An Outlook on Projected Global Temperatures in Relation to Excess Carbon Emissions

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1: Introduction

The Earth's climate system is a complex interplay of various factors and reactions involving the sun, ocean, atmosphere, clouds, ice, land, and life. Central to this system is the role of greenhouse gases, which have become a focal point of scientific research and public discourse. Greenhouse gases, named for their ability to trap heat like the glass panes of a greenhouse, play a pivotal role in temperature regulation on Earth [1]. Through the Greenhouse Gas Effect, solar radiation reaches Earth, with some reflected back into space and the rest absorbed by land and oceans, warming the planet. As Earth emits heat towards space, greenhouse gases trap a portion of the heat, ensuring temperatures that are necessary and sufficient for life to form on this planet [2]. Some of the most prominent greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [3].

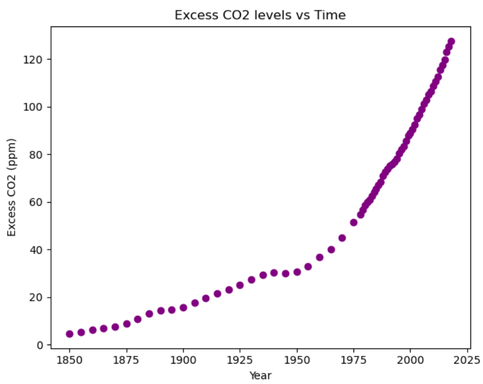
Remarkably, CO_2's role as a greenhouse gas was first pinpointed in 1856 by Eunice Foote. At a prominent U.S. science conference, she theorized that an atmosphere rich in CO_2 would lead to a higher global temperature, suggesting that historical atmospheric compositions could have varied in their CO_2 content and thus, their temperature [4]. Around the time of Foote's speech was the dawn of the Industrial Revolution—the inflection point in history where the large-scale combustion of fossil fuels began. Around the end of the 19th century, in 1896, Svante Arrhenius further theorized that the increasing CO_2 from such activities might elevate the planet's average temperature [5].

Concerns about the increase in global temperatures widely stayed in the realm of academia and research until towards the end of the 20th century, when concerns amongst the scientific community spread to the public in 1988 [5]. Scientists across the world at that time convened with one another and issued a warning to the world, stating that efforts to lower greenhouse gas emissions must be put into place. The concentration of Earth's atmospheric CO_2 since 1850 has increased from 280 parts per million to 416 parts per million [3]. Earth's global temperature has increased a noticeable degree alongside this increase in carbon concentration, causing scientific research and political discourse surround this issue to grow.

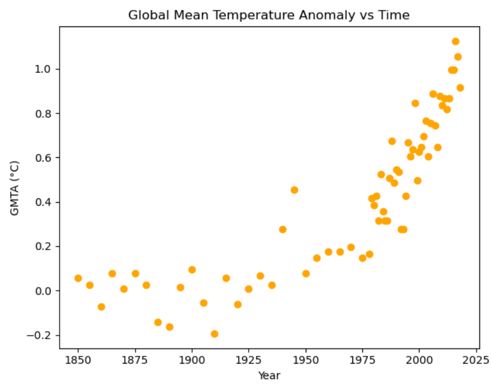
This paper aims to dive deep into the complex relationship between CO_2 levels and global temperature measurements since 1850. Through a comprehensive examination of historical data, I hope to shed light on the correlation between human-induced CO_2 emissions and the changes in temperature. This understanding is pivotal in shaping informed policies and strategies for a sustainable future, especially since views on climate change are based more so on partisanship and ideology rather than data-driven insights [6].

2: Data and a Linear Model

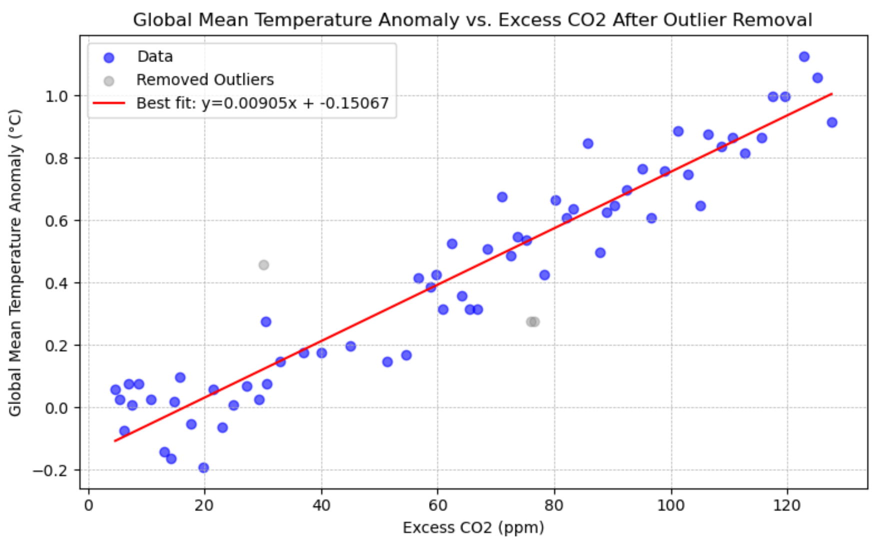
To obtain an understanding of the nuances of climate change, it is necessary to observe exactly how greenhouse gas emissions like CO_2 and global temperature coincide with one another. The course of CO_2 emission growth and the growth in global temperatures from 1850 to 2018 can be seen in **Figure 1** [7, 8].



(a) *ECO_2 Time Series Plot (1850–2018)*



(b) *GMTA Time Series Plot (1850–2018)*



(c) *GMTA vs. ECO_2 Levels from 1850 – 2018*

$$\hat{GMTA} = -0.15067 + (0.00905 \times ECO_2) \quad | \quad R^2 = 0.9202$$

Figure 1: *Overall Behavior of ECO_2 Concentration & GMTA from 1850 – 2018*

As displayed in **Figure 1**, there's an observable trend indicating a synchronous rise in "Excess CO_2" (ECO_2) and the "Global Mean Temperature Anomaly" (GMTA) from 1850 onward. While ECO_2 showcases a relatively consistent upward trajectory in **Figure 1(a)**, the GMTA data points appear more dispersed in **Figure 1(b)**. This variance can be attributed to multiple climatic phenomena. For instance, while ECO_2 plays a significant role in influencing GMTA, other factors, such as periodic El Niño cycles, also leave a mark on global temperatures. These cycles, characterized by fluctuations in sea surface temperatures, can significantly impact weather patterns and consequently, global temperature anomalies.

There appears to be a strong positive correlation between human-induced CO_2 levels in the atmosphere and recorded global temperature levels according to **Figure 1(c)**. The data largely follows the positive linear pattern, but as seen in both **Figure 1(a)** and **Figure 2(b)**, global temperature levels often deviate from the line of best fit but still largely follow the pattern. There are a couple extreme outliers in the plot, however, based on that ought to be eliminated from the dataset to ensure the linear model does not capture much bias.

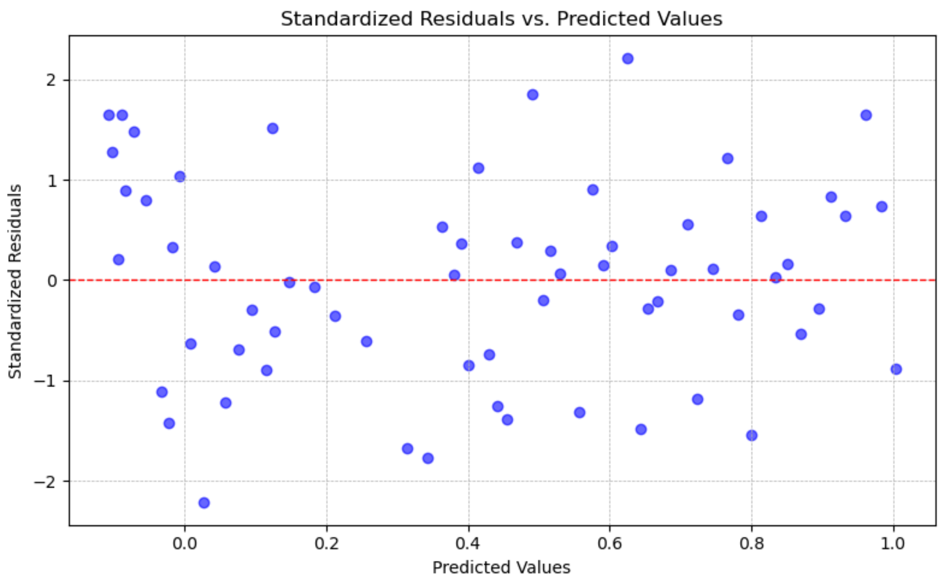


Figure 2: *Residual Plot for Line of Best Fit from Figure 1(c) Predicting GMTA from ECO_2*

In the data, certain years—1945, 1992, and 1993—appear to be anomalies in the overall trend, as seen marked in gray **Figure 1(c)**. During these years, GMTA recorded values of 0.456364, 0.276364, and 0.276364 respectively, while ECO2 registered at 30.10, 75.90, and 76.63. These deviations in 1992 and 1993 can potentially be attributed to the after-effects of the Mt. Pinatubo eruption Mt. Pinatubo eruption, which led to significant global climate disturbances [9]. Similarly, 1945, the year during a severe El Niño effect and when atomic bombs were dropped on Hiroshima and Nagasaki, also shows unusual data points [10]. Global temperature data points are collected every August [8], the same month when both these bombs were dropped. To ensure the accuracy and consistency of our analysis, these points have been excluded from the overall model, as they distract from the analysis.

Examining the residual plot shown in **Figure 2**, we see that the differences between the predicted and actual global temperature anomalies (the residuals) seem to scatter randomly around the center line. This lack of a trend in the residual plot indicates that the linear model in **Figure 1(c)** performing well and closely follows the pattern of the data. If the residuals had shown a clear pattern, it would mean that our model was missing some consistent trend present in the actual data. The high R^2 value of 0.9202 further indicates the strong performance in the model. It tells us that our model, which relates atmospheric CO_2 to global temperatures, can explain about 92% of the changes in global temperatures since 1850. This is quite significant and emphasizes the deep connection between human activities that release CO_2 into the atmosphere and the observed changes in global temperatures over time.

The validation of this linear model paints a disconcerting picture. Many prominent climate scientists have voiced concerns about a world where the global temperature rises by 1.5°C from 1850 levels. The urgency of these concerns was echoed in 2015 when the United Nations made a declaration at the Paris climate negotiations, pledging efforts to curb this alarming trajectory [11]. Ever since then to the year 2018, the increasing trend in excess CO_2 emissions and GMTA has remained largely unchanged. If the existing trend between atmospheric CO_2 and the global temperature anomaly continues, this critical threshold will soon be reached. An atmospheric CO_2 concentration of 182.39 ppm is projected to result in a global mean temperature anomaly of 1.5°C. With the 2018 ECO_2 levels registered at 127.58 ppm, and considering the current CO_2 emissions rate of 2.5 ppm/year, our model suggests that by 2040, we would hit the temperature anomaly of 1.5°C. This timeline brings forth imminent challenges, as surpassing this threshold is believed by many climate scientists to trigger the most severe consequences of global warming.

3: The "Business as Usual" Scenario

The present emissions rate of 2.5 ppm/year is likely not constant from year to year, suggesting that the global temperature anomaly of 1.5°C may even arrive sooner. The rate of emissions has continuously increased from about 1.0 ppm/year in 1965 to about 2.5 in the year 2020. If this increase steadily accelerated over time, the acceleration rate r would equal $\frac{3}{110}$ ppm/year^2, meaning that the climate catastrophe threshold would arrive even sooner than 2040.

However, whether the acceleration rate of emissions is constant remains uncertain. If emissions were to hypothetically increase by 2.5 ppm in the year 2020, by $2.5 \times (1 + \frac{3}{110})$ ppm in the year 2021, and then by $2.5 \times (1 + \frac{3}{110})^2$ ppm in the year 2022, and the ECO_2 emissions at the beginning of 2020 summed up to 134, then, for every year x after 2020, the total ECO_2 emissions could be represented by **Equation 1**. This situation is known as the "Business as Usual" (BAU) scenario, because it assumes that human-induced CO_2 emissions will increase every single year and not diminish whatsoever.

$$(ECO_2)_{year} = 134 \text{ ppm } + (\sum_{x=2021}^{year} 2.5 \times (1 + \frac{3}{110})^{x-2021}) \text{ ppm} \tag{1}$$

Assuming the accelerated increase in atmospheric CO_2 exhibited in **Equation 1** resembled reality, the increase in the global mean temperature anomaly would be exponential, signaling serious concerns amongst climate scientists.

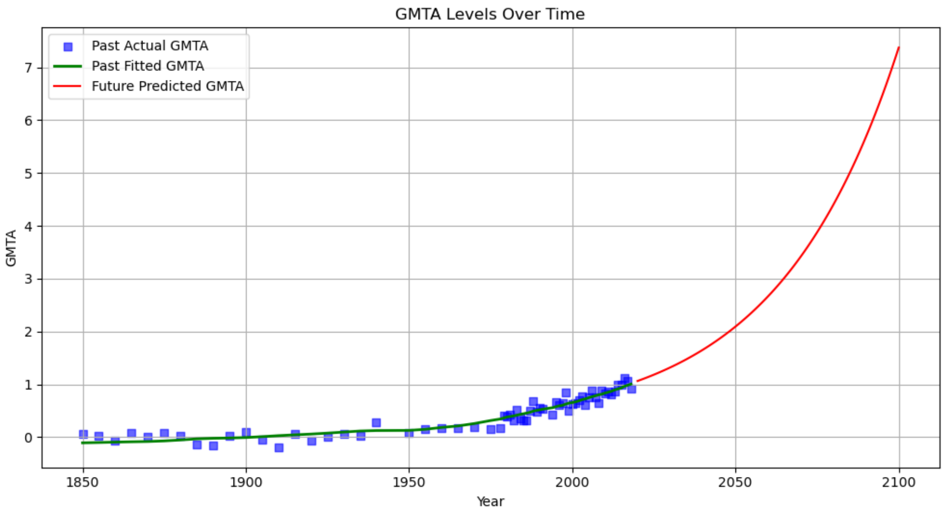


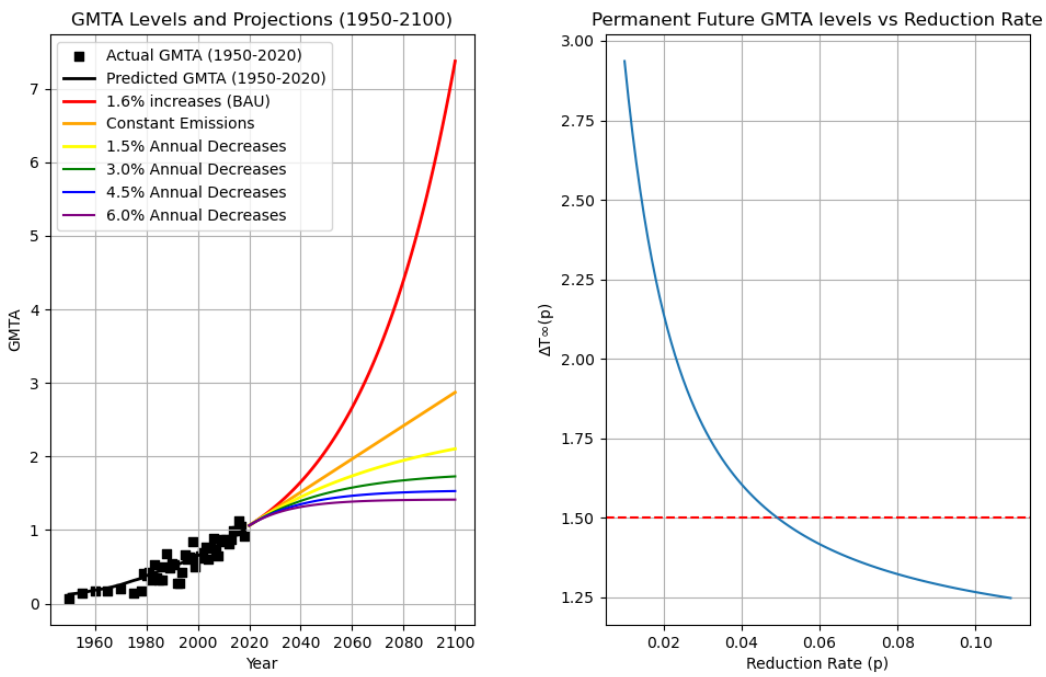
Figure 3: *Time Series of Recorded GMTA Values, Predictions, & Forecasts (1850 – 2100)*

The exponential trajectory of the global mean temperature anomaly, as projected to the year 2100 in **Figure 3**, paints a chilling portrait of our shared future. By the close of this century, we may witness a world transformed in ways that are profoundly disturbing. With GMTA values potentially soaring to around 7.376°C above pre-industrial levels, we would be entering into uncharted climate territory, which is extremely different than the more stable and predictable climate system upon which our modern societies have been built. GMTA, however, is an average value that encompasses the whole globe [12]. The entire globe is 70% ocean, and water does not warm as easily and absorbs heat much more effectively than land, leading to expected temperature increases on land almost doubling the global average. Intuitively in the United States, the perceived impact of temperature anomaly on land by the year 2100 could amount to approximately 26.5°F, which would lead to catastrophic consequences.

Such drastic climatic alterations would likely have severe societal implications. Coastal cities, home to billions worldwide, could become uninhabitable due to rising sea levels and more frequent and severe storm surges. Entire regions of the world may face inevitable droughts, rendering agriculture untenable and leading to widespread famine. Geopolitical tensions could arise to conflicts over resource scarcity. Mass migrations on a scale never before seen could occur as more places become genuinely uninhabitable, leading to potential socio-political crises in areas that are not equipped with the ability to solve these problems. Moreover, intensified heatwaves could make some regions of Earth, especially those already grappling with extreme temperatures near the Equator [13], completely unlivable. The future depicted in **Figure 3** is a daunting vision if the acceleration in ECO_2 emissions increased yearly on such an exponential trajectory every single year. In this situation based on **Equation 1** and the predicted GMTA in **Figure 3**, by 2036 (only 13 years after the publication of this paper), the Earth will have reached a point that climate scientists believe will yield major consequences for our entire civilization, and that increase would only grow every single year.

4: Alternative Scenarios

In the "Business as Usual" (BAU) scenario—as discussed in **Section 3** and proven useful by **Equation 1** and an accelerating increase in CO_2 emissions—we base our assumptions on the fact that there will be no stringent policies to regulate the fossil fuel industry. Hence, human-induced CO_2 emissions will continue to rise annually at an alarming rate. However, these assumptions are based on the assumption that leading carbon emitters such as China, the United States, India, and Russia [14] do not take any strong action to decrease their carbon footprint. If these countries and others were to actively work in curbing their carbon outputs and embarking on a trajectory of annual decreases instead of increases, the cumulative impact on global mean temperature anomalies would be significant, as can be seen in **Figure 4**.



(a) *GMTA Projections from 2020 – 2100* (b) *Future GMTA Levels for p as $t \to \infty$*

Figure 4: Future Trajectories of GMTA Based on Reduction Rate (p) for Near & Distant Future

In examining **Figure 4(a)**, the orange linear progression represented by the constant emissions scenario stands in contrast to the dangerous and alarming exponential increase illustrated by the red BAU model. The yellow curve in **Figure 4(a)** highlights the profound impact even modest annual reductions in CO_2 emissions can have on GMTA trajectories. While the green, blue, and purple curves suggest that deeper cuts in emissions yield diminishing returns in terms of GMTA reductions, they nonetheless showcase the importance of initiating and maintaining a downward CO_2 emission trend. From a climate perspective, altering the current trajectory—even if slightly—can mitigate the severity of future climatic events.

From **Figure 4(b)**, the convergence value of the GMTA, based on different annual CO_2 reduction rates as time progresses towards infinity, is illustrated, and it can be mathematically represented as $\Delta T^{\infty}(p)$—representing "permanent" future levels of GMTA calculated from "permanent" values of ECO_2 concentration, or $\lim_{t\to\infty} \Delta C(t;p) = \Delta C^{\infty}(p)$. The y-axis represents the GMTA, while the x-axis signifies the proportional annual decrease in ECO_2 emissions, assuming that decrease rate is kept constant starting at the year 2020. It's evident that the gains from intensifying the reduction percentage diminish after a point. As a result, nations might need to evaluate the cost-benefit dynamics meticulously, especially if the target is to stay beneath the critical 1.5°C GMTA threshold, which in that case would mean that an overall 5% decrease rate would need to be maintained. This threshold itself poses a significant challenge. However, even the act of steering towards a negative trajectory in CO_2 emissions is crucial. Otherwise, we remain on an exponentially escalating path that could lead to catastrophic climatic repercussions.

5: Conclusion

This paper has shown through a comprehensive analysis of historical data the undeniable correlation between human-induced CO_2 emissions and the rise in global temperatures. The "Business as Usual" scenario, if left unchecked, presents a grave picture of our future, with potential temperature anomalies soaring to levels that are largely considered catastrophic by experts in the scientific community.

However, as highlighted in the alternative scenarios, there is hope. While it is critical to acknowledge the undeniable impact of human activities on the environment, it is equally imperative to realize the potential for positive change. Even minor reductions in CO_2 emissions can have profound impacts on the future trajectory of global temperatures. Major world economies, policy-makers, industries, and communities must come together, acknowledging the scientific data, to make informed decisions and actions that can shape a more sustainable future.

The findings in this paper stress the urgent need for a global response. With polarization and global conflict being so rampant in our society today, it is difficult to envision policy-makers in the United States working with one another to approach this issue. Moreover, it is hard to see the United States working with its enemies, China and Russia, in curbing the BAU exponential trend. Nevertheless, the decisions made in the next decade will determine the fate of countless generations to come. While the data can paint a grim picture, it also shows the pathway to hope. With collective willpower, technological advancements, and policy reforms, humanity can strive towards a sustainable future where the balance between human activities and the planet's health is harmoniously maintained.

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7: Appendix (ChatGPT Usage)

I used ChatGPT on this paper for two separate overarching tasks. For one, I have been using it as a writing assistant tool, in that I will pass in a decently strong paragraph I wrote that needs touch-ups, then send it into ChatGPT to fix up grammar and word flow. This primarily happened in the Intro and Conclusion, but I also used it a little bit in fine-tuning my writing near **Figure 2** to ensure that I explained everything in the context of climate change and didn’t incorporate too much statistical jargon. Also, I aggressively used ChatGPT in my Python code to generate Matplotlib plots that I wanted given my description of the plot I wanted, as well as the stored data that I had generated and ran in and where I have it stored, and I used it for knowing what LaTeX code to use when putting my plots into (a), (b), (c) format.