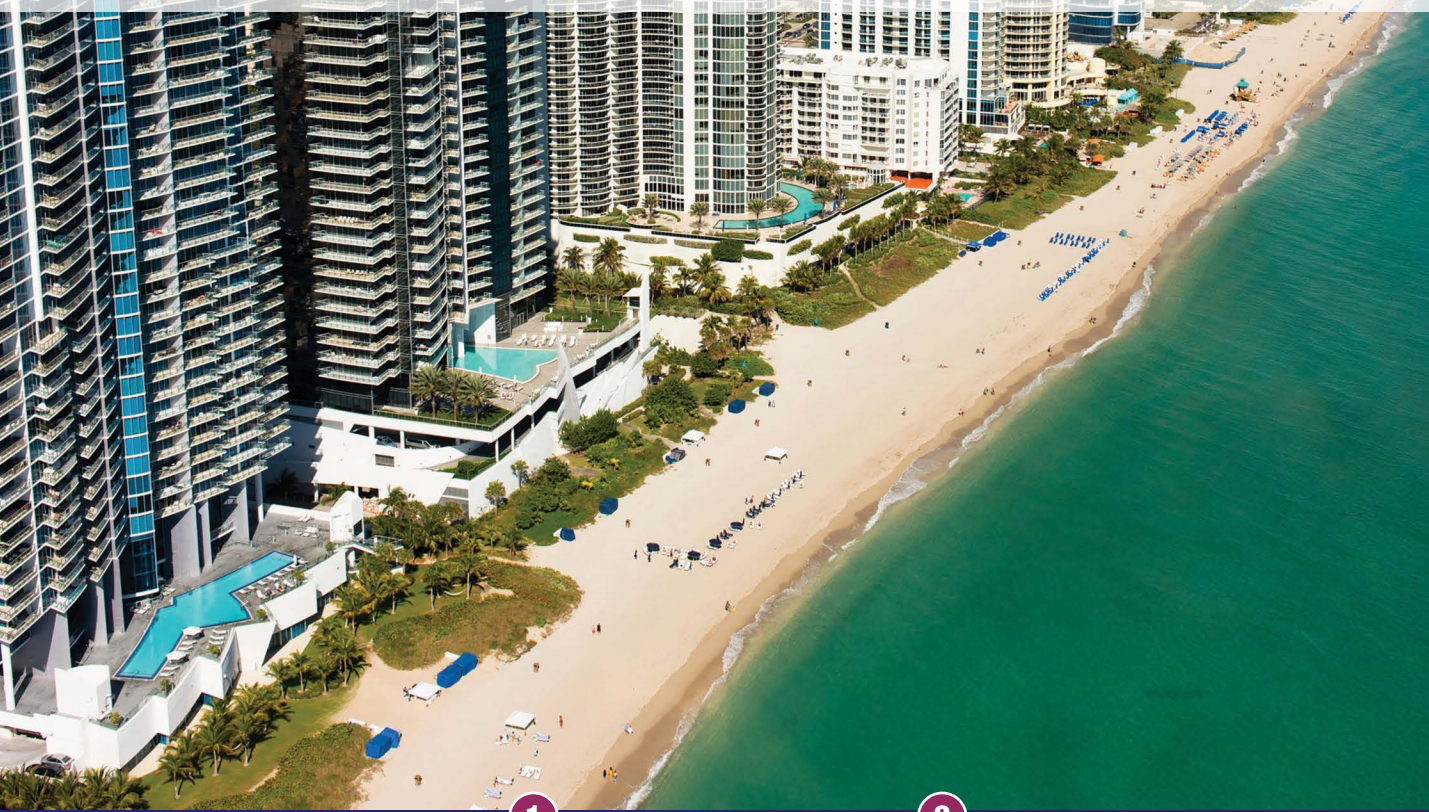
Sunny Isles Beach near Miami **has more than $10 billion in resort and other property that is becoming vulnerable to climate change with rise in sea level that causes coastal flooding events.**

12



APPLYING the 5 fundamental concepts Sea-level rise: Miami, Florida

1

Science helps us predict hazards.

Studying sea level change in the Miami area and predicting future changes are key to understanding the hazards linked to sea-level rise.

2

Knowing hazard risks can help people make decisions.

Understanding potential risk of damage to land and property from sea-level rise is critical in making decisions to manage the hazards of coastal flooding in Miami.

Climate Change and Natural Hazards

Poster Child for Climate Change in a Time of Sea-level rise and Denial

Miami Beach and adjacent areas in southern Florida, from Miami north to Fort Lauderdale and Palm Beach (including the famous Mar-a-Lago Estate), is at the forefront of climate change and sea-level rise that are causing ever higher and more frequent coastal flooding. Population is growing rapidly in South Florida, and property worth many billions of dollars are at risk from coastal flooding, especially during the highest tides of the year known as King Tides (Figure 12.1).

As a result of accelerating sea-level rise in South Florida, the number of coastal (tidal) flooding events has increased about 400 percent since about 2006.[1] The famous beach resorts of Sunny Isles

< Sunny Isles Beach, South Florida
With its high-rise hotels, Sunny Isles Beach has more than $10 billion in development. The beach is on a narrow barrier island between the Atlantic Ocean and Coastal Waterway. Accelerating rise in sea level as a result of human-induced climate change is threatening much of the South Florida coastline. *(Alamy)*

LEARNING objectives

Many natural hazards, such as drought, heat waves, floods, hurricanes, blizzards, and wildfire, are related to climate and climate change. A basic understanding of climate science is needed to comprehend the mechanisms of these hazards. After reading this chapter, you should be able to:

LO:1 Explain the difference between climate and weather and how their variability is related to natural hazards.

LO:2 Describe the basic concepts of atmospheric science, such as the structure, composition, and dynamics of the atmosphere.

LO:3 Synthesize how we have studied past climate change.

LO:4 Summarize how climate has changed during the past million years through glacial and interglacial conditions and how human activity is altering our current climate.

LO:5 Name and explain the potential causes of climate change and link these causes to natural hazards.

LO:6 Speculate on how we might better predict future climate change.

LO:7 Propose ways to mitigate climate change and associated hazards.

3

Linkages exist between natural hazards.

Coastal erosion and flooding from sea-level rise are linked to rising sea level due to global warming. Sea-level rise also increases the cyclones and tsunami hazard for coastal areas.

4

Humans can turn disastrous events into catastrophes.

Worldwide population growth has compounded the effects of climate change, such as sea-level rise due to warming, in addition to increasing the global risk from rising seas due to dense urbanization of low-lying coastal regions.

5

Consequences of hazards can be minimized.

Consequences of sea-level rise can be temporarily minimized at specific locations by engineering projects, but global solutions will require international cooperation to reduce carbon emissions that are driving much of recent sea-level rise.



FIGURE 12.1
Tidal flooding in South Florida State. Coastal highway is flooded in 2013 during a high tide. Such flooding has increased dramatically in recent years. *(Alamy)*

and Hollywood Beach (see opening photograph), with property value in excess of $10 billion, that are located on a narrow barrier island between the Atlantic Ocean and the inland waterway are particularly vulnerable to future sea-level rise. All the red flags are up, but the real crunch and impact from rising sea level in Florida is most likely to be 50 to 100 years in the future. Thus, South Florida has some time, as does the world, to attempt to reduce the impact from climate change, but such preparations could take decades to enact.

Ironically, top Florida State Officials in 2015 all but outlawed and censored the use of the terms "global warming" and "sea-level rise," as if not saying the words would make the problem go away. This situation made national news before being partly backed away from. Denying climate change and sea-level rise is a doomed strategy. Officials finally said something must be done other than talk and state their personal beliefs. The science is clear: sea level is rising, largely from human-induced global warming. What officials say or believe has no merit when the data speaks for itself. It is estimated that by the year 2050, there will be many more coastal flood events than today.[2] We will return to the South Florida coastal flooding issue at the end of the chapter and apply the fundamental concepts.

12.1 Global Change and Earth System Science: An Overview

Preston Cloud, a famous Earth scientist who studied the history of life on Earth, human impact on the environment, and the use of resources, proposed two central goals for the Earth sciences:[3]

1. Understand how Earth works and how it has evolved from a landscape of barren rock to the complex landscape dominated by the life we see today.
2. Apply that understanding to better manage our environment.

Until recently, it was thought that human activity caused only local or, at most, regional environmental change. It is now generally recognized that the effects of human activity on Earth are so extensive that we are actually involved in an unplanned planetary experiment. To recognize and perhaps modify the changes we have initiated, we need to understand how the entire Earth works as a system. The discipline, called **Earth System Science**, seeks to further this understanding by learning how the various components of the system—the atmosphere, oceans, land, and biosphere—are linked on a global scale and interact to affect life on Earth.[4] A major goal of Earth System Science is to predict future changes that are relevant to society and people today.

12.1 CHECK your understanding

1. Define Earth System Science and describe its goals.

12.2 Climate and Weather

Many people who hear about global warming form opinions based on day-to-day or week-to-week changes in the weather. They do not appreciate the important distinction between climate and weather. **Climate** refers to the characteristic atmospheric conditions of a given region over long periods of time, such as years or decades. **Weather** refers to the atmospheric conditions of a given region for short periods of time, such as days or weeks. For example, when we think of the coast of the Pacific Northwest, we think of mild temperatures, high humidity, and lots of rain. Thus, when planning a trip to Vancouver, British Columbia, or Seattle, Washington, we might use our knowledge of the climate to help us remember to bring an umbrella! It is possible, however, that during a weeklong stay in Vancouver or Seattle, we may enjoy only bright, sunny, dry weather because day-to-day weather conditions can vary greatly.

Although we generally think of temperature and precipitation as climatic factors, climate is more than average high and low temperatures and/or the amount of rainfall at a given location. In fact, it is possible for two locales to have the same average annual temperature but

be in different climate zones. For example, San Diego, California, has an average annual temperature of around 18°C (~64°F) and small temperature changes from month to month. In contrast, El Paso, Texas, has close to the same average annual temperature but experiences large changes in temperature, ranging from a January average of 7°C (~45°F) to a July average of 28°C (~82°F). Although the two areas have the same average annual temperature, it is clear that they have different climates.

CLIMATE ZONES

Climate may be classified in many different ways. The simplest classification is by temperature and precipitation, but climate at a particular place or region may be complex. For example, it may depend on infrequent or extreme seasonal patterns, such as rain in the monsoon season in much of India. The major climatic zones on Earth are shown in Figure 12.2. Selected processes and changes that produce and maintain the climate system are shown in Figure 12.3. For example, ocean currents can affect the temperature and precipitation of areas far removed from the coast; warm currents traveling northward along the eastern Atlantic bring mild temperatures to northern Europe. Mountain ranges and plateaus can significantly affect precipitation patterns and seasons, which can influence temperature as well; for example, Asia's Tibetan Plateau is partly responsible for the Asian monsoon, and the Rocky Mountains are important factors in the southwestern U.S. monsoon.

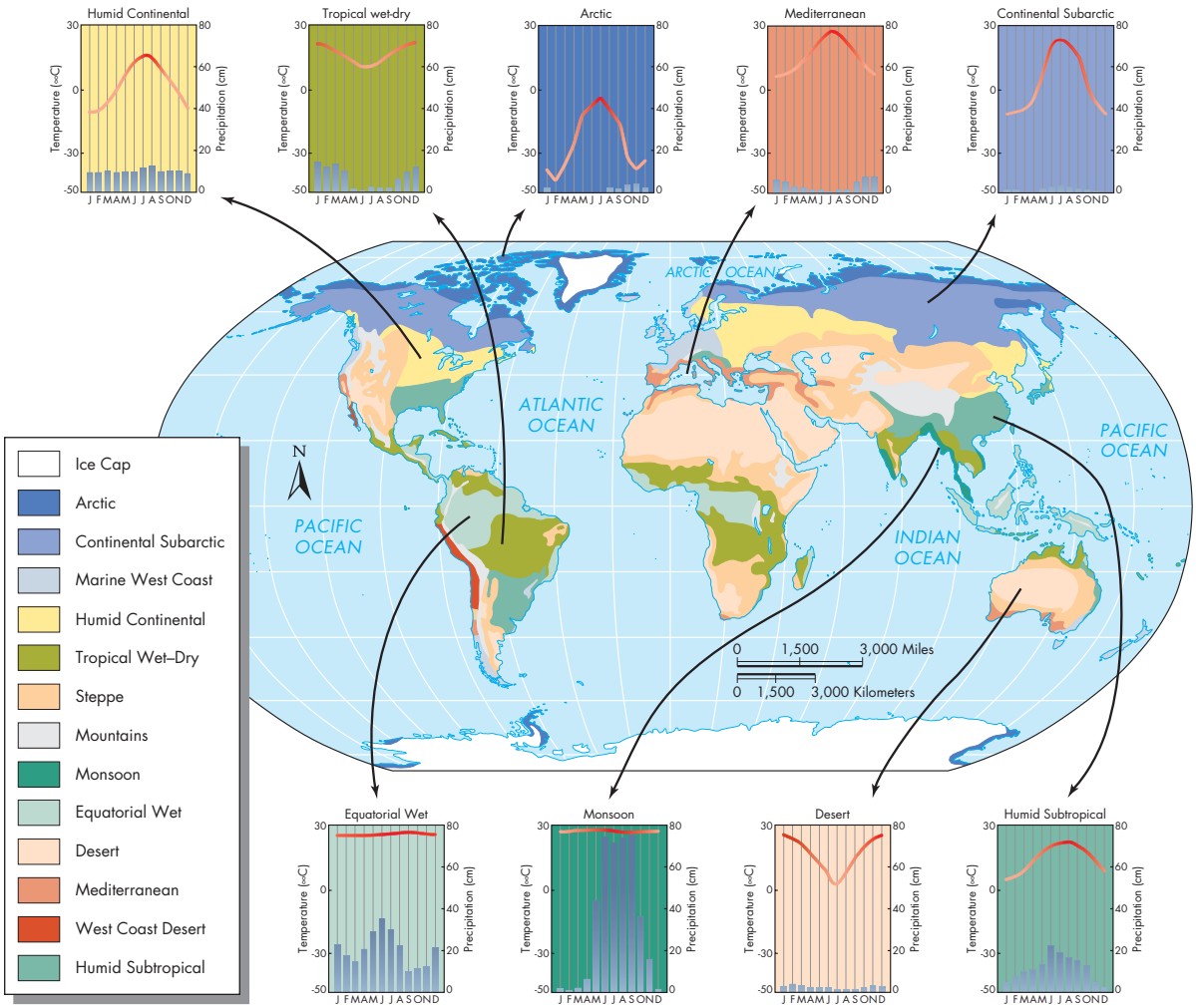


FIGURE 12.2 Climates of the World

Characteristic temperature and precipitation conditions. Temperature is represented by the red line, and precipitation is shown as bars. *(Based on Marsh, W. M., and Dozier, J.* Landscapes: An Introduction to Physical Geography. *Copyright © 1981. John Wiley & Sons.)*

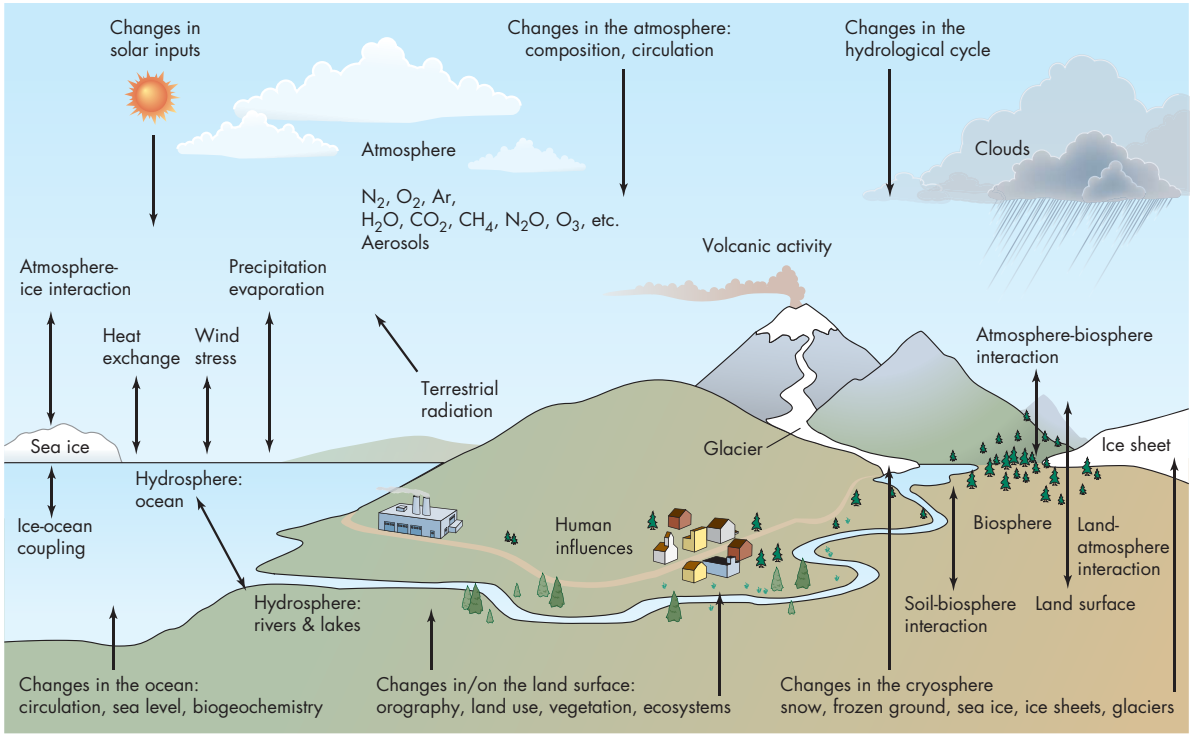


FIGURE 12.3 Complex components of the climate system
Idealized diagram showing the complex, linked components and changes of the climate system that produce, maintain, and change the climates of the world. *(IPCC. 2007. The Physical Science Basis: Working Group I. Contribution to the Fourth Assessment Report. IPCC. New York: Cambridge University Press.)*

Climate zones exert a major influence on natural processes and, thus, on natural hazards. Flooding is, in part, dependent on rainfall amount and intensity, landslides may be more common in areas with rainy climates, and wildfires are more likely to occur in areas with a dry season. A familiarity with Earth's climate zones is a first step toward recognizing the threat from natural hazards. Applying climate classification provides not only a map of world climates but also information about the relationship between climate and vegetation.[5] Not all dry areas, for example, are prone to wildfires, but some dry areas are at significantly more risk than others.

12.2 CHECK your understanding

1. Distinguish weather from climate.
2. What are the two main variables used to define climate zones? What other factors influence climate in a region?
3. How is climate classification useful to understanding natural hazards?

12.3 The Atmosphere and the Cryosphere

ATMOSPHERIC COMPOSITION

As described in Chapter 9, our atmosphere is composed mainly of nitrogen and oxygen with smaller amounts of other gases. Compounds, such as nitrogen (N_2), that form a constant proportion of the mass of the atmosphere are called permanent gases, whereas gases whose proportions vary in time and space, such as carbon dioxide, are considered variable gases. The atmosphere also contains microscopic particles called aerosols, whose proportions also vary in time and space.

The major permanent gases, which are those that remain essentially constant by percentage of total volume, include nitrogen (~78 percent), oxygen (~21 percent), and argon (~1 percent). Together, these gases comprise about 99 percent by volume of all atmospheric gases. Nitrogen generally occurs as molecules of paired nitrogen atoms (N_2) and composes about 78 percent of the volume of all permanent gases. Although N_2 molecules make up the greatest volume of the

atmosphere, they are relatively unimportant in atmospheric dynamics unless nitrogen forms compounds with other gases, such as oxygen.

The second largest component is oxygen, composing 21 percent of the atmosphere by volume. Like nitrogen, oxygen molecules consist mainly of paired atoms of oxygen (O_2). As we humans well know, oxygen is critical to the existence of most life forms on Earth. Like nitrogen, O_2 is relatively unimportant to atmosphere dynamics. However, as discussed later, other oxygen compounds, such as ozone (O_3), play an extremely important role in the atmospheric-climate system.

Argon makes up most of the remaining 1 percent of the permanent gases, along with lesser amounts of neon, helium, krypton, xenon, and hydrogen. With the exception of hydrogen, these permanent gases are not chemically reactive and have little or no effect on climate.

Although the variable gasses, with the exception of water vapor (0.2–4 percent), account for only a small percentage of the total mass of the atmosphere, some of them play important roles in atmospheric dynamics. These gases include carbon dioxide, ozone, methane, and nitrous oxide. The atmosphere also contains a variable amount of aerosols. An aerosol is not a gas but a microscopic liquid or solid particle. In the atmosphere, these particles act as nuclei around which water droplets condense to form clouds. Aerosols have a wide variety of natural and anthropogenic sources. Natural sources include desert dust, wildfires, sea spray, and major periodic contributions from volcanoes.[6] Anthropogenic sources include the burning of forests in land clearing and sulphate particles and soot from the burning of fossil fuels.

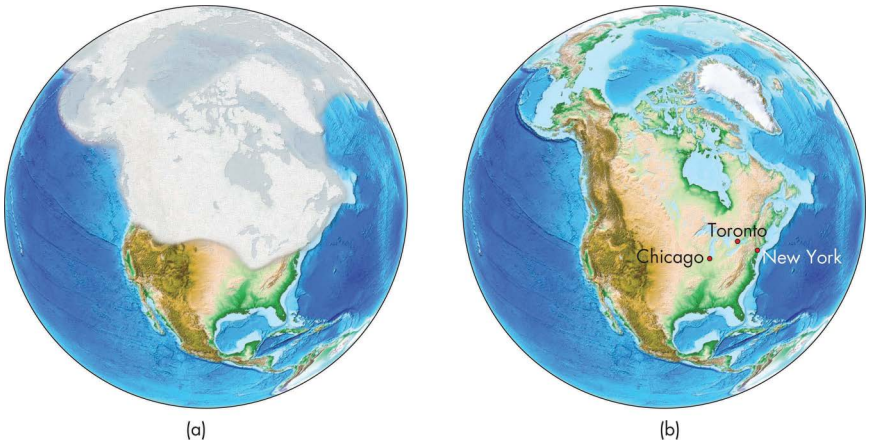
HYDROSPHERE AND CRYOSPHERE

A study of climate change is, to a great extent, the study of changes in the atmosphere and linkages between the atmosphere and the lithosphere, hydrosphere, cryosphere, and biosphere (see Chapter 1). The hydrosphere is the water part of the global Earth system and includes the oceans, lakes, and rivers, as well as the water in the armosphere. Of particular significance are the processes that transport the water from the ocean to the land and back to the ocean known as the hydrologic cycle (see Figure 1.8 and Table 1.3).

The cryosphere is the part of the hydrosphere in which most of the water stays frozen year-round. Major components of the cryosphere include permanently frozen ground (permafrost), sea ice, and glacial ice. The ice in permafrost and sea ice is either fixed in place or floating. In contrast, glacial ice is an accumulation of ice, snow, rock, sediment, and liquid water that flows from high areas to low areas due to gravity acting on the weight of this accumulated ice. Thus, **glaciers** are landbound, moving masses of glacial ice. In this chapter, we will discuss the giant ice sheets in polar areas, as well as valley and mountain glaciers. Like beaches, glaciers have budgets with inputs and outputs (see Chapter 11). Inputs consist of new snow recrystallizing to form ice at higher elevations, and outputs occur at lower elevations where ice is lost by melting, evaporation, and blocks breaking off the front of the glacier or ice sheet. Glaciers and ice sheets advance when their budget is positive and retreat when they have a net loss of ice.

Over the past 2.5 million years, Earth's climate system has fluctuated greatly and alternated between periods of major continental glaciation, referred to as glacial intervals, and times of warmer climate with significantly less glaciation, referred to as interglacial intervals. During glacial intervals, large ice sheets covered northern North America and Europe, and glaciers expanded in mountainous regions. In interglacial intervals, individual glaciers and large ice sheets retreated. Today, we live in interglacial conditions, with warm temperatures not experienced since the last interglacial interval 125,000 years ago. We will discuss why Earth's climate changes from glacial to interglacial later in this chapter with a more specific discussion of why climate changes.

Major continental glacial events (ice ages) have been relatively rare during the 4.6 billion years of Earth history. However, during the past 1 billion years, several major glacial events have occurred. We are now living during one of these events—one that began approximately 2.5 million years ago when glaciers began to repeatedly advance and retreat across much of the landscape. The last series of glacial and interglacial intervals took place during the Pleistocene Epoch, which included multiple ice ages when continental glaciers advanced. During the Pleistocene Epoch, glaciers covered as much as 30 percent of the land area of Earth, including the present sites of major cities such as New York, Toronto, and Chicago (Figure 12.4). Pleistocene continental glaciers achieved their maximum extent about 21,000 years ago. Because large quantities of the world's freshwater were stored in the ice of these glaciers, global sea level was more than 100 m (~330 ft.) lower than its current level. Today, glacial ice covers only about 10 percent of Earth's land. Nearly all this ice is contained in the Antarctic ice sheet; lesser amounts are found in the Greenland ice sheet and the mountain glaciers of Alaska, British Columbia, southern Norway, the Alps, New Zealand, and elsewhere. We are presently in an interglacial interval, so the abundance of ice is relatively low. Nevertheless, we are probably still living in a glacial event (ice age), and ice sheets may again advance in the future.



< FIGURE 12.4 Extent of North American Ice Sheets
(a) Ice sheets about 21,000 years ago. (b) Ice sheets today. *(From NOAA. www.ncdc.noaa.gov. Accessed 9/25/10.)*

12.3 CHECK your understanding

1. What are the major permanent and variable gases in the atmosphere?
2. Define glacier and how the extent of glaciers has changed in the past 21,000 years.
3. Differentiate between the hydrosphere and the cryosphere

12.4 How We Study Past Climate Change and Make Predictions

The data gathered to document and better understand climate change are from a variety of time scales and variable regions, from continents, oceans, hemispheres, and the entire planet. Data are available for three main time periods:[7]

- *The instrumental record.* Starting about 1880, temperature measurements have been made at various locations on land and in the oceans. Earliest records are from the late seventeenth and early eighteenth centuries, and the network of stations has significantly increased over time. About 1,000 records exist from the late nineteenth century. Today, temperature is measured at about 7,000 stations around the world. The concentration of carbon dioxide in the atmosphere has been measured since about 1960. Accurate measurement of the production of solar energy has been taken over the past several decades.
- *The historical record.* A variety of historical records go back several hundred years. Included are people's written recollections (books, newspapers, journal articles, personal journals, etc.) of the Medieval Warm Period and the Little Ice Age, as well as ships' logs, travelers' diaries, and farmers' crop records. These are not generally quantitative data, but they contain qualitative information about the climate of the past.
- *The paleo-proxy record.* The instrumental record is short, and most of the historical information is not quantitative. As a result, there has been a need to extend the record back further. Paleoclimatology (the study of past climates) is part of Earth Science. It is clear that the paleo-record of Earth's climate has provided some of the strongest data to support and test recent climate change. The term **proxy data** refers to data that are not strictly climatic but can be correlated with climate, such as temperature of the land or sea.[7] Some of the information gathered as proxy data includes natural records of climate variability, as indicated by tree rings, ocean sediments, ice cores, fossil pollen, corals, and carbon-14 (^{14}C).

The disadvantages of paleoclimate proxy data are obvious; the data are not a direct measurement of temperature, and, therefore, temperature must be inferred from the data. In spite of this, the paleoclimate proxy data preserved in the geologic record provide the best evidence of change that predates the historical and instrumental records. A discussion of the various data sources for paleo-proxy records follows.

Tree Rings The growth of trees is influenced by climatic conditions, such as the amount of rainfall and the variability in temperature. Most trees put on one growth ring per year, and the width, density, and isotopic composition of annual rings provide information about past climate—referred to as dendroclimatology.

Thus, tree rings contain proxy climate information, such as relative rainfall or periods of drought. By counting rings within living and older dead trees that overlap with the living record, scientists have developed a dendroclimatology proxy record that extends about several thousand years.

Sediments The oceans of the world are a repository for the sediments from the land delivered by rivers, wind, and volcanic eruptions, as well as sediment from the ocean itself (such as shells of dead organisms). Lakes, bogs, and ponds accumulate sediment over time that can be sampled for a climate signal. When sediment deposits are sampled and dated, these provide paleo-proxy data sources for climate change. Sediments are recovered by drilling in the bottom of an ocean basin or lake (Figure 12.5). From the cores, samples may be taken of small fossils and chemicals that are contained within the sediments that may be interpreted to better understand past climate change. Some of the strongest evidence for past climate change comes from these proxy records.

Ice Cores Glaciers contain an accumulation record of the snow that has been transformed into glacial ice over hundreds of thousands of years. Ice cores are obtained by drilling into the ice and obtaining a core, which can be studied in detail in order to learn about past conditions (Figure 12.6). Ice cores from glaciers often contain small bubbles of air deposited at the time of the snow. The composition and ratio of past atmospheric gases preserved in the ice may be studied and used to infer a number of paleoclimatic variables. Ice cores also contain a variety of chemicals and other materials, such as volcanic ash and dust, which can provide proxy data to assist in evaluating climate change. The ice itself may be studied to determine the paleo-isotopic composition of the water, which provides information about the volume of ice on the land, as well as processes occurring in the paleo-oceans (oceans of the past as determined from sediments).

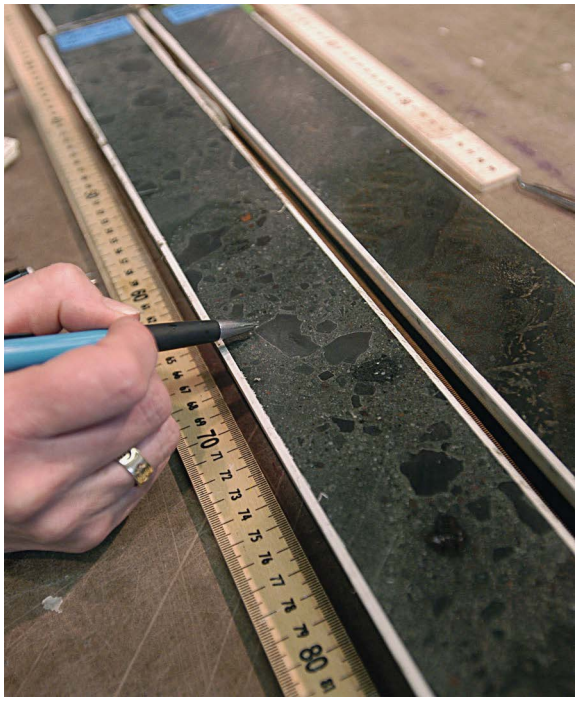


FIGURE 12.5 Examining Cores
Marine sediment core from seafloor under the Antarctic Ice Shelf is being examined. (*Peter West, Office of Polar Programs, National Science Foundation)*



FIGURE 12.6 Ice Core
Preparing a 2005 ice core from the Greenland Ice Cap for examination of the climate record it contains. *(Simon Fraser/Science Source)*

Pollen Pollen (from flowers, trees, and other plants), along with other sediment, accumulates in a variety of environments, including oceans, bogs, and lakes. Scientists study the abundance and types of pollen in order to investigate past climate. For example, if the climate cools, there will be a change in the types and quantities of pollen found in sediments that reflect the change in climate. Pollen, if found in sufficient quantity, may be dated. Since the grains are preserved in sedimentary layers that also might be dated, a chronology can be developed. Based on the types of plants found at different times, the climatic history can be reconstructed.

Corals Coral reefs consist of corals (and other organisms) that have hard skeletons composed of calcium carbonate ($CaCO_3$) extracted by the corals from the seawater. The calcium carbonate contains isotopes of oxygen, as well as a variety of trace metals, that can be used to estimate the temperature of the water in which the coral grew. Thus, corals are a source of paleo-proxy data that can help us interpret climate change. Corals may be dated by several dating techniques, and a chronology of change over time may be constructed.

Carbon-14 The production of carbon-14 (^{14}C) produced in the upper atmosphere is caused by collisions between neutrons and nitrogen-14 (^{14}N). The nitrogen is part of what are called cosmic rays that come from outer space and are a product of the energy from the sun. Solar activity can be observed from the frequency of sunspots, which are dark areas on the sun surrounded by a lighter area. As sunspot activity increases, the energy from the sun that reaches Earth also increases. The frequency of sunspots has been accurately measured for decades and observed by people for about 1,000 years. When sunspot activity is high, an associated solar wind, which produces ionized particles consisting predominately of protons and electrons, emanates from the sun. The solar wind reflects cosmic rays (including N-14,^{14}N). As a result, the amount of ^{14}C is reduced. The record of ^{14}C in the atmosphere is correlated to tree ring chronology, known as dendrochronology. Each ring of wood of known age contains carbon, and the amount of ^{14}C can be measured. If the climatic record for a period of time is known, it may be correlated with ^{14}C. Thus, we can examine solar energy output, extending back thousands of years, by studying tree rings and the carbon-14 they contain.

Based on the ^{14}C record and its link to solar energy, it appears that the production of solar energy was slightly higher around A.D. 1000, during the Medieval Warm Period, and was slightly lower during the Little Ice Age from about A.D. 1400 to 1800. The effect of solar radiation on recent climate change (during the instrumental record) can account for a small percentage of observed changes in climate. However, the variability of solar energy is not sufficient to explain the warming since about 1960.

Carbon Dioxide The concentration of global carbon dioxide in the atmosphere is arguably the most important proxy for global temperature change. There are carbon dioxide measurements from the instrumental record, and these have been extended back through the measurements from trapped air in glacial ice (Figure 12.7). Figure 12.8 illustrates strong positive correlation between CO_2 in the atmosphere collected

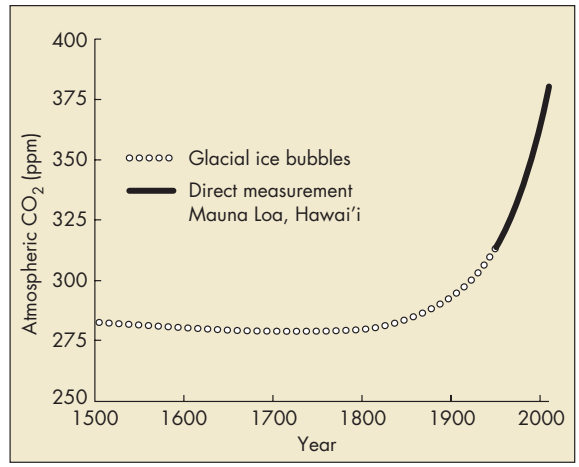


FIGURE 12.7 Carbon Dioxide in the Atmosphere
Atmospheric concentration of carbon dioxide measured at Mauna Loa, Hawaii since 1958, as well as average concentration of atmospheric carbon dioxide from 1500 to 2000, based on measurements of air bubbles trapped in glacial ice. Source: NOAA Mauna Loa Observatory in Hawaii. *(Data in part from Post, W. M. et al.,* American Scientist*, 78(4): 210–26, 1990)*

from ice cores to the paleo-temperature record. The time between carbon dioxide emission and most of the warming from the emission is about one decade and will persist for about a century.[8] This short period from emission to warming suggests that if we act to reduce emissions of carbon dioxide (from burning fossil fuels), we may reap the benefits of avoiding climate change within our lifetime.

GLOBAL CLIMATE MODELS

Scientists develop mathematical models to represent real-world phenomena. These models describe numerically the linkages and interactions between natural processes. Mathematical models have been developed to predict the flow of surface water and groundwater, erosion and deposition of stream sediment, and the global circulation of water in the ocean and air in the atmosphere.

The mathematical models used by scientists to study climate and climate change have their origin in the first attempts to use computers to prepare weather forecasts in the 1950s.[9] Computers in the 1950s were in their infancy—large and extremely slow machines with vacuum tubes that could take 24 hours of processing time to produce a 24-hour weather forecast. Early mathematical models run on computers were, by necessity, regional in extent and used primarily to describe the general circulation of the atmosphere. Called general circulation models, these mathematical models were the foundation for the first truly global

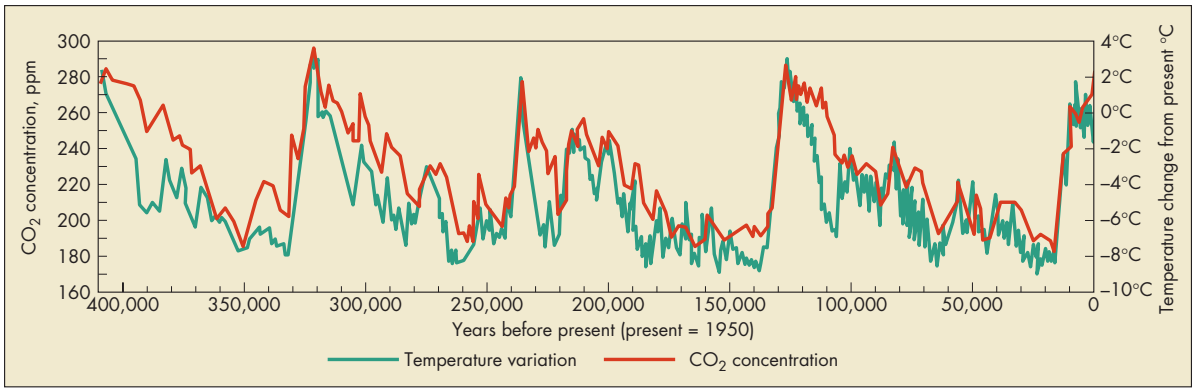


FIGURE 12.8 Air Temperature Changes Correspond Closely to Atmospheric CO_2

Measurement of the carbon dioxide content in air bubbles in glacial ice from cores taken at Vostok, Antarctica, show that atmospheric CO_2 levels have corresponded closely to air temperature for more than 410,000 years. Records from other ice cores show a similar pattern extending back more than 800,000 years. *(Based on Petit, J. R., Jouzel, J., et al., "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core in Antarctica,"* Nature *399: 429–36, © 1990 AAAS)*

climate models. From the 1980s to the present, atmospheric general circulation models have been coupled with mathematical models of other Earth subsystems, such as the land surface, ocean and sea ice, aerosols, and the carbon cycle.[10]

The framework for the general circulation model is that of a large stack of boxes (Figure 12.9a). Each box is a three-dimensional cell that is several degrees of latitude and longitude on each side. A typical cell is generally rectangular in shape and has an area about the size of the state of Oregon. Each cell varies in height, depending on how many cells are used to subdivide the lower atmosphere. Most models use 6 to 20 layers of cells to represent the atmosphere up to an

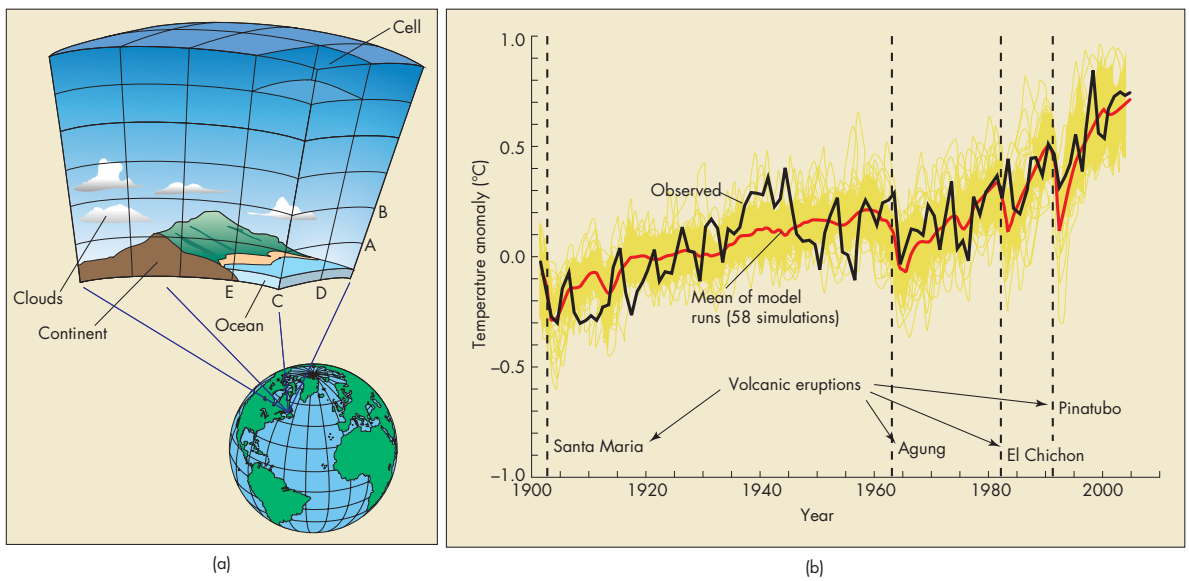


FIGURE 12.9 Modeling Climate

(a) Idealized diagram illustrating the cells used in climate models. (b) Observed (black) and predicted temperature changes 1900–2005. The predicted mean (red line) is the average of 58 different simulations, using 14 different climate models. The yellow is the variability in simulations. *(IPCC. 2007. The Physical Science Basis: Working Group I.* Contribution to the Fourth Assessment Report. IPCC. *New York: Cambridge University Press.)*

altitude of around 30 km (~19 mi.). Data are arranged into each cell, and boundary conditions are established for the overall model. Mathematical equations based on the principles of physics are used to describe the major atmospheric processes that interact between the cells. Models are run backward to see if they accurately describe historic, and even prehistoric, changes in climate. Like general circulation models for forecasting weather, global climate models are constantly being adjusted and evaluated to better make predictions.[11] Global climate models are primitive in terms of predicting details of climate but are reasonably consistent with global temperature change from 1900 to the present (Figure 12.9b).

Global climate models are valuable in solving the complex problems of climate change. These models provide information for evaluating Earth as a system. The models also identify additional data that are needed to produce better and more detailed models in the future. Today, global climate models provide useful guidance on regions that are likely to be relatively wetter or drier and hotter or colder in the future. Current models are sophisticated, and predictions from modeling are generally consistent. However, one of the greatest difficulties in using global climate models to predict future climate change is our inability to anticipate human behavior and the paths that our civilization will take in dealing with climate change.

Modeling the climate generates hypotheses that scientists can test with data. It is important to acknowledge that these models do not produce data. Models use data-linked mathematical calculations with the purpose of better understanding the global climate systems and making predictions. The most important evidence (and only data) for global warming is from the measurements in the past 150 years derived from proxy evidence (such as ocean sediments and tree rings over the past few thousand to few hundred thousand years).

12.4 CHECK your understanding

1. For climate data, define and differentiate between the instrumental record, the historical record, and the paleo-proxy record.
2. Describe several sources of paleo-proxy climate data.
3. Why is the study of carbon dioxide in the atmosphere so important?
4. What are global climate models, and why are they important?

12.5 Global Warming

Global warming is defined as the observed increase in the average temperature of the near-surface land and ocean environments of Earth during the past 60 years. A growing volume of evidence suggests that we are now in a period of global warming, resulting from burning vast amounts of fossil fuels. Does this mean we are experiencing human-induced global warming? Yes! The data collected over several decades strongly suggest that climate change from human processes, as well as natural processes, are contributing significantly to global warming.[12–14]

THE GREENHOUSE EFFECT

For the most part, the temperature of Earth is determined by three factors: the amount of sunlight Earth receives, the amount of sunlight Earth reflects (and, therefore, does not absorb), and the amount of reradiated heat retained by the atmosphere[13] (see Chapter 9, which discusses the basics of Earth's energy balance between incoming and outgoing energy).

Earth's energy balance today is slightly out of equilibrium, with about 1 watt per m^2 (W/m^2) more energy coming from the sun than is lost to space. This measure of energy, W/m^2, is energy per unit time (joules/sec) per unit area m^2. When we speak of solar energy, we use these units to represent solar power per unit area. This measure is widely used in global warming and climate change research.[12–14] Earth receives energy from the sun in the form of electromagnetic radiation (including visible light, infrarad radiation, radio waves, and X rays). Radiation from the sun is relatively short in wavelength and mostly visible, whereas Earth radiates relatively longwave infrared radiation. The hotter an object, whether it is the sun, the Earth, a rock, or a lake, the more electromagnetic energy it emits. The sun, with a surface temperature of 5800°C (~10,472°F), radiates much more energy per unit area than does Earth, which has an average surface temperature of 15°C (~59°F).

Absorbed solar energy warms Earth's atmosphere and surface, which then reradiate the energy back into space as infrared radiation.[12] Water vapor and several other atmospheric gases, including carbon dioxide (CO_2), methane (CH_4), and chlorofluorocarbons (CFCs, human-made chemicals used in air conditioners and refrigerators), tend to trap heat. That is, they absorb some of the energy radiating from Earth's surface and are thereby warmed. As a result, the lower atmosphere of Earth is much warmer than it would be if all of the infrared radiation escaped into space without this intermediate absorption and warming. This effect is somewhat analogous to the trapping of heat by the windows of a

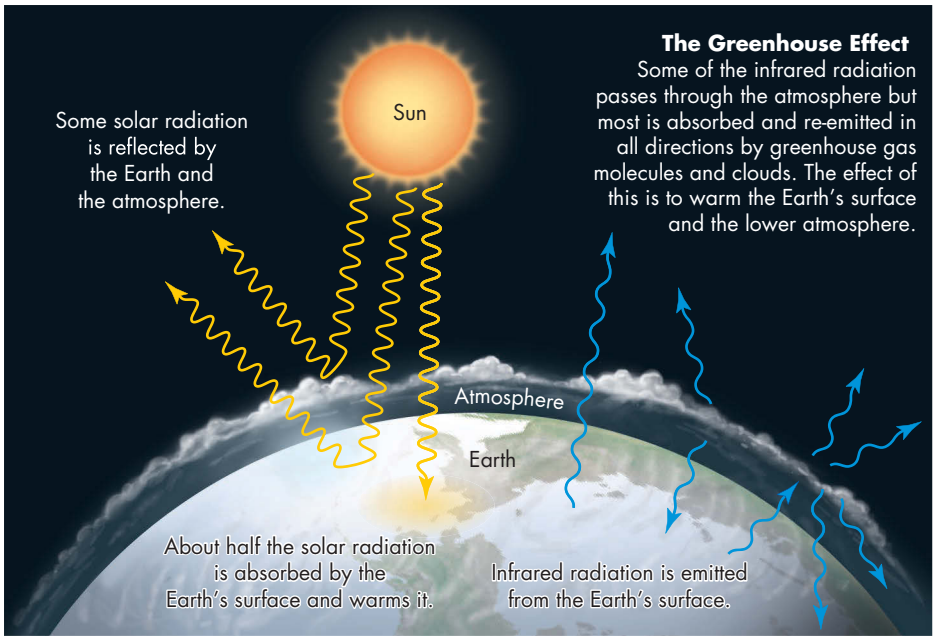


FIGURE 12.10 Greenhouse Effect

Idealized diagram showing the greenhouse effect. Incoming visible solar radiation (sunshine) is absorbed by Earth's surface, warming it. Infrared radiation is then emitted at the surface of Earth as earthshine to the atmosphere and outer space. Most of the infrared radiation emitted from Earth is absorbed by the atmosphere, heating it and maintaining the greenhouse effect. *(Based on Climate Change Connection, www.climatechangeconnection.org/science/Greenhouseeffect_diagram.htm. Accessed 11/17/13.)*

greenhouse, which allows the sun's warmth in and keeps it from reradiating back out, and is therefore referred to as the **greenhouse effect** (Figure 12.10).

It is important to understand that the greenhouse effect is a natural phenomenon that has been occurring for millions of years on Earth, as well as on other planets in our solar system. Without heat trapped in the atmosphere, Earth would be much colder than it is now, and all surface water would be frozen. Most of the natural "greenhouse warming" is due to water vapor and small droplets of water in the atmosphere. However, potential global warming resulting from human activity is related to carbon dioxide, methane, nitrogen oxides, and chlorofluorocarbons. In recent years, the atmospheric concentrations of these gases and others have been increasing because of human activities. These gases tend to absorb infrared radiation from Earth, and it has been hypothesized that Earth is warming because of the increases in the amounts of these so-called greenhouse gases. Table 12.1 shows the rate of increase of these atmospheric gases resulting from human-induced emissions and their relative contribution to the anthropogenic, or human-caused, component of the greenhouse effect. Notice that carbon dioxide accounts for 60 percent of the relative contribution.

TABLE 12.1 Rate of Increase and Relative Contribution of Several Gases to the Anthropogenic Greenhouse Effect

	Rate of Increase (% per year)	Relative Contribution (%)
CO_2	0.5	60
CH_4	<1	15
N_2O	0.2	5
O_3[a]	0.5	8
CFC-11[b]	4	4
CFC-12[b]	4	8

[a] In the troposphere.

[b] CFC—chlorofluorocarbon (human-made chemical).

Source: Data from Rodhe, H. "A Comparison of the Contribution of Various Gases to the Greenhouse Effect," *Science* 248: 1218, table 2. Copyright 1990 by the AAAS.

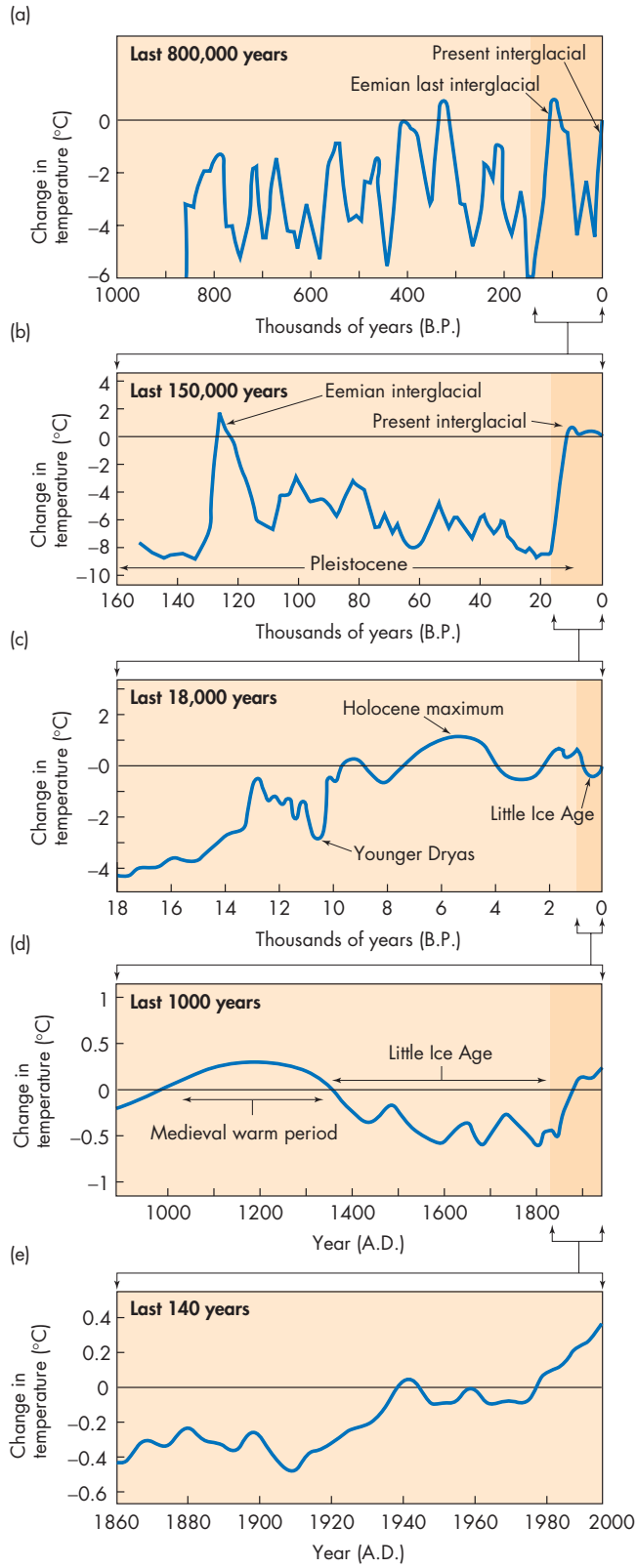
Measurements of carbon dioxide trapped in air bubbles of the Antarctic ice sheet suggest that, during most of the past 160,000 years, the atmospheric concentration of carbon dioxide has varied from a little less than 200 parts per million (ppm) to about 300 ppm.[13]

The highest recorded levels are during major interglacial periods that occurred approximately 125,000 years ago and today. Major interglacials occurred about four times during the past 400,000 years—about every 100,000 years. During each of these periods, the concentration of CO_2 in the atmosphere was similar to that of the most recent interglacial event about 125,000 years ago (see Figure 12.8).[15]

At the beginning of the Industrial Revolution, the atmospheric concentration of carbon dioxide was approximately 280 ppm. Since 1860, fossil fuel burning has contributed to the exponential growth of the concentration of carbon dioxide in the atmosphere. The change, based on measurements made from air bubbles trapped in glacial ice from approximately 1500 to 1958, is shown in Figure 12.7. The concentration of carbon dioxide in the atmosphere today is approximately 400 ppm, and it is predicted to reach at least 450 ppm—more than 1.5 times the preindustrial level—by 2050. Changes in atmospheric concentration of carbon dioxide at Mauna Loa, Hawaii, from the mid-twentieth century to today, are also shown in Figure 12.7.

GLOBAL TEMPERATURE CHANGE

The Pleistocene ice ages began approximately 2 million years ago; since then, there have been numerous changes in Earth's mean annual temperature. Figure 12.11 shows the changes of approximately the past million years on several time scales. The first scale shows the entire million years (Figure 12.11a), during which major climatic changes involved swings of several degrees Celsius in mean temperature. Low temperatures have coincided with major glacial events that have greatly altered the landscape; high temperatures are associated with interglacial conditions. Interglacial and glacial events become increasingly prominent in the scales, showing changes over 150,000 and 18,000 years. The last major interglacial warm period, even warmer than today, was the Eemian (Figure 12.11b). During the Eemian, sea level was a few meters higher than it is today. The cold period that occurred about 11,500 years ago is known as the Younger Dryas; it was followed by rapid warming to the



> FIGURE 12.11 Changes in Global Temperature

Changes in temperature over different periods of time during the past million years. Graphs (a) to (d) are over time periods of 100,000 to 1,000 years. The rapid rise from about 1900 to 2008 of nearly 0.9°C is shown in (e). Note the very rapid rise, since about 1970, of about 0.12°C per decade. See text for further explanation. *(Based on University Corporation for Atmospheric Research, Office for Interdisciplinary Studies, Science Capsule, "Changes in Time in the Temperature of the Earth,"* EarthQuest *5(1), 1997; and the UK Meteorological Office, "Climate Change and its Impacts: A Global Perspective," 1997)*

TABLE 12.2 Evidence Supporting the Late Twentieth and Early Twenty-First-Century Rise in Global Temperature: Global Temperature Data from the United States (NOAA) and Europe (WMO)

Earth's surface temperature in 2016 was the warmest year on record (since 1880) and the third year in a row to set a new record global average. Average global surface temperature in 2016 was about 0.99 degrees Celsius warmer than the mid-twentieth-century mean.
The Earth's surface temperature has risen about 1.1 degrees Celsius since the late nineteenth century.
Most of the warming occurred in the past 35 years, with 16 of the 17 warmest years occurring since 2001.

Note: A few years of high temperatures with drought, heat waves, and wildfires are not by themselves an indication of longer term global warming. Likewise, a halt in warming for a decade is not sufficient to justify saying that global warming over the next few decades will not continue.

Holocene maximum, which preceded the Little Ice Age (Figure 12.11c).

A scale of 1,000 years shows several warming and cooling trends that have affected people (Figure 12.11d). For example, a major warming trend from approximately A.D. 1100–1300 allowed the Vikings to colonize Iceland, Greenland, and northern North America. When glaciers made a minor advance around 1400 during a cold period known as the Little Ice Age, the Viking settlements in North America and parts of Greenland were abandoned.

In approximately 1750, an apparent warming trend began that lasted until approximately the 1940s, when temperatures cooled slightly. Over 1860–2000 more changes are apparent, and the event of the 1940s is clearer (Figure 12.11e). It is evident from the record that from 1860–2000, global mean annual temperature increased by approximately 0.8°C (~1.4°F). Most of the increase has been since the 1970s, with the 1990s and the first two decades of the twenty-first century having the warmest temperatures since global temperatures have been monitored. Table 12.2 lists evidence for the current warming trend.

The persistent trend of increasing temperatures over several decades (1970–2017) is compelling evidence that global warming is real and is happening. Figure 12.12a shows observed globally averaged combined land and ocean surface temperture change from 1850 to the present. Figure 12.12b shows decadal averaged data. Notice the sharp increase in the past four decades. This is the late twentieth- to early twenty-first-century rise in temperature that continues today.

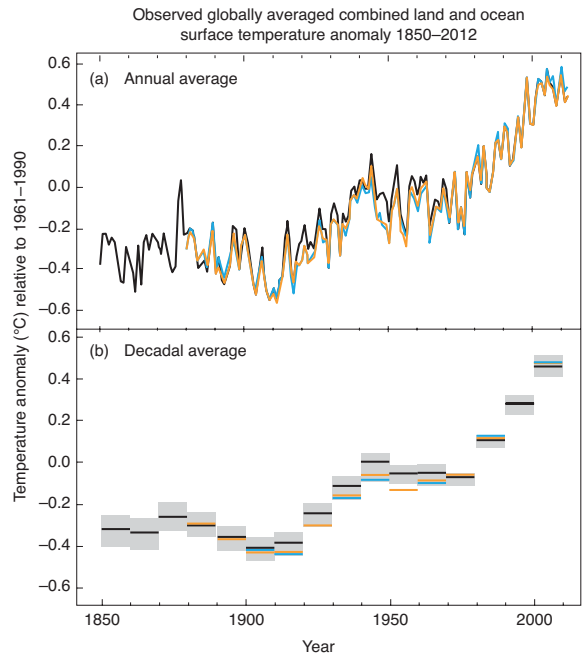


FIGURE 12.12 Changes in Global Temperature 1850–2015
(a) Annual data where different colors are different data sets. (b) Decadal average values where shaded areas are uncertainty. Notice the dramatic increase in the last four decades. *(IPCC. 2015.* Climate Change 2014: Synthesis Report. Intergovernmental Panel on Climate Change. *Geneva, Switzerland.)*

WHY DOES CLIMATE CHANGE?

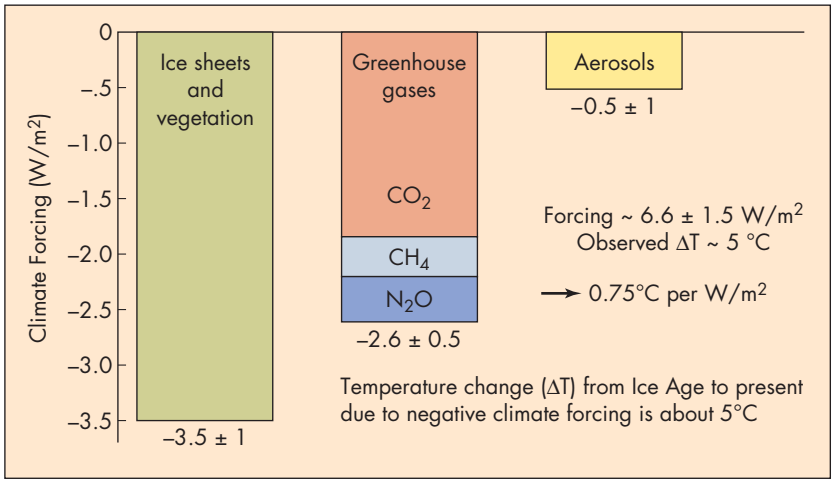
The question that begs to be answered is this: Why does climate change? Examination of Figure 12.11 suggests that there are cycles of change lasting 100,000 years, separated by shorter cycles of 20,000 to 40,000 years in duration. These cycles were first identified by Milutin Milankovitch in the 1920s as a hypothesis to explain climate change. Milankovitch realized that the spinning Earth is like a wobbling top, unable to keep a constant position in relationship to the sun; this instability partially determines the amount of sunlight reaching and warming Earth. He discovered that variability in Earth's orbit around the sun follows a 100,000-year cycle that is correlated with the major glacial and interglacial periods shown in Figure 12.11a. Earth's orbit varies from a nearly circular ellipse to a more elongated ellipse. Over the 100,000-year cycle,

when Earth's orbit is most elliptical, solar radiation reaching Earth is greater than during a more circular orbit. Cycles of approximately 40,000 and 20,000 years are the result of changes in the tilt and wobble of Earth's axis.

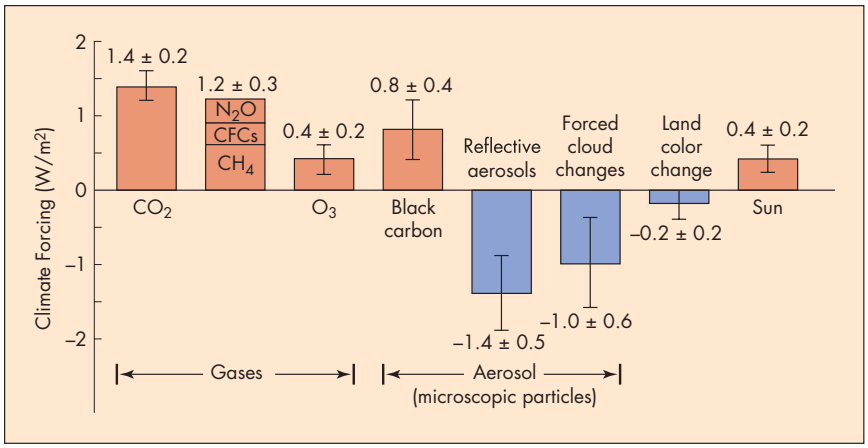
Milankovitch cycles reproduce most of the long-term cycles observed in the climate, and they do have a significant effect on climate. However, the cycles are not sufficient to produce all of the observed large-scale global climatic changes. Therefore, these cycles, along with other processes, must be invoked to explain global climatic change. Thus, the Milankovitch cycles that force (push) the climate in one direction or another can be looked at as natural processes (forcing) that, when linked to other processes (forcing), produce climatic change.[16,17] We now will consider this concept of climate forcing in more detail.

Climate forcing is defined as an imposed change of Earth's energy balance. The units for the forcing are W/m^2, and they can be positive if a particular forcing increases global mean temperature or negative if temperature is decreased. For example, if the energy from the sun increases, then Earth will warm (this is positive climate forcing). If CO_2 were to decrease, causing Earth to cool, that would be an example of negative climate forcing.[18] Climate sensitivity refers to the response of climate to a specific climate forcing after a new equilibrium has been established, and the time required for the response to a forcing to occur is the climate response time.[19] A significant implication of climate forcing is that if you maintain small climate forcing for a long enough time, large-scale climate change can occur.[12] Figure 12.13 shows the negative climate forcing that produced the last ice age 22,000 years ago (last glacial maximum).[12,19] Notice that a negative energy input change of 1 W/m^2 produces a temperature change of about 0.75°C (~1.3°F). Climate forcing in the industrial age is shown in Figure 12.14. Total positive forcing is about 1.6 W/m^2, most of which is due to greenhouse gas inputs (CO_2, CH_4, and N_2O). Figure 12.15 clearly shows that the atmospheric concentrations of these greenhouse gases have dramatically increased in the past 100 years.[13]

We now believe that our climate system may be inherently unstable and capable of changing quickly from one state to another in as short a time as a few decades.[20] However, very short or **abrupt climate change** is unlikely. Part of what may drive the climate system and its potential to change is the ocean conveyor belt, a global-scale circulation of ocean waters, characterized by strong northward movement of 12° to 13°C (~54° to 55°F) near-surface waters in the Atlantic Ocean that are cooled to 2° to 4°C (~35° to 39°F) when they arrive near Greenland (Figure 12.16).[20] As the water cools, it becomes saltier due to sea ice formation at the ocean surface. The salinity increases the water's density and causes it to sink to the bottom. The current then flows southward around Africa, adjoining the global pattern of ocean currents. The flow in this conveyor belt current is huge, equal to about 100 Amazon Rivers. The amount of warm water and heat released to the atmosphere, along with the stronger effect of relatively warm winter air moving east and northeast across the Atlantic Ocean, is sufficient to keep northern Europe 5° to 10°C (~8.5° to 17°F) warmer than it would otherwise be. If the conveyor belt were to shut down, it would have an effect on the climate of Europe. However, the effect would not be catastrophic to England and France in terms of producing extreme cold and icebound conditions.[21]



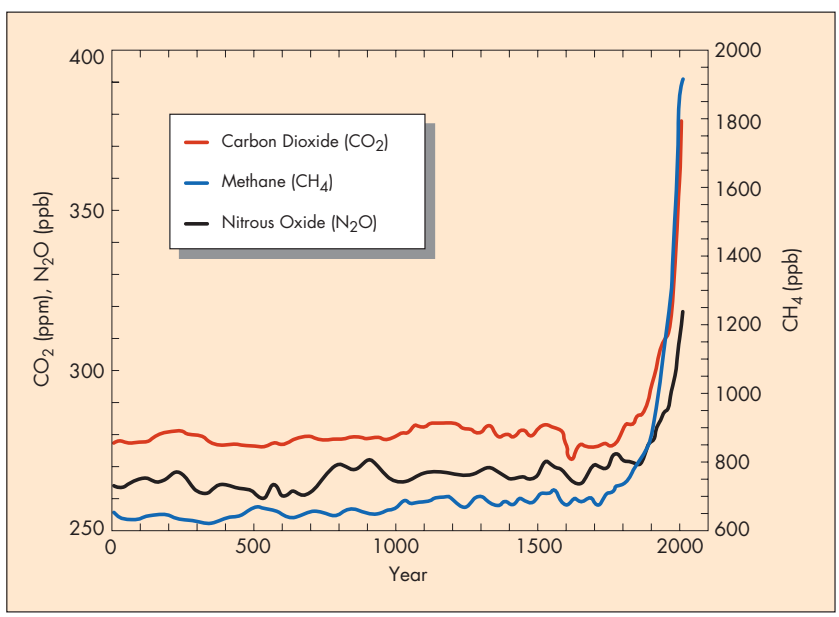
< FIGURE 12.13 Climate Forcing – W/m^2 During Last Ice Age
Negative climate forcings 22,000 years ago, when glacial ice was last at a maximum. *(Based on Hansen, J. 2003. Can we defuse the global warming time bomb? Edited version of presentation to the Council on Environmental Quality. June 12. Washington DC; also Natural Science. www.naturalscience.com.)*



< FIGURE 12.14 Climate Forcings in the Industrial Age Starting in 1750

Positive forcings warm, and negative forcings cool. Human-caused forcings in recent years dominate over natural forcings. Total forcing is about 1.6 ± 0.1 W/m^2, consistent with observed rise in air surface temperature over the past few decades. *(Based on Hansen, J. NASA Goddard Institute for Space Studies and Columbia University Earth Institute, 2003)*

- Increases of greenhouse gases (except O_3) are known from observations and bubbles of air trapped in ice sheets. The increase of CO_2 from 285 parts per million (ppm) in 1850 to 368 ppm in 2000 is accurate to about 5 ppm. The conversion of this gas change to a climate forcing (1.4 W/m^2), from calculation of the infrared opacity, adds about 10 percent to the uncertainty.
- Increase of CH_4 since 1850, including its effect on stratospheric H_2O and tropospheric O_3, causes a climate forcing about half as large as that by CO_2. Main sources of CH_4 include landfills, coal mining, leaky natural gas lines, increasing ruminant (cow) population, rice cultivation, and waste management. Growth rate of CH_4 has slowed in recent years.
- Tropospheric O_3 is increasing. The United States and Europe have reduced O_3 precursor emissions (hydrocarbons) in recent years, but increased emissions are occurring in the developing world.
- Black carbon ("soot"), a product of incomplete combustion, is visible in the exhaust of diesel-fueled trucks. It is also produced by biofuels and outdoor biomass burning. Black carbon aerosols are not well measured, and their climate forcing is estimated from measurements of total aerosol absorption. The forcing includes the effect of soot in reducing the reflectance of snow and ice.
- Human-made reflective aerosols include sulfates, nitrates, organic carbon, and soil dust. Sources include burning fossil fuel and agricultural activities. Uncertainty in the forcing by reflective aerosols is at least 35 percent.



< FIGURE 12.15 Concentrations of Greenhouse Gases During the Past 2000 Years

Atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased rapidly in recent decades. *(Based on IPCC,* The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report, IPCC. *New York: Cambridge University Press. p. 989, 2007.)*

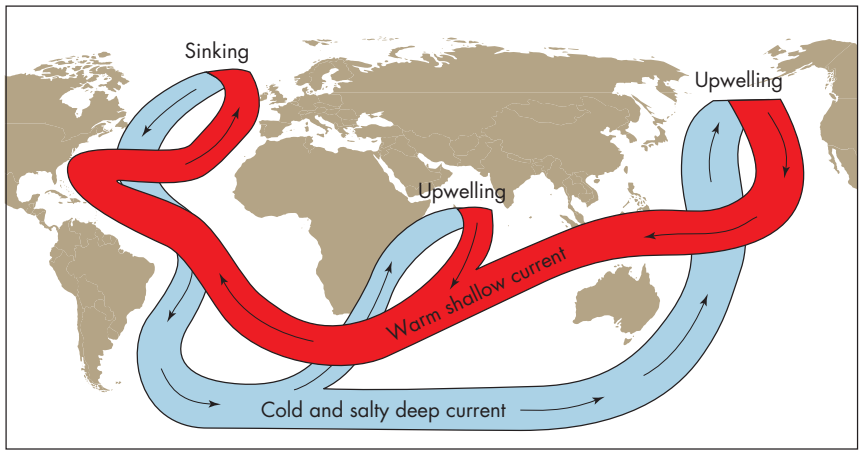


FIGURE 12.16 Ocean Conveyor Belt
Idealized diagram of the ocean conveyor belt. Although the actual system is more complex than the diagram, in general, warm surface water (red) is transported westward and northward (increase in salinity, owing to sea ice formation, is very important in the high salinity of sinking water) to near Greenland, where it cools from contact with cold Canadian air. As the water increases in density, it sinks to the bottom and flows south, then east to the Pacific, where upwelling occurs. The masses of sinking and upwelling waters balance, and the total flow rate is about 20 million m^3 (706 million $ft.^3$) per second. The heat released to the atmosphere from the warm water helps keep northern Europe warmer than it would be if the oceanic conveyor belt were not present. *(Based on Broecker, W., "Will Our Ride Into the Greenhouse Future be a Smooth One?"* Geology Today *7(5): 2–6, 1997)*

Although some scientific uncertainties still exist, sufficient evidence exists to state that:[13,14]

- There is a significant, discernible human influence on global climate
- Warming is now occurring and probably accelerating
- The mean surface temperature of Earth will likely increase by at least 2° C during the twenty-first century
- The Arctic region will continue to warm more rapidly than at midlatitude areas (as for example, the USA)
- The mean warming over the ocean will be less than over most land areas
- At daily and seasonal timescales over most land areas, there will be fewer cold and more hot temperature extremes.

Human-induced global warming results from increased emissions of gases that tend to trap heat in the atmosphere. There is good reason and lots of scientific evidence to confidently state that increases in carbon dioxide and other greenhouse gases are increasing the mean global temperature of Earth. Over the past few hundred thousand years, there has been a strong correlation between the concentration of atmospheric CO_2 and global temperature (see Figure 12.8). When CO_2 has been high, temperature has also been high and, conversely, low concentrations of CO_2 have been correlated with a low global temperature. However, in order to better understand global warming, we need to consider major forcing variables that influence global warming, including solar emission, volcanic eruption, and anthropogenic input.

SOLAR FORCING

Since the sun is responsible for heating Earth, solar variation should be evaluated as a possible cause of climate change. When we examine the history of climate during the past 1,000 years, the variability of solar energy plays a role. Examination of the solar record reveals that the Medieval Warm Period (A.D. 1000–1300) corresponds with a time of slightly increased solar radiation, comparable to that which we see today. The record also suggests that minimum solar activity occurred during the fourteenth century, coincident with the beginning of the Little Ice Age (see Figure 12.11d). Therefore, it appears that variability of the input of solar energy to Earth can partially explain climatic variability during the past 1,000 years. However, the effect is relatively small, only 0.25 percent; that is, the difference between the solar forcing from the Medieval Warm Period to the Little Ice Age is only a fraction of

1 percent.[22,23] Brightening of the sun is unlikely to have had a significant effect on global warming since the beginning of the Industrial Revolution.[24]

VOLCANIC FORCING

Upon eruption, volcanoes can hurl vast amounts of particulate matter, known as aerosols, as high as 15–25 km (~9–16 mi.) into the atmosphere. The aerosol particles are transported by strong winds around Earth. They reflect a significant amount of sunlight and produce a net cooling that may offset much of the global warming expected from the anthropogenic greenhouse effect.[13,25] For example, increased atmospheric aerosols over the United States (from air pollution) are probably responsible for mean temperatures being roughly 1°C (~1.7°F) cooler than they would be otherwise. Aerosol particle cooling may, thus, help explain the disparity between model simulations of global warming and actual recorded temperatures that are lower than those predicted by models.[26]



FIGURE 12.17 Volcanic Eruption Temporarily Cools Climate

This eruption of Mount Pinatubo in the Philippines in 1991 ejected vast amounts of volcanic ash and sulfur dioxide aerosols up to about 30 km (~19 mi.) into the stratosphere. (*USGS*)

Volcanic eruptions add uncertainty in predicting global temperatures. For instance, consider the cooling effect of the 1991 Mt. Pinatubo eruption in the Philippines (Figure 12.17). Tremendous explosions sent volcanic ash to elevations of 30 km (~19 mi.) into the stratosphere, and as with similar past events, the aerosol cloud of ash and sulfur dioxide remained in the atmosphere, circling Earth, for several years. The particles of ash and sulfur dioxide scattered incoming solar radiation, resulting in a climatic forcing of about 3 W/m^2, cooling Earth about 2.3°C (~4°F) in 1991 and 1992. Calculations suggest that aerosol additions to the atmosphere from the Mt. Pinatubo eruption counterbalanced the warming effects of greenhouse gas additions through 1992. However, by 1994, most aerosols from the eruption had fallen out of the atmosphere, and global temperatures returned to previous higher levels.[27] Volcanic forcing from pulses of volcanic eruptions is believed to have significantly contributed to the cooling of the Little Ice Age (see Figure 12.11d).[23]

ANTHROPOGENIC FORCING

Anthropogenic climate forcing refers to human-related forcing. Most important are emissions of greenhouse gases (especially carbon dioxide and emissions of aerosol particles). Evidence of anthropogenic forcing resulting in a warmer world is based, in part, on the following:

- Recent warming over the past few decades of 0.12°C (~0.24°F) per decade cannot be explained by natural variability of the climate over recent geologic history.
- Industrial age forcing of 1.6 W/m^2 (see Figure 12.14) is mostly due to emissions of carbon dioxide that, with other greenhouse gases, have greatly increased in concentration in the past few decades (see Figure 12.15).
- Climate models suggest that natural forcings in the past 100 years cannot be responsible for what we know to be a nearly 1°C (~1.8°F) rise in global land temperature (see Figure 12.14). When natural and anthropogenic forcings are combined, the observed changes can be explained (Figure 12.14).

Human processes are also causing a slight cooling. Reflection from air pollution particles (aerosols) has reduced incoming solar energy by as much as 10 percent. This is termed global dimming. Negative forcing from aerosols in the industrial age is –1.4 W/m^2 (Figure 12.14) and may be offsetting up to 50 percent of the expected warming resulting from greenhouse gases.

In summary, abundant evidence supports the hypothesis that recent (1970–2015) warming greatly exceeds the natural variability (climate forcing) and closely agrees with the response predicted from models of human induced greenhouse gas forcing.[13]

12.5 CHECK your understanding

1. What is meant by global warming?
2. What are the major greenhouse gases? Explain how the greenhouse effect works.
3. What are Milankovitch cycles, and why are they important?
4. Define climate forcing. What can you conclude from studying climate forcings in the last ice age with climate forcings in the industrial age?
5. Explain the ocean conveyor belt.
6. What is the impact of solar forcing since the Industrial Revolution?
7. Define volcanic forcing.
8. Give examples of anthropogenic forcing.
9. What are the three lines of evidence that support the hypothesis that anthropogenic forcing rather than natural forcing is responsible for most of the warming in the past few decades?

12.6 Effects of Climate Change

All climate models are consistent in predicting that warming will continue as a result of the greenhouse gases now in the atmosphere and will possibly accelerate in the coming decades. That holds true even if greenhouse gas emissions by people are almost completely eliminated—warming of about 0.5 to 1.0°C (~0.9 to 1.8°F) would still occur in coming decades. Therefore, we need to carefully examine the potential effects of such warming.

If carbon dioxide in the atmosphere doubles from pre-industrial levels, as expected, it is estimated that the average global temperature will rise about 2.0° to 4.5°C (~3.6° to 8.1°F), with significantly greater warming at the polar regions.[13] Specific effects of this temperature rise in a specific region are difficult to predict, but they include: changes in glaciers and sea ice; change in climate pattern; rise in sea level; change in the biosphere; and change in occurrences of natural hazard events such as floods, droughts, hurricane, landslides, glacial movements, wildfires, earthquakes, tsunamis, and volcanic eruptions. The above changes and hazards are not mutually exclusive and there are linkages between them. For example, melting of glacial ice contributes to sea-level rise that is linked to coastal erosion, coastal flooding, landsliding, and even volcanic eruptions and tsunamis. We will discuss the influence of human-induced global change on natural hazards individually and illustrate important linkages between them. Remember from Chapter 1 the principle of environmental unity: that our actions (in this case, burning huge amounts of fossil fuels) is setting in motion in our dynamic Earth a chain of likely and possible events that constitutes perhaps the largest challenge to our future well being and safety that humanity has faced as a result of our own activity. The famous human ecologist Garrett Harden emphasized that everything affects everything else, and "we can never merely do one thing."

GLACIERS AND SEA ICE

Global warming is resulting in accelerated melting of glacial ice of the Greenland ice sheet (Figure 12.18 and Figure 12.19) and mountain glaciers. The latter are of particular importance in Europe and South America as

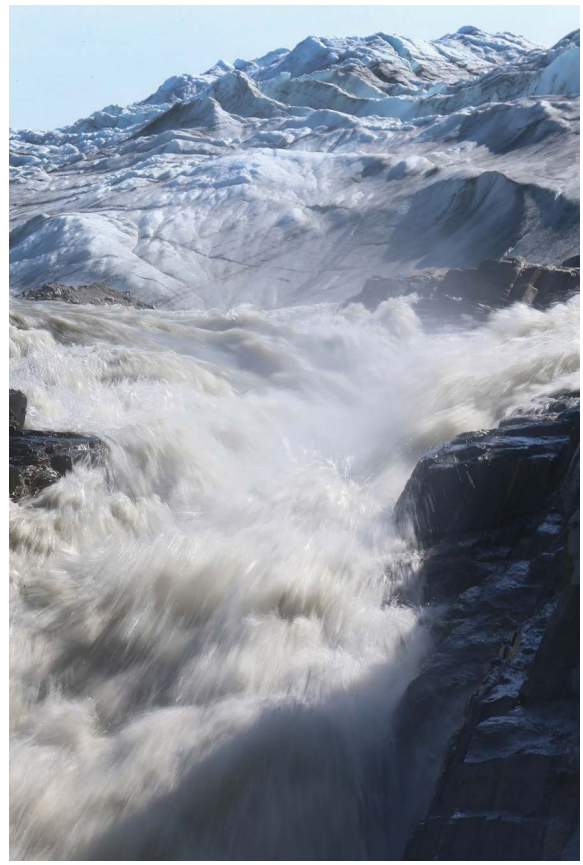
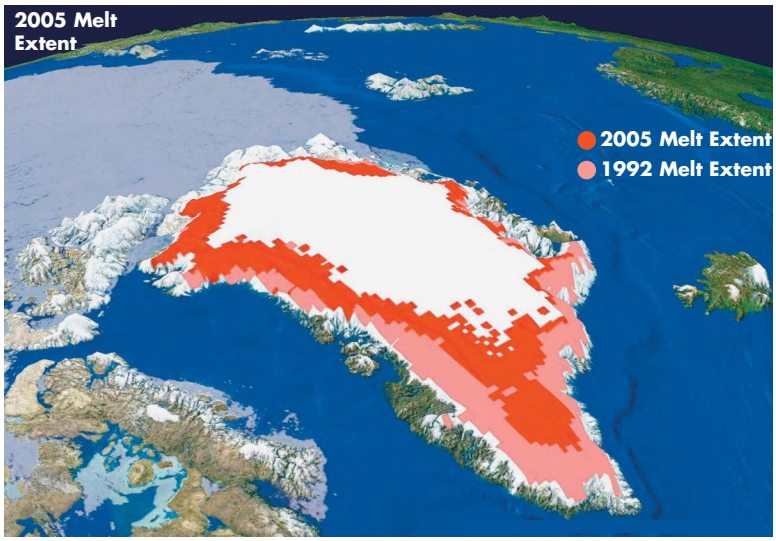


FIGURE 12.18 Shrinking of Greenland Ice Sheet
This summer meltwater stream on the Greenland ice sheet illustrates that surface melting is one of several ways that ice is being lost from the large Greenland ice sheet. The ice sheet is also losing large amounts of ice through outflow glaciers shedding icebergs into the ocean. *(Joe Raedle/Getty Images)*



< FIGURE 12.19 Increased Melting of Greenland Ice Sheet

Between 1992 (salmon colored) and 2005 (salmon and red color combined), the portion of the Greenland ice sheet that experienced surface melting during the summer increased considerably. The area of greatest increase was in the southern third of Greenland where the entire ice sheet experienced surface melting during summer months. An extreme melt event occurred in July 2012, due to a ridge of warm air over Greenland. *(Courtesy Russell Huff and Konrad Steffan/University of Colorado CIRES)*

water resources for people and ecosystems farther down the mountain. In Bolivia, a 70-year-old ski resort on a glacier is all but shut down because the small glacier on which the ski runs are built has just about disappeared.

Many glaciers in the Pacific Northwest of the United States are currently retreating (Figure 12.20); those in Europe, China, and Chile are retreating or decreasing more, in terms of thickness of ice (typically 10–30 percent of ice thickness since 1977), rather than advancing or increasing in thickness.[28,29] The increase in the number of retreating glaciers is accelerating in the Cascades of the Pacific Northwest, in Switzerland, and in Italy. Evidently, this acceleration is in response to a mean global temperature that has averaged 0.4°C (~0.68°F) above the long-term mean temperature from 1977 to 1994. On Mt. Baker in the Northern Cascades, for example, all eight glaciers were advancing in 1976. By 1990, all eight were retreating. In addition, four of 47 alpine glaciers observed in the Northern Cascades have disappeared since 1984. Most of the glaciers in Glacier National Park may be gone by 2030 and those of the European Alps by the end of the century.[28,30]

Annual melting of the Greenland ice sheet from 2002 to 2011 was about six times as great as from 1992 to



(a) (b)

∧ FIGURE 12.20 Most Glaciers Are Retreating

Global warming is the primary cause for retreat of most of the world's glaciers, like Muir Glacier in Glacier Bay National Park, Alaska, shown here. (a) Photograph taken on August 13, 1941. *(USGS)* (b) Photograph taken from the same vantage on August 31, 2004. Between 1941 and 2004, this glacier retreated more than 12 km (~7 mi.) and thinned by more than 800 m (~875 yd.). Vegetation in the foreground of (b) is now growing where there was only bare rock in 1941. *(USGS)*

2001. Melting produces surface water that flows through openings and fractures (crevasses) and down to the base of the glacier, where it lubricates the bottom of the ice, resulting in an acceleration of glacial movement. Most glaciers in the southern half of the ice sheet are accelerating and losing ice more rapidly than previously. In 2005 alone, about 200 km^3 (~48 $mi.^3$) of glacial ice was lost.[28]

When glacial ice melts and bare ground is exposed, there is a positive feedback because white ice reflects sunlight (absorbing less energy), whereas darker rock reflects less sunlight while absorbing more. The more ice that melts, the faster the warming and increased melting occur. This is a classic positive feedback cycle—warming leads to more warming. This explains, in part, why warming at higher latitudes and elevations may exceed that in other areas.[13]

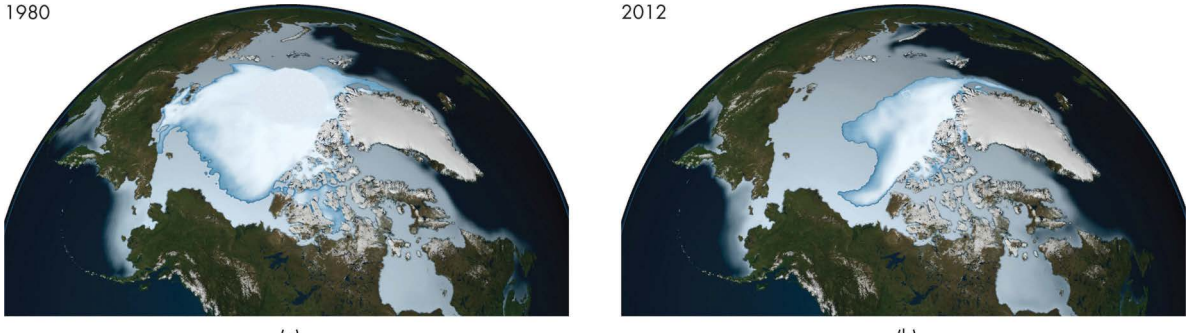
Sea ice in the Arctic Ocean is at a minimum each September. Based on satellite images, sea ice in September has declined an average of about 10 percent per decade (Figure 12.21). If these trends continue, the Arctic Ocean might be seasonally ice free on or before 2030.[31] Sea ice covered about 3.4 million km^2 (~1.3 million $mi.^2$) in September 2012, a record low for the Arctic Ocean (Figure 12.21b). The total lost ice would cover an area five times the size of Texas. However, the impact of sea ice loss is more than just total area covered by the ice. For example, the depth and age of the ice are also important. Newer ice is thinner and, as a result, stores a lesser amount of water.

Methods of studying changes of glacial ice in Antarctica and Greenland have significantly improved in recent years. Scientists now use repeated measurements from satellites to estimate the mass of ice sheets. Change in ice mass can also be measured from satellites by observing polar gravity, which changes with the mass of ice.[31]

The loss of glacial ice on Greenland between 1992 and 2011 was approximately 2700 +/– 930 billion metric tons (Gt) of ice. During the same period, loss of glacial ice on Antarctica was about 1350 +/– 1010 Gt of ice. Thus, during the period of measurement, Greenland lost about twice as much ice as did Antarctica. The loss of the glacial ice on both land masses during this period is equivalent to increasing mean sea level by 11.2 +/– 3.8 mm (0.44 +/– 0.15 in.).[31]

12.1 CASE study Loss of Glacial Ice in Antarctica

Antarctica is also losing sea ice and glacial ice. The loss of glacial ice is greatest at the west end of Antarctica, which has been losing ice since at least 2000. The Antarctic Peninsula (the relatively narrow land that points toward South America) is known to be one of the most rapidly warming regions on Earth. New studies suggest that the warming extends well beyond the peninsula to include most of West Antarctica. Although the trend is partly offset by East Antarctic's cooling in the autumn, the trend for Antarctica is positive climate forcing, resulting in warming. The causes of warming are complex, but they require changes in atmospheric circulation with temperature changes (warmer sea surface water and sea ice). The most likely direct cause is anthropogenic greenhouse gas forcing, resulting from increasing concentrations of greenhouse gases in the atmosphere.[31,32] On the other hand, the East Antarctic ice sheet has been growing in volume, albeit at a relatively low rate compared to the rate of loss of the West Antarctic ice sheet. The increase in the mass of



▲ FIGURE 12.21 Decreasing Arctic Sea Ice
Arctic sea ice is seasonal, growing during the northern hemisphere winter and shrinking to a minimum in late summer (September). Since arctic sea ice data collection began in 1980 (a), annual minimum sea ice has decreased by about 10 percent per decade, reaching an all time low in September of 2012 (b). *(From NOAA)*

glacial ice in the East Antarctic ice sheet is the result of increased snowfall in that part of Antarctica. Increased snowfall results because of increased moisture in the atmosphere as temperatures warm (keep in mind that "warm" here is a relative term, as temperatures in Antarctica are always very cold).

Melting of glacial ice has increased on the West Antarctic ice sheet, due in part to acceleration of the collapse of the ice shelf in the sea. Large icebergs break off from the ice sheets at the coast, falling into the sea. There was a massive 6200 square kilometer (2400 square mile) collapse of part of the Larson ice shelf on the Antarctic Peninsula in July of 2017. The area of ice that broke off was about the size of the state of Delaware, and the weight of that ice was about 1 trillion metric tons. The collapse was predicted for years but occurred suddenly, much to the surprise of the general public. More large collapses are expected as the Antarctic continues to warm. When broad ice shelves are present, they tend to buttress the glaciers and slow down the movement of the ice toward the ocean. With the loss of ice sheets, glacier movement increases, sometimes surging (like the flow of maple syrup when the cap is removed), and more glacial ice enters the sea. Melting sea ice does not raise sea level, but melting glacial ice does.

As Earth warms, more snowfall on Antarctica is predicted. Satellite measurement from 1992 to 2003 suggested that the East Antarctic ice cap on Antarctica increased in mass during the measurement period by about 50 billion tons per year[33] (a very small amount, given the enormous size of Antarctica—less than 0.5 percent of the land mass, covered to a depth of 1 m (~3 ft.)). Another study, using computer simulation and ice core records, reported that there has been no statistically significant increase in snowfall over Antarctica since the 1950s, suggesting that there is neither a reduction of sea-level rise by increased Antarctic snowfall nor an increase in the mass of glacial ice that would store water.[34] What is clear is that Antarctica is a complex place where more basic data research is needed to better understand the consequences of global warming.

In summary, although there is considerable variability in the rate of loss of glacial ice in Greenland and West Antarctica and, in some years, there may be an increase in glacial ice, measurements from 1992 to 2012 clearly suggest a continuous loss of glacial ice at both polar regions.[31]

Glacial Hazards Although at first thought, glaciers may not seem to present a particularly threatening hazard to people, that is not the case. Glaciers are huge, actively flowing masses of ice and rock debris whose movement and melting have been responsible for property damage, injuries, and deaths. Their irregular, cracked surfaces have always presented hazards to people crossing them for scientific exploration or mountaineering, and surface snow may hide deep cracks in the ice, known as crevasses, into which a traveler may fall. On some steep slopes, glacial ice falling from above is an additional hazard.

Changes in the flow of glaciers present hazards that have been well-documented, particularly in the Alps of southern Switzerland.[35] Glaciers can expand or surge and overrun villages, fields, roads, or other structures. They may also advance and cross a stream valley, producing an ice dam and temporary lake. Such a dam can lead to major downstream flooding if lake water undercuts or spills over the ice dam or if the dam is otherwise destroyed. When glaciers move from the land into the sea, large blocks of ice often break off from the front of the glacier and drop into the water in a process known as calving. This process is spectacular to observe—at a distance, that is—because the blocks are often as large as a house or a small building. Calving produces blocks of floating ice, known as icebergs, which can float into shipping lanes and create a hazard to navigation. This danger was dramatically illustrated on April 14, 1912, when the *Titanic*, a luxury ocean liner on its maiden voyage from England to the United States, struck an iceberg and sank in the North Atlantic. That tragic accident claimed 1,517 lives. It is interesting that large icebergs may also be beneficial to us. They are being looked at as potential sources of fresh water if they could be towed economically to areas where water is scarce.

CLIMATE PATTERNS AND METEOROLOGICAL HAZARDS

The nature and extent of future impacts from climate change with more extreme meteorological events such as floods and hurricanes result from risk. The risk depends not only on the extreme events that occur, but also on exposure to people and property at risk, as well as their vulnerability (see Chapter 1).

Wet regions will get wetter and dry regions drier in the future. Global warming is changing the frequency and increasing the intensity of violent storms as warming oceans feed more energy into the atmosphere.[13] For example, hurricanes are apparently becoming more

intense, as are the energy and precipitation in atmospheric rivers (see Chapter 6) that may deliver extreme rain events with a warmer world. More or larger coastal storms will increase the hazard of living in low-lying coastal areas, many of which are experiencing rapid growth of human populations. Global and regional climatic changes also have an effect on the incidence of hazardous natural events, such as storm damage, landslides, drought, and fires. These hazards are illustrated by El Niño, which is a natural climatic event that occurs on an average of once every few years. **El Niño** is both an oceanic and an atmospheric phenomenon, involving unusually high surface temperatures in the eastern equatorial Pacific Ocean and droughts and high-intensity rainstorms in various places on Earth.[36]

El Niño events probably start from random, slight reductions in the trade winds that, in turn, cause warm water in the western equatorial Pacific Ocean to flow eastward (Figure 12.22). This change further reduces the trade winds, causing more warm water to move eastward, until an El Niño event is established.[36]

El Niños are thought to bring about an increase in some natural hazards on a nearly global scale by putting a greater amount of heat energy into the atmosphere. The heat energy in the atmosphere increases as more water evaporates from the warm ocean to the atmosphere. The increase of heat and water in the atmosphere produces more violent storms, such as hurricanes. Figure 12.23 shows the extent of natural disasters that have been attributed, in part, to the El Niño event of 1997–98, when worldwide hurricanes, floods, landslides, droughts, and fires killed people and caused billions of dollars in damages to crops, ecosystems, and human structures. Australia, Indonesia, the Americas, and Africa were particularly hard hit. There is some disagreement about how much damage and loss of life are directly attributable to El Niño, but few disagree on its significance.[37,38] We do not yet completely understand the cause of El Niño events. They occur every few years, to a lesser or greater extent, including the large El Niño events of 1982, 1997, and 2015.

El Niño events can cause havoc by increasing the occurrence of hazardous natural events, and there is concern that human-induced climate change may, through global warming, produce more and stronger El Niño events in the future. This effect would result, in part, because burning more fossil fuels and emitting more greenhouse gases into the atmosphere will further warm the oceans, and differential warming in various parts of the ocean may increase the frequency and intensity of El Niño events in the Pacific Ocean.

The opposite of El Niño is La Niña, in which eastern Pacific waters are cool, and droughts rather than floods may result in Southern California. The alternation from El Niño to La Niña is a natural Earth cycle that has only recently been recognized.[39]

Decadal Oscillations Storm tracks and, thus, climate and weather in North America and Western Europe are influenced by the natural climate phenomena known as decadal oscillations. Examples include the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO), and the North Atlantic Oscillation (NAO).[40]

The PDO is recognized in the North Pacific Ocean by a relatively warm surface water (positive) phase or relatively cool surface water (negative) phase. The PDO changes phases on average every 20 to 30 years, alternating relatively wetter and warmer (positive phase) or drier and cooler (negative phase) cycles. The PDO has important climatic and ecologic implications

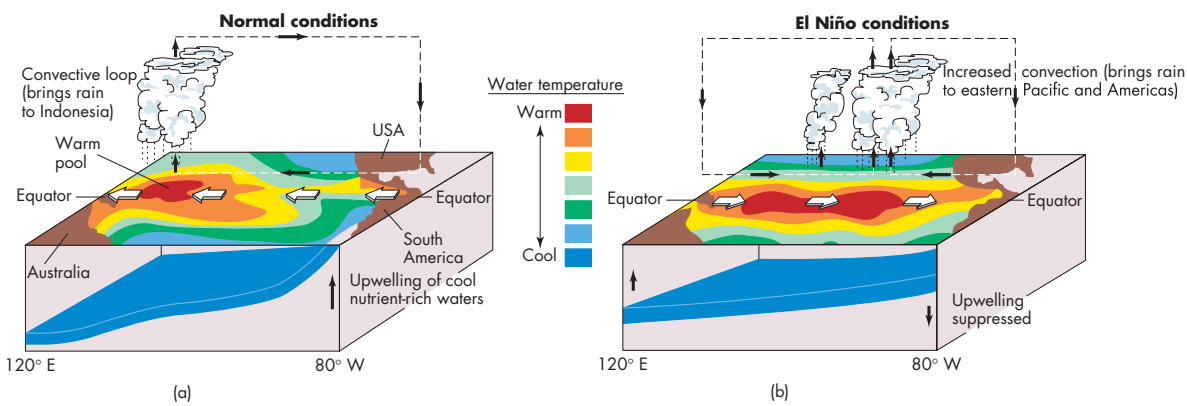
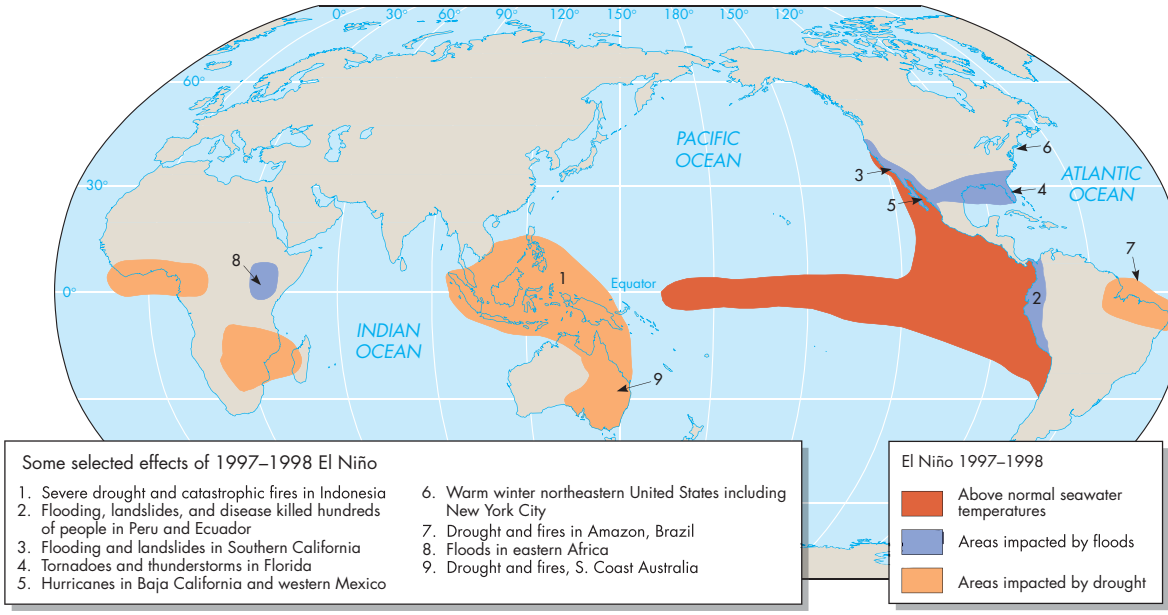


FIGURE 12.22 Effects of El Niño

Idealized diagrams contrasting (a) normal conditions and processes with (b) those of El Niño. *(Based on National Oceanic and Atmospheric Administration. (www.elnino.noaa.gov/)*



▲ FIGURE 12.23 The 1997–1998 El Niño Event

Map showing the general extent of the El Niño effects and the regions damaged by floods, fires, or drought.
(Data from National Oceanic and Atmospheric Administration, 1998)

for people (rainfall and drought) and marine resources (especially salmon).

The AO and NAO work in the same direction. The positive states of the AO and NAO are characterized by the existence of a strong polar vortex that helps to constrain cold arctic air further north. On the other hand, a negative AO and NAO is characterized by weaker atmospheric pressure in both the subtropics and subarctic. This produces a weakened polar vortex, which allows breakouts of cold air from the Arctic to move further south. This brings cold temperatures to the East Coast of the United States. There is not a general movement to the south of cold air masses, but there are periodic breakouts of cold that extend southward as the southern jet stream dips toward lower latitudes. This allows cold air to move south, both in the United States and in parts of Europe.[40]

In summary, we now know that natural oscillations of the ocean, linked to the atmosphere, can produce warmer or cooler periods for a few years or a decade or more. The effects of the oscillations can be as much as 10 times as strong in a given year as the long-term warming that we have observed over the last century. The changes may be considerably larger over a period of a few decades than our human-induced climate change. By comparison, the annual increase in warming, thought to be due to human activity (1970–2000), was about 0.02°C (~0.04°F) per year. Some scientists have speculated that the cold winter of 2009–10 was a result of natural ocean-atmospheric oscillations. Scientists have learned by studying the phenomena of periodic cycles in the Pacific, Atlantic, and Arctic areas that our climate system is incredibly complex. As a result, interactions with global warming can also be complex. Putting it all together, we now have a better explanation for changes in winter storms from year to year in terms of interactions between both natural cycles and global warming.

Global rise in temperature is changing rainfall patterns, soil moisture relationships, and other climatic factors that are important to agriculture. Scientists have predicted that some northern areas such as Canada and Eastern Europe may become more productive, whereas others, including the southwestern United States, will become more arid. Stable or expanding global agricultural activities are crucial to people throughout the world who depend on the food grown in the major grain belts. Hydrologic changes associated with climatic change resulting from global warming might seriously affect food supplies worldwide. Less water may be available in California and the San Joaquin Valley, where much of the fruits and vegetables for the United States are raised. Much of the irrigation water comes from runoff from spring snowmelt in the Sierra Nevada to the east of the valley. With global warming, winter rainfall will likely increase, but the snowpack will be less. As

a result, runoff will be more rapid, filling reservoirs before it is needed to irrigate crops. Water may have to be released from filled reservoirs and lost to the sea.

A lesson learned from the Medieval Warm Period 1,000 years ago is that warming and reduced rainfall in the southwestern United States, Mexico, Central America, and parts of Africa, China, India, and Southeast Asia may result in prolonged (intergenerational) drought that will threaten water supply and the ability to grow crops. As a result, if long droughts occur with global warming, the most serious potential threat is that we will not have an adequate supply of food for the expected 9 to 10 billion people by 2050.

SEA-LEVEL RISE

A rise of sea level is a potentially serious problem related to global warming. Global ocean temperature to a depth of at least 3 km (~1.9 miles) has increased since about 1960. The oceans of the world, in that time, have absorbed about four-fifths of the heat that has been added to Earth's climate system.

Warming of the oceans causes the water to expand (thermal expansion), producing a rise in sea level. The rate of sea-level rise resulting from thermal expansion from 2005 to 2015 is estimated to be about 1.0 mm (0.04 in.) per year (Figure 12.24).[41]

Added water (predominantly melting of glacial ice) is the largest contributor to sea-level rise, at about 2.0 mm (0.08 in.) per year from 2005 to 2015 (approximately two-thirds of observed rise of about 3 mm (0.12 in.) per year from 2005 to 2015 (Figure 12.24).[41] Keep in mind that sea-level rise in a specific location such as Southern California, Hawaii, or South Florida may be more or less than the global average of about 3 mm per year. This may result from subsidence, erosion, or ocean currents. For example, at Santa Barbara, California, the rate is less than 1 mm per year, and at South Florida, the rate probably exceeds 5 mm per year.

Melting of sea ice (floating ice) does not cause a rise in sea level (you can verify this by placing ice in a glass of water and observing the water level in the glass while waiting for the ice to melt).

Several tentative conclusions may be put forth concerning rise in sea level:

- Both thermal expansion and melting glacial ice have contributed significantly to observed sea-level rise since 1993.
- The difference between the observed global and local rise in sea level is considerable, suggesting that additional research is needed to better understand sea-level rise.
- The rates of both thermal expansion and melting glacial ice are accelerating.
- The contribution of the Greenland Ice Sheet to global sea-level rise has increased several times in recent decades, consistent with surface observations of accelerated melting of glacial ice.

Estimates of the rise expected in the next century vary widely. Global mean sea level, with high confidence from scientists, will rise at least 20 cm (~8 in.), but no more than 2.0 m (6.6 ft.), by 2100.[42] Precise estimates are not possible at this time. However, a 20 cm (~8 in.) rise in sea level would have significant environmental impacts. Such a rise could cause increased coastal erosion on open beaches of up to 40 m (~130 ft.), rendering buildings and other structures more vulnerable to waves generated from high magnitude storms. In areas with coastal estuaries, a 20 cm (~8 in.) sea-level rise would cause a landward migration of existing estuaries, again putting pressure on human-built structures in the coastal zone. Communities would have to choose

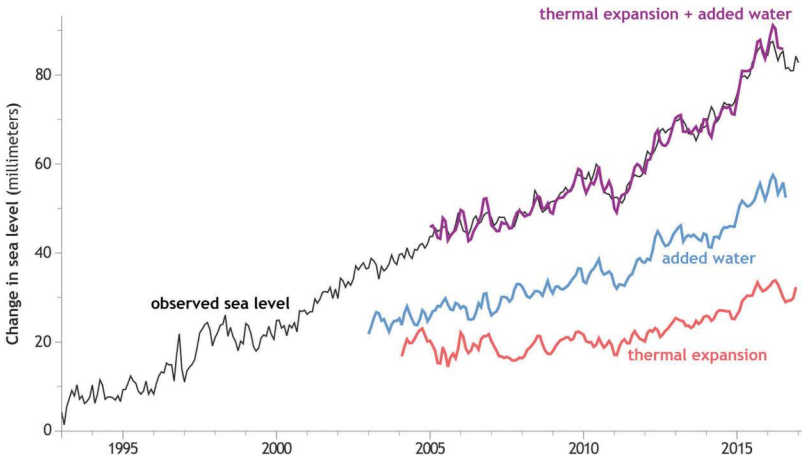


FIGURE 12.24 Relative Contribution to Sea-Level Rise
Melting glacial ice and thermal expansion are the two main components of sea-level rise. *(Lindsey, R. 2016. Climate change: global sea level. www. climate.gov)*

between making substantial investments in controlling coastal erosion or allowing beaches and estuaries to migrate landward over wide areas.[13,42,43] A sea-level rise of about 40 cm (~16 in.) would flood the San Francisco International Airport and parts of San Francisco Bay (Figure 12.25).

The coastline of northwestern and northern Alaska is experiencing rapid erosion from rising sea level, melting permafrost soil, and loss of sea ice that can protect a coastline from erosion.[44] Some small islands may disappear, and some villages have already been moved inland.

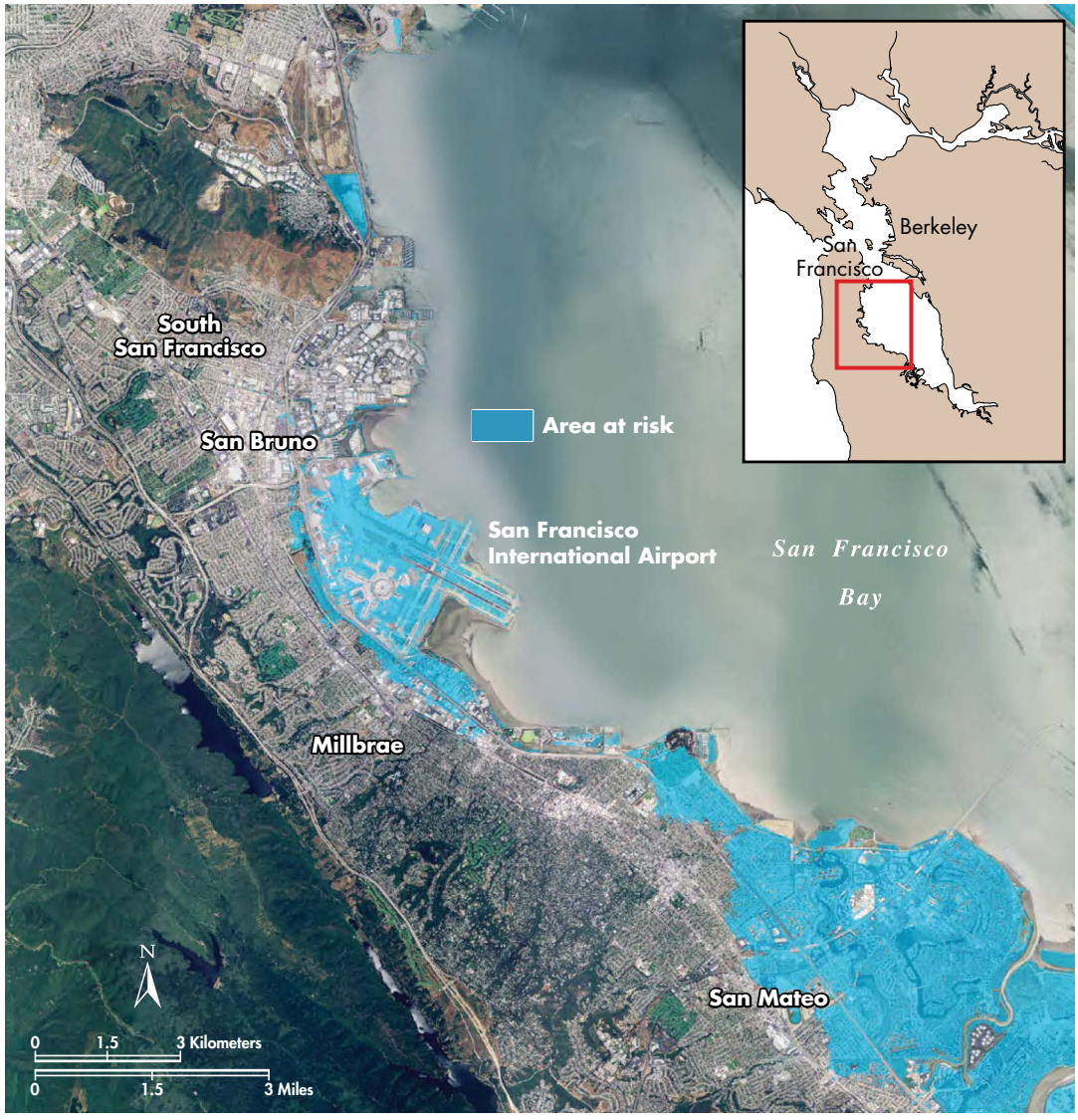


FIGURE 12.25 San Francisco Airport at Risk

A sea-level rise of 40 cm (~16 in.) would inundate densely developed low-land regions along the San Francisco Bay, including the San Francisco International Airport. *(Inundation data used in these maps do not account for existing shoreline protection or wave activity. These maps are for informational purposes only. Users agree to hold harmless and blameless the State of California and its representatives and its agents for any liability associated with the use of the maps. The maps and data shall not be used to assess actual coastal hazards, insurance requirements, or property values or be used in lieu of Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA).)*

12.2 CASE study

Disappearing Islands: Tuvalu, South Pacific

Rising sea level is already threatening some small islands in the tropical Pacific Ocean. Let's think a little deeper. The island nation of Tuvalu consists of about six atolls and three islands (Figure 12.26). People first inhabited the islands of Funafuti and other atolls of Tuvalu about 2,000 years ago when stable islets formed.[45–47] The population now totals nearly 11,000, with well over half living on the main island of Funafuti. Because total land area is small, only 26 km^2 (~10 $mi.^2$), Tuvalu's population density is a very high 423 persons per square kilometer. Global rise in sea level during most of the twentieth century was about 1.8 mm (~0.07 in.) per year as a result of global warming. The rate increased to about 2.5 mm (~0.1 in.) per year during the last decade of the twentieth century and about 4 mm (~0.16 in.) per year during the first decade of the twenty-first century. In 50 years' time, sea level will be about 200 mm (~8 in.) higher. Although scientists use models to predict the amount of global sea-level rise, current sea-level rise at Tuvalu for a particular year cannot be recognized, as the change is small relative to short-term seasonal effects of changing trade winds (200 mm) and natural climate cycles that span a few years, such as El Niño and La Niña events (500 mm [~20 in.]). However, effects of rising sea level over several decades will become apparent as increasing erosion begins to threaten the stability of the islets of Tuvalu by eroding the more resistant underpinnings of these islets.[45–47]

The prediction of future changes of Tuvalu is complex and related to the geologic history of the atolls, linked to past changes in sea level that are responsible for the atolls we observe today. Recent sea-level rise is now threatening Funafuti Atoll, especially during high tides that enhance wave attack and flooding. During high tide flood events, people report water bubbling up from the ground, contributing to the flooding of low-lying areas (Figure 12.27). With continued sea-level rise, the future ability of Funafuti and other atolls to support people is uncertain. The 11,000 people on Funafuti could become the first to be displaced by rising sea level.

The islands of Tuvalu do not have streams or rivers to supply fresh water. As with most islands, there is a lens (of variable thickness) of fresh groundwater that rides on top of salt water.[45,46] Therefore, Tuvalu has little potable (drinking) water, and most of the land will not support agriculture. Study of groundwater at the Fongafale Islet, a small island 16 km long and 400 m wide (~10 mi. long and 0.25 mi. wide) on the northeastern side of Funafuti Atoll, suggests that the area is vulnerable to rising sea level and tidal changes (tidal forcing). As much as half the islet is reclaimed swampland, filled with porous coral blocks. Shallow,

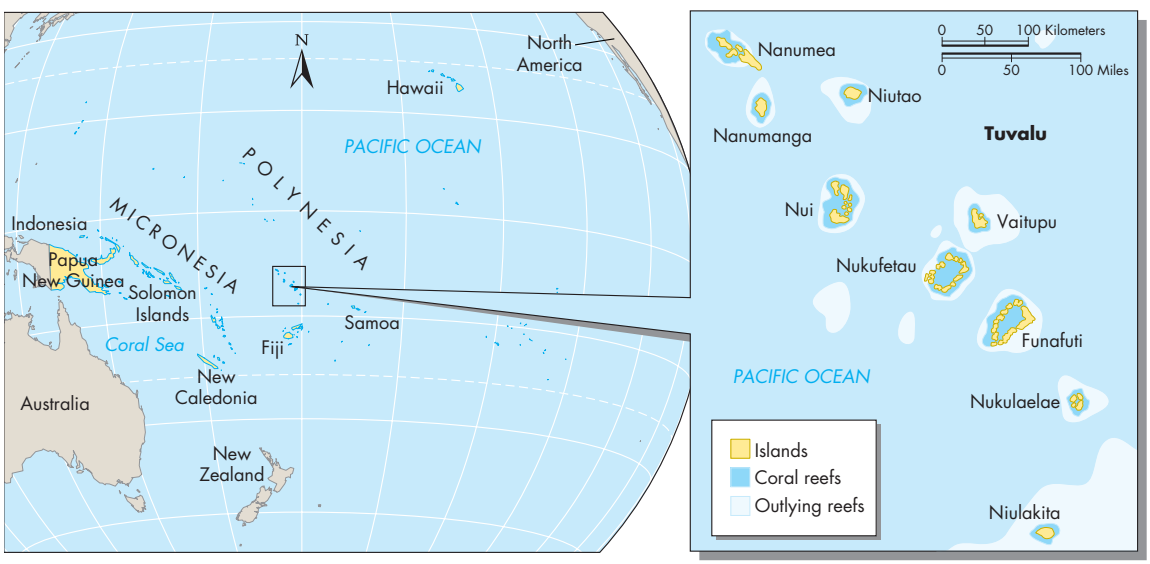


FIGURE 12.26 Islands of Tuvalu, South Pacific Ocean
Many South Pacific islands are at risk of losing land due to sea-level rise that will result from global warming. Tuvalu, a nation of low-elevation Polynesian islands, is especially vulnerable to hazards linked to climate change.

thin sheets of freshwater and brackish water (less salty than seawater but saltier than freshwater) are present in the islet, but there are no thick freshwater lenses that are often present in other atoll islands of similar size. Thin freshwater lenses are found at elevations above general high tide or below taro swamps (taro is a cultivated tuber plant, a food staple that can be grown in swampy ground), but at lower elevations, periodic salinization (increase in salinity of the soil) occurs in phase with tidal cycles. The thin nature of the brackish and freshwater lenses suggests that taro fields and fresh groundwater resources are very vulnerable to increasing salinization as climate changes and sea-level rises.[46] Assessing the vulnerability of the water resources will require continued study of the linkages between topography, geology (uplift, subsidence, erosion, and deposition), and potential climate change with sea-level rise.

On February 28, 2006, maximum sea level on Funafuti was about 3.4 m (~11 ft.) on an island where the average elevation is about 2 m (~7 ft.). Widespread flooding occurred (Figure 12.27). Local people on the island call this event the "King Tide," which now occurs once or twice per year. These floods damage plants by bringing salt water into contact with the roots, and they degrade the freshwater resources as the water table rises. Tide gauge data, as well as satellite altimetry data, suggests that in the past 18 years, sea level has risen above 3.2 m (~10 ft.) 23 times. Compilations of sea-level trends from 1977 to 2011, utilizing tide gauge records, suggest that sea-level rise is about 3.7 ± 2.9 mm (~0.15 ± 0.11 in.) per year, which is very imprecise. What the record does show is that, if this rate is correct, sea level will rise approximately 0.4 m (~1.3 ft.) per century. However, the tide gauge records show large fluctuations above 0.6 m (~2 ft.) every few years, which is about twice as high as the projected rise of sea level over the next 100 years. These transient (short-lived) rises in sea level are likely due to El Niño and La Niña events, which push the water first east and then west across the Pacific Ocean.[47]

Recent coastal erosion of the Funafuti Atoll shorelines is modest because the emergent mid-Holocene reef rubble that is cemented together protects modern unconsolidated calcareous sand from direct wave attack (Figure 12.28). The main shoreline modification over recent years has been accretion (building up) rather than erosion of large rubble ramparts as, for example, those installed during Cyclone Bebe in 1972.[47]

Atoll formation in Tuvalu is intimately related to reef growth and erosion and to changing sea level. During the past 20,000 years, sea level has been anything but stable. Atolls such as Funafuti in Tuvalu have formed by the following general processes:[47]

- During the Last Glacial Maximum (LGM), sea level was about 120 m (~400 ft.) lower than today, with erosion of the carbonate (limestone) platforms present in the area.
- Following the LGM, sea level rose, and carbonate platforms grew with the sea-level rise. The modern Holocene reef began building about 8,000 years ago, and sea level reached a peak known as the mid-Holocene highstand (the time during which sea level is at its highest) about 4,000 years ago. The reefs grew above present sea level during this highstand and are the backbone of the stable atoll islets that rim the atoll today.
- Since the mid-Holocene highstand, sea level has dropped about 2.3 m (~7.5 ft.) on Tuvalu. This has allowed the emergence of the reef islets, which were discovered and colonized by seafaring people about 2,000 years ago.



FIGURE 12.27 "King Tide" on Funafuti, 2006
Regular seasonal flooding on Funafuti affects everyone on this densely populated island. *(Ashley Cooper/Corbis)*



FIGURE 12.28
White material is sand on top of older mid-Holocene coral reef, which provides a buffer to erosion. *(William Dickenson)*

Today, the atolls of Tuvalu are marginal environments for people. The surfaces (reef islets) are generally less than 3 m (~10 ft.) above the sea. As sea level continues to rise, sometime between 2070 and 2140, the islets will likely be overtopped. It should be pointed out that there are major uncertainties involved in predicting future sea level, and these dates are more of an indication of when that will likely happen than a conclusion based upon analysis. However, before overtopping takes place, the reef islets will become unstable and increasingly vulnerable to wave attack. In fact, they might well be seriously eroded before overtopping occurs. When this happens, the islets will likely be unfit for human occupation. If the indicated rise in sea level occurs, then the people of these atoll islets have between 60 and 130 years to prepare for and adapt to changing conditions.

Adaption to changing conditions on Tuvalu islands may eventually become unfeasible, and people will need to migrate to places higher above sea level. Some residents have already left the country, migrating to Fiji or New Zealand. Potential adjustments in coming decades to sea-level rise and erosion, along with flooding, on Tuvalu include the following:

- Defending the coast with seawalls
- Planting mangrove trees along the coast to buffer islets from wave attack
- Planting salt-resistant crops for human consumption, so that agricultural activities may continue
- Improving storage of rainwater to augment freshwater supply or importing water.

WILDFIRES

There is a complex relationship between climate change and fires, and the two phenomena interact on a variety of levels. Global warming is predicted to lead to an increase in droughts, which will set the stage for wildfires. For example, scientists in Spain studied a strip of Mediterranean coastline between 1968 and 1994, comparing the number of forest fires to the temperature and aridity of the area. They found that as the coastal area warmed and became more arid, both the number of fires and the size of the area burned increased.[48] Another investigation used four different global circulation models (GCMs) for the atmosphere. Historical weather data were input into the models to project forest fire danger levels in Canada and Russia under a warmer climate. These models suggested that there will be more frequent and severe forest fires, and that the number of years between successive fires in a given location will decrease.[48,49]

LANDSLIDE HAZARD

Worldwide, landslides kill several tens of thousands of people per year. Future global change that involves increase in temperature, as well as amount, frequency, and intensity of precipitation events in landslide-prone areas, will likely increase the occurrence of many types of landslides and from shallow slides, such as soil slips, debris flows, and rockfalls (see Chapter 7) associated with intense precipitation. Deeper, larger slides might involve much larger areas and cubic kilometers of slide material. For example, if the flank of a volcano on the coast or island were to collapse (slide) suddenly into the sea, the slide could cause a tsunami.[50,51] Several landslide-linked tsunami in the past few thousand years occurred (before the human-induced warming), causing widespread damages and deaths (catastrophes). Global warming linked to melting ice, rock weathering, raising ground water tables, and more intense rainfall reduces slope stability on high, steep slopes of volcanoes or other coastal rock slopes. These changes in rock and water will increase the probability of large, damaging landslides. Finally, if the leading edge of a glacier retreats upslope, blocks of ice may fall off in ice avalanches into the valley below, destroying property and perhaps taking human lives. For example, in 1962, a combined ice and debris avalanche, known as the Huascaran Avalanche, killed 4,000 people and destroyed six villages in Peru. The avalanche moved approximately 16 km (~10 mi.) from its source as it descended almost 4000 m (~13,000 ft.) of vertical elevation. A similar avalanche in Peru, triggered by a great earthquake in 1970, killed an estimated 20,000 people while burying several villages in debris (Figure 12.29).[35] More recently, in September 2002, a huge mountain glacier broke loose in southern Russia, sending a torrent of ice, mud, and rocks downslope. The debris buried villages and killed at least 100 people.

Rapidly moving landslides that cause many deaths in the tropics and subtropics are associated with high steep slopes, shallow soil, and abundant vegetation, as, for example, in Central and South America. A common landslide trigger is intense rainfall on saturated soil that will likely increase with global warming. Landslide-prone areas that have rapid population growth and people pushed by poverty to live on steep slopes (as, for example, in Brazil) will be faced with increasing exposure and vulnerability to the landslide hazard. As a result, the total risk increases (see Chapter 1).[50]

High mountain areas in the Alps, Himalayas, and Alaska are also warming. As ice that previously stabilized broken rock on slopes melts, the slope stability will make large to small landslides more likely.[51]

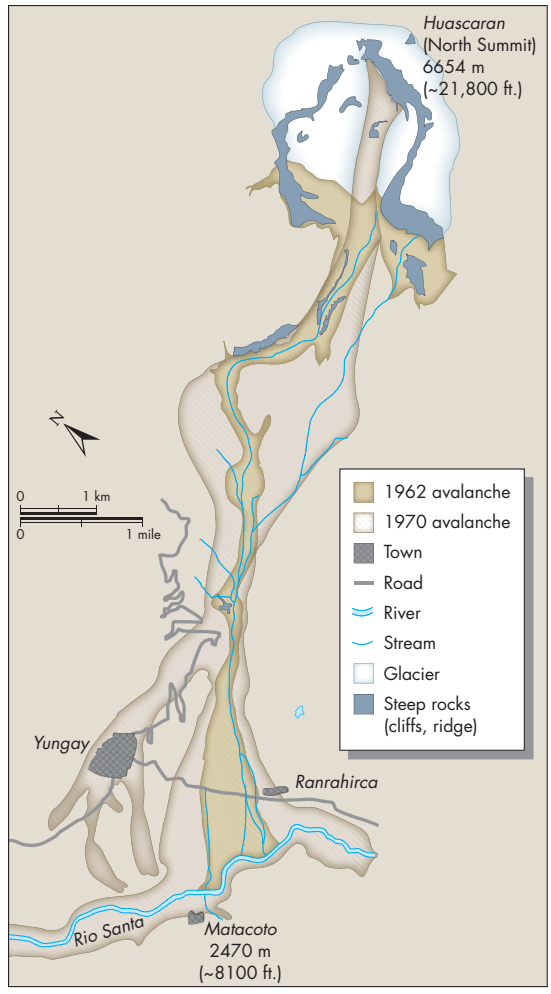
Debris flows in southern California and other fire-prone areas will likely become more common as wildfires increase in frequency and intensity. More and more



(a)



(b)



(c)

▲ FIGURE 12.29 Glacial Ice Contributes to Debris Avalanches

(a) Yungay, Peru, prior to the earthquake and debris avalanche. Snow-covered Mount Huascaran is on the skyline. *(Lloyd S. Cluff/PEER Center, University of California at Berkeley)* (b) The town site after the 1970 earthquake and avalanche. *(Lloyd S. Cluff/PEER Center, University of California at Berkeley)* (c) Tracks of the 1962 (yellow) and 1970 (area shaded with diagonal lines) avalanches down Mount Huascaran. *(From Welsh, W., and Kinzl, H., "Der Gletschersturz vom Huascaran [Peru] am 31. Mai 1970, Die grosste Gletscherkatastrophe der Geschichte."* Zeitschrift für Gletscherkunde und Glazialgeologie *6: 181–92, 1970. Reprinted by permission of the author.)*

people are exposed to the debris flow hazard as new development continues in and adjacent to brush lands and forests of the American Southwest and similar areas around the world. We will return to wildfire and debris flows in Southern California in Chapter 13.

VOLCANIC, EARTHQUAKE, AND TSUNAMI HAZARDS

The crust of Earth often seems solid and steady. In fact, it is always flexing, uplifting, subsiding, and changing because of a variety of geologic processes that are loading the crust or releasing a load. For example, glacial ice in polar ice sheets have depressed (pushed down) the crust by many meters, and when the glacial ice thins and melts from a warming world, the crust rebounds (uplifts), often hundreds to a thousand kilometers from the ice sheet. The unloading may reactivate active faults, producing moderate to large earthquakes. The unloading (removal of pressure) may also trigger subglacial volcanic eruption. It is more difficult for magma that is formed and stored in subglacial volcanoes to reach the surface when covered by thick glaciers. Thus, with global warming and melting of glaciers, pressure is lessened and rock can melt quicker. More magma can lead to more eruptions, and dormant volcanoes may come to life. Iceland is being split apart along the Mid-Atlantic

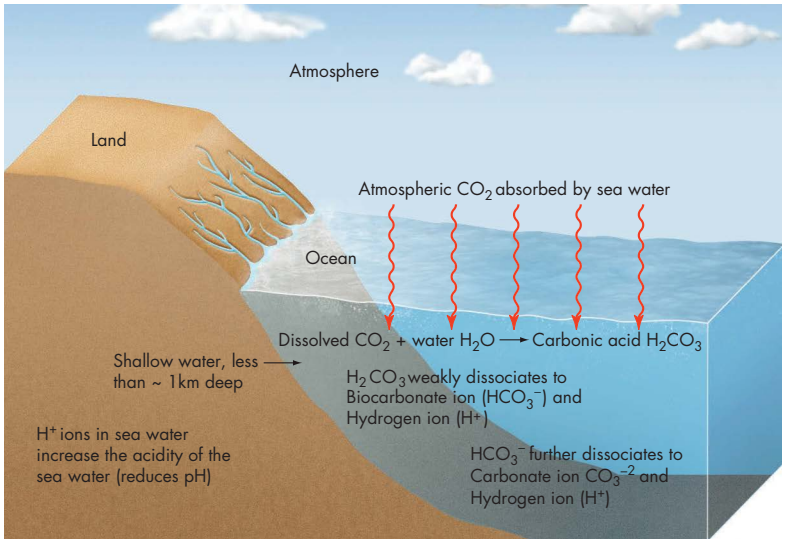
Ridge (see Chapter 2). There are many Icelandic volcanoes that are linked to the glaciers above them. The Vatnajökull glacier (ice cap) in Iceland that has an area of about 7800 square kilometers (3000 square miles) has many volcanoes beneath the ice. Melting (thinning) of the glacier causes about 14 million cubic meters (18 million cubic yards) of new magma to form in subglacial volcanoes. Thus, with global warming, an increase in volcanic eruptions below the glacier is predicted.[50,52] The Eyjafjallajokull volcano beneath a smaller ice cap in Iceland erupted in 2010, and the huge ash cloud caused airlines to cancel thousands of European flights for several days (see Chapter 5).

Many volcanoes are within 250 km (150 mi.) of the sea, and there are many volcanic islands. The loading from rising sea level may bend the crust and lead to magma being squeezed and, therefore, easier to erupt. This may lead to more explosive volcanism and even lateral blasts that may produce large, sudden submarine or sea cliff landslides (a volcano flank collapse that could produce tsunamis). While this scenario is speculative, there are examples in the recent geologic past,[50] and future events cannot be ruled out.

CHANGES IN THE BIOSPHERE

A growing body of evidence indicates that global warming is initiating a number of changes in the biosphere, threatening both ecological systems and people. An ecosystem is a community of species and their nonliving environment in which energy flows through the system and chemicals cycle. Sustained life is a function of ecosystems, not individual species. Changes to ecosystems resulting from global warming include risk of regional extinction of species in the system as land and hydrology change (e.g., forested land changes to grassland). Other changes include shifts in the range of plants and animals, with a variety of potential consequences. For example, mosquitoes carrying diseases, including malaria and dengue fever in Africa, South America, Central America, and Mexico, are migrating to higher elevations; butterfly species are moving northward in Europe; some bird species are moving northward in the United Kingdom; subalpine forests in the Cascade Mountains in Washington State are migrating to higher meadows; alpine plants in Austria are shifting to higher elevations; sea ice melting in the Arctic is placing stress on seabirds, walruses, and polar bears; and warming and increasing acidity of shallow water in the Florida Keys, Bermuda, Australia's Great Barrier Reef, and many other tropical ocean areas are believed to be contributing to the bleaching of coral reefs.[13,49,53]

Ocean Acidification Approximately one-third of the carbon dioxide emitted into the atmosphere by human activity becomes dissolved into the world's ocean, thereby minimizing the input of greenhouse gas into the atmosphere. Although this process minimizes the positive forcing of global warming, it does so at the expense of the oceans. Dissolved carbon dioxide and water form carbonic acid $CO_2 + H_2O \rightarrow H_2CO_3$. The acid dissociates to bicarbonate ion HCO_3^- and hydrogen ion H^+. As H^+ increases, ocean waters become more acidic (Figure 12.30) and their pH lowers; over the past 15 years, ocean acidity has increased about 30 percent. The increased acidity of the oceans and ecosystems is fundamentally changing the structure and function of ocean chemistry by stressing marine organisms, ranging from plankton to coral and shellfish, as they attempt to adapt



< FIGURE 12.30 Changes in Seawater
Idealized diagram showing processes that change the acidity of seawater.

to increasing acidity. The stress for some species may be manifested by reduced growth rates and reproduction. These changes could occur if organisms need to expend more energy to maintain their internal pH, resulting in less energy for growth and reproduction. How individual species and ecosystems will respond to further acidification in the future is a complex problem that is the subject of increasing research.[54,55] Increased acidity of seawater may make it more difficult for some marine organisms that produce carbonate shells, such as oysters, coral, and some plankton, to draw carbonate from the seawater to make their shells.

In response to the warming atmosphere over the past 100 years, heat has been transferred to the upper water layers of the oceans. As a result, the average temperature of the upper 700 m (~2300 ft.) of the sea has increased by about 0.6°C (~1°F) over the past century. Temperature increase has a fundamental effect on biological processes of marine organisms through increased metabolic rates that impact ecosystem processes of energy expenditure and chemical cycling. Marine organisms have the ability to adapt to temperature change within a particular range of temperatures. If the range is exceeded, the ability to adapt is reduced, and populations may decline or be driven to local extinction.[56] Mobile species such as fish can swim to other areas or deeper water where the temperature is closer to what they prefer. Those species tied to the bottom, such as shellfish, may slowly migrate if change is sufficiently slow. The change of temperature and acidity of seawater appears to be accelerating, which may make adaptation more difficult for some species. On the other hand, some species of coral are apparently adapting to more acidic seawater.[57]

Adaptation of Species to Global Warming As a result of global warming some species will experience stress. Most vulnerable will be those species that are not mobile, such as some vegetation on land and shellfish in the ocean. Many species will migrate toward higher altitudes in an attempt to adapt to warming. With global warming, temperature and precipitation change in different regions, which stresses ecosystems. During the past 25 years or so, plants and animals have shifted their ranges by about 6 km (~3.7 mi.) per decade toward the polar areas. In addition, spring is arriving earlier, and plants, as a consequence, are blooming earlier, frogs are breeding earlier, and migrating birds are arriving earlier in various places. The rate of change has been about 2.3 days per decade. In addition, it has been reported that tropical pathogens have moved up in latitude and elevation, affecting species that may not be adapted to them. Climate change may have caused the first extinction of a mammal, a species of opossum that has apparently disappeared from Queensland, Australia. It was reported that the opossum lived only at an elevation of 1000 m (~3280 ft.) and was susceptible to being exposed to higher temperatures, even for a short period of time.[58]

A problem with past evaluations of the potential threats to species or their possible regional extinction was that they were based on simple models that primarily considered temperature and precipitation, perhaps along with soil type and hydrology, that determine, in part, where a particular species lives. This information would then be put into a standard climate model to predict where a particular species might migrate in order to avoid adverse effects of climate change. We now know that these simple envelope models that use a few climate and topographic variables are not sufficient, and newer models that incorporate additional biological elements, including competition among species and genetics, are being used to evaluate evolutionary responses to climate change.[59]

One controversial suggestion is that we might assist migration of some species that are unable to migrate with climate change. To some, this is a drastic step that may be unacceptable because of the risk of, essentially, creating an invasive species. Assisted migration worries ecologists and conservation biologists because they have spent a lot of time and effort working against invasive species, some of which cause ecosystem problems and the extinction of other species. Before seriously considering assisted migration, much more research is needed to better understand the habitats of threatened and endangered species, including where they can do well, what might threaten them, and what they might threaten.[58]

12.6 CHECK your understanding

1. How are glaciers and sea ice changing in the Arctic and Antarctic?
2. How might global warming change the intensity and frequency of violent storms? Describe the process.
3. What are the two main physical processes in the warming of seawater that cause sea-level rise?
4. How might global warming impact landslides, volcanic eruptions, earthquakes, and tsunamis?
5. How is global warming affecting the occurrence of wildfires?
6. How does ocean acidification occur, and why is it a potentially significant problem?
7. How is global warming influencing the biosphere, and how is life adapting?

12.7 Predicting the Future Climate

WHAT DOES OUR RECENT HISTORY TELL US ABOUT POTENTIAL CONSEQUENCES OF FUTURE GLOBAL WARMING?

The famous philosopher George Santayana stated in 1905 that "those that cannot remember the past are condemned to repeat it." It is a matter of debate whether cycles in human history actually repeat themselves, but the repetitive nature of many natural processes and hazards, even if they result from different reasons, is indisputable. So, what can we learn by examining the past with reference to global climate change and, in particular, global warming? It turns out that over an approximate 300-year period from A.D. 950 to 1250, Earth was considerably warmer than normal (normal meaning the average surface temperature during the past century or some shorter interval, such as between 1961 and 1990). This period is known as the Medieval Warm Period (MWP), and we can learn some lessons from that event. Although it occurred only a few hundred years ago, we don't know much about the MWP except that it was, in fact, warm and perhaps nearly as warm as it is today. Most scientists who study indicators of past climate state that it probably wasn't quite as warm, but certain parts of the world, Western Europe and the North Atlantic in particular, may have been warmer some of the time than they were in the last decade of the twentieth century. During the MWP, there were winners and losers. In Western Europe, there was a flourishing of culture and activity, as well as population growth, as harvests were plentiful and people generally prospered. Many of Europe's grand cathedrals were constructed during this period, and the first global trade routes opened from Europe to China, helped by favorable climate and connected by camel caravans.[60,61]

During the MWP, sea temperatures in the North Atlantic evidently were warmer, and there was less sea ice. The famous Viking explorer Erik the Red embarked on a voyage of exploration near the end of the tenth century. When he arrived at Greenland with his ships and people, they set up settlements that flourished for several hundred years, and they were able to grow a variety of crops, including corn, that had never before been cultivated in Greenland. They were also able to raise their animals and, in general, enjoy a prosperous life. During the same warm period, Polynesian people in the Pacific, taking advantage of winds flowing throughout the ocean, were able to sail to and colonize islands over vast areas of the Pacific, including Hawaii.[61]

Although some prospered in Western Europe and the Pacific during the MWP, other cultures were not so fortunate. Associated with the warming period were long, persistent droughts (lasting perhaps a human generation) that appear to have been partially responsible for the collapse of sophisticated cultures in North and Central America. The collapses were not sudden but occurred over a period of many decades; in some cases, the people just moved away. These included the people living near Mono Lake on the eastern side of the Sierra Nevada in California, the Chacoan people in what is today Chaco Canyon in New Mexico, as well as the Maya civilization in the Yucatan of southern Mexico and Central America.

Today, we are worried about the present warming trends. Should they continue and accelerate or increase, we may face a prolonged drought in the southwestern United States again, as well as in other parts of the world, which may wreak havoc on the ability to produce the food that the 9 billion people on Earth will soon require.[61]

When the MWP ended, it was followed by the Little Ice Age (LIA) that lasted several hundred years from the mid-1400s to 1700.[60] The cooling of the LIA made it more difficult for people in Southeast Asia and Western Europe. Angkor Watt, with its palace and temple in Cambodia, was constructed in 1181. The region flourished for several hundred years as canals and reservoirs irrigated vast rice fields. The water supply from summer monsoon rains was reliable, and people prospered. With climate change and the transition to the LIA, monsoon rains weakened, and water became scarce. The Ankorian civilization was in decline by the fifteenth century and collapsed by the end of the sixteenth. The collapse was gradual as people left the city, moving to smaller communities. Why the collapse occurred is not fully understood, but it was in part due to the onset of the Little Ice Age and a more volatile climate with reduced monsoon rains and drought. In short, the food supply diminished as water resources became scarce.[61]

During the Little Ice Age, there were storms, wet periods, extremes of heat and cold, and climate change that caused a number of problems in Europe. Some winters were very cold, and during one such winter in 1683–84, the River Thames in London was frozen solid for two months and sea ice extended for kilometers into the North Sea, closing harbors and significantly restricting shipping. Crop failures occurred in Western Europe, and the population was devastated by the Black Plague that reached out into the Atlantic and Iceland by about 1400.

With the cooling times, increasing sea ice, and more environmental stress, trade was restricted with Greenland. Eventually, the colonies in North America and Greenland were mostly abandoned. Part of the reason for the abandonment in North America and, particularly, in Newfoundland was because the Vikings may not have been able to adapt to the changing

conditions, as did the Inuit peoples living there. As times became tough, the two cultures collided, and the Vikings, despite their fierce reputation, were not as able to adapt to the changing, cooler times as were the Inuit.

We do not know what caused the Medieval Warm Period, and the details about it are somewhat obscured by the lack of sufficient climate data during that period to estimate temperatures. We do know that it was warm in Western Europe and the North Atlantic, and we can't blame that on the burning of fossil fuels. What this may suggest is that more than one factor can cause warming; the present warming, for the most part, is clearly the result of the emission of carbon dioxide into the atmosphere from burning fossil fuels and land-use changes. Perhaps a lesson for us is that changes in the most recent past warming, the MWP, resulted in winners and losers. Today, the world population is greater than 7 billion, and half of us live in cities. The world population during the MWP was about 500 million, and agriculture was booming. However, persistent droughts during the MWP apparently caused pain and suffering over much of the semiarid areas of the world, from coastal California to the southwestern United States, as well as in Central and South America. This is a red flag! The potential effects of prolonged, persistent drought and loss of food production for the world, should present warming continue, is a serious threat.[61]

PREDICTING FUTURE CLIMATE IS PROBLEMATIC

Predicting the future climate is problematic because predicting the future has always been difficult. People who make predictions have often been wrong. For climate and its effects on living things, we can attempt to apply the geological concept of uniformitarianism, which assumes that processes that occurred in the past occur today and will occur in the future. This approach has led to investigations of atmospheric concentrations of greenhouse gases in the geologic record, which we have explored in this chapter. However, the time of particular interest to us is the one that is the most difficult from which to collect climate data. That time is the past few centuries to 1,000 years ago, during the scientific and technological revolutions.

The problem we face is that temperature records have been kept, at best, for only about 150 years, and the early records are from only a few places. Until the advent of satellite remote sensing, measurements of air temperature over the oceans were taken only where ships traveled, which did not provide the kind of sampling that satisfies statisticians. Many places on Earth have never had good, long-term, ground-based temperature measurements. So, when we want to know what the temperatures were like in the 19 centuries before carbon dioxide concentrations began to rise from the burning of fossil fuels, experts have to find ways to extrapolate, interpolate, and estimate. The Hadley Meteorological Center in Great Britain is an outstanding example of a group of scientists that is attempting to reconstruct such temperature records from the mid-nineteenth century to the present.

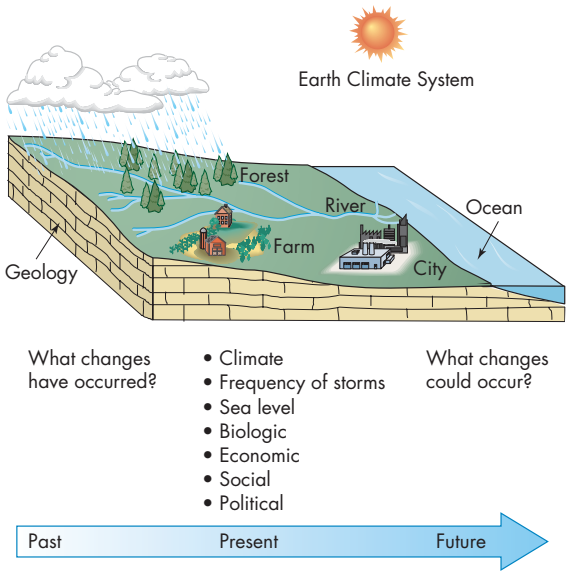
The situation has improved greatly in recent years, with the establishment of ocean platforms with automatic weather-monitoring equipment, coordinated by the World Meteorological Organization. Thus, we have records that are particularly good since about 1960. What is emerging from the climate data is that the warming we have experienced over the past few decades (1970–2010) exceeds that of anytime in the past 400+ years. This is supported by a large variety of reliable data. There is less confidence in temperature reconstructions from about A.D. 950 to 1250 because the data are sparse and not yet quantified. This period of sparse data includes the Medieval Warm Period. Limited data suggest that some specific locations during the MWP may have been as warm as or even a bit warmer than today. Data available for specific locations suggest that the latter part of the twentieth century was warmer than the MWP. Prior to A.D. 900, there is little confidence in global mean surface or water temperatures, because uncertainties associated with the proxy evidence for past temperatures are large over both space and time.[13]

12.7 CHECK your understanding

1. What have we learned from the Medieval Warm Period?
2. Why is it difficult to predict future climate change?

12.8 Strategies for Reducing the Impact of Global Warming

An important unsolved question about climate change being vigorously researched is the following: What is the origin of rapid climate change over decades to about 100 years that we believe has happened during geologic time (past 1 million years)? Two other important questions concerning the Earth climate system and people are (1) What changes have occurred? and (2) What changes could occur in the future? Answering these questions requires geologic evaluation of prehistoric changes, and the prediction, through modeling and simulation, of future change (Figure 12.31).



▲ FIGURE 12.31 Earth Climate System
Two big questions concerning Earth's climate system are linked to people and environment: What changes have occurred? What changes could occur? *(Based on International Panel on Climate Change 2001, at www.ipcc)*

Because we now know global warming is due, in part, to the increased concentration of greenhouse gases, reduction of these gases in the atmosphere is a primary management strategy. This was the subject of the 2016 Paris Climate Agreement. The objective of the United Nations Convention was to produce an international agreement to reduce emissions of greenhouse gases, especially carbon dioxide. The agreement was signed by 195 countries including the United States, but in 2017, the United States pulled out of the agreement, much to the disappointment of other nations, especially its European allies. As a result, the leadership in controlling global warming has shifted from the United States to the European Union.

International Agreements The United States is not committed to any international agreements to address climate change. A comprehensive energy plan that would have included climate change was killed in the Senate. Powerful lobbies from the fossil fuel industry, combined with some senators from states with abundant fossil fuels or those who fear changing energy policy or do not believe global warming from burning fossil fuels is occurring, used a filibuster to stop the legislation that would have initiated a more rapid change to alternative energy sources. In spite of this, the United States has significantly reduced carbon emissions to levels not thought likely, due to drilling technology that has allowed for greatly increasing the production of natural gas. Many coal-burning power plants are switching to natural gas systems that emit significantly less carbon and are a less expensive fuel.

Dilemma We are faced with a dilemma with respect to burning fossil fuels. On the one hand, fossil fuels are vital to our society and necessary for continued economic development and growth, as well as for human well-being. On the other hand, scientific evidence suggests that burning fossil fuels is contributing significantly to global warming. Burning fossil fuels is linked to environmental problems that include a rise in sea level, increased surface temperatures, air pollution, and increased frequency and intensity of storms such as hurricanes. Impacts associated with fossil fuels depend on how much the global temperature will actually rise. If the increase is close to 2°C, we can probably adapt with minimal disturbance. If the increase in temperature is higher, more adverse impacts are likely. Even if carbon emissions were reduced to zero, warming will continue during this century. There is 0.5° to 1.0°C warming in the Earth climate system now.

Assuming that the reduction of carbon emissions is necessary to reduce impacts of global warming, we need to take action. The reduction must occur at a time when human population and energy consumption are increasing. There are several ways that we might reduce emissions of carbon dioxide into the environment: improved engineering of fossil fuel-burning power plants (develop and use coal-burning power plants that sequester the carbon and place it in safe storage); use those fossil fuels that release less carbon into the atmosphere, such as natural gas, which, on burning, releases less carbon dioxide than does coal or oil (as is occurring in the United States); conserve energy to reduce our dependence on fossil fuels; use more alternative energy sources; and store carbon in Earth's systems, such as forests, soils, and rocks below the surface of Earth.

Sequestration of Carbon Sequestration is attractive because the residence time of carbon in the geologic environment is generally long, potentially thousands to hundreds of thousands of years.

The general principle of geologic sequestration of carbon is fairly straightforward. The idea is to capture carbon dioxide from power plants and industry and inject the carbon into the subsurface geologic environment. Two geologic environments have received considerable attention in this regard. The first is sedimentary rocks that contain salty water. These rocks, known as saline aquifers, are fairly widespread at numerous locations on Earth and have large reservoir capacity with the potential to sequester many years of human-produced carbon dioxide emissions. They could provide the necessary time to transition to an energy economy not dependent on fossil fuels.[62] The second (but related) geologic environment for sequestration of carbon is

depleted oil and gas fields. The process of placing carbon dioxide in the geologic environment involves compressing the gas to a mixture of liquid and gases and then injecting it underground, using wells. Injecting carbon dioxide into depleted oil and gas fields has an added advantage, in that the carbon dioxide is not only stored but also serves as a way to enhance recovery of remaining oil and gas in the reservoir. The injected carbon dioxide helps move the oil toward production wells.

A demonstration project is now ongoing in Saskatchewan, Canada. The Weyburn oil field started production in the 1950s and was considered to be depleted. However, with enhanced recovery and storage of carbon dioxide, production is likely to last for several more decades. The source of carbon dioxide for the Weyburn field comes from a coal-burning plant in North Dakota by way of a pipeline that delivers several thousand tons of carbon per day.[63]

Another carbon sequestration project is located beneath the North Sea. Carbon dioxide is injected into a saltwater aquifer located below a natural gas field. The project, which started in 1996, injects about 1 million tons of carbon dioxide into the subsurface environment each year. It is estimated that the entire facility can hold about the amount of carbon dioxide that is projected to be produced from all of Europe's fossil fuel plants in the next few hundred years.[62] The cost of sequestering the carbon beneath the North Sea is high. However, it saves the company from having to pay taxes for emitting carbon dioxide into the atmosphere. Finally, pilot projects to demonstrate the potential and usefulness of storing carbon in the United States have been initiated in Texas beneath depleted oil fields. The good news is that immense salt aquifers are common beneath many areas of the United States, including the Gulf Coast, Texas, and Louisiana, and the potential to store carbon is immense.[64]

If we decide that we must stabilize the concentration of atmospheric carbon dioxide in the future, it will be necessary to go through a transition from fossil fuel energy sources to alternative sources that produce much less carbon dioxide. However, based on studies of glacial ice cores from Greenland, there are indications that significant climatic change may occur abruptly, perhaps in as short a time as a few years. A quick natural or human-induced warming or cooling is probably unlikely, but, if one does occur, the potential impacts could be fast and serious.

ABRUPT CLIMATE CHANGE

A large-scale change in the global climate system that takes place over a few decades or less is considered an abrupt climate change. Rapid changes are thought to have occurred in the past, but little is known about them or why they happened. Such change is anticipated to persist for at least a few decades and will cause substantial disruptions to both human and natural systems.[65] Several types of abrupt climate change that could cause a serious risk to humans and the natural environment in terms of our ability to adapt include the following:

- A rapid change of sea level as a result of changes in the glaciers and ice sheets.
- Droughts and floods, resulting from widespread rapid changes to the hydrologic cycle.
- Abrupt change in the pattern of circulation in the Atlantic Ocean that is characterized by northward flow of warm, salty water in the upper layers of the ocean.
- A rapid release of methane (a strong greenhouse gas) to the atmosphere from both melting permafrost and the ocean's sediment.

The U.S. Climate Change Science Program has addressed these four potential abrupt climate changes.[65] A major question is whether or not there will be an abrupt change in sea level. We know that even small changes in sea-level rise may have significant repercussions for society with serious economic impacts, including coastal erosion as well as an increase in coastal flooding and a loss of coastal wetlands. Current climate models do not adequately capture all aspects of sea level changes resulting from melting glacial ice. However, there is concern that projections for sea-level rise in the future, as presented by the Intergovernmental Panel on Climate Change,[13] probably underestimate the amount of sea-level rise during the twenty-first century.

The second question involves the potential for abrupt changes in the hydrologic cycle, especially those changes that affect water supply, especially through protracted droughts. Of particular significance is recognizing that droughts can develop faster than people and society are able to adapt to them. Thus, droughts that last from several years to a decade or more have serious consequences to society. It has been pointed out that long droughts have occurred in the past and are still likely to reoccur in the future, even in the absence of global warming, as a result of increased greenhouse gas forcing.[65]

A third question concerning abrupt climate change involves the Atlantic Ocean circulation system, which carries warm water to the North Atlantic, where it becomes saltier and sinks to become a cold water bottom current that moves south. The warm water is partly responsible for keeping Western Europe more comfortable and hospitable. However, it is primarily the large expanse of the ocean itself that accomplishes this. The strength of the current is expected to decrease approximately 25 to 30 percent as a result of global warming in the twenty-first century. However, it appears unlikely that the ocean current system in the Atlantic will undergo a collapse or an abrupt transition to a weakened state in the next 100 years.[65]

A final question is whether or not there will be a rapid change in atmospheric methane. This is a significant question because methane is a strong greenhouse gas that, if greatly increased in concentration in the atmosphere, would accelerate global warming. It is generally concluded that a very rapid change in the release of methane during the next 100 years or so is very unlikely. However, ongoing warming will increase emissions of methane from both ocean sediments and wetlands. Wetlands in the northern high latitudes are particularly susceptible to releasing additional methane because there is accelerated warming, along with enhanced precipitation, in permafrost areas that contain a lot of stored methane. Thus, it appears that, in future decades, methane levels will likely increase and cause additional warming.[65]

In conclusion, it appears that abrupt climate change during the next century is unlikely and, thus, we will probably have time to respond to potential adverse consequences of global warming. However, time is growing short and, because it takes time to initiate policy changes, a serious response to global warming from all countries is necessary in the near future.

A better understanding of past abrupt changes in climate, through the collection and analysis of geologic data, is necessary to fully understand what may cause future change. Geologic data provide the most direct evidence of past change. Geologic data from sediments and glacial ice, along with monitoring, help us understand the causes of long-term changes in ocean and glacial conditions and how these are linked to atmospheric response. With this knowledge, we may be better able to forecast both long- and short-term droughts that have serious consequences to humans and the natural environment.

Human civilization began and has developed into our present highly industrialized society in only about 7,000 years. That period has been characterized by a relatively stable, warm climate that is probably not characteristic of longer periods of Earth history. It is difficult to imagine the human suffering that might result late in the twenty-first century from a quick climate change to harsher conditions, when there are as many as 9 to 10 billion or more people on Earth to feed.

12.8 CHECK your understanding

1. What two big questions concerning Earth's climate system are linked to people and environment?
2. Define abrupt climate change.
3. If we control greenhouse gas emissions (especially carbon dioxide) in the next few decades, why might we not see real improvements for years, decades, or even 100 years after significant control?

APPLYING the 5 Fundamental Concepts

South Florida

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

Tidal floods in Miami Beach and South Florida are much more common today than they were a decade ago. South Florida has more property at risk from climate change than any other location in the United States. Figure 12.32 shows estimates of future rise in sea level at South Florida from three different agencies. Estimates reported by the Southeast Florida Regional Climate Change Compact (SFRCC) of sea-level rise by 2030 will be at about 15 to 25 cm (6 to 10 in.) above the 1992 level. By 2060, sea-level rise (from SFRCC) in Florida may be about 36 to 66 cm (14 to 26 in.) above the 1992 level. A recent study suggests that sea-level rise in Miami was about 3 +/–2 mm per year before 2006, but since 2006, is about 9 +/–4 mm per year.[1] A rise of about 30 cm (1 ft.) over 35 years into the future may seem to be a small number, but if standing water from tidal flooding surrounds your beach home, condominium, or

hotel, it is a big problem that damages property and disrupts the daily lives of people.

The Southeast Florida Regional Climate Change Compact is working with communities to reduce the coastal flood hazard. Miami Beach has a plan to minimize future flooding that involves seawalls, drains, and pumps. The construction will cost several $100 million over the next few years. Some pumps have already been installed to pump floodwaters into Biscayne Bay, and there is fear that the water quality will suffer as urban floodwater is pumped into the bay. As sea level continues to rise, controlling floodwater may become more and more difficult as the volume of water to pump increases. Decisions will also have to be made concerning what neighborhoods in South Florida will be protected by engineering structures and what areas will not. All this will occur as population continues to increase. People are becoming worried about their investments in beach property that is becoming exposed and vulnerable to flooding. One man I met last year said that his parents had a beach house in Miami Beach, and sea-level rise was on his mind. He was attempting to persuade his elderly parents, who probably love the beach retirement, to sell their home and move before the flood threat drives property values down. He was worried about his inheritance.

APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. Climate modeling techniques have predicted continuing sea-level rise in South Florida. Can the timing and extent of inundation of future floods be accurately predicted? Why or why not?
2. The people of South Florida are making decisions for their future, based on perceived and identified risks. Summarize their options and discuss which adaptions are likely to work best and why.
3. Link the known hazards of sea-level rise at South Florida to other natural hazards, such as water pollution.
4. Describe how South Florida's tidal flooding is a result of human activities, both at a local scale and at the global scale.
5. Propose ways to minimize the hazards facing South Florida.

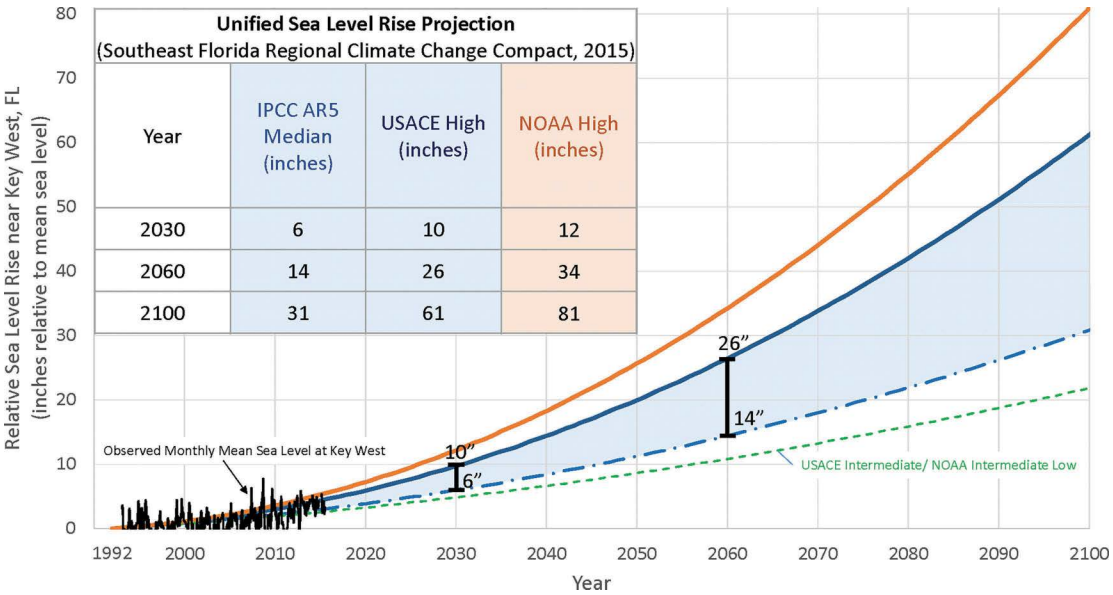


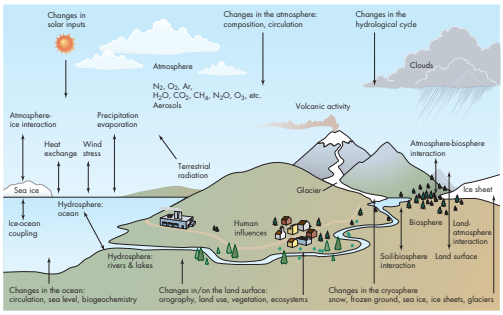
FIGURE 12.32 Southeast Florida Rise in Sea Level
Projected rise in sea level from 1992 reference level to 2100. A rise of 15 cm (6 in.) to 25 cm (10 in.) is considered a likely scenario. *(Southeast Florida Regional Climate Change Compact)*

CONCEPTS in review

12.1 and 12.2 Global Change and Earth System Science: An Overview Climate and Weather

LO:1 Explain the difference between climate and weather and how their variability is related to natural hazards.

- The concept of Earth system science has the goal of understanding how Earth works and applying that knowledge to better manage the environment.
- Global changes on a time frame significant to people (such as temperature increase) and sea-level rise are apparently occurring. Because these are short-term predictions, Earth System Science is relevant to people everywhere.
- Climate refers to the characteristic atmospheric conditions of a given region over long periods of time, such as years or decades. Weather refers to the atmospheric conditions of a given region for short periods of time, such as days or weeks.
- Climate exerts a major influence on natural processes; a familiarity with Earth's climate zones is a first step toward recognizing the threat from natural hazards.



KEY WORDS

Earth System Science (p. 486), **climate** (p. 486), **weather** (p. 486)

12.3 The Atmosphere and the Cryosphere

LO:2 Describe the basic concepts of atmospheric science, such as the structure, composition, and dynamics of the atmosphere.

- The major permanent gases, which are those that remain essentially constant by percentage, include nitrogen, oxygen, and argon. Together, these gases comprise about 99 percent by volume of all atmospheric gases.
- Over the past 2.6 million years, Earth's climate system has fluctuated greatly and alternated between periods of major continental glaciation, referred to as glacial intervals, and times of warmer climate with significantly less glaciation, referred to as interglacial intervals.
- Glaciers are huge, actively flowing masses of ice and rock debris whose movement and melting have been responsible for property damage, injuries, and deaths.



KEY WORDS

glacier (p. 489)

12.4 How We Study Past Climate Change and Make Predictions

LO:3 Synthesize how we have studied past climate change.

- Methods of studying climate change include examination of the geologic record from lake sediments, glacial ice, and other Earth materials; gathering of real-time data from monitoring stations; and development of mathematical models to predict change.



KEY WORDS

proxy data (p. 490)

12.5 and 12.6 Global Warming Effects of Global Climate Change

LO:4 Summarize how climate has changed during the past million years through glacial and interglacial conditions and how human activity is altering our current climate.

LO:5 Name and explain the potential causes of climate change and link these causes to natural hazards.

- Global warming is defined as the observed increase in the average temperature of the near-surface land and ocean environments of Earth during the past 60 years. A growing volume of evidence suggests that we are now in a period of global warming, resulting from burning vast amounts of fossil fuels. Many scientists now believe that human processes, as well as natural ones, are contributing significantly to global warming.
- The trapping of heat by the atmosphere is generally referred to as the greenhouse effect. Water vapor and several other gases, including carbon dioxide, methane, and chlorofluorocarbons, tend to trap heat and warm Earth because they absorb some of the heat energy radiating from Earth.
- Climate forcing is defined as an imposed change of Earth's energy balance. The units for the forcing are W/m^2, and they can be positive if a particular forcing increases global mean temperature or negative if temperature is decreased.
- Natural climate forcing mechanisms that may cause climatic change include Milankovitch cycles, solar variability, and volcanic activity. Anthropogenic causes include air pollution and an increase in greenhouse gases, especially carbon dioxide.
- The potential effects of global warming are sea-level rise; increased wildfire; more intense storms; increase in drought; changes in landslide, volcanic, and tsunami hazards; and changes in the biosphere.



KEY WORDS

climate forcing (p. 498), **global warming** (p. 494), **greenhouse effect** (p. 495), **El Niño** (p. 506)

12.7 Predicting the Future Climate

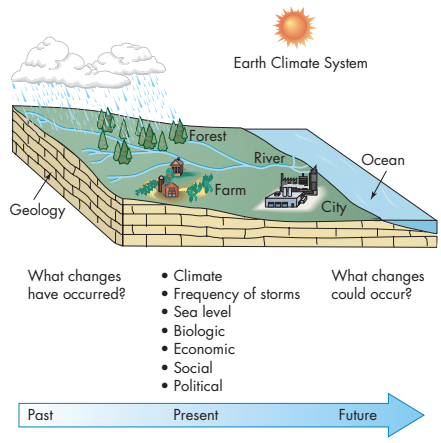
LO:6 Speculate on how we might better predict future climate change.

- Over an approximately 300-year period from a.d. 950 to 1250, Earth was considerably warmer than normal (normal meaning the average surface temperature during the past century or some shorter interval, such as between 1961 and 1990). This period is known as the Medieval Warm Period (MWP).
- During the MWP, sea surface temperatures in the North Atlantic evidently were warmer, and there was less sea ice.
- Associated with the warm period were long, persistent droughts (lasting perhaps as long as a human generation) that appear to have been partially responsible for the collapse of sophisticated cultures in North and Central America. The collapses were not sudden but occurred over a period of many decades, and, in some cases, the people just moved away.
- Perhaps a lesson for us from the MWP is that changes in the most recent past warming (MWP) resulted in winners and losers.
- The potential effects of prolonged, persistent drought and loss of food production for the world, should present warming continue, is a serious threat.
- Predicting the future climate is problematic because predicting the future has always been difficult. People who make predictions have often been wrong.

12.8 Strategies for Reducing the Impact of Global Warming

LO:7 Propose ways to mitigate climate change and associated hazards.

- We now understand that global climate can change rapidly over a time period of a few decades to a few hundred years.
- Two important questions are (1) What is the nature and extent of past climate change? and (2) What climate changes will occur in the future?
- The science of global warming is well-understood. Human-induced global warming is occurring. There is no reason for gloom and doom, but we need to take appropriate action soon to slow or stop global warming and associated environmental consequences.
- Adjustments to global warming will range from adapting to change to reducing emissions of carbon dioxide and sequestration of carbon. Several different and simultaneous adjustments are likely.



KEY WORDS

abrupt climate change (p. 498)

CRITICAL thinking questions

1. In this chapter, we discussed some possible effects of continued global warming. Which types of hazards would you expect to increase in your area as the climate changes? Would you expect to see any decrease in the types of hazards? Think about the ways that climate change might alter the lives and lifestyles of people living in your area. Do you see any evidence of climate change where you live?
2. Assessing the rate and cause of change is important in many disciplines. Have a discussion with a parent or someone of similar age and write down the major changes that have occurred in his or her lifetime and in your lifetime. Characterize these changes as gradual, abrupt, surprising, chaotic, or another descriptive word of your choice. Analyze these changes and discuss which ones were most important to you personally. Which of these changes affected your environment at the local, regional, or global level?
3. How do you think climate change is likely to affect you in the future? What adjustments will you have to make? What can you do to mitigate the effects?

4. Some people, for cultural, political, religious, or other reasons, do not accept the conclusion that climate change is primarily caused by human activities. What do you see as the basis for their opinions or beliefs? How do you think that they might be convinced otherwise? If you share their opinions or beliefs, indicate why you do and what it would take to convince you that climate change is the result of human activities.

References

1. **Wdowinski, S., Bray, R., Kirtman, B.P.,** and **Zhaohua, W.** 2016. Increasing flooding hazard in coastal communities due to rising sea level: Case study of Miami Beach Florida. *Ocean and Coastal Management* 126: 1–6.
2. **Union of Concerned Scientists.** 2015. The truth about Florida's attempt to censure climate change. *Got Science* April.
3. **Cloud, P.** 1990. Personal written communication.
4. **National Aeronautics and Space Administration (NASA).** 1990. *EOS: A mission to planet Earth*. Washington, DC: NASA.
5. **Aguado, E.,** and **Burt, J. E.** 2007. *Understanding weather & climate*, 4th ed. Upper Saddle River, NJ: Prentice Hall.
6. **Houghton, J.** 2004. *Global warming: The complete briefing*, 3rd ed. New York: Cambridge University Press.
7. **NOAA.** 2009. Paleo-proxy data. In *Introduction to paleoclimatology*. www.ncdc.noaa.gov. Accessed 3/24/10.
8. **Ricks, K. L.** and **Caldeire, K.** 2014. Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters* 9: 124002.
9. **Weart, S. R.** 2003. *The discovery of global warming*. Cambridge, MA: Harvard University Press.
10. **Oldfield, F.** 2005. *Environmental change: Key issues and alternative approaches*. New York: Cambridge University Press.
11. **Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R. F., Parker, D. E.,** and **Somerville, R. C. J.** 2007. Recent climate observations compared to projections. *Science* 316: 709.
12. **Hansen, J.** 2004. Defusing the global warming time bomb. *Scientific American* 290(3): 68–77.
13. **IPCC.** 2015. Climate Change 2014: Synthesis Report. Intergovernmental Panel on Climate Change. Geneva, Switzerland.
14. **Ruddiman, W. F.** 2008. *Earth's climate past and future*, 2nd ed. New York: W. H. Freeman.
15. **Hansen, J.,** and **Sato, M.** 2004. Greenhouse gas growth rates. *Proceedings of the National Academy of Sciences* (PNAS) 101: 16109–14.
16. **Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.,** and **Medina-Elizade, M.** 2006. Global temperature change. *Proceedings of the National Academy of Sciences* (PNAS) 103: 14288–93.
17. **Kennett, J.** 1982. *Marine geology*. Englewood Cliffs, NJ: Prentice Hall.
18. **Hansen, J.,** and **44 others**. 2005. Efficacy of climate forcing. *Geophys Res.* 110: D18104.
19. **Hansen, J.** 2003. Can we defuse the global warming time bomb? Edited version of presentation to the Council on Environmental Quality. June 12. Washington DC. www.naturalscience.com.
20. **Broecker, W.** 1997. Will our ride into the greenhouse future be a smooth one? *GSA Today* 7(5): 1–7.
21. **Seager, R.** 2006. The source of Europe's mild climate. *American Scientist* 94: 334–41.
22. **Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G.,** and **Ni, F.** 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326: 1256–60.
23. **Crowley, T. J.** 2000. Causes of climate change over the past 1000 years. *Science* 289: 270–77.
24. **Foukal, P., Frohlich, C., Spruit, H.**, and **Wigley, T.** 2006. Variations in solar luminosity and their effect on the earth's climate. *Nature* 443(14): 161–66.
25. **Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A. J., Hansen, J. E.,** and **Hofmann, D. J.** 1992. Climate forcing by anthropogenic aerosols. *Science* 255: 423–30.
26. **Kerr, R. A.** 1995. Study unveils climate cooling caused by pollutant haze. *Science* 268: 802.
27. **McCormick, P. P., Thomason, L. W.,** and **Trepte, C. R.** 1995. Atmospheric effects of the Mt. Pinatubo eruption. *Nature* 373: 399–436.
28. **Appenzeller, T.** 2007. The big thaw. *National Geographic* 211(6): 56–71.
29. **Pelto, M. S.** 1996. Recent changes in glacier and alpine runoff in the North Cascades, Washington. *Hydrological Processes* 10: 1173–80.
30. **U.S. Geological Survey. USGS repeat photography project documents retreating glaciers in Glacier National Park.** www.nrmsc.usgs.gov/repeatphoto/. Accessed 4/10/09.
31. **Shepherd, A.,** and **44 others**. 22012. A reconciled estimate of ice sheet mass balance. *Science* 338: 1183–89
32. **Steig, E. J.,** and **5 others.** 2006. Warming of the Antarctic ice-sheet surface since the 1957 International Geophysical Year. *Nature* 457: 459–62.

33. Davis, C. H., and **4 others.** 2005. Snowfall-driven growth in East Antarctic ice sheet mitigates recent sea-level rise. *Science* 308(5739): 1898–901.

34. Monagham, A. J., and **15 others.** 2006. Insignificant change in Antarctic snowfall since the International Geophysics year. *Science* 313(5788): 827–31.

35. Tufnell, L. 1984. *Glacier hazards*. New York: Longman.

36. University Corporation for Atmospheric Research. 1994. *El Niño and climate prediction*. Washington, DC: NOAA Office of Global Programs.

37. Dennis, R. E. 1984. A revised assessment of worldwide economic impacts: 1982–1984 El Niño/ southern oscillation event. *EOS, Transactions of the American Geophysical Union* 65(45): 910.

38. Canby, T. Y. 1984. El Niño's ill winds. *National Geographic* 165: 144–81.

39. Philander, S. G. 1998. Who is El Niño? *EOS, Transactions of the American Geophysical Union* 79(13): 170.

40. Greene, C. H. 2012. The winters of our discontent. *Scientific American* 307(6): 50–55.

41. Lindsey, R. 2016. *Climate Change: Global Sea Level*. www. climate .gov.

42. Titus, J. G., Leatherman, S. P., Everts, C. H., Moffatt and Nichol Engineers, Kriebel, D. L., and **Dean, R. G.** 1985. *Potential impacts of sea-level rise on the beach at Ocean City, Maryland*. Washington, DC: U.S. Environmental Protection Agency.

43. Anderson, D. R., and **5 others.** 2009. *Coastal sensitivity to sea-level rise*. Washington DC: U.S. Climate Change Program.

44. Kumar, M. 2007. Alaska melting into the sea. *Geotimes* 52(9): 8–9.

45. Frontline/World. 2005. *Tuvalu: That sinking feeling*. www.pbs.org/frontlineworld.

46. Nakada, S., and **3 others.** 2012. Groundwater dynamics of Fongafale Islet, Funafuti Atoll, Tuvalu. *Groundwater* 50: 639–44.

47. Dickinson, W. R. 2009. Pacific atoll living: How long already and until when. *GSA Today* 19(3):4–10.

48. Pinol, J., Terradas, J., and **Lloret, F.** 1998. Climate warming, wildfire hazard, and wildfire occurrence in coastal eastern Spain. *Climatic Change* 38: 345–57.

49. U.S. Climate Change Program. 2008. *Climate change and ecosystems*. Washington DC: Author.

50. McGuire, B. 2012. *Waking the Giant*. Oxford: Oxford University Press.

51. Gariano, S. L., and **Guzzetti, F.** 2016. Landslides in a changing climate. *Earth-Science Reviews* 162: 227–252.

52. Handler, E. 2015. Iceland's volcanic activity to increase from climate change. *Yale Scientific*. www. yalescientific.org

53. Union of Concerned Scientists. 2003. *Early warning signs: Coral reef bleaching*. www.ucsusa.org. Accessed 4/10/09.

54. Doney, S. C. 2010. The growing human imprint on coastal and open-ocean biogeochemistry. *Science* 238: 1512–16.

55. Hoegh-Gulburg, O., and **Bruno, J. F.** 2010. The impact of climate change on the world's marine ecosystems. *Science* 238: 1523–28.

56. Hardt, M. J., and **Safina, C.** 2010. Threatening ocean life from the inside out. *Scientific American* 303(2): 66–73.

57. Brashis, D. J. and **6 others.** 2013. Genomic basis for coral resilience to climate change. *Proceedings of the National Academy of Sciences* 110(4): 1387–92.

58. Appell, D. 2009. Can "assisted migration" save species from global warming? *Scientific American* 30(3): 378–30.

59. Botkin, D. B., and **18 others.** 2007. Forecasting effects of global warming on biodiversity. *BioScience* 57(3): 227–36.

60. Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and **Ni, F.** 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326: 1256–60.

61. Fagan, B. M. 2008. *The great warming: Climate change and the rise and fall of civilizations*. New York. Bloomsbury Press.

62. Friedman, S. J. 2003. Storing carbon in Earth. *Geotimes* 48(3): 16–20.

63. Nameroff, T. 1997. The climate change debate is heating up. *GSA Today* 7(12): 11–13.

64. Bartlett, K. 2003. Demonstrating carbon sequestration. *Geotimes* 48(3): 22–23.

65. McGeehin, J. P., Barron, J. A., Anderson, D. M., and **Verardo, D. J.** 2008. *Abrupt climate change. Final Report, Synthesis and Assessment Product 3.4*. Washington, DC: U.S. Climate Change Science Program.


Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com