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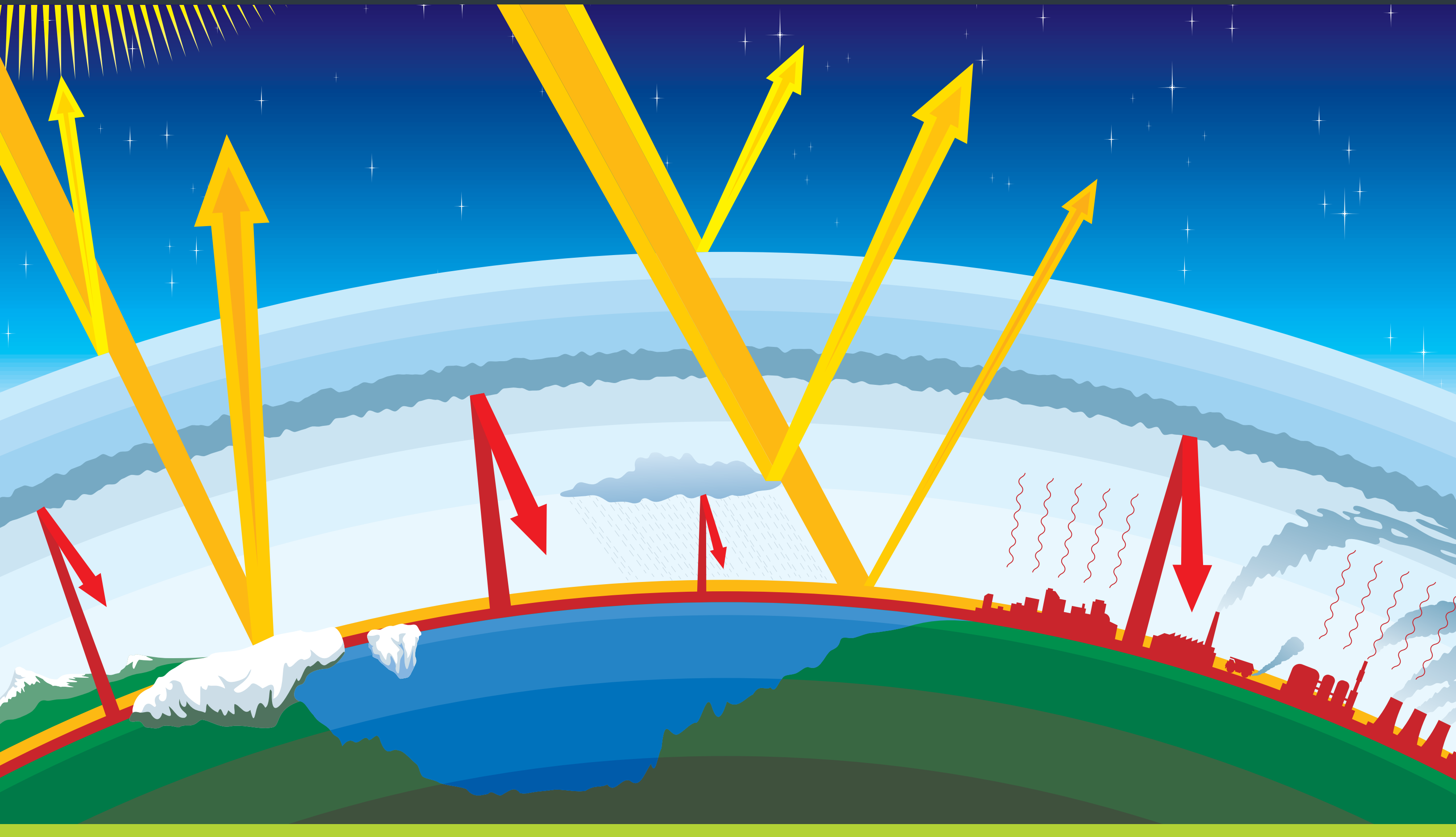
CLIMATE SCIENCE AND LAW FOR JUDGES

What is Causing Climate Change?



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The Environmental Law Institute makes law work for people, places, and the planet. Since 1969, ELI has played a pivotal role in shaping the fields of environmental law, policy, and management, domestically and abroad. Today, in our sixth decade, we are an internationally recognized, non-partisan publishing, research, and education center working to strengthen environmental protection by improving law and governance worldwide.

ENVIRONMENTAL LAW INSTITUTE

CJP CLIMATE JUDICIARY PROJECT™

What is Causing Climate Change?

by Inez Y. Fung

This module explains why levels of greenhouse gases in the atmosphere are related to global temperatures and how climate scientists have used this relationship to project temperatures into the future. It also describes some of the measures being taken at the local, state, federal, and international levels to mitigate climate change.

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I. Introduction

Svante Arrhenius, who won the 1903 Nobel Prize in Chemistry, wrote in 1896 that doubling carbon dioxide in the atmosphere would increase temperatures at the surface by about 5 degrees Celsius. His warming estimate is in the range 3 +/- 1.5 degrees Celsius estimated in the 1979 report from the U.S. National Academy of Sciences (NAS).[1] The NAS report relied on two early models of climate, one led by NASA's Jim Hansen, and the other led by NOAA's Syukuro Manabe, who was awarded the 2021 Nobel Prize in Physics. The fundamentals of Earth's energy budget are well-established. Climate models since have included complex processes in the atmosphere, as well as interactions of the atmosphere with the oceans, land surface, the cryosphere, and the biosphere. With advances in observations, computing power, and research, climate scientists have gained an increasingly detailed understanding of why the climate has been different in the past, what is making it change today, and how it could change in the future.

This module is based primarily on a joint publication from the Royal Society in the United Kingdom and the National Academy of Sciences in the United States, *Climate Change: Evidence and Causes: Update 2020*.[2] It also draws upon the most recent assessment of the climate system conducted by Working Group I of the Intergovernmental Panel on Climate Change (IPCC)[3] and on Volume I of the Fourth National Climate Assessment overseen by the U.S. Global Change Research Program.[4]

II. The Greenhouse Effect

Earth's atmosphere, which consists mainly of nitrogen and oxygen, naturally contains minute quantities of gases, known as greenhouse gases, that make the planet warmer than it would be if these gases were not in the atmosphere.[5] Earth's climate system is powered by the Sun, which is over 90 million miles away and has a temperature exceeding 10,000 degrees Fahrenheit. Some of the Sun's energy is reflected back to space by clouds and the surface, some of it is scattered in all directions, but most passes through the atmosphere without being absorbed. This solar energy heats the land and oceans, raising their temperature. The ground and surface of the oceans, at temperatures of about 60 degrees Fahrenheit, re-emit part of this energy as less energetic infrared radiation—such as that emitted by our bodies and detected by infrared thermometers. Greenhouse

[1] NAT'L ACAD. OF SCI., CARBON DIOXIDE AND CLIMATE: A SCIENTIFIC ASSESSMENT (1979), https://nap.nationalacademies.org/catalog/12181/carbon-dioxide-and-climate-a-scientific-assessment.
[2] NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020 (2020). [hereinafter CLIMATE CHANGE: EVIDENCE & CAUSES].
[3] IPCC, AR6 CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS (2021) [hereinafter AR6 CLIMATE CHANGE].
[4] U.S. GLOBAL CHANGE RES. PROGRAM, CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT VOL. 1 (2017) [hereinafter CLIMATE SCIENCE SPECIAL REPORT].
[5] *See generally id.* at 75.

gases in the atmosphere capture part of this infrared radiation by being excited to a higher energy state, thereby reducing the amount of energy escaping to space and raising the temperature of the atmosphere. The most important greenhouse gases include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). The warmer atmosphere emits infrared radiation in all directions, with the upward radiation balancing the net incoming solar radiation at the top of the atmosphere, and the downward radiation further warming the surface (Figure 1). Without the naturally occurring greenhouse gases in the atmosphere, the average temperature at Earth's surface would be below the freezing point of water, and life as it exists today would not have developed on the planet. Human activities have added greenhouse gases to the atmosphere over the past two centuries, thereby perturbing Earth's energy balance and changing the climate of our planet.

Other than water vapor, the most abundant greenhouse gas is carbon dioxide, a molecule consisting

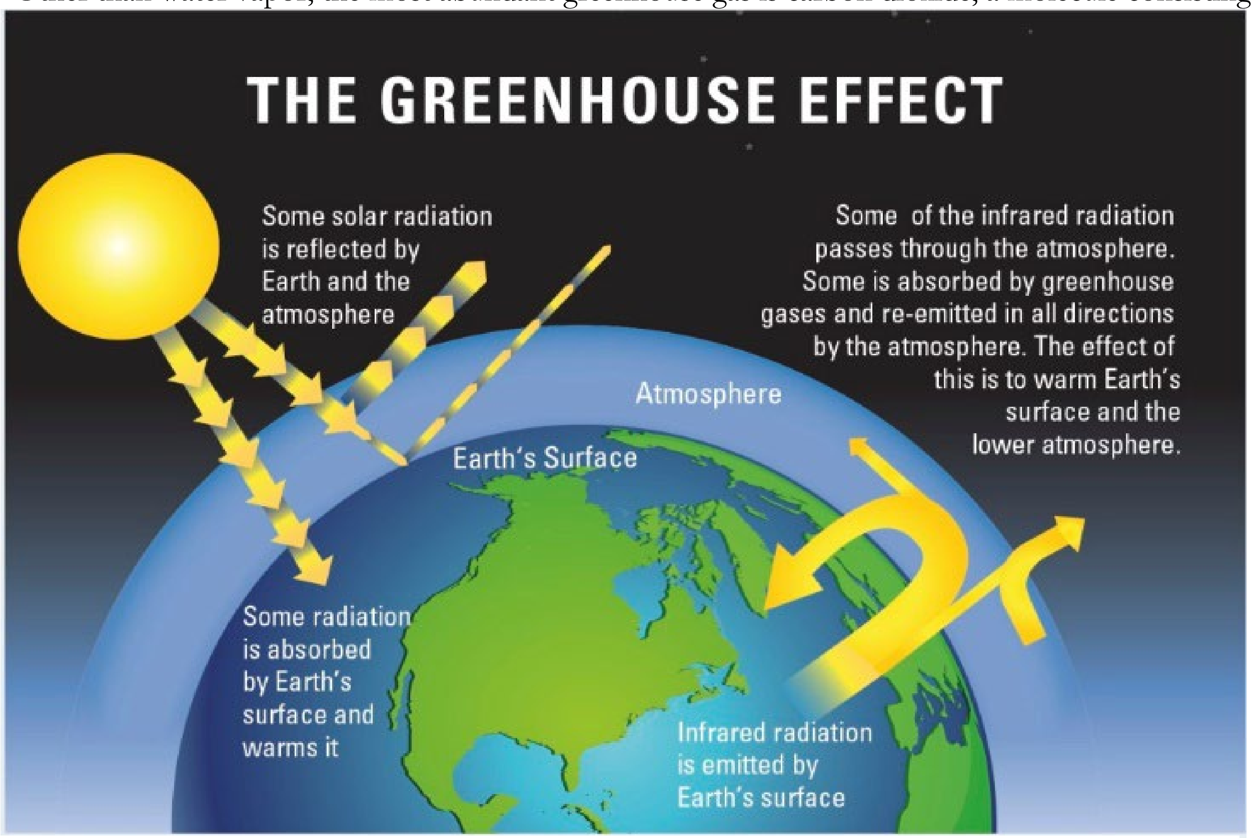

Figure 1. Greenhouse gases in Earth's atmosphere absorb heat energy emitted by the land and ocean, preventing it from escaping into space and raising the atmosphere's temperature. Source: NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020, at B1 (2020).

of one carbon atom and two oxygen atoms (CO_2). Earth's atmosphere naturally contains carbon dioxide emitted from volcanoes and other sources as well as carbon dioxide that cycles continuously among the atmosphere, the oceans, and the land and marine biospheres. Before the Industrial Revolution of the 18th and 19th centuries, the levels of carbon dioxide in Earth's atmosphere were about 280 parts per million—that is, of every million molecules in the atmosphere, 280 of them were carbon dioxide molecules.[6]

Coal, petroleum, and natural gas are derived from ancient (hundreds of millions of years old) plant and animal detritus that escaped decomposition and was buried and transformed via high temperature and pressure into what we know as fossil fuels. When fossil fuels are combusted, the

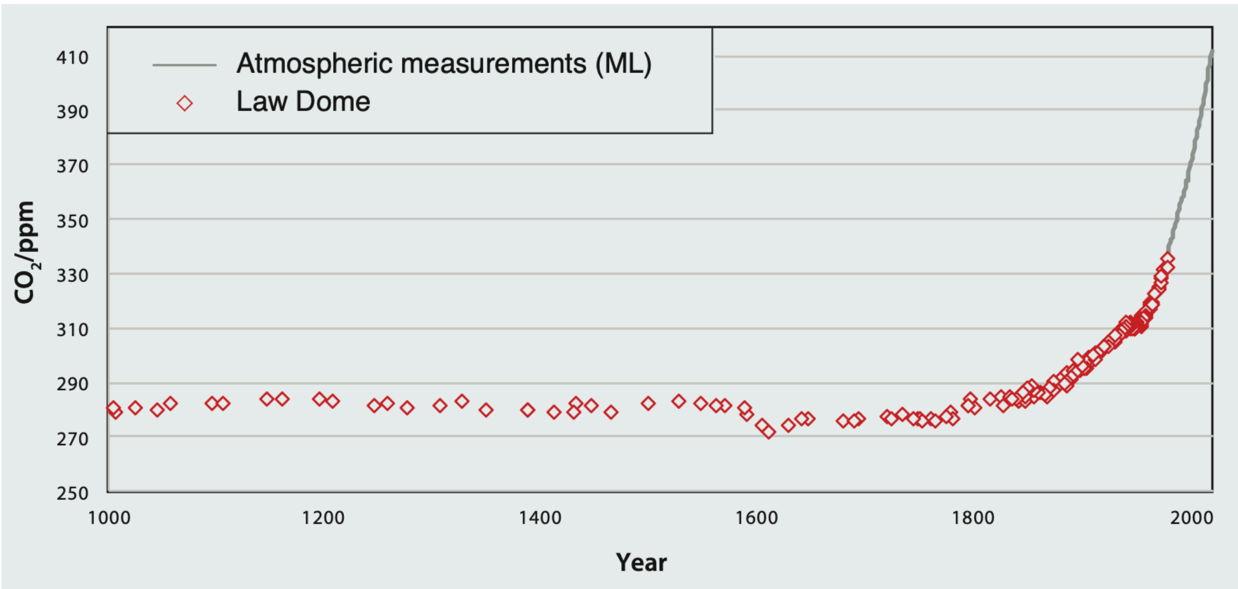

Figure 2. Since the 1950s, scientists have been directly measuring the amount of carbon dioxide in the atmosphere. For times before that, they have measured levels of atmospheric carbon dioxide trapped in ice bubbles, such as those from Antarctica's Law Dome ice core. These measures show that the carbon dioxide level in Earths' atmosphere has increased by about 50% since the beginning of the Industrial Revolution. Source: NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020, at B3 (2020).

carbon in them combines with oxygen to form carbon dioxide. The great expansion of fossil fuel use since the Industrial Revolution has therefore caused an increase in the amount of carbon dioxide and a concomitant decrease in oxygen (albeit in very minute amounts, parts per million) in the atmosphere. From 280 parts per million, the concentration of atmospheric carbon dioxide has risen to more than 415 parts per million in 2022, an increase of about 50% (Figure 2).[7] More than half this increase in atmospheric carbon dioxide levels has occurred since 1970.

Other gases in the atmosphere also absorb infrared radiation emitted from Earth's surface and by the atmosphere, adding to the greenhouse effect.[8] One is methane, which is produced by microbes in anaerobic (oxygen-free) environments such as wetlands, stomachs of cattle, rice paddies, and landfills. Emissions from these environments, together with venting and flaring at oil wells, leakage from coal mines and natural gas pipelines, have more than doubled methane levels in the atmosphere to about 2 parts per million over the past 150 years. Nitrous oxide, which in the United

[6] CLIMATE CHANGE: EVIDENCE & CAUSES, *supra* note 1, at B3.
[7] *Id.*
[8] *Id.* at 2.

States comes largely from the use of nitrogen-based fertilizers, has increased in concentration by about 25% to about 335 parts per billion over the same period. A class of chemicals known as halocarbons, which are used as refrigerants and fire retardants and include chlorofluorocarbons (CFCs), are almost entirely human-produced. Even though their atmospheric abundance is miniscule, of order parts per trillion, they are especially powerful greenhouse gases.[9] The production of most CFCs has been banned by international treaties because they damage the ozone layer in the upper atmosphere, and their atmospheric concentrations are declining. However, many of the replacement chemicals for CFCs are also potent greenhouse gases, and their concentrations and the concentrations of other halocarbons have continued to increase.

Different greenhouse gases stay in the atmosphere for different lengths of time. If emissions stopped, carbon dioxide would be absorbed by the oceans on time scales of centuries, but a fraction would remain in the atmosphere for tens of thousands of years before it is converted into ocean sediments. A methane molecule lasts in the atmosphere for an average of about a decade, a nitrous oxide molecule for more than 100 years, and a halocarbon molecule for up to hundreds of years before they are destroyed by chemical reactions in the atmosphere.

There are other human activities that drive climate change. Modification of the land surface, such as conversion of forests to pasture with greater reflectivity, changes the amount of sunlight absorbed. Combustion creates many byproducts; important for climate are aerosols, minute solid particles or liquid droplets suspended in the atmosphere, that include smog, sulfate aerosols from burning coal and oil at power plants, black carbon and other aerosols from human-started forest fires or fires of built structures. These aerosols mostly scatter sunlight and reduce the amount of sunlight reaching the surface.

Between 1750 and 2019, rising levels of carbon dioxide accounted for about three-quarters of the enhanced greenhouse effect, while rising levels of other gases accounted for the remainder.[10] Thus, carbon dioxide remains the most important greenhouse gas being added to the atmosphere by humans, but the others also make significant contributions to the planet's warming. It is estimated that the net cooling from land use and anthropogenic aerosols counter less than 40% of the warming from greenhouse gases (Figure 7.7 from IPCC AR6 WG1).

III. A History of Warming

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[9] *Id.* at B3.

[10] U.S. ENV'T PROT. AGENCY, *Climate Change Indicators: Global Greenhouse Gas Emissions*, https://www.epa.gov/climate-indicators/climate-change-indicators-global-greenhouse-gas-emissions (last updated Dec. 22, 2021).

The use of thermometers to measure ambient air temperatures became widespread in the 19th century. The thermometer record shows that in 2021 average air temperature at the surface of Earth is about 2.1 degrees Fahrenheit, or 1.15 degrees Celsius, warmer than it was before carbon dioxide levels in the atmosphere began increasing during the 1800s (Figure 3). More than half that warming has occurred since the mid-1970s, and the rate of increase has been accelerating over the past decade. The speed of warming is not uniform over the record and is modulated by the many modes of natural climate variation that influence daily weather and seasonal climate. The most prominent of these modes are El Niño-La Niña cycles, which recur on two-to-seven-year time scales. Global temperatures are slightly higher, by about 0.4 degrees Fahrenheit, during El Niño years than La Niña years.[11] Despite the ongoing La Niña conditions, 2022 may still rank as the 5th or 6th warmest year on record. Other modes vary on decadal and longer time scales. When the temperature record is averaged over long periods, say 10 or 30 or 60 years, the natural variability signal is minimized, and the long-term rise in temperature is clearly evident.

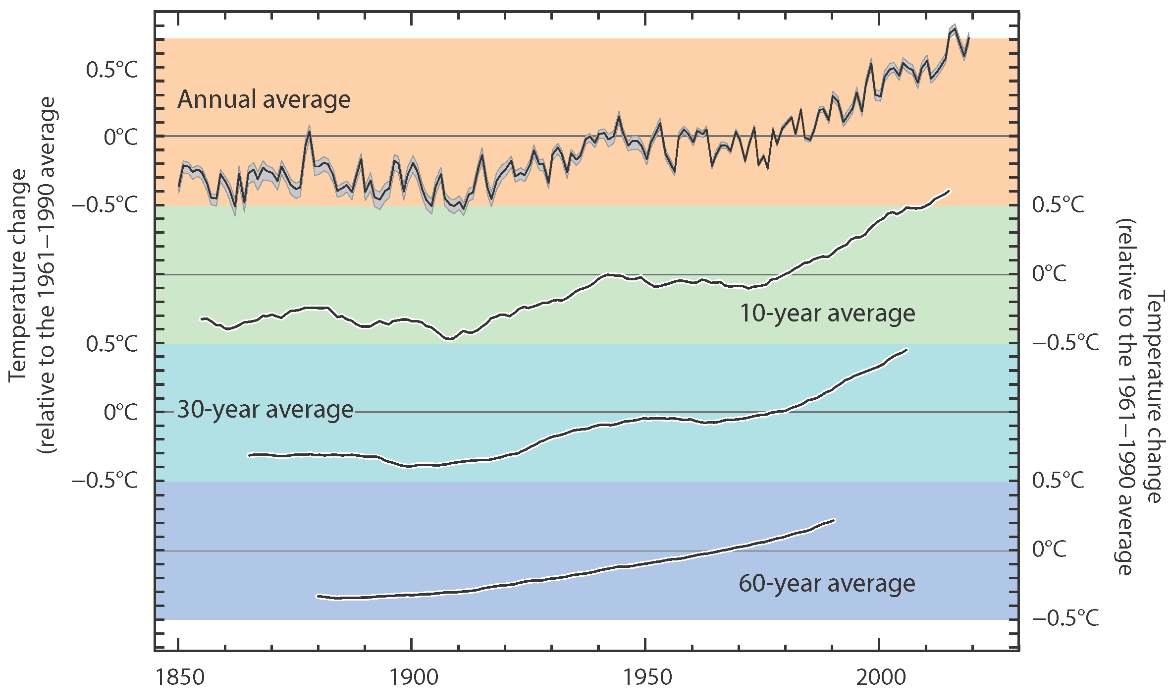
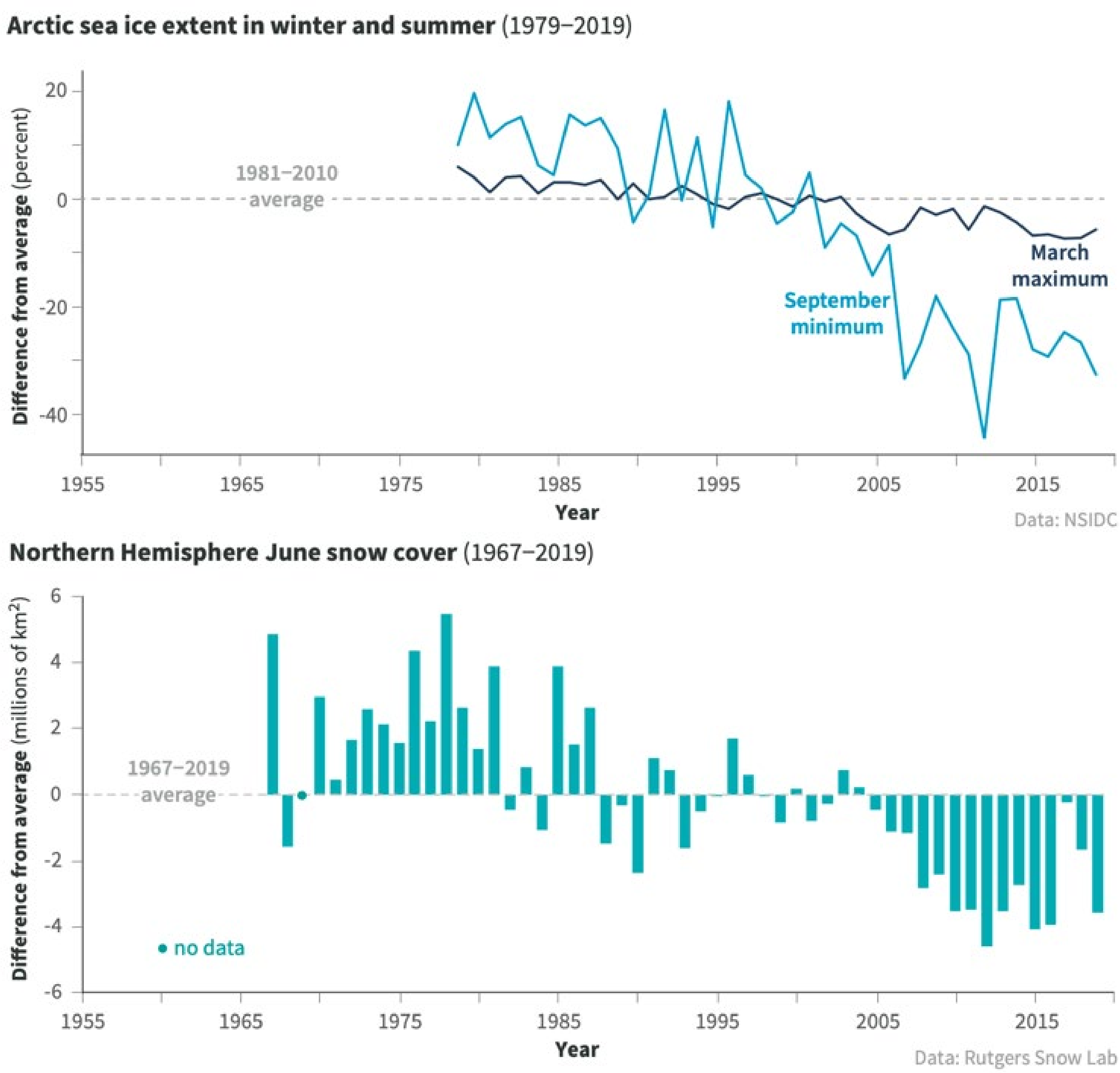


Figure 3. The average global surface temperature is about 2.0 degrees Fahrenheit (1.2 degrees Celsius) warmer than in the two decades before 1900. Averages taken over 10-year, 30-year, and 60-year intervals smooth out the interannual variability and more clearly reveal the trend of constantly increasing temperatures. Source: NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020, at 11 (2020).

[11] U.S. GLOBAL CHANGE RESEARCH PROGRAM, *Warming Trend and Effects of El Niño/La Niña* (last visited Nov. 21, 2022), https://www.globalchange.gov/browse/multimedia/warming-trend-and-effects-el-niñola-niña.

Other measures also indicate that temperatures have been rising in recent decades (Figure 4).[12] The oceans have been warming; mountain glaciers have been shrinking, and parts of the ice sheets on Greenland and Antarctica have been shrinking as they are in contact with air and ocean water that have warmed up. Sea water expands with warming; together with the addition of melt water from ice sheets and mountain glaciers, sea level has, on average, risen by about 6 inches since 1900. The area of sea ice in the Arctic Ocean varies from year-to-year, but its extent at the end of the summer (the September minimum) has declined, as has the extent of snow cover in the Northern Hemisphere. Ranges of mammals, fish, insects, plants, and other organisms have been shifting toward the poles



[12] *See id.* at 4.

and higher elevations. These and other trends all provide further evidence that the planet has been warming as carbon dioxide levels in the atmosphere have increased.

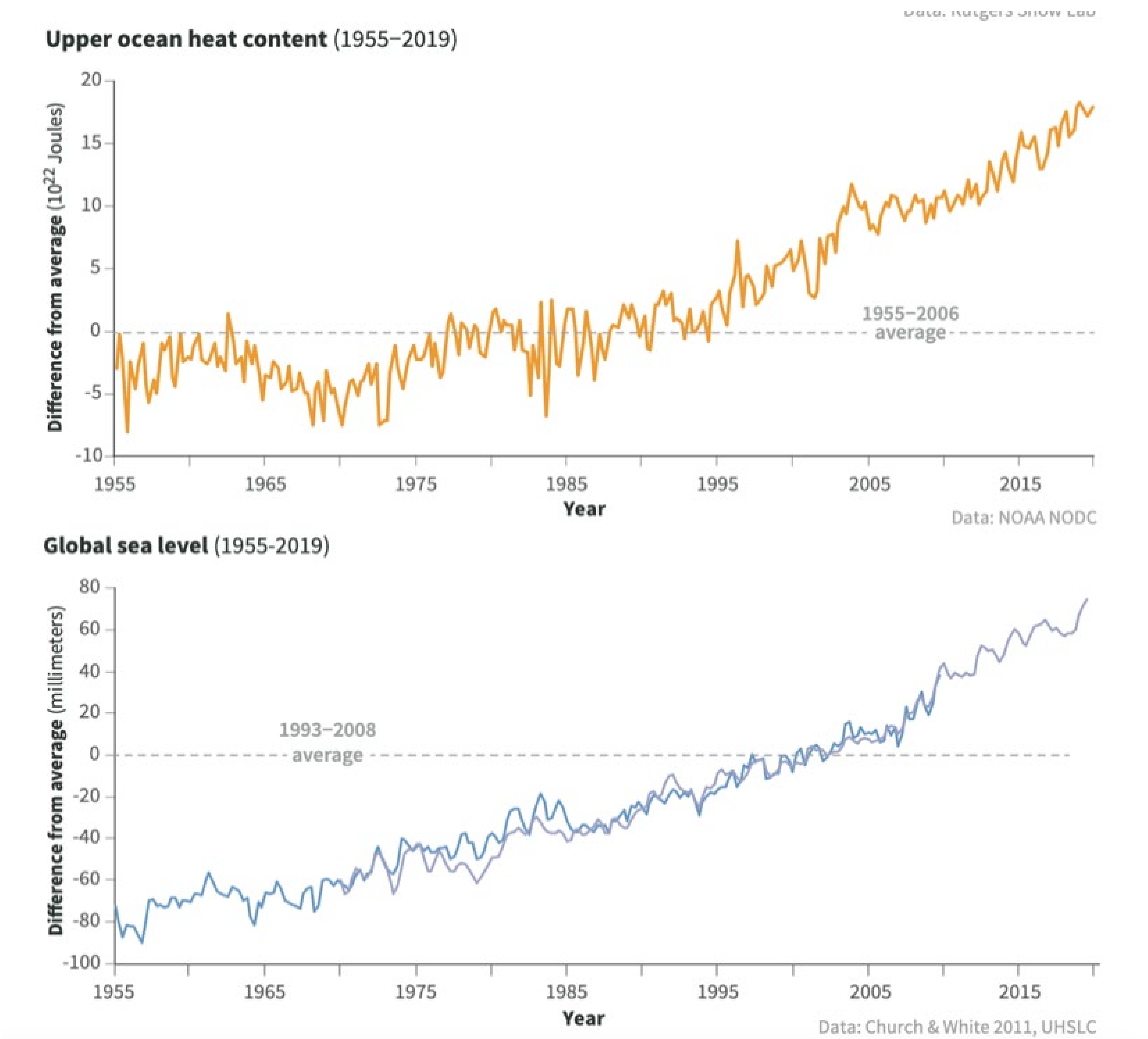


Figure 4. Changes in Arctic sea ice extent, snow cover in the Northern Hemisphere, the heat content of the upper ocean, and global sea level all reflect the warming of recent decades. Source: NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020, at 4 (2020).

Ocean acidification is another measure of rising carbon dioxide levels. The carbon dioxide responsible for warming the planet is only about half of the total carbon that has been added to the atmosphere from fossil fuel combustion and other human activities. About one-quarter of the added carbon dioxide has gone into the land biosphere, with the remaining quarter absorbed by the oceans, making ocean water more acidic.[13] This acidification of the oceans on top of the warming threatens marine organisms and the ecosystems of which they are a part. For example, corals and some shellfish have more difficulty forming or maintaining shells as water grows more acidic.

[13] *See* IPCC, SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE (2019).

IV. Carbon Dioxide and Temperatures Over Geological Time

For times before thermometers, temperatures can be reconstructed using climate-sensitive materials ("proxies") such as tree rings and marine sediments.[14] The thick ice sheet on Antarctica contains ancient air and ice, and their analysis yields the co-variation of carbon dioxide and temperature for the past 800,000 years. These paleo-climate records show that the correlation between temperatures and atmospheric carbon dioxide levels extends much further back in time than the past few centuries.[15]

Before the 19th century, carbon dioxide stayed in the range of 260 to 280 parts per million for the previous 10,000 years, a period when human civilizations took shape and flourished. Even though there were periods of regional warming and cooling, such as the Medieval Warm Period (~ 950-1250 AD) in Western Europe, and the Little Ice Age (between 14th and 19th centuries) in Europe and North America, globally averaged temperatures were roughly the same as they were during the pre-industrial era, with small fluctuations of plus or minus about 0.4 degrees Fahrenheit (+/-0.2 degrees Celsius).

During extended periods known as ice ages, such as 20,000 years ago, carbon dioxide levels fell as low as 170 parts per million, and globally averaged temperatures, which rise and fall with Antarctic temperatures, were much lower (Figure 5). Massive ice sheets covered large portions of the Northern Hemisphere, and sea level was much lower because of the large volume of water trapped in the ice sheets.

Proxies in sediments yield climate information on geologic time scales. The periodic ice ages that the world has experienced in at least the past 2.6 million years have been triggered and paced by variations in Earth's axis of rotation and its orbit around the Sun, which have caused Earth to receive slightly more or less solar energy overall or in different seasons. The decrease in solar energy during an ice age alters the land surface (e.g., distribution of ecosystems, extent of wetlands) as well as the processes that exchange carbon dioxide and other greenhouse gases with the atmosphere (e.g., photosynthesis and the decomposition of plant detritus on land, or carbonate chemistry in the ocean), thus lowering the level of carbon dioxide and methane in the atmosphere and amplifying the cooling effect of solar energy reduction. The resulting expansion of ice sheets lowers the temperature further because their bright surfaces reflect more of the Sun's energy back into space.

The last time carbon dioxide levels approached 400 parts per million was about 3 million to 5 million years ago, when average global surface temperatures were 3.6 to 6.3 degrees Fahrenheit (2 to 3.5 degrees Celsius) higher than in the pre-industrial era. This alerts us to the fact that the warming potential from the excess carbon dioxide already in the atmosphere today has not yet been fully realized. It takes a long time to warm the massive volume of water in the oceans, and continued addition of water vapor from the warming oceans, inter alia, adds to the warming. Carbon dioxide levels were even higher 50 million years ago, perhaps more than 1,000 parts per million. At that time, the average global temperature was 18 degrees Fahrenheit (10 degrees Celsius) warmer than today, Earth had little ice, and sea level was more than 200 feet higher than it is today.

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[14] CLIMATE CHANGE: EVIDENCE & CAUSES, *supra* note 1, at B4-5.
[15] *See generally* AR6 CLIMATE CHANGE, *supra* note 2, at 2-6.

Even though global temperatures have changed over time, the speed of the recent ongoing change is unprecedented. The past eight years, 2015-2022, were the warmest eight years in the 220-year thermometer record.[16] The current rapid increase in carbon dioxide and atmospheric warming is happening more than 10 times faster than the warming at the end of the last ice age.[17] This rapid change in temperature has not been experienced before, and has made it difficult for the human and natural worlds to adapt to new conditions.

V. Models of the Climate System

To better understand how Earth's climate has changed in the past and will change in the future, climate scientists have constructed mathematical models that simulate the interactions of the atmosphere, oceans, ice, and land.[18] These models are based on equations that represent the best understanding of the laws of physics, chemistry, and biology that govern Earth's climate. Models start with well-established principles, such as global energy balance and infrared energy absorption by different greenhouse gases, and incorporate mechanisms that alter Earth's energy balance and influence temperatures, rainfall, winds, and other features of a given location's weather. Given a climate forcing, say a change in carbon dioxide levels or solar energy input, many processes act to amplify or diminish the effects of the forcing, i.e., they are feedback processes.

The most important feedbacks involve various forms of water. A warmer atmosphere can hold more water vapor, itself a potent greenhouse gas. In this way, higher levels of water vapor amplify the warming caused by carbon dioxide and other greenhouse gases in the atmosphere.

One complex feedback involves clouds. As temperatures increase, cloud cover could increase or decrease and various types of clouds could become more or less common. Increases in the horizontal extent of low shallow clouds, such as maritime stratus off the California coast, decrease warming by reflecting sunlight, while increases in tall thick clouds, such as cumulonimbus clouds in the tropics, increase warming by losing less infrared energy to space (because taller clouds have cooler cloud tops). Representing how different types of clouds form, grow, and dissipate remains one of most challenging aspects of climate models. The latest assessment of the science indicates that the net effect of changes in cloud cover is likely to amplify rather than dampen atmospheric warming.

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[16] *Id.* at 11; WORLD METEOROLOGICAL SOC'Y, *Provisional State of the Global Climate in 2022*, https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate (last visited Dec. 14, 2022).
[17] NASA, *Climate Change: How Do We Know?*, https://climate.nasa.gov/evidence/ (last visited Apr. 25, 2022).
[18] *See generally* CLIMATE SCIENCE SPECIAL REPORT, *supra* note 3, at 133-60.

The large ice sheets in Greenland and Antarctica, smaller glaciers on land, and sea ice in the Arctic

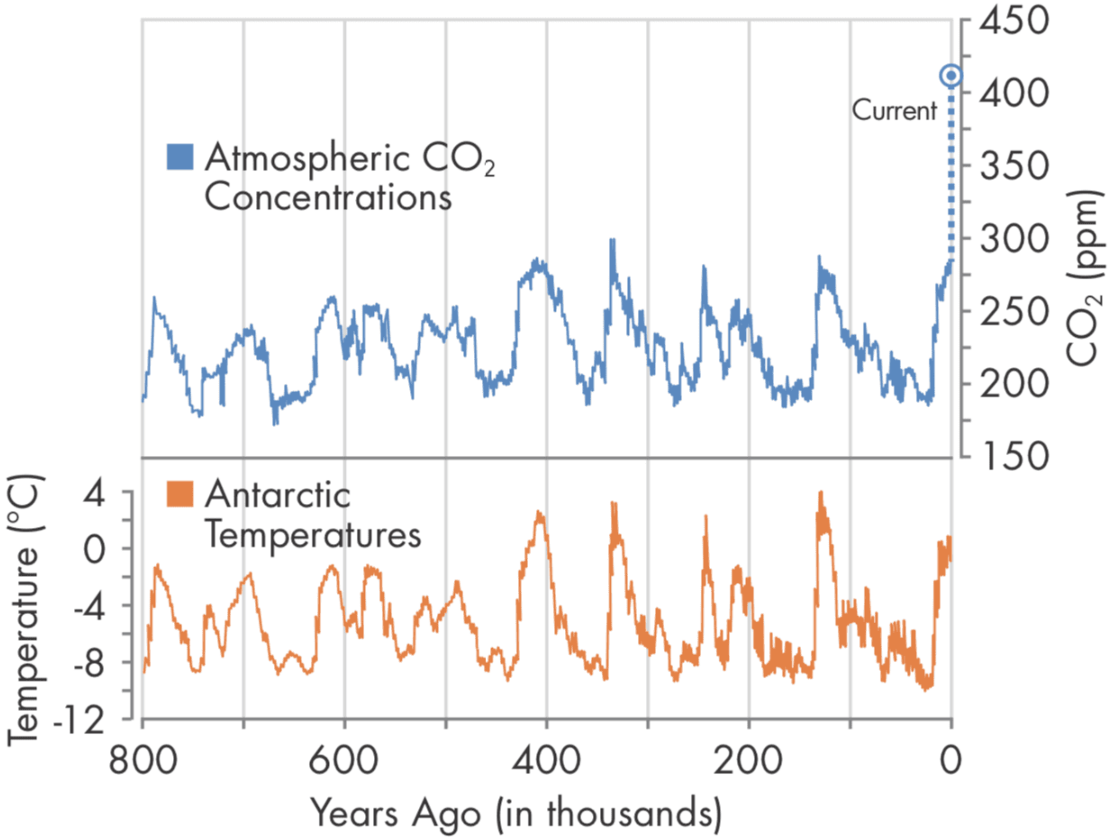

Figure 5. Carbon dioxide levels and temperatures have changed in tandem from 800,000 years ago until the present day. The carbon dioxide levels were derived from analysis of the trapped air bubbles, while temperatures were derived from the abundance of deuterium in the ice at different depths of the Antarctic ice sheet. Source: NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020, at 10 (2020).

and southern oceans have bright surfaces and reflect the Sun's energy to space and reduce Earth's average temperature. When the ice melts, it exposes a darker ocean and land surface that can absorb more solar energy, thereby amplifying warming. Recent studies have shown that snow and ice are not pristine and have deposits of soot, soil on their surfaces. The dirty snow and ice surfaces are less bright, and would accelerate the melting and warming.

Aerosols-also alter Earth's energy balance. Depending on their size and chemical composition, aerosols may absorb, scatter, or reflect sunlight. For example, smog, while injurious to health, reflects sunlight and contributes to cooling, while soot absorbs solar energy and warms the atmosphere. Aerosols may also modify the size and lifetime of cloud droplets. Recent advances in remote sensing have yielded geographic distributions of aerosols around the world. However, most aerosols from human activities are short-lived (with lifetimes of less than an hour to several days), observations of the processes of their growth, transformation, and demise are challenging, and so estimation of their historical abundance and future climate impact has relatively large uncertainties. Nevertheless, the net effect from all the aerosols is cooling at a rate that is insufficient to offset the warming from greenhouse gases.

The oceans have the capacity to absorb and retain large amounts of heat from the atmosphere[19]; indeed, over 90% of the excess energy from contemporary increases in greenhouse gases has been absorbed by the ocean. Warm water, being less dense than the cold water below, tends to stay near the surface, so heat penetration to the cold depths below is slower as the oceans warm. Ultimately, how fast the climate warms depends on how fast the heat can penetrate to depth.
Climate change is more than responses to external perturbations such as volcanic eruptions and solar variability or to changes in composition of the atmosphere. Internal to the climate system are El Niños, La Niñas, and longer time scale modes of natural variability that arise from nonlinear interactions in the system. Climate models take into account these modes of natural variations, because they modify storm tracks, as well as regional temperature and rainfall patterns. Including these modes is equally important for attributing climate change of the last two centuries to human activities: the warming signal must be considered on time scales longer than those of natural variability and the signal must exceed any transient warming from these natural modes (cf. Figure 3).

Climate models take these and other feedback processes and interactions into account. In this way, they have been able to re-create a wide range of past and current climate variations, including meanders in the jet stream, the development of individual storms, and the climate changes of the last few centuries.

With advances in observations, computing power, and research, the models continuously have become more sophisticated over the past four decades. The current generation of climate models, called Earth System Models, include not only atmospheric chemistry and detailed cloud and aerosol processes, but also the diverse structure and function of terrestrial and ecosystems that also feed back onto the climate. The Earth System Models have yielded richer and more accurate reconstructions of past climates as well as more confident projections of future climates.

VI. Modeling the Factors Responsible for Warming

Models have been combined with observations to examine the factors responsible for the warming of the past 150 years. One question, for example, is what role variations in the output of the Sun, including those from solar storms (which are associated with sunspots), could account for the warming that has been observed.[20] Measurements from satellites show that the energy emitted by the Sun has not increased since the late 1970s, even as surface temperatures have gone up (and models of the Sun indicate that changes in its output have been quite small for many more decades). On longer time scales—for example, during the ice ages—the reduction in the amount of solar energy input to the Earth system triggered lowering of the greenhouse gases in the atmosphere, but the solar energy reductions by themselves were too small to explain the observed cooling.

Models also have been used to show that internal fluctuations in the climate system cannot account for the warming of the past 150 years.[21] As demonstrated by the temperature record, the average global temperature does vary from year to year and decade to decade, reflecting the natural variability of the system. However, El Niño and La Niña and other modes of variation redistribute heat between the atmosphere and the oceans and from one region to another. They cannot account

[19] *See generally* AR6 CLIMATE CHANGE, *supra* note 2, at 9-5.
[20] *See* CLIMATE CHANGE: EVIDENCE & CAUSES, *supra* note 1, at 7.
[21] *See* AR6 CLIMATE CHANGE, *supra* note 2, at 1-48.

for the concomitant increases in temperature in both the atmosphere and oceans as well as the melting of snow and ice.

The only factor that can clearly explain the rising temperatures of the two centuries is the increasing level of atmospheric greenhouse gases, modulated by land cover change and increases in atmospheric aerosols (pollutants) from human activities. When climate models are run with pre-industrial levels of greenhouse gases and aerosols in the atmosphere, they show little surface warming or even a slight cooling over the 20th century and first part of the 21st century. But when rising levels of greenhouse gases and aerosols are included in the models, they produce warming and many other changes consistent with those observed.

Model performance has been improving with advances in our observations and understanding of Earth processes. Nevertheless, current models have not been able to reproduce every observed feature of Earth's warming, as there remain regional and local processes hitherto unknown or unaccounted for in the models. For example, to capture the feedback between the terrestrial ecosystems, rising CO_2, and the changing climate would need to include the physiology of local plant species as well as the availability of resources such as water and nutrients.

All in all, models combined with other evidence demonstrate that the global warming of the past 150 years cannot be explained by natural causes or by variations in the Sun's output. Rather, it is a result of the carbon dioxide and other greenhouse gases added to the atmosphere as well as aerosols from human activities.

VII. Projections of Future Warming

Models that accurately simulate past and present changes in climate are used to project how temperatures will rise and how storminess will change given continued increases in atmospheric greenhouse gas concentrations. In the event that emissions continue to increase at the current rate, the global average temperature by the end of the 21st century could be 4.7 to 8.6 degrees Fahrenheit (2.6 to 4.8 degrees Celsius) higher than today's temperature (Figure 6).[22] The consequences of this "business-as-usual" scenario for both human life and the natural world would be catastrophic.

If very aggressive efforts are made to reduce emissions, it may be possible to limit warming to another 0.7 degrees Fahrenheit, representing a total of 2.7 degrees Fahrenheit of warming (or 1.5 degrees Celsius) above pre-industrial levels. However, emissions of carbon dioxide and other greenhouse gases will need to decline extremely quickly.[23] To date, humans have released about 2,400 billion metric tons of carbon dioxide to the atmosphere. (For reference, a solid cube of pure graphite containing this much carbon would be more than 4 miles across.) To have a two-thirds chance of staying within 2.7 degrees Fahrenheit, only about 370 billion additional metric tons of carbon dioxide may be released. At the current rate of carbon dioxide emissions, that will take only about a decade! Even if carbon emissions were somehow cut to zero, atmospheric carbon dioxide levels would only decline slowly on a time scale of hundreds of years. Global temperature would likely not decline, since the remaining carbon dioxide and associated feedback processes would

[22] CLIMATE CHANGE: EVIDENCE & CAUSES, *supra* note 1, at 18.
[23] *See* AR6 CLIMATE CHANGE, *supra* note 2, at 5-9.

continue to contribute to warming even as the deep oceans continues to slowly take up the heat.[24] Carbon dioxide and global temperatures will not return to pre-industrial-era levels for tens of thousands of years, not until the added carbon is buried in ocean sediments.

Later modules will describe in greater detail the impacts of continued warming. They include longer and more intense heatwaves, heavier rainfall and snowfall events, longer droughts that wither crops and increase the chance of wildfires, more powerful tropical storms, sea-level rise and greater storm surge, flooding, erosion, and saltwater intrusion along shorelines. However, different places on Earth will experience the impacts of climate change in different ways.[25] Warming will be greater over land than over the oceans, greater in polar regions than in the tropic. Storm tracks are likely to change, bringing severe weather to areas where it was less likely before and drought to areas that used to receive more rainfall.[26]

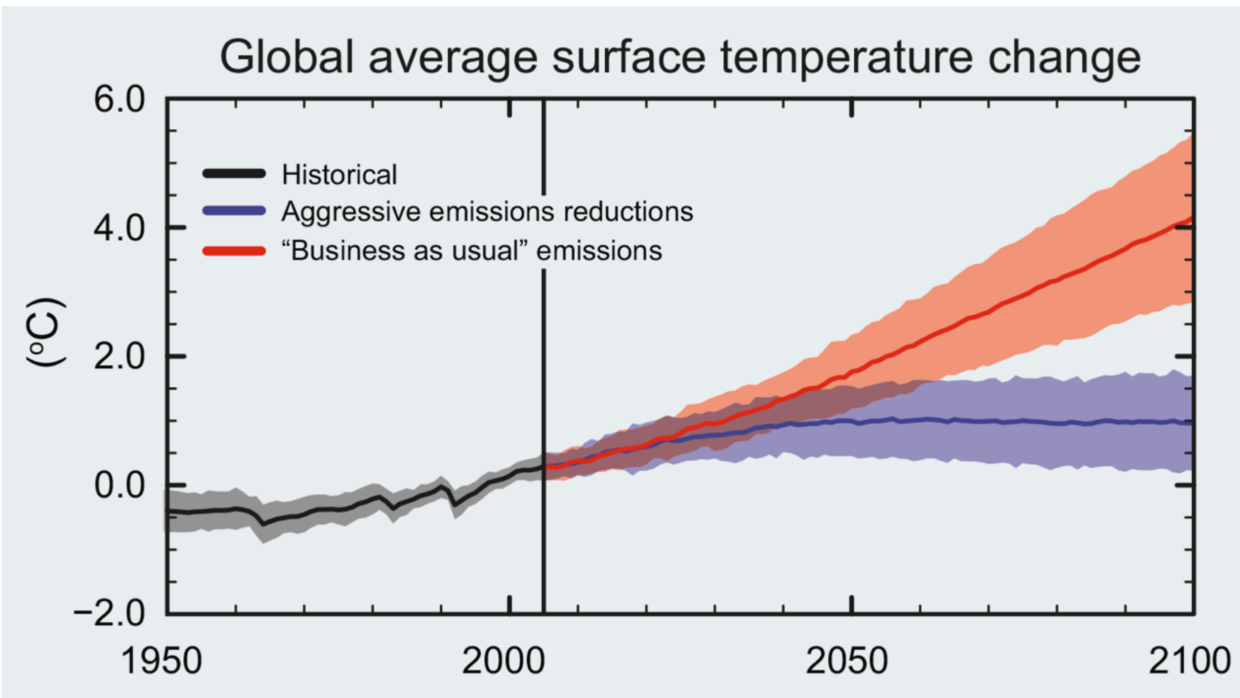

Figure 6. Strict controls on future greenhouse gas emissions could limit future warming during the 21st century to another 0.7 degrees Fahrenheit. Source: NAT'L ACAD. OF SCI. & THE ROYAL SOC'Y, CLIMATE CHANGE: EVIDENCE & CAUSES UPDATE 2020, at B8 (2020).

Scientists are combining models and observations to investigate the possibility of large-scale and high-impact changes in the climate system.[27] Possibilities include dramatic changes in ocean currents that could suddenly alter weather patterns, accelerated loss of the Greenland or Antarctic ice caps that could raise sea level by at least several additional feet by the end of the century relative to the current levels of about 8 inches over the last century, and a greatly accelerated release of methane

[24] Susan Solomon et al., *Irreversible Climate Change Due to Carbon Dioxide Emissions*, 106 PNAS 1704 (2009).
[25] *See generally* AR6 CLIMATE CHANGE, *supra* note 2, at 10-122.
[26] *See* AR6 CLIMATE CHANGE, *supra* note 2, at 8-98.
[27] NAT'L RES. COUNCIL, ABRUPT IMPACTS OF CLIMATE CHANGE: ANTICIPATING SURPRISES, at 16 (2013).

from ocean sediments or melting permafrost that could cause even more abrupt climate changes. The later type of events do not have a high probability of occurring in the 21st century, but they are hard to predict and cannot be ruled out. In addition, gradual change in the climate can cross thresholds that trigger abrupt change in other systems. Rising sea levels can overtop existing infrastructure, thawing permafrost can lead to massive release of methane and the collapse of buildings or roads, forests can suddenly die back as conditions change, or species can quickly go extinct beyond certain climate thresholds.

VIII. Sources of Greenhouse Gas Emissions

Every sector of the economy is responsible for greenhouse gas emissions, and every sector will be involved in reducing those emissions.

In the United States, transportation generated the largest proportion of greenhouse gas emissions in 2020, mostly from the burning of gasoline and diesel in cars, trucks, planes, ships, and trains (Figure 7).[28] Emissions from this sector have increased since 1990 as population and the number of vehicle miles traveled grew. The sales of new electric and hybrid vehicles in the United States doubled between 2020 and 2021,

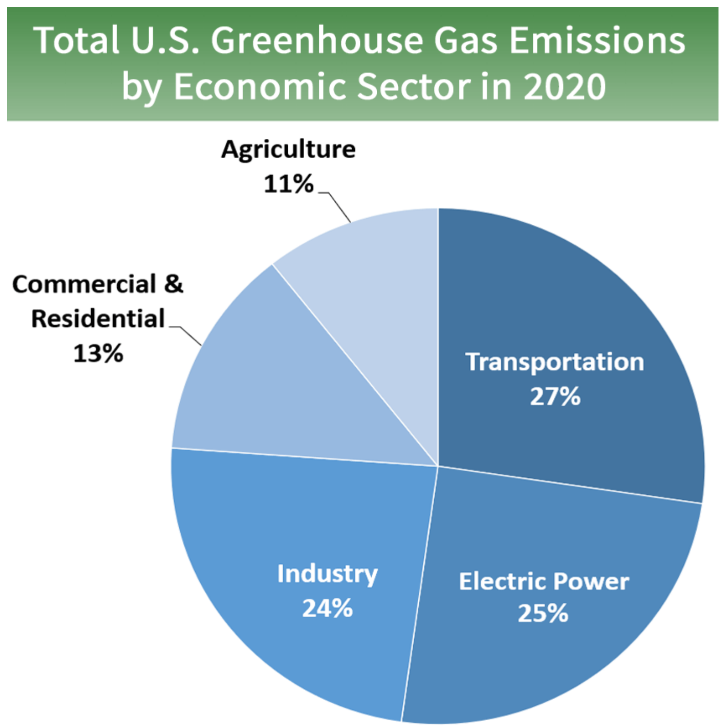

Figure 7. Total US greenhouse gas emissions by economic sector in 2020. Source: U.S. ENV'T PROT. AGENCY, *Sources of Greenhouse Gas Emissions*, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (last updated Aug. 5, 2022).

[28] U.S. ENV'T PROT. AGENCY, *Sources of Greenhouse Gas Emissions*, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (last updated July 27, 2021).

but accounted for less than 10% of total sales of new highway vehicles in 2021.[29]

Electricity generation represented the second largest source (25%) of greenhouse gas emissions in 2020. Currently, the burning of fossil fuels accounts for about 60% of U.S. electricity generation, with about 40% from natural gas and about 24% from coal. However, since coal is carbon-intensive, it accounts for 54% of the sector's carbon dioxide emissions but only 20% of the electricity generated in the United States in 2020. Renewable energy sources, including hydroelectric power, wind, solar, and biomass, produce 20% of the nation's electricity, and nuclear power generated also about 20%. As lower and non-emitting sources of electricity expanded and end-use energy efficiency improved, greenhouse gas emissions from electricity generation declined steadily, by about 12%, in the last three decades.[30]

The industry sector directly produced 24% of U.S. greenhouse gases in 2020 through burning fuel for power or heat, through chemical reactions, and through leaks from industrial processes or equipment. When combined with the electricity produced off-site for industrial processes, industry account for about 30% of U.S. 2020 emissions, a total that was about 22% lower than it was in 1990.

The commercial and residential sector includes businesses and homes and was responsible for 13% of greenhouse gas emissions in 2020. Sources include the use of fossil fuels for heating and cooking, emissions from waste and wastewater, and leaks of refrigerants from refrigerators and other equipment. Consumption of natural gas represented 79% of fossil fuel carbon dioxide emissions from this sector in 2020. The direct greenhouse gas emissions in homes and businesses increased slightly, by 2%, between 1990 and 2020, while indirect emissions associated with electricity usage decreased to approximately 10% below 1990 levels.

Finally, agriculture produced about 11% of greenhouse gas emissions in 2020. Slightly over half come from various management practices on agriculture soils, such as the application of synthetic and organic fertilizers and the growth of nitrogen-fixing crops. Most of the remaining emissions are from livestock and treatment of their manure, with small contributions from rice cultivation, burning of crop residues, and other soil treatments. Emissions from this sector increased by about 6% between 1990 and 2020, with 62% of the increase driven by emissions from the livestock manure management systems.

In contrast to these sectors, the land use and forestry sector could be a net sink (also referred to as negative emission) of carbon dioxide in the United States. Plants absorb carbon dioxide and use it to generate biomass both above and below the ground, thereby storing carbon away from the atmosphere. However, the storage is not long-lived. When plants die, their detritus is slowly decomposed by microbes, which returns carbon dioxide back to the atmosphere. In 2020, the land use and forestry sector removed 14% of total U.S. greenhouse gas emissions, though this amount

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[29] U.S. DEP'T OF TRANSP., BUREAU OF TRANSP. STATISTICS, *Hybrid-Electric, Plug-in Hybrid-Electric and Electric Vehicle Sales* https://www.bts.gov/content/gasoline-hybrid-and-electric-vehicle-sales (last visited Dec. 14, 2022); https://www.bts.gov/content/gasoline-hybrid-and-electric-vehicle-sales (last visited Dec. 14, 2022); U.S. DEP'T OF TRANSP., BUREAU OF TRANSP. STATISTICS, *U.S. Sales or Deliveries of New Aircraft, Vehicles, Vessels, and Other Conveyances*, https://www.bts.gov/content/us-sales-or-deliveries-new-aircraft-vehicles-vessels-and-other-conveyances (last visited Dec. 14, 2022).

[30] U.S. ENV'T PROT. AGENCY, *Sources of Greenhouse Gas Emissions*, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (last updated Aug. 5, 2022).

has been declining as forests and cropland are urbanized and as forest fires release the carbon stored in biomass.

On a global scale, the sources of greenhouse gas emissions are somewhat different. The burning of fossil fuels for electricity and heat production remains the largest emitter of greenhouse gases, at about 25% of the total. Transportation, in contrast, accounts for only 14% of global emissions, while agriculture, forestry, and land use, mainly from the cultivation of crops and livestock and deforestation, account for 24% globally, a larger share of emissions than in the United States.[31]

IX. National and International Agreements on Climate Change

As of 2022, the U.S. Congress has passed significant legislation to tackle climate change. The 2021 Bipartisan Infrastructure Law and the 2022 Inflation Reduction Act provide support for reducing greenhouse gas emissions, for transitioning to renewable energy, and for adapting to climate change. Individual states and groups of states have put cap-and-trade systems in place to limit emissions. In addition, many public, private, and voluntary programs are aimed at reducing greenhouse gas emissions and mitigating climate change.[32] Examples include the Climate Alliance of over 20 state governors,[33] and the Oil and Gas Climate Initiative.[34] Energy-efficiency standards for vehicles, buildings, appliances, and manufacturing systems as well as the promotion of renewable sources of energy, nuclear energy, and carbon capture and storage are aimed at emissions reduction and energy security. Programs to reduce methane emissions, transition away from climate-damaging hydrofluorocarbons, and reduce nitrous oxide emissions from agriculture are meant to reduce emissions of non-carbon dioxide greenhouse gases.

Internationally, the UN Framework Convention on Climate Change (UNFCCC) was opened for signatures at the 1992 Earth Summit in Rio de Janeiro. The goal of the convention, which has been ratified by almost every country in the world, is to stabilize greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system."[35] The convention further states that "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."[36] Recognizing that countries vary in their past contributions to climate change and in their capacities to address it, the convention establishes the principle of "common but differentiated responsibilities and respective capabilities."[37] While committing all nations to take steps to mitigate greenhouse gas emissions, it also commits developed countries to assist developing countries in reducing emissions and coping with climate impacts.[38] The convention established an international forum, the

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[31] U.S. ENV'T PROT. AGENCY, *Global Greenhouse Gas Emissions Data*, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (last updated Feb. 25, 2022).

[32] *See generally* KATE C. SHOUSE ET AL., CONG. RESEARCH SERV., R46947, U.S. CLIMATE CHANGE POLICY (2021).

[33] U.S. Climate Alliance, *States United For Climate Action*, http://www.usclimatealliance.org/ (last visited Dec. 14, 2022).

[34] OIL & GAS CLIMATE INIT., https://www.ogci.com (last visited Dec. 14, 2022).

[35] United Nations Framework Convention on Climate Change, May 9, 1992, S. Treaty Doc. No. 102-38, at art. 2.

[36] *Id.*

[37] *Id.* at art. 4.

[38] UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, *What Is the United Nations Framework Convention on Climate Change?*, https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change (last visited Dec. 14, 2022).

Conference of the Parties (COP), that meets annually to review and make decisions necessary to implement the convention. The COP complements the UNFCCC's Intergovernmental Panel on Climate Change, which "was created to provide policymakers with regular scientific report on climate change, its implications and potential future risks, as well as to put forward adaption and mitigation options."[39]

At the first meeting of the UNFCCC COP in Berlin, Germany, in 1995, the parties agreed to establish binding targets and timetables for the developed but not developing countries to reduce greenhouse gas emissions. The Kyoto Protocol, adopted at COP3 in 1997, required developed countries to reduce emissions by an average of 5% below 1990 levels. Facing political pushback, President Bill Clinton did not submit the protocol to the U.S. Senate, and President George W. Bush announced shortly after his election that the United States would not ratify it. Though the protocol ended up covering a relatively small portion of global emissions, it established a rigorous monitoring, review, and verification system, a compliance system to hold the parties to the protocol to account, and a system of carbon markets enabling countries to trade emissions units and encourage sustainable development.[40]

At COP15 in Copenhagen in 2009, the parties had intended to finalize a successor to the Kyoto Protocol but could agree only on a nonbinding document. However, the Copenhagen Accord acknowledged that global average temperature should not increase by 2 degrees Celsius (3.8 degrees Fahrenheit). It also called on countries to develop mitigation pledges and to create a $100 billion public and private fund "to address the needs of developing countries."[41]

After several contentious and inconclusive meetings, the most important global climate agreement to date was adopted following COP21 in Paris in 2015. The Paris Agreement requires almost all countries to set emissions reductions goals in the form of "nationally determined contributions" (NDCs). The agreement set goals of preventing global average temperature from rising 2 degrees Celsius and pursuing efforts to keep temperatures at the end of the 21st century within 1.5 degrees Celsius of pre-industrial levels.[42] The United States joined the agreement in 2016, but in June 2017 President Donald Trump announced his decision to withdraw from the agreement, effective on November 4, 2020. On his first day in office in 2021 President Joe Biden signed the instrument to re-enter the United States into the agreement.

Before COP26 in Glasgow, Scotland, in 2021, more than 100 countries submitted updated NDCs proposing more ambitious targets.[43] President Biden announced that the United States would seek

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[39] IPCC, *The Intergovernmental Panel on Climate Change*, https://www.ipcc.ch/#:~:text=The%20IPCC%20was%20created%20to,of%20knowledge%20on%20climate%20chang e (last visited Dec. 14, 2022).

[40] UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, *History of the Convention*, https://unfccc.int/process/the-convention/history-of-the-convention#eq-1 (last visited Dec. 14, 2022).

[41] CTR. FOR CLIMATE & ENERGY SOLUTIONS, *COP 15 Copenhagen*, https://www.c2es.org/content/cop-15-copenhagen/ (last visited Apr. 25, 2022).

[42] *See* IPCC, SPECIAL REPORT: GLOBAL WARMING OF 1.5°C (2018).

[43] UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE, *COP26: Update to the NDC Synthesis Report*, https://unfccc.int/news/cop26-update-to-the-ndc-synthesis-report (Nov. 4, 2021).

to reduce its emissions by 2030 to roughly half of what they were in 2005.[44] The conference produced an agreement on reducing subsidies for coal and fossil fuel use and encouraged governments to produce more ambitious emissions reduction targets by 2022.[45]Also, the United States, together with the European Union, made a Global Methane Pledge[46] to reduce methane emissions by at least 30% from 2020 levels by 2030. International agreements recognize that different nations and communities have different vulnerabilities and capacities to adapt to climate change. Nevertheless, options need to be discussed at a global scale because many of the communities that are most vulnerable to climate change control were responsible for relatively few emissions in the past and have control over comparatively few future emissions.

X. Continued Progress

The science of climate change has become much richer in the past four decades. Of course, questions remain; there will always be "unknown unknowns"; and new observations of until-now unexplored aspects of the changing Earth will reveal surprises that will be exciting challenges for scientists. Observations of the changing planet have confirmed many of the broad features projected by early climate models, and many important details have been filled in over the past four decades. Enough is now known to make confident projections of how the climate has changed and will continue to change in response to human activities. The remaining uncertainties are unlikely to change these relationships. Temperatures are going up and will continue to increase. This will increase the severity of storms, change weather patterns, raise sea level, and alter the chemistry of the oceans. It will cause unprecedented flooding, heat waves and droughts, wildfires, and destruction of wildlife habitat.

Findings from the science of climate change can be alarming, but the science is also encouraging. It shows us what needs to be done to avoid the most harmful impacts of climate change and how humans can continue to prosper on this planet.

[44] Remarks by President Biden at the COP26 Leaders Statement (Nov. 1, 2021), https://bidenwhitehouse.archives.gov/briefing-room/speeches-remarks/2021/11/01/remarks-by-president-biden-at-the-cop26-leaders-statement/.

[45] *See* UNFCCC, GLASGOW CLIMATE PACT (2021).

[46] CLIMATE & CLEAN AIR COALITION, *Global Methane Pledge*, https://www.globalmethanepledge.org (last visited Nov. 21, 2022).