Simulation of Global Warming in the Continental United States Using Agent-Based Modeling

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Abstract

As the population increases, the carbon footprint of the United States increases, further accelerating the effects of global warming. This project studies the effects that global warming will have on population. The purpose of this experiment is to combine the effects that population will have on greenhouse gas output and then the effect that the resulting temperature and sea-level changes will have on the population. The objective is to show the detrimental effects that global warming will have in the United States if nothing is done to limit the greenhouse gas output and display the results of several scenarios dealing with emission, death rate and birth rate change. Since similar population increases are expected to occur around the world, the implications of this project should apply to countries other than the United States.

Keywords: global warming, greenhouse gases, agent-based modeling, netLogo, population changes

1 Introduction

This research project uses data on global warming to estimate the effect of climate change on population size and location. To understand the implications and variables of the project, general knowledge of global warming data is needed.

If the Earth had a completely balanced Energy model, the amount of heat energy received from the sun and absorbed by the Earth would be successfully released in the form of infrared radiation back to the atmosphere. However, natural gases, mainly consisting of water vapor (H_2O), carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), and Ozone (O_3), are called greenhouse gases and contribute to a phenomenon called the greenhouse effect [9]. These gases essentially trap IR radiation from the Earth, preventing it from leaving the system. This entrapment of energy causes the Earth's mean temperature to increase in a process called radiative forcing[9]. Currently, the greenhouse effect has increased the mean surface temperature by 33 °C [17] to a total temperature of 14.63 °C or 287.78 K [14].

It is difficult to tell how much each gas contributes to the greenhouse effect since the effects are not additive, but it is known that water vapor is the strongest contributor. On a clear day, H_2O accounts for 33% to 66% and for 66% to 85% on a cloudy day [11]. However, humans do not significantly increase or decrease the amount of atmospheric water vapor [11] so it is not considered to be an anthropogenic gas like carbon dioxide, nitrous oxide, and methane. The amount of radiative forcing is dependent on the concentration of the anthropogenic greenhouse gases in the atmosphere. Each of the gases has been assigned a Global Warming Potential (GWP), which sets up a means of comparing the gas' ability and likeliness to absorb IR radiation. GWP uses 1 kg of CO_2 as a basis of comparison, so CO_2 would have a GWP of 1.[9] Methane, even though it has a lower atmospheric concentration, has a GWP of 21 and nitrous oxide is listed with a GWP of 310 [15]. An increase in gases with higher GWP would significantly increase the greenhouse effect and radiative forcing, since more IR radiation would be absorbed, and therefore would contribute to surface temperature increase [12]. The atmospheric concentration of greenhouse gases has increased significantly since the pre-industrial era (around 1750). From trapped gases in ice core samples, researches have concluded that CO_2 emissions have increased by 36%, CH_4 by 148% and N_2O by 18% since that time. [9]

In 2007, the United States had an annual greenhouse gas emission of 7150.1 Tg CO_2 Eq. (atmospheric gas amounts are given in units equivalent to a million metric tons of CO_2). This amount has increased by over 17% since 1990 (about 99 Tg CO_2 Eq.) with an average of a 1.3% increase each year. [9] Carbon dioxide alone contributes to 85.4% of the total emissions and 94% percent of that is contributed to fossil fuel burning, and since higher emissions contribute to higher atmospheric concentrations [10], this is cited as the cause for the increase of the atmospheric CO_2 concentration during the industrial era. Currently, the atmospheric CO_2 concentration is 387 ppm by volume, 104 ppmv higher than the pre-industrial value of 280 ppmv [17]. Using recent rates of concentration increase, scientists have estimated that these amounts will reach 541 to 970 ppmv by 2100 [10].

With higher greenhouse gas emissions and increasing temperatures, the Earth's waters will expand [18]. Also, the greatest temperature increase will be felt around the poles, leading to melting glaciers and ice sheets [12]. Both of these factors will contribute to eventual sea level rise. The Intergovernmental Panel on Climate Change (IPCC) has estimated that by 2100, there will be an average global sea level rise of 18 to 59 cm [12].

Population changes are the backbone of greenhouse gas emission scenarios [16]. An increase in the population change will lead to more energy consumption and thus an accelerated scale and intensity of human induced changes [4]. While future birth and death rates affecting the size of the population are unpredictable, researchers agree that the global population will drastically increase in the next century, with one of the models proposing a world population of 9 billion by 2040 [13]. The population size will also be affected by the effects that temperature increase has on mortality rates. Death rates increase with heat waves and infectious diseases have been shown to be affected by climate variability. With changing climates, scientists have predicted an increase in the spread of various diseases such as malaria, dengue, tick-related diseases such as Lyme, cholera and other diarrheal diseases. In fact, by the 2080s, 5 to 6 billion people will be at risk for dengue compared to 3.5 billion without any temperature changes. Currently, the general population is quickly aging, and elderly people are more vulnerable to injury from weather extremes, further increasing the possible future death rates. [7]

2 Background

There are various approaches to modeling complex systems, and the ones used in this project are agent-based modeling and system dynamics. These two methods were implemented in NetLogo, a modeling environment based on agents with specific rules meant to simulate natural and social phenomena. Uri Wilensky from Northwestern University designed NetLogo in 1999. It is written in Java and can be easily run on major platforms such as Mac, Windows, Linux, etc.[2] NetLogo provides an option for creating a system dynamics model, which concentrates on connecting variables with equations that closely simulate a phenomenon. The system dynamics of the project is described in a section below.

Agent-based complex systems are dynamic networks of many interacting agents [5]. NetLogo uses three agents: turtles, patches and the observer. The turtles are the moving agents that move around in their environment which is composed of a lattice of patches. The observer is the entity that overlooks both the turtles and the patches and applies the given equations to determine their relationships. The interface is the window where the user can use sliders and observers to monitor variables, have running graphs and include visuals of the location of the turtles and patches. The procedures tab of the program allows the user to write his or her own code. Certain NetLogo commands and reporters tell each individual agent what to do. The whole system is composed of agents individually deciding what they want to do and how their decisions affect the environment of other agents around them.

It is possible to create and access various variables. Global variables can be accessed by all types of agents and apply to the whole system as a whole. Each agent (patch or turtle), however, can have its own variable that can only be changed by commanding the individual agent to do so. It is also possible to create more agents, assign them names, variables, and a shape which is used to represent their location in the visual representation of the Interface.

NetLogo was chosen for this project for two main reasons. First, it allows the user to incorporate both an agent-based system and a system dynamics. Second, it is free, easy to use, and does not take up much space. For climate modeling, the system dynamics controls the macro level modeling [4]. This means that the overall system is based on generic algorithms that are dependent on each other. In this project, the macro level system is the earth energy balance system which takes into account the energy held by the Earth, atmosphere, and the input from solar radiation. The micro level modeling is provided by the agent-based system [4], since their movements are based on a set of rules. Each agent acts independently from the other agent, based on its own ”mental model” or heuristic made available to it by the program, and only has access to limited information at any given time [3].

Climate modeling is used by scientists to predict the evolution of temperature with sufficient regional detail to be useful to people around the world [1]. The IPCC has defined two types of models: simple and complex. Complex models take into account the different environments that contribute to the Earth's climate: clouds, land surface, oceans, atmospheric motions, carbon cycle, ice sheets, and atmospheric chemistry [18]. These models require each of these environments to interact with each other and thus need multiple processors to run simultaneously [1]. For a yearlong individual project, creating a complex model would not have been feasible. Instead, a simple climate model was created based on the Earth energy budget and atmospheric chemistry. This limited number of variables contributing to the model of climate change is one of the possible sources of error. A lack of a model of the ocean, sometimes referred as the flywheel of the climate system, may be the main shortcoming of this project [1].

Currently, the main source of information on climate change comes from scenarios created and run by the IPCC. All of their programs involve complex models that take into account the different environments that contribute to climate stability and change [18]. However, none of them involve the possible changes that climate change may have on population.

3 Development

The programmers of NetLogo have provided the user with various premade models that can be run and modified. One of these is a Continental Divide searching algorithm which includes a colored map of the United States [20]. The elevation map from the Continental Divide project was the basis for the temperature map of the United States and is shown in Figure 1. For the purpose of this project, the dimensions of the map were edited and a border was added between Canada and the U.S. A python code erased all of the numbers except for the borders of the continent to prepare the map for temperatures. After indicating the approximate locations of large cities

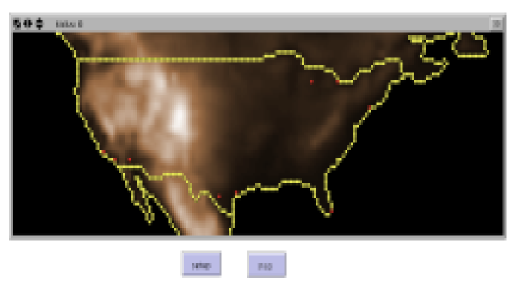

Figure 1: Image of the Elevation map

in the United States by special green house images, WeatherBase provided the average annual temperatures that were converted to Celsius [19]. Linear interpolation was used to fill out the rest of the map since it would be nearly impossible to figure out the accurate average temperature of every point in the United States. For linear interpolation, two cities' temperatures were used as endpoints, and a linear model was created to estimate the data points in between the two, depending on how many there are.

$$dT = \frac{C1^2 - C2^2}{P1^2 - P2^2}$$

The C1 and C2 are representative of the temperatures of two end-point cities, and the P1 and P2 represent the patches that they were on. dT is the amount that the temperature would change for each patch between the two cities. At time, it was impossible to find out the horizontal interpolation of temperatures, since there are not enough major cities. In that case, vertical linear interpolation was used. All the code for the horizontal and vertical interpolation was written using Python. In case there were two lines of patches with an unfilled one in between, another code was written to average the two temperatures to figure out the approximate temperature of the middle patch. Figure 2 shows the resulting temperature of the U.S. with current estimated average temperatures.

After the temperature map was completed, the city agents (green houses) had to be added to the project. Each house agent has three different variables:

- Name
- Average Salary
- Percent Below Poverty Level (povpercent)

Figure 2: Image of the screen with the temperature map

All of this data was found from the US 2000 census data which also includes population estimates for 2007 for each city. Since the average size of a family is 2.5 members, the poverty level annual salary is 15,800 per year. At the patch of each city, according to its private variables, people agents were created. The percentage determined by povpercent has a salary of a random number between 0 and 15800. Then, .5 - povpercent percent of people have a random salary between 15,800 and the city's average salary. Half of the people have a salary somewhere between the average salary and twice the average salary. Of course this isn't a completely accurate indication of salaries in the United States, but it makes sense with the distribution of people under poverty level and those with above-average salaries.

Each person agent has two variables

- Salary
- Money

Their salary figure is determined by which city they are created in (and then that city's povpercent and average salary), and their money variable is updated once at birth to equal their annual salary and then each year after that. The determination of how long a year is will be addressed later. Using the patches, agents, and cities, the program is able to run. However, the System Dynamics model runs the changes in the temperature of the model. The function of the System Dynamics model is described in the following section.

The most important agents in this program are the patches themselves. NetLogo automatically creates them when the size of the interface is set, but they are assigned different variables.

- Elevation
- Temperature
- Original Temperature
- Original Elevation
- Death Rate
- Original Death Rate

The temperature and elevation variables are set through a set of numbers that is representative of the size of the interface itself. Each created patch has its own number that is read into a list and assigned into the Temperature and Elevation variables. Once setup is hit on the interface (but not step) then each variable is equal to its 'Original' variables. Two copies are made, and as the program runs one of them always remains the same to keep a record of how much each variable has actually changed. The System Dynamics drives the temperature to 288.43 K, which is when any changes start happening with the people-agents. As the number of people increases, then the temperature of each patch starts to increase. Temperature - Original temperature indicates the current change in temperature which then indicates the change in death rate for that given patch. The change in temperature is divided by d(death rate) and then added to or subtracted (depending on whether the temperature has increased or decreased) from the death rate of the patch.

The atmospheric absorption coefficient controls the temperature increase and decreases and essentially connects the agent-based model and the system dynamics. The coefficient represents the magnitude of IR absorption by greenhouse gases. A coefficient of 1 would mean that greenhouse gases absorbed all of the IR radiation emitted by the Earth. People often forget the magnitude of water vapor's contribution to the greenhouse gas effect. The estimated contributions of the major greenhouse gases to the entire effect are listed [6]:

- 60% H_2O
- 26% CO_2
- 8% O_3
- 6% CH_4 and N_2O

These values aren't exact since the contributions are not additive and many of them overlap. Also, these percentages have been estimated for completely clear days (with no contribution from water vapor in clouds) [6]. Since humans do not have a significant effect on the amount of water vapor in the atmosphere, only 40% of the atmospheric absorption coefficient can be changed.

The initial value is set at 0.25628, a number received from trial-and-error. As the System Dynamics runs, the temperature steeply increases and then reaches a plateau. The atmospheric absorption coefficient was set at the value at which the graph reached a plateau at 287.78 degrees Kelvin, the current average Earth surface temperature. The number of agents and the amount of greenhouse gases that the agents collectively release changes the coefficient. In 2007, the U.S. greenhouse gas emissions were 7150.1 Tg CO_2 Eq. (units of teragrams of carbon dioxide equivalents) [9], so the program assumes that at this level of greenhouse emissions, the coefficient is 0.25628. The total U.S. population at the setup of the program is 3520 agents, equivalent to 35,200,000 people. This means that the greenhouse gas output per agent is 2.031 Tg CO_2 Eq (or 2,031,000,000 kg). The 40% of the atmospheric absorption coefficient that is affected by greenhouse gases other than water vapor then changes according to the percentage of the greenhouse gas output to the recorded constant value of 7150.1 Tg CO_2 Eq.

When Setup is hit in the project's interface, the patches are assigned their elevation and temperature values and the initial elevation or temperature map is created (a switch controls which map is displayed). The go button is a series of infinite steps. At each step, agents go through a set algorithm.

1. Generate random number. If below death rate, die. If in the range of birth rate, reproduce an identical turtle.

2. If temperature is above 22 °C, enable the agent to move.

3. Divide agent's money by 10000, the result is a radius

4. Search for a random patch radius*10 patches from current location

5. If the new location is on land and cooler than current, move there

6. If a random number from 0 - 1 is less than .06, move 1 in a random direction

With this algorithm, the agents have a chance to move to a cooler location if their current one is unfavorable. The final random number is added so people do not move to the same location, and to make sure that the numbers of agents in an area are visible (if more than one agent inhabits a patch, then they are represented by only one icon). The locations that the agents move to then determine their death rate and thus the size of the population. The size of the population then determines the total greenhouse gas emissions and thus the atmospheric absorption coefficient that determines the average surface temperature.

4 System Dynamics

The System Dynamics model for this program was taken from a model geosystems STELLA lab. It sets up the fundamental mathematical processes that determine the energy input and output of the Earth, taking into consideration both the surface of the Earth and the atmosphere around it. The relationships between the variables is as follows:

- Atmospheric Absorption Coefficient = 0.25628
- Earth Albedo = .3
- Earth Diameter = 12742000
- Density of water = 1000
- Specific Head of Water = 4218
- Water Depth = 100
- Earth to Atmosphere = atmospheric absorption coefficient * surface radiation * dt
- Atmosphere to Earth =

$$atmosphericirradiation * \frac{1}{2} * dt$$

- Atmosphere to Space =

$$atmosphericirradiation * \frac{1}{2} * dt$$

- Solar to Earth =

$$solarconstant * (1 - earthalbedo) *$$

$$\Pi * ((\frac{earthdiameter}{2})^2) x dt$$

- Earth to Space =

$$1 - atmosphericabsorptioncoefficient$$

$$* surfaceradiation * dt$$

- Surface Radiation =

$$\Pi * (earthdiameter^2) * StefanBoltzmann$$

$$*earthtemperature^2$$

- Atmospheric IR Radiation =

$$\Pi earthdiameter^2 * StefanBoltzmann$$

$$*atmospherictemperature^4$$

- Solar Constant =

$$1368 * 3.14476 * 10^7$$

- Atmospheric Heat Capacity =

$$5.14 * 10^1 8 * 1004$$

- Atmospheric Temperature =

$$\frac{atmosphericenergy}{atmosphericheatcapacity}$$

- Earth Temperature =

$$\frac{earthenergy}{heatcapacity}$$

- Stefan Boltzmann =

$$5.67 * 10^8 * 3.15576 * 10^7$$

- Heat Capacity =

$$\Pi * earthdiameter^2 * waterdepth$$

$$*waterdensity * specificwaterheat$$

The System Dynamics runs parallel with the rest of the program through the line system-dynamics-go. However, the program always starts out with the Earth Energy, temperature, and Atmospheric Energy at 0 and then works its way up to a current temperature of 287.78 Kelvin, the current average Earth temperature. The graphs next to the map of the United States depend on the System Dynamics to report back the average temperature which is then used to change the temperature of each patch.

5 Data and Analysis

The multiple runs from this project clearly showed a success in creating a relationship between population size and average surface temperature. Figure 3 shows the clear relationship between the two variables. As the population size increases, the temperature increases. The temperature reaches a certain level after which the population begins to decrease, followed by a decrease in the temperature. The effect seems to be slowly oscillating, but the frequency and amplitude of the oscillations seem to be dampened over time.

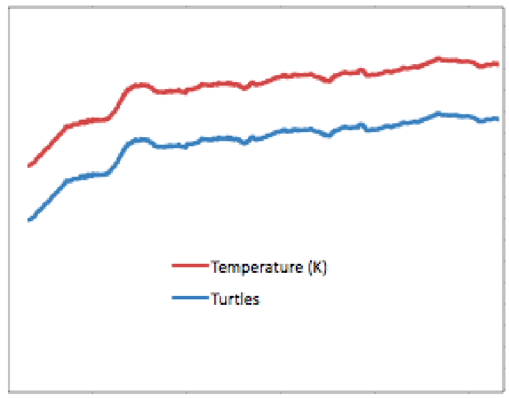

Figure 3: Graph of the temperature and number of people

Figure 3, however, is run using the original and current birth rate of .1418 and a 'd(death rate)' (the change in death rate as temperature increases or decreases) of an arbitrary number of 101. The U.S. population will most likely not have a constant birth or death rate over the next hundred years, so it is necessary to test various scenarios that could alter the effect of temperature on population.

By changing three variables (birth rate, 'd(death rate)' and the emissions per person), the range and averages of the data of both the number of turtles and the temperature changes. BehaviorSpace is a small part of NetLogo that can be used for manipulating, running, and collecting data. The program asks for an input of which variables will change and which will remain constant through various runs. All of the output data can be recorded in a table or a spreadsheet which also calculates the minimum, maximum, and average values for each run.

The first independent variable is 'd(death rate)'. As the temperature of the United States increases, then without an improvement in technology, the death rate would increase. There will be possibilities of more infectious diseases which spread easily in heat. Also, warm weather encourages the reproduction of mosquitoes which can spread diseases. However, it is impossible to predict how and how much the death rate will change. D(death rate) is a variable indicating the relationship between temperature and death rate. The amount of increase in the death rate is

$$\frac{\Delta temperature}{d(deathrate)}$$

. If the variable is low, then technology hasn't improved and humans are more susceptible to heat strokes and diseases. However, if the variable is higher, then death rate will not increase or decrease dramatically.

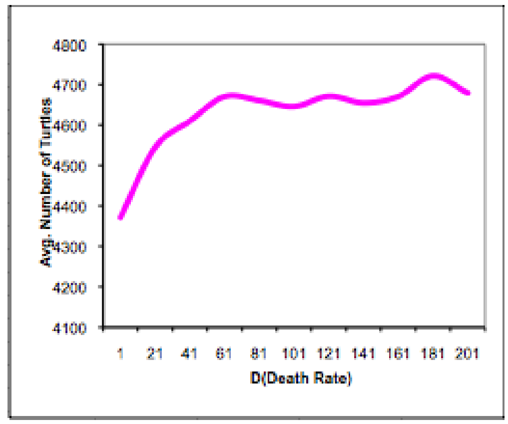

Figure 4: D(death rate) and average number of turtles

Figure 4 shows the changes in the average number of turtles as d(death rate) changes. The data was collected by running the program 5 times for each variable interval for 2000 ticks and getting the average of the results. The overall relationship shows that there is a direct relationship between the two variables. If d(death rate) is low (meaning higher death rate changes with increasing temperatures) then the number of turtles is also lower. More turtles would die faster as soon as temperature increased. The temperature graph had an almost identical result. Interestingly, the average number of turtles seems to oscillate once d(death rate) hits 81. This may have to do with the fact that when the death rate doesn't change much, the number of turtles is more arbitrary and dependent on the random locations that the turtles decide to move to.

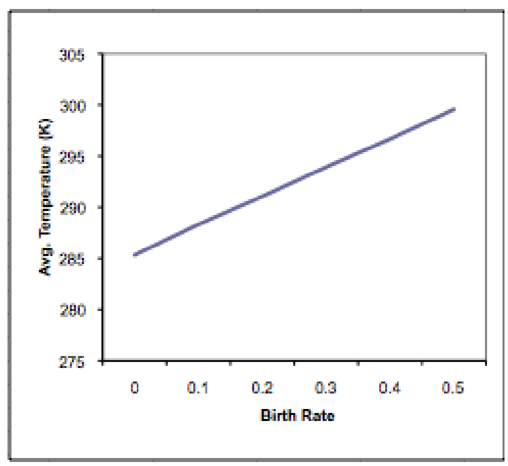

Figure 5: Birth rate and average temperature

The current U.S. birth rate is .1418/ 10,000 people. However, this is unlikely to remain exactly the same over the next one hundred years. Thus, the project makes it possible to manipulate the average and see what would happen to the population if the birth rate increased or decreased. Unfortunately NetLogo is not capable of managing very large numbers, so only birth rates up to .6 could be tested. A higher birth rate would cause the population to multiply at extremely high rates, resulting in sudden increases in the temperature that the program could not handle. Figure 5 shows the graph of the average temperature (in Kelvin) as birth rate increases. As with the previous graph, the program was run 5 times for each interval and the results were averaged. The graphs show a direct relationship between temperature and birth rate. As more people are born, the greenhouse gas emissions increase and thus the temperature increases. However, the fact that d(death rate) remained constant (at 101) throughout these runs could have caused this relationship. If d(death rate) had been lower, then the steep increase in temperature at higher birth rates would have quickly increased the death rate, resulting in a smaller slope (or even a negative one) of the temperature - birth rate graph.

The most fascinating results came from manipulating the emissions per person variable. Hopefully people will figure out how to decrease emissions in the future, but it is also possible that they will increase. The emissions per person variable ranges from 0 to 2, the fraction of the current emissions. If the variable is set at 1.8, then every person would be releasing 80% more greenhouse gases than today. An emission per person variable of .1 would mean that each agent was releasing only 10% of current emissions. The variable was run with a stable birth rate of .1418 and d(death rate) of 101.

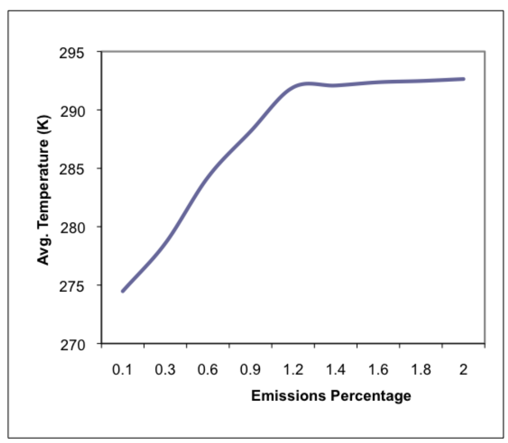

Figure 6: Emissions and average temperature

Figure 6 shows that with an increased emissions rate, the temperature clearly increases. However, if the number of emissions reaches 20% higher than the current rate, then the average temperature levels off around 293 Kelvin. This may be due to the fact that with the stable d(death rate) and birth rate, at a certain temperature the two variables cancel each other out and thus the population doesn't change the temperature after a certain point. However, it is possible that this may be due to a glitch in the program where more emissions are not contributing to the atmospheric absorption coefficient and thus it just reaches a maximum limit and thus does not increase the temperature.

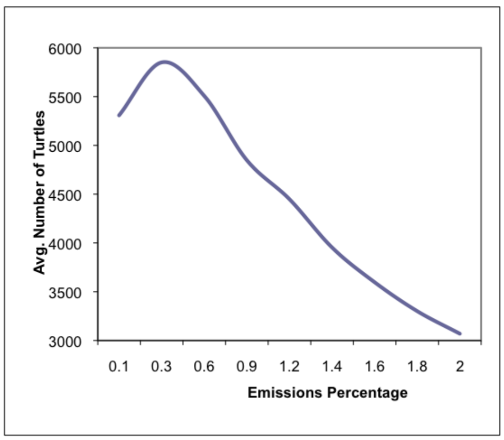

Figure 7: Emissions and average number of turtles

The emissions change shows an inverse relationship between the number of turtles and the temperature, which was expected. The higher the rate of emissions, the lower the average number of turtles. Figure 7 shows the clear decreasing relationship between an emissions percentage of 30% and 200%. The notable anomaly at .1 is due to the fact that the program assumes that all of the greenhouse gases (other than water vapor) are anthropogenic and at .1, only 10% of the carbon dioxide and methane are in the air. This program falls short from accounting for volcanic activities and other natural sources of carbon dioxide, since the amount cannot be accurately determined since the effects of the greenhouse gases are not additive. Also, historic readings of CO_2 content and temperature have shown that there is a certain (but unpredictable) natural oscillation, which accounts for the ice ages and the intermediate periods. Since they cannot be accurately predicted, they were not included in this project.

6 Results and Recommendations

The main purpose of this experiment was to show a possible bleak future scenario of what will happen when nothing is done about global warming. The expected real results are unknown, but will most likely show that over time, the population will first increase due to favorable conditions and a longer lifetime due to improved technology. However, as the population increases, more greenhouse gases are produced and thus the climate changes and heats up. As infectious diseases start to spread and sea levels start to rise, the population will decrease, now decreasing the amount of greenhouse gases in the atmosphere. The climate will now cool down, and the death rate will once again decrease, enabling the birth of more agents. There should be a slow oscillating relationship between the population and greenhouse gases in the atmosphere. However, the majority of the population will move north, away from the coastal areas to escape high temperatures and flooded cities. The poorer population will not have as many options to move away from unfavorable conditions, and thus the people below the poverty level will have a harder time coping with climate change. More affluent agents will be able to move to favorable areas.

The Gaia Hypothesis states that the Earth acts as a self-regulating body. If there is a forcing in one area, then the Earth will change another to counterbalance it. The Earth will most likely try to get rid of the cause of the climate change - the humans. However, there are various problems that will conflict with the validity of this program. First of all, as technology and thus medicine improve, the rates of the increasing and decreasing death rates will change. It is possible that the increasing death rates due to the increasing temperature will be counterbalanced by the improving health care.

This project has in the most part shown that it is possible to create a relationship between population size and the amount of greenhouse gases released into the atmosphere. However, there are many fallbacks with this project that could be fixed given more time and resources. First of all, the initial average surface temperatures were estimated using interpolation and known endpoints. Also, the program assumes that the entire population of the United States is in the top 20 major cities. A more realistic model would show a more accurate spread of the population over the continental U.S. Next, the project assumes that the entirety of the carbon dioxide, ozone, methane, and nitrous oxide content of the atmosphere is anthropogenic, which changes the results of the emissions percentage tests. Using pre-industrial era greenhouse gas readings from ice cores and comparing to current levels to get a percentage of increase can easily solve this issue. This would lower the percentage that anthropogenic emissions would contribute to the atmospheric absorption coefficient.

With more resources, it is also suggested that this program be paired with models of other Earth systems, such as the ocean and wind movements.

There are more factors to global warming other than surface temperature and population size, but this project just concentrated on creating the relationship between temperature and the U.S. population.

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