Are We All Doomed? A Model of Climate Change

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***Abstract*—**As a team, we were able to create a radiative forcing model of global temperature and how it changed with various factors such as land use changes and greenhouse gases. This was achieved by using equations from the most recent IPCC report and other sources, and we used historical data to see if our model would accurately predict the change in temperature for the earth from 1880 to 2020 to make sure our model was valid. By extrapolating trends in the concentration of greenhouse gases since 1960, we were able to predict future temperatures of the planet.

We concluded that if we were to carry on emitting at current trends and no action was taken to reduce our impact on the climate, then temperatures would rise by 1.78 above the 14°C temperature anomaly used. Current theory suggests this would lead to severe consequences for both natural ecosystems and human populations in places with extreme weather and temperatures.

We also simulated two other scenarios, one where we limit our emissions starting from today and another where we started limiting our emissions back in 1990. The conclusions that we were able to draw from these is that in both cases, temperatures would remain below the levels that would cause the most dramatic consequences. In addition, we realised that if we started taking actions in 1990, the temperature in 50 years would probably be lower than it is today. We also made a projection which included predicting random volcanic eruptions into the future to observe the consequences that these have on global warming.

I. Background

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Global warming is one of the most pressing issues facing the planet today; global temperatures are rising at unprecedented rates. More than ever, there is great interest in quantifying how much the planet will warm this century and what the impacts will be. The idea for this project was first suggest by LB, which was unanimously approved for its relevance and feasibility for the scope of a one term project. The initial goals were:

- Understand the underlying theory for atmospheric driven warming of the planet and identify the most important factors for global warming.
- Create a simple computational model for global warming and add complexity as we go along. Then use this to predict the temperature rise. Support these models with data for greenhouse gases and other atmospheric componentents, provided by institutions such as NASA.
- As climate science is an incredibly complex field, with some researchers dedicating their entire careers to making climate models as accurate as possible, we also needed to be realistic in how accurate our projections could expect to be, but hoped that our predictions were realistic and reasonably close to current projections.

Further goals included:

- Investigating how different temperature rises would impact the climate in areas such as extreme weather events and
ocean level rises.
- Perhaps creating our own model for how ice sheets would melt as temperatures increase and the consequences on sea level rises. Factoring feedback effects may also be achievable.
- Considering how much we can change the course of the climate by limiting emission and to what extent action needs to taken such that we can avoid extreme and permanent consequences.
- Calculate how strongly we would need to cut emissions to hit targets such as the Paris Agreement and prevent specific negative impacts from occurring.

After meeting with our first meeting with our supervisor, the best approach seemed to be a radiative forcing model.

A.Project start-up

Our project began with our first meeting on the 2nd of May, with discussion of our formal title and our starting points to start working on our project. In this meeting, the majority of the goals outlined above were decided. We then had our first meeting with our supervisor on the 11th of May 2021. As no one in our team had much knowledge on the topic of atmospheric physics, our supervisor recommended us the book 'An Introduction to Atmospheric Physics' by David G Andrews, which was available through the Imperial College Library. We each read chapters 1, 3 and 8 of this book prior to our next meeting, which gave us a good foundation of knowledge to develop our models form. TC then created a very simple model based on the transmittance of CO_2, which produced very inaccurate values. This initial model led to using a radiative forcing model going forwards.

Our supervisor recommended we start off our model without an atmosphere, using a simple equilibrium equation between energy input from the Sun and energy output via black-body radiation from the Earth. We then used the IPCC report to find relevant equations that gave the radiative forcing of greenhouse gases as a function of their concentration in the atmosphere. Due to the large volume of data we would be required to incorporate, this needed to be a computational project. We decided to use Python to develop our models as we all had experience with this thanks to our First Term computing course.

Since we were collaborating on many complex files, a GitHub repository was set up to improve our workflow. We continued to meet with our supervisor for one hour a week, and have a separate team-only meeting for 1-2 hours a week. We set up a shared OneNote where LE wrote up minutes for each meeting. This helped every Team Member to stay on top of any actionable items, and allowed us to easily retrace our steps and ideas. Finally, we set up a WhatsApp group chat to enable easy communication on all project-related matters.

B.Development of the model

Essentially, the model comprises two factors that affect the temperature of the earth: the heat capacity of the earth, and the effective net increase in energy coming into the planet. For the heat capacity of the earth, we took it to be 70% water by surface area and land to be the remaining amount. We then took the depth of soil heated to be 1.6m and 70m depth for water – this is because the ability of water to move around in currents allow much more of it to be heated. By then taking estimates for the surface of the earth, we were able to come up with an estimate for the heat capacity of the earth. This was done by LB.

Then we had to factor in how the net energy of the planet changed over time. Using the initial temperature in 1880 provided by NASA and assuming that to be the equilibrium temperature – which is not a bad assumption given that human activity had little impact on the climate before then – TC calculated the increase in radiative forcing due to CO_2, N_2O, and CH_4 using equations from the IPCC report.

The NASA data was then all compiled in a csv file by LE. Since the data came from a range of projects (some data was drawn from an amalgamation of more than 30 data-gathering projects), LE used Python to calculate a mean value for each relevant gas or forcing for each year between 1880 and 2020. In calculating these means, LE used interpolation to fill in any missing values, and took an average when more than one value was supplied for a certain year. LB then used these values and their associated radiative forcing functions (where applicable) to find the expected temperature from 1880 to 2020. LB found that the calculated temperature change followed a very similar trajectory to the real temperature anomaly data provided by NASA. However, our predictions were slightly higher at all parts of the curve.

C.Using further factors and projections

Although these 3 greenhouse gases we initially considered are responsible for most of the greenhouse effect, we wanted to improve our model so that it would more closely resemble the temperature change from 1880 to present. We then decided to consider other factors which affect the climate such as changes in CFCs, Ozone, solar radiation, land use changes, snow albedo, aerosols, sulphates and the effect of volcanoes. A similar process was used to find data on how these changed the amount of net energy into the atmosphere.

Several issues arose here, particularly with volcanos – upon gathering a large amount of data summarising volcanic sulphate emissions between 1880 and 2020, LE found that the exact impact these have on global temperature is still not completely understood. The Intergovernmental Panel on Climate Change stated that further scientific development was required to develop a radiative forcing expression for sulphates. We decided that we were unlikely to accomplish in one term what many dedicated scientists had not yet achieved in multiple years, so looked for another way to incorporate the temperature impact of volcanic emissions. LE found a dataset giving the annual forcing of different categories of sulphate aerosols – this closely mimicked the volcanic behaviour we were attempting to model, so we incorporated this into our model to represent the impact of volcanoes on climate.

This sulphate aerosol data did however have a large uncertainty, which we represented in several of our final output graphs. As the factors we were incorporating became more complex, their uncertainties naturally also increased. This overall increase in the uncertainty of our model was however mitigated by the relatively small changes that including factors like land use change and sulphate aerosols had on our overall results. So, although the uncertainty in their direct temperature effect is large, the temperature effect itself is very small. Therefore, these factors didn't make our model any less valid. Working on the time and spatial scales of the entire planet's climate also means that uncertainty will inevitably be rather high. Due to this we focused more on agreement with past data than statistical uncertainty when deciding to add a new impact to out model.

Having gathered the relevant data, we combined the aforementioned effects into our model. Radiative forcings tend to sum linearly, so we were able to simply keep adding in more factors as we found them. Once these effects were considered, the overall radiative forcing decreased slightly, and the result was roughly concordant with NASA's value for the temperature rise from 1880-2020.

Now that we were satisfied with the accuracy of the model up to the present, we needed to find a way to use it to predict the temperature rise for the future. NR created functions capable of both linear and exponential projections; in the end no other kinds of projection were necessary, as these curves produced close fits for all the gases whose concentrations were projected. This was all achieved with the curve_fit function from the scipy.optimize library; using historic data for CO2, NO2, CH_4, CFC-11 and CFC-12 since 1960 and fit an exponential curve, as appropriate, to them, which was then extrapolated from 2020 to 2070 (CFC-12 was however a linear fit as this fit the data much better). This was used for our "business as usual" projection, which assumed that we would take no further action to limit our impact on the climate i.e. All gases would carry on at their current trajectory.

For the volcanic projections, LE used several volcanic peaks from the stratospheric aerosol data to generate similar, randomly produced peaks, which were then inserted into the 2020-2070 period. To generate this random data, LE selected 5 clear sections of volcanic behaviour, numbered these from one to five and used a random number generator to decide the order in which they were inserted into the model. LE initially attempted to create a function that generated completely random volcanic peaks at random time intervals, but due to the complexity involved here we were uncertain if this function would give anything approximating real-world behaviour. We decided that since human behaviour has a negligible impact on the frequency and severity of volcanic eruptions, it would be valid to simply randomise some past data and project this into the future.

Then we went about investigating two further "what-if" scenarios: the first set attainable goals for carbon dioxide, methane and nitrous oxide by 2070 (the goal for CO2 was based on an IPCC statement) and assumed that we would be 'neutral' with regard to all of these gases once that target was reached. To achieve this, a 'target function' was developed by NR, which was capable of projecting real data up to a specific target concentration and year, with the curve flattening at this point. The function produced approximately linear increases, flattening in the manner of an exponential decay as the target year was approached. The second was done using a very similar method, but the target function started from 1990 instead of 2020, essentially giving us more time to go carbon neutral.

D. Pursuing extended goals and finalising results

During the final month of the project, we changed our meeting schedule to two weekly half hour meetings with our supervisor, instead of an hour once a week. We began meeting in person in Blackett Lecture Theatre 3, and after our half-hour discussion and review with our supervisor we would have a team meeting ranging from 1 to 4 hours depending on the amount of collaboration required to complete our work. We met for 5 hours on the 20th of June to collate all of our work into a video script and PowerPoint, and then for 3 hours on the 21st to film and edit this material.

In total, we completed 16 meetings over the course of our project, with a combined duration of more than 40 hours. We made use of an enormous amount of data, as reflected by our bibliography. After having incorporated the most significant factors (e.g Greenhouse gases, volcanic eruptions and aerosol emissions), we found that adding increased complexity had very little effect on our overall results, since many of the minor effects end up cancelling each other out. Despite this, we attempted to account for as many influences as possible for completions sake.

Due to the computational nature of our project, we experienced a lot of trial and error, encountering several factors that we were unable to incorporate despite our best efforts. For example, we were not able to create models of sea level rises as the temperature of the earth increases. There was limited data available on how to incorporate this directly via a radiative forcing. Sea level rise seems to generally be incorporated into highly advanced General Circulation Climate Models rather than Radiative Forcing models, which require time and computational power far beyond our means.

However, our results coincided with a temperature rise of around 2 degrees of warming for a business-as-usual scenario and 1.5 degrees of warming for a reduced emissions scenario. These results and scenarios are of particular interest as the Paris agreement was made to ensure that warming stays around 1.5 degrees. It is also widely acknowledged in the scientific community that 2 degrees would be catastrophic. We could easily find information on the impact of both models on extreme weather patterns, sea level rises, and much more as NASA makes the information public for free. However, this went beyond the scope of our project as our focus was on modelling and predicting the actual temperature increase rather than cataloguing all its potential impacts.

E.Equipment used and purchased

As this project was entirely computational, we did not need to purchase any equipment to complete this project. The only equipment we used is our personal laptops, books, online resources via our Imperial OpenAccess accounts, and python. We also used the facilities from lecture theatre 3 in Blackett to record our video.

II.Summary of Results

The aim of our project was to come up with a figure for global temperature rise in 50 years' time, that is, in 2070. This has been achieved and we can therefore consider our project successful. We ended up doing 4 projections for the future, using 4 different scenarios with different consequences to answer our initial question of 'How doomed are we?'.

From our first projection, where we decided to model the changes in greenhouse gases concentration in the atmosphere by following the trends over the past 60 years, i.e., a projection assuming humanity makes no attempt to slow down the warming, we were able to come up with the conclusion that in 50 years' time, we would reach a tipping point for the Earth's climate that would have disastrous consequences for the future. On the other hand, our optimistic projection, where we reach the targets set by the Paris agreement, and therefore remain below the limit of 1.5° warming above pre-industrial level gives us more hope for the future. The third projection, where we projected what would have happened if we started to act in 1990, shows us that the temperature increases by 2070 would be lower than the temperature already is today. We made our fourth projection, where we projected random volcanoes, to show the uncertainty that random effects such as eruptions can have on the data. We were however able to conclude that these were only short terms effect, at least for volcanoes, and that the effect on the overall trend was unsignificant.

III. Conclusion

The initial goals of the project were met, and we were able to come up with sensible projections which were within reasonable agreement with not only historical data, but more advanced models that governments and international organisations use to predict how the planet will warm. Given the relatively limited scope for this project it was quite successful, however there were limitations for the model.

Many factors that we considered are very difficult to project, as the trends are unclear and the uncertainty high, such as snow albedo, land use changes and aerosols, so we projected most of these as remaining constant, because that is what the trends seemed to show. However, we have reason to believe that our projections for the most important factors are reliable, and therefore we are confident in the validity of our model. If we had had more time, we would have investigated this further and have tried creating a basic model for sea level rises and ice caps melting. From our research, we can conclude that the levels of warming that we expect to see in the future would lead to more devastating consequences and that by limiting emissions, we can minimise damage done to ecosystems and humanity.

IV. Bibliography

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