Revisiting CO2 emissions and global warming: Implications for society

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Revisiting CO_2 Emissions and Global Warming: Implications for Society

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Abstract

This paper revisits the relationship between CO2 emissions and global warming by analysing over 60 million daily temperature observations from over 1600 global weather stations, with continuous records spanning from the pre-1900 era to 2024. Employing fixed effects models to isolate temperature trends from station-specific and seasonal variations, the study finds an overall warming trend of 0.0054°C per year after controlling for urban built-up areas. The analysis reveals a significant disconnect between the rise in annual anthropogenic CO2 emissions and the rate of temperature change. Notably, the period of the sharpest warming occurred in the early 20th century when CO2 emission levels were modest. In contrast, subsequent periods with rapidly accelerating CO2 emissions experienced slower warming or even cooling trends. These findings challenge the conventional assumption that human-induced CO2 is the primary driver of global warming, highlighting key gaps in our understanding and calling for a more critical approach in research, education, and a thorough reassessment of the premise underlying current climate policies.

Keywords: Global warming; CO2 emissions; Temperature trends; Climate change; Climate policy; AGW

JEL codes: Q54; Q56; Q58; C23

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1 Introduction

The premise that Carbon dioxide (CO2) warms the planet is a foundational concept in modern climate science. An early, influential study by Manabe and Wetherald (1967) estimated that a doubling of atmospheric CO2 levels would lead to an approximate 2°C increase in atmospheric temperature, assuming constant relative humidity. Building upon this, a substantial body of contemporary research attributes the phenomenon of global warming primarily to human emissions of CO2. For example, Matthews and Wynes, (2022) suggest that human-induced warming is likely to push global temperatures beyond the 1.5°C threshold in less than a decade. Other research treats this link as a foregone conclusion; Hönisch et al., (2025) synthesized 66 million years of paleo-CO2 records, while Jones et al. (2023) take anthropogenic global warming (AGW) as a given to calculate national contributions from CO2 and other greenhouse gases. Empirical studies, such as Stips et al. (2016), argue for a one-way causality from greenhouse gases to global mean surface temperature anomalies since 1850, identifying CO2 as the main driver of recent warming. This perspective is central to policy discussions, with Kotz et al. (2024) highlighting how the financial burden of climate mitigation varies significantly based on emission trajectories. The reliance on this relationship is further noted by . Sautner et al., (2023), who state, "*Scientists have developed complex models that estimate the effect of greenhouse gas emissions on the global climate.*" The presumed impact of CO2 extends to other climatic phenomena, with Iwakiri et al. (2025) finding that CO2 mitigation could influence the frequency of El Niño events.

However, other climate studies highlight significant uncertainties and alternative explanations for observed warming, challenging the singular focus on CO2. Hegerl et al. (2018) note that the most pronounced warming in the historical record - the Early Twentieth Century Warming (ETCW) - occurred when CO2 emissions were still modest, and caution that the contribution of each causal factor remains uncertain. Looking at longer timescales, Schurer et al. (2013) find that changes in solar activity and major volcanic eruptions were the dominant influences on climate between 1400 and 1900, though they also identify a role for greenhouse gases in cooler periods. Examining more recent data, Lansner and Pepke Pedersen (2018) report a lack of warming in ocean air-sheltered temperature data after 1950. In a critical review for the US Department of Energy, Christy et al., (2025) argue that induced warming appears less economically damaging than commonly believed and that aggressive mitigation strategies could be more harmful than beneficial. More fundamentally, some researchers propose different primary drivers entirely; Nikolov and Zeller (2024) argue that warming trends are attributable to planetary albedo and solar irradiance variations, with no connection to CO2.

Despite this ongoing debate, the idea of a near-total scientific consensus on AGW, often cited as 97% (Cook et al., 2013), has gained significant traction. However, the basis for this consensus claim raises several concerns. First, the finding that 3,896 papers endorsed AGW over a 21-year period (1991–2011) implies an average of one new paper on the topic every other day, which could suggest a herd mentality rather than a proliferation of independent evidence. If one strong piece of empirical evidence for AGW exists, such repetitive endorsement would be unnecessary. Second, it is unclear how many of these studies have made their data publicly available for independent scrutiny. This claim of consensus was nevertheless presented as "fact" and "not theories" in a US Congressional Hearing[1] in June 2013, attributed to NASA. The link provided as a reference, however, leads to an error page[2], raising further doubt about the veracity of the evidence underpinning the consensus. Despite these issues, the claim of 97% consensus maintains strong socio-political currency, as evidenced by its use in congressional hearings and its promotion by former US President Obama on Twitter one day after its publication. [3]

Against this backdrop of conflicting research and questions surrounding the proclaimed consensus, it is imperative to re-examine the raw evidence directly. This study aims to investigate whether global warming trends, as recorded by actual weather stations, can be primarily attributed to human emissions of CO2. By employing a comprehensive dataset of publicly available daily temperature records spanning from the pre-1900 era to 2024, this paper uses econometric fixed-effects models to isolate temperature trends over various time windows. By comparing these empirically derived trends with the historical record of human CO2 emissions, this analysis offers a transparent and visual assessment of the relationship, seeking to clarify the extent to which human-induced CO2 is associated with the global warming phenomenon.

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[1] H.R. 2231, OFFSHORE ENERGY AND JOBS ACT PART 1 AND 2 | Congress.gov | Library of Congress

[2] `https://science.nasa.gov/climate/evidence` (accessed September 15 2024)

[3] Cook et al. paper was published on 15 May 2013; President Obama's tweet was posted on 16 May 2013.

2 Data

The primary data source for this analysis is the Global Historical Climatology Network (GHCN) daily dataset [4], which was downloaded on 02 August 2025. This dataset provides weather information for various weather stations across the globe including station identifier, country name, date, minimum temperature, and maximum temperature. An average daily temperature is computed as the mean of the minimum and maximum daily temperature for each station.

Initial daily temperature records from all stations exceed 105 million observations. Seemingly erroneous observations are discarded. This includes temperature more than 57 °C or less than -90 °C; and observations where daily minimum temperatures are higher than the daily maximum temperatures for any stations. Discarding theses erroneous observations drop available observations to 102 million records. The dataset is further filtered to include only those stations with a continuous and extensive observational history, specifically those with records commencing on or before the year 1900 and extending to at least the year 2020. This selection criterion isolates a consistent cohort of stations, which is fundamental for minimizing biases that could arise from changes in the network of stations over time. We further drop observations for year 2025 as the year is not complete at the time of writing. After this cleaning process, the final sample for analysis has 42,456,992 records showing both minimum and maximum temperature from 992 weather stations across 29 countries.

Among these 992 stations, a vast majority are situation in the USA (840) followed by Germany (32), Russia (32), Sweden (16) and Canada (12), as shown in Figure 1.

Full list of number of stations by country is provided in Appendix 1.

Data on annual human CO2 emissions is from Our World In Data. As the emission level of 2024 is not available at the time of writing, it is assumed to be 38.29 billion tons for the year (derived by adding 2023 emission figure with the marginal increase during the year). Full list of number of stations by country is provided in Appendix 1.

Data on annual human CO2 emissions is from Our World In Data. As the emission level of 2024 is not available at the time of writing, it is assumed to be

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[4] ghcnd_all.tar.gz file downloaded from `https://www.ncei.noaa.gov/pub/data/ghcn/daily/`

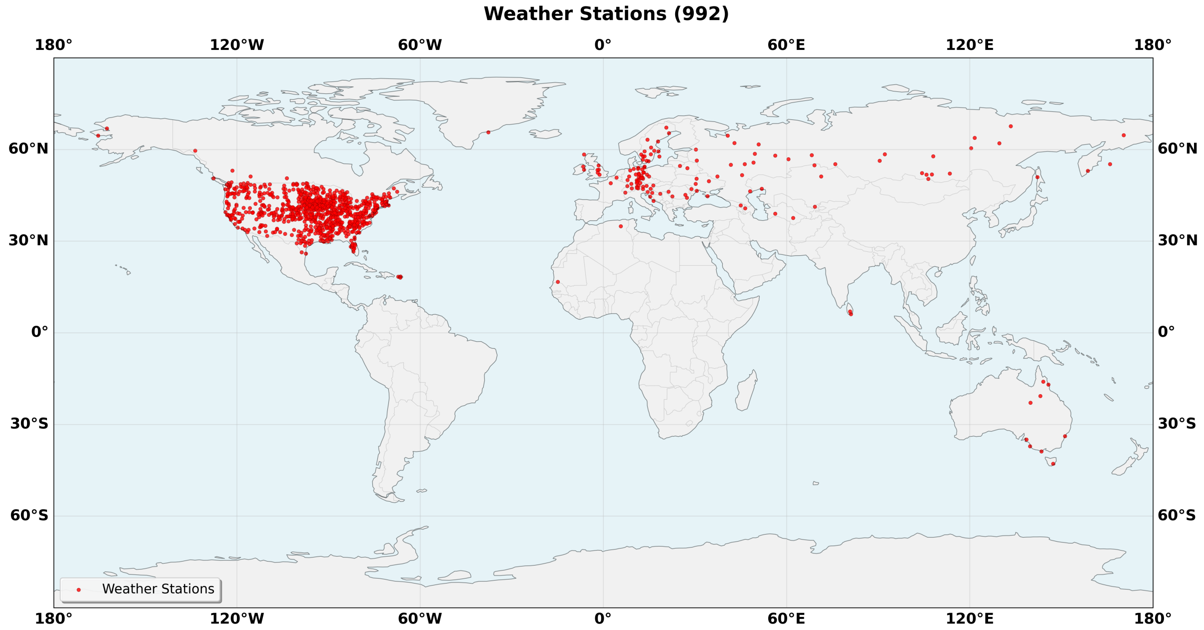

Figure 1: Location of weather stations globally in the final sample

38.29 billion tons for the year (derived by adding 2023 emission figure with the marginal increase during the year).

2.1 Statistical Modelling of Temperature Trends

To quantify temperature trends, a panel fixed-effects regression model is employed. The model is specified to estimate the trend in a temperature variable as a function of time. We also control for seasonal cycles and level of urbanization later.

The basic regression is of the following form:

$$\text{Temperature}_{i,t} = f(\text{Time}_{i,t}) + \epsilon_{i,t} \tag{1}$$

where i indexes for individual weather station and t indexes for days.

We later control for earth's orbital distance from the sun (seasonal trends) using month dummy variables for each month.

The core of the regression isolates the underlying trend by including fixed effects for each station and for each month of the year. The station-level fixed effects absorb all unique, time-invariant attributes of a station, such as its specific geography, elevation, and local microclimate. This ensures that the model estimates the warming within each station over time, rather than being influenced by baseline temperature differences between stations.

Similarly, the inclusion of monthly fixed effects provides a seasonal adjustment, effectively removing the predictable annual temperature cycle from the data. This allows for a precise estimation of the long-term trend, independent of seasonal variability. To ensure the statistical validity of the results, the model assumes that the error terms are clustered at the station level and the standard errors are corrected accordingly by station (Petersen, 2009). As an alternative to control for possible spatial dependence, standard errors are calculated by clustering the errors based on geographical proximity of stations. This is discussed in more detail in Section 3.1.

Temperature trends could be influenced by urban heat island (UHI) warming effects (Estrada and Perron, 2021; Spencer et al., 2025) since temperature in a given station could be influenced by urbanization over the years. To control for such UHI effects, we include the built-up percentage within a 10-km radius of the station. The built-up surface area data for this purpose is sourced from Pesaresi et al. (2024). Since the data is available from 1975 onwards in five-year intervals, we control for urbanization only in the final time window of the regressions. Available data is projected to the next four years until new data becomes available. So in essence, urbanization level would be the same for each station for years 1975-1979; and the new built-up data from 1980 would remain the same until 1984, and so on.

The analysis is done iteratively on subsets of the data, focusing on the top stations as ranked by the number of available observations. Initially 100 stations with the highest number of observations are chosen. While 100 stations may offer a rich dataset with minimal missing values, it may also raise question about the generalizability of such trends owing to ‘small’ number of stations. To address this, we employ an iterative process for cohorts of 100, 200, and up to 1,000 top stations based on data availability. As the number of stations increases thereby allowing for a more generalizable sample, the missing values also increase. Hence, there is a trade-off in terms of choosing the number of stations. We also take an alternative approach of prioritizing stations based on the least level of missing data, as further discussed in section 3.2 later.

First, a full-period analysis is conducted by fitting a single regression model across the entire historical timeframe. The resulting trend lines for minimum, maximum, and average temperatures are plotted over a scatter plot of the raw daily temperature readings. This visualization offers a comprehensive overview of the long-term temperature trajectory.

Second, a multi-period analysis is performed to investigate potential changes in the rate of warming over time. The full historical period is partitioned into five, six, seven and 10 contiguous, equal-duration segments. A separate fixed-effects regression is independently fitted to the data within each of these segments. The resulting trend lines for each period are then plotted on a single chart, facilitating a direct visual comparison of the warming rates across different historical eras.

The annual human emission of CO2 is then superimposed over warming trends over the same X-axis (year) but with a secondary Y-axis that displays global annual CO2 emissions, allowing for a visual comparison between warming trends and annual CO2 output. So, though our initial approach to find temperature trends rely on robust econometric techniques using fixed effects, the visualization approach is simpler for comparison purposes and hopefully more intuitive. Also considering predominantly two-dimensional nature of the analysis of the data (warming over time; and CO2 emissions over time assuming absence of other factors like seasonal trends and urbanization), we refrain from using complex statistical tools purely for simplicity as the charts are in two-dimensional planes as well and allows for intuitive visualization.

3 Findings

For illustrative purposes, we start with 100 stations located across 12 countries with the highest number of observations available in the dataset and draw a single trendline over the entire duration of 1814 to 2024. The trendline for average global temperature (TAVG) is 0.0092 °C per year (p-value: 0.0000). As can be seen in Figure 2, the scatter plots prior to 1900 are dominated by warmer regions. More temperature data from other stations become available as year progresses. It is inconceivable that the temperature grew constantly over the entire duration but this gives an initial indication of the rise in global temperatures over the years.

To investigate potential changes in the rate of warming over time, we now use the same 100 stations but subdivide the overall duration of 210 years into multiple contiguous timeframes of 21 years (10 equal periods), 30 years (7 equal periods), 35 years (6 equal periods) and 42 years (5 equal periods).

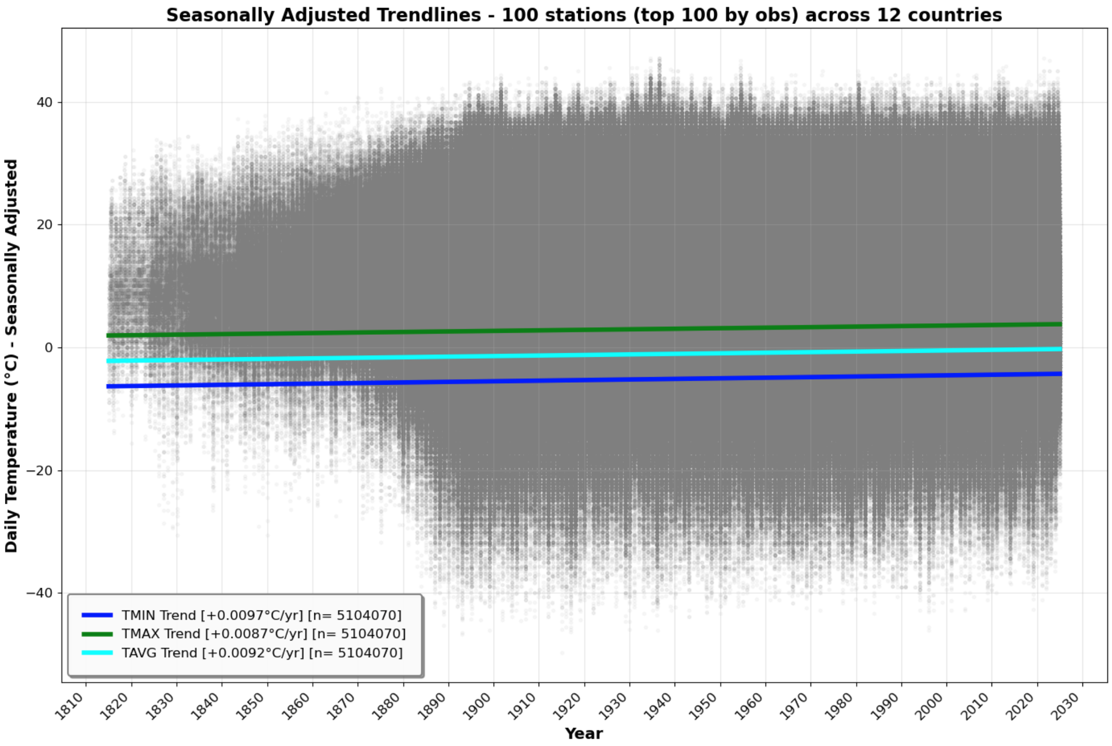

Figure 2: Global temperature trendline based on 100 weather stations

To simplify our discussion, we first consider five contiguous, equal-duration segments of 42 years each, as shown in Figure 3. Annual CO2 emissions are also plotted on the chart, highlighting a clear discontinuity in trendlines across distinct time periods. The number of observations start being comparable starting from 1899, with all the three time-windows after than point having more than 1.4 million observations each. This also signifies that the missing data is less than 2.5% for the weather stations during the last three time periods.[5] Interestingly, the highest rate of increase in temperature can be observed during the most recent 1983-2024 period at the rate of 0.0239 °C per year for TAVG (average temperature), after controlling for seasonal variations and UHI. Without controlling for UHI, trend for this latest period is higher at 0.0293 °C per year.

The second highest rate of increase was during 1899-1940 (0.0169 per year). This is higher than the rate of warming during 1941 -1982 when a cooling trend of -0.0065 per year is observed. A visual inspection shows that CO2 emission was relatively low during 1899-1940 whereas it has steadily increased during the subsequent periods (Figure 3). Comparative CO2 emissions and rate of rise during

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[5] The number of observations for 1899-1940 is 1,498,715 against maximum possible daily observations of approximately 1,533,000 (=100*42*365), registering a data availability of 97.8%.

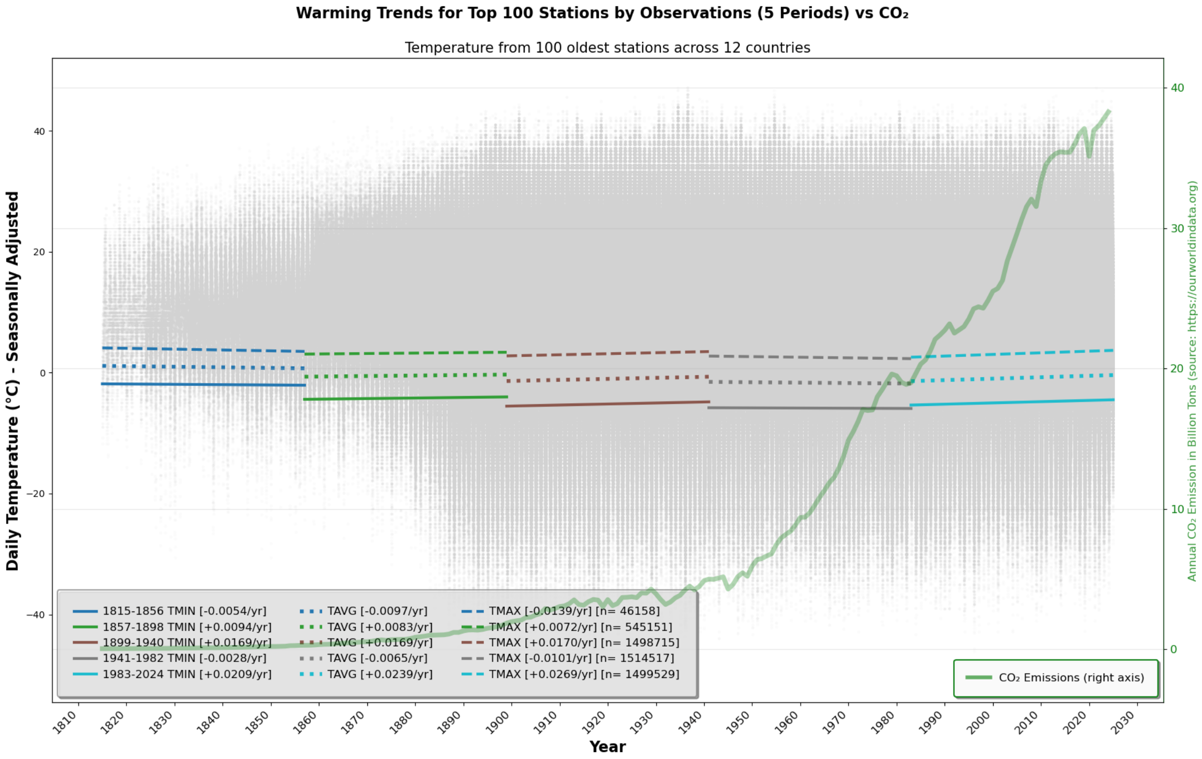

Figure 3: Global temperature trendlines based on 100 weather stations across 5 equal time periods

each of the 42-year time frames are presented in Table 1. It can be noted that cumulative CO2 emissions during the cooling period of 1941-1982 (460 billion tons) was 3.3 times more than that during 1899-1940 (139.6). This is counterintuitive to the idea that CO2 is the main driver of global warming, at least during 1941-1982.

Table 1: Temperature trend and cumulative CO2 emission over 42-year time frames based on 100 weather stations with highest number of daily observations

42-Year Period	Number of Obs	Temp change per year (°C)	p-value	Cum. CO2 emission (Billion Tons)
1815-1856	46,158	-0.010	0.323	4.9
1857-1898	545,151	0.008	0.132	35.1
1899-1940	1,498,715	0.017	0.000	139.6
1941-1982	1,514,517	-0.0065	0.000	460.0
1983-2024	1,499,529	0.024	0.000	1209.8

For the other timeframes of 35 years, 30 years and 21 years, we present the summary statistics in tables below in turn. In all of the tables Table 2, Table 3, and Table 4 there are instances of temperature rise being higher during a given time frame despite the CO2 emissions being a fraction of later time frames when temperature rise was slower. For instance, during 1905-1934 in Table 3, the temperature rose by 0.0238 (CO2 emission: 101) compared to slower rise in temperature during 1965-1994 (0.0236) despite the CO2 emission being more than five times higher (551.9).

Table 2: Temperature trend and cumulative CO2 emission over 35-year time frames based on 100 weather stations with highest number of daily observations

35-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1849	32,701	-0.0081	0.500	3.3
1850-1884	180,194	0.0004	0.963	18.0
1885-1919	1,124,691	0.0080	0.000	77.5
1920-1954	1,253,462	0.0048	0.015	158.0
1955-1989	1,266,832	0.0083	0.000	528.2
1990-2024	1,246,190	0.0246	0.000	1064.5

Table 3: Temperature trend and cumulative CO2 emission over 30-year time frames based on 100 weather stations with highest number of daily observations

30-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1844	23,625	-0.0185	0.188	2.4
1845-1874	84,925	0.0049	0.592	10.6
1875-1904	696,607	0.0131	0.000	39.4
1905-1934	1,066,804	0.0238	0.000	101.0
1935-1964	1,080,967	-0.0102	0.000	193.7
1965-1994	1,086,336	0.0236	0.000	551.9
1995-2024	1,064,806	0.0333	0.000	950.3

We now focus on 500 weather stations for better generalization Figure 4. These weather stations offer a compromise in that they cover more than half of the weather stations available in our final sample (of 992) and have highest number of daily observations available. The overall warming trend for the entire duration stands at 0.0052 C per year (p-value: 0.0000) which is substantially lower than what was observed with just 100 stations (0.0092 C per year).

Though we have increased the number of stations, the number of missing values also increase. Against the possible number of observations of approximately 7.66 million (=500*42*365), the observations in the last three periods (Figure 5) are all in excess of 7.33 million, which shows that less than 4.4% of observations are missing.

Table 4: Temperature trend and cumulative CO2 emission over 21-year time frames based on 100 weather stations with highest number of daily observations

21-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1835	12,919	0.0484	0.000	1.4
1836-1856	33,239	0.0092	0.393	3.5
1857-1877	82,025	0.0033	0.802	10.2
1878-1898	463,126	0.0254	0.000	24.9
1899-1919	746,277	-0.0036	0.078	58.7
1920-1940	752,438	0.0127	0.000	80.8
1941-1961	754,886	-0.0041	0.235	136.8
1962-1982	759,631	0.0113	0.000	323.2
1983-2003	759,086	0.0321	0.000	486.0
2004-2024	740,443	0.0416	0.000	723.8

The breakdown of entire duration into five contiguous equal-duration segments of 42 years each reveals further insights into how temperatures evolved over the years. Among the last three time-windows with highest number of observations (more than 7.3 million in each), the time period of 1899-1940 witnessed the sharpest rate of rise in global temperature (0.0213 C per year; p-value: 0.0000), which is higher than the rate in the most recent period of 1983-2024 (0.016 per year for TAVG, after controlling for UHI). The temperature trend during this recent period without controlling for UHI is 0.0205 C per year, which is still lower than that during 1899-1940.

More detailed summary information along with cumulative CO2 emissions during each of the time frames are presented in Table 5. It can be observed that 1899-1940 witnessed the sharpest rise in temperature with cumulative CO2 emissions of 139.6 billion tons whereas subsequent time frames register a slower rate of rising and even cooling despite having CO2 emissions higher by 3.2 times and 8.6 times during 1941-1982 (cooling -.0143 per year) and 1983-2024 (0.0168 per year) respectively.

Cumulative CO2 emissions and accumulated temperature based on statistically significant trends for each of the 42-year timeframe are depicted in Figure 6.

For the other timeframes of 35 years, 30 years and 21 years, the summary statistics based on 500 weather stations are presented in tables below in turn. In each of the tables, instances of higher warming trend can be seen in earlier

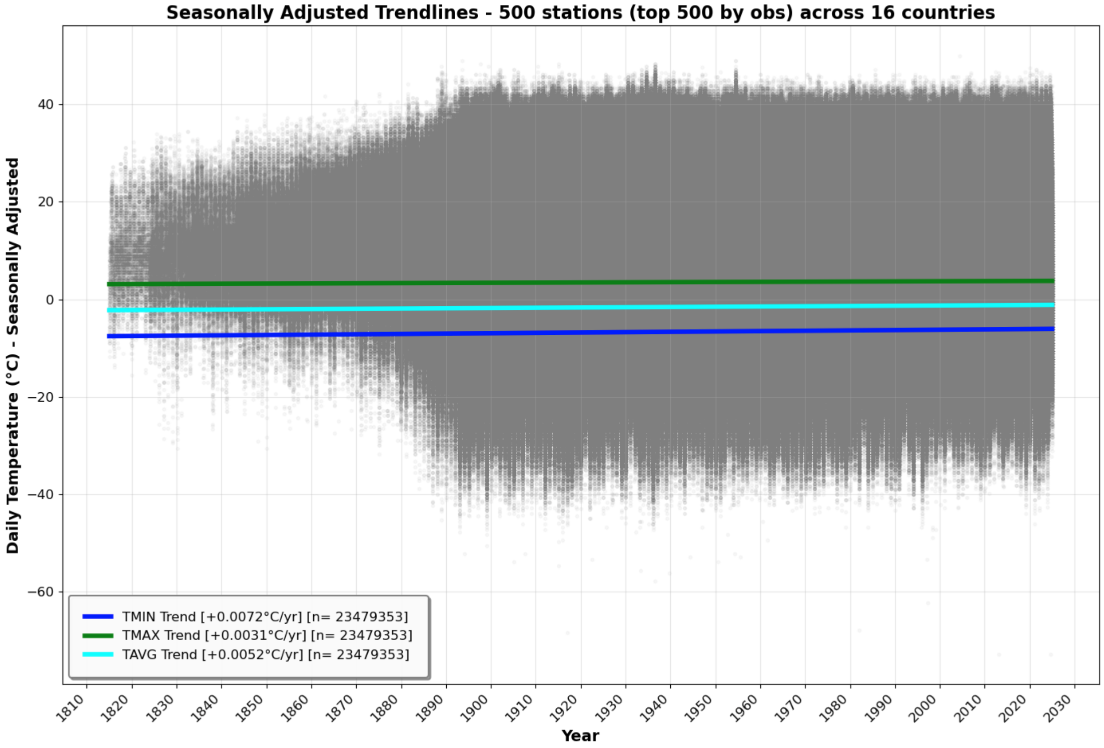

Figure 4: Global temperature trendline based on 500 weather stations

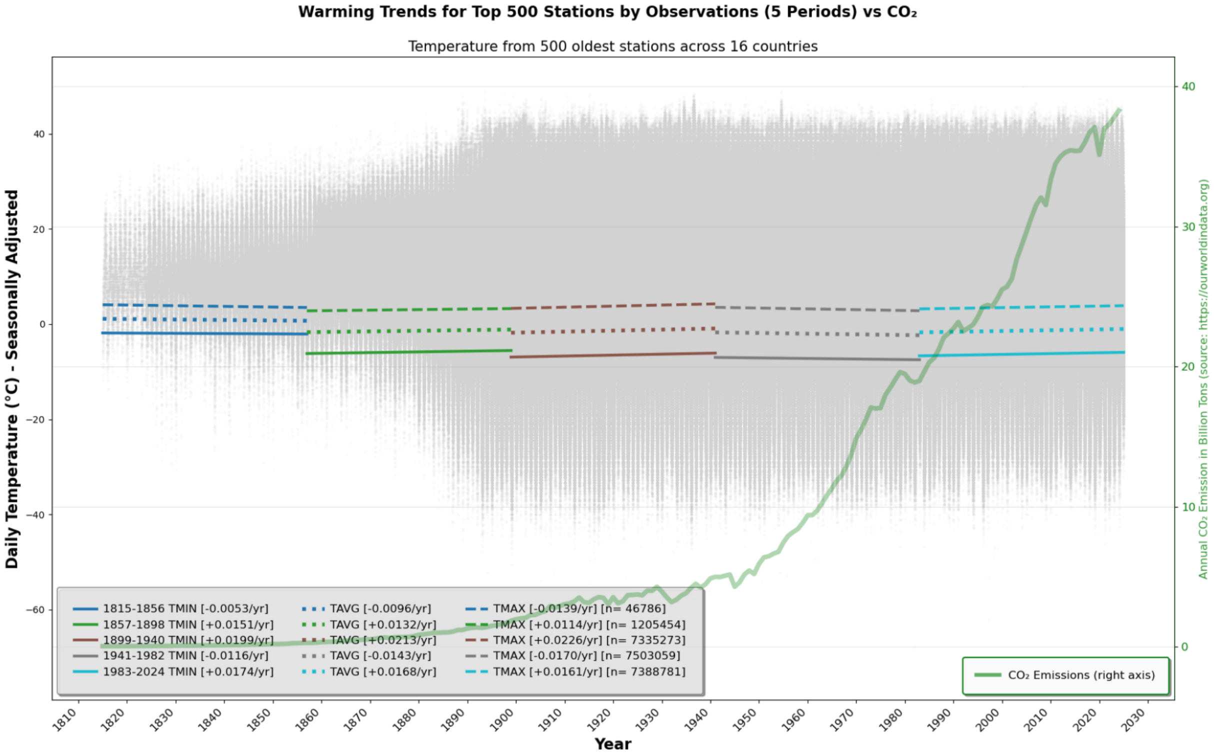

Figure 5: Global temperature trendlines based on 500 weather stations across 5 equal time periods

Table 5: Temperature trend and cumulative CO2 emission over 42-year time frames based on 500 weather stations with highest number of daily observations

42-Year Period	Number of Obs	Temp change per year (°C)	p-value	Cum. CO2 emission (Billion Tons)
1815-1856	46,786	-0.0096	0.325	4.9
1857-1898	1,205,454	0.0132	0.011	35.1
1899-1940	7,335,273	0.0213	0.000	139.6
1941-1982	7,503,059	-0.0143	0.000	460.0
1983-2024	7,388,781	0.0168	0.000	1209.8

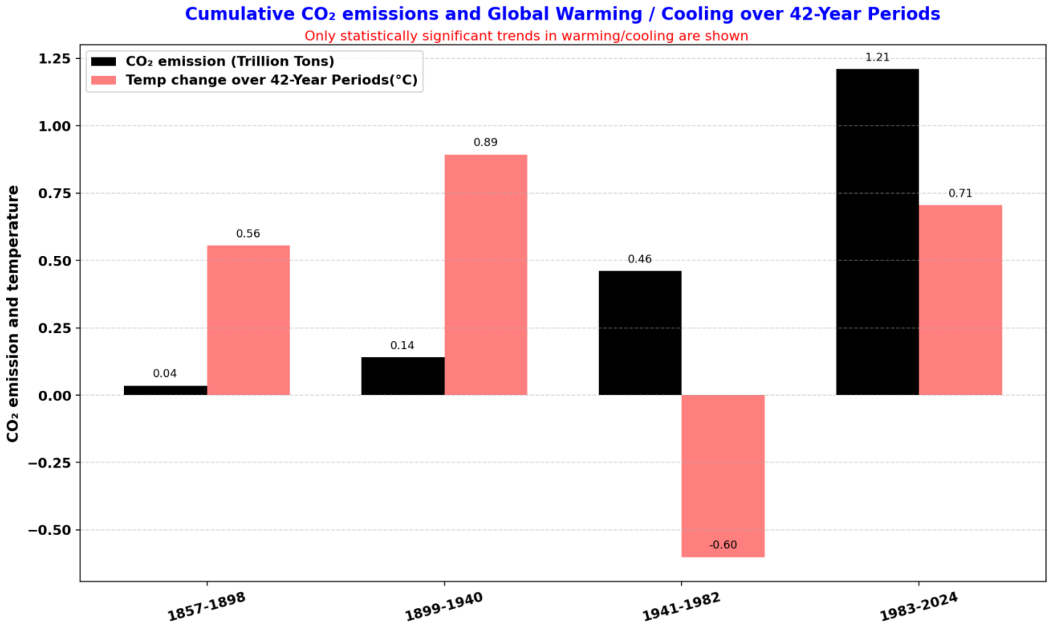

Figure 6: Cumulative CO2 emissions and cumulative temperature changes based on 500 weather stations across 5 equal time periods of 42 years (only statistically significant temperature trends are shown)

periods with moderate levels of CO2 emissions. For instance, the duration 1885-1919 (Table 6), 1905-1934 (Table 7), 1878-1898 (Table 8) exhibit higher rise than some or all of the subsequent periods with much higher CO2 emissions.

It is noted that the p-values (>0.1) in some cases do not denote statistical significance during recent periods, especially when the time frame is divided in six equal periods and 10 equal periods. The 35-year period during1955-1989 especially stands out in Table 6.

For brevity, we provide only one figure (for 10 periods of 21 years each) to depict cumulative CO2 emissions and temperature change based on 500 weather stations in Figure 7.

Table 6: : Temperature trend and cumulative CO2 emission over 35-year time frames based on 500 weather stations with highest number of daily observations

35-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1849	32,701	-0.0081	0.500	3.3
1850-1884	206,326	0.0022	0.762	18.0
1885-1919	4,628,354	0.0041	0.000	77.5
1920-1954	6,195,520	0.0029	0.001	158.0
1955-1989	6,276,268	0.0005	0.570	528.2
1990-2024	6,140,184	0.0190	0.000	1064.5

Table 7: Temperature trend and cumulative CO2 emission over 30-year time frames based on 500 weather stations with highest number of daily observations

30-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1844	23,625	-0.0185	0.188	2.4
1845-1874	94,344	0.0066	0.471	10.6
1875-1904	2,139,076	0.0029	0.264	39.4
1905-1934	5,253,327	0.0298	0.000	101.0
1935-1964	5,349,448	-0.0128	0.000	193.7
1965-1994	5,369,078	0.0163	0.000	551.9
1995-2024	5,250,455	0.0242	0.000	950.3

We now examine the full set of weather stations available in the final sample. There are 992 stations across 29 countries. The proportion of missing observations also increase due to this. For example, out of possible 15.2 million observations in each period, 13.94 million observations are available during the most recent period denoting a loss of data of approximately 9.2% and the findings should be seen within this context.

The overall trend of warming stands at (0.0054 °C TAVG per year; p-value: 0.0000) (Figure 8), which is similar to the earlier finding based on 500 stations. As we divide the years into five contiguous equal-duration segments of 42 years each, the overall message remains qualitatively similar.

Earlier time window (1899-1940) registered the sharpest rate of rise in global temperature (0.0213 °C per year; p-value: 0.0000) despite annual CO2 emissions (139.6 bl tons) being at modest levels Figure 9 and Table 9, whereas later periods corresponding to sharp increase in CO2 emissions show lower rate of rise

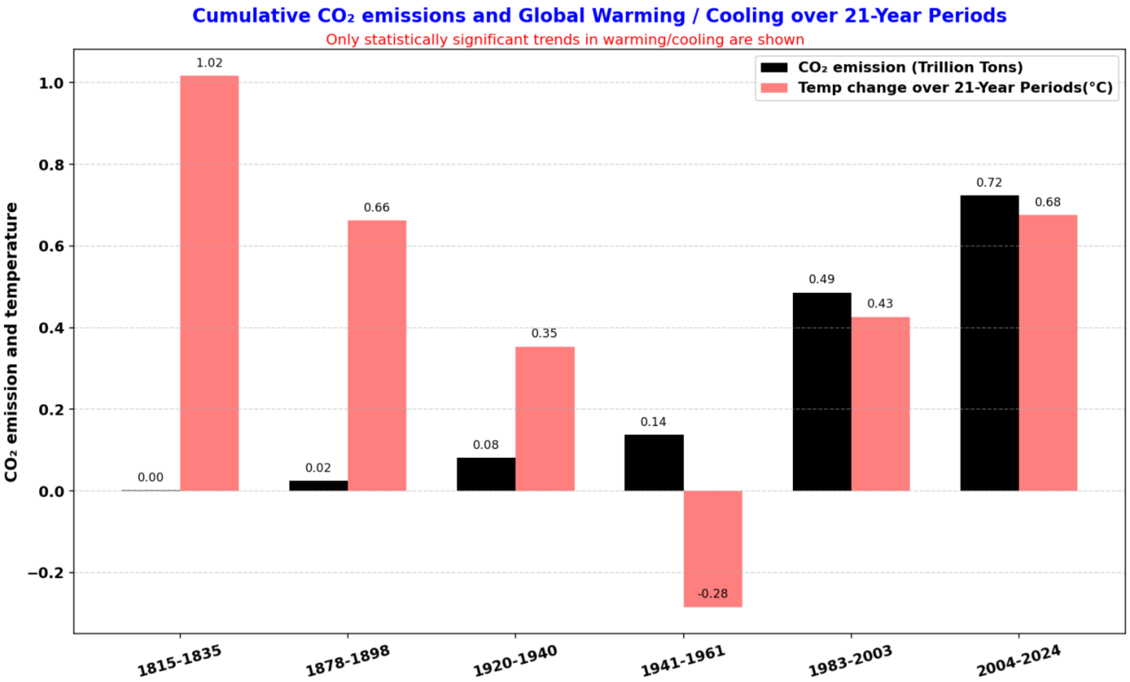

Figure 7: Cumulative CO2 emissions and cumulative temperature changes based on 500 weather stations across 10 equal time periods of 21 years (only statistically significant temperature trends are shown)

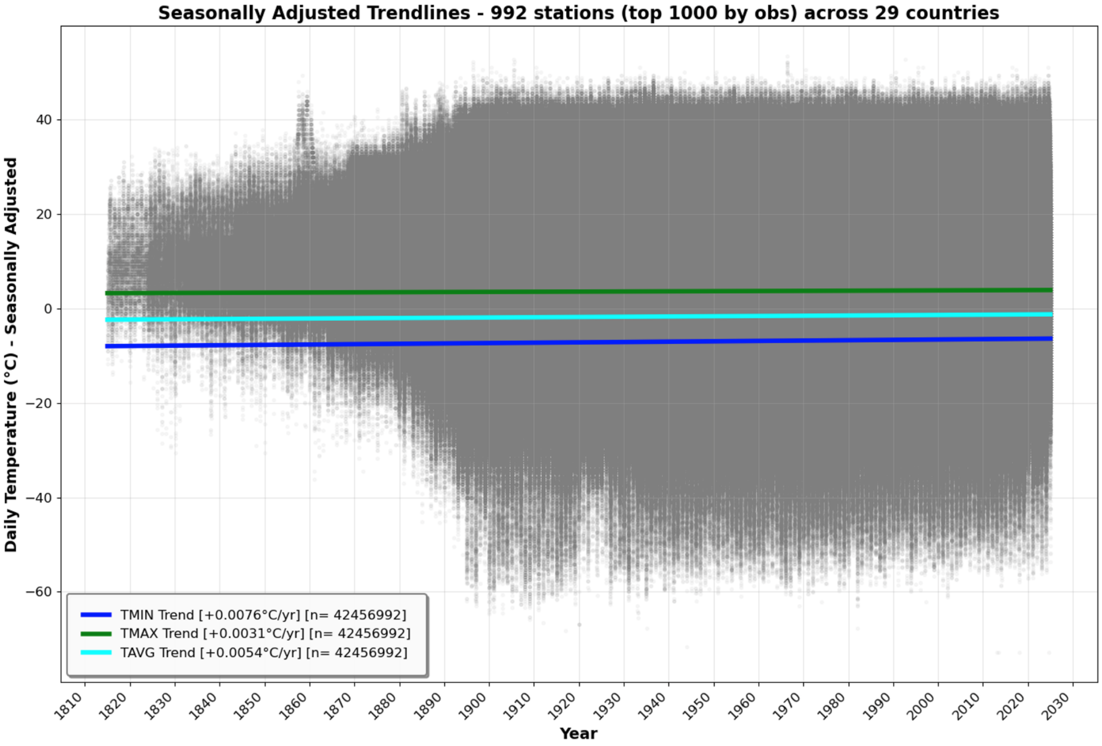

Figure 8: Global temperature trendline based on all available (992) weather stations

Table 8: : Temperature trend and cumulative CO2 emission over 21-year time frames based on 500 weather stations with highest number of daily observations

21-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1835	12,919	0.0484	0.000	1.4
1836-1856	33,867	0.0094	0.383	3.5
1857-1877	93,437	0.0036	0.765	10.2
1878-1898	1,112,017	0.0316	0.000	24.9
1899-1919	3,615,141	0.0000	0.984	58.7
1920-1940	3,720,132	0.0168	0.000	80.8
1941-1961	3,732,304	-0.0136	0.000	136.8
1962-1982	3,770,755	-0.0007	0.609	323.2
1983-2003	3,744,617	0.0203	0.000	486.0
2004-2024	3,644,164	0.0322	0.000	723.8

(0.0167 °C per year during 1983-2024, after allowing for UHI[6]; p-value: 0.0000) or even cooling ((-0.0133 °C per year during 1941-1982; p-value: 0.0000) in global temperatures (Table 9).

The cumulative CO2 emissions and temperature change based on all 992 weather stations over five equal timeframes of 42 years are shown in Table 9 and Figure 10. The cumulative emissions and cumulative temperature depiction for 10 periods of 21 years each is relegated to Appendix 2.

Table 9: Temperature trend and cumulative CO2 emission over 42-year time frames based on all available (992) weather stations in the final sample

42-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**Cum. CO2 emission (Billion Tons)**
1815-1856	46,786	-0.0096	0.325	4.9
1857-1898	1,725,382	0.0126	0.007	35.1
1899-1940	12,542,904	0.0213	0.000	139.6
1941-1982	14,197,820	-0.0133	0.000	460.0
1983-2024	13,944,100	0.0167	0.000	1209.8

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[6] The temperature trend without allowing for UHI for the final period 1983-2024 stands at 0.0209 °C per year.

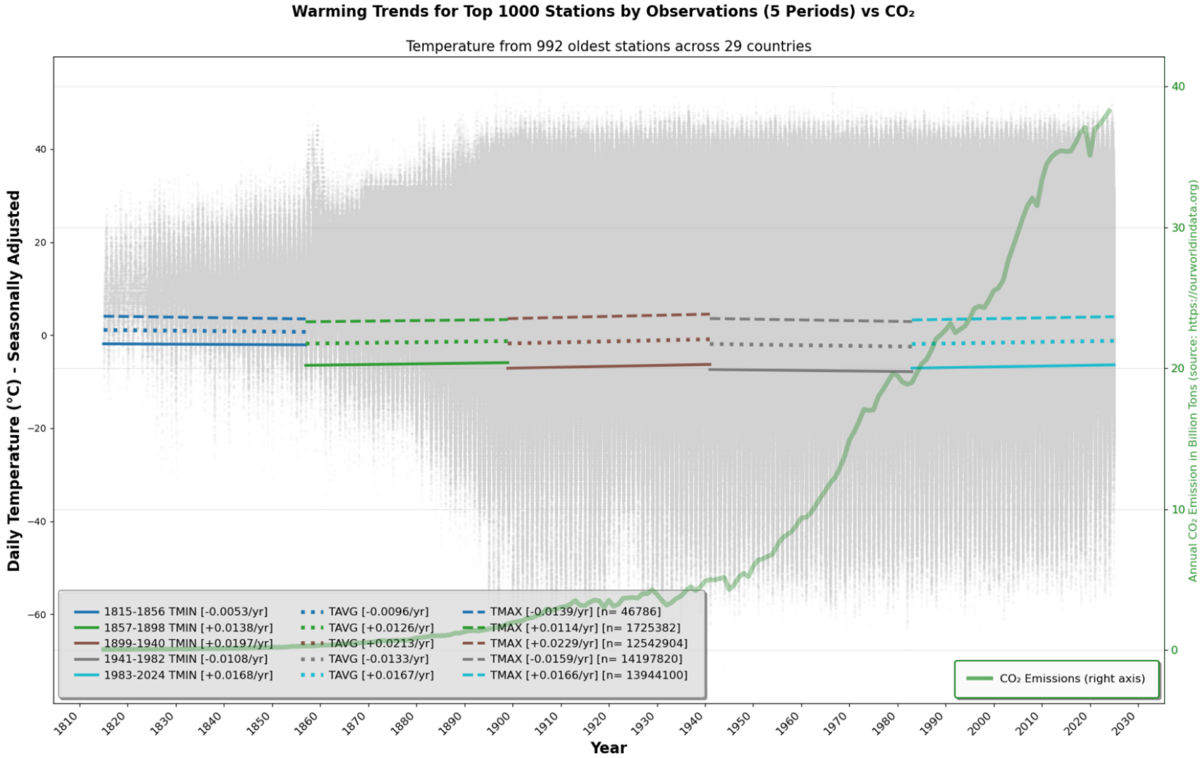

Figure 9: Global temperature trendlines based on all (992) weather stations across 5 equal time periods

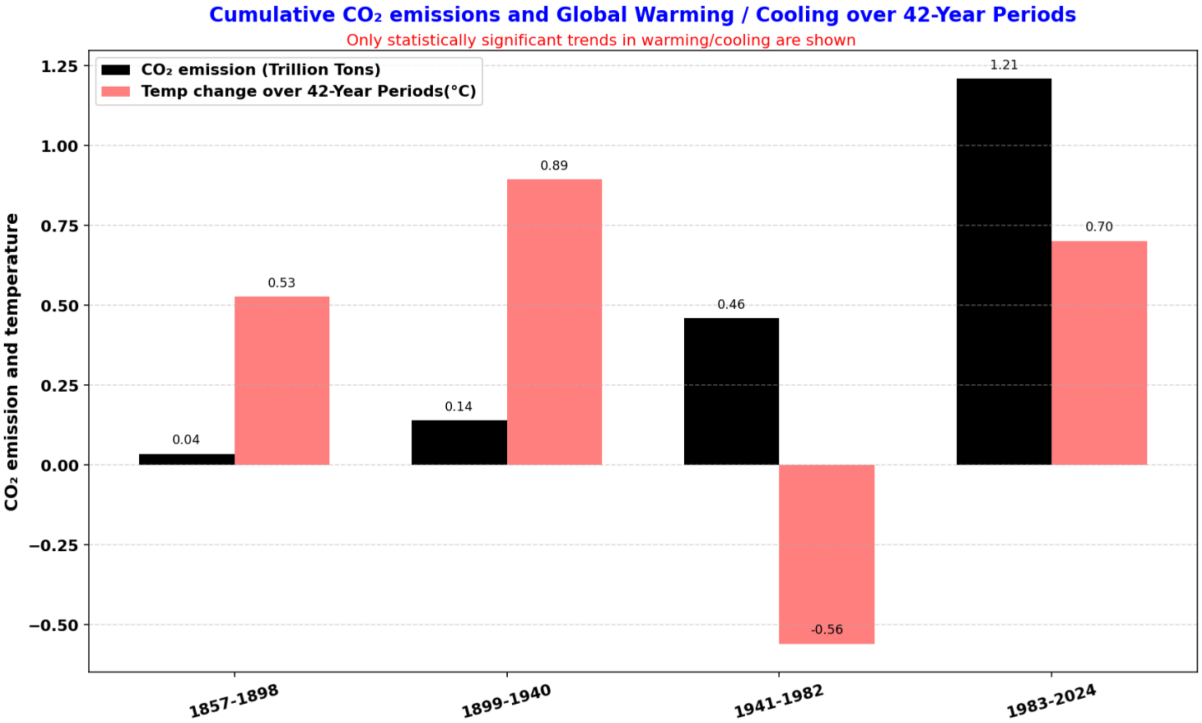

Figure 10: Cumulative CO2 emissions and cumulative temperature changes based on 992 weather stations across 5 equal time periods of 42 years (only statistically significant temperature trends are shown)

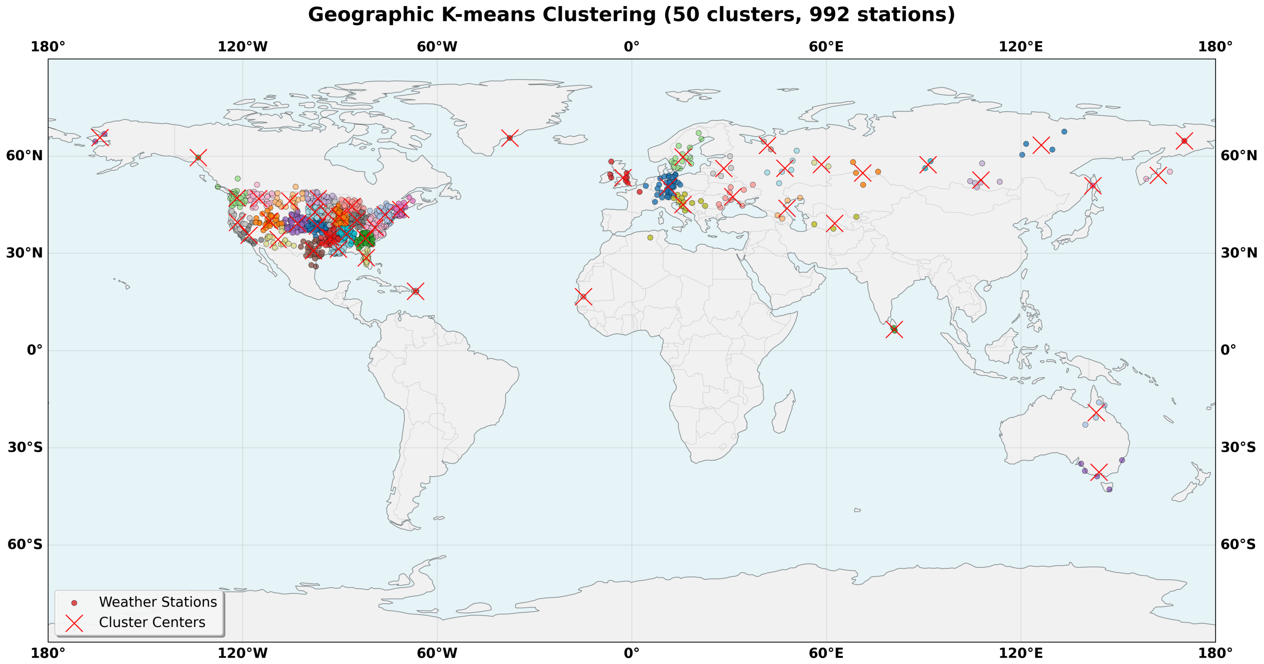

Figure 11: Geographical clusters for full sample of weather stations

4 Robustness Checks

4.1 Alternative standard errors

As an alternative to correcting for possible spatial dependence, we implement two-way clustered standard errors, correcting for both station-level autocorrelation and spatial dependence across stations based on geographical clusters. Geographic clusters are created using K-Means clustering[7] on station coordinates and we arbitrarily create 50 such clusters, as depicted in Figure 11. Results (available on request) do not alter the statistical significance of the findings so far.

4.2 Selecting weather station based on least missing data

We re-run the regression models by prioritising weather stations with the least missing data. A weather station with records starting in 1816 could have more observations than a weather station with records starting in 1900, despite the latter having more observations available per year. Hence, instead of taking into account the number of observations for each station, we prioritise stations based with less than 5% missing data. The overall results remain qualitatively similar.

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[7] Clusters are created using KMeans package from `https://scikit-learn.org` . Random state of 42 is used to ensure replicability.

Results are not shown for brevity but are available on request from the author.

4.3 Selecting additional weather stations

We relax our selection criteria to include stations where data is available from at least 1920 (relaxed from 1900 from baseline results). This still allows for examining stations with at least 100 years of daily recorded temperature and increases the number of weather stations in the sample to 1622 from 40 countries. The number of observations also increase to 66.39 million but overall trends and results remain qualitatively similar to earlier findings. The temperature (TAVG) trend based on this expanded set of stations for the overall period stands at 0.006 C per year (p-value 0.0000 based on 50 geographical clusters) [see Appendix 3] and the periodic trends are also qualitatively similar to previous findings.

Table 10: Temperature trend and cumulative CO2 emission over 42-year time frames based on expanded set of 1622 weather stations

42-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**SE cluster by**	**Cum. CO2 emission (Billion Tons)**
1815-1856	46,786	-0.0096	0.325	Station	4.9
1857-1898	1,725,382	0.0126	0.040	Geographic	35.1
1899-1940	18,656,120	0.0221	0.000	Geographic	139.6
1941-1982	23,199,221	-0.0106	0.000	Geographic	460.0
1983-2024	22,762,157	0.0167	0.000	Geographic	1,209.8

Table 11: Temperature trend and cumulative CO2 emission over 35-year time frames based on expanded set of 1662 weather

35-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**SE cluster by**	**Cum. CO2 emission (Billion Tons)**
1815-1849	32,701	-0.0081	0.500	Station	3.3
1850-1884	246,249	0.0032	0.680	Geographic	18.0
1885-1919	9,488,998	0.0009	0.648	Geographic	77.5
1920-1954	18,146,505	0.0046	0.006	Geographic	158.0
1955-1989	19,627,963	0.0018	0.324	Geographic	528.2
1990-2024	18,847,250	0.0179	0.000	Geographic	1,064.5

The statistical significance gets affected in a number of time-frames when the error terms are assumed to be clustered around geographical clusters. Tables showing trends over various time windows, along with the statistical significance,

Table 12: Temperature trend and cumulative CO2 emission over 30-year time frames based on expanded set of 1662 weather stations

35-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**SE cluster by**	**Cum. CO2 emission (Billion Tons)**
1815-1844	23,625	-0.0185	0.188	Station	2.4
1845-1874	108,705	0.0060	0.501	Geographic	10.6
1875-1904	3,401,262	-0.0018	0.753	Geographic	39.4
1905-1934	13,701,738	0.0291	0.000	Geographic	101.0
1935-1964	16,288,173	-0.0094	0.000	Geographic	193.7
1965-1994	16,807,653	0.0171	0.000	Geographic	551.9
1995-2024	16,058,510	0.0215	0.000	Geographic	950.3

for this expanded set of stations are presented in Table 10, Table 11, Table 12 and Table 13.

Table 13: Temperature trend and cumulative CO2 emission over 21-year time frames based on expanded set of 1662 weather stations

35-Year Period	**Number of Obs**	**Temp change per year (°C)**	**p-value**	**SE cluster by**	**Cum. CO2 emission (Billion Tons)**
1815-1835	12,919	0.0484	0.000	Station	1.4
1836-1856	33,867	0.0094	0.383	Station	3.5
1857-1877	111,981	0.0088	0.473	Geographic	10.2
1878-1898	1,613,401	0.0300	0.000	Geographic	24.9
1899-1919	7,995,780	-0.0030	0.299	Geographic	58.7
1920-1940	10,660,340	0.0223	0.000	Geographic	80.8
1941-1961	11,401,160	-0.0075	0.067	Geographic	136.8
1962-1982	11,798,061	-0.0010	0.759	Geographic	323.2
1983-2003	11,702,110	0.0256	0.000	Geographic	486.0
2004-2024	11,060,047	0.0283	0.000	Geographic	723.8

5 Concluding Remarks and Limitations

Interdisciplinary research has moved beyond simply acknowledging global warming to exploring the complex interplay between environmental challenges and societal outcomes. Studies in academic journals reveal how CO2 emissions influence firm performance, investor behaviour, disclosure practices, and broader economic costs. Key research themes include the pricing of carbon risk in financial markets, the role of corporate disclosure in reducing emissions, and methods for measuring

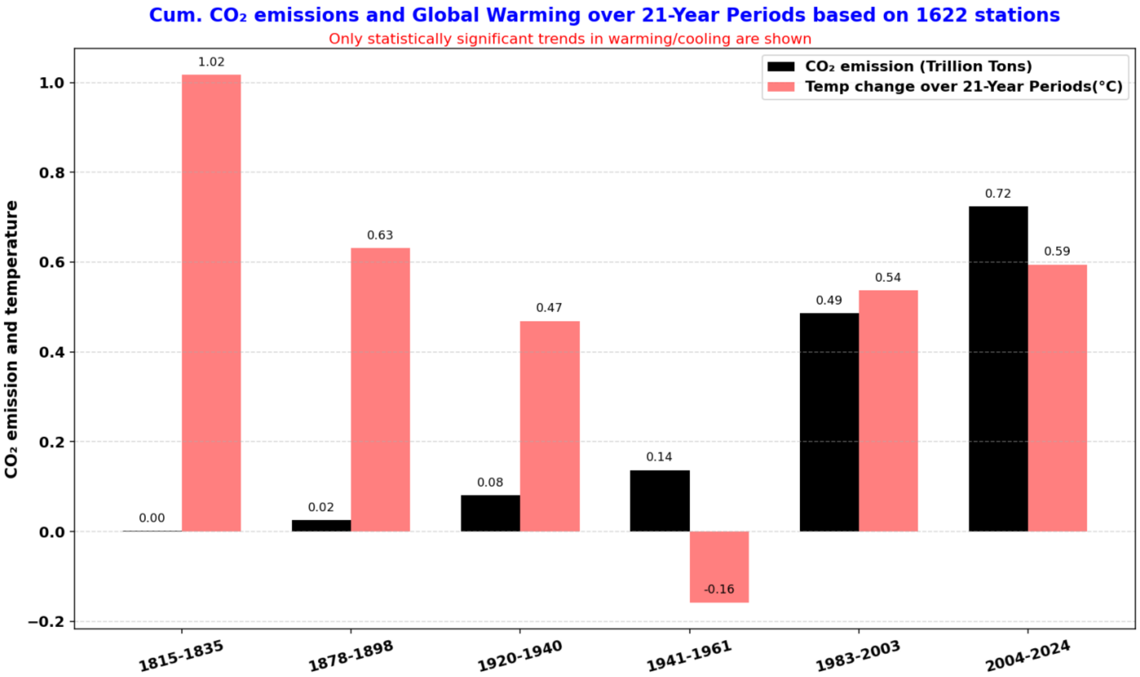

Figure 12: Cumulative CO2 emissions and cumulative temperature changes based on expanded set of 1622 weather stations across 10 equal time periods of 21 years (only statistically significant temperature trends are considered)

and hedging climate-related exposures. This body of work consistently highlights the negative environmental and societal consequences linked to increased CO2 emissions.

However, a direct examination of publicly available daily temperature data from weather stations does not align with the notion that CO2 is the primary driver of global warming. If this were the case, periods with higher CO2 emissions would exhibit a faster rate of warming than periods with lower emissions. In contrast, this study finds that some recent periods have witnessed global cooling despite sharp increases in CO2 emissions. Furthermore, the long-term temperature rise was steeper in earlier periods when CO2 emissions were modest compared to current levels.

The evidence presented herein raises serious questions about the established assumption regarding the impact of CO2 emissions on global warming. While Intergovernmental Panel on Climate Change (IPCC) (2023) states that " *Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming...*", the empirical evidence presented herein does not provide support to such straightforward relationship.

5.1 Implications for academia

Given these findings, academic research should approach the concept of anthropogenic global warming (AGW) with a degree of caution. Rather than treating AGW as a foregone conclusion, scholars in all fields should be encouraged to acknowledge the existing uncertainties. When building models or theories that assume CO2 is the primary driver, it would be prudent to include a caveat in the limitations section noting that the empirical evidence for this direct link is still a subject of debate.

This call for critical appraisal extends to education. Educational materials, particularly for school children, should present the topic of global warming with more nuance. Instead of teaching AGW as an absolute and settled truth, curricula should aim to provide a more balanced perspective that includes the scientific method's reliance on questioning and verification. Fostering an environment of critical inquiry will better equip students to understand the complexities of climate science.

5.2 Implications for policymakers

The findings carry significant and actionable implications for policymakers. A tremendous amount of effort and resources has been expended towards containing CO2 emissions, with the de facto assumption that CO2 drives global warming. As this premise now warrants closer scrutiny, a comprehensive review of all climate policies built upon this foundation is essential to ensure they are effective, economically sound, and aligned with the full scope of empirical evidence.

5.3 Limitations

This study has its limitations. One of the concerns relates to the quality of data. It is known that raw temperature data from some weather stations are not digitized properly. For example, UK weather stations from Armagh, Oxford, Sheffield, Durham and Stornoway are some of the longest-running stations. Upon a Freedom of Information request for raw daily temperature data from these stations, the Met Office UK in their letter dated 27 March 2025 stated that "*Data that has not been through the QC processes (Version 0' values) remain undigitized and are only available in paper form prior to 1960 so we have not been able to* *provide that dataset.*" This can raise issues about the quality of the reconstructed data when raw data itself remains undigitized. Similarly, given that the data goes through a quality control process, the possibility of noise being introduced in such reconstructed data remains. Future research would benefit from a systematic effort to digitize these historical archives, which would enable a more robust and direct analysis.

Second, stations are mainly land-based and concentrated in the US and Europe, with very sparse representation from Africa, India, China, South America, and Southeast Asia. This can raise questions about whether the warming and cooling trends observed in this study apply to these under-represented areas. Further research is necessary to validate these findings with comprehensive data from these regions to determine if the conclusions are globally applicable. The findings of this study should be seen within this context.

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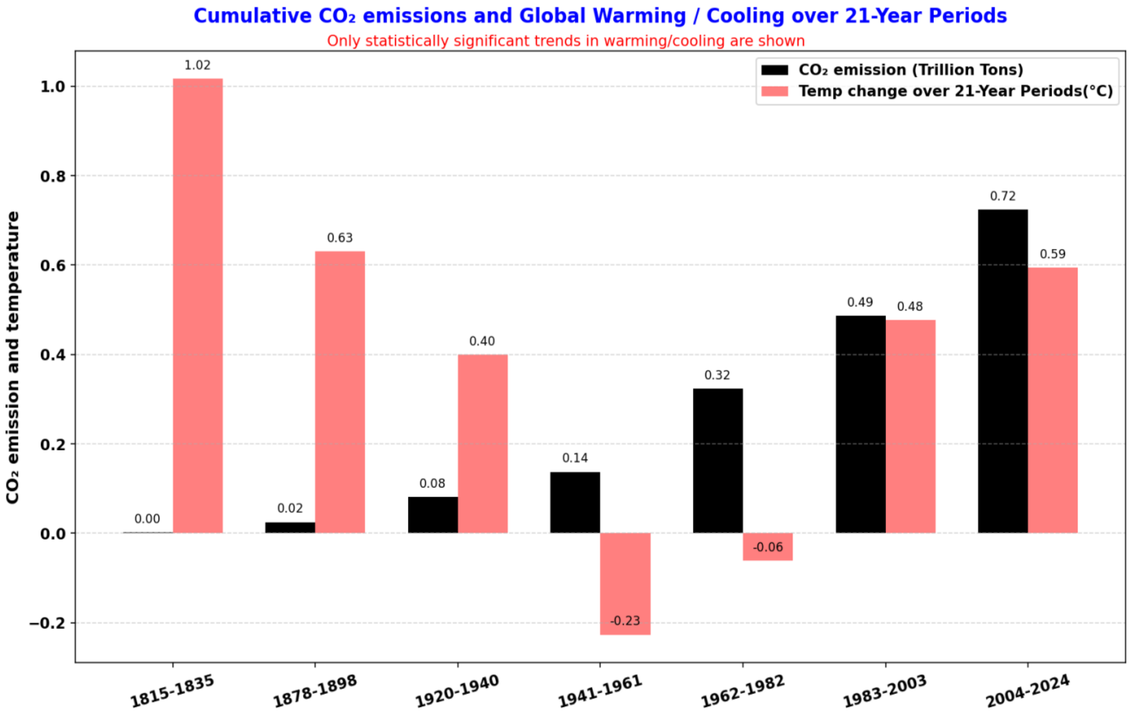
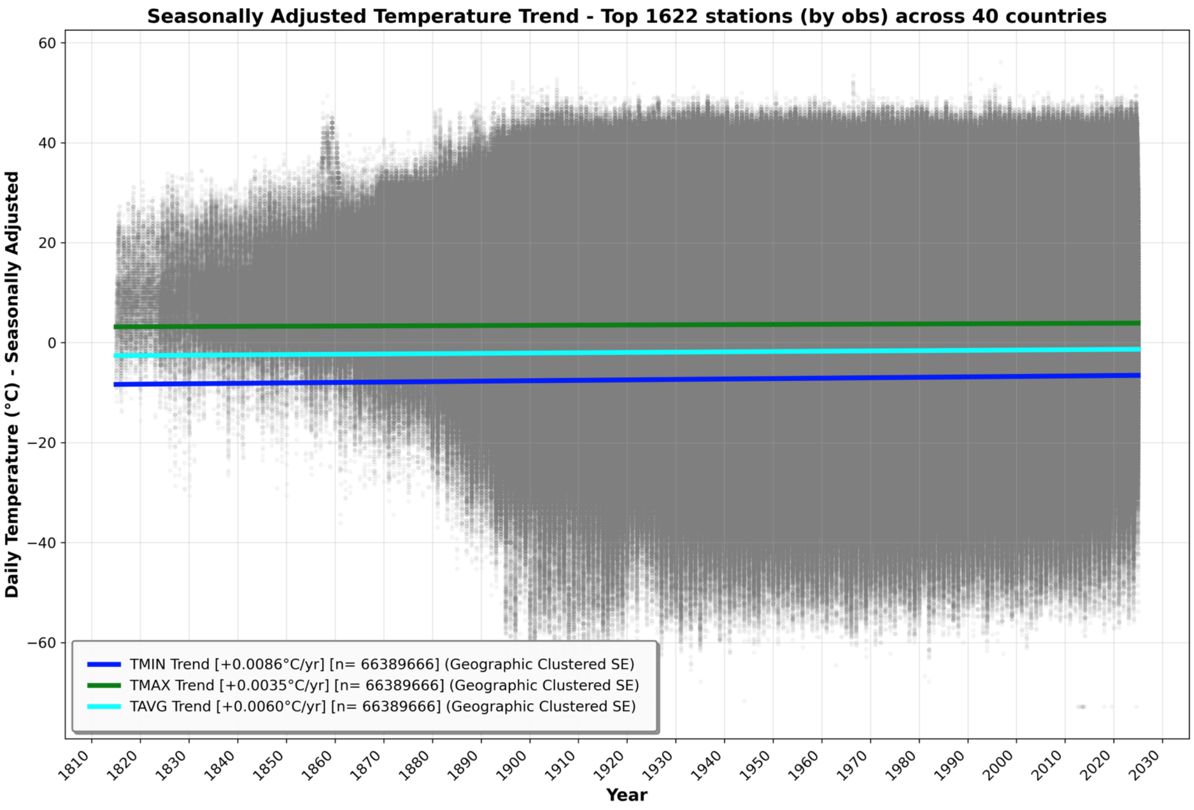
Appendices

Appendix 1: Number of weather stations by country

Country	**Number of stations**	**Country**	**Number of stations**
United States	840	Sri Lanka	2
Germany	32	Belgium	1
Russia	32	Ireland	1
Sweden	16	Slovenia	1
Canada	12	Greenland [Dk]	1
Australia	9	Uzbekistan	1
United Kingdom	7	France	1
Austria	6	Lithuania	1
Ukraine	5	Georgia	1
Romania	4	Belarus	1
Croatia	4	Moldova	1
Kazakhstan	3	Azerbaijan	1
Puerto Rico [US]	3	Algeria	1
Turkmenistan	2	Senegal	1
Switzerland	2		

Appendix 2: Cumulative CO2 emissions and cumulative temperature changes based on 992 weather stations across 10 equal time periods of 21 years (only statistically significant temperature trends are shown)





Appendix 3: Global temperature trendline based on expanded set of weather stations