



Global Warming Assessment through Temperature Anomalies, CO₂ Forcing, and Climate Dynamics

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Abstract

This paper presents a physics-based study of long-term global surface temperature variations. Time series of annual temperature anomalies obtained from the National Aeronautics and Space Administration GISTEMP database and atmospheric CO₂ concentration data obtained from the National Oceanic and Atmospheric Administration have been used to examine the trends and changes in global warming. It was found that there is a statistical evidence of a warming trend up to 2025 with recent anomalies exceeding ~1.2 °C. The change point analysis shows that there is a transition around 1974, signifying the beginning of the rapid warming period. The nonlinear regression model shows that the trend is not linear but accelerating, showing that the system is not in equilibrium. The spectral analysis shows no strong periodicity, but the correlation analysis shows a significant positive association ($r \approx 0.97$) between temperature anomaly and CO₂ concentration. A logarithmic relationship between temperature and CO₂ is found to be consistent with the theory behind radiative forcing. The decadal analysis shows that there has been increased warming in recent decades, while the uncertainty analysis proves that the findings are statistically valid. The novelty of this study lies in integrating multiple statistical and physics-based approaches within a unified framework to provide a comprehensive understanding of global temperature dynamics.

Keywords: Global warming, temperature anomaly, time-series analysis, radiative forcing, climate physics, change-point detection, nonlinear trend, CO₂ correlation, energy balance, uncertainty analysis

Introduction

The comprehension of the changing climatic behavior of our planet is one of the key scientific problems for the present day. The temperature on Earth's surface can be viewed as one of the primary characteristics that reflects climate change due to natural variations and human activity. Over the last century, there has been a sharp and never before seen growth of the global average temperature, which is associated primarily with the fast growth in the concentration of greenhouse gases like CO₂ since the onset of industrialization (Jafrey et al. 2018; Jones et al. 2013; Steffen et al. 2013).

The physics behind global warming stems from the radiation balance of our planet (Mauritsen et al. 2025; Trenberth et al. 2022). In order to sustain thermal equilibrium, there must be a balance between the amount of incoming sunlight and terrestrial outgoing infrared radiation (Krivova et al. 2021). Disturbances of this balance, which are mainly due to enhanced levels of greenhouse gases (Ponater et al. 2012), result in decreased long wave radiation output and positive radiative forcing, causing a surplus of energy, and hence heating (Charlson et al. 2005; Donohoe et al. 2014). This is a scientifically proven phenomenon in thermodynamic and climate physics models and has been extensively validated through both observational and modeling studies (Kramer et al. 2021).

The use of high-quality observational data sets has been essential in this respect. For instance, the National Aeronautics and Space Administration's Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) is seen as the most reliable data set in the examination of global temperature anomalies, while atmospheric carbon dioxide (CO₂) measurements by the National Oceanic and Atmospheric Administration and the Scripps Institution of Oceanography have been employed in tracking the changes in the concentration of greenhouse gases. These data sets reveal an almost perfect relationship between rising CO₂ concentrations and temperature anomalies (Hansen et al. 2010; Friedlingstein et al. 2023)

Previous work has extensively analyzed the changes in global temperatures using observations and models. One of the first quantitative works to discover the relationship between elevated concentrations of atmospheric CO₂ and global warming is Hansen et al. (1981). Later analysis using data from sources such as NASA GISS and NOAA again demonstrated warming trends in the 20th century (Hansen et al. 2010). The work performed by Jones et al. (2012) greatly improved the accuracy of global temperature measurements and showed very good agreement across many independent data sets. However, in subsequent studies carried out by the IPCC, the significance of the impact of anthropogenic greenhouse gases on global warming is recognized (Kramer et al. 2021). Nonlinear approaches have also been taken into account in climatology; for example, Rahmstorf (2007) argued that global warming does not occur in a linear fashion but rather accelerates over time in recent decades. Time series approach, such as change-point analysis and spectrum analysis, have also been employed to detect shifts in regimes and periodicities in climate data (Reeves et al. 2007; Franzke 2012). Despite all these advancements, however, the majority of these earlier studies

have confined themselves to one form of analysis only, thereby giving rise to the need for a framework for the use of several forms of analysis techniques, as in the case of the present study.

While the earlier studies focused on linear trends in explaining global warming, it is now found that the climate of the earth operates in a nonlinear way and exhibits rapid changes owing to the existence of positive feedback systems, such as vapor amplification, ice albedo, and cloud interaction (Mudelsee 2019; Huang et al. 2021). This has made advanced forms of analysis methodologies, including nonlinear regression, change point detection, and spectral analysis, gain prominence in capturing the complex dynamics of climate variability (Mudelsee 2019).

In addition to this, structural changes within climate time series have also been recognized as an area of growing interest for research. Change point techniques enable the detection of changes in the characteristics of temperature time series, making it easier to understand the transition from one climate regime to another (Xueheng et al. 2022; Yu et al. 2019). Frequency domain techniques may also be used to identify natural cyclical dynamics (such as the ENSO phenomenon) from externally induced trends (Edmonds et al. 2025). Moreover, it is essential that trend analyses be accompanied by appropriate measures of uncertainty, thus ensuring statistically sound results.

Considering this, the current research makes use of a multi-dimensional framework to analyze the trends of global warming. As opposed to conventional methods that have relied on one single technique, this paper combines the use of linear and non-linear modeling, moving averages, change point analysis, frequency approaches, and the relationship between temperature and carbon dioxide in the atmosphere. The interaction between temperature and CO₂ is further analyzed through the use of logarithms based on the concept of radiative forcing theory.

The primary objectives of this study are to: (i) quantify long-term warming trends, (ii) detect structural changes in temperature evolution, (iii) examine nonlinear and accelerating behavior, (iv) identify periodic components in the data, (v) establish the empirical relationship between CO₂ concentration and temperature, and (vi) assess the statistical reliability of the results through uncertainty analysis. All findings are interpreted within the framework of Earth's energy balance, providing a physically grounded understanding of global warming as a non-equilibrium thermodynamic process.

Methodology

The present research uses a mixed methodology consisting of statistics, time series analysis, and physical laws governing climate to study changes in global surface temperature on a long-term basis. A temperature anomaly is described in the context of the present research as a deviation from a given reference standard, as shown in Fig. 1 below. A temperature anomaly is a measure of how much a given temperature differs from a reference temperature, which is used to assess trends of warming or cooling. This method is preferred over absolute temperatures for its accuracy and absence of geographical prejudice.

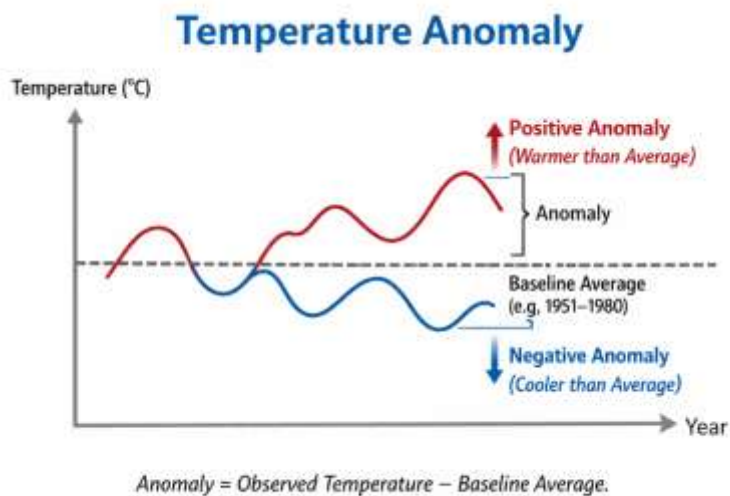


Fig 1 Schematic representation of temperature anomaly showing deviation from a baseline average

Global surface temperatures were retrieved from the Goddard Institute for Space Studies (GISS) data series offered by the National Aeronautics and Space Administration (NASA). This database consists of temperature anomalies in relation to an underlying climate norm per annum. To capture the contribution of greenhouse gases to temperature changes, atmospheric carbon dioxide (CO₂) concentrations were obtained from the National Oceanic and Atmospheric Administration (NOAA) from the Mauna Loa observation site. These data sets are widely used and accepted as a benchmark for studying the long-term trends in climate changes and understanding its physical causes.

The initial data was prepared using Python libraries by removing missing and non-numeric elements and standardizing required variables. The first step was visual exploration of the data set, which consisted of representing the relation

between temperature anomaly and time. Linear regression was used to study long-term warming. In order to remove short-term noise from data, moving averages were calculated.

In order to extract more intrinsic features about the dataset, more sophisticated techniques of time-series analysis were applied. The change point method was applied to detect any changes in the structure of temperature and find out when warming started to accelerate. Non-linear regression was applied to see if there is any curve in the temperature trend that shows acceleration in warming. Frequency-domain analysis using Fourier techniques was conducted to identify periodic components and distinguish natural variability from long-term trends.

The correlation analysis method was used to investigate the connection between temperature anomalies and CO₂ concentration in the atmosphere. The logarithmic dependency was considered as well to account for the physics idea of radiative forcing that is related to the logarithm of CO₂ concentration. The results obtained were explained through the energy balance of the Earth where the increased greenhouse gases contribute to the decreased outflow of infrared radiation leading to the radiative forcing effect. Also, decadal averaging was performed to examine long-term variations and highlight the acceleration of warming over time.

The uncertainty analysis was conducted taking into account the outcomes of the regression analysis results. The confidence interval was calculated to take into consideration the natural variability and measurement uncertainties, making the results more reliable.

Results and Discussion

This part of the paper provides the outcomes of various types of analyses, including trend analysis, smoothing, change point analysis, non-linear analysis, frequency analysis, and correlation with atmospheric CO₂. All the results have been analyzed both from the data analytical viewpoint and from the perspective of the physical processes occurring in the Earth's climate system, particularly in its energy budget.

The study begins with an initial graphing of the temperature anomaly versus time, then progresses to increasingly complex analyses that reveal hidden trends and correlations within the data set. To identify the overall trend in global temperatures, one must look at the change in temperature anomaly with respect to time, as shown in Fig 2.

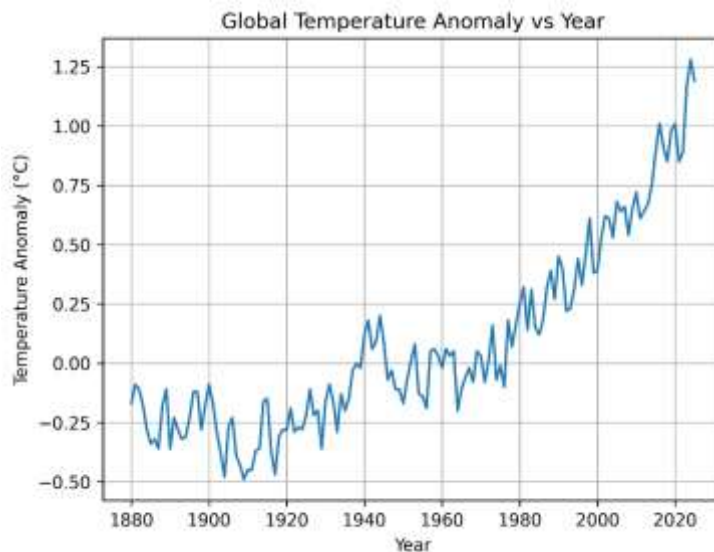


Fig 2 Global temperature anomaly as a function of year showing long-term warming trend

The chart depicts a strong trend of increasing temperatures globally. Over the period from 1880 to 1930, which marks the end of the nineteenth century and the beginning of the twentieth century, temperature deviations are mostly negative, suggesting that global temperatures were lower than the baseline average. There is variability in temperatures during this time; however, there is no sign of warming occurring.

From about 1930 to 1970, an upward trend in temperature can be seen, but it is rather gradual, with cooling periods occurring from time to time. However, beyond the 1970s, there is a clear-cut trend of increasing temperatures on the chart. This is an indication of a great change in the climate trends and the emergence of the phenomenon known as global warming.

The trend becomes steep starting from the year 1980, with high temperature anomalies going above zero points. The recent years (2000-2025) have had the highest temperature anomalies going above 1.0°C on some occasions and reaching a maximum point of around 1.25-1.30°C. This fast change can be considered to mean that there is accelerated warming, suggesting non-linear climate behavior.

The short-term fluctuations on the graph can be explained by natural variability including volcano eruptions, interactions between the oceans and atmosphere, and variations in solar radiation. But they do not affect the overall increasing trend. To determine the rate at which warming is occurring, we perform a linear regression analysis as shown in Fig 3.

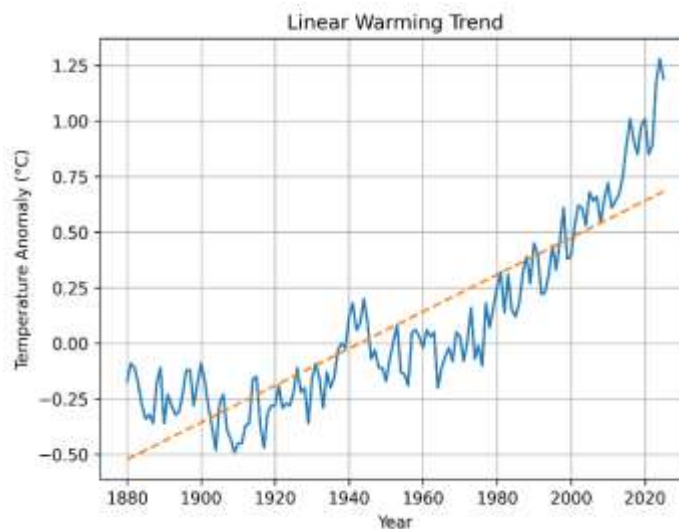


Fig 3 Linear regression fit to temperature anomaly data indicating the rate of global warming

From Fig 3, it can be noted that the fitted straight line follows a general upward trend, thereby showing an increase in the global temperature over time. The slope of the regression line is positive, meaning that there is an increase in temperature and, therefore, the earth has been getting warmer since the last hundred years.

While there are obvious fluctuations in the actual temperature measurements, the linear model averages out these irregularities to show the underlying trend. The extent to which individual observations differ from the trend line shows variation arising naturally due to climate conditions like ocean currents and volcanic eruptions. Notably, even though the linear function is used to predict the overall trend, it fails to capture the rapid increase in temperatures seen more recently. This implies that the increase in temperatures is not necessarily linear but may accelerate, as will be shown in later analysis.

To better visualize the underlying trend by reducing short-term fluctuations, smoothing techniques are applied.

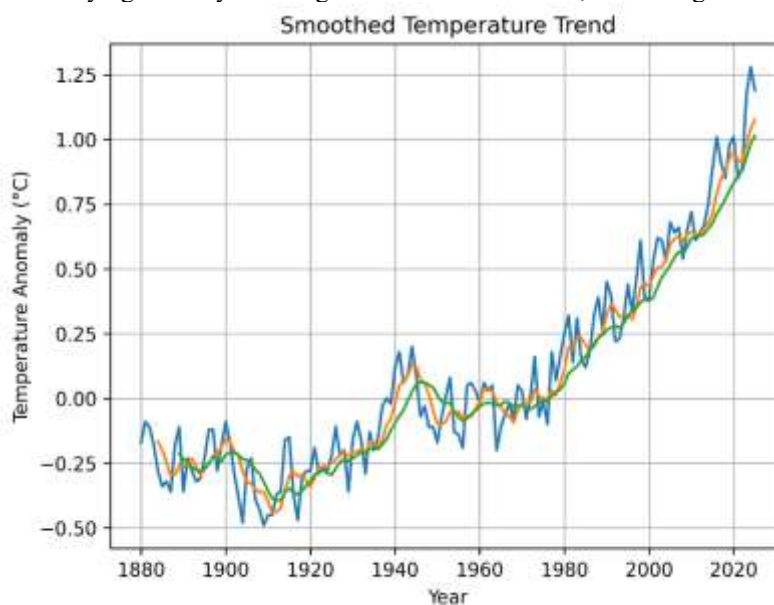


Fig 4 Smoothed temperature trends using 5-year and 10-year moving averages to highlight long-term variations

Fig 4 represents the results for smoothing of temperature data employing the use of moving average method on the temperature anomaly series. Apart from the original temperature anomaly series, the smoothed graphs representing both short term and long term moving averages are also shown to minimize high frequency oscillations. There is a great deal of variation in temperature year after year from the raw data; however, this variation is filtered out by employing moving averages and reveal the underlying long-term trend more clearly.

The trends from the smoothed curves show that there was a steady warming period from the early twentieth century to the 1970s, followed by a more significant warming period post-1970s. In particular, the trends derived from the moving averages reveal a consistent trend of increasing temperatures in the earth's climate, which suggests that the observed warming trend is a long-term phenomenon and not an effect of short-term variations. Additionally, the

discrepancies in some parts between the unsmoothed data and the smoothed trends show natural variations, while the similarities in long-term trends show consistency in warming.

Although smoothing highlights long-term behavior, it does not identify structural shifts. Therefore, change-point analysis is performed, as shown in Fig 5.

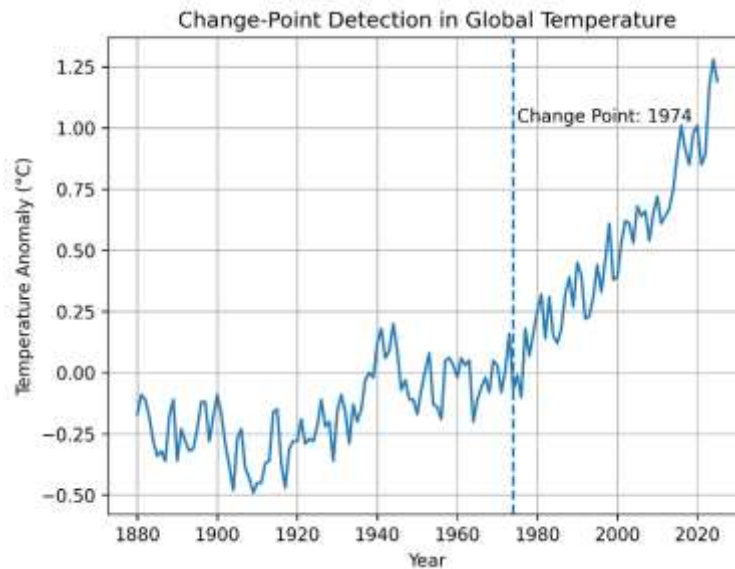


Fig 5 Change-point detection in global temperature anomaly indicating a significant shift in warming trend around 1974

The change-point analysis is done by fitting piecewise linear regression models to the temperature anomaly data set to find the year with minimum residuals. In this case, there is an important change-point year around 1974 represented by the dashed vertical line in the graph. This indicates an important turning point year in the behavior of the temperature time series data. Prior to 1974, temperature changes are rather moderate, with lower slopes and fluctuation of temperatures above the baseline temperature. However, after 1974, there is a distinct trend towards rising temperatures. The graph clearly shows that temperatures become steeper while the anomalies are generally positive, reflecting a transition to a warmer climate regime.

This is physically significant since it corresponds to the time at which the effect of anthropogenic impacts on climate, especially the dramatic rise in greenhouse gas emissions, became evident. The existence of this phase shows that global warming occurs in different stages, and therefore, the process cannot be described using a single approach. This is clear evidence of climate transition, indicating the move from one stage to another characterized by faster warming. This can be regarded as one of the main findings of the study, and hence there is a need for further nonlinear and physics-based analysis in the following sections.

The identification of a structural shift suggests that the warming trend may not be purely linear. This is further examined using nonlinear regression models in Fig 6

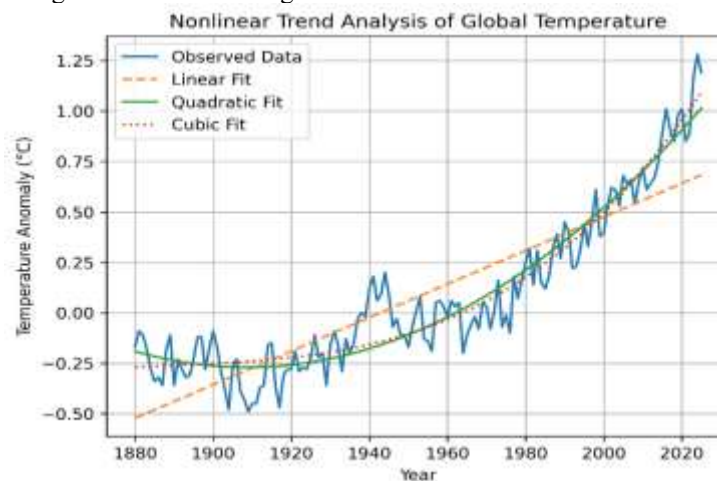


Fig 6 Nonlinear Trend Analysis of Global Temperature

Temperature data obtained through observations have an evident upward trend; however, the linear model does not sufficiently account for curvature present in the data, particularly in recent decades. On the other hand, the quadratic and cubic polynomial models account for the data much better than the linear function. Notably, the nonlinear models

illustrate an upward curvature in the temperature trend, suggesting that the increase in temperatures has an accelerating trend and is not constant. This can be demonstrated by the increased inclination of the curves produced by the quadratic and cubic models relative to the linear one. The cubic fit, in particular, captures subtle variations and provides the closest approximation to the observed data.

Such behavior indicates the presence of nonlinearity in the warming process, which can be justified by the existence of feedback effects like water vapor enhancement, albedo of ice effect, and greenhouse gases concentration increase. The accelerating trend indicates deviation from the system's equilibrium state, which is a core component of statistical physics and climate dynamics.

Whereas nonlinearity analysis demonstrates acceleration, it cannot show periodic variations. In order to study such properties, frequency analysis is conducted in Fig 7.

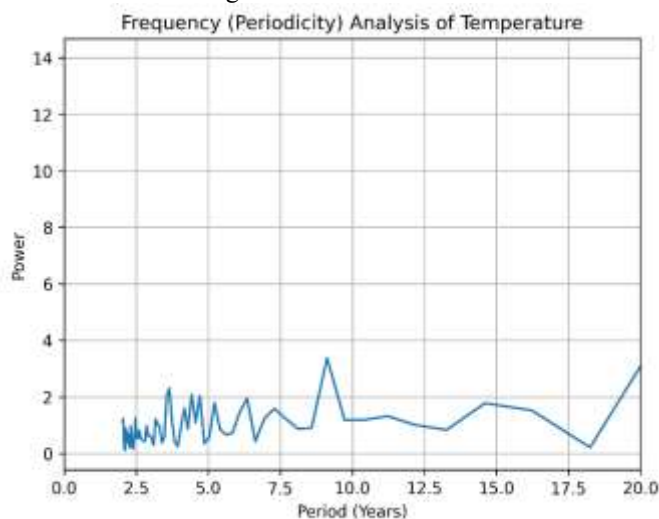


Fig 7 Frequency (Periodicity) Analysis of Global Temperature

Plot shows the distribution of power at various time spans (in years), which helps to recognize any patterns that occur repeatedly in the temperature data set. The highest peaks on the graph denote the prominent periodicity factors.

Based on the graph, some relatively low peaks can be seen between 3 to 7 years, which may relate to the variations in climatic conditions such as oceanic and atmospheric interactions like El Nino-Southern Oscillation phenomena. A broader and less sharp peak is also visible around 8–10 years, indicating longer-term variability.

Nevertheless, considering the lack of any very prominent and sharp peaks, it can be said that periodic fluctuations do not control global temperature variability in any way. On the contrary, the temperature signal is driven predominantly by weakly fluctuating periodic components and one strong component showing an increasing tendency. In other words, for periods greater than approximately 15 years, the power grows slowly showing it is mostly controlled by long-term rather than short-term oscillations. This coincides with the existence of a continuous warming trend identified in earlier figures.

After analyzing the variable itself, the next important aspect involves examining its causes. The link between temperature and carbon dioxide concentrations is shown in Fig 8.

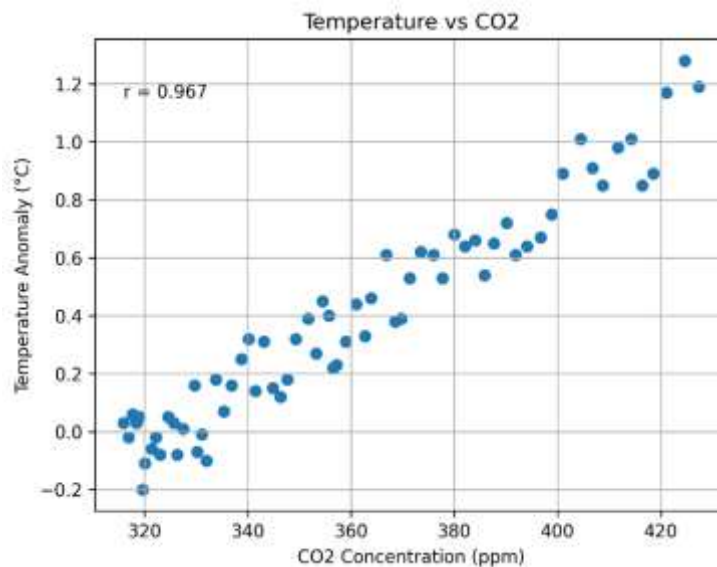


Fig 8 Correlation between Temperature and CO₂ Concentration

The scatter plot presented above indicates that there exists a positive relationship between the level of carbon dioxide in ppm and temperature anomaly in °C. From the graph, it is clear that as the level of CO₂ increases, so does temperature anomaly. This means that the levels of CO₂ are responsible for global warming. The value of correlation coefficient is 0.967, which is close to +1, signifying an extremely strong linear relationship between the two variables. This suggests that variations in atmospheric CO₂ are closely linked to changes in global temperature.

From a physics perspective, the above relationship is in line with the idea of radiative forcing, whereby higher CO₂ concentrations lead to increased trapping of outgoing infrared radiation. It results in lower heat dissipation from the earth's surface, hence causing an energy imbalance and an increase in temperature. While there is a very high correlation, it can be noted that there is some scattered pattern in the graph, implying that besides carbon dioxide, there are other forces affecting temperature, such as solar variability, internal climate dynamics and aerosols. The strong rising trend, however, suggests that CO₂ plays the leading role in recent climate change. Whereas the relationship is linear, theory suggests a logarithmic one, which will be discussed next.

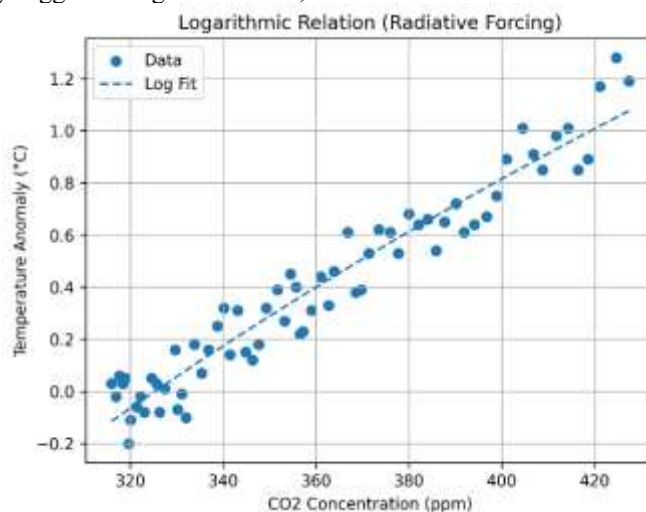


Fig 9 Logarithmic Relation between Temperature and CO₂ (Radiative Forcing)

Unlike the linear relationship described previously, this diagram also includes a logarithmic function, which is justified from a physical point of view because of climate science. Based on the radiative forcing effect, the rise in Earth's temperature depends on the logarithm of CO₂ concentration and not directly on CO₂ itself.

As can be seen in the plot above, the logarithmic function matches the data well, reproducing the rising tendency without increasing the slope too much for higher CO₂ concentrations. This illustrates a vital physical insight in that as more carbon dioxide is added to the atmosphere, each subsequent addition adds less and less to the radiative forcing, although cumulatively the result is substantial warming. There are small differences because of differences in nature; however, there is consistency with what would be expected theoretically. On the physical level, this happens because of the saturation of atmospheric CO₂ IR bands, and radiation will depend logarithmically on the amount of CO₂.

Since long-term trends need to be shown, the analysis will be conducted for a period of ten years.

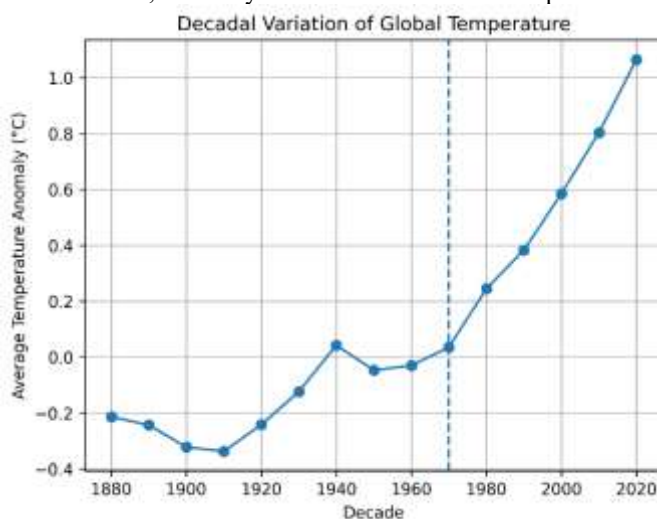


Fig 10 Decadal Variation of Global Temperature

The graph is a clear depiction of the long-term trends of the temperature fluctuations on a decade-by-decade basis. As such, it is less likely to be affected by any form of random fluctuations, thereby making it easier for the underlying

trends to be more pronounced. Within the timeframe from the late 19th to the early 20th century (1880-1910), the temperature anomaly has been found to remain negative, implying that there were low temperatures on a global scale. Following this period is an observable rise in the temperature anomaly, which then levels out from 1940 to 1970. A turning point is noted to happen around the 1970s (indicated by the dashed line). This is because, from then on, the temperature anomaly starts showing an increasing tendency. Since 1980, each following decade is characterized by a higher average temperature compared to that of the previous decade, reflecting a strong trend towards warming. Recent decades (2000-2020) have shown temperature anomalies of more than 0.5°C and nearing 1.0°C. It is seen that the rate of increase in this time period is very fast, signifying the rapid pace of global warming, confirming results obtained from earlier analyses such as nonlinear trend fitting and change-point detection. Finally, to assess the reliability of the observed trends, uncertainty analysis is performed using confidence intervals, as presented in Fig 11.

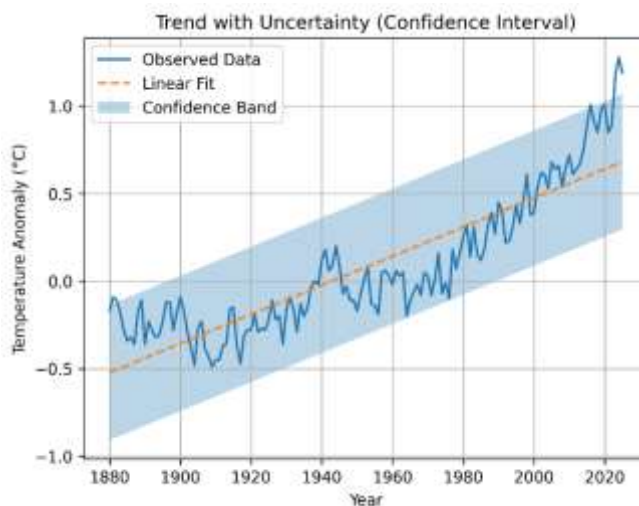


Fig 11 Trend with Uncertainty (Confidence Interval)

The solid line in this graph illustrates the temperatures anomaly observations, whereas the dashed one denotes the trend based on the best fitting linear regression line. In addition, there is a shaded area illustrating the confidence level in regard to the observed trend line.

As can be seen from this graph, although some year-to-year variation is evident, the general rising trend has been clearly identified. Moreover, in regard to the confidence level of the linear model, it should be noted that most of the data lies within the confidence range, indicating that the linear model provides a statistically consistent representation of the long-term trend. A wide confidence band shows uncertainty associated with the estimate of regression. A gradual widening of the confidence band is expected on the edges of data due to less restriction on them in statistical estimation. However, this does not affect the overall pattern as the confidence band is still positive-sloped, strengthening the evidence in favor of warming trend.

Scientifically speaking, it becomes clear that the global warming effect exists and is significant enough since this finding cannot be attributed to chance and other random factors. The inclusion of error terms and, thus, uncertainty makes the experiment more credible.

Conclusion

In the current investigation, an exhaustive analysis of surface temperature trends worldwide was conducted based on observational data from NASA, and atmospheric CO₂ concentrations from NOAA. It has been found that global surface temperature has increased steadily for the last century, with a noticeable increase in this process in the recent few decades.

It should be mentioned that one of the important conclusions reached in this research was the detection of a change-point at about 1974, implying that the trend of temperature has undergone some structural changes. The latter implies the existence of a transition from an equilibrium state to a new regime of accelerated warming, which can be interpreted as a non-equilibrium response of the climate system.

Additionally, the analysis of nonlinear regression shows that the phenomenon of global warming does not only have linear features, but also has a tendency to acceleration, which has been proven by the use of the quadratic and cubic curves. It confirms the existence of the feedback loop. Spectral (frequency) analysis proves the existence of the short-period oscillations, especially in several years' time; however, the major component of the entire temperature dynamics is the tendency towards an increase. This indicates that natural variability alone cannot explain the observed warming. A highly positive correlation ($r \approx 0.97$) between CO₂ concentration and temperature anomaly is evident, offering empirical proof for their association. In addition, the log fit confirms that the temperature variation follows radiative forcing theory, implying that warming increases exponentially with logarithms of CO₂ concentrations.

Decadal analysis highlights an increase in warming rates during each subsequent decade, particularly from the 1970s onwards. This result is consistent with the results of change point and non-linear regression analyses. Firstly, the use of uncertainty analysis through confidence intervals increases the reliability of the findings because it indicates the statistical significance of the warming trend. Secondly, the current paper not only confirms the fact that global warming occurs, but it also provides an understanding of how global warming emerges. The joint use of statistical analysis and physical processes in climate allows for gaining an interesting understanding of the phenomenon under study.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose

Data Availability

The datasets generated during and/or analysed during the current study are available in the GISS Surface Temperature Analysis (GISTEMP v4), Global Annual Mean Surface Temperature Change] repository [<https://data.giss.nasa.gov/gistemp/>] and *Trends in Atmospheric Carbon Dioxide (Annual Mean CO₂ Data, Mauna Loa Observatory* [<https://data.giss.nasa.gov/gistemp/>]

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