CLIMATE CHANGE EVIDENCE & CAUSES

UPDATE 2020

An overview from the Royal Society and the US National Academy of Science

THE ROYAL SOCIETY

FOREWORD

CLIMATE CHANGE IS ONE OF THE DEFINING ISSUES OF OUR TIME. It is now more certain than ever, based on many lines of evidence, that humans are changing Earth's climate. The atmosphere and oceans have warmed, which has been accompanied by sea level rise, a strong decline in arctic sea ice, and other climate-related changes. The impacts of climate change on people and nature are increasingly apparent. Unprecedented flooding, heat waves, and wildfires have cost billions in damages. Habitats are undergoing rapid shifts in response to changing temperatures and precipitation patterns.

The Royal Society and the US National Academy of Sciences, with their similar missions to promote the use of science to benefit society and to inform critical policy debates, produced the original *Climate Change: Evidence and Causes* in 2014. It was written and reviewed by a UK-US team of leading climate scientists. This new edition, prepared by the same author team, has been updated with the most recent climate data and scientific analyses, all of which reinforce our understanding our understanding of human-caused climate change.

The evidence is clear. However, due to the nature of science, not every detail is ever totally settled or certain. Nor has every pertinent question yet been answered. Scientific evidence continues to be gathered around the world. Some things have become clearer and new insights have emerged. For example, the period of slower warming during the 2000s and early 2010s has ended with a dramatic jump to warmer temperatures between 2014 and 2015. Antarctic sea ice extent, which has been increasing, began to decline in 2014, reaching a record in 2017 that has persisted. These and other recent observations have been woven into the discussions of the questions addressed in this booklet.

Calls for actions are getting louder. The 2020 Global Risks Perception Survey from the world Economic Forum ranked climate change and related environmental issues as the top five global risks likely to occur within the next ten years. Yet, the international community still has far to go in showing increased ambition on mitigation, adaptation, and other ways to tackle climate change.

Scientific information is a vital component for society to make informed decisions about how to reduce the magnitude of climate change and how to adapt to its impacts. This Booklet serves as a authoritative answers about the current state of climate-change science.

We are grateful that six years ago, under the leadership of Dr. Ralph J. Cicerone, former President of the National Academy of Science, and Sir Paul Nurse, former President of the Royal Society these two organizations partnered to produce a high-level overview of climate change science. As current President of these organizations, we are pleased to offer an update to this key reference, supported by the generosity of the Cicerone Family.

Marcia McNutt
President, National Academy of Sciences

Venki Ramakrishnan
President, Royal Society

FOR FURTHER READING

For more detailed discussion of the topics addressed in this document (including references to the underlying original research), see:

□ Intergovernmental Panel on Climate change (IPCC), 2019:
Special Report on the Ocean and Cryosphere in a Changing Climate
[https://www.ipcc.ch/srocc]

□ National Academies of Sciences, Engineering, and Medicine (NASEM), 2019:
Negative Emissions Technologies and Reliable Sequestration: A Research Agenda
[https://www.nap.edu/catalog/25259]

□ Royal Society, 2018: *Greenhouse gas removal*
[https://raeng.org.uk/greenhousegasremoval]

□ U.S. Global Change Research Program (USGCRP), 2018:
Fourth National Climate Assessment Volume II:
Impacts, Risks, and Adaptation in the United States
[https://nca2018.globalchange.gov]

□ IPCC, 2018: Global Warming of 1.5°C [https://www.ipcc.ch/sr15]

□ USGCRP, 2017: *Fourth National climate Assessment Volume I: Climate Science Special Reports* [https://science2017.globalchange.gov]

□ NASEM, 2016: Attribution of Extreme Weather Events in the Context of Climate Change [https://www.nap.edu/catalog/21852]

□ IPCC, 2013: *Fifth Assessment Report (AR5) Working Group 1.*
Climate Change 2013: The Physical Science Basis
[https://ipcc.ch/report/ar5/wg1]

□ NRC, 2013: Abrupt Impacts of Climate Change: Anticipating Surprises

[https://www.nap.edu/catalog/18373]
□ NRC, 2011: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia*
[https://www.nap.edu/catalog/12877]

□ Royal Society 2010: *America's Climate Choices: Advancing the Science of Climate Change* [https://royalsociety.org/tipics-policy/publications/2010/climate-change-summery-science]

□ NRC, 2010: *America's Climate Choices: Advancing the Science of Climate Change* [https://www.nap.edu./catalog/12782]

Much of the original data underlying the scientific findings discussed here are available at:
□ https://data.ucar.edu/
□ https://climatedataguide.ucar.edu
□ https://iridl.ldeo.columbia.edu
□ https://ess-dive.lbl.gov
□ https://www.ncdc.noaa.gov/
□ https://www.esrl.noaa.gov/gmd/ccgg/trends/
□ https://scrippsco2.ucsd.edu
□ https://hahana.soest.hawaii.edu/hot

THE NATIONAL ACADEMY OF SCIENCE (NAS) was established to advise the United States on Scientific and Technical issues when President Lincoln signed a Congressional charter in 1863. The National Research Council, the operating arm of the National Academy of Science and the National Academy of Engineering, has issued numerous reports on the causes of and potential responses to climate change. Climate change resources from the National Research Council are available at nationalacademies.org/climate.

THE ROYAL SOCIETY is a self-governing Fellowship of many of the world's most distinguished scientists. Its members are drawn from all areas of science, engineering, and medicine. It is the national academy of science in the UK. The Society's fundamental purpose, reflected in its founding Charters of the 1660s, is to recognize, promote, and support excellence in science, and to encourage the development and use of science for the benefit of humanity. More information on the Society's climate change work is available at royalsociety.org/policy/climate-change

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SUMMARY

GREENHOUSE GASES such as carbon dioxide (CO_2) absorb heat (infrared radiation) emitted from Earth's surface. Increases in the atmospheric concentrations of these gases cause Earth to warm by trapping more of this heat. Human activities—especially the burning of fossil fuels since the start of the Industrial Revolution—have increased atmospheric CO_2 concentrations by more than 40%, with over half the increase occurring since 1970. Since 1900, the global average surface temperature has increased by about 1°C (1.8 °F). This has been accompanied by warming of the ocean, a rise in sea level, a strong decline in Arctic sea ice, widespread increases in the frequency and intensity of heatwaves, and many other associated climate effects. Much of this warming has occurred in the last five decades. Detailed analyses have shown that the warming during this period is mainly a result of the increased concentrations of CO_2 and other greenhouse gases. Continued emissions of these gases will cause further climate change, including substantial increases in global average surface temperature and important changes in regional climate. The magnitude and timing of these changes will depend on many factors, and slowdowns and accelerations in warming lasting a decade or more will continue to occur. However, long-term climate change over many decades will depend mainly on the total amount of CO_2 and other greenhouse gases emitted as a result of human activities.

Q&A
1 IS THE CLIMATE WARMING?

Yes. Earth's average surface air temperature has increased by about 1 °C (1.8 °F) since 1900, with over half of the increase occurring since the mid-1970s [Figure1a]. A wide range of other observations (such as reduced Arctic sea ice extent and increased ocean heat content) and indications from the natural world (such as poleward shifts of temperature-sensitive species of fish, mammals, insects, etc.) together provide incontrovertible evidence of planetary-scale warming.

The clearest evidence for surface warming comes from widespread thermometer records that, in some places, extend back to the late 19th century. Today, temperatures are monitored at many thousands of locations, over both the land and ocean surface. Indirect estimates of temperature change from such sources as tree rings and ice cores help to place recent temperature changes in the context of the past. In terms of the average surface temperature of Earth, these indirect estimates show that 1989 to 2019 was very likely the warmest 30-year period in more than 800 years; the most recent decade, 2010-2019, is the warmest decade in the instrumental record so far (since 1850).

A wide range of other observations provides a more comprehensive picture of warming throughout the climate system. For example, the lower atmosphere and the upper layers of the ocean have also warmed, snow and ice cover are decreasing in the Northern Hemisphere, the Greenland ice sheet is shrinking, and sea level is rising [Figure 1b]. These measurements are made with a variety of land-,ocean-, and space-based monitoring systems, which gives added confidence in the reality of global-scale warming of Earth's climate.

FIGURE1A. Earth's global average surface temperature has risen as shown in this plot of combined land and ocean measurements from 1850 to 2019, derived from three independent analyses of the available data sets. The temperature changes are relative to the global average surface temperature of 1961-1990.
Source: NOAA Climate. Gov; data from UK Met Office Hadley Centre (maroon), US National Aeronautics and Space Administration Goddard Institute for Space Studies (red), and US National Oceanic and Atmospheric Administration National Centers for Environmental Information (orange).

□ Q&A

FIGURE 1B. A large amount of observational evidence besides surface temperature records shows that Earth's climate is changing. For example, additional evidence of a warming trend can be found in the dramatic decrease in the extent of Arctic sea ice at its summer minimum (which occurs in September), the decrease in June snow cover in the Northern Hemisphere, the increases in the global average upper ocean (upper 700 m or 2300 feet) hear content (shown relative to the 1955-2006 average), and the rise in global se level. *Source: NOAA Climate.gov*

2 HOW DOES THE SCIENTIST KNOW THAT RECENT CLIMATE CHANGE IS LARGELY CAUSED BY HUMAN ACTIVITES?

Scientists know that recent climate change is largely caused by human activities from an understanding of basic physics, comparing observations with models, and fingerprinting the detailed patterns of climate change caused by different human and natural influences.

Since the mid-1800s, scientists have known that CO_2 is one of the main greenhouse gases of importance to Earth's energy balance. Direct measurements of CO_2 in the atmosphere and in air trapped in ice show that atmospheric CO_2 increased by more than 40% from 1800 to 2019. Measurements of different forms of carbon (isotopes, see Question 3) reveal that this increase is due to human activities. Other greenhouse gases (notably methane and nitrous oxide) are also increasing as a consequence of human activities. The observed global surface temperature rise since 1900 is consistent with detailed calculations of the impacts of the observed increase in atmospheric greenhouse gases (and other human-induced changes) on Earth's energy balance.

Different influences on climate have different signatures in climate records. These unique fingerprints are easier to see by probing beyond a single number (such as the average temperature of Earth's surface), and by looking instead at the geographical and seasonal patterns of climate change. The observed patterns of surface warming, temperature changes through the atmosphere, increases in ocean heat content, increases in atmospheric moisture, sea level rise, and increased melting of land and sea ice also match the patterns scientists expect to see due to human activities (see Question 5).

The expected changes in climate are based on our understanding of how greenhouse gases trap heat. Both this fundamental understanding of the physics of greenhouse gases and pattern-based fingerprint studies show that natural causes alone are inadequate to explain the recent observed changes in climate. Natural causes include variations in the Sun's output and in Earth's orbit around the Sun, volcanic eruptions, and internal fluctuations in the climate system (such as El Niño and La Niña). Calculations using climate models (see infobox, p.20) have been used to simulate what would have happened to global temperatures if only natural factors were influencing the climate system. These simulations yield little surface warming or even a slight cooling, over the 20th century and into the 21st. Only when models include human influences on the composition of the atmosphere are the resulting temperature changes consistent with observed changes.

3 CO_2 IS ALREADY IN THE ATMOSPHERE NATURALLY, SO WHY ARE EMISSIONS FROM HUMAN ACTIVITY SIGNIFICANT?

Human activities have significantly disturbed the natural carbon cycle by extracting long-buried fossil fuels and burning them for energy, thus releasing CO_2 to the Atmosphere.

In nature, CO_2 is exchanged continually between the atmosphere, plants, and animals through photosynthesis, respiration, and decomposition, and between the atmosphere and ocean though gas exchange. A very small amount of CO_2 (roughly 1% of the emission rate from fossil fuel combustion is also emitted in volcanic eruptions. This is balanced by an equivalent amount that is removed by chemical weathering of rocks.

The CO_2 level in 2019 was more than 40% higher than it was in the 19th century. Most of this CO_2 increase has taken place since 1970, about the time when global energy consumption accelerated. Measured decreases in the fraction of other forms of carbon (the isotopes ^{14}C and ^{13}C) and a small decrease in atmospheric oxygen concentration (observations of which have been available since 1990) show that the rise in CO_2 is largely from combustion of fossil fuels (which have low ^{13}C fractions and no ^{14}C). Deforestation has disturbed the balance of the carbon cycle, because the natural processes that could restore the balance are too slow compared to the rates at which human activities are adding CO_2 to the atmosphere. As a result, a substantial fraction of the CO_2 emitted from human activities accumulates in the atmosphere, where some of it will remain not just for decades or centuries, but for thousands of years. Comparison with the CO_2 levels measured in air extracted from ice cores indicate that the current concentrations are substantially higher than they have been in at least 800,000 years (see Question 6).

4 WHAT ROLE HAS THE SUN PLAYED IN CLIMATE CHANGE IN RECENT DECADES?

The Sun provides the primary source of energy driving Earth's climate system, but its variations have played very little role in the climate change observed in recent decades. Direct satellite measurements since the late 1970s show no net increase in the Sun's output, while at the same time global surface temperatures have increased [FIGURE 2].

For periods before the onset of satellite measurements, knowledge about solar changes is less certain because the changes are inferred from indirect sources — including the number of sunspots and the abundance of certain forms (isotopes) of carbon or beryllium atoms, whose production rates in Earth's atmosphere are influenced by variations in the Sun. Ther is evidence that the 11-year solar cycle, during which the Sun's energy output varies by roughly 0.1%, can influence ozone concentrations, temperatures, and winds in the stratosphere (the layer in the atmosphere above the troposphere, typically from 12 to 50km above earth's surface, depending on latitude and season). These stratospheric changes may have a small effect on the surface climate over the 11-year cycle. However, the available evidence does not indicate pronounced long-term changes in the Sun's output over the past century, during which time human-induced increases in CO_2 concentrations have been dominant influence on the long-term global surface temperature increase. Further evidence that current warming is not a result of solar changes can be found in the temperature trends at different altitudes in the atmosphere (see Question 5).

FIGURE 2. Measurements of the Sun's energy incident on Earth show no net increase in solar forcing during the past 40 years, and therefore this cannot be responsible for warming during that period. The data show only small periodic amplitude variations associated with the Sun's 11-year cycle. *Source: TSI data from Physikalisch-Meterorologisches Ovservatorium Davos, Switzerlandon the new VIRGO scale from 1978 to mid-2018; temperature data for same time period from the HadCRUT4 dataset, UK Met Office, Hadley Centre.*

□ **Q&A**

5 WHAT DO CHANGES IN THE VERTICAL STRUCTURE OF ATMOSPHERIC TEMPERATURE — FROM THE SURFACE UP TO THE STRATOSPHERE CAUSES OF RECENT CHANGE CLIMATE CHANGE?

The observed warming in the lower atmosphere and cooling in the upper atmosphere provided us with key insights into the underlying causes of climate change and reveal that natural factors alone cannot explain the observed changes.

In the early 1960s, results from mathematical/physical models of the climate systems first showed that human-induced increases in CO_2 would be expected to lead to gradual warming of the lower atmosphere (the troposphere) and cooling of higher levels of the atmosphere (the stratosphere). In contrast, increases in the Sun's output would warm both the troposphere and the full vertical extent of the stratosphere. At that time, there was insufficient observational data to test this prediction, but temperature measurements from weather ballons and satellites have since confirmed these early forecasts. It is now known that the observed pattern of tropospheric warming and stratospheric cooling over the past 40 years is broadly consistent with computer model simulations that include increases in CO_2 and decreases in stratospheric ozone, each caused by human activities. The observed pattern is not consistent with purely natural changes in the Sun's energy output, volcanic activity. Or natural climate variations such as El Niño and La Niña.

Despite this agreement between the global-scale patterns of modelled and observed atmospheric temperature change, there are still some differences. The most noticeable differences are in the tropics, where models currently show more warming in the troposphere that has been observed, and in the Arctic, where the observed warming of the Troposphere is greater than in most models.

6 CLIMATE IS ALWAYS CHANGING, WHY IS CLIMATE CHANGE OF CONCERN NOW?

All major climate changes, including natural ones, are disruptive. Past climate changes led to extinction of many species, population migrations, and pronounced changes in the land surface and ocean circulation. The speed of the current climate change is faster than most of the past events, making it more difficult for human's societies and the natural world to adapt.

The largest global-scale climate variations in Earth's recent geological past are the ice age cycles (see infobox, p.B4), which are cold glacial periods followed by shorter warm periods [FIGURE 3]. The last few of these natural cycles have recurred roughly every 100,000 years. They are mainly paced by slow changes in Earth's orbit, which alter the way the Sun's energy is distributed with latitude and by season on Earth. These orbital changes are very small over the last several hundred years, and alone are not sufficient to cause the observed magnitude of change in temperature since the Industrial Revolution, nor to act on the whole Earth. On ice-age timescales, these gradual orbital variations have led to changes in the extent of ice sheets and in the abundance of CO_2 and other greenhouse gases, which in turn have amplified the initial temperature change.

Recent estimates of the increase in global average temperature since the end of the last ice age are 4 to 5°C (7 to 9°F). That change occurred over a period of about 7,000 years, starting 18,000 years ago. CO_2 has risen more than 40% in just the past 200 years, much of this since the 1970s, contributing to human alteration of the planet's energy budget that has so far warmed Earth by about 1°C (1.8°F). If the rise in CO_2 continues unchecked, warming of the same magnitude as the increase out of the ice age can be expected by the end of this century or soon after. This speed of warming is more than ten times that at the end of an ice age, the fastest known natural sustained change on a global scale.

7 IS THE CURRENT LEVEL OF ATMOSPHERIC CO_2 CONCENTRATION UNPRECEDENTED IN EARTH'S HISTORY?

The present level of atmospheric CO_2 concentration is almost certainly unprecedented in the past million years, during which time modern humans evolved and societies developed. The atmospheric CO_2 concentration was however higher in Earth's more distant past (many millions of years ago), at which time paleoclimatic and geological data indicate that temperatures and sea levels wee also higher than they are today.

Measurements of air in cores show that for the past 800,000 years up until the 20th century, the atmospheric CO_2 concentration stayed within the range 170 to 300 parts per million (ppm), making the recent rapid rise to more than 400 ppm over 200 years particularly remarkable [FIGURE 3]. During the glacial cycles of the past 800,000 years both CO_2 and methane have acted as important amplifiers of the climate changes triggered by variations in Earth's orbit around the Sun. As Earth warmed from the last ice age, temperature

Continued

□ Q&A

and CO_2 started to rise at approximately the same time and continued to rise in tandem from about 18,000 to 11,000 years ago. Changes in ocean temperature, circulation, chemistry, and biology caused CO_2 to be released to the atmosphere, which combined with other feedbacks to push Earth into an even warmer state. For earlier geological times, CO_2 concentrations and temperatures have been inferred from less direct methods. Those suggest that the concentration of CO_2 last approached 400 ppm about 3 to 5 million years ago, a period when global average surface temperature is estimated to have been about 2 to 3.5°C higher than in the pre-industrial period. At 50 million years ago, CO_2 may have reached 1000 ppm, and global average temperature was probably about 10°C warmer than today. Under those conditions, Earth had little ice, and sea level was at least 60 meters higher than current levels.

Figure 3. Data from ice cores have been used to reconstruct Antarctic temperatures and atmospheric CO_2 concentrations over the past 800,000 years. Temperature is based on measurements of the isotopic content of water in the Dome C ice core. CO_2 is measured in air trapped in ice, and is a composite of the Dome C and Vostok ice core. The current CO_2 concentration (blue dot) is from atmospheric measurements. The cyclical pattern of temperature variations constitutes the ice age/ interglacial cycles. During these cycles, changes in CO_2 concentrations (in blue) track closely with changes in temperature (in orange). As the record shows, the recent increase in atmospheric CO_2 concentration is unprecedented in the past 800,000 years. Atmospheric CO_2 concentration surpassed 400 ppm in 2016, and the average concentration in 2019 was more than 411 ppm. *Source: Based on figure by Jeremy Shakun, data from Lüthi et al., 2008 and Jouzel et al., 2007*

8 IS THERE A POINT AT WHICH ADDING MORE CO_2 WILL NOT CAUSE FURTHER WARMING?

No. Adding more CO2 to the atmosphere will cause surface temperatures to continue to increase. As the atmospheric concentrations of CO2 increase, the addition of extra CO2 becomes progressively less effective at trapping Earth's energy, but surface temperature will still rise.

Our understanding of the physics by which CO2 affects Earth's energy balance is confirmed by laboratory measurements, as well as by detailed satellite and surface observations of the emission and absorption of infrared energy by the atmosphere. Greenhouse gases absorb some of the infrared energy that Earth emits in so-called bands of stronger absorption that occur at certain wavelengths. Different gases absorb energy at different wavelengths. CO2 has its strongest heat-trapping band centered at a wavelength of 15 micrometers (millionths of a meter), with absorption that spreads out a few micrometers on either side. There are also many weaker absorption bands. As CO2 concentrations increase, the absorption at the Centre of the strong band is already so intense that it plays little role in causing additional warming. However, more energy is absorbed in the weaker bands and away from the Centre of the strong band, causing the surface and lower atmosphere to warm further.

9 DOES THE RATE OF WARMING VARY FROM ONE DECADE TO ANOTHER?

Yes. The observed warming rate has varied from year to year, decade to decade, and place to place, as is expected from our understanding of the climate system. These shorter-term variations are mostly due to natural causes, and do not contradict our fundamental understanding that the long-term warming trend is primarily due to human-induced changes in the atmospheric levels of CO_2 and other greenhouse gases.

Even as CO_2 is rising steadily in the atmosphere, leading to gradual warming of Earth's surface, many natural factors are modulating this long-term warming. Large volcanic eruptions increase the number of small particles in the stratosphere. These particles reflect sunlight, leading to short-term surface cooling lasting typically two to three years, followed by a slow recovery. Ocean circulation and mixing vary naturally on many time scales, causing variations in sea surface temperatures as well as changes in the rate at which heat is transported to greater depths. For example, the tropical Pacific swings between warm El Niño and cooler La Niña events on timescales of two to seven years. Scientists study many different types of climate variations, such as those on decadal and multi-decadal timescales in the Pacific and North Atlantic Oceans. Each type of variation has its own unique characteristics. These oceanic variations are associated with significant regional and global shifts in temperature and rainfall patterns that are evident in the observations.

Warming from decade to decade can also be affected by human factors such as variations in emissions of greenhouse gases and aerosols (airborne particles that can have both warming and cooling effects) from coal-fired power plants and other pollution sources.

These variations in the temperature trend are clearly evident in the observed temperature record [FIGURE 4]. Short-term natural climate variations could also affect the long-term human-induced climate change signal and vice-versa, because climate variations on different space and timescales can interact with one another. It is partly for this reason that climate change projections are made using climate models (see infobox, p.20) that can account for many different types of climate variations and their interactions. Reliable inferences about human-induced climate change must be made with a longer view, using records that cover many decades.

FIGURE 4. The climate system varies naturally from year to year and from decade to decade. To make reliable inferences about human-induced climate change, multi-decadal and longer records are typically used. Calculating a “running average” over these longer timescales allows one to more easily see long-term trends. For the global average temperature for the period 1850-2019 (using the data from the UK Met Office Hadley Centre relative to the 1961-90 average) the plots show (top) the average and range of uncertainty for annually averaged data; (2nd plot) the annual average temperature for the ten years centered on any given date; (3rd plot) the equivalent picture for 30-year; and (4th plot) the 60-year averages. *Source: Met Office Hadley Centre, based on the HadCRUT4 dataset from the Met Office and Climatic Research Unit (Morice et AL., 2012).*

□ **Q&A**

10 DID THE SLOWDOWN OF WARMING DURING THE 2000S TO EARLY 2010S MEAN THAT CLIMATE CHANGE IS NO LONGER HAPPENING?

No. After the very warm year 1998 that followed the strong 1997-98 El Niño, the increase in average surface temperature slowed relative to the previous decade of rapid temperature increases. Despite the slower rate of warming, the 2000s were warmer than the 1990s. The limited period of slower warming ended with a dramatic jump to warmer temperatures between 2014 and 2015, with all the years from 2015-2019 warmer than any preceding year in the instrumental record. A short-term slowdown in the warming of Earth's surface does not invalidate our understanding of long-term changes in global temperature arising from human-induced changes in greenhouse gases.

Decades of slow warming as well as decades of accelerated warming occur naturally in the climate system. Decades that are cold or warm compared to the long-term trend are seen in the observations of the past 150 years and are also captured by climate models. Because the atmosphere stores very little heat, surface temperatures can be rapidly affected by heat uptake elsewhere in the climate system and by changes in external influences on climate (such as particles formed from material lofted high into the atmosphere from volcanic eruptions).

More than 90% of the heat added to the Earth system in recent decades has been absorbed by the oceans and penetrates only slowly into deep water. A faster rate of heat penetration into the deeper ocean will slow the warming seen at the surface and in the atmosphere, but by itself it will not change the long-term warming that will occur from a given amount of CO_2. For example, recent studies show that some heat comes out of the ocean into the atmosphere during warm El Niño events, and more heat penetrates to ocean depths in cold La Niña's. Such changes occur repeatedly over timescales of decades and longer. An example is the major El Niño event in 1997–98 when the globally averaged air temperature soared to the highest level in the 20th century as the ocean lost heat to the atmosphere, mainly by evaporation.

Even during the slowdown in the rise of average surface temperature, a longer-term warming trend was still evident (see Figure 4). Over that period, for example, record heatwaves were documented in Europe (summer 2003), in Russia (summer 2010), in the USA (July 2012), and in Australia (January 2013). Each of the last four decades was warmer than any previous decade since widespread thermometer measurements were introduced in the 1850s. The continuing effects of the warming climate are seen in the increasing trends in ocean heat content and sea level, as well as in the continued melting of Arctic sea ice, glaciers and the Greenland ice sheet.

THE BASICS OF CLIMATE CHANGE

Greenhouse gases affect Earth's energy balance and climate

The Sun serves as the primary energy source for Earth's climate. Some of the incoming sunlight is reflected directly back into space, especially by bright surfaces such as ice and clouds, and the rest is absorbed by the surface and the atmosphere. Much of this absorbed solar energy is re-emitted as heat (longwave or infrared radiation). The atmosphere in turn absorbs and re-radiates heat, some of which escapes to space. Any disturbance to this balance of incoming and outgoing energy will affect the climate. For example, small changes in the output of energy from the Sun will affect this balance directly.

If all heat energy emitted from the surface passed through the atmosphere directly into space, Earth's average surface temperature would be tens of degrees colder than today. Greenhouse gases in the atmosphere, including water vapour, carbon dioxide, methane, and nitrous oxide, act to make the surface much warmer than this because they absorb and emit heat energy in all directions (including downwards), keeping Earth's surface and lower atmosphere warm [Figure B1]. Without this greenhouse effect, life as we know it could not have evolved on our planet. Adding more greenhouse gases to the atmosphere makes it even more effective at preventing heat from escaping into space. When the energy leaving is less than the energy entering, Earth warms until a new balance is established.

FIGURE B1. Greenhouse gases in the atmosphere, including water vapour, carbon dioxide, methane, and nitrous oxide, absorb heat energy and emit it in all directions (including downwards), keeping Earth's surface and lower atmosphere warm. Adding more greenhouse gases to the atmosphere enhances the effect, making Earth's surface and lower atmosphere even warmer. Image based on a figure from US Environmental Protection Agency.

BASICS OF CLIMATE CHANGE

Greenhouse gases emitted by human activities alter Earth's energy balance and thus its climate. Humans also affect climate by changing the nature of the land surfaces (for example by clearing forests for farming) and through the emission of pollutants that affect the amount and type of particles in the atmosphere.

Scientists have determined that, when all human and natural factors are considered, Earth's climate balance has been altered towards warming, with the biggest contributor being increases in CO_2.

Human activities have added greenhouse gases to the atmosphere.

The atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased significantly since the Industrial Revolution began. In the case of carbon dioxide, the average concentration measured at the Mauna Loa Observatory in Hawaii has risen from 316 parts per million (ppm)1 in 1959 (the first full year of data available) to more than 411 ppm in 2019 [Figure B2]. The same rates of increase have since been recorded at numerous other stations worldwide. Since preindustrial times, the atmospheric concentration of CO_2 has increased by over 40%, methane has increased by more than 150%, and nitrous oxide has increased by roughly 20%. More than half of the increase in CO_2 has occurred since 1970. Increases in all three gases contribute to warming of Earth, with the increase in CO_2 playing the largest role. See page B3 to learn about the sources of human emitted greenhouse gases.

Scientists have examined greenhouse gases in the context of the past. Analysis of air trapped inside ice that has been accumulating over time in Antarctica shows that the CO_2.

FIGURE B2. Measurements of atmospheric CO_2 since 1958 from the Mauna Loa Observatory in Hawaii (black) and from the South Pole (red) show a steady annual increase in atmospheric CO_2 concentration. The measurements are made at remote places like these because they are not greatly influenced by local processes, so therefore they are representative of the background atmosphere. The small up-and-down saw-tooth pattern reflects seasonal changes in the release and uptake of CO_2 by plants. *Source: Scripps CO2 Program* concentration began to increase significantly in the 19th century [Figure B3], after staying in the range of 260 to 280 ppm for the previous 10,000 years. Ice core records extending back 800,000 years show that during that time, CO_2 concentrations remained within the range of 170 to 300 ppm throughout many "ice age" cycles—see infobox, pg. B4 to learn about the ice ages—and no concentration above 300 ppm is seen in ice core records until the past 200 years.

Figure B3. CO_2 variations during the past 1,000 years, obtained from analysis of air trapped in an ice core extracted from Antarctica (red squares), show a sharp rise in atmospheric CO_2 starting in the late 19th century. Modern atmospheric measurements from Mauna Loa are superimposed in gray. *Source: figure by Eric Wolff, data from Etheridge et al., 1996; MacFarling Meure et al., 2006; Scripps CO_2 Program.*

Learn about the sources of human-emitted greenhouse gases:

□ **Carbon dioxide (CO_2)** has both natural and human sources, but CO_2 levels are increasing primarily because of the combustion of fossil fuels, cement production, deforestation (which reduces the CO_2 taken up by trees and increases the CO_2 released by decomposition of the detritus), and other land use changes. Increases in CO_2 are the single largest contributor to global warming.

□ **Methane (CH_4)** has both human and natural sources, and levels have risen significantly since pre-industrial times due to human activities such as raising livestock, growing paddy rice, filling landfills, and using natural gas (which is mostly CH_4, some of which may be released when it is extracted, transported, and used).

□**Nitrous oxide (N_2O)** concentrations have risen primarily because of agricultural activities such as the use of nitrogen-based fertilisers and land use changes.

□ **Halocarbons**, including chlorofluorocarbons (CFCs), are chemicals used as refrigerants and fire retardants. In addition to being potent greenhouse gases, CFCs also damage the ozone layer. The production of most CFCs has now been banned, so their impact is starting to decline. However, many CFC replacements are also potent greenhouse gases and their concentrations and the concentrations of other halocarbons continue to increase.

BASICS OF CLIMATE CHANGE

Measurements of the forms (isotopes) of carbon in the modern atmosphere show a clear fingerprint of the addition of “old” carbon (depleted in natural radioactive 14C) coming from the combustion of fossil fuels (as opposed to “newer” carbon coming from living systems). In addition, it is known that human activities (excluding land use changes) currently emit an estimated 10 billion tonnes of carbon each year, mostly by burning fossil fuels, which is more than enough to explain the observed increase in concentration.

These and other lines of evidence point conclusively to the fact that the elevated CO_2 concentration in our atmosphere is the result of human activities.

Climate records show a warming trend.

Estimating global average surface air temperature increase requires careful analysis of millions of measurements from around the world, including from land stations, ships, and satellites. Despite the many complications of synthesising such data, multiple independent teams have concluded separately and unanimously that global average surface air temperature has risen by about 1 °C (1.8 °F) since 1900 [Figure B4]. Although the record shows several pauses and accelerations in the increasing trend, each of the last four decades has been warmer than any other decade in the instrumental record since 1850.

Going further back in time before accurate thermometers were widely available, temperatures can be reconstructed using climate-sensitive indicators “proxies”

Learn about the ice ages:

Detailed analyses of ocean sediments, ice cores, and other data show that for at least the last 2.6 million years, Earth has gone through extended periods when temperatures were much lower than today and thick blankets of ice covered large areas of the Northern Hemisphere. These long cold spells, lasting in the most recent cycles for around 100,000 years, were interrupted by shorter warm ‘interglacial’ periods, including the past 10,000 years.

Through a combination of theory, observations, and modelling, scientists have deduced that the ice ages* are triggered by recurring variations in Earth’s orbit that primarily alter the regional and seasonal distribution of solar energy reaching Earth. These relatively small changes in solar energy are reinforced over thousands of years by gradual changes in Earth's ice cover (the cryosphere), especially over the Northern Hemisphere, and in atmospheric composition, eventually leading to large changes in global temperature. The average global temperature change during an ice-age cycle is estimated as 5 °C ± 1 °C (9 °F ± 2 °F).

*Note that in geological terms Earth has been in an ice age ever since the Antarctic Ice Sheet last formed about 36 million years ago. However, in this document we have used the term in its more colloquial usage indicating the regular occurrence of extensive ice sheets over North America and northern Eurasia.