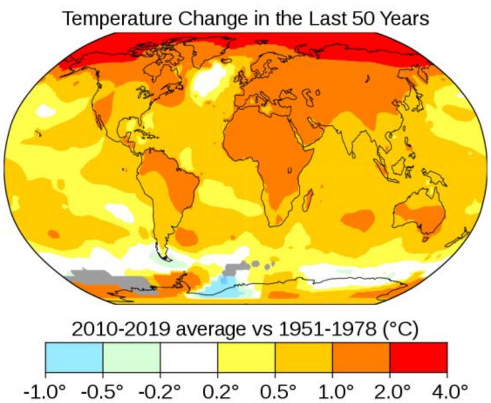
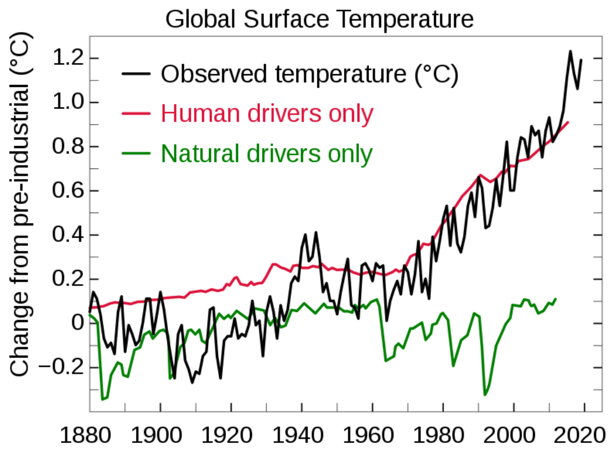
Global warming

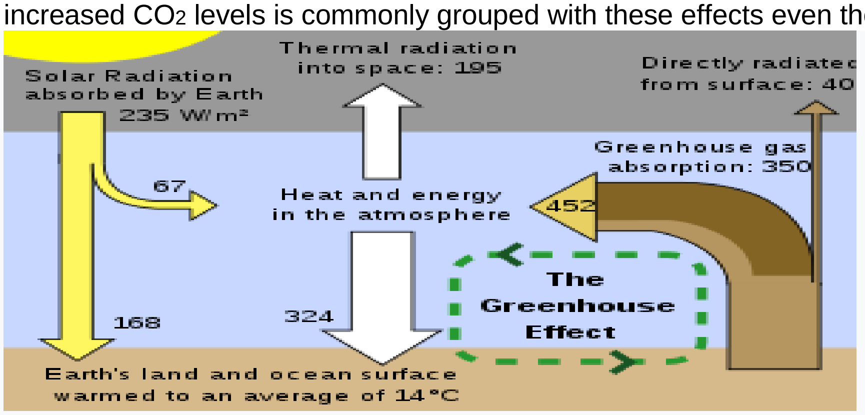
Global warming is the mainly human-caused rise of the average temperature of the Earth's climate system and has been demonstrated by direct temperature measurements and by measurements of various effects of the warming.[5] It is a major aspect of **climate change** which, in addition to rising global surface temperatures,[6] also includes its effects, such as changes in precipitation.[7] While there have been prehistoric periods of global warming,[8] observed changes since the mid-20th century have been unprecedented in rate and scale.[9]





The Intergovernmental Panel on Climate Change (IPCC) concluded that, "human influence on climate has been the dominant cause of observed warming since the mid-20th century".[10] These findings have been recognized by the national science academies of the major industrialized nations[11] and are not disputed by any scientific body of national or international standing.[12][13] The largest human influence has been the emission of greenhouse gases such as carbon dioxide, methane, and nitrous oxide. Fossil fuel burning is the principal source of these gases, with agricultural emissions and deforestation also playing significant roles.[14]

The effects of global warming include rising sea levels, regional changes in precipitation, more frequent extreme weather events such as heat waves, and expansion of deserts.[15] Surface temperature increases are greatest in the Arctic, which have contributed to the retreat of glaciers, permafrost, and sea ice. Overall, higher temperatures bring more rain and snowfall, but for some regions droughts and wildfires increase instead.[16] Climate change threatens to diminish crop yields, harming food security, and rising sea levels may flood coastal infrastructure.[17] Environmental impacts include the extinction or relocation of many species as their ecosystems change, most immediately in coral reefs, mountains, and the Arctic.[18] Some impacts, such as loss of snow cover, increased water vapour, and melting permafrost, cause feedback effects that further increase the rate of global warming.[19] Ocean acidification caused by increased CO_2 levels is commonly grouped with these effects even though it is not driven by temperature.



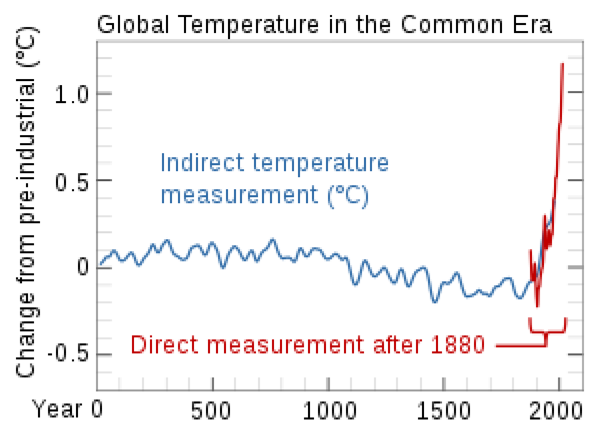
Greenhouse effect schematic showing energy flows between space, the atmosphere, and Earth's surface. Energy exchanges are expressed in watts per square meter (W/m²).

Mitigation efforts to address global warming include the development and deployment of low carbon energy technologies, policies to reduce fossil fuel emissions, reforestation, forest preservation, as well as the development of potential climate engineering technologies. Societies and governments are also working to adapt to current and future global warming impacts, including improved coastline protection, better disaster management, and the development of more resistant crops.

Countries work together on climate change under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC), which entered into force in 1994 and has near-universal membership. The ultimate goal of the convention is to "prevent dangerous anthropogenic interference with the climate system".[20] Although the parties to the UNFCCC have agreed that deep cuts in emissions are required[21] and that global warming should be limited to well below 2 °C (3.6 °F) in the Paris Agreement of 2016,[22] the Earth's average surface temperature has already increased by about half this threshold.[23] With current policies and pledges, global warming by the end of the century is expected to reach just over 2 °C to 4 °C, depending on how sensitive the climate is to emissions.[24] The IPCC has stressed the need to keep global warming below 1.5 °C compared to pre-industrial levels in order to avoid irreversible impacts.[25] At the current greenhouse gas (GHG) emission rate, the carbon budget for staying below 1.5 °C would be exhausted by 2028.[26]

Observed temperature rise

Main articles: Temperature record of the past 1000 years and Instrumental temperature record



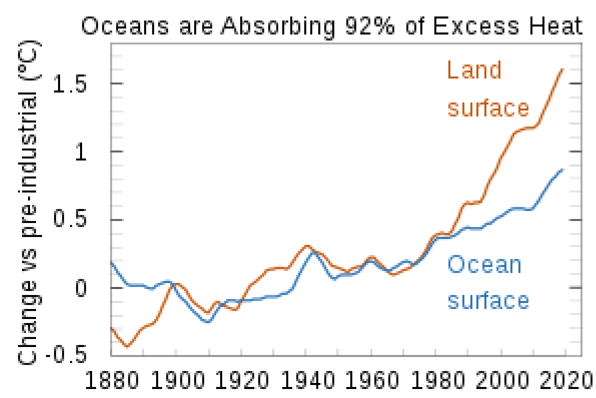
Global surface temperature reconstruction over the last millennia using proxy data from tree rings, corals, and ice cores in blue.[27] Observational data is from 1880 to 2019.[1]

Climate proxy records show that natural variations offset the early effects of the Industrial Revolution, so there was little net warming between the 18th century and the mid-19th century,[28][29] when thermometer records began to provide global coverage.[30] The Intergovernmental Panel on Climate Change (IPCC) has adopted the baseline reference period 1850–1900 as an approximation of pre-industrial global mean surface temperature.[28]

Multiple independently produced instrumental datasets confirm that the 2009–2018 decade was 0.93 ± 0.07 °C warmer than the pre-industrial baseline (1850–1900).[31] Currently, surface temperatures are rising by about 0.2 °C per decade.[32] Since 1950, the number of cold days and nights have decreased, and the number of warm days and nights have increased.[33] Historical patterns of warming and cooling, like the Medieval Climate Anomaly and the Little Ice Age, were not as synchronous as current warming, but may have reached temperatures as high as those of the late-20th century in a limited set of regions.[34] The observed rise in temperature and CO_2 concentrations have been so rapid that even abrupt geophysical events do not approach current rates.[35]

Although the most common measure of global warming is the increase in the near-surface atmospheric temperature, over 90% of the additional energy in the climate system over the last 50 years has been stored in the ocean, warming it.[36] The remainder of the additional energy has melted ice and warmed the continents and the atmosphere.[37]

The warming evident in the instrumental temperature record is consistent with a wide range of observations, documented by many independent scientific groups;[38] for example, in most continental regions the frequency and intensity of heavy precipitation has increased.[39] Further examples include sea level rise,[40] widespread melting of snow and land ice,[41] increased heat content of the oceans,[42] increased humidity,[43] and the earlier timing of spring events,[44] such as the flowering of plants.[45]



NASA data[1][2] shows that land surface temperatures have increased faster than ocean temperatures.[46]

Regional trends

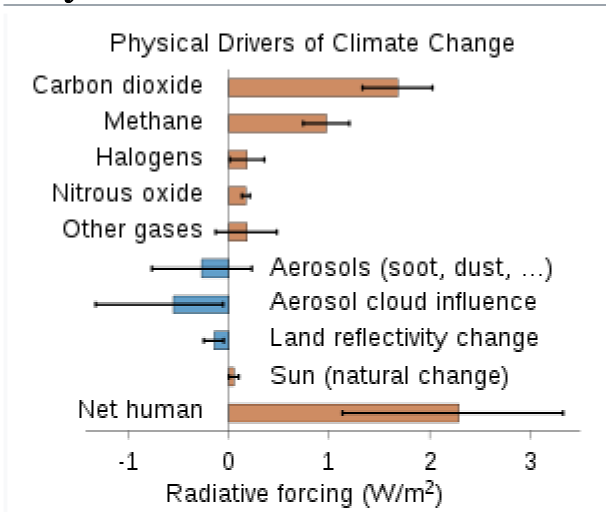
Global warming refers to global averages, with the amount of warming varying by region. Since the pre-industrial period, global average land temperatures have increased almost twice as fast as global average temperatures.[47] This is due to the larger heat capacity of oceans and because oceans lose more heat by evaporation.[48] Patterns of warming are independent of the locations of greenhouse gas emissions because the gases persist long enough to diffuse across the planet; however, localized black carbon deposits on snow and ice do contribute to Arctic warming.[49]

The Northern Hemisphere and 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 snow area and sea ice, because of how the land masses are arranged around the Arctic Ocean. As these surfaces flip from being reflective to dark after the ice has melted, they start absorbing more heat. The Southern Hemisphere already had little sea ice in summer before it started warming.[50] Arctic temperatures have increased and are predicted to continue to increase during this century at over twice the rate of the rest of the world.[51] As the temperature difference between the Arctic and the equator decreases, ocean currents that are driven by that temperature difference, like the Gulf Stream, weaken.[52]

Warmer and colder years

Although record-breaking years attract considerable media attention, individual years are less significant than the overall global surface temperature which are subject to short-term fluctuations that overlie long-term trends.[53] An example of such an episode is the slower rate of surface temperature increase from 1998 to 2012, which was described as the global warming hiatus.[54] Throughout this period, ocean heat storage continued to progress steadily upwards, and in subsequent years, surface temperatures have spiked upwards. The slower pace of warming can be attributed to a combination of natural fluctuations, reduced solar activity, and increased reflection sunlight of by particles from volcanic eruptions.[55]

Physical drivers of recent climate change



Radiative forcing of different contributors to climate change in 2011, as reported in the fifth IPCC assessment report.

Main article: Attribution of recent climate change

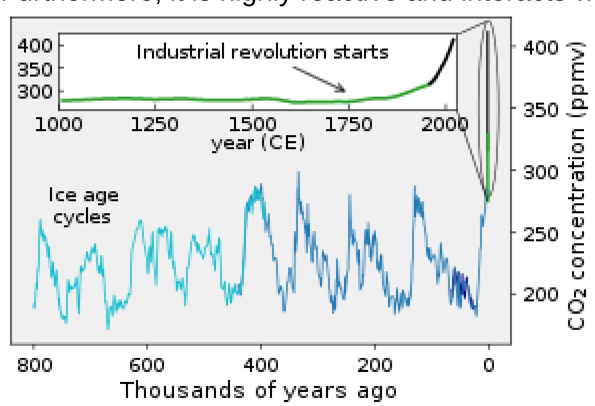
By itself, the climate system experiences various cycles which can last for years (such as the El Niño–Southern Oscillation) to decades or centuries.[56] Other changes are caused by an imbalance of energy at the top of the atmosphere: external forcings. These forcings are "external" to the climate system, but not always external to the Earth.[57] Examples of external forcings include changes in the composition of the atmosphere (e.g. increased concentrations of greenhouse gases), solar luminosity, volcanic eruptions, and variations in the Earth's orbit around the Sun.[58]

Attribution of climate change is the effort to scientifically show which mechanisms are responsible for observed changes in Earth's climate. First, known internal climate variability and natural external forcings need to be ruled out. Therefore, a key approach is to use computer modelling of the climate system to determine unique "fingerprints" for all potential causes. By comparing these fingerprints with observed patterns and evolution of climate change, and the observed history of the forcings, the causes of the observed changes can be determined.[59] For example, solar forcing can be ruled out as major cause because its fingerprint is warming in the entire atmosphere, and only the lower atmosphere has warmed as expected for greenhouse gases.[60] The major causes of current climate change are primarily greenhouse gases, and secondarily land use changes, and aerosols and soot.[61]

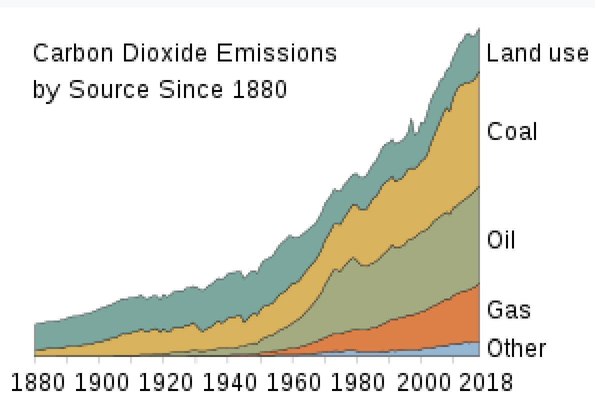
Greenhouse gases

Main articles: Greenhouse gas, Greenhouse effect, and Carbon dioxide in Earth's atmosphere

Greenhouse gases trap heat radiating from the Earth to space.[62] This heat, in the form of infrared radiation, gets absorbed and emitted by these gases in the atmosphere, thus warming the lower atmosphere and the surface. Before the Industrial Revolution, naturally occurring amounts of greenhouse gases caused the air near the surface to be warmer by about 33 °C (59 °F) than it would be in their absence.[63] Without the Earth's atmosphere, the Earth's average temperature would be well below the freezing temperature of water. [64] While water vapour (~50%) and clouds (~25%) are the biggest contributors to the greenhouse effect, they increase as a function of temperature and are there fore considered feedbacks. Increased concentrations of gases such as CO_2 (~20%),ozone and N_2O are external forcing on the other hand.[65] Ozone acts as a greenhouse gas in the lowest layer of the atmosphere, the troposphere. Furthermore, it is highly reactive and interacts with other greenhouse gases and aerosols.[66]



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



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

Human activity since the Industrial Revolution, mainly extracting and burning fossil fuels,[67] has increased the amount of greenhouse gases in the atmosphere. This CO_2, methane, tropospheric ozone, CFCs, and nitrous oxide has increased radiative forcing. As of 2011, the concentrations of CO_2 and methane had increased by about 40% and 150%, respectively, since pre-industrial times.[68] In 2013, CO_2 readings taken at the world's primary benchmark site in Mauna Loa surpassing 400 ppm for the first time.[69] These levels are much higher than at any time during the last 800,000 years, the period for which reliable data have been collected from ice cores.[70] Less direct geological evidence indicates that CO_2 values have not been this high for millions of years.[71]

Global anthropogenic greenhouse gas emissions in 2018 excluding land use change were equivalent to 52 billion tonnes of carbon dioxide. Of these emissions, 72% was carbon dioxide from fossil fuel burning and industry, 19% was from methane, 6% was from nitrous oxide, and 3% was from fluorinated gases.[72] A further 4 billion tonnes of CO_2 was released as a consquence of land use change, which is primarily due to deforestation.[73] Current patterns of land use affect global warming in a variety of ways. While some aspects cause significant GHG emissions, processes such carbon fixation in the soil and photosynthesis act as a significant carbon sink for CO_2, more than offsetting these GHG sources. The net result is an estimated removal (sink) of about 6 billion tonnes annually, or about 15% of total CO_2 emissions.[74] Using life-cycle assessment to estimate emissions relating to final consumption, the dominant sources of 2010 emissions were: food (26–30% of emissions);[75] washing, heating, and lighting (26%); personal transport and freight (20%); and building construction (15%).[76] Agriculture emissions were dominated by livestock.[77]

Land surface change

Humans change the Earth's surface mainly to create more agricultural land. Today agriculture takes up 50% of the world's habitable land, while 37% is forests,[78] and that latter figure continues to decrease,[79] largely due to continued forest loss in the tropics.[80] This deforestation is the most significant aspect of land use change affecting global warming. The main causes are: deforestation through permanent land use change for agricultural products such as beef and palm oil (27%), forestry/forest products (26%), short term agricultural cultivation (24%), and wildfires (23%).[81]

In addition to impacting greenhouse gas concentrations, land use changes affect global warming through a variety of other chemical and physical dynamics as well. Changing the type of vegetation in a region impacts the local temperature by changing how much sunlight gets reflected back into space, called *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 contribute to changing temperatures by affecting the release of aerosols and other chemical compounds that affect clouds; and by changing wind patterns when the land surface has different obstacles.[82] Globally, these effects are estimated to have led to a slight cooling, dominated by an increase in surface albedo.[83] But there is significant geographic variation in how this works. In the tropics the net effect is to produce a significant warming, while at latitudes closer to the poles a loss of albedo leads to an overall cooling effect.[82]

Aerosols and soot

Ship tracks can be seen as lines in these clouds over the Atlantic Ocean on the East Coast of the United States as an effect of aerosols.

Solid and liquid particles known as *aerosols* – from volcanoes, plankton, and human-made pollutants – reflect incoming sunlight, cooling the climate.[84] From 1961 to 1990, a gradual reduction in the amount of sunlight reaching the Earth's surface was observed, a phenomenon popularly known as *global dimming*,[85] typically attributed to aerosols from biofuel and fossil fuel burning.[86] Aerosol removal by precipitation gives tropospheric aerosols an atmospheric lifetime of only about a week, while stratospheric aerosols can remain in the atmosphere for a few years.[87] Globally, aerosols have been declining since 1990, removing some of the masking of global warming that they had been providing.[88]

In addition to their direct effect by scattering and absorbing solar radiation, aerosols have indirect effects on the Earth's radiation budget. Sulfate aerosols act as cloud condensation nuclei and thus lead to clouds that have more and smaller cloud droplets. These clouds reflect solar radiation more efficiently than clouds with fewer and larger droplets.[89] This effect also causes droplets to be of more uniform size, which reduces the growth of raindrops and makes clouds more reflective to incoming sunlight.[90] Indirect effects of aerosols are the largest uncertainty in radiative forcing.[91]

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.[92] Limiting new black carbon deposits in the Arctic could reduce global warming by 0.2 °C by 2050.[93] When soot is suspended in the atmosphere, it directly absorbs solar radiation, heating the atmosphere and cooling the surface. In areas with high soot production, such as rural India, as much as 50% of surface warming due to greenhouse gases may be masked by atmospheric brown clouds.[94]

Natural forcings

Further information: Solar activity and climate

As the Sun is the Earth's primary energy source, changes in incoming sunlight directly affect the climate system.[95] Solar irradiance has been measured directly by satellites,[96] and indirect measurements are available beginning in the early 1600s.[95] There has been no upward trend in the amount of the Sun's energy reaching the Earth, so it cannot be responsible for the current warming.[97] Physical climate models are also unable to reproduce the rapid warming observed in recent decades when taking into account only variations in solar output and volcanic activity.[98] Another line of evidence for the warming not being due to the Sun is how temperature changes differ at different levels in the Earth's atmosphere.[99] According to basic physical principles, the greenhouse effect produces warming of the lower atmosphere (the troposphere), but cooling of the upper atmosphere (the stratosphere).[100] If solar variations were responsible for the observed warming, warming of both the troposphere and the stratosphere would be expected, but that has not been the case.[60]

Climate change feedback

Main articles: Climate change feedback and Climate sensitivity

Sea ice reflects 50 to 70 percent of incoming solar radiation while the dark ocean surface only reflects 6 percent, so melting sea ice is a positive feedback.[101]

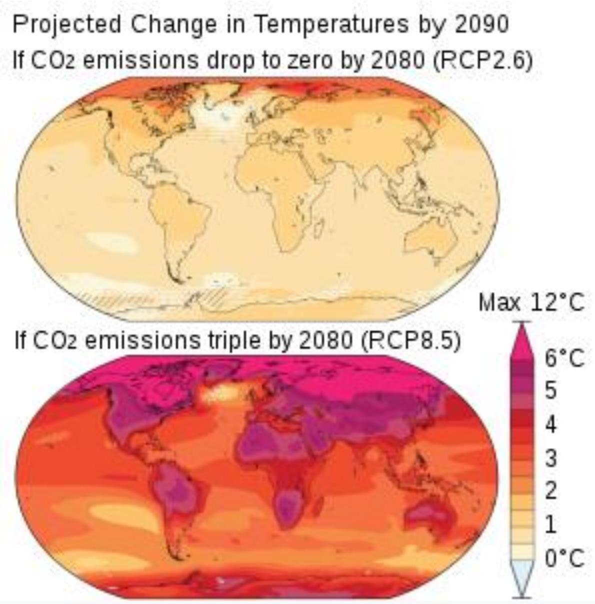
The response of the climate system to an initial forcing is increased by self-reinforcing *feedbacks* and reduced by balancing feedbacks.[102] The main balancing feedback to global temperature change is radiative cooling to space as infrared radiation, which increases strongly with increasing temperature.[103] The main reinforcing feedbacks are the water vapour feedback, the ice–albedo feedback, and probably the net effect of clouds.[19] Uncertainty over feedbacks is the major reason why different climate models project different magnitudes of warming for a given amount of emissions.[104]

As air gets warmer, it can hold more moisture. After an initial warming due to emissions of greenhouse gases, the atmosphere will hold more water. As water is a potent greenhouse gas, this further heats the climate: the *water vapour feedback*.[19] The reduction of snow cover and sea ice in the Arctic reduces the albedo of the Earth's surface.[105] More of the Sun's energy is now absorbed in these regions, contributing to Arctic amplification, which has caused Arctic temperatures to increase at more than twice the rate of the rest of the world.[106] Arctic amplification also causes methane to be released as permafrost melts, which is expected to surpass land use changes as the second strongest anthropogenic source of greenhouse gases by the end of the century.[107]

Cloud cover may change in the future. If cloud cover increases, more sunlight will be reflected back into space, cooling the planet. Simultaneously, the clouds enhance the greenhouse effect, warming the planet. The opposite is true if cloud cover decreases. It depends on the cloud type and location which process is more important. Overall, the net feedback over the industrial era has probably been self-reinforcing.[108]

Roughly half of each year's CO_2 emissions have been absorbed by plants on land and in oceans.[109] Carbon dioxide and an extended growing season have stimulated plant growth making the land carbon cycle a balancing feedback. Climate change also increases droughts and heat waves that inhibit plant growth, which makes it uncertain whether this balancing feedback will persist in the future.[110] Soils contain large quantities of carbon and may release some when they heat up.[111] As more CO_2 and heat are absorbed by the ocean, it is acidifying and ocean circulation can change, changing the rate at which the ocean can absorb atmospheric carbon.[112]

Models, projections and carbon budget



CMIP5 average of climate model projections for 2081–2100 relative to 1986–2005, under low and high emission scenarios.

A climate model is a representation of the physical, chemical, and biological processes that affect the climate system.[113] Computer models attempt to reproduce and predict the circulation of the oceans, the annual cycle of the seasons, and the flows of carbon between the land surface and the atmosphere.[114] There are more than two dozen scientific institutions that develop climate models.[115] Models not only project different future temperature with different emissions of greenhouse gases, but also do not fully agree on the strength of different feedbacks on climate sensitivity and the amount of inertia of the system.[116]

Climate models incorporate different external forcings.[117] For different greenhouse gas inputs four RCPs (Representative Concentration Pathways) are used: "a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG [greenhouse gas] emissions (RCP8.5)".[118] Models also include changes in the Earth's orbit, historical changes in the Sun's activity, and volcanic forcing.[119] RCPs only look at concentrations of greenhouse gases, factoring out uncertainty as to whether the carbon cycle will continue to remove about half of the carbon dioxide from the atmosphere each year.[120] Climate model projections summarized in the report indicated that, during the 21st century, the global surface temperature is likely to rise a further 0.3 to 1.7 °C (0.5 to 3.1 °F) in a moderate scenario, or as much as 2.6 to 4.8 °C (4.7 to 8.6 °F) in an extreme scenario, depending on the rate of future greenhouse gas emissions and on climate feedback effects.[121]

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These models are also used to estimate the remaining carbon emissions budget. According to the IPCC, global warming can be kept below 1.5 °C with a two-thirds chance if emissions after 2018 do not exceed 420 or 570 $GtCO_2$ depending on the choice of the measure of global temperature. This amount corresponds to 10 to 13 years of current emissions. There are high uncertainties about the budget in either direction.[122]

The physical realism of models is tested by examining their ability to simulate contemporary or past climates.[123] Past models have underestimated the rate of Arctic shrinkage[124] and underestimated the rate of precipitation increase.[125] Sea level rise since 1990 was underestimated in older models, but now agrees well with observations.[126] The 2017 United States-published National Climate Assessment notes that "climate models may still be underestimating or missing relevant feedback processes".[127]

A subset of climate models add societal factors to a simple 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 how greenhouse gas emissions may vary in the future. This output is then used as input for physical climate models to generate climate change projections.[128] Emissions scenarios, estimates of changes in future emission levels of greenhouse gases, depend upon uncertain economic, sociological, technological, and natural developments.[129] In some scenarios emissions continue to rise over the century, while others have reduced emissions.[130] Fossil fuel reserves are abundant, and will not limit carbon emissions in the 21st century.[131]

Emission scenarios can be combined with modelling of the carbon cycle to predict how atmospheric concentrations of greenhouse gases might change in the future.[132] According to these combined models, by 2100 the atmospheric concentration of CO_2 could be as low as 380 or as high as 1400 ppm, depending on the Shared Socioeconomic Pathway (SSP) the world takes and the mitigation scenario.[133] The 10th Emissions Gap Report issued by the United Nations Environment Programme (UNEP) predicts that if emissions continue to increase at the same rate as they have in 2010–2020, global temperatures would rise by as much as 4 °C by 2100.[134]

Effects

Main article: Effects of global warming

The primary causes[135] and the wide-ranging effects[136][137] of global warming and resulting climate change. Some effects are feedback mechanisms that intensify climate change and move it toward climate tipping points.[138]

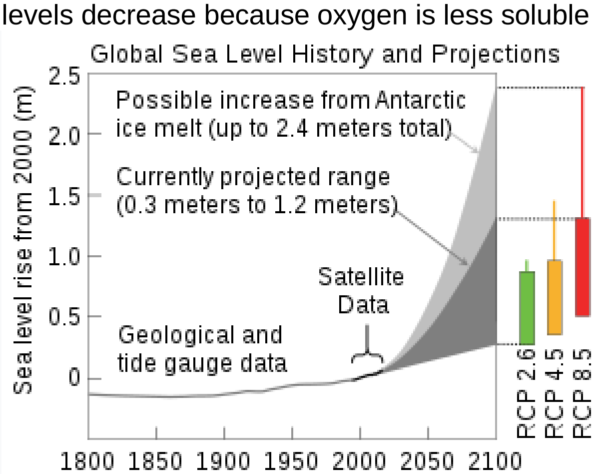
Physical environment

Main article: Physical impacts of climate change

The environmental effects of global warming are broad and far-reaching. They include effects on the oceans, ice, and weather and may occur gradually or rapidly. Evidence for these effects come from studying climate change in the past, modelling and modern observations.[139]

Between 1993 and 2017, the global mean sea level rose on average by 3.1 ± 0.3 mm per year, with an acceleration detected as well.[140] Over the 21st century, the IPCC projects that in a very high emissions scenario the sea level could rise by 61–110 cm.[141] The rate of ice loss from glaciers and ice sheets in the Antarctic is a key area of uncertainty since this source could account for 90% of the potential sea level rise:[142] increased ocean warmth is undermining and threatening to unplug Antarctic glacier outlets, potentially resulting in more rapid sea level rise.[143] The retreat of non-polar glaciers also contributes to sea level rise.[144]

Global warming has led to decades of shrinking and thinning of the Arctic sea ice, making it vulnerable to atmospheric anomalies.[145] Projections of declines in Arctic sea ice vary.[146] 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 2.0 °C,[147] increasing the ice–albedo feedback.[148] Higher atmospheric CO_2 concentrations have led to an increase in dissolved CO_2, which causes ocean acidification.[149] Furthermore, oxygen levels decrease because oxygen is less soluble in warmer water, an effect known as *ocean deoxygenation*.[150]



Historical sea level reconstruction and projections up to 2100 published in January 2017 by the U.S. Global Change Research Program.[151]

Many regions have probably already seen increases in warm spells and heat waves, and it is virtually certain that these changes will continue over the 21st century.[152] Since the 1950s, droughts and heat waves have appeared simultaneously with increasing frequency.[153] Extremely wet or dry events within the monsoon period have increased in India and East Asia.[154] Various mechanisms have been identified that might explain extreme weather in mid-latitudes from the rapidly warming Arctic, such as the jet stream becoming more erratic.[155] The maximum rainfall and wind speed from hurricanes and typhoons are likely increasing.[156]

The long-term effects of global warming include further ice melt, ocean warming, sea level rise, and ocean acidification. On the timescale of centuries to millennia, the magnitude of global warming will be determined primarily by anthropogenic CO_2 emissions.[157] This is due to carbon dioxide's very long lifetime in the atmosphere.[157] Carbon dioxide is slowly taking up by the ocean, such that ocean acification will continue for hundrends to thousands of years.[158] The emissions are estimated to have prolonged the current interglacial period by at least 100,000 years.[159] Because the great mass of glaciers and ice caps depressed the Earth's crust, another long-term effect of ice melt and deglaciation is the gradual rising of landmasses, a process called *post-glacial rebound*.[160] Sea level rise will continue over many centuries, with an estimated rise of 2.3 metres per degree Celsius (4.2 ft/°F) after 2000 years.[161]

If global warming exceeds 1.5 °C, there is a greater risk of passing through 'tipping points', thresholds beyond which certain impacts can no longer be avoided even if temperatures are reduced.[162] Some large-scale changes could occur abruptly, i.e. over a short time period.. One potential source of abrupt tipping would be the rapid release of methane and carbon dioxide from permafrost, which would amplify global warming.[163] Another example is the possibility for the Atlantic Meridional Overturning Circulation to slow or shut down,[164] which could trigger cooling in the North Atlantic, Europe, and North America.[165] If multiple temperature and carbon cycle tipping points re-inforce each other, or if there were to be a strong tipping points in cloud cover, there could be a global tipping into a hothouse Earth.[166] A 2018 study tried to identify such a planetary threshold for self-reinforcing feedbacks and found that even a 2 °C (3.6 °F) increase in temperature over pre-industrial levels may be enough to trigger such a hothouse Earth scenario.[167]

Biosphere

Main article: Climate change and ecosystems

In terrestrial ecosystems, the earlier arrival of spring, as well as poleward and upward shifts in plant and animal ranges, have been linked with high confidence to recent warming.[168] It is expected that most ecosystems will be affected by higher atmospheric CO_2 levels and higher global temperatures.[169] Global warming has contributed to the expansion of drier climatic zones, such as, probably, the expansion of deserts in the subtropics.[170] Without substantial actions to reduce the rate of global warming, land-based ecosystems risk major shifts in their composition and structure.[171] Overall, it is expected that climate change will result in the extinction of many species and reduced diversity of ecosystems.[172] Rising temperatures push bees to their physiological limits, and could cause the extinction of their populations.[173]

The ocean has heated more slowly than the land, but plants and animals in the ocean have migrated towards the colder poles as fast as or faster than species on land.[174] Just as on land, heat waves in the ocean occur more due to climate change, with harmful effects found on a wide range of organisms such as corals, kelp, and seabirds.[175] Ocean acidification threatens damage to coral reefs, fisheries, protected species, and other natural resources of value to society.[176] Higher oceanic CO_2 may affect the brain and central nervous system of certain fish species, which reduces their ability to hear, smell, and evade predators.[177]

Humans

A helicopter drops water on a wildfire in California. Drought and higher temperatures linked to climate change are driving a trend towards larger fires.[178]

Further information: Effects of global warming on human health, Climate security, Economics of global warming, and Climate change and agriculture

The effects of climate change on human systems, mostly due to warming and shifts in precipitation, have been detected worldwide. The social impacts of climate change will be uneven across the world.[179] All regions are at risk of experiencing negative impacts,[180] with low-latitude, less developed areas facing the greatest risk.[181] Global warming has likely already increased global economic inequality, and is projected to do so in the future.[182] Regional impacts of climate change are now observable on all continents and across ocean regions.[183] The Arctic, Africa, small islands, and Asian megadeltas are regions that are likely to be especially affected by future climate change.[184] Many risks increase with higher magnitudes of global warming.[185]

Food and water

Crop production will probably be negatively affected in low-latitude countries, while effects at northern latitudes may be positive or negative.[186] Global warming of around 4 °C relative to late 20th century levels could pose a large risk to global and regional food security.[187] The impact of climate change on crop productivity for the four major crops was negative for wheat and maize, and neutral for soy and rice, in the years 1960–2013.[188] Up to an additional 183 million people worldwide, particularly those with lower incomes, are at risk of hunger as a consequence of warming.[189] While increased CO_2 levels help crop growth at lower temperature increases, those crops do become less nutritious.[189] Based on local and indigenous knowledge, climate change is already affecting food security in mountain regions in South America and Asia, and in various drylands, particularly in Africa.[189] Regions dependent on glacier water, regions that are already dry, and small islands are also at increased risk of water stress due to climate change.[190]

Health and security

Aerial view over southern Bangladesh after the passage of Cyclone Sidr. The combination of rising sea levels and increased rainfall from cyclones makes countries more vulnerable to floods.[191]

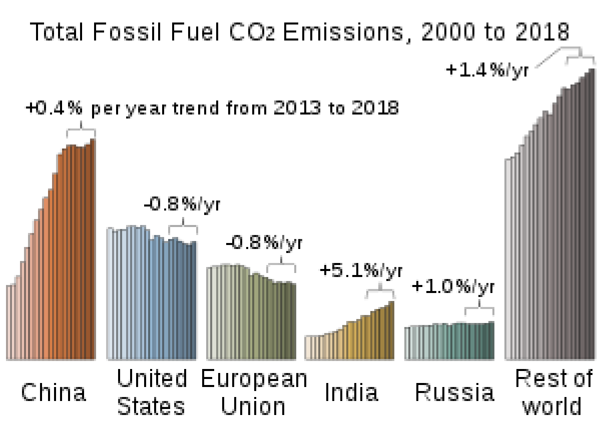
Generally, impacts on public health will be more negative than positive.[192] Impacts include the direct effects of extreme weather, leading to injury and loss of life;[193] and indirect effects, such as undernutrition brought on by crop failures.[194] Various infectuous diseases are more easily transmitted in a warming climate, such as dengue fever, which affects children most severely, and malaria.[195] Young children are further the most vulnerable to food shortages, and together with older people to extreme heat.[196] Temperature rise has been connected to increased numbers of suicides.[197] Climate change has been linked to an increase in violent conflict by amplifying poverty and economic shocks, which are well-documented drivers of these conflicts.[198] Links have been made between a wide range of violent behaviour including fist fights, violent crimes, civil unrest, and wars.[199]

Livelihoods, industry, and infrastructure

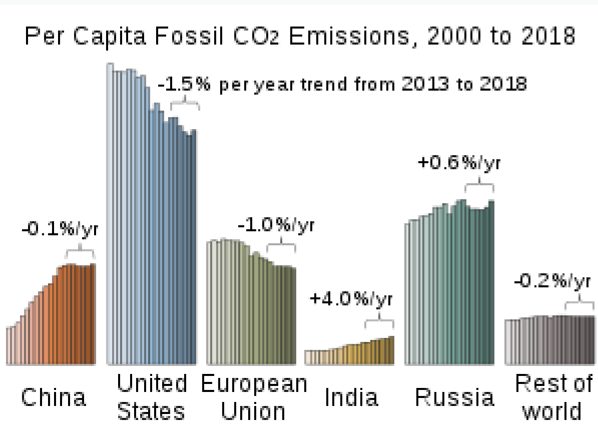
In small islands and mega deltas, inundation from sea level rise is expected to threaten vital infrastructure and human settlements.[200] This could lead to homelessness in countries with low-lying areas such as Bangladesh, as well as statelessness for populations in island nations, such as the Maldives and Tuvalu.[201] Climate change can be an important driver of migration, both within and between countries.[202]

The majority of severe impacts of climate change are expected in sub-Saharan Africa and South-East Asia, where existing poverty is exacerbated.[203] Current inequalities between men and women, between rich and poor and between people of different ethnicity have been observed to worsen as a consequence of climate variability and climate change.[204] Existing stresses include poverty, political conflicts, and ecosystem degradation. Regions may even become uninhabitable, with humidity and temperatures reaching levels too high for humans to survive.[205] In June 2019, U.N. special rapporteur Philip Alston indicated that global warming could "push more than 120 million more people into poverty by 2030 and will have the most severe impact in poor countries, regions, and the places poor people live and work".[206]

Responses



Since 2000, rising CO_2 emissions in China and the rest of world have eclipsed the output of the United States and Europe.[207]



Per person, the United States generates carbon dioxide at a far faster rate than other primary regions.[208]

Mitigation of and adaptation to climate change are two complementary responses to global warming. Successful adaptation is easier if there are substantial emission reductions. Many of the countries that have contributed least to global greenhouse gas emissions are among the most vulnerable to climate change, which raises questions about justice and fairness with regard to mitigation and adaptation.[209]

Mitigation

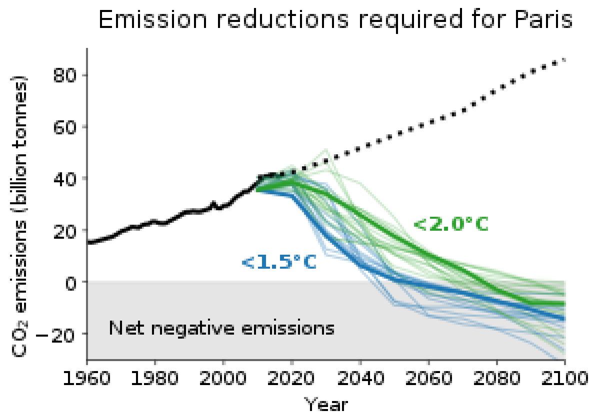
Main article: Climate change mitigation

Climate change can be mitigated through the reduction of greenhouse gas emissions or the enhancement of the capacity of carbon sinks to absorb greenhouse gases from the atmosphere.[210] Near- and long-term trends in the global energy system are inconsistent with limiting global warming to below 1.5 or 2 °C relative to pre-industrial levels.[211] Pledges made as part of the Paris Agreement would lead to about 3 °C of warming at the end of the 21st century, relative to pre-industrial levels.[212] To keep warming under 1.5 °C, a far-reaching system change on an unprecedented scale is necessary in energy, land, cities, transport, buildings, and industry.[213] Over the last three decades of the twentieth century, gross domestic product per capita and population growth were the main drivers of increases in greenhouse gas emissions.[214] CO_2 emissions are continuing to rise due to the burning of fossil fuels and land-use change.[215]

Technology

Low-carbon energy technologies such as solar energy, wind energy have seen substantial progress over the last few years, but nuclear energy, and carbon capture and storage have not improved similarly.[216] Renewables are currently the cheapest source of new power generation[217] but require energy storage for a continuous supply. Another approach is the installation of wide-area super grids in order to minimize local fluctuations of wind and solar energy.[218] In addition to the expansion of renewable energy, decarbonisation in the energy sector also requires electrification and building a smarter and more flexible energy grid.[219] The use of bioenergy may bring negative consequences for food security.[220] Further measures in the energy sector include energy conservation and increased energy efficiency and decarbonizing buildings and transport.[221]

On land, emissions reductions can be achieved by preventing deforestation and preventing food waste. Furthermore, certain carbon sink can be enhanced, for example, reforestation.[222] Soils can sequester large quantities of CO_2 and as such better soil management in croplands and grassland is an effective mitigation technology.[223] Many 1.5 °C and 2 °C mitigation scenarios depend heavily on negative emission technologies. However, these technologies are typically not yet mature and may be too expensive for large scale deployment.[224]



The graph shows multiple pathways to limit climate change to 1.5 °C or 2 °C. All pathways include negative emission technologies such as afforestation and bio-energy with carbon capture and storage.

Policies and measures

It has been suggested that the most effective and comprehensive policy to reduce carbon emissions is a carbon tax[225] or the closely related emissions trading.[226] Alternative effective policies include a moratorium on burning coal and a phase-out of energy subsidies which promote fossil fuel use,[227] redirecting some to support the transition to clean energy.[228] The development and scaling-up of clean technology, such as cement that produces less CO_2,[229] is critical to achieve sufficient emission reductions for the Paris agreement goals.[230] Individual action on climate change to reduce a person's carbon footprint include: limiting overconsumption,[231] living car-free,[232] forgoing air travel[233] and adopting a plant-based diet.[234] Co-benefits of climate change mitigation may help society and individuals more quickly.[235] For example, policies to reduce greenhouse gas emissions often also limit air pollution, improving public health.[236]

Adaptation

Main article: Climate change adaptation

Climate change adaptation is "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities".[237] While some adaptation responses call for trade-offs, others bring synergies and co-benefits.[238] Examples of adaptation are improved coastline protection, better disaster management, and the development of more resistant crops.[239] Increased use of air conditioning allows people to better cope with heat, but also increases energy demand.[240] The adaptation may be planned, either in reaction to or anticipation of global warming, or spontaneous, i.e. without government intervention.[241] Adaptation is especially important in developing countries since they are predicted to bear the brunt of the effects of global warming.[242] The capacity and potential for humans to adapt, called *adaptive capacity*, is unevenly distributed across different regions and populations, and developing countries generally have less capacity to adapt.[243] The public sector, private sector, and communities are all gaining experience with adaptation, and adaptation is becoming embedded within certain planning processes.[244]

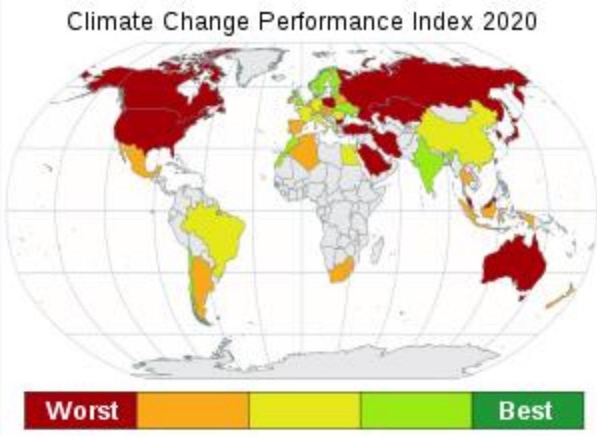
Climate engineering

Main article: Climate engineering

Geoengineering or climate engineering is the deliberate large-scale modification of the climate to counteract climate change.[245] Techniques fall generally into the categories of solar radiation management and carbon dioxide removal, although various other schemes have been suggested. A study from 2014 investigated the most common climate engineering methods and concluded that they are either ineffective or have potentially severe side effects and cannot be stopped without causing rapid climate change.[246]

Society and culture

Political response



The Climate Change Performance Index ranks countries by greenhouse gas emissions (40% of score), renewable energy (20%), energy use (20%), and climate policy (20%).

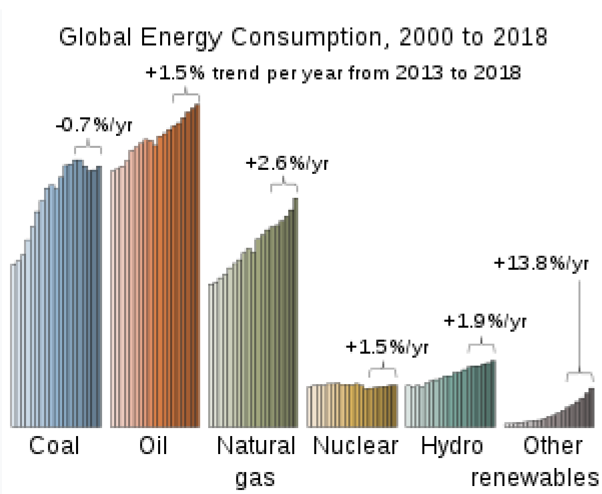
Main article: Politics of global warming

The geopolitics of climate change is complex and was often framed as a prisoners' dilemma, in which all countries benefit from mitigation done by other countries, but individual countries would lose from investing in a transition to a low-carbon economy themselves. Net importers of fossil fuels win economically from transitioning, and net exporters face stranded assets: fossil fuels they cannot sell.[247] Furthermore, the benefits to individual countries in terms of public health and local environmental improvents of coal phase out exceed the costs, potentially eliminating the free-rider problem.[248] The geopolitics may be further complicated by the supply chain of rare earth metals, which are necessary to produce clean technology.[249]

UN Framework Convention

As of 2020 nearly all countries in the world are parties to the United Nations Framework Convention on Climate Change (UNFCCC).[250] The objective of the Convention is to prevent dangerous human interference with the climate system.[251] As stated in the Convention, this requires that greenhouse gas concentrations are stabilized in the atmosphere at a level where ecosystems can adapt naturally to climate change, food production is not threatened, and economic development can be sustained.[252] The Framework Convention was agreed on in 1992, but global emissions have risen since then.[14] Its yearly conferences are the stage of global negotiations.[253]

This mandate was sustained in the 1997 Kyoto Protocol to the Framework Convention.[254] In ratifying the Kyoto Protocol, most developed countries accepted legally binding commitments to limit their emissions. These first-round commitments expired in 2012.[255] United States President George W. Bush rejected the treaty on the basis that "it exempts 80% of the world, including major population centres such as China and India, from compliance, and would cause serious harm to the US economy".[256] During these negotiations, the G77 (a lobbying group in the United Nations representing developing countries)[257] pushed for a mandate requiring developed countries to "[take] the lead" in reducing their emissions.[258] This was justified on the basis that the developed countries' emissions had contributed most to the accumulation of greenhouse gases in the atmosphere, per-capita emissions were still relatively low in developing countries, and the emissions of developing countries would grow to meet their development needs.[259]



Coal, oil, and natural gas remain the primary global energy sources even as renewables have begun rapidly increasing.[260]

In 2009 several UNFCCC Parties produced the Copenhagen Accord,[261] which has been widely portrayed as disappointing because of its low goals, leading poorer nations to reject it.[262] Nations associated with the Accord aimed to limit the future increase in global mean temperature to below 2 °C.[263] In 2015 all UN countries negotiated the Paris Agreement, which aims to keep climate change well below 2 °C. The agreement replaced the Kyoto Protocol. Unlike Kyoto, no binding emission targets are set in the Paris Agreement. Instead, the procedure of regularly setting ever more ambitious goals and reevaluating these goals every five years has been made binding.[264] The Paris Agreement reiterated that developing countries must be financially supported.[265] As of November 2019, 194 states and the European Union have signed the treaty and 186 states and the EU have ratified or acceded to the agreement.[266] In November 2019 the Trump administration notified the UN that it would withdraw the United States from the Paris Agreement in 2020.[267]

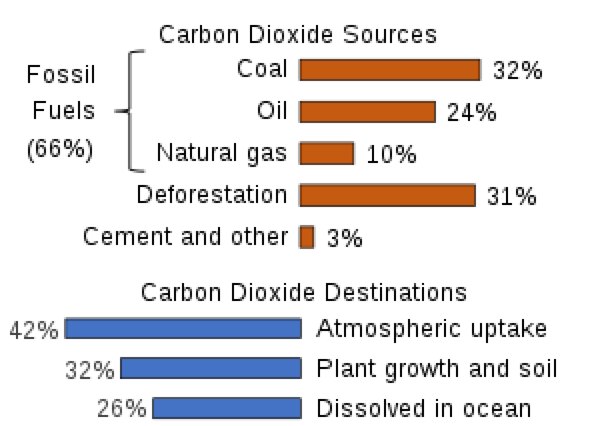
Other policy

In 2019, the British Parliament became the first national government in the world to officially declare a climate emergency.[268] Other countries and jurisdictions followed.[269] In November 2019 the European Parliament declared a "climate and environmental emergency",[270] and the European Commission presented its European Green Deal with which they hope to make the EU carbon-neutral in 2050.[271]

While the ozone layer and climate change are considered separate problems, the solution to the former has significantly mitigated global warming. The estimated mitigation of the Montreal Protocol, an international agreement to stop emitting ozone-depleting gases, is estimated to have been more effective than the Kyoto Protocol, which was specifically designed to curb greenhouse gas emissions.[272] It has been argued that the Montreal Protocol, may have done more than any other measure, as of 2017, to mitigate climate change as those substances were also powerful greenhouse gases.[273]

Scientific consensus

Main article: Scientific consensus on climate change



While there is little debate that excess carbon dioxide in the industrial era has mostly come from burning fossil fuels, the future effect of land and ocean carbon sinks is an area of study.[274]

In the scientific literature, there is an overwhelming consensus that global surface temperatures have increased in recent decades and that the trend is caused mainly by human-induced emissions of greenhouse gases.[275] No scientific body of national or international standing disagrees with this view.[276] Scientific discussion takes place in journal articles that are peer-reviewed, which scientists subject to assessment every couple of years in the Intergovernmental Panel on Climate Change reports.[277] The scientific consensus as of 2013, as stated in the IPCC Fifth Assessment Report, is that it "is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century".[278]

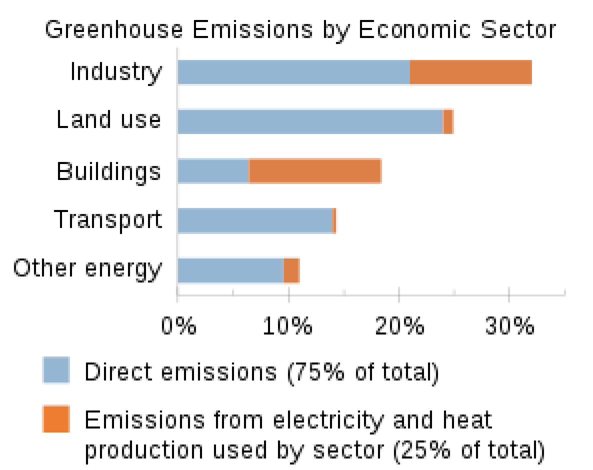
National science academies have called on world leaders to cut global emissions.[279] In November 2017, a second warning to humanity signed by 15,364 scientists from 184 countries stated that "the current trajectory of potentially catastrophic climate change due to rising greenhouse gases from burning fossil fuels, deforestation, and agricultural production – particularly from farming ruminants for meat consumption" is "especially troubling".[280] In 2018 the IPCC published a Special Report on Global Warming of 1.5 °C which warned that, if the current rate of greenhouse gas emissions is not mitigated, global warming is likely to reach 1.5 °C (2.7 °F) between 2030 and 2052, risking major crises. The report said that preventing such crises will require a swift transformation of the global economy that has "no documented historic precedent".[281] In 2019, a group of more than 11,000 scientists from 153 countries named climate change an "emergency" that would lead to "untold human suffering" if no big shifts in action takes place.[282] The emergency declaration emphasized that economic growth and population growth "are among the most important drivers of increases in CO_2 emissions from fossil fuel combustion" and that "we need bold and drastic transformations regarding economic and population policies".[283]

Public opinion and disputes

Further information: Public opinion on climate change and Media coverage of climate change

The global warming problem came to international public attention in the late 1980s.[284] Significant regional differences exist in how concerned people are about climate change and how much they understand the issue.[285] In 2010, just a little over half the US population viewed it as a serious concern for either themselves or their families, while 73% of people in Latin America and 74% in developed Asia felt this way.[286] Similarly, in 2015 a median of 54% of respondents considered it "a very serious problem", but Americans and Chinese (whose economies are responsible for the greatest annual CO_2 emissions) were among the least concerned.[285] Worldwide in 2011, people were more likely to attribute global warming to human activities than to natural causes, except in the US where nearly half of the population attributed global warming to natural causes.[287] Public reactions to global warming and concern about its effects have been increasing, with many perceiving it as the worst global threat.[288] In a 2019 CBS poll, 64% of the US population said that climate change is a "crisis" or a "serious problem", with 44% saying human activity was a significant contributor.[289]

Due to confusing media coverage in the early 1990s, issues such as ozone depletion and climate change were often mixed up, affecting public understanding of these issues.[290] Although there are a few areas of linkage, the relationship between the two is weak.[291]



Economic sectors with more greenhouse gas contributions have a greater stake in climate change policies.

Controversy

See also: Fossil fuels lobby and climate change denial

From about 1990 onward, American conservative think tanks had begun challenging the legitimacy of global warming as a social problem. They challenged the scientific evidence, argued that global warming would have benefits, warned that concern for global warming was some kind of socialist plot to undermine American capitalism,[292] and asserted that proposed solutions would do more harm than good.[293] Organizations such as the libertarian Competitive Enterprise Institute, as well as conservative commentators, have challenged IPCC climate change scenarios, funded scientists who disagree with the scientific consensus, and provided their own projections of the economic cost of stricter controls.[294]

Global warming has been the subject of controversy, substantially more pronounced in the popular media than in the scientific literature,[295] with disputes regarding the nature, causes, and consequences of global warming. The disputed issues include the causes of increased global average air temperature, especially since the mid-20th century, whether this warming trend is unprecedented or within normal climatic variations, whether humankind has contributed significantly to it, and whether the increase is completely or partially an artifact of poor measurements. Additional disputes concern estimates of climate sensitivity, predictions of additional warming, what the consequences of global warming will be, and what to do about it.[296] One suggestion is that the best individual actions include having fewer children[297] but some disagree with encouraging people to stop having children, saying that children "embody a profound hope for the future", and that more emphasis should be placed on lifestyle choices of the world's wealthy, fossil fuel companies, and government inaction.[298]

In the 20th century and early 2000s some companies, such as ExxonMobil, challenged IPCC climate change scenarios, funded scientists who disagreed with the scientific consensus, and provided their own projections of the economic cost of stricter controls.[299] In general, since the 2010s, global oil companies do not dispute that climate change exists and is caused by the burning of fossil fuels.[300] As of 2019, however, some are lobbying against a carbon tax and plan to increase production of oil and gas,[301] but others are in favour of a carbon tax in exchange for immunity from lawsuits which seek climate change compensation.[302]

September 2019 climate strike in Sydney, Australia

Protest and litigation

Main article: climate movement

Protests seeking more ambitious climate action have increased in the 2010s in the form of fossil fuel divestment,[303] worldwide demonstrations,[304] and a school strike for climate.[305] Mass civil disobedience actions by Extinction Rebellion and Ende Gelände have ended in police intervention and large-scale arrests.[306] Litigation is increasingly used as a tool to strengthen climate action, with governments being the biggest target of lawsuits demanding that they become ambitious on climate action or enforce existing laws. Cases against fossil-fuel companies, from activists, shareholders and investors, generally seek compensation for loss and damage.[307]