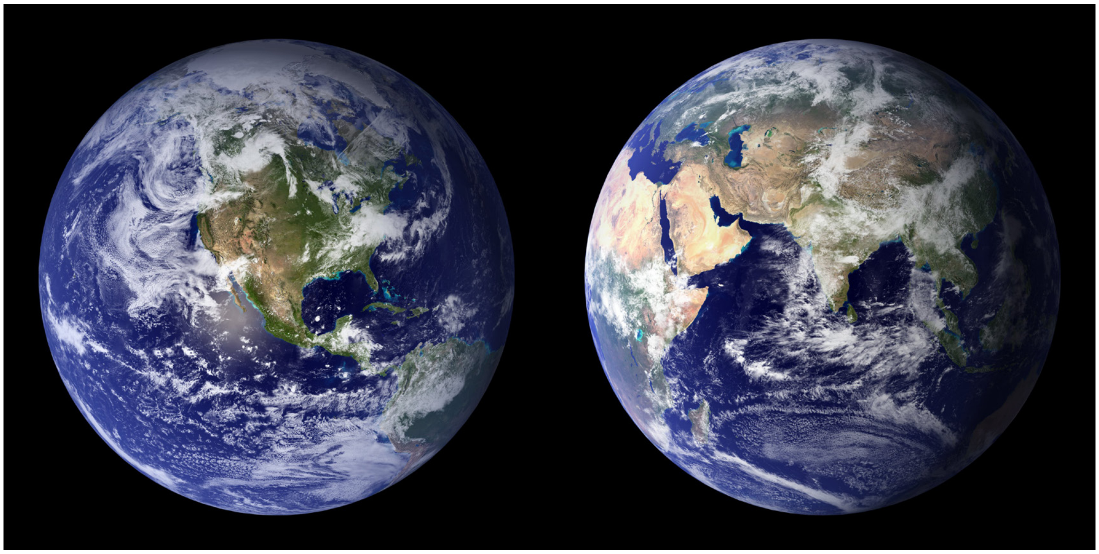
The Teacher-Friendly Guide™ to Climate Change



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On the front cover: the "Blue Marble." Composite images produced by NASA in 2001-2002.

On the back cover: Atmospheric CO_2 concentration at Mauna Loa Observatory from 1958 to 2014 (NOAA).

Chapter 3: What is Climate?

1. Climate is a System

One can describe **climate** as a symphony of weather, taking into account the entire range of weather conditions in a region, the extremes as well as the average.[1] Climatologists technically define climates through the calculation of “climate normals”: thirty-year averages of variables such as daily temperature, rainfall, snowfall, and frost and freeze dates that can be compared with thirty-year averages of these variables from other time periods. Fluctuations in these variables that last hours, days, or up to two weeks are called **weather**.

Weather is what we all feel when we step outside: if you want to know what today’s weather is, just go outside! No one ever actually experiences the climate in the present, because no one can ever step outside and feel that day’s climate.[2] One practical way to think about the difference between climate and weather is that knowing the weather tells you what clothing to wear on a given day, whereas knowing the climate tells you what clothing you need to own.

Life is possible on Earth because the climate is favorable for it to flourish. In particular, the average range of surface temperatures on Earth allows for abundant liquid water, which is essential for life as we know it. Earth’s average surface temperature has changed over time; for example, average global temperature may have been as much as 11°C (20°F) higher than today during parts of the **Mesozoic** Era, the time of the dinosaurs. But for most of Earth history it has fluctuated within a range that allows for liquid water in the oceans and in land water bodies. Temperature on our planet is controlled, in part, by the fact that we have a thin atmosphere of gases surrounding us; this thin layer acts to hold in some of the energy that the Earth radiates after being warmed by sunlight.

See Chapter 4: Past Climates for more detail on climate change through Earth’s history.

Our two closest neighbor planets, Mars and Venus, have very different atmospheres from Earth, and hence, very different surface temperatures. Venus is similar to the Earth but is closer to the sun, and the additional heat has caused what we call a “runaway greenhouse effect” in which increased temperatures increased the levels of greenhouse gases, which further increased the temperature, which further increased greenhouse gases, and so on. The end

climate *• a description of both the average weather conditions (temperature, precipitation, wind, etc.) and the extremes that a region experiences.*

weather *• fluctuations in variables such as temperature, rainfall, snowfall, and wind that last hours, days, or up to two weeks.*

Mesozoic *• a geologic time era that spans from 252 to 66 million years ago. This era is also called the “age of reptiles” since dinosaurs and other reptiles dominated both marine and terrestrial ecosystems. During this time, the last of the Earth’s major supercontinents, PANGAEA, formed and later broke up, producing the Earth’s current geography.*

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[1] Climate as a “symphony of weather” is a term used by Dr. Arthur T. DeGaetano, Professor of Earth and Atmospheric Sciences at Cornell University.

[2] Interesting blog posts on this concept and more—including climate models— have been written by Dr. Ben Brown-Steiner and can be found on the Climate Change 101 Blog (see http://climatechange101.blogspot.com/2014/10/whats-climate-like-outside-today.html and other entries from 2014 and 2015).

result is that the temperatures on Venus now can exceed 450° C (842° F) and the atmosphere is nearly 100 times denser than the Earth's atmosphere. The atmosphere surrounding Venus is 96% carbon dioxide (CO_2) (*Box 3.1*). Mars, farther than Earth from the sun, has an atmosphere similar to Venus, with 95% CO_2, but the total atmosphere is much less dense than that on Earth, about 50 times less dense than the air at the top of Mount Everest. With such a thin "blanket," little total heat is trapped, thus the average surface temperature on Mars is -53°C (-63°F). The relationship between Venus, Earth, and Mars is an example of what has been called the **Goldilocks Principle**—the temperature on Earth is not too hot and not too cold, but "just right" for life to exist.

The Earth's climate is a **system** (*Box 3.2*). This means that it has many parts that interact with each other to create behaviors that might not occur if each part were isolated. The Earth's climate is a *complex* system, meaning that it has many parts with many interactions. Complexity reduces (or at least makes more difficult) the predictability of the overall behavior of the system. Yet, scientists have enough understanding of the physical and chemical laws that govern Earth's climate system that they can build computer models which can accurately replicate historical climate data. These same models can be run to predict future climates under different scenarios.

The Earth's climate system consists of air, water, land, and life (or, as they are often called, the **atmosphere**, **hydrosphere, geosphere**, and **biosphere**). Phenomena outside of the Earth (mainly the sun, but also cosmic dust and meteorite impacts) also affect its climate. All of these components interact over time to create the climate conditions that we observe. Life on Earth evolves partly in response to changes in climate, but living systems also influence climate through absorption or emission of greenhouse gases such as CO_2 and **methane** (CH_4).

See Section 3 in this chapter on the greenhouse effect.

The **atmosphere**—the blanket of gas surrounding the Earth (commonly called "air")—is where most of what we think of as weather and climate happen. Other planets, such as Mars and Venus, also have atmospheres, but they are very different from that on Earth. Our atmosphere consists mostly (approximately 80%) of nitrogen, with oxygen making up most of the rest. Other gases exist in much smaller quantities (*Table 3.1*) and are called **trace gases**. Despite their small quantities in terms of percentage of the atmosphere, some of these other gases—such as water vapor, carbon dioxide, methane, and **ozone**—control the Earth's climate system because of their influence on temperature.

The **hydrosphere** includes all the liquid and frozen water at the Earth's surface. The oceans contain approximately 97% of the water on Earth. Because water holds heat for longer than land, the oceans play a very important role in storing and circulating heat around the globe. The **currents** in the oceans, in fact, are driven primarily by differences in density, influenced by temperature and also by the salt content. The surface of the ocean receives heat from the sun. This warm water is less dense than colder water found deeper in the oceans. Atmospheric winds and forces that result from the rotation of the Earth create ocean currents

system • *a combination of interacting parts whose interaction creates behaviors that might not occur if each part were isolated.*

atmosphere • *the layer of gases that surrounds a planet.*

hydrosphere • *all of the water on Earth.*

geosphere • *the solid portion of the Earth.*

biosphere • *all plants, animals, and people, both living and non-living, on Earth.*

methane • CH_4, *a greenhouse gas formed from organic matter under heat and pressure from burial and from fermentation of organic matter by bacteria in low oxygen settings, including the digestion of animals.*

trace gases • *gases whose volume makes up less than 1% of the Earth's atmosphere.*

ozone • *a molecule* (O_3) *found in the STRATOSPHERE which absorbs ultraviolet light. When found near the surface of the Earth, ozone is considered a pollutant because it is a component of smog and can cause lung irritation.*

currents • *directional movements of a fluid mass.*

Box 3.1: Why all the fuss about carbon dioxide?

Carbon dioxide (CO_2) is a molecule made of one atom of carbon and two atoms of oxygen. Within the range of temperatures found on Earth, CO_2 usually takes the form of a gas. It is a natural component of Earth's atmosphere, exhaled by **aerobic** organisms such as plants, animals, fungi, protists, and many bacteria, and used by plants in the process of photosynthesis. Thus, concentrations of CO_2 in the atmosphere vary seasonally as a result of **deciduous plants** in the northern hemisphere that, in the summer, absorb more CO_2 than they release.

CO_2 is part of the **carbon cycle** (see *Figure 3.7*), which includes carbon found in living things, the atmosphere, oceans, and Earth's crust—in **limestone**, and in **oil**, **natural gas**, and **coal** deposits. Because carbon usually cycles slowly through the ocean (thousands of years) and the crust (millions or billions of years), these are called "**carbon sinks**." Without human intervention the carbon cycle is generally in **equilibrium**, with approximately as much carbon being released into the atmosphere each year as is absorbed by sinks worldwide.

Large forests are carbon sinks, storing carbon in their biomass until they die and decay. Some large forests, such as the Amazon rainforest, are shrinking because of human activities such as deforestation. As the forests are destroyed they release their carbon back into the atmosphere and switch from carbon sinks to carbon sources.

Human burning of **fossil fuels**, such as oil, natural gas, and coal, releases the carbon stored in the ancient **organic matter** as CO_2 gas. Because these sinks have been long-term repositories for carbon, their rapid release into the atmosphere has caused an imbalance which results in increasing levels of CO_2 in our atmosphere and oceans.

This additional emission of CO_2 into the environment, and the reduction of some carbon sinks, tips the equilibrium of the carbon cycle, so that each year the concentration of CO_2 in the atmosphere grows by about 1%. This is believed to be the primary cause of current climate change.

Once emitted into the atmosphere, CO_2 can stay there for hundreds of years, causing imbalances that can last thousands of years, so increased levels of CO_2 resulting from human activities can impact the climate for thousands of years.

that allow cold bottom water to well up to the surface. In the tropics, most of the warm water at the surface is pushed by wind to the centers of large rotating masses of water called **gyres** (*Figure 3.1*). Some of the water, such as the **Gulf Stream**, moves toward the poles. When warm water approaches the poles, it mixes with colder water. Evaporation and formation of sea ice leave behind slightly saltier surface water. This cold, salty sea water, which forms especially in the North Atlantic and near Antarctica, is relatively dense and sinks. It then begins to move under the surface back toward the equator, sliding underneath the warmer and less dense surface waters. This is the primary driver of deep ocean circulation, which can take hundreds or thousands of years to complete one cycle.

aerobic • *involving free oxygen.*

deciduous plants • *plants which lose their leaves, typically in autumn, and regrow them the following spring.*

carbon cycle • *the exchange and recycling of carbon between the geosphere, hydrosphere, atmosphere, and biosphere.*

limestone • *a sedimentary rock composed of calcium carbonate ($CaCO_3$). Most limestones are formed by the deposition and consolidation of the skeletons of marine invertebrates; a few originate in chemical precipitation from solution.*

oil • *a naturally occurring, flammable liquid found in geologic formations beneath the Earth's surface and consisting primarily of hydrocarbons. Oil, also called PETROLEUM, is a fossil fuel, formed when large masses of dead organisms (usually algae or plankton) are buried underneath sediments and subjected to intense heat and pressure.*

natural gas • *a hydrocarbon gas mixture composed primarily of methane ($CH4$), but also small quantites of hydrocarbons such as ethane and propane. See also FOSSIL FUEL.*

Climate System

coal • *a rock formed from ancient plant matter that can be burned as fuel. Since coal is formed from fossilized plant remains it is considered a FOSSIL FUEL..*

carbon sink • *a system or part of a system which absorbs carbon.*

equilibrium • *a state of balance in opposing forces, amounts, or rates.*

fossil fuel • *a non-renewable, carbon-based fuel source like OIL, NATURAL GAS, or COAL, developed from the preserved organic remains of fossil organisms.*

organic matter • *decomposed remains of plants, animals, and their wastes.*

gyres • *large- (i.e., global-) scale rotating masses of ocean water.*

Gulf Stream • *a current in the Atlantic Ocean which transports warm water from the Gulf of Mexico along North America's East Coast, then across the Atlantic in two streams, one traveling to Northern Europe and one to West Africa.*

Box 3.2: How systems work

A **system** is a collection of parts that interact with each other. Earth's climate system is made up of all of the objects and processes that have a global impact on climate. To begin to understand a system as complicated as the Earth's climate system, scientists observe and analyze the components and their interactions and how a change in one component (a forcing) impacts the other components (a response).

The term **forcing** refers to factors that cause change; **responses** are the changes that result. Forcings can produce responses at various rates. These rates can be directly proportional to the magnitude of the forcing, in which case they are called **linear**. For example, pushing a merry-go-round harder will result in a linear increase in the speed of the merry-go-round. Or they can be produced in some more complex, **non-linear** pattern. For example, a small push to a ball at the top of a hill can cause a much larger change if the ball rolls down the hill. A forcing might induce a response immediately after it is applied, or only after some period of time has passed (**lag**). For instance, when grass seed is planted, there is a lag before your yard is covered by grass, and that amount of time is determined by rainfall, exposure to the sun, and other factors. Forcing can be applied at a variety of **magnitudes** (strong or weak) and **durations** (long or short).

A very important behavior of all systems is **feedback** between components. Feedbacks can either amplify a behavior (positive or reinforcing feedback) or suppress it (negative or balancing feedback).[3]

An example of a positive or reinforcing feedback cycle in the climate system is melting of sea ice. Sea ice forms when seawater freezes at the surface of the ocean, and it is much brighter (more reflective) than the water around it. Since it is bright it reflects much of the incoming sunlight back to the atmosphere. If a little bit of sea ice melts, more ocean water is available to soak up the heat from the sun, and this warmer water melts more of the nearby ice. This process can amplify until the ice is completely melted. At this point the system of sea ice and seawater has crossed a **threshold**, that is, it has changed dramatically.

An example of negative or balancing feedback is the impact of clouds on global warming. Warm air contains more water vapor than cold air and more water vapor leads to more clouds, so a warmer Earth will have more clouds. However, clouds are white and reflect sunlight, so more clouds will result in less sunlight reaching the Earth, cooling the climate. Clouds have the potential to counteract global warming, although we do not know exactly by how much.

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[3] Dr. Kim Kastens, in her 2010 article "Going Negative on Negative Feedback," discusses the confusion often generated by the colloquial meaning of the words "positive" and "negative" and the use of these words in describing feedback in systems. She suggests alternative terms of "reinforcing" and "balancing" feedback. Her article can be found at http://serc.carleton.edu/earthandmind/posts/negativefeedbac.html.

Table 3.1: Composition of Earth's atmosphere.

Gas	% in Atmosphere
Nitrogen (N_2)	78
Oxygen (O_2)	21
Water vapor (H_2O)	1 to 4*
Argon (Ar)	0.93
Carbon dioxide (CO_2)	0.041**
Neon (Ne)	0.0018
Helium (He)	0.00052
Methane (CH_4)	0.00017
Krypton (Kr)	0.00011
Hydrogen (H_2)	0.000055
Nitrous oxide (N_2O)	0.00003
Carbon monoxide (CO)	0.00001
Xenon (Xe)	0.000009
Ozone (O_3)	0.000007
Nitrogen dioxide (NO_s)	0.000002

* The concentration of water vapor in the atmosphere varies from about 1% to 4%, depending on the temperature. If temperatures warm, more water vapor can be held in the air, increasing the greenhouse effect from water.

** The concentration of CO2 is rising (407 parts per million as of March 2017); see the most recent data at: https://www.esrl.noaa.gov/gmd/ccgg/trends/index.html.

The movement of ocean currents, carrying heat energy to different parts of the globe and transferring energy to the atmosphere, plays an extremely large role in global climate. Therefore, the configuration of the continents, around which the ocean currents flow, also plays a large role in their respective regional climates.

Ice at the Earth's surface includes **sea ice**, **glaciers**, and continental **ice sheets**, which altogether hold approximately 2% of the water on Earth. Scientists refer to this system as the **cryosphere**. Sea ice forms when seawater freezes at -1.9°C (29°F), which is lower than "freezing" (0°C or 32°F) because of the salt content. Like all ice, frozen seawater is less dense than liquid water, and floats atop it. Sea ice acts as an insulating barrier that prevents the ocean from interacting with the atmosphere. When ice is present, heat from the ocean is not lost to the atmosphere, and the water can remain much warmer than the air. Glacial ice occurs as **mountain glaciers** or continental ice sheets. Mountain glaciers can occur anywhere in the world, but in the tropics they cannot form below 5 kilometers (about 16,400 feet) altitude, where it is too warm.

There are currently two continental ice sheets on Earth, covering most of Greenland and Antarctica. These large continental glaciers lock up great quantities of water that would otherwise be in the ocean, resulting in lower

system *• a combination of interacting parts whose interaction creates behaviors that might not occur if each part were isolated.*

linear *• a mathematical relationship where a variable is directly proportional to another variable.*

non-linear *• a mathematical relationship where a variable is not directly proportional to another variable.*

lag *• a period of time between events, such as between the incidence of solar radiation and a certain amount of warming of the Earth.*

magnitude *• the size of a quantity.*

duration *• the length of time an event or activity lasts.*

feedback *• the response of a system to some change that either balances/opposes or reinforces/enhances the change that is applied to a system. Balancing feedback (sometimes called negative feedback) tends to push a system toward stability; reinforcing feedback (sometimes called positive feedback) tends to push a system towards extremes.*

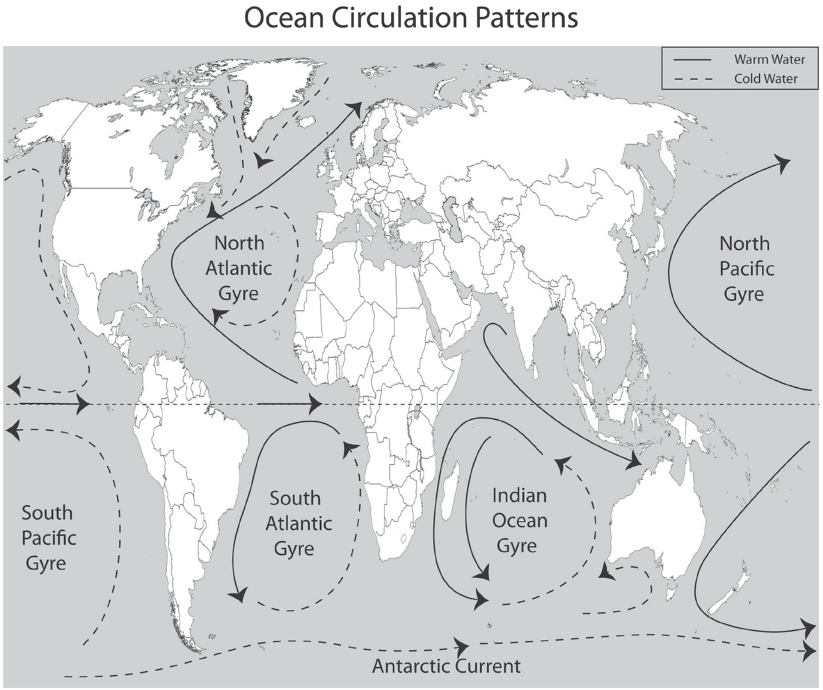

Figure 3.1: Modern ocean surface circulation. Ocean currents play a huge role in transporting heat energy from equatorial regions to temperate and polar regions. Surface circulation of a relatively thin layer of water is driven by the wind and by the Coriolis force, an effect of rotation of the Earth, which drives gyres in the Atlantic and Pacific Ocean. Subsurface circulation, which is not shown, is driven by cold salty water that sinks near the poles, especially in the North Atlantic. When the warm water begins to cool at higher latitudes, such as around northern Europe, its heat is lost to the atmosphere, contributing significantly to warming the air. Land near water in these regions is therefore usually warmer than land far from the coast. For instance, the average yearly temperature in London is 14°C (57°F). At the same latitude across the Atlantic in Calgary, Alberta, Canada, the average yearly temperature is 4°C (39°F). This is because the Gulf Stream carries warm water from near the equator in the Atlantic Ocean northeast to London, but Calgary is in the middle of North America, far away from the moderating influence of ocean currents.

sea levels. If these ice sheets were to melt entirely, global sea level could rise as much as 70 meters (approximately 230 feet). Ice also affects climate itself through its **albedo**. Albedo is the reflectivity of a surface; high albedo means that a surface is very reflective of light energy, and low albedo means that it absorbs light energy. Ice has high albedo compared with the ocean or land; it reflects back a high percentage of sunlight into the atmosphere, cooling the surface. Continental glaciers can be thousands of feet thick, and can therefore also actually block or redirect air flow, causing warm air to deflect away from the area covered by the ice sheet, and preventing or slowing the warming process.

The geosphere is the solid Earth, from the surface to the core. We might not often think of rocks as being connected to the atmosphere, but they very much are, especially over long stretches of time. For example, even though oxygen makes up 20% of the atmosphere, there is about 200 times more oxygen in the crustal rocks below the surface of the Earth. Exposed rock reacts with atmospheric oxygen by absorbing it, removing oxygen from the atmosphere. The solid Earth affects the climate in many ways. Volcanic eruptions can put large amounts of gas and particles into the atmosphere. Particulates temporarily suspended in the atmosphere can affect how much of the sun's heat reaches the surface and how much of that is retained; after a large volcanic eruption,

threshold *• a magnitude of a quantity beyond which the behavior of a system changes or a phenomenon occurs. See also TIPPING POINT.*

sea ice *• frozen seawater at the surface of the ocean.*

glacier *• a very large piece of ice that sits at least partially on land and moves under the force of gravity.*

ice sheet *• a mass of glacial ice that covers part of a continent and has an area greater than 50,000 square kilometers (19,000 square miles).*

cryosphere *• the part of Earth's surface where water exists in solid form. This includes all major forms of ice, such as SEA ICE, GLACIERS, ICE SHEETS and permafrost.*

mountain glacier *• a glacier found in high mountains, often spanning across multiple peaks.*

sea level *• global sea level is the average height of Earth's oceans. Local sea level is the height of the ocean as measured along the coast relative to a specific point on land.*

albedo *• the fraction of solar energy that a surface reflects back into space.*

the global climate may cool by a few degrees for several years. The different land surfaces have different albedos, variously absorbing and reflecting energy from the sun. Further, **sediments** and rocks hold a large amount of the Earth's carbon, impacting the concentration of CO_2 in the atmosphere (see Section 4.2 for more discussion).

The biosphere includes all of the life on Earth. Life on Earth is more than just a green layer sitting passively on the surface of a rocky ball: life is an integral part of the geology and climate of the planet. Living things have enormous effects on many atmospheric, oceanic, and geological processes. For example, **soil** is a byproduct of life; without organic matter, soil would be no more than rock dust (like on the moon). Life also profoundly affects the atmosphere. It is only because of the photosynthetic activity of green plants, along with small organisms like **protists** and **bacteria**, that the Earth's atmosphere contains so much oxygen. These organisms can also act as sinks for the carbon that they contain when they die and are buried in sediment that may become rock.

A wide range of organisms help to cycle carbon back to the atmosphere. Plants stabilize the land and limit **physical weathering** (erosion) from wind and water and simultaneously contribute to **chemical weathering** of rocks by changing the acidity of the soil. Animals (not to mention humans) alter the landscape in a wide variety of ways, from churning up seafloors and soils to building major structures like coral reefs, beaver ponds, and termite mounds. The remains of dead plants, animals, and microbes form vast deposits of sediment that become layers of rock in the Earth's crust. All of the coal, oil, and natural gas and most of the limestone in the world, for example, were formed by the accumulated body parts of once-living things.

2. Measuring Climate

The main indicators of a region's climate are temperature and precipitation. The most basic way to measure precipitation is with a standard **rain gauge**: a graduated cylinder, 4 centimeters in diameter, fed by a funnel and inside a larger cylinder that can catch any spillover (see *Box 3.3*). The amount of rain that falls in a certain time period, typically 24 hours, is measured in inches or centimeters of water height captured by the gauge. If the precipitation fell as snow then the standard measurement is the liquid water equivalent of ice, measured by melting the snow captured by the gauge and then reading the height of the melted liquid in the gauge.

Rain gauge measurements have their limits. For example, they may not capture accurate measurements of rainfall during storms with high winds because winds may direct the rain horizontally and out of reach of the gauge. They also only give point measurements at the location of the gauge. The National Weather Service's rain gauges are spaced about 20 miles apart on average. The gaps in this network of measurements may be filled in by citizen scientists, particularly by members of the Community Collaborative Rain, Hail, and Snow Network (cocorahs.org) (see *Box 3.3*).

For broader coverage of precipitation measurements we now can rely on satellite data. Early satellite instruments could only measure precipitation in the

sediments • *grains of broken rock, crystals, skeletal fragments, and ORGANIC MATTER.*

soil • *the accumulation of natural materials that collect on Earth's surface above the bedrock.*

protists • *a diverse group of single-celled eukaryotes (organisms with complex cells containing a nucleus and organelles).*

bacteria • *single-celled microorganisms with cell membranes but without organelles or a nucleus.*

physical weathering • *the breaking down of rock through physical processes such as wind and water erosion and cracking from expansion of freezing water.*

chemical weathering • *the breaking down of rock through chemical processes.*

rain gauge • *an instrument used to measure precipitation by collecting rainfall.*

What is Climate?

near-surface *• near the surface of the Earth; typically within a few meters above the surface.*

Box 3.3: CoCoRaHS

The Community Collaborative Rain, Hail, and Snow Network, or CoCoRaHS, is a great way to get students involved in making climate measurements. All one needs is a standard rain gauge and a relatively open place to put it. Students can enter their measurements online at cocorahs.org and immediately see a map of measurements contributed by citizen scientists across the country. The CoCoRaHS website contains tutorials about how to obtain, place, and set up a rain gauge and how to make measurements.

Standard rain gauge. Measurements of rainfall from this gauge are sent to the Community Collaborative Rain, Hail, and Snow Network's database.

tropics and could not detect light rain or snow. In February 2014, NASA and JAXA, Japan's space agency, launched the Global Precipitation Measurement (GPM) Core Observatory, with sensors that can detect a range of precipitation from light rain to heavy snow, and that provide data from the tropics to near the poles.

The temperatures that we hear or read about in the local daily weather report are almost always measurements of air temperature obtained by thermometers in particular locations close to the ground (referred to as **near-surface**) at particular moments (e.g., taken at a nearby airport at 8:00 a.m., or taken at a station on the roof of a local school). These individual measurements are likely to be similar to one another, but rarely are they identical, and they can be averaged to produce assessments of temperatures over some geographic area or a length of time (e.g., this morning's mean temperature for the Northeastern US, or Florida's daily high from yesterday). Extreme values are smoothed away if the data are averaged over large areas over long periods of time, and the site-to-site and day-to-day variability converges to an area or time average.

There are also differences from year to year. We all know that July is going to be hotter than January, but the high temperature on July 15th of this year is going to be different than the high temperature of last July 15th, or the July 15th from ten years ago. These differences are caused by natural cycles in our Earth climate system. **El Niño**, for example, is a well-known example of an interannual cycle, in which the temperature or rainfall of a region can be higher or lower than average depending on the strength of El Niño that year. There are also differences on decadal time scales. For example, in the 1930s a severe drought together with land use changes (millions of acres plowed for farming) caused the famous "Dustbowl" conditions in the American West and Midwest. More recently, California experienced a prolonged and exceptionally severe drought from 2012 to 2016 (*Figure 3.2*).

El Niño *• also called the El Niño – Southern Oscillation (ENSO); is represented by fluctuating temperatures and air pressures in the tropical Pacific Ocean. During an El Niño event, the eastern Pacific experiences warmer water and higher air pressure than the western Pacific, changing rainfall patterns, eastern Pacific upwelling, and weather variables globally. ENSO events typically occur every 3 to 7 years.*

Satellite-based sensors also provide surface temperature measurements, and climate scientists have developed sophisticated models to provide temperature and precipitation data over geographic grids and to obtain coverage between point weather stations. These models, such as the Parameter-elevation Regressions on Independent Slopes Model (PRISM)[4], have been shown to be very accurate and are widely accepted by the scientific community, government agencies, and businesses that need these data.

The average global surface temperature (the average of near-surface air temperature over land and sea surface temperature) on Earth during the 20th century was approximately 14.8°C (58.6°F).[5] It is important to note that there were very few moments when the actual temperature in any given location was exactly that temperature. This value is a long-term global average. As of 2016, the average global surface temperature has increased since 1880 by about

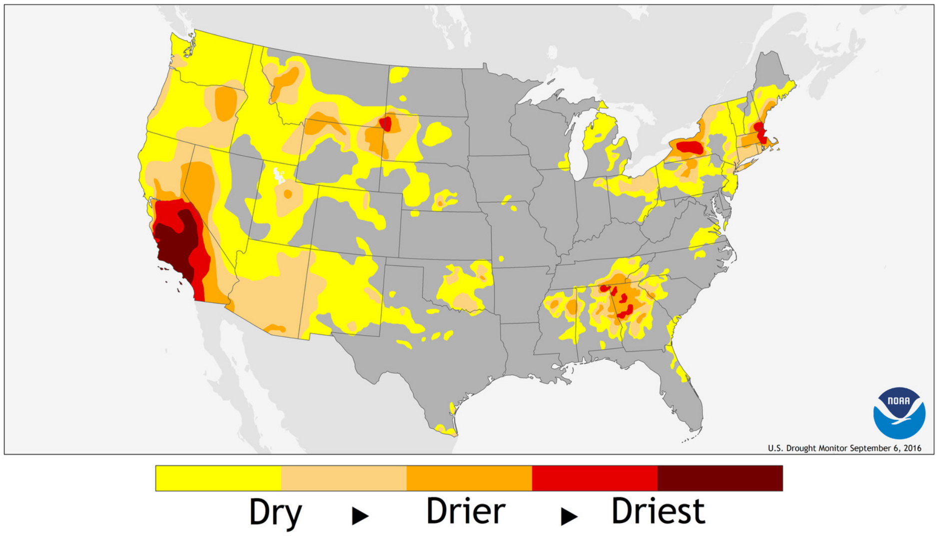

Figure 3.2: Drought conditions across the continental US as of September 6, 2016. A large part of southern California was experiencing Exceptional Drought, the most severe category. (See Teacher-Friendly Guide website for a full color version.)

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[4] This model has been developed by the PRISM Climate Group at Oregon State University, http://prism.oregonstate.edu/.

[5] This measurement and many climate datasets are available from the NOAA National Centers for Environmental Information, https://www.ncdc.noaa.gov/sotc/.

heat island • *an urban area which experiences higher temperatures than do surrounding rural areas as a result of pollution, pavement, and the surfaces of buildings magnifying localized heating.*

rain shadow • *an area on one side of a mountain that experiences little rainfall.*

lake effect snow • *snowfall caused by the movement of cold weather systems over a relatively warm lake, in which an air mass picks up water from the lake and deposits it in the form of snow across an adjacent land mass.*

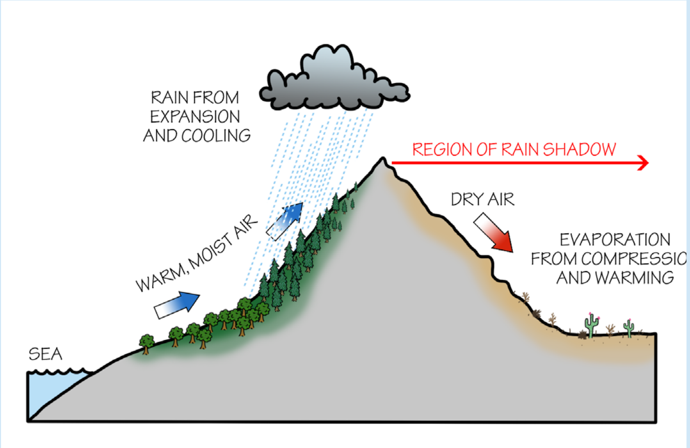
Box 3.4: Regional weather and climate patterns

Just as weather and climate are affected globally by the placement of continents and oceans, smaller features such as topography and local human land use can affect regional weather and climate patterns, frequently making it difficult to predict what effect climate change will have in a given area. It is also difficult to extrapolate from such regional patterns to global patterns. These regional features create regional and local effects, such as **heat islands**, **rain shadows**, and **lake effect snow**.

Heat islands occur in urban areas, with the result that such areas are often warmer than nearby rural areas. The building materials used to create metropolitan structures absorb heat in the day and then release it at night. This can cause some urban areas in extreme circumstances to be up to 9°C (16°F) warmer than their rural counterparts.

Rain shadows refer to the areas adjacent to a mountain range that receive little rain. The mountains separate the area in a rain shadow from a significant water source, like an ocean. As warm air moves over the ocean it collects water in the form of water vapor, which can run into a mountain range where it is forced upward. When air is forced upwards, it expands and cools. Warm air can contain more water vapor than cool air, so as this air cools water vapor condenses out to form clouds and rain. The rain falls on the windward side of the mountains closer to the water source, leaving the opposite side (leeward) of the mountains and adjacent areas very dry, in a rain shadow.

Lake effect snow refers to a type of snowfall pattern in which cold air flows over the warmer water of a large lake. As water evaporates from the lake it interacts with the cold air, forming clouds over the lake. These then get carried to shore by the winds, which deposit snow (sometimes a lot of snow) on land in the path of the winds. Regions along the eastern shores of large lakes, such as the eastern shores of Lake Michigan (Traverse City and Grand Rapids), Lake Erie (south of Buffalo) and Lake Ontario (Syracuse and Watertown), can have significantly different snowfall patterns than areas farther from the lakes.



Key characteristics of a rain shadow. (See Teacher-Friendly Guide website for a full color version.)

See Chapter 6 for a review of climate change in different regions of the U.S.

0.8°C (1.4°F). The temperature that you feel when you step outside today will be different from this average value due to many factors such as land use, elevation, topography, and proximity to bodies of water (*Box 3.4*).

3. Greenhouse Gases and Global Temperature

The Earth's surface temperature is controlled by the only major source of energy in our solar system: the sun. **Radiation** from the sun reaches the Earth throughout the year, but the Earth's temperature depends on the complex interaction of different components of the solar radiation with the atmosphere and with the Earth's surface (*Figure 3.3*). Sunlight consists of radiation at a variety of wavelengths. The shortest wavelengths (**ultraviolet light**) are rapidly absorbed and filtered by the atmosphere and do not reach the Earth's surface. The same is true for the longest wavelengths (**infrared light** or **thermal radiation**). The middle wavelengths (**visible light**) pass through the atmosphere largely unobstructed and allow us to see the world around us.

When visible light from the sun is absorbed by the Earth's surface, its energy is transformed to heat energy that increases the temperature of the surface. Some of this energy is re-emitted back into the atmosphere as infrared light. Since the atmosphere absorbs infrared light, some of this light is captured by the atmosphere and then reemitted both up into space and back down to the surface again, effectively trapping heat. This phenomenon is called the **greenhouse effect** (*Box 3.5*) and depends on the levels of **greenhouse gases** (*Table 3.2*)—carbon dioxide, methane, water vapor, and others—that make up only a tiny fraction of the gases in our atmosphere.

The surface of the Earth, therefore, is heated both by direct radiation from the sun, but also by this trapped and retransmitted radiation. This greenhouse effect is very important for life on Earth. Without it, the average surface temperature would be below the freezing point of water, and there would be little or no liquid water, and therefore possibly no life on Earth!

While greenhouse gases keep the Earth's surface warmer than it would be otherwise, other factors also affect the Earth's surface temperature. Since the equator gets more direct solar radiation than either of the poles, and thus more energy per square meter, the temperature in the tropics is warmer than in the polar regions. Warm air at the equator rises and flows toward the poles, then cools, sinks, and flows back toward the equator. This process is called **convection** and a zone where the convection process occurs is called a **convection cell**. The Earth's rotation forces the poleward-moving air sideways (a phenomenon called the **Coriolis effect**), so the poleward moving air doesn't make it as far as the pole, but rather descends in a high pressure band around 30 degrees latitude in each of the northern and southern hemispheres. For related reasons, two additional convection cells, at mid latitudes and high latitudes, form in each hemisphere. These latitudinal convection cells are host, from equator to pole, of the **trade winds**, westerlies, and polar easterlies. Overall, the global movement

Radiation • *emission of electromagnetic energy from an object.*

ultraviolet light • *electromagnetic radiation in the part of the spectrum with wavelengths from 10 to 400 nanometers.*

infrared light • *electromagnetic radiation in the part of the spectrum with wavelengths from 750 nanometers to 1 millimeter. People sense infrared radiation as heat.*

thermal radiation • *the emission of electromagnetic radiation from all materials, from the motion of charged particles.*

visible light • *electromagnetic radiation in the part of the spectrum with wavelengths from about 400 to 750 nanometers.*

greenhouse effect • *the influence of GREENHOUSE GAS molecules in the Earth's atmosphere to retain heat (infrared radiation) radiating from the Earth's surface that would otherwise escape into space.*

greenhouse gas • *a gas that absorbs and re-radiates energy in the form of heat; carbon dioxide, water vapor, and methane are examples.*

convection • *movement of a fluid, such as air or water, resulting from gravitational force on the fluid. Warmer, less dense matter rises and cooler, more dense matter sinks, producing heat transfer.*

convection cell • *a zone where warm, less dense air or water rises and cool, more dense air or water sinks, creating a repetitive pattern of motion.*

Coriolis effect • *the apparent deflection of air masses in the atmosphere, which are moving relative to the rotating reference frame of the Earth.*

trade winds • *persistent, large-scale winds in the tropical oceans which blow from the northeast in the Northern Hemisphere and from the southeast in the Southern hemisphere.*

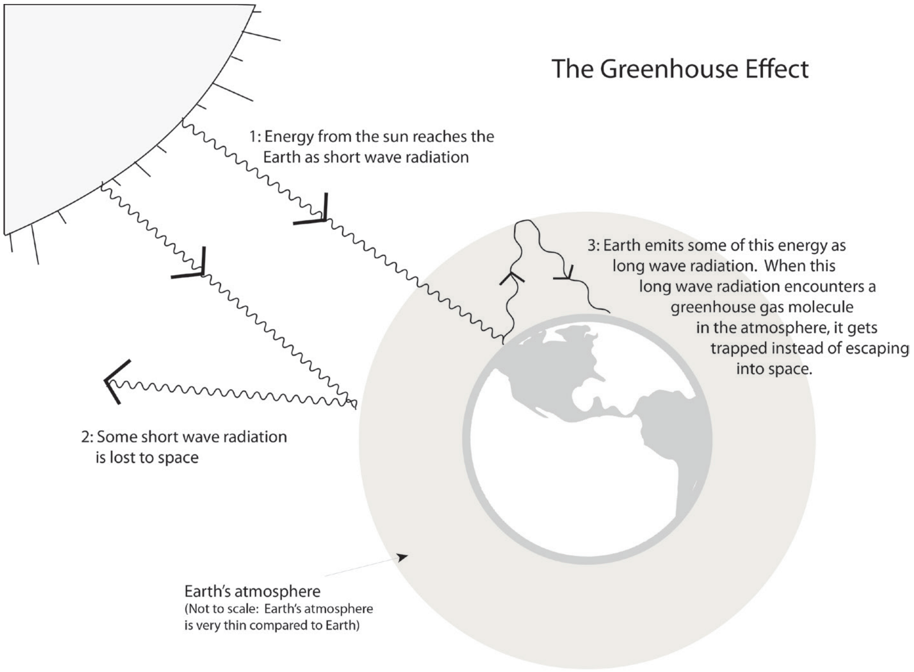


Figure 3.3: The greenhouse effect. Incoming solar radiation passes through the Earth's atmosphere, with some being reflected back before entering. The Earth absorbs visible (shortwave) sunlight and re-radiates infrared, longwave light (heat). The atmosphere acts somewhat like a blanket, trapping some of re-radiated heat and keeping Earth warm enough to sustain life. It does this through atmospheric greenhouse gases such as CO_2 which absorb infrared light and re-radiate it both out to space and back to Earth. The thicker the blanket, that is, the more greenhouse gases in the atmosphere, the more heat is trapped.

of air distributes heat from the equator to the poles and keeps the surface temperature within the bounds currently experienced on Earth.

Among greenhouse gases, water vapor actually has the greatest capacity to absorb longer-wavelength radiation. In studying changes in the Earth's surface temperature over time scales of more than a few weeks, however, more attention is usually given to CO_2 because water vapor concentration in the atmosphere changes much more quickly than does CO_2. For example, a molecule of water vapor, such as might evaporate from the ocean, will remain in the atmosphere for approximately two weeks, whereas an average molecule of CO_2, such as you might exhale, will remain in the atmosphere for hundreds of years.

The average annual concentration of CO_2 in the atmosphere prior to the Industrial Revolution (when large quantities of fossil fuels began to be burned by humans) was approximately 280 ppm (see *Box 3.6* for information about the unit of ppm). This has been determined by measuring CO_2 trapped in air bubbles in ice sheets. By the mid-twentieth century, atmospheric CO_2 concentrations were well above this, around 310 ppm, and now they have reached over 400 ppm (see *Figure 3.4*). Scientists suspected as early as the late 1890s that CO_2 concentrations might influence the temperature of the Earth, but it was not until the 1950s that scientists began to systematically measure the concentration of CO_2 in the atmosphere with high degrees of accuracy and on a regular basis.

CO_2 concentration in the modern atmosphere varies seasonally over a range of 5-6 ppm, as seen in the cyclical pattern in the trend line in *Figure 3.4*. This

Box 3.5: The greenhouse effect and the greenhouse metaphor

A greenhouse works by letting energy from the sun in through its windows, and then trapping warmed air from escaping with the same windows. In the atmosphere, what is commonly referred to as the “Greenhouse Effect” is more complex.

Step 1: Earth absorbs energy from the sun in the form of shortwave radiation (visible light), which heats the planet’s surface.

Step 2: Earth emits some of this heat in the form of long-wave (infrared) radiation.

Step 3: Some of the longwave radiation being given off by the planet strikes molecules of greenhouse gases in the atmosphere and is absorbed. These gases re-radiate infrared light, warming the air.

Step 4: Because of the chemistry of greenhouse gases, longwave radiation is more easily trapped than shortwave radiation. As a result, much of the heat given off by Earth is retained by the atmosphere instead of being allowed to pass through.

The greenhouse metaphor is not a perfect one. Greenhouse windows let light into a building, which heats the air. The windows then protect that heat from being dissipated or carried away by winds, locally providing heat to the plants inside. Earth’s atmosphere, on the other hand, is open, so air is not being trapped. Rather, greenhouse gas molecules in the atmosphere are radiating heat back towards the Earth.

Table 3.2: Common greenhouse gases.

Gas	Formula
Water vapor	H_2O
Carbon dioxide	CO_2
Methane	CH_4
Ozone	O_3
Nitrous oxide	N_2O
Chlorofluorocarbons (CFC’s)	Composition varies, but commonly include C, Cl, F, and H

is because of the growth of forests in the Northern Hemisphere. Forests take in more CO_2 (through photosynthesis) than they give off (in respiration) in the spring and summer, and mostly release CO_2 (through respiration) in the fall and winter. The cycle is reversed in the Southern Hemisphere, but there is much less land area and so fewer forests in the Southern Hemisphere; therefore the Southern Hemisphere effect is much smaller and seasons in the Northern Hemisphere dominate the annual CO_2 cycle.

cloud *• a visible aggregation of condensed water vapor in the atmosphere.*

Box 3.6: Measuring gases in the atmosphere

The concentration of a gas in the atmosphere is commonly measured in parts per million (ppm). A value of 1 ppm means that one molecule is present in every million molecules of air. One molecule in a million does not sound like a lot of molecules, but one cubic centimeter of air at the Earth's surface contains approximately 2.7 x 10^{19} molecules, so a 1 ppm concentration of a gas has 2.7 x 10^{13} molecules in the same small volume. That's 27 trillion molecules of CO_2 in the space of a sugar cube!

The emission of CO_2 into the atmosphere is commonly expressed in tons. A single ton (2,000 pounds) of carbon corresponds to 3.67 tons of CO_2 because of the additional weight of the oxygen. To raise the atmospheric concentration of CO_2 by 1 ppm requires 7.8 x 10^9 (7.8 billion or 7,800,000,000) tons of CO_2, which is approximately 1 ton of CO_2 per person on Earth. Human burning of fossil fuels currently adds approximately 9 x 10^9 (9 billion or 9,000,000,000) tons of carbon to the atmosphere annually.

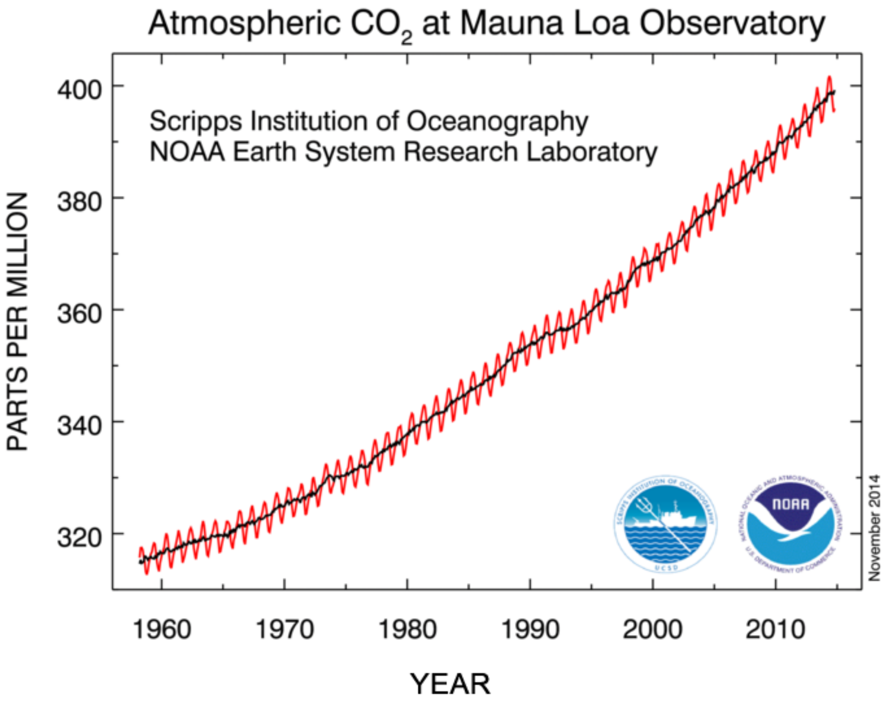


Figure 3.4: Atmospheric CO_2 concentration at Mauna Loa Observatory from 1958 to 2014.

Greenhouse gases are not the only components of the atmosphere that affect global temperature. **Clouds** (masses of tiny water droplets) influence climate in a variety of ways and on a variety of spatial and temporal scales. Clouds can cool the Earth by reflecting sunlight back into space. They can also warm the Earth by reflecting infrared radiation back to Earth through the greenhouse gas effect described above. The amount of water vapor (and thus of clouds) in the atmosphere is sensitive to temperature: the warmer it is, the more water evaporates, and the more water that the air can hold—approximately 6% more water vapor for every °C of additional heat. This creates a reinforcing feedback in the climate system: the warmer it gets, the more water vapor there will be in the atmosphere, and this will cause still more warming.

Other important compounds in our atmosphere that influence the Earth's climate are **aerosols**, which are solid, liquid, or mixtures of solid and liquid particles suspended in the air—from volcanic eruptions, storms, or anthropogenic emissions. Aerosols can cool the Earth by both reflecting incoming sunlight and also serving as "seeds," or **condensation nuclei**, for clouds. The number and size of aerosol particles determines whether the water in clouds condenses into a few large droplets or many small ones, and this strongly affects the amount of sunlight that clouds reflect and the amount of radiation that they absorb. The increased reflection of sunlight into space by aerosols usually outweighs their greenhouse effect, but because aerosols remain in the atmosphere for only a few weeks the impact of greenhouse gases in the long run is much more significant.

aerosol • *the suspension of very fine solid or liquid particles in a gas.*

condensaton nuclei • *suspended particles in the air which can serve as "seeds" for water molecules to attach to, in the first step in the formation of clouds. See also NUCLEATION SITES.*

4. Natural Causes of Climate Change

In this section we address climate changes caused not by human activities, but by natural forces within and outside of Earth's climate system.

4.1 Scale

As we ask and answer the question of why climate changes, we must simultaneously consider the temporal scale of our discussion, that is, the extent of time over which changes occur (*Table 3.3*). Earth has been in existence for 4.6 billion years, and life has been visibly thriving on it, in one form or another, for most of that time. Thus, what has happened in the last 100 years is only a tiny part of the history of Earth and its life and climate. Some causes of climate change have tremendous influence, but are only apparent over a million years or more. Others are smaller, but their impacts are seen more readily over shorter time scales, in decades or hundreds of years.

On the scale of millions of years, climates change because of plate tectonic activity. Plate tectonics, the mechanism that moves the continents across the globe and forms new ocean floor, has many effects on global climate. Plate tectonic activity, for example, causes volcanism, and extended periods of high volcanic activity can release large amounts of greenhouse gases into the atmosphere. Volcanism also creates new rock, as magma is expelled from the interior of the Earth and cools on the surface. In underwater volcanic activity, new rock can displace ocean water and increase global sea level, which changes the way the oceans distribute heat, and further impacts global climate. For example, the Cretaceous Period, from 145 million to 66 million years ago, was a particularly warm period in Earth's history, in part due to the high amounts of greenhouse gas emission from volcanism, and was also a time of higher global sea level.

For information about how human activity is shaping our climate, see Chapter 5: Evidence and Causes of Recent Climate Change.

Table 3.3: Some common causes of climate change in Earth's history and their temporal scale.

Climate Change Cause	Scale of Change
Position in the solar system	billions of years
Heat generated by the sun	billions of years
Evolution of photosynthesis, other biological impacts	millions to billions of years
CO_2 input from volcanism	millions of years
CO_2 removal from weathering	millions of years
Movement of tectonic plates	millions of years
Shape of Earth's orbit around the sun (eccentricity)	hundreds of thousands of years
Tilt of Earth's axis relative to the sun (obliquity)	tens of thousands of years
"Wobble" of Earth's axis (precession)	tens of thousands of years

Plate tectonics also impacts climate on the scale of millions of years due to the changing location of the continents. Climate on land is heavily influenced by ocean currents, so global climate is significantly different when the continents are close together (as in the supercontinent Pangea, which came together approximately 250 million years ago) versus when they are more widely separated, as in modern times. Also, land masses in the equatorial regions have a different impact on climate than continents in higher latitudes because of how heat is distributed from equatorial regions north- and southward around land masses. Therefore, the position of plates over time has had significant impacts on past global climate.

On the scale of hundreds of thousands of years, climates change because of periodic oscillations of the Earth's orbit around the sun, called astronomical or **Milankovitch cycles** (see *Box 3.7, Figure 3.5*). These oscillations primarily affect the subtly varying amount of sunlight received over the course of the year and the distribution of that sunlight across latitudes. Glacial intervals can occur when, in part as a result of these orbital variations, high latitudes receive less summer sunlight, so that their cover of ice and snow does not melt as much. Thus, the Pleistocene Ice Age record of dramatic warming followed by slow, steady cooling (seen in *Figure 3.6*) reflects repeated glaciations every 100,000 years or so, caused in part by Milankovitch cycles. Understanding these cycles has turned out to be critical to understanding natural variation in the Earth's climate system over the past several million years and beyond.

On the scale of millennia (thousands of years), climates during the last glacial-interglacial cycle have been influenced by cyclic events such as **Heinrich events**. Heinrich events occurred approximately every 7,000-13,000 years and are evidenced by sediment layers on the northern Atlantic Ocean floor, deposited by the melting of huge ice sheets with small rocks and debris contained in them. Scientists believe that these were caused by large **icebergs** that were released from Canada that, after floating into warmer waters, melted and released large quantities of freshwater into the North Atlantic. This changed ocean circulation because the large, quick releases of freshwater are less

Milankovitch cycles • *cyclical changes in the amount of heat received from the sun, associated with how the Earth's orbit, tilt, and wobble alter its position with respect to the sun. These changes affect the global climate, most notably alterations of glacial and interglacial intervals.*

Heinrich events • *periods during the last 100,000 years when large volumes of freshwater entered the ocean from icebergs which broke off glaciers and ice sheets in the Arctic and floated into the North Atlantic Ocean. This release of freshwater changed ocean circulation because freshwater and seawater have different densities.*

iceberg • *a large chunk of ice, generally ranging in height from 1 to 75 meters (3 to 246 feet) above sea level, that has broken off of an ice sheet or glacier and floats freely in open water.*

dense than the seawater, decreasing the density of the ocean surface and diminishing the sinking of dense water that drives ocean circulation. These large, abrupt releases of freshwater caused a switch from glacial to interglacial types of ocean current patterns.

On the scale of human experience and history (centuries to decades), climates change for a number of reasons. Some are cyclic, and others are the culmination of small changes in topography, land use, and other factors that occur in this relatively short span of time. Two examples of changes on this scale are the **Younger Dryas** event and the **Little Ice Age**. The Younger Dryas event was a 1,200-year interval of colder temperatures that punctuated a warming trend that began approximately 13,000 years ago. Scientists have ascertained that a shift from warming to cooling happened over the course of only a few decades, and brought back glacial climate characteristics such as mountain glaciers in New Zealand and intense windstorms in Asia. One hypothesis suggests that the Younger Dryas was triggered by an ice dam breaking and sending large amounts of freshwater into the northern Atlantic Ocean, reducing flow of warm Gulf Stream water into the area. Other hypotheses have been offered to explain the Younger Dryas, including one postulating icebergs breaking off of an Arctic ice sheet and floating southward, again sending large amounts of freshwater into the North Atlantic. One thing seems certain—the Younger Dryas is an example of how a single event can reverse or significantly change global climate within a matter of decades.

The Little Ice Age occurred between approximately the years 1200 and 1800 CE and followed a time in history called the **Medieval Warm Period**, which peaked approximately 1,000 years ago. The difference in temperature between the Medieval Warm Period, which allowed the Viking people to inhabit Greenland, and the Little Ice Age, which kept Icelandic fishermen frozen in port for up to three months per year from the 1600s through 1930, was only approximately 1°C (1.8°F) globally.

Many factors affect weather and climate on the scale of a few years, and some of these can be cyclic or nearly so. One of the most important of these is **El Niño**. El Niño is a climate pattern that occurs across the tropical Pacific Ocean every 3-7 years, characterized by warming ocean surface temperatures and accompanying major shifts in precipitation in the Americas and ocean circulation in the eastern Pacific.

The sun also plays a role in a short-term climate cycle through its frequency of **solar flares**, or **sunspots**, which increase and decrease on an 11-year cycle. When solar flares occur more frequently, the sun has a larger number of “spots” on its surface and emits more solar energy, which increases the intensity of energy (**irradiance**) that the Earth receives from the sun. Direct measurements of solar output since 1978 show a rise and fall over the 11-year **sunspot cycle**, but there is no overall up- or downward trend in the strength of solar irradiance that might correlate with the temperature increase that Earth has experienced. Similarly, there is no trend in direct measurements of the sun’s ultraviolet output or in cosmic rays. Thus, even though solar irradiance is the primary energy that heats our planet, because sunspots have shown no major directional increases or decreases in their recorded history, they do not appear to be related to the current, directional change in global climate.

Younger Dryas *• an abrupt shift in the Northern Hemisphere from a warm to a cold climate and then an abrupt shift back again, occurring over about 1,200 years starting around 13,000 years ago. The shift back to a warmer climate occurred with a 10°C (18°F) rise in temperature over only a decade.*

Little Ice Age *• a relatively modest cooling (less than 1° C) of the Northern Hemisphere in the 16th – 19th centuries.*

Medieval Warm Period *• a period of warm climate in the North Atlantic region during approximately the years 950 to 1100.*

solar flare *• a sudden release of energy near the Sun's surface which appears very bright from the Earth.*

sunspots *• dark areas on the surface of the Sun that are cooler than surrounding regions. Sunspots typically last from a few days to a few months. SOLAR FLARES can erupt from sunspots.*

irradiance *• the intensity of radiated energy received, for example, by the Earth from the sun.*

sunspot cycle *• an 11-year cycle over which the number of SUNSPOTS varies, associated with a cyclical variation in the Sun's magnetic field.*

insolation *• the amount of solar radiation reaching the Earth.*

Box 3.7: Milankovitch Cycles: the sun and orbital variations

The sun is the source of most incoming energy on Earth; it is this solar energy over a given area and time known as **insolation** that controls the energy that drives Earth's climate. Climate models indicate that a relatively small change in the amount of heat retained from the sun can have a lasting impact on Earth's temperature.

Because nearly all of Earth's atmospheric energy is ultimately derived from the sun, it makes sense that the planet's position and orientation relative to the sun would have an effect on climate. The Earth's orbit around the sun is not a perfect circle, but an ellipse. The distance from the Earth to the sun changes as the Earth travels its yearly path (see *Figure 3.5*). In addition, the axis of the Earth (running from pole to pole) is not vertical with respect to the sun, but is currently tilted approximately 23.5°. Earth's tilt is responsible for the seasons, which various parts of the world experience differently. It is summer in the Northern Hemisphere during the part of the year that it is tilted toward the sun and receives the sun's rays more directly; conversely, when Earth is on the other side of its orbit and the Southern Hemisphere is tilted toward the sun, it is summer in the Southern Hemisphere.

Earth's orbit also changes on a longer time scale. Milankovitch Cycles (see *Figure 3.5*) describe how the position of Earth changes over time in predictable patterns of alternations of the proximity and angle of Earth to the sun, and therefore have an impact on global climate. These are:

- **Eccentricity**, the change of Earth's orbit from a round orbit to an elliptical one, which occurs on a 100,000-year cycle. When Earth's orbit varies between more circular and more elliptical (i.e. more extreme eccentricity), the length of the seasons change.

- **Obliquity**, the tilt of the Earth on its orbital axis, which can range from 22-24° from vertical, and occurs on a roughly 40,000-year cycle. The tilt of the Earth impacts how much insolation is absorbed by the planet at different latitudes.

- **Precession**, commonly called "wobble," because it is the small variation in the direction of Earth's axis as it points relative to the fixed stars in the galaxy. Because of precession, the point in Earth's orbit when the Northern Hemisphere is angled toward the sun changes over a cycle of approximately 20,000 years.

These three variables interact with each other in ways that can be very complex, but are predictable mathematically. For example, the influence of the shape of the orbit on Earth's climate depends very much on the angle of tilt that Earth is experiencing at the time. The orbital variations described by Milankovitch Cycles are predictable based on the known laws of planetary motion. Confirmation of their climatic effects, however, comes from the geological record, where, in deep-sea sediment cores stretching back further than 5,000,000 years, scientists have found indications of temperature fluctuating in ways similar to what Milankovitch Cycles would predict.

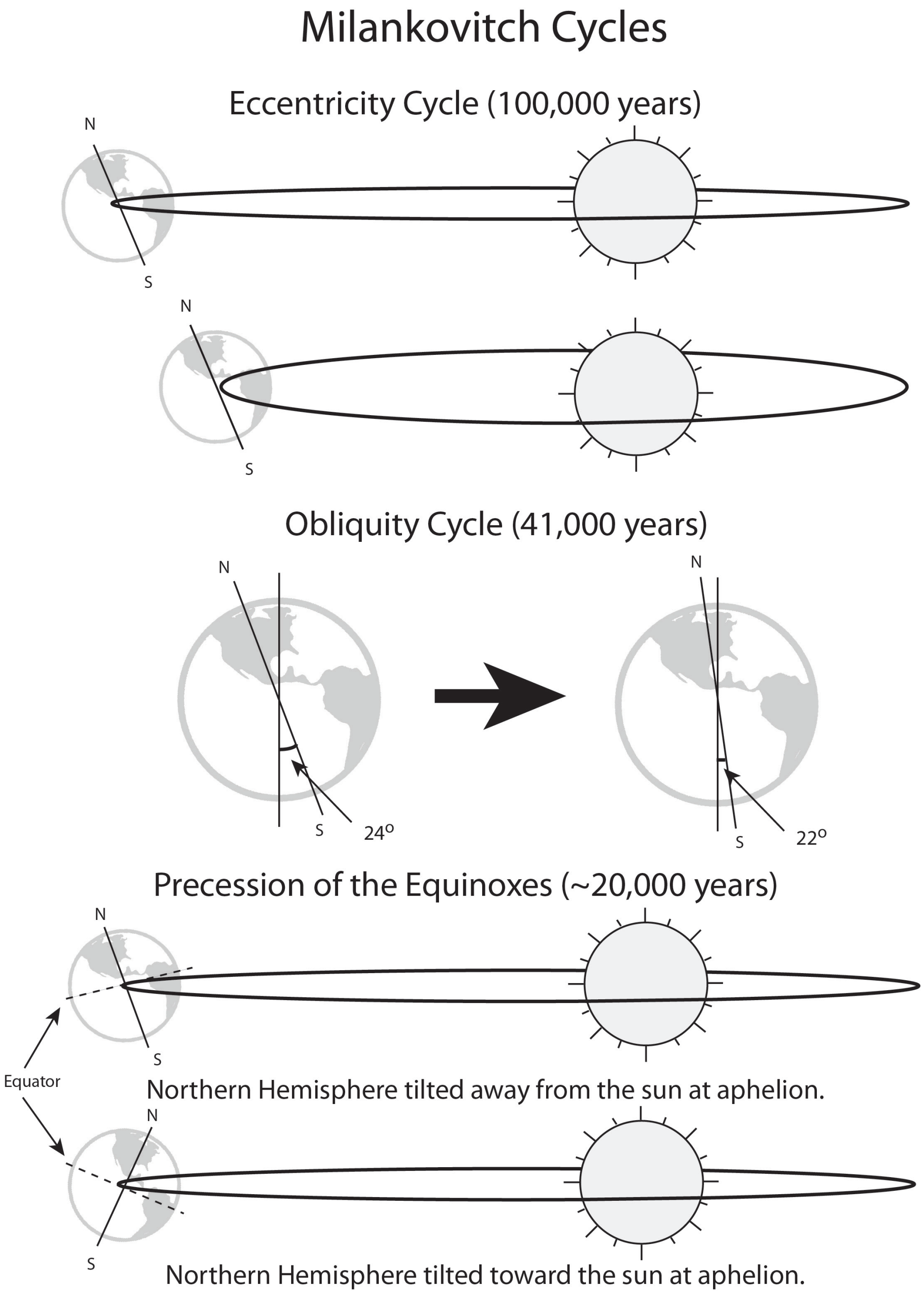


Figure 3.5: Milankovitch Cycles. The Earth's orbital variation around the sun experiences cyclic changes in shape. Eccentricity, caused by gravitational forces from other planets in our solar system, changes the shape of the orbit on a 100,000-year cycle from a circular to a more elliptical shape. Obliquity is the change of the angle of Earth's axis, which ranges from 22° to 24° from normal, and occurs on a 40,000-year cycle. Precession, commonly called the "wobble" of Earth's axis, affects the positions in Earth's orbit at which the Northern and Southern Hemispheres experience summer and winter. Precession changes on an approximately 20,000-year cycle.

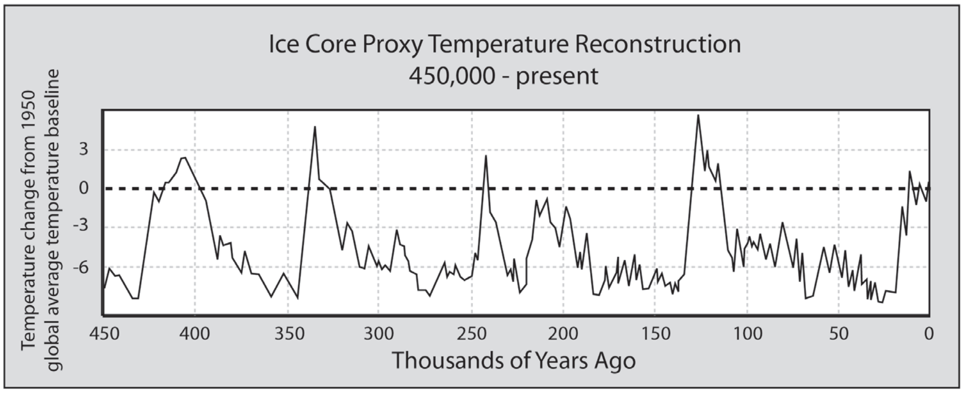


Figure 3.6: 100,000-year temperature cycles. Ice age temperature changes for the last 450,000 years in this diagram are represented as differences of temperature (in °C) from a modern baseline. These differences are called temperature anomalies. The graph shows abrupt temperature spikes approximately every 100,000 years, each followed by slower cooling. The highest temperatures occurred just after the global climate changed from glacial to interglacial intervals. These temperature changes correlate with changes in the shape of Earth's orbit (due to Milankovitch Cycles). According to this pattern, Earth should now (during this interglacial period) be experiencing slow cooling, not warming.

4.2 The Carbon Cycle

The element carbon plays a crucial role in the way that the Earth works. Because of its ability to readily form up to four bonds with other elements and other particular chemical properties, carbon constitutes the basic building block of living things as well as major constituents of the atmosphere, crust, and oceans. Individual carbon atoms combine with other elements in a variety of ways as they move between these various Earth systems in a series of steps known as the carbon cycle (*Figure 3.7*). Understanding the role of CO_2 in the Earth's climate starts with understanding how carbon behaves in this cycle.

CO_2 that enters the atmosphere from volcanoes is approximately balanced (in the absence of humans) by removal of CO_2 from the atmosphere by two processes. One is long-term burial of organic matter—that is, the products of photosynthesis not recycled. This occurs when, for example, dead phytoplankton sink to the bottom of the ocean and are covered by sediment. The other is chemical weathering, or the breakdown of rocks at the surface by chemical change. During chemical weathering, water reacts with minerals in rocks and CO_2 from the atmosphere. The CO_2 is thus removed from the air and transferred into other compounds, which eventually become stored in the sediments that accumulate in the ocean and ultimately become part of sedimentary rocks (*Figure 3.7*).

Evolutionary changes in organisms throughout geologic time have had a strong effect on the global carbon cycle. The evolution of organisms capable of photosynthesis, over 3 billion years ago, drew CO_2 out of the atmosphere and created the first significant amounts of atmospheric oxygen. The first appearance of large animals in the early Cambrian, 540 million years ago, and the evolution of land plants in the Devonian, approximately 380 million years ago, accelerated the cycling of carbon and its burial in sediments. It is widely believed that the evolution of land plants led to a significant drop in CO_2 concentrations in the

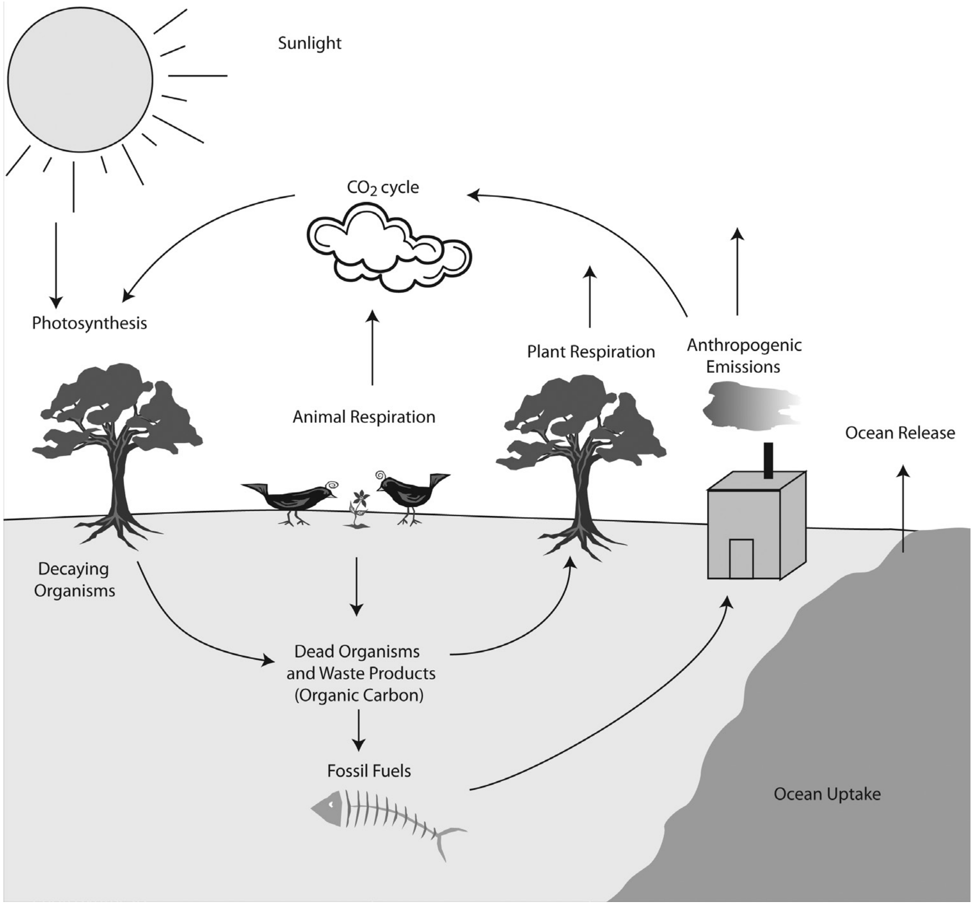


Figure 3.7: The carbon cycle (a very simplified view). Every living thing contains carbon. When animals exhale, CO_2 is emitted into the atmosphere. It is absorbed by plants through the process of photosynthesis and gets incorporated into their structures. When plants and animals die, the carbon in their bodies gets incorporated into sediments, which might eventually become rocks in the Earth's crust, where it usually remains for millions of years. The extraction and burning of this carbon in the form of fossil fuels emits CO_2 into the atmosphere, and some of it becomes incorporated into carbon sinks like oceans and forests. Omitted from this figure are biological processes in the oceans, volcanoes, weathering of rocks, and the formation of limestone.

atmosphere and caused the widespread glaciation of the Carboniferous Period (360 to 295 million years ago).

See Chapter 4: Past Climates for further information about the history of Earth's climate and the evolution of life.

The carbon cycle functions on a variety of time scales. A single atom of carbon that you exhale (as part of a molecule of CO_2) will on average remain in the atmosphere for hundreds of years, before being absorbed by a plant or other photosynthesizing organism. When the plant dies, that carbon atom could in a few weeks or months be taken up by another plant, or oxidize back into CO_2 and re-enter the atmosphere, or it might be buried in the Earth's crust and remain there for millions of years. When we burn fossil fuels—oil, natural gas, and coal extracted from the Earth—we very quickly release carbon into the atmosphere from sources that took millions of years to form.

Box 3.8: The faint young sun paradox

On the scale of billions of years, the Earth's climate has been controlled by the balance between its distance from the sun and the composition of its atmosphere. If we compare Earth to its planetary neighbors, Mars and Venus, we see what might have happened on Earth, but didn't. Earth's original atmosphere came from volcanism that emitted gases from the planet's interior. The high concentration of CO_2 and methane (CH_4) in this early atmosphere kept the Earth warm when the sun was younger and fainter. Some of the first life on Earth put oxygen into the atmosphere by the process of photosynthesis, and drew down CO_2. Lower levels of greenhouse gases in the atmosphere helped to compensate for the brightening sun, which otherwise would have warmed Earth too much for living organisms, or even liquid water, to be present. Thus, the greenhouse effect allowed life to exist on Earth when it might not have otherwise.

4.3 Plate Tectonics

The Earth's surface is like a jigsaw puzzle. It is made up of many huge pieces, or plates, which slide around the globe very slowly, at about the rate that your fingernails grow. The continents are embedded in these **tectonic plates** (*Figure 3.8).* Where these plates come together or move apart, earthquakes, mountain building, and many other geologic processes can occur. Plate movement is thought to be driven by the Earth's internal heat, as convection currents from the lower mantle heat the rock above, lowering its density and pushing it upward.

Plate movement can significantly affect climate over millions of years, in several ways. The position of a plate on the globe, and of any continents that might be on top of it, is one determinant of whether that continent will experience glaciation or tropical temperatures. For example, if the plate that now holds North America and Greenland were shifted a bit to the north, North America might now be covered in a continental ice sheet. Instead, only Greenland is covered in ice because it is positioned farther north today. Plate movement also affects climate because when two plates come together, volcanoes often result, adding CO_2 to the atmosphere when they erupt. When plates move apart, in a process known as **seafloor spreading**, hot **magma** is often released directly into the ocean, bringing CO_2 with it.

5. Summary

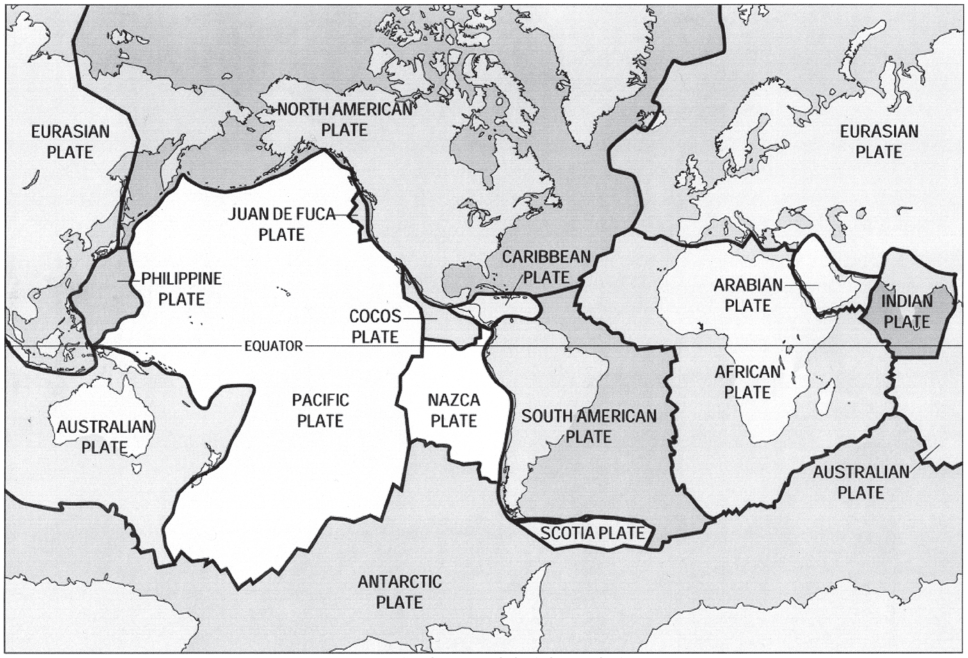
Climate is a system, driven by solar radiation and interactions of the atmosphere, hydrosphere, geosphere, and biosphere. A number of natural phenomena contribute to Earth's climate. These phenomena—plate tectonics and weathering, evolution of new life, and others—have interacted via the carbon cycle to change the amount of CO_2 in the atmosphere and cause temperatures to change throughout geologic time.

Humans are now influencing Earth's climate in a dramatic way (see Chapter 5). To understand the scope of this influence, it is useful to first look at the history of climate change in the past (Chapter 4).

tectonic plate *• a section of the Earth's lithosphere that moves along the surface of the Earth. The scientific theory of plate tectonics is that Earth's crust consists of a series of 7 or 8 large plates and numerous small ones. Plate tectonics are responsible for the distribution of the Earth's continents, for the uplift and position of mountain ranges, and for many other features of the Earth's surface.*

seafloor spreading *• the formation of new crust around an oceanic ridge when two adjacent oceanic plates move in opposite directions and lava erupts from between them, hardens, and then the new material moves apart.*

magma *• molten rock located below the surface of the Earth.*



Tectonic plates and their boundaries

Figure 3.8: Plate tectonics. A world map with all of the individual tectonic plate boundaries highlighted. The plates move around like puzzle pieces over the globe.

Online Resources

The Greenhouse Effect

1. An interactive simulation in which one can vary the concentration of greenhouse gases in the atmosphere and see the changes in infrared radiation in the atmosphere and the effect on Earth's temperature: https://phet.colorado.edu/en/simulation/greenhouse.

2. A brief (approximately 2 minute) video by Cornell University Professor Toby Ault which explains the greenhouse effect and illustrates the roles of visible and infrared light using simple props and an infrared camera: https://www.youtube.com/watch?v=7perebgdXAQ.

3. A brief (approximately 2 minute) video from National Academy of Sciences *Lines of Evidence* series, explaining the greenhouse effect: https://www.youtube.com/watch?v=3JX-ioSmNW8&feature=youtu.be.

Climate Measurements

1. An article about satellite measurements of precipitation and the Global Precipitation Measurement Core Observatory: https://pmm.nasa.gov/education/videos/for-good-measure.

2. A website with information about the Community Collaborative Rain, Hail, and Snow Network, a citizen scientist project that generates measurements of precipitation all over the US. The site contains maps, data, and information about how to join the project and make measurements. http://www.cocorahs.org/Login.aspx.

Climate Change Over Geologic Time

Paleomap Project: a set of detailed maps of the world showing the past positions of the continents and describing Earth's past climates, going back to the Cambrian period: http://www.scotese.com/climate.htm .

Recent Climate Change: Data and Visualizations

1. NASA Vital Signs of the Planet website, an excellent overview of key climate change data: http://climate.nasa.gov . This site also contains many links to articles, information about solutions, images, videos, interactives, education resources, and information about NASA missions.

2. An animation of global temperature change from 1884 to 2014: http://climate.nasa.gov/climate_resources/25/.

3. A source of time-series graphs of global climate indicators such as temperature, CO_2, sea ice, sea level, and more: https://www.climate.gov/maps-data#global-climate-dashboard.

4. NOAA Climate Data Snapshots: maps of monthly US climate data including temperature, precipitation, drought, and severe weather. The time records of the datasets vary, but the earliest go back to 2000. https://www.climate.gov/maps-data/data-snapshots/start.

5. Climate Change Indicators in the United States: a website with access to maps and graphs of many different climate change indicators as well as a summary report. https://www.epa.gov/climate-indicators.

6. The Third National Climate Assessment: a comprehensive overview of climate change in the US and its impacts: http://nca2014.globalchange.gov/ . The National Climate Assessment is updated every few years.

General Climate Change Teaching Resources

1. Teaching resources associated with the Third National Climate Assessment (2014), which give examples of how to use key figures in the National Climate Assessment to illustrate points about climate change in the US. Resources are organized by geographic region. https://www.climate.gov/teaching/national-climate-assessment-resources-educators/2014-national-climate-assessment-resources.

2. A reviewed collection of teaching resources: Climate Literacy and Energy Awareness Network (CLEAN); http://cleanet.org/index.html.

Carbon Cycle

1. An interactive carbon budget tool which allows users to explore altering sources and sinks and see the effects on atmospheric CO_2: http://carboncycle.aos.wisc.edu/carbon-budget-tool/.

2. A set of clearly written and illustrated articles on the carbon cycle: http://earthobservatory.nasa.gov/Features/CarbonCycle/.

Contributions (Natural and Anthropogenic) to Climate Change

1. An infographic on potential causes of climate change from 1880-2005 and their effects, based on datasets from NASA: http://www.bloomberg.com/graphics/2015-whats-warming-the-world/.

2. Charts of US greenhouse gas emissions by type of gas, fuel source, and sector: https://www.eia.gov/environment/emissions/ghg_report/ghg_overview.cfm.

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What is Climate?

Online Resources

Weather Simulation

Weather in a Tank: http://paoc.mit.edu/labguide/, https://www.youtube.com/watch?v=uWdKVpQ94Ns, and https://vimeo.com/user14026932/videos. These sites contain information about and videos of a system for running rotating fluid laboratory experiments, allowing one to simulate dynamics of the atmosphere and ocean.