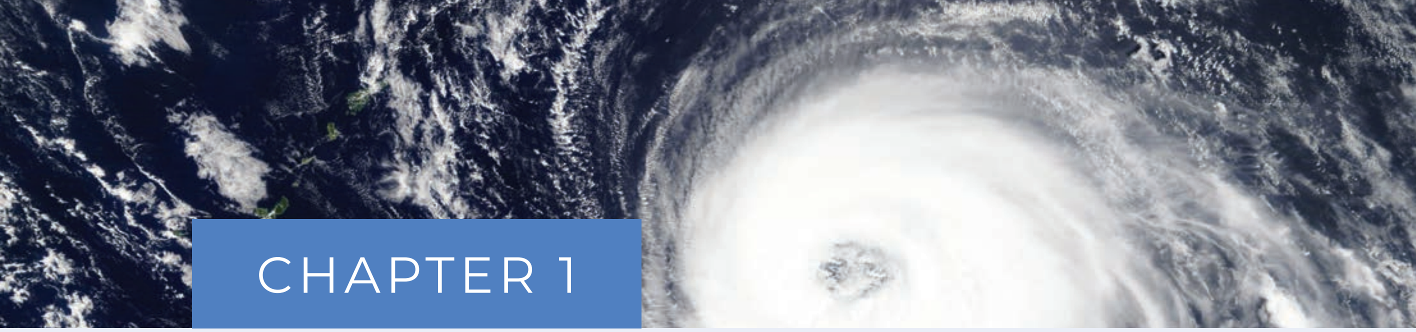

CHAPTER 1

Introduction to the Climate Crisis

KEY TERMS

Climate change
Weather
Climate
Greenhouse effect
Greenhouse gases (GHGs)
Radiative forcing
Global warming potential (GWP)
Carbon sinks
El Niño–Southern Oscillation (ENSO)
El Niño
La Niña
Climate models
Intergovernmental Panel on Climate Change (IPCC)
United Nations Framework Convention on Climate Change (UNFCCC)
Kyoto Protocol
Paris Agreement
Climate mitigation
Climate adaptation
Climate finance
Nationally determined contributions (NDCs)
Project Drawdown

LEARNING OBJECTIVES

- List the principal greenhouse gases and their major anthropogenic sources.
- Describe how greenhouse gas emissions lead to net warming of the Earth.
- Describe the major observed changes happening to the Earth's climate.
- Understand generally how future climate changes are predicted.
- Understand generally how countries are committing to climate action under the Paris Agreement.

"**Climate change is the biggest global health threat of the 21st century**." So said a group of health experts raising the alarm in 2009.[1] In the years since, the world has witnessed time and again the impacts of extreme heat, weather disasters, air pollution, drought-fueled crop failures, and human migrations. In 2020 alone, record-setting wildfires in Australia and the western United States killed scores of people, displaced hundreds of thousands more, and cost billions of dollars. The 2020 Atlantic hurricane season saw a record 30 named storms, including Hurricanes Eta and Iota, which devastated regions of Central America after making landfall in the same part of Nicaragua just two weeks apart. Historic monsoon rainfall in

Chapter opener photo: Reproduced from NASA Earth Observatory image by Kathryn Hansen, using MODIS data from LANCE/EOSDIS Rapid Response. https://earthobservatory.nasa.gov/images/92628/typhoon-soulik

China, the most expensive natural disaster in the world in 2020, killed hundreds and displaced at least a million people.[2] Erratic rainfall and prolonged drought in parts of East Africa, coupled with a destructive locust outbreak and the COVID-19 pandemic, increased severe food insecurity for millions of people.[3,4]

The year 2020 was one of the warmest three years on record, along with 2016 and 2019.[5] In 2020, the average global temperature was 1.2°C (2.2°F) above the preindustrial level from 1850–1900. Much of the world experienced extreme heat in 2020 (dark brown regions in **Figure 1.1**), and the northern hemisphere set a record of 1.28°C (2.30°F) warmer than the 20th-century average.[6] The decade from 2011 to 2020 was the warmest on record, and 2020 was the 44th consecutive year that was warmer than the 20th-century average.[6] Since the late 1970s, the United States has seen many more record *high* temperatures set than record *low* temperatures, and this trend is growing.[7] Since 2000, the land area in the contiguous 48 U.S. states where "unusually hot" daily high temperatures are recorded is growing, and "unusually hot" daily low temperatures are rising even faster.[8]

In 2020, the United States set a record for the most billion-dollar weather and climate disasters (22): 13 severe storms, six hurricanes, one tropical storm, one drought, and one wildfire event (**Figure 1.2**).[9] These disasters directly or indirectly affected the health, well-being, and livelihoods of millions of Americans.

Climate change is a profoundly human crisis and a health **threat magnifier**, in that

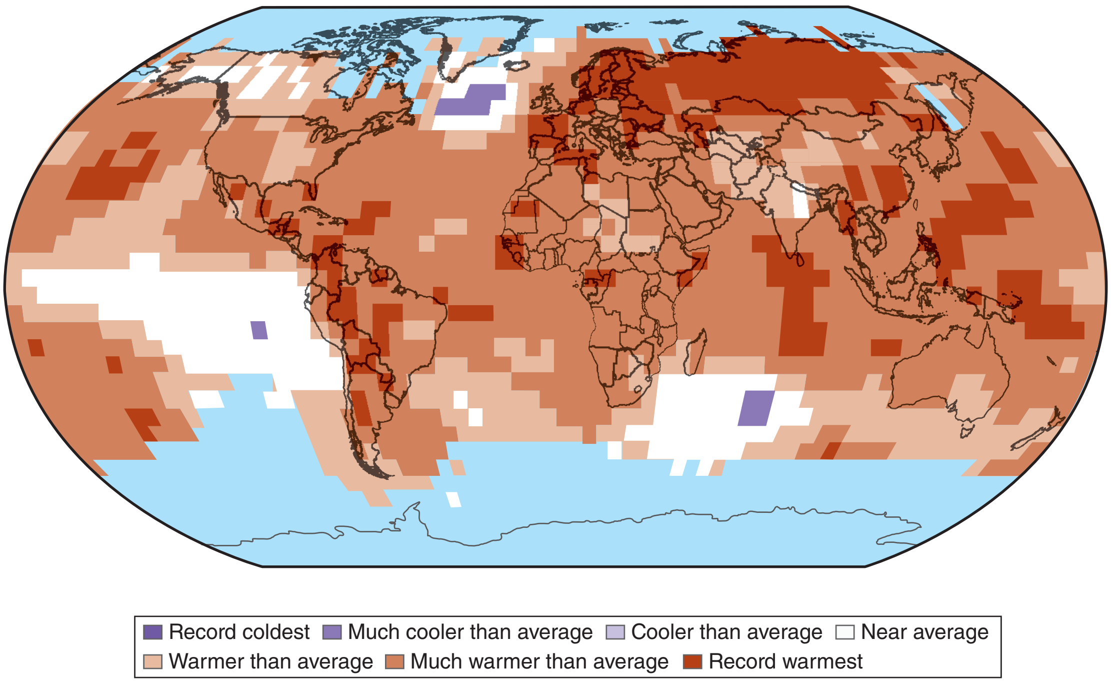

Figure 1.1 Map Depicting Global Average Land and Ocean Temperatures in 2020. Dark brown regions had record-warmest temperatures, and lighter brown colors indicate regions warmer or much warmer than average.

Reproduced from National Oceanic and Atmospheric Administration. 2020 was Earth's 2nd-hottest year, just behind 2016. Published January 14, 2021. Accessed February 14, 2021. https://www.noaa.gov/news/2020-was-earth-s-2nd-hottest-year-just-behind-2016

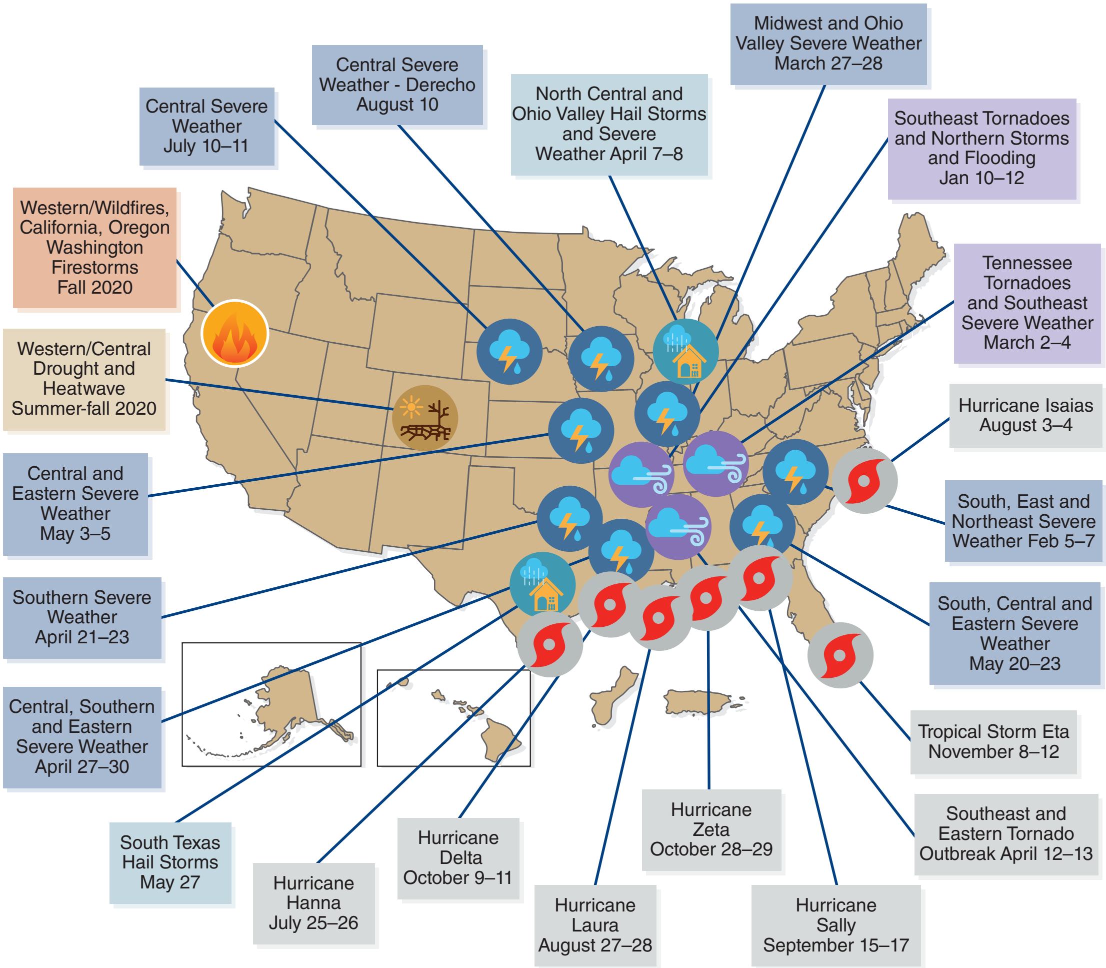

Figure 1.2 All 22 Weather and Climate Disasters That Occurred in the United States in 2020 Cost at Least $1 Billion. NOAA has tracked billion-dollar disasters in the United States since 1980.

Reproduced from National Oceanic and Atmospheric Administration National Centers for Environmental Information. Billion-dollar weather and climate disasters: overview. Accessed February 19, 2021. https://www.ncdc.noaa.gov/billions

it makes existing human health burdens and inequities worse. Understanding how, where, and why human well-being is threatened is essential to minimizing and preparing for the impacts of the climate crisis. Climate action will help to prevent these health threats and at the same time represents **"the largest public health opportunity in more than a century"** because of all the health benefits that will come with a rapid and equitable energy transition.[10]

What Is Climate Change?

Climate change refers to changes in the Earth's climate, attributed directly or indirectly to human activities, that are altering the composition of the global atmosphere and are in addition to natural climate variability observed over the same time period.[11] Climate change impacts weather patterns, but climate and weather are distinct phenomena.

Weather refers to the state of the air and atmosphere—specifically, *temperature*, *rain*, *clouds*, and *storms*—at a specific time and place. **Climate** refers to "average weather," the statistical description of the mean, extremes, and variability of features such as *temperature*, *precipitation*, and *wind* over a period that can range from months to thousands of years but is typically three decades.

The primary change in climate being observed on Earth is increased surface temperatures driven by an enhanced **greenhouse effect**, the phenomenon in which heat-trapping **greenhouse gases (GHGs)** in the atmosphere absorb and emit radiation coming from the Earth's surface, the atmosphere, and clouds after they are heated by the sun. This has the effect of warming the Earth's surface and troposphere (lower layer of the atmosphere). The greenhouse effect occurs naturally and creates a temperature range on Earth that allows for life, but fossil fuel burning and other human activities have increased GHGs in the atmosphere such that the greenhouse effect has become amplified, leading to increased warming (**Figure 1.3**).

The magnitude of the **anthropogenic** (*human-caused*) greenhouse effect is expressed by **radiative forcing**, a measure of the energy imbalance on Earth that is calculated by subtracting the energy flowing out into space (radiating away from the Earth's surface and troposphere) from the sun's energy flowing in. This number is measured in watts per square meter of surface. A positive number indicates warming, and a negative number indicates cooling. Radiative forcing has increased since the preindustrial reference year of 1750 (**Table 1.1**).

Most of the increase in radiative forcing in recent decades is due to human activities that produce heat-trapping greenhouse gases. Natural phenomena, such as volcanic eruptions and plant decomposition, also release GHGs, but anthropogenic sources predominate today. The primary GHGs are

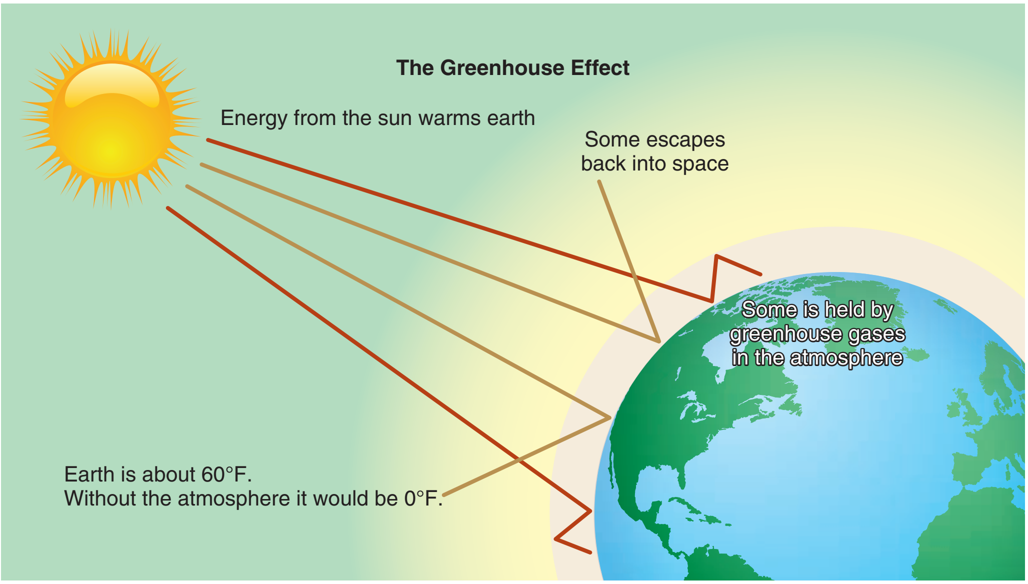

Figure 1.3 Diagram of the Greenhouse Effect, Showing Energy from the Sun Warming the Earth, and the Atmosphere Trapping Some of This Energy as it Radiates Away from the Earth's Surface.

Reproduced from Climate Central. The greenhouse effect. https://medialibrary.climatecentral.org/uploads/general/2018GreenhouseEffect.png

Table 1.1 **Increasing Radiative Forcing in Recent Years Relative to 1750.**

Year	Radiative Forcing (watts/m²)
1750	0
1950	0.57
1980	1.75
1990	2.17
2000	2.47
2010	2.80
2020	3.18

Data from National Oceanic and Atmospheric Administration. The NOAA Annual Greenhouse Gas Index (AGGI). Updated Spring 2021. Accessed June 16, 2021. https://www.esrl.noaa.gov/gmd/aggi/aggi.html; Intergovernmental Panel on Climate Change. Summary for Policymakers. In: Stocker TF, Qin D, Plattner G-K, et al., eds. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press; 2013. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_SPM_FINAL.pdf

carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases such as sulfur hexafluoride (SF_6), and water vapor.[12]

Carbon dioxide (CO_2) is the principal anthropogenic GHG. **Figure 1.4** shows GHG emissions, of which CO_2 is the primary component, in the United States in 2019 and in the world in 2015.[12,13] CO_2 is an atmospheric by-product of fossil fuel combustion, land-use changes such as deforestation and vegetation and peat burning that release stored carbon, and industrial processes, including cement production, in which limestone ($CaCO_3$) is heated and releases CO_2. CO_2 is removed from the atmosphere primarily when it is absorbed by plants via photosynthesis and by oceans and soils as part of the carbon cycle.

In the 1950s, the geochemist **Dr. Charles Keeling** developed an accurate system for measuring atmospheric CO_2 concentration.

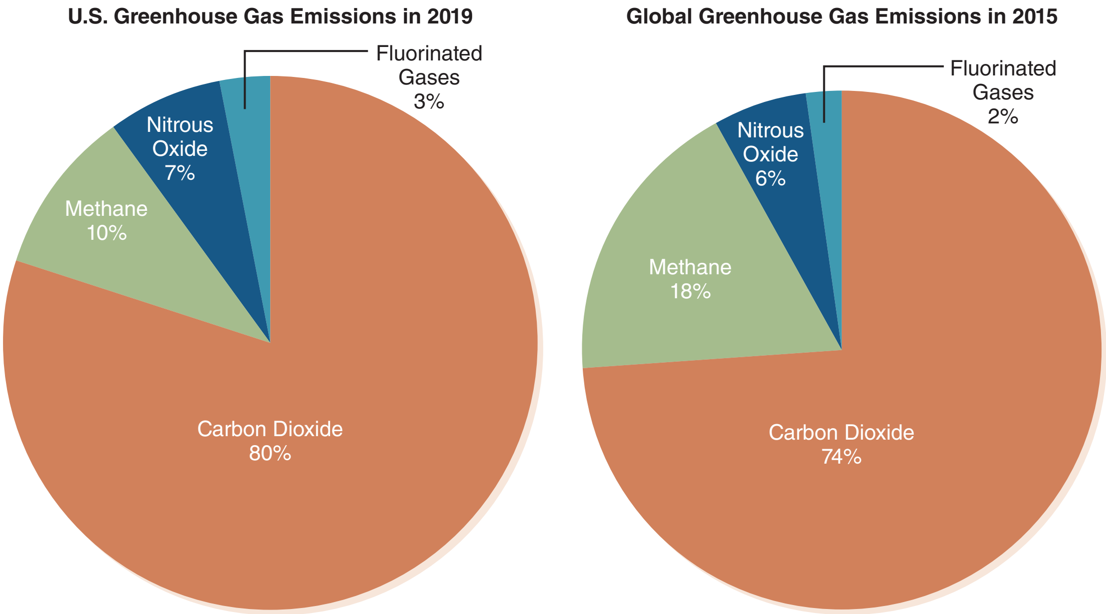

Figure 1.4 Left: U.S. Greenhouse Gas Emissions in 2019. Right: Global Greenhouse Gas Emissions in 2015.

Left: Reproduced from Environmental Protection Agency. Overview of greenhouse gases. Accessed June 7, 2021. https://www.epa.gov/ghgemissions/overview-greenhouse-gases; Right: Data from Environmental Protection Agency. Climate change indicators: global greenhouse gas emissions. Updated April 2021. Accessed June 7, 2021. https://www.epa.gov/climate-indicators/climate-change-indicators-global-greenhouse-gas-emissions

Since 1958, continuous CO_2 measurements have been made at the Mauna Loa Observatory in Hawaii and recorded on the **Keeling Curve** (**Figure 1.5**), which is updated daily and made publicly available.[14] The regular periodic oscillation in CO_2 concentration shown on the curve reflects the seasonal difference in CO_2 uptake via plant photosynthesis. Vegetative leaf cover is more abundant during summers in the northern hemisphere, where land and extratropical forested areas exceed those in the southern hemisphere. Atmospheric CO_2 concentration has increased steadily since 1958, exceeding 420 parts per million (ppm) for the first time in recorded history on April 3, 2021.[14]

Other principal GHGs include methane, nitrous oxide, and fluorinated gases. **Methane** (**CH_4**) is a gas emitted during the production, distribution, and use of fossil fuels; by livestock digestion and agricultural practices; and when organic waste decays, largely in solid waste landfills. Drilling, flaring, and transport of natural gas, which is composed mostly of methane, constitute a particularly significant source of methane emissions. **Nitrous oxide** (**N_2O**) is a gas emitted during agricultural and industrial activities, fossil fuel and solid waste combustion, and wastewater treatment. Importantly, N_2O is a by-product of microbial metabolism of nitrogen in synthetic fertilizers used in agriculture. **Fluorinated gases** are synthetic gases containing fluorine that are used in a variety of industrial applications. One such gas is **sulfur hexafluoride**, **SF_6**, used as an insulating chemical in electricity generation and transmission.

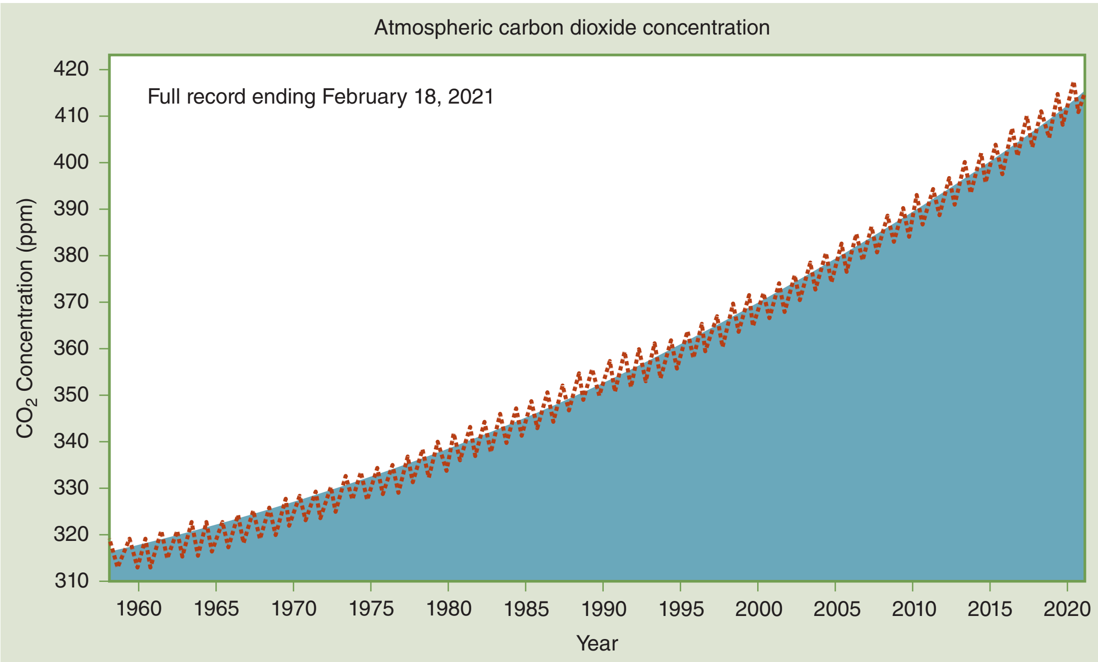

Figure 1.5 The Keeling Curve, a Plot of Global Atmospheric Carbon Dioxide Concentration Recorded at Mauna Loa Observatory in Hawaii and Maintained by Scripps Institution of Oceanography at the University of California San Diego. On February 18, 2021, the CO_2 concentration was 417 ppm.

Reproduced from Scripps Institution of Oceanography at the University of California San Diego. The Keeling Curve. Accessed February 17, 2021. https://keelingcurve.ucsd.edu

The relative heat-trapping property of each GHG is expressed as **global warming potential (GWP)**, a measure of how much energy the emissions of one ton of a GHG will absorb over a given period—usually 100 years—relative to the emissions of one ton of CO_2 (**Table 1.2**). The larger the GWP, the more a given gas warms the Earth compared with CO_2. Even though SF_6 is a trace gas in the atmosphere, it has the highest GWP (23,500 times higher than CO_2) and thus contributes significantly to warming. CH_4 and N_2O are also present at lower concentrations than CO_2, but they have higher GWPs.

Another component of the atmosphere that affects warming is **aerosols**, tiny airborne solid or liquid particles of varying chemical composition that absorb and scatter atmospheric radiation, influence cloud formation and properties, and depending on conditions and composition, may cause warming or cooling. Warming is counteracted by **sinks**, processes that remove a GHG, an aerosol, or their precursor chemicals from the atmosphere. **Carbon sinks** remove CO_2 from the atmosphere via **sequestration**, which has the effect of increasing the content of carbon pools on land and in water. Major carbon sinks on Earth are forests, where trees and other plants take up and store CO_2 during photosynthesis, oceans, where CO_2 is dissolved and also taken up by photosynthetic marine plants, and soils.

Table 1.2 Global Warming Potentials of Principal Greenhouse Gases.

Greenhouse Gas	Global Warming Potential (GWP)
Carbon dioxide (CO_2)	1
Methane (CH_4)	28
Nitrous oxide (N_2O)	265
Sulfur hexafluoride (SF_6)	23,500

Data from Intergovernmental Panel on Climate Change. *AR5 Climate Change 2013: The Physical Science Basis*. Published 2013. Accessed February 19, 2021. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf

A Brief History of Climate Science

The phenomenon of global warming was first proposed in 1856 by **Eunice Newton Foote**, an American scientist and women's rights advocate. She reported on an experiment she conducted, showing that carbon dioxide is a GHG:

> My investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun. The highest effect of the sun's rays I have found to be in carbonic acid gas [CO_2]. An atmosphere of that gas would give to our earth a high temperature.[15]

Five years later, Irish physicist **John Tyndall** reported a similar observation: that "carbonic acid diffused through the air" must "produce a change of climate."[16] In 1896, Swedish scientist **Svante Arrhenius** quantified the heat-trapping effects of water vapor and CO_2, reporting, "We now possess all the necessary data for an estimation of the effect on the earth's temperature which would be the result of a given variation of the aerial carbonic acid." Arrhenius noted that among the sources of CO_2 was "the industrial development of our time," including coal, which can be "transformed into carbonic acid."[17]

Many other scientists have made important contributions, including **Guy Callendar**, who published a 1938 paper that linked fossil fuel burning to atmospheric CO_2 and global warming. He reported that human combustion activities had contributed 150,000 tons of CO_2 to the atmosphere and that recorded global temperature measurements at the time showed 0.005°C of warming per year.[18] Two decades later, physicist **Gilbert Plass** published a paper entitled "Carbon Dioxide and the Climate," in which he concluded that the burning of fossil fuels was the major source of atmospheric CO_2 and would lead to an average temperature increase of 1.1°C per century.

A major turning point in the public's focus on climate change came in June 1988, when climate scientist **Dr. James Hansen**, director at the time of NASA's Goddard Institute for Space Studies, testified at a hearing before the U.S. Senate's Energy and Natural Resources Committee. Hansen reported that "the greenhouse effect has been detected, and it is changing our climate now."[19]

> I would like to draw three main conclusions. Number one, the earth is warmer in 1988 than at any time in the history of instrumental measurements. Number two, the global warming is now large enough that we can ascribe with a high degree of confidence a cause and effect relationship to the greenhouse effect. And number three, our computer climate simulations indicate that the greenhouse effect is already large enough to begin to affect the probability of extreme events such as summer heat waves.[19]

Today, more than three decades later, warming continues to occur, and scientists have learned a great deal about its impacts on our weather and climate systems. People all over the world are experiencing climate-change-fueled extreme events and their devastating consequences for health, well-being, and livelihoods.

Observing a Changing Climate

So how much has the Earth warmed since preindustrial times? Scientific institutions such as the U.S. National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) continuously monitor climate change indicators, including atmospheric CO_2 levels, surface temperature (land, sea, or both combined), ocean heat content, sea level rise, ocean acidification (due to CO_2 dissolving in water, forming carbonic acid), glacier extent, and Arctic and Antarctic sea ice extent. **Figure 1.6** shows the change in global land and ocean surface temperature from 1880 to 2020 relative to average temperatures in the reference period 1951–1980. Some variability exists, but net warming has been occurring since the mid-20th century. In 2020, one of the three hottest years on record, the average temperature anomaly was 1.02°C (1.84°F) above the 1951–1980 average.[20]

Warming is often described globally, but it also occurs regionally or locally. The map in **Figure 1.7** illustrates how much of the world was warmer than average in 2020, particularly in northern Russia. Arctic regions are warming much faster than the world overall.

Average global sea height has risen each year since 1993, when satellite observations began (**Figure 1.8**). Sea level rise is caused by melting ice sheets and glaciers adding meltwater to the oceans, as well as thermal expansion of seawater as it absorbs heat. As of September 2020, overall sea level had risen 97 mm (nearly 4 inches) above 1993 levels, with an annual rate of change of 3.3%.[21] By 2100, even if warming is limited to 2°C, oceans are predicted to rise 1–2 feet above 1986–2005 levels.[22]

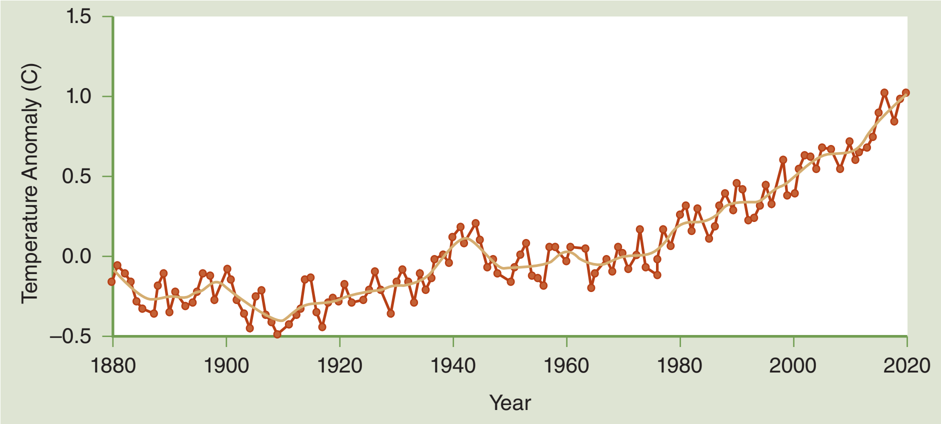

Figure 1.6 Change in Global Land and Ocean Surface Temperature from 1880 to 2020 Relative to Average Temperature in the Reference Period 1951–1980.

Reproduced from National Aeronautical and Space Administration. Facts: global temperature. Accessed February 19, 2021. https://climate.nasa.gov/vital-signs/global-temperature

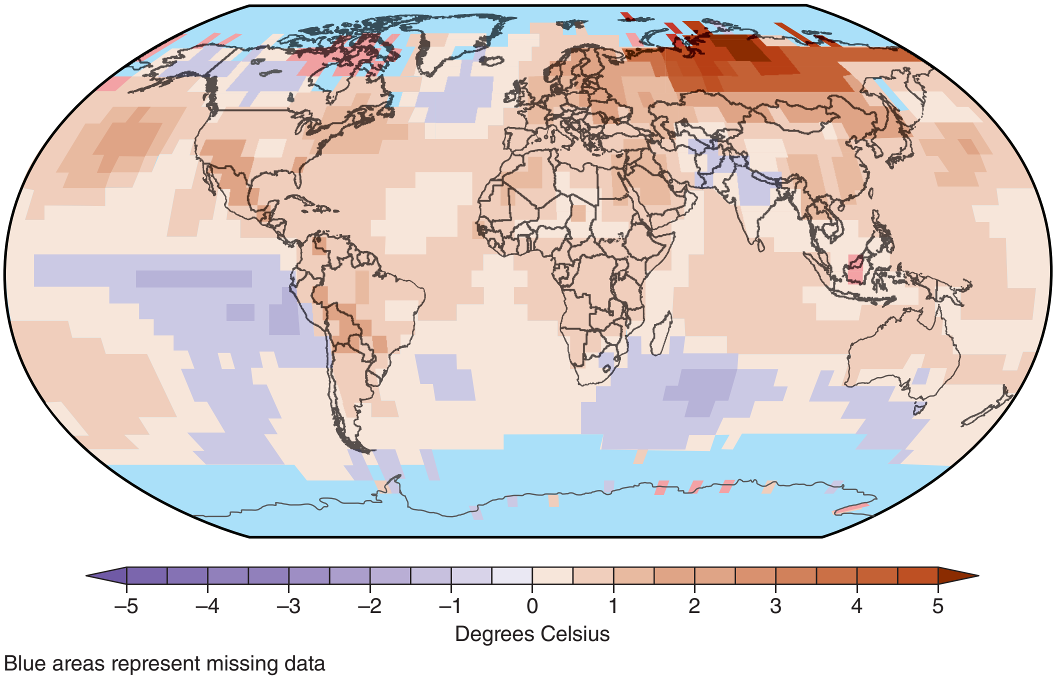

Figure 1.7 Deviation of Land and Ocean Temperature During 2020 from a Baseline Average Temperature, 1980–2010. Brown and pink indicate warming.

Reproduced from National Oceanic and Atmospheric Administration National Centers for Environmental Information. Global temperature and precipitation maps. Accessed February 19, 2021. https://www.ncdc.noaa.gov/temp-and-precip/global-maps

Arctic sea ice, which reaches a yearly minimum in September, is declining at a rate of 13% per decade relative to the 1981–2010 median extent, as measured by satellites (**Figure 1.9**). The lowest sea ice extent in the satellite record was measured in 2012, and the second lowest extent was measured in 2020.[23] Land ice sheets in Antarctica and

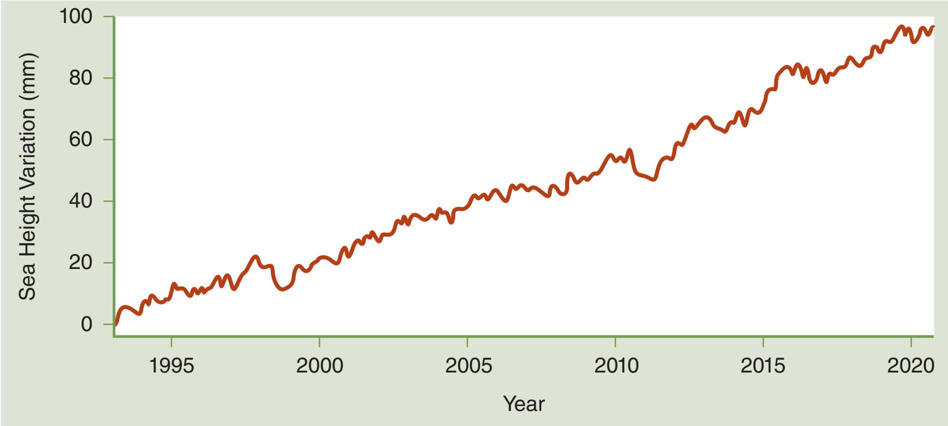

Figure 1.8 Global Sea Level Rise as Measured by Annual Sea Height Relative to the Value in 1993.

Reproduced from National Aeronautical and Space Administration. Facts: sea level. Accessed February 19, 2021. https://climate.nasa.gov/vital-signs/ocean-heat

Greenland have been losing billions of metric tons of mass since 2002.[24]

These changes in turn impact precipitation levels (**Figure 1.10**), which vary greatly across the globe, resulting in increased risks of floods, storms, droughts, and coastal erosion. Additional impacts of increased temperature, sea level rise, and/or altered rainfall patterns include saltwater intrusion into freshwater and soils, loss of storm-protective coastal sea ice in regions with cold climates, permafrost melt, more frequent and extreme wildfires, changes in agricultural productivity, greater water scarcity, and increased air pollution—all of which impact human health and well-being.

Global GHG emissions fueling these changes have risen steadily since preindustrial times, including in recent years (**Figure 1.11**).[25] CO_2 is by far the most predominant GHG,

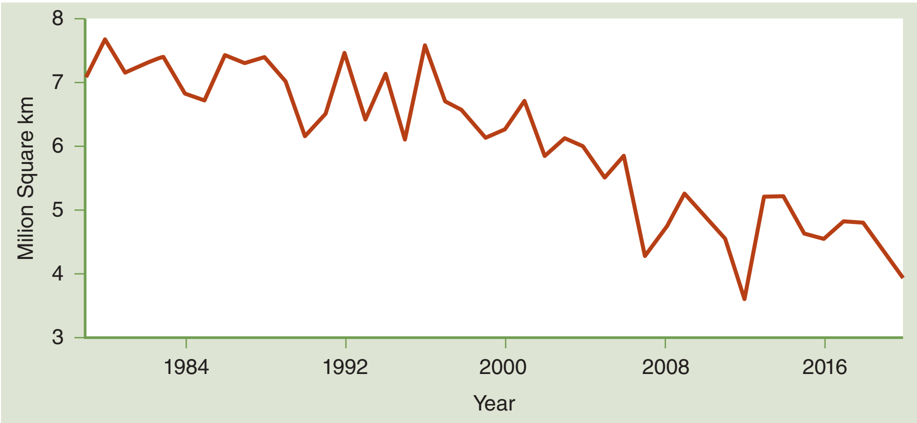

Figure 1.9 Average Monthly Arctic Sea Ice Extent Each September (When Arctic Sea Ice Reaches Its Minimum) Since 1979, Derived from Satellite Measurements. The 2012 sea ice extent is the lowest in the satellite record.

Reproduced from National Aeronautical and Space Administration. Facts: arctic sea ice minimum. Accessed February 19, 2021. https://climate.nasa.gov/vital-signs/arctic-sea-ice

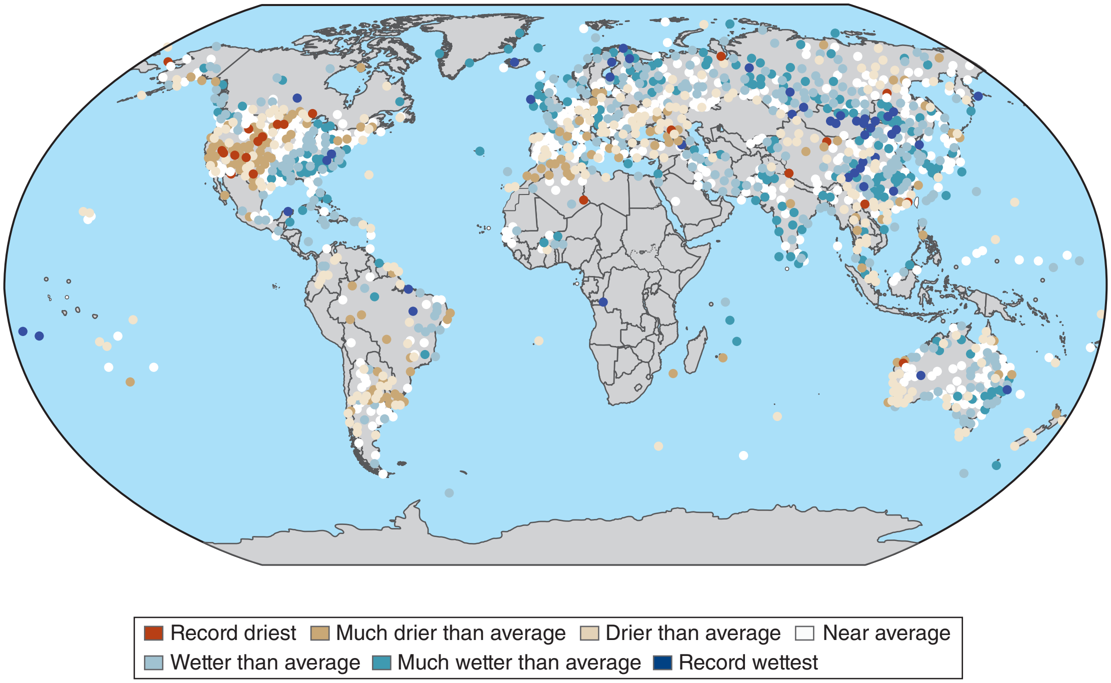

Figure 1.10 Precipitation in 2020 Indicated as Deviations from Average. Blue dots indicate wetter conditions, and brown dots indicate drier conditions.

Reproduced from National Oceanic and Atmospheric Administration National Centers for Environmental Information. Global temperature and precipitation maps. Accessed February 19, 2021. https://www.ncdc.noaa.gov/temp-and-precip/global-maps

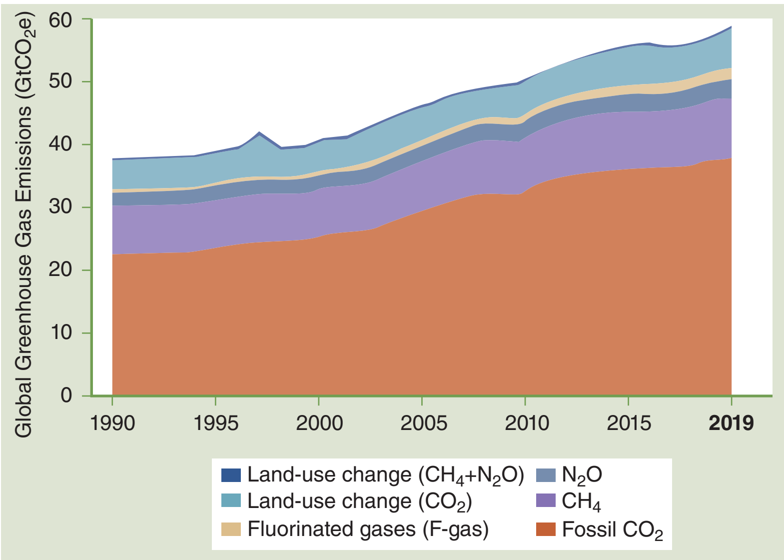

Figure 1.11 Global Increase in Emissions of the Primary Greenhouse Gases (in Gigatons of CO_2 Equivalents) from 1990 to 2019.

Reproduced from United Nations Environment Programme. *Emissions Gap Report 2020.* United Nations Environment Programme; 2020:Figure ES.1. https://www.unep.org/emissions-gap-report-2020

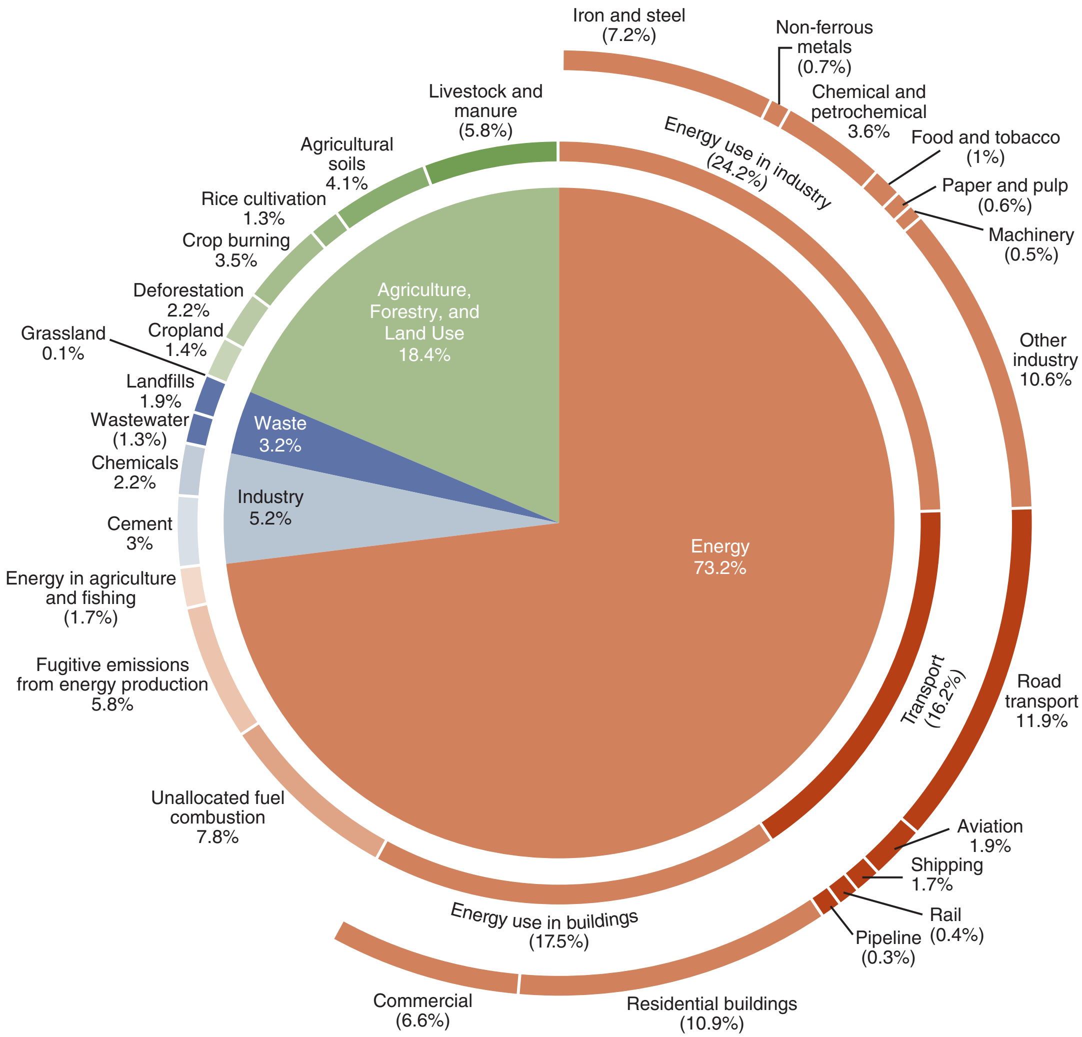

Figure 1.12 Global Greenhouse Gas Emissions by Sector in 2016.

Reproduced from Ritchie H, Roser M. Emissions by sector. Our World In Data. Accessed February 21, 2021. https://ourworldindata.org/emissions-by-sector

arising primarily from fossil fuel combustion, deforestation, and other land use changes. The energy sector, including transportation and electricity and heat generation, is the greatest source of GHGs, followed by agriculture, forestry, and land use changes (**Figure 1.12**). Industrial and waste management practices are also important sources.

In 2020, global GHG emissions decreased by 7%, due primarily to the COVID-19 pandemic and resulting lockdowns, reduced human activities, and economic slowdown (**Figure 1.13**).[25] Lower emissions from ground transport had the biggest impact, followed by power generation, industry, and aviation—particularly from March to June, the period of greatest emissions reduction in 2020.

GHG emissions vary starkly by country and by income level. Countries with the highest *total* and *per capita* GHG emissions

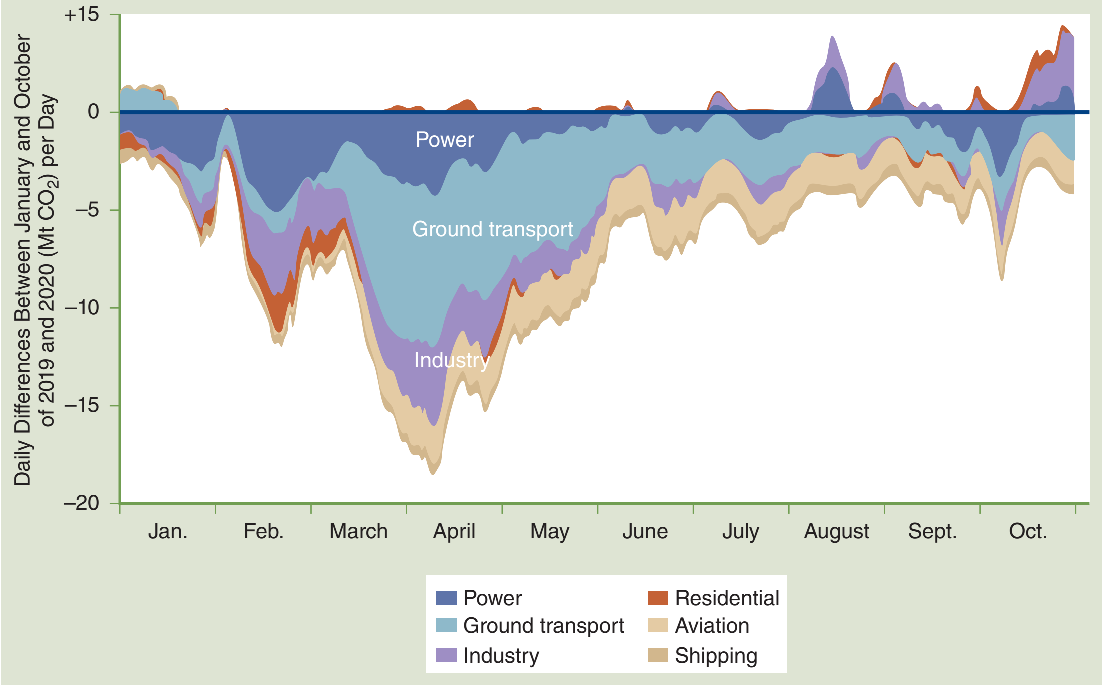

Figure 1.13 Global Reduction in CO_2 Emissions Due to COVID-19 Pandemic Shutdowns in 2020.

Reproduced from United Nations Environment Programme. *Emissions Gap Report 2020*. United Nations Environment Programme; 2020:Figure ES.3. https://www.unep.org/emissions-gap-report-2020

in 2019 are shown in **Figure 1.14**. China had the highest *total* emissions, followed by the United States, EU27+UK (27 European Union member countries plus the United Kingdom), Russia, and Japan.[25] In addition to country-level emissions, international transport is a leading global source. Globally, GHG emissions increased 43% from 1990 to 2015.[8] Since 2005, *total* U.S. GHG emissions have declined 12%.[8] The United States had the highest emissions on a *per capita* basis, followed by Russia, Japan, China, and EU27+UK.[25] Per capita emissions have declined recently in the United States, Japan, and the EU and have risen in China and India, where increased fossil fuel use has powered economic growth and development.

The world's richest 1% of income earners are responsible for more than twice the *total* GHG emissions as the bottom 50% of income earners. The richest 1% also have about 35 times higher *per capita* emissions than the global average level needed by 2030 to limit global warming to 1.5°C (**Figure 1.15**).

In addition to weather and climate variability caused by anthropogenic GHG emissions, natural phenomena also lead to shifting weather patterns, the largest of which is the **El Niño–Southern Oscillation (ENSO)**. ENSO is caused by periodic fluctuations in the temperature of surface waters in much of the tropical Pacific Ocean. Every 3–7 years, these waters warm or cool 1–3°C compared with the average and alter global air currents, which influences surface temperatures and precipitation around the world. The three phases of ENSO are **El Niño** (warmer waters), **La Niña** (cooler waters), and **Neutral** (neither warming nor

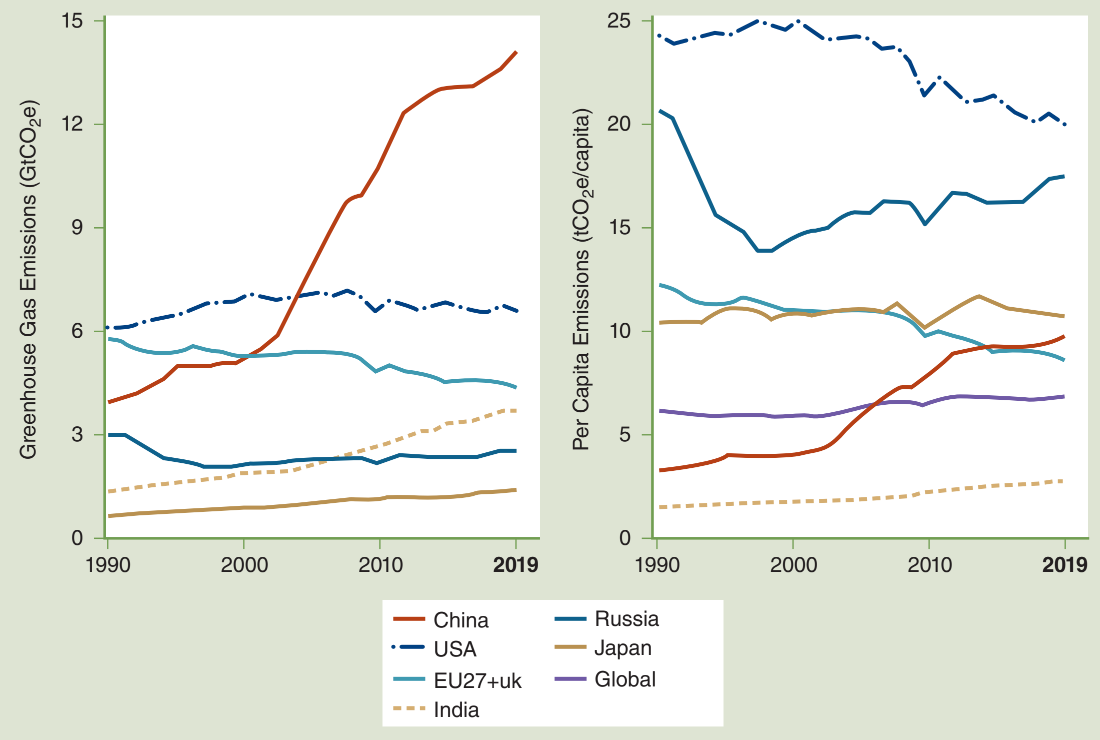

Figure 1.14 GHG Emissions by the Major Emitting Countries, 1990–2019. Left: Total emissions. Right: Per capita emissions.

Reproduced from United Nations Environment Programme. *Emissions Gap Report 2020.* United Nations Environment Programme; 2020:Figure ES.2. https://www.unep.org/emissions-gap-report-2020

cooling). El Niño and La Niña events may be categorized as *strong*, *moderate*, or *weak*.[26] The impacts of El Niño and La Niña vary regionally and may greatly impact regional temperature and precipitation (**Figure 1.16**).

In North America, El Niño tends to cause warmer temperatures and drier conditions in the northern United States and Canada, particularly in the winter months (**Figure 1.17**), and more rainfall in the southeastern United States and coast of the Gulf of Mexico. In a La Niña year, weather patterns typically grow warmer and drier across the southern United States and northern Mexico, and cooler and wetter across the north. That 2020 was one of the hottest years on record is particularly alarming given that a La Niña event occurred in the second half of 2020, which usually results in cooler than average temperatures in many places. La Niña may also coincide with an active hurricane season in the northern Atlantic Ocean, as was the case in 2020.

Projecting Future Climate Change

Given what we know about current changes to the Earth's climate, trends in GHG emissions, and patterns of socioeconomic development, how is future climate change projected? Scientists use **climate models**, sophisticated computational representations of climate systems that incorporate a range of plausible scenarios about end-of-century

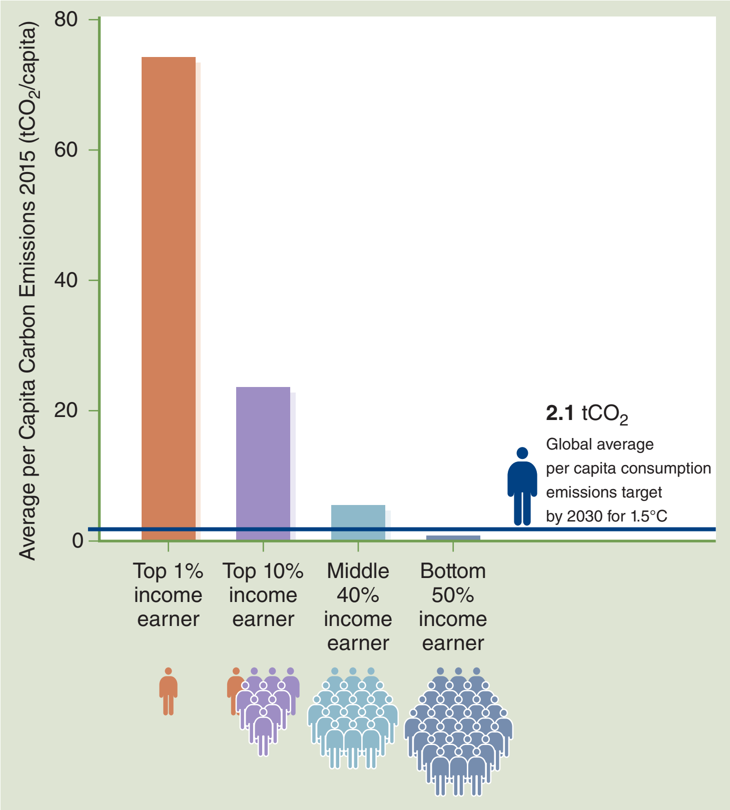

Figure 1.15 Per Capita Carbon Emissions by Global Income Level, 2015. The blue line indicates the global average per capita GHG emissions needed by 2030 to limit global warming to 1.5°C.

Reproduced from United Nations Environment Programme. *Emissions Gap Report 2020.* United Nations Environment Programme; 2020:Figure ES.8. https://www.unep.org/emissions-gap-report-2020

GHG emissions, as well as pathways of development that likely influence drivers of and responses to climate change.[27] Results from climate models are used by researchers, governments, and international and civil society organizations and are incorporated into many scientific reports, including those produced by the **Intergovernmental Panel on Climate Change (IPCC)**. Created in 1988, the IPCC is the United Nations (UN) body that assesses the state of the science of climate change, its impacts and future risks, and climate adaptation and mitigation pathways. Thousands of scientists and other experts from countries around the world contribute to the work of the IPCC, which informs climate change decision-making at local, national, and international scales. The IPCC's latest report, the *Sixth Assessment Report* (**AR6**), was released in sections in 2021 and 2022.[28] All reports are publicly available on the IPCC website.

One example of climate model output is illustrated in **Figure 1.18**. The models used to project the changes shown for average surface temperature and precipitation in 2081–2100 are from the IPCC's 2013–2014 *Fifth Assessment Report* (**AR5**), for which scientists defined four emissions scenarios, called Representative Concentration Pathways (RCPs). Each RCP is labeled according

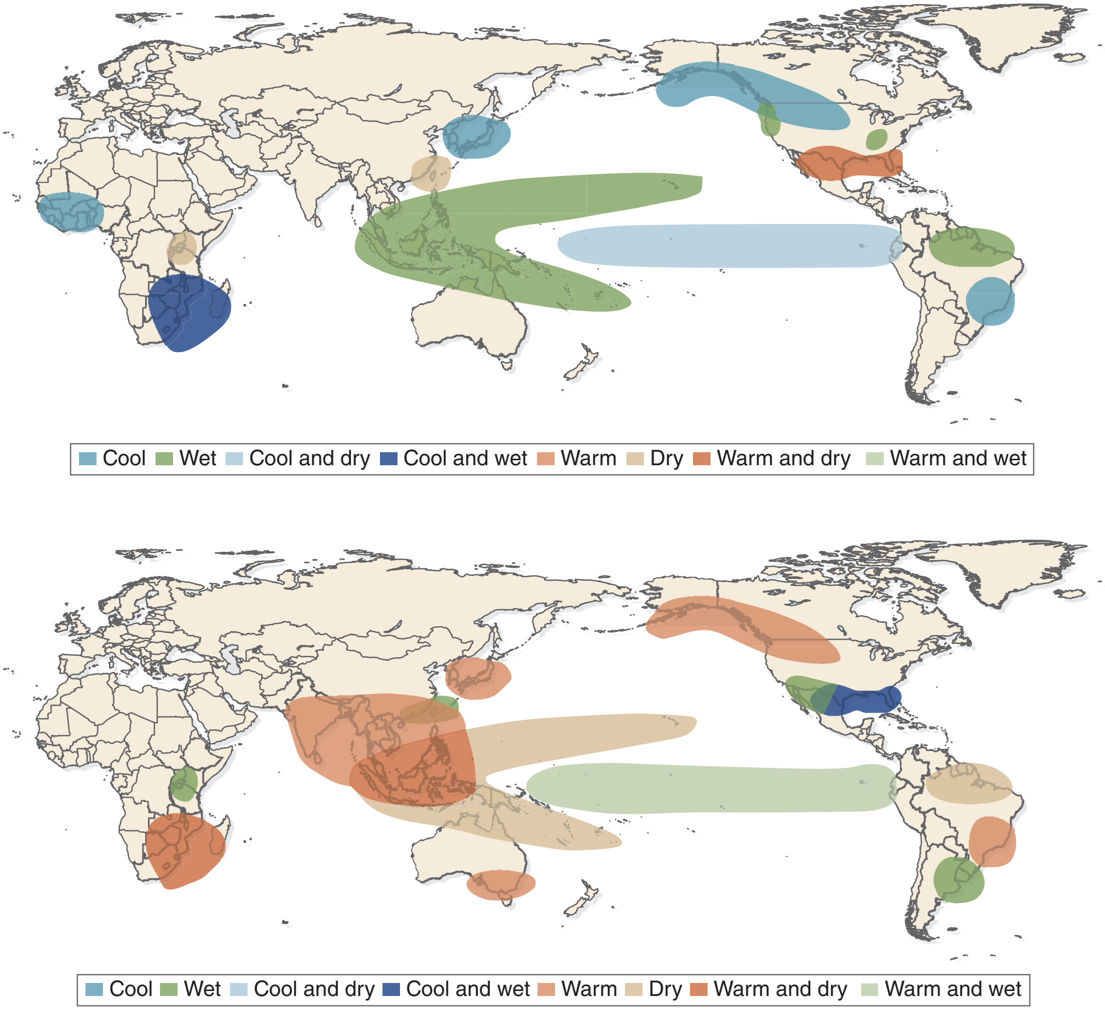

Figure 1.16 Temperature and Precipitation Variations in December, January, and February during La Niña (Top) and El Niño (Bottom) Events.

Reproduced from Lindsay R. Global impacts of El Niño and La Niña. Published February 9, 2016. Accessed February 21, 2021. https://www.climate.gov/news-features/featured-images/global-impacts-el-ni%C3%B1o-and-la-ni%C3%B1a

to its radiative forcing level in the year 2100 relative to 1750 and is linked to a specific climate policy approach (**Table 1.3**).[29]

In these RCP scenarios, concentrations of CO_2 equivalents in the atmosphere range from 475 to 1313 ppm and warming from 1.0°C to 3.7°C above 1986–2005 levels. Figure 1.18 shows projected future temperature increases and changes in precipitation under two of these emissions scenarios, RCP2.6 and RCP8.5. Significantly greater temperature increases and precipitation changes are predicted under RCP8.5, which is a very high-GHG-emissions scenario.

Climate models in the IPCC's *Sixth Assessment Report* (AR6) use a set of future scenarios called Shared Socioeconomic Pathways (SSPs), which combine assumptions about climate change, socioeconomic growth, technological advances, and human population

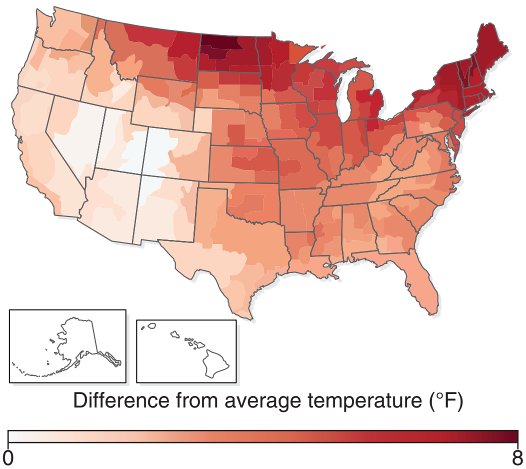

Figure 1.17 Winter Temperature Differences from Average in the U.S. during the Strong El Niño in 2015–2016.

Reproduced from Lindsay R. U.S. winter temperatures for every El Niño since 1950. Published October 24, 2018. Accessed February 21, 2021. https://www.climate.gov/news-features/featured-images/us-winter-temperatures-every-el-ni%C3%B1o-1950

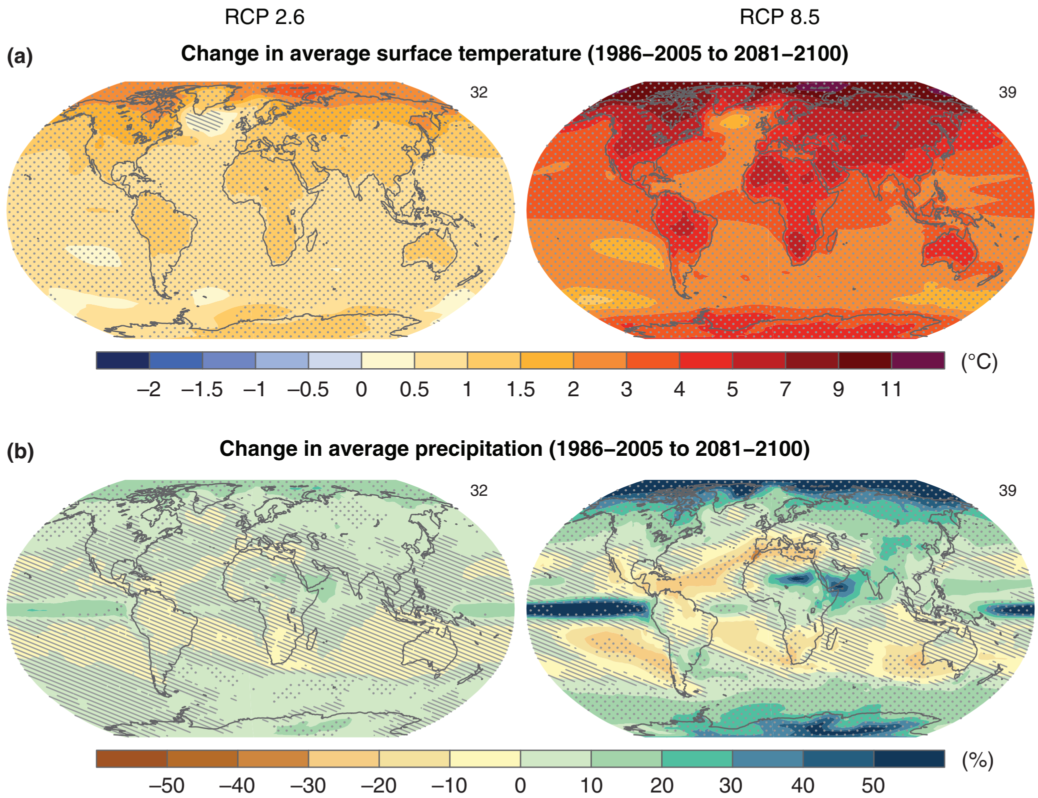

Figure 1.18 Predicted Warming and Precipitation Changes in 2080–2100 Compared with 1986–2005 Using Two Emissions Scenarios, RCP 2.6 (with GHG Emissions Mitigation) and RCP 8.5 (with No Action).

Data from Intergovernmental Panel on Climate Change. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change; 2014. https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

Table 1.3 Summary of Representative Concentration Pathways (RCPs) Presented in the IPCC's AR5.

Scenario	Radiative Forcing Compared with 1750 (watts/m^2)	Climate Policy Pathway	Projected Global Average Temperature Increase in 2100 Compared with 1986–2005 (°C)
RCP2.6	2.6	Reduce GHG emissions	1.0
RCP4.5	4.5	Stabilize GHG emissions at current levels	1.8
RCP6.0	6.0		2.2
RCP8.5	8.5	Take no action	3.7

Data from Intergovernmental Panel on Climate Change. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change; 2014. https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

dynamics. Each SSP is labeled according to a radiative forcing level and contextual "narrative," from sustainable growth and equality to unconstrained growth and energy use (**Table 1.4**).[27] The eight SSPs expand the range of possible scenarios, including SSP1-1.9, the scenario associated with the least future warming by century's end (best estimate below 1.5°C). AR6 includes a novel publicly available interactive atlas to explore observed and projected climate data at global and regional scales.

Future climate scenarios do not forecast what is inevitable by this century's end; instead, they present a wide range of plausible outcomes, some more probable than others. In IPCC reports, the **likelihood** of a climate change or impact occurring, including a human health impact, is expressed as a probability of certainty ranging from "virtually

Table 1.4 Summary of Shared Socioeconomic Pathways (SSPs) Presented in the IPCC's AR6.

Scenario	Narrative	Radiative Forcing (watts/m^2)
SSP1	"A world of sustainability-focused growth and equality"	1.9, 2.6
SSP2	"A 'middle of the road' world where trends broadly follow their historical patterns"	4.5
SSP3	"A fragmented world of 'resurgent nationalism'"	7
SSP4	"A world of ever-increasing inequality"	3.4, 6.0
SSP5	"A world of rapid and unconstrained growth in economic output and energy use"	3.4, 8.5

Data from Hausfather Z. CMIP6: the next generation of climate models explained. Published December 2, 2019. Accessed February 21, 2021. https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

Table 1.5 ***Likelihood*** **Language Used by the IPCC.**

Likelihood Term	Probability of the Outcome
Virtually certain	99–100%
Extremely likely	95–100%
Very likely	90–100%
Likely	66–100%
More likely than not	>50–100%
About as likely as not	33–66%
Unlikely	0–33%
Very unlikely	0–10%
Extremely unlikely	0–5%
Exceptionally unlikely	0–1%

Data from Intergovernmental Panel on Climate Change. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change; 2014. https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

certain" to "exceptionally unlikely" (**Table 1.5**). In addition, **confidence** in a finding is reported from "very low" to "very high" based on the status of the **evidence** for this finding, categorized as *limited*, *medium*, or *robust*, and the level of scientific **agreement** about this finding, categorized as *low*, *medium*, or *high*.[29]

Taking Climate Action

Future scenarios project major climate impacts, including significant adverse effects on human health and well-being. These impacts are mostly distributed along deeply etched fault lines of inequality, burdening some people more than others. These are not inevitable outcomes, however, if swift and aggressive climate action is taken to reduce GHG emissions and prepare for these impacts.

Progress by countries to adopt climate policies and programs has been catalyzed in part by international negotiations and resulting climate change agreements and treaties. The **United Nations Framework Convention on Climate Change (UNFCCC)** is the overarching international convention on climate change. It was signed by 154 countries in 1992 at the UN Conference on Environment and Development in Rio de Janeiro, Brazil (often referred to as the "Rio Summit" or "Earth Summit") and entered into force in 1994. The main objective of the UNFCCC is

> stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic human-induced interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.[30]

The **Conference of the Parties** (**COP**) of the UNFCCC is the decision-making body that represents all Parties to the convention. **Parties** are countries that have ratified or otherwise legally approved international agreements and treaties and thus are bound to follow them. The COP meets annually to negotiate and review the implementation of the convention and its legal instruments. Non-Party stakeholders also participate in COP meetings, including representatives of states, provinces, and cities, Indigenous peoples, civil society organizations, and businesses.

The UNFCCC itself does not set binding or enforceable GHG emissions limits, but provides the framework for international negotiations on specific treaties that do so, including the Kyoto Protocol and Paris Agreement. The **Kyoto Protocol** was adopted in 1997, and entered into force in 2005. It committed developed countries to limit their GHG emissions under the principle of "common but differentiated responsibility and respective capabilities," recognizing that developed countries are largely responsible for the high levels of atmospheric GHG emissions and thus have a greater obligation to act.[31] Currently, there are 192 Parties to the protocol. The United States is the only country that signed but did not ratify the Kyoto Protocol and thus is not bound to reduce its GHG emissions under this specific treaty. In the first phase of the Kyoto Protocol (2008–2012), 37 countries plus the European Union exceeded the pledged target of GHG emissions reductions of an average of 5% compared with 1990 levels.[31]

A second major milestone in international climate policy is the **Paris Agreement**, a treaty that compels all countries to commit to ambitious climate action—not just developed countries, as is the case under the Kyoto Protocol. It was adopted by 196 Parties at COP21, the international climate conference in Paris, France, in December 2015, and it entered into force in November 2016 (**Figure 1.19**). The main objectives of the Paris Agreement are **climate mitigation**, efforts to reduce GHG emissions to limit global warming to well below 2°C (3.6°F) and preferably below 1.5°C (2.7°F) compared with preindustrial levels, **climate adaptation** to build the capacity of countries to respond to the adverse impacts of climate change, and **climate finance** mechanisms whereby high-income countries assist low- and middle-income countries in funding low-carbon and climate-resilient development projects.[32]

The Paris Agreement sets up five-year cycles of increasingly ambitious climate action in which countries are required to prepare, communicate, and implement **nationally determined contributions (NDCs)** that outline national plans to meet emissions reductions targets and climate adaptation goals. The Paris Agreement calls for reducing GHG emissions as soon as possible, with the goal of climate neutrality (net-zero GHG emissions) by midcentury. NDCs may contain "unconditional" contributions that can be

Figure 1.19 Left: U.S. Secretary of State John Kerry Signs the Paris Agreement While Holding His Granddaughter at the United Nations in New York City, April 22, 2016. Kerry is the U.S. Special Presidential Envoy for Climate in the Biden administration. Right: Climate Activists Stage a Protest for Climate Justice at the COP21 UN climate summit in Paris, France, December 1, 2015.

Left: © Andrew Gombert/EPA/Shutterstock; Right: © Ryan Rodrick Beiler/Shutterstock.

implemented based on a country's own financial resources and capabilities, and "conditional" contributions that countries would undertake if international financial support is available or if "collective ambition" rises among countries to do more.[33]

The current magnitude and pace of change of GHG emissions has put the world on a dangerous warming course. As of late 2020, the world is on track for greater than 3°C of warming by century's end, and in 2021, the World Meteorological Organization predicted a 40% chance that the average annual global temperature will temporarily reach 1.5°C of warming at some point in the next five years.[34] In 2021, the UN released its first assessment of the potential for current NDCs to achieve the goal of limiting warming to below 2°C, and ideally by 1.5°C, by 2100. The report concluded that global GHG emissions must be *45% below 2010 levels by 2030*.[35] Numerous countries have pledged stricter emissions reduction targets, including net-zero emissions in some cases.

Climate change, human impacts, and actions by governments are changing rapidly. Advances in the near future, including those resulting from the COP26 climate negotiations in Glasgow, Scotland, in November 2021, are expected. The United States, a leading contributor to global GHG emissions, is playing catch-up after the Trump administration abandoned its commitments under the Paris Agreement. One of President Biden's first actions after taking office in January 2021 was to rejoin the Paris Agreement, and in April 2021, the United States announced a target to reduce its net GHG emissions by 50–52% below 2005 levels in 2030.[36] The United States has also promised to honor its financial commitments to support climate mitigation and adaptation in low- and middle-income countries[37] and to accelerate U.S. climate action in an equitable manner by ensuring that 40% of the benefits from federal investments in clean energy, energy efficiency, improved housing, and public transport go to "disadvantaged communities."[38]

Climate action is also being taken at regional scales. For example, dozens of cities around the world have set emissions targets and developed climate adaptation plans. Reykjavik, Iceland, has already achieved 100% renewable energy use, due mostly to its plentiful geothermal energy supply, and several other cities, including Paris, San Francisco, and Canberra, have committed to the goal of 100% renewable energy.[39] In the United States, the first mandatory GHG emissions reduction program has been the successful **Regional Greenhouse Gas Initiative** (**RGGI**), an ongoing cooperative effort among nine northeastern U.S. states to cap and reduce CO_2 emissions from the power generation sector. Since 2005, CO_2 emissions from power plants have declined by more than half while economic growth increased (**Figure 1.20**).

Also in the United States, a broad coalition of nonfederal actors has committed to the goals of the Paris Agreement. Half of U.S. states; more than 500 cities and counties; hundreds of tribes; more than 250 colleges and universities; and hundreds of faith groups, cultural institutions, healthcare organizations, and businesses and investors have signaled their intention to work toward emissions targets. In 2020, this coalition represented 68% of U.S. GDP, 65% of the U.S. population, and 51% of U.S. GHG emissions.[40]

Meeting ambitious GHG emissions targets requires **decarbonizing** energy transformations that phase out carbon-intensive fossil fuels in favor of renewable energy sources. This shift must be implemented in equitable ways so that everyone benefits, especially

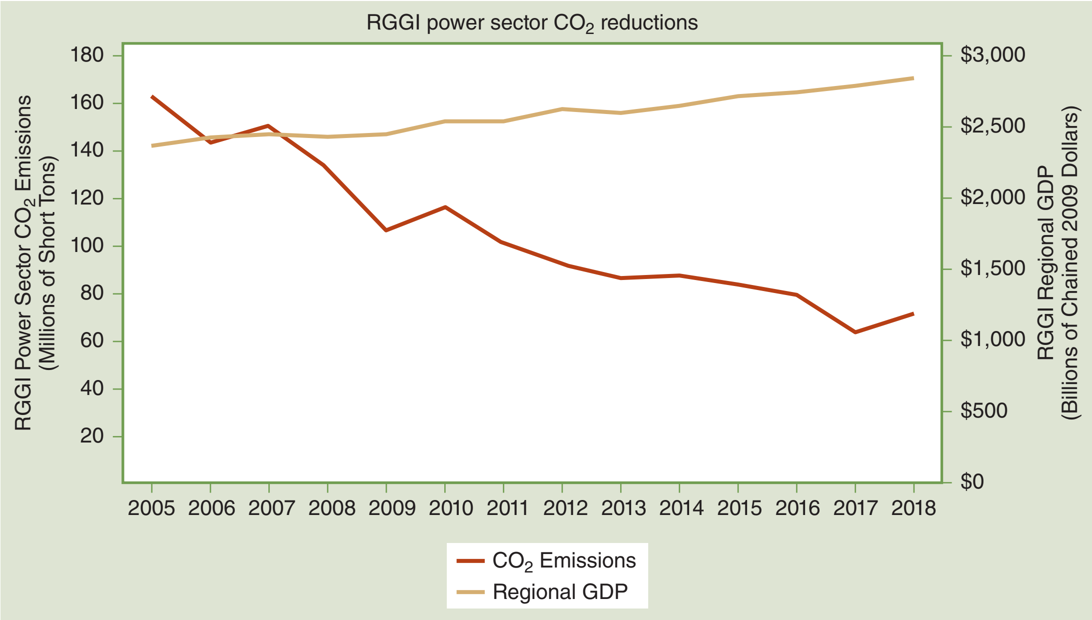

Figure 1.20 Reduction in CO_2 Emissions from the Power Sector in Nine RGGI States, and Regional GDP Increase, 2005–2018.

Reproduced from Regional Greenhouse Gas Initiative. *The Investment of RGGI Proceeds in 2018.* Regional Greenhouse Gas Initiative; 2020. https://www.rggi.org/sites/default/files/Uploads/Proceeds/RGGI_Proceeds_Report_2018.pdf

at-risk populations, vulnerable countries, and those who have contributed very little to climate change yet bear disproportionate burdens of the impacts. Ways to incentivize this transition include eliminating government subsidies paid to fossil energy companies, implementing carbon pricing on fuels that reflects their climate impacts, and enacting subsidies for clean energy from solar, wind, geothermal, and ocean sources. From 2011 to 2020, renewable energy use for U.S. electricity generation increased from 13% to 20% of all energy sources, while use of the dirtiest energy source, coal, declined from 42% to 19% (**Figure 1.21**).[41] Energy efficiency measures must be introduced simultaneously, and carbon sinks, such as forests, soils, and peatlands, must be expanded.

Alternative energy choices take into account impacts primarily on GHG emissions, but human health must also be considered. For example, in 2020, natural gas had replaced coal as the primary energy source for U.S. electricity generation, which benefits human health by reducing CO_2 emissions

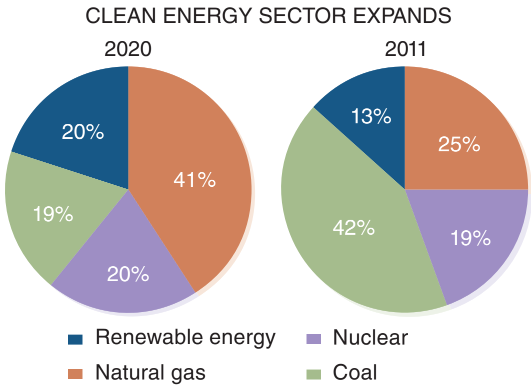

Figure 1.21 Energy Sources for U.S. Electricity Generation in 2011 and 2020.

Reproduced from Business Council for Sustainable Energy. *Sustainable Energy in America 2021: Factbook at-a-Glance.* Accessed June 3, 2021. https://bcse.org/wp-content/uploads/2021-Sustainability-In-America-Factbook-At-A-Glance.pdf and eliminating hazardous by-products of coal burning, such as coal ash, airborne mercury, and particulate matter. However, the composition of natural gas is about 95% methane, a potent GHG, and fugitive methane emissions during all phases of natural gas production contribute significantly to overall GHG emissions and resulting warming. The predominant method of extracting natural gas today is hydraulic fracturing, which is associated with a broad range of health impacts, including respiratory illnesses, cancers, and adverse birth outcomes from exposure to contaminated air and water, mental illness and substance abuse among workers, and deterioration of the social fabric and economic prospects of fracking communities.[42] Generating solar energy produces no GHG emissions but requires photovoltaic cells that use toxic chemicals and create hazardous waste. Advances in alternative energy sources must prioritize less harmful means of extraction, production, use, and disposal to minimize impacts on human health.

An excellent source of information about climate solutions is **Project Drawdown**, a nonprofit organization committed to helping the world reduce GHG emissions and providing information on climate solutions for governments, businesses, institutions, activists, and scholars.[43] Project Drawdown highlights three connected areas where action is needed:

- "**Reduce Sources** [by] bringing emissions to zero"
- "**Support Sinks** [by] uplifting nature's carbon cycle"
- "**Improve Society** [by] fostering equality for all"[43]

Global climate solutions are ranked by Project Drawdown based on predicted impacts on global carbon emissions. To limit warming to 2°C, the top five most impactful solutions turn out to not relate directly to energy choices: reduce food waste, invest in education, particularly of girls and women, eat plant-rich diets, manage refrigerant chemicals that are GHGs, and restore tropical forests.[43] Successful climate action plans will incorporate a wide range of strategies like these to mitigate GHG emissions and adapt to climate change impacts.

Climate Activism

Since Dr. James Hansen publicly raised the alarm about climate change in his congressional testimony in 1988, many activists and civil society organizations have played a key role in advancing climate change awareness and action. Dr. Hansen inspired one of the most effective climate activists, writer Bill McKibben, to pen his popular book on climate change, *The End of Nature*, in 1989, in which he called for a radical repositioning of the relationship between humans and nature. Many environmental groups began focusing seriously on climate change, and in 2008, McKibben and several undergraduate students at Middlebury College launched 350, the first global grassroots organization fighting climate change. The group is named for the upper bounds of parts per million of carbon dioxide that can safely be in the atmosphere without catastrophic global warming, a level greatly exceeded at the current time. McKibben and the student leaders of 350 led the early charge to organize large-scale national and global protests, as well as local activism, to raise awareness about the need for climate action. They have supported campaigns against fossil fuel use by blocking pipeline projects and urging institutions to divest their financial holdings from fossil fuel interests. Today, many organizations large and small are fighting climate change from every place on Earth and doing impactful work on both a global scale and in their local communities.

In recent years, many youth activists have taken the lead in the climate movement and inspired a new generation to get involved, make changes in their communities, and influence world leaders on the biggest stages. Swedish activist Greta Thunberg is perhaps the most recognizable, having started the School Strike for Climate campaign and inspired young activists involved in many climate organizations, including Fridays for Future, an international youth-led coalition fighting climate change. Two youth leaders making a big difference are Xiye Bastida and Alexandria Villaseñor, co-organizers for Fridays for Future U.S. (**Figure 1.22**).

Xiye Bastida, a member of the Otomi-Toltec Nation, was a firsthand witness to catastrophic drought and flooding growing up in Mexico, and then the legacy of Hurricane Sandy after she moved with her family to New York City. Youth are using "every tool at their disposal, from traditional media to memes, to tell the world what we know and why it matters to us," she wrote recently.[44] "You don't have to know the details of the science to be part of the solution. And if you wait until you know everything, it will be too late for you to do anything. That's why we, the youth who are leading on climate, are calling this an emergency." She is focused on creating a diverse and intergenerational collaboration to work toward a "vibrant, fair and regenerative future."[44]

Alexandria Villaseñor wrote in 2020,

> I am fifteen years old and spend a lot of my time on conference calls, sending emails, speaking publicly, and going to protests. Those are probably different memories than you were making at my age, but we youth know we need to make our voices heard now—because our generation will feel climate impacts the most.[45]

Her activism was inspired by witnessing the deadliest wildfire in California's history, the 2018 Camp Fire, which caused dangerously unhealthy air pollution that exacerbated her asthma and made her very

Figure 1.22 (Top) Alexandria Villaseñor speaks at the 2019 C40 World Mayors Summit in Copenhagen, Denmark. (Bottom) Xiye Bastida speaks at the 2019 NOVUS #WeThePlanet forum at the United Nations in New York City.

Top: © OJPHOTOS/Alamy Stock Photo; Bottom: © Rob Kim/Getty Images Entertainment/Getty Images.

sick. "Do [I] miss just being a regular teenager?"[50] she asks.

> The answer is yes. I miss doing theater, playing volleyball, and hanging out with my friends. But the climate crisis threatens every aspect of my future. So what other choice do I have? It is a moral obligation to fight for this planet. My fight for climate action is not going to end until our planet and all its people are safe.[45]

In the United States, people of all racial and ethnic backgrounds have long been working and advocating for environmental protection, climate action, and the health of their communities, including **Heather McTeer Toney**, former U.S. EPA administrator for the Southeast Region and now climate justice liaison to Environmental Defense and senior advisor to Moms Clean Air Force (**Figure 1.23**). Growing up in Mississippi, Toney says she was "surrounded by the interweaving of nature with Black culture, poverty, and the rural South." She stresses that "it is the Black part of American culture that is . . . largely missing from the public conversations about environmental and climate solutions."[46] She sees solutions in her own community, where people are experiencing climate impacts today, including flooded rivers, more heat, disease pest invasions, and problems growing food, although she laments that "no one [has been] listening to the voices of the poor, of rural folk, of southerners."[51] She points out that women of color are not waiting to be told what to do, but rather are already climate leaders, finding ways to make change in their communities, just as they have long been on the frontlines fighting industrial polluters so prevalent in Gulf Coast states. Toney also notes that when she worked at EPA, 90% of her executive team were women of color.[46]

Figure 1.23 Heather McTeer Toney, Senior Advisor, Moms Clean Air Force.

Courtesy of Heather McTeer Toney.

Jacqueline Patterson is senior director of the Climate and Environmental Justice Program of the National Association for the Advancement of Colored People, a U.S. civil rights organization. She points out,

> It is all too clear that justice is not possible in a capitalist system predicated on there being winners and losers, a system rooted in racism, sexism, and xenophobia. This is the system that has put us on the path to catastrophic climate change. The only path to liberation for Black folks and all oppressed people is through revolution—total systems change.[47]

Indigenous peoples are also vital participants in the environmental movement, both in the United States and around the world. Many Indigenous peoples defend their ancestral lands, which hold much of the world's remaining biodiversity, as well as their traditional knowledge systems and practices, which provide a road map for how to respond to the climate crisis. **Sherri Mitchell**, a member of the Penobscot Nation, is an attorney, author, and founding director of the Land Peace Foundation, dedicated to the global protection of Indigenous lands, waters, and ways of life. She calls for incorporating into climate science and action Indigenous knowledge systems "based on the millennia-long study of the complex relationships that exist among all systems within creation."[48] Indigenous peoples provide the world with what she calls "living models of sustainability that are rooted in ancient wisdom and that inform us how to live in balance with all of our relations on Mother Earth." She warns, "Today prophecies are unfolding all around us. We are all observers and participants. The annihilation of Indigenous peoples is also the annihilation of humankind."[48]

Maulian Dana is the Tribal Ambassador of Penobscot Nation and cofounder of the Wabanaki Alliance in Maine, focused on protecting tribal sovereignty and improving education about Indigenous peoples. She recently helped create a comprehensive climate plan for Maine as a member of the governor-appointed Maine Climate Council.

> Frontline communities like tribal nations, new Mainers, those in poverty, people of color, and more are disproportionately affected by the climate crisis. A society is only as strong as its most vulnerable populations, and this holds true in climate work. As we make policy, we need to work from a place of inclusivity and equity to make sure our work is lasting and meaningful.[49]

Tara Houska is an attorney, member of Couchiching First Nation, and founder of the Indigenous advocacy group Giniw Collective (**Figure 1.24**). She and many other Indigenous activists are leading the charge against fossil fuel development in the United States and Canada, including protesting the Dakota Access Pipeline, which crosses the Missouri River north of the Standing Rock Sioux reservation. In 2021, Houska organized the fight against the proposed "Line 3" replacement tar sands pipeline in northern Minnesota that crosses untouched wetlands in treaty territory of Anishinaabe peoples and the headwaters of the Mississippi River. "To be humbled by the lived knowledge that our bodies cannot survive without water is to move water from the conceptual into the actual."[50]

Mitchell, Dana, and Houska each call for everyone to join them in their work, which "will require non-Indigenous people to stand with us and ensure that our lands, waters, and ways of life are not further eroded by government and industrial intrusion."[48] Houska urges Americans to "please find your bravery. Defending the land is a beautiful thing, it's a beautiful risk to take."[51]

Figure 1.24 Tara Houska, Couchiching First Nation.

Courtesy of Tara Houska.

Discussion Questions

1. How does the greenhouse effect work?
2. What are the principal greenhouse gases? What are the major anthropogenic sources of each? How can greenhouse gas emissions from these sources be reduced?
3. How are temperature, precipitation, sea level, and sea ice extent changing?
4. What are the targets for global warming in the Paris Agreement? Given current levels of climate action, how likely is it that these targets will be met? What needs to happen to achieve these goals?
5. What is the role of the IPCC?
6. How is climate activism making a difference? Describe how youth, people of color, and Indigenous peoples are contributing to the climate movement.

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