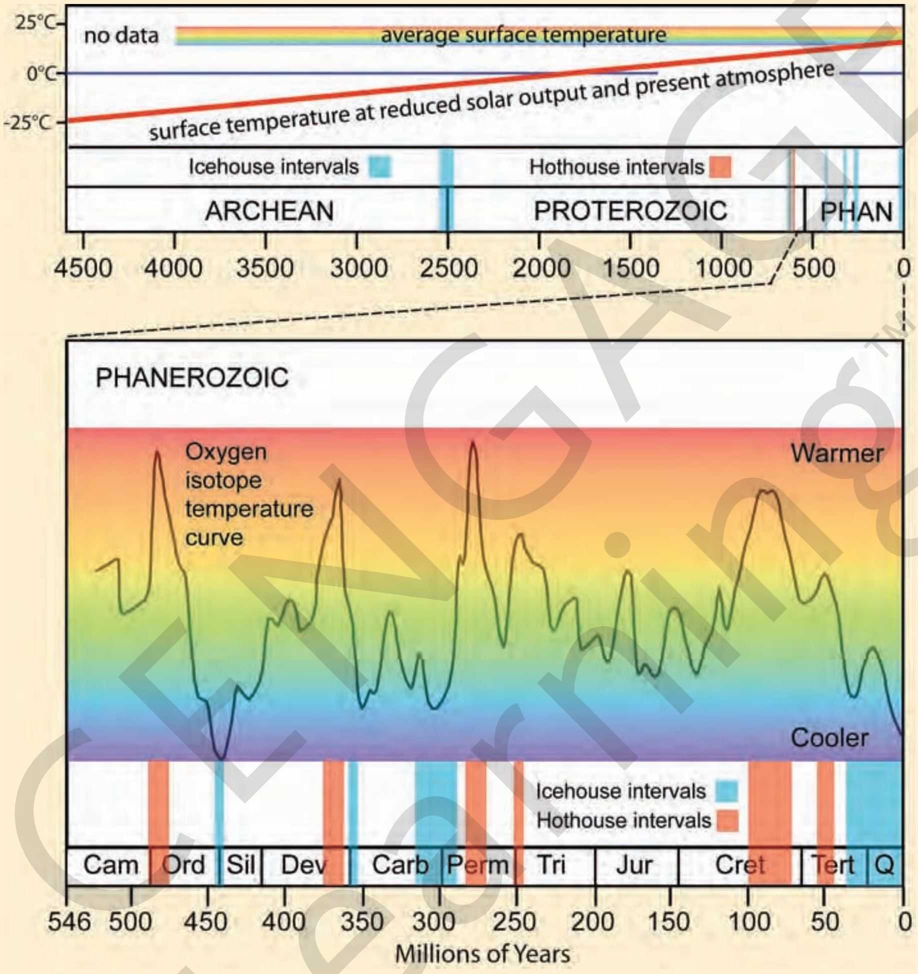
In talking about the study of Earth history, geologists are fond of saying, "The present is the key to the past." In the study of climate, the reverse is equally true—the past is the key to the present, as well as the future. If we want to understand the controls on our current climate and if we want to predict how climate will change in the future, we need to know the history of climate and how it has responded in the past to changes in Earth systems. This is the realm of the science of **paleoclimatology**. As a general rule, the further back in time you go, the less information is available to reconstruct the past and the less precise are your data and conclusions. What scientists know about the Earth of 10,000 years ago would fill a small library. What they know about the Earth of 2 billion years ago might only fill one shelf in that library. Fortunately, the time interval most relevant to understanding our modern climate is the last 2 million years (the Pleistocene Epoch), about which we continue to amass increasingly detailed data.

Paleoclimatologists gather the clues needed to reconstruct the climate history of the Earth from a wide variety of sources. Because they can't directly observe climate or measure temperature in the past, paleoclimatology relies on climate and temperature **proxies**—bodies of evidence from which climate can be inferred. Fossil evidence indicates that life has existed on the Earth for at least 3.5 billion years. The oldest rocks and minerals on Earth indicate that liquid water has existed on the surface of the Earth for at least 4 billion years. From these observations we can conclude that the average global temperature of the Earth has not deviated significantly from its present value throughout most of its history. At no time in the last 3 to 4 billion years did the Earth become cold enough to completely freeze the oceans, nor did it ever become hot enough to vaporize the oceans. Either event would have extinguished most, if not all, life on Earth.

The relative stability of the Earth's global temperature is remarkable in light of what astronomers call the **faint young sun paradox**. Based on models of how nuclear reactions evolved in our sun's interior, astronomers have concluded that the newly formed sun of 4.5 billion years ago was only about 70% as radiant as it is today and that it has grown progressively more luminous throughout the history of the solar system. If the Earth's early atmosphere had been the same composition as it is today, the average surface temperature of the young Earth would have been well below freezing due to the fainter radiance of the young sun (top of Figure Carbon Cycle.11). What kept the young Earth warm enough to support liquid oceans and life in its early history? One likely possibility is the existence of a strong greenhouse in the Earth's early atmosphere. If the atmosphere of the young Earth were predominantly carbon dioxide (as are the atmospheres of both Mars and Venus), then there would have been a much greater CO_2 greenhouse.

Another important greenhouse gas in the atmosphere of the early Earth may have been methane. Before the evolution of photosynthesis and the resulting biological production of oxygen, methane would have been able to accumulate in Earth's oxygen-poor atmosphere. A strong carbon dioxide and methane greenhouse would have compensated for the low energy output of the sun by trapping more heat in the Earth's atmosphere. But what happened later in Earth's

Figure Carbon Cycle and Climate Change.11 Climate through geologic time. Average surface temperature has remained close to the present value for at least the previous 4 billion years in spite of the reduced solar output of the young sun. Long-term variation in global climate is revealed by geologic evidence for glacial (icehouse) intervals, intervals of equator-to-pole warmth (hothouse), and estimates of ocean temperature based on oxygen isotope ratios measured in fossil shells.



history, as the sun continued to warm? Why didn't the Earth overheat as the sun grew more luminous? One explanation is the loss of most of the methane greenhouse as oxygen from photosynthesis began to accumulate in the atmosphere about 2 billion years ago. An equally important explanation is that carbon dioxide was progressively removed from the atmosphere by the carbon cycle thermostat (see Figure Carbon Cycle.10) adjusting the carbon dioxide greenhouse to balance the changing output from the sun. If not for the inorganic carbon cycle locking up most of the Earth's original CO_2 atmosphere in carbonate rock, the Earth would have grown too hot to support liquid water and life long before the evolution of the first animals 540 million years ago.

The global distribution of ancient environments interpreted from sedimentary rocks can indicate whether the Earth was generally warm or cool in the distant past. For example, globally widespread coral reefs suggest a period of climate warming, whereas widespread glacial deposits indicate a cooler Earth. Geologists recognize intervals of significant global cooling (**icehouse** conditions) from glacial deposits of the early Proterozoic (Earth's first "ice age," about 2500 million years ago), the late Proterozoic (700 million years ago, the so-called Snowball Earth Period, when much of the surface of the Earth may have been covered in ice), the Late Ordovician (445 million years ago), the Late Devonian (360 million years ago), the Carboniferous (about 300 million years ago), and the Quaternary (starting about 2 million years ago and still in progress) (see Figure Carbon Cycle.11). Fossils provide important clues to climate because certain kinds of organisms are associated with particular climates. For example, the Cretaceous Period is recognized as a time of widespread global warmth (**hothouse** conditions) in part because dinosaur and temperate zone plant fossils are found at polar latitudes. Likewise, crocodilian fossils from the Eocene are found as far north as southern Canada, indicating warmer average temperatures than exist today. Tree rings preserved in fossil wood can be correlated to climate. A lack of rings generally indicates a tropical climate, thick rings indicate a long favorable growing season, and thin rings are associated with cool climates and short growing seasons.

Figure Carbon Cycle and Climate Change.12 Ocean drilling ship JOIDES Resolution used by geoscientists to extract sediment cores for the analysis of paleoclimate.

Ocean Drilling Program science operator at Texas A&M University

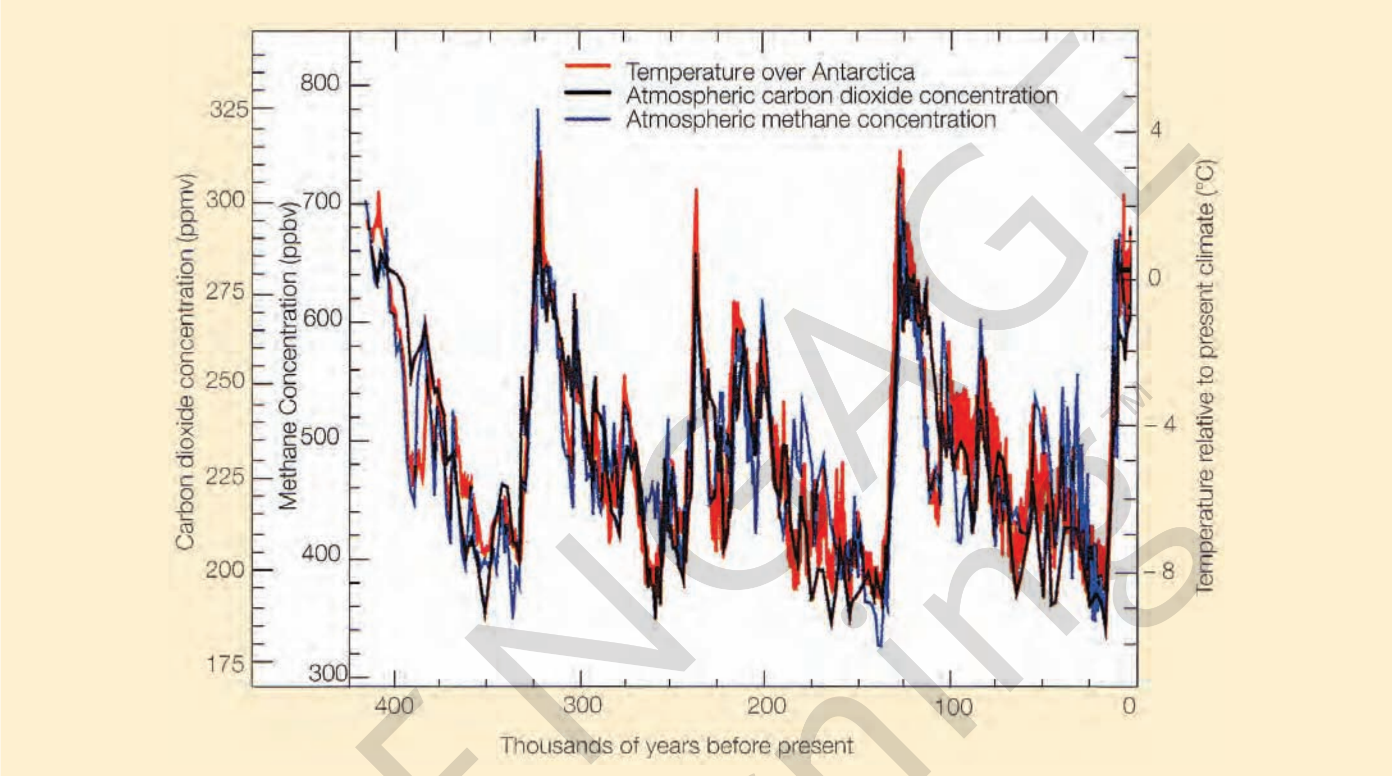
Perhaps the most useful fossils for characterizing paleoclimate are tiny, shelled protists called **foraminifera**. Forams (as they are called by most geologists) live in the mud on the sea floor (benthic forams) and are also found floating in the surface waters of the oceans (planktonic forams). Some foram species live within a narrow range of temperature in the modern oceans. A change in the types or abundances of fossil foram species through time can often be correlated with a change in water temperature and climate. Even more useful is the fact that most forams construct their shells out of calcium carbonate. When calcium carbonate precipitates in the ocean, the oxygen isotope ratio (the relative proportion of the isotopes ^{16}O and ^{18}O) in the mineral is dependent on water temperature. At cooler temperatures, the shells become enriched in ^{18}O and at warmer temperatures the shells have less ^{18}O. Cool climates also increase the proportion of ^{18}O in foram shells because water containing the lighter ^{16}O is preferentially evaporated and becomes locked up in glacial ice on land, increasing the concentration of ^{18}O in ocean water. Oxygen isotope ratios measured from the shells of marine organisms have been used to reconstruct climate trends back to the beginning of the Phanerozoic Eon, more than 500 million years ago (see Figure Carbon Cycle.11).

To reconstruct past climates and climate changes in detail, paleoclimatologists require a continuous record of climate proxies. Geologists drill down into the sediment on the seafloor and extract continuous cores of mud that can be dissected layer by layer, dated, and analyzed for climate proxy data (Figure Carbon Cycle.12). Layers of marine mud contain forams and other microfossils that can be used to reconstruct a record of both deep and surface ocean temperature. Changes in the quantity of dust in deep-sea layers indicate alternating humid and arid climates on the continents. Small particles of rock carried out to sea and dropped by melting icebergs (**ice-rafted debris**) provide evidence for the active growth of glaciers in a cooling climate. Sediment cores can also be obtained from lakes and ponds and analyzed for pollen grains that document how vegetation has changed through time in an area. Warming and cooling trends are mirrored by corresponding changes in regional vegetation as ecosystems shift north or south with changing temperature.

Another important continuous record of climate change is obtained by coring through continental ice sheets in Greenland and Antarctica. Each year, snowfall on a glacier accumulates and eventually compacts to form a discrete layer of ice. Coring down through a glacier can provide a record of annual ice going back many thousands of years. Climatologists drilling into the East Antarctic ice sheet at Vostok Station have developed a record of climate extending back 420,000 years. A more recent ice core drilled where the ice is thicker at Dome C on the Antarctic Plateau contains a record of climate as far back as 720,000 years. Samples from the ice cores can be analyzed to determine the oxygen isotope composition of the ice, which is a proxy for local air temperature. Also contained within the ice are wind-blown dust, soot from forest fires, volcanic ash, radioisotopes, and air bubbles. Layers of ice can be processed at low temperature to release the trapped air, providing direct samples of the former atmosphere that can be analyzed to determine how the concentration of CO_2, methane, and other gases has changed with climate in the past.

Studies of deep sea cores show that the Earth's climate began a long cooling trend after the Eocene hothouse interval, about 40 million years ago, culminating in the repeating cycles of global glaciation that have characterized the last 1.8 million years of the Pleistocene Epoch. Global climate has gone through eight cycles of glaciation and interglacial warming over the past 720,000 years (four in the past 400,000 years), with the most recent glacial cycle reaching its maximum cooling 20,000 years ago, at which time the climate began to rapidly warm to its present temperature. The rhythm of the glacial cycles indicates that cooling and

▶ **Figure Carbon Cycle and Climate Change.13** Trends in climate data measured from air bubbles and oxygen isotope values taken from Antarctic ice cores extending back 400,000 years. Temperature (*red line,* °C), carbon dioxide (*black line,* ppmv), and methane (*blue line,* ppbv).



Source: Ahrens CD: Essentials of Meteorology ed. 5, p. 397. Cengage Learning Brooks/Cole, 2008, 2005. Houghton JT et al: Climate Change 2001: The Scientific Basis, Cambridge, UK: Cambridge University Press, 2001. Reprinted with permission of the Intergovernmental Panel on Climate Change

warming are initiated by cyclical changes in the shape of the Earth's orbit, which alter the distribution of solar energy between the northern and southern hemispheres from winter to summer. Ice core data show a tight correlation between changing temperature and levels of CO_2 and methane through all of the glacial cycles (Figure Carbon Cycle.13), demonstrating that greenhouse gases play an important role in maintaining and amplifying the climate changes triggered by the Earth's orbital cycles.

Section 5 Summary

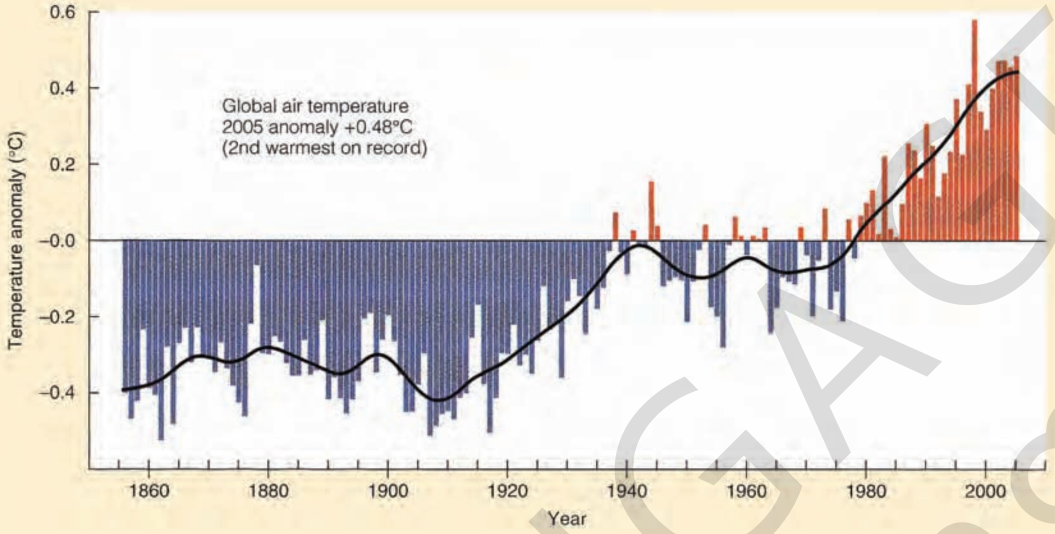
- Paleoclimatologists work to reconstruct the long and complicated climate history of the Earth using a variety of proxies for climate and temperature preserved in rock, sediment, and ice, including fossils, oxygen isotopes, gas bubbles, tree rings, dust, and glacial deposits.
- Evidence for the Earth's climate having remained within livable limits in spite of changes in the sun's energy output suggest that the inorganic carbon cycle has adjusted the greenhouse effect over time to compensate for the sun's increasing luminosity.
- Earth's climate for the last 500 million years has alternated between icehouse and hothouse intervals. Evidence from deep sea sediments and ice cores shows that global climate has experienced eight cycles of glaciation and warming over the last 800,000 years. Samples of the atmosphere taken from ice cores show that CO_2 and methane play an important role in driving and amplifying climate shifts initiated by other factors such as orbital cycles.

Carbon Cycle and Climate Change.6

Anthropogenic Climate Change

In 1895 a Swedish chemist named Svante Arrhenius presented calculations to the Stockholm Physical Society showing that an increase in atmospheric carbon dioxide would cause the surface temperature of the Earth to rise due to the greenhouse effect. Later Arrhenius predicted that the burning of fossil fuels would eventually lead to **anthropogenic** warming of global climate. By all measures, Arrhenius was correct; the climate of the Earth is warming, and recent studies show that the rate of warming is accelerating. Currently the average Earth temperature is warmer than it has been since 1400,

▶ **Figure Carbon Cycle and Climate Change.14** Record of the annual deviation from the 150-year average of combined global marine and terrestrial temperature. Data are from proxy climate indicators (ice cores, corals, tree rings) and historical and instrumental records.

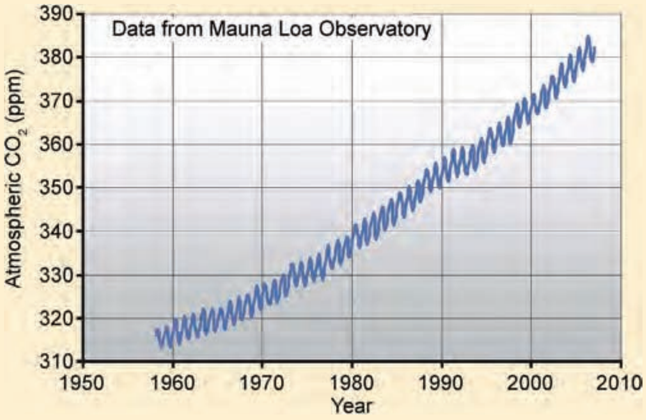


Source: B. Pipkin, D.D. Trent, R. Hazlett, and P. Bierman: Geology and the Environment, ed. 5, p. 333. Cengage Learning Brooks/Cole, 2007. Courtesy of Phil Jones and Jean Palutikof, Climatic Research Unit, University of Anglia

and this may be the warmest the Earth has been in the last 1000 years. The year 1998 was the warmest in 341 years, and each year of the twenty-first century has been consistently far above the average for the previous 150 years (Figure Carbon Cycle.14). At the same time, global consumption of fossil fuels has been increasing, resulting in an accelerating rise in the amount of CO_2 being released into the atmosphere. The U.S. Department of Energy estimates that 28 billion metric tons of CO_2 were produced by the global consumption and flaring of fossil fuels in 2005, and worldwide emissions of CO_2 rose 3.5% per year from 2000 to 2007, almost four times the rate of increase in the 1990s. Conversion of forest to agricultural land, particularly in the developing tropics, results in the burning of forest biomass and the oxidation of organic carbon stored in soils, releasing additional CO_2 into the atmosphere. Measurements taken near the summit of Mauna Loa in Hawaii show a steady rise in the amount of CO_2 in the atmosphere, from 315 parts per million (ppm) in 1958 up to 380 ppm in 2005 (Figure Carbon Cycle.15). Levels of methane are also rising in the atmosphere. Sources of additional methane include landfills, natural gas production, livestock, and rice cultivation. Measurements of past atmospheric CO_2 and methane levels obtained from the Dome C ice core in Antarctica show that there is currently 30% more CO_2 in the atmosphere and 130% more methane than there has been at any time in the past 650,000 years and that the current rate of increase in CO_2 added to the atmosphere is 200 times faster than any rate of increase observed in the ice cores.

Although there is a strong correlation between rising temperatures and rising levels of anthropogenic greenhouse gases, it has been argued by some that this is a coincidence and that some other natural climate change mechanism is responsible for the current warming trend. Although it might be comforting to believe that humans are not responsible for global warming, the evidence does not support this point of view. First, the physical laws governing the effect of greenhouse gases on heat in the atmosphere are well understood. If levels of greenhouse gases are rising, as we know they are, then the atmosphere should be getting warmer. In fact, satellite measurements of the **troposphere** show that it is warming by 0.2°C per decade, which is close to the amount of warming that has been measured taking place at the surface. Satellite measurements have also confirmed that the **stratosphere** is cooling, which would be expected if more heat were being trapped in the troposphere by greenhouse gases.

▶ **Figure Carbon Cycle and Climate Change.15** Rising levels of carbon dioxide in the atmosphere measured from the Mauna Loa Observatory in Hawaii. Measured in parts per million (ppm). The annual oscillations are due to the uptake of CO_2 by plants during northern hemisphere spring and summer and its release back into the atmosphere during autumn and winter.

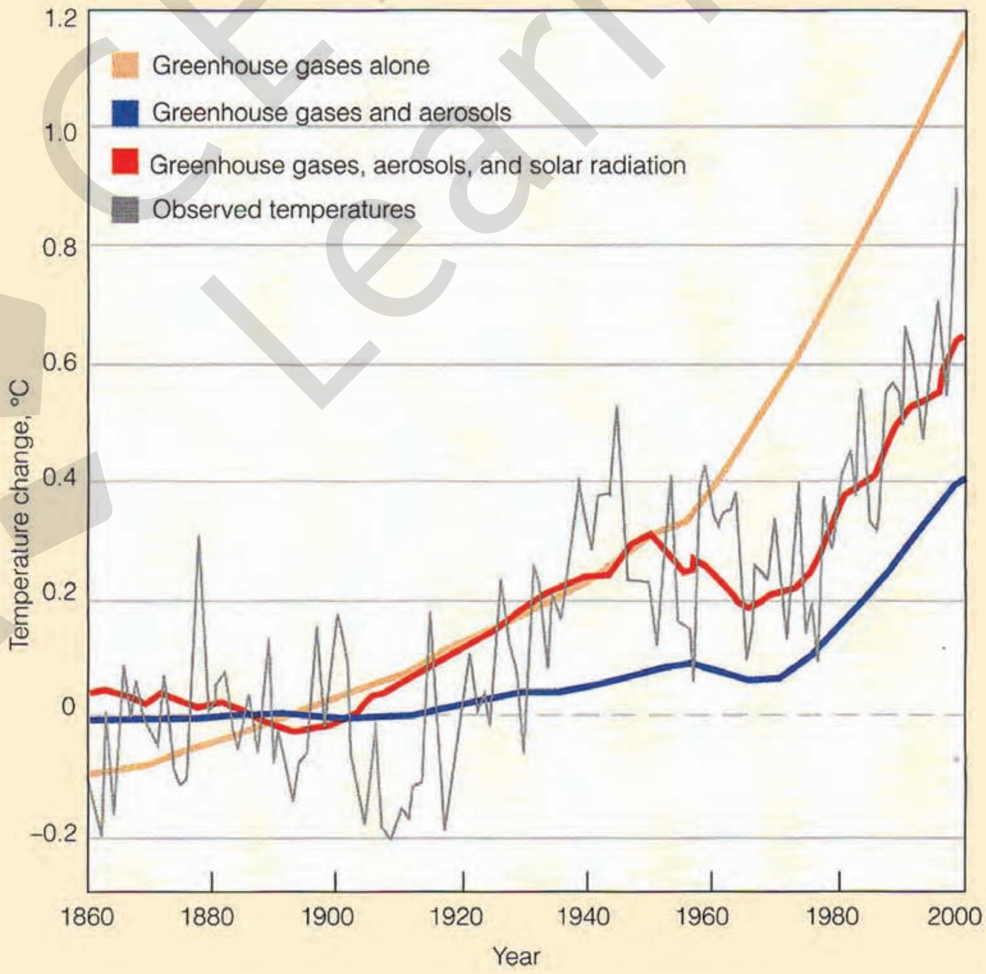


Another compelling confirmation of the role of anthropogenic greenhouse gases comes from computer modeling of the Earth's climate system. Computer models can be programmed to calculate the response of the oceans and atmosphere to different climate forcing mechanisms such as rising levels of greenhouse gases and variations in solar radiation. The accuracy of these **Atmosphere-Ocean General Circulation Models** (AOGCMs) is tested by how closely the model output matches observed temperature trends in the past. Climate model simulations of surface air temperature going back 150 years closely reproduce the pattern of recent climate change when they incorporate a combination of climate forcing variables, including greenhouse gases, aerosols, and variations in solar radiation (Figure Carbon Cycle.16). Model simulations also show that carbon dioxide is the most significant factor driving temperature and the warming trend of the past 100 years.

In 2007 the **Intergovernmental Panel on Climate Change** (IPCC) released its fourth assessment report, stating that "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." The IPCC is an international scientific body composed of more than 2000 climate scientists from member nations of the World Meteorological Organization and the United Nations Environment Organization. The function of the IPCC is to evaluate published scientific research related to climate and to evaluate the risk of climate change caused by human actions. In the carefully measured language of the IPCC reports, "very likely" means a 90% probability, based on existing research, that humans are driving climate change.

One of the main tasks of the IPCC is to predict future climate change so that policymakers can respond appropriately to the risks associated with a warming climate. Because of the uncertainties involved in forecasting the future, the IPCC issues a range of predictions based on several possible scenarios of global development. For example, it is not

► **Figure Carbon Cycle and Climate Change.16** Projected surface air temperature from 1860 to 2000 estimated from climate models incorporating different variables. Actual temperature is shown in *gray*. Model temperature output assuming greenhouse gases alone is shown in *yellow*. Model incorporating greenhouse gases and aerosols shown in *blue*. Model incorporating greenhouse gases, aerosols, and solar radiation shown in *red*. Note that this last model closely reproduces actual temperature trends. Zero temperature change is defined as the mean temperature from 1880 to 1999.



Source: Ahrens DC: Essentials of Meteorology, ed. 5, p. 404. Cengage Learning Brooks/Cole, 2008, 2005. Redrawn from Wigley TM: The Science of Climate Change, Pew Center of Global Climate Change known for certain how much carbon dioxide levels will rise in the atmosphere through the remainder of the twenty-first century. This will depend on many variables, including the rate at which large industrializing countries like India and China increase their consumption of fossil fuels, the rate at which other developing countries convert forest to agricultural land, and the rate that CO_2 can be taken up by various sinks in the carbon cycle. The IPCC projects that, if measures are not taken to reduce the production of greenhouse gases, atmospheric carbon dioxide concentration by 2100 will range from 650 to 970 ppm (more than double the present concentration). As a result, the IPCC estimates, average global temperature will most likely rise by 1.8°C to 4.0°C (3.2°F to 7.2°F) between 1990 and 2100. Even if greenhouse gas emissions were held constant at year 2000 levels, temperature would continue to rise by 0.3°C to 0.9°C (0.5°F to 1.6°F) to the end of the twenty-first century. Human activities, mainly the combustion of fossil fuels and expansion of agriculture, are rapidly moving carbon from long-term storage in rock and soils back into the atmosphere. This is causing the average surface temperature of the Earth to rise and will continue to do so long into the foreseeable future. The questions that remain to be answered are: How warm will it get, and what effects will warming have on the biosphere, hydrosphere, atmosphere, and geosphere?

Section 6 Summary

- Average global temperature has increased in concert with rising levels of greenhouse gases in the Earth's atmosphere generated by human activities such as fossil fuel consumption and conversion of forested land to agriculture.
- Direct evidence for increased greenhouse warming includes satellite measurements showing that the troposphere is warming while the stratosphere is cooling and computer climate models reproducing observed temperature trends using greenhouse gas forcing.
- A recent review of climate research conducted by the Intergovernmental Panel on Climate Change (IPCC) concluded that it is very likely that human activities are significantly warming the planet and that they will continue to do so through the end of this century.

Carbon Cycle and Climate Change.7

Consequences of Climate Change

As the old saying goes, the only constant is change. Certainly this is true for climate throughout the history of the Earth. On a geologic scale, climate is always changing and the present is no exception. At times in the past the Earth has been much warmer than it is today and life thrived. So why should we be concerned about climate change? Some have even argued that a warmer world will be beneficial to humanity, with fewer deaths due to cold and exposure, longer growing seasons, and more CO_2 in the atmosphere for plants to utilize. Unfortunately, the benefits of climate change will almost certainly pale in comparison to the costs for the simple reason that humanity is heavily invested in the world as it has been for the past 100 years. We are economically and geographically adjusted to the climate of the twentieth century. If the climate of the twenty-first century is significantly different, societies across the globe will have to adapt or suffer a variety of disruptions to established ways of life. This is not a prediction. Climate change is already in progress, and we are currently witnessing its effects in both natural systems and human societies. The following is a summary of changes in Earth systems being driven by climate warming that are being observed around the globe.

Atmosphere

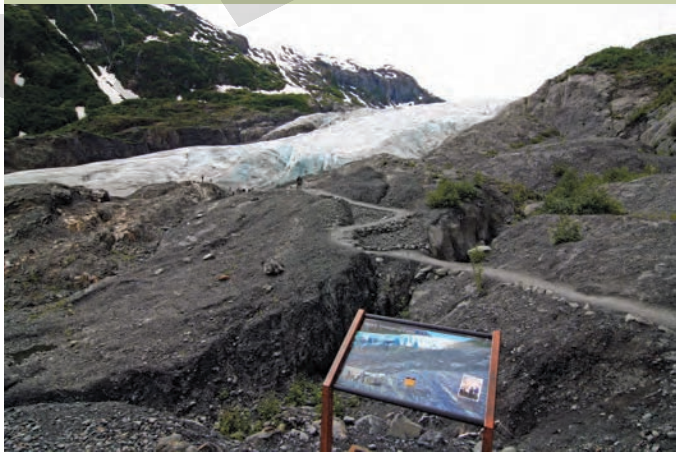
By now, many people are beginning to notice the effects of a warmer atmosphere on their local environment, although the long-term trends of climate change are often masked by the day-to-day and year-to-year variability of weather. Average annual temperature is rising and will continue to rise through the twenty-first century to between 1°C/1.8°F (if we stabilize greenhouse gas emissions) and 6°C/10.8°F (if greenhouse gas emissions rise at the maximum projected rate) above the present value. The main effect of a warmer atmosphere will be to alter established patterns of precipitation and to produce more weather extremes such as longer, hotter heat waves and more intense storms. Computer models predict an increase in precipitation at middle to higher latitudes and a decrease in precipitation at lower to middle latitudes. The American Southwest, which is currently suffering from a long-term drought, is predicted to increase in aridity through the twenty-first century, whereas the northern United States and Canada are predicted to become wetter. Northern Africa is becoming increasingly arid. Some large continental areas such as the Amazon Basin and Europe are forecast to become more monsoonal, with most precipitation occurring during one half of the year. These changes in the distribution of rainfall will force agricultural regions to adapt or relocate and will place increasingly greater stress on scarce freshwater supplies in arid regions. Shortages of water for drinking and irrigation will become increasingly acute in regions such as the Middle East, Northern Africa, and the American Southwest.

Weather extremes will become more prevalent in a warmer world. Additional heat energy in the oceans and atmosphere may cause storms such as hurricanes and tornadoes to become more intense and will result in more temperature extremes. Warmer surface waters in the ocean may be responsible for an increase in the frequency of category 4 and 5 hurricanes (although other effects might reduce the overall number of hurricanes). Greater heating of the land earlier in the spring appears to be causing a rise in the number of strong thunderstorms associated with tornadoes in the mid-continent of the United States. In the last 45 years, the average number of days per year when the temperature exceeds 90°F/32°C in the northeastern United States has doubled. By the end of the twenty-first century, cities in the Northeast such as Boston and New York will see between 30 and 60 days per year reach 90°F/32°C or higher, with between 14 and 28 days exceeding 100°F/38°C. Heat waves are not simply a nuisance; a string of days with record high temperatures in Europe in August 2003 is blamed for the deaths of more than 35,000 people. In addition, record numbers of wildfires broke out across Europe as the high temperatures made vegetation more prone to combustion.

Hydrosphere

As the climate warms, snow and ice are melting all around the world. At high latitudes and on mountains, snow cover is building up later in the fall and melting earlier in the spring. Valley glaciers in mountain ranges are retreating and many are predicted to completely disappear by the end of the century. Glacier National Park in Montana had 150 active glaciers in the 1850s; now there are only 37 remaining, and at present rates of melting most of these will be gone by 2030. In Alaska, Portage Glacier near Whittier is no longer visible from the observation deck of the visitor center that was built in 1986 and Exit Glacier near Seward has retreated more than 1000 feet in the last ten years (Figure Carbon Cycle.17). Summer melting of arctic sea ice in 2007 was the most extreme on record, with ice cover over the Arctic Ocean reduced by 40% from its twentieth-century average (Figure Carbon Cycle.18). Ice cover in the summer of 2008 was the second lowest on record, and some climate scientists predict that the Arctic may be completely ice-free in the summertime by as early as 2013. Although the continental ice sheets covering Antarctica may not warm enough to melt significantly (they could even increase in volume if climate warming results in increased snowfall in the interior of Antarctica), melting is occurring around the margins of Antarctica and **ice shelves** that have been stable for thousands of years are melting and breaking off into the sea. In 2002 the Larson B ice shelf collapsed, causing the breakup into the ocean of a sheet of ice the size of Rhode Island. More recently, a 400 square kilometer section of the Wilkins ice shelf collapsed in 2008. In Greenland, the continental ice sheet covering most of the landmass is melting faster than most computer models predict it should. During recent summers, pools and streams of meltwater have formed at higher and higher elevations on the ice. Crevasses and tunnels carry meltwater deep into the glacier, possibly promoting additional melting. It is not known how much of Greenland's ice will melt or how rapidly, but the accelerating rate of melting has many climate scientists concerned that we are witnessing the beginning of the end of Greenland's ice sheet.

▶ Figure Carbon Cycle and Climate Change.17 Exit Glacier, near Seward, Alaska. In 1998 the ice margin of the toe of the glacier was located just beyond the signpost in the photo. Ten years later it has retreated more than 1000 feet into the distance.



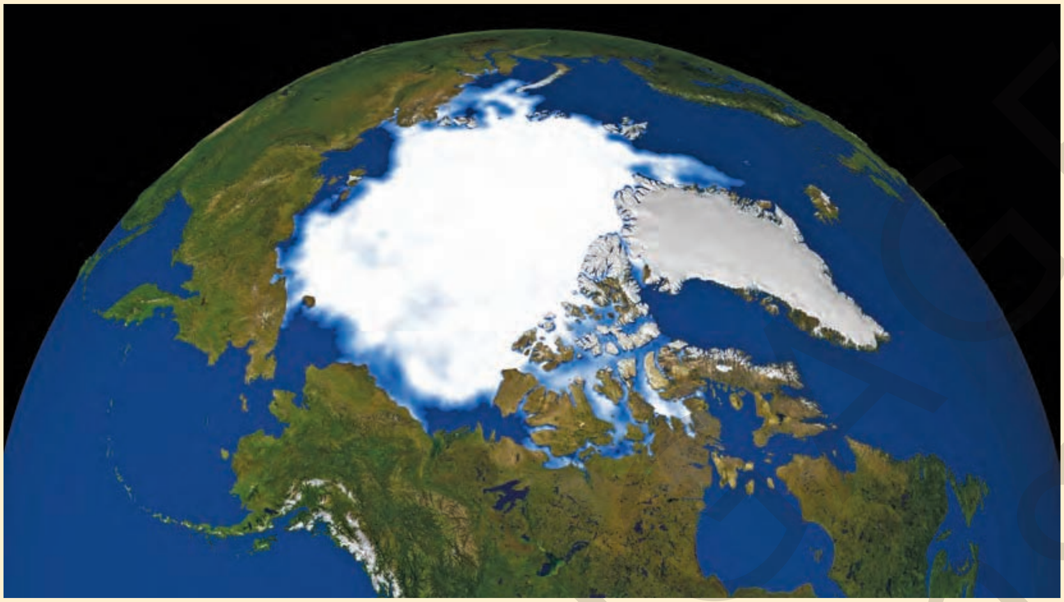
J Bret Bennington

As glaciers, ice shelves, and ice sheets melt, water moves from storage on land into the oceans. As the warming atmosphere heats up the oceans, water undergoes thermal expansion, increasing in volume. Both these effects cause the sea level to rise. During the twentieth century, global sea level rose approximately 17 cm (6.7 inches). Currently, global average sea level is rising at about 33 cm (13 inches) per century, but this rate is likely to rise along with global average temperature. During the twenty-first century, global sea level is predicted to rise by an additional 30 (11.8 inches) to 50 cm (19.7 inches) because of the impact of climate change on the volume of water in the oceans. Although 50 cm (almost 2 feet) of sea level rise may not seem like a lot, it would be enough to submerge large regions of coastline worldwide and render populated shoreline areas more susceptible to coastal storms (Figure Carbon Cycle.19). In regions where much of the population is living at or close to sea level (e.g., Bangladesh, the Netherlands, coral atolls in the Pacific Ocean, Florida, and Long Island), sea level rise will displace millions of people from their homes and expose tens of millions to greater risk of property loss and injury from storms. In the United States, more than 50% of the population lives near the coast and will have to adapt to rising sea levels. For example, the streets, buildings, and subway tunnels of lower Manhattan are currently expected to flood during storms on average once every 100 years. By 2100, the same magnitude "100-year flood" will likely happen every 20 years, and maybe every 5 years, due to sea level rise. Similar scenarios are predicted for low-lying areas of other coastal cities in the United States, such as Boston, Washington, Houston, and San Francisco.

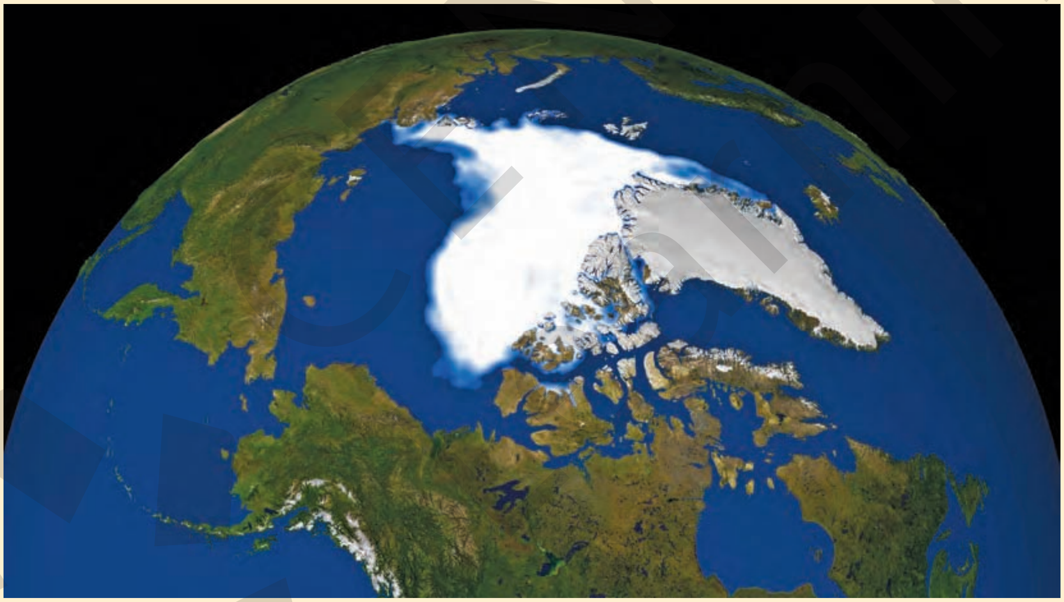
Biosphere

The effects of a warming climate on the biosphere include shifting species ranges and changes in the lifecycles of species tied to the seasons. Perhaps the first people to take note of climate change are gardeners, who have observed that many species of plants are sprouting and blooming

Figure Carbon Cycle and Climate Change.18 Comparison of the minimum summer cover of arctic sea ice from 1980 to 2007.



a September 5, 1980.

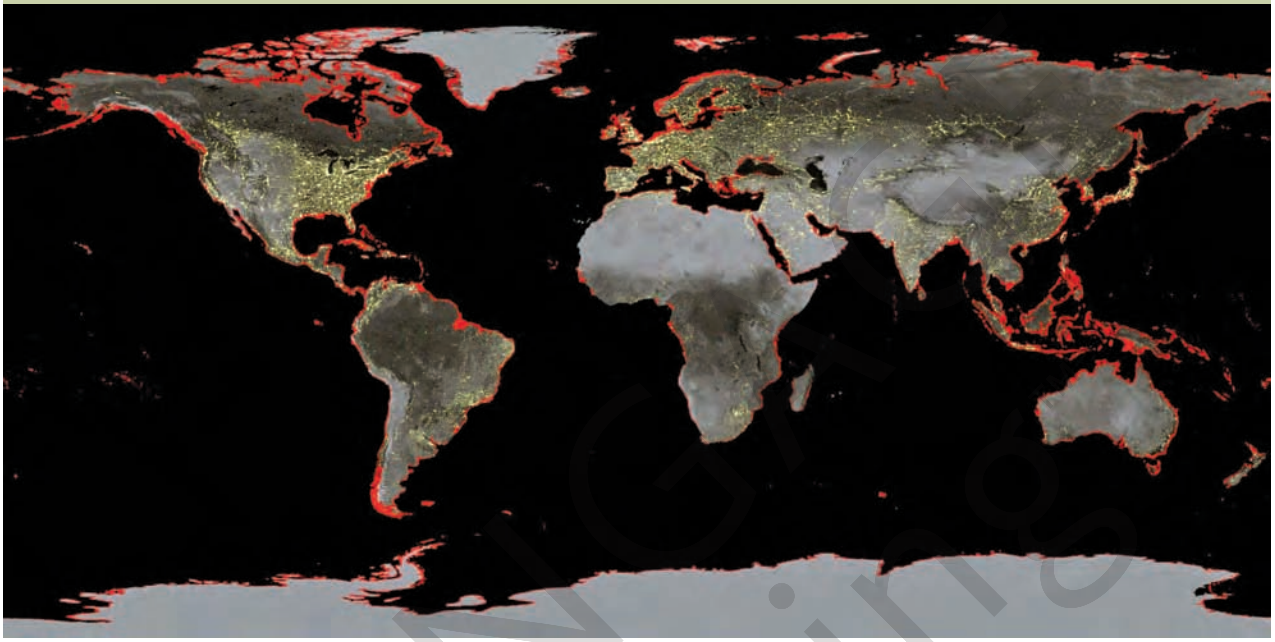


b September 14, 2007.

NASA/Goddard Space Flight Center Scientific Visualization Studio

earlier in the spring than ever before. Birders are also noticing changes in the timing of bird migrations as spring arrives earlier and the onset of cold weather later. Tree species are shifting their ranges toward higher latitudes following their optimal growth temperature, as are many animal species. This creates problems for ecosystems because organisms become stressed as local climate changes, rendering them more vulnerable to disease. Also, species shift their ranges at different rates in response to climate change, causing existing ecosystems to fragment, bringing unfamiliar species in contact with one another. Across the globe, these ecosystem stresses are threatening increasing numbers of species with local **extirpation** and complete extinction. These changes are most notable when they impact species that are important to humans. For example, Canada and Alaska are witnessing the largest die-off of spruce trees on record (Figure Carbon Cycle.20). The problem is that an existing insect pest, the spruce bark beetle, is undergoing a population explosion caused by longer, warmer summers. Enormous tracts of spruce forest are now stands of dead timber because the trees cannot survive the onslaught of the beetle infestation. Species that already exist at high latitudes face the unfortunate circumstance that, as climate warms, they cannot shift their ranges much farther toward the poles

▸ Figure Carbon Cycle and Climate Change.19 Global map showing coastal areas that would be flooded by a 1-meter rise in sea level (shown in *red*), which is not much greater than what is currently predicted for the end of the twenty-first century and much less than what occurred during the last warm interglacial period.



NASA

than they already are. In the Arctic, polar bears are threatened with extinction as the summer ice floes they depend on for feeding disappear, as are penguins in the Antarctic.

Climate change is also impacting ocean species. Coral reefs are bleaching and then dying around the globe, and the trigger appears to be elevated water temperatures. Another stress that coral face comes from the impact of higher CO_2 levels on the pH of the oceans. As CO_2 levels rise in the atmosphere, the solubility pump (see Figure Carbon Cycle.7) moves increasing amounts of CO_2 into the oceans, which

▸ Figure Carbon Cycle and Climate Change.20 Forest on the Kenai Peninsula near Hope, Alaska, showing large numbers of dead spruce trees killed by the proliferating spruce bark beetle.

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causes the pH of ocean water to become more acidic. As the oceans acidify, corals and other carbonate-secreting organisms such as plankton and algae are less able to maintain their calcium carbonate skeletons and become more vulnerable to disease and predation. Warming oceans are also causing marine species to shift their ranges, including a number of commercially important species. In the northeastern United States, the waters around Long Island mark the southernmost habitat for the American lobster. In the late 1990s, lobster began dying off, and the lobster fishery in the region has since been devastated. The immediate cause of the die-off was outbreaks of disease, but the underlying stress appears to be the gradual warming of the bottom waters in the lobster's habitat. Cod is another commercially important species that will likely experience a northward contraction of its range as climate warms through the twenty-first century.

Besides commercially important species, other species that are shifting their ranges include a variety of insect pests and vector-borne diseases such as malaria. Mosquitoes reproduce more effectively in warmer temperatures, and this has resulted in a measurable increase in mosquito-borne diseases such as malaria, dengue fever, and West Nile virus in Asia and Europe. Disease-bearing mosquitoes are also increasing their latitudinal range; in 2006, larvae of the *Anopheles* mosquito, the malaria carrier, were found for the first time as far north as Moscow. Red fire ants, an invasive South American species introduced into the southern United States in the mid-1930s, are steadily expanding their range northward as the range of winter ground freezing contracts due to climate warming.

Section Carbon Cycle and Climate Change.7 Summary

- Climate change due to increasing global temperature is already underway. Scientists are observing the effects of climate change on the atmosphere, hydrosphere, and biosphere.
- The warming of the atmosphere is altering patterns of global precipitation, causing longer and more intense heat waves and more intense thunderstorms and hurricanes.
- Warming of the hydrosphere is causing global melting of glaciers, ice shelves, and ice sheets. This in turn is causing the rate of global sea level rise to accelerate, putting low-lying countries and coastal communities at greater risk of flooding and storm damage.
- Climate change is altering the biosphere by forcing species to shift their established ranges, resulting in extinctions and disruption of ecological communities. Warmer temperatures are also promoting the increase and spread of many invasive and pest species, as well as disease vectors such as the malaria-bearing mosquito.

Carbon Cycle and Climate Change.8

Preventing Climate Change

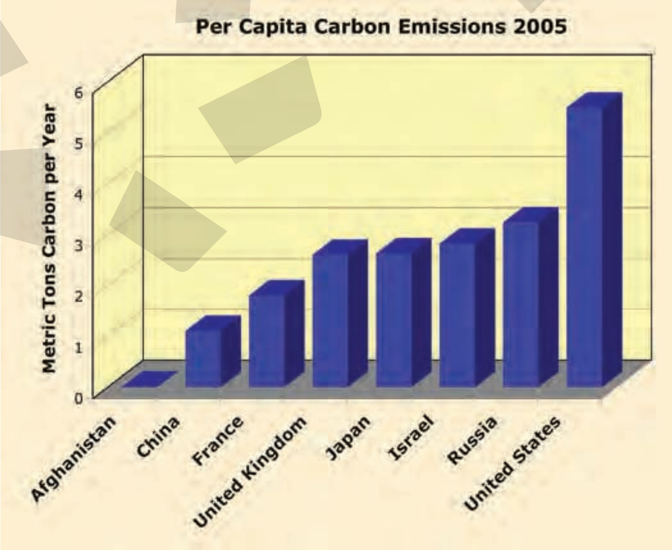
In spite of a well-funded campaign of misinformation designed to cast doubt on the reality of "global warming," climate scientists around the world have succeeded in convincing most policy makers that anthropogenic climate change is a serious problem, perhaps *the most* serious long-term problem currently facing humanity. If that is the case, what can we do to stop anthropogenic climate change? The various options for preventing or mitigating climate change are best understood in the context of the carbon cycle. The ultimate cause of anthropogenic climate change is the buildup of greenhouse gases in the Earth's atmosphere, particularly carbon dioxide, from emissions generated by human activities. Looking to the carbon cycle, we might first ask if the excess CO_2 in our atmosphere will be removed by natural mechanisms. As we learned earlier, the Earth's climate is regulated by negative feedbacks that prevent the global climate from swinging to extremes. For example, the solubility pump and the biological pump both transport excess carbon dioxide from the atmosphere to the deep ocean over time. Because the cold water of the deep ocean can hold more than 50 times as much carbon dioxide as the atmosphere, the oceans should have no problem absorbing most of the anthropogenic carbon dioxide humanity produces. Although this is true, both ocean CO_2 pumps work very slowly relative to the rate at which we are adding carbon dioxide to the atmosphere. Currently, the oceans appear to be absorbing only about one third of anthropogenic CO_2 emissions. Furthermore, as the oceans continue to absorb CO_2, they become more acidic, reducing their ability to absorb additional CO_2. The biological pump is limited by the availability of nutrients such as iron and phosphorus required by plankton for growth. Therefore, increasing the amount of CO_2 in the oceans will not significantly accelerate the uptake of carbon by the biological pump. The weathering of silicate minerals by carbonic acid and the subsequent formation of carbonate minerals in the oceans is another natural mechanism capable of removing CO_2 from the atmosphere. However, these mechanisms are also exceedingly slow and would require many thousands, if not millions, of years to significantly reduce anthropogenic CO_2 levels in the atmosphere. The problem is that humans are adding greenhouse gases to the atmosphere too rapidly for natural mechanisms to compensate on a time scale relevant to humans. We can't wait 10,000 years for nature to clean up our greenhouse gases—we must look to ourselves for solutions.

The majority of carbon dioxide being added to the atmosphere is from the combustion of fossil fuels. To reduce the anthropogenic greenhouse, humanity has two main options. We can reduce our consumption of fossil fuels, or we can find ways to increase the uptake of anthropogenic

CO_2 into long-term carbon sinks. Reducing fossil fuel consumption can be accomplished in two ways, by increasing the efficiency with which we use fossil fuels and by switching to non–fossil fuel energy sources. Increasing efficiency means using less fuel to accomplish the same amount of activity or changing our habits to consume less fuel. An estimate of how much carbon dioxide a person or group generates from the energy used to support their lifestyle is called their **carbon footprint**. Americans have the largest per capita carbon footprint of any society on Earth. The average American is responsible for emitting about 5.5 metric tons of carbon to the atmosphere every year (Figure Carbon Cycle.21). For comparison, other industrialized countries have typical per capita emissions of about 2.5 metric tons per year and China has per capita emissions of less than 1 metric ton per year. The main reason for the difference in carbon emissions between the United States and other countries is that Americans own more cars and drive more miles than any other society. Therefore, an obvious target for increasing fossil fuel efficiency is the automobile. A car with an average fuel efficiency of 25 miles per gallon (mpg) driven 15,000 miles annually emits about 9 tons of CO_2 into the atmosphere each year. If all U.S. cars and light trucks were engineered to have a combined fuel efficiency of 40 mpg by the year 2020, it would reduce the national carbon footprint by 133 million metric tons of CO_2 per year and reduce the demand for crude oil by 3.6 million barrels per day (about 15% of total U.S. consumption). As a solution to climate change, increased energy efficiency is easy to get people to commit to because it saves them money. When gas costs $4 per gallon, having a car that burns half as much fuel becomes very desirable. Other forms of energy efficiency include better insulated buildings and homes, more energy-efficient appliances, low-energy fluorescent lighting, and automatic timers and sensors that turn off lights, heat, and appliances when they are not needed (not to mention just turning off the lights and the TV when you leave a room). Unfortunately, there is a limit to how much efficiency can reduce greenhouse gas emissions when the energy is still being generated by fossil fuels. Also, the reduction in fossil fuel demand realized with even the most efficient technologies will pale in comparison to the tremendous increase in fossil fuel consumption that will come as billions of people in rapidly industrializing nations such as China and India demand ever increasing amounts of electricity and gasoline in pursuit of a higher, more "American" standard of living.

Our entire civilization and modern infrastructure is predicated on the availability of cheap, portable energy from oil, natural gas, and coal. To wean societies off fossil fuels, we will need to invest in a whole new suite of energy capture and storage technologies. Unfortunately, most other sources of energy are currently more expensive than fossil fuels, at least initially, and are not as portable. However, the supply of fossil fuels is finite and nonrenewable, while the global appetite for them is increasing. The laws of supply and demand dictate that the cost of fossil fuels will continue to rise as their availability continues to decline. Non–carbon-emitting energy sources include solar, wind, hydroelectric, and nuclear power (Figure Carbon Cycle.22). Each of these has advantages and

▶ **Figure Carbon Cycle and Climate Change.21** Graph comparing the average number of metric tons of carbon emitted per person per year (carbon footprint) between the United States and a selection of other countries.



▶ **Figure Carbon Cycle and Climate Change.22** Power-generating wind turbines recently erected on a hilltop in central New York state.

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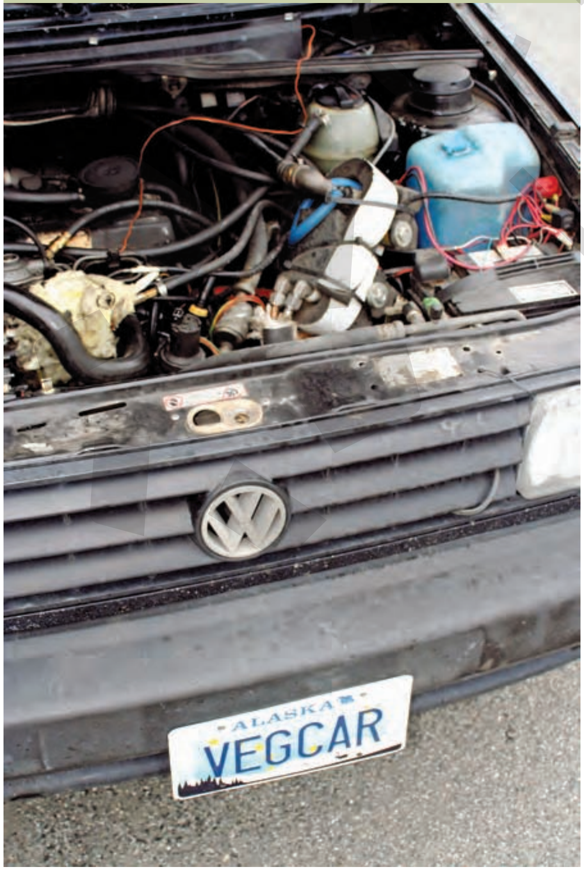
disadvantages, but all can be harnessed to generate electricity without adding carbon dioxide to the atmosphere. Many governments are experimenting with policies to encourage power-generating companies to become more fuel efficient and to invest in and develop alternative noncarbon energy sources. One way to do this is to enact a **carbon tax**, which imposes a tax penalty on each ton of CO_2 emitted. A more complex scheme, referred to as **cap and trade**, sets a limit to how much CO_2 each company is permitted to emit and allows companies to buy and sell the rights to emit additional CO_2. Thus, a more efficient company that emits less CO_2 than its cap can sell the right to emit the remaining CO_2 to a less efficient company that exceeds its cap.

Other alternative energy sources are **biofuels**, which are carbon fuels made from sugar, plant oils, or animal fat. Currently, ethanol made from corn sugar is a common biofuel additive to gasoline. Biodiesel is manufactured from vegetable oil or animal fat and usually blended with petrodiesel before being used as a fuel. It is even possible to modify diesel engines to run on unprocessed vegetable oil (Figure Carbon Cycle.23). Burning biofuels emits carbon dioxide into the atmosphere, but because this CO_2 was recently removed from the atmosphere by photosynthesis to grow the organic carbon compounds contained in the fuel, there is no net addition of carbon to the atmosphere. Biofuels seem like an attractive alternative to fossil fuels, but there are problems that prevent them from significantly replacing fossil fuels. There simply isn't enough land in the world to grow a sufficient quantity of plant stocks (corn, soybeans, etc.) to satisfy the global demand for energy. Also, processing biofuels can be very energy intensive, reducing their efficiency. For example, although not conclusive, some studies have claimed that producing a gallon of corn ethanol and bringing it to market requires more than a gallon of fossil fuel, making ethanol more carbon polluting than gasoline! Others have questioned the wisdom of using food to manufacture fuel, which has the potential to create shortages and drive up the cost of basic food staples such as corn. One promising avenue of research is the development of biofuel crops that are not food crops and that can be grown on land too arid for most other agriculture.

▶ Figure Carbon Cycle and Climate Change.23
The "VEGCAR," a car whose engine has been modified to run on used vegetable oil (a biofuel).



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Other ways to reduce the amount of anthropogenic carbon dioxide in the atmosphere involve the various sinks in the carbon cycle. A significant source of CO_2 emissions is related to the oxidation of organic carbon in biomass and soils caused by deforestation, particularly in the tropics. Slowing or stopping deforestation would decrease anthropogenic carbon emissions. Restoring land to forest converts atmospheric CO_2 into standing plant biomass and eventually returns carbon back to storage in the soil. After being cleared for agriculture and logged for firewood in the eighteenth and nineteenth centuries, many rural regions in the eastern United States gradually reforested in the twentieth century. The uptake of carbon dioxide by reforestation partly offset the emissions of CO_2 from the burning of fossil fuels until the rapid industrialization of the United States and Europe following World War II.

One technology under development for controlling greenhouse gas emissions is **carbon capture and storage (CSS)**, which is also referred to as **carbon sequestration**. CSS involves capturing CO_2 emissions from large point sources such as coal-fired power plants, compressing the CO_2, and storing it by pumping the CO_2 into deep geologic formations, reducing carbon emissions to the atmosphere by 80% to 90%. As of this writing, there are no commercially functioning CSS facilities, although several pilot projects are either under construction or starting up. There is great interest in CSS because it would allow the vast coal reserves in the United States and other countries to be exploited as a low-carbon fuel in spite of the large CO_2 emissions produced by the combustion of coal. However, widespread use of CSS faces several obstacles, including the high cost of the initial investment in the technology, the cost of the additional fuel needed to capture and compress CO_2, the cost of transporting the compressed CO_2, and the need to locate suitable geologic formations for storage of CO_2 that will not leak over time. In effect, carbon sequestration is a method for artificially returning to the crust of the Earth the carbon liberated by the combustion of fossil fuels. Other, more radical approaches to slowing or stopping climate change include fertilizing the surface waters of the open ocean to stimulate the biological carbon pump and artificially increasing the amount of incoming sunlight that is reflected back into space. These approaches are still in the theoretical stage and are unlikely to be developed anytime soon due to the technological, political, and legal problems they pose.

The generation of abundant, cheap energy from fossil fuels has driven much of the rise in global economic productivity and prosperity over the last 150 years. Unfortunately, exploiting fossil fuels also carries an environmental cost in the form of rapid climate change generated by a spike in atmospheric greenhouse gases that is unprecedented in recent geologic history. Successfully reducing the buildup of anthropogenic greenhouse gases in our atmosphere and the resulting increase in global temperature through the remainder of the twenty-first century and beyond will almost certainly require that all these strategies be developed and deployed. This will be an expensive investment, but the costs we will incur by doing nothing to address anthropogenic climate change will most certainly be much higher.

Section Carbon Cycle and Climate Change.8 Summary

- The natural carbon cycle pathways that remove carbon dioxide from the atmosphere are unable to keep up with the extremely rapid rate at which CO$_2$ from anthropogenic emissions is being added to the atmosphere.
- More efficient use of fossil fuels is one strategy for reducing greenhouse gas emissions, but it will not be a sufficient solution to the problem of anthropogenic climate change because of the rapidly expanding global demand for fossil fuels.
- Alternative energy sources are needed to replace fossil fuels, such as solar, wind, hydroelectric, and nuclear power, as well as biofuels.
- Carbon capture and storage might provide a means for burning fossil fuels such as coal without adding large quantities of greenhouse gases into the atmosphere.

Review Workbook

ESSENTIAL QUESTIONS SUMMARY

Carbon Cycle and Climate Change.1 Introduction

■ *Where is carbon found in the major Earth systems (biosphere, atmosphere, hydrosphere, geosphere)?*
Carbon is found in organic molecules in the biosphere, in carbon dioxide and methane gas in the atmosphere, in bicarbonate ions in the hydrosphere, and in carbonate minerals and fossil fuels (hydrocarbons) in the geosphere.

■ *What is meant by the term* carbon cycle?
The carbon cycle describes the chemical pathways by which carbon is transferred from one Earth system to another and the reservoirs and sinks in which carbon is stored in different Earth systems.

Carbon Cycle and Climate Change.2 Organic Carbon Cycle

■ *What is the chemical process by which carbon dioxide in the atmosphere is transformed into organic carbon in the biosphere? What is the reverse chemical process?*
Photosynthesis is the process by which plants, algae, and some bacteria use solar energy to capture carbon dioxide from the atmosphere and convert it into organic carbon, releasing oxygen as a byproduct. Respiration is the reverse chemical process whereby cells (both animal and plant) utilize oxygen to break down organic molecules, releasing energy and carbon dioxide.

■ *What is a fossil fuel? What is the impact on the atmosphere of the burning of fossil fuel?*
Fossil fuels are geologic deposits of organic carbon that can be extracted and burned to produce energy. Burning fossil fuels adds millions of years of sequestered carbon dioxide back into the atmosphere over a relatively short period.

Carbon Cycle and Climate Change.3 Inorganic Carbon Cycle

■ *How does the solubility pump transfer carbon dioxide from the atmosphere and store it in the oceans?*
Carbon dioxide dissolves in seawater and chemically reacts to form bicarbonate ion. Sinking of cold ocean water moves dissolved CO$_2$ and bicarbonate ion to the deep ocean.

■ *How does chemical weathering transfer carbon dioxide from the atmosphere and store it in rock?*
Chemical weathering produces calcium and bicarbonate ions by the reaction of carbonic acid with silicate minerals. Bicarbonate reacts with calcium in the oceans to form limestone.

■ *What is the mechanism by which carbon dioxide is returned to the atmosphere from the geosphere?*
Carbonate minerals in limestone can react with quartz during metamorphism, producing carbon dioxide gas, which eventually can escape into the atmosphere during volcanic eruptions.

Carbon Cycle and Climate Change.4 Atmosphere and Climate

■ *What are the important greenhouse gases and how do they function to warm the Earth's surface and atmosphere?*
Water vapor, carbon dioxide, and methane are the important gases because they absorb infrared radiation (heat) radiated from the surface to heat the atmosphere. The atmosphere then returns most of this heat to the surface, preventing it from escaping into space.

■ *How does the carbon cycle thermostat regulate the surface temperature of the Earth within a range suitable for living organisms?*
The carbon cycle thermostat is a negative feedback system based on volcanism, chemical weathering, and carbonate mineral formation. As the climate of the Earth warms, chemical weathering and carbonate formation increase, drawing CO$_2$ out of the atmosphere, reducing the greenhouse effect, and cooling the planet. As the Earth cools, chemical weathering and carbonate formation slow down and remove less and less CO$_2$ from the atmosphere. At the same time, volcanic eruptions add CO$_2$ to the atmosphere, increasing the greenhouse effect and warming the planet.

■ *What other factors have an impact on the climate of the Earth?*
Other factors the influence climate on the Earth are changes in solar luminosity, plate tectonic movements of continents, the Earth's orbital geometry and tilt, the global rate of sea floor spreading and volcanism, mountain building, and ocean circulation.

Carbon Cycle and Climate Change.5 Earth's Climate History

■ *What mechanisms have maintained a stable climate through the history of the Earth, in spite of the gradually increasing energy output from the sun?*
The early Earth was likely kept warm in spite of a weaker sun by a strong carbon dioxide and methane greenhouse. As the sun progressively increased its energy output through time, the carbon cycle thermostat maintained a livable temperature on the surface of the Earth by removing carbon dioxide from the atmosphere and storing it as carbonate rock in the crust of the Earth.

■ *Give three examples of evidence used as a proxy for reconstructing the climates and temperatures of the past.*
Examples of climate and temperature proxies include: the distribution of fossils of climate sensitive organisms such as corals and crocodilians, the presence of geologic indicators of climate such as glacial deposits, the thickness of tree rings in fossil wood, the types and abundances of fossil spores and pollen, and the ratio of oxygen isotopes in fossil shells.

■ *How are sediment cores and ice cores used by paleoclimatologists to reconstruct the climate history of the Earth?*
Sediment and ice cores provide a continuous record of climate proxies. Foraminifera fossils from sediment cores can be analyzed for oxygen isotopes to determine past changes in ocean temperature. Ice-rafted debris in sediment cores indicates times of active glacial advance. Oxygen isotope ratios from ice cores provide a continuous record of local temperature, and trapped air bubbles are analyzed to determine how levels of greenhouse gases have changed through time.

Carbon Cycle and Climate Change.6 Anthropogenic Climate Change

■ *What is the evidence that recent climate warming is related to increasing levels of greenhouse gases in the atmosphere?*
Satellite measurements show that the troposphere is warming while the overlying stratosphere is cooling, indicating that greenhouse gases in the troposphere are trapping additional heat, preventing it from radiating back into space. Also, computer climate models that simulate the greenhouse effect from rising levels of atmospheric CO_2 and methane are able to accurately reproduce observed temperature trends seen in the recent past.

■ *In terms of the carbon cycle, what are the main sources of anthropogenic greenhouse gases?*
The main source of anthropogenic greenhouse gases is carbon dioxide released by the combustion of carbon stored in the crust as fossil fuels. A secondary source is the conversion to carbon dioxide of organic carbon stored as plant biomass and in soils as forest is converted to agricultural land in the developing tropics.

Carbon Cycle and Climate Change.7 Consequences of Climate Change

■ *Why is climate change likely to be a problem for most societies, rather than a benefit?*
Climate change is a problem because global societies are adapted to climate as it has been for the past 100 years. Our culture, technology, agriculture, and industries are predicated on existing climates and ecosystems. If climate changes, we will have to adapt to new conditions, which will be costly and disruptive, even dangerous, for hundreds of millions of people.

■ *What are some of the likely impacts of climate change on the atmosphere, hydrosphere, and biosphere?*
As the atmosphere warms, weather patterns will shift, causing more rain in some regions and more droughts in others. Temperature extremes such as heat waves and weather extremes such as violent storms and flooding will become more frequent. Melting glaciers and warming ocean waters will raise global sea level, flooding coastlines and making coastal storms more destructive. Species will respond by shifting their ranges, disrupting established ecosystems and causing the loss of commercially valuable species from regions where they are important to the local economy. Mosquito-borne diseases will expand their traditional ranges, as will many pests.

Carbon Cycle and Climate Change.8 Preventing Climate Change

■ *Why aren't the climate-regulating feedbacks inherent in the carbon cycle preventing anthropogenic climate change?*
The carbon cycle mechanisms that naturally work to remove CO_2 from the atmosphere are the biological pump, the solubility pump, and the chemical weathering/carbonate formation reactions. All these mechanisms work too slowly to effectively counteract the rapid rise in anthropogenic CO_2.

■ *What are some of the strategies for reducing the rate at which greenhouse gases are being emitted into the atmosphere?*
Strategies for reducing greenhouse gas emissions include more efficient use of fossil fuels, replacement of fossil fuels with noncarbon alternative energy (solar, wind, nuclear), replacement of fossil fuels with biofuels, reforestation, and carbon capture and storage.

ESSENTIAL TERMS TO KNOW

Albedo – the extent to which an object diffusely reflects light. Surfaces with a high albedo appear lighter than darker surfaces with a low albedo.

Anthropogenic – caused by the actions of humans.

Archaea – single-celled organisms that are superficially similar to bacteria and that commonly produce methane as a byproduct of anaerobic metabolism.

Atmosphere – the collection of gases (nitrogen, oxygen, carbon dioxide, methane, water vapor, etc.) that envelops the surface of the Earth.

Atmosphere-Ocean General Circulation Model – a computer model that simulates processes in both the oceans and atmosphere used to predict how climate will change over time in response to forcing mechanisms such as greenhouse gases and solar output.

Biofuel – organic carbon-based fuels such as ethanol and biodiesel manufactured from sugars, vegetable oils, or animal fat.

Biological pump – the process whereby carbon from CO_2 in the atmosphere is fixed by photosynthesis in the surface waters of the ocean and transferred to the deep sea.

Biomineralization – the precipitation of mineral crystals by organisms, usually for the purpose of constructing shells and skeletal elements.

Biosphere – all living things and nondecomposed organic matter on Earth.

Cap and trade – a method for regulating CO_2 emissions that places a limit on CO_2 emissions and then allows companies that emit less than their cap to profit by selling the rights to emit their additional CO_2 to other companies that exceed their cap.

Carbon – the element with six protons in the atomic nucleus capable of forming four discrete atomic bonds. The building block of most organic molecules.

Carbon capture and storage (CSS) – collecting CO_2 as it is produced at a point source such as a coal-fired power plant, compressing it, and pumping it into the Earth for long-term storage (carbon sequestration).

Carbon cycle thermostat – the negative feedback system formed by the inorganic carbon cycle that causes the Earth's atmosphere to adjust its carbon dioxide greenhouse to compensate for extremes of global warming or cooling over geologic time.

Carbon fixation – the biochemical process by which photosynthesizing organisms transform inorganic carbon dioxide into molecules of organic carbon.

Carbon footprint – the total amount of carbon dioxide emitted to the atmosphere that can be attributed to the activities and lifestyle of a person or group.

Carbon sequestration – see *Carbon capture and storage (CSS)*.

Carbon tax – a tax based on the quantity of CO_2 emitted by a business or municipality.

Carbonate minerals – minerals such as calcite and dolomite that contain carbon in the form of the complex ion CO_3^{-2}.

Carbonate rock – rocks composed predominately of the carbonate minerals calcite and dolomite (limestone, dolostone, and marble).

Carbonic acid – a weak acid (H_2CO_3) formed by the reaction of carbon dioxide and water that is an important agent in chemical weathering.

Catabolism – the chemical breakdown of complex molecules into simple ones, often for the purpose of extracting energy.

Chemical weathering – the chemical alteration of minerals exposed to the Earth's atmosphere.

Cryosphere – the Earth system composed of glacial ice, sea ice, and snow cover.

Extirpation – a local extinction; the complete disappearance of a species from one region while it still remains in others.

Faint young sun paradox – the problem of explaining how the young Earth maintained average surface temperatures above freezing in spite of astronomical models that indicate that the young sun had a significantly lower energy output insufficient to prevent the Earth from freezing.

Foraminifera – single-celled marine organisms related to amoeba that secrete a shell composed of calcium carbonate mineral, providing an important proxy for ocean temperature in deep ocean sediment cores.

Fossil fuels – sedimentary deposits of organic carbon that can be extracted and burned to generate energy. Examples include peat, coal, tar, oil, and natural gas.

Geosphere – the rocky portion of the Earth, including the crust, mantle, and core.

Greenhouse effect – the process wherein certain gases in the atmosphere of the Earth trap infrared energy being radiated from the surface into space, redirecting that energy back toward the surface.

Greenhouse gases – gases in the atmosphere of the Earth, including water vapor, carbon dioxide, and methane, that are transparent to incoming solar radiation but trap outgoing infrared radiation (heat).

Hothouse – an interval of time when the climate of the Earth is warm across a wide range of latitude.

Hydrosphere – the water of the Earth, including oceans, freshwater bodies, and ice.

Hydrocarbons – molecules consisting mainly of carbon and hydrogen, with the carbon atoms frequently forming chains. Fossil fuels are composed of hydrocarbon molecules.

Hydrolysis – the chemical reaction of a mineral with a hydrogen ion derived from the splitting of a water molecule. Hydrolysis commonly involves the breakdown of silicate minerals by reaction with carbonic acid.

Icehouse – describes an interval of time when the climate of the Earth is cool enough to trigger the formation of extensive continental ice sheets.

Ice-rafted debris – small rock fragments found in deep ocean sediment cores that indicate active growth of glaciers and formation of icebergs that carry rock debris far out to sea and release it during melting.

Ice shelf – a large area of ice covering a continental embayment that is partially floating and partially supported by the surrounding land.

Inorganic carbon cycle – the collection of pathways and reservoirs in the carbon cycle that involve inorganic processes such as chemical weathering and metamorphism.

Intergovernmental Panel on Climate Change (IPCC) – an international body of climate scientists charged by the United Nations with studying the impact of human activities on Earth's climate and with making periodic reports on climate change to guide the decisions of policymakers.

Little Ice Age – a period of climate cooling following the Medieval Warm Period that lasted from the mid-1400s to the mid-1800s, bringing unusually cold winters and cool, wet summers to Europe and North America.

Medieval Warm Period – an interval of several hundred years, centered around 1000 CE, when climate in the northern hemisphere was exceptionally warm.

Milankovitch Cycles – cyclical changes in the parameters of the Earth's orbit that change the distribution of sunlight across the surface of the globe through the year, causing the Earth to experience corresponding climate changes.

Organic carbon cycle – the collection of pathways and reservoirs in the carbon cycle that involve organic processes and transfers of carbon into and out of the biosphere.

Paleoclimatology – the study of the Earth's climate in the past.

Photosynthesis – the chemical capture of solar energy to build organic molecules from carbon dioxide and water used by plants, algae, and archaea.

Proxy – a body of evidence that can be used to infer past climate and temperature.

Respiration – the biochemical process wherein cells utilize oxygen to break down organic molecules to produce chemical energy.

Sink – a reservoir where quantities of carbon can accumulate in a particular form and remain for long periods.

Solubility pump – the mechanism whereby carbon dioxide dissolves in surface waters and is transported to deep water by downwelling of cold water at high latitudes, storing carbon from CO_2 in the atmosphere as dissolved CO_2 and bicarbonate ion in the deep ocean.

Stratosphere – the layer of the atmosphere situated above the troposphere, between an average of 10 km (6 miles) and 50 km (31 miles) altitude.

Troposphere – the lowermost layer of the atmosphere, containing about 75% of its gases and most of its water vapor.

REVIEW QUESTIONS

1. What are the significant reservoirs of carbon in the atmosphere, hydrosphere, biosphere, and geosphere?

2. How is carbon transferred between the atmosphere and biosphere in the organic carbon cycle? Describe the processes in the organic carbon cycle that can lead to the formation of fossil fuels.

3. How is carbon transferred between the atmosphere, hydrosphere, and geosphere in the inorganic carbon cycle?

4. What are the important greenhouse gases in the Earth's atmosphere? Describe the mechanism by which greenhouse gases warm the Earth.

5. How have chemical weathering, carbonate formation, and volcanism interacted to regulate the climate of the Earth over geologic time?

6. What are some of the proxies that paleoclimatologists use to reconstruct past climates on Earth?

7. What is the evidence that anthropogenic greenhouse gas emissions are causing the Earth's climate to become warmer?

8. What are some of the adverse impacts of a warmer global climate on human civilization?

9. Why are the mechanisms in the carbon cycle that work to transfer carbon from the atmosphere to the biosphere, hydrosphere, and geosphere not compensating for the buildup of anthropogenic greenhouse gases such as carbon dioxide and methane?

10. What are some of the strategies that could be employed to diminish or stop anthropogenic climate change?

APPLY YOUR KNOWLEDGE QUESTIONS

1. Visit the U.S. Department of Energy's Fuel Economy website at http://www.fueleconomy.gov/feg/sbs.htm to find out what the mileage rating and annual carbon footprint is for the car that you drive. Use the "personalize annual miles" option to set the number of miles of city and highway driving you do annually.

2. Make a list of your daily activities that add to your personal carbon footprint. Using the Internet as an information source (e.g., go to the U.S. Environmental Protection Agency's individual emissions page at http://www.epa.gov/climatechange/emissions/individual.html), try to calculate your daily, monthly, and annual carbon footprint.

3. Using the list of activities that contribute to your carbon footprint, create a plan for reducing your carbon footprint. Calculate how much your plan would reduce your daily, monthly and annual carbon footprint.

The collection of chemical pathways by which carbon moves between Earth systems is called the **carbon cycle** and it is the flow of carbon through this cycle that ties together the functioning of the Earth's atmosphere, biosphere, geosphere, and oceans to regulate the climate of our planet. This means that as drivers of planet Earth, anything we do to change the function or state of one Earth system will change the function and state of all Earth systems. If we change the composition of the atmosphere, we will also cause changes to propagate through the biosphere, hydrosphere, and geosphere, altering our planet in ways that will likely not be beneficial to human welfare. Understanding the functioning of the carbon cycle in detail so that we can predict the effects of human activities on the Earth and its climate is one of the most important scientific challenges of the 21st century.

Package this module with any Cengage Learning text where learning about the carbon cycle and humanity's impact on the environment is important.

About the Author

Dr. J Bret Bennington grew up on Long Island and studied geology as an undergraduate at the University of Rochester in upstate New York. He earned his doctorate in Paleontology from the Department of Geological Sciences at Virginia Tech in 1995 and has been on the faculty of the Department of Geology at Hofstra University since 1993.

Dr. Bennington's research is focused on quantifying stability and change in marine benthic paleocommunities in the fossil record and on integrating paleontological and sedimentological data to understand the development of depositional sequences in both Carboniferous and Cretaceous marine environments. The results of these studies have been published in journals such as Palaeogeography-Palaeoclimatology-Palaeoecology, Paleobiology, and PALAIOS, and have been presented at a variety of regional, national, and international meetings. Recently, Dr. Bennington has been working with an international group of researchers hosted by the Smithsonian Institution in an effort to combine the work of paleoecologists and ecologists to better understand and predict the impacts of climate change on modern ecosystems.

In addition to leading undergraduate students on regional field trips to support his courses in physical geology, historical geology, paleontology, and geomorphology, Dr. Bennington conducts field workshops on the regional geology of New York and New Jersey for high school teachers and is a frequent public lecturer on topics of paleontology, evolution, and regional geology. He is also the co-director of Hofstra University's study abroad program in the Evolutionary Ecology and Geology of the Galapagos Islands and Ecuador, as well as an occasional Charles Darwin impersonator.

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