

LONG-TERM TRENDS IN GLOBAL MEAN TEMPERATURE AND ATMOSPHERIC GREENHOUSE GASES

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Abstract- Global warming represents one of the most significant environmental challenges of the present century, driven primarily by the increasing accumulation of greenhouse gases in the atmosphere. The present study examines long-term trends in global mean temperature, atmospheric carbon dioxide (CO₂) concentration, and methane (CH₄) growth rates using observational data reported in the World Meteorological Organization (WMO)-referenced material. The analysis covers global mean temperature from 1850 to 2025, atmospheric CO₂ concentrations from 1984 to 2024, and annual growth rates of methane concentrations from 1985 to 2024. The findings reveal a substantial increase in global mean temperature anomaly, from 0.0613°C in 1850 to 1.4158°C in 2025, representing an increase of approximately 1.35°C. The year 2024 recorded a temperature anomaly of 1.538°C, the highest

value reported in the analysed series. Atmospheric CO₂ concentration increased from 344.6 ppm in 1984 to 423.9 ppm in 2024, reflecting a net rise of 79.3 ppm. Methane growth rates exhibited considerable interannual variability, with a marked resurgence in recent decades and a peak annual increase of 17 ppb in 2021. Collectively, these observations demonstrate persistent global warming alongside sustained greenhouse gas accumulation. The study highlights the importance of long-term atmospheric monitoring, greenhouse gas emission reduction, and strengthened climate mitigation strategies to address the continuing transformation of the global climate system.

Keywords: Carbon Dioxide (CO₂); Methane (CH₄); Atmospheric Concentration; Temperature Anomaly

I. INTRODUCTION

Climate change has emerged as a major global environmental concern because of its far-reaching implications for ecosystems, water resources, agricultural productivity, biodiversity, human settlements, and socioeconomic development (Wu et al., 2011). The Earth's climate system is influenced by natural variability as well as changes in atmospheric composition (Bilgili et al., 2024). However, the persistent increase in greenhouse gas concentrations resulting from human activities has substantially altered the planet's radiative balance, contributing to the long-term rise in global mean temperature (Semenov & Bengtsson, 2002). Among the principal greenhouse gases, carbon dioxide (CO₂) and methane (CH₄) play important roles in contemporary climate change (Bruhwiler et al., 2021). Carbon dioxide is released primarily through fossil fuel combustion, cement production, industrial activities, deforestation, and land-use change (Solomon et al., 2010). Its long atmospheric persistence and cumulative behaviour make it a major contributor to long-term global warming (Dyominov & Zadorozhny, 2008). Methane, although shorter-lived in the atmosphere than CO₂, is a potent greenhouse

gas whose concentration changes can significantly influence near-term warming. Major anthropogenic methane sources include agriculture, livestock production, fossil fuel extraction and distribution, waste management, and other biological and industrial processes (Golitsyn et al., 1996).

Long-term observations of global mean temperature provide essential evidence for understanding the magnitude, persistence, and changing rate of climate warming (Sagar et al., 2025). Temperature anomalies, expressed relative to a specified reference period, allow researchers to evaluate departures from a baseline and identify broad climatic trends (Gu et al., 2016). From the mid-1970s onward, the record shows a pronounced and persistent increase in global mean temperature, with particularly high anomalies in the twenty-first century (Hamdan et al., 2023). The reported temperature anomaly of 1.538°C in 2024 illustrates the exceptional warmth observed in recent years.

The continuous rise in atmospheric greenhouse gas concentrations is a major concern in the context of global climate change (Rao & Riahi, 2006). Increasing atmospheric carbon dioxide (CO₂), primarily associated with fossil fuel combustion,

industrial activities, and land-use changes, contributes to the enhanced greenhouse effect and the observed warming of the Earth's climate (Ledley et al., 1999). Methane (CH₄), another important greenhouse gas, also plays a significant role in global warming, although its atmospheric growth exhibits greater temporal variability (Lu, 2022). Following a period of relatively slow growth around the turn of the century, methane concentrations have increased more rapidly since the late 2000s. The concurrent increase in greenhouse gas concentrations and global temperature highlights the importance of examining long-term atmospheric changes to understand the evolving climate system (Mokhov & Smirnov, 2018). However, distinguishing the individual contributions of different greenhouse gases from natural climate variability requires further investigation using appropriate statistical analyses and climate attribution methods (Qian et al., 2021). Although temperature anomalies and greenhouse gas concentrations represent different components of the climate system, their combined examination helps establish the temporal correspondence between increasing atmospheric greenhouse gases and global warming (Mokhov & Smirnov,

2022). Nevertheless, observational trends alone do not quantify the independent contribution of each gas or separate anthropogenic influences from natural climate variability. Such attribution requires additional evidence and appropriate statistical or climate-model-based analyses (Patel et al., 2025).

Against this background, the present study analyses the long-term evolution of global mean temperature and atmospheric greenhouse gases using the observational trends reported in the accompanying results and discussion. The principal objectives are to (i) examine global temperature changes from 1850 to 2025, (ii) evaluate the evolution of atmospheric CO₂ concentration between 1984 and 2024, (iii) assess changes in annual methane concentration growth rates from 1985 to 2024, and (iv) interpret the combined trends in relation to contemporary global warming and the need for effective climate mitigation. The study aims to provide an integrated observational perspective on the changing global climate and the importance of sustained greenhouse gas monitoring.

II. MATERIALS AND METHODS

2.1 Study Design and Data Sources

The study employed a retrospective observational approach based on the historical global temperature and atmospheric greenhouse gas records presented in the supplied results and discussion document. The figures and accompanying descriptions identify the World Meteorological Organization (WMO, <https://wmo.int/>) as the source of the reported global temperature and greenhouse gas information. The analysis was organised into three principal datasets: global mean temperature anomalies, atmospheric CO₂ concentrations, and annual CH₄ concentration growth rates.

The analysis covered global mean temperature observations from 1850 to 2025, atmospheric CO₂ concentrations from 1984 to 2024, and annual growth rates of methane concentrations from 1985 to 2024. The datasets were examined to identify long-term directional changes, variations between successive periods, notable annual values, and differences in the patterns of temperature and greenhouse gas evolution.

The precise underlying WMO publications, original downloadable datasets, reference period for temperature anomalies, and data-processing procedures were not specified in the supplied results section. Therefore, the

present methodology describes the analysis supported by the available material. These source details should be verified and documented before final journal submission.

2.2 Presentation and Interpretation of Results

The observational trends were presented through the figures identified in the supplied document: the global mean temperature series for 1976–2000 and 2001–2025, the complete temperature record for 1850–2025, the atmospheric CO₂ series for 1984–2000 and 2001–2023, and the methane growth-rate series for 1985–2024.

Numerical comparisons were based on the values explicitly reported in the accompanying discussion. Arithmetic differences were used to describe changes over specified periods, while graphical patterns and selected annual observations were used to interpret temporal variability and long-term trends.

The analysis was primarily descriptive. In the absence of documented uncertainty estimates, a fully specified temperature baseline, and a verified original data table, the results were not treated as a substitute for formal statistical trend testing. The findings should therefore be interpreted as

an observational synthesis of the reported records rather than as an independent causal assessment of global climate change.

III. RESULT AND DISCUSSION

3.1 Global Mean Temperature Trend during 2001–2025

Figure 1-2 shows the most recent and warmest period in the entire record. Every year after 2001 remained well above 0.79°C , demonstrating that elevated temperatures have become the new climatic norm. Major milestones include 2010 (0.9826°C), 2016

(1.2789°C), 2020 (1.2705°C), 2023 (1.4405°C), and the record high of 2024 (1.538°C).

Although slight fluctuations occur in some years, the overall trend remains strongly positive. Figure 2 confirms that warming has intensified in the 21st century, with anomalies now exceeding 1.0°C on a sustained basis. This rapid increase reflects continued greenhouse gas emissions, ocean heat accumulation, and positive climate feedback mechanisms.

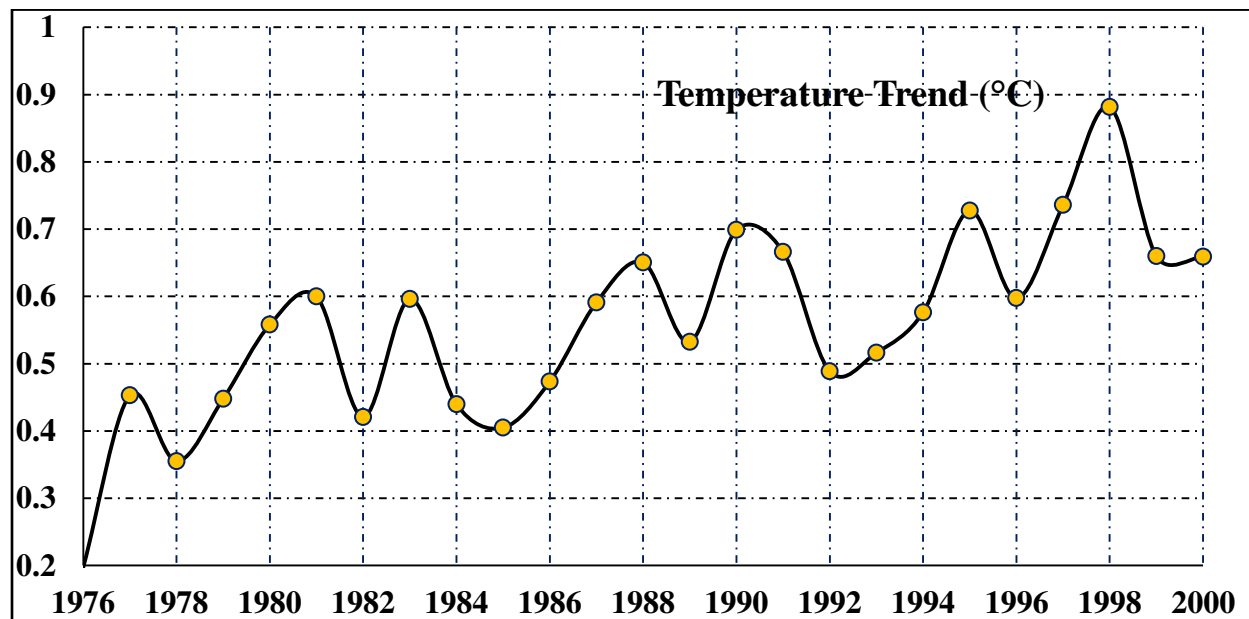


Figure 1: Trend of global mean temperature between 1976 and 2000 (World Meteorological Organization, WMO)

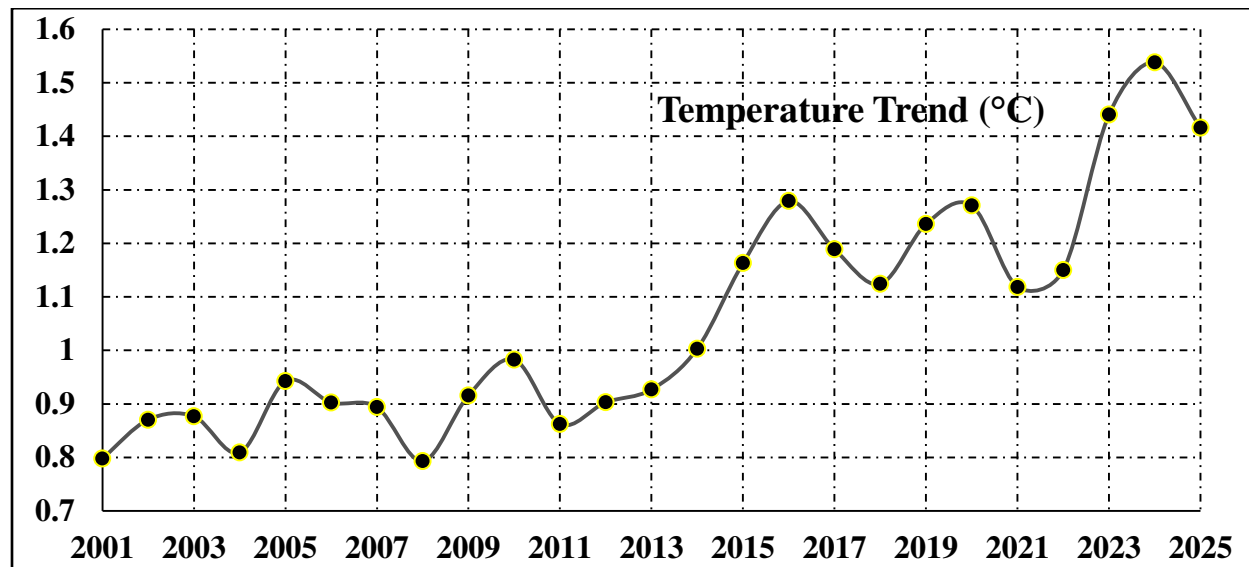


Figure 2: Trend of global mean temperature between 2001 and 2025 (World Meteorological Organization, WMO)

3.2 Complete Global Temperature Scenario (1850 – 2025)

Figure 3 integrates the full temperature record from 1850 to 2025 and provides the clearest evidence of long-term global warming. The graph shows three broad phases:

- 1850–1910:** Low anomalies with strong interannual variability and no sustained warming.
- 1910–1975:** Gradual warming with intermittent pauses and moderate increases.

- 1976–2025:** Rapid and unprecedented warming with record-breaking temperatures.

From an anomaly of 0.0613°C in 1850 to 1.4158°C in 2025, the net increase exceeds 1.35°C . This confirms that contemporary warming is historically exceptional within the observational record.

3.3 Comparative Discussion with Global Perspectives

The figure-wise analysis demonstrates that modern climate change is distinguished not only by higher temperatures but also by the rate and persistence of warming. Earlier warm periods, such as the late 19th century or the early 1940s, were temporary and of

limited magnitude. In contrast, post-1976 warming is continuous, accelerating, and global in scale.

The warming observed after 2000 is particularly significant because it coincides with increased frequency of extreme weather events, glacier retreat, sea-level rise, biodiversity stress, and disruptions to agriculture and water systems worldwide. Crossing the 1.5°C threshold in recent years, as shown by the 2024 anomaly (1.538°C), has major implications for international climate targets such as the Paris Agreement.

These findings indicate that the present global climate status is fundamentally different from that of the 19th and early 20th centuries. Human influence has become the dominant driver of temperature change, pushing the Earth system into a new and warmer climatic state.

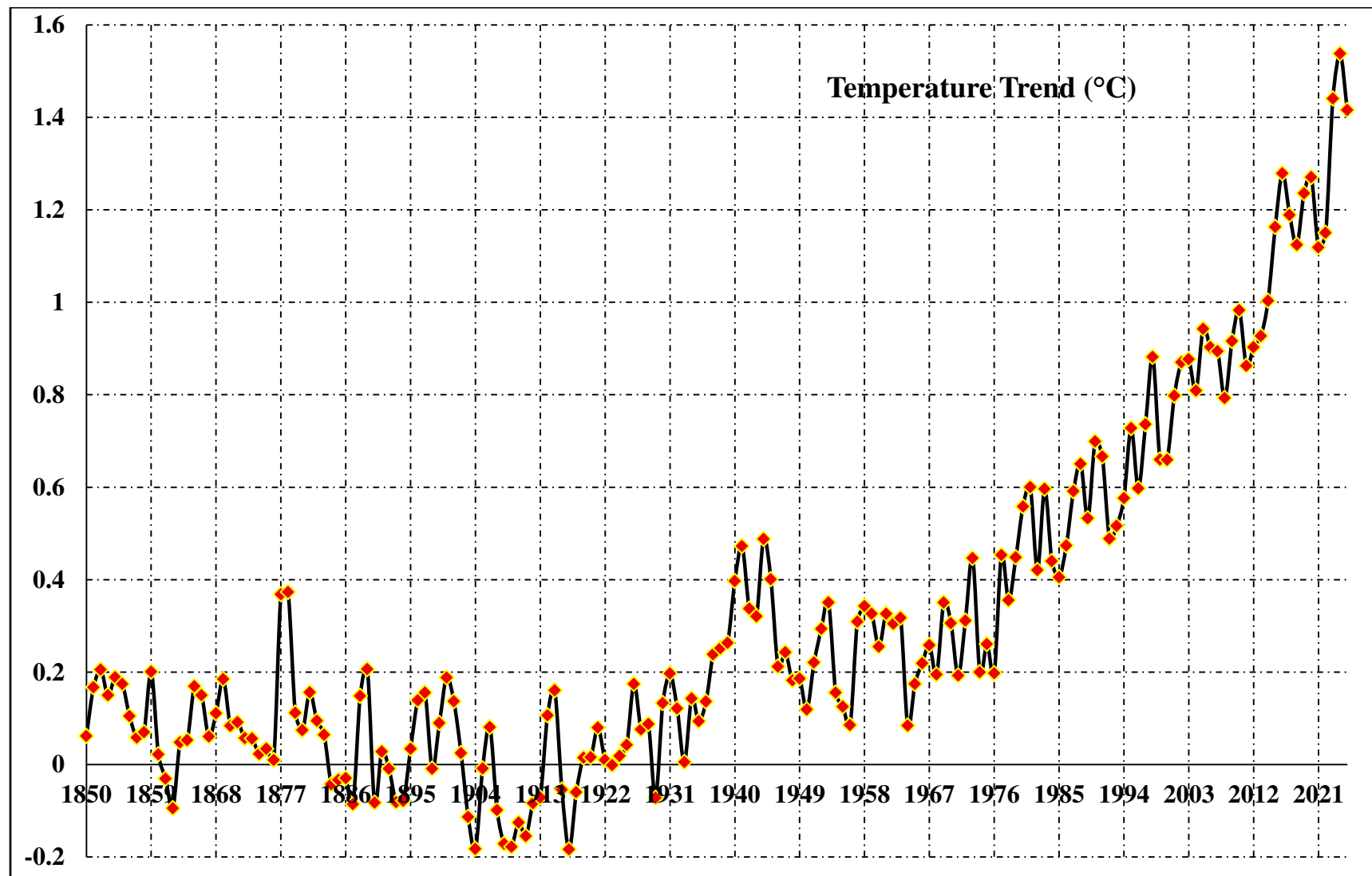


Figure 3: Complete scenario of global mean temperature from 1850 to 2025 (World Meteorological Organization, WMO)

3.4 Atmospheric Greenhouse Gas Trends: CO₂ and CH₄ Dynamics

The figures and annexure data provide critical evidence that the contemporary global climate crisis is closely linked with the continuous rise in atmospheric greenhouse gas concentrations, particularly carbon dioxide (CO₂) and methane (CH₄). These gases are the primary drivers of radiative forcing and global warming.

The long-term trends presented in Figures 4–6 reveal not only sustained increases in atmospheric concentrations but also an acceleration in growth rates during recent decades. The analysis of these greenhouse gas trajectories complements the earlier temperature findings and strengthens the conclusion that modern climate change is anthropogenic in origin.

3.5 Global Atmospheric CO₂ Concentration (1984 – 2000)

Figure 4 illustrates the trend of global atmospheric carbon dioxide concentration from 1984 to 2000. During this period, CO₂ levels increased consistently from 344.6 ppm in 1984 to 369.8 ppm in 2000, representing a net rise of 25.2 ppm within sixteen years.

The figure shows a smooth, uninterrupted upward trajectory, with no evidence of long-term decline or stabilisation. Annual increases were generally between 1 and 2 ppm, indicating that global emissions from fossil fuel combustion, industrialisation, deforestation, and land-use change were already exceeding the natural absorption capacity of oceans and terrestrial ecosystems.

The trend is particularly important because the period from the mid-1980s to 2000 corresponds with rapid globalization, industrial expansion, urban growth, and rising energy demand across many regions of the world. During these years, atmospheric CO₂ crossed important milestones, including 350 ppm in 1988, 360 ppm in 1995, and nearly 370 ppm by 2000.

From a climate perspective, Figure 5 marks the beginning of the modern era of greenhouse gas escalation. Although warming was already detectable, CO₂ concentrations during this phase were substantially lower than present-day values, highlighting how much the climate system has changed in only a few decades.

3.6 Global Atmospheric CO₂ Concentration (2001 – 2023)

Figure 5 continues the CO₂ record from 2001 to 2023 and shows an even stronger increase in atmospheric concentration. CO₂ rose from 371.3 ppm in 2001 to 420.4 ppm in 2023, an increase of 49.1 ppm over 22

years. This growth is nearly double the increase observed during 1984–2000, indicating a clear acceleration in accumulation.

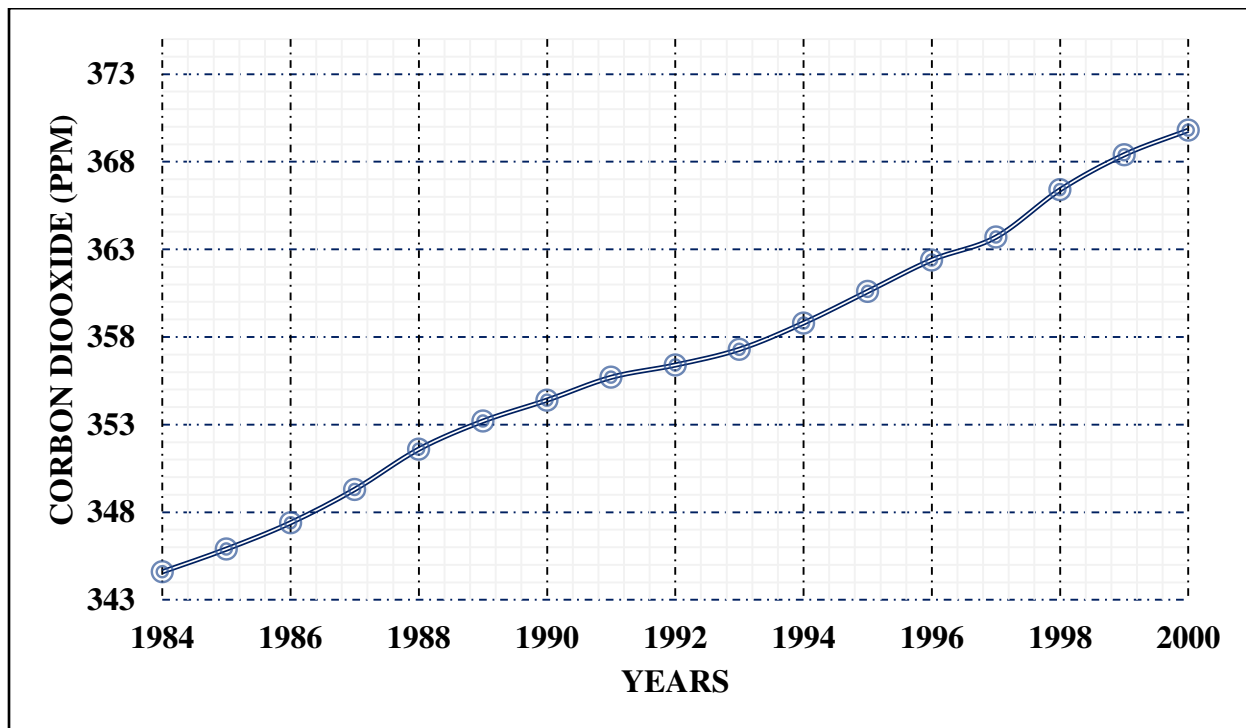


Figure 4: Global atmospheric CO₂ concentration from 1984 to 2000 (World Meteorological Organization, WMO)

Several symbolic thresholds were crossed during this period:

- 400 ppm in 2015 (400.5 ppm)
- 410 ppm in 2019 (410.8 ppm)
- 420 ppm in 2023 (420.4 ppm)

These milestones are scientifically significant because such concentrations have

not been observed in human civilization. Figure 5 shows that even with growing awareness of climate change and international agreements, atmospheric CO₂ has continued to rise steadily.

The annual increments after 2000 are generally larger than those in the earlier period, reflecting increased global emissions from fossil fuels, transport, cement production, and industrial activities.

Although renewable energy adoption expanded during this period, it was insufficient to offset rising energy demand and to break the continued dependence on carbon-intensive systems.

The persistent upward slope in Figure 5 confirms that atmospheric CO₂ is cumulative

in nature. Even if annual emissions fluctuate, continued net emissions cause concentrations to rise. This has major implications because CO₂ remains in the atmosphere for decades to centuries, committing the planet to long-term warming.

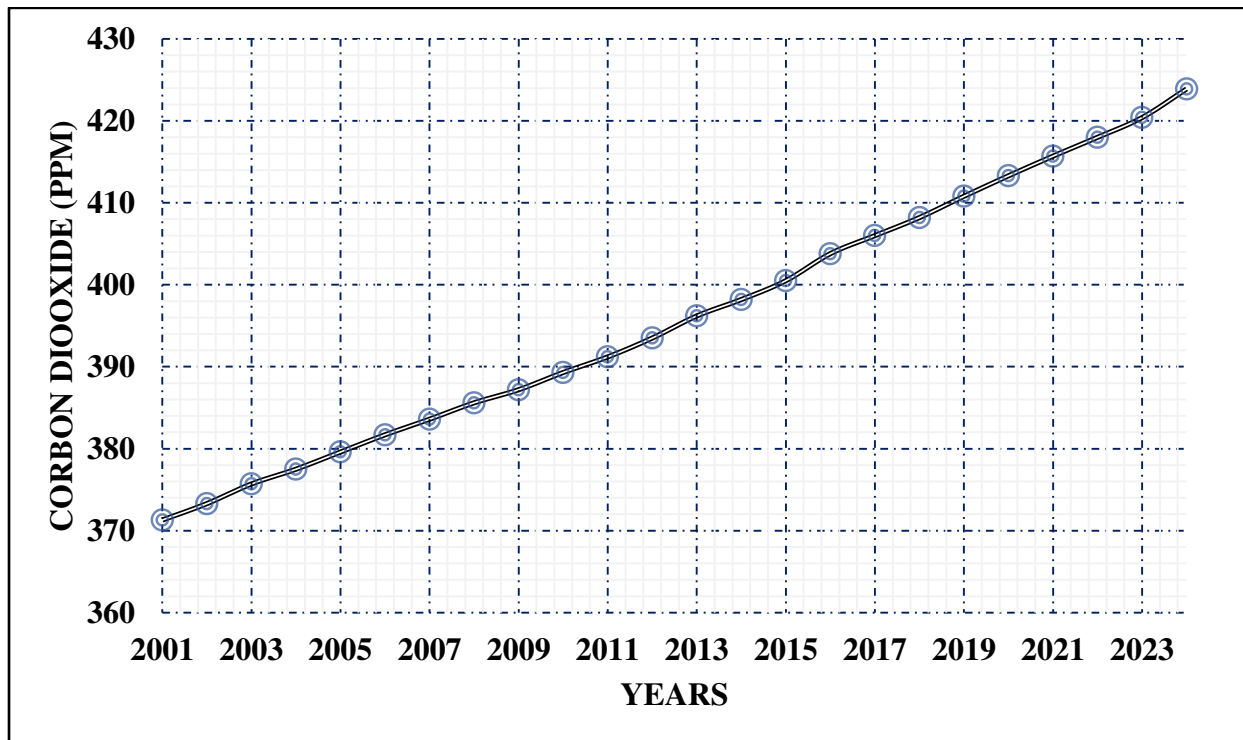


Figure 5: Global atmospheric CO₂ concentration from 2001 to 2023 (World Meteorological Organization, WMO)

3.7 Overall CO₂ Scenario (1984 – 2024): Comparative Interpretation

When Figures 4 and 5 are considered together with Annexure 2, the long-term CO₂ trend becomes even more striking. Global atmospheric CO₂ increased from

344.6 ppm in 1984 to 423.9 ppm in 2024, a total rise of 79.3 ppm in forty years.

This change can be divided into two phases:

Phase I: Gradual but Persistent Rise (1984–2000)

- Increase of 25.2 ppm
- Moderate annual increments
- Early evidence of anthropogenic forcing

Phase II: Accelerated Growth (2001–2024)

- Increase of 54.1 ppm (2001–2024)
- Larger annual increments
- Rapid crossing of historic thresholds

The second phase clearly shows faster accumulation than the first, indicating that climate mitigation efforts have not yet reversed or stabilized global emissions trends.

The data also demonstrate that atmospheric CO₂ growth is not a temporary fluctuation but a long-term structural trend driven by the global economic system. Because CO₂ is the dominant anthropogenic greenhouse gas, this trajectory strongly explains the rapid temperature increases observed in recent decades.

3.8 Global Growth of Methane Concentration (1985 – 2024)

Figure 6 presents the annual growth rate of atmospheric methane (CH₄) concentrations

from 1985 to 2024. Unlike CO₂, which shows a smooth cumulative rise, methane growth rates are more variable from year to year. However, the long-term pattern indicates renewed and accelerated increases in methane in the 21st century.

During the late 1980s and early 1990s, methane growth rates were relatively high, ranging from 10 to 13 ppb, with peaks of 13 ppb in 1986 and 12 ppb in 1985, 1987, and 1991. This was followed by a slowdown during the late 1990s and early 2000s, including:

- 1 ppb in 2000
- -1 ppb in 2001
- 0 ppb in 2004
- -1 ppb in 2005

These near-zero or negative growth years suggest temporary stabilization in methane emissions or enhanced atmospheric sinks.

However, after 2007, methane growth resumed strongly. Growth rates increased gradually through the 2010s, reaching:

- 9 ppb in 2014
- 10 ppb in 2015
- 11 ppb in 2020

The most alarming increase occurred in the early 2020s:

- 17 ppb in 2021
- 16 ppb in 2022

- 11 ppb in 2023
- 8 ppb in 2024

These recent values indicate that methane has entered a new phase of rapid atmospheric growth.

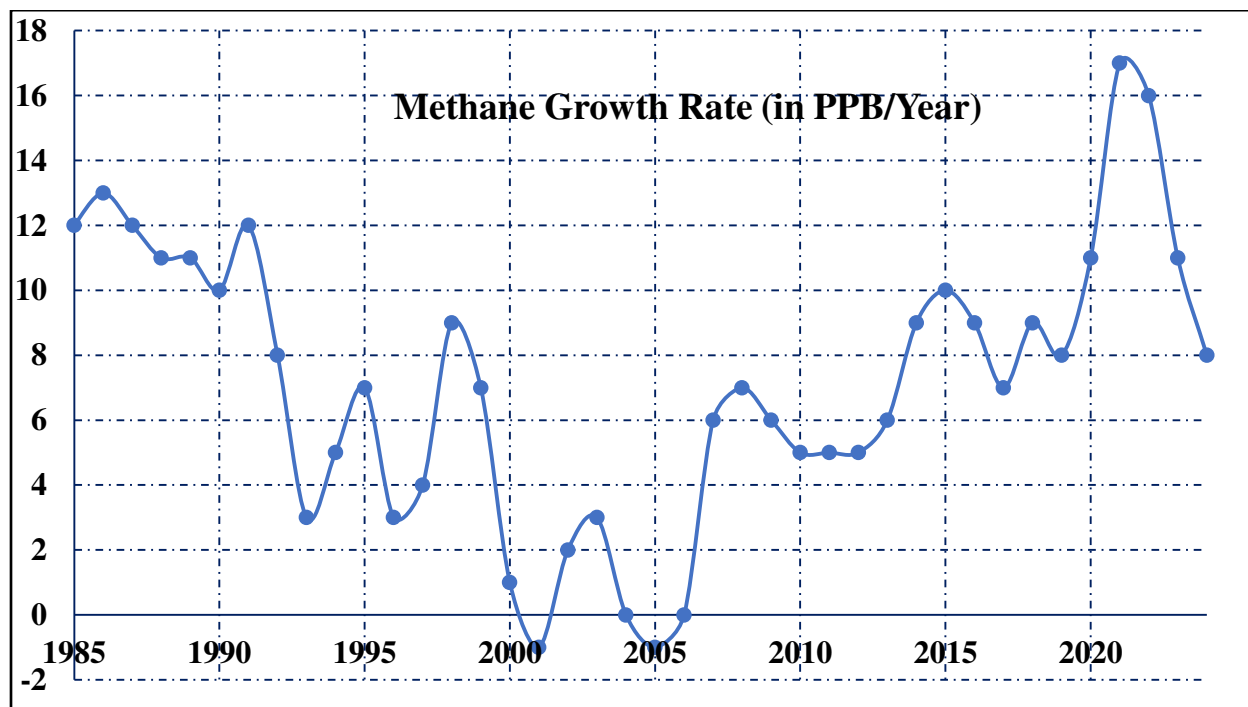


Figure 6: Global growth of CH₄ concentration between 1985 and 2024 (World Meteorological Organization, WMO)

IV. CONCLUSION

The study reveals a substantial long-term increase in global mean temperature and atmospheric greenhouse gas concentrations. Global temperature anomalies increased by approximately 1.35°C between 1850 and 2025, while atmospheric CO₂ concentration rose from 344.6 ppm in 1984 to 423.9 ppm

in 2024. Methane growth rates also showed renewed increases in recent decades, reaching 17 ppb/year in 2021. These findings highlight the persistence of global warming and the importance of reducing greenhouse gas emissions through low-carbon energy, forest conservation, and effective methane mitigation. Further

research using verified datasets and statistical trend analysis is recommended to strengthen these findings and support evidence-based climate mitigation strategies.

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