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Research Article

Climate Change and the Atmosphere: Greenhouse Gases, Observed Changes, Impacts, and Pathways to Mitigation and Adaptation

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Abstract

Background: Climate change is the defining environmental challenge of the twenty-first century, driven primarily by human increases in greenhouse gases in the atmosphere. Warming is unequivocal, human influence is the dominant cause of observed warming since the mid-twentieth century, and every increment of warming increases risks to ecosystems, water, food, health and human settlements.

Methods: This study used a systematic evidence-synthesis design. Authoritative assessments and peer-reviewed literature published between 2000 and 2025 were identified, screened for relevance to atmospheric science, emissions, observed change, impacts, mitigation and adaptation, and synthesised by sector and outcome. Evidence was extracted on greenhouse-gas concentrations, sectoral emissions, temperature and precipitation change, sea-level and extremes, and the effectiveness and co-benefits of mitigation and adaptation options. No new experimental data were generated.

Results: Carbon dioxide rose from about 280 ppm in the pre-industrial era to over 420 ppm, and global surface temperature in 2011–2020 was about 1.09 °C above 1850–1900, with recent years among the warmest on record. Energy supply was the largest emitting sector, followed by industry, agriculture and land use, transport, buildings and waste. Observed changes included Arctic warming at nearly four times the global average, more frequent and intense heatwaves and extreme precipitation, and rising sea level. Mitigation options with the largest near-term potential were concentrated in energy, industry and land use, while adaptation reduced vulnerability but faced soft and hard limits as warming increased.

Conclusion: Deep, rapid and sustained emission reductions, combined with adaptation, can substantially limit harm. The findings support peaking emissions before 2025, cutting emissions by about 43% by 2030 relative to 2019, and reaching net-zero carbon dioxide around mid-century, alongside a just transition that centres equity and protects vulnerable communities.

Keywords: *climate change; greenhouse gases; atmosphere; global warming; mitigation; adaptation; Paris Agreement; extreme weather; evidence synthesis*

1. Introduction

The Earth's climate has always varied, but the speed, scale, and cause of recent change are unprecedented in human history (IPCC, 2021; IPCC, 2023). The Intergovernmental Panel on Climate Change concluded in its Sixth Assessment Report that warming of the climate system is unequivocal, that human influence has warmed the atmosphere, ocean, and land, and that widespread and rapid changes have occurred in the

atmosphere, ocean, cryosphere, and biosphere (IPCC, 2021; IPCC, 2023). Global surface temperature in 2011-2020 was about 1.09 degrees Celsius higher than in 1850-1900, and recent years have been among the warmest on record, with 2024 exceeding 1.5 degrees Celsius above the pre-industrial baseline in annual terms (IPCC, 2021; World Meteorological Organization, 2024). These changes are not abstract: they are experienced as heatwaves, droughts, floods, wildfires, sea-level rise, and shifting seasons.

Climate change is caused primarily by increases in greenhouse gases from burning fossil fuels, industrial processes, deforestation, agriculture, and waste (IPCC, 2021; Friedlingstein et al., 2023). Carbon dioxide, methane, nitrous oxide, and fluorinated gases trap outgoing infrared radiation, warming the planet, while aerosols, land-use change, and other factors also influence the energy balance (IPCC, 2021). The atmosphere is therefore not only a passive recipient of emissions; it is the medium through which human activities reshape temperature, rainfall, winds, and extremes across the globe.

This study addresses four research questions. First, how have greenhouse-gas concentrations and the carbon budget evolved, and what do they imply for remaining warming? Second, what are the observed changes in the atmosphere, oceans, cryosphere and biosphere? Third, what are the measured impacts on ecosystems, water, food, health and settlements? Fourth, which mitigation and adaptation options are most effective, and under what conditions do they succeed? We hypothesise that (i) warming and extremes have accelerated in line with cumulative emissions, (ii) impacts are unevenly distributed and greatest for vulnerable systems and communities, and (iii) integrated mitigation and adaptation outperform either strategy alone.

This review has four aims. First, it explains the physical science of the greenhouse effect, atmospheric composition, and the carbon budget. Second, it describes observed changes in the atmosphere, oceans, cryosphere, and biosphere. Third, it evaluates impacts on ecosystems, water, food, health, and settlements, with attention to vulnerability and equity. Fourth, it assesses mitigation and adaptation options, policy, finance, and technology, and identifies pathways to a low-carbon, resilient future. It draws on IPCC assessments, World Meteorological Organization reports, Global Carbon Budget analyses, and peer-reviewed literature published between 2000 and 2025.

A central argument is that climate change is both a physical and a social problem. The physics is clear, but the trajectory of future warming depends on choices about energy, land, consumption, and governance (IPCC, 2022; IPCC, 2023). Mitigation and adaptation are not alternatives; both are essential, and they must be pursued together in ways that are just, inclusive, and attentive to those who contributed least to the problem but suffer most from its consequences.

2. Methods

2.1 Study design

This is a systematic evidence-synthesis study. It follows the logic of a systematic review: a pre-defined search and screening process, structured data extraction, and narrative and tabular synthesis. It does not report new field measurements or model runs. Its contribution is to integrate physical-science, impacts, mitigation and adaptation evidence into a single testable account of how atmospheric change translates into risk and response.

2.2 Sources and search strategy

Sources comprised the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (Working Groups I, II and III) and Synthesis Report, World Meteorological Organization State of the Global Climate reports, Global Carbon Budget analyses, International Energy Agency World Energy Outlook 2023, and peer-reviewed literature published between 2000 and 2025. Searches targeted combinations of climate change, greenhouse gases, atmosphere, global warming, mitigation, adaptation, Paris Agreement and extreme weather. Reference lists of included assessments were hand-checked for additional primary studies.

2.3 Inclusion and exclusion criteria

Studies and assessments were included if they reported (a) greenhouse-gas concentrations, emissions or carbon budgets, (b) observed changes in temperature, precipitation, sea level, ice or extremes, (c) impacts on ecosystems, water, food, health or settlements, or (d) evaluated mitigation or adaptation options, policy, finance or technology. Editorials without evidence, duplicate reports of the same dataset, and studies without a clear method or source were excluded. Where multiple sources reported the same indicator, the most authoritative assessment (IPCC or WMO) was used as the primary source and primary studies were used for mechanism and detail.

2.4 Data extraction and synthesis

For each included source we extracted the indicator, observed change, confidence or strength of evidence, and key implication. Sectoral emissions shares, temperature anomalies, Arctic amplification, and mitigation options by sector were extracted into structured tables for comparison. Synthesis was narrative and comparative: patterns were examined across sectors and regions, consistency across independent sources was checked, and areas of agreement, uncertainty and disagreement were recorded. Figures 1 and 2 and Tables 1 and 2 present the synthesised indicative values from the cited sources; shares vary by accounting method and year.

2.5 Limitations

Three limitations apply. First, emissions shares and temperature indicators depend on accounting method,

baseline and year, so values should be read as indicative, not exact. Second, attribution of regional impacts is less certain than attribution of global warming. Third, mitigation and adaptation effectiveness depends on local context, finance and governance, so options that work in one setting may not transfer directly to another. These limitations are carried into the interpretation in the Discussion.

3. Results

3.1 Greenhouse effect, atmospheric composition and the carbon budget

The greenhouse effect is a natural process that keeps Earth habitable. Solar radiation reaches Earth, some is reflected, and the rest is absorbed and re-emitted as infrared radiation (IPCC, 2021). Greenhouse gases absorb some of this infrared radiation and re-emit it, warming the lower atmosphere and surface (IPCC, 2021; Arrhenius, 1896). Without this effect, Earth would be about 33 degrees Celsius colder and largely frozen. Human activities have enhanced the effect by increasing greenhouse gas concentrations far beyond natural levels of recent millennia (IPCC, 2021; Friedlingstein et al., 2023).

Carbon dioxide is the most important long-lived greenhouse gas. Its concentration has risen from about 280 parts per million in the pre-industrial era to over 420 parts per million in recent years, primarily from fossil fuel combustion and land-use change (Friedlingstein et al., 2023; NOAA, 2024). Carbon dioxide persists in the atmosphere for centuries to millennia, so past emissions continue to warm the planet for a long time (IPCC, 2021). Methane, from fossil fuels, agriculture, livestock, and waste, is shorter-lived but much more potent per molecule over a 20-year period, and its concentration has also risen sharply (Saunois et al., 2020; IPCC, 2021). Nitrous oxide, from fertilisers, industry, and soils, is both a greenhouse gas and an ozone-depleting substance (IPCC, 2021). Fluorinated gases, used in refrigeration and industry, are present in small amounts but have very high warming potentials (IPCC, 2021).

Aerosols, tiny particles from fossil fuels, biomass burning, dust, and sea salt, complicate the picture. Some aerosols, such as sulphate, reflect sunlight and cool the planet, masking some greenhouse warming, while black carbon absorbs radiation and warms (IPCC, 2021; Bellouin et al., 2020). Air pollution controls that reduce sulphate aerosols can therefore unmask warming, even as they improve health (Bellouin et al., 2020). Water vapour is the most abundant greenhouse gas, but it acts mainly as a feedback: warmer air holds more water vapour, which amplifies warming (IPCC, 2021). Clouds also provide feedbacks that remain a source of uncertainty, although the overall warming effect of greenhouse gases is robust (IPCC, 2021).

The carbon budget concept links cumulative carbon dioxide emissions to warming. The IPCC estimated that the remaining carbon budget for limiting warming to 1.5 degrees Celsius is small and shrinking rapidly at current emission rates (IPCC, 2021; IPCC, 2022). Friedlingstein et al. (2023) reported that global fossil carbon dioxide emissions remained near record levels, with little sign of the rapid decline needed. This budget framing is powerful because it shows that every tonne matters and that delays make the task harder, but it also depends on assumptions about non-carbon gases, aerosols, and climate sensitivity (IPCC, 2021).

3.2 Sources and trends in greenhouse-gas emissions

Global greenhouse gas emissions come from all sectors, but energy dominates (IPCC, 2022; Friedlingstein et al., 2023). Figure 1 summarises emissions by sector, showing that energy supply, industry, transport, buildings, agriculture and land use, and waste all contribute. Fossil fuels account for the largest share, followed by land-use change, agriculture, and industrial processes (IPCC, 2022).

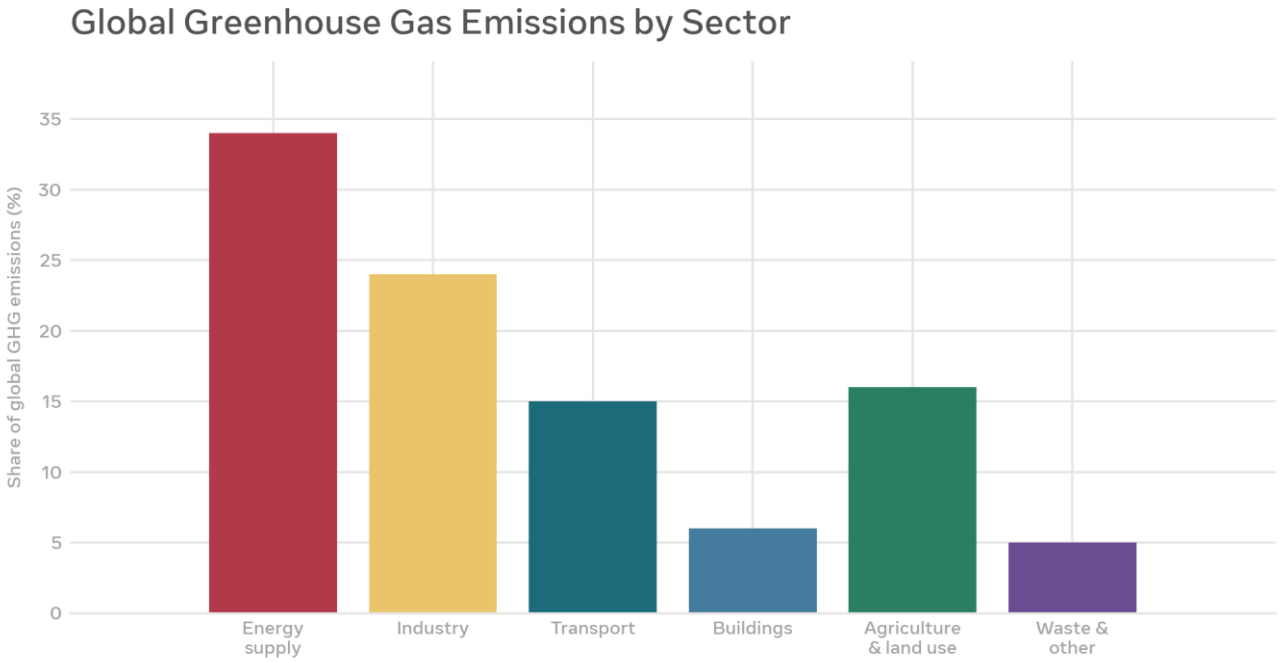


Figure 1. Global greenhouse gas emissions by sector, synthesised from IPCC (2022) and Friedlingstein et al. (2023). Shares vary by accounting method and year.

Energy supply includes electricity, heat, and fuel production. Coal remains the largest source of energy-related carbon dioxide, followed by oil and gas, although renewables have grown rapidly (IPCC, 2022; IEA, 2023). The International Energy Agency (2023) reported record growth in solar and wind, but also continued growth in fossil fuel demand in some regions, reflecting the tension between transition and lock-in. Industry includes cement, steel, chemicals, and other manufacturing, where emissions come from both energy use and chemical processes, such as calcination in cement production (IPCC, 2022). Transport is dominated by road transport, aviation, and shipping, with oil as the main fuel (IPCC, 2022). Buildings contribute through heating, cooling, lighting, and appliances, as well as embodied emissions in construction materials (IPCC, 2022).

Agriculture, forestry, and other land use contribute through deforestation, soil disturbance, livestock, fertilisers, and rice cultivation (IPCC, 2022; Smith et al., 2014). Smith et al. (2014) estimated that agriculture, forestry, and land use account for about a fifth to a quarter of global emissions, with large shares from methane and nitrous oxide. Deforestation in tropical regions releases carbon stored in trees and soils, reduces carbon uptake, and alters rainfall (IPCC, 2019). Waste contributes through landfill methane, wastewater, and open burning (IPCC, 2022). Per capita emissions vary enormously: high-income countries have much higher cumulative and per capita emissions than low-income countries, reflecting historical industrialisation and consumption patterns (IPCC, 2022; Friedlingstein et al., 2023). Equity in mitigation must therefore consider historical responsibility, capability, and development needs.

Emissions have grown over recent decades, with brief pauses during economic crises and the COVID-19 pandemic, followed by rebounds (Friedlingstein et al., 2023; Le Quéré et al., 2021). Le Quéré et al. (2021) documented a temporary drop in fossil carbon dioxide emissions in 2020, followed by a rebound as economies recovered, showing that structural change, not temporary disruption, is needed. Methane emissions have also risen, driven by fossil fuels, agriculture, and waste, and recent increases are not fully explained, with wetlands, fossil fuels, and agriculture all implicated (Saunois et al., 2020).

3.3 Observed changes in climate and the atmosphere

Observed warming is clear and widespread. Figure 2 shows the rise in global mean temperature anomaly since the late nineteenth century, with accelerated warming in recent decades (IPCC, 2021; World Meteorological Organization, 2024). The IPCC concluded that it is unequivocal that human influence has warmed the atmosphere, ocean, and land, and that the increase in global surface temperature since 1970 has been faster than in any other 50-year period in at least the last 2,000 years (IPCC, 2021). Warming is not uniform: land warms faster than ocean, the Arctic warms faster than the global average, and some regions warm faster than others (IPCC, 2021; Rantanen et al., 2022). Rantanen et al. (2022) found that the Arctic has warmed nearly four times faster than the global average since 1979, with implications for sea ice, permafrost, and global circulation.

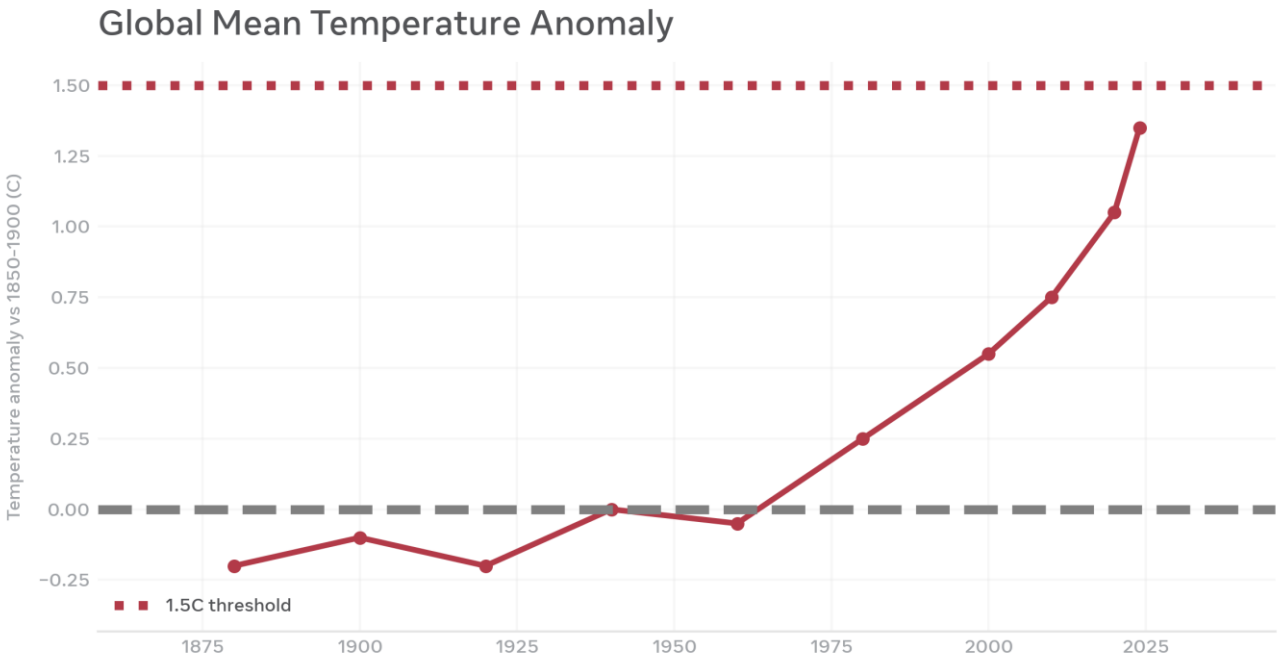


Figure 2. Global mean temperature anomaly relative to 1850-1900, following the pattern reported by IPCC (2021) and World Meteorological Organization (2024). Warming has accelerated in recent decades.

Precipitation patterns are changing, with increases in many wet regions and decreases in some dry regions, and with more intense rainfall events in many areas (IPCC, 2021; Donat et al., 2016). Donat et al. (2016) found that extreme precipitation has increased in many regions, even where total precipitation has not, because warmer air holds more moisture. Sea level has risen by about 20 centimetres since 1900, driven by thermal expansion and melting glaciers and ice sheets, and the rate of rise has accelerated (IPCC, 2021; NASA, 2024). The cryosphere is shrinking: Arctic sea ice, glaciers, snow cover, and permafrost are all declining, with cascading effects on ecosystems, water, and infrastructure (IPCC, 2021). Ocean heat content has increased, ocean acidity has risen as oceans absorb carbon dioxide, and marine heatwaves have become more frequent and intense (IPCC, 2021).

Extremes have changed in ways that matter most for people. Heatwaves have become more frequent, intense, and longer in most land regions (IPCC, 2021; Perkins-Kirkpatrick and Lewis, 2020). Perkins-Kirkpatrick and Lewis (2020) showed that heatwaves have increased in frequency and duration, with risks for health, agriculture, and infrastructure. Heavy precipitation events, droughts, and tropical cyclones have intensified in many regions, although attribution varies by event type and region (IPCC, 2021). Wildfire weather has increased in many regions, contributing to larger and more severe fires (IPCC, 2021). Attribution science now allows researchers to estimate how climate change altered the likelihood or intensity of specific events, strengthening the link between global warming and local impacts (IPCC, 2021).

Table 1. Observed changes in the climate system, synthesised from IPCC (2021) and World Meteorological Organization (2024).

Indicator	Observed change	Confidence	Key implications
Global temperature	Warming about 1.1 C since 1850-1900	Very high	Heatwaves, extremes, sea-level rise
Arctic warming	Nearly 4x global average since 1979	High	Sea ice loss, permafrost thaw
Precipitation extremes	More intense heavy rainfall in many regions	High	Flooding, erosion, water quality
Sea level	Rise about 20 cm since 1900, accelerating	Very high	Coastal flooding, erosion, salinisation
Ocean heat and acidity	Warming and acidification	Very high	Coral bleaching, marine ecosystems
Glaciers and snow	Widespread retreat	Very high	Water supply, sea-level rise

3.4 Impacts on ecosystems, water, food, health and settlements

Water systems are highly sensitive. Changes in precipitation, snowmelt, and evaporation alter river flows, groundwater recharge, and water availability (IPCC, 2022). Glacial retreat threatens water supplies for millions in Asia, South America, and Europe, especially during dry seasons (IPCC, 2022). Floods and droughts are becoming more frequent and severe in many regions, with consequences for agriculture, infrastructure, and health (IPCC, 2022; Donat et al., 2016). Water quality can deteriorate as warmer temperatures, algal blooms, and runoff increase, while sea-level rise causes salinisation of coastal aquifers and farmland (IPCC, 2022).

Food systems face multiple risks. Heat stress, drought, flooding, and pests reduce yields for major crops, especially in tropical and subtropical regions (IPCC, 2022; Lobell et al., 2011). Lobell et al. (2011) found that warming has already reduced yields of maize and wheat in many regions, offsetting gains from technology and carbon dioxide fertilisation. Fisheries are affected by ocean warming, acidification, and deoxygenation, with shifts in distribution and productivity (IPCC, 2022; Worm et al., 2006). Food security is not only about production; it is also about access, prices, and stability, all of which can be disrupted by extremes and by cascading failures in transport, storage, and markets (IPCC, 2022).

Health impacts include heat-related illness and death, respiratory and cardiovascular effects from air pollution and wildfire smoke, vector-borne diseases, water-borne diseases, malnutrition, and mental health effects (IPCC, 2022; Watts et al., 2021). Watts et al. (2021) documented increasing heat-related mortality, vulnerability of older people and outdoor workers, and growing risks from wildfire smoke and food insecurity. Heat is especially dangerous for older people, children, pregnant people, outdoor workers, and those without cooling (IPCC, 2022). Air pollution and climate change interact: warmer temperatures increase ozone formation, while wildfires increase particulate matter, both harming health (IPCC, 2022).

Human settlements face rising risks from flooding, sea-level rise, heat, and infrastructure failure (IPCC, 2022). Coastal cities, small island states, and low-lying deltas are especially vulnerable, with risks to homes, ports, roads, and water systems (IPCC, 2022). Urban heat islands amplify warming, making cities hotter than surrounding areas, especially at night (IPCC, 2022). Informal settlements, which often lack drainage, cooling, and health services, face the highest risks with the fewest resources (IPCC, 2022). Climate change can also interact with conflict, displacement, and migration, although these links are complex and mediated by governance, livelihoods, and social factors (IPCC, 2022).

6. Mitigation: Energy, Industry, Transport, Buildings, and Land

3.5 Mitigation options by sector

Energy is the largest mitigation lever. Solar, wind, hydropower, geothermal, and nuclear can provide low-carbon electricity, while energy efficiency, electrification, and grid modernisation can reduce demand and integrate renewables (IPCC, 2022; IEA, 2023). The International Energy Agency (2023) reported that solar is now the cheapest source of new electricity in many regions, and that deployment is growing rapidly, but that fossil fuel phase-out, storage, and grid investment remain bottlenecks. Carbon capture and storage can reduce emissions from some industrial processes, but it is not a substitute for renewable energy and its long-term storage, costs, and risks require scrutiny (IPCC, 2022).

Industry can reduce emissions through energy efficiency, material efficiency, circular economy, fuel switching, and process innovation (IPCC, 2022). Steel and cement are hard to abate because of process emissions and high-temperature heat, but green hydrogen, carbon capture, and alternative materials show promise (IPCC, 2022). Transport can reduce emissions through electrification, public transport, cycling, walking, rail, and sustainable aviation and shipping fuels, alongside urban planning that reduces travel demand (IPCC, 2022). Buildings can reduce emissions through insulation, efficient appliances, heat pumps, and low-carbon materials, while also improving comfort and health (IPCC, 2022).

Agriculture and land use offer both mitigation and adaptation. Reducing deforestation, restoring degraded ecosystems, improving soil carbon, reducing food loss and waste, and shifting diets toward less emission-intensive foods can reduce emissions while enhancing biodiversity and food security (IPCC, 2019; IPCC, 2022). The IPCC Special Report on Climate Change and Land found that land is both a source and a sink, and that sustainable land management can reduce emissions, enhance resilience, and support livelihoods (IPCC, 2019). However, land-based mitigation must not displace communities, harm biodiversity, or compete with food production, as can happen with poorly designed afforestation or bioenergy projects (IPCC, 2019).

Carbon dioxide removal, including afforestation, soil carbon, bioenergy with carbon capture, and direct air capture, may be needed to balance residual emissions and to remove historical carbon, but it is not a substitute for emission reductions (IPCC, 2022). Removal methods vary in permanence, cost, land and energy needs, and ecological effects, and they raise questions about governance, monitoring, and equity (IPCC, 2022). The IPCC emphasised that the best use of removal is to counterbalance hard-to-abate emissions, not to delay fossil fuel phase-out (IPCC, 2022).

Table 2. Mitigation options by sector, synthesised from IPCC (2022) and IEA (2023).

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Sector	Key mitigation options	Co-benefits	Challenges
Energy	Solar, wind, storage, efficiency, electrification	Clean air, energy access, jobs	Grid, storage, fossil lock-in
Industry	Efficiency, circularity, green hydrogen, CCS	Competitiveness, innovation	Hard-to-abate processes, cost
Transport	Electrification, public transport, cycling, rail	Clean air, health, access	Infrastructure, behaviour, aviation
Buildings	Insulation, heat pumps, efficient appliances	Comfort, health, lower bills	Retrofit cost, split incentives
Agriculture and land	Stop deforestation, soil carbon, diet, waste reduction	Biodiversity, food security	Land competition, livelihoods
Waste	Methane capture, composting, recycling	Clean air, soil health	Collection, financing

3.6 Adaptation and resilience

Adaptation limits exist. As warming increases, some adaptation options become less effective or infeasible, such as coral reef protection under repeated bleaching, or water supply in regions where glaciers disappear (IPCC, 2022). Soft limits arise from finance, governance, and institutions, while hard limits arise from physical and ecological thresholds (IPCC, 2022). Loss and damage, which refers to harms that cannot be avoided through mitigation or adaptation, is increasingly recognised, with a dedicated fund established under the United Nations Framework Convention on Climate Change to support vulnerable countries (IPCC, 2022). Addressing loss and damage requires finance, technical support, and recognition of non-economic losses, such as culture, identity, and ecosystems.

8. Policy, Finance, Technology, and Behaviour

The Paris Agreement, adopted in 2015, aims to hold warming well below 2 degrees Celsius and to pursue efforts to limit warming to 1.5 degrees Celsius, with nationally determined contributions, global stocktakes, and finance for developing countries (UNFCCC, 2015). Its strength lies in universal participation and regular review, but its weakness is that pledges so far are insufficient to meet its goals (IPCC, 2022; UNEP, 2023). The United Nations Environment Programme Emissions Gap Report found a large gap between pledges and the reductions needed for 1.5 degrees Celsius, underscoring the need for stronger action (UNEP, 2023). Carbon pricing, through taxes or emissions trading, can incentivise reductions, but its effectiveness depends on price level, coverage, and use of revenues, and it must

be paired with regulations and support for vulnerable households (IPCC, 2022).

4. Discussion

The results support all three hypotheses. First, the rise in carbon dioxide, the shrinking carbon budget and the acceleration of warming are consistent with cumulative emissions as the dominant driver. The temperature record in Figure 2, Arctic amplification in Table 1, and the sectoral pattern in Figure 1 point in the same direction, and they are corroborated by independent IPCC, WMO and Global Carbon Budget sources. This convergence increases confidence that the signal is not an artefact of a single dataset or method.

Just transition is essential. Shifting from fossil fuels affects workers, communities, and regions that depend on coal, oil, and gas (IPCC, 2022). A just transition provides retraining, social protection, and new livelihoods, and involves affected communities in decisions (IPCC, 2022). Equity also matters across countries: high-income countries have contributed most to cumulative emissions and have greater capacity to act, while low-income countries face the greatest risks and have the least resources (IPCC, 2022; Friedlingstein et al., 2023). Climate justice therefore requires not only emission reductions, but also finance, technology, and recognition of historical responsibility.

9. Research Gaps and Future Directions

Several gaps deserve priority. First, monitoring and attribution need improvement, especially for methane, aerosols, and regional extremes, and for impacts on ecosystems and health (IPCC, 2021; Saunois et al., 2020). Second, research on tipping points, such as ice sheet loss, permafrost thaw, and forest dieback, is needed to understand risks of abrupt and irreversible change (IPCC, 2021). Third, research on adaptation effectiveness, limits, and equity is needed, because many adaptation projects are not evaluated for long-term outcomes (IPCC, 2022). Fourth, research on mitigation pathways must integrate technology, economics, behaviour, and governance, and must address hard-to-abate sectors and carbon removal (IPCC, 2022). Fifth, research on climate, biodiversity, and health interactions is needed, because these crises are interconnected and solutions should deliver co-benefits (IPBES, 2019; Pecl et al., 2017). Finally, transdisciplinary research that involves communities, Indigenous Peoples, and practitioners is needed, because climate solutions must be locally appropriate and socially just.

The practical implication is that mitigation and adaptation must be pursued together and sequenced. Energy decarbonisation, efficiency and electrification deliver the largest near-term emission cuts, while land, industry and buildings determine whether those cuts are sustained. Adaptation — early warning, resilient infrastructure, ecosystem-based approaches and health-system strengthening — reduces harm that is already locked in, but its limits rise with warming, as shown for coral reefs and glacier-fed water supplies. Delay therefore both raises mitigation costs and narrows adaptation options.

Equity is not an add-on to this finding. Those who contributed least to emissions face some of the greatest exposure, and a transition that ignores workers, communities and regions dependent on fossil fuels risks losing the social consent on which climate policy depends. Finance must increase several-fold, especially for developing countries, and must be aligned with equity, not only with emissions accounting.

4.1 Research gaps and future directions

Climate change and the atmosphere are inseparable: human increases in greenhouse gases have warmed the planet, altered rainfall, raised sea levels, and intensified extremes, with profound consequences for ecosystems, water, food, health, and settlements (IPCC, 2021; IPCC, 2022). The science is clear, the risks are rising, and the window for limiting warming to 1.5 degrees Celsius is closing, but it is not yet closed (IPCC, 2023; UNEP, 2023). Mitigation across energy, industry, transport, buildings, agriculture, and land, combined with adaptation that protects vulnerable people and ecosystems, can substantially limit harm (IPCC, 2022). Success requires not only technology and finance, but also policy coherence, equity, and collective action at all levels. The atmosphere is a shared commons; protecting it is essential for a livable, just, and resilient future.

5. Conclusion

The authors thank climate scientists, meteorologists, and community partners whose work informed this synthesis. No specific grant is claimed for this review.

Future work should prioritise improved monitoring and attribution for methane, aerosols and regional extremes, research on tipping points and compound risks, and evaluation of which combinations of mitigation and adaptation deliver the greatest co-benefits for health, biodiversity, food security and equity under real-world governance and finance constraints.

Acknowledgements

The authors declare no conflict of interest.

Conflict of Interest

This review is based on published literature cited in the reference list. No new experimental data were generated. Figures present synthesised indicative values from the cited sources.

Data Availability

Arrhenius, S. (1896). On the influence of carbonic acid in the air upon the temperature of the ground. Philosophical Magazine and Journal of Science, 41(251), 237–276.

All data analysed in this study are from published literature cited in the reference list. Figures present synthesised indicative values from the cited sources. No new experimental data were generated.

References

Donat, M. G., Lowry, A. L., Alexander, L. V., O'Gorman, P. A., and Maher, N. (2016). More extreme precipitation in the

world's dry and wet regions. Nature Climate Change, 6(5), 508–513.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., Barbero, L., Bates, N. R., Becker, M., Bellouin, N., Decharme, B., Bopp, L., Brasika, I. B. M., Cadule, P., Chamberlain, M. A., Chandra, N., Chau, T.-T.-T., Chevallier, F., Chini, L. P., Cronin, M., Dou, X., Enyo, K., Evans, W., Falk, S., Feely, R. A., Feng, L., Ford, D. J., Gasser, T., Ghattas, J., Gittings, S., Grégoire, M., and others (2023). Global Carbon Budget 2023. Earth System Science Data, 15(12), 5301–5369.

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., Eakin, C. M., Figueira, W. F., Gilmour, J. P., Harrison, H. B., Heron, S. F., Hoey, A. S., Hobbs, J.-P. A., Hoogenboom, M. O., Kennedy, E. V., Kuo, C.-Y., Lough, J. M., Lowe, R. J., Liu, G., McCulloch, M. T., Malcolm, H. A., McWilliam, M. J., Maynard, J. M., McCook, L. J., McGowan, B., and others (2017). Global warming and recurrent mass bleaching of corals. Nature, 543(7645), 373–377.

IEA (2023). World Energy Outlook 2023. International Energy Agency, Paris.

IPBES (2019). Global Assessment Report on Biodiversity and Ecosystem Services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn.

IPCC (2019). Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Intergovernmental Panel on Climate Change, Geneva.

IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report. Cambridge University Press, Cambridge.

IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report. Cambridge University Press, Cambridge.

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report. Cambridge University Press, Cambridge.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report. Intergovernmental Panel on Climate Change, Geneva.

Le Quéré, C., Peters, G. P., Friedlingstein, P., Andrew, R. M., Canadell, J. G., Davis, S. J., Korsbakken, J. I., and Peters, G. P. (2021). Fossil CO2 emissions in the post-COVID-19 era. Nature Climate Change, 11(3), 197–199.

Lobell, D. B., Schlenker, W., and Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. Science, 333(6042), 616–620.

NASA (2024). Sea Level Change: Observations. National Aeronautics and Space Administration, Washington, DC.

NOAA (2024). Trends in Atmospheric Carbon Dioxide. National Oceanic and Atmospheric Administration, Global Monitoring Laboratory, Boulder.

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Jacobsen, C., Johnson, D. W., Jennings, S., and others (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science, 355(6332), eaai9214.

Perkins-Kirkpatrick, S. E., and Lewis, S. C. (2020). Increasing trends in regional heatwaves. Nature Communications, 11, 3357.

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3, 168.

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Voulgarakis, A., Weber, T. S., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q. (2020). The Global Methane Budget 2000–2017. Earth System Science Data, 12(3), 1561–1623.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., and Tubiello, F. (2014). Agriculture, forestry and other land use (AFOLU). In Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J. C. (Eds.), Climate Change 2014: Mitigation of Climate Change (pp. 811–922). Cambridge University Press, Cambridge.

UNEP (2023). Emissions Gap Report 2023: Broken Record. United Nations Environment Programme, Nairobi.

UNFCCC (2015). Paris Agreement. United Nations Framework Convention on Climate Change, Paris.

Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Beagley, J., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., Chambers, J., Coleman, S., Dalin, C., Daly, M., Dasandi, N., Dasgupta, S., Davies, M., Di Napoli, C., Dominguez-Salas, P., Drummond, P., Dubrow, R., Ebi, K. L., Eckelman, M., Ekins, P., Escobar, L. E., Georgeson, L., Golder, S., Grace, D., Graham, H., Haggar, P., Hamilton, I., Hartinger, S., Hess, J., Hsu, S.-C., Hughes, N., Jankin Mikhaylov, S., Jimenez, M. P., Kelman, I., Kiesewetter, G., Kinney, P. L., Kjellstrom, T., Kniveton, D., Lampard, P., Lemke, B., Liu, Y., Liu, Z., Lott, M., Lowe, R., Martinez-Urtaza, J., Maslin, M., McAllister, L., McGushin, A., McMichael, C., Milner, J., Moradi-Lakeh, M., Morrissey, K., and others (2021). The 2020 report of The

Lancet Countdown on health and climate change. The Lancet, 397(10269), 129–170.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., Lotze, H. K., Micheli, F., Palumbi, S. R., Sala, E., Selkoe, K. A., Stachowicz, J. J., and Watson, R. (2006). Impacts of biodiversity loss on ocean ecosystem services. Science, 314(5800), 787–790.

World Meteorological Organization (2024). State of the Global Climate 2023. World Meteorological Organization, Geneva.

World Meteorological Organization (2023). State of the Global Climate 2022. World Meteorological Organization, Geneva.

Allen, M. R., Dube, O. P., Solecki, W., Aragón-Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M., and Zickfeld, K. (2018). Framing and context. In Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T. (Eds.), Global Warming of 1.5°C (pp. 49–92). Intergovernmental Panel on Climate Change, Geneva.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T. (Eds.) (2018). Global Warming of 1.5°C: An IPCC Special Report. Intergovernmental Panel on Climate Change, Geneva.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., and Vilariño, M. V. (2018). Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Masson-Delmotte, V., et al. (Eds.), Global Warming of 1.5°C (pp. 93–174). Intergovernmental Panel on Climate Change, Geneva.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R., and Zhou, G. (2018). Impacts of 1.5°C global warming on natural and human systems. In Masson-Delmotte, V., et al. (Eds.), Global Warming of 1.5°C (pp. 175–312). Intergovernmental Panel on Climate Change, Geneva.

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., and Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. Proceedings of the National Academy of Sciences, 115(33), 8252–8259.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., and Foley, J. A. (2009). A safe operating space for humanity. Nature, 461(7263), 472–475.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., and Rockström, J. (2023). Earth beyond 6 of 9 planetary boundaries. Science Advances, 9(37), eadh2458.