How do greenhouse gas emissions influence climate?

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Summary

This synthesis reviews how human activities have altered the carbon cycle, and how the release of carbon dioxide (CO_2), methane, and non-carbon greenhouse gases (GHGs) have affected the Earth's climate.

We also assess the impacts of current and future emissions on climate stability and extreme weather.

Key Drax take-aways

- There's overwhelming scientific consensus that:
    - Human activities have altered the carbon cycle, with a rapid shift of carbon from geological reservoirs into oceanic, terrestrial, and atmospheric reservoirs.
    - The increased concentrations of CO_2, methane, and other GHGs have altered the radiative balance of the Earth. This has caused average temperatures to rise about 1.1°C since the 1850-1900 reference period.
- Rising temperatures have negative consequences for people and for biodiversity, causing sea levels to rise, increased flooding and drought, and the degradation of habitats.
- The need to limit warming to 2°C, and ideally 1.5°C was enshrined in the Paris Agreement. There's consensus that meeting this goal requires emissions to peak around 2025, and to reach net zero by 2050.

Report

The balance of energy from the Sun that reaches the Earth's atmosphere, oceans, and surface and the amount of energy lost from the planet to space, control Earth's climate. A number of factors affect this balance, including the reflectivity of ground cover, the concentration and reflectivity of clouds, and the amount of aerosols in the atmosphere. The concentration of heat-trapping gases, known as greenhouse gases (GHGs), is also a factor.

Human activities have altered all these factors, with the rate of change increasing rapidly since the industrial revolution (IPCC, 2021). In sum, these changes have resulted in an energy imbalance of 0.79Wm^{-2} from 2006 to 2018, relative to the period from 1850 to 1900. Since 1971, the global energy inventory has increased by an estimated 434ZJ (a zettajoule is equivalent to 1021 Joules) (Arias *et al.*, 2021). Consequently, average surface temperatures have warmed between 0.95 and 1.2°C since pre-industrial times (Arias *et al.*, 2021). This rate of warming is unprecedented compared to any other warming event in the last 66 million years (Zeebe *et al.*, 2016).

Human impacts on climate

Human activities have altered the Earth's climate through several different mechanisms. The IPCC groups these as CO_2, non-CO_2 GHGs, and "other", which includes further emissions and changes to the Earth's land surface (Figure 1; IPCC, 2021b).

CO_2 and non-CO_2 GHGs

The IPCC assesses the concentration and radiative forcing associated with three well-mixed GHGs: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Since these gases have a comparatively long atmospheric lifetime,

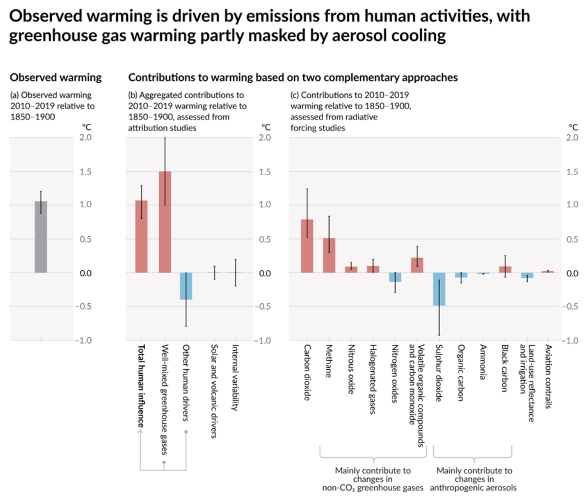


Figure SPM.2 | Assessed contributions to observed warming in 2010–2019 relative to 1850–1900

Panel (a) Observed global warming (increase in global surface temperature). Whiskers show the *very likely* range.

Panel (b) Evidence from attribution studies, which synthesize information from climate models and observations. The panel shows temperature change attributed to: total human influence; changes in well-mixed greenhouse gas concentrations; other human drivers due to aerosols, ozone and land-use change (land-use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers show *likely* ranges.

Panel (c) Evidence from the assessment of radiative forcing and climate sensitivity. The panel shows temperature changes from individual components of human influence: emissions of greenhouse gases, aerosols and their precursors; land-use changes (land-use reflectance and irrigation); and aviation contrails. Whiskers show *very likely* ranges. Estimates account for both direct emissions into the atmosphere and their effect, if any, on other climate drivers. For aerosols, both direct effects (through radiation) and indirect effects (through interactions with clouds) are considered.

{Cross-Chapter Box 2.3, 3.3.1, 6.4.2, 7.3}

they're evenly distributed throughout the atmosphere. Some halogenated compounds also persist for several years, but are typically considered alongside short-lived climate forcers (SLFCs) due to similarities in chemistry and impacts (IPCC, 2021).

These gases are assigned a global warming potential, which is a measure of the energy absorbed by the gas relative to CO_2 for a given time. Of the three gases considered here, on a 100-year timescale, N_2O has the highest global warming potential, 265 (IPCC, 2013). This means, on a ton-by-ton basis, N_2O will absorb 265 times more energy than CO_2.

However, N_2O is found at a considerably lower concentration (332ppb in 2019) than either methane (1,866ppb in 2019) or CO_2 (410ppm in 2019) (Arias *et al*., 2021). On average, the atmospheric residence time of N_2O is 120 years. Anthropogenic emissions of N_2O are primarily due to agriculture and agricultural soil management, fuel combustion, the manufacture of fertiliser and other chemicals, and changes in land use (EPA, 2023). N_2O is also emitted naturally by the bacterial decomposition of organic matter. Bacterial utilisation, UV breakdown, and other chemical reactions remove N_2O from the atmosphere.

The carbon cycle controls both CO_2 and methane (which are both species of carbon). Carbon is cycled by living organisms and by chemical reactions; these biotic and abiotic fluxes occur over timescales of hours to millions of years. Of the two species, methane has a higher 100-year global warming potential (28; IPCC 2013) but a much shorter residence time of 12 years (EPA, 2023). By contrast, CO_2 has an atmospheric residence time of 200 to 2,000 years, with a longer tail of up to 7,000 years to return to steady state once a perturbation ceases (Archer *et al*., 2009).

Other climate forcers

Albedo

This is the fraction of sunlight reflected from the Earth's surface – and an important control on climate. Naturally, albedo varies seasonally due to changes in snow and ice cover and the angle of solar radiation. Anthropogenic activities such as deforestation and afforestation, trends in the extent of snow and ice cover due to warming, and land use changes also alter albedo, leading to regional cooling or warming (Betts, 2000).

SLCFs

The IPCC considers gases and other emissions with a typical lifetime of hours to months as short-lived climate forcers (SLCFs). These include halogenated compounds and aerosols, which can have a warming or cooling effect depending on the chemical composition.

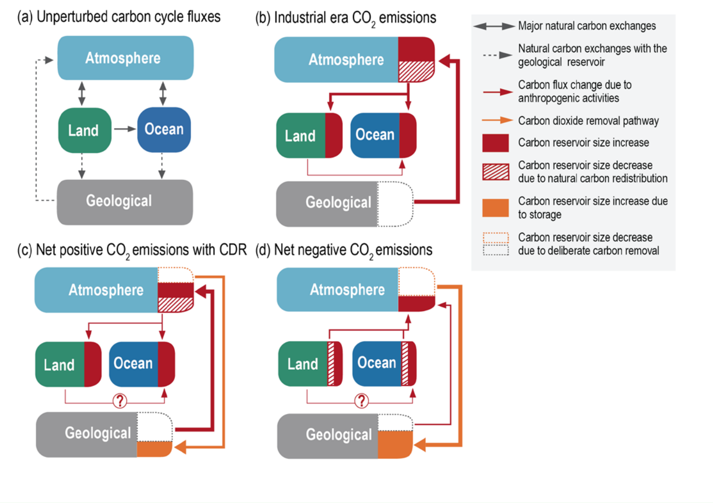
The carbon cycle

Chemical reactivity and the mechanisms by which the species are produced and consumed through biological activity and abiotic reactions control the differing residence times of methane and CO_2. These factors affect how carbon is cycled between states and reservoirs. In simple terms, the reservoirs are divided into the atmospheric, terrestrial, oceanic, and geologic reservoirs.

Atmosphere

The atmospheric reservoir is the smallest of the carbon reservoirs, and carbon will cycle quickly between the atmosphere, biosphere, and surface ocean (Carlson *et al.* 2001). The predominant form of carbon in the atmosphere is CO_2, estimated at 875GtC, with annual anthropogenic emissions of about 10GtC pa from fossil fuel combustion and about 1GtC pa from land use change in 2022 (Friedlingstein *et al*., 2002).

These emissions occur against a background of natural CO_2 emissions to the atmosphere from respiration and decomposition, and to a lesser extent from volcanic



Box 5.3, Figure 1 in Canadell *et al.* (2021)

outgassing and natural seeps. CO_2 is removed on shorter timescales by photosynthesis, which fixes CO_2 in organic matter, and ocean equilibration, which transfers CO_2 to the surface ocean. CO_2 is also removed through the weathering of rock; on thousand- to million-year timescales, this process is a major stabiliser of climate (Penman *et al.* 2020).

Methane is present in lower concentrations than CO_2. It's emitted through anthropogenic activities such as: agriculture; land use change; the production, processing and transport of natural gas and crude oil; and the decomposition of landfill waste. Methane is also released from natural systems such as sediments and wetlands; and emissions that can be accelerated by the effects of climate change, such as the melting of permafrost, which can expose organic matter to decomposition (Miner *et al.*, 2022). On longer timescales, methane is released by volcanic activity and the destabilisation of methane hydrates. Microbial uptake and oxidation reactions that convert methane to CO_2 or volatile organic carbons (VOCs) remove methane from the atmosphere (Chen *et al.*, 2019).

Carbon is also found in the atmosphere in the form of VOCs and carbonaceous aerosols. Some VOCs, such as some halogenated compounds, are considered SLCFs. A particular class of carbonaceous aerosols – that absorb light – also have significant climate impacts. Carbonaceous aerosols are short-lived, and concentrations will fall rapidly if emissions are reduced.

Terrestrial

The total terrestrial carbon stock is on the order of 2,500GtC (IPCC, 2000), of which live biomass comprises around 380GtC (Xu *et al.*, 2021). Most of the remaining carbon is found in soils.

Between 2009 and 2016, the terrestrial biosphere took up about 34% of total anthropogenic emissions, as the net productivity of forests in the tropics, subtropics, and temperate North America increased (Keenan & Williams, 2018). Carbon is taken up by photosynthesis and transferred into soils through decomposition and the physical breakdown of organic matter. Carbon is released naturally through respiration, decomposition, wildfire and land disturbance. Carbon in soils and terrestrial biomass can also be transferred to the oceans through weathering and runoff.

Anthropogenic causes of terrestrial carbon loss include land use change and land management and biomass harvesting. Some human activities can also enhance carbon storage on land, for instance the deposition of anthropogenic forms of nitrogen acts as a fertiliser in forests. Deliberate afforestation and re-forestation also increases the amount of carbon stored in terrestrial biomass. Increased atmospheric concentrations of CO_2 will further support enhanced photosynthesis, but this may be countered by concomitant climate change that, for example, increases water stress, wildfire occurrence or soil erosion (Keenan & Williams, 2018).

Carbon cycling in the terrestrial ecosystem is fast, relative to geologic carbon cycle and aspects of the marine carbon cycle. Carbon will cycle between biomass, surface carbon pools and the atmosphere over days to centuries. Recovery of carbon fluxes and total biomass from disturbances such as wildfire or drought occurs over tens of years, with a century or more required for recovery from major events like deforestation (Fu *et al.*, 2017).

However, the recovery of carbon stocks doesn't necessarily imply a full recovery in ecosystem diversity and functioning, and recovery from prolonged anthropogenic degradation can take considerably longer (Moreno-Mateos *et al.*, 2017). It takes tens of thousands to millions of years for carbon from living organisms (biogenic carbon) to enter geologic reservoirs through deep burial and subduction (Hilton & West, 2020).

Oceans

The oceanic carbon reservoir is the second largest and hosts physical, geological, and biological carbon cycling. The relative speed of cycling means that, on timescales of decades to millennia, the ocean is the primary natural controller of atmospheric CO_2 concentrations (DeVries, 2022). In the surface ocean, CO_2 is exchanged with the atmosphere to meet equilibrium with atmospheric CO_2 concentrations. The point of equilibrium is determined by ocean temperature and salinity. Once dissolved CO_2 enters the surface oceans, it will then cycle through either the inorganic carbon cycle or the biological carbon cycle, with some points of overlap such as biological calcification.

In the inorganic carbon cycle, CO_2 will react to form carbonic acid, further breaking down into bicarbonate and carbonate ions. The balance across them controls ocean pH, which is naturally on the order of 8. Increasing input of CO_2 will shift the pH of seawater to lower values (ocean acidification). Higher concentrations of bicarbonate and carbonate in the presence of cations (positively charged ions) like calcium and magnesium lead to the precipitation of carbonate minerals such as calcite and aragonite. These carbonate minerals will sink from the ocean surface. Both pelagic and sessile organisms also precipitate carbonates: in the surface ocean, foraminifera and coccolithophores form carbonate as part of their internal and external structures. At the shallow seafloor, corals produce aragonite skeletons and calcareous algae secrete calcite. Other marine invertebrates such as molluscs and echinoderms also secrete carbonates as part of their endoskeletons or exoskeletons.

In the surface ocean, photosynthetic organisms will use CO_2 to create organic matter, much of which is subsequently respired or decomposed back to CO_2. Some organic matter will sink to the deep ocean, particularly if it's associated with a mineral like carbonate. An even smaller fraction may reach the marine sediment layer at the bottom of the ocean. Non-living organic matter occurs in particulate and dissolved forms in both the surface and deep ocean.

Dissolved CO_2 and inorganic carbon species also enter the deep ocean through the sinking of intermediate- and deep-water masses. These flow through the global ocean on timescales of 1,500 years. Through the respiration of organic matter, deep water accumulates further CO_2 and releases it to the atmosphere when it resurfaces in regions like the North Pacific and Southern Ocean.

Anthropogenic activities have altered the marine carbon cycle directly through inputs, as well as warming-related changes in ocean properties and behaviour. Increasing concentrations of atmospheric CO_2 have been taken up by the ocean, with about 25% of emissions thought to have been directly absorbed. This uptake has decreased the pH of the surface ocean, with that change carried to depth by sinking water masses. Further acidification is expected to hinder the growth and productivity of calcareous organisms, which will have an impact upon the biological pump and the survival of coral reefs (Hönisch *et al.* 2012).

Fertiliser that has entered waterways and been carried to the coastal ocean is causing plankton blooms and increased organic matter oxidation at depth. This can contribute to the development of regions of hypoxia, known as ocean dead zones. Warming of the surface decreases the solubility of CO_2 (DeVries, 2022) and limits further CO_2 uptake. Changes in atmospheric circulation and ocean warming alter ocean circulation and patterns of sea ice formation, which can further hinder CO_2 uptake or lead to enhanced outgassing of CO_2 (Menviel *et al.*, 2023; Shadwick *et al.* 2021).

Geological

The geological carbon reservoir is the largest reservoir, and the slowest to exchange with other reservoirs under natural conditions. Carbon is found in both organic and inorganic forms, and in solid and fluid forms. In the lithosphere, carbon occurs as carbonate minerals and cements, graphite, diamond and as organic carbon species, particularly in marine and terrestrial sediments buried over time. Carbon is also found in the Earth's crust as methane hydrates, which occur in terrestrial sediments and sedimentary rocks in polar regions and in marine sediments.

When organic carbon reaches sufficient temperatures and pressures due to burial, chemical reactions lead to the formation of oil, gas (including CO_2), and coal. Under natural conditions, most carbon in this form is locked away for millions of years, with a small proportion released to the surface through seeps. Inorganic forms of carbon are also contained in sediments, including in minerals that are generated because of chemical weathering. The deep burial of organic and inorganic carbon in sediments is the primary mechanism by which CO_2 is removed from the atmosphere on thousand- to million-year timescales (Hilton & West, 2020).

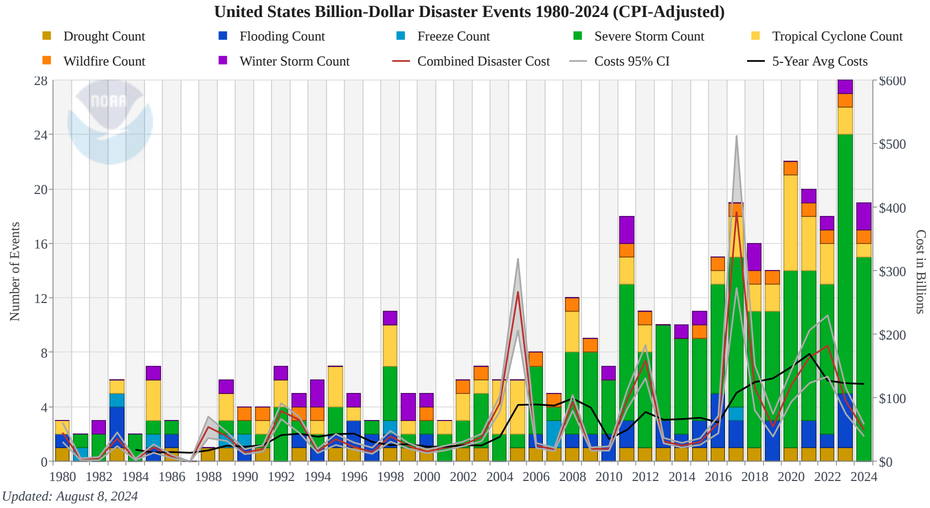
Carbon-bearing rocks and sediments may also be subducted into the mantle. This carbon undergoes dissolution and decarbonation reactions and is transferred to the overlying mantle wedge as CO_2 (Frezzotti *et al.*, 2011). CO_2 is then released back to the atmosphere through volcanic outgassing and continental and oceanic rifting (Wong *et al.*, 2019), or naturally trapped in sedimentary reservoirs. Carbon may also be released through the uplift or exposure of buried sedimentary rocks (Hilton & West, 2020). Under natural conditions, the geologic carbon cycle operates over thousands to millions of years.

The exploitation of fossil fuels means that carbon that was sequestered for hundreds of millions of years has been released rapidly to the ocean-atmosphere-terrestrial system. This has raised atmospheric and oceanic CO_2 concentrations quickly, as this release greatly exceeds the rate of removals possible by geologic processes (Wong *et al.*, 2019).

The cumulative climate effect

In sum, global average temperatures have warmed almost 1.1°C since the 1850-1900 reference period. This is the result of warming caused by anthropogenic emissions of greenhouse gases and light-absorbing carbonaceous aerosols, offset by a small amount of cooling from emissions of other aerosols. This rate of change is unprecedented in at least two millennia, and probably tens of millions of years (Arias *et al.*, 2022).

The effects of climate change are not uniform, and will worsen with continued emissions of greenhouse gases (Arias *et al.*, 2022). The impact of climate change was detectable in every day of global weather records since 2012, according to work completed in 2020 (Sippel *et al.* 2020). These impacts include unprecedented flooding, drought, wildfires, temperature extremes, the desertification of drylands, and the loss of snow and ice cover in high latitudes (Arias *et al.* 2022).



The costs associated with weather extremes are also increasing exponentially, with at least half these losses attributable to the impacts of climate change (Newman & Noy, 2023). Data collected from the U.S. shows a substantial increase in the number of events that cause one billion dollars or more in damages (CPI-adjusted) past 20 years (Figure 3; NCEI, 2024). These events also cause loss of life. There doesn't appear to be an agreed figure that specifically attributes loss of life to climate change, with deaths only attributable to extreme weather events overall. However, recent work suggests that one million tons of CO_2 emissions will cause excess mortality of 266 people (Bressler, 2021).

In recognition of the devastating impacts that accelerating climate change will bring, 196 parties adopted the legally-binding Paris Agreement in 2015. The goal is to limit further warming to well below 2°C relative to the pre-industrial period and pursuing a strategy to limit the temperature increase to 1.5°C. This goal requires that emissions peak before 2025 and reach net zero by 2050 (UNFCCC Secretariat, 2021).

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