

Subject 1: CO2 concentration in the atmosphere since 1958

The Keeling Curve and purpose of the quantitative analysis

Since 1958, American scientist Charles David Keeling has performed continuous measurement of atmospheric carbon dioxide (CO₂) at the Mauna Loa Observatory in Hawaii. This long-term dataset has become known as the Keeling Curve, serving as clear evidence of the ongoing increase in atmospheric CO₂ concentrations, which is primarily caused by human activity.

The initial objective of the observations was to study seasonal variation in CO₂, which was occurred because of natural processes such as photosynthesis and respiration. Over time, however, the focuses eventually turned to understanding the long-term upward trend in the context of climate change. This was occurred due to the steady year over year increase in CO₂ concentrations provided measurable evidence of impact of human activities, particularly fossil fuel combustions on the global ecosystem.

Objectives of the Quantitative analysis

Quantitative evaluation aims to explore and model the time series of CO₂ measurements from Mauna Loa.

Specifically, the objectives are:

- to create a plot showing the superposition of seasonal oscillations and a slower systematic trend.
- to separate the seasonal component and describe it.
- to construct a model for the long-term trend and estimates its parameters, i.e. slope and offset.
- to extrapolate the trend up to the year 2025, providing a forecast for future changes in concentration of CO₂ in atmosphere.

The data used in this quantitative analysis is a local copy of CO₂ observations from the [Scripps CO2 Program](https://scrippsco2.ucsd.edu/data/atmospheric_co2/primary_mlo_co2_record.html) (https://scrippsco2.ucsd.edu/data/atmospheric_co2/primary_mlo_co2_record.html).

Load and prepare the dataset to perform the quantitative analysis

```
In [1]: import pandas as pd
import matplotlib.pyplot as plt
from statsmodels.tsa.seasonal import seasonal_decompose
import numpy as np
```

Importing the CO2 dataset, which was downloaded from the [Scripps CO2 Program website](https://scrippsco2.ucsd.edu/data/atmospheric_co2/primary_mlo_co2_record.html) (https://scrippsco2.ucsd.edu/data/atmospheric_co2/primary_mlo_co2_record.html).

As the original file includes metadata in the first 61 rows, it is necessary to skip them when reading the file. Afterwards, the column names were assigned.

```
In [2]: df=pd.read_csv("monthly_in_situ_co2_mlo.csv", skiprows=61)
df.columns=['Year', 'Month', 'Excel', 'DecimalDate', 'CO2', 'CO2_season_adj',
            'CO2_fit', 'CO2_adj_fit', 'CO2_filled', 'CO2_adj_filled', 'Sta']
```

Filter out invalid or missing values

Some rows may contain non-numeric values, particularly in the "Year" columns

```
In [3]: df=df[pd.to_numeric(df['Year'], errors='coerce').notnull()].copy()
```

The "Year" and "Month" columns were converted to integers, which ensure the CO2 values are numeric.

```
In [4]: df['Year']=df['Year'].astype(int)
df['Month']=df['Month'].astype(int)
df['CO2']=pd.to_numeric(df['CO2'], errors='coerce')
```

A full datetime column was created to represent mid-month measurements.

```
In [5]: df['Date']=pd.to_datetime(dict(Year=df['Year'], Month=df['Month'], Day=15))
```

"Date" column was set as the index of the DataFrame to facilitate time series analysis

```
In [6]: df=df[df['CO2']>0]
df.set_index('Date', inplace=True)
```

Plot the Raw CO2 time series

It is possible to visualize the monthly CO2 measurement from the **Mauna Loa Observatory**.

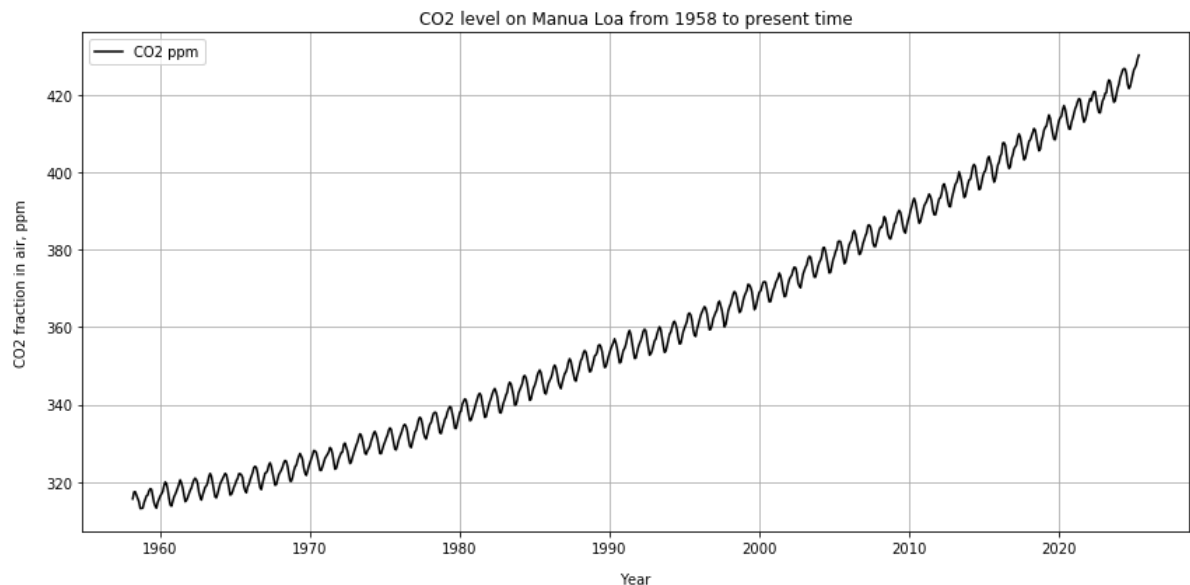
The first plot illustrates the raw atmospheric CO2 concentrations over time, showing both seasonal periodic oscillations and a long-term upward trend.

The graph below demonstrates the measured atmospheric CO2 concentration at Mauna Loa Observatory from 1958 to the present. As a result of quantitative analysis, it has been revealed two key features:

- Upward long-term trend in CO2 level, indicating a continuous increase over the decades.
- A periodic oscillations, reflecting seasonal variation in CO2 concentration within each year.

These seasonal cycles are caused by natural processes and human activities, which dominate global CO2 exchange.

```
In [7]: plt.figure(figsize=(12,6))
plt.plot(df.index, df['CO2'], label='CO2 ppm', color='black')
plt.title('CO2 level on Manua Loa from 1958 to present time')
plt.xlabel('Year',labelpad=12)
plt.ylabel('CO2 fraction in air, ppm', labelpad=12)
plt.grid(True)
plt.legend()
plt.tight_layout()
plt.show()
```



Seasonal oscillation of CO2

We performed a seasonal decomposition of the CO2 data in order to separate the peoridic component from the trend and residuals. An additive model was used with frequency of 12 months.

```
In [8]: Decomposition=seasonal_decompose(df['CO2'], model='additive', freq=12)
#drop missing values to ensure exact quantitative analysis
Seasonal=Decomposition.seasonal.dropna()
```

Now, we convert the seasonal component to a DataFrame and extract the month from the datetime index for monthly grouping. Furthermore, the average seasonal deviation was computed for each month by grouping the data by month.

```
In [9]: Seasonal_Monthly=Seasonal.to_frame(name='Seasonality')
Seasonal_Monthly['Month']=Seasonal_Monthly.index.month
Monthly_Avg=Seasonal_Monthly.groupby('Month')['Seasonality'].mean()
```

Plot the average seasonal oscillation of CO2 concentration

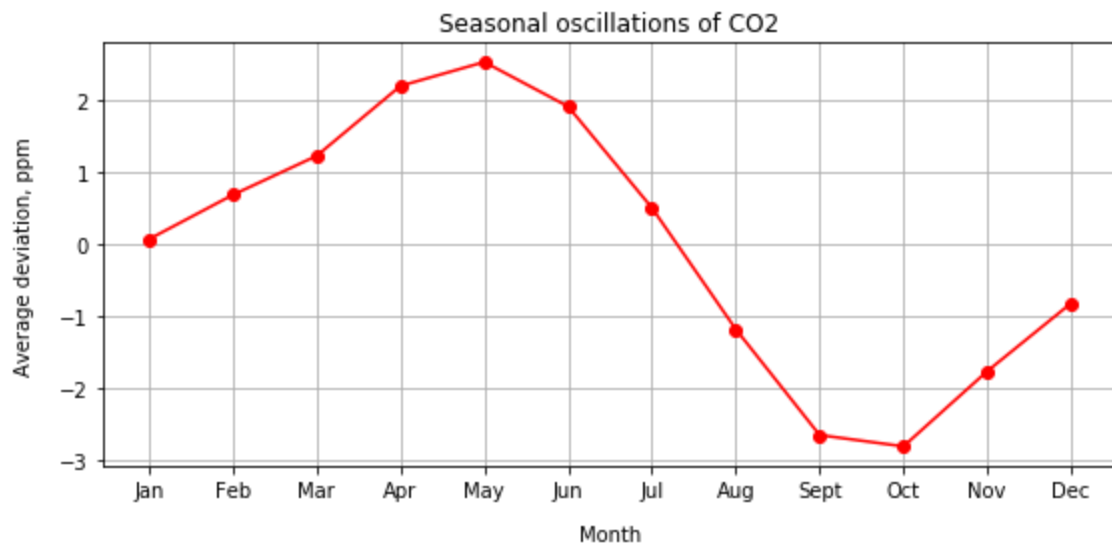
The plot below presents the mean deviation for each month across all years, clearly highlighting the periodic nature of CO2 level.

Moreover, the average seasonal variation in CO2 concentration is observed across different months of the year. Notably, CO2 levels peak in May, when plant growth has not yet removed considerable amount of CO2 from the atmosphere. Conversely, the lowest concentration occurs in September and October, due to enhanced photosynthetic activity during summer, when vegetation actively absorbs CO2. After October, CO2 concentrations begin to rise again, mainly because deciduous plants shed their leaves, and photosynthesis slows down, while decomposition process continues, realising CO2 back into the atmosphere. This seasonal CO2 cycle leads to the regular annual fluctuation in its concentration.

```
In [10]: plt.figure(figsize=(8,4))
plt.plot(Monthly_Avg.index, Monthly_Avg.values, marker='o', linestyle='--', color='red')
plt.title('Seasonal oscillations of CO2')
plt.xlabel('Month',labelpad=12)
plt.ylabel('Average deviation, ppm', labelpad=12)

plt.xticks(range(1,13), ['Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun',
                        'Jul', 'Aug', 'Sept', 'Oct', 'Nov', 'Dec'])

plt.grid(True)
plt.tight_layout()
plt.show()
```



Linear Trend Evaluation and Extrapolation

We construct a linear regression model to estimate the long-term trend in CO2 concentration:

- the model was computed manually using the least squares method.
- The tren was extrapolated to predict CO2 level up to the year 2025.

```
In [11]: df_clean = df.dropna(subset = ['CO2', 'DecimalDate']).copy()
df_clean['CO2']=pd.to_numeric(df_clean['CO2'], errors='coerce')
df_clean['DecimalDate']=pd.to_numeric(df_clean['DecimalDate'], errors='coerce')

df_clean=df_clean.dropna(subset = ['CO2', 'DecimalDate'])
x = df_clean['DecimalDate'].values
y = df_clean['CO2'].values

x_mean = np.mean(x)
y_mean = np.mean(y)

numerator = np.sum((x-x_mean)*(y-y_mean))
denominator = np.sum((x-x_mean)**2)

a_tr = numerator / denominator
b_tr = y_mean - a_tr*x_mean

y_pred_tr = a_tr*x + b_tr

x_future = np.arange(x.max(), 2026.0, 1/12)
y_future_pred = a_tr*x_future + b_tr
```

Plot of the Linear Trend and Extrapolated CO2 Level

This plot combined three elements:

- Trend line (red dashed) is a linear regression model showing the long-term increase in atmospheric CO2.
- Observed variation in CO2 concentrations (black lines) is actual monthly measurement.
- Extrapolated trend (blue dotted) is predicted CO2 values up to the year 2025 based in the model.

In this plot, the observed short-term variability is separated from the long-term systematic rise in CO2 concentrations.

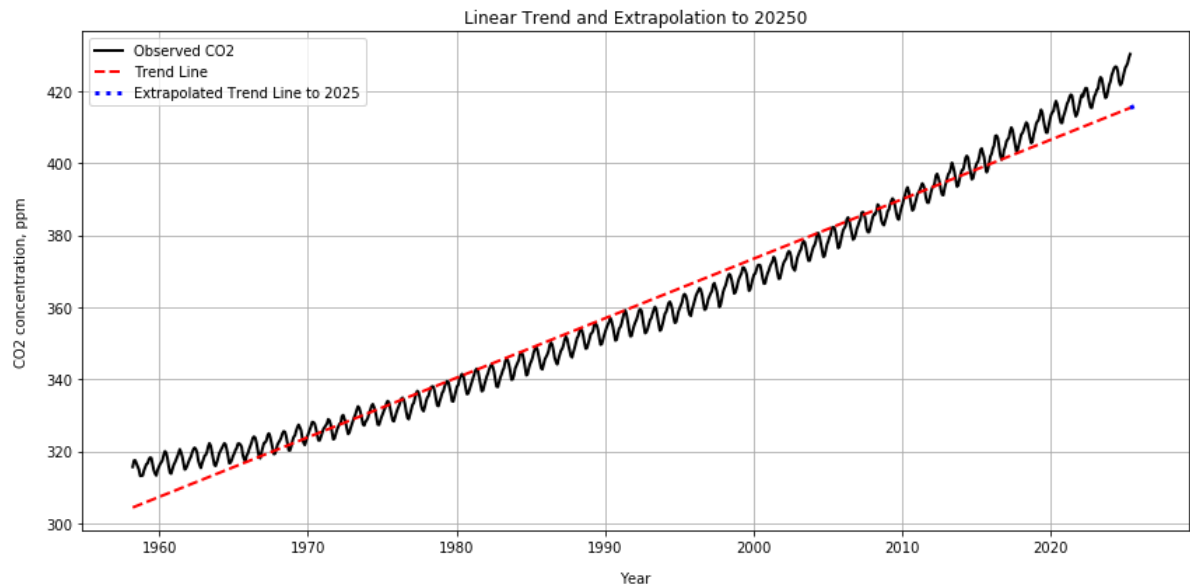
```
In [12]: plt.figure(figsize=(12,6))

plt.plot(x,y, label='Observed CO2', color='black', linewidth=2)

plt.plot(x,y_pred_tr, label='Trend Line', color='red', linestyle='--', linewidth=2)

plt.plot(x_future, y_future_pred, label='Extrapolated Trend Line to 2025', color='blue', linestyle=':', linewidth=3)

plt.xlabel('Year', labelpad=12)
plt.ylabel('CO2 concentration, ppm', labelpad=12)
plt.title('Linear Trend and Extrapolation to 20250')
plt.legend()
plt.grid(True)
plt.tight_layout()
plt.show()
```



Yearly CO₂ Statistics

In this section, the dataset is grouped by year to compute key statistics for atmospheric CO₂ concentration: minimum, maximum, and mean values for each year. This allows us to observe not only the general trend over time but also the seasonal variation within each year.

```
In [13]: yearly_stats=df.groupby('Year')['C02'].agg(['min', 'max', 'mean']).reset_index  
        ()  
        yearly_stats.columns  
  
        print(yearly_stats)
```


	Year	min	max	mean
0	1958	313.21	317.51	315.335000
1	1959	313.33	318.29	315.980833
2	1960	313.83	320.03	316.909167
3	1961	314.99	320.58	317.643333
4	1962	315.42	321.02	318.454167
5	1963	315.98	322.24	318.991667
6	1964	316.71	322.25	319.202222
7	1965	317.30	322.17	320.037500
8	1966	318.10	324.08	321.367500
9	1967	319.25	325.00	322.178333
10	1968	320.25	325.57	323.050000
11	1969	321.78	327.38	324.620833
12	1970	323.06	328.13	325.681667
13	1971	323.36	328.93	326.320000
14	1972	324.84	330.07	327.456667
15	1973	327.19	332.48	329.681667
16	1974	327.38	333.10	330.250833
17	1975	328.35	333.98	331.160833
18	1976	328.95	334.89	332.161667
19	1977	331.17	336.76	333.910833
20	1978	332.56	338.02	335.515000
21	1979	333.87	339.48	336.860833
22	1980	335.90	341.48	338.700000
23	1981	336.71	342.93	339.951667
24	1982	337.88	344.16	341.150833
25	1983	339.89	345.77	342.798333
26	1984	341.13	347.52	344.498333
27	1985	342.77	348.92	345.890000
28	1986	344.16	350.19	347.134167
29	1987	346.09	351.84	348.856667
..	...	...	...	...
38	1996	359.32	365.29	362.511667
39	1997	360.08	366.68	363.649167
40	1998	363.80	369.19	366.523333
41	1999	364.54	371.04	368.214167
42	2000	366.53	371.74	369.384167
43	2001	367.88	373.94	370.938333
44	2002	370.18	375.48	373.022500
45	2003	372.92	378.28	375.572500
46	2004	373.99	380.56	377.307500
47	2005	376.39	382.21	379.567500
48	2006	378.77	384.89	381.774167
49	2007	380.83	386.38	383.563333
50	2008	382.75	388.48	385.418333
51	2009	384.32	390.15	387.343333
52	2010	386.85	393.24	389.914167
53	2011	388.98	394.33	391.695000
54	2012	391.09	396.96	393.947500
55	2013	393.47	400.06	396.649167
56	2014	395.49	401.98	398.706667
57	2015	397.43	404.03	400.867500
58	2016	400.94	407.60	404.207500
59	2017	403.20	409.84	406.515833
60	2018	405.53	411.23	408.527500
61	2019	408.40	414.75	411.424167
62	2020	411.12	417.16	413.947500

63	2021	412.93	418.95	416.113333
64	2022	415.31	420.78	418.216667
65	2023	418.06	423.78	420.773333
66	2024	421.60	426.70	424.347500
67	2025	426.42	430.20	428.118000

[68 rows x 4 columns]

Conclusion

Thus, the measurements of CO₂ concentration collected at the Mauna Loa Observatory show a gradual increase from 315.335 ppm in 1958 to 424.348 ppm in 2024. This rise is primarily attributed to the burning of fossil fuels and has been accelerating in recent years. Since CO₂ is a greenhouse gas, this upward trend has significant implications for future global warming.

In []: