MODELING CLIMATE CHANGE AND TESTING
EDGCM EFFECTIVENESS

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ABSTRACT

EdGCM is a climate modeling software suite, created by Columbia University and based on Goddard Institute for Space Studies’ General Circulation Model II, which is computationally efficient enough for use on personal computers. As such, it has great potential as a research and learning tool in an undergraduate setting. To evaluate the program for future use, a series of diagnostic tests of climate sensitivity were conducted to facilitate comparison of the performance of EdGCM to peer and current-generation models currently in use at research institutions. The response to various magnitudes of change in atmospheric carbon dioxide concentration of global average air and sea surface temperatures, as well as selected elements of the hydrological cycle, were analyzed. These results provide a framework for students who wish to design experiments with specific perturbations in mind. Additionally, the results of these tests can be used to place data obtained with EdGCM in the context of the wider modeling field, and help identify variables in the system which may contribute to uncertainty.
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I. INTRODUCTION TO CLIMATE MODELING

The global climate is a complex machine with many interacting components. From the astronomical scale of solar radiation traveling towards the earth, to the ecological scale of growing forests changing carbon dioxide and soil moisture patterns, to the atomic scale of greenhouse gas molecules absorbing and re-radiating thermal energy, many separate pieces combine to make the Earth a comfortable place for life to flourish. For humans, who experience only the most local effects of climate on short-term timescales, it is difficult for some to visualize the underlying long-term structure of atmospheric dynamics and heat transport. Climate models allow the user to shrink this planetary-scale system to the size of a computer monitor. They also allow the user to conduct experiments that would be impossible or, at the very least, irresponsible to test on the only Earth available. As such, they are important tools for climate scientists and policymakers who wish to understand climates of the past or to predict future effects of changes to the system, whether natural or anthropogenic.

Global climate models can also be important tools for students to experience firsthand the complexity of the system they live in, and how each part in the system interacts with the others to maintain conditions for life on earth. This is the stated purpose of EdGCM, a program designed for students to use on their own classroom computers (Chandler et. al. 2005). EdGCM allows students to design their own simulations and analyze many different elements of the climate, with little prior technical experience or financial investment necessary. As the state of the climate becomes a topic of increasing importance, and more curricula begin to include issues of climate change, EdGCM could prove to be a useful tool for students. However, the mechanics of the program must be understood and tested before it can be used for future research projects.
In order to reduce the complexity of the climate system enough that it can be simulated on a computer, global climate models divide the Earth into a three-dimensional grid scheme and iterate numeric calculations over each grid cell (Ananthaswamy 2011). The variables in the system are sorted into two categories: parameters and forcings. Parameters are non-dynamic variables, such as land cover and topography, which are specified within the program and serve as boundary conditions for the grid cell. Some dynamic processes are often approximated by parameterization if the grid resolution in the model is too low to properly calculate them. Forcings, by contrast, are independent variables which are allowed to change throughout the course of a simulation. Solar radiation is the Earth’s primary forcing, but atmospheric greenhouse gas concentrations and orbital variations also play essential roles.

None of the pieces of the climate system exist in isolation; instead, they interact with and rely upon each other in nontrivial ways. These interactions manifest in what climate scientists refer to as feedback loops. Feedback loops occur when a change in one variable affects a change in a second variable, which in turn reinforces and amplifies the initial change in the first variable (although they can be much more complex and involved than two variables alone). For example, an increase in air temperature near the surface in the south pole would cause snow and ice cover to decrease. This would lessen the surface albedo in that region, causing less solar radiation to be reflected back into space and more to be absorbed by the surface. In turn, this would result in a greater rate of infrared radiation from the surface, which amplifies the initial increase in air temperature, which then amplifies snow and ice melt. Feedback loops are responsible for the majority of climate change, as they can quickly propagate what were initially small changes in a single variable through changing many other interacting variables.
If these feedback mechanisms were not present, Earth would behave as a black-body radiator, with the radiating temperature as seen from space defined by:

\[
T_e = (s/\sigma)^{1/4} \quad (1)
\]

where \( s \) is the mean solar flux per area and \( \sigma \) is the Stefan-Boltzmann constant (Hansen et. al. 1984). This would yield an average surface temperature of 14.85°C. Comparing this value to actual results allows us to quantify the total effects of feedback loops. In the simplest technique, this quantification is made by defining a net feedback factor \( f \):

\[
\Delta T_{obs} = f \Delta T_e \quad (2)
\]

where \( \Delta T_e \) is a change in surface temperature as a result of changing solar flux from Equation 1, and \( \Delta T_{obs} \) is the actual observed resulting change (Hansen et. al. 1984). Individual feedback strengths can be quantified through independently changing individual variables in the model, and then comparing the change in variable to the resulting change in temperature:

\[
f_i = \frac{\Delta R_i}{\Delta T_{obs}} \quad (3)
\]

where \( \Delta R_i \) is the change of variable \( i \) (Colman 2003). This allows for a relationship between \( \Delta T_e \) and \( \Delta T_{obs} \) based on individual feedback strengths such that:

\[
\Delta T_{obs} = \frac{\Delta T_e}{(1-k) \sum_i \frac{\Delta R_i}{T_{obs}}} \quad (4)
\]

where \( k \) is the surface temperature feedback as calculated in Equation 3 (Colman 2003). Both the net feedback factor and feedback strengths are in units W/m²·K.
The EdGCM program is based on the Goddard Institute for Space Studies’ General Circulation Model II, first documented in 1983. A graphical interface has been added to the program to make it suitable for less technical users, and to allow it to run on a PC or Mac operating system. However, the underlying code is the same (Chandler et. al. 2005). Like any climate model, the foundation of the program is a spatial longitude-latitude grid scheme. EdGCM retains Model II’s original spatial resolution of $8^\circ \times 10^\circ$, vertical resolution of nine separate layers, two ground layers (one to model surface absorption and one to model deep ground properties) and two ocean layers (Hansen et. al. 1983). Calculations for each grid cell are iterated in fifteen-minute (simulation time) timesteps throughout the duration of the simulation (Lee 2009).

The fundamental physical equations which the model computes are the conservation of momentum in a rotating frame:

$$\frac{dV}{dt} = -2\Omega X V - \rho^{-1} \Delta \rho \quad (5)$$

where $\Omega$ is the planetary angular rotation and $\rho$ is atmospheric density; the first law of thermodynamics:

$$\frac{dl}{dt} = -\frac{pd}{dt} \rho^{-1} + Q \quad (6)$$

where $Q$ is heat capacity of the atmosphere, ground, or ocean layer; conservation of mass and energy; the ideal gas law; and equations of state (Hansen et. al. 1983). Together, these equations account for heating rates and work done on atmospheric gases. Other equations used in the model account for friction, the Coriolis effect, and distribution of gases based on pressure differentials. Water vapor is modeled using
\[
\frac{d\pi q}{dt} = -\nabla \cdot \pi Uq - \frac{\partial \pi q}{\partial q} + \pi (E - C) \quad (7)
\]

where \(U\) is the horizontal velocity in a vertical \(\sigma\) pressure-dependent coordinate scheme, \(q\) is the water vapor mixing ratio, \(E\) is the evaporation rate, and \(C\) is the condensation rate. Additionally, adiabatic convection is calculated on a sub-grid level, allowing for heat, gas, and water vapor transfer between grid cells.

Solar radiation, the primary driver of the climate system, is first input into the upper layer of the atmosphere, and continues downward layer-by-layer with calculated reflection and transmission rates for each atmospheric layer (Hansen et al. 1983). To effectively model scattering, a pressure-dependent distribution of absorption coefficients is included. Spectral profiles of clouds, aerosols, water vapor, carbon dioxide, ozone, oxygen, and nitrogen dioxide allow for accurate scattering and absorption of radiation. Model II calculates ocean albedo and land albedo separately: ocean albedo is dependent on surface wind speed and solar angle, while land albedo is a function of vegetation parameter values and snow cover.

Cloud cover in Model II is determined by the water vapor levels present in each grid cell (Hansen et al. 1983). Total cloud cover is assigned to a grid cell by use of a random number generator; if the randomly generated number is greater than the calculated saturation, cloud cover is assigned, and if it less, cloud cover is not assigned to that grid cell. Precipitation is triggered when the humidity in a grid cell exceeds 100%. Likewise, snowfall is triggered when precipitation occurs in a grid cell with below-freezing temperature value.

Model II is a steady-state, rather than dynamic, model (Sohl 2006). Some values which would vary over time in the real climate, such as vegetation that might change with precipitation levels, are simplified to constant parameters. This reduces the sophistication of the model, but allows for greater computational efficiency. As an additional simplification, Model II uses a
multi-layer “slab” ocean scheme, which does not model complex current dynamics, inter-annual cycles such as El Niño, or the atmosphere-ocean interactions which result in heat and carbon sequestration (Chandler 2006). It does allow for thermal diffusion between the layers, and limited horizontal heat transport.

In EdGCM, users cannot change the values of parameters (Chandler 2005). They can, however, change forcings such as greenhouse gas concentrations, solar radiation, and planetary orientation. For each of these forcings, the user can select an initial value and add linear, exponential, or step function trends to specify changes throughout the duration of the simulation. Data tables can also be input, allowing the user to create more complex changes in forcings or to use historically observed values in a reconstruction simulation. The software allows users to extract data for dynamic variables like surface air temperature, sea surface temperature, net radiation absorbed by ground, or ground moisture, either through selecting a specified timeframe or averaging multiple calculations. Using the EdGCM Visualization Application (EVA) or Panoply (a Java-based predecessor to EVA also developed by GISS), the user can visualize this information in spatial map, vertical or longitudinal slice, or timeline format. EVA also allows the user to create differencing graphs between two data sets, so that users can visualize either changes between two time intervals in the same simulation or two different simulations.

II. TUTORIAL FOR EDGCM

The following is a basic tutorial on the use of EdGCM for the type of experiments set up in the following sections.

Step 1: Open EdGCM through the folder on the desktop and see the menu on the left hand side. This menu includes all the different runs available and options to create, delete, etc. the runs.
Step 2: Go to Window, and in the drop down menu click on Setup Simulations. The set-up menu for individual runs will then show up.

Fig. II-1: Step 1

Fig. II-2A: Step 2A (above)

Fig. II-2B: Step 2B (below)
Step 3: Label the top options as you wish. Keep initial conditions of forcings equal to the year when you would like to start your run (ie. if you begin runs from 1958, have your initial conditions set to 1958.) To change your trends, go below forcings to the greenhouse gases section and alter the trends for any of them. Four types of trends can be set: step, constant, linear and exponential. Click on the graph image on the right to bring up a menu to verify the trend.

Fig. II-3A: Step 3

Step 4: EVA will start up and show a window asking what to do with the data. Click on plot on the bottom right. EVA will bring up a graph showing what your greenhouse gas trend looks like over time.

Fig. II-4A: Step 4A

Fig. II-4B: Step 4B
Step 5: Once you are satisfied with your set-up, click the Play button in the first EdGCM menu (as seen in Fig II-1) and the program will begin the run. It will stop after a few seconds, saying that the first hour is over. Simply click on the Play button on the bottom right of the window that pops up and the run will begin. This process can take anywhere from two hours to four days.

Step 6: Once the run has completed, you are ready to analyze results. Click on the run on the left menu that has just finished. Then proceed to Window and in the drop down menu click on Analyze Output.

Fig. II-6: Step 6
Step 7: An EVA window will show up. On the left side, click on the years that you would like to average (Fig. II-7 shows the selection from 2010-2014), and click on the Average button. After that process, go through the maps tab and select what data you would like to extract. Click on Extract at the bottom. The data that was extracted will show up in image form in the View Images tab.

Fig. II-7: Step 7
Step 8: Under the View Images column, click on the data you would like to view, and click the View button. An EVA window (Fig. II-8) will appear.
Step 9: Click on Open on the bottom left to add in the image data for another set of averages (in this case the data from 2096-2100.)

Fig. II-9: Step 9
Step 10: Once that image data has been added, the information maps can be created. Click on the sets of data you would like to compare in the File menu. Pick the data you would like to view in Variable. Under the Differencing… drop down menu, click on Data 2 – Data 1 (or whatever order in which your data was selected.)

![EVA Data Browser screenshot](image)

Fig. II-10: Step 10
Step 11: The graphic map will show up in the EVA browser. You can manipulate the data in whichever manner, however in this case, the data was centered at zero (by clicking the Center on 0 option.)

Now that the process is understood, various scenarios can be conducted, as shown in the following sections.

**III. PROCEDURE AND EXPERIMENTAL SET UP**

EdGCM is capable of various different scenario models, including altering the percentages of land mass compared to water distribution and varying values of the solar luminosity. For the testing of various CO$_2$ trends over a period of time until the year 2100, the option for ‘forcings’ in the program was changed.

EdGCM allows for the CO$_2$ trends to be changed for any amount of years, but within the limitations of time, only two trends were used. Each run used the initial conditions for temperature, luminosity and precipitation beginning in December of 1957. The program then simulated all the data for the years after 1957 for all dependent variables based on the independent variable, CO$_2$. The years 1958 to 2010 used a text file that provided historically
recorded average CO$_2$ values as collected by the IPCC. The years following, 2010 to 2100, EdGCM calculated CO$_2$ values based upon the trends that were set for the experiment.

Many factors were not changed due to lack of time. Each scenario takes upwards of 100 hours to model, so only a few different scenarios were tested. The only system parameter examined was CO$_2$ and its influence on the dynamic variables, including temperature, albedo, global ice mass, etc. Albeit unrealistic, as the other greenhouse gases clearly do affect global trends of dependent variables, they were kept constant to allow for the program to focus on only one setting.

Four separate scenarios were run using the program. The first scenario followed the historical CO$_2$ trend and at 2010 any increase or decrease of CO$_2$ was capped off. This means that whatever average value of CO$_2$ was set for the last moment of 2009 is the final value for the increasing CO$_2$ trend, see Fig. III-1 below:

![CO2 Capped Off after 2010](image)

**Fig. III-1: Carbon Dioxide Historical Trend, Capped off in 2010**

As can be seen, there is an almost exponential increase in the CO$_2$ trend from 1958 to 2010 at which point there is no longer any CO$_2$ increases.
The second scenario explored the possibility of something more realistic, a linear trend of CO₂ increase rather than a cap-off. In these scenarios, all the run settings are exactly the same, except for the second trend in CO₂ from 2010 to 2100. In this scenario specifically, the CO₂ increases at a rate of 1 ppm per year (one part per million per year) which is a slope considerably smaller than what would be expected from a continuation of the historical trend, see Fig. III-2 below:

![Linear Increase in CO₂ (1 ppm per year)](image)

At 2010, the linear trend takes over and results in an overall increase of CO₂ by over 150 ppm since 1958 and almost a 100 ppm just from 2010.

The third scenario attempts to see what would happen if the world decided to take a drastic turn in carbon dioxide emissions. This is an exponential decrease beginning in 2010 to CO₂ values below 1958 values, see Fig. III-3 below:
A linear decrease may have also worked but EdGCM was not capable of handling a negative slope for linear trends. This trend clearly shows that CO$_2$ peaks in 2010 and decreases from then with an overall decrease of almost 90 ppm.

In the last scenario, perhaps the most realistic possibility was tested, which incorporates a delay time of 25 years before CO$_2$ is capped-off. During this 25 year delay, the historical carbon dioxide trend is extended until 2035, resulting in a much higher peak in CO$_2$ ppm, which is then carried through until 2100, see Fig. III-4 below:
In the following sections, each trend will be analyzed to see which are the best and worst for global dependent variables, specifically temperature and precipitation.

**IV. RESULTS AND ANALYSIS**

Data from the scenarios was analyzed based upon trends in temperature and precipitation which provides a relative idea of what direction the world is going in climatically. The first scenario of a CO₂ cap off in 2010 leads to various interesting results in average annual global temperature and precipitation, see Fig. IV-1 below:
This graph shows the average surface temperature of the Earth globally as directly affected by the CO$_2$ trend. As you can see, on average, the temperature from 1958 has increased dramatically by almost an entire degree centigrade by 2010. The temperature increase historically is dramatic and results in various consequences.

Even though the CO$_2$ was capped off in 2010, the results clearly show that the global temperature does not begin to level off until approximately 2060. The temperature actually continues to increase from 2010 to 2060, albeit more slowly than the period from 1958 to 2010. The global temperature takes a considerable amount of time to level out, due to the inertia of system earth, so an immediate cap off of CO$_2$ does not even see positive results for 50 years. The temperature however may not decrease, as it is quite possible that by 2100 the global temperature is reaching equilibrium rather than decreasing. Most likely, the temperature will not decrease due to the fact that CO$_2$ itself is not decreasing. It seems that CO$_2$ emissions fluctuations are directly related to fluctuations in temperature. Furthermore, Fig. IV-2a is shown below to accentuate which portions of the world are seeing the most effects of the CO$_2$ trend.
Fig. IV-2a: Global map showing differences in average temperature per region between 2010 and 2100. Red = Temperature Increase, Blue = Temperature Decrease

The above map shows the temperature difference between an average of the years from 2096-2100 and 2010-2014, in other words showing how average global temperature has changed in 90 years beginning in 2010 and ending in 2011. According to the graph, the average overall increase was 0.32 degrees with a max of 3.32 degrees and a minimum of -1.85 degrees, signifying that some portions of the Earth actually begin to cool as the CO$_2$ has been capped off. However, one must realize that the average still shows an increase in temperature by 2100, which again is not the ideal solution.

Similarly, looking at portions of the map that are generally covered in snow or mostly ice such as the poles and the northern parts of the northern hemisphere, there is a definite
temperature increase which would most likely cause melting of those areas. Areas around the equator show a general increase in temperature. Some sections of Earth do have an overall decrease in temperatures which signifies that even though there is small average increase in temperature, the climate remains relatively consistent with the 2010 values by 2100. Below is Figure IV-2b denoting the difference in average precipitation on Earth between 2100 and 2010 (with the same five year average as for the temperature.)

The precipitation graph is clearly not as indicative as the temperature graph in terms of increased or decreased precipitation. As would be expected, the higher the temperature there should be an increase in precipitation due to higher rates of evaporation, however it would also
be expected that these rates would become regional so that some regions see a large decrease in precipitation while others see large increases.

The graph shows that overall there is an increase in precipitation by 0.02 mm/day averaged for a year. There are equal maximums and minimums of precipitation of 1.31 and -1.31 mm/day respectively; however there is no apparent trend in the regional effects of the CO$_2$ trend.

The second scenario depicts an even more extreme case of global climate change, see Fig. IV-3 below:

![Surface Temp Trend with Linear CO2 Increase](image)

**Fig. IV-3: Resultant Temperature Trend from 2010 Carbon Dioxide Linear Increase**

Unlike the previous scenario, a clear increase in temperature is seen. As CO$_2$ increases, so does the temperature, with an increase of almost 1 degree from 1958 to 2010 and an increase of almost 2 degrees between 2010 and 2100, implying a slight increase in slope in the second trend. This is clearly indicative of rises in temperatures globally, see Fig. IV-4a:
Global increase in temperature on average is 1.67 degrees. Even the minimum temperature difference between 2100 and 2010 is 0.29 degrees, signifying that not a single region globally has a decrease in temperature. The maximum reaches all the way to 5.42 degrees, which is close to a 140% increase in temperature since 1958. The south pole shows the largest increase in temperature, which most likely indicates a severe melting of the ice caps, leading to flooding along the coasts in various portions of the southern hemisphere. Places such as the Sahara Desert in Africa and mid-South America also show high increases of temperature, whereas the minimum increases occur in the middles of oceans. The trend seems to show that the southern hemisphere is much more severely affected.
Precipitation has an interesting result; there is no clear pattern whatsoever in the global precipitation change. There are regions close to the equator that show higher precipitation, but there is no pattern in this result. There are also small portions of higher precipitation in random points in the Pacific Ocean and off the coast of South America and Africa. On average, precipitation has increased by 0.14 mm/day even though there are clearly sections such as in the north of sub-continental Asia that show extreme drought. Clearly, the increase in temperature shows neither benefits nor negative consequences to the globe in terms of precipitation. The southern hemisphere shows higher precipitation than the northern, but once again there is no clear indicator of why that may be.
The third scenario puts forth the best results for the global climate. In this case the CO₂ trend decreases exponentially from 2010 until 2100 which directly causes the temperature to decrease, see Fig. IV-5 below:

Fig. IV-5: Resultant Temperature Trend from 2010 Carbon Dioxide Exponential Decrease

Clearly, the temperature has an increasing trend from 1958 to 2010; although the exponential decrease begins right at 2010, a decreasing trend in temperature is not seen until approximately 2018. This is a clear indicator that the global climate takes a certain amount of time to be affected by immediate changes in CO₂ production, effects are not immediate. One must also notice that the decrease is not a straight line; it has various bumps or increases and decreases throughout the process, so that even at certain points in the 2020 – 2040 decade the temperature is higher than what it was in 2010.
An apparent turnaround occurs with the newest scenario. The average global temperature sees a dramatic decrease between 2010 and 2100, averaging -0.86 degrees globally. Temperature decreases as high as 3.58 degrees are also seen, especially around the poles, which tend to indicate that the polar caps would freeze once again (if they melted before 2018) or simply remain at an appropriate temperature. The maximum increase in temperature is 0.33 degrees, but as seen, only minimal parts of the Earth see any sort of temperature increase with decreased CO$_2$. There is no clear indication of regional cooling anywhere besides the poles. Most other areas show very little change from 2010 to 2100. This means that even with the extreme scenario of an exponential decrease in CO$_2$, temperature does not decrease that much in 90 years, with some
areas even showing increases in temperature still. Apparently, CO\textsubscript{2} trends do require a large amount of time before causing a significant change in average temperatures.

Global precipitation sees a general decrease, but once again there is no clear trend that is visible. There are small points in the western hemisphere at the equator that show very large decreases in precipitation, up to -1.48 mm/day, and the poles show a general decrease in precipitation. This is due to decreases in temperature which leads to lesser evaporation and less precipitation as a result. As of yet there is still no clear correlation between CO\textsubscript{2} and precipitation, but temperature is clearly related.

Temperature becomes a drastic issue considering the fourth scenario. Although the CO\textsubscript{2} trend is capped off in 2035, the high levels as seen by the historic trend create huge increases in
temperature. As can be seen by the graph below, temperature rises until the year 2070, even with the earlier cut off, and only begins to level off after that. Previously, it was seen that equilibrium takes approximately 8 years to reach, however this trend shows that equilibrium takes 35 years to reach when the CO₂ levels are so high before the cut-off point. Instead of being capped at approximately 390 ppm, the levels reach approximately 485 ppm before capping. Apparently, the initial condition for CO₂ levels has a drastic effect on the time till equilibrium.

![Surface Temperature Trend with 2035 CO₂ Cap Off](image.png)

Fig. IV-7: Resultant Temperature Trend from 2010 Carbon Dioxide Cap Off in 2035

Figure IV-7 shows the temperature results from the fourth scenario of CO₂ trends, in which the carbon dioxide levels were allowed to continue upon the historic trend as predicted by IPCC and only be capped off in 2035. This provides the most realistic scenario as world powers are unlikely to cap off, begin a slow increase or exponentially decrease the carbon dioxide emissions in one year. Once a plan is developed it will take a few years before it is implemented and even then not everyone will agree on it.
The temperature rises based on this CO₂ trend are immense, with maximums of almost 7 degrees, and an average increase of almost 2 degrees. This type of temperature increase will have drastic effects on the global climate including ice cap melting and flooding where land is close to sea level. Glaciers and such are already melting at the current average surface air temperature of approximately 13.4 degrees, and if an increase of almost 7 degrees was to occur, the average would jump up to over 20 degrees, which is in theory, devastating. Consider the portions of the map that show the least temperature increase of approximately 0.5 degrees, this is almost equivalent to the entire temperature rise from 1958 to 2010.

Fig. IV-8a: Global map showing differences in average temperature per region between 2010 and 2100, Red = Temperature Increase, Blue = Temperature Decrease
The southern hemisphere does show a larger temperature increase than the northern, and this is most likely due to the presence of larger landmasses of ice which heat up quicker. The poles once again do show more temperature increases than the rest of the world and even less around the equator which was the hottest area to begin with. Although previously hot areas are not rising in temperature as quickly, which may make some consider that CO₂ does not affect temperature changes, the evidence from the poles are a clear demonstration of the possible destructive powers of greenhouse gases. Precipitation is once again, inconclusive:

![Annual Precipitation Map](image)

Fig. IV-8b: Global map showing differences in average precipitation per region between 2010 and 2100. Red = Precipitation Decrease, Blue = Precipitation Increase

There is an overall increase in precipitation, but there is no particular region that is more or less affected than the others. Sub-continental Asia has portions of extreme drought along with small portions off the east coast of Africa, the middle of the Pacific Ocean and the middle
coastal-east of North America. These areas do not share many commonalities, so a connection is hard to make. The rest of the world seems to be fare well in terms of precipitation, with the global precipitation values averaging an increase of 0.15 mm/day, albeit there being various small blocks of decreased precipitation. This does not conclusively show that CO$_2$ emission trends are good or bad for the Earth.

There are certain clear conclusions that can be made by the results found above. Higher CO$_2$ emissions show a clear correlation to higher global temperatures. The theory behind this states that greenhouse gases create a heavy layer of particles in the atmosphere causing the Earth not to be able to release as much of its blackbody radiation or the radiation it receives from the Sun. Considering that only CO$_2$ was tested, this implies that if any of the other greenhouse gases including methane (CH$_4$) or N$_2$ were to also increase, this particle layer would become more dense, hence causing more radiation to stay within the confines of Earth’s atmosphere, resulting in higher temperatures globally. However, this does not conclude whether higher CO$_2$ emissions are entirely bad for the world’s climate.

It was seen that higher carbon dioxide emissions cause a temperature rise which may result in more precipitation globally. However, depending on some scenarios, precipitation does not show the same trends in terms of region that temperature shows. There are a few reasons for this: first is that precipitation is not as affected by CO$_2$ as other dependent variables, second is that there are various other factors such as ice and land mass and different types of bodies of water that may affect precipitation much more directly than simply carbon dioxide and temperature increase.

A possible result however is that although precipitation may not show clear trends either way, it is possible that higher CO$_2$ emissions cause precipitation to become much more
regionalized. For example, one region may show extreme drought while another shows large increases in precipitation. The average may convey that on average there is an increase in precipitation, the region that is experiencing an extreme drought is in much worse condition than a wetter region. Although the average is in favor of more precipitation, certain areas may be devastated, which in the long run is still impacting the environment negatively.

V. HISTORICAL RECONSTRUCTION

a. Purpose

One major aspect which needed to be addressed was the accuracy of the EdGCM program. The purpose was to ensure that the data being collected was an accurate representation of what could happen in the future if these forcings took place. The way this was done was to test the output temperature from EdGCM during the years 1958-2010 and compare the results against confirmed surface air temperature from known dates. The general idea of this experiment was to input the known CO$_2$ levels and record the output data. This data can be directly compared to the historical global temperature data. NASA’s specific program, Goddard Institute for Space Studies (GISS) which is for monitoring global change on the environment and observing both the man-made and natural changes was the program used by the group. Specifically, GISTEMP refers to the surface temperature analysis from the data collected from the Goddard Institute (GISTEMP 2010).

Within the past few years there have been advancements in data collecting for this program, such as including raises in temperature due to “urban heating effects” or urban heat island effect which find that the temperature seem to be higher in metropolitan areas than their
surrounding areas. With the increase in precision to replicate these effects in the models, the users of the program will have a more accurate representation of future climate systems.

The GISTEMP analysis only includes variations in temperature as opposed to the absolute temperature at the requested date. The data collected was averaged from 1951-1980, which GISTEMP uses as their base temperature. Against this baseline, the deviation in temperatures from 1880 up until the present are illustrated. This experiment was focused on temperature data from 1958 to 2010 (GISTEMP 2010). As seen on the graph below, the zero on the y-axis aligns with the temperature in the years 1951-1980.

![Global Land–Ocean Temperature Index](image)

Figure IVa-1: The figure above illustrates the global annual temperature mean and the deviation from the base temperature of 14°C. Although the analysis in this report only concerns the data from 1958 to 2010, the data of GISTEMP has been compiled back until 1880. There is a clear increase in global temperatures from roughly 1960 until the present.

### b. Procedure and Analytical Methodology

As previously mentioned, comparing the GISTEMP data with the output temperature from EdGCM was a way to verify that EdGCM was producing reliable data. Using EdGCM, an
input text file containing the CO$_2$ levels for 1958 up until 2010 was used to simulate the past climate, including temperature and precipitation, during these years. Additional forces, such as other greenhouse gases, earth’s orbit or solar luminosity, were not manipulated during these runs. Instead, they were kept at the given values from the program’s reference year of 1958. Data was analyzed in EVA and Microsoft Excel. When creating a simulation run for EdGCM, only the CO$_2$ levels are inputted into the calculations. From these values, the data is analyzed and the temperatures are evaluated. Once EdGCM has completed the run, it creates an output including all of the yearly averaged temperatures from that run. The temperatures that were calculated from EdGCM were placed into a Microsoft Excel spreadsheet and compared to the GISTEMP temperature data.

c. Results

Figure IVc-1: The graph above illustrates the EdGCM projected surface air temperature data from 1958 to 2010 as well as the actual surface air temperature as recorded by GISTEMP data. The data used by GISTEMP is based off of the average temperature from 1950-1980. That average was used as the base temperature for that data.
As shown by the graph, the two data sets do not match up completely. Although they do follow a similar increasing trend, the EdGCM trend is below the GISTEMP data trend. The EdGCM trend replicates the fact that there was a relatively constant global temperature from 1960-1980 as seen from the GISTEMP values during this period. However, after 1980, the EdGCM data has a somewhat larger slope.

d. Discussion

One possible conclusion for this variation is due to the fact that to fix the y-axis offset in the temperature graph the GISTEMP data set uses an average temperature over the time period of 1951-1980. Since it does not directly deal with the absolute temperatures, there is a possibility that during the base time period the historical temperature average was higher than normal. The base time period is during a time where there was known to be an increase in global temperatures and thus, could have led to a higher average temperature to begin with. However, the GISTEMP data found the average temperature over the base year period of 1951-1980 and measured the temperature variation from that base value. In the data, this base temperature value was found to be 14°C. Instead of the average temperature from 1951-1980, a different base period could have been used and a new average calculated. This could vary the results and produce a better relationship between the EdGCM data and the GISTEMP data. Also, if the absolute temperature data was used there could be a closer correlation.

Another deviation that could have led to the digression in the two trends is the exclusion of weather phenomena. With this being said, it is important to recognize that the EdGCM data does not include or project for natural disasters or extreme weather happenings. EdGCM simply does not have the computational capability, at least with regard to the edition that was used
during this project. It would be extremely difficult to include and project both the occurrences of these actions or the extent of their impact and repercussions on the global weather system.

EdGCM is not able to include abnormalities in weather such as hurricanes or other tropical storms and it cannot predict them happening. Things such as an earthquake in an ocean and an ensuing tsunami, or a volcano eruption that releases a massive amount of CO$_2$ and ash into the atmosphere, would not have been included in the calculations of EdGCM even though it could have a drastic impact on the surrounding areas and play a role in various feedbacks. Thus, none of the repercussions of this event would be modeled in its projections either. This is definitely a cause for some margin of error in EdGCM’s protuberance when compared to the actual data.

Although the EdGCM temperature output does not match exactly with the GISTEMP values, it does seem to follow its basic trend. The EdGCM trend does follow very similarly the recorded GISTEMP increases in temperature.

VI. SUGGESTIONS FOR FURTHER WORK

Climate modeling with EdGCM allows for plethora experiments and data collection. There are forcings programmed into EdGCM which were not touched on in this experiment and leaves open the possibility for further work. While this research specifically focused on the effects of strictly CO$_2$, other greenhouse gasses such as methane (CH$_4$), ozone (O$_3$) and water vapor (H$_2$O) were also available for perturbation. These same runs and trials could have also either included these forcings, or could have been completely focused on them. While including the additional greenhouse gasses in the tests might have provided a better rounded and realistic projection for what the effects of greenhouse gasses creates for the environment, the results
compiled in this report show the distinction that CO$_2$ levels on their own affect the global climate. Future researchers might wish to include the various other greenhouse gasses within their experiments.

Similarly, when including different greenhouse gas forcings, EdGCM offers numerous areas to focus on and view the specific effects on certain aspects to the global climate. For example, as shown in this report, both surface air temperature and precipitation were represented. These are only two of the many other options. Areas such as cloud cover, variations in wind speed, and changes in ocean ice coverage or increases in topography and land coverage are all options to explore.

Regarding further investigation of possible outcomes due to greenhouse gasses, there are plenty of runs still to be tested. An opportunity to get a realistic picture of the future global climate could involve the current population trend. With the increase in global population, there becomes a scarcity of resources as well as an increase of industrialization and waste. Currently, developing countries do not have high CO$_2$ emissions relative to more developed countries. However, developing countries do have the highest rates of projected population increase and because of that their emissions are expected to increase drastically. Therefore it is specifically recommended to test what affect the increase in global population will have on the climate. With that experiment, the researchers could model the trend of population increase and compare it to the increase in CO$_2$ emissions or other forcings. Then, this comparison could be lengthened out and used to project, specifically, how the increase in global population could impact the global climate. (Baumert et al. 2005)

There are many additional opportunities for further research within the domain of global climate modeling. However, they are not strictly restrained to using the EdGCM program as
many other climate modeling programs have been produced. A few of these programs include the Arctic Climate Modeling Program (ACMP), the Program for Climate Model Diagnosis and Intercomparison (PCMDI) as well as many others. The field of climate modeling is one that is up and coming and the ability to use these programs as an educational tool is an important way to promote awareness about the possibilities that the world will face in upcoming years.

VII. APPENDIX – COMPARATIVE RESULTS OF FOUR DEPENDENT VARIABLES

In this section, each of the four CO₂ scenarios as discussed previously is compared in terms of a few other dependent variables: planetary albedo, potential evaporation, percentage of snow and ice coverage, and snowfall. Each of these dependent variables are analyzed in the same way as temperature and precipitation, by averaging the years 2010 to 2014 and subtracting that average from the average of years 2096 to 2100, to better see the entire change between the present and the year 2100.

Planetary Albedo

Scenario 1 – 2010 CO₂ Cap Off  
Scenario 2 – CO₂ Linear Increase
Scenario 3 – CO₂ Exponential Decrease  

Scenario 4 – 2035 CO₂ Cap Off

Fig VI-1: Global maps showing differences in planetary albedo per region between 2010 and 2100 for four carbon dioxide scenarios, Red = Albedo Increase, Blue = Albedo Decrease

The above graphs show the percent change in planetary albedo from 2010 to 2100. No particular regions are greatly changed in terms of albedo, but an observation can be made that decreased CO₂ leads to higher albedo, so that more of the Sun’s radiation is reflected off the Earth resulting in temperatures not as high. Once again, higher CO₂ values seem to create more radiation capture within Earth’s atmosphere.

Potential Evaporation

Scenario 1 – 2010 CO₂ Cap Off  

Scenario 2 – CO₂ Linear Increase
Scenario 3 – CO₂ Exponential Decrease

Scenario 4 – 2035 CO₂ Cap Off

Fig VI-2: Global maps showing differences in potential evaporation per region between 2010 and 2100 for four carbon dioxide scenarios, Red = Evaporation Decrease, Blue = Evaporation Increase

Potential evaporation shows similar results as precipitation. There doesn’t seem to be a clear trend seen within the four scenarios, at most a hypothesis can be made that higher CO₂ emissions increase evaporation due to increased temperatures. This is shown by the average values apparent in each resulting graph. Scenario 2 and 4 show overall increased evaporation. Those are the same scenarios that showed the highest temperatures increases based on higher carbon dioxide emissions, effectively supporting the hypothesis.

Snow and Ice Cover

Scenario 1 – 2010 CO₂ Cap Off

Scenario 2 – CO₂ Linear Increase
Scenario 3 – CO₂ Exponential Decrease

Scenario 4 – 2035 CO₂ Cap Off

Fig VI-3: Global maps showing differences in snow and ice cover per region between 2010 and 2100 for four carbon dioxide scenarios, Red = Snow/Ice Cover Decrease, Blue = Snow/Ice Cover Increase

These graphics (Fig VI-3) show the amount of snow and ice cover per area based on percentage on an annually averaged basis. The third scenario is the only scenario that shows increased snow and ice coverage globally on average, each of the others show considerable percentage decrease. This seems rather evident: higher carbon dioxide emissions directly affect precipitation (as shown earlier) and the amount of ice and snow within a given area.

Snowfall

Scenario 1 – 2010 CO₂ Cap Off

Scenario 2 – CO₂ Linear Increase
Very similarly to precipitation, snowfall doesn’t show particular trends in either direction. All of the averages are quite close to zero; however there is a quite plausible reason for this. The regions in the maps that are not the poles show a general standstill in terms of snowfall, this greatly effects the overall average. This may be a result that EdGCM is not as readily able to process, however the more likely reason is that those regions of Earth are generally hot and have been hot historically, which results in no snow having fallen there previously, so an increase or decrease is not that possible.

VIII. REFERENCES


