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Stratospheric Aerosols: Establishing a Novel Optical Thickness Benchmark for Effective Climate Change Mitigation

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Abstract: Global warming has been a problem at the heart of Earth's environmental issues for nearly 5 decades, with the potential to affect a significant portion of the global population. Changes in Earth's climate due to the rise in global temperatures will have an enormous impact on communities around the world, along with a drastic displacement of humans and an extreme loss in natural biodiversity. Current methods of combating this issue have proven to be ineffective, requiring a more comprehensive and innovative approach. This project aims to propose a potential solution to mitigate the effects of global warming and limit temperatures to sustainable levels through the use of stratospheric aerosols. Through a process of data collection, experimentation, and modeling, we were able to correlate the presence of aerosols in the stratosphere to a consequent drop in temperatures and utilize regression prediction to forecast a 16% drop in global temperatures after examining the effects of volcanic ash in the stratosphere. We were also able to compare monthly aerosol concentration levels to declines in the temperature growth, finding a benchmark to stabilize global temperatures. By implementing the changes to Earth's atmosphere, we can reflect heat from the Sun and create a cooling effect for the planet.

Keywords: Aerosols; Stratosphere; Climate Change; Global Warming; Regression

Introduction

In recent years, the urgency for a new method to combat the seemingly inevitable impacts of Climate Change has only increased. Conventional approaches, such as that of reducing carbon emissions and eliminating pollution have been rather ineffective as yearly temperature growth trends show near to no change in overall trends even with extensive attempts to slow down emissions. By utilizing stratospheric aerosols, we propose a new method of limiting climate change through solar dimming. As of now few attempts to implement this research to combat global warming have been tried. The potential impact of this technology makes it imperative to perform experiments to examine the viability of stratospheric aerosols in a tool to sustain temperatures on Earth. Some researchers, such as those at Harvard from the SCoPEx paper by (Dykema et al., 2014) have attempted to perform physical and experimental trials on the subject, but regulation has made this challenging. Therefore, a holistic approach to the solution is needed to determine the effect of the new technology.

Background

Evidence of aerosols and other particle concentrations in the upper atmosphere reducing temperatures has been seen for many centuries, with accounts of major volcanic eruptions dropping temperatures drastically being seen in the 1700s. The Laki Eruption of 1783 in Iceland reportedly dropped temperatures in the Northern Hemisphere by nearly 2 degrees celsius, due to the extreme amount of volcanic ash being shot up into the atmosphere following the catastrophic eruptions. More recently, the eruption of Mount Pinatubo in 1991 was followed by a near 3 year drop in global temperatures. Data from the MERRA-2 data set, distributed from NASA Goddard Earth Science Data and Information Services Center (GES DISC) has shown that following recent major eruptions, a significant amount of aerosols have been deposited in the upper atmosphere, as evidenced by a noticeable global decrease in aerosol optical depth (AOD), a measure of the amount of light lost due to the presence of aerosols. Average monthly AOD readings from 550nm have shown that in the months following a volcanic eruption, a mass of aerosols near the equator seem to cause a drastic decrease in the amount of solar light that reaches the surface of the Earth. The research performed in this paper examines the impact this aerosol concentration has on global temperatures, and proposes guidelines under which it may be possible to stop or limit global warming via reflecting excess sunlight with stratospheric aerosols.

Related Works

As mentioned earlier, due to strict aerospace regulations, it has been rather challenging to perform experiments involving aerosols in the atmosphere. Some groups have attempted to investigate the idea of stratospheric aerosol injection (SAI), a method involving the use of artificial injection of particles into the atmosphere to block sunlight. Examples of this include the paper by (Schmeisser et al., 2017) discusses the properties and characteristics of different aerosol materials that are suitable for SAI, including sulfuric acid and aluminum oxide. Modeling performed by (Ramanathan et al., 2001) also explores the concept of artificial aerosols, by examining the potential impacts of SAI on the global climate using numerical models, including effects on temperature, precipitation patterns, and atmospheric circulation. Research on the feasibility of utilizing stratospheric aerosols to combat climate change has been brief however, with much focus being put on the potential costs and resources necessary to perform a real world implementation of the idea, as done in the paper by (Moriyama et al., 2017), assessing the potential cost of implementing SAI and discussing the trade-offs between cost and value. My paper builds off of previous research on the topic and provides a novel way of analyzing the efficacy of stratospheric aerosols by using satellite data to develop and examine the global impacts of the technology.

Volcanoes and Solar Dimming

NASA's MERRA-2 Dataset reveals that major volcanic eruptions release significant amounts of aerosols into the stratosphere. This results in a decrease in aerosol optical depth near the equator for several months following the eruption. While not all volcanic eruptions affect measurements, those that release aerosols into the stratosphere above the 10-mile layer have consistently resulted in a decrease in global temperatures for several years. This correlation can be attributed to solar dimming, where the aerosols in the stratosphere create a reflective layer that scatters sunlight back into space, reducing the amount of sunlight that reaches the Earth's surface and causing cooling effects. Analysis of historical data on light-chemical interactions in the upper atmosphere suggest that the presence of obstructive compounds emitted from volcanic events like ash and dust greatly decrease surface levels of light radiation due to the absorption and reflection of light waves by the chemicals.

Examination of components of stratospheric emissions from volcanic eruptions shows that sulfates and oxides make up a majority of the released compounds, unsurprisingly chemicals that are responsible for the highest levels of light extinction in the stratosphere. The single compound sulfur dioxide for instance makes up about 70% of volcanic aerosols while eliminating between 60% and 80% of incoming light radiation.

Table 1. Components of Volcanic Aerosols by % of Total UV Reduction Caused by Respective Chemical.

Data from (Haywood et al., 2010), (Robock et al., 2000).

Volcanic Aerosol Composition	
Component	**% of UV Reduction**
SO2	70%
H2O	10-20%
CO2	5-10%
HCl	5%
HF	<1%

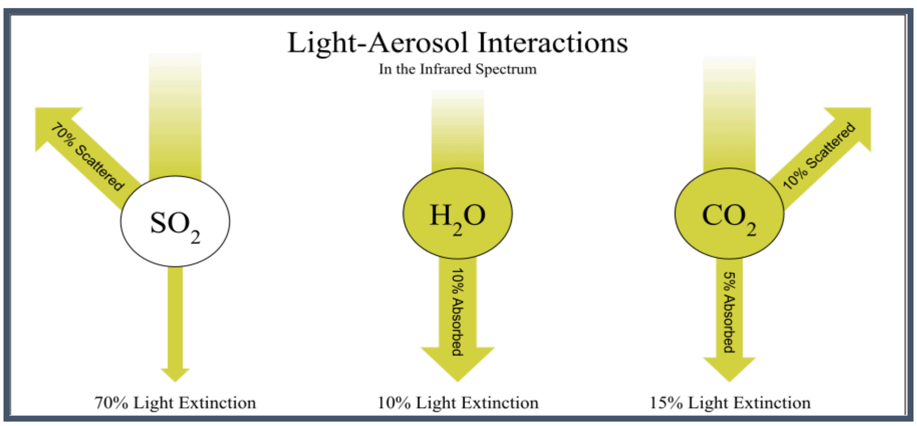

Figure 1. SO2, H2O, CO2 and Their Respective Light Extinction Percentages.

Data from (Madronich et al., 1998), (Forster et al., 2007).

Consistent drops in global temperature following major volcanic eruptions such as those of El Chicon and Mt Pinatubo in 1982 and 1991 which deposited thousands of kilotons of aerosols into the stratosphere show how the natural process of solar dimming caused by stratospheric aerosols is promising for a solution to climate change. While it is challenging to determine the exact cause of the drops in warming due to other sources of change such as decreases in carbon emissions, in the years following major volcanic eruptions, there has consistently been a decrease in temperatures, suggesting that reductions in temperatures caused by solar dimming may be a factor in the change.

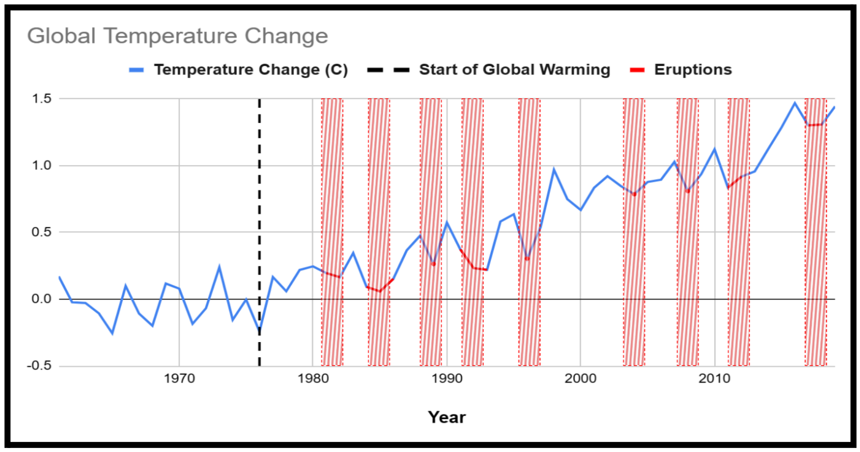

Figure 2. Graph of Global Temperatures per Year, Highlighting Years Following Major Eruptions.

Volcanic Activity on Temperatures

Yearly data on temperature change is publicly made available by the United Nations Food and Agriculture Organization. By using machine learning regression techniques, we can forecast the temperature on Earth in different scenarios. The following graph displays current data and forecasted levels of global warming by 2030 for different situations of climate mitigation. The blue line demonstrates the current growth level of temperatures, with a predicted temperature level in 2030 of 1.674 C, as shown in the bar chart on the side. RCP4.5 is the US governments more up to date strategy to combat global warming, focusing mainly on reducing carbon emissions and migrating to renewable sources of energy. An alternative solution however, is present when considering temperature changes displayed by volcanic eruptions. By using modeling techniques, we can impute missing data between major eruptions, and forecast the temperature in 2030 of 1.411 C. This projected level of warming is not only below the Paris Agreement threshold to limit climate change as displayed by the bar chart, but represents a significant 16% drop in warming. This standard modeling highlights the need to evaluate stratospheric aerosol methods in the fight against climate change.

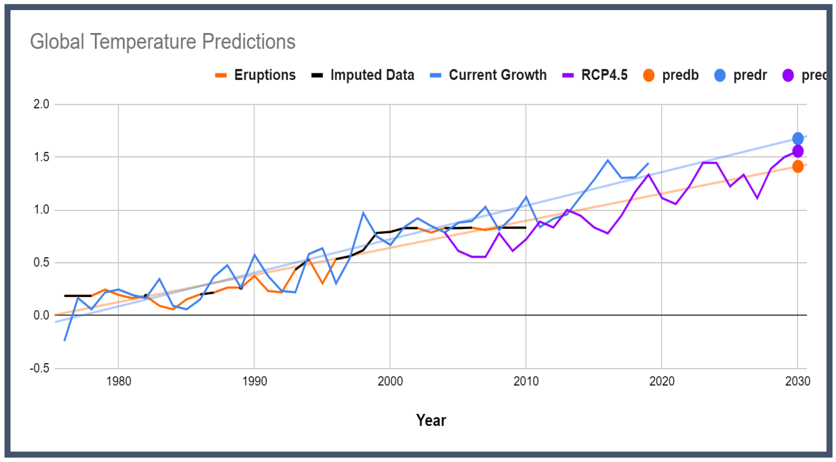

Figure 3. Graph of Current Methods of Combating Global Warming and Calculated Eruptions Forecast.

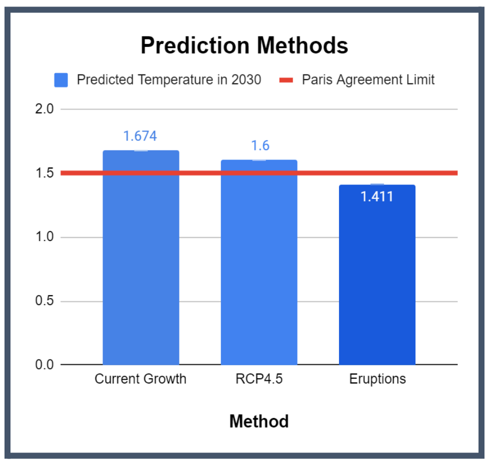

Figure 4. Table of Figure 3 Forecasts in 2030 and Paris Agreement Threshold.

Aerosol Optical Depth Limit

The Global Aerosol Climatology Project (GACP) from Goddard Institute for Space Studies releases data on stratospheric aerosol concentration levels from 1983 to 2009. Extracting and displaying the data from 1983 to 1997 shows monthly concentrations of aerosols in the oceans around the world in years in which the stratospheric aerosol concentration varied heavily. This gives us a decent size of N=185 samples of data to analyze and draw conclusions from.

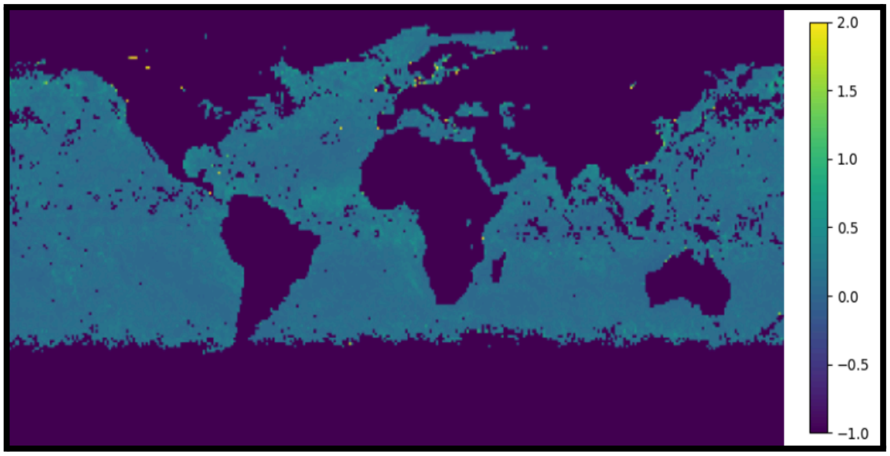

Figure 5. Global Aerosol Optical Depth Map from GACP, May 1995 (Negative Values Represent Null Data).

By averaging out all of the 1x1 grid boxes of data per month, we can get a measurement of the mean level of global aerosol optical depth every month. Comparing this data with the monthly changes in global temperature from the Food and Agriculture Organization allows us to recognize a clear relationship between fluctuations in global average AOD and drops in temperatures. The following graph displays this relationship between the features, with AOD scaled by a factor of 3 to highlight subtle changes.

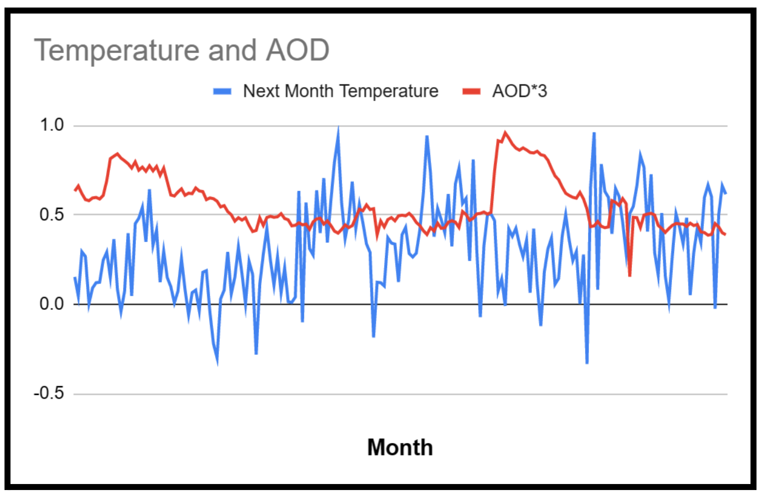

Figure 6. AOD Monthly Measurements and Next Month Temperatures.

There is an evident relationship between higher values of the AOD measurement and decreases in temperatures. As the measurement represents the amount of light scattered due to the presence of aerosols, with a value of 0 representing no light lost and larger values representing more light lost due to solar dimming from stratospheric particles, it is clear that there is a connection. Quantifying this relationship allows us to more numerically define a value at which there is a significant amount of global warming drop from the reflection of sun rays due to the aerosols. To do this, we utilize a 20 month running maximum value for the global warming measurement to have a benchmark of the highest temperatures for the time period. To most effectively capture the light extinction of the aerosols, we also offset the actual global temperatures by 20 months. A 2017 paper from (Yu et al., 2017) states that particles in the stratosphere from wildfires were seen nearly 8 months after the initial presence of the aerosols. Other estimates suggest that the amount of time aerosols are in the stratosphere varies from 8 months to 2 years. To stay consistent with prior research and my own rough benchmarks, a 20 months offset seemed accurate. Calculating the difference between each of the monthly temperatures and the running 20 month max allowed me to numerically represent the change in temperatures from an estimate of the potential temperature during the rough time period.

This process quantifies monthly stratospheric aerosol thickness readings and the future impact each month's worth of aerosols on the global temperature from the approximate potential temperature during the time period. These values could be used to find the aerosol thicknesses at which there was an evident drop in warming caused by dimming. By averaging the corresponding aerosol levels for the samples in which there was a negative temperature change, or a drop in surface temperatures from the rough potential maximum, resulted in a projected level of 0.185. This value represents the average thickness of the aerosol concentration in the stratosphere over all of the Earth at which there is typically a drop in global temperatures.

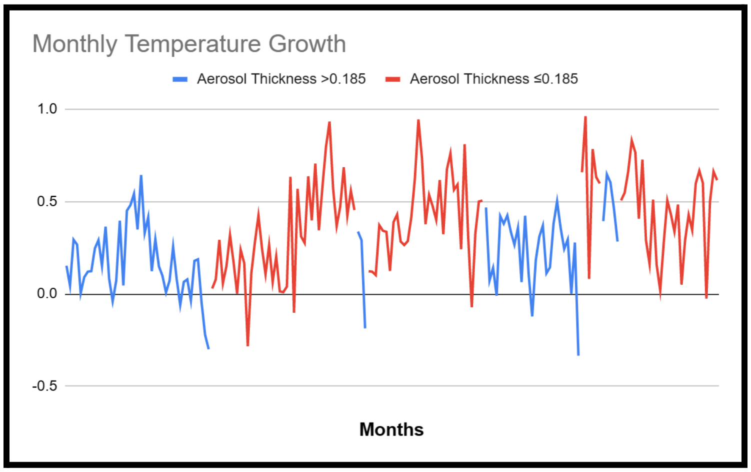

Figure 7. Graph Displaying Monthly Temperatures, Highlighting Years In Which Aerosol Thickness is Over 0.185

The graph above displays the relationship, showing how in times when stratospheric aerosol concentration is above 0.185, there is decline in temperatures. The 4 prominent blue sections on the figure all commonly display a decreased final temperature from the initial level of warming, in accordance with the conclusions of my research. We can quantify the magnitude of these drops by also averaging the drops in temperatures in months during which the aerosol thickness was over 0.185. The resultant value of 0.279 C suggests that when the thickness of the aerosol layer in the atmosphere is above 0.185, there is, on average, a drop in global temperatures by 0.279 C.

Conclusions and Future Work

This research highlights the importance of utilizing aerosols to combat climate change, citing the impacts and numerical drop in global temperatures following major volcanic eruptions. We also propose a novel aerosol thickness benchmark which sets a minimum level at which aerosols must be present in the stratosphere to significantly limit global warming.

By using linear regression techniques, we forecast the magnitude of global warming in the year 2030 both with and without the presence of volcanic aerosols. Analysis on data on the general growth of warming resulted in a forecasted temperature increase of 2.542 C, a level deemed unsustainable by volumes of research and the Paris Agreement. Imputing fragments of data relating to the temperatures of the Earth following major volcanic eruptions however led to a forecasted global warming of only 1.3872 C, a 45% drop in predicted temperature in 2030, and a level of temperature that would allow for the sustenance of the planet. This analysis evidenced the hypothesis that increased levels of aerosols in the stratosphere would be a factor in the decrease of global temperatures.

To quantify this relationship, we compared monthly aerosol thickness values to a rough calculation of the approximate difference in temperatures 8 months after with their respective potential maximum temperature, numerically representing the change in global temperatures caused by each of the monthly aerosol thickness measurements. Averaging the features of the new data showed that typically, a drop in global temperatures was present after a month in which the aerosol thickness exceeded 0.185. Further analysis showed that months in which the aerosol optical thickness was over 0.185 displayed a strong downward trend in global temperatures. By averaging the temperatures in the months succeeding periods of elevated aerosol thickness measurements,we conclude that by keeping aerosol optical thickness over 0.185, the global temperature would typically decrease by 0.279 C.

To further improve on this work,we plan to perform and collect data on my own experiment involving stratospheric aerosols, potentially allowing me to analyze the impacts my proposals have in the real world, rather than on historical data. We also hope to do future research in order to fully understand the implications and impacts of using aerosols as a tool to combat climate change, as it is crucial to understand the effects of short-term impacts, such as changes in temperature, precipitation, and atmospheric circulation, as well as longer-term impacts, such as changes in ocean currents and sea-level rise. While research on stratospheric aerosols is still relatively new and more work must be done to understand the impacts of such an approach, the results of the research presented in this paper are promising and suggest that this is a field with great potential for future work and advancement.

In conclusion, the improvements in potential global temperature analyzed through this project due to the presence of volcanic stratospheric aerosols show that this approach to combating global warming can have a significant impact in ongoing efforts to limit climate change. Additionally, by following proposals researched in my project pertaining to a minimum threshold of global average stratospheric aerosol thickness, it is possible to mitigate many of the effects of climate change, and potentially even reverse global warming. Therefore, the research presented in this paper underscores the critical importance of stratospheric aerosols in mitigating the effects of climate change and safeguarding the future of our planet.

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