Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA27649

Mechanisms of Anthropogenic Emissions and Climate Change Impacts on the Oceanic and Terrestrial Carbon Cycles

Changye Qian

College of Environmental Science and Engineering, Southwest Jiaotong University, Chengdu, China
1806880866@qq.com

Abstract. Anthropogenic emissions, as well as the ever-growing rate of climate change, enter into a global carbon cycle, which lies at the core of the climatic regulation of the planet. Although terrestrial and oceanic systems have in the past played a key carbon sink role, current evidence indicates that the ability of these systems to absorb carbon is being nullified by a complicated mixture of human interference combined with climate change-related feedback processes. It has been noted, in this paper, that the underlying mechanisms between anthropogenic emissions and climate change leading to modification of the carbon cycle on land and oceanic platforms have been investigated. The research assesses the processes that cause change in carbon uptake, storage and release, in a critical way that reflects on the new and recent advances in the study of Earth system modeling, satellite remote sensing, and observational studies. According to the analysis, the signs of stability weakening appear on both oceanic and terrestrial carbon sinks, and the risks of tipping points leading to the degradation of such sinks to sources are growing. The results highlight the seriously threatened state of the carbon cycle worldwide that necessitates better surveillance, flexible government, and policy action to protect the global carbon cycle integrity during temporary environmental variation.

Keywords: Carbon cycle, Anthropogenic emissions, Climate change, Ocean carbon sink, terrestrial carbon sink

1. Introduction

The biogeochemical carbon cycle orchestrates the transfer of carbon among atmospheric, oceanic, and terrestrial reservoirs, constituting Earth's fundamental climate regulatory mechanism. During the last 100 years, anthropogenic practices mainly the use of fossil fuels and land-use alteration contributed to the significant increase in the concentration of atmospheric carbon dioxide (CO_2) up to a record 419.2 ppm in 2023 [1]. This intensification has enhanced the greenhouse effect to cause global warming and consequent climate change. Dynamically, ocean and land systems have been significant in compensating these effects by taking up about 50 percent of evolved anthropogenic CO_2 emissions annually [2]. Nevertheless, recent reports point to the fact that various feedbacks associated with climate are damaging the effectiveness of these natural sinks, including the rise in

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.KA27649

the frequency of droughts, warming of the oceans, and their acidification. Such modifications do not only pose a threat to the stability of the carbon cycle but also pose serious uncertainties to projections of future climates. Despite advancements in Earth system models and remote sensing, which have narrowed knowledge gaps in feedback processes and regional limitations controlling carbon fluxes, significant uncertainties remain [3]. As one example, the resilience and resistance of the carbon sinks are becoming more variable and the likelihood of ecosystems reaching ecological thresholds that lead to sink sinks to sources is increasing. This study aims to provide a detailed assessment of recent trends, processes, and emerging risks by integrating the most current model outputs, satellite observations, and empirical analyses. The primary objectives are to inform climate policy, influence carbon management approaches, and identify future research priorities in an era of accelerated environmental change.

2. The global carbon cycle

The global climate system operates through continuous carbon cycling between atmospheric, oceanic, and terrestrial reservoirs, constituting Earth's primary regulatory mechanism. The carbon cycle forms part of the overall climate system of the planet mediating the flow of carbon between the atmosphere, the oceans, and the land. As shown in Figure 1, anthropogenic activities, particularly the upward trend of CO_2 concentration in the atmosphere due to the combustion of fossil fuel and change of land use, have led to a significant increase in atmospheric CO_2— the greenhouse effect and global warming. The accelerating trend of greenhouse gases can be illustrated with the use of the Keeling Curve that has been measuring the amount of CO_2 in the atmosphere since the 1960s [4]. Conventionally, 50 percent of the anthropogenic emissions of CO_2 are either taken up by land and ocean sinks, which retards the rate of climatic change [5].

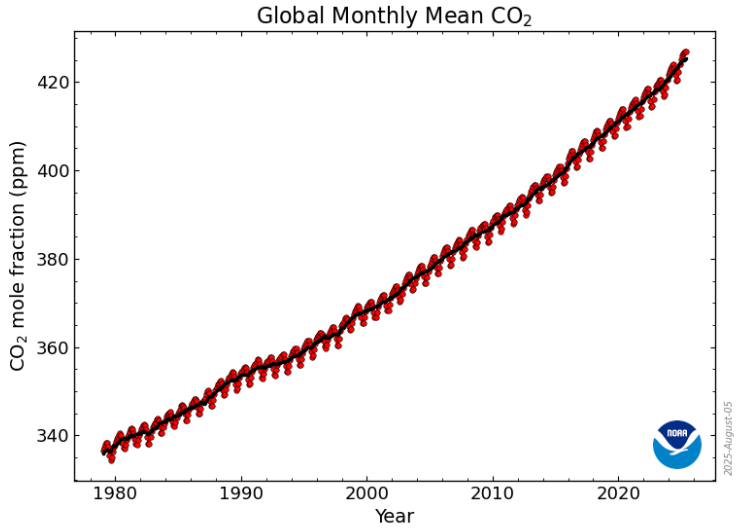

Figure 1. Global monthly CO_2 mean [5]

The closely coupled photosynthesis and respiration on land, solubility, and biological pumps in the ocean make up central processes that help us maintain this balance [6]. Nonetheless, this is not a balanced and unchangeable balance. Biogeochemical-climate feedback mechanisms dynamically modulate carbon fluxes, with permafrost thawing and ENSO variability being the most critical yet least understood pathways. The most notable feedbacks involve the release of methane from thawing

DOI: 10.54254/2755-2721/2026.KA27649

permafrost and the El Niño–Southern Oscillation (ENSO). Warmer temperatures in high-enough latitudes will cause thawing permafrost to release methane — a potent greenhouse gas — into the atmosphere; this can further hasten the warming effect. Recent research indicates that, if the current warming trend continues, permafrost regions could release up to 150 billion tons of carbon by 2100, with methane accounting for a significant portion of this release [7]. In contrast, ENSO events cause significant interannual variability in the global carbon cycle by altering temperature and precipitation patterns, which in turn affect the carbon uptake capabilities of terrestrial and ocean ecosystems. As an example, severe El Niños usually limit tropical forest sequestration and can cause more wildfires and droughts, which further contribute to further increases in atmospheric CO_2 concentrations [8]. An example of a feedback process is the discussion of the strength and endurance of the CO_2 fertilization impact. Recent data indicate that the positive effect of elevated CO_2 on plant growth—known as the CO_2 fertilization effect—has been declining. In Nature Climate Change, global terrestrial carbon uptake due to CO_2 fertilization has slowed in the past decade, primarily due to nutrient limitations (especially nitrogen and phosphorus) and increased environmental stressors such as drought and heatwaves [9]. This suggests that the land carbon sink may become less effective at offsetting emissions in the future. Similarly, oceanic uptake is also vulnerable to rising temperature-induced stratification, established solubility, and biological processes like phytoplankton productivity, which are sensitive to acidification and nutrient availability [10]. Even model projections have a variance range of as much as ±20 percent in ocean sink capacity by the year 2100, illustrating the uncertainty characterizing future trends [11].

2.1. Anthropogenic emissions: source, trends, and direct impacts

Human-made carbon emissions are mostly a result of the burning of fossil fuels, the production of cement, and the changing use of land, such as through deforestation and increased agricultural land. Worldwide, fossil fuels make up a large proportion of about 75 percent of emissions, whereas the other 25% combines land use change [12]. These emissions are also extremely unbalanced in terms of spatial distribution as industrialized as well as fast developing regions share a much larger share of the global total [13]. Despite mitigation efforts, anthropogenic emissions have continued to rise, driving atmospheric CO_2 concentrations to unprecedented levels. The effects of these emissions are in dimensional terms. High levels of CO_2 intensify the greenhouse effect that leads to warming and changes in the pattern of precipitation, which then influence the operation of the carbon sinks. Change in land use does not only mobilize stored carbon but it also lowers potential sequestration rates of the ecosystems, resulting in a positive feedback cycle that increases levels of CO_2 in the atmosphere [14]. Equilibrium Climate Sensitivity (ECS) models quantify the emission-warming relationship, yet their outputs remain highly sensitive to feedback assumptions and spatial variability. Further complicating the scenario, even if emissions ceased immediately, carbon cycle equilibration timescales ensure legacy effects would persist for decades to centuries [15].

2.2. Ocean carbon cycle response

Isolating the ocean from other provinces of the global carbon cycle is impossible since it serves as a huge reservoir, giving and taking carbon in the atmosphere and the biosphere. Presently, the ocean carries away an estimated 25 percent of the man-made CO_2 emissions annually, a way that has played a significant enactment in mediating the degree of atmospheric CO_2 rise and by extension global warming [12]. Nevertheless, the role of the ocean in carbon sink does not stay fixed; it

DOI: 10.54254/2755-2721/2026.KA27649

depends on the complex of physical, chemical, biological processes that are changed by climate change and humans.

2.2.1. Physical driver: warming and stratification

The ocean's capacity to absorb and store carbon is primarily driven by physical processes. The influence of climate change on the ocean's carbon sink is one of the most direct effects, with the concentration of CO_2 reflecting the impact of warming on its solubility. Empirical observations indicate that CO_2 becomes less soluble in warmer oceans, with a decrease of about 3 percent per 1°C rise in water temperature [16]. This implies that as the ocean warms, its ability to absorb atmospheric CO_2 is forever reduced, hence the predominance of emissions in the atmosphere and propagating climate change.

Surface warming, along with the freshening of ocean surfaces due to increased snow and ice melting, promotes ocean stratification and reduces solubility. Stratification is the process of developing layers in the ocean that has warm and lighter water on the top and colder and denser water on the bottom. Such stratification inhibits vertical mixing, which is crucial for nutrient transport from the deep ocean to the euphotic zone, where photosynthesis and biological carbon uptake occur [11]. Decreased mixing has the dual effect of reducing both nutrient availability and primary productivity and preventing the downward flux of carbon in consequence inhibiting the efficacy of what is colloquially termed the biological pump. The warming action combined with that of stratification therefore forms a major hazard in the ocean as a carbon sink and the possibility of generating positive feedbacks that make warming even stronger [10].

2.2.2. Biological drivers: acidification and phytoplankton dynamics

In addition to physical processes, biological processes are also crucial for the ocean's ability to capture carbon. The biological pump refers to the processes by which planktonic algae in the surface ocean capture CO_2 through photosynthesis, converting it into organic matter that can be exported to the deep ocean via sinking particles. This reaction is far more vulnerable to alteration of the ocean chemistry and ecology, especially the ones caused by human-generated CO_2 emissions. Another direct result of the rising amount of dissolved CO_2 in the oceans known as ocean acidification has become one of the greatest dangers to marine life and the effectiveness of the biological pump. Acidification raises the levels of acidity in the ocean reducing the number of available carbonate ions necessary to form calcium carbonate shells and skeletons of some creatures like coccolithophores, foraminifera, and a variety of zooplankton. Acidification of the laboratory and the field revealed that it suppresses the growth and calcification rates of these organisms at the expense of their ability to play a role in carbon export and long-term sequestration. The way of loss, or loss of calcifiers, may also cascade, impacting the food webs and ecosystem structure, further destabilizing the carbon cycle [17].

2.2.3. Frontier discovery: microbial communities in the ocean

Recent research has highlighted the increasing role of microbial communities in the ocean carbon cycle. Microbes, including bacteria and archaea, are now recognized as key drivers of carbon transformation and sequestration in marine environments. These communities mediate the decomposition of organic matter, influence the efficiency of the biological pump, and can even produce climate-relevant gases such as methane and nitrous oxide. Advances in metagenomics and

DOI: 10.54254/2755-2721/2026.KA27649

ocean observing systems have revealed that shifts in microbial community composition—driven by warming, acidification, and nutrient changes—can significantly alter the rates and pathways of carbon cycling in the ocean [18].

2.3. Regional variability and tipping point risks

The ocean carbon sink does not show the same proportionality all over the globe, but it is regionally more variable, which represents diversity in terms of physical circulation, biological productivity and climate forcing. High latitude regions, including the North Atlantic and the Southern Ocean, are especially significant in global carbon uptake because these cold surface waters, significant wind speeds, and active deep-water formations make them hotspots [11]. Nevertheless, the same regions are also those that are at risk of being affected by climate-based changes.

Observational data indicate a 15% reduction in North Atlantic carbon sink capacity (2000-2020), attributable to weakened overturning circulation and altered surface water properties [19]. This reduction is alarming due to the North Atlantic posing a major gateway through which anthropogenic carbon is transferred to the deep sea and its destabilization may have out of proportion effects on the overall carbon budget in the world. Likewise, up to 40% of the oceanic CO_2 uptake in the world occurs in the Southern Ocean which is both highly variable interannually, and sensitive to wind driven upwelling and sea ice processes [11].

Polar amplification refers to the phenomenon where temperature increases in polar regions are greater than the global average. This has profound implications for the carbon cycle, particularly in the Arctic and Antarctic. In the Arctic, rapid warming accelerates permafrost thaw, releasing large amounts of greenhouse gases, including CO_2 and methane, from previously frozen soils. In the Southern Ocean, polar amplification affects sea ice extent, ocean circulation, and biological productivity, all of which influence regional and global carbon uptake. Polar amplification now constitutes a critical tipping element in the global carbon cycle, capable of activating self-reinforcing feedback loops that exacerbate climate change [20].

2.4. Terrestrial carbon cycle response

The terrestrial ecosystems, such as the forests, grasslands, wetlands, and soils, are the center of carbon circulation at various rates around the globe, serving as both the source and sink of the gaseous carbon dioxide, otherwise known as CO_2, in the atmosphere. In the past, these sinks have taken up a large proportion of anthropogenic emissions hence curbing the rate of change in climate [12]. But the ability of terrestrial ecosystems to store carbon is increasingly jeopardized by a synergy of biogeochemical, climate-induced disturbances and land-use transition.

2.4.1. CO_2 fertilization and nutrient limitation

The so-called "CO_2 fertilization effect" is defined as the stimulation of photosynthesis and growth in plants when the concentration of CO_2 in the atmosphere increases. This has been one of the major terrestrial carbon sinks over the past decades where the global satellite and ground measurements have come up with the greening trends [21]. Yet, the viability of CO_2 fertilization over the long-term has become dubious. Although elevated CO_2 has the potential to have a positive impact on photosynthesis rates and water-use efficiency, the effect depends on the availability of critical nutrients (mostly nitrogen (N) and phosphorus (P)) and water supply.

DOI: 10.54254/2755-2721/2026.KA27649

Recent large-scale experiments and ecosystem modeling demonstrate that nutrient availability fundamentally constrains both the magnitude and temporal persistence of the CO_2 fertilization effect. As an illustration, nutrient limitation has been shown to potentially lead to up to a 30 percent reduction in the long-term carbon sink capacity of temperate forests, an observation supported by both field-based and whole earth modeling studies [6]. Recent research continues to reinforce and refine this finding. For example, nitrogen and phosphorus limitations have constrained the terrestrial carbon sink more than previously estimated, with some temperate forests showing reductions in carbon uptake of 20–40% under elevated CO_2 conditions due to nutrient scarcity [22]. Similarly, Nutrient availability remains a dominant control on the magnitude and persistence of the CO_2 fertilization effect in forests worldwide [23]. Further CO_2 might not increase biomass in nutrient-deficient areas, because such plants cannot utilise the nutrients necessary to enable prolonged growth.

2.4.2. Frontier discovery: microbial communities in terrestrial systems

Recent discoveries have shown that soil microbial communities play a pivotal role in regulating terrestrial carbon cycling. Microbes are responsible for the decomposition of organic matter and the release or sequestration of carbon in soils. Climate-driven alterations in temperature, moisture, and nutrient availability induce microbial community restructuring, with documented cases of accelerated soil carbon mineralization under warming conditions. The expansion of microbial activity in thawing permafrost and warming soils is now recognized as a key feedback that could increase atmospheric greenhouse gas concentrations [24].

2.4.3. Extreme events and disturbances

The increased frequency and intensity of extreme events, such as droughts, heatwaves, storms, and wildfires, are exacerbating and threatening the stability of terrestrial carbon sinks. These disturbances may cause sudden and significant depletion of sequestered carbon, so years or even decades of carbon sequestration may be easily counteracted. For instance, the 2019-2020 Australian bushfires released an estimated 715 million tonnes (Mt) of CO_2, as evidenced by satellite and atmospheric inversion data, effectively counteracting five years of regional forest carbon uptake [18].

Immediate carbon emissions generated in the process of combustion and putrefaction are the results of extreme events. Additionally, they could also have long-term effects on ecosystem structure and functions. As an example, extreme dry spells may cause massive death of trees, decreasing forest biomass and changing the direction of a succession [19]. Chronic disturbances can cause ecosystems to shift from carbon sinks to sources, particularly when these disturbances are slow and incomplete. Furthermore, climate change is likely to exacerbate the occurrence of concurrent events, such as droughts and heatwaves, which may have synergistic effects on carbon cycling and ecosystem resilience [12]. Such trends reveal the vulnerability of terrestrial carbon sinks to climatic extremes and how they should be managed using adaptivity since it enhances their resilience.

3. Conclusion

The global carbon cycle continues to play a central role in climate regulation on the planet, although this stability is now under siege by the large volume of anthropogenic activities and the associated

DOI: 10.54254/2755-2721/2026.KA27649

complex climate feedbacks. This review demonstrates how anthropogenic emissions, primarily from fossil fuel use and land-use change, have disrupted the natural carbon exchange balance among the atmosphere, oceans, and land ecosystems. The natural sinks (oceans, forests, and soils) historically performed an essential part of reducing the emissions, but now due to the warming and acidification of the ocean and nutrient shortages in soil habitats and the rising frequency of extreme events, they are acting as obstacles to this reduction. More recent studies of microbial communities and of polar amplification affirm that carbon cycling activity is dynamic and intrinsically linked and subject to sudden and unpredictable variation. Such observations stress the imperativeness of productive climate policy and adaptive management practices to make the carbon sinks more resilient and help preserve the stability of the global climate system.

Acknowledgement

I would like to express profound gratitude to my college professors and university teachers who have helped me throughout all the steps of writing this thesis. In addition, I wish to give gratitude to all my friends and parents, who have encouraged and supported me. I would not have been able to write my thesis without all their educating and wonderful goodness.

References

[1] M. Kabir, U. Habiba, M. Z. Iqbal, M. Shafiq, Z. R. Farooqi, A. Shah W. Khan. 2023. Impacts of anthropogenic activities & climate change resulting from increasing concentration of carbon dioxide on environment in 21st century: A critical review. In IOP Conference Series: Earth and Environmental Science, Vol. 1194, No. 1, p. 012010. IOP Publishing.
[2] B. Wang, L. Hua, H. Mei, X. Wu, Y. Kang, N. Zhao. 2024. Impact of climate change on the dynamic processes of marine environment and feedback mechanisms: An overview. Archives of Computational Methods in Engineering, 31(6), 3377–3408.
[3] M. Dai, J. Su, Y. Zhao, E. E. Hofmann, Z. Cao, W. J. Cai, Z. Wang. 2022. Carbon fluxes in the coastal ocean: Synthesis, boundary processes, and future trends. Annual Review of Earth and Planetary Sciences, 50(1), 593-626.
[4] C. D. Keeling, T. P. Whorf, M. Wahlen, J. van der Plicht. 1995. Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. Nature, 375, 666–670.
[5] X. Lan, P. Tans K. W. Thoning. 2025. Trends in globally-averaged CO_2 determined from NOAA Global Monitoring Laboratory measurements. doi: 10.15138/9N0H-ZH07.
[6] J. L. Sarmiento, N. 2002. Gruber. Sinks for anthropogenic carbon. Physics Today, 55(8), 30–36.
[7] A. Demetriades-Frigård. 2025. Chemical mechanisms and environmental consequences of greenhouse gas emissions from thawing permafrost—a review of carbon dioxide (CO_2) and methane (CH_4) emissions and their role in accelerating permafrost thaw feedback loops and global warming. Bachelor's thesis, NTNU.
[8] E. Berenguer, G. D. Lennox, J. Ferreira, Y. Malhi, L. E. Aragão, J. R. Barreto, et al. 2021. Tracking the impacts of El Niño drought and fire in human-modified Amazonian forests. Proceedings of the National Academy of Sciences, 118(30), e2019377118.
[9] J. Peñuelas, P. Ciais, J. G. Canadell, I. A. Janssens, M. Fernández-Martínez, J. Carnicer, et al. 2017. Shifting from a fertilization-dominated to a warming-dominated period. Nature Ecology & Evolution, 21(10), 1438–1445.
[10] D. Carroll, D. Menemenlis, S. Dutkiewicz, J. M. Lauderdale, J. F. Adkins, et al. 2022. Attribution of space-time variability in global-ocean dissolved inorganic carbon. Global Biogeochemical Cycles, 36(3), e2021GB007162.
[11] N. Gruber, D. C. E. Bakker, T. DeVries, L. Gregor, J. Hauck, et al. 2023. Trends and variability in the ocean carbon sink. Nature Reviews Earth & Environment, 4(2), 119–134.
[12] P. Friedlingstein, M. W. Jones, M. O'Sullivan, et al. 2023. Global Carbon Budget 2023. Earth System Science Data, 15, 5301–5365.
[13] S. Sitch, P. Friedlingstein, N. Gruber, et al. 2015. Recent trends and drivers of regional sources and sinks of carbon dioxide. Biogeosciences, 12, 653–679.
[14] L. V. Gatti, L. S. Basso, J. B. Miller, et al. 2021. Amazonia as a carbon source linked to deforestation and climate change. Nature, 595, 388–393.
[15] IPCC. Climate Change. 2021: The Physical Science Basis. Cambridge University Press.

DOI: 10.54254/2755-2721/2026.KA27649

[16] R. Wanninkhof, et al. 2013. Global ocean carbon uptake: magnitude, variability and trends. Geophysical Research Letters, 40(9), 2154–2160.
[17] J. J. Middelburg, K. Soetaert, M. Hagens. 2020. Ocean alkalinity, buffering and biogeochemical processes. Reviews of Geophysics, 58(3), e2019RG000681.
[18] D. A. Hutchins, D. G. Capone. 2022. The marine nitrogen cycle: new developments and global change. Nature Reviews Microbiology, 20(7), 401–414.
[19] P. R. Halloran, B. B. B. Booth, C. D. Jones, F. H. Lambert, D. J. McNeall, et al. 2015. The mechanisms of North Atlantic CO_2 uptake in a large Earth System Model ensemble. Biogeosciences, 12(14), 4497–4508.
[20] IPCC. Sixth Assessment Report: Climate Change. 2023. Intergovernmental Panel on Climate Change, 2023.
[21] S. Wang, Y. Zhang, W. Ju, et al. 2020. Recent global decline of CO_2 fertilization effects on vegetation photosynthesis. Science, 370(6522), 1295–1300.
[22] E. Du, C. Terrer, A. F. Pellegrini, A. Ahlström, C. J. van Lissa, X. Zhao, et al. 2020. Global patterns of terrestrial nitrogen and phosphorus limitation. Nature Geoscience, 13(3), 221–226.
[23] P. Baldrian, R. López-Mondéjar, P. Kohout. 2023. Forest microbiome and global change. Nature Reviews Microbiology, 21(8), 487–501.
[24] Y. Song, X. Cheng, C. Song, M. Li, S. Gao, Z. Liu, et al. 2022. Soil CO_2 and N_2O emissions and microbial abundances altered by temperature rise and nitrogen addition in active-layer soils of permafrost peatland. Frontiers in Microbiology, 13, 1093487.