Climatic Change

Climate change includes both **global warming** driven by human-induced emissions of greenhouse gases and the resulting large-scale shifts in weather patterns. Though there have been previous periods of climatic change, since the mid-20th century humans have had an unprecedented impact on Earth's climate system and caused change on a global scale. The largest driver of warming is the emission of gases that create a greenhouse effect, of which more than 90% are carbon dioxide (CO_2) and methane. Fossil fuel burning (coal, oil, and natural gas) for energy consumption is the main source of these emissions, with additional contributions from agriculture, deforestation, and manufacturing. The human cause of climate change is not disputed by any scientific body of national or international standing. Temperature rise is accelerated or tempered by climate feedbacks, such as loss of sunlight-reflecting snow and ice cover, increased water vapour (a greenhouse gas itself), and changes to land and ocean carbon sinks. Temperature rise on land is about twice the global average increase, leading to desert expansion and more common heat waves and wildfires. Temperature rise is also amplified in the Arctic, where it has contributed to melting permafrost, glacial retreat and sea ice loss. Warmer temperatures are increasing rates of evaporation, causing more intense storms and weather extremes. Impacts on ecosystems include the relocation or extinction of many species as their environment changes, most immediately in coral reefs, mountains, and the Arctic. Climate change threatens people with food insecurity, water scarcity, flooding, infectious diseases, extreme heat, economic losses, and displacement. These impacts have led the World Health Organization to call climate change the greatest threat to global health in the 21st century. Even if efforts to minimise future warming are successful, some effects will continue for centuries, including rising sea levels, rising ocean temperatures, and ocean acidification.

Many of these impacts are already felt at the current level of warming, which is about 1.2 °C (2.2 °F). The Intergovernmental Panel on Climate Change (IPCC) has issued a series of reports that project significant increases in these impacts as warming continues to 1.5 °C (2.7 °F) and beyond. Additional warming also increases the risk of triggering critical thresholds called tipping points. Responding to climate change involves mitigation and adaptation. Mitigation – limiting climate change – consists of reducing greenhouse gas emissions and removing them from the atmosphere; methods include the development and deployment of low-carbon energy sources such as wind and solar, a phase-out of coal, enhanced energy efficiency, reforestation, and forest preservation. Adaptation consists of adjusting to actual or expected climate, such as through improved coastline protection, better disaster management, assisted colonisation, and the development of more resistant crops. Adaptation alone cannot avert the risk of "severe, widespread and irreversible" impacts. Under the 2015 Paris Agreement, nations collectively agreed to keep warming "well under 2.0 °C (3.6 °F)" through mitigation efforts. 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. Limiting warming to 1.5 °C (2.7 °F) would require halving emissions by 2030 and achieving near-zero emissions by 2050.

Terminology

Before the 1980s, when it was unclear whether warming by greenhouse gases would dominate aerosol-induced cooling, scientists often used the term *inadvertent climate modification* to refer to humankind's impact on the climate. In the 1980s, the terms *global* *warming* and *climate change* were popularised, the former referring only to increased surface warming, while the latter describes the full effect of greenhouse gases on the climate. Global warming usually refers to human-induced warming of the Earth system, whereas climate change can refer to natural as well as anthropogenic change. The two terms are often used interchangeably. Various scientists, politicians and media figures have adopted the terms *climate crisis* or *climate emergency* to talk about climate change, while using *global heating* instead of global warming.

Observed temperature rise

Evidence of warming from air temperature measurements are reinforced with a wide range of other observations. There has been an increase in the frequency and intensity of heavy precipitation, melting of snow and land ice, and increased atmospheric humidity. Flora and fauna are also behaving in a manner consistent with warming; for instance, plants are flowering earlier in spring. Another key indicator is the cooling of the upper atmosphere, which demonstrates that greenhouse gases are trapping heat near the Earth's surface and preventing it from radiating into space. While locations of warming vary, the patterns are independent of where greenhouse gases are emitted, because the gases persist long enough to diffuse across the planet. Since the pre-industrial period, global average land temperatures have increased almost twice as fast as global average surface temperatures. This is because of the larger heat capacity of oceans, and because oceans lose more heat by evaporation. Over 90% of the additional energy in the climate system over the last 50 years has been stored in the ocean, with the remainder warming the atmosphere, melting ice, and warming the continents. 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, because of how the land masses are arranged around the Arctic Ocean. As these surfaces flip from reflecting a lot of light to being dark after the ice has melted, they start absorbing more heat. Localised black carbon deposits on snow and ice also contribute to Arctic warming. 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. Melting of glaciers and ice sheets in the Arctic disrupts ocean circulation, including a weakened Gulf Stream, further changing the climate.

Drivers of recent temperature rise

The climate system experiences various cycles on its own which can last for years (such as the El Niño–Southern Oscillation), decades or even centuries. Other changes are caused by an imbalance of energy that is "external" to the climate system, but not always external to the Earth. 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. To determine the human contribution to climate change, known internal climate variability and natural external forcings need to be ruled out. A key approach is to determine unique "fingerprints" for all potential causes, then compare these fingerprints with observed patterns of climate change. For example, solar forcing can be ruled out as a major cause because its fingerprint is warming in the entire atmosphere, and only the lower atmosphere has warmed, as expected from greenhouse gases (which trap heat energy radiating from the surface). Attribution of recent climate change shows that the primary driver is elevated greenhouse gases, but that aerosols also have a strong effect.

Greenhouse gases

The Earth absorbs sunlight, then radiates it as heat. Greenhouse gases in the atmosphere absorb and reemit infrared radiation, slowing the rate at which it can pass through the atmosphere and escape into space. Before the Industrial Revolution, naturally-occurring amounts of greenhouse gases caused the air near the surface to be about 33 °C (59 °F) warmer than it would have been in their absence. While water vapour (~50%) and clouds (~25%) are the biggest contributors to the greenhouse effect, they increase as a function of temperature and are therefore considered feedbacks. On the other hand, concentrations of gases such as CO_2 (~20%), tropospheric ozone, CFCs and nitrous oxide are not temperature-dependent, and are therefor considered external forcings. Human activity since the Industrial Revolution, mainly extracting and burning fossil fuels (coal, oil, and natural gas), has increased the amount of greenhouse gases in the atmosphere, resulting in a radiative imbalance. In 2018, the concentrations of CO_2 and methane had increased by about 45% and 160%, respectively, since 1750. These CO_2 levels are much higher than they have been at any time during the last 800,000 years, the period for which reliable data have been collected from air trapped in ice cores. Less direct geological evidence indicates that CO_2 values have not been this high for millions of years.

Despite the contribution of deforestation to greenhouse gas emissions, the Earth's land surface, particularly its forests, remain a significant carbon sink for CO_2. Natural processes, such as carbon fixation in the soil and photosynthesis, more than offset the greenhouse gas contributions from deforestation. The land-surface sink is estimated to remove about 29% of annual global CO_2 emissions. The ocean also serves as a significant carbon sink via a two-step process. First, CO_2 dissolves in the surface water. Afterwards, the ocean's overturning circulation distributes it deep into the ocean's interior, where it accumulates over time as part of the carbon cycle. Over the last two decades, the world's oceans have absorbed 20 to 30% of emitted CO_2.

Aerosols and clouds

Air pollution, in the form of aerosols, not only puts a large burden on human health, but also affects the climate on a large scale. 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. Globally, aerosols have been declining since 1990, meaning that they no longer mask greenhouse gas warming as much. In addition to their direct effects (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. This effect also causes droplets to be more uniform in size, which reduces the growth of raindrops and makes clouds more reflective to incoming sunlight. Indirect effects of aerosols are the largest uncertainty in radiative forcing.

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. Limiting new black carbon deposits in the Arctic could reduce global warming by 0.2 °C (0.36 °F) by 2050. Humans change the Earth's surface mainly to create more agricultural land. Today, agriculture takes up 34% of Earth's land area, while 26% is forests, and 30% is uninhabitable (glaciers, deserts, etc.). The amount of forested land continues to decrease, largely due to conversion to cropland in the tropics. This deforestation is the most significant aspect of land surface change affecting global warming. The main causes of deforestation are: permanent land-use change from forest to agricultural land producing products such as beef and palm oil (27%), logging to produce forestry/forest products (26%), short term shifting cultivation (24%), and wildfires (23%). In addition to affecting greenhouse gas concentrations, land-use changes affect global warming through a variety of other chemical and physical mechanisms. Changing the type of vegetation in a region affects the local temperature, by changing 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 contribute to changing temperatures by affecting the release of aerosols and other chemical compounds that influence clouds, and by changing wind patterns. In tropic and temperate areas the net effect is to produce significant warming, while at latitudes closer to the poles a gain of albedo (as forest is replaced by snow cover) leads to an overall cooling effect. Globally, these effects are estimated to have led to a slight cooling, dominated by an increase in surface albedo.

Solar and volcanic activity

Physical climate models are unable to reproduce the rapid warming observed in recent decades when taking into account only variations in solar output and volcanic activity. As the Sun is the Earth's primary energy source, changes in incoming sunlight directly affect the climate system. Solar irradiance has been measured directly by satellites, and indirect measurements are available from the early 1600s. There has been no upward trend in the amount of the Sun's energy reaching the Earth. Further evidence for greenhouse gases being the cause of recent climate change come from measurements showing the warming of the lower atmosphere (the troposphere), coupled with the cooling of the upper atmosphere (the stratosphere). 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. Explosive volcanic eruptions represent the largest natural forcing over the industrial era. When the eruption is sufficiently strong (with sulfur dioxide reaching the stratosphere) sunlight can be partially blocked for a couple of years, with a temperature signal lasting about twice as long. In the industrial era, volcanic activity has had negligible impacts on global temperature trends. Present-day volcanic CO_2 emissions are equivalent to less than 1% of current anthropogenic CO_2 emissions.

Climate change feedback

The response of the climate system to an initial forcing is modified by feedbacks: increased by self-reinforcing feedbacks and reduced by balancing feedbacks. The main reinforcing feedbacks are the water-vapour feedback, the ice–albedo feedback, and probably the net effect of clouds. The primary balancing feedback to global temperature change is radiative cooling to space as infrared radiation in response to rising surface temperature. In addition to temperature feedbacks, there are feedbacks in the carbon cycle, such as the fertilizing effect of CO_2 on plant growth. Uncertainty over feedbacks is the major reason why different climate models project different magnitudes of warming for a given number of emissions. As air gets warmer, it can hold more moisture. After initial warming due to emissions of greenhouse gases, the atmosphere will hold more water. As water vapour is a potent greenhouse gas, this further heats the atmosphere. If cloud cover increases, more sunlight will be reflected back into space, cooling the planet. If clouds become more high and thin, they act as an insulator, reflecting heat from below back downwards and warming the planet. Overall, the net cloud feedback over the industrial era has probably exacerbated temperature rise. The reduction of snow cover and sea ice in the Arctic reduces the albedo of the Earth's surface. More of the Sun's energy is now absorbed in these regions, contributing to amplification of Arctic temperature changes. Arctic amplification is also melting permafrost, which releases methane and CO_2 into the atmosphere.

Around half of human-caused CO_2 emissions have been absorbed by land plants and by the oceans. On land, elevated CO_2 and an extended growing season have stimulated plant growth. Climate change increases droughts and heat waves that inhibit plant growth, which makes it uncertain whether this carbon sink will continue to grow in the future. Soils contain large quantities of carbon and may release some when they heat up. As more CO_2 and heat are absorbed by the ocean, it acidifies, its circulation changes and phytoplankton takes up less carbon, decreasing the rate at which the ocean absorbs atmospheric carbon. Climate change can increase methane emissions from wetlands, marine and freshwater systems, and permafrost.

Impacts

Physical environment

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. Since the decades ago, droughts and heat waves have appeared simultaneously. The maximum rainfall and wind speed from hurricanes and typhoons is likely increasing. Global sea level is rising as a consequence of glacial melt, melt of the ice sheets in Greenland and Antarctica, and thermal expansion. Climate change has led to decades of shrinking and thinning of the Arctic sea ice, making it vulnerable to atmospheric anomalies. While ice-free summers are expected to be rare at 1.5 °C (2.7 °F) degrees of warming, they are set to occur once every three to ten years at a warming level of 2.0 °C (3.6 °F). Higher atmospheric CO_2 concentrations have led to changes in ocean chemistry. An increase in dissolved CO_2 is causing oceans to acidify. In addition, oxygen levels are decreasing as oxygen is less soluble in warmer water, with hypoxic dead zones expanding as a result of algal blooms stimulated by higher temperatures, higher CO_2 levels, ocean deoxygenation, and eutrophication.

Tipping points and long-term impacts

The greater the amount of global warming, the greater the risk of passing through ‘tipping points’, thresholds beyond which certain impacts can no longer be avoided even if temperatures are reduced. The long-term effects of climate change include further ice melt, ocean warming, sea level rise, and ocean acidification. On the timescale of centuries to millennia, the magnitude of climate change will be determined primarily by anthropogenic CO_2 emissions. This is due to CO_2's long atmospheric lifetime. Oceanic CO_2 uptake is slow enough that ocean acidification will continue for hundreds to thousands of years.

Nature and wildlife

Recent warming has driven many terrestrial and freshwater species poleward and towards higher altitudes. Higher atmospheric CO_2 levels and an extended growing season have resulted in global greening, whereas heatwaves and drought have reduced ecosystem productivity in some regions. The future balance of these opposing effects is unclear. Climate change has contributed to the expansion of drier climate zones, such as the expansion of deserts in the subtropics. The size and speed of global warming is making abrupt changes in ecosystems more likely. The oceans have heated more slowly than the land, but plants and animals in the ocean have migrated towards the colder poles faster than species on land. Just as on land, heat waves in the ocean occur more frequently due to climate change, with harmful effects found on a wide range of organisms such as corals, kelp, and seabirds. Ocean acidification is impacting organisms who produce shells and skeletons, such as mussels and barnacles, and coral reefs; coral reefs have seen extensive bleaching after heat waves. Harmful algae bloom enhanced by climate change and eutrophication cause anoxia, disruption of food webs and massive large-scale mortality of marine life. Coastal ecosystems are under particular stress, with almost half of wetlands having disappeared as a consequence of climate change and other human impacts.

Humans

The effects of climate change on humans, mostly due to warming and shifts in precipitation, have been detected worldwide. Regional impacts of climate change are now observable on all continents and across ocean regions, with low-latitude, less developed areas facing the greatest risk. Continued emission of greenhouse gases will lead to further warming and long-lasting changes in the climate system, with potentially "severe, pervasive and irreversible impacts" for both people and ecosystems. Climate change risks are unevenly distributed, but are generally greater for disadvantaged people in developing and developed countries.

Food and health

Health impacts include both the direct effects of extreme weather, leading to injury and loss of life, as well as indirect effects, such as undernutrition brought on by crop failures. Various infectious diseases are more easily transmitted in a warmer climate, such as dengue fever, which affects children most severely, and malaria. Young children are the most vulnerable to food shortages, and together with older people, to extreme heat. Climate change is affecting food security and has caused reduction in global mean yields of maize, wheat, and soybeans between 1981 and 2010.

Livelihoods

Economic damages due to climate change have been underestimated, and may be severe, with the probability of disastrous tail-risk events being nontrivial. Climate change has likely already increased global economic inequality, and is projected to continue doing so. Most of the severe impacts are expected in sub-Saharan Africa and South-East Asia, where existing poverty is already exacerbated. The World Bank estimates that climate change could drive over 120 million people into poverty by 2030. Current inequalities between men and women, between rich and poor, and between different ethnicities have been observed to worsen as a consequence of climate variability and climate change. Low-lying islands and coastal communities are threatened through hazards posed by sea level rise, such as flooding and permanent submergence. This could lead to statelessness for populations in island nations, such as the Maldives and Tuvalu. In some regions, rise in temperature and humidity may be too severe for humans to adapt to. With worst-case climate change, models project that almost one-third of humanity might live in extremely hot and uninhabitable climates, similar to the current climate found mainly in the Sahara. These factors, plus weather extremes, can drive environmental migration, both within and between countries. Displacement of people is expected to increase as a consequence of more frequent extreme weather, sea level rise, and conflict arising from increased competition over natural resources. Climate change may also increase vulnerabilities, leading to "trapped populations" in some areas who are not able to move due to a lack of resources.

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