This chapter introduces the basics of the climate system and climate change. How do we know climate is changing? How are future changes simulated? What causes natural and anthropogenic climate change? These questions are answered here, forming the foundation of climate change understanding needed to explore biological responses.

**THE CLIMATE SYSTEM**

The Earth’s climate system is composed of the atmosphere, the oceans, and the Earth’s land surface (Figure 2.1). Dynamic elements of the system are hydrology and the movement of gases, including water vapor. Elements external to the climate system but very important in determining its behavior include the sun, variations in the Earth’s orbit in relation to the sun, and the shape and position of continents and oceans.

The atmosphere traps energy by capturing and re-radiating radiation that would otherwise escape into space. Long-wave radiation (heat) given off by the land surface and oceans is absorbed by greenhouse gases in the atmosphere. This energy is then re-radiated in all directions, the net effect being a trapping of a portion of the energy in the Earth’s atmosphere near the surface. Clouds in the atmosphere can reflect incoming solar energy, cooling the surface. During the day, this effect can outstrip the warming effect of the water vapor in the clouds, whereas at night the warming effect of clouds dominates. The main constituents of the atmosphere are nitrogen (78%) and oxygen (21%). Water vapor and CO₂ are minor constituents of the atmosphere but potent greenhouse gases.

The oceans are the second major component of the climate system. From a climatic standpoint, the greatest importance of the oceans is as vast reservoirs of water and dissolved gas. The oceans contribute most of the water vapor found in the atmosphere. Warmer oceans give off more water vapor. They also
produce larger and more severe storms such as hurricanes. The oceans absorb CO₂, reducing its concentration in the atmosphere.

The land surface consists of vegetation, exposed soil and rock, human structures, and snow and ice. The reflective properties of these surfaces make a large difference in how the planet warms. Dark surfaces absorb solar energy and re-radiate it as heat that may be trapped by greenhouse gases in the atmosphere. Light surfaces reflect sunlight back into space in wavelengths not trapped by greenhouse gases, so they have a cooling effect.

Snow and ice are particularly important parts of the Earth’s surface in the climate system because they reflect the sun well. White surfaces reflect solar energy, cooling the Earth’s surface. Glaciers, snowpack, and sea ice all measurably cool the Earth by reflecting sunlight. Increases in average global temperature reduce the area of ice and snow by melting, thus reducing the resultant reflectivity of the planet and producing a positive feedback loop in the climate system as the Earth warms still further (Figures 2.2–2.4).
FIGURE 2.2 Boulder Glacier, Glacier National Park, 1932.
Reproduced with permission from Archives and Special Collections, Mansfield Library, The University of Montana.

FIGURE 2.3 Boulder Glacier, 1988.
Reproduced with permission from Archives and Special Collections, Mansfield Library, The University of Montana.
Hydrology is the movement of water within and between elements of the climate system. Because water vapor has powerful heating (greenhouse gas) and cooling (daytime clouds) effects, the movement of water is of unparalleled importance in the climate system. Water moves through the hydrologic cycle, evaporating from the oceans, condensing as clouds, and then raining out over land to form freshwater that flows to the sea. Increases in global temperature can accelerate this hydrologic cycle by speeding up evaporation from the ocean surface.

**Evolution of the Earth’s Climate**

The atmosphere as we know it is made possible by life. The atmosphere, in turn, made higher life-forms possible. The Earth was formed 4.5 billion years ago,
and within approximately 1 billion years single-celled life appeared. Microbial photosynthesis over hundreds of millions of years produced enough oxygen to make it a major component of the atmosphere. Much of this photosynthesis occurred in microbial mats, some of which formed stony structures known as stromatolites, which are stony accretions that are dominant in the fossil record for billions of years. By approximately 600 million years ago, oxygen buildup was sufficient to support the formation of an ozone layer in the upper atmosphere. Sunlight bombarding the upper atmosphere split oxygen atoms to create free oxygen radicals, some of which recombined with oxygen to form ozone. At this point, even though atmospheric oxygen levels were still only a fraction of modern levels, the major characteristics of modern atmosphere were in existence—oxygen, nitrogen, water vapor, and an ozone layer.

The ozone layer allowed terrestrial life to emerge. Previously, life had only been possible in the oceans, where the water column shielded organisms from damaging UV radiation. With the emergence of the ozone layer, UV radiation was screened out in the upper atmosphere, allowing life-forms to emerge onto land. Photosynthetic organisms were still dominant, allowing the continuing buildup of oxygen in the atmosphere.

The interaction of the atmosphere, water, and continental configurations began to govern climate. Major changes in climate were associated with the periodic formation of supercontinents, glacial episodes, and volcanism. At least three supercontinents have existed in the past billion years of Earth history. Rodinia existed from approximately 1 billion years ago to 750 million years ago. Pannotia was formed approximately 600 million years ago and lasted for 50–60 million years. The most recent supercontinent, Pangaea, was formed approximately 250 million years ago and later broke into its constituent components of Gondwanaland and Laurasia. Among several episodes of volcanism, the greatest was the massive outpouring that formed the Siberian Traps 250 million years ago.

The Earth’s climate alternated between “icehouse” and “greenhouse” conditions once the modern atmosphere had evolved. There have been four major warm periods and four major cool or cold periods during the past 500 million years. During cool or cold phases, there is polar ice and substantial ice on land, and the global mean temperature is low. In the warm periods, there is little or no polar ice or ice on land. The warm periods generally are associated with high atmospheric CO₂ levels, whereas the icehouse periods are associated with low CO₂. Warm greenhouse conditions dominated for most of deep time (100 million to 1 billion years ago) but were punctuated by several icehouse episodes. More recently, a gradual cooling has dominated, leading to the ice ages of the past 2 million years. The current 10,000-year interglacial period is one of several brief warm blips in the predominantly icehouse conditions of the past 2 million years (Figure 2.5).
Major icehouse episodes in deep time occurred between 800 and 600 million years ago and again at 300 million years ago. The Earth has generally been warmer than present since emerging from icehouse conditions approximately 280 million years ago, but there have been remarkable increases and decreases in temperature as well.

During the past 100 million years, the slight cooling trend gradually reversed approximately 80 million years ago and then was interrupted by a dramatic, brief warm period approximately 55 million years ago. During this warm spike, global mean temperature rose several degrees very rapidly and then dropped again only a few million years later. This spike, known as the Late Paleocene Thermal Maximum, was followed by gradual warming that led to a longer warm period known as the Early Eocene Climatic Optimum (Figure 2.6).

Cooling dominated from 50 to 30 million years ago, leading to ice formation in both the northern and southern polar regions approximately 40 million years ago. This ice cover was sporadic at first and then became continuous in Antarctica in a rapid cooling event approximately 34 million years ago. Slight warming kept the ice cover in the Northern Hemisphere sporadic until approximately 2 million years ago, when the Pleistocene ice ages began.

Climate dynamics have been particularly pronounced during the past 2 million years as the Earth has plunged into, and more briefly back out of, glacial periods (Figure 2.7). Glacial conditions have dominated this period, with greenhouse warm intervals coming at roughly 100,000-year intervals and lasting only a few thousand years each. This period has been characterized by much climatic variability, including very rapid climate “flickers”—sudden shifts to warmer or colder conditions that occurred in less than 1000 years.

Glacial/interglacial transitions are driven by solar forcing of climate. When conditions are right for land ice to last through many summers in the large
landmasses of the Northern Hemisphere, an ice age is initiated. As solar input to northern landmasses changes with variations in the Earth’s orbit, the northern land ice melts, initiating a warm, greenhouse interval.

The last glacial period gave way to the current warm period starting approximately 20 million years ago. After several climate flickers, climate became very stable and has persisted as unusually warm and stable for the past 11,000 years. Solar forcings are unusual in this period and may result in an interglacial considerably longer than those of the past 500,000 years. It is onto this unusually warm, stable climate that human greenhouse gas emissions are pushing climatic warming.

**NATURAL DRIVERS OF CHANGE**

Energy from the sun drives the climate system. The sun’s warmth is unevenly distributed across the planet, which sets winds and ocean currents in motion, transporting heat from the equator to the relatively cooler poles. Energy from the sun drives the hydrologic cycle as well, evaporating water from the oceans and freshwater bodies.
The climate system is forced by both natural and human-driven processes. Solar forcing is particularly important in driving natural change. It includes variations in the Earth’s orbit that result in relatively more or less solar radiation reaching the Earth. The Earth’s orbit is not perfectly round, the tilt of the Earth on its axis varies in its orientation to the sun, and the tilt itself wobbles—it changes with time. All of these factors result in changes in incoming solar energy and drive changes in the climate system. Volcanic activity puts large amounts of particulates into the atmosphere, causing cooling, and is another forcing external to the climate system (Figures 2.7 and 2.8). Finally, most recently and most dramatically, human pollution of the atmosphere with greenhouse gases has resulted in radiative forcing of the climate system—changes that affect the re-radiation of the energy of the sun and warm the atmosphere.
FIGURE 2.8 Global Temperature Change.
Global temperature cooled measurably in the years immediately after the Mount Pinatubo eruption (bold line). This global temperature trace indicates major volcanic events that drove decreases in global temperature. It is coupled with mean temperature projections from global climate model (GCM) computer simulations (colored lines) showing that the actual temperature record can only be fully reproduced when human forcings, primarily burning of fossil fuels and deforestation, are included in the GCM simulations. From Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Figure TS.23. Cambridge University Press.
The energy reaching the top of the Earth’s atmosphere is estimated to average 342 watts per square meter (W/m²). Some of that energy is reflected back into space by fine particles in the atmosphere, clouds, or the Earth’s surface, leaving approximately 235 W/m² to warm the atmosphere and the surface of the Earth (Figure 2.9). Over the whole Earth, this is an immense amount of energy—approximately 150 million times more energy than is produced by the world’s largest power station.

The exact amount of energy reaching the Earth varies, however, as does the distribution of that energy to different parts of the world. Changes in the orbit of the Earth bring it closer to the sun or farther away or tilt one part of the planet closer to the sun. The energy output of the sun may vary as well, up to several tenths of 1%. These variations in orbit affect the amount of energy reaching the Earth, changing the sun’s warming effect, and hence changing climate.

There are three main types of orbital variation affecting the Earth’s climate. The first, called eccentricity, relates to the shape of the Earth’s orbit around the sun. The path that the Earth carves in space varies from nearly circular to strongly egg shaped (elliptical). When the orbit is elliptical, the Earth will be much closer to the sun in some parts of its orbit, changing seasonal heating. The Earth wobbles on its axis as it circles the sun, giving rise to the second and third types of solar forcing. The amount of tilt varies and is referred to as obliquity. The direction of tilt slowly rotates and is called precession.
All three of these solar forcings affect the distribution of heating between seasons or between hemispheres more strongly than they affect the overall amount of solar energy reaching the Earth. Their effect on climate is therefore due to amplifications and dynamic effects rather than to changes in raw energy input.

The most pronounced of these amplifications are the ice ages, which are driven by the unequal amounts of land in the Northern and Southern Hemispheres. North America and Eurasia have huge landmasses near the poles. When the Northern Hemisphere receives less heat, particularly in summer, ice may form on this land. The ice reflects sunlight and cools the entire planet. When the Northern Hemisphere receives more heat, the ice melts and the planet warms. Warming and cooling of the Southern Hemisphere has no such effect due to the lack of land near the poles. There is very little land near the poles in South America and Africa because both taper as they approach the South Pole.

Precession determines which hemisphere tilts toward the sun in summer. Precession varies on a 23,000-year cycle. When the Northern Hemisphere is tilted toward the sun in summer, summers are very hot and ice cannot build up on the large northern landmasses.

Obliquity is the amount of tilt in the Earth's axis. The Earth wobbles on its axis like a spinning top. When the tilt is strong toward the Northern Hemisphere, it is difficult for continental ice sheets to form. There is a 41,000-year periodicity to obliquity. Obliquity is sometimes referred to as tilt.

Eccentricity is the shape of the Earth’s orbit around the sun. This shape varies from more circular to more oval with two cyclic periods—100,000 and 400,000 years. The more circular orbit results in more even distribution of solar energy. The more oval orbit can result in less solar energy reaching the Northern Hemisphere’s large, ice-prone landmasses and can help trigger a glacial period.

Glacial periods start with cool summers. Combinations of solar forcings that lead to cool summers allow ice to be retained through the warm season and continental ice sheets to form in North America and Europe. The Northern Hemisphere landmasses are particularly important because they offer enough high-latitude landmass for the formation of continental ice sheets. A similar dynamic for the Southern Hemisphere does not exist because there is little landmass to hold ice in South America or Africa at high latitudes. In the late 1800s, scientists believed that cold winters led to ice ages. Milutin Milankovitch, a Serbian geophysicist and engineer, recognized that cool summers were the key to ice buildup. Cycles in solar forcing—Milankovitch cycles—bear his name in recognition of his contribution to understanding their role in the ice ages.
Recent research points to a role for the Southern Hemisphere in the formation and termination of glacial periods as well, also driven by Milankovitch forcings. Low obliquity (tilt) brings cool summers to both hemispheres, which favors ice buildup in the north and intensified circumpolar current in the south. The intensification of the circumpolar current reduces upwelling of CO₂-rich water. The reduction in atmospheric CO₂ cools the planet, facilitating continental ice sheet buildup in the north. The Southern Hemisphere may also push the Northern Hemisphere along as glacial periods end—high obliquity results in warmer summers in both hemispheres. This begins to melt the continental ice sheets in the north, whereas in the south it intensifies circumpolar currents and winds, pumping CO₂-rich water to the surface and warming the planet (Figure 2.10).

**FIGURE 2.10 Solar Forcings.**
Three major solar forcings affect the amount of solar radiation incident on Earth. The Earth’s orbit is oval rather than round, resulting in more radiation reaching the Earth when it is closer to the sun. This effect is eccentricity (E). The tilt of the Earth (T; also referred to as obliquity) varies, which affects the amount of radiation reaching the Northern Hemisphere. Finally, the time of year during which the Northern Hemisphere is tilted toward the sun varies, which is called precession of the equinoxes (P). These forcings are often referred to as Milankovitch forcings, for the Serbian physicist who recognized that the amount of solar radiation received in summer in the Northern Hemisphere determined the timing of ice ages. From Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

**MAJOR FEATURES OF PRESENT CLIMATE**

Energy from the sun drives circulation patterns in both the oceans and the atmosphere. Atmospheric circulation is driven by the principle that warm air is less dense than cool air and therefore rises. Ocean circulation is driven by both temperature and salinity. Warm water rises, cool water sinks, and salty water is more dense than freshwater, leading salty water to sink and less salty water to rise.
The Earth receives more heat from the sun at the equator than it does at the poles. A pot off-center on the stove also receives heat unequally, resulting in water roiling to the top where the heat is received and moving out to the cooler edges of the pot. The sun’s heat received at the Earth’s equator acts in the same way, causing the Earth’s atmosphere to roil—warm hot air rises and builds up in the tropics, pushing toward the cooler poles. As air masses move from the tropics toward the poles, they cool, descend, and eventually return to the tropics in a giant loop. This movement of heat, known as heat transport, creates large, systematic patterns of circulation in the atmosphere.

This heat imbalance sets up gradients that drive heat transfer from the equator toward the poles. Warm air and water rise, pooling at the equator, setting up circulation patterns typified by rising warm air or water near the equator and sinking cold air or water near the poles, with movement in between.

In the atmosphere, these circulation patterns are known as Hadley cells. There are two Hadley cells between the equator and each pole. Hadley cells have both vertical and horizontal structures. Viewed in cross section, air masses in a Hadley cell rise at the equator, move toward the pole, and then descend. From above, the circulation is clockwise, as moving air is deflected by the Coriolis effect imparted by the Earth’s rotation (Figure 2.11).

In counterpart to the Hadley cells, in the tropics there are East–West-oriented circulation cells. These circulation patterns arise when pressure differences across ocean basins drive surface winds in one direction, balanced by transfers aloft in the opposite direction. Over the Pacific Ocean, the circulation is known as Walker cell circulation or the “Southern Oscillation.” It drives easterly surface winds across the Pacific. Breakdown in Walker cell circulation in the tropical Pacific results in an El Niño event.

Trade winds are surface winds caused by air movement and Hadley cells being deflected by the Coriolis effect. The trade winds are easterly, meaning that they blow from the east. They move westward along the equator in both the Northern and the Southern Hemisphere. Where the trade winds converge along the equator, a zone of uplift and cloud formation results, which is known as the Intertropical Convergence Zone. The trade winds are balanced by return flows in the mid-latitudes by west-to-east blowing winds known as the westerlies.

Major ocean circulation patterns follow the wind patterns, forming large gyres with east-to-west flow along the equator and west-to-east flow at the mid-latitudes. However, ocean current direction varies from wind direction by 15–45° progressively with depth, an effect known as the Ekman spiral. When surface ocean currents strike continents, they deflect and follow the shoreline, forming boundary currents.
Upwelling results when along-shore winds move ocean water. The wind-driven surface movement is deflected by the Ekman spiral, resulting in transport of water away from the coast. This moving water has to be replaced, so water from depth is drawn to the surface. The movement of this cold, nutrient-rich water from depth to the surface is referred to as upwelling (Figure 2.12).

In the oceans, the equator-to-pole circulation is the thermohaline circulation. It is more complex because it must work its way around landmasses and because it involves salinity as well as warmth. Warm water at the equator evaporates, leaving behind water that is both warmer and more salty, and hence more dense. This salty warm water moves toward the poles, where it cools and sinks, renewing the circulation (Figure 2.13).

The influence of the thermohaline circulation is especially strong in the North Atlantic, bringing in massive quantities of heat from the equator. This
FIGURE 2.12 Forces Driving Upwelling.
Longshore winds create water movement that is deflected by Eckman forces. Replacement water rises from the depths, creating upwelling. From Wikimedia Commons.

FIGURE 2.13 Thermohaline Circulation.
Major circulation features in the oceans are established when seawater warms at the equator, evaporating and becoming more saline, and then moves near the surface (red) toward the poles, where it cools and sinks. It then moves near the bottom (blue) back to the equator, to rise and begin the process anew on timescales of hundreds of years. Because it involves both temperature and salinity, this feature is termed thermohaline circulation. Reproduced with permission from Yale University Press.
portion of the thermohaline circulation is known as the Gulf Stream. When the Gulf Stream shuts off, it robs heat from two major landmasses near the poles, greatly accelerating ice buildup. Glacial periods appear to end when the Gulf Stream strengthens, pumping energy northward to melt the ice sheets. Whereas the onset of glacial periods appears to be more gradual, the end of the glacial periods can be dramatically rapid. Climate flickers such as the Younger Dryas can be initiated when the thermohaline circulation shuts down during the glacial/interglacial transition. Changes in the thermohaline circulation are therefore an important trigger for climate change.

**STABLE STATES OF THE SYSTEM**

The circulation patterns of the Earth’s climate system change over time. Like freeway traffic that either moves freely or backs up clear across town, atmospheric circulation may exhibit dramatically different patterns at different times, frequently switching back and forth among two or more relatively stable states. As the Earth spins, its rotation sets up waves in atmospheric circulations, much as water in a river rapid sets up standing waves. In such systems, it is natural that a wave crest or “high” in one region will be connected to wave troughs or “lows” in neighboring regions.

El Niño events are among the best known of these multiple-state patterns (Figures 2.14 and 2.15). During El Niño events, ocean circulation patterns change across the Pacific Ocean. Rain patterns shift and atmospheric circulation changes in response to alterations in ocean water temperatures. These effects are felt in the Pacific but are also reflected in other, far distant parts of the globe. Thus, El Niño years are associated with less upwelling of deep ocean water and enhanced rainfall in the Pacific but also with decreases in rainfall and drought in Africa. These long-distance effects are the result of global circulation patterns sitting next to, and driving, one another, almost like gears. What happens in one circulation cell is passed on to the next and may result in consequences in faraway places. Such long-distance, linked impacts are called “teleconnections.” Teleconnections are not random; they tend to be linked to complementary “sister” states. They often involve coupled changes in ocean and atmospheric states. For instance, the complement to El Niño conditions are La Niña events, in which upwelling in the Pacific is enhanced and rainfall reduced. The oscillation between these two conditions is known as the El Niño/Southern Oscillation or ENSO.

Other large-scale modes of atmospheric variability include the North Atlantic Oscillation and the Pacific Decadal Oscillation. The Pacific Decadal Oscillation affects the North Pacific Ocean and switches states approximately every 10 years,
as its name implies. The North Atlantic Oscillation is dominated by two modes, one in which arctic air pounds Europe and another in which European weather is considerably more pleasant. The thermohaline circulation is an excellent example of a teleconnection because what happens in the North Atlantic may affect climate across the entire planet.

**FIGURE 2.14 El Niño.**
Periodically, the gross circulation of the southern Pacific Ocean changes, in a phenomenon known as El Niño. Under El Niño conditions, the thermocline becomes more shallow and upwelling is reduced along western South America. This results in pooling of warm water in the central Pacific and changes in precipitation and convection patterns. Reproduced with permission from Yale University Press.
CHAPTER 2: The Climate System and Climate Change

Rising atmospheric CO₂ was first measured by Charles Keating at the Mauna Loa observatory on the island of Hawaii. Keating worked at the Scripps Institute of Oceanography in San Diego and along with Roger Revelle, the director of the institute, concluded that direct measurement of changing CO₂ was needed. In the late 1950s, Keating settled on the remote slopes of Mauna Loa to escape local variation in CO₂ caused by urban emissions or vegetation. The program begun by Keating continues today and has provided incontrovertible evidence of the effect of human pollution on the atmosphere.

FIGURE 2.15 El Niño Teleconnections.

HUMAN-DRIVEN CHANGE: RISING CO₂

The rise of CO₂ due to fossil fuel burning and deforestation has been traced in a simple study on the Mauna Loa volcano in Hawaii. Air intakes atop the mountain capture samples that are then analyzed for CO₂ content. Mauna Loa was chosen because its island location and high elevation place it far away from short-term contamination from any city air pollution. The record of CO₂ at Mauna Loa is therefore pure: It shows what is happening in the atmosphere very plainly—and plainly CO₂ is rising dramatically.

CHARLES KEATING

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