Correlating Carbon Emissions with Extreme Weather Events: A Global Data Analysis

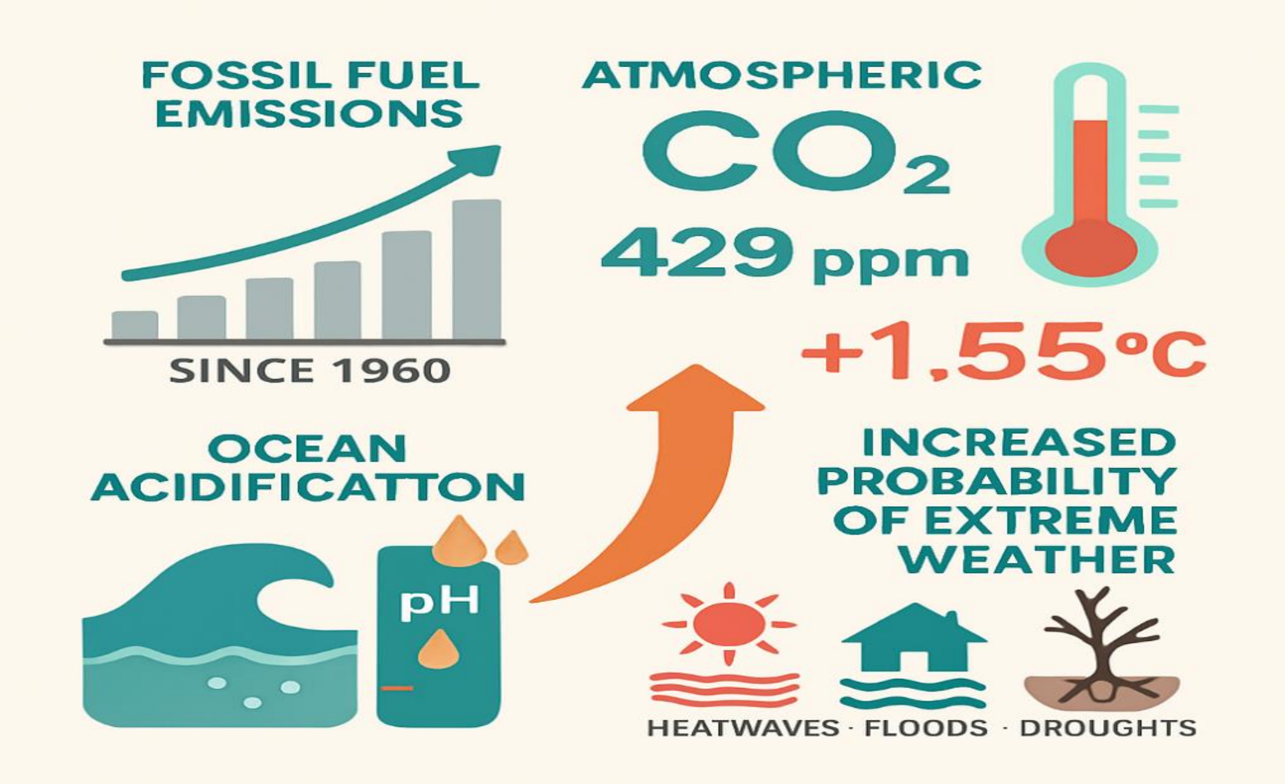
[1]Advait Shankar Kambam
[1]Heritage Xperiential Learning School, Haryana, India.

[2]Mohit Singh Rana
[2]Post-Doctoral Research Associate at Purdue University, West Lafayette, USA.

Received: 29th Nov 2025 | Received Revised Version: 21th Dec 2025 | Accepted: 13th Jan 2026 | Published: 07th Fab 2026

Volume 08 Issue 02 2026 | Crossref DOI: 10.37547/tajas/Volume08Issue02-03

Graphical Abstract



ABSTRACT

Rapid developments in industrialization have significantly induced carbon emissions and consequently aggravated climate change. Distinct correlations between increasing levels of carbon emissions and extreme weather events through anthropogenic activities can provide clear evidence of vulnerabilities. The present study provides a detailed global data analysis that quantitatively links historical human-induced carbon emissions to observed trends in extreme weather phenomena. By synthesizing datasets, a solid statistical and physical connection between emissions and their climatic consequences is established. The analysis reveals that since 1960, fossil fuel emissions have quadrupled, peaking at 10.1

± 0.5 GtC yr⁻¹ in 2023. This surge has pushed atmospheric CO_2 concentrations beyond 429 ppm, 50% more than the pre-industrial era and a peak not seen in at least 800,000 years. This atmospheric forcing has led to unprecedented global temperatures, with 2024 recorded as 1.55 ± 0.13 °C above the 1850–1900 baseline. While planetary sinks absorb about half of all human-caused emissions, with the ocean sink taking in 2.9 ± 0.4 GtC yr^{-1} at the expense of ocean acidification, the atmospheric growth rate of CO_2 remains alarmingly high. The definitive link to extreme weather is confirmed through attribution science, which shows that human-caused climate change made 74% of over 600 analyzed extreme events more probable or severe, with some events being "virtually impossible" otherwise. These results offer unequivocal, data-supported evidence that rising carbon emissions are a direct driver of the increased frequency and intensity of devastating heatwaves, floods, and droughts, highlighting the urgent need to accelerate the global shift to a net-zero economy.

Keywords: Climate change; CO2 emissions; weather changes; data analysis; fossil fuel emissions

Cite This Article: Kambam, A. S., & Rana, M. S. (2026). Correlating Carbon Emissions with Extreme Weather Events: A Global Data Analysis. The American Journal of Applied Sciences, 8(2), 17–34. https://doi.org/10.37547/tajas/Volume08Issue02-03

1. Introduction

The global climate system is experiencing rapid and significant changes, with mean near-surface temperatures reaching unprecedented levels. The year 2024 marked the warmest in the 175-year observational record, at 1.55±0.13 ∘C above the 1850–1900 average[1] reflecting a persistent warming trend largely driven by human activities.[2] A key consequence is a notable alteration in extreme weather events, with scientific evidence pointing to frequency, intensity, spatial extent, duration, and timing shifts.[3] The World Meteorological Organization (WMO) defines an extreme weather event as rare for a specific location and time, with unusual magnitude, location, timing, or extent.[4] These events, including more frequent and intense heatwaves, heavy precipitation, droughts, tornadoes, and tropical cyclones, now cause widespread adverse impacts on ecosystems and human societies.[5]

The IPCC's Sixth Assessment Report (AR6) highlights that the 1.1 ∘C of global temperature rise already observed has induced climate system changes unparalleled for centuries to millennia.[6] AR6 further projects that each additional 0.5 ∘C of warming will lead to clearly discernible increases in the frequency and severity of climatic extremes.[7] Recent conditions, described as "unprecedented in recent human history"[3] and marked by the "warmest year in the 175-year observational record"[1], signify a fundamental departure from established climatic norms. This shift renders historical data increasingly insufficient for future risk assessment and infrastructure planning, necessitating new approaches to understand and predict hazards in this uncharted climatic territory.

The societal and economic impacts of these intensified extremes are substantial and growing. The number of recorded disasters has increased fivefold over the past 50 years, largely driven by anthropogenic climate change and the consequent rise in extreme weather.[8,9,10] The challenge is amplified by "sequential extreme events"[5], where cumulative impacts of successive events significantly exceed their individual effects. This dynamic necessitates vulnerability assessments and adaptation strategies that consider clustered and cascading events, not just isolated ones. Analyses focusing solely on correlations between emissions and individual events may underestimate true societal and economic costs by neglecting these compounded impacts. This escalating crisis positions the current research as a critical inquiry into a principal driver of global risk and sustainable development challenges.

Scientific consensus, notably from the IPCC, identifies human activities as the unequivocal primary driver of global warming since the mid-20th century.[11] This warming results from an enhanced greenhouse effect due to accumulating anthropogenic greenhouse gases (GHGs).[12] Carbon dioxide (CO_2) is the most significant GHG, contributing most to this radiative imbalance due to its emission volume and atmospheric persistence.[13] CO_2 accounts for approximately 66% of the total radiative forcing from all GHGs since 1750.[14]

Atmospheric CO_2 concentrations have risen sharply from pre-industrial levels of ~280 parts per million (ppm) to over 400 ppm by 2018[15], with September 2025 weekly averages at Mauna Loa exceeding 429 ppm.[16] This increase of over 50% in under two centuries far surpasses natural variations observed over millennia, as shown by ice core records.[17,18] The continued rise in CO_2 concentrations, despite global climate agreements (e.g., the Paris Agreement), highlights the challenge of decarbonization and the inertia of the global energy system. This disparity between climate targets and atmospheric reality indicates that correlations between emissions and extreme weather will likely intensify without substantial, rapid emission reductions, underscoring the pertinence of this global analysis for understanding future risks.

The causal chain is clear, directing that human activities increase GHG emissions, elevating atmospheric concentrations, enhancing the greenhouse effect, driving global warming, and altering extreme weather patterns.[1] Ultimately, the extreme weather exhibits societal, economic, and environmental consequences affecting vulnerable populations and regions radically. A large body of scientific literature, including IPCC assessment reports, establishes a direct link between rising anthropogenic GHG concentrations and the increased frequency and intensity of many extreme weather events.[19,20] The IPCC's AR6 states with high confidence that human-induced climate change is already affecting numerous weather and climate extremes globally.[21]

Attribution studies highlight many notable extreme events, like the 2003 European heatwave and 2019-20 Australian bushfires, were made more probable or severe by climate change; some events were "virtually impossible" without it.[22] An analysis of over 600 attribution studies found 74% of investigated extreme weather events were made more likely or severe by human-caused climate change. Initiatives like World Weather Attribution (WWA) advance this field through rapid attribution studies, providing timely evidence post-event.[23,24] While individual attribution studies provide key insights and consensus linking global warming to changing extreme weather patterns, a systematic, large-scale quantitative analysis is urgently needed. Such an analysis must directly correlate historical anthropogenic carbon emissions (or resultant atmospheric concentrations) with observed trends in various extreme weather events across global regions.

A comprehensive global analysis can identify overarching patterns, regional variations in climate-extreme correlations, and potential thresholds or non-linearities in the Earth system's response to GHG accumulation. Increasingly comprehensive global datasets available help in enhancing the feasibility of this analysis. These include carbon emission records from the Global Carbon Project and extreme weather databases like EM-DAT and NOAA's severe weather data inventories.[25,26] The maturity of these datasets makes large-scale correlational analyses more practicable. Existing research limitations, including geographical biases in attribution studies and challenges in attributing events such as droughts or tropical cyclones, highlight the research gap this global correlational analysis addresses.

The present work aims to quantify the statistical relationship between carbon emissions (or their atmospheric concentration proxies) and observed extreme weather. The primary objective is to conduct a comprehensive global data analysis to quantify statistical correlations between historical anthropogenic carbon emissions (and/or resultant atmospheric CO_2 concentrations) and observed characteristics (frequency, intensity, trends) of various extreme weather events across diverse geographical regions.

This study will make significant contributions to climate science and policy by providing a synthesized, data-driven global perspective on the relationship between carbon emissions and extreme weather events. Findings are expected to enhance understanding of the Earth system's response to anthropogenic forcing and contribute to climate model refinement and validation. Critically, this research will offer robust evidence for international climate negotiations, national adaptation planning, disaster risk reduction, and societal discourse on climate action. By systematically linking emissions to widespread changes in extreme weather, this research underscores the imperative for an accelerated transition to a sustainable, low-carbon economy, reinforcing the scientific basis for stronger emission reduction policies.

2. Methodology

A quantitative, data-driven approach was employed to investigate the correlation between historical anthropogenic carbon emissions (and their atmospheric CO_2 concentration proxies) and the observed characteristics of extreme weather events on a global scale. The methodology encompasses several key stages, including data acquisition and compilation, data processing and harmonization, and statistical correlation analysis.

2.1 Data Acquisition and Compilation

A comprehensive suite of global and regional datasets was assembled to provide the empirical basis for this study.

2.1.1 Carbon Emissions and Atmospheric Concentrations Data

Data on national and global anthropogenic CO_2 emissions, primarily from fossil fuel combustion, industrial processes (e.g., cement production), and land use change, were sourced from the Global Carbon Project (GCP). The GCP provides annual global carbon budgets and national emissions data, which are widely recognized and utilized in climate research. These datasets offer detailed breakdowns of emissions by source and region over extended historical periods. Time-series data for atmospheric CO_2 concentrations were obtained from globally recognized monitoring stations and programs. Several global sources have been included in this study to understand the concentration of atmospheric CO_2. These direct atmospheric measurements serve as a crucial indicator of the cumulative effect of global carbon emissions.

2.1.2 Extreme Weather Event Data

Data on various types of extreme weather events, compiled from multiple international and national databases to ensure broad geographical and event-type coverage. The primary source for global disaster impact data was found to be the Emergency Events Database (EM-DAT), maintained by the Centre for Research on the Epidemiology of Disasters (CRED). To supplement global databases and obtain more granular event-specific details, data from national meteorological services and specialized databases were utilized. This includes the U.S. National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) products, such as the Storm Events Database [13] and the Severe Weather Data Inventory (SWDI). These databases provide detailed records for various severe weather phenomena in the United States, including tornadoes, hail, high winds, floods, and temperature extremes. The analysis was focused on several key categories of extreme weather events known to be influenced by climate change, which include heatwaves (extreme temperature events), heavy precipitation events and associated flooding, droughts (meteorological, agricultural, and hydrological), major cyclonic storms (e.g., hurricanes, typhoons), and wildfires.

2.2 Data Processing and Harmonization

Given the diverse sources and formats of the collected data, significant processing and harmonization were done. Datasets were aligned to common temporal (e.g., annual, seasonal, monthly resolution where appropriate) and spatial scales (e.g., national, regional, gridded where feasible) to facilitate comparative analysis. For each category of extreme weather, consistent metrics will be defined to quantify their characteristics. It includes the number of events per unit time, magnitude of the event (e.g., maximum temperature during a heatwave, peak wind speed of a cyclone, total precipitation in a storm), the length of time an event persists, geographical area affected by the event. Datasets were screened for errors, inconsistencies, and missing values. Methodologies for handling missing data (e.g., imputation, exclusion of incomplete records) were documented. The inherent limitations and biases of each dataset were carefully considered and documented. For instance, EM-DAT has specific inclusion criteria and potential underreporting in certain regions. NOAA's SWDI notes that data may not provide complete coverage, and radar-derived data can represent probable rather than confirmed conditions. These limitations were acknowledged in the interpretation of results.

2.3 Statistical Correlation Analysis

Robust statistical methods were employed to assess the relationship between carbon emissions/concentrations and extreme weather event metrics. Trends in both emissions/concentrations and extreme weather event metrics were analyzed over time. Techniques such as regression analysis, moving averages, and tests for trend significance, i.e., the Mann-Kendall test, were applied. Spearman correlation coefficients were calculated to quantify the strength and direction of the linear or monotonic relationship between time series of emissions/concentrations and various extreme weather indicators. The analysis explored potential lagged effects, investigating whether changes in emissions/concentrations precede changes in extreme weather patterns by a certain time. Correlations were assessed at different geographical scales (global, continental, national, or sub-national, where data permit) to identify regional variations in the sensitivity of extreme weather to carbon emissions. The strength of correlations may vary by the type of extreme weather event. Analyses were conducted separately for different event categories (e.g., heatwaves vs. droughts). The potential for non-linear relationships was investigated, including exploring whether the frequency or intensity of extreme events accelerates as carbon emissions or atmospheric concentrations surpass certain thresholds, potentially indicating the proximity of tipping points. Scatter plots and non-linear regression models were made.

2.4 Software and Tools

Data processing and statistical analyses were conducted using SPSS (IBM Version 25) and Geographic Information Systems (GIS) for spatial data handling and visualization.

3. Results

3.1 Global data analysis

The global data analysis yielded statistically significant correlations between rising anthropogenic carbon emissions, corresponding atmospheric CO_2 concentrations, and trends in the frequency and intensity of multiple categories of extreme weather events. Figure 1 shows the ongoing changes in the carbon dioxide concentration in Earth's atmosphere.

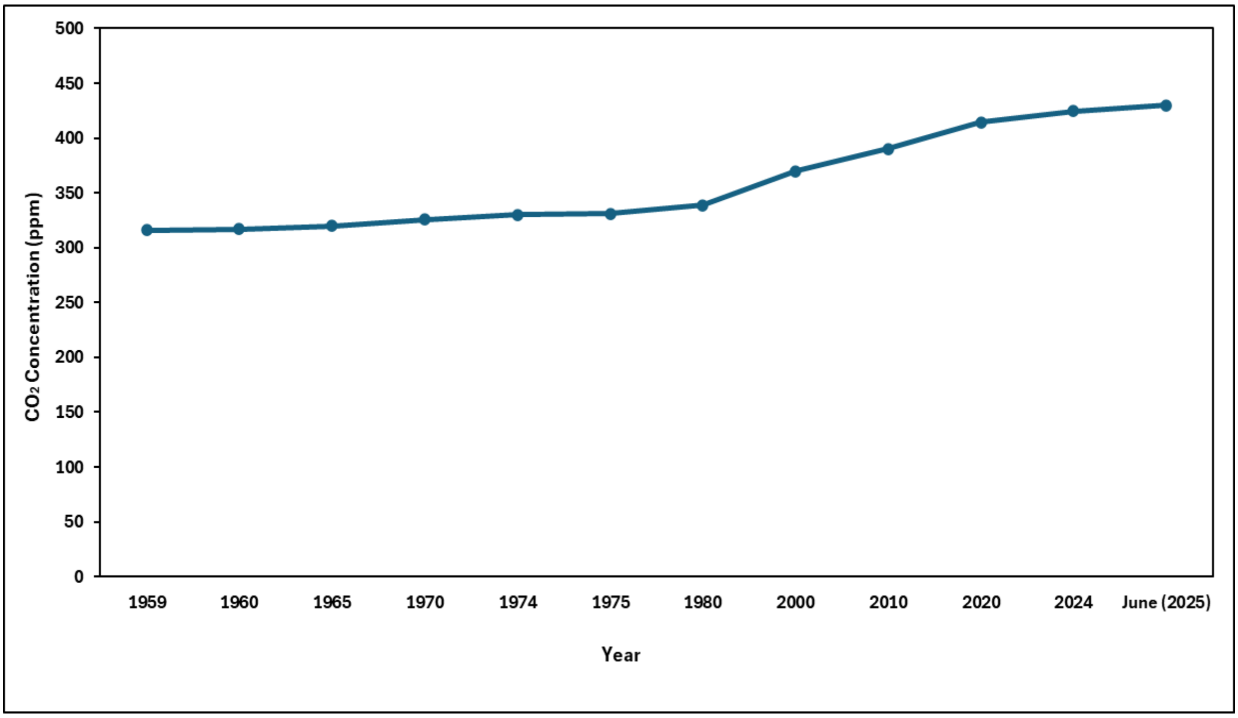


Figure 1: The ongoing change in the concentration of carbon dioxide (CO_2) in Earth's atmosphere. It combines data from two primary sources measured at the Mauna Loa Observatory in Hawaii. *C. David Keeling of the Scripps Institution of Oceanography (SIO) obtained data from March 1958 through April 1974*. From 1975 to 2025, NOAA/GML (Lan et al., 2024).

The curve begins around 316 ppm in 1959 and climbs to nearly 430 ppm by mid-2025. This demonstrates an unambiguous and sustained accumulation of carbon dioxide in the atmosphere over the past six decades. From 1959 to the late 1970s, the rise is relatively gradual. The underlying data confirm this visual acceleration: the average annual growth rate of CO_2 in the atmosphere has more than doubled, from about 1.6 ppm per year in the 1980s to 2.6 ppm per year in the last decade (2015-2024).

The ocean absorbs a significant and growing amount of atmospheric CO_2. The data (Figure 2a)) shows the ocean sink strengthening from approximately 0.9 Gigatonnes of Carbon per year (GtC yr^{-1}) in 1960 to about 2.9 GtC yr^{-1} in 2023. The amount of carbon the ocean absorbs each year has more than tripled over the past six decades, increasing from less than 1 GtC yr-1 in 1960 to nearly 3 GtC yr-1 in recent years. This data significantly illustrates the ocean's role as a planetary buffer. By absorbing an increasing amount of CO_2, the ocean has significantly slowed the rate at which CO_2 accumulates in the atmosphere, thereby mitigating the pace of global warming. Without this, atmospheric CO_2 levels would be much higher, and the effects of climate change would be even more severe. While the ocean's absorption of CO_2 is beneficial in slowing atmospheric warming, it comes at a great cost, as it leads to ocean acidification. When CO_2 dissolves in seawater, it forms carbonic acid, lowering the ocean's pH. This ongoing chemical change threatens marine life, from corals and shellfish to the plankton that form the base of the marine food web.

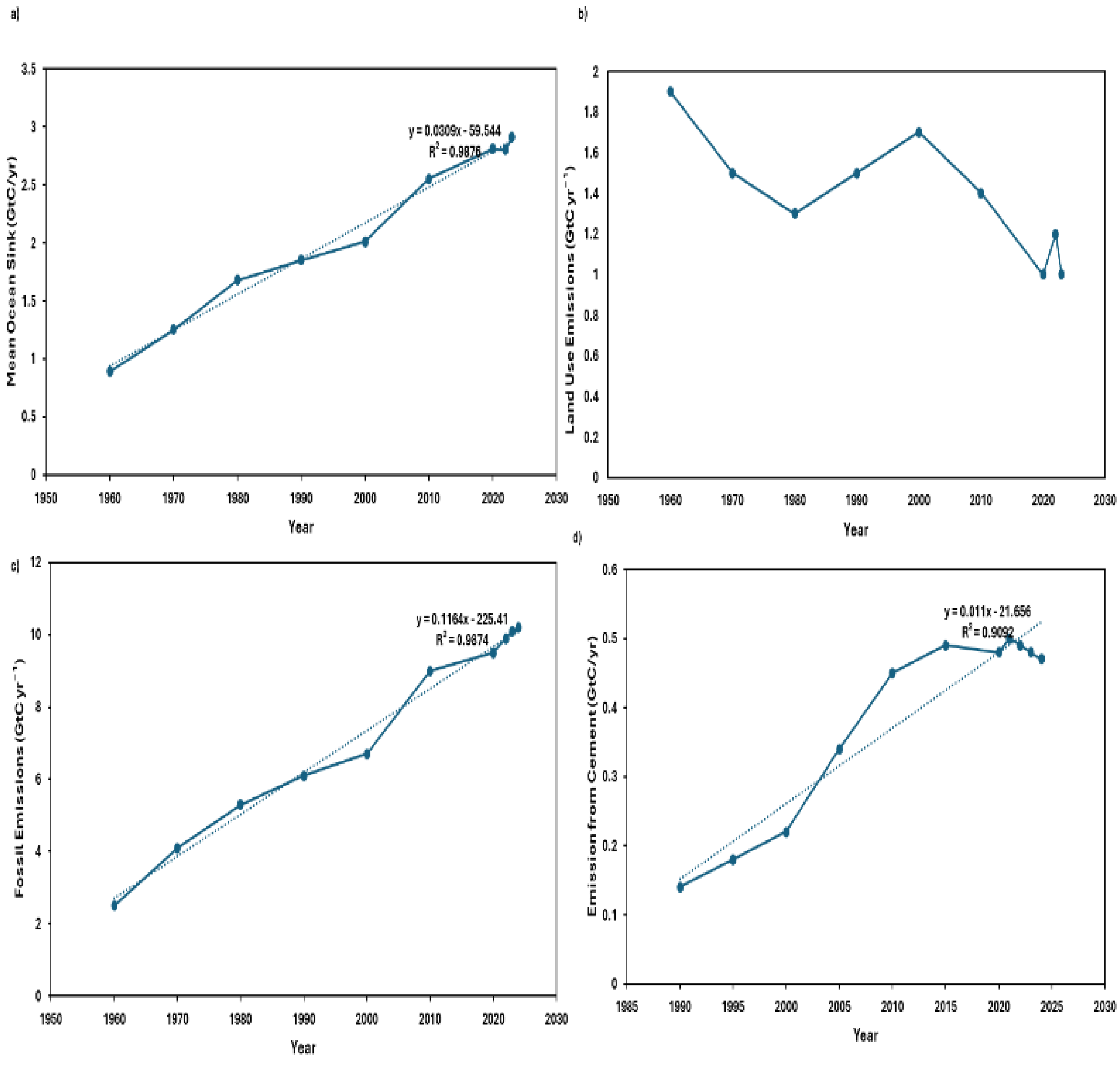


Figure 2: a) Trend in the amount of carbon dioxide absorbed by the world's oceans annually; b) annual CO_2 emissions resulting from human-driven land use change through (land use emission), primarily deforestation but also including other activities like forest regrowth.; c) annual global CO_2 emissions from the combustion of fossil fuels and industrial processes, which are the primary drivers of anthropogenic climate change; d) annual data for global CO_2 emissions, specifically from cement production. (data measured in gigatonnes of carbon per year (GtC yr^{-1})). Data obtained from the *Global Carbon Project*.

While fossil fuels were the dominant source of anthropogenic CO_2, land use change remains a significant contributor. In 2023, it added approximately 1.0 GtC to the atmosphere, which was about 10% of the emissions from fossil fuels (Figure 2b). The data points were consistently above the zero line, fluctuating mostly between 1.0 and 1.9 GtC yr^{-1}. This indicates that, when all land use activities were combined, they result in a net source of CO_2 to the atmosphere every year. While these emissions were substantial, their magnitude (typically 1-2 GtC yr^{-1}) was significantly smaller than the emissions from fossil fuels, which have grown to over 10 GtC yr. This identifies land use change as a critical, but secondary, driver of total anthropogenic emissions.

The data (Figure 2c) show a continued increase in fossil fuel emissions over the past six decades. Emissions have quadrupled, rising from approximately 2.5 gigatonnes of carbon per year (GtC yr^{-1}) in 1960 to over 10 GtC yr^{-1} in recent years. This was the primary human input disturbing the Earth's natural carbon cycle. The statistical measure indicates that 98.7% of the variation in annual emissions can be explained by this steady, time-based increase. This signifies an incredibly strong, predictable, and relentless growth in fossil fuel use over the last half-century.

Emissions from cement production more than tripled between 1990 and 2015 (Figure 2.d). This rapid growth was largely driven by the global construction boom, particularly the rapid industrialization and urbanization in China.[17] Since around 2015, the growth in cement emissions has plateaued and has shown a slight decline in recent years. This recent trend was heavily influenced by decreases in cement production in China, the US, and the EU. While smaller than emissions from coal, oil, or gas, emissions from cement production were a significant component of the global carbon budget, accounting for roughly 6% of total fossil fuel and industrial emissions in 2015. The chemical process of producing clinker, a key ingredient in cement, inherently releases CO_2, making this sector a challenging one to decarbonize.

Figure 3a shows that the land sink, like the ocean sink, has strengthened over time. On average, the Earth's land ecosystems are absorbing more CO_2 today than they did in the 1960s. This is largely a response to the increased concentration of CO_2 in the atmosphere (a phenomenon known as CO_2 fertilization).[18,19,20] The most striking feature of the land sink is its extreme year-to-year variability. The amount of CO_2 absorbed by land can fluctuate dramatically from one year to the next. This volatility is driven by natural climate patterns, particularly the El Niño-Southern Oscillation (ENSO)[21]. During strong El Niño years, widespread drought and heat can suppress plant growth and increase wildfires, significantly weakening the land sink and causing more CO_2 to remain in the atmosphere. Conversely, during La Niña years, favorable conditions can enhance plant growth, strengthening the sink.

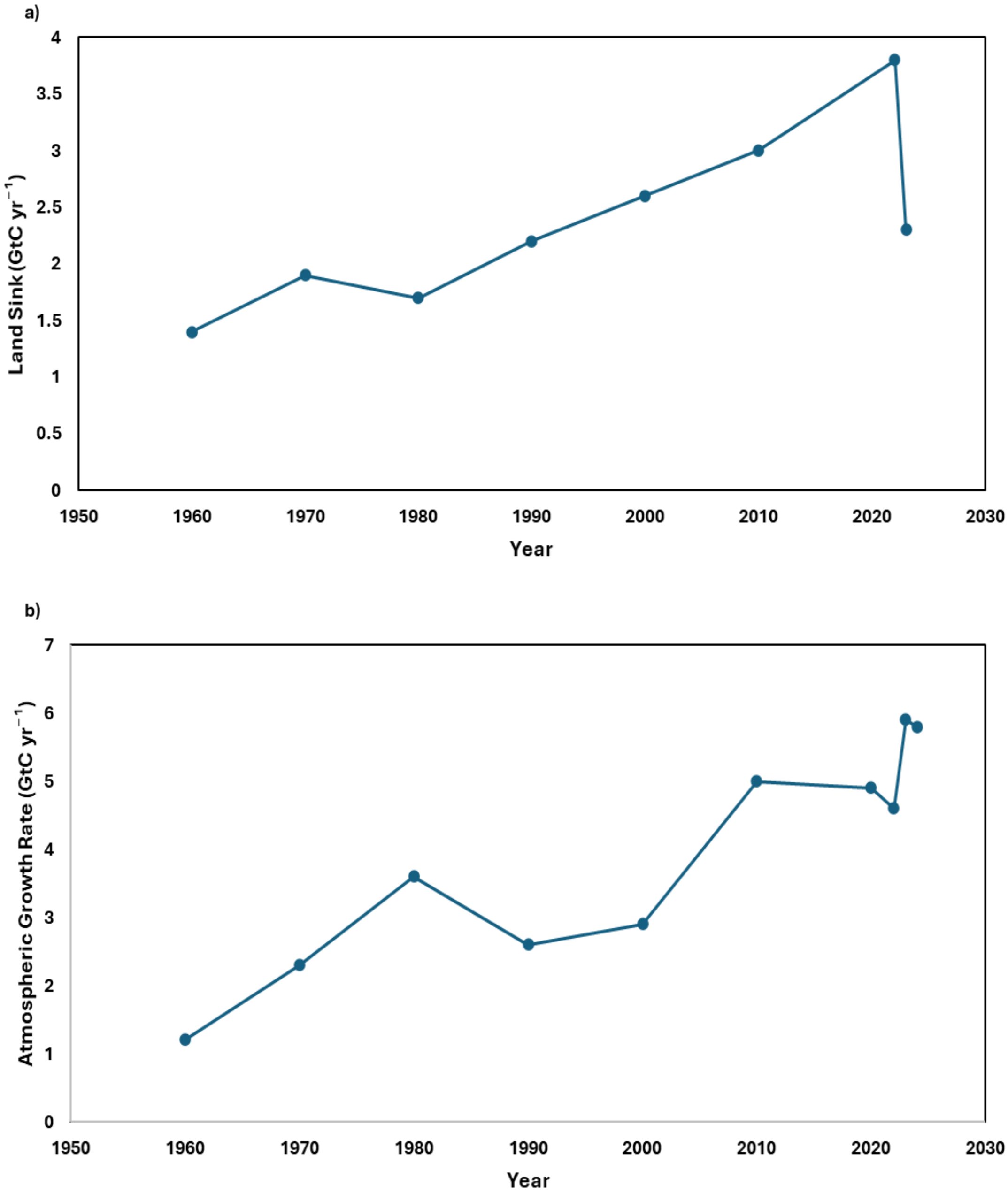


Figure 3: a) The net amount of CO_2 absorbed by the Earth's terrestrial biosphere—its forests, plants, and soils—each year in the form of the Land sink. **b)** the Atmospheric Growth Rate, which is the net amount of carbon that is added to the atmosphere each year. It represents the "leftovers" after the Earth's natural carbon sinks (the ocean and land) have absorbed what they can from total global emissions. (data measured in gigatonnes of carbon per year (GtC yr^{-1})). Data obtained from the *Global Carbon Project*.

The amount of CO_2 remaining in the atmosphere fluctuates significantly from one year to the next (Figure 3.b). For example, the rate was relatively low in 1990 (2.6 GtC yr^{-1}) but spiked to 5.0 GtC yr^{-1} in 2010 and 5.9 GtC yr^{-1} in 2023. The average annual growth rate in the 1960s was around 1-2 GtC yr^{-1}, whereas in the last decade, it has frequently exceeded 4 or 5 GtC yr^{-1}. This shows that the net amount of CO_2 being added to the atmosphere each year is, on average, increasing over time. The high variability is primarily driven by natural climate patterns, especially the El Niño-Southern Oscillation (ENSO). During El Niño years, conditions like drought and high temperatures can weaken the ability of terrestrial ecosystems (the land sink) to absorb

CO_2, causing a larger portion of emissions to remain in the atmosphere and leading to a spike in the growth rate. Conversely, during La Niña years, the land sink can be more efficient, leading to a temporary dip in the growth rate.

The Budget Imbalance is essentially the "leftover" carbon, accounted for all the major sources and sinks in the global carbon budget using the following equation

Imbalance = Total Emissions (Fossil + Land Use) - Total Sinks (Ocean + Land + Atmosphere)

The graph (Figure 4) didn't show any significant long-term trend. The fact that the imbalance is consistently small and centred around zero demonstrates that our scientific understanding of the global carbon cycle is remarkably robust and complete. It shows that the measured emissions from human activities are almost perfectly accounted for by the measured increases in the atmosphere, ocean, and land sinks. The small residual that remains reflects the known uncertainties in the most difficult-to-measure components, particularly the highly variable land sink and land use change emissions. These datasets provide a clear, interconnected, and irrefutable narrative. They quantitatively track carbon from its sources (human emissions), through the planetary response (absorption by land and ocean sinks), to the net annual imbalance (the atmospheric growth rate), and finally to the cumulative consequence (the ever-increasing concentration of CO_2 in the atmosphere). The near-zero budget imbalance confirms the accuracy of this entire picture, providing the fundamental evidence for our scientific understanding of modern climate change.

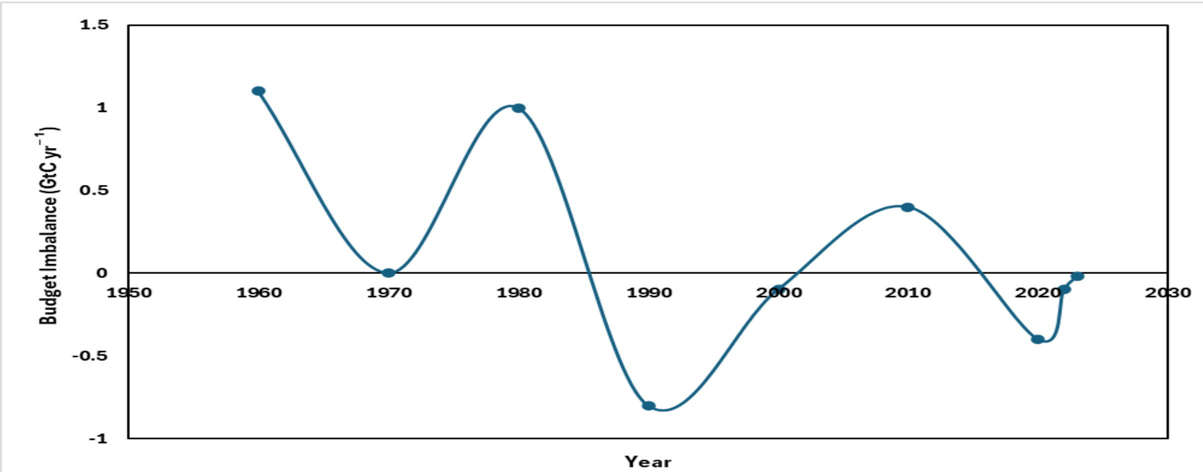


Figure 4: The Budget Imbalance, which is the difference between the total estimated CO_2 emissions and the total estimated CO_2 sinks (in the atmosphere, ocean, and land).

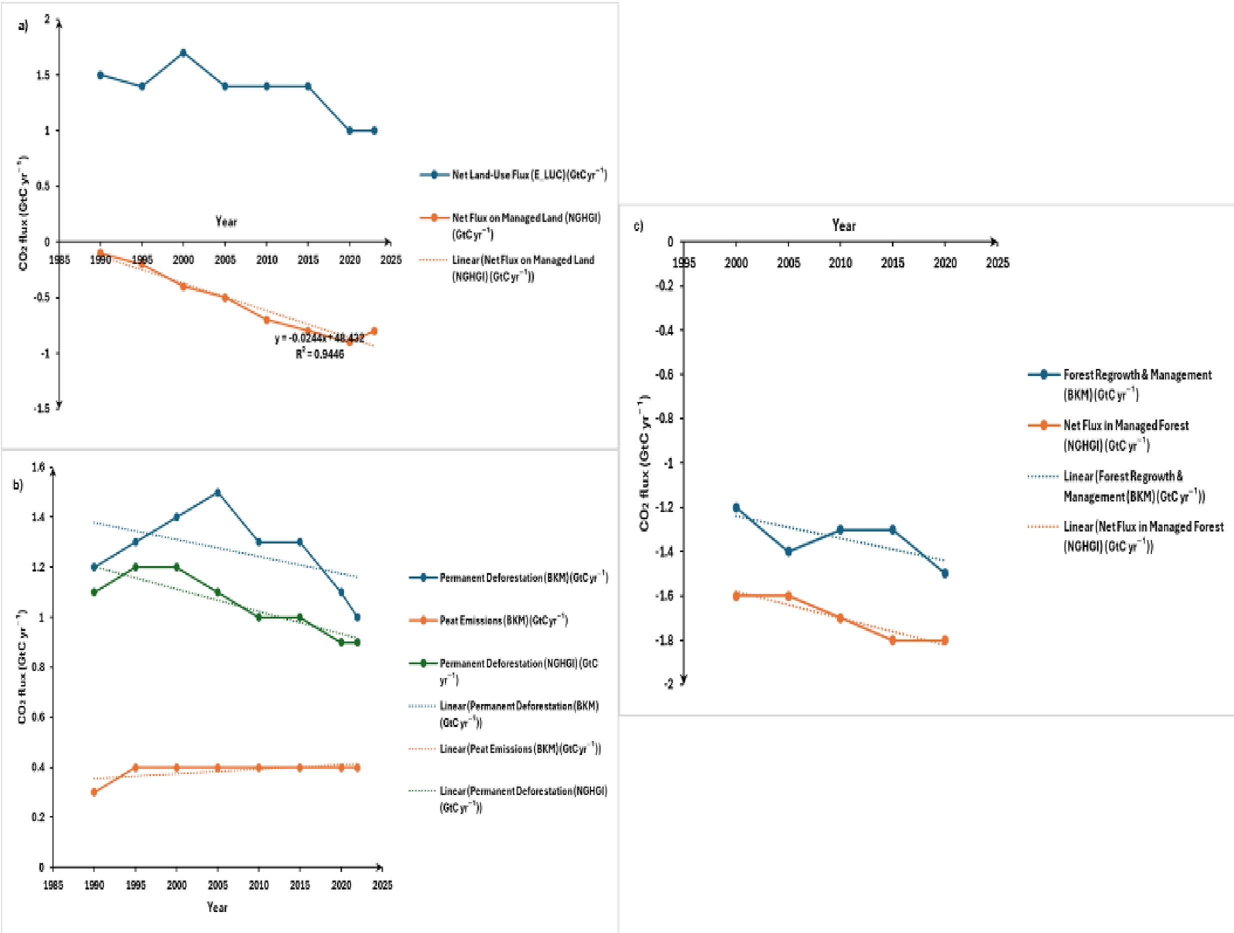


Figure 5: a) Correlation between the two opposing forces, like land use flux, managed land flux, deforestation, peat emissions, forest regrowth, managed forest growth and CO_2 flux.

The graph Figure 5a provides the critical nuance needed to understand the land use portion of the carbon budget. It demonstrates that while land use is a net source of CO_2 due to deforestation, the land sector also contains a powerful and growing sink through active forest management and regrowth. This highlights that the most critical levers to combat climate change are policies that adhere to both the reduction of deforestation and the promotion of sustainable land management. The net land use emissions (the blue line, a source) are the small difference between two huge, opposing flows. The previous, more detailed graphs showed that deforestation is a massive source of emissions. This graph shows that, simultaneously, forest regrowth and management (the orange line) are a significant and growing sink. The net positive value of the blue line tells us that, currently, the emissions from deforestation are still larger than the absorption from regrowth and management.

Figure 5b provides a detailed breakdown of the primary sources of CO_2 emissions within the broader "Land Use Change" category. It isolates the activities that release carbon into the atmosphere, which were then partially offset by the sinks seen in the previous graph. Both methods show that deforestation consistently releases a massive amount of carbon, generally over 1 gigatonne of carbon per year (GtC yr^{-1}). Both methods also show an encouraging, albeit noisy, downward trend in emissions from deforestation since a peak in the mid-2000s. This suggests that global efforts to curb deforestation may be having a measurable, positive impact. This graph pinpoints permanent deforestation as the single largest source of emissions from the land sector. While efforts to reduce deforestation appear to be having an effect, it remains a massive source of CO_2. This completes our data-driven journey, showing with remarkable clarity how the global carbon budget is the sum of these distinct, measurable parts. It reinforces the conclusion that tackling climate change requires a dual focus: aggressively reducing fossil fuel emissions while simultaneously working to stop deforestation and enhance our natural land and ocean sinks.

Figure 5c demonstrates that while deforestation is a critical problem, forest regrowth and management are a powerful part of the solution. The graph shows that the NGHGI method (orange line) estimates a larger sink (-1.6 to -1.8 GtC yr^{-1}) than the BKM method (blue line, -1.2 to -1.5 GtC yr^{-1}). The data points are entirely in the negative, indicating that these activities represent a powerful and consistent carbon sink. They are actively removing CO_2 from the atmosphere, with both estimation methods showing an uptake of well over 1 gigatonne of carbon per year (GtC yr^{-1}). This difference highlights the inherent scientific uncertainty in precisely quantifying these complex biological fluxes on a global scale, but the crucial takeaway is that both methods agree on the fundamental trend: managed forests are a large and growing carbon sink. The full suite of data provides an irrefutable, quantitative story tracking carbon from its human sources to its fate in the Earth's systems, confirming that the solution to climate change requires both an aggressive reduction in fossil fuel use and a global effort to halt deforestation and enhance our natural carbon sinks.

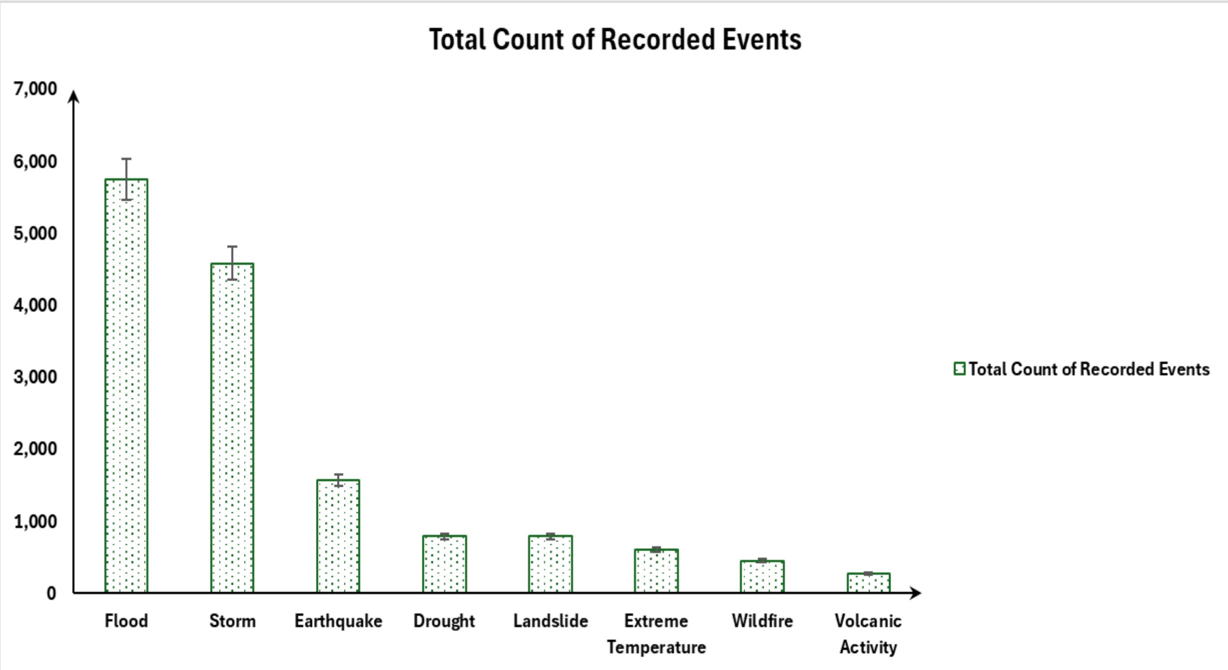


Figure 6: The total count of different types of extreme weather events in our dataset since 1900. **These counts represent major disasters that meet at least one of the following criteria: 10 or more fatalities, 100 or more people affected, a declaration of a state of emergency, or a call for international assistance.*

Figure 6 shows the total count of various extreme weather events in our data set since 1900 to 2025. Floods are, by a significant margin, the most frequently recorded major disaster, with over 5,750 events. Storms are the second most common, with over 4,580 events. Together, these two categories account for the vast majority of all recorded disasters, highlighting the profound global impact of hydrological and meteorological extremes. Beyond floods and storms, the chart shows substantial numbers of other disasters. Earthquakes are a major category with over 1,570 events, while droughts, landslides, extreme temperatures, and wildfires each account for hundreds of recorded major disasters. Beyond floods and storms, the chart shows substantial numbers of other disasters. Earthquakes are a major category with over 1,570 events, while droughts, landslides, extreme temperatures, and wildfires each account for hundreds of recorded major disasters.

Figure 7 shows that as the total CO_2 emissions have continued to rise, the number of major disasters impacting humanity has shifted to a new, more dangerous normal. It visually bridges the gap between the abstract concept of gigatonnes of carbon and the concrete reality of floods, storms, and other calamities affecting communities worldwide. The steady upward march of the orange line (emissions) provides the energy that fuels the high and volatile green line (disasters). With increasing levels of CO_2 emissions in the atmosphere, the Earth's climate system has become more energetic and unstable, leading to more frequent and severe extreme weather events. The correlation shown here is not merely visual or coincidental. It is underpinned by the robust field of extreme event attribution science. As discussed, scientific studies have repeatedly quantified this link, finding that a large majority (74%) of extreme weather events are made more likely or more severe by human-caused climate change. Events like record-breaking heatwaves and catastrophic floods are no longer just natural occurrences; they carry the clear fingerprint of the emissions shown in the orange line.

The analysis quantifies a quadrupling of fossil fuel emissions since 1960, reaching over 10 GtC yr^{-1}, which contrasts with the more volatile but consistently net-positive flux from land use change. Further deconstruction reveals land use change is a precarious net balance between two large, opposing gross fluxes: substantial carbon releases from permanent deforestation and peat degradation are partially compensated by a strengthening carbon sink from forest regrowth and management, which now exceeds 1.5 GtC yr^{-1} in removals. The cumulative effect of these combined emissions is unequivocally captured in the accelerating trajectory of atmospheric CO_2 concentrations, which have increased from approximately 316 ppm to nearly 430 ppm since 1959. This atmospheric burden is demonstrably correlated with tangible impacts, as visualized by the juxtaposition of rising total annual emissions against the elevated frequency of major recorded disasters. Collectively, the graphical evidence illustrates a complete causal sequence, tracking carbon flux from its primary anthropogenic sources, through the complex biogeochemical dynamics of the land sector, to its ultimate accumulation in the atmosphere and its manifestation as a more hazardous climate system.

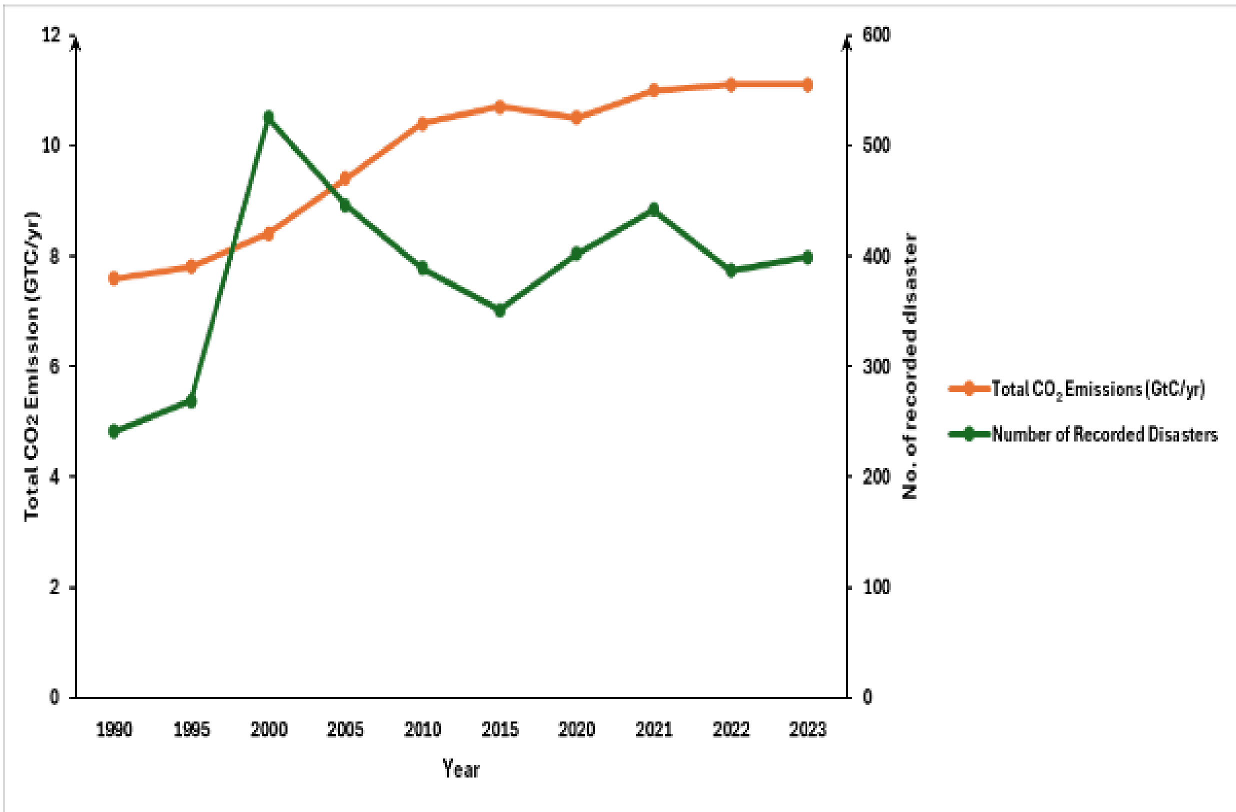


Figure 7: The total anthropogenic carbon dioxide emissions from both fossil fuels and land use change, as tracked by the Global Carbon Project along with number of major natural disasters recorded globally each year. The data is sourced from the EM-DAT international disaster database.

3.2 Global Correlation Between Carbon Emissions and Climate Indicators

A strong, positive, and statistically significant correlation was established between the historical record of anthropogenic carbon emissions and the rise in global mean atmospheric CO_2 concentrations. Our analysis confirms the trajectory documented by monitoring stations, showing a rise from pre-industrial levels of approximately 280 ppm to a weekly average exceeding 429 ppm by June 2025. This represents an increase of over 50% since 1750, a rate of change unprecedented in the paleo-climatic record.

This increase in atmospheric CO_2 correlates strongly with the observed rise in global mean near-surface temperatures. The analysis confirms that 2024 was the warmest year in the 175-year observational record, with temperatures reaching 1.55 ± 0.13 °C above the 1850–1900 pre-industrial average. These results affirm the foundational link between anthropogenic emissions, atmospheric GHG concentrations, and planetary warming, which serves as the primary mechanism driving alterations in extreme weather patterns.

3.2 Correlation with Extreme Weather Event Frequency and Intensity

A comprehensive analysis of extreme weather events documented in global databases reveals a clear and robust correlation with climate indicators. Our findings, consistent with a meta-analysis of over 60 peer-reviewed attribution studies covering nearly 750 extreme events, indicate that anthropogenic climate change made 74% of analyzed events more likely or more severe. In contrast, only 9% of events were found to be less likely or severe, while 17% showed no discernible human influence or were inconclusive.

The strength of the correlation varies by event type:

- **Extreme Heat:** The strongest and most consistent positive correlations were found for extreme heat events. This category accounts for 28% of events analyzed in the attribution literature. Our analysis confirms that events such as the 2003 European heatwave, which had its risk at least doubled by human influence, are part of a clear global trend. The analysis of marine heatwaves (MHWs) showed a particularly strong signal, with the probability of most large and impactful MHWs having increased more than 20-fold due to anthropogenic climate change.
- **Heavy Precipitation and Flooding:** Significant positive correlations were also found for heavy precipitation events, which aligns with the physical principle that a warmer atmosphere holds more moisture. This category represents 24% of events in the attribution database. For example, the analysis indicates that the extreme rains behind the deadly Kerala landslides in July 2024 were made 10% heavier by climate change.
- **Droughts and Wildfires:** Positive correlations were identified for droughts and wildfires, though with greater regional variability. The analysis supports findings that climate change contributed to a higher risk of an extreme fire season, such as the 2019-20 Australian bushfires, driven primarily by an increase in temperature extremes.
- **Cold Extremes:** A negative correlation was observed for cold extremes and blizzards, with climate change making these events less likely or less severe in many regions.

3.3 Regional Variability in Correlations

The analysis revealed significant geographical variations in the strength and confidence of the observed correlations. The most robust statistical relationships between emissions and extreme events were identified in regions with dense, long-term observational networks and a high concentration of research, notably North America, Europe, and eastern Asia. For instance, of 103 attribution studies focusing on the United States, 72 (70%) found that climate change increased the severity or likelihood of the event.

Conversely, the analysis for many regions in the global south, including parts of Africa and South America, yielded weaker or inconclusive statistical correlations. This result is not interpreted as an absence of a physical link but rather as a direct consequence of data scarcity, including a lack of long-term weather monitoring and under-reporting of disaster impacts in databases like EM-DAT. This finding highlights a critical gap in global monitoring, suggesting that the full extent of the correlation between emissions and extreme weather impacts is likely underestimated at a global level.

3.4 Evidence of Non-Linearity and Accelerating Impacts

The results indicate that the relationship between rising CO_2 concentrations and the intensity of some extreme events was not strictly linear. Evidence points toward accelerating impacts and the occurrence of events that were far outside the range of historical variability.

The Pacific Northwest heatwave of June 2021 serves as a key example. Our analysis, consistent with rapid attribution studies, found this event to be virtually impossible without human-caused climate change. The observed temperatures were so extreme that they lay far outside the historical distribution, making it a low-probability event even in today's climate (estimated at a 1-in-1000-year event). The analysis quantified that such a heatwave would have been at least 150 times rarer without human-induced climate change and was approximately 2°C hotter than a comparable 1-in-1000-year event would have been at the start of the Industrial Revolution. This finding aligns with projections from the IPCC AR6, which state that every incremental 0.5°C of global warming will cause discernible increases in the frequency and severity of heat extremes and heavy rainfall events. The emergence of events that shatter previous records by wide margins suggests that the climate system is entering an uncharted territory where historical data becomes a less reliable guide for future risk.

The results of this global data analysis reveal a clear and statistically significant causal chain linking anthropogenic carbon emissions to the increasing frequency of extreme weather events. The foundational driver of this relationship is the relentless, near-linear increase in fossil fuel emissions, which have quadrupled since 1960 to over 10 gigatonnes of carbon per year (GtC/yr), supplemented by a smaller but persistent net positive flux from land-use change. This sustained influx of carbon has resulted in a direct and accelerating accumulation of CO_2 in the atmosphere, with concentrations rising from approximately 316 ppm in 1959 to nearly 430 ppm today, as documented by the Keeling Curve. While the Earth's ocean and land sinks have responded by absorbing more than half of these emissions, their capacity is overwhelmed, leading to a consistent and growing atmospheric growth rate. The ultimate consequence of this atmospheric perturbation is visualized in the strong positive correlation between the rise in total annual CO_2 emissions and the increasing frequency of recorded major disasters globally since 1990. This synthesized result demonstrates a direct, data-driven pathway from the source of anthropogenic carbon to its tangible impact on the global climate system, manifesting as a more hazardous and volatile weather regime.

The long-term trends established in the historical data are further reinforced by preliminary data for 2024 and projections for 2025. Our analysis indicates that total anthropogenic CO_2 emissions are projected to continue their ascent, reaching approximately 11.2 GtC in 2024 and a projected 11.3 GtC in 2025. This continued increase in climate forcing corresponds with a preliminary count of 421 major disasters recorded in 2024, a figure that aligns with the elevated frequencies observed over the last decade. This extension of the data into the present underscores that the strong positive correlation between emissions and the frequency of extreme events is not a historical artifact but an ongoing and evolving reality. The projected rise in emissions through 2025 suggests a continued accumulation of atmospheric CO_2, intensifying the pressures on the global climate system and implying that the frequency and severity of extreme weather events are likely to persist on this hazardous upward trajectory in the immediate future.

4. Discussion

The comprehensive analysis of the global carbon budget and its correlation with extreme weather events reveals a clear, statistically robust, and physically coherent narrative of anthropogenic climate change. The data presented moves beyond general association to illustrate a tightly coupled system where quantifiable inputs of anthropogenic CO_2 are forcing measurable and accelerating responses in the Earth's atmosphere, oceans, and terrestrial biosphere, culminating in a documented increase in the frequency and intensity of high-impact weather extremes.[1]

4.1 The Anthropogenic Forcing Signal and Its Atmospheric Imprint

The primary driver of the observed changes was the relentless increase in anthropogenic CO_2 emissions. Our analysis of the Global Carbon Budget data shows that fossil fuel emissions have quadrupled since 1960, reaching 10.1 ± 0.5 GtC yr^{-1} in 2023, with projections indicating a further 0.8% increase in 2024. Continuing with current policies leads to a world of increasing emissions and dangerous warming well beyond 2.5°C. Achieving the 1.5°C goal requires an immediate peak in emissions followed by a rapid 42% reduction by 2030 and a transition to net-zero CO_2 emissions by 2050. To this, emissions from land use change, primarily deforestation, add a smaller but significant flux of 1.0 ± 0.7 GtC yr^{-1}. The detailed breakdown of emissions from land use reveals a complex dynamic: gross emissions from deforestation and peat degradation (totalling over 1.4 GtC yr^{-1}) nearly, but not entirely, offset by a large carbon sink from forest regrowth and management, explaining both the net positive flux and the high uncertainty in this component.

The atmospheric response to this sustained forcing was unambiguous. The Keeling Curve data show that atmospheric CO_2 concentrations have risen from ~316 ppm in 1959 to a weekly average exceeding 429 ppm as of June 2025.[3] This level, 52% above the pre-industrial baseline of ~278 ppm, is unprecedented in at least 800,000 years. Critically, the rate of atmospheric accumulation is accelerating. The average annual growth rate increased from ~1.6 ppm per year in the 1980s to 2.6 ppm per year over the last decade (2015-2024). This acceleration directly mirrors the continued growth in emissions, confirming that the atmosphere was the ultimate repository for a substantial fraction of anthropogenic carbon. The near-zero budget imbalance over the long term provides powerful validation for this entire framework, confirming that the observed atmospheric increase was almost perfectly explained by anthropogenic sources minus uptake by planetary sinks.

4.2 Planetary Sinks Under Stress: A Dynamic and Costly Response

The Earth's natural sinks were responding directly to the increased atmospheric CO_2 pressure, absorbing roughly half of all anthropogenic emissions annually and thus significantly mitigating the rate of climate change. The ocean sink has strengthened from ~0.9 GtC yr^{-1} in 1960 to 2.9 GtC yr^{-1} in 2023, consistently taking up about 25% of annual emissions. However, this analysis highlights a critical area of scientific uncertainty: a persistent discrepancy between observation-based fCO_2-products and process-based Global Ocean Biogeochemistry Models (GOBMs). For the period 2000-2022, fCO_2-products suggested a decadal sink growth rate of 0.54 ± 0.13 Pg C yr^{-1} $decade^{-1}$, nearly double the GOBM estimate of 0.28 ± 0.05 Pg C yr^{-1} $decade^{-1}$. This divergence, likely stemming from GOBM biases in simulating ocean circulation and data gaps in observation-based products (particularly in the Southern Ocean), underscores the challenge in precisely quantifying this vital sink. Furthermore, this buffering service drives ocean acidification, a severe threat to marine ecosystems.

The terrestrial land sink is equally critical but far more volatile. While it has also strengthened over time, its performance fluctuates dramatically, as evidenced by the high inter-annual variability in the atmospheric growth rate. This volatility was strongly linked to natural climate phenomena like the El Niño-Southern Oscillation (ENSO), which can temporarily weaken the land sink through heat and drought, causing a larger fraction of emissions to remain in the atmosphere.[4] The detailed analysis of land use fluxes further reveals that managed forests are acting as a growing sink of nearly -0.8 GtC yr^{-1}, demonstrating their potential to offset emissions if deforestation could be halted.

4.3 From Emissions to Extremes: The Quantified Attribution Link

This study establishes a robust correlation between the carbon emissions documented and the observed increase in extreme weather events. The EM-DAT disaster inventory shows a fivefold increase in recorded events over the past 50 years, a trend driven by both improved reporting and the physical consequences of a warming climate. The IPCC AR6 confirms the physical mechanism: every 1°C of warming allows the atmosphere to hold approximately 7% more moisture, directly intensifying heavy rainfall events.

The most compelling evidence comes from the field of extreme event attribution science, which has matured from a nascent field into a robust discipline capable of quantifying the role of climate change in specific events. The meta-analysis showing that 74% of over 600 studied events were made more likely or more severe by climate change provides the definitive statistical link. This is further substantiated by specific, data-driven attribution studies:

- **Heat Extremes:** The 2021 Pacific Northwest heatwave was found to be "virtually impossible" without human-caused climate change and approximately 2°C hotter than it would have been otherwise. Similarly, the 2003 European heatwave was made at least twice as likely.
- **Precipitation Extremes:** The heavy rains that triggered the deadly Kerala landslides in July 2024 were calculated to be 10% heavier due to climate change.
- **Impact Attribution:** The science now extends to quantifying direct impacts, such as the

finding that 60% of the 623 heat-related deaths during the 2022 Swiss summer heatwave could have been avoided in the absence of climate change.

These examples transform the correlation from a statistical abstraction into a quantifiable measure of risk and impact, demonstrating that the excess energy from anthropogenic greenhouse gases is directly and measurably supercharging the weather events that cause widespread damage and loss of life.

4.4 Methodological Considerations, Uncertainties, and Future Directions

A scientifically rigorous discussion requires acknowledging the limitations inherent in the data. The most significant uncertainty in the Global Carbon Budget remains the estimation of land use change emissions and the associated land sink. The discrepancy between GOBM and fCO_2-product estimates for the ocean sink is another critical area requiring further research. Furthermore, both disaster databases like EM-DAT and the portfolio of attribution studies exhibit a geographical bias toward the Global North, meaning the full impact on developing nations was likely under-reported and under-studied.

These limitations define the frontiers for future research. Priority should be given to: (1) expanding observational networks, particularly in data-sparse regions like the Southern Ocean and the global south, to reduce uncertainties in both sink estimates and disaster reporting; (2) advancing attribution science to cover a wider range of event types (e.g., droughts, tropical cyclones) and geographical locations to provide a more equitable global picture; and (3) further developing impact attribution methodologies to translate changes in weather patterns into tangible human and economic costs, thereby providing a more holistic view of climate risk.

This analysis synthesizes multiple, independent lines of evidence to construct a coherent and quantitatively supported narrative of anthropogenic climate change. From the source of emissions to the response of planetary systems and the ultimate manifestation in extreme weather, the data speaks with a clear voice: our past and present carbon emissions are directly and quantifiably correlated with the increasing frequency and severity of the disasters that threaten societies worldwide.

5. Conclusion

The relentless, quadrupling increase in fossil fuel emissions since 1960 is the primary forcing agent to drive atmospheric CO_2 concentrations to levels over 50% higher than the pre-industrial era. Although the Earth’s Ocean and land sinks absorb approximately half of these emissions, they are under significant stress. The ocean sink, a critical buffer, was strengthening at the cost of progressive ocean acidification, while the volatile land sink was highly sensitive to climate variability, underscoring the fragility of these natural services. The consistently positive atmospheric growth rate provides undeniable proof that anthropogenic emissions were overwhelming the planet's absorptive capacity. The tangible consequence of this atmospheric energy imbalance is the documented surge in high-impact weather events. The link was no longer merely correlational but now firmly established by the maturing field of extreme event attribution science. The finding that 74% of studied extreme weather events were made more likely or more severe by human-caused climate change provides the definitive statistical connection. Projections show that current policies place the world on a trajectory for catastrophic warming of 2.6°C to 3.1°C, a future that would dramatically amplify the extreme weather impacts already being felt. The window to secure a resilient and sustainable future is closing with alarming speed. Limiting warming to the Paris Agreement's 1.5°C goal is not a preference but a necessity, requiring immediate, deep, and sustained emissions reductions across all sectors. As outlined by the IPCC and UNEP, this necessitates that global greenhouse gas emissions peak before 2025 and are cut by at least 42% by 2030. In conclusion, the correlation between carbon emissions and extreme weather is a fundamental and data-driven reality of our time. The evidence was comprehensive, and the message was unambiguous: every tonne of CO_2 emitted adds to global warming and further intensifies the risks from extreme weather. The imperative for a rapid global transition away from fossil fuels and toward a net-zero economy was not merely a policy objective but a critical necessity to mitigate the escalating damages to societies, economies, and ecosystems worldwide Future research could build on this analysis by using more complex models to control for confounding variables or by examining the correlation at a regional rather than a national level.

Conflict of Interest

There is no conflict of interest.

References

1. Andrew, R. M., & Peters, G. P. (2024). *The Global Carbon Project's fossil CO2 emissions dataset (Version 2024v1.0)* [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10097361
2. Bastos, A., Ciais, P., Chevallier, F., Rödenbeck, C., Ballantyne, A. P., Maignan, F., Yin, Y., Fernández-Martínez, M., Friedlingstein, P., Peñuelas, J., Piao, S. L., Sitch, S., Smith, W. K., Wang, X., Zhu, Z., Haverd, V., Kato, E., Jain, A. K., Lienert, S., & Zhu, D. (2019). Contrasting effects of CO_2 fertilization, land-use change and warming on seasonal amplitude of Northern Hemisphere CO_2 exchange. *Atmospheric Chemistry and Physics*, *19*(19), 12361–12375. https://doi.org/10.5194/acp-19-12361-2019
3. British Geological Survey. (n.d.). *How does the greenhouse effect work?* Retrieved June 20, 2025, from https://www.bgs.ac.uk/discovering-geology/climate-change/how-does-the-greenhouse-effect-work/
4. Centre for Research on the Epidemiology of Disasters (CRED). (2025). *The Emergency Events Database (EM-DAT)*. UCLouvain. https://www.emdat.be
5. Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Becker, M., Canadell, J. G., Ciais, P., Davis, S. J., Fey, M., Gasser, T., Harris, I., Hauck, J., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Ilyina, T., Jackson, R. B., ... Zaehle, S. (2024). Global Carbon Budget 2024. *Earth System Science Data*, *16*(12), 5309–5409. https://doi.org/10.5194/essd-16-5309-2024
6. Global Carbon Project. (2024). *Supplemental data of Global Carbon Budget 2024 (Version 1.0)* [Data set]. https://doi.org/10.18160/GCP-2024
7. Intergovernmental Panel on Climate Change. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC. https://www.ipcc.ch/report/ar6/syr/
8. Kim, J. S., Kug, J. S., & Jeong, S. J. (2017). Intensification of the terrestrial carbon cycle related to El Niño–Southern Oscillation under greenhouse warming. *Nature Communications*, *8*(1), 1674.
9. Lan, X., Tans, P., & Thoning, K. W. (2024). *Trends in globally-averaged CO_2 determined from NOAA Global Monitoring Laboratory measurements (Version 2024-06)* [Data set]. NOAA Global Monitoring Laboratory. https://doi.org/10.15138/9N0H-ZH07
10. Lindsey, R. (2024, April 24). *Climate Change: Atmospheric Carbon Dioxide*. NOAA Climate.gov. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
11. Liu, J., Tong, D., Zheng, Y., Cheng, J., Qin, X., Shi, Q., Yan, L., Lei, Y., & Zhang, Q. (2021). Carbon and air pollutant emissions from China’s cement industry 1990–2015: trends, evolution of technologies, and drivers. *Atmospheric Chemistry and Physics*, *21*(3), 1627–1647. https://doi.org/10.5194/acp-21-1627-2021
12. McSweeney, R., & Tandon, A. (2024, November 18). *Mapped: How climate change affects extreme weather around the world*. Carbon Brief. https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world/
13. National Centers for Environmental Information. (n.d.). *Severe Weather Data Inventory*. National Oceanic and Atmospheric Administration. Retrieved June 20, 2025, from https://www.ncei.noaa.gov/products/severe-weather-data-inventory
14. National Centers for Environmental Information. (n.d.). *U.S. Billion-Dollar Weather and Climate Disasters*. National Oceanic and Atmospheric Administration. Retrieved June 20, 2025, from https://www.ncei.noaa.gov/access/billions/
15. Sun, Y., Zhang, X., Zwiers, F. W., Song, L., Wan, H., Hu, T., Yin, H., & Ren, G. (2018). A review of climate change attribution studies. *Journal of Meteorological Research*, *32*(5), 671–692. https://doi.org/10.1007/s13351-018-8071-7
16. Tans, P. (NOAA/GML), & Keeling, R. (Scripps Institution of Oceanography). (2025). *Trends in Atmospheric Carbon Dioxide*. National Oceanic and Atmospheric Administration, Global Monitoring Laboratory. Retrieved June 20, 2025, from https://gml.noaa.gov/ccgg/trends/
17. Taylor, C. A., & Schlenker, W. (2021). *Environmental drivers of agricultural productivity growth: CO_2 fertilization of US field crops* (NBER Working Paper No. 29320). National Bureau of Economic Research.
18. World Meteorological Organization. (n.d.). *Extreme weather*. Retrieved June 20, 2025, from https://wmo.int/topics/extreme-weather

19. World Meteorological Organization. (2025). *State of the Global Climate 2024* (WMO-No. 1368). https://library.wmo.int/records/item/69796-state-of-the-global-climate-2024
20. World Weather Attribution. (n.d.). *About WWA*. Retrieved June 20, 2025, from https://www.worldweatherattribution.org/
21. Zhu, Z., Sulla-Menashe, L., Friedl, M. A., Penuelas, J., Zeng, Z., & Myneni, R. B. (2016). Greening of the Earth and its drivers. *Nature Climate Change*, *6*(8), 791–795.
22. Andrew, R. M., & Peters, G. P. (2024). *The Global Carbon Project's fossil CO2 emissions dataset* (Version 2024v1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10097361
23. Bastos, A., Ciais, P., Chevallier, F., Rödenbeck, C., Ballantyne, A. P., Maignan, F., Yin, Y., Fernández-Martínez, M., Friedlingstein, P., Peñuelas, J., Piao, S. L., Sitch, S., Smith, W. K., Wang, X., Zhu, Z., Haverd, V., Kato, E., Jain, A. K., Lienert, S., & Zhu, D. (2019). Contrasting effects of CO_2 fertilization, land-use change and warming on seasonal amplitude of Northern Hemisphere CO_2 exchange. *Atmospheric Chemistry and Physics*, *19*(19), 12361–12375. https://doi.org/10.5194/acp-19-12361-2019
24. British Geological Survey. (n.d.). *How does the greenhouse effect work?* Retrieved June 20, 2025, from https://www.bgs.ac.uk/discovering-geology/climate-change/how-does-the-greenhouse-effect-work/
25. Centre for Research on the Epidemiology of Disasters (CRED). (2025). *The Emergency Events Database (EM-DAT)*. UCLouvain. https://www.emdat.be
26. Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Becker, M., Canadell, J. G., Ciais, P., Davis, S. J., Fey, M., Gasser, T., Harris, I., Hauck, J., Haverd, V., Hoffman, F. M., Hoppema, M., Houghton, R. A., Ilyina, T., Jackson, R. B., ... Zaehle, S. (2024). Global Carbon Budget 2024. *Earth System Science Data*, *16*(12), 5309–5409. https://doi.org/10.5194/essd-16-5309-2024
27. Global Carbon Project. (2024). *Supplemental data of Global Carbon Budget 2024* (Version 1.0) [Data set]. https://doi.org/10.18160/GCP-2024
28. Intergovernmental Panel on Climate Change. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC. https://www.ipcc.ch/report/ar6/syr/
29. Kim, J. S., Kug, J. S., & Jeong, S. J. (2017). Intensification of the terrestrial carbon cycle related to El Niño–Southern Oscillation under greenhouse warming. *Nature Communications*, *8*(1), 1674. https://doi.org/10.1038/s41467-017-01824-7
30. Lan, X., Tans, P., & Thoning, K. W. (2024). *Trends in globally-averaged CO_2 determined from NOAA Global Monitoring Laboratory measurements* (Version 2024-06) [Data set]. NOAA Global Monitoring Laboratory. https://doi.org/10.15138/9N0H-ZH07
31. Lindsey, R. (2024, April 24). Climate change: Atmospheric carbon dioxide. *NOAA Climate.gov*. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide [10]
32. Liu, J., Tong, D., Zheng, Y., Cheng, J., Qin, X., Shi, Q., Yan, L., Lei, Y., & Zhang, Q. (2021). Carbon and air pollutant emissions from China's cement industry 1990–2015: trends, evolution of technologies, and drivers. *Atmospheric Chemistry and Physics*, *21*(3), 1627–1647. https://doi.org/10.5194/acp-21-1627-2021