Climate Change
Evidence & Causes

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

NATIONAL ACADEMY OF SCIENCES

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, accompanied by sea-level rise, a strong decline in Arctic sea ice, and other climate-related changes.

The evidence is clear. However, due to the nature of science, not every single detail is ever totally settled or completely certain. Nor has every pertinent question yet been answered. Scientific evidence continues to be gathered around the world, and assumptions and findings about climate change are continually analysed and tested. Some areas of active debate and ongoing research include the link between ocean heat content and the rate of warming, estimates of how much warming to expect in the future, and the connections between climate change and extreme weather events.

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, offer this new publication as a key reference document for decision makers, policy makers, educators, and other individuals seeking authoritative answers about the current state of climate-change science. The publication makes clear what is well established, where consensus is growing, and where there is still uncertainty. It is written and reviewed by a UK-US team of leading climate scientists. It echoes and builds upon the long history of climate-related work from both national science academies, as well as the newest climate-change assessment from the United Nations' Intergovernmental Panel on Climate Change.

Scientific information is a vital component of the evidence required for societies to make sensible policy decisions. Climate-change science will continue to help society make informed decisions about how to reduce the magnitude of climate change and to adapt to its impacts. The Royal Society and the US National Academy of Sciences will continue to support the use of robust science toward these critical goals.

In 2008 Raymond and Beverly Sackler established the USA-UK Scientific Forum to help the scientists of the United Kingdom and the United States forge an enduring partnership on topics of worldwide scientific concern. As Presidents of the Royal Society and National Academy of Sciences, we are pleased to introduce the latest piece of work supported by the Sacklers' inspired generosity.

Dr. Ralph J. Cicerone
President, National Academy of Sciences

Sir Paul Nurse
President, Royal Society

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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 about 40%, with more than half the increase occurring since 1970. Since 1900, the global average surface temperature has increased by about 0.8 °C (1.4 °F). This has been accompanied by warming of the ocean, a rise in sea level, a strong decline in Arctic sea ice, and many other associated climate effects. Much of this warming has occurred in the last four 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 0.8 °C (1.4 °F) since 1900, with much of this increase taking place since the mid-1970s (FIGURE 1A). 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. In some places, these records 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 1983 to 2012 was probably the warmest 30-year period in more than 800 years.

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 monitoring systems, which gives added confidence in the reality that Earth's climate is warming.

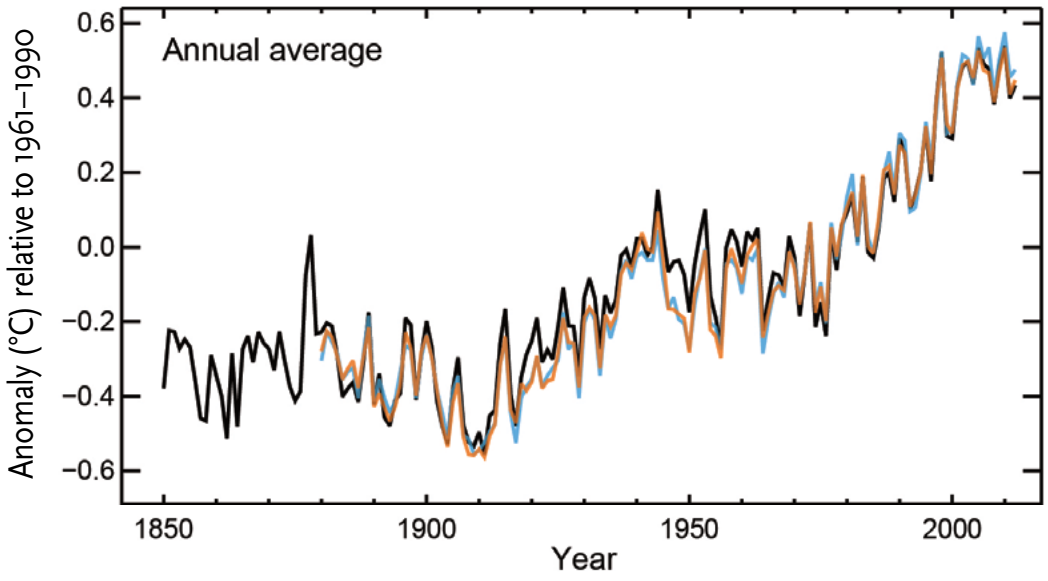
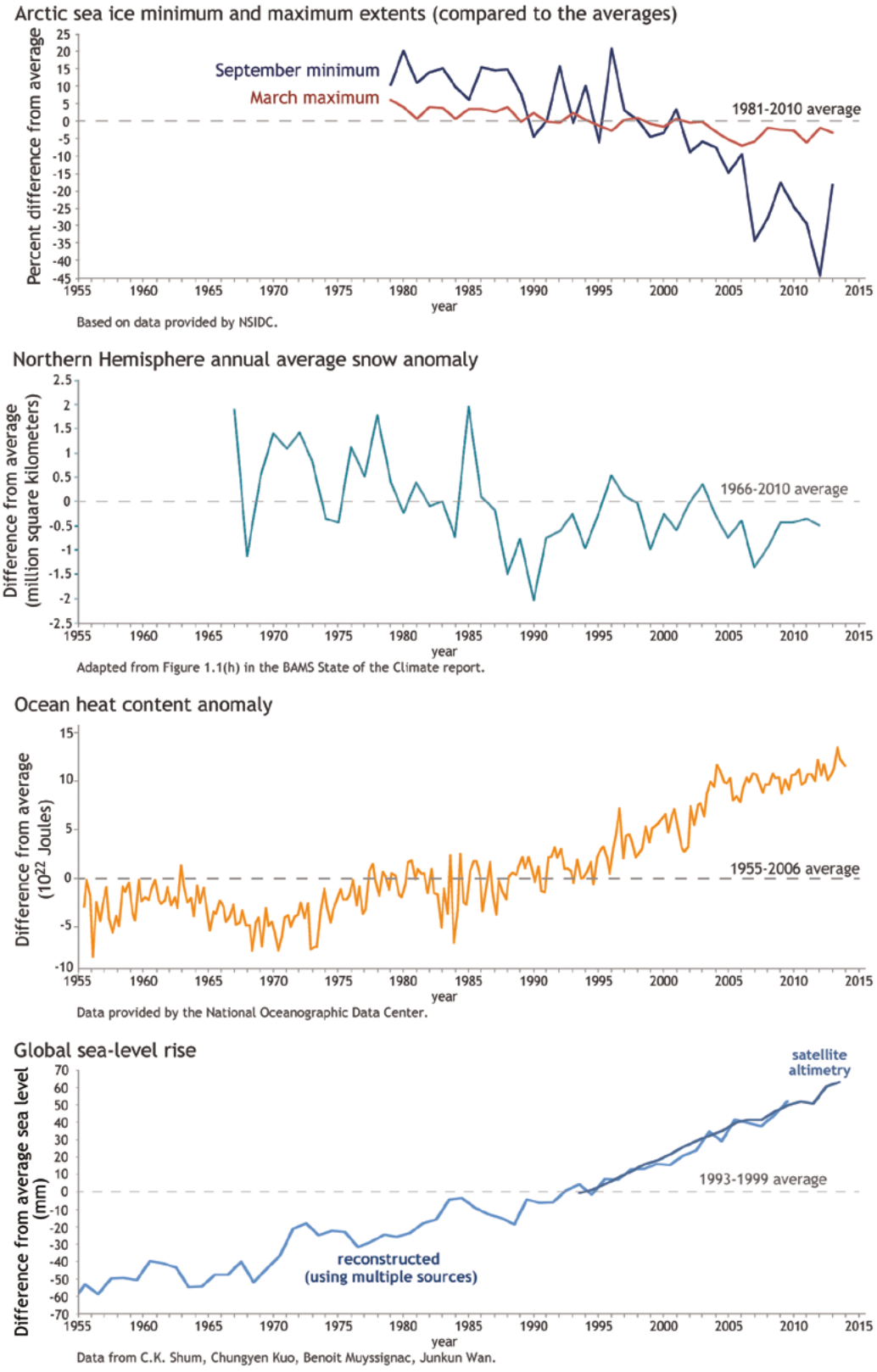


FIGURE 1A. Earth's global average surface temperature has risen as shown in this plot of combined land and ocean measurements from 1850 to 2012, derived from three independent analyses of the available data sets. The temperature changes are relative to the global average surface temperature of 1961–1990. *Source: IPCC AR5, data from the HadCRUT4 dataset (black), UK Met Office Hadley Centre, the NCDC MLOST dataset (orange), US National Oceanic and Atmospheric Administration, and the NASA GISS dataset (blue), US National Aeronautics and Space Administration.*

FIGURE 1B. A large amount of observational evidence besides the 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), decrease in spring snow cover in the Northern Hemisphere, increases in the global average upper ocean (upper 700 m or 2300 feet) heat content (shown relative to the 1955–2006 average), and in sea-level rise.
Source: NOAA climate.gov



2 How do scientists know that recent climate change is largely caused by human activities?

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 about 40% from 1800 to 2012. 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 CO_2 (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 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 rising levels of CO_2 and other human-induced changes (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 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 warming, or even a slight cooling, over the 20th century. 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 through 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 2012 was about 40% higher than it was in the nineteenth 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 and other land use changes have also released carbon from the biosphere (living world) where it normally resides for decades to centuries. The additional CO_2 from fossil fuel burning and 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 indicates that the current concentrations are 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 changes 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 earlier periods, solar changes are less certain because they 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. There 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 50 km, depending on latitude and season). These stratospheric changes may have a small effect on 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 the 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).

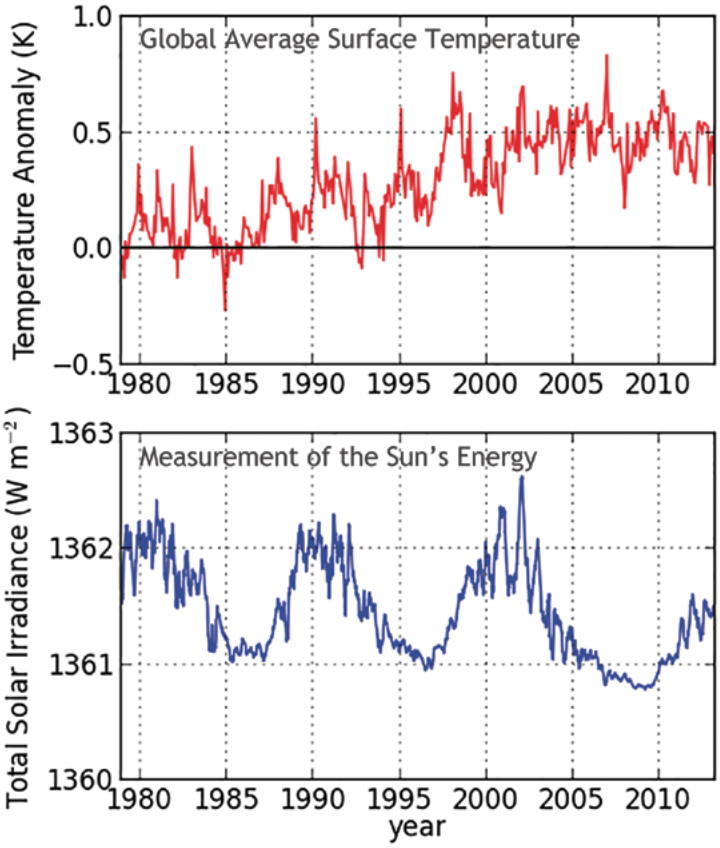


Figure 2. Measurements of the Sun's energy incident on Earth show no net increase in solar forcing during the past 30 years, and therefore this cannot be responsible for warming during that period. The data show only small periodic amplitude variations associated with the Sun's 11-year cycle. Figure by Keith Shine. *Source: TSI data from Physikalisch-Meteorologisches Observatorium Davos, Switzerland, adjusted down by 4.46 W m^{-2} to agree with the 2008 solar minimum data from Kopp and Lean, 2011; temperature data from the HadCRUT4 dataset, UK Met Office, Hadley Centre*

5 What do changes in the vertical structure of atmospheric temperature—from the surface up to the stratosphere—tell us about the causes of recent climate change?

The observed warming in the lower atmosphere and cooling in the upper atmosphere provide 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 system 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 balloons 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 30 to 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 tropical troposphere, where models currently show more warming than 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 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 changes alone are not sufficient to cause the observed magnitude of change in temperature, nor to act on the whole Earth. Instead they lead to changes in the extent of ice sheets and in the abundance of CO_2 and other greenhouse gases which amplify the initial temperature change and complete the global transition from warm to cold or vice versa.

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 by 40% in just the past 200 years, contributing to human alteration of the planet's energy budget that has so far warmed Earth by about 0.8 °C (1.4 °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 palaeoclimatic and geological data indicate that temperatures and sea levels were also higher than they are today.

Measurements of air in ice 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 nearly 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

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 metres higher than current levels.

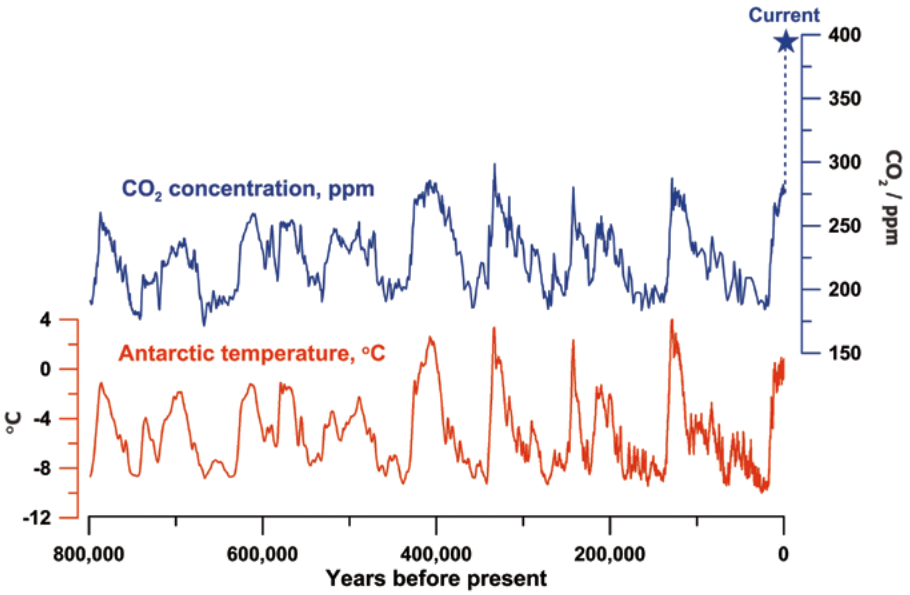


FIGURE 3. Data from ice cores have been used to reconstruct Antarctic temperatures and atmospheric CO_2 concentrations over the past 800,000 years. Temperature is based on measurements of the isotopic content of water in the Dome C ice core. CO_2 is measured in air trapped in ice, and is a composite of the Dome C and Vostok ice core. The current CO_2 concentration (blue star) 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 red). As the record shows, the recent increase in atmospheric CO_2 concentration is unprecedented in the past 800,000 years. *Source: 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 CO_2 to the atmosphere will cause surface temperatures to continue to increase. As the atmospheric concentrations of CO_2 increase, the addition of extra CO_2 becomes progressively less effective at trapping Earth's energy, but surface temperature will still rise.

Our understanding of the physics by which CO_2 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. CO_2 has its strongest heat-trapping band centred at a wavelength of 15 micrometres (millionths of a metre), with wings that spread out a few micrometres on either side. There are also many weaker absorption bands. As CO_2 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 in the wings 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 that 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 know of and study many different types of climate variations, such as those on decadal and multi-decadal timescales in the Pacific and North Atlantic Oceans, each with 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 the emissions, from coal-fired power plants and other pollution sources, of greenhouse gases and of aerosols (airborne particles that can have both warming and cooling effects).

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.

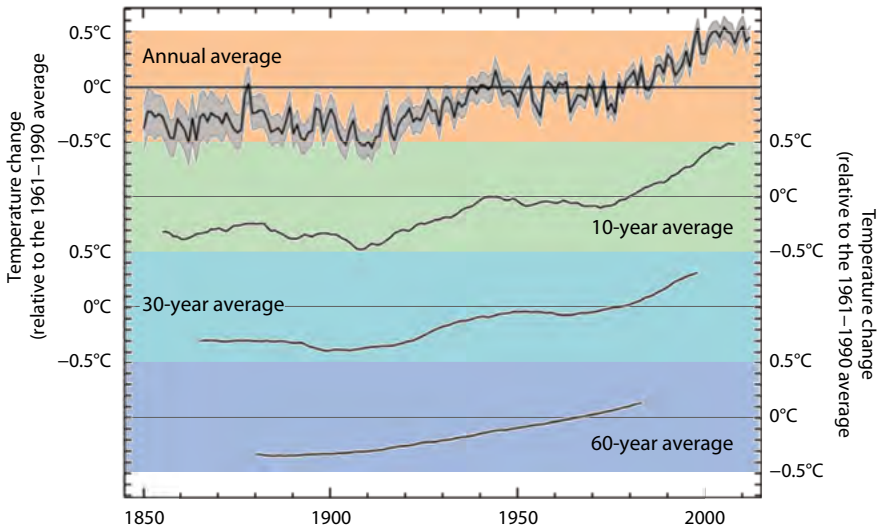


Figure 4. As the climate system varies naturally from year to year and from decade to decade, reliable inferences about human-induced climate change must be made with a longer view, using multi-decadal and longer records. Calculating a 'running average' over these longer timescales allows one to more easily see long-term trends. For the global average temperature for the period 1850-2012 (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 temperature given for any date is the average for the ten years about that date; (3rd plot) the equivalent picture for 30-year; and (4th plot) the 60-year averages. *Source: Met Office, based on the HadCRUT4 dataset from the Met Office and Climatic Research Unit (Morice et al., 2012).*

10 Does the recent slowdown of warming mean that climate change is no longer happening?

No. Since the very warm year 1998 that followed the strong 1997-98 El Niño, the increase in average surface temperature has slowed relative to the previous decade of rapid temperature increases. Despite the slower rate of warming the 2000s were warmer than the 1990s. 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 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 Earth is 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 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 Niñas. 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.

Recent studies have also pointed to a number of other small cooling influences over the past decade or so. These include a relatively quiet period of solar activity and a measured increase in the amount of aerosols (reflective particles) in the atmosphere due to the cumulative effects of a succession of small volcanic eruptions. The combination of these factors, both the interaction between the ocean and the atmosphere and the forcing from the Sun and aerosols, is thought likely to be responsible for the recent slowdown in surface warming.

Despite the decadal slowdown in the rise of average surface temperature, a longer-term warming trend is still evident (see Figure 4). Each of the last three decades was warmer than any other decade since widespread thermometer measurements were introduced in the 1850s. Record heatwaves have occurred in Australia (January 2013), USA (July 2012), in Russia (summer 2010), and in Europe (summer 2003). The continuing effects of the warming climate are also 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.

11 If the world is warming, why are some winters and summers still very cold?

Global warming is a long-term trend, but that does not mean that every year will be warmer than the previous one. Day to day and year to year changes in weather patterns will continue to produce some unusually cold days and nights, and winters and summers, even as the climate warms.

Climate change means not only changes in globally averaged surface temperature, but also changes in atmospheric circulation, in the size and patterns of natural climate variations, and in local weather. La Niña events shift weather patterns so that some regions are made wetter, and wet summers are generally cooler. Stronger winds from polar regions can contribute to an occasional colder winter. In a similar way, the persistence of one phase of an atmospheric circulation pattern known as the North Atlantic Oscillation has contributed to several recent cold winters in Europe, eastern North America, and northern Asia.

Atmospheric and ocean circulation patterns will evolve as Earth warms and will influence storm tracks and many other aspects of the weather. Global warming tilts the odds in favour of more warm days and seasons and fewer cold days and seasons. For example, across the continental United States in the 1960s there were more daily record low temperatures than record highs, but in the 2000s there were more than twice as many record highs as record lows. Another important example of tilting the odds is that over recent decades heatwaves have increased in frequency in large parts of Europe, Asia and Australia.

12 Why is Arctic sea ice decreasing while Antarctic sea ice is not?

Sea ice extent is affected by winds and ocean currents as well as temperature. Sea ice in the partly-enclosed Arctic Ocean seems to be responding directly to warming, while changes in winds and in the ocean seem to be dominating the patterns of climate and sea ice change in the ocean around Antarctica.

Sea ice in the Arctic has decreased dramatically since the late 1970s, particularly in summer and autumn. Since the satellite record began in 1978 (providing for the first time a complete and continuous areal coverage of the Arctic), the yearly minimum Arctic sea ice extent (which occurs in early to mid-September) has decreased by more than 40% [Figure 5]. Ice cover expands again each Arctic winter but the ice is thinner than it used to be. Estimates of past sea ice extent suggest that this decline may be unprecedented in at least the past 1,450 years. The total volume of ice, the product of ice thickness and area, has decreased faster than ice extent over the past decades. Because sea ice is highly reflective, warming is amplified as the ice decreases and more sunshine is absorbed by the darker underlying ocean surface.

Sea ice in the Antarctic has shown a slight increase in extent since 1979 overall, although some areas, such as that to the west of the Antarctic Peninsula, have experienced a decrease. Changes in surface wind patterns around the continent have contributed to the Antarctic pattern of sea ice change while ocean factors such as the addition of cool fresh water from melting ice shelves may also have played a role. The wind changes include a recent strengthening of westerly winds, which reduces the amount of warm air from low latitudes penetrating into the southern high latitudes and alters the way in which ice moves away from the continent. The change in winds may result in part from the effects of stratospheric ozone depletion over Antarctica (i.e., the ozone hole, a phenomenon that is distinct from the human-driven changes in long-lived greenhouse gases discussed in this document). However, short-term trends in the Southern Ocean, such as those observed, can readily occur from natural variability of the atmosphere, ocean and sea ice system.

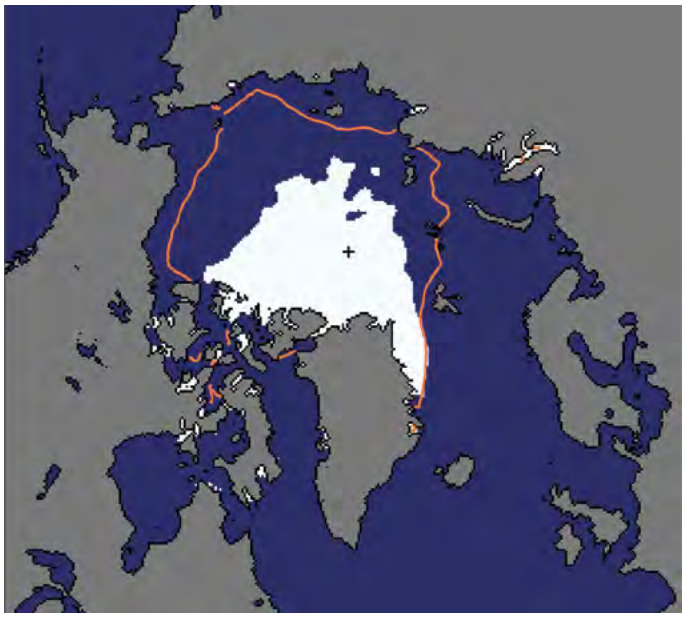


Figure 5. The Arctic summer sea ice extent in 2012, (measured in September) was a record low, shown (in white) compared to the median summer sea ice extent for 1979 to 2000 (in orange outline). In 2013, Arctic summer sea ice extent rebounded somewhat, but was still the sixth smallest extent on record. *Source: National Snow and Ice Data Center*

13 How does climate change affect the strength and frequency of floods, droughts, hurricanes, and tornadoes?

Earth's lower atmosphere is becoming warmer and moister as a result of human-emitted greenhouse gases. This gives the potential for more energy for storms and certain severe weather events. Consistent with theoretical expectations, heavy rainfall and snowfall events (which increase the risk of flooding) and heatwaves are generally becoming more frequent. Trends in extreme rainfall vary from region to region: the most pronounced changes are evident in North America and parts of Europe, especially in winter.

Attributing extreme weather events to climate change is challenging because these events are by definition rare and therefore hard to evaluate reliably, and are affected by patterns of natural climate variability. For instance, the biggest cause of droughts and floods around the world is the shifting of climate patterns between El Niño and La Niña events. On land, El Niño events favour drought in many tropical and subtropical areas, while La Niña events promote wetter conditions in many places, as has happened in recent years. These short-term and regional variations are expected to become more extreme in a warming climate.

There is considerable uncertainty about how hurricanes are changing because of the large natural variability and the incomplete observational record. The impact of climate change on hurricane frequency remains a subject of ongoing studies. While changes in hurricane frequency remain uncertain, basic physical understanding and model results suggest that the strongest hurricanes (when they occur) are likely to become more intense and possibly larger in a warmer, moister atmosphere over the oceans. This is supported by available observational evidence in the North Atlantic. Some conditions favourable for strong thunderstorms that spawn tornadoes are expected to increase with warming, but uncertainty exists in other factors that affect tornado formation, such as changes in the vertical and horizontal variations of winds.

14 How fast is sea level rising?

Long-term measurements of tide gauges and recent satellite data show that global sea level is rising, with best estimates of the global-average rise over the last two decades centred on 3.2 mm per year (0.12 inches per year). The overall observed rise since 1901 is about 20 cm (8 inches) [Figure 6].

This sea-level rise has been driven by (in order of importance): expansion of water volume as the ocean warms, melting of mountain glaciers in most regions of the world, and losses from the Greenland and Antarctic ice sheets. All of these result from a warming climate. Fluctuations in sea level also occur due to changes in the amounts of water stored on land. The amount of sea level change experienced at any given location also depends on a variety of other factors, including whether regional geological processes and rebound of the land weighted down by previous ice sheets are causing the land itself to rise or sink, and whether changes in winds and currents are piling ocean water against some coasts or moving water away.

The effects of rising sea level are felt most acutely in the increased frequency and intensity of occasional storm surges. If CO_2 and other greenhouse gases continue to increase on their current trajectories, it is projected that sea level may rise by a further 0.5 to 1 m (1.5 to 3 feet) by 2100. But rising sea levels will not stop in 2100; sea levels will be much higher in the following centuries as the sea continues to take up heat and glaciers continue to retreat. It remains difficult to predict the details of how the Greenland and Antarctic Ice Sheets will respond to continued warming, but it is thought that Greenland and perhaps West Antarctica will continue to lose mass, whereas the colder parts of Antarctica could start to gain mass as they receive more snowfall from warmer air that contains more moisture. Sea level in the last interglacial (warm) period around 125,000 years ago peaked at probably 5 to 10 m above the present level. During this period, the polar regions were warmer than they are today. This suggests that, over millennia, long periods of increased warmth will lead to very significant loss of parts of the Greenland and Antarctic Ice Sheets and to consequent sea level rise.

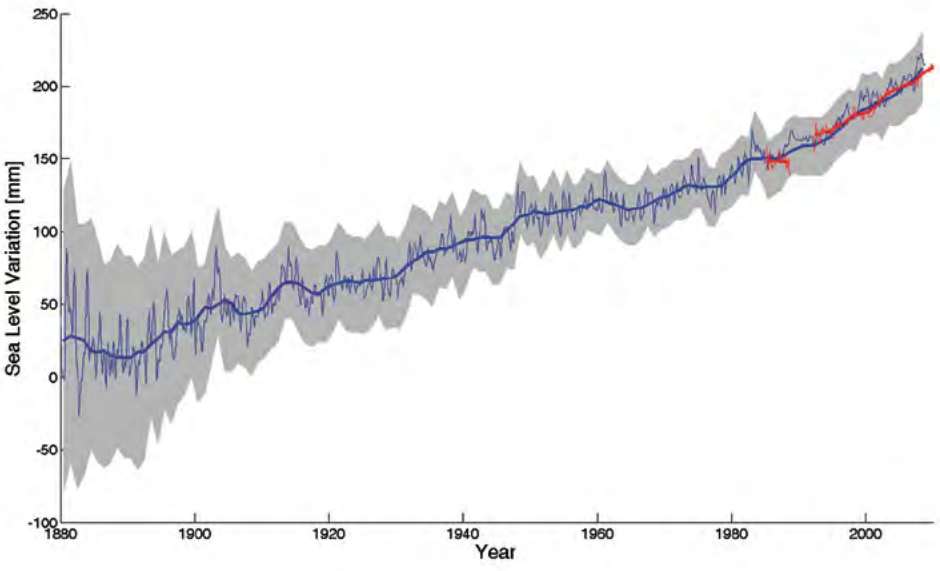


Figure 6. Observations show that the global average sea level has risen by about 20 cm (8 inches) since the late 19th century. Sea level is rising faster in recent decades; measurements from tide gauges (blue) and satellites (red) indicate that the best estimate for the average sea level rise over the last two decades is centred on 3.2 mm per year (0.12 inches per year). The shaded area represents the sea level uncertainty, which has decreased as the number of gauge sites used in the global averages and the number of data points have increased. *Source: Shum and Kuo (2011)*

15 What is ocean acidification and why does it matter?

Direct observations of ocean chemistry have shown that the chemical balance of seawater has shifted to a more acidic state (lower pH) [FIGURE 7]. Some marine organisms (such as corals and some shellfish) have shells composed of calcium carbonate which dissolves more readily in acid. As the acidity of sea water increases, it becomes more difficult for them to form or maintain their shells.

CO_2 dissolves in water to form a weak acid, and the oceans have absorbed about a third of the CO_2 resulting from human activities, leading to a steady decrease in ocean pH levels. With increasing atmospheric CO_2, the chemical balance will change even more during the next century. Laboratory and other experiments show that under high CO_2 and in more acidic waters, some marine species have misshapen shells and lower growth rates, although the effect varies among species. Acidification also alters the cycling of nutrients and many other elements and compounds in the ocean, and it is likely to shift the competitive advantage among species, with as-yet-to-be-determined impacts on marine ecosystems and the food web.

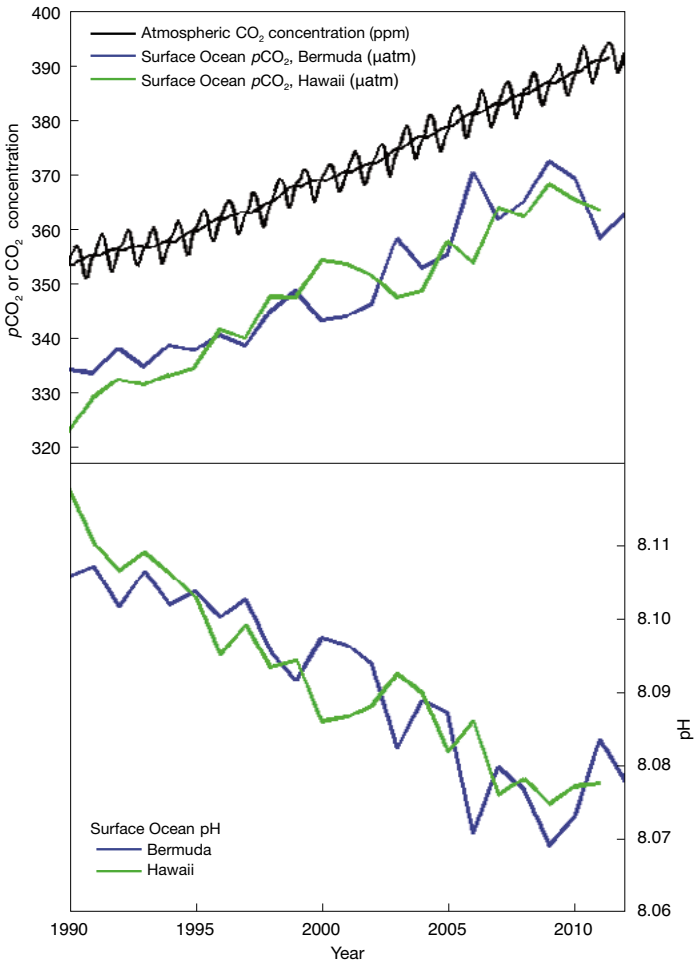


FIGURE 7. As CO_2 in the air has increased, there has been an increase in the CO_2 content of the surface ocean (upper box), and a decrease in the seawater pH (lower box). *Source: adapted from Dore et al. (2009) and Bates et al. (2012).*

16 How confident are scientists that Earth will warm further over the coming century?

Very confident. If emissions continue on their present trajectory, without either technological or regulatory abatement, then warming of 2.6 to 4.8 °C (4.7 to 8.6 °F) in addition to that which has already occurred would be expected by the end of the 21st century.

Warming due to the addition of large amounts of greenhouse gases to the atmosphere can be understood in terms of very basic properties of greenhouse gases. It will in turn lead to many changes in natural climate processes, with a net effect of amplifying the warming. The size of the warming that will be experienced depends largely on the amount of greenhouse gases accumulating in the atmosphere and hence on the trajectory of emissions [Figure 8]. If the total cumulative emissions since 1870 are kept below about 1 trillion (million million) tonnes of carbon, then there is a two-thirds chance of keeping the rise in global average temperature since the pre-industrial period below 2 °C (3.6 °F). However, over half this amount has already been emitted.

Based just on the established physics of the amount of heat CO_2 absorbs and emits, a doubling of atmospheric CO_2 concentration from pre-industrial levels (up to about 560 ppm) would by itself, without amplification by any other effects, cause a global average temperature increase of about 1 °C (1.8 °F). However, the total amount of warming from a given amount of emissions depends on chains of effects (feedbacks) that can individually either amplify or diminish the initial warming.

The most important amplifying feedback is caused by water vapour, which is a potent greenhouse gas in the atmosphere as warmer air can hold more moisture. Also, as Arctic sea ice and glaciers melt, more sunlight is absorbed into the darker underlying land and ocean surfaces causing further warming and further melting of ice and snow. The biggest uncertain factor in our knowledge of feedbacks is in how the properties of clouds will change in response to climate change. Other feedbacks involve the carbon cycle. Currently the land and oceans together absorb about half of the CO_2 emitted from human activities, but the capacities of land and ocean to store additional carbon are expected to decrease with additional warming, leading to faster increases in atmospheric CO_2 and faster warming. Models vary in their projections of how much additional warming to expect, but all such models agree that the overall net effect of feedbacks is to amplify the CO_2-only warming by a factor of 1.5 to 4.5.

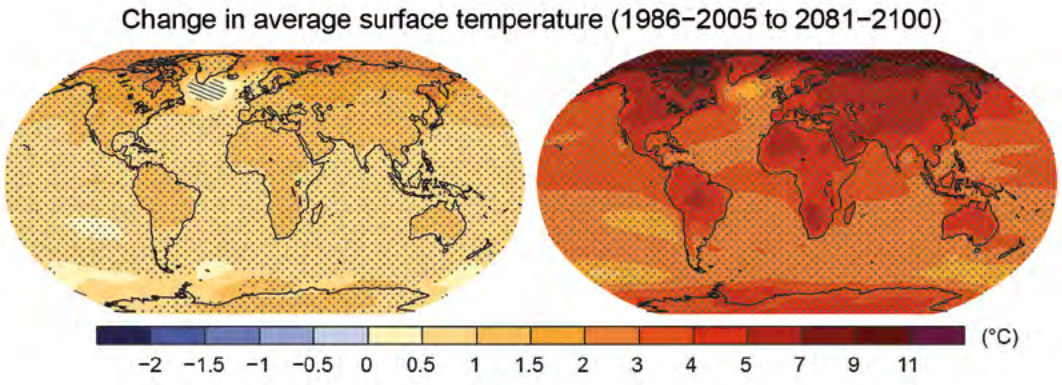


Figure 8. If emissions continue on their present trajectory, without either technological or regulatory abatement, then the best estimate is that global average temperature will warm a further 2.6 to 4.8 °C (4.7 to 8.6 °F) by the end of the century (right). The figure on left shows projected warming with very aggressive emissions reductions. The figures represent multi-model estimates of temperature averages for 2081-2100 compared to 1986–2005. *Source: IPCC AR5*

17 Are climate changes of a few degrees a cause for concern?

Yes. Even though an increase of a few degrees in global average temperature does not sound like much, global average temperature during the last ice age was only about 4 to 5 °C (7 to 9 °F) colder than now. Global warming of just a few degrees will be associated with widespread changes in regional and local temperature and precipitation as well as with increases in some types of extreme weather events. These and other changes (such as sea level rise and storm surge) will have serious impacts on human societies and the natural world.

Both theory and direct observations have confirmed that global warming is associated with greater warming over land than oceans, moistening of the atmosphere, shifts in regional precipitation patterns and increases in extreme weather events, ocean acidification, melting glaciers, and rising sea levels (which increases the risk of coastal inundation and storm surge). Already, record high temperatures are on average significantly outpacing record low temperatures, wet areas are becoming wetter as dry areas are becoming drier, heavy rainstorms have become heavier, and snowpacks (an important source of freshwater for many regions) are decreasing.

These impacts are expected to increase with greater warming and will threaten food production, freshwater supplies, coastal infrastructure, and especially the welfare of the huge population currently living in low-lying areas. Even though certain regions may realise some local benefit from the warming, the long-term consequences overall will be disruptive.

18 What are scientists doing to address key uncertainties in our understanding of the climate system?

Science is a continual process of observation, understanding, modelling, testing and prediction. The prediction of a long-term trend in global warming from increasing greenhouse gases is robust and has been confirmed by a growing body of evidence. Nevertheless, understanding (for example, of cloud dynamics, and of climate variations on centennial and decadal timescales and on regional-to-local spatial scales) remains incomplete. All of these are areas of active research.

Comparisons of model predictions with observations identify what is well-understood and, at the same time, reveal uncertainties or gaps in our understanding. This helps to set priorities for new research. Vigilant monitoring of the entire climate system—the atmosphere, oceans, land, and ice—is therefore critical, as the climate system may be full of surprises.

continued

Together, field and laboratory data and theoretical understanding are used to advance models of Earth's climate system and to improve representation of key processes in them, especially those associated with clouds, aerosols, and transport of heat into the oceans. This is critical for accurately simulating climate change and associated changes in severe weather, especially at the regional and local scales important for policy decisions.

Simulating how clouds will change with warming and in turn may themselves affect warming, remains one of the major challenges for global climate models, in part because many cloud processes occur on scales smaller than the current models can resolve. Greater computer power may enable some of these processes to be resolved in future-generation models.

Dozens of groups and research institutions work on climate models, and scientists are now able to analyse results from essentially all of the world's major Earth-System Models and compare them with each other and with observations. Such opportunities are of tremendous benefit in bringing out the strengths and weaknesses of various models and diagnosing the causes of differences among models, so that research can focus on the relevant processes. The differences among models allow estimates to be made of the uncertainties in projections of future climate change, and in understanding which aspects of these projections are robust.

Studying how climate responded to major changes in the past is another way of checking that we understand how different processes work and that models are capable of performing under a wide range of conditions.

Why are computer models used to study climate change?

The future evolution of Earth's climate as it responds to the present rapid rate of increasing atmospheric CO_2 has no precise analogues in the past, nor can it be properly understood through laboratory experiments. As we are also unable to carry out deliberate controlled experiments on Earth itself, computer models are among the most important tools used to study Earth's climate system.

Climate models are based on mathematical equations that represent the best understanding of the basic laws of physics, chemistry, and biology that govern the behaviour of the atmosphere, ocean, land surface, ice, and other parts of the climate system, as well as the interactions among them. The most comprehensive climate models, Earth-System Models, are designed to simulate Earth's climate system with as much detail as is permitted by our understanding and by available supercomputers.

The capability of climate models has improved steadily since the 1960s. Using physics-based equations, the models can be tested and are successful in simulating a broad range of weather and climate variations, for example from individual storms, jet stream meanders, El Niño events, and the climate of the last century. Their projections of the most prominent features of the long-term human-induced climate change signal have remained robust, as generations of increasingly complex models yield richer details of the change. They are also used to perform experiments to isolate specific causes of climate change and to explore the consequences of different scenarios of future greenhouse gas emissions and other influences on climate.

19 Are disaster scenarios about tipping points like 'turning off the Gulf Stream' and release of methane from the Arctic a cause for concern?

Results from the best available climate models do not predict abrupt changes in such systems (often referred to as tipping points) in the near future. However, as warming increases, the possibilities of major abrupt change cannot be ruled out.

The composition of the atmosphere is changing towards conditions that have not been experienced for millions of years, so we are headed for unknown territory, and uncertainty is large. The climate system involves many competing processes that could switch the climate into a different state once a threshold has been exceeded.

A well-known example is the south-north ocean overturning circulation, which is maintained by cold salty water sinking in the North Atlantic and which involves the transport of extra heat to the North Atlantic via the Gulf Stream. During the last ice age, pulses of freshwater from the ice sheet over North America led to slowing down of this overturning circulation and to widespread changes in climate around the Northern Hemisphere. Freshening of the North Atlantic from the melting of the Greenland ice sheet is however, much less intense and hence is not expected to cause abrupt changes. As another example, Arctic warming could destabilise methane (a greenhouse gas) trapped in ocean sediments and permafrost, potentially leading to a rapid release of a large amount of methane. If such a rapid release occurred, then major, fast climate changes would ensue.

Such high-risk changes are considered unlikely in this century, but are by definition hard to predict. Scientists are therefore continuing to study the possibility of such tipping points beyond which we risk large and abrupt changes.

20 If emissions of greenhouse gases were stopped, would the climate return to the conditions of 200 years ago?

No. Even if emissions of greenhouse gases were to suddenly stop, Earth's surface temperature would not cool and return to the level in the pre-industrial era for thousands of years.

If emissions of CO_2 stopped altogether, it would take many thousands of years for atmospheric CO_2 to return to 'pre-industrial' levels due to its very slow transfer to the deep ocean and ultimate burial in ocean sediments. Surface temperatures would stay elevated for at least a thousand years, implying extremely long-term commitment to a warmer planet due to past and current emissions, and sea level would likely continue to rise for many centuries even after temperature stopped increasing [FIGURE 9]. Significant cooling would be required to reverse melting of glaciers and the Greenland ice sheet, which formed during past cold climates. The current CO_2-induced warming of Earth is therefore essentially irreversible on human timescales. The amount and rate of further warming will depend almost entirely on how much more CO_2 humankind emits.

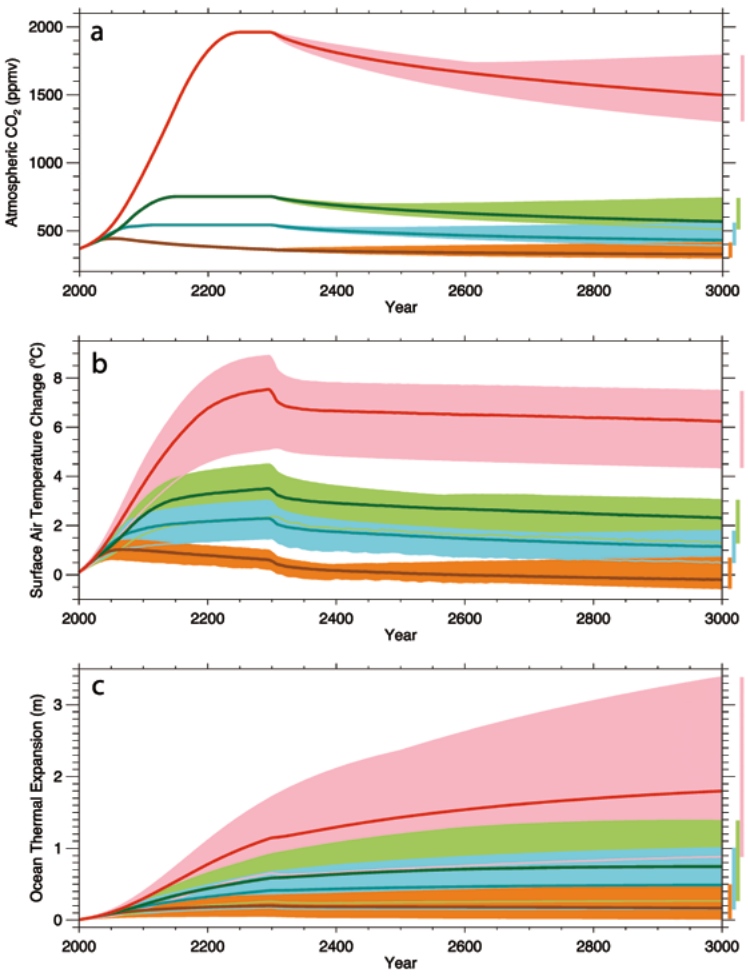


FIGURE 9. If global emissions were to suddenly stop, it would take a long time for surface air temperatures and the ocean to begin to cool, because the excess CO_2 in the atmosphere would remain there for a long time and would continue to exert a warming effect. Model projections show how atmospheric CO_2 concentration (a), surface air temperature (b), and ocean thermal expansion (c) would respond following a scenario of business-as-usual emissions ceasing in 2300 (red), a scenario of aggressive emission reductions, falling close to zero 50 years from now (orange), and two intermediate emissions scenarios (green and blue). The small downward tick in temperature at 2300 is caused by the elimination of emissions of short-lived greenhouse gases, including methane. *Source: Zickfeld et al., 2013*

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.

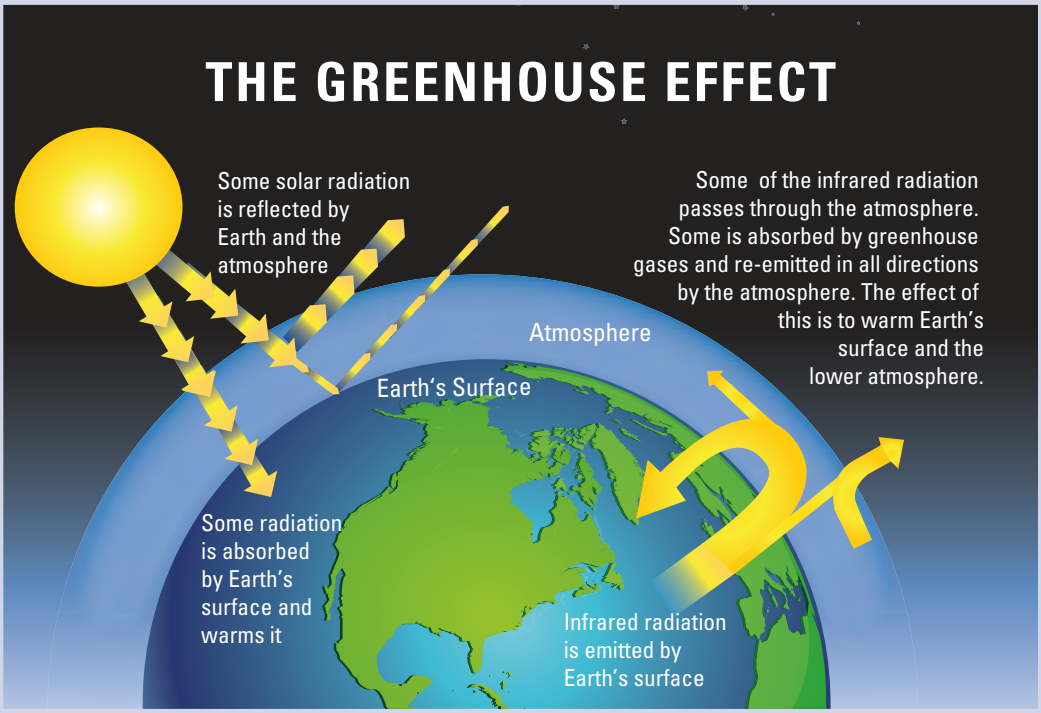


FIGURE B1. Greenhouse gases in the atmosphere, including water vapour, carbon dioxide, methane, and nitrous oxide, absorb heat energy and emit it in all directions (including downwards), keeping Earth's surface and lower atmosphere warm. Adding more greenhouse gases to the atmosphere enhances the effect,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

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 396 ppm in 2013 [FIGURE B2]. The same rates of increase have since been recorded at numerous other stations worldwide. Since pre-industrial times, the atmospheric concentration of CO_2 has increased by 40%, methane has increased by about 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

1 *that is, for every million molecules in the air, 316 of them were CO_2*

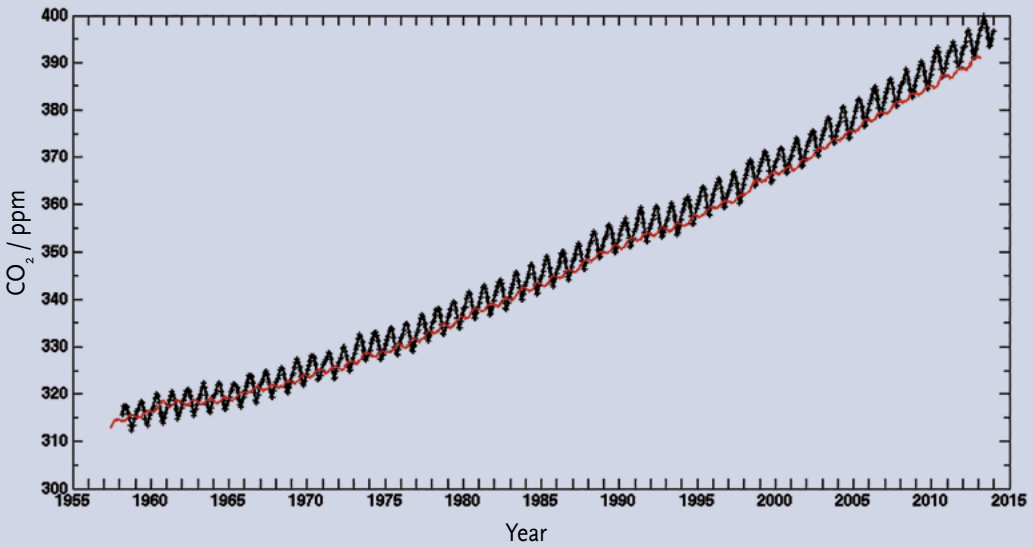


FIGURE B2. Measurements of atmospheric CO_2 since 1958 from the Mauna Loa Observatory in Hawaii (black) and from the South Pole (red) show a steady annual increase in atmospheric CO_2 concentration. (The measurements are made at remote places like those because they are not greatly influenced by local processes, so therefore 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 CO_2 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 page B4 to learn about the ice ages—and no concentration above 300 ppm is seen in ice core records until the past 200 years.

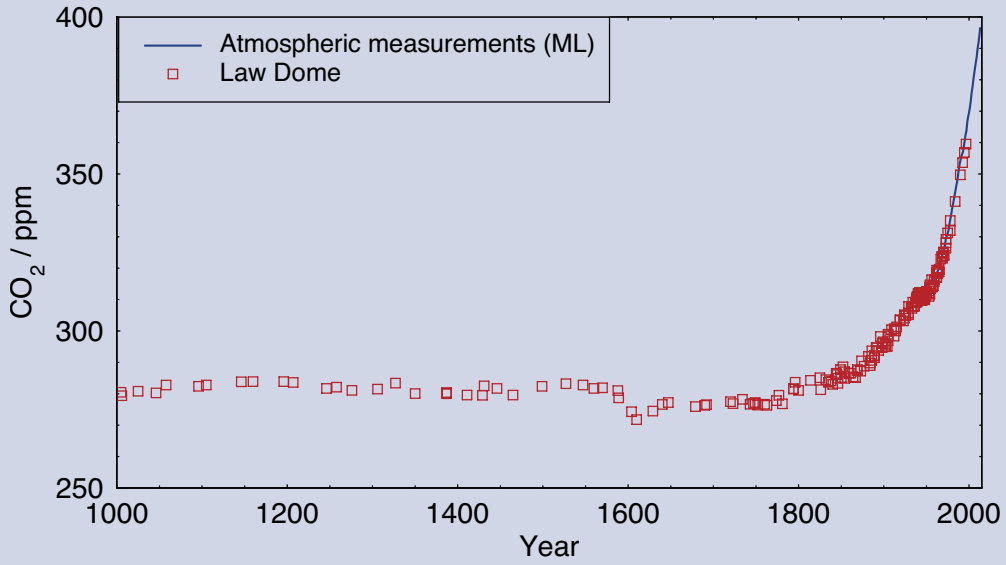


FIGURE B3. CO_2 variations during the past 1,000 years, obtained from analysis of air trapped in an ice core extracted from Antarctica (red squares), show a sharp rise in atmospheric CO_2 starting in the late 19th century. Modern atmospheric measurements from Mauna Loa are superimposed in blue. *Source: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

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.

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 ^{14}C) 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 0.8 °C (1.4 °F) since 1900 [FIGURE B4]. Although the record shows several pauses and accelerations in the increasing trend, each of the last three 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.*

in materials such as tree rings, ice cores, and marine sediments. Comparisons of the thermometer record with these proxy measurements suggest that the time since the early 1980s has been the warmest 30-year period in at least eight centuries, and that global temperature is rising towards peak temperatures last seen 5,000 to 10,000 years ago in the warmest part of our current interglacial period.

Many other impacts associated with the warming trend have become evident in recent years. Arctic summer sea ice cover has shrunk dramatically. The heat content of the ocean has increased. Global average sea level has risen by approximately 20 cm (8 inches) since 1901, due both to the expansion of warmer ocean water and to the addition of melt waters from glaciers and ice sheets on land. Warming and precipitation changes are altering the geographical ranges of many plant and animal species and the timing of their life cycles. In addition to the effects on climate, some of the excess CO_2 in the atmosphere is being taken up by the ocean, changing its chemical composition (causing ocean acidification).

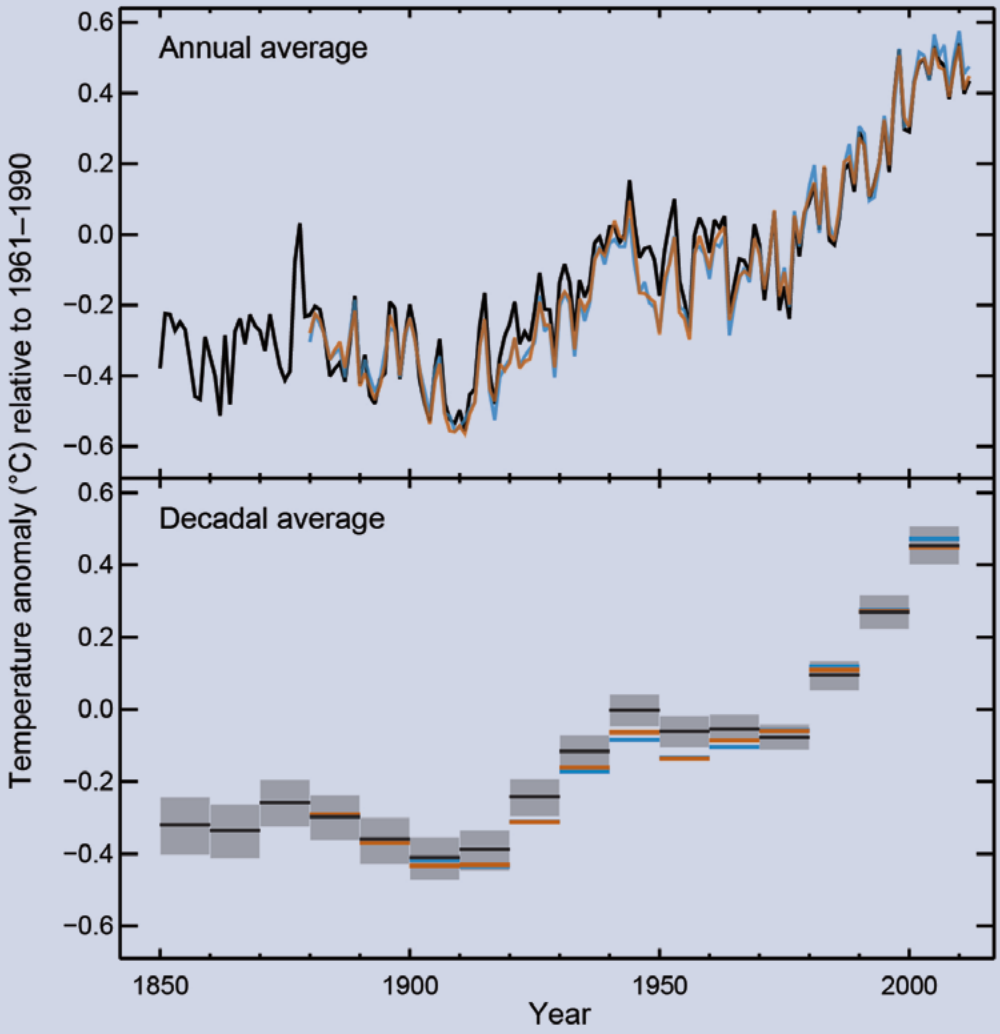


FIGURE B4. Earth's global average surface temperature has risen as shown in this plot of combined land and ocean measurements from 1850 to 2012, derived from three independent analyses of the available data sets. The top panel shows annual average values from the three analyses, and the bottom panel shows decadal average values, including the uncertainty range (grey bars) for the black (HadCRUT4) dataset. The temperature changes are relative to the global average surface temperature, averaged from 1961–1990. *Source: IPCC AR5, data from the HadCRUT4 dataset (black), UK Met Office Hadley Centre, the NCDC MLOST dataset (orange), US National Oceanic and Atmospheric Administration, and the NASA GISS dataset (blue), US National Aeronautics and Space Administration.*

Many complex processes shape our climate

Based just on the physics of the amount of energy that CO_2 absorbs and emits, a doubling of atmospheric CO_2 concentration from pre-industrial levels (up to about 560 ppm) would, by itself, cause a global average temperature increase of about 1 °C (1.8 °F). In the overall climate system, however, things are more complex; warming leads to further effects (feedbacks) that either amplify or diminish the initial warming.

The most important feedbacks involve various forms of water. A warmer atmosphere generally contains more water vapour. Water vapour is a potent greenhouse gas, thus causing more warming; its short lifetime in the atmosphere keeps its increase largely in step with warming. Thus, water vapour is treated as an amplifier, and not a driver, of climate change. Higher temperatures in the polar regions melt sea ice and reduce seasonal snow cover, exposing a darker ocean and land surface that can absorb more heat, causing further warming. Another important but uncertain feedback concerns changes in clouds. Warming and increases in water vapour together may cause cloud cover to increase or decrease which can either amplify or dampen temperature change depending on the changes in the horizontal extent, altitude, and properties of clouds. The latest assessment of the science indicates that the overall net global effect of cloud changes is likely to be to amplify warming.

The ocean moderates climate change. The ocean is a huge heat reservoir, but it is difficult to heat its full depth because warm water tends to stay near the surface. The rate at which heat is transferred to the deep ocean is therefore slow; it varies from year to year and from decade to decade, and helps to determine the pace of warming at the surface. Observations of the sub-surface ocean are limited prior to about 1970, but since then, warming of the upper 700 m (2,300 feet) is readily apparent. There is also evidence of deeper warming.

Surface temperatures and rainfall in most regions vary greatly from the global average because of geographical location, in particular latitude and continental position. Both the average values of temperature, rainfall, and their extremes (which generally have the largest impacts on natural systems and human infrastructure), are also strongly affected by local patterns of winds.

Estimating the effects of feedback processes, the pace of the warming, and regional climate change requires the use of mathematical models of the atmosphere, ocean, land, and ice (the cryosphere) built upon established laws of physics and the latest understanding of the physical, chemical and biological processes affecting climate, and run on powerful computers. Models vary in their projections of how much additional warming to expect (depending on the type of model and on assumptions used in simulating certain climate processes, particularly cloud formation and ocean mixing), but all such models agree that the overall net effect of feedbacks is to amplify warming.

Human activities are changing the climate

Rigorous analysis of all data and lines of evidence shows that most of the observed global warming over the past 50 years or so cannot be explained by natural causes and instead requires a significant role for the influence of human activities.

In order to discern the human influence on climate, scientists must consider many natural variations that affect temperature, precipitation, and other aspects of climate from local to global scale, on timescales from days to decades and longer. One natural variation is the El Niño Southern Oscillation (ENSO), an irregular alternation between warming and cooling (lasting about two to seven years) in the equatorial Pacific Ocean that causes significant year-to-year regional and global shifts in temperature and rainfall patterns. Volcanic eruptions also alter climate, in part increasing the amount of small (aerosol) particles in the stratosphere that reflect or absorb sunlight, leading to a short-term surface cooling lasting typically about two to three years. Over hundreds of thousands of years, slow, recurring variations in Earth's orbit around the Sun, which alter the distribution of solar energy received by Earth, have been enough to trigger the ice age cycles of the past 800,000 years.

Fingerprinting is a powerful way of studying the causes of climate change. Different influences on climate lead to different patterns seen in climate records. This becomes obvious when scientists probe beyond changes in the average temperature of the planet and look more closely at geographical and temporal patterns of climate change. For example, an increase in the Sun's energy output will lead to a very different pattern of temperature change (across Earth's surface and vertically in the atmosphere) compared to that induced by an increase in CO_2 concentration. Observed atmospheric temperature changes show a fingerprint much

Learn more about other human causes of climate change

In addition to emitting greenhouse gases, human activities have also altered Earth's energy balance through, for example:

- **Changes in land use.** Changes in the way people use land — for example, for forests, farms, or cities — can lead to both warming and cooling effects locally by changing the reflectivity of Earth's surfaces (affecting how much sunlight is sent back into space) and by changing how wet a region is.
- **Emissions of pollutants (other than greenhouse gases)**. Some industrial and agricultural processes emit pollutants that produce aerosols (small droplets or particles suspended in the atmosphere). Most aerosols cool Earth by reflecting sunlight back to space. Some aerosols also affect the formation of clouds, which can have a warming or cooling effect depending on their type and location. Black carbon particles (or 'soot') produced when fossil fuels or vegetation are burned, generally have a warming effect because they absorb incoming solar radiation.

closer to that of a long-term CO_2 increase than to that of a fluctuating Sun alone. Scientists routinely test whether purely natural changes in the Sun, volcanic activity, or internal climate variability could plausibly explain the patterns of change they have observed in many different aspects of the climate system. These analyses have shown that the observed climate changes of the past several decades cannot be explained just by natural factors.

How will climate change in the future?

Scientists have made major advances in the observations, theory, and modelling of Earth's climate system; and these advances have enabled them to project future climate change with increasing confidence. Nevertheless, several major issues make it impossible to give precise estimates of how global or regional temperature trends will evolve decade by decade into the future. Firstly, we cannot predict how much CO_2 human activities will emit, as this depends on factors such as how the global economy develops and how society's production and consumption of energy changes in the coming decades. Secondly, with current understanding of the complexities of how climate feedbacks operate, there is a range of possible outcomes, even for a particular scenario of CO_2 emissions. Finally, over timescales of a decade or so, natural variability can modulate the effects of an underlying trend in temperature. Taken together, all model projections indicate that Earth will continue to warm considerably more over the next few decades to centuries. If there were no technological or policy changes to reduce emission trends from their current trajectory, then further warming of 2.6 to 4.8 °C (4.7 to 8.6 °F) in addition to that which has already occurred would be expected during the 21st century [FIGURE B5]. Projecting what those ranges will mean for the climate experienced at any particular location is a challenging scientific problem, but estimates are continuing to improve as regional and local-scale models advance.

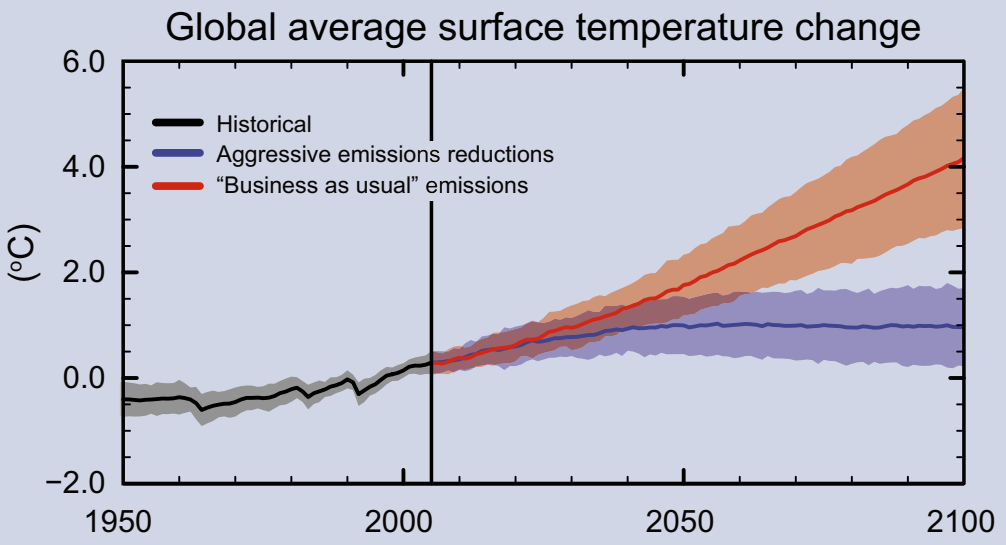


FIGURE B5. The amount and rate of warming expected for the 21st century depends on the total amount of greenhouse gases that humankind emits. Models project the temperature increase for a business-as-usual emissions scenario (in red) and aggressive emission reductions, falling close to zero 50 years from now (in blue). Black is the modelled estimate of past warming. Each solid line represents the average of different model runs using the same emissions scenario, and the shaded areas provide a measure of the spread (one standard deviation) between the temperature changes projected by the different models. All data are relative to a reference period (set to zero) of 1986-2005. *Source: IPCC AR5*

Conclusion

This document explains that there are well-understood physical mechanisms by which changes in the amounts of greenhouse gases cause climate changes. It discusses the evidence that the concentrations of these gases in the atmosphere have increased and are still increasing rapidly, that climate change is occurring, and that most of the recent change is almost certainly due to emissions of greenhouse gases caused by human activities. Further climate change is inevitable; if emissions of greenhouse gases continue unabated, future changes will substantially exceed those that have occurred so far. There remains a range of estimates of the magnitude and regional expression of future change, but increases in the extremes of climate that can adversely affect natural ecosystems and human activities and infrastructure are expected.

Citizens and governments can choose among several options (or a mixture of those options) in response to this information: they can change their pattern of energy production and usage in order to limit emissions of greenhouse gases and hence the magnitude of climate changes; they can wait for changes to occur and accept the losses, damage and suffering that arise; they can adapt to actual and expected changes as much as possible; or they can seek as yet unproven 'geoengineering' solutions to counteract some of the climate changes that would otherwise occur. Each of these options has risks, attractions and costs, and what is actually done may be a mixture of these different options. Different nations and communities will vary in their vulnerability and their capacity to adapt. There is an important debate to be had about choices among these options, to decide what is best for each group or nation, and most importantly for the global population as a whole. The options have to be discussed at a global scale, because in many cases those communities that are most vulnerable control few of the emissions, either past or future. Our description of the science of climate change, with both its facts and its uncertainties, is offered as a basis to inform that policy debate.

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For further reading

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

- IPCC 2013, *Climate change 2013: The physical science basis*. Fifth Assessment Report (AR5) Working Group 1.
  visit site
- NRC 2010, *America's climate choices: Advancing the Science of Climate Change*.
  visit site
- NRC 2011, *Climate stabilization targets: Emissions, Concentrations, and Impacts over Decades to Millennia.*
  visit site
- NRC 2013, *Abrupt impacts of climate change: Anticipating Surprises.*
  visit site
- Royal Society 2010, *Climate Change: A Summary of the Science.*
  visit site

Much of the original data underlying the scientific findings discussed here are available at:

- metoffice.gov.uk/hadobs
- www.cru.uea.ac.uk
- cdp.ucar.edu
- climatedataguide.ucar.edu
- iridl.ldeo.columbia.edu
- cdiac.ornl.gov
- ncdc.noaa.gov
- esrl.noaa.gov/gmd/ccgg/trends
- scrippsco2.ucsd.edu
- hahana.soest.hawaii.edu/hot

THE NATIONAL ACADEMY OF SCIENCES (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 Sciences 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 nas-sites.org/americasclimatechoices.

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