Forecasting the climate’s response to anthropogenic greenhouse emissions using a simple 1D energy balance model

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*We attempt to create a simplified 1D energy balance model of Earth’s climate that accounts for the anthropogenic emissions of greenhouse gasses and the effect that they have, and will have, on the planet; we validate the model using the past 200 years of climate data and forecast the climate’s state into the future, under various greenhouse gas emission pathways as described by the IPCC.*

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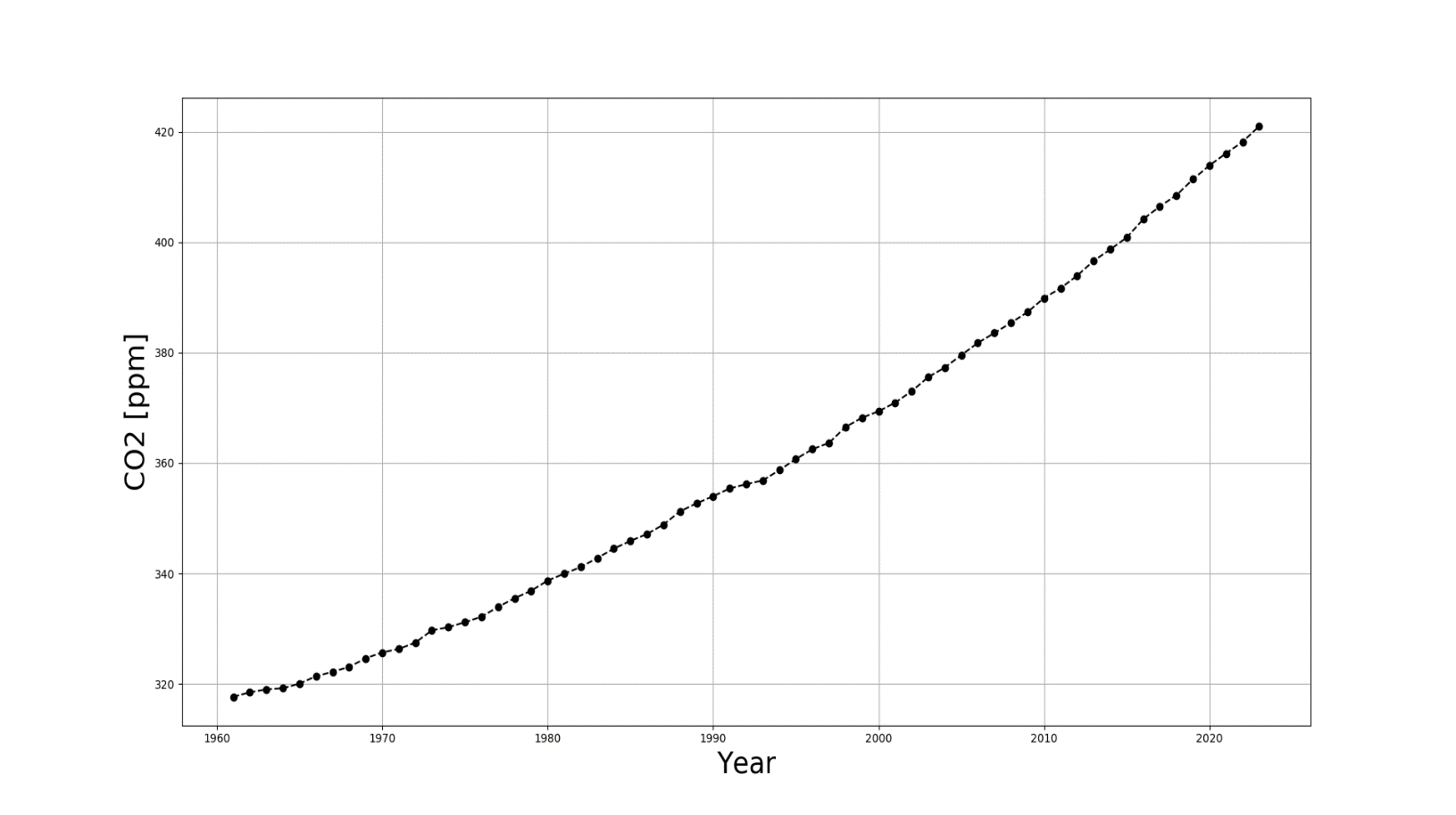
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**Motivation**

In the last 250 years our species has been subject to various technological transformations; the most relevant being the industrial and digital revolutions.

The 18th century ushered in the industrial revolution, where industry and machine manufacturing dominated the British landscape. It was during this era that coal was heavily utilised as a fuel source, burning it enabled us to power the production machinery that populated the factories, as well as the piston engines that allowed transportation of goods and people across the globe. More recently, we have seen the mass proliferation of electricity within our society; it is utilised everywhere from operating power plants to controlling the appliances within our homes.

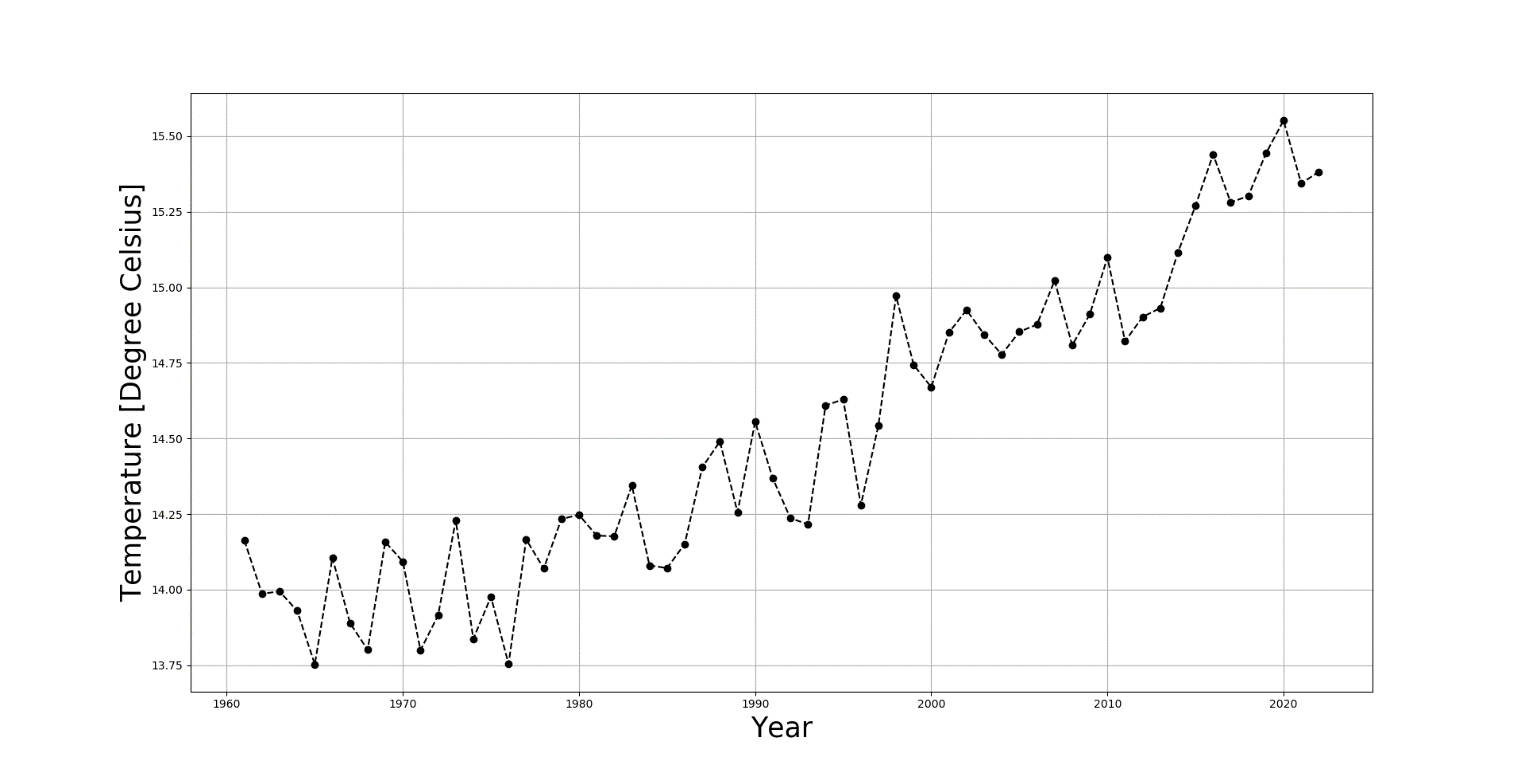
The figure below shows how the recent burning of fuel since the late 1900s has increased the levels of carbon dioxide that is present within our atmosphere.



*Figure 1 A plot of CO2 concentration (ppm) within Earth’s atmosphere, from 1961-2023. Dataset sourced from the Scripps CO2 program*

We know now that carbon dioxide has an insulting effect on the plant’s climate[10]; that is to say that it increases the likelihood that radiation will be reflected back towards the plant’s surface, instead of escaping into outer space. Therefore, the consequence of a high carbon dioxide concentration within the atmosphere, is an increase in global average temperature due to the increase in trapped radiation from the sun.

The figure below shows recent observations of the global average temperature, where we can see that the data is consistent with what we would expect, given the recent increase in atmospheric CO2 concentrations.



*Figure 2: A plot of the absolute global average temperature (degrees Celsius) from 1960-2023.*

An increase in frequency of more severe weather events; melting of the polar ice caps, submerged land masses, and possible extinction of plants and animal species, are all likely repercussions of a warmer global climate.

Looking ahead, we can safely say that the demand for energy isn’t slowing down; in-fact it will only increase. Developing nations are constantly increasing their energy consumption as they catch up to the more developed; our current digital infrastructure that enables the internet and other digital services to function will require more investment and energy over the coming years due to increasing usage; and the cutting-edge technologies of today such as artificial intelligence and electric vehicles will ensure that the demand for energy will only continue to increase.

The rate at which we wean ourselves off of these types of fuels will determine to what degree our planet will heat up over the coming decades, and therefore to what degree we will suffer the consequences of polluting the atmosphere with greenhouse gasses for all these years.

**Context**

The 2003 paper by Johns et al [6], applied the HadCM3 climate model presented in the prior work by C. Gordon et al in 1999 [7], to model the climate response from 1860 until the present day, due to anthropogenic greenhouse emissions; the paper then attempts to predict the climate’s response through to the year 2100, based on the SRES emission scenarios that have been developed by the IPCC [5].

Their analysis found that the A1FI emission scenario saw the highest increase in surface temperature in the year 2100, of 5.3x the global average temperature of the period 1880-1920. Meanwhile the B1 emission scenario saw the lowest increase in global average temperature of 2.5x.

Furthermore, their analysis found that, relative to the sea level during 1900, the oceans would rise by 34cm and 21cm for the A1FI and B1 emission pathways, respectively.

Additionally, they found that the average sea temperature for the A1F1 emission scenario was again the highest out of all of the emission models, seeing a 4.25x increase in temperature during the year 2100, relative to the base period; whereas the B1 emission model only saw a 2.1x increase in average sea temperatures.

The Intergovernmental Panel on Climate Change (IPCC) report, published in 2023, performed an extensive analysis on the effects on the climate and life of the planet, for various global average temperature increases. [4]

Their analysis found that for a warming of the climate by 1.5°, the hottest-day of the year would see an increase in around 1-2°; whereas for a warming of 4° in the climate, they found that the hottest-day of the year would see an increase in temperature of around 8°.

The IPCC’s analysis found that the agricultural industry will be greatly affected by a warming climate, yielding less food to feed our growing population.

Specifically, they found that for a warming of ~1.5° there would be around a 3% decrease a crop yield across large swathes of the globe; the yield from fisheries is also expected to decrease within region within or nearby the equator, with regions the least affected seeing around a 3% decrease in yield, and those most affected seeing around a 30% decrease in fishing yields; other regions of the globe, mainly around the north pole, could be expected to see a slight or modest increase in yield in the range of 3-35%.

For a global warming of 4°, the IPCC found that crop yield would decrease more significantly, around the 20% mark, and fishing yields would be expected to fall by more than 35% across the majority of the equatorial regions of the globe, with the north pole regions potentially seeing a similar 30-35% increase in fishing yields.

Furthermore, the analysis included the number of days per year that would experience levels of temperature and humidity that would be considered a danger to human life. A warming of 2° would see large parts of southern America , northern Africa and southern Asia experience a handful of these life-threatening days per year, with regions south of China experiencing large proportions of the year at these dangerous temperature and humidity levels. A global warming of 4° would see regions concentrated around the equator, experience large portions of the year at these dangerous temperature and humidity levels.

From the paper by Johns et al, a future in which we continue to heavily rely on fossil fuels (A1FI) for a source of energy will result in the highest possible increase in global average temperature, global average sea temperature, and global sea level rise; alternatively, a future in which we prioritise the introduction of clean and resource efficient technologies (B1) will see the smallest increase in these climate metrics, and is therefore the future that we should aim towards in order to minimise the damage on both the planet and ourselves. [5]

Due to the relatively small timeframes that we see and expect these changes in global average temperature to occur, wildlife cannot simply adapt fast enough. The IPCC report shows that with only a 1.5° warming in the climate, large regions of the planet will experience land temperatures unsafe for over 30,000 various species of animals and seagrasses; with the severity of this risk drastically increasing to around 100% across the equatorial regions for a warming of 4°.

The aim of this research project is to develop a simplified computational model that can approximately reproduce the last several hundred years of recorded climate data, and then forecast the climate’s behaviour into the near future, for various plausible emission pathways laid out by the IPCC.

**Background Theory**

Within this research we use a one-dimensional energy balance model; such a model provides granularity along the planet’s latitudinal axis, and so we can inspect how the climate responds to various forcings in various parts of the globe.

A 1D EBM governs the climate’s latitudinal temperature profile via the following partial differential equation

where is the temperature of the band at latitude at time . [1]

The value of represents the amount of solar radiation that reaches the planet per unit time, and the value of represents the planet’s albedo, which is the fraction of incoming radiation that is reflected back into outer space. Thus the term that appears in the differential equation, gives the amount of solar radiation that is absorbed by the planet’s climate system.

The term involving first and second order spatial derivatives of the planet’s temperature profile, in conjunction with the diffusivity constant (, attempts to model the complex effects of thermal transport within the atmosphere that occur via convection within Hadley cells and other thermal energy transportation mechanisms.

Earth is seen to behave as an approximate blackbody emitter, and thus emits radiation in various wavelengths; the term, named the IR-Cooling function, models how much radiation in each part of the electromagnetic spectrum Earth emits out into space.

Combing these terms into the differential equation above, with the heat capacity , provides a way to calculate what the temporal rate of change will be in the temperature of a specific latitude band.

In order to compute a value for in the differential equation, we must first find the Earth-Sun distance, . We approximate the true anomaly of the elliptical Earth-Sun orbit, at some time , by using a series expansion that is valid for eccentricities less than the Laplace limit, of 0.6627 [3]; as is true for the Earth-Sun orbit with eccentricity is 0. 01671[8]. We then apply the definition of an ellipse to obtain the distance between the Earth and Sun, at some time .

The value we take as is in-fact the diurnally (day) averaged solar radiation that hits Earth, given by applying the inverse square law to the emitted radiation from the sun, and then calculating the average amount of solar radiation that hits Earth over the course of a day.

The albedo term, represented by , tells us how much solar radiation is reflected back into outer space. The prescription for our albedo model was model-2 from Spiegel et al[2]*.* For temperatures below 263K, the albedo is taken to be 0.7, in order to signify the high reflectivity of snow and ice that forms at these lower temperatures. For temperatures above 273K, the albedo is taken to be 0.3 as to reflect the much higher absorption of dry land. For temperatures that fall between these two values, the albedo model smoothly interpolates between the 0.3 and 0.7; as can be seen in the following figure.

A graph of a temperature

Description automatically generated

*Figure 3: plot of the model-2 albedo function for both below and above freezing temperatures [2]*

The diffusivity constant ( was based on the work done by Spiegel et al which found a value of 0.5394 to best reproduce the presently seen climate metrics of Earth. [2]

The prescription for heat capacity was based on the work done by G. Vladilo et al [7]. The paper presents numeric values for ocean, land, and ice heat capacities; with the heat capacity of ice depending on the temperature, as to account for the latent heat of the phase transition between the solid and liquid forms.

Additionally, an ice-fraction model is utilised, originally from WK97, that outputs the fraction of the latitude band that is covered in ice, given the band’s temperature at that moment in time. [1][7]

As can be seen from the figure below, the model considers latitude bands with temperatures exceeding 273K to have zero snow/ice as the temperature is above the freezing point of water; for bands below 273K, the model considers the band to form snow/ice on the land and water surfaces, with colder temperatures leading to significantly higher fractions of snow/ice coverage over the band’s surface.

A graph of a temperature

Description automatically generated

*Figure 4: plot of ice fraction model for above and below freezing temperatures.*

Using these numeric values for the fundamental heat capacities, the ice fraction model proposed originally in the WK97 paper, and using a lookup table for ocean fraction () that describes the Earth’s present geography, we can calculate the average heat capacity of a latitude band at a given moment in time, via the formula proposed in the paper

We used the prescription of the IR-Cooling function () based on the work done by WK97, where they presented a polynomial expansion of in terms of latitude band temperature , and the carbon dioxide concentration within the atmosphere; the model attempts to capture the complex greenhouse gas effects present within the atmosphere. [1]

A graph of a temperature

Description automatically generated with medium confidence

*Figure 5: plot of WK97’s greenhouse gas IR-Cooling function for the min/max/middle CO2 atmospheric concentrations (p), over the valid temperature range.*

A limitation of this model is that we ignore altitude information within the latitude bands. This causes a problem for Antarctica due to its high elevation above sea level of 2500m. Our model calculates the temperatures at sea level for each latitude band, and we then see a cyclic pattern of snow/ice form and melt throughout the year for bands that contain the Antarctic continent. This leads to a significant deviation between our simulation and our observations of our climate, due to the large fluctuations in albedo for the southern latitude bands throughout the year.

To rectify this, we apply an altitude correction to the computed sea level temperatures for bands that contain the continent; the correction is derived from the lapse rate [9] and yields temperatures that the surfaces of the Antarctic continent actually experience, and thus giving a continent that is covered in snow/ice all year round.

References

1. “Habitable Planets with High Obliquities”, D. Williams & J. Kasting, 1997.
2. “Habitable Climates: The influence of Obliquity”, D.S Spiegel et al, 2008.
3. “Celestial Mechanics”, Moulton.
4. “Climate Change 2023, Synthesis Report”, IPCC, 2023.
5. “IPCC Special Report, Emissions Scenarios”, IPCC, 2000.
6. “Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios”, T.C Johns et al, 2003.
7. “The Habitable Zone of Earth-Like Planets With Different Levels of Atmospheric Pressure”, G. Vladilo et al, 2013.
8. "Numerical expressions for precession formulae and mean elements for the Moon and planets", Simon et al, 1994.
9. “ Fundamentals of Atmospheric Modelling”, Jacobson et al, 2005.
10. “The greenhouse effect and carbon dioxide”, W. Zhong et al, 2013