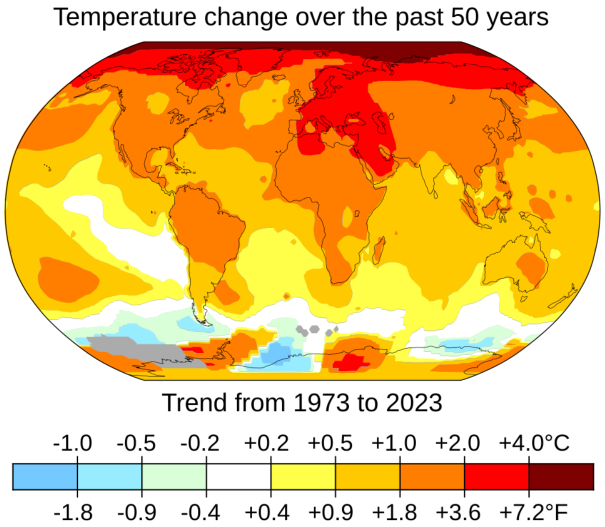
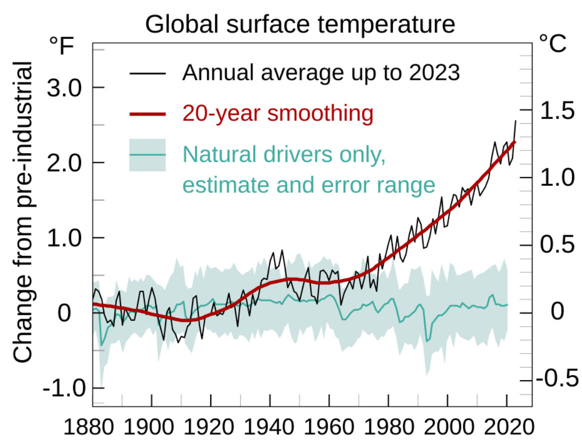
Climate change

Present-day **climate change** includes both **global warming**—the ongoing increase in global average temperature—and its wider effects on Earth's climate system. Climate change in a broader sense also includes previous long-term changes to Earth's climate. The current rise in global temperatures is driven by human activities, especially fossil fuel (coal, oil and natural gas) burning since the Industrial Revolution.[3][4] Fossil fuel use, deforestation, and some agricultural and industrial practices release greenhouse gases.[5] These gases absorb some of the heat that the Earth radiates after it warms from sunlight, warming the lower atmosphere. Carbon dioxide, the primary gas driving global warming, has increased in concentration by about 50% since the pre-industrial era to levels not seen for millions of years.[6]



Changes in surface air temperature over the past 50 years.[1] The Arctic has warmed the most, and temperatures on land have generally increased more than sea surface temperatures.



Earth's average surface air temperature has increased almost 1.5 °C (about 2.5 °F) since the Industrial Revolution. Natural forces cause some variability, but the 20-year average shows the progressive influence of human activity.[2]

Climate change has an increasingly large impact on the environment. Deserts are expanding, while heat waves and wildfires are becoming more common.[7] Amplified warming in the Arctic has contributed to thawing permafrost, retreat of glaciers and sea ice decline.[8] Higher temperatures are also causing more intense storms, droughts, and other weather extremes.[9] Rapid environmental change in mountains, coral reefs, and the Arctic is forcing many species to relocate or become extinct.[10] Even if efforts to minimize future warming are successful, some effects will continue for centuries. These include ocean heating, ocean acidification and sea level rise.[11]

Climate change threatens people with increased flooding, extreme heat, increased food and water scarcity, more disease, and economic loss.[12] Human migration and conflict can also be a result.[13] The World Health Organization calls climate change one of the biggest threats to global health in the 21st century.[14] Societies and ecosystems will experience more severe risks without action to limit warming.[15] Adapting to climate change through efforts like flood control measures or drought-resistant crops partially reduces climate change risks, although some limits to adaptation have already been reached.[16] Poorer communities are responsible for a small share of global emissions, yet have the least ability to adapt and are most vulnerable to climate change.[17][18]

Many climate change impacts have been observed in the first decades of the 21st century, with 2024 the warmest on record at +1.60 °C (2.88 °F) since regular tracking began in 1850.[20][21] Additional warming will increase these impacts and can trigger tipping points, such as melting all of the Greenland ice sheet.[22] Under the 2015 Paris Agreement, nations collectively agreed to keep warming "well under 2 °C". However, with pledges made under the Agreement, global warming would still reach about 2.8 °C (5.0 °F) by the end of the century.[23]

There is widespread support for climate action worldwide,[24][25] and most countries aim to stop emitting carbon dioxide.[26] Fossil fuels can be phased out by stopping subsidising them, conserving energy and switching to energy sources that do not produce significant carbon pollution. These energy sources include wind, solar, hydro, and nuclear power.[27] Cleanly generated electricity can replace fossil fuels for powering transportation, heating buildings, and running industrial processes.[28] Carbon can also be removed from the atmosphere, for instance by increasing forest cover and farming with methods that store carbon in soil.[29][30][31]

Examples of some effects of climate change: Wildfire intensified by heat and drought, bleaching of corals occurring more often due to marine heatwaves, and worsening droughts compromising water supplies.

Terminology

Before the 1980s, it was unclear whether the warming effect of increased greenhouse gases was stronger than the cooling effect of airborne particulates in air pollution. Scientists used the term *inadvertent climate modification* to refer to human impacts on the climate at this time.[32] In the 1980s, the terms *global warming* and *climate change* became more common, often being used interchangeably.[33][34][35] Scientifically, *global warming* refers only to increased global average surface temperature, while *climate change* describes both global warming and its effects on Earth's climate system, such as precipitation changes.[32]

Climate change can also be used more broadly to include changes to the climate that have happened throughout Earth's history.[36] *Global warming*—used as early as 1975[37]—became the more popular term after NASA climate scientist James Hansen used it in his 1988 testimony in the U.S. Senate.[38] Since the 2000s, usage of *climate change* has increased.[39] Various scientists, politicians and media may use the terms *climate crisis* or *climate emergency* to talk about climate change, and may use the term *global heating* instead of *global warming*.[40][41]

Global temperature rise

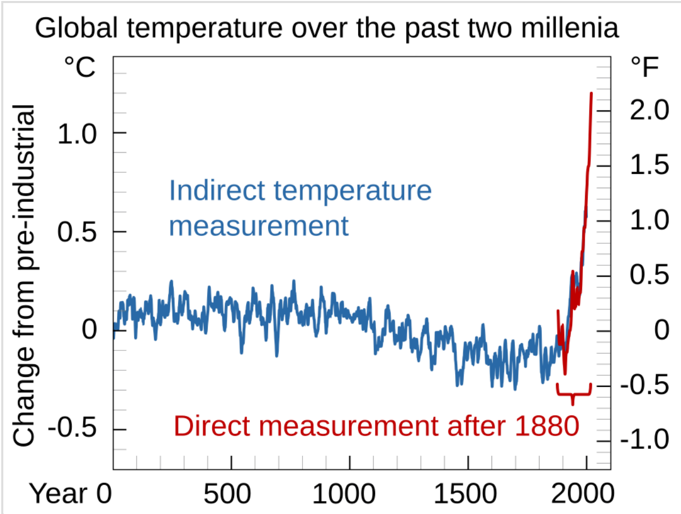
Temperatures prior to present-day global warming

Over the last few million years the climate cycled through ice ages. One of the hotter periods was the Last Interglacial, around 125,000 years ago, where temperatures were between 0.5 °C and 1.5 °C warmer than before the start of global warming.[44] This period saw sea levels 5 to 10 metres higher than today. The most recent glacial maximum 20,000 years ago was some 5–7 °C colder. This period has sea levels that were over 125 metres (410 ft) lower than today.[45]

Temperatures stabilized in the current interglacial period beginning 11,700 years ago.[46] This period also saw the start of agriculture.[47] Historical patterns of warming and cooling, like the Medieval Warm Period and the Little Ice Age, did not occur at the same time across different regions. Temperatures may have reached as high as those of the late 20th century in a limited set of regions.[48][49] Climate information for that period comes from climate proxies, such as trees and ice cores.[50][51]

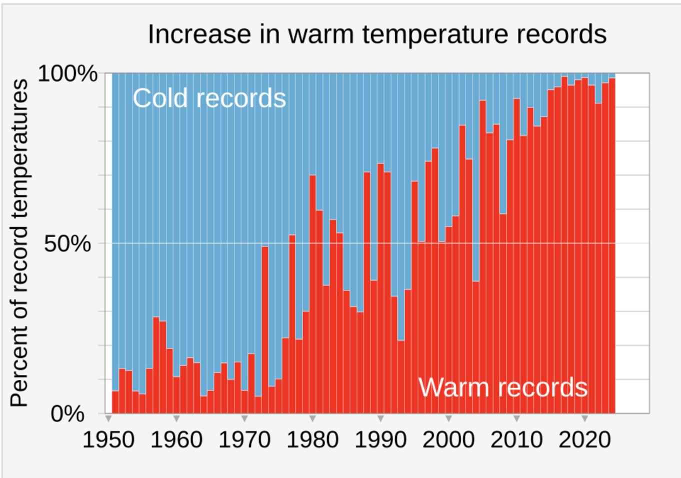
Warming since the Industrial Revolution

Around 1850 thermometer records began to provide global coverage.[54] Between the 18th century and 1970 there was little net warming, as the warming impact of greenhouse gas emissions was offset by cooling from sulfur dioxide emissions. Sulfur dioxide causes acid rain, but it also produces sulfate aerosols in the atmosphere, which reflect sunlight and cause global dimming. After 1970, the increasing accumulation of greenhouse gases and controls on sulfur pollution led to a marked increase in temperature.[55][56][57]



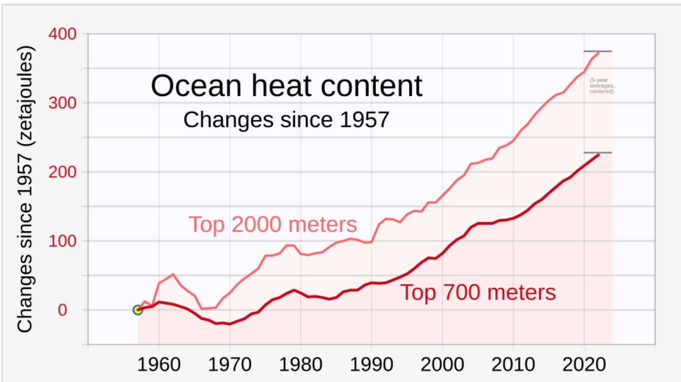
Global surface temperature reconstruction over the past 2000 years using proxy data from tree rings, corals, and ice cores in blue.[42] Directly observed data is in red.[43]

Ongoing changes in climate have had no precedent for several thousand years.[58] Multiple datasets all show worldwide increases in surface temperature,[59] at a rate of around 0.2 °C per decade.[60] The 2014–2023 decade warmed to an average 1.19 °C [1.06–1.30 °C] compared to the pre-industrial baseline (1850–1900).[61] Not every single year was warmer than the last: internal climate variability processes can make any year 0.2 °C warmer or colder than the average.[62] From 1998 to 2013, negative phases of two such processes, Pacific Decadal Oscillation (PDO)[63] and Atlantic Multidecadal Oscillation (AMO)[64] caused a short slower period of warming called the "global warming hiatus".[65] After the "hiatus", the opposite occurred, with 2024 well above the recent average at more than +1.5 °C.[66] This is why the temperature change is defined in terms of a 20-year average, which reduces the noise of hot and cold years and decadal climate patterns, and detects the long-term signal.[67]:5[68]



In recent decades, new high temperature records have substantially outpaced new low temperature records on a growing portion of Earth's surface.[52]

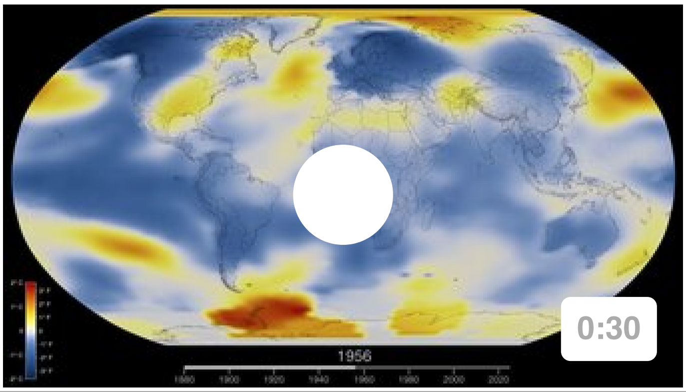
A wide range of other observations reinforce the evidence of warming.[69][70] The upper atmosphere is cooling, because greenhouse gases are trapping heat near the Earth's surface, and so less heat is radiating into space.[71] Warming reduces average snow cover and forces the retreat of glaciers. At the same time, warming also causes greater evaporation from the oceans, leading to more atmospheric humidity, more and heavier precipitation.[72][73] Plants are flowering earlier in spring, and thousands of animal species have been permanently moving to cooler areas.[74]



There has been an increase in ocean heat content during recent decades as the oceans absorb over 90% of the heat from global warming.[53]

Differences by region

Different regions of the world warm at different rates. The pattern is independent of where greenhouse gases are emitted, because the gases persist long enough to diffuse across the planet. Since the pre-industrial period, the average surface temperature over land regions has increased almost twice as fast as the global average surface temperature.[75] This is because oceans lose more heat by evaporation and oceans can store a lot of heat.[76] The thermal energy in the global climate system has grown with only brief pauses since at least 1970, and over 90% of this extra energy has been stored in the ocean.[77][78] The rest has heated the atmosphere, melted ice, and warmed the continents.[79]

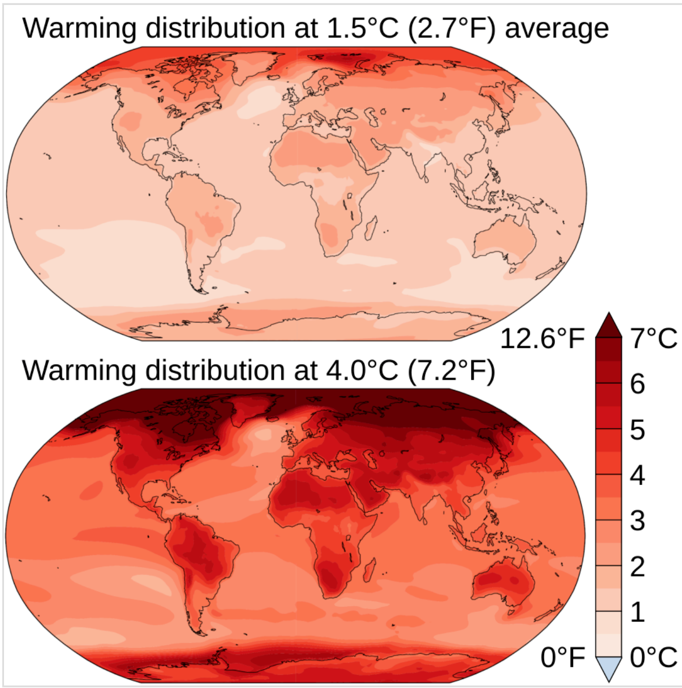


NASA animation portraying global surface temperature changes from 1880 to 2023. The colour blue denotes cooler temperatures and red denotes warmer temperatures.

The Northern Hemisphere and the North Pole have warmed much faster than the South Pole and Southern Hemisphere. The Northern Hemisphere not only has much more land, but also more seasonal snow cover and sea ice. As these surfaces flip from reflecting a lot of light to being dark after the ice has melted, they start absorbing more heat.[80] Local black carbon deposits on snow and ice also contribute to Arctic warming.[81] Arctic surface temperatures are increasing between three and four times faster than in the rest of the world.[82][83] Melting of ice sheets near the poles weakens both the Atlantic and the Antarctic limb of thermohaline circulation, which further changes the distribution of heat and precipitation around the globe.[84][85][86][87]

Future global temperatures

The World Meteorological Organization estimates there is almost a 50% chance of the five-year average global temperature exceeding +1.5 °C between 2024 and 2028.[90] The IPCC expects the 20-year average to exceed +1.5 °C in the early 2030s.[91]



CMIP6 multi-model projections of global surface temperature changes for the year 2090 relative to the 1850–1900 average. The current trajectory for warming by the end of the century is roughly halfway between these two extremes.[23][88][89]

The IPCC Sixth Assessment Report (2021) included projections that by 2100 global warming is very likely to reach 1.0–1.8 °C under a scenario with very low emissions of greenhouse gases, 2.1–3.5 °C under an intermediate emissions scenario, or 3.3–5.7 °C under a very high emissions scenario.[92] The warming will continue past 2100 in the intermediate and high emission scenarios,[93][94] with future projections of global surface temperatures by year 2300 being similar to millions of years ago.[95]

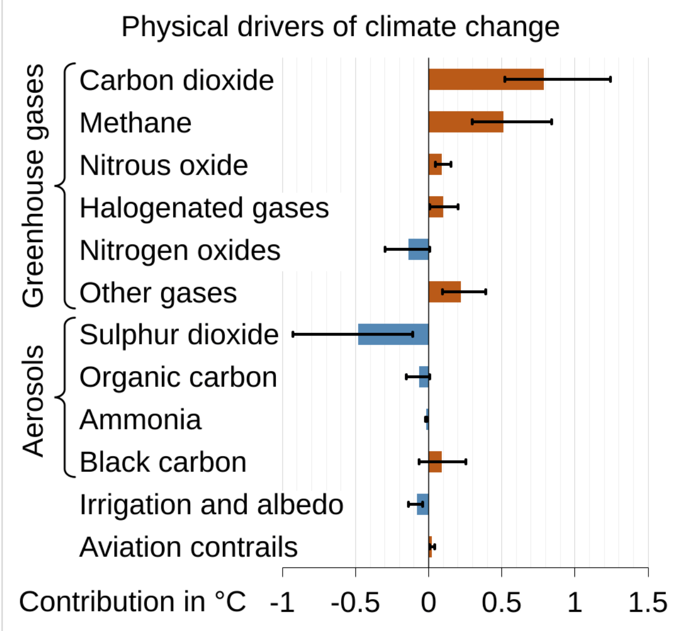
The remaining carbon budget for staying beneath certain temperature increases is determined by modelling the carbon cycle and climate sensitivity to greenhouse gases.[96] According to UNEP, global warming can be kept below 2.0 °C with a 50% chance if emissions after 2023 do not exceed 900 gigatonnes of CO_2. This carbon budget corresponds to around 16 years of current emissions.[97]

Causes of recent global temperature rise

The climate system experiences various cycles on its own which can last for years, decades or even centuries. For example, El Niño events cause short-term spikes in surface temperature while La Niña events cause short term cooling.[98] Their relative frequency can affect global temperature trends on a decadal timescale.[99]

Other changes are caused by an imbalance of energy from external forcings.[100] Examples of these include changes in the concentrations of greenhouse gases, solar luminosity, volcanic eruptions, and variations in the Earth's orbit around the Sun.[101]

To determine the human contribution to climate change, unique "fingerprints" for all potential causes are developed and compared with both observed patterns and known internal climate variability.[102] For example, solar forcing—whose fingerprint involves warming the entire atmosphere—is ruled out because only the lower atmosphere has warmed.[103] Atmospheric aerosols produce a smaller, cooling effect. Other drivers, such as changes in albedo, are less impactful.[104]

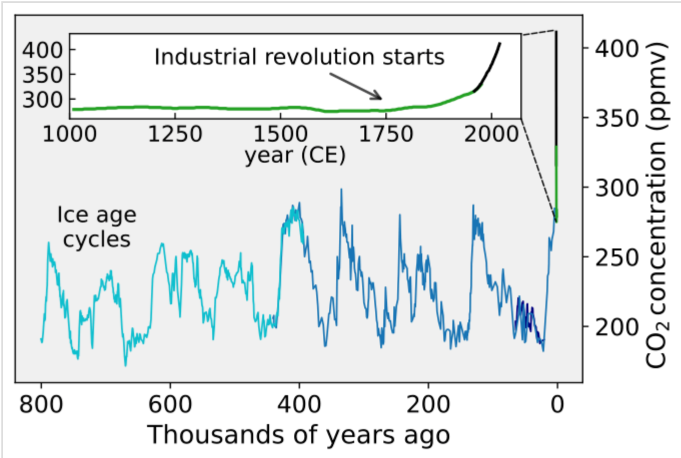


Physical drivers of global warming that has happened so far. Future global warming potential for long lived drivers like carbon dioxide emissions is not represented. Whiskers on each bar show the possible error range.

Greenhouse gases

Greenhouse gases are transparent to sunlight, and thus allow it to pass through the atmosphere to heat the Earth's surface. The Earth radiates it as heat, and greenhouse gases absorb a portion of it. This absorption slows the rate at which heat escapes into space, trapping heat near the Earth's surface and warming it over time.[105]

While water vapour (≈50%) and clouds (≈25%) are the biggest contributors to the greenhouse effect, they primarily change as a function of temperature and are therefore mostly considered to be feedbacks that change climate sensitivity. On the other hand, concentrations of gases such as CO_2 (≈20%), tropospheric ozone,[106] CFCs and nitrous oxide are added or removed independently from temperature, and are therefore considered to be external forcings that change global temperatures.[107]

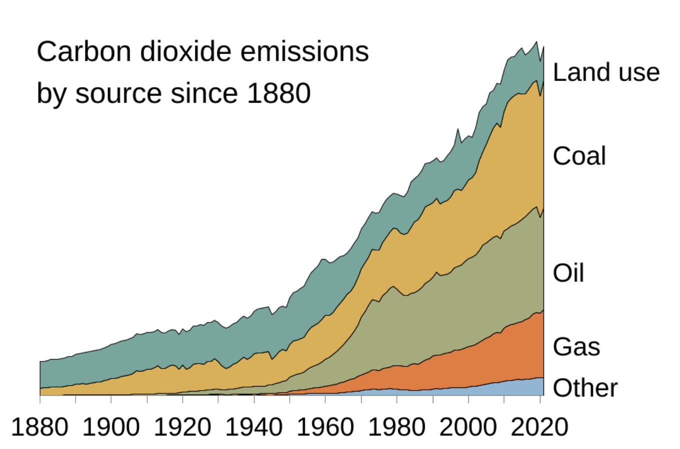


CO_2 concentrations over the last 800,000 years as measured from ice cores (blue/green) and directly (black)

Before the Industrial Revolution, naturally occurring amounts of greenhouse gases caused the air near the surface to be about 33 °C warmer than it would have been in their absence.[108][109] Human activity since the Industrial Revolution, mainly extracting and burning fossil fuels (coal, oil, and natural gas),[110] has increased the amount of greenhouse gases in the atmosphere. In 2022, the concentrations of CO_2 and methane had increased by about 50% and 164%, respectively, since 1750.[111] These CO_2 levels are higher than they have been at any time during the last 14 million years.[112] Concentrations of methane are far higher than they were over the last 800,000 years.[113]

Global human-caused greenhouse gas emissions in 2019 were equivalent to 59 billion tonnes of CO_2. Of these emissions, 75% was CO_2, 18% was methane, 4% was nitrous oxide, and 2% was fluorinated gases.[114] CO_2 emissions primarily come from burning fossil fuels to provide energy for transport, manufacturing, heating, and electricity.[5] Additional CO_2 emissions come from deforestation and industrial processes, which include the CO_2 released by the chemical reactions for making cement, steel, aluminium, and fertilizer.[115][116][117][118] Methane emissions come from livestock, manure, rice cultivation, landfills, wastewater, and coal mining, as well as oil and gas extraction.[119][120] Nitrous oxide emissions largely come from the microbial decomposition of fertilizer.[121][122]

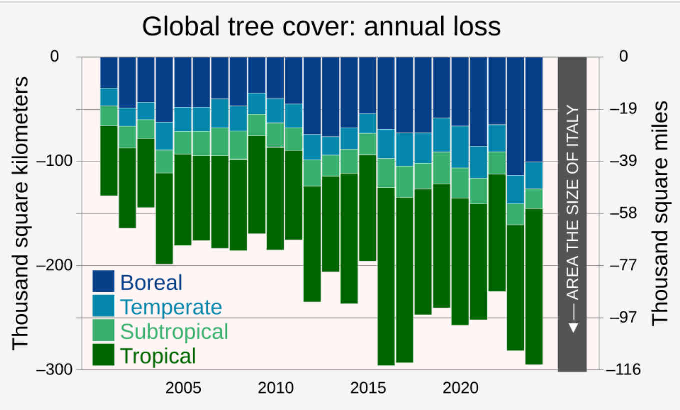
While methane only lasts in the atmosphere for an average of 12 years,[123] CO_2 lasts much longer. The Earth's surface absorbs CO_2 as part of the carbon cycle. While plants on land and in the ocean absorb most excess emissions of CO_2 every year, that CO_2 is returned to the atmosphere when biological matter is digested, burns, or decays.[124] Land-surface carbon sink processes, such as carbon fixation in the soil and photosynthesis, remove about 29% of annual global CO_2 emissions.[125] The ocean has absorbed 20 to 30% of emitted CO_2 over the last two decades.[126] CO_2 is only removed from the atmosphere for the long term when it is stored in the Earth's crust, which is a process that can take millions of years to complete.[124]



The Global Carbon Project shows how additions to CO_2 since 1880 have been caused by different sources ramping up one after another.

Land surface changes

Around 30% of Earth's land area is largely unusable for humans (glaciers, deserts, etc.), 26% is forests, 10% is shrubland and 34% is agricultural land.[128] Deforestation is the main land use change contributor to global warming,[129] as the destroyed trees release CO_2, and are not replaced by new trees, removing that carbon sink.[130] Between 2001 and 2018, 27% of deforestation was from permanent clearing to enable agricultural expansion for crops and livestock. Another 24% has been lost to temporary clearing under the shifting cultivation agricultural systems. 26% was due to logging for wood and derived products, and wildfires have accounted for the remaining 23%.[131] Some forests have not been fully cleared, but were already degraded by these impacts. Restoring these forests also recovers their potential as a carbon sink.[132]



The rate of global tree cover loss has approximately doubled since 2001, to an annual loss approaching an area the size of Italy.[127]

Local vegetation cover impacts how much of the sunlight gets reflected back into space (albedo), and how much heat is lost by evaporation. For instance, the change from a dark forest to grassland makes the surface lighter, causing it to reflect more sunlight. Deforestation can also modify the release of chemical compounds that influence clouds, and by changing wind patterns.[133] In tropic and temperate areas the net effect is to produce significant warming, and forest restoration can make local temperatures cooler.[132] At latitudes closer to the poles, there is a cooling effect as forest is replaced by snow-covered (and more reflective) plains.[133] Globally, these increases in surface albedo have been the dominant direct influence on temperature from land use change. Thus, land use change to date is estimated to have a slight cooling effect.[134]

Other factors

Aerosols and clouds

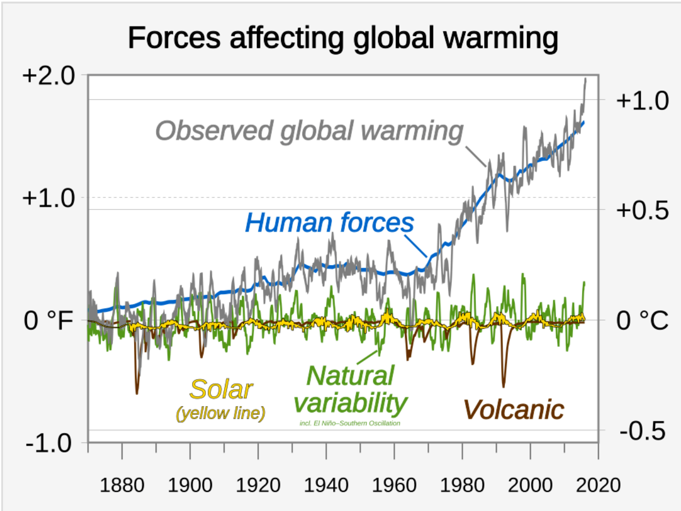
Air pollution, in the form of aerosols, affects the climate on a large scale.[135] Aerosols scatter and absorb solar radiation. From 1961 to 1990, a gradual reduction in the amount of sunlight reaching the Earth's surface was observed. This phenomenon is popularly known as *global dimming*,[136] and is primarily attributed to sulfate aerosols produced by the combustion of fossil fuels with heavy sulfur concentrations like coal and bunker fuel.[57] Smaller contributions come from black carbon (from combustion of fossil fuels and biomass), and from dust.[137][138][139] Globally, aerosols have been declining since 1990 due to pollution controls, meaning that they no longer mask greenhouse gas warming as much.[140][57]

Aerosols also have indirect effects on the Earth's energy budget. Sulfate aerosols act as cloud condensation nuclei and lead to clouds that have more and smaller cloud droplets. These clouds reflect solar radiation more efficiently than clouds with fewer and larger droplets.[141] They also reduce the growth of raindrops, which makes clouds more reflective to incoming sunlight.[142] Indirect effects of aerosols are the largest uncertainty in radiative forcing.[143]

While aerosols typically limit global warming by reflecting sunlight, black carbon in soot that falls on snow or ice can contribute to global warming. Not only does this increase the absorption of sunlight, it also increases melting and sea-level rise.[144] Limiting new black carbon deposits in the Arctic could reduce global warming by 0.2 °C by 2050.[145] The effect of decreasing sulfur content of fuel oil for ships since 2020[146] is estimated to cause an additional 0.05 °C increase in global mean temperature by 2050.[147]

Solar and volcanic activity

As the Sun is the Earth's primary energy source, changes in incoming sunlight directly affect the climate system.[143] Solar irradiance has been measured directly by satellites,[150] and indirect measurements are available from the early 1600s onwards.[143] Since 1880, there has been no upward trend in the amount of the Sun's energy reaching the Earth, in contrast to the warming of the lower atmosphere (the troposphere).[151] The upper atmosphere (the stratosphere) would also be warming if the Sun was sending more energy to Earth, but instead, it has been cooling.[103] This is consistent with greenhouse gases preventing heat from leaving the Earth's atmosphere.[152]



The Fourth National Climate Assessment ("NCA4", USGCRP, 2017) includes charts illustrating that neither solar nor volcanic activity can explain the observed warming.[148][149]

Explosive volcanic eruptions can release gases, dust and ash that partially block sunlight and reduce temperatures, or they can send water vapour into the atmosphere, which adds to greenhouse gases and increases temperatures.[153] These impacts on temperature only last for several years, because both water vapour and volcanic material have low persistence in the atmosphere.[154] volcanic CO_2 emissions are more persistent, but they are equivalent to less than 1% of current human-caused CO_2 emissions.[155] Volcanic activity still represents the single largest natural impact (forcing) on temperature in the industrial era. Yet, like the other natural forcings, it has had negligible impacts on global temperature trends since the Industrial Revolution.[154]

Climate change feedbacks

The climate system's response to an initial forcing is shaped by feedbacks, which either amplify or dampen the change. *Self-reinforcing* or *positive* feedbacks increase the response, while *balancing* or *negative* feedbacks reduce it.[157] The main reinforcing feedbacks are the water-vapour feedback, the ice–albedo feedback, and the net cloud feedback.[158][159] The primary balancing mechanism is radiative cooling, as Earth's surface gives off more heat to space in response to rising temperature.[160] In addition to temperature feedbacks, there are feedbacks in the carbon cycle, such as the fertilizing effect of CO_2 on plant growth.[161] Feedbacks are expected to trend in a positive direction as greenhouse gas emissions continue, raising climate sensitivity.[162]

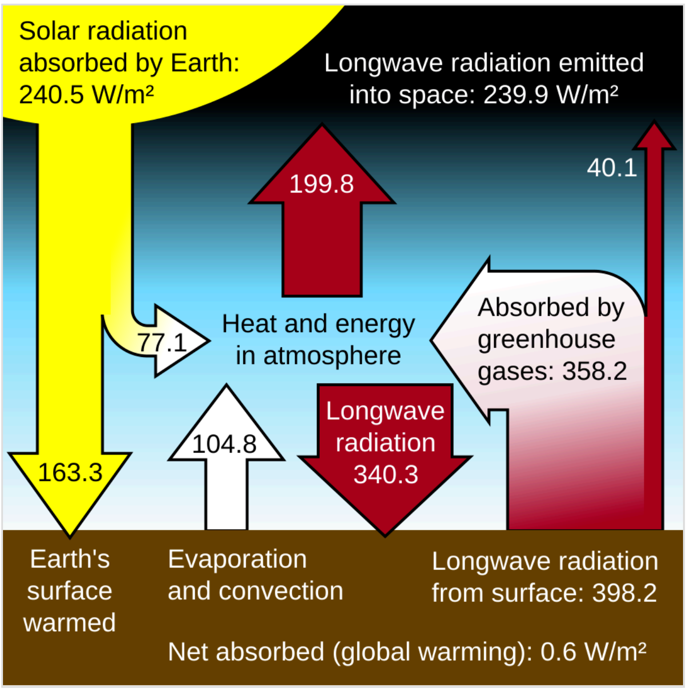
These feedback processes alter the pace of global warming. For instance, warmer air can hold more moisture in the form of water vapour, which is itself a potent greenhouse gas.[158] Warmer air can also make clouds higher and thinner, and therefore more insulating, increasing climate warming.[163] The reduction of snow cover and sea ice in the Arctic is another major feedback, this reduces the reflectivity of the Earth's surface in the region and accelerates Arctic warming.[164][165] This additional warming also contributes to permafrost thawing, which releases methane and CO_2 into the atmosphere.[166]

Sea ice reflects 50% to 70% of incoming sunlight, while the ocean, being darker, reflects only 6%. As an area of sea ice melts and exposes more ocean, more heat is absorbed by the ocean, raising temperatures that melt still more ice. This is a positive feedback process.[156]

Around half of human-caused CO_2 emissions have been absorbed by land plants and by the oceans.[167] This fraction is not static and if future CO_2 emissions decrease, the Earth will be able to absorb up to around 70%. If they increase substantially, it'll still absorb more carbon than now, but the overall fraction will decrease to below 40%.[168] This is because climate change increases droughts and heat waves that eventually inhibit plant growth on land, and soils will release more carbon from dead plants when they are warmer.[169][170] The rate at which oceans absorb atmospheric carbon will be lowered as they become more acidic and experience changes in thermohaline circulation and phytoplankton distribution.[171][172][85] Uncertainty over feedbacks, particularly cloud cover,[173] is the major reason why different climate models project different magnitudes of warming for a given amount of emissions.[174]

Modelling

A climate model is a representation of the physical, chemical and biological processes that affect the climate system.[175] Models include natural processes like changes in the Earth's orbit, historical changes in the Sun's activity, and volcanic forcing.[176] Models are used to estimate the degree of warming future emissions will cause when accounting for the strength of climate feedbacks.[177][178] Models also predict the circulation of the oceans, the annual cycle of the seasons, and the flows of carbon between the land surface and the atmosphere.[179]



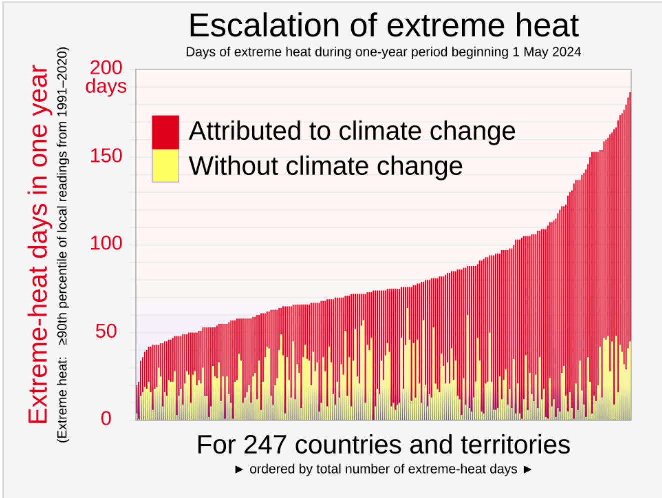
Energy flows between space, the atmosphere, and Earth's surface. Most sunlight passes through the atmosphere to heat the Earth's surface, then greenhouse gases absorb most of the heat the Earth radiates in response. Adding to greenhouse gases increases this insulating effect, causing an energy imbalance that heats the planet up.

The physical realism of models is tested by examining their ability to simulate current or past climates.[180] Past models have underestimated the rate of Arctic shrinkage[181] and underestimated the rate of precipitation increase.[182] Sea level rise since 1990 was underestimated in older models, but more recent models agree well with observations.[183] The 2017 United States-published National Climate Assessment notes that "climate models may still be underestimating or missing relevant feedback processes".[184] Additionally, climate models may be unable to adequately predict short-term regional climatic shifts.[185]

A subset of climate models add societal factors to a physical climate model. These models simulate how population, economic growth, and energy use affect—and interact with—the physical climate. With this information, these models can produce scenarios of future greenhouse gas emissions. This is then used as input for physical climate models and carbon cycle models to predict how atmospheric concentrations of greenhouse gases might change.[186][187] Depending on the socioeconomic scenario and the mitigation scenario, models produce atmospheric CO_2 concentrations that range widely between 380 and 1400 ppm.[188]

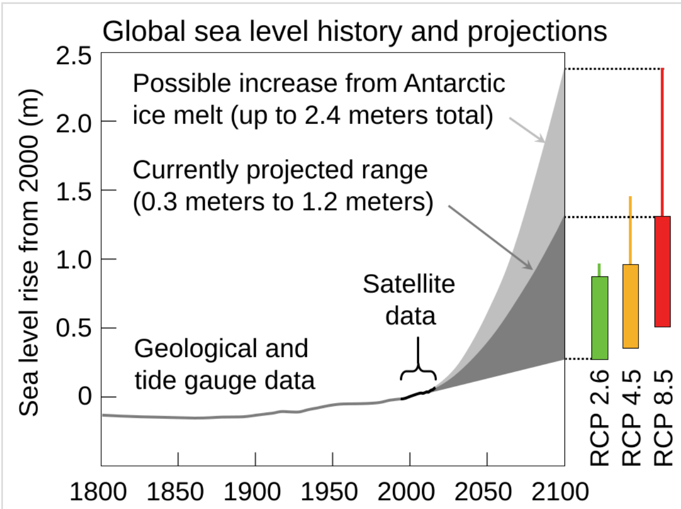
Impacts

Environmental effects



In virtually all countries and territories around the world, scientists in the field of extreme event attribution have concluded that human-caused global warming has increased the number of days of extreme heat events over long-term norms.[189]

The environmental effects of climate change are broad and far-reaching, affecting oceans, ice, and weather. Changes may occur gradually or rapidly. Evidence for these effects comes from studying climate change in the past, from modelling, and from modern observations.[190] Since the 1950s, droughts and heat waves have appeared simultaneously with increasing frequency.[191] Extremely wet or dry events within the monsoon period have increased in India and East Asia.[192] Monsoonal precipitation over the Northern Hemisphere has increased since 1980.[193] The rainfall rate and intensity of hurricanes and typhoons is likely increasing,[194] and the geographic range likely expanding poleward in response to climate warming.[195] The frequency of tropical cyclones has not increased as a result of climate change.[196]



Historical sea level reconstruction and projections up to 2100 published in 2017 by the U.S. Global Change Research Program[197]

Global sea level is rising as a consequence of thermal expansion and the melting of glaciers and ice sheets. Sea level rise has increased over time, reaching 4.8 cm per decade between 2014 and 2023.[198] Over the 21st century, the IPCC projects 32–62 cm of sea level rise under a low emission scenario, 44–76 cm under an intermediate one and 65–101 cm under a very high emission scenario.[199] Marine ice sheet instability processes in Antarctica may add substantially to these values,[200] including the possibility of a 2-meter sea level rise by 2100 under high emissions.[201]

Climate change has led to decades of shrinking and thinning of the Arctic sea ice.[202] While ice-free summers are expected to be rare at 1.5 °C degrees of warming, they are set to occur once every three to ten years at a warming level of 2 °C.[203] Higher atmospheric CO_2 concentrations cause more CO_2 to dissolve in the oceans, which is making them more acidic.[204] Because oxygen is less soluble in warmer water,[205] its concentrations in the ocean are decreasing, and dead zones are expanding.[206]