An Assessment of Carbon Dioxide Emissions

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Overview

The Intergovernmental Panel on Climate Change (IPCC) claims that "human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C." Moreover, the IPCC argues that limiting CO_2 emissions is essential for mitigating anthropogenic climate change: "limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers" (Report available at: https://www.ipcc.ch/sr15/).

Given the exponential increase in CO_2 emissions since the industrial revolution, the IPCC's recommendation represents an enormous challenge, requiring a clear-eyed understanding of CO_2 emissions. Accordingly, this report will summarize important trends related to atmospheric CO_2 concentrations and global CO_2 emissions. The analysis will draw on four publicly available datasets (see below) containing information on atmospheric CO_2, historical CO_2 emissions (by region and country), and per capita CO_2 emissions.

Data Selections and Cleaning

This report makes use of four publicly available datasets related to CO_2 emissions and atmospheric concentrations:

1) "Carbon Dioxide Levels in Atmosphere: Atmospheric carbon dioxide data from Mauna Loa Observatory since 1958" (https://www.kaggle.com/ucsandiego/carbon-dioxide). This data set contains monthy measurements of atmospheric CO_2 at the Mauna Loa Observatory (HI) from 1958-2017. Measurements were recorded on the 15th day of each month at midnight. This dataset provides excellent insight into historical trends related to atmospheric CO_2. The data are already "clean" with the exception of a few NAs.
2) "CO_2 and GHG emission data of different countries from 1750 - 2019" (https://www.kaggle.com/srikantsahu/CO2-and-ghg-emission-data). This dataset contains yearly measurements of CO_2 emissions from 1751 to 2017 for nearly every country/region in the world. It provides an excellent overview of historical trends related to CO_2 emissions. This dataset was originally "wide" format. I used dplyr's "gather" function to convert it to "long" format. I also cleaned the "Year" column by removing extraneous text.
3) "Global Carbon Atlas" (http://www.globalcarbonatlas.org/en/CO2-emissions). This dataset contains yearly measurements of every country's CO_2 emissions from 1960-2017. It is helpful for determining which countries produce the most CO_2. It does not contain as much historical detail as "CO_2 and GHG emission data" (see above), but it is more consistent with respect country names. So it is more useful in tracking CO_2 emissions by country. The dataset was originally in "wide" format. I used dplyr's "gather" function to convert it to "long" format.
4) "CO_2 Emissions Per Capita" (https://ourworldindata.org/CO2-and-other-greenhouse-gas-emissions). This dataset tracks CO_2 emissions per capita from 1800-2017 for nearly every country in the world. It is very useful for assessing trends in per capita carbon emissions. The dataset was assembled from other datasets relating to CO_2 emissions and population. It did not require further cleaning.

Research Questions & Exploratory Data Analysis

Data show that CO_2 atmospheric concentration and total emissions are increasing and that the United States is a major producer of CO_2. So, for example, the mean atmospheric CO_2 content (ppm) was 317 in 1960 and 406 in 2017– an increase of 28%. Similarly, the worldwide emission of CO_2 went from 3.07×10^{11} in 1960 to 1.58×10^{12} in 2017– an increase of 415%. Additionally, from 2007 to 2017, the US accounted for an average of 27% of worldwide yearly CO_2 emissions.

These preliminary descriptive statistics point toward a number of interesting research topics. This report will consider the following questions:

1) What are the historical trends in atmospheric CO_2 concentration?
2) What are the historical trends in worldwide CO_2 emissions?

3) Which countries produce the most CO_2, and how have their emissions changed over time?

4) What are the per capita CO_2 emissions for major producers of CO_2, and how have per capita emissions changed over time?

Statistical Analysis

This section contains four subsections corresponding to the four research questions listed above. Each section contains graphical and numerical summaries of relevant data.

Atmospheric CO_2 Concentration

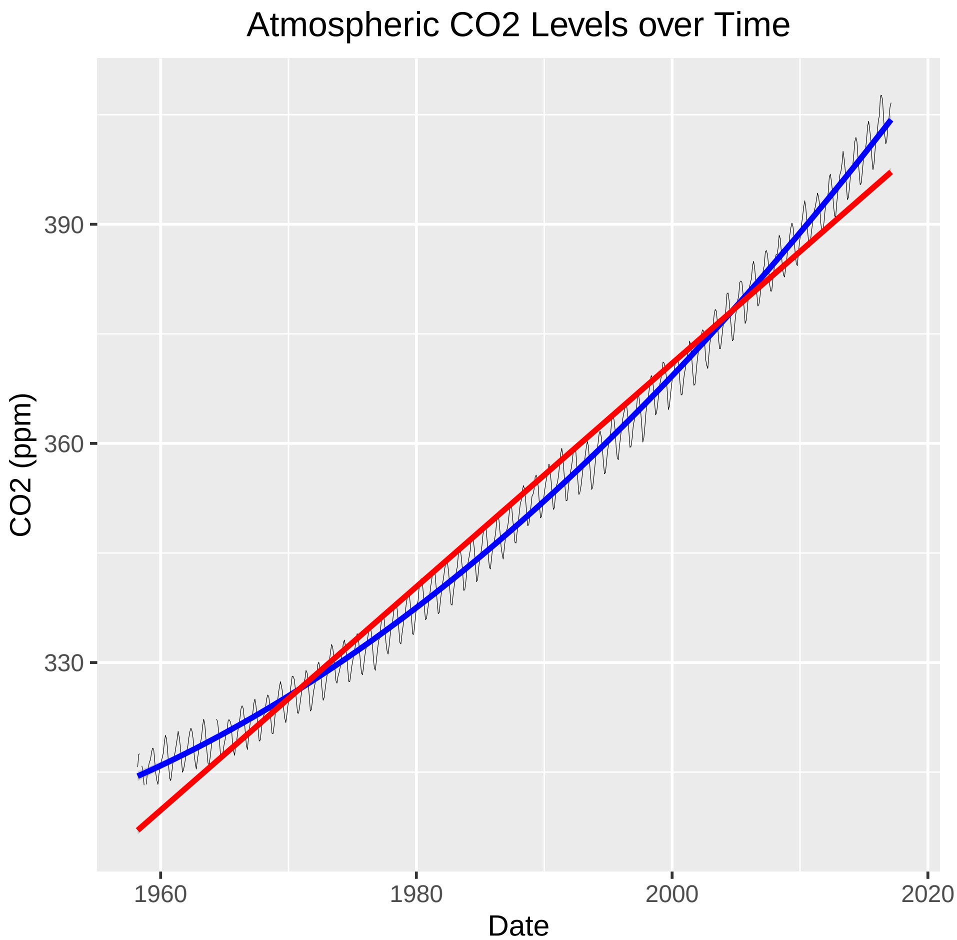
The following table summarizes data collected at Mauna Loa Observatory (HI). It shows a marked increase in mean atmospheric CO_2 levels by decade from 1960 to 2017, where mean conentration is defined as:

$$\frac{\sum \text{concentration(ppm)}}{\text{n measurements per decade}}$$

Table 1: Average Atmospheric CO2 Levels (ppm) by Decade

Decade_Start	Mean CO2
1960	320.2726
1970	330.8942
1980	345.3336
1990	360.4303
2000	378.4410
2010	396.7658

The following plot further demonstrates the magnitude of increases in atmospheric CO_2 from 1958-2017. It shows all CO_2 measurements with a linear trend line in red and polynomial trend line (degree=3) in blue. The zig-zag pattern is due to seasonal fluctations, but the overall trend is clear: atmospheric CO_2 is increasing. It is worth noting that the data appear linear for the most part, but after 2005 the difference between the blue (polynomial) trend line and the red (linear) trend line suggests that atmospheric CO_2 increased at a rate greater than the linear model would predict. This may indicate that the *rate* of CO_2 increase is accelerating in recent years.



Since this data is a fairly linear, we can conduct a simple linear regression in order to develop predictions with respect to atmsopheric CO_2 concentrations. Results of the linear regression are summarized below:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-2688	17.36	-154.8	0
Decimal.Date	1.53	0.008734	175.1	0

Observations	Residual Std. Error	R^2	Adjusted R^2
703	3.926	0.9777	0.9776

A linear regression of atmospheric CO_2 data yields the following equation,

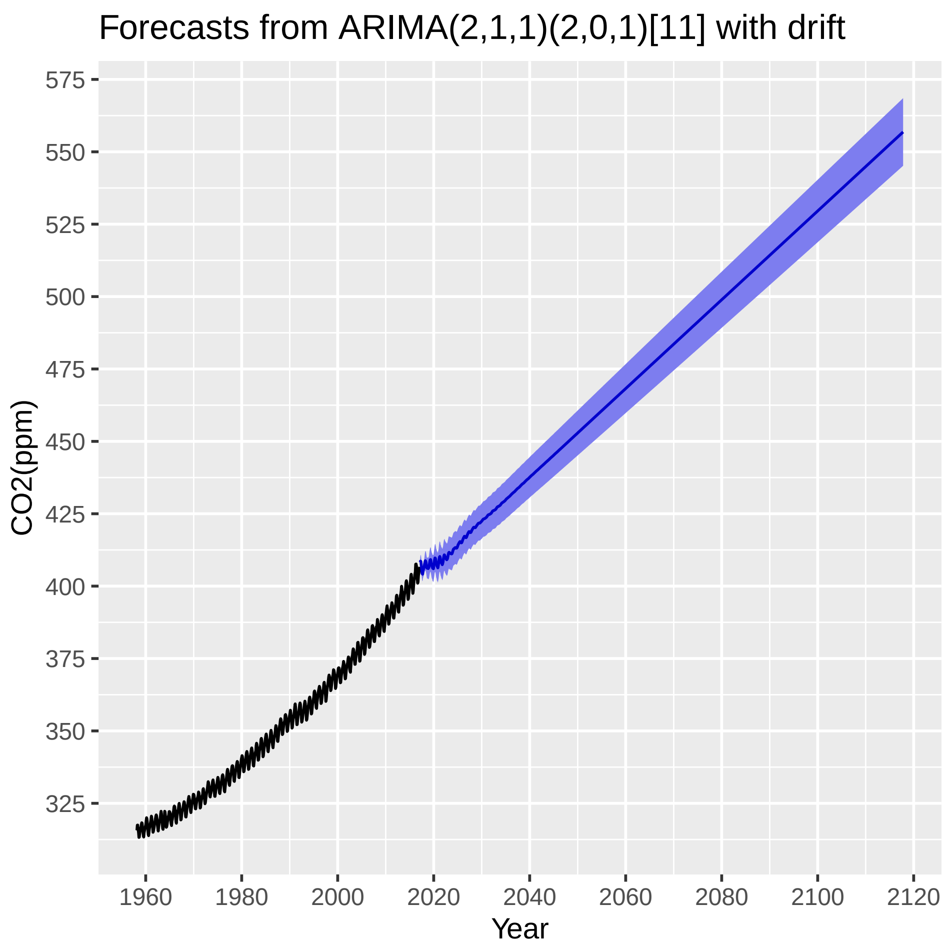
$$y = 1.53x - 2688$$

, where y=CO_2(ppm) and x=year. The R^2 value (.98) tells us that 98% of the variability in the data can be attributed to the linear model. In other words, our equation is a good fit for the data! The following table shows predictions for various concentrations of atmospheric CO_2.

Table 4: Predicted Years for Various Atmospheric CO2 Levels

CO2(ppm)	Year
425	2034
450	2050
475	2066
500	2082
525	2098
550	2114

It was noted above that the *rate* of CO_2 increase is accelerating in recent years. This implies that predictions based on simple linear regression could be inaccurate. We can improve on the simple linear model by using an ARIMA model for time series forecasting. The following plot shows CO_2 levels forecasted for the next 100 years. The blue bands represent a 95% confidence interval.



The following table shows predictions for various concentrations of atmospheric CO_2 using the ARIMA model.

Table 5: Predicted Years for Various Atmospheric CO2 Levels (ARIMA)

Year	CO2.ppm	Lo.95	Hi.95
2032	425	419	431
2048	450	442	457
2064	475	466	483
2065	475	467	484
2081	500	490	510
2097	525	514	536
2113	550	538	561

To put this data in context, consider that the central goal of the Paris Climate Accord is to limit the global rise in temperature to 2^oC (3.6^oF) by 2100. In order to meet that goal, the IPCC found that atmospheric concentrations of CO_2 will need to be kept below 450ppm: "Mitigation scenarios in which it is likely that the temperature change caused by anthropogenic GHG emissions can be kept to less than 2°C relative to pre-industrial levels are characterized by atmospheric concentrations in 2100 of about 450 ppm CO_2 (high confidence)."

According to predictions based on our ARIMA model, we will likely reach 450ppm by the middle of this century. The Paris Accord's goal of restricting atmospheric CO_2 to 450ppm by 2100 appears extremely unlikely!

CO_2 Emissions

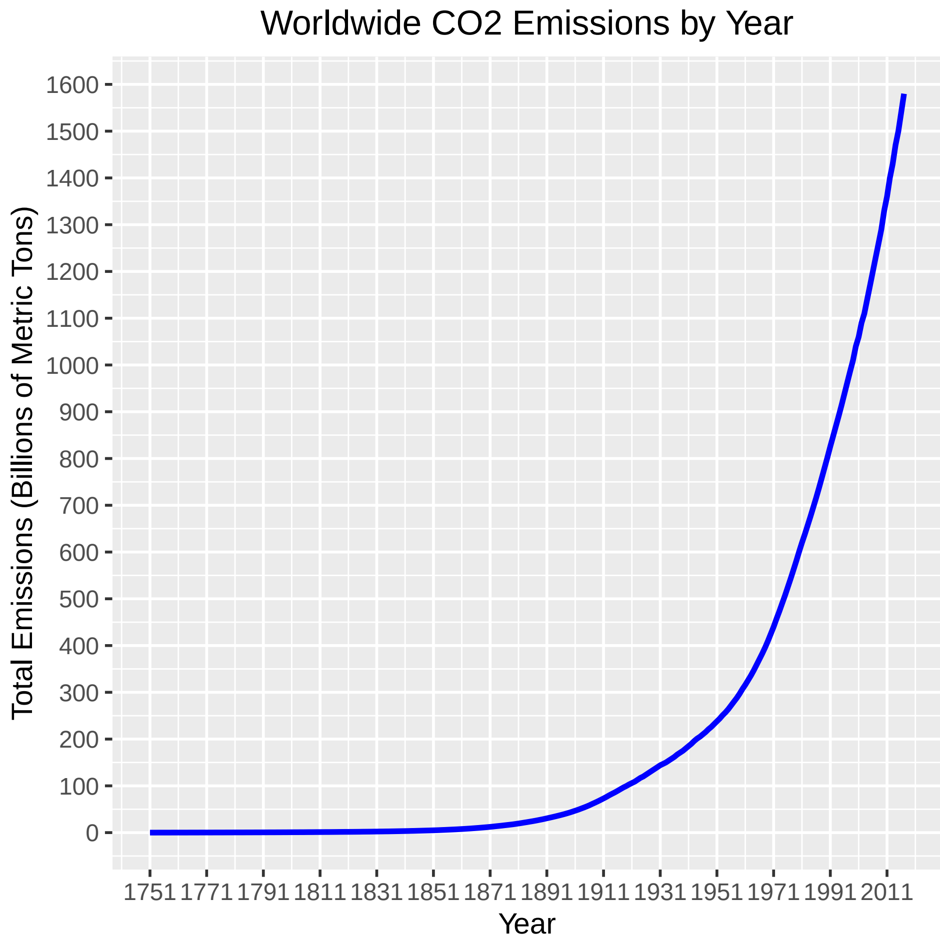
CO_2 emissions reflect various political, social, geographical, and economic factors– each of which deserves further research. Yet the overall trend in CO_2 emissions is clear. The following table shows worldwide CO_2 emissions for the last 20 years. The average yearly increase in total CO_2 emissions over that time period is 3.085×10^{10} metric tons per year.

$$\text{Average Yearly Increase} = \frac{\sum \text{(Current Year Total - Previous Year Total)}}{\text{n Years}}$$

Table 6: Worldwide CO 2 Emissions in Metric Tons)

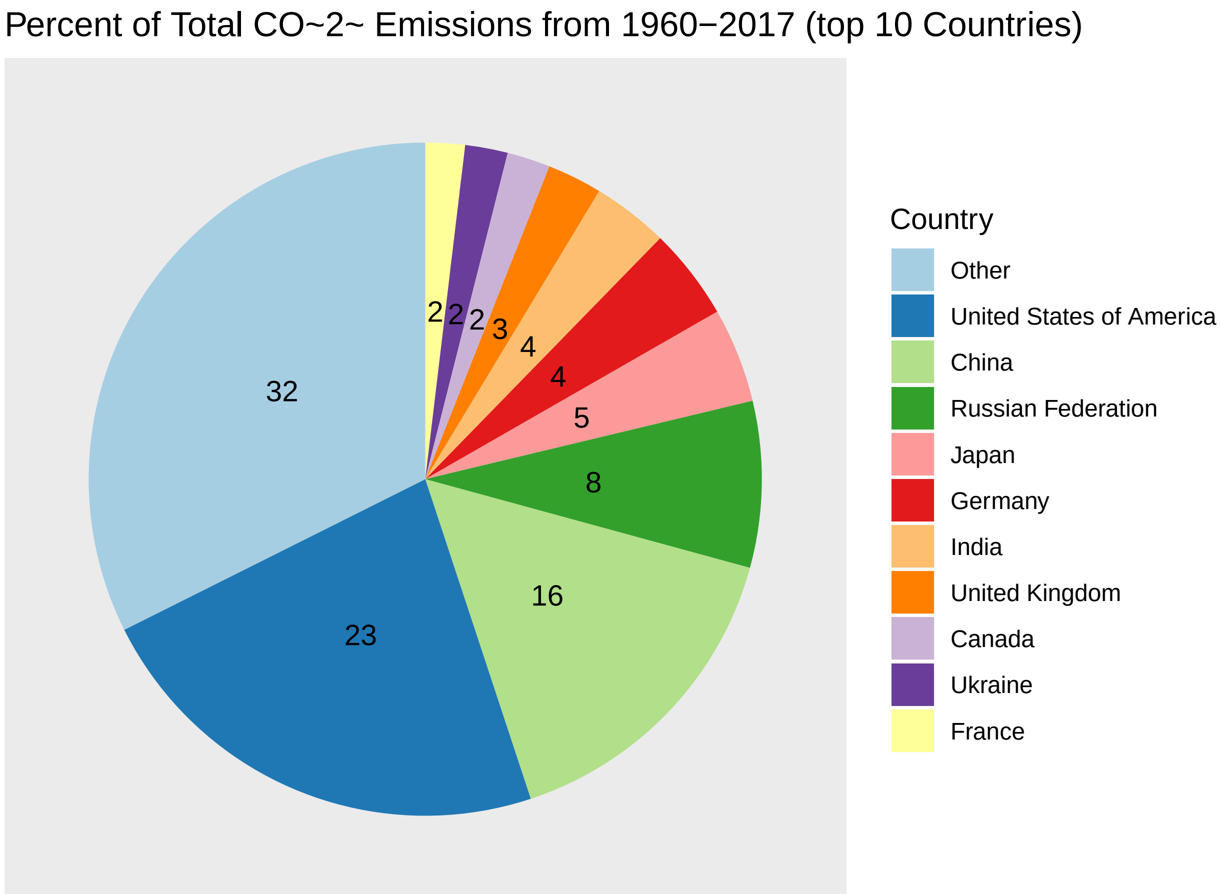
Year	Value	YearlyIncrease
2017	1.58e+12	4.0e+10
2016	1.54e+12	4.0e+10
2015	1.50e+12	3.0e+10
2014	1.47e+12	4.0e+10
2013	1.43e+12	3.0e+10
2012	1.40e+12	4.0e+10
2011	1.36e+12	3.0e+10
2010	1.33e+12	4.0e+10
2009	1.29e+12	3.0e+10
2008	1.26e+12	3.0e+10
2007	1.23e+12	3.0e+10
2006	1.20e+12	3.0e+10
2005	1.17e+12	3.0e+10
2004	1.14e+12	3.0e+10
2003	1.11e+12	2.0e+10
2002	1.09e+12	3.0e+10
2001	1.06e+12	2.0e+10
2000	1.04e+12	3.0e+10
1999	1.01e+12	2.3e+10
1998	9.87e+11	2.4e+10

The following plot shows worldwide CO_2 emissions (measured in billions of metric tons) from 1751 to 2017. The increase is dramatic. CO_2 emissions accelerate at an exponential rate, particularly after the mid-19th century.



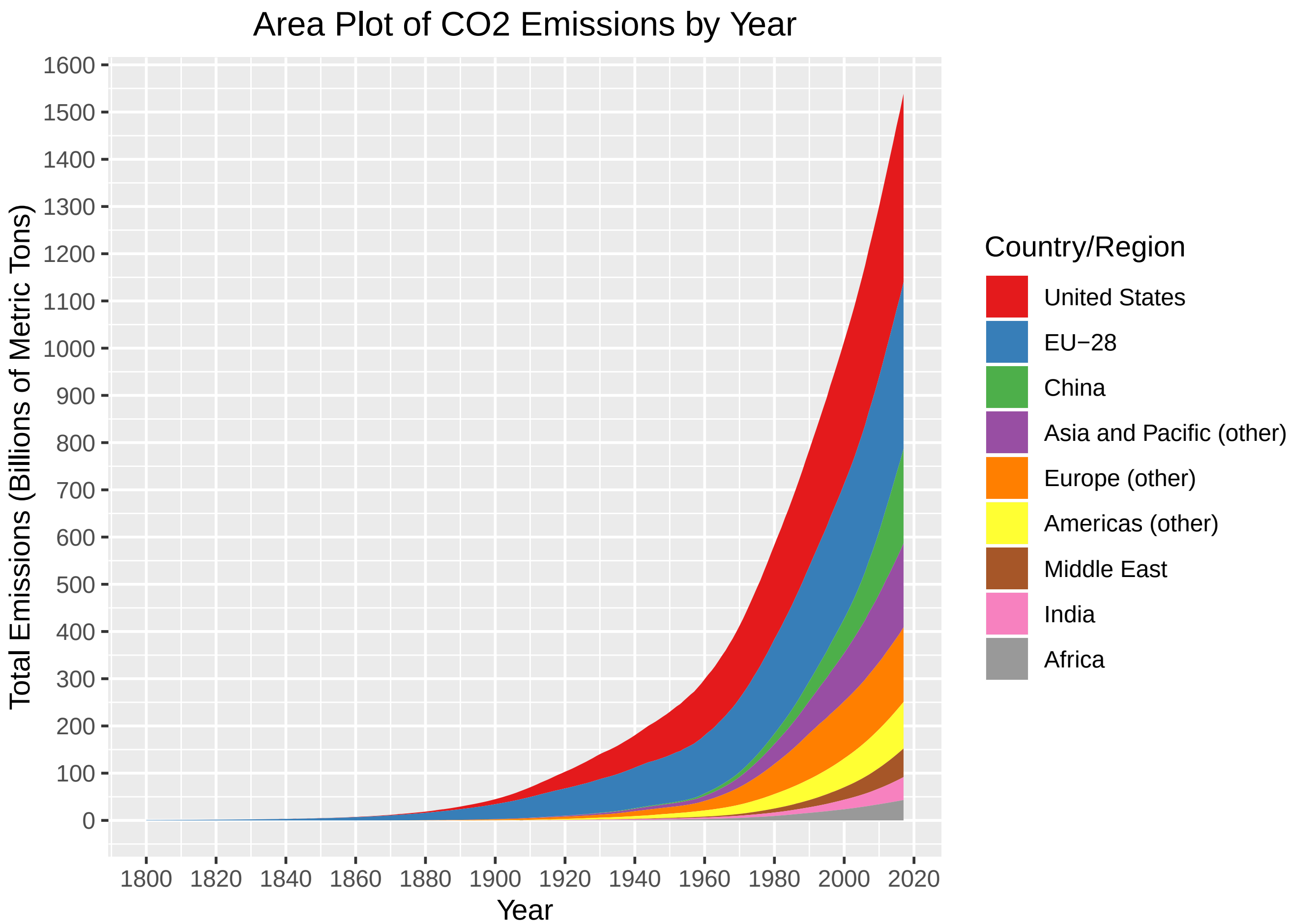
CO_2 Emissions by Country/Region

The following pie chart shows the percentage of total CO_2 emissions from 1960 to 2017 for the top ten countries ranked by total emissions. Note the relatively large proportion attributable to the United States, China, and the European Union. (Note: I am not including a separate table of numerical summaries for this subsection because numerical proportions are included in the pie chart)



Similarly, the following plot shows the contributions to worldwide emissions by nine major countries/regions over time. There are a few noteworthy observations: 1) There is an exponential increase in CO_2 emissions after the mid-19th century likely due to increasing industrialization. 2) CO_2 emissions increase rapidly in China–and Asia more broadly–after 1960. 3) The United States and European Union account for a large share of total emissions.

(Note: "Asia & Pacific (other)" refers to Asia and Oceania minus China and India. "Americas (other)" refers to North, Central, South America and the Caribbean minus the USA. "Europe (other)" refers to Western and Eastern Europe minus the EU-28.)



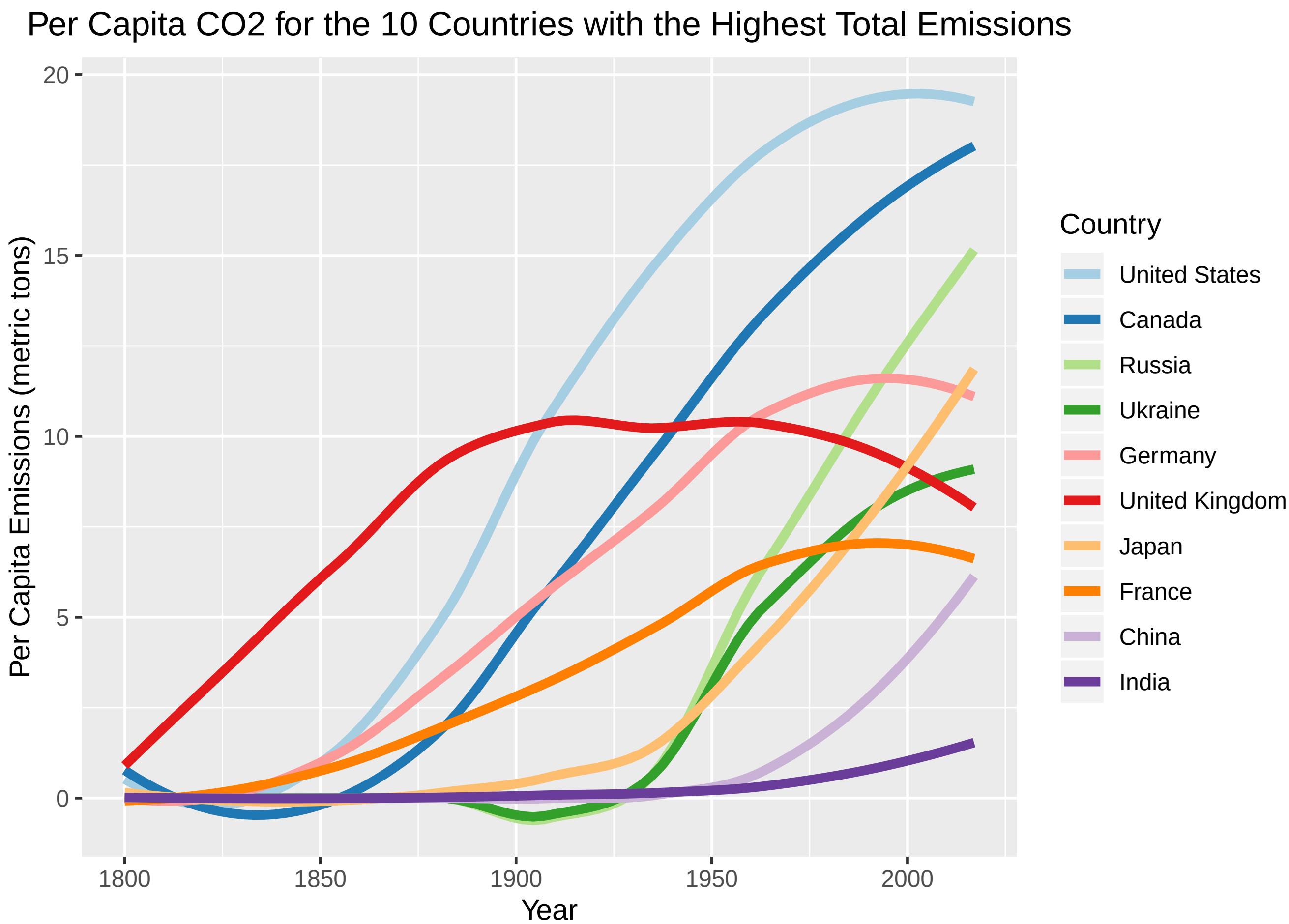
Per Capita CO_2 Emissions

The following table shows the average per capita CO_2 emissions (in metric tons) from 2007-2017 for the top 10 producers of CO_2 (measured by total emissions). Note the relatively high rate of per capita emissions for the US, Canada, and Russia. The per capita emissions of India and China are far less than that of the US, despite much larger populations and increasing industrialization and urbanization.

Table 7: Average Per Capita CO2 Emissions in Metric Tons)

Country	MeanPerCap
United States	17.827634
Canada	16.243953
Russia	11.633373
Germany	10.036910
Japan	9.693567
United Kingdom	7.389595
China	6.498036
Ukraine	6.141226
France	5.903782
India	1.540172

The following plot shows per capita CO_2 emissions for those countries ranked in the top 10 by total CO_2 emissions over time. There are a few noteworthy trends: 1) The United States, Canada, and Russia have relatively high CO_2 emissions per capita. 2) There is a significant increase in emissions per capita for developing countries (particularly China and India) after 1950. 3) The United Kingdom has expereinced a marked decline in emissions per capita starting around 1950.



Conclusions and Future Work

This report analyzed trends in CO2 emissions and atmospheric concentrations, focusing on four main topics:

First, trends in atmospheric CO_2 concentrations were analyzed using data from the Mauna Loa Observatory. We noted a preciptious increase (28%) in CO_2 concentrations between 1960 and 2017. Using this data, we were able to develop a linear model, which predicted a concentration of 450ppm by 2048. In future work, it would be interesting to modify the model to take into account planned reductions in atmospheric CO_2. How long would it take to reach 450ppm if annual increases in atmospheric CO_2 were reduced in accordance with the Paris Agreement, for example?

Second, historical trends in worldwide CO_2 emissions were analyzed. We found that CO_2 emissions increased precipitously after the industrial revolution. Additionally, the *rate* of increase continues to accelarate. In fact, worldwide CO_2 emissions have increased 415% since 1960 alone! In the future, it would be interesting to examine the relationship between worldwide CO_2 emissions and atmospheric CO_2 concentration. While both have increased dramatically, CO_2 emissions have increased far more rapidly than atmospheric concentrations. Why is that? Is some CO_2 being absorbed or otherwise recaptured? How do CO_2 emissions affect natural systems that cannot be fully captured by atmospheric data (oceans and waterways, for example)?

Third, we examined the contributions of individual countries and regions to worldwide CO_2 emissions. The United States and European Union were responsible more than half of the world's yearly CO_2 emissions over the last few decades. Even as developing countries, like India and China, represent a larger share of the world population, they account for a much smaller proportion of CO_2 emissions. In future research, it would be interesting to analyze sources of CO_2 emissions within each country. Are the US's emissions relatively high because US citizens tend to drive more? Is there something about Western economies or political systems that encourages CO_2 production?

Fourth, per capita CO_2 emissions were examined for the ten countries that produce the most CO_2. The US had the highest per capita CO_2 production (17.83 metric tons) followed by Canada (16.24 metric tons) and Russia (11.63 metric tons). Per capita CO_2 emissions have increased rapidly in India and China since 1950. In the future, it would be interesting to look for other correlations with per capita emissions. Do the US, Canada, and Russia have relatively large per capita levels because they have lower ratios of population to geographical area, for example?