CO_2–Temperature Relationship in Glacial Cycles and Current Scenario: Cause or Effect?

CM-618 Course Project — Group 10

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Github Repository: https://github.com/YashMehta25/CM618_Group10_Project

1 Introduction and Motivation

Ice core records reveal a strong correlation between atmospheric CO_2 concentration and global temperature across glacial–interglacial cycles. Understanding this interplay is essential to explain the mechanisms behind past climate variations and to predict future climate behavior under anthropogenic influence.

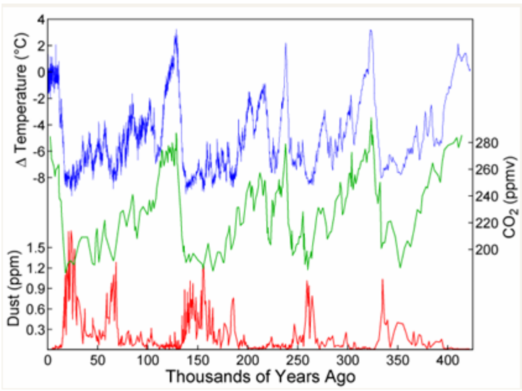

Figure 1: Vostok Ice Core showing CO_2–Temperature relationship in glacial cycles

In glacial cycles, CO_2 acted primarily as a feedback amplifier — warming oceans released CO_2, which in turn trapped more heat and amplified warming.

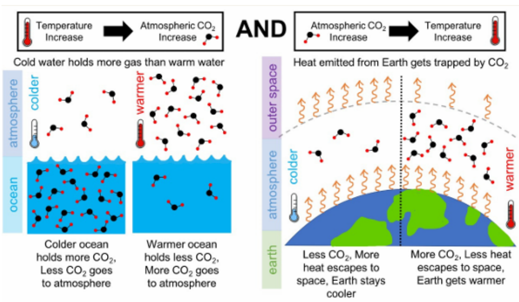

Figure 2: Effect of CO_2 and Temperature on each other

However, in the modern era, the unprecedented rate of anthropogenic CO_2 emissions raises the question: *Does CO_2 still lag temperature, or has its role reversed?*

2 Background and Literature Review

Previous studies (Petit et al., 1999; Lorius et al., 1990; Shakun et al., 2012) indicate that during glacial periods:

- Temperature increases were initially triggered by Milankovitch orbital forcing
- Warming oceans released CO_2 after a lag of **200–800 years**
- CO_2 amplified the warming through greenhouse feedback

CO_2 thus acted as the "great amplifier," responsible for roughly **one-third** of total glacial–interglacial warming, while other feedbacks (ice–albedo, water vapor) accounted for the rest.

3 Hypothesis

Research Question: Does CO_2 still lag temperature in the modern climate system as it did during glacial cycles?

Null Hypothesis (H_0)

Even in the present climate system, CO_2 still lags temperature as in glacial cycles — implying that temperature variations are driven primarily by other factors (e.g., methane or ocean–atmosphere feedbacks), and CO_2 responds subsequently.

Alternative Hypothesis (H_1)

In the modern era, anthropogenic CO_2 emissions lead the temperature rise, making CO_2 the primary forcing.

4 Methodology

We primarily focus on **methane** as the claimed driver of temperature increase in current scenario. Hence, in order to not reject our null hypothesis, we need to prove two things:

- CO_2 concentration in the atmosphere **significantly** lags the increasing global temperature
- Methane emissions and/or concentration in the atmosphere **significantly** leads the increasing global temperature

If we are able to establish the two conditions above, it is then essential to examine the **causal relationships** between methane and temperature, as well as between temperature and CO_2. A simple lead–lag analysis alone cannot fully capture the underlying directional dependencies or causal influences among these variables.

4.1 Data Description

We have considered following data in our analysis:

- Global Atmospheric CO_2 Concentrations (1958–Present) averaged on a monthly basis – NOAA Mauna Loa Observatory
- Global Atmospheric CH_4 Concentrations (1984–Present) averaged on a monthly basis – NOAA Global Monitoring Laboratory
- ERA5 Reanalysis Global Temperature Dataset (1951–Present) on a monthly basis (data of first day of every month) – Copernicus Climate Data Store
- Human-Induced CH_4 Emissions (Mt/year) on an yearly basis – Climate Change Tracker

4.2 Cross Correlation for Lead/Lag Analysis

The cross-correlation function quantifies the similarity between two time series as one is shifted in time relative to the other, allowing identification of whether one variable leads or lags the other.

We do cross-correlation analysis of following combinations of time series:

- Global CO_2 Concentration and Temperature
- Global Methane Concentration and Temperature
- Human-Induced CH_4 Emissions and Temperature

Before applying cross correlation, it is important to get rid of noise and periodic fluctuations. Hence, we first de-trend and smoothen our time-series using a **48-month rolling mean**

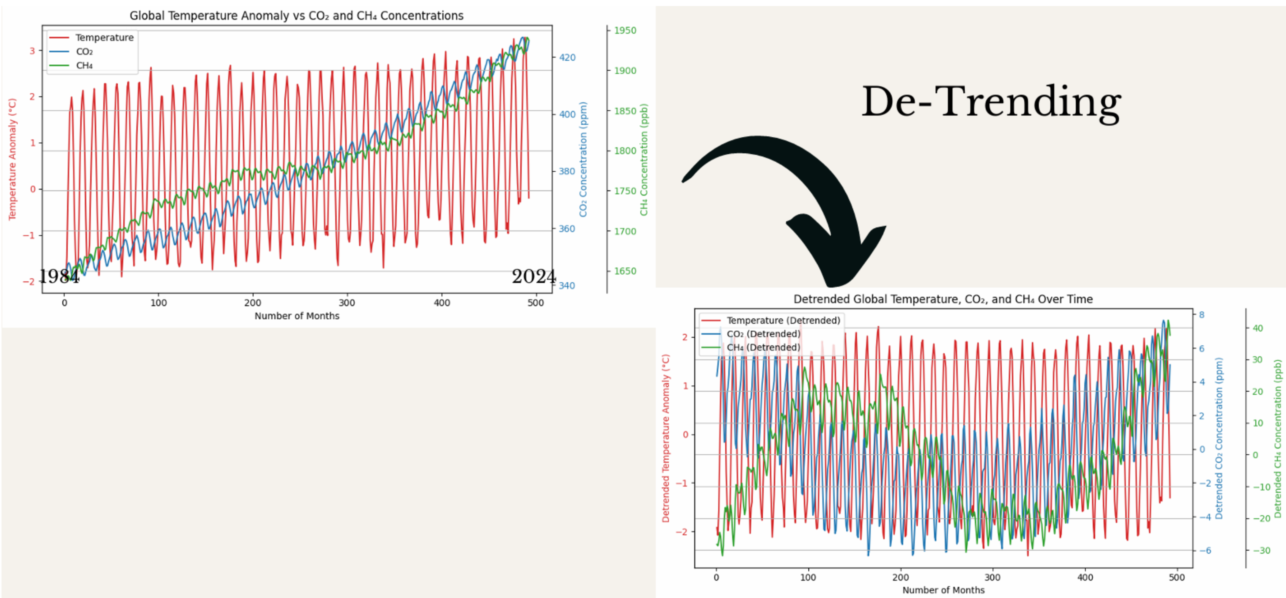

Figure 3: Cross-Correlation between CO_2, CH_4, and global temperature

4.2.1 Cross Correlation Analysis of CO_2 Conc. and Temperature

After shifting CO_2 series and using cross correlation, we found out that: CO_2 concentration significantly ($p < 0.05$) **lags** global temperature with a pearson coefficient of **0.6** and lag of **15 months**.

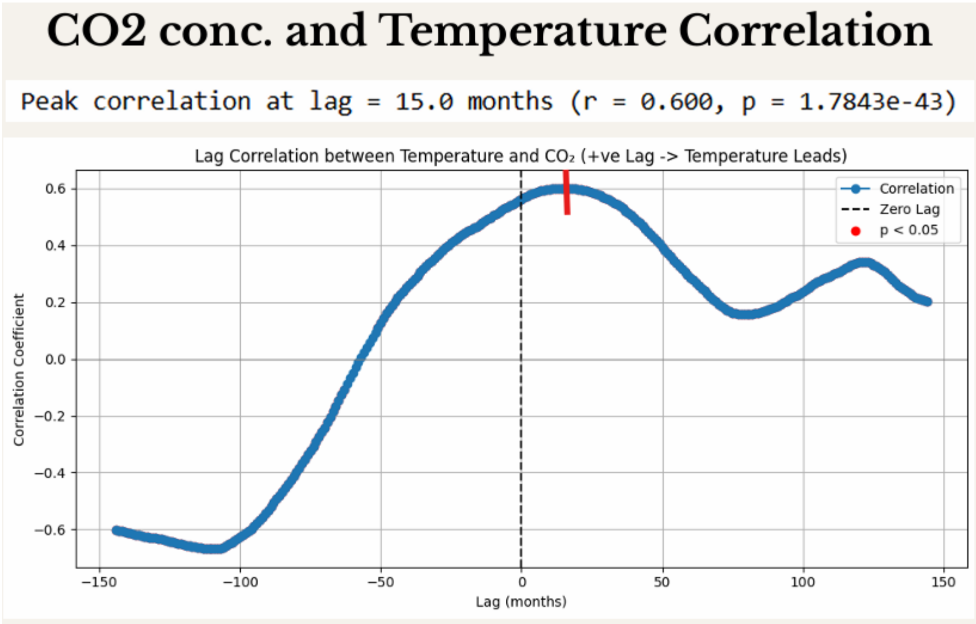

Figure 4: Cross Correlation between CO_2 Concentration and Temperature

4.2.2 Cross Correlation Analysis of Methane Conc. and Temperature

After shifting methane series and using cross correlation, we found out that: methane concentration significantly ($p < 0.05$) **leads** global temperature with a pearson coefficient of **0.604** and lead of **47 months**.

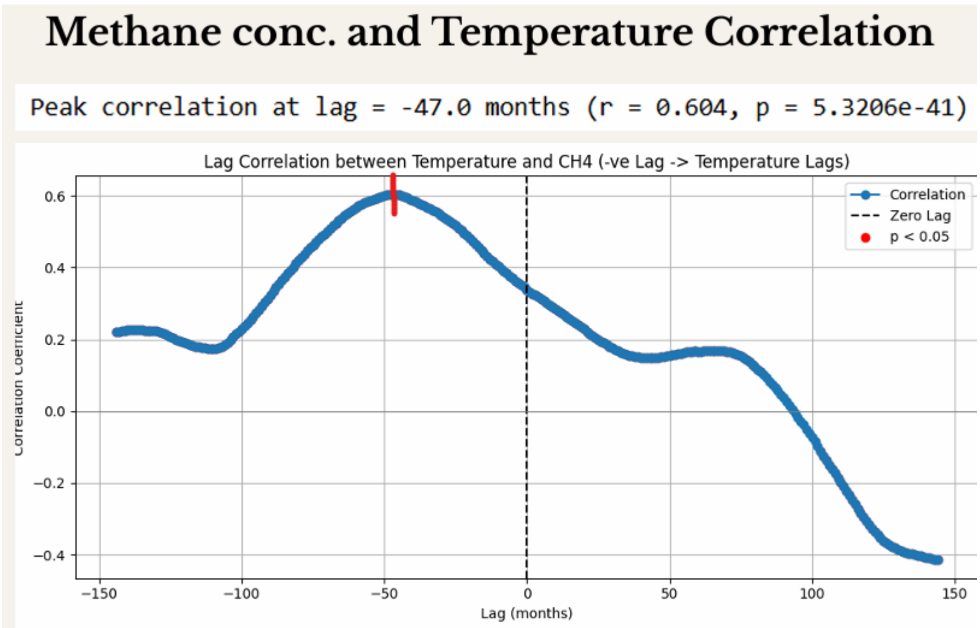

Figure 5: Cross Correlation between Methane Concentration and Temperature

4.2.3 Cross Correlation Analysis of Methane Emissions and Temperature

The time series for human-induced methane emissions was available on an annual scale from 1951 onward. Consequently, the global temperature dataset, originally recorded on a monthly basis, was averaged to annual means for consistency in temporal resolution. Due to the relatively limited number of data points in the yearly dataset, only detrending was applied by subtracting a **10-year rolling mean** from each data point.

Visual inspection of the resulting trends indicates that **methane emissions tend to lead global temperature** (refer 6), with increases in methane emissions preceding corresponding rises in temperature.

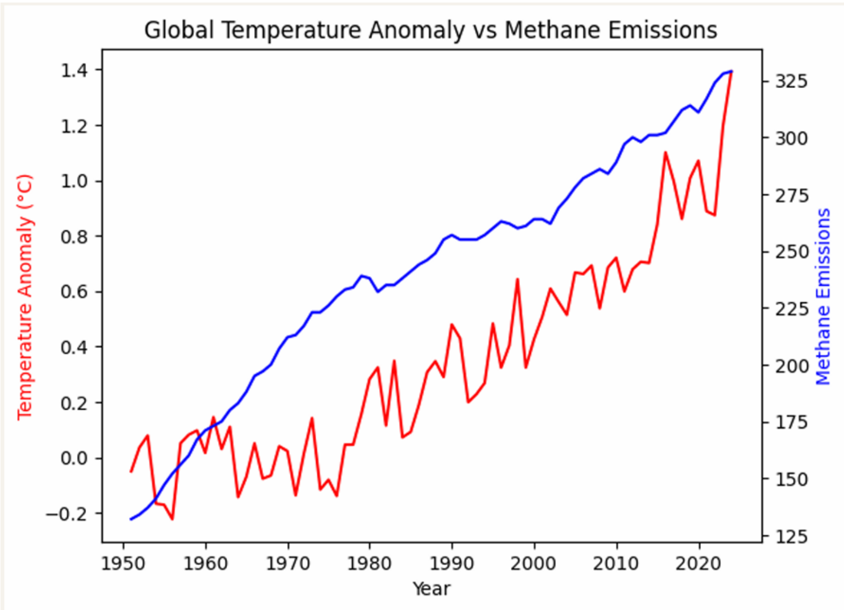

Figure 6: Visual Inspection

After shifting temperature series and using cross correlation, we found out that: methane emissions significantly ($p < 0.05$) **lead** global temperature with a pearson coefficient of **0.393** and lead of **17 months**.

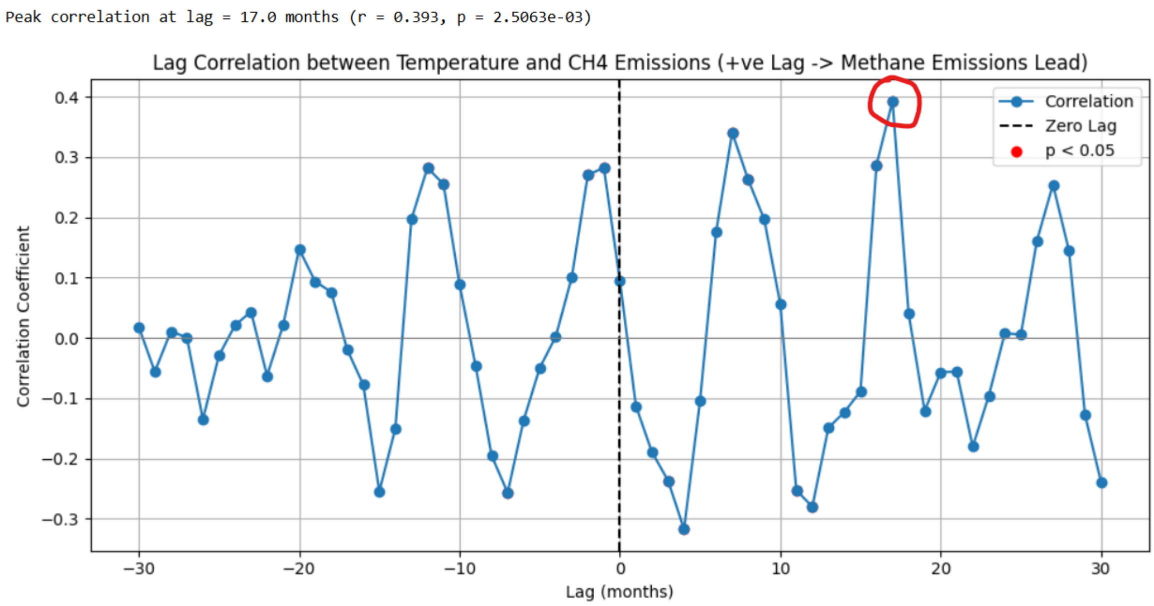

Figure 7: Cross Correlation between Methane Emissions and Temperature

4.3 Causality Analysis

In the previous section, we were able to prove the two things we had mentioned in our proposed approach. Hence, we now try to capture the directional dependencies among the variables. We do so by using two different methods:

- **Granger Causality Test** to check causality between CO_2 conc. and global temperature
- **Transfer Entropy Analysis** to assess directional influence between Methane Emissions and Temperature as well as CO_2 Conc. and Temperature

4.3.1 Granger Causality Test

The **Granger Causality Test** determines whether past values of one time series contain statistically significant information that helps predict future values of another, by comparing regression models with and without the potential causal variable.

Here, we try to check if past values of temperature are able to predict future values of CO_2 and vice versa.

Our Results

```
Granger test: Does CO₂ → Temp?
  Best lag up to 24 months = 24; p-value = 0.026

Granger test: Does Temp → CO₂?
  Best lag up to 24 months = 20; p-value = 5.45e-11
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Figure 8: Results of Granger Causality Test

The Granger test results indicate that while CO_2 has a weak predictive influence on temperature, temperature strongly and significantly predicts CO_2 fluctuations, suggesting that short-term CO_2 variations primarily respond to temperature changes.

4.3.2 Transfer Entropy based Analysis

Transfer Entropy quantifies how much knowing the past of X improves the prediction of Y's future, capturing nonlinear and directional dependencies that correlation or Granger Causality Test might miss.

Thumb Rule

If **TE (X→Y) > TE (Y→X)**,
then the information flow from X to Y is greater than from Y to X,
implying that **X has a stronger causal (predictive) influence on Y**

Figure 9: Thumb Rule of Transfer Entropy

We carry out this analysis (using the thumb rule) for Methane Emissions and Temperature as well as CO_2 Conc. and Temperature. We get the following results:

- TE(Temperature $\rightarrow$ CO_2) > TE(CO_2 $\rightarrow$ Temperature)
- TE(Methane Emissions $\rightarrow$ Temperature) > TE(Temperature $\rightarrow$ Methane Emissions)

Our Results

Transfer Entropy (Temperature → CO_2): 0.8498
Transfer Entropy (CO_2 → Temperature): 0.6058

Transfer Entropy (Methane → Temp): 0.6384594482692192
Transfer Entropy (Temp → Methane): 0.20624450076430245

Figure 10: Results of Transfer Entropy Analysis

Hence, we can say that human-induced methane emissions have a strong causal influence on global temperature and global temperature further has a causal influence on CO_2 concentrations in the atmosphere

5 Conclusion

The evidence from our analysis provides a clear direction for further exploration and indicates a tendency towards **not rejecting the null hypothesis**. To be more specific, we cannot directly conclude/believe that the current trend has reversed with respect to the glacial trend. There are a lot of interdependencies involved in current scenario. Clearly, the lag has shortened dramatically in the modern era—from **several 100 years** during the ice ages to just a **few months** in the present scenario. Hence, **there is surely an impact of human activities in the current trend**, although the trend might not have been reversed.

Nevertheless, a more detailed study incorporating advanced statistical techniques and additional factors - such as **radiative forcing, feedback loops and other greenhouse gases** - would allow us to confirm this conclusion with greater confidence.

References

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Appendix

Cross Correlations at different smoothening:

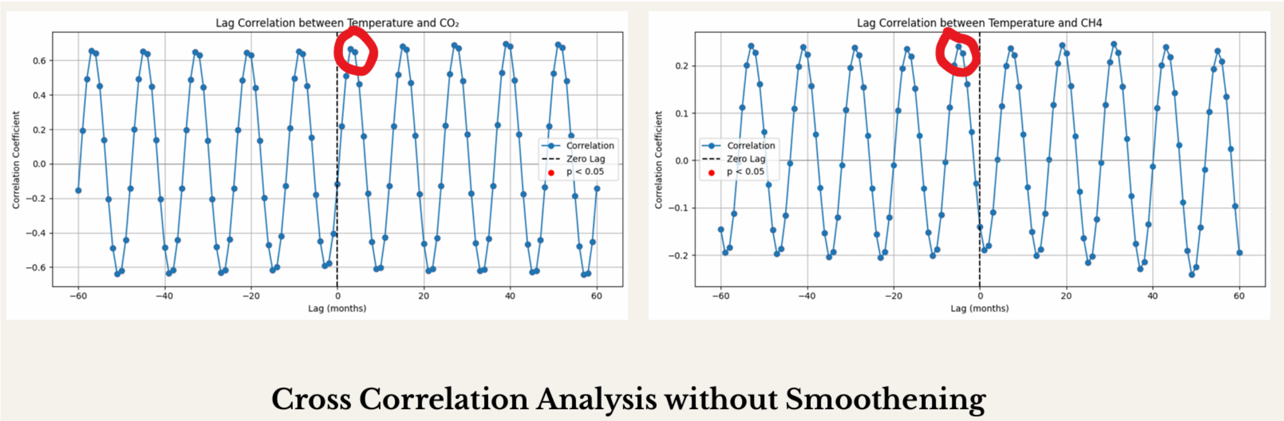

Figure 11: No Smoothening (Check the nearest peak on either side)

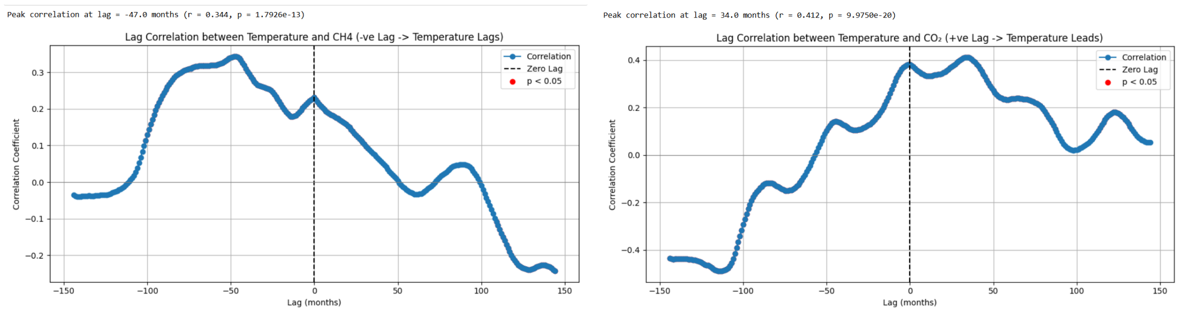

Figure 12: 12 Years Smoothening: (a) Methane vs. Temperature and (b) CO_2 vs. Temperature.

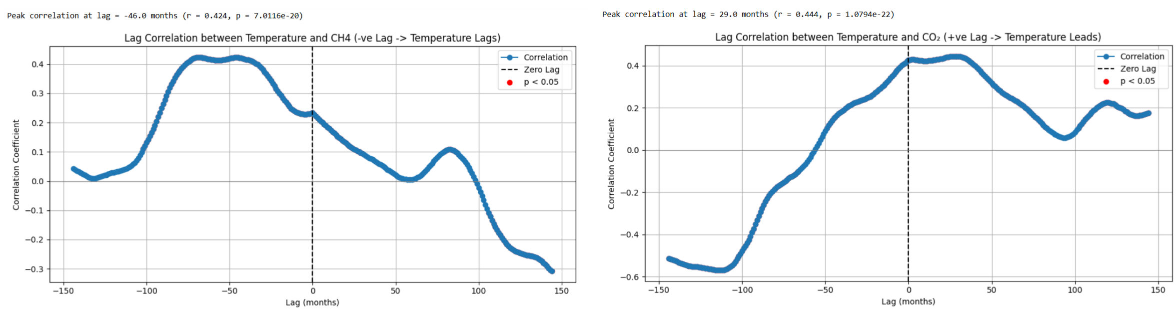

Figure 13: 24 Years Smoothening: (a) Methane vs. Temperature and (b) CO_2 vs. Temperature.