

CM - 618 Course Project

“CO₂–TEMPERATURE RELATIONSHIP IN GLACIAL CYCLES: CAUSE OR EFFECT?”

Group 10

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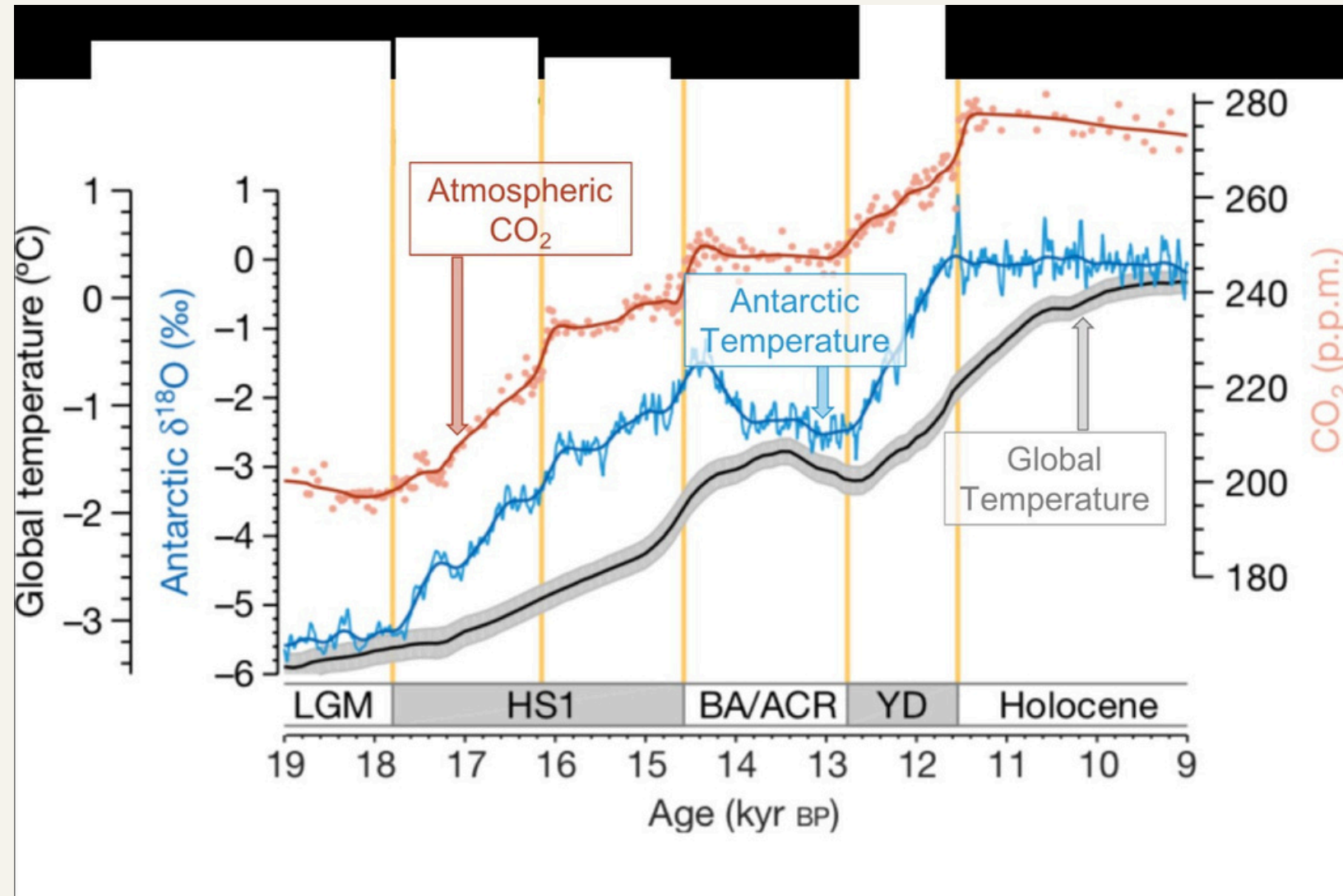
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Glacial Cycles



Vostok Ice-core graph

- During glacial–interglacial transitions, temperature increases occurred first, due to orbital (Milankovitch) forcing.
- CO₂ lagged temperature by ~200–800 years, mainly because warming oceans released dissolved CO₂.
- CO₂ did not initiate the warming, but acted as a positive feedback amplifier, increasing total warming magnitude.
- Without the CO₂ feedback, orbital forcing alone cannot account for the full ~5–6°C warming.

Hypothesis (H_1):

- During past glacial cycles, temperature rise occurred first and CO_2 increased later as a feedback amplifier.
- However, in the current era, human-driven CO_2 emissions are leading the temperature rise, making CO_2 the primary forcing today.

Null Hypothesis (H_0):

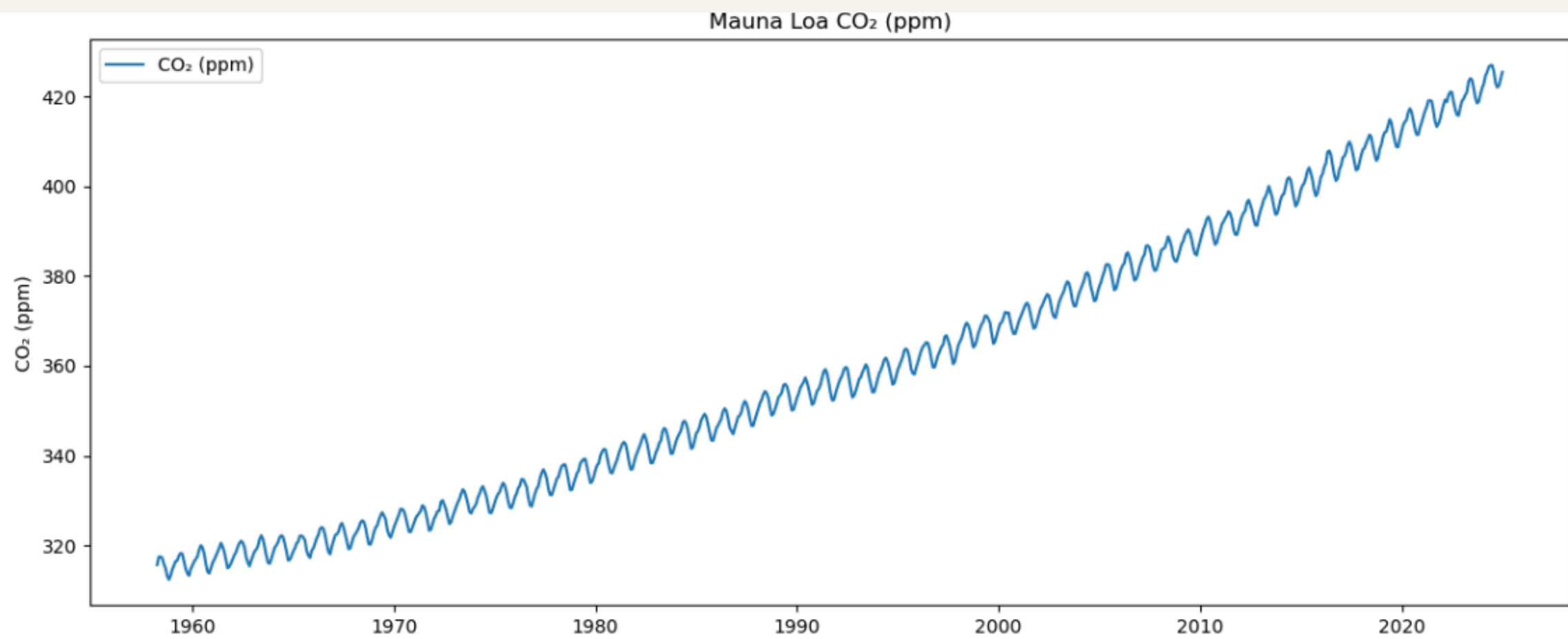
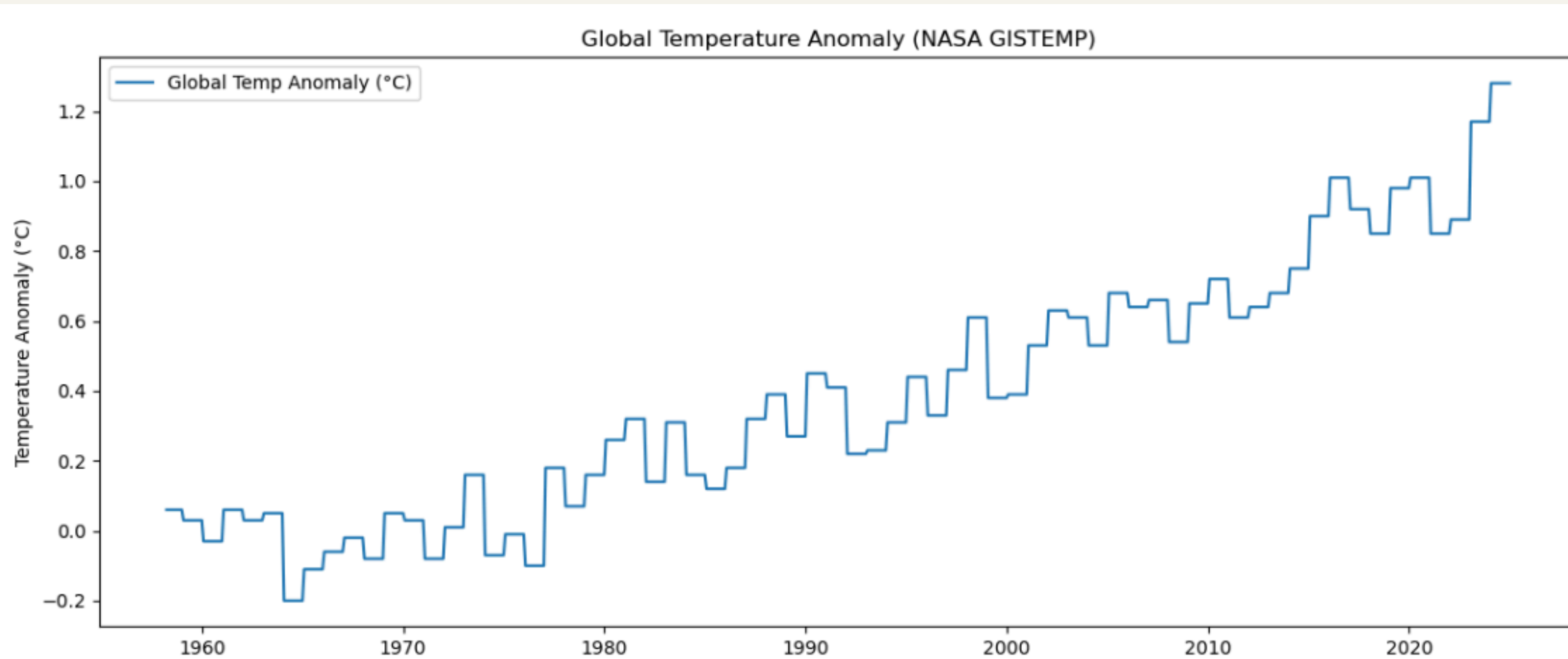
- Even in the present climate system, CO_2 still lags temperature as in glacial cycles.
- This implies temperature change is primarily initiated by other factors (e.g., methane, natural variability or ocean-atmosphere dynamics), and CO_2 only reacts afterward.

Data Sources and References

- **Global Atmospheric Methane Concentration Trends** - NOAA Global Monitoring Laboratory (1950–Present)
- **Global Atmospheric CO₂ Concentration Trends** - NOAA Global Monitoring Laboratory (Mauna Loa, 1958–Present)
- **Human-Induced Methane (CH₄) Emissions by Sector & Year** - Climate Change Tracker
- **ERA5 Reanalysis Climate Dataset** - Copernicus Climate Data Store (Hourly Global Gridded Fields)

- Humlum, O., Stordahl, K., & Solheim, J.-E. (2013), Global and Planetary Change, 100, 51–69.
- Mar et al. (2022), Environmental Science & Policy, 134, 127–136.

Modern Era (Post 1950)



Methodology and Results

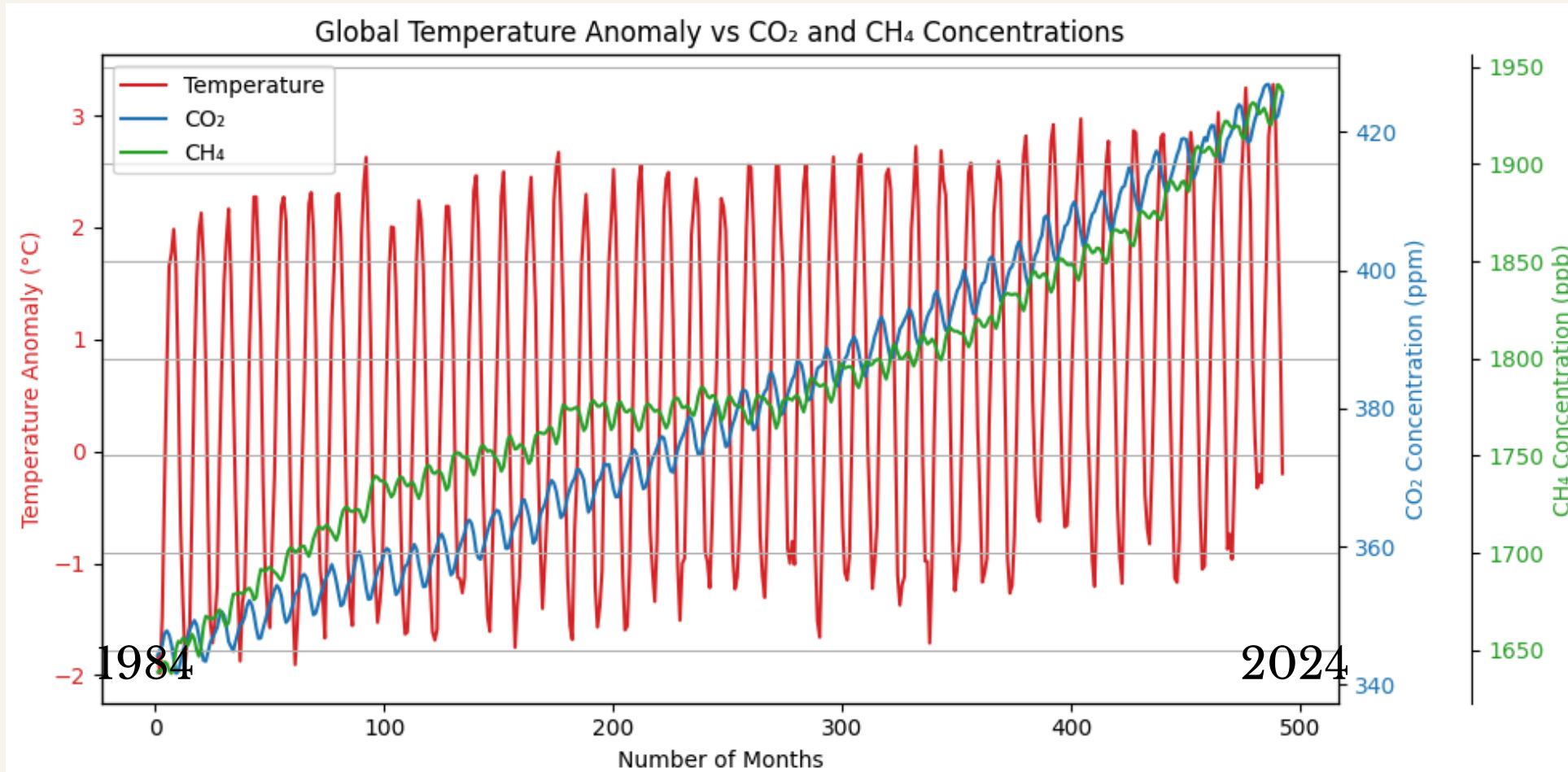
We specifically focus on **methane** in our analysis

In order to not reject our null hypothesis, we need to prove following things:

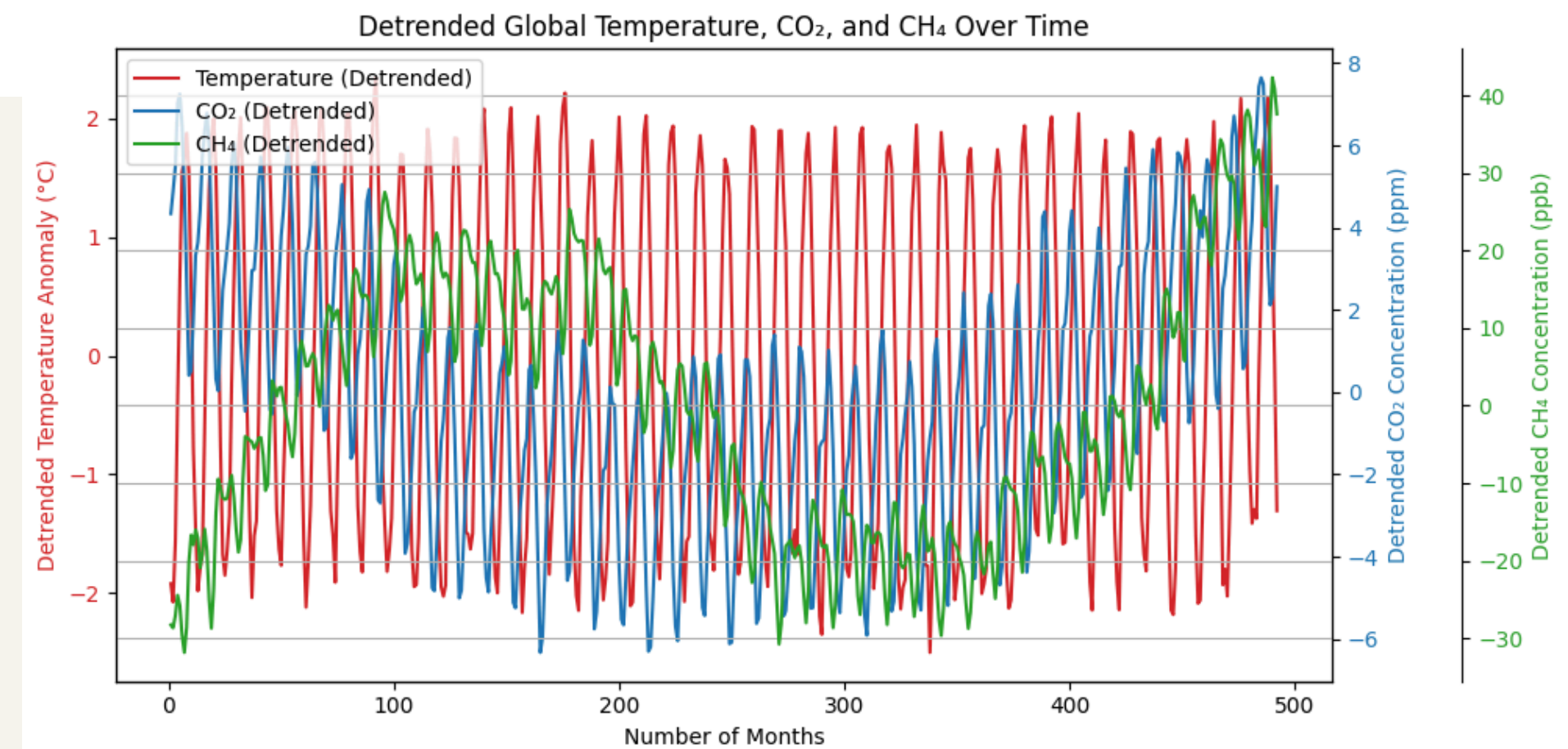
- CO₂ concentration **significantly** lags the increasing global temperature
- Methane emissions and/or concentration **significantly** leads the increasing global temperature

1. Cross Correlation

1.1 CO₂ and Methane Concentrations



De-Trending



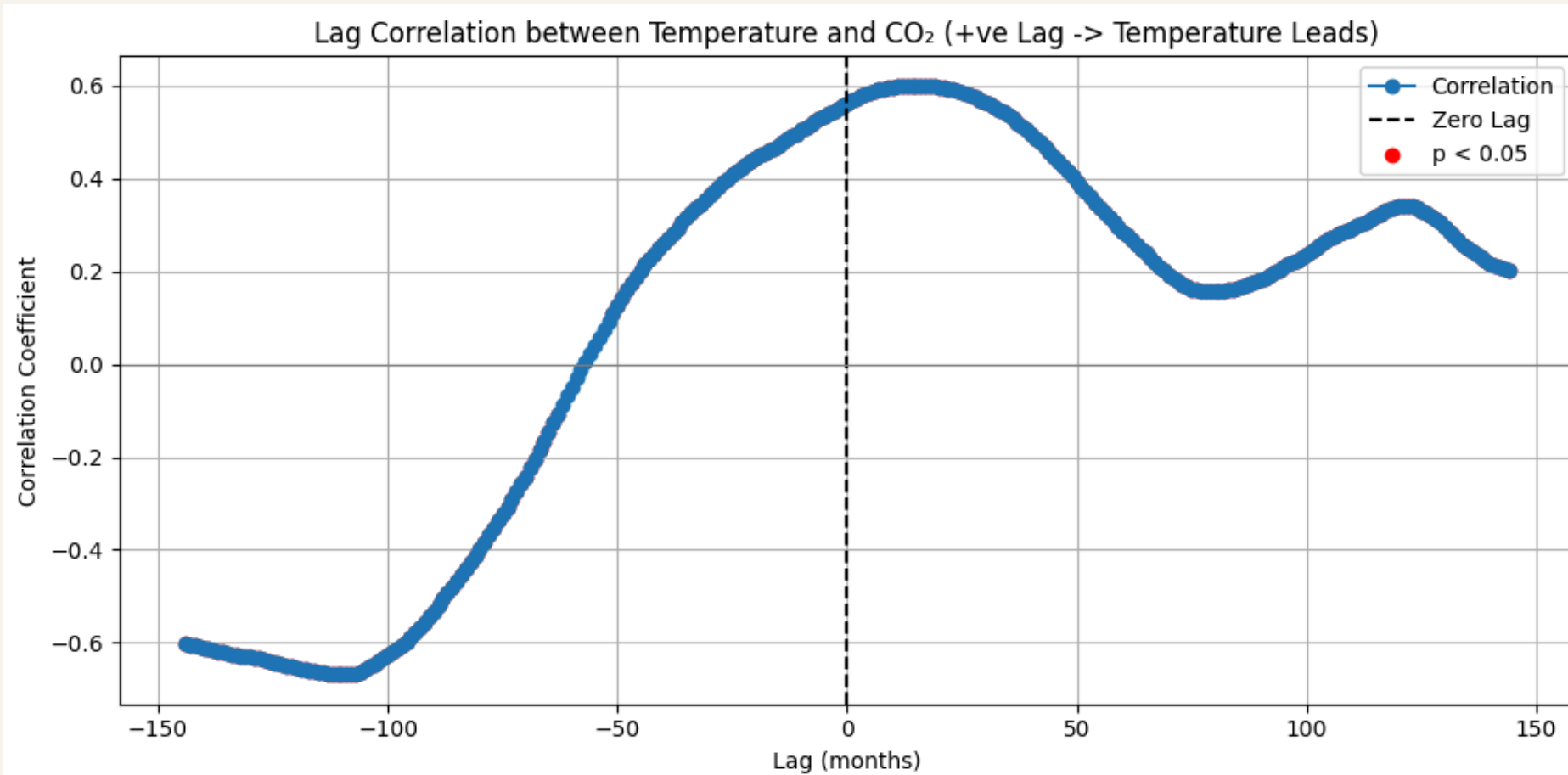
1. Cross Correlation

1.1 CO2 and Methane Concentrations

Smoothened the de-trended data by applying rolling mean over 48 months (4 years) to remove periodicities in the data as well as correlations

CO2 conc. and Temperature Correlation

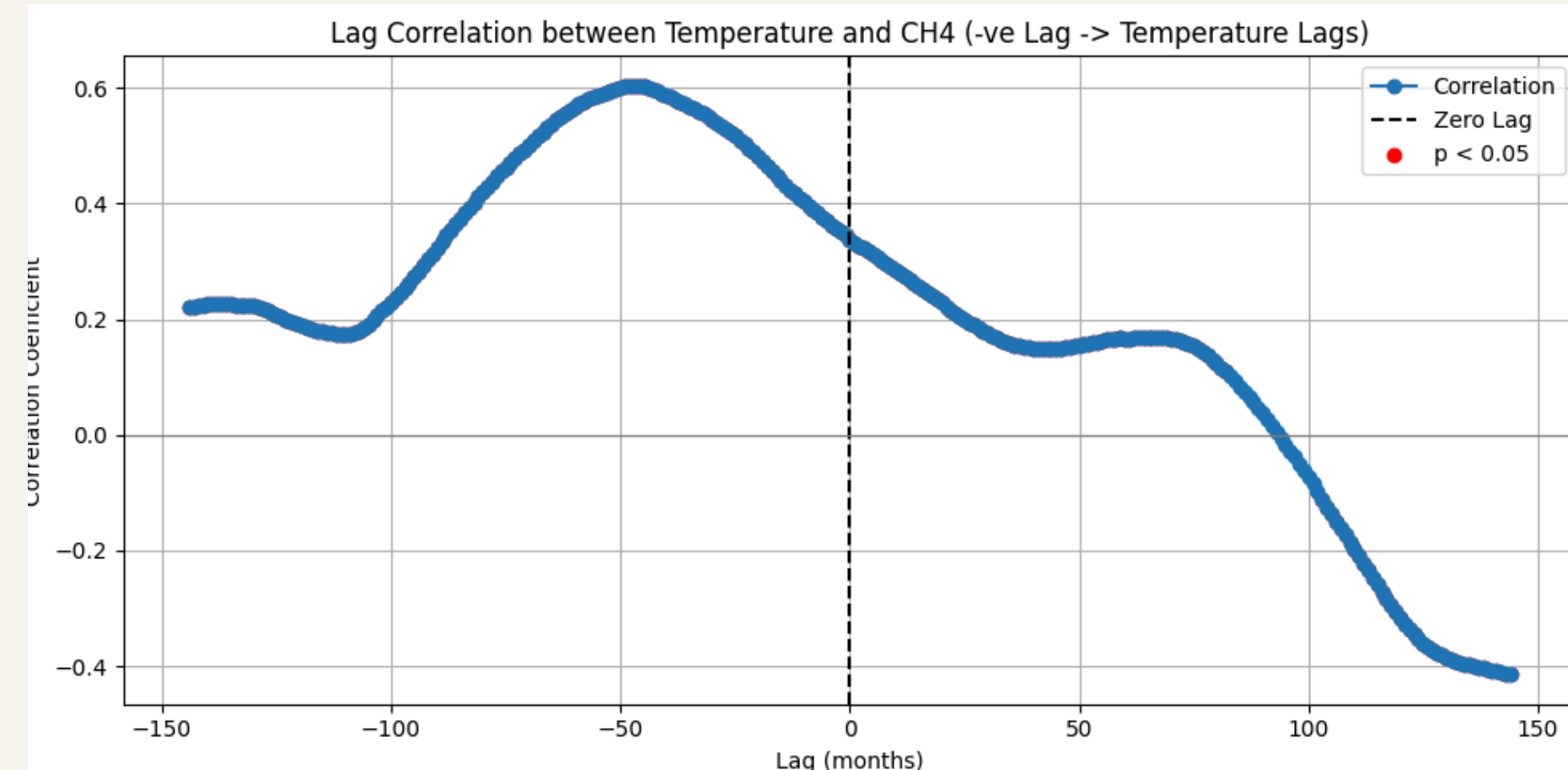
Peak correlation at lag = 15.0 months ($r = 0.600$, $p = 1.7843e-43$)



CO2 conc. significantly ($p < 0.05$) lags the increasing temperature

Methane conc. and Temperature Correlation

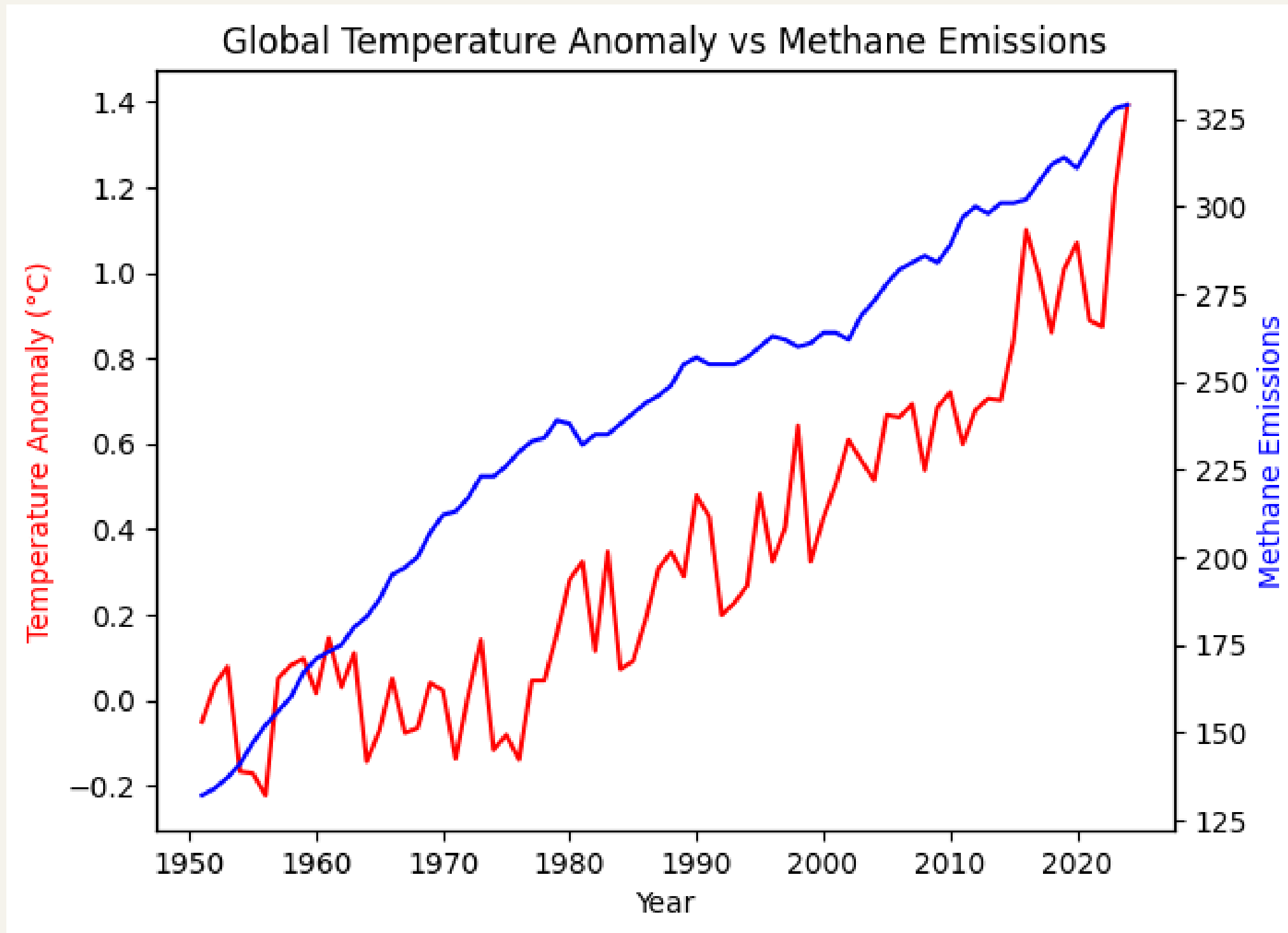
Peak correlation at lag = -47.0 months ($r = 0.604$, $p = 5.3206e-41$)



Methane conc. significantly ($p < 0.05$) lead the increasing temperature

1. Cross Correlation

1.2 Human Activities based Methane Emissions



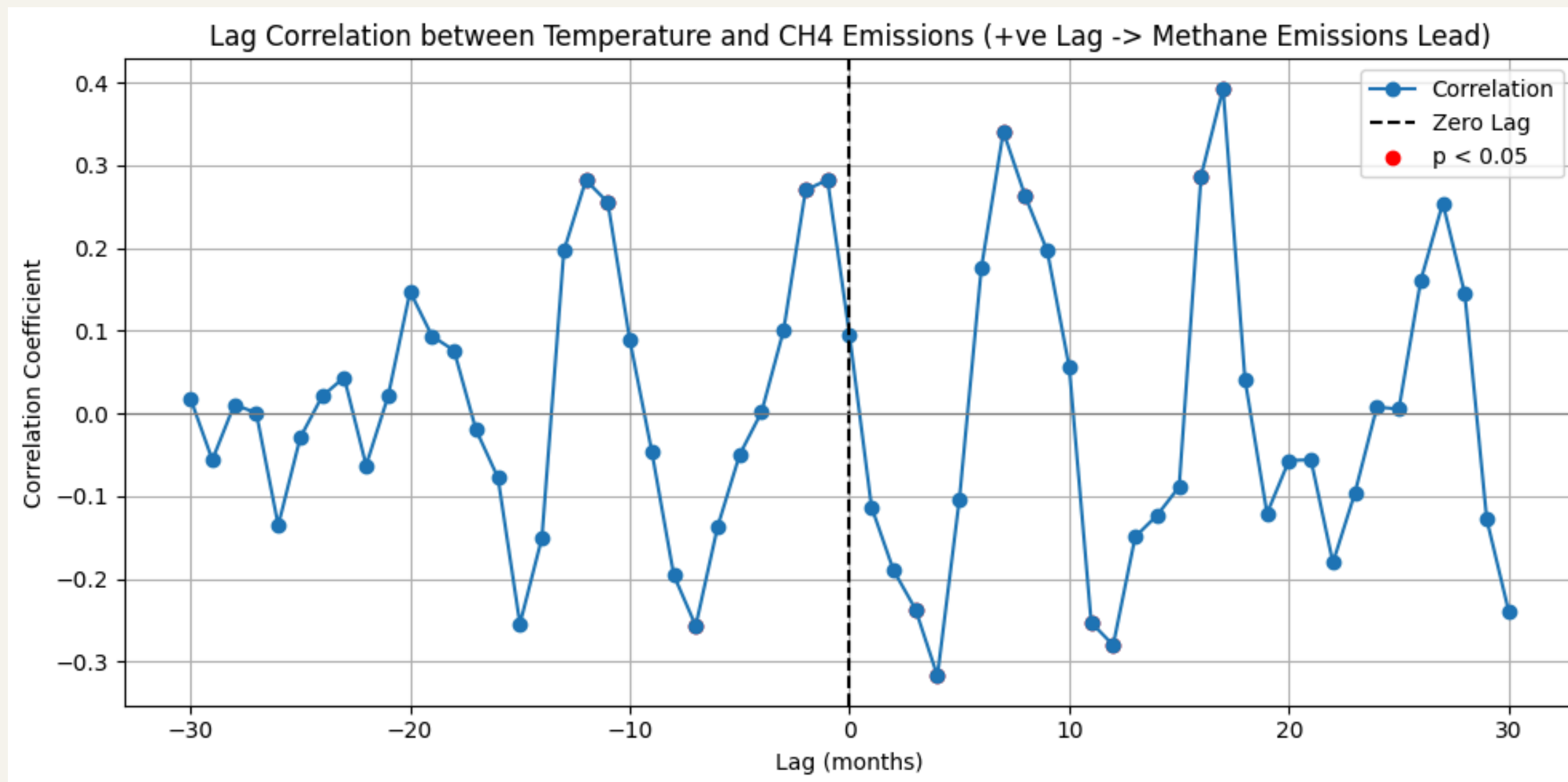
Visually, we can see that
Methane Emissions lead
Temperature

1. Cross Correlation

1.2 Human Activities based Methane Emissions

Methane Emissions significantly ($p < 0.05$) lead the increasing temperature

Peak correlation at lag = 17.0 months ($r = 0.393$, $p = 2.5063e-03$)



2. Granger Causality Test for CO₂ conc. and Temperature

Granger Causality Test is a statistical test used to determine if one time series is useful for forecasting another

Our Results

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Granger test: Does CO2 → Temp?
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Best lag up to 24 months = 24; p-value = 0.026
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Granger test: Does Temp → CO2?
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Best lag up to 24 months = 20; p-value = 5.45e-11
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Monthly data captures carbon cycle feedbacks, so temp predicts short-term CO₂ fluctuations strongly

3. 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 $TE(X \rightarrow Y) > TE(Y \rightarrow X)$,
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

Our Results

Transfer Entropy (Temperature \rightarrow CO₂): 0.8498
Transfer Entropy (CO₂ \rightarrow Temperature): 0.6058

Transfer Entropy (Methane \rightarrow Temp): 0.6384594482692192
Transfer Entropy (Temp \rightarrow Methane): 0.20624450076430245

Conclusion

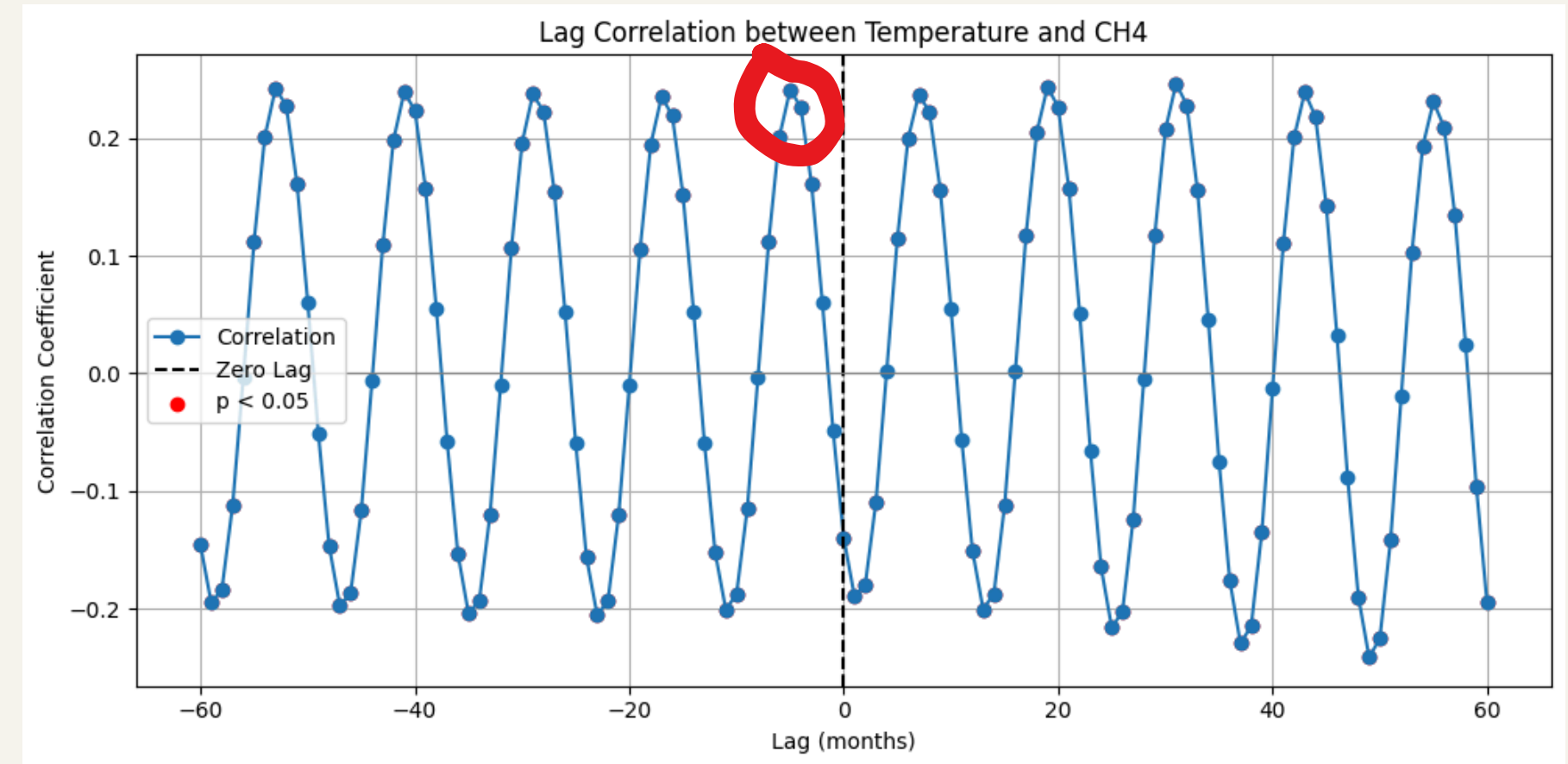
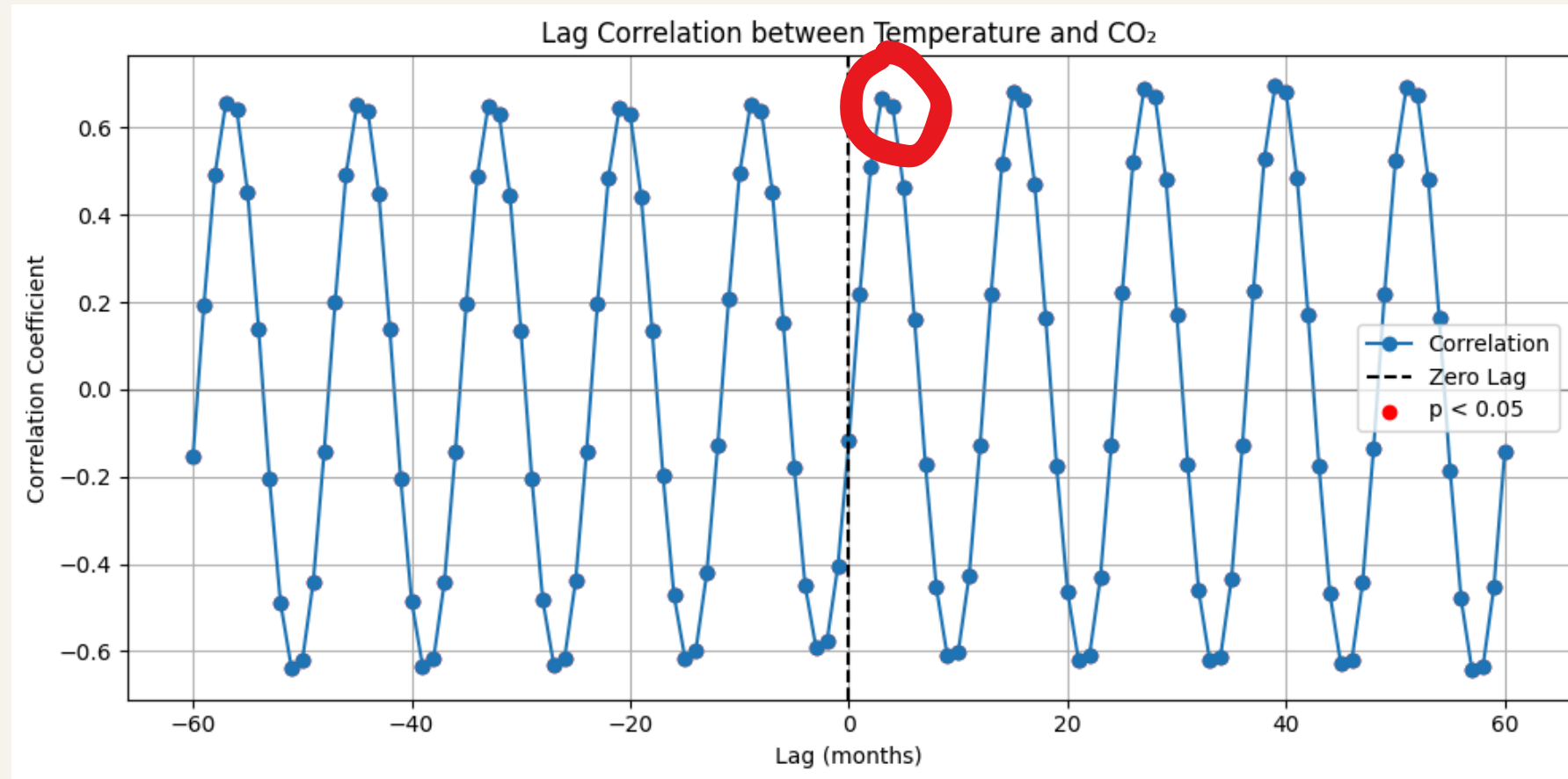
The evidence from our analysis provides a clear direction for further exploration and indicates a tendency towards **not rejecting the null hypothesis**. To be more specific, we cannot directly conclude/believe that the current trend has reversed with respect to the glacial trend. There are a lot of interdependencies involved in current scenario. Clearly, the lag (as clear from our analysis) has come down to months in the current scenario, from 100s of years in ice ages. Hence, **there is surely an impact of human activities** in the current trend.

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

Individual Contribution

Roll No.	Name	Contribution
22B1502	Rohit Jangir	Literature Review & Slide Preparation
22B1504	Yash Mehta	Model Formulation and Analysis
22B0452	Manthan Sawsakde	Model Formulation and Analysis
22B2247	Kuldeep Pujari	Literature Review & Slide Preparation
22B2246	Akshar Goyal	Model Formulation and Analysis

Appendix



Cross Correlation Analysis without Smoothing