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Trace Gases & Their Effects

An Interactive Qualifying Project

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Degree of Bachelor of Science

by

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Abstract

The role played by trace gases as a regulator of radiative forcing delivered to the Earth establishes it as a significant research topic with implications important to the quality of human life and the environment. We researched the effects on carbon dioxide concentrations in the lower atmosphere as a result of the world pursuing different energy policies over the next few decades. Through our research, we demonstrated that a nontrivial reduction in CO_2 emissions can be obtained using different policies.

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Executive Summary

Due to the anthropogenic nature of carbon dioxide emissions in the lower atmosphere, we researched the effects on future carbon dioxide (CO_2) concentrations by exploring different energy policies pursued by the world. Specifically, we observed CO_2 increases and decreases due to changes in the world's electricity generation from the year 2005 to 2030. We started by first analyzing the percentage use of each energy source that the United States (US) and the rest of the world were using in the year 2005. Next, we researched the amount of CO_2 released per kWh through life cycle analysis for coal, liquid, natural gas, hydro, solar, nuclear, and wind energy sources. This data, in addition to using the predicted electricity consumption of the world in 2030 by the Energy Information Agency (EIA) and also a seven reservoir CO_2 Matlab model, was used to compute future CO_2 concentrations in the lower atmosphere using a numerical method technique and varying the percentage contribution of each energy source while still keeping the total electricity generation from all energy sources constant.

The conclusions that we reached were that if the United States converted 20% of its electricity consumption to wind power in 2005, a reduction of 1.44 ppm of CO_2 can be achieved from the energy policy projected from the EIA by the year 2030. If we were to continue onto the energy path predicted by those from the EIA in 2030, however, an increase of 1.89 ppm of CO_2 will be realized from our energy policy in 2005. If the world were to embrace both nuclear energy and renewable energy sources more openly for roughly 50% of its electricity generation (19.9 % nuclear and 29.9% renewable) then a reduction of 4.46 ppm of carbon dioxide can be reached from the levels projected from the EIA in 2030. If the world switched to hydroelectric power for 24% of its electricity generation a reduction of 3.09 ppm carbon dioxide can be realized. If the world were to embrace nuclear energy for 78% of its electric energy needs similar to the energy policy of France, a change of 17.43 *ppm* can be achieved. Of course, what should be kept in mind while reading these numbers is that these energy policies are assuming that the change in energy use were to occur instantaneously in 2005.

We hope that our research into the use of alternative energy sources compared to energy sources which are much more harmful to the environment, such as those derived from fossil fuels, can help people see the benefits of reducing carbon dioxide concentrations by simply pursuing other viable energy policies in the future. We have already made some observations that climate change in the past has had dramatic effects on the human population such as influences

in migrational paths and decreases in crop yields. Further increases in CO_2 concentration levels in the future might prove to have more dreadful results in our daily way of life.

Chapter 1

Introduction

The goal of any Interactive Qualifying Project (IQP) at Worcester Polytechnic Institute (WPI) is for students to tackle a real world project and apply the knowledge acquired in the sciences to solve a problem which is either currently being investigated or hasn't been thought of yet. Specifically, this project must relate to a problem affecting society in some way or has some type of benefit to them. The subject of trace gases qualifies as an IQP because it is an area that impacts not only individuals, but, the whole populous across the world. It is also a subject that has international roots both in cause and effects. What this means is that everyone should inherently have a self interest in trace gases and its effects (climate change) because even if they themselves do not feel any immediate impacts from it, the next generation of humanity will.

Climate change is currently seen as a controversial issue for many people mainly due to the often contradicting views that many scientists and researchers have on the present and newly gathered data. This clash of opinions from professionals has created confusion not just for the general population, but, even for students and faculty from academia who should have the knowledge to understand not just the basic concepts and ideas such as the greenhouse effect and its effects on climate change, but, also the various debates presented such as whether or not the current climate trend is caused by human induced activities or normal fluctuations within the Earth's climate system. Part of the reason both of us wanted to partake in this IQP was because not only did we want to clarify some of the misconceptions related to climate change in a way that was understandable to people with a basic understanding of the sciences, we ourselves wanted to acquire a better understanding to become more informed citizens.

Another reason we both wanted to become involved with this particular IQP is because the analysis of a problem of this magnitude requires the knowledge of many different branches of the sciences such as physics, chemistry, math, and economics. Being the case that one of us is a physics major and the other is a chemical engineering major makes this project even more interesting since we should be able to give our interpretations of climate change from different perspectives using our knowledge of what we have learned from our undergraduate studies so far. This is important in a more subtle sense because due to the fundamental nature of climate change itself complex mathematical models that predict the future climate trends need to be introduced as well as chemical concepts to explain the interaction of trace gases with radiation.

What we hope to accomplish by the end of this project is to not only try to add some type of contribution to the discussion of climate change, but, also to see if we can take something away from it ourselves in terms of the research skills we can acquire. As mentioned earlier, the environmental damage resulting from climate change will have major impacts not just on the environment itself, but on industrial plant designs and specifications. The assessments of these impacts are one of the major responsibilities of chemical engineers. Likewise, the ability to create mathematical models of physical systems forms one of the core foundations of physicists. Ultimately, we wanted to help change the way most people think about climate change because an individual alone cannot divert us from the path that current climate models predict the Earth to be heading towards. In order for the populous to learn about the results of our IQP, we plan on distributing the results of this IQP in WPI's IQP Archives for future referencing and possibly having it published in a professional journal.

Chapter 2

Trace Gases & Their Role

2.1 Greenhouse Effect

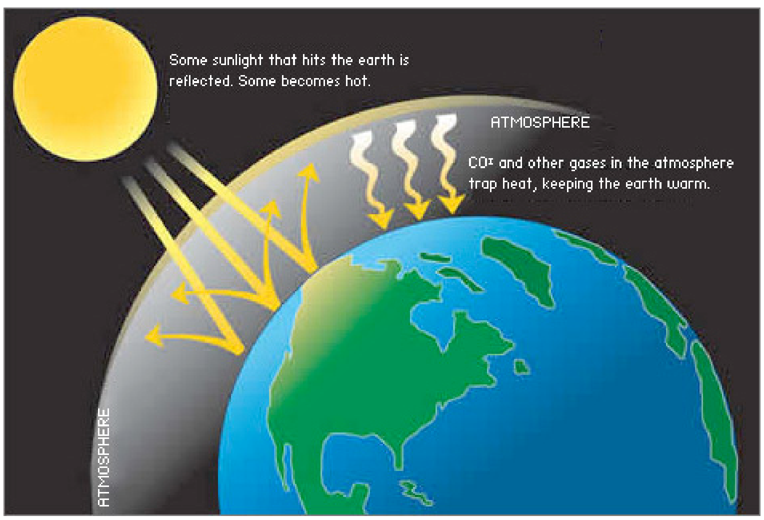


Figure 2.1: Illustrative description of the greenhouse effect. Greenhouse gases trap infrared radiation given off by the Earth after it absorbs incoming radiation from the sun. [56]

Trace gases are the air molecules that comprises less than 1% of the total volume of the Earth's atmosphere. [9] Among these molecules are a subset of molecules known as the greenhouse gases (ghgs) such as carbon dioxide and water vapor. As suggested by their names, they play an integral part in a event known as the greenhouse effect. As shown in Figure 2.1, some of the incoming radiation from the sun becomes absorbed by the Earth's atmosphere which then gets absorbed by its surface and causes it to heat up and release heat in the form of infrared radiation. When the infrared radiation from the Earth propagates back to the Earth's lower atmosphere, the greenhouse gases absorb the heat and one of the following two events occur: either the greenhouse gases emit the

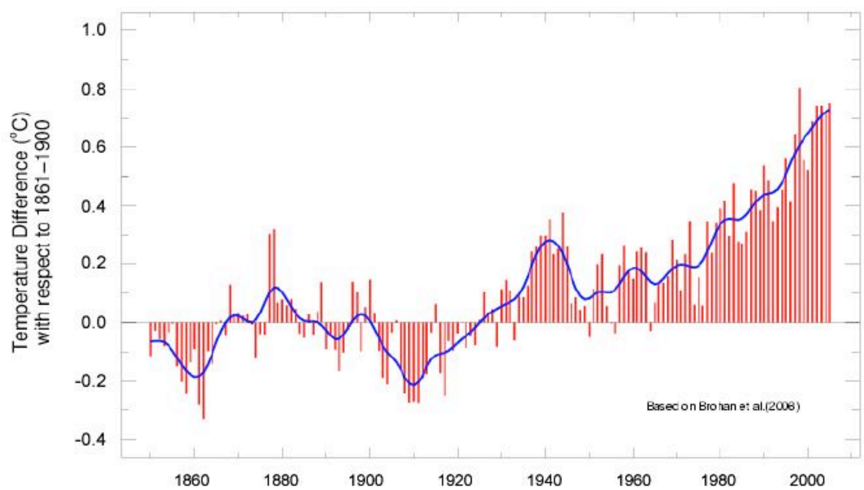


Figure 2.2: A trend of rising global surface temperature is shown. [38]

absorbed heat away from the Earth and thus cool the temperature of the Earth, or they emit the heat back towards the Earth which results in a rising of surface temperatures across the Earth.

Shown in Figure 2.2 is the change in the world's global surface temperatures deviating from time interval 1861-1900. Analyzing the overall trend from this data shows a rising temperature trend from the start of the industrial age to the present time. Although there exists data dating back 1000 years ago showing a sharp increase in temperature around the industrial age, also known as the hockey stick debate due to the shape of the graph's appearance, opponents against the view that the Earth is observing a gradual temperature rise blame this to a lack of precision in the instrumentation for the measurements made.

2.2 Importance of Carbon Dioxide

For our IQP, we focused our efforts on the carbon dioxide greenhouse gas. To help explain why we decided to focus on carbon dioxide individually instead of the other greenhouse gases, it is necessary to look at the absorption spectrum of each of the greenhouse gases. As mentioned earlier, when the Earth absorbs incoming radiation from the sun it releases heat in the form on infrared radiation. This means that the greenhouse gases which absorb a higher percentage of radiation along the infrared spectrum should produce a larger rise in the Earth's surface temperatures. By looking at the absorbtion spectrum shown in Figure 2.3, it is clear that water vapor covers most of the infrared spectrum with carbon dioxide being second. So, why study carbon dioxide over water vapor if water vapor absorbs much more of the infrared radiation spectrum compared to carbon dioxide?

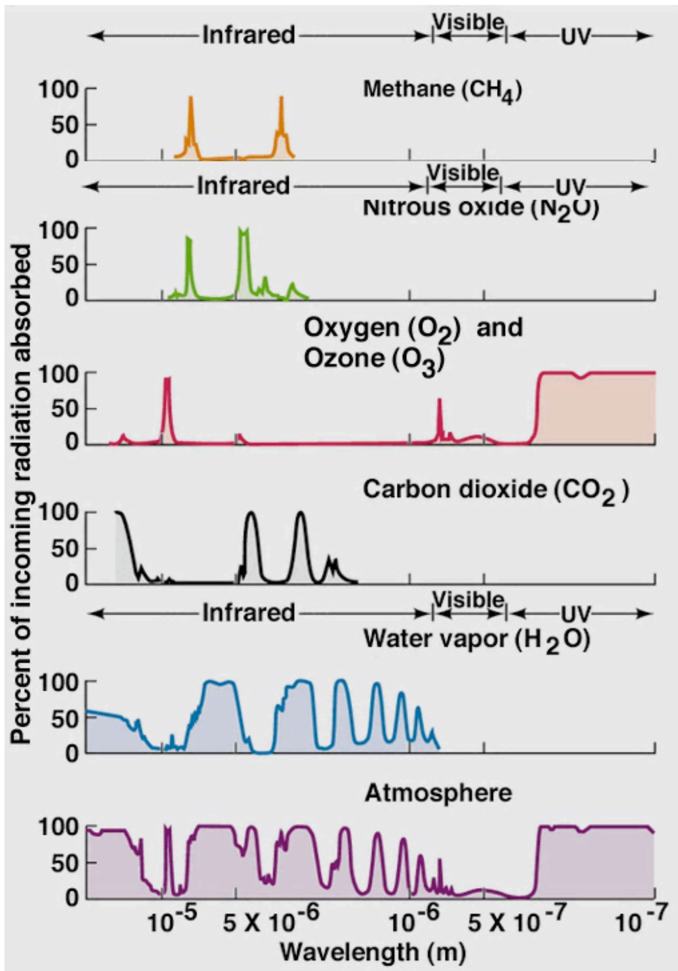


Figure 2.3: Absorbtion spectrum for several of the greenhouse gases. [25]

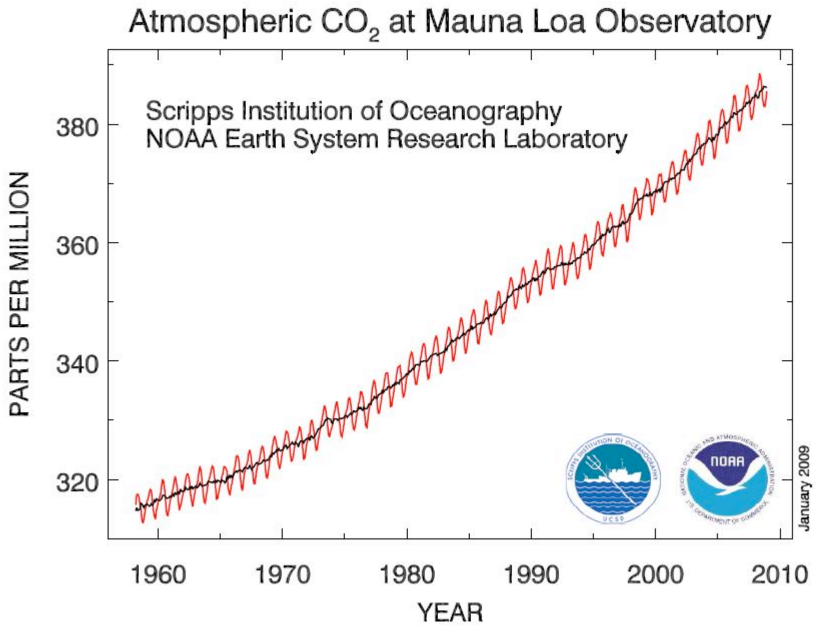


Figure 2.4: Concentration of carbon dioxide measured in the atmosphere at the Mauna Loa Observatory. [22]

The difference in choosing to study carbon dioxide over water vapor comes down to a subtle fact: much of the increase in carbon dioxide concentrations in the atmosphere for the past couple of decades is a result of anthropogenic emissions meaning that much of the current carbon dioxide levels in the atmosphere can be linked to emissions caused by human activities. Human activities can vary from acts such as running a coal plant to burning gas in vehicles. Data from the Mauna Loa Observatory in Hawaii has shown a steady increase in carbon dioxide concentrations from 1960 to the present time as shown in Figure 2.4.

The effects of increasing and decreasing greenhouse gas concentrations, especially carbon dioxide, can help influence the climate across the world and is believed to be partially responsible for the record surface temperature levels observed in some parts of the world in just the past few years. Such changes in climate can influence the migrational paths of the human population, increase the intensities of natural weather such as hurricanes, and affect the growth of crops as well. We hope that our research into the use of alternative energy sources compared to other sources which are much more harmful to the environment, such as fossil fuel plants currently in large use, can help people see the large benefits of reducing carbon dioxide emissions by simply pursuing other viable energy options in the future.

Chapter 3

Motivations for Research

3.1 Early Human Migration

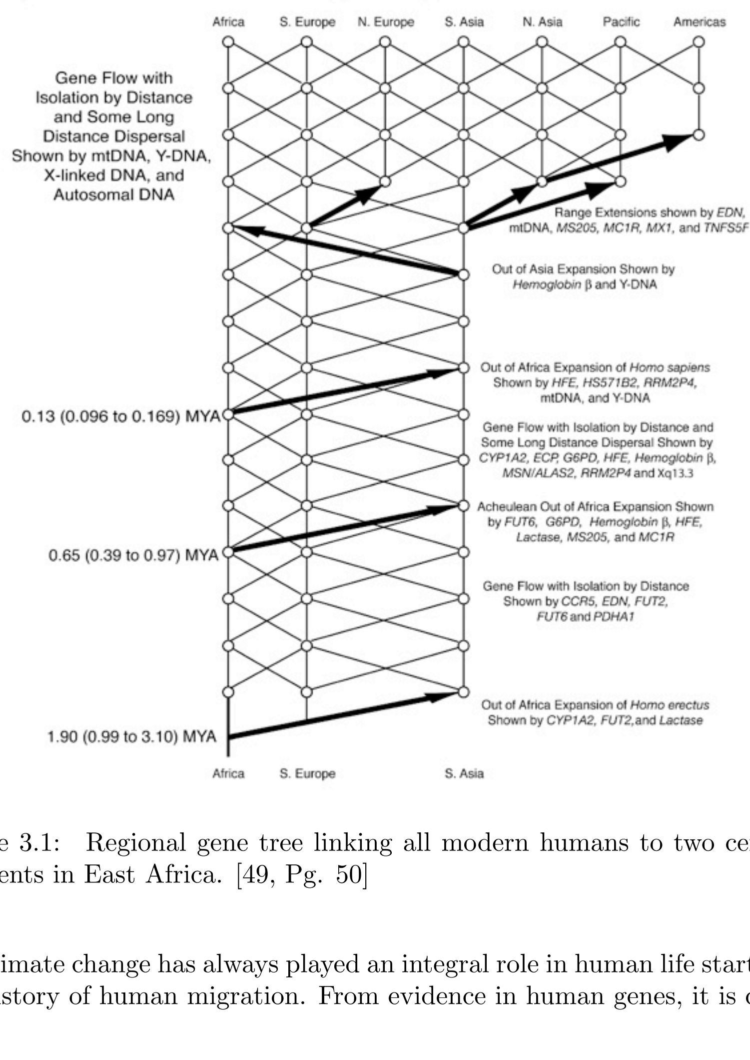


Figure 3.1: Regional gene tree linking all modern humans to two central descendents in East Africa. [49, Pg. 50]

Climate change has always played an integral role in human life starting with the history of human migration. From evidence in human genes, it is currently

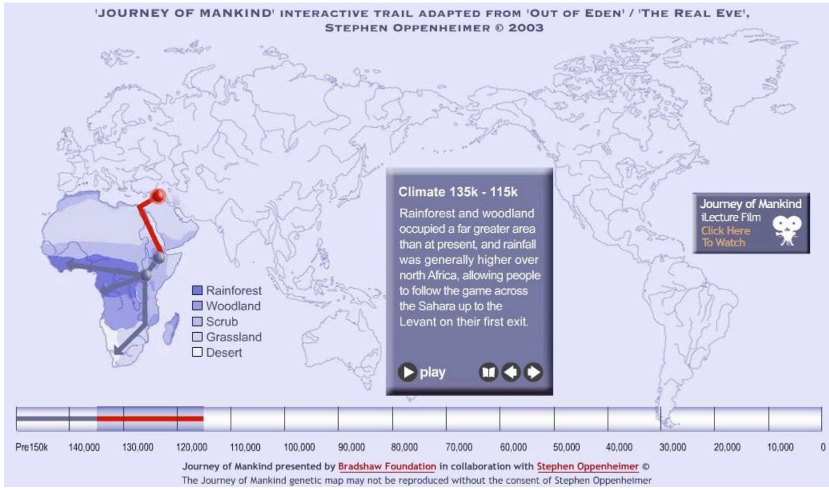


Figure 3.2: The first humans originated from East Africa and eventually propagated throughout the continent. [4]

believed that human life originated in East Africa some 150,000 to 200,000 years ago. It is also believed by many genealogists that every single human being can be traced back to two common ancestors, one male and female ancestor who were inhabitors of East Africa. The evidence for this lies in every male and female's genes. Normally, when hereditary information is passed down from the parents to the offspring their genes are passed down, but, with some slight differences due to an event known as recombination in which the genes reshuffle themseles when being passed on. In women, a specific DNA known as mitochondrial DNA, or mtDNA, is passed down from the mother to the daughter. In males the Y chromosome, which is passed on only to them, contain a specific set of genes which do not go through recombination. This is what allows genealogists to construct a so-called a regional gene tree as shown in Figure 3.1 which is able to link all human beings to a common site in Africa.

The first generation offsprings from this group carrying the first generation mtDNA started from East Africa and spreaded throughout Africa as shown in Figure 3.2. Some eventually transversed through the Sahara desert and up the Nile River. Rain forest was also aplenty in Northern African at the time with much rainfall. However, an extreme freeze killed off a large majority of the people at the time. A new group of people eventually reformed crossing the Red Sea towards India and formed the ancestors of non-African people around eighty-five thousand years ago. Extreme desert shown in Figure 3.3 forced migration along the coastline of Southeast Asia.

Six thousand years later, the eruption of Mt. Toba, the largest volcanic eruption in the history of the Earth evidently, decreased the population immensely to less than ten thousand people and was followed by an ice-age period. Nine thousand years after the eruption of Mt. Toba, the human population regrouped and started to spread to parts of Europe and Australia which the warming of

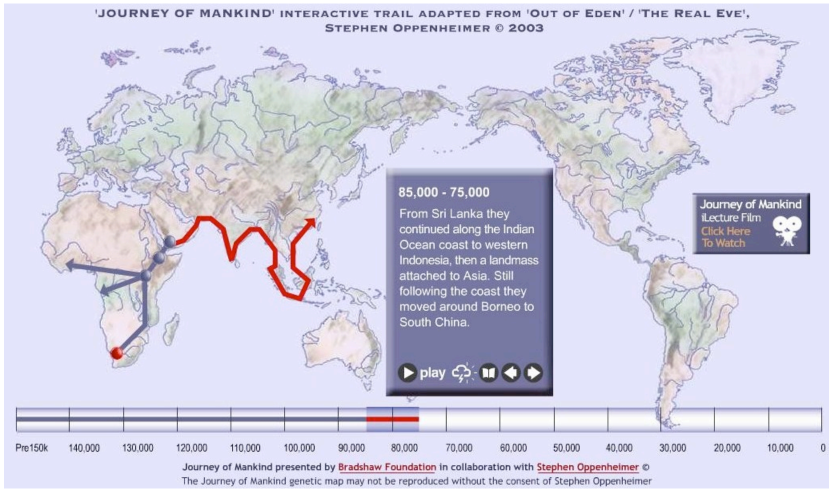


Figure 3.3: Dry desert climate forced our early ancestors to migrate along the coastlines of Southeast Asia. [4]

the climate gave them the ability to do as shown in Figure 3.4.

In twenty-five thousand B.C., humans started crossing the Bering land bridge when sea levels were at a point low enough for humans to cross as shown in Figure 3.5. This continued for roughly three thousand years until the event of the last ice age known as the Last Glacial Maximum as shown in Figure 3.6. Although this inhibited human migration in the northern hemisphere, people were still somewhat free to roam to the south.

Once the last ice age started to pass by, human migration once again flourished and allowed humans to again pass across the bering land bridge as shown in Figure 3.7. This gateway to the Americas, however, would begin to stop once sea levels were no longer low enough to expose the shallow sea bed as shown in Figure 3.8.

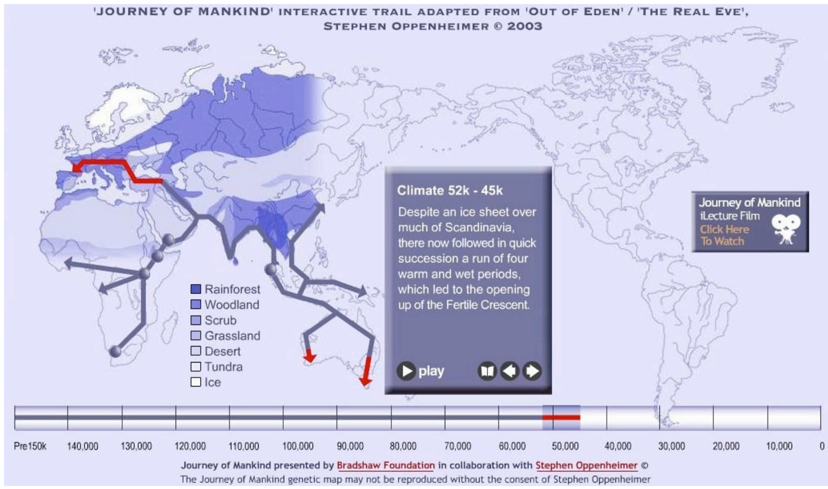


Figure 3.4: Nine thousand years after the eruption of Mt. Toba, humans migrated from Africa to parts of Europe and Australia. [4]

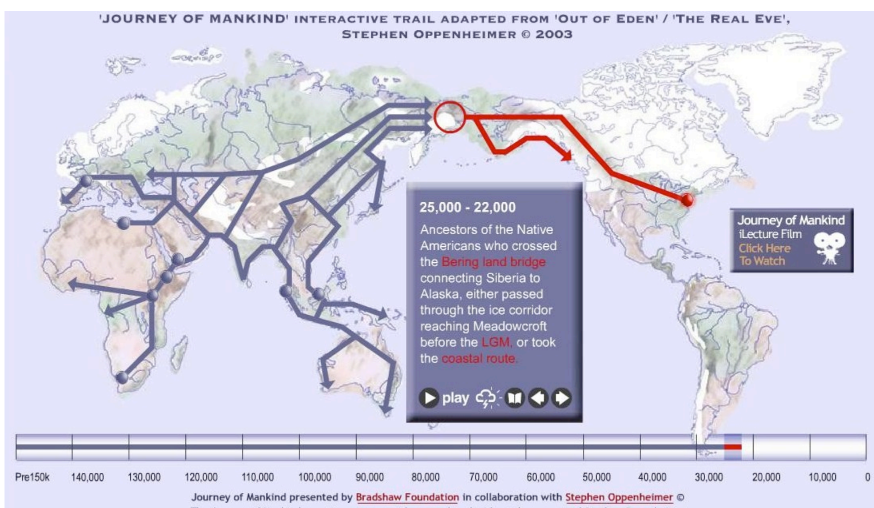


Figure 3.5: Low sea levels allowed humans to cross the Bering land bridge thousands of years ago. [4]

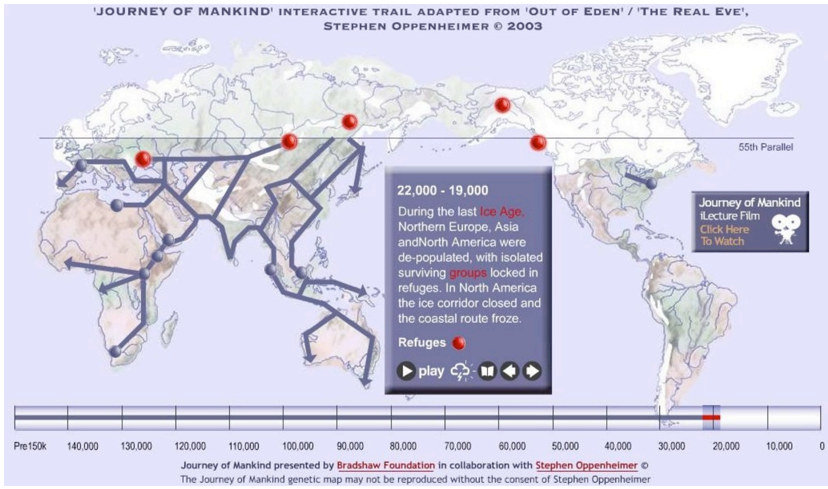


Figure 3.6: The Last Glacial Maximum (LGM) ice age occurred 19,000-15,000 years ago. This inhibited migration in the norther hemisphere, but, still allowed humans to move towards the south. [4]

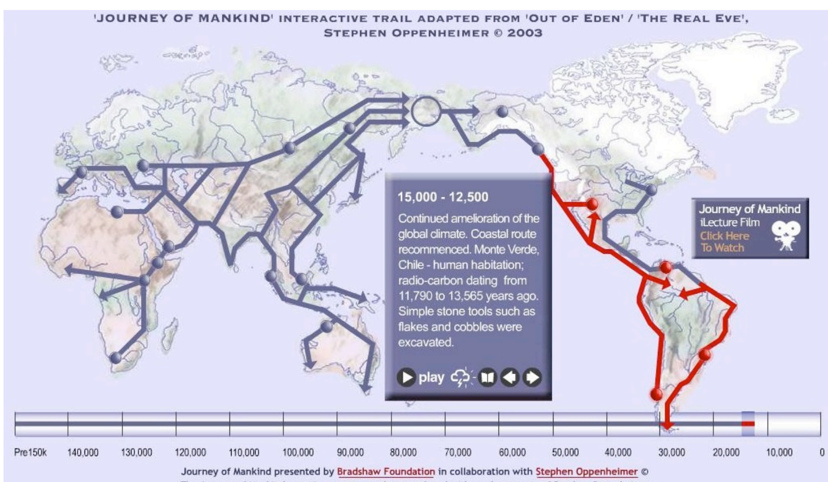


Figure 3.7: Warming of the last ice age allowed humans to once again cross the Bering land bridge and continue migrating in the south further still. [4]

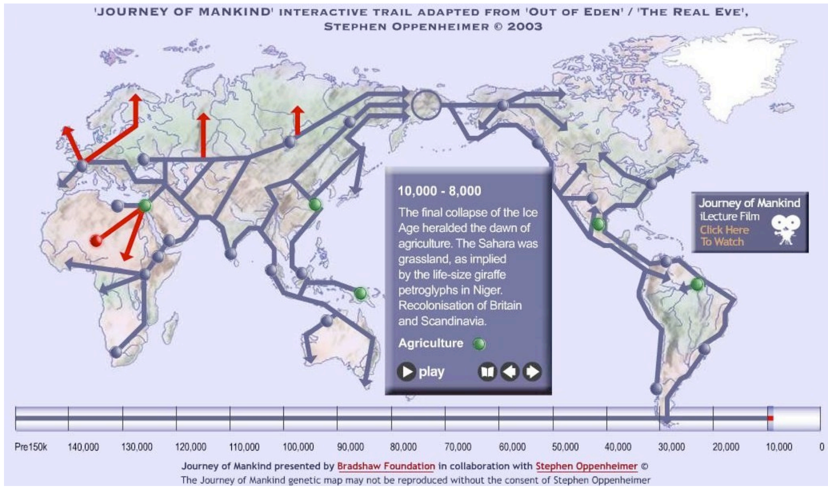


Figure 3.8: The final end of the last ice age no longer prohibited migrational paths of humans, although the Bering land bridge no longer gave a pathway between Europe and North America. [4]

3.2 Moden Migration

Migration related to climate change has also shown itself in the modern period as demonstrated in the migrational paths of Americans in the mid 1900s. Shown in Figure 3.9 are the migrational paths for people migrating to the south from 1965 to 1970. In addition to other reasons for migration at the time, which includes growing job opportunities, climate played a huge factor with warm weather and favorable long growing seasons attracting large numbers of people to the southern regions of the United States. [44, Pgs 67-72]

A high correlation between population density and humid climate within a particular region is also evident. To show evidence of this, we'll refer to the

Climate	Description
Af	No dry season
Aw	Winter dry season
BS	Low-lattitude dry
BW	Mid-lattitude dry
Cw	Mild with dry winter, hot summer
Cs	Mild with dry, hot summer
Cf	Mild with no dry season, warm summer
Df	Hot with severe, dry winter
Dw	Severe winter, cool summer
ET	Polar tundra, no true summer

Table 3.1: Köppen classification system.

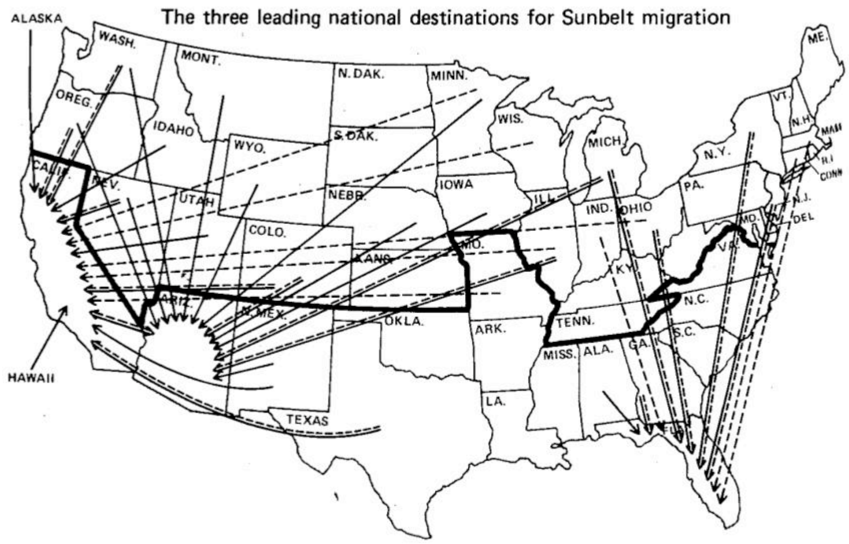


Figure 3.9: Common migrational paths from 1965-1970. This migration was motivated by a combination of warm weather and favorable growing conditions in addition to growing job opportunities in these regions. [44, Pg. 152]

Köppen climate classification system as as shown in Table 3.1. The Köppen climate classification system is a popular method in which the world is divided into 5 major climate regions, listed from A to E, based on average precipitation and temperature. C to Df in particular represent warm and humid climates which are located in the lower to middle lattitudes. Shown in Figure 3.11 is the world map of the various climate regions and shown in Figure 3.10 is the population density per climate region according to the Köppen climate classification system in 1950. C to Df climate regions are more populated compared to locations which are either too hot or too cold which are significantly less inhabited and are represented by the climate types Df to ET as shown in Table 3.2.

Climate Type	Africa	Asia	Europe	Oceania	North America	South America	All
Af	17.4	8.2	-	20.8	8.7	25.1	8.0
Aw	31.8	12.7	-	3.5	4.2	14.7	10.7
BS	18.0	5.4	5.3	1.4	7.7	10.0	6.7
BW	4.5	1.5	0.1	-	0.4	2.4	1.4
Cw	18.0	43.7 -	2.8	4.6	15.7	27.4	-
Cs	10.4	0.9	12.2	9.7	3.2	2.9	4.4
Cf	-	10.4	46.3	61.8	38.8	25.3	20.8
Df	-	6.9	36.1	-	32.5	-	14.06
Dw	-	10.2	-	-	-	5.8	-
ET	-	0.2	-	-	-	4.1	0.3

Table 3.2: Population densities for each climate region in the Köppen classification system. [44, Pg. 69]

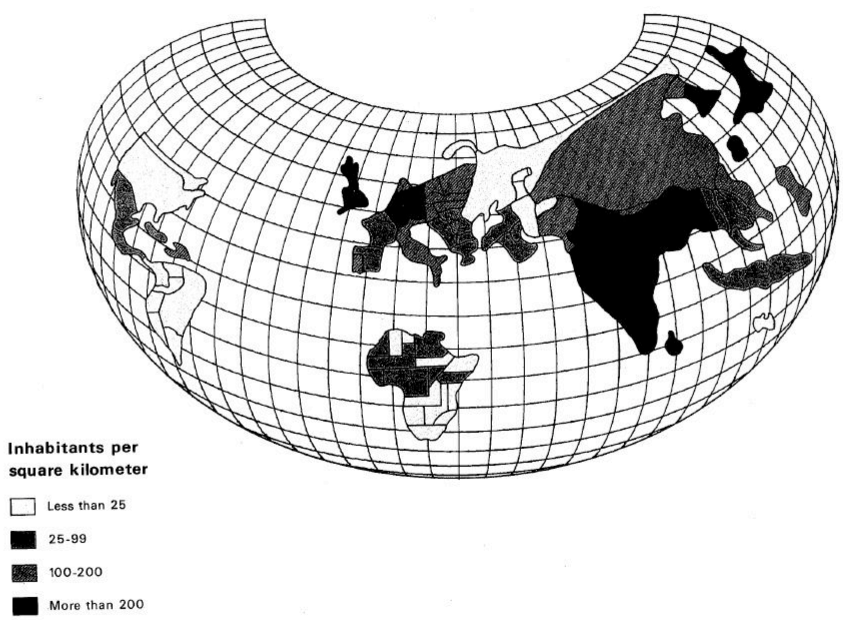


Figure 3.10: Population density of the United States in 1980. [44, Pg. 42]

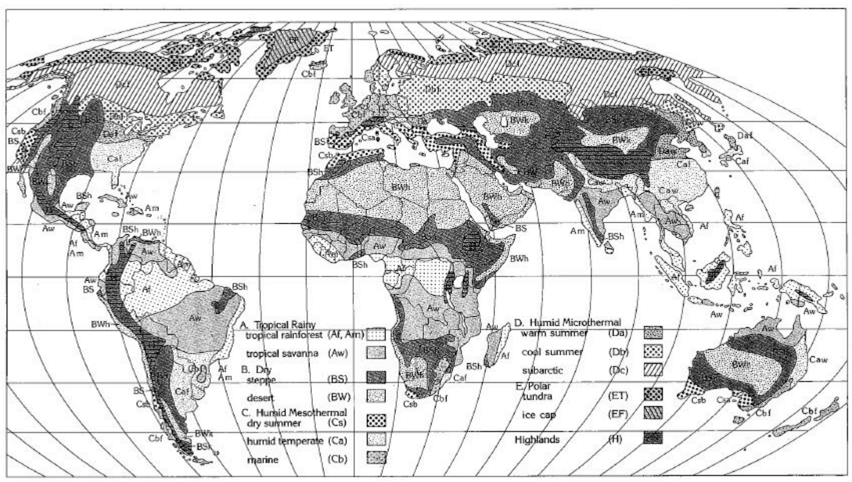


Figure 3.11: Climate is divided into serveral regions and subregions in the Köppen climate classification system. [44, Pg. 68]

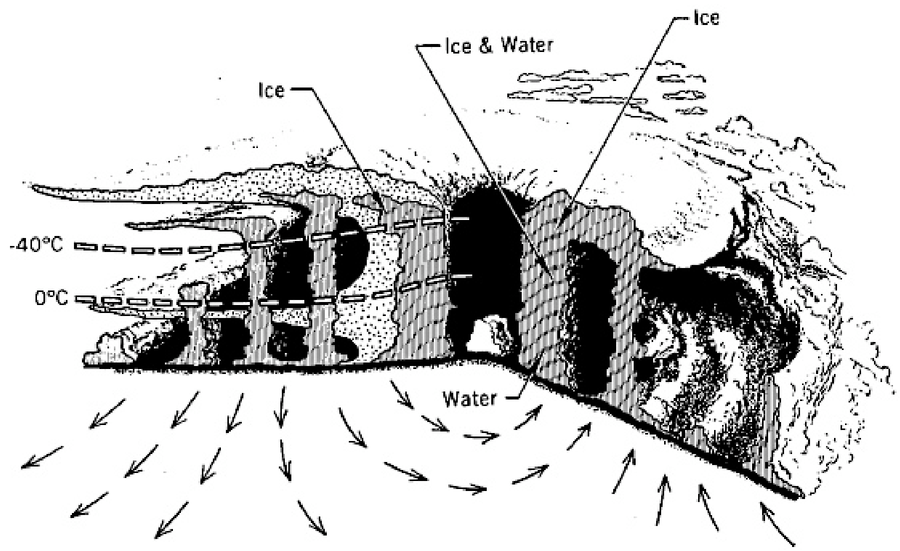


Figure 3.12: Inside structure of a hurricane. [55]

3.3 Hurricanes

Large scale weather phenomena such as hurricanes present major problems for countries with regions adjacent to coastal areas such as parts of the United States, Japan, the Phillipines, and many others due to climate conditions present there that favor hurricane formation. The results of such hurricane occurrences have been detrimental which has resulted in the lost of human and wild life, damage to town and city infrastructures, and private and public property damages that can run easily in the hundreds of milllion to even the billion dollar range. We explore the structure of hurricanes and their formation and the possibilities of reducing such phenomena. [20]

It is important to note at the beginning here that similar to the debate of climate change itself there has been arguments of whether or not climate change has had any noticeable effect on the increase of the number of hurricane events per year or an increase in intensity. An article from *Emanuel*, for example, claims that the power dissipated by tropical cyclones has doubled over the past 30 years. [18] On the other side of the argument, *Pielke et al* claims that no definitive link between climate change and hurricane impacts has been established and also that such claims are premature. [39] However, it is a fact from the fundamental sciences that higher temperature ocean waters have a higher potential to create much more energetic storms and thus, it is important to research this topic relative to the subject of climate change.

3.3.1 Structure and Properties

Hurricanes are defined as tropical cyclones with sustained wind speeds of at least 74 [*mph*] which develop mostly around tropical regions near the equator.

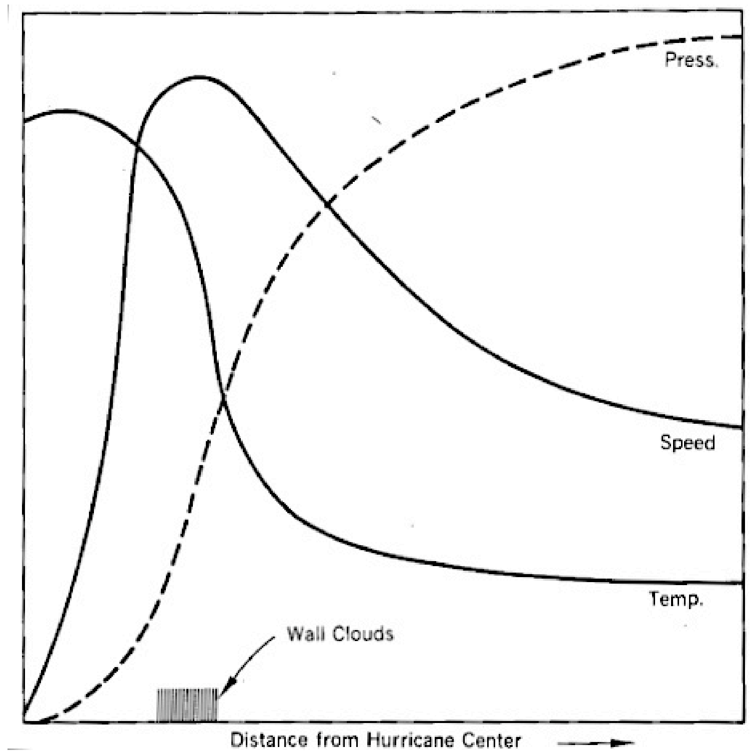


Figure 3.13: Wind velocity, pressure, and temperature in a hurricane relative to its eye.

As shown in Figure 3.12, the center of a hurricane is an area of low pressure known as the hurricane eye. The sections of spiraling clouds are known as rain bands with heavy precipitation. Figure 3.13 shows the wind velocity, pressure, and temperature profile of hurricane in a two-dimensional view. The source of their energy comes largely from the heat and warm moisture in the ocean waters which means that higher temperature ocean waters have the potential to produce much more energetic hurricanes. High relative humidities in the lower atmosphere also help to promote hurricane growth due to the production of more latent heat via a continuous cycle known as CISK (Conditional Instability of the Second Kind). Higher relative humidities imply a high rate of condensation which means that latent heat is being released in the atmosphere as molecules transition from the gas phase to the liquid phase. The release of this latent heat warms the surrounding atmosphere which creates a pressure gradient towards the center of this region above the ocean waters. The warm surface ocean water below then gets pulled along this pressure gradient as shown in Figure 3.14 and warms the atmosphere which further increases the release of latent heat and creates more energy for hurricanes [57].

Typically, water temperatures above 26.5 [$^\circ C$] are needed to for the development of a hurricane. Figure 3.15 shows a map of the sea surface temperatures across the world in Septenber 2008. [53] Yellow, orange, and red hues indicate

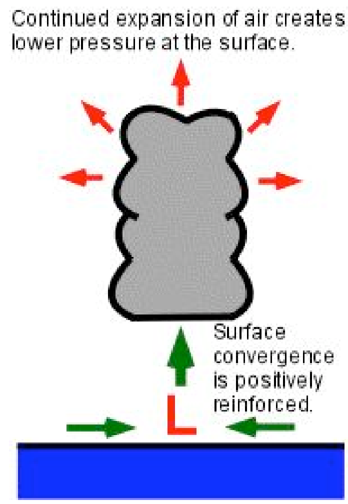


Figure 3.14: CISK (Conditional Instability of the Second Kind) [57].

regions with water temperatures greater than 26.5 [$^\circ C$] and the potential for the development of hurricanes. Weak wind shear also promotes the development of higher intensity storms as opposed to stronger wind shears which spread the latent heat released over a wider region and thus weakens the storm. [57]

From classical mechanics, we know that the force in a non-inertial reference frame on a mass m is given by the following

$$\vec{F} = m\vec{a} - 2m\vec{\Omega} \times \vec{v} - m\vec{\Omega} \times (\vec{\Omega} \times \vec{r}) \tag{3.1}$$

where Ω is the rotation vector of the rotating coordinate system (directed out of the page in Figure 3.16) and v is the velocity of the object (directed to the top of the page in Figure 3.16). In particular, we are interested in the force component denoted by

$$\vec{F_C} = -2m\vec{\Omega} \times \vec{v} \tag{3.2}$$

which is known as the Coriolis force. This force can be though of as a fictitious force in an intertial reference frame and provides an explaination for why hurricans rotate counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. In the northern hemisphere for example, hurricanes rotate counterclockwise due to the combination of the effects of the Coriolis force acting towards the right of the hurricane and the pressure gradient directed towards the low pressure region in the eye as shown in Figure 3.16.

3.3.2 General Circulation

When speaking about the circulation of the climate, what is generally meant is the overall state and trend of the atmospheric climate which is averaged over

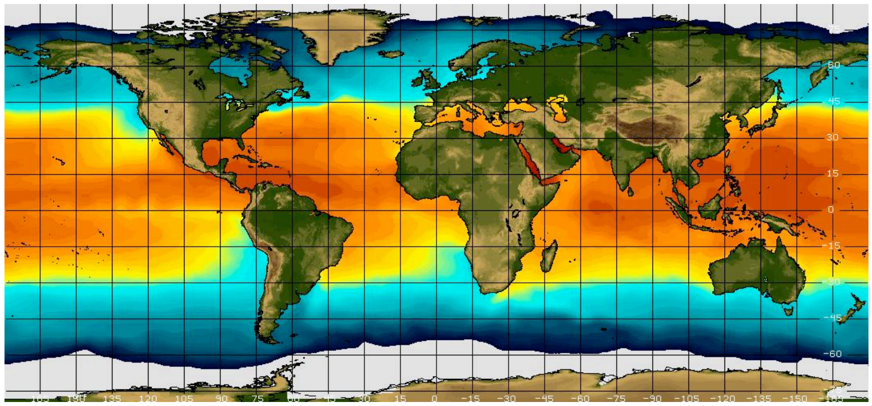


Figure 3.15: Sea surface temperatures from September 16, 2008 [53].

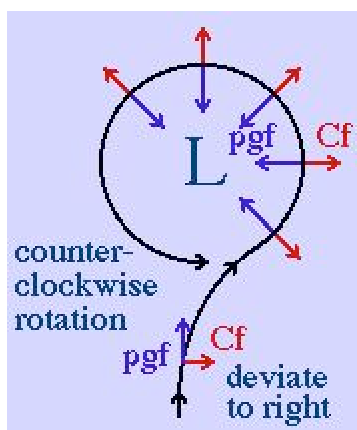


Figure 3.16: Hurricanes rotate counterclockwise in then northern hemisphere due to the net effect of the Coriolis force to the right of the hurricane and the pressure gradient directed towards the low pressure region in the eye [36].

small variations within individual weather systems. However, enough detail needs to be retained so that predictions about seasonal weather patterns and changes can still be made. In this section, the focus is on the region of the Atlantic Ocean and the origin of hurricanes in this area is discussed as well. In addition, atmospheric circulation cells are also briefed upon. [20]

Atlantic Hurricanes

In the middle of the North Atlantic Ocean there exists an area of high pressure near the Azores Archipelago and Bermuda Islands during the summer and fall seasons (hurricane season) that averages roughly 1026 [mBa] as shown in Figure 3.17. Along the equator, the prevailing winds from the immediate north and south, the north easterly and south easterly winds, respectfully, converge into an area known as the Intertropical Convergence Zone (ITC). This is a region of low pressure with its surface pointing perpendicular to the sun and also changes with time. The ITC can vary from a region of hardly any width to a width of 50-100 miles. The width of the ITC can have great effects with larger widths of the ITC invoking tropical storms with help from the rotation of the Earth itself.

Within the area of the ITC is also a subregion called the doldrums. This region is an area of less intense winds compared to other regions in the ITC. One misconception about hurricanes in the Atlantic is that they form in the region of the doldrums or ITC. Although it is somewhat true in the sense that they "originate" from these regions as shown in Figure 3.18, their intensities reach hurricane levels only towards regions diverging away from the ITC and doldrums. Figure 3.19 shows the regions in the Atlantic in which hurricanes become maturely developed which is clearly a significant distance away from the ITC zone.

Circulation Cells

The region along the equator is where the heat flux from the Earth is near its greatest due to the surface normal along that region being more perpendicular to the sun's incoming solar radiation compared to other regions which are higher or lower in lattitude. This is evident by looking back at Figure 3.15 at the sea surface temperatures and noting that the regions of water with high average temperature are located along this area. Because of the higher than normal absorption of electromagnetic radiation in this region compared to others, a thermal convection of air is induced in which masses of air are being heated. This causes the air mass to rise and propagate towards the subtropic regions.

While air masses propagate towards the poles of the Earth, they deflect to the right and left in the nothern and southern hemisphere, respectively, due to the effect of the coriolis force. This resultant path of winds in these region agrees with the easterly winds observed in the tropic regions near the equator. After a certain altitude is reach by these air masses, they eventually fall back down as precipitation.

In addition to high precipitation, the flow of hot air masses from the equator

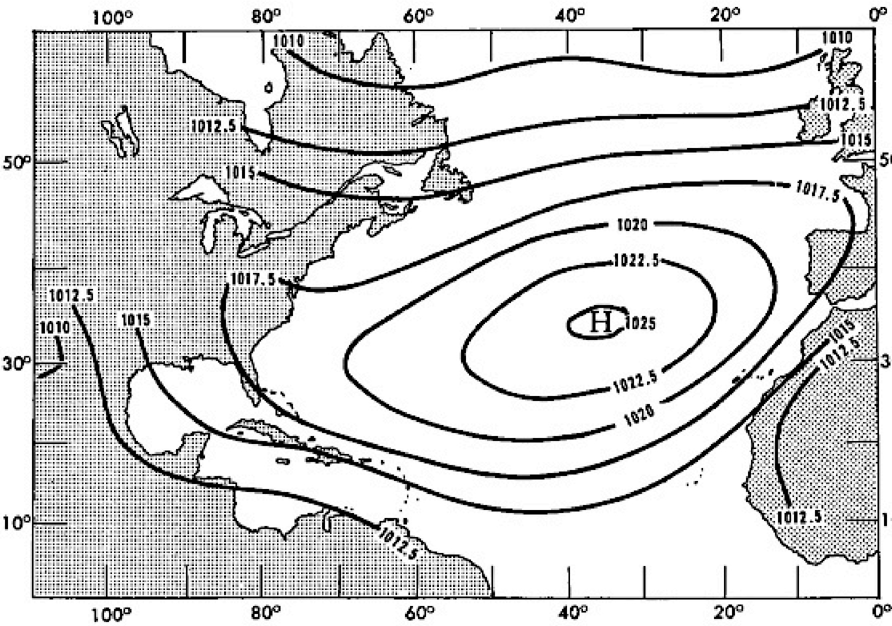


Figure 3.17: Mean sea level pressure in the North Atlantic Ocean in August [13], Pg 16.

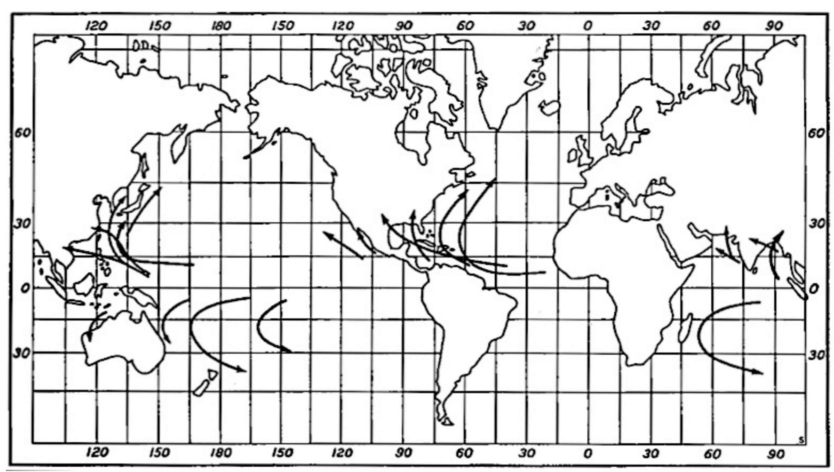


Figure 3.18: Location of tropical cyclone formations [13], Pg 16.

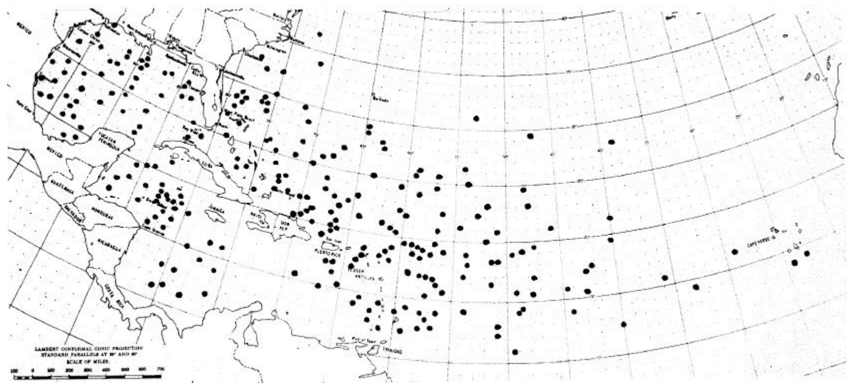


Figure 3.19: Regions in which tropical cyclones reach hurricane level intensities [13, Pg. 16].

to subtropic regions also creates a pressure gradient as well. The air circulation cell, extending from the equator (0°) to ±30° lattitude, resulting from the coriolis force and pressure gradient, is known as the Hadley Cell as shown in Figure 3.20. Two other circulation cells also exists called the Ferrel and Polar Cells which lie beyond ±30° lattitude line. The existence of these other cells is also accredited to the effect of the coriolis force and pressure gradient on the circulation of air in the atmosphere.

3.3.3 Effects on Human Life & Migration

Due to the sheer size of hurricanes and the large land masses they can quickly cover, human migration is often associated with the arrival of hurricanes. As mentioned in the earlier sections, climate has in the past played a crucial role in the migration paths of our early human ancestors and still plays a significant factor in the locations people choose to live in the present day. However, instead of dealing with migrational paths influenced by climate over an extended period of time, we're dealing with disaster events that occur over a period of a few hours or days.

Human migration can be seen as a pre-emptive or post-event response to such natural disasters. Forms of migration can be broken down demographically as follows:

1. Flight - Escape to new location in response to immediate threats
2. Evacuation - Pre-emptive plan to relocate to new location
3. Displacement - Forcing of people to relocate from their homes
4. Relocation - The permanent result of displacement
5. Forced migration - Relocation of people to new and distant locations

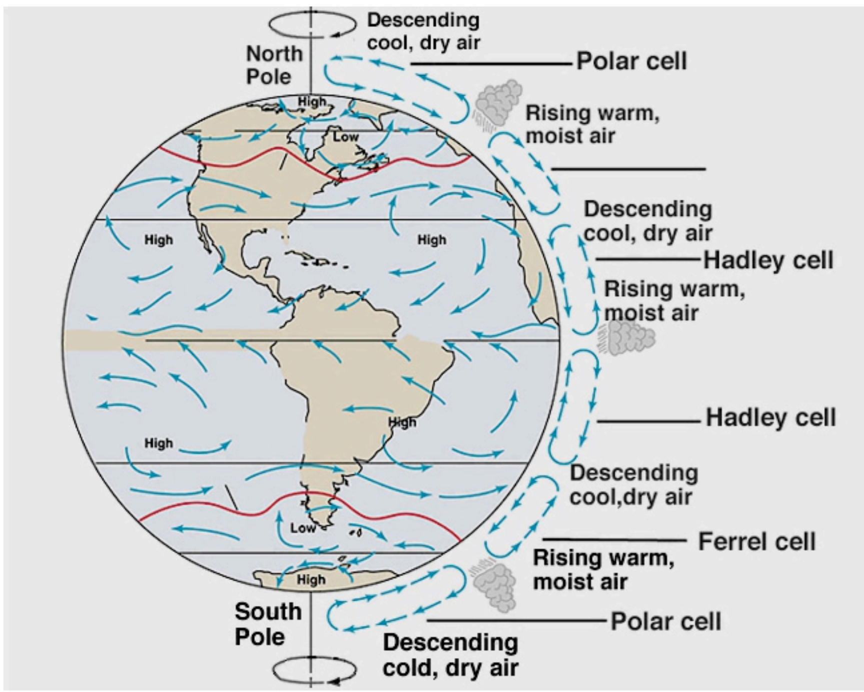


Figure 3.20: Three circulation cells exist due to the effect of the coriolis force from the rotation of the Earth. [24]

Furthermore, each form of migration may be described by one of the two terms in the following list depending on the status one person has with his/her social and economic environment:

1. Pro-active - Reactive
2. Temporary - Permanent
3. Voluntary - Forced
4. Physical danger - Economic danger
5. Administered - Not administered

One of the more devastating hurricanes to have occurred recently was the arrival of Hurricane Katrina which impacted the southern region of the United States on August 28, 2005. Labeled as a category 3 hurricane with sustained winds of 125 mph when it arrived on the coast of New Orleans, it eventually moved along the southern coast of the United States ultimately affecting regions in Louisiana, Alabama, and Mississippi. Hurricane Katrina is reported to have been the most costliest hurricane in terms of damaged performed which is estimated at $81 billion. In addition, 85% of the population escaped the impact of the hurricane with an unfortunate number of more than 1800 people whose lives were lost over the course of the hurricane. At the present time half the population of New Orleans has yet to return with a study by *RAND* estimating that a little over half of the population to be reach towards the end of 2008. [46] [41]

What's interesting to note here is that based on an anaylisis of 729 victims in New Orleans it was found that the average age of death for a victim was 75 years or older. This fact may be attributed to several reasons:

1. Older people may perceive weathering the storm to have less of an impact on themselves than attempting to escape
2. Older people may perceive the storm to be similar to ones they have weathered in the past
3. Older people may be neglected in favor of the younger generation

Also, when an evacuation was in order there were only two official locations for people with special medical needs both which were located over 200 miles from New Orleans. Hurricane Katrina gave evidence to the fact that the evacuation plans for people in New Orleans wasn't as well planned as it could've been not only for everyone, but, for the elderly and clinically disabled especially. [46]

In terms of the economic effects of Hurricane Katrina, they will be far-reaching mostly due to the reconstruction needed to rebuild the infrastructure in parts of Louisiana, Alabama, and Mississippi which is lost opportunity cost that could've gone elsewhere had Hurricane Katrina not impacted the United States at all. Gas prices was also affected due to interruptions in oil production in the Gulf of Mexico as Hurricane Katrina passed through. This shock in rising gas prices, however, was only temporary as oil activity in the Gulf of Mexico returned to full production soon afterwards. Job loss was also something which was hugely impacted after Hurricane Katrina. At the lowest point after the effects of Hurricane Katrina job loss was at an outstanding 105,300 in November 2005. At the current pace it is estimate that rebuilding New Orleans will take toughly 20-25 years. [12]

3.3.4 Past Hurricane Modification Experiments

Although the thought of controlling natural weather phenomena as violent as hurricanes may seem ridiculously implausible at first thought, there has been previous attempts in doing so. The first experiment to attempt modification of hurricanes was made on October 13, 1947 by a group led by Irving Langmuir, Nobel Laureate in chemistry, called Project Cirrus. Previous research leading up to this event included those perfomed by Langmuir's colleague, Vincent Schaefer, in the area of supercooled fluid where he also discovered that at very high altitudes, hurricanes contained large amounts of this type of fluid. That is, fluid formed from condensed water vapor with temperatures below freezing that is not in the solid phase. It was observed previously that dropping finely grounded dry ice on supercooled liquid droplets caused freezing and later on with AgI as well. The basic idea behind cloud seeding is to cause the supercooled water vapor to freeze which would eventually falls towards Earth as snow or precipitation depending on the climate conditions at the time. Because an experiment on modifiying natural phenomena as large as hurricanes had never been performed before the purpose of this experiment was to simply observe the effects of dropping 200 lbs of dry ice outside the eye wall of a hurricane in Jacksonsville, Florida. The observed results after seeding the hurricane was that instead of moving to sea as was expected of the hurricane, it moved inland. However, years after the experiment was performed it was concluded that the effects of the seeding could not have possibly affected the course of the hurricance and that the air circulation surrounding the hurricane was able to account for the change in path. [45]

From 1961 to 1983, Project Stormfury was conducted as a joint research program between the U.S. Weather Bureau and U.S. Navy and later on with the National Oceanic and Atmospheric Administration and U.S. Airforce. The purpose of this research project was "to investigate possible thermodynamic imbalances which may permit the modification of the structure and movement of hurricanes." Because of the sparse occurances of hurricanes suitable for seeding, hurricanes with well developed eye walls and hi-wind speeds, only several hurricanes were chosen for seeding. Located 400 miles north of Puerto Rico, Hurricane Esther was the first storm chosen for seeding on Sept 16, 1961. Part of the reason for picking Hurricane Esther and the other storms chosen for Project Stormfury was because of their distances away from mainland. This was to avoid any complications that had occured earlier with the hurricane chosen for experimentation in Project Cirrus which had moved inland and caused an uproar. The first day of seeding showed signs of decreasing storm intensity and a wind speed change of -10%. However, the second day of seeding was not as successful due to the seed canisters being dropped outside of the eye wall of the hurricane. Nonetheless, the results from this first experiment were promising and led to two more hurricanes being seeded. [45, Pg. 165]

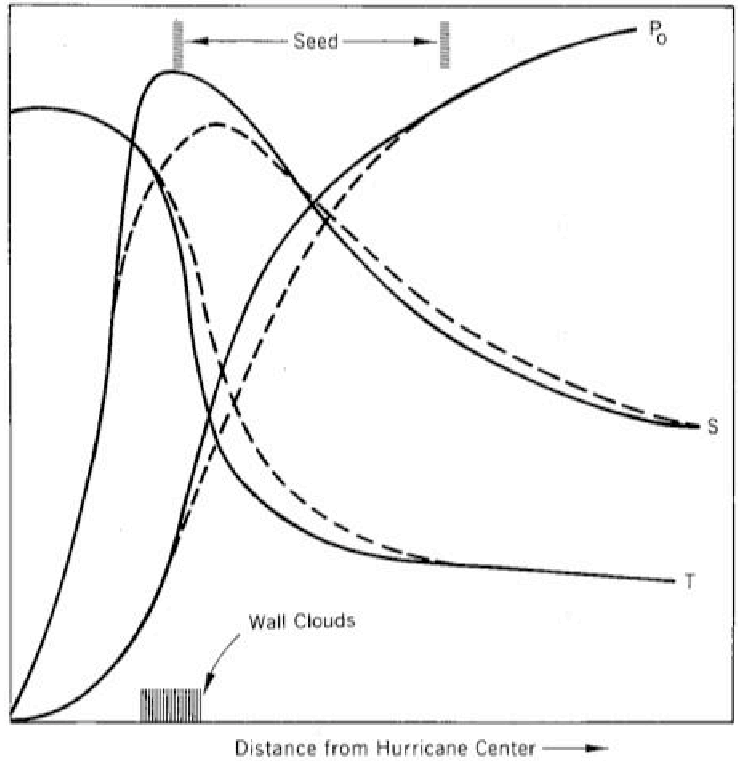


Figure 3.21: Region within hurricane which was seeded with AgI crystals. [20]

Hurricane	Date	Seedings	AgI Used $[kg]$	Speed Change [%]
Esther	Sept. 16, 1961	1	35.13	-10
Esther	Sept. 17, 1961	1	35.13	0
Beulah	Aug. 23, 1963	1	219.96	0
Beulah	Aug. 24, 1963	1	235.03	-14
Debbie	Aug. 18, 1969	5	185.44	-30
Debbie	Aug. 20, 1969	5	185.82	-15

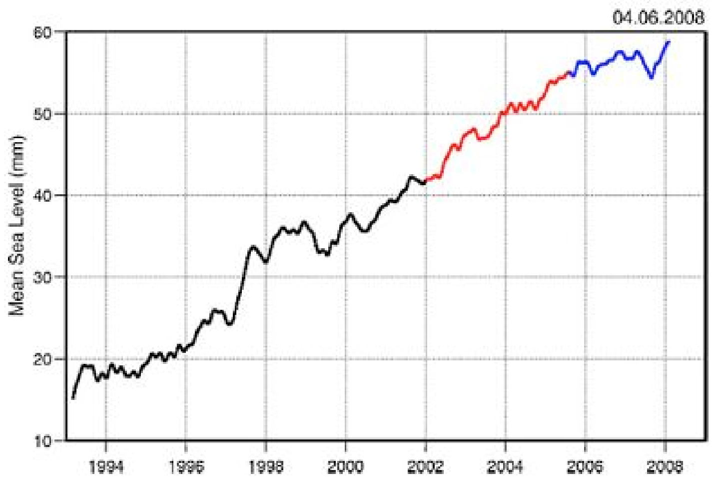
Table 3.3: Observed wind speed changes for various number of seedings and AgI used. [20]

Hurricane Beulah was the next hurricane chosen for seeding on August 23, 1963, located approximately the same location where Hurricane Esther was. The first day turned out to be a failure due to the researchers missing their target with the seeding and less than ideal wind speeds (90 [*mph*]). The next day proved more successful which gaves hurricane speeds of up to 115 [*mph*] which was suitable enough for seeding. A decrease in wind speed of 14% was measured for the next day. Part of the reason for improvements in pecentage decrease in wind speed over Hurricane Esther might be attributed to the use of an improved silver iodide deployment sytem which was more effective than the one used for Hurricane Esther. [45]

Seeding resumed again on Aug 18, 1969 when Hurricane Debbie arrived 700 miles east of Puerto Rico. The seeding technology had increased by this point in time and also, it was decided that the seeding time would increase as well. Wind speeds decreased from 115 [*mph*] to 80 [*mph*], a 30% decrease. However, 24 hours after seeding the hurricane the winds increased back to 115 [*mph*]. Once it was reseeded again on the 20th, the wind speeds decreased down to 100 [*mph*]. Later analysis of the hurricane status on the 18th showed that large-scale weather patterns could've accounting for the large percentage decrease measured. However, the seeding was declared a success overall. Figure 3.21 shows the region in which seeding took place and Table 3.3 displays the results obtained from seedings for Hurriances Esther, Beulah, and Debbie. [45]

3.4 Melting Polar Ice Caps

There are many questions to ask when it comes to what the effects of the melting polar ice caps will have on the world and how quickly they will occur. There have been satellites recording the sea levels over the past 15 years and includes the satellites Topex, Poseidon and Jason-1 as shown in Figure 3.22. The overall average rate of sea level rise for this data is about 3.1 ± 0.1 mm/yr. A correction for the fact that the comparison between altimetry-based sea level change and tide gauge records over their overlapping time span suggests a more realistic error of 0.4 mm/yr. Since there is global deformation of ocean basins due to postglacial rebound (or glacial isostatic adjustment [GIA]) another correction is needed. After these corrections the rate of sea level rise is 3.4 ± 0.4 mm/yr. [6]



Sea level curve from Topex/Poseidon and Jason-1 satellite altimetry over 1993–2008 (data averaged over 65°N and 65°S; three-month smoothing applied to the raw 10-day data). Black: Topex/Poseidon; red: Topex/Poseidon plus Jason-1; blue: Jason-1.

Figure 3.22: [6]

But, before satellite data there was data from tide gauges, reconstruction methods that combine tide gauge records and regional variability from Topex/-Poseidon altimetry, thermal expansion data or general ocean circulation model outputs. The past 50 years of the data in Figure 3.23 gives an average sea level rise of 1.7 mm/yr. [6] But the sea level rise is not linear; it is increasing, even though it is not at a rapid rate. Within the fluctuations in the rate of sea level rise there is usually a 20 year decrease in sea level instead of a rise in sea level. There is a possibility that the increased rate of sea level rising is caused by global warming. If so, it is estimated that there will be a 15 to 30 cm rise in sea level by 2050 and a 34 to 65cm rise by 2100, although, this only accounts for greenhouse warming and not other factors. [50]

The sea level could rise even faster if the Antarctic Ocean temperatures increase by 5°C or if the temperature of Greenland rises by more than 10°C.

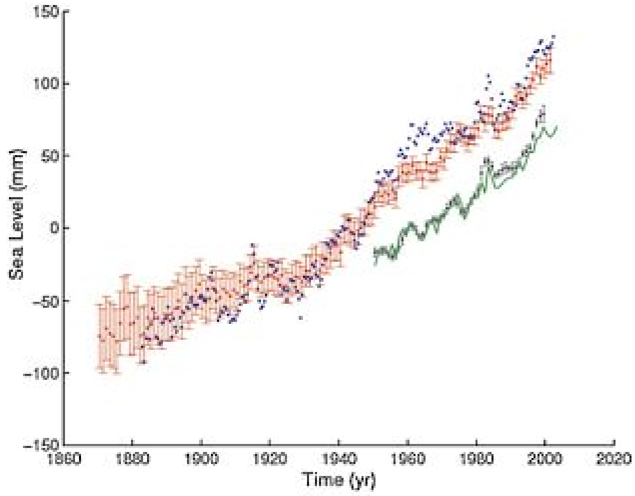


Figure 3.23: Sea level curve for the 20th century base on different tide gauges data and reconstruction analyses. [6]

However, these are not likely to occur in the near future. [50] The higher latitudes will experience a larger temperature change than the mid-latitudes making this temperature change more likely. Ice mass loss around the costal regions of Greenland are caused by surface melting and runoff into the sea and glaciers moving outward away from the land are pulling ice from the interior. About 50% of the ice mass loss is due to surface ice melting and runoff into sea. The other 50% is due to outlet glacier motions draining ice from the interior of the ice sheet. Although the Greenland ice sheet has a slight increase in mass in the center of the ice sheet due to snow, overall there is a major loss of ice. As for the Antarctic, the ice mass lost is about even, but, slightly favoring mass loss. The Western half is losing mass at an accelerated rate while the East is gaining mass since there was a small increase in snow precipitation. Because of these opposing forces the Antarctic ice sheet is nearly in balance, but, slightly favoring mass loss like the Greenland ice sheet. Sea level rise contributions from Greenland and Antarctica are .2 ± 0.04 mm/yr and .21 ± 0.17 mm/yr respectively (1993-2003). [6]

Mountain glaciers and small ice caps have been melting and receding over the recent decades. It is estimated that the glaciers ice melt contribution to sea level rise over the past four decades was about 0.5 mm/yr since 1960. From 1993 to 2003, their contribution was a sea level rise of 0.8 ± 0.17 mm/yr. The most recent estimates suggest that sea level rise has accelerated since 2003." [6]

The GRACE mission has provided new tools since 2002 that can directly measure the mass balances of the ice sheets. It uses gravity sensors to detect changes in mass, assuming that the mass change is from changes in snow mass. It has also given data on the ice sheets that suggest a net mass loss on both the Greenland and Antarctic ice sheets. GRACE is still in its initial stages so it is not

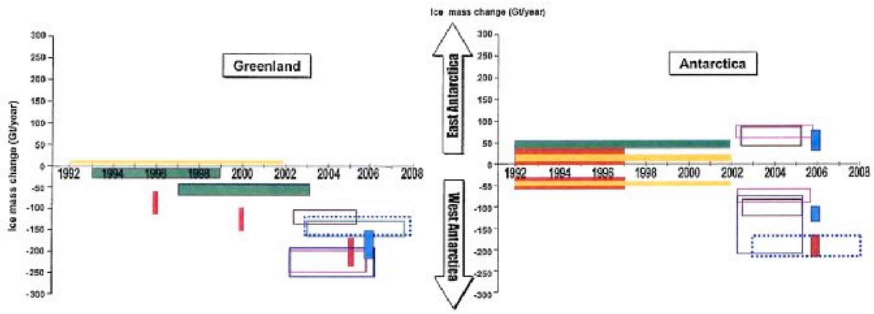


Figure 3.24: Ice volume change of the ice sheets (in Gt/year) estimated over the recent years from different remote sensing techniques. Left panel: Greenland ice sheet; right panel: Antarctica ice sheet. [6]

completely certain that this data may be reliable. However, other sensing equipment are recording similar results.

Changes in land water storage have also contributed to a rise in sea levels and may be linked to human activities and climate variability. "Changes in the amount of water stored in soils, reservoirs and aquifers result from dam building, underground water mining, irrigation, urbanization, deforestation, etc." It has been reported that there arent dramatic changes in sea levels due to changes in land water storage. These changes happen over decades in fluctuations of about 1-2 mm. GRACE observations can estimate the total land water contribution to sea level and the contribution is about 0.2 ± 0.1 mm/yr. Land water storage only plays a significant role on a short time scale and rather insignificant on a larger one. [6]

The rate of the sea level rising could be slowed if there was stabilization in greenhouse emissions. If greenhouse emissions are stabilized by 2050 through alternative energy sources, the sea level rate would likely be reduced by 15 percent in 2100 compared to the normal expected rate. If we could somehow stabilize emissions by 2025, the sea level rate would likely be reduced by 50 percent in 2100. But if there is a significant growth in greenhouse gas emissions in the next century the rate of the sea level rising could increase to 6.2 mm/yr. [50]

Sea level rises not just from melting glaciers and ice sheets but also from the thermal expansion of seawater and changes in seawater density due to temperature and salinity changes. These contributions to sea level changes are characterized as steric changes. The oceans are the major storages of energy. Due to the shear mass and the large heat capacity of sea water, the oceans hold between 10 to 15 times the amount of heat than the heat stored by the land and atmosphere. Over the past 50 years, the steric changes accounted for an increase of 0.2 to 0.4 mm/yr in sea level, but in recent years this rate has increased to 1.5 ± 0.3 mm/yr. Most of the time temperature and salinity contributions compensate for each other. Sea level changes are not uniform over the entire Earth. These changes go in cycles between the Pacific and Atlantic

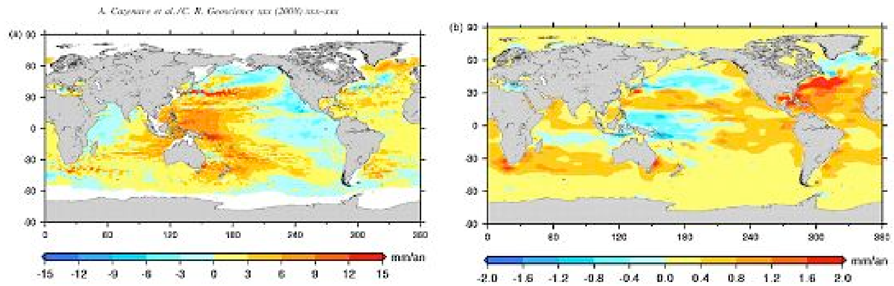


Figure 3.25: a. Spatial patterns in thermal expansion trends over 19932003. b. Spatial patterns in thermal expansion trends over 19552003. [6]

Oceans. These changes are called the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO) phenomena. [6]

From 1993 to 2003 the climate related changes in sea level contributed a rise in sea level of 3.0 mm/yr. This summation of data is very close to the actual altimetry-derived rate of sea level rise of 3.1 mm/yr. Sea levels have been rising at an increasing rate since the early 1990s. The ice sheets are also melting at an increased rate and are accounting for the majority of the rise in sea levels with steric effects and land water effecting it slightly.

3.5 Marine Life

The oceans can be greatly affected by climate change. As CO_2 concentrations increase the mean temperature of the water would also increases. This would lead to a decrease in oxygen solubility in the oceans. This would disrupt the ocean food chains and possibly force certain species into extinction. Also as CO_2 concentrations increase in the atmosphere, the concentration of CO_2 in the oceans would also increase due to Le Chatelier's principle. Increasing the concentration of CO_2 in the oceans would lead to an acidification of the deep ocean. These two effects would have major impacts on the marine ecosystems.

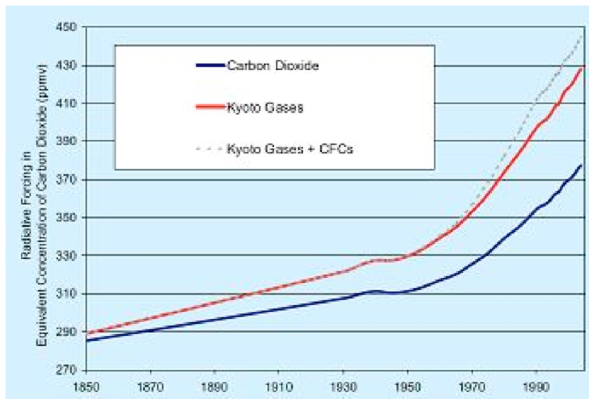


Figure 3.26: Rising levels of greenhouse gases The figure shows the warming effect of greenhouse gases (the radiative forcing) in terms of the equivalent concentration of carbon dioxide (a quantity known as the CO_2 equivalent). The blue line shows the value for carbon dioxide only. The red line is the value for the six Kyoto greenhouse gases (carbon dioxide, methane, nitrous oxide, PFCs, HFCs and SF6)6 and the grey line includes CFCs (regulated under the Montreal Protocol). The uncertainty on each of these is up to 10%. The rate of annual increase in greenhouse gas levels is variable year-on-year, but is increasing. [48]

As CO2 concentrations increase so does the amount of radiative forcing as shown in Figure 3.26. Radiative forcing in turn increases the temperature of the Earth. This would cause the temperature of the ocean waters to heat up. When the temperature of ocean water increases the amount of oxygen that is able to be absorbed into the water decreases as shown in 3.27. This change in oxygen concentration affects the amount of organisms ability to live, grow and reproduce in the oceans. Lower oxygen concentrations also cause slowed growth rates to metabolic impairment, and eventually death. This would have a major effect on the fishing community because if the reproduction rate of fish and marine organisms is slowed down, the potential for adult sized fish to be caught annually would also decrease. [51]

The temperature of higher-latitudes would increase faster than lower-latitudes, so disrupting northern marine ecosystems more drastically. The northern marine organism that would be affected greatly are pink salmon, broad whitefish

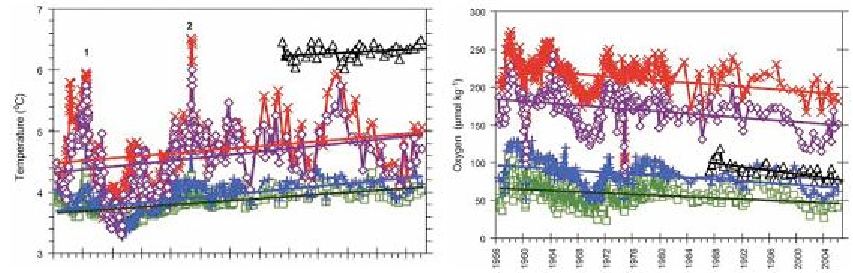


Figure 3.27: Temperature and oxygen trends at Ocean Station P (50°N, 145°W) on the 26.5 (×; 140 ± 15 m), 26.7 (⋄; 168 ± 17 m), 26.9 (+; 278 ± 27 m) and 27.0 (□; 370 ± 44 m) isopycnal surfaces and at station P4 (△; 48.66°N, 126.67°W) on the 26.7 surface. P4 is warming at 0.0084°C $y1$, with O_2 declining at 1.22 μmol kg1 y1. Two mesoscale eddies are labeled 1 and 2. [51]

(Coregonas nasus), Arctic char (Salvelinus alpinus), Arctic grayling (Thymallus arcticus) and Arctic cisco (Coregonus autumnalis) since they are very sensitive to temperature change and prefer a small range of optimal temperature. Also with increasing temperature there are fewer icebergs year round (3.28) and the oceans are clear for fishing more of the year, so more of these fish will be caught on an annual basis. These two effects would greatly decrease the fish population in these oceans. As the temperatures of the oceans increases, so does the line between marine ecosystems. This makes it easier for species invasions to occur and possibly bring along diseases to higher-latitudes and affect the ecosystems even more. Also a food supply for most fish, phytoplankton, has been shown to decrease both in biomass and reproduction rate when the ocean waters warm up. Shrinking icebergs also affect the marine ecosystem in a different way. The krill population, a major food source for the Antarctic, has decreased with decreasing sea ice concentrations. Other species that have adapted to living on the edge of sea ice also have and will continue to decrease such as crustaceans, penguins, seals, polar cod, polar bears and narwhals. [51]

Warmer sea water decreases the solubility of CO_2, but since there is a greater concentration of CO_2 in the atmosphere, it is still being dissolved into the oceans increasing the concentration of CO_2 in the oceans. This is mainly due to Le Chatelier's principle, which states that if a chemical system at equilibrium experiences a change in concentration, temperature, volume, or total pressure, then the equilibrium shifts to partially counter-act the imposed change. So an increase in concentration of CO_2 in the atmosphere will increase the concentration of CO_2 in the oceans. To find the concentration of CO_2 in the ocean water for a given atmospheric concentration can be described by Henrys Law since the CO_2 concentration in the sea water is relatively small to the concentration of water. The equations for Henrys Law are

$$y_{CO_2} P = x_{CO_2} H_{CO_2} \tag{3.3}$$

$$y_{H_2O} P = x_{H_2O} P^{sat}_{H_2O} \tag{3.4}$$

Where y is the mole fraction of substance 1 in the gas phase, x is the mole fraction of substance 2 in the liquid phase, P is the pressure, H is Henrys constant,

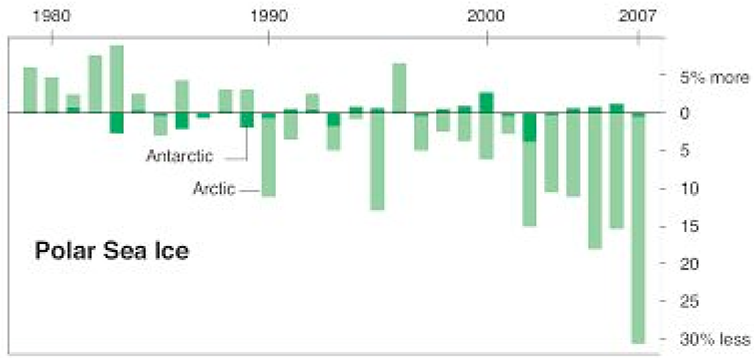


Figure 3.28: Sea ice in the Arctic and Antarctic Oceans: Sea ice has declined in the Arctic in both summer and winter, and slightly increased around Antarctica in summer. Above is average deviation from August. [51]

and Psat is the saturation pressure of water. Both H and Psat depend on temperature, so as temperature increases H and Psat increase. This simplification to phase equilibrium assumes that the mole fraction of $x_{1(co_2)}$ is near 0, the mole fraction of CO_2 in sea water is in the hundredths or thousandths. While the mole fraction of x_{H2O}, water in sea water, is near 1. These equations might not be able to be used since sea water has NaCl dissolved in it and the system actually has three variables that are dissolved in the sea water.

When CO_2 is in water it reacts with water to form carboxylic acid (H_2CO_3). The amount of reactants (CO_2) that reacts and forms the product (carboxylic acid) depends on the equilibrium constant, k. The equilibrium equation is

$$k_{eq} = \frac{[C]^c[D]^d}{[A]^a[B]^b} \tag{3.5}$$

for the general reaction of

$$A^a + B^b \Leftrightarrow C^c + D^d \tag{3.6}$$

The equilibrium equation for the reaction of carbon dioxide and water to form carboxylic acid is

$$k_{eq} = \frac{[H_2CO_3]}{[CO_2][H_2O]} \tag{3.7}$$

The equilibrium reaction is

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \tag{3.8}$$

There are two more equilibrium reactions that can occur.

$$H_2CO_3 \Leftrightarrow HCO_3^- + H^+ \tag{3.9}$$

$$HCO_3^- \Leftrightarrow CO_3^{2-} + H^+ \tag{3.10}$$

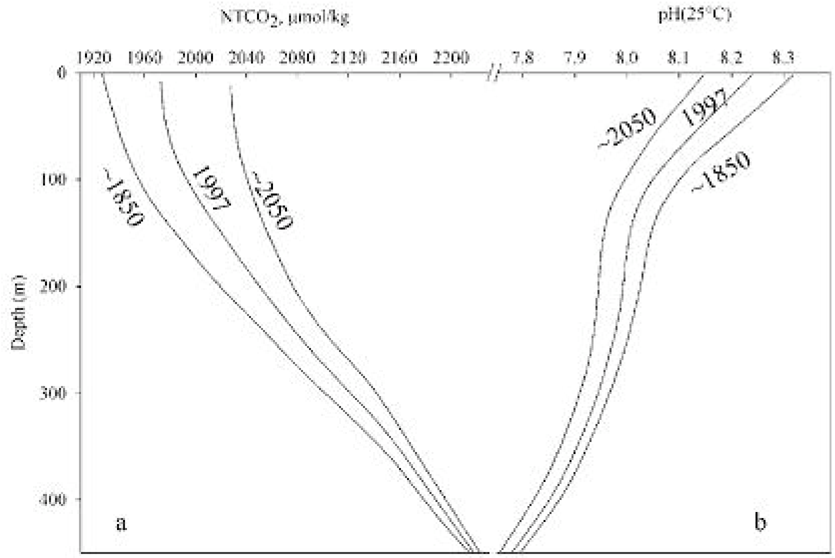


Figure 3.29: Typical pre-industrial (1850), present (1997) and projected (2050) (a) NTCO_2 (total CO_2 concentration at a salinity of 35) and (b) pH vertical profiles of seawater in the South China Sea. [51]

The most preferred product of these reactions is the HCO_3^- (bicarbonate ion) since the carboxylic acid dissociates in water to form a bicarbonate ions and hydrogen ions. The hydrogen ions formed by this reaction forces the reaction where the product is carbonate ion (CO_3^{2-}) toward the reactants and forms bicarbonate ions. So the reactions that actually take place are

$$H_2CO_3 \rightarrow HCO_3^- + H^+ \tag{3.11}$$

$$HCO_3^{2-} \rightarrow HCO_3^- \tag{3.12}$$

Thus, showing that the reactions favor the direction were the HCO3- ion is the product. These reactions release H+ ions and consume H+ ions, thus the overall acidity would stay the same, but it would take time for equilibrium to be reached. Thus it would make the upper ocean water layers more basic while the lower ocean water layers would be more acidic (3.29). 3.30 shows the concentrations of these compounds at different pH, where

$$pH = -log_{10}[H^+] \tag{3.13}$$

so as the concentration of H+ ions increases the pH decreases. [34]

Having the lower ocean water layers more acidic and the upper ocean water layers more basic disrupts the marine ecosystem. Making the ocean more acidic has a more detrimental effect then making the oceans more basic because the oceans are basic to begin with. This mainly affects cold-water corral (also known as deep-water and deep-sea corral) and the purple sea urchin, Strongylocentrotus purpuratus, since they live on the deep ocean floors. [52] The reason acidic sea water is so detrimental to these marine organisms is that they need Calcium

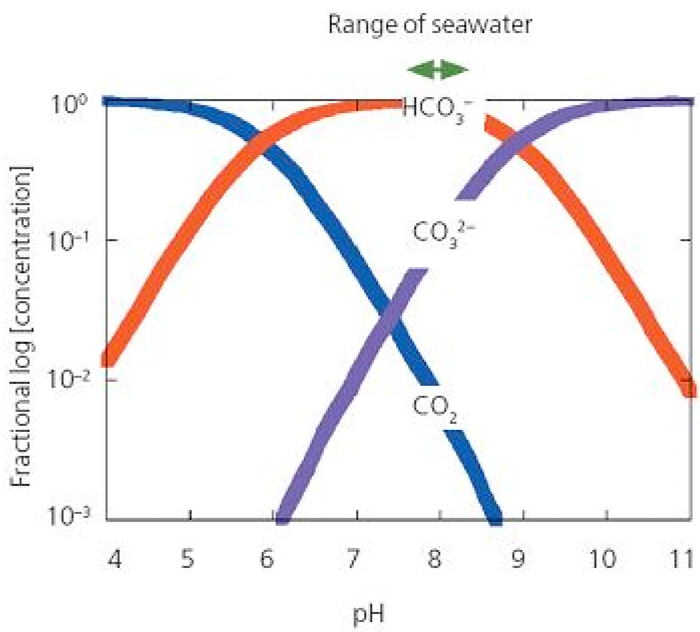


Figure 3.30: Relative proportions of the three inorganic forms of CO_2 dissolved in seawater. Note the ordinate scale (vertical axis) is plotted logarithmically. [34]

Carbonate ($CaCO_3$) to produce their exoskeletons and grow properly. The flowing reaction shows the equilibrium between carbonate ion and calcium ion

$$CO_3^{2-} + Ca^{2+} \Leftrightarrow CaCO_3 \tag{3.14}$$

Since the reaction is under acidic conditions the equilibrium is pulled toward the reactants, dissolving the $CaCO_3$, because of Le Chatelier's principle thus depriving these organisms the carbon material they use to live. [34]

3.6 Crop Yields

Using both models and site data very interesting facts about crops and how climate change will effect their growth. It has been predicted that both the temperature and CO_2 concentrations will rise in the years to come. This will have many effects on the Earth's ecosystem and one way that it will affect it is the growth of plants. The SWAP model, which was developed in the Netherlands, was used to simulate plant growth and to see exactly how changing the CO_2 concentrations and the temperature will affect plant growth. Changes in CO_2 concentrations will have more of an affect on wheat than maze because wheat is a C3 plant, CO_2 concentrations have a positive effect on plant growth, and maze is a C4 plant, CO_2 concentrations for the most part does not effect growth rate.

Plants need sunlight, water and CO_2 to survive and to create food for themselves and other life forms. The increase in CO_2 concentration will have a positive affect on plant growth. Increasing temperature on the other hand will inhibit plant growth since there will be less water in the soil for the plants to absorb. The model aims at simulating water, solute and heat transport in relation to plant growth at field scale level and for entire growing seasons. The SWAP model integrates soil-water balance and crop growth originally developed as the WOFOST model to describe daily phenological development and growth in response to environmental factors such as soils and climate, and crop management (Boogaard et al., 1998). The model is eco-physiological process-based, simulating photosynthesis, evapotranspiration, and other major plant and soil processes. The major processes for crop growth are phenological development, CO_2-assimilation, respiration, partitioning of assimilates to the various organs and dry matter formation." [58] The model takes into account the differences in climate (solar radiation, maximum and minimum temperatures, relative humidity, wind speed and rainfall), soil (soil water retention and hydraulic functions) and crop management data (crop calendar, some growth parameters, irrigation etc.).

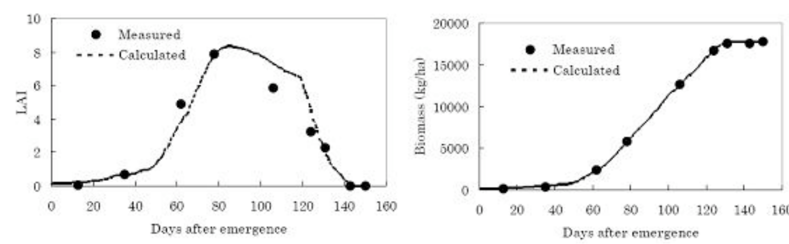


Figure 3.31: Comparison between calculated LAI (leaf area index) and biomass, and the measured ones of wheat. [58]

If the concentration of CO_2 is doubled the crop yield in biomass will increase by 3.93 ton/ha (ha=hectare) [+25%] for wheat, but if the temperature would also increase, the crop yield in biomass will decrease by 1.5 ton/ha [-8.5%] for each increase in degree Celsius. For maze, if the CO_2 concentration was doubled the crop yield in biomass will only increase by 1.71 ton/ha [+6.3%].

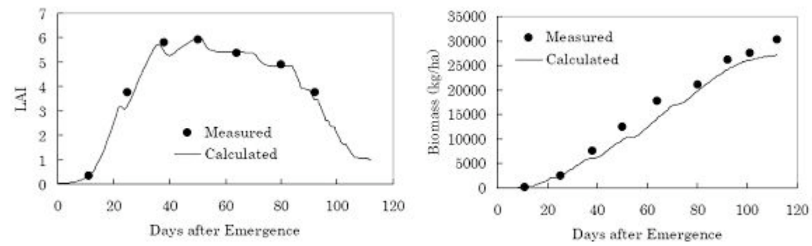


Figure 3.32: Comparison between calculated LAI and biomass, and the measured ones of maize. [58]

If the temperature was to increase, the crop yield for the maze will decrease by 1.74 ton/ha [-6.4%] for each increase in degree Celsius. Increasing the CO_2 concentrations increases the crop yield for most plants since they need CO_2 to grow, so the more abundant that resource is the more they will grow. Increased CO_2 will decrease the number of growth days for C3 plants, wheat, but wont affect the number of growth days for C4 plants, maze. Increasing the temperature decreases the number of growth days for both wheat and maze.

Evapotranspiration (ET) is the effects of both evaporation and transpiration of water from the land to the atmosphere through plants. Evapotranspiration increases by 1 mm and decreases by 19.4 mm for wheat and maze respectively when CO_2 concentrations are doubled. It decreases rapidly in a logarithmic fashion when the temperature rises for wheat and decreases by about $13.3mm/°C$ for maze. As temperature increases, the affect it has on the plant growth is very significant, it decreases the total biomass growth of the plant, the duration of its growth and its ability to transport water. If the temperature rises, it affect on food sources will be significant.

The temperature and CO_2 concentration predictions for the year 2030 if the energy policies of the world would stay as they are would increase by .524°C and increase from 395 ppm to 474 ppm. This .524°C change would cause a decrease in the biomass yield by 2.86% and 3.36% for wheat and maze respectively. A change of 20% in the CO_2 concentration would only increase the biomass yield by 4.43% and 1.26% for wheat and maze respectively. For wheat the crop biomass yield would actually increase by .062% and for maze the crop biomass yield would decrease by 2.1%. This is a very significant amount for maze. While wheat yields increased by an insignificant amount, thus will most likely stay the same. If the CO_2 concentration is doubled and the temperature increases by 2.62°C, wheat biomass yield will increase by .309 %, and maze biomass yield will decrease by 10.5 %. If we are underestimating the effect CO_2 concentrations will have on the temperature of the Earth then the biomass yields for each plant will be lower than the current calculations predict.

Rice grain production must increase by approximately 1% each year to keep up with increasing demand for rice. Rice yields declined as the average minimum temperature of a season increased, but was insignificantly affected by the average maximum temperature. Data was collected at a weather station set up at the

Wheat (17.74 ton/ha)						
CO2 conc	395	474	553	632	711	790
increase	0	0.786	1.572	2.358	3.144	3.93
Temp Δ	0	0.524	1.048	1.572	2.096	2.62
decrease	0	-0.77505	-1.5501	-2.32515	-3.10019	-3.87524
TOTAL	0	0.010952	0.021903	0.032855	0.043806	0.054758

Figure 3.33: How wheat biomass yield is effected by CO_2 concentrations and its corresponding temperature.[58]

Maze (27.14 ton/ha)						
CO2 conc	395	474	553	632	711	790
increase	0	0.342	0.684	1.026	1.368	1.71
Temp Δ	0	0.524	1.048	1.572	2.096	2.62
decrease	0	-0.91176	-1.82352	-2.73528	-3.64704	-4.5588
TOTAL	0	-0.56976	-1.13952	-1.70928	-2.27904	-2.8488

Figure 3.34: How maze biomass yield is effected by CO_2 concentrations and its corresponding temperature.[58]

research farm of IRRI at lat 14°11N, long 121°15E and an elevation of 21 m. Data recording began on January 1, 1979. The site measures 10.5 × 9.5 m and is surrounded by irrigated rice throughout the year. For the dry season the average minimum temperature has increased by about 1.13°C and the average maximum temperature has increased by 0.35°C from 1979-2003. In the wet season the average minimum temperature has increased by about 0.80°C and the average maximum temperature has increased by 0.35°C from 1979-2003. Since it seems like rice crop yields are mostly affected by the increase in the average minimum temperature, the relationship is that for every 1°C increase in the average minimum temperature there is a decrease in the rice yield by 10% or about 15% decrease for every 1°C increase when comared to the daily mean temperature. Increases in the average minimum temperature decreases the grain yield using the correlation,

$$GrainYield = -423.6 + 39.2T - 0.89T^2 \tag{3.15}$$

where T is the temperature, see figure 2-D. Increase in the average radiation increases the yield using the correlation

$$GrainYield = -48.7 + 5.6R - 0.14R^2 \tag{3.16}$$

where R is the radiation in MJ/m2day, see figure 2-G. The predicted value for the grain yield for rice in the year 2030 would be 4.9 ton/ha, this is 50.5% of the grain yield value in 2005, 9.6 ton/ha. The effect that the minimum temperature will have on the grain yield of the rice is significant and will drastically affect the food sources of many countries unless something is done to combat the temperature change or genetically improve the rice to withstand or compensate for the change in temperature.

This decrease in the rice grain yield would need to be looked into further to see what can be done to mitigate this decrease, otherwise the world would have

Factor	Biomass (ton/ha)	Grain yield (ton/ha)	Growth days	ET (mm)
Control	17.74	4.71	164	370.4
2xCO2	21.67	5.74	162	371.4
+1 ℃	16.41	4.14	155	350.3
+3 ℃	13.21	3.96	141	310.4
+5 ℃	10.37	4.01	128	254.3

Figure 3.35: Effects of doubling CO_2 concentration(2xCO_2) and rise in air temperature (+T) on crop growth and ET for wheat without ET reduction.[58]

Factor	Biomass (ton/ha)	Grain yield (ton/ha)	Growth days	ET (mm)
Control	27.14	17.29	120	378.4
2xCO2	28.85	17.98	120	359.0
+1 ℃	25.13	15.83	116	361.7
+3 ℃	21.71	13.14	110	335.2
+5 ℃	18.62	10.79	107	314.4

Figure 3.36: Effects of doubling CO_2 concentration(2xCO_2) and rise in air temperature (+T) on crop growth and ET for maze without ET reduction.[58]

a serious problem since rice provides more than one-fifth of the worlds calorie intake. Rice is a very labor intensive crop to grow. Rice is grown in patty fields, which are flooded mud fields. The fields must be level and flooded to the right amount. Too much water and the rice will die from suffocation. Too little water and the rice will either die from pests or weeds or wont grow well due to a limited water supply. The main contributor to why rice yields are expected to decrease by a significant amount is because at higher temperatures it is harder for the rice plants roots to absorb Phosphorous at higher temperatures then lower ones. Phosphorous is a vital nutrient needed for the plant to store energy from sunlight and create stores of food for the plant and eventually for humans. Also rising temperature causes Iron and Aluminum to move from the roots of the rice plant to the stalks, which is toxic to the stalks of plant and thus the rice plant is more likely to die and less or no yield would come from that plant. Rising temperature will have a major impact on rice yields and the world supply of food would be greatly affected by the decrease in rice grain yields. [35, 40, 42]

Rice	2005	2010	2015	2020	2025	2030
Radiation	17.355	17.81	18.265	18.72	19.175	19.63
increase	0	0.30799	0.558012	0.750068	0.884156	0.960278
%	1	1.048728	1.088285	1.118671	1.139886	1.151929
Min Temp	24.325	24.55	24.775	25	25.225	25.45
decrease	0	-0.96722	-2.02455	-3.17199	-4.40955	-5.73722
%	1	0.708844	0.390562	0.045154	-0.32738	-0.72704
TOTAL	0	-0.65923	-1.46654	-2.42193	-3.52539	-4.77694
%	1	0.931633	0.84791	0.748829	0.634392	0.504598

Figure 3.37: Effects of Radiation and Minimum Temperature on Grain Yields for predicted Radiation and Temperature Increases.

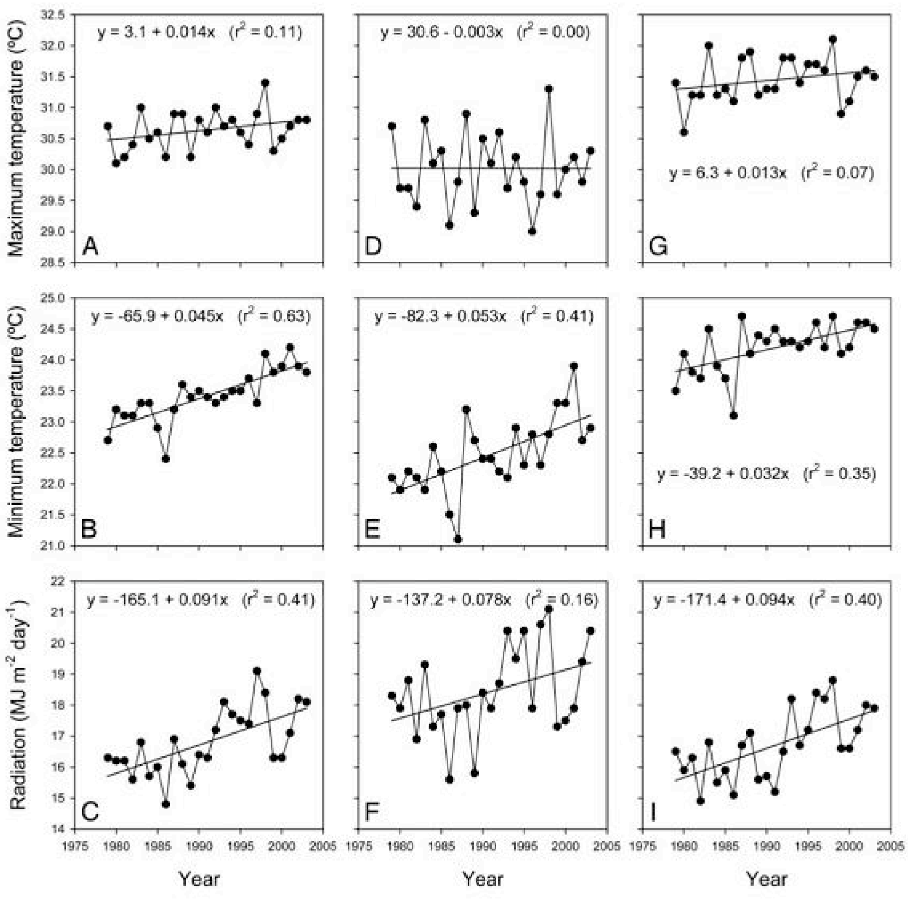


Figure 3.38: Figure 1: Trends in maximum and minimum temperatures and radiation from 1979 to 2003 for the whole year (AC), dry season (January to April) (DF), and wet season (June to September) (GI) at the IRRI Farm. [35]

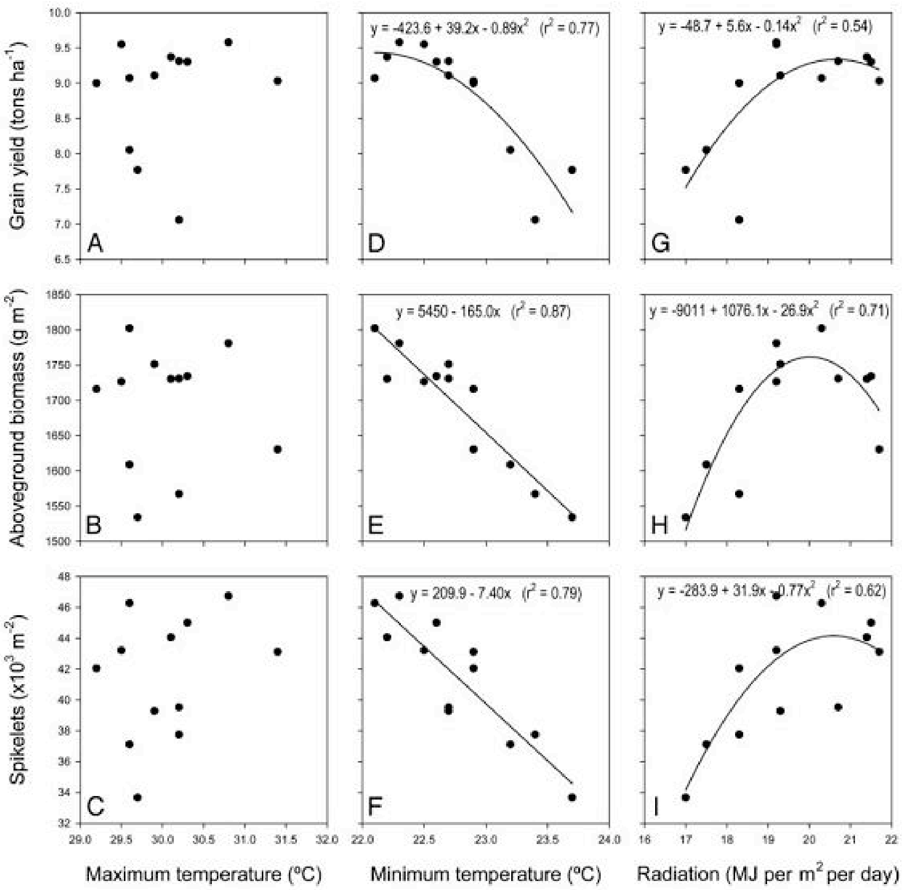


Figure 3.39: Figure 2: The relationship between rice-yield attributes (grain yield, above-ground total biomass, and spikelets per m2) and growing-season mean maximum temperature (AC), minimum temperature (DF), or radiation (GI). Yield-attribute data were obtained from irrigated field experiments in which cropmanagement practices were optimized to achieve the highest possible yields from rice cultivar IR72 at the IRRI Farm in the dry seasons from 1992 to 2003. Growing-season mean maximum and minimum temperatures and radiation were calculated from daily values for the entire growing season from transplanting to harvest. [35]

Chapter 4

Alternative Energy Sources

4.1 Nuclear Energy

The United Sates uses a significant amount of energy per year. On average, the typical U.S. citizen uses about $5x10^{11}$ J per year. It would take about 20 tons of coal, 500,000 cubic feet of natural gas at 1 atm, 2,800 gallons of gasoline, or .0056 grams of mass conversion, nuclear fusion or fission, to satisfy that amount of energy. [26] Although mass conversion is the most dense energy source, it is not possible to convert all of the mass into energy, only a fraction can be converted into energy by nuclear fusion or fission.

Energy can be produced from nuclear fusion and fission because the strength of nuclear binding energy varies for nuclei of differing atomic mass. The most tightly bound nuclei are in $^{62}_{28}Ni$, then $^{58}_{26}Fe$, and then $^{56}_{26}Fe$. Professionals use this notation to differentiate between different isotopes of each element. Isotopes are atoms of the same element but have a different atomic mass number, thus having a different number of neutrons in the nucleus. In this notation the top number in front of the element gives the atomic mass number of the atom, while the bottom one gives the number of protons in the nucleus of the atom, a.k.a. the element. Deviating from the iron isotopes and the nickel isotope the bonding energy decreases as by the curve in Fig:4.1.

The mass of the neutrons and protons that make up a nucleus are always less than the sum of the individual protons and neutrons masses when not in an atom. This difference in mass gives rise to the nuclear binding energy of that nucleus. The nuclear bonding energy is calculated by using Einsteins equation for mass-energy equivalence, $E = mc^2$. Thus the equation for the nuclear binding energy is

$$Nuclear\, Binding\, Energy = \Delta mc^2 \tag{4.1}$$

As an example, when you combine the individual particles of an alpha particle, two protons with a mass of 1.00728 amu (atomic mass unit) each and two neutrons with a mass of 1.00866 amu each, the change in mass is .03035 amu. The conversion factor for 1 amu is $1.66054x10^{-27}$ for kilograms or 931.494 MeV/c^2 for (mega-electron volt per light constant squared). If you use the nuclear bind-

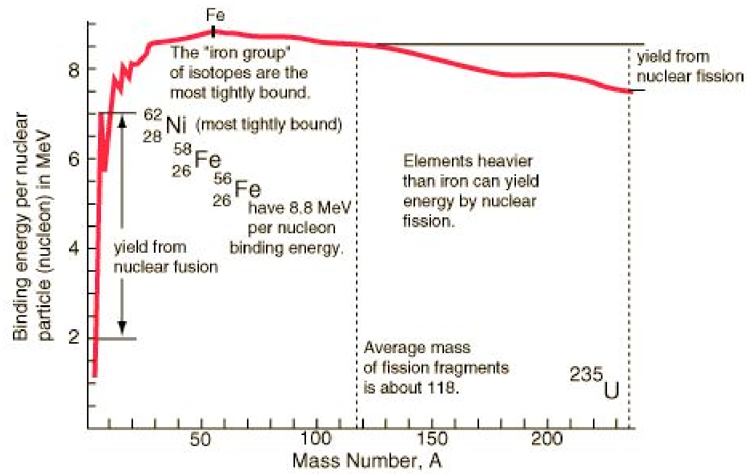


Figure 4.1: Nuclear Binding Energy Curve [26]

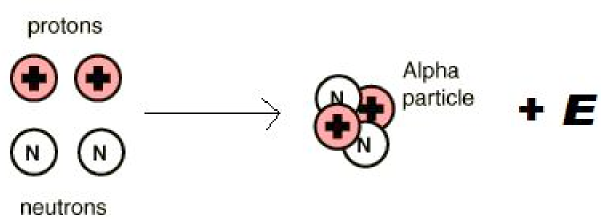


Figure 4.2: Nuclear Binding of an Alpha Particle [26]

ing equation, 4.1, with the given information it yields:

$$Nuclear\ Binding\ Energy = \Delta mc^2 \quad (4.2)$$

$$= [(2 \cdot 1.00728\, amu + 2 \cdot 1.00866\, amu) - 4.00153\, amu] \cdot \frac{931.494 MeV}{1 amu \times c^2} c^2 \quad (4.3)$$

$$= 28.27\, MeV \quad (4.4)$$

Comparing this energy to the amount of energy it takes to ionize a hydrogen atom, 13.6 eV, the nuclear bonding energy is about two million times greater in energy. Fission is the splitting of a large nucleus, like Uranium-235, into smaller nuclei with higher nuclear boning energies. Other reactive isotopes that are usually used are plutonium-239, uranium-233, and thorium-232. The nuclear reaction starts when a low energy neutron, also called the slow neutron, collides into one of the nuclei to start a chain reaction of fission. You need a low energy neutron so the neutron can absorb the neutron and start the fission reaction, but if the neutron has too much energy then the neutron wont be absorbed by the nucleus and reflect off of it and no fission will occur. Uranium-235 usually splits into unequal masses of 95 and 137 rather than splitting into equal masses, see Fig:4.3. Most of the fragments that form from the fission reaction are very

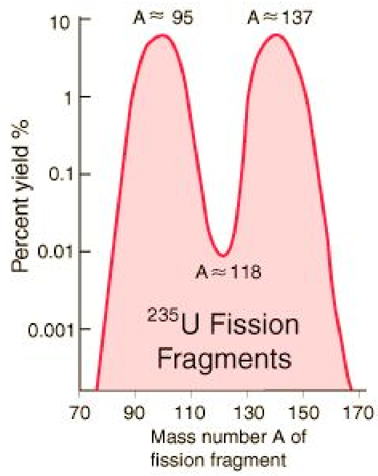


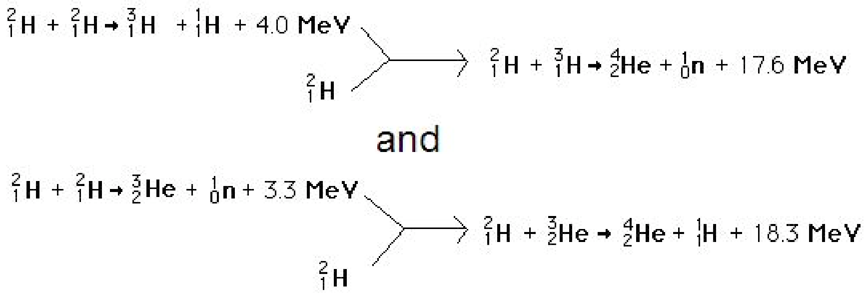
Figure 4.3: Probability of Uranium-235 Fragments. [26]

radioactive and unstable, and they would have devastating effects if released into the environment.

Some of the most dangerous radioactive materials are cesium-137, strontium-90, and Iodine-131. Cesium-137 has a half-life of about 30 years, so it would be around for hundreds of years. On the other hand, this means its not highly radioactive, but cesium-137 can be mistaken for potassium, fluid electrolytes, by living organisms and through the food chain, can be found in concentrated amounts. It can also be deposited into bones but it is eventually excreted from the bone, luckily. Strontium-90 is similar to cesium-137 in every way except that it tastes like calcium instead of potassium, and can also be deposited into bones. Though it is much harder, if not impossible, to excrete the strontium-90 and thus has the potential to cause cancer or damage bone marrow cells. Iodine-131 is one of the top concerns when radiation is released from a nuclear reaction. It is very radioactive and unstable, thus having an eight day half-life. It can also travel quickly because it is a gas. It is very dangerous for humans because it is collected by the thyroid and concentrates the iodine-131 there. One way to combat this is by overloading the thyroid with iodine by taking potassium iodide pills to keep the concentration of the iodine-131 low.

Fusion is the opposite of fission. Instead of going from heavy nuclei and splitting them into lighter nuclei, you combine light nuclei to form heavier nuclei. The nuclear reactions that occur in stars are fusion reactions. Fusion of deuterium and tritium contained in a magnetic field is the most likely way for humans to create fusion. The most promising of the hydrogen fusion reactions can emit 17.6 MeV of energy, but requires the reaction to take place at 40 million Kelvin. The energy needed to start a fusion reaction is a substantial amount, but the amount of energy that would be produced from fusion out weighs this initial input. There is plenty of deuterium for the reaction, but tritium is scarce and you would need to breed it from lithium or the deuterium cycle. Deuterium can be obtained from seawater. About 1 out of 5000 hydrogen atoms is a deuterium atom. So one gallon of sea water could produce as much energy as 300 gallons of gasoline. [26]

The deuterium cycle of fusion is a set of fusion reactions. All reactants are either deuterium or products from deuterium. Thus you would only need deuterium as fuel for this fusion reaction.



The overall balance for the set of reactions is:

$$6\,{}^{2}_{1}H \rightarrow 2\,{}^{4}_{2}He + 2\,{}^{1}_{1}H + 2\,{}^{1}_{0}n + 43.2\ MeV$$

Another way to get tritium is from Lithium. It can be obtained by low energy neutron bombardment of lithium-6, but only 7.4% of lithium occurs as that isotope. Lithium-7 is more abundant than lithium-6 and can also be used to produce tritium by high energy neutron bombardment.

$${}^{6}_{3}Li + {}^{1}_{0}n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H + 4.8\ MeV$$
$${}^{1}_{0}n(fast) + {}^{7}_{3}Li \rightarrow {}^{3}_{1}H + {}^{4}_{2}He + {}^{1}_{0}n(slow)$$

Either way, a reliable source of tritium needs to be established in order for fusion to be a viable source of energy and a way needs to be found to either sustain the reaction at 40 million Kelvin or some way to lower the activation energy of the reaction. Fusion reactors are just a theoretical concept and have not yet been successfully developed yet, so right now there are only fission reactors.

Nuclear energy has been a rapidly growing source of electricity ever since humans have found out about the power of nuclear reactions. The United States was the leader in nuclear power. President Eisenhower proposed the idea in 1953 calling it the Atoms for Peace program. "The first commercial nuclear power plant was designed by Westinghouse. It was a pressurized water reactor

Figure 4.4: Nuclear Reactors in the US. [27]

of 250 MWe (Megawatt electrical) named Yankee Rowe. It started up in 1960 and continued operating until 1992. During the same time as the pressurized water reactor, the Argonne National Laboratory developed the boiling water reactor. The first commercial plant, Dresden-1 of 250 MWe, designed by General Electric and started up in 1960." [27] These new energy reactors of 1000 MWe were being built all around the United States until the Three Mile Island incident occurred in 1979, and building almost ceased to a halt even though the United States was among the world leaders in safety and net capacity. In 2007 there are a total of 104 US nuclear reactors.

The Three Mile Island incident almost ended in a reactor meltdown. The first problem that occurred was the shutdown of the main feedwater pump. To compound the problem, the auxiliary feedwater pumps had their valves closed so there was no feedwater going to the reactor to absorb the heat it was producing. Thus the secondary loop boiled dry, superheating the primary loop. This maked the pressure in the reactor rise above 2350 psi. When this happened a safety valve opened to relieve the pressure and the radioactive steam and water moved to the quench tank. Then the safety valve failed to reset all the way, but it did close enough so it triped a switch that told the operators that the vale was closed, but it was not! The quench tank then ruptured from the pressure and overfilling. The leaking radioactive water was then pumped into an auxiliary tank, but that also overflowed. Then volatile radioactive material was released into the atmosphere, even though there is a sophisticated filter to stop this from happening, since noble gases pass through the filter because they dont interact with other compounds. Radioactive Xenon-135 and Krypton-85 with half-lifes of about 3 days and 10 years respectively were released into the atmosphere.

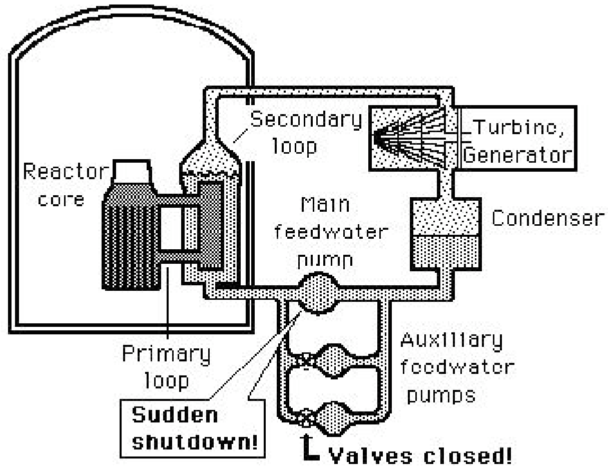


Figure 4.5: Schematic for the Nuclear Reactor. [26]

The operator noticed that the secondary loop was boiling dry and thus opens the auxiliary feedwater pumps. This makes the pressure in the reactor core drop since the relief valve was still open. The Emergency Core Cooling System starts when the pressure drops to 1600 psi, filling the core with water. The reactor then scrammed, dropped all of the control rods, and stopped the fission reaction, but residual reactions were still taking place producing about 6% of the total heating power, 144 MW (Mega Watts). The operators then shut off the Emergency Core Cooling System since they were afraid that the water level would be to high and the reactor would "go solid," this is when the concentration of solid in the water reaches 33% and the reactor would be completely plugged and if the reactor was filled with water, it would force the lid of the reactor off. This all happened in two and a half minutes. An hour later the coolant pumps were shut off and the core was finally recovered with water after 6.5 hours. [26]

In 2006 the US generated 4260 billion kWh of electricity. This is, on average, 12,300 kWh per capita annually. The demand for electricity in the United States is projected to increase from 4300 billion kWh today to 5000 billion kWh in 2030. The United States needs to find a way to produce that much energy while keeping green house gas emissions low. This can be accomplished by having incentives to build more green electricity production facilities. "From 1992 to 2005, 270,000 MWe of new gas-fired plants were built, and only 14,000 MWe of new nuclear and coal-fired capacity came on line." [27] Still coal and nuclear energy make up a majority of the electricity production. In order for nuclear plants to stay at 19%, there needs to be 3 plants built every 2 years in order to keep up with he rise in electricity usage. "The Energy Policy Act 2005 then provided a much-needed stimulus for investment in electricity infrastructure including nuclear power. New reactor construction is expected to start about 2010, with operation in 2014." [27] They hope to have nuclear reactors supplying about 25.5% of the electricity.

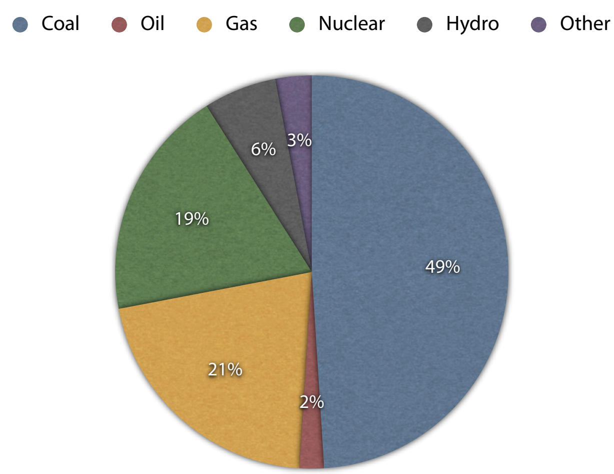


Figure 4.6: Sources of Electricity Production for the US in 2006. [33]

Why are we pushing towards nuclear power? Nuclear power has a very low carbon emission life-cycle compared to other types of energy sources. Nuclear reactors, themselves dont emit any green house gases or nitrogen oxides, but the mining, purifying and transport of the uranium ore produces these gases. "The total emissions of CO2 from electricity generated at Torness power station, calculated on a lifecycle basis, are estimated to be just over 5 g/kWh. This compares to emissions of CO2 from a typical UK coal plant of around 900 g/kWh, based upon the operational stage alone. Typical gas power station emissions of CO2 are around 400 g/kWh." [33] The other sources of energy that are close to nuclear plants are hydro dams, geothermal and wind energy generation, energy resources that are considered green electricity generation. Critics of nuclear power say that new nuclear plants will need to use lower grade uranium fuel, which will increase emission of CO2. Of course it will increase CO2 emissions, but only by marginal amounts. "British Energy conducted a study that showed that even with a very low uranium ore grade; CO2 emissions would remain very small. If Torness used this ore for all its fuel, its emissions would only rise from 5.05 g/kWh to 6.85 g/kWh." [33]

The only thing that is bad about nuclear reactors is the fact that the waste it produces is radioactive. Some of these radioactive products are only around for seconds or minutes, while others are around for years, even centuries. Temporary storage of this waste are at the nuclear plants themselves. They have steel-lined concrete water-filled vaults. Then they wait for the radiation decay or until it becomes less radioactive and the water is there to keep the waste cool.

Generation Option	Greenhouse gas emissions gram equiv. (in CO2/kWh)	Sulfur dioxide emissions (in milligrams/kWh)	Nitrogen oxide emissions (in milligrams/kWh)	NMVOC (in milligrams /kWh**)	Particulate matter (in milligrams /kWh)
Hydropower	2 – 48	5 – 60	3 – 42	0	5
Nuclear	2 – 59	3 – 50	2 – 100	0	2
Wind	7 – 124	21 – 87	14 – 50	0	5 – 35
Solar photovoltaic	13 – 731	24 – 490	16 – 340	70	12 – 190
Biomass forestry waste combustion	15 – 101	12 – 140	701 – 1,950	0	217 – 320
Natural gas (combined cycle)	389 – 511	4 – 15,000[*]	13 – 1,500	72 – 164	1 – 10
Coal – modern plant	790 – 1,182	700 – 32,321	700 – 5,273	18 – 29	30 – 663

[*] The sulfur content of natural gas when it comes out of the ground can have a wide range of values. When the hydrogen sulfide content is more that 1 percent, the gas is usually known as sour gas. Normally, almost all of the sulfur is removed from the gas and sequestered as solid sulfur before the gas is used to generate electricity. Only in the exceptional case when the hydrogen sulfide is burned would the high values of sulfur dioxide emissions occur.

** NMVOC means non-methane volatile organic compounds.

Figure 4.7: Emissions Produced by 1 Kilowatt-hour of Electricity Based on Life-Cycle Analysis [30]

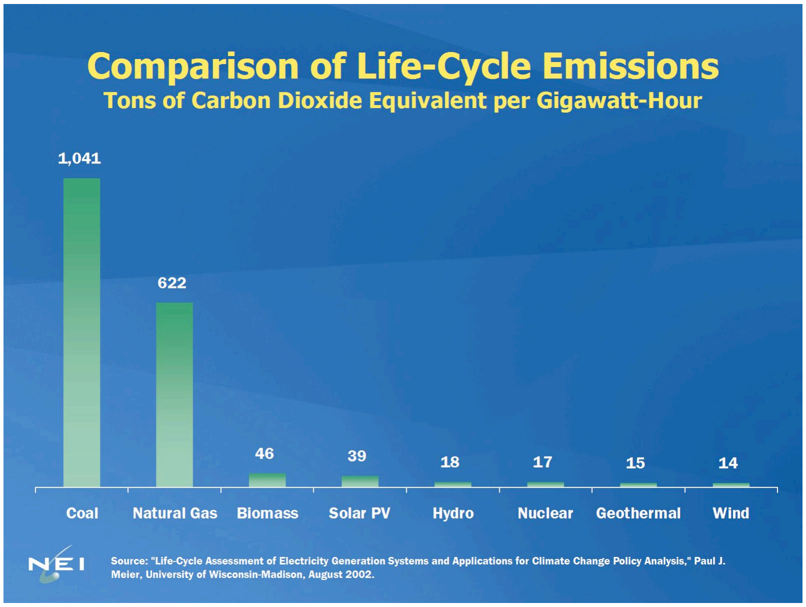


Figure 4.8: Comparison of Average Life-Cycle Emissions. [33]

These storage spaces are only temporary until the waste can be transported to a safe location. "Federal law required the U.S. Department of Energy to begin moving used fuel from plant sites in 1998, but it has not yet begun to do so" [33] since Yucca Mountain repository has yet to be finished. It is now expected to be built by 2020 because of major delays. So the plants had to store the nuclear waste in massive, above ground airtight canisters made of steel, steel-reinforced concrete or steel-enclosed concrete. Monitoring and maintenance ensures that these canisters are safe.

The United States is now trying to research ways to recycle nuclear waste. The two types of fuel for the reactors are "closed" and "open" fuel cycle. The government is currently researching each of these cycles. The "closed" fuel cycle, the recycled fuel, is currently under research trying to find a way to extract uranium from the waste without extracting plutonium also. The extracted uranium will be used in commercial reactors, while the plutonium will be used in advanced nuclear reactors. If this new research can succeed in finding a way to extract uranium effectively then the volume, heat and toxicity level of the nuclear waste, but there will still be byproducts from the initial nuclear waste that was recycled.

Over the past 20 years in the United States, funding for research and development for nuclear reactors was on a steady decline. In 1997 the funding for R&D for nuclear reactors was at US$ 37 million, only 2% of the total funds for energy R&D. With the Nuclear Energy Research Initiative (NERI) and Plant Optimization programs set up the funding for nuclear development increased.

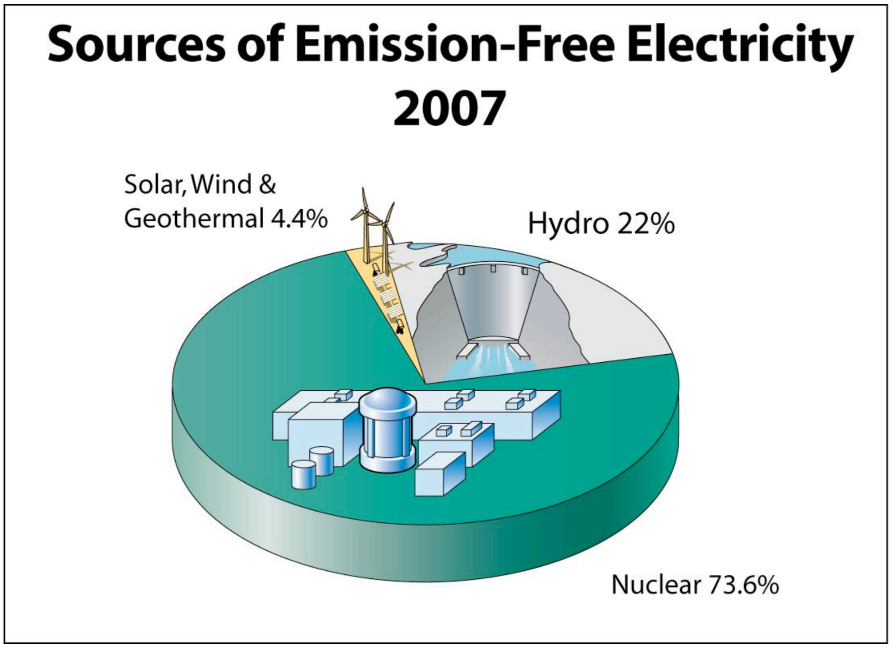


Figure 4.9: Sources of Emission-Free Electricity. [33]

45 NERI grants were awarded in 1999 signaling the federal governments interest in nuclear research. [27] "The Department of Energy is seeking $ 875 million for its nuclear energy programs. The Advanced Fuel Cycle Initiative for closing the fuel cycle and supporting the Global Nuclear Energy Partnership would receive $ 395 million of this and Generation-IV R&D would get $ 36 million, chiefly for the very high temperature reactor. The Nuclear Power 2010 program aimed at early deployment of advanced reactors would get $ 114 million." [27] There have already been 2 new reactor designs that were approved by the US government meeting all safety specifications and 3 in review. These reactor designs are AREVA U.S. EPR, 1,600 MW pressurized water reactor; GE Hitachi Nuclear Energy Advanced Boiling Water Reactor (ABWR), 1,350 to 1,600 MW boiling water reactor (approved); GE Hitachi Nuclear Energy ESBWR, 1,520 MW boiling water reactor; Mitsubishi Heavy Industries Ltd. US-APWR, 1,700 MW pressurized water reactor; and Westinghouse AP1000, 1,117 to 1,154 MW pressurized water reactor (approved). They plant to have these plants operating by 2015 and many more designs are expected to be completed, approved and operating by 2030. [33]

Increasing the efficiency of plants in the current infrastructure can increase the capacity factor (output proportion of their nominal full-power capacity). "In 1980 the average capacity factor for all US reactors was 54%, by 1991 it was 68%, in 2001 it had risen to 90.7% and in 2007 it was 91.8%. Exelon's 17 reactors achieved a capacity factor of 94.4% in 2001" [33]. Another way to get more energy out of existing plants is to not only update and revamp older nuclear reactors but also with improved maintenance of the plant. With these

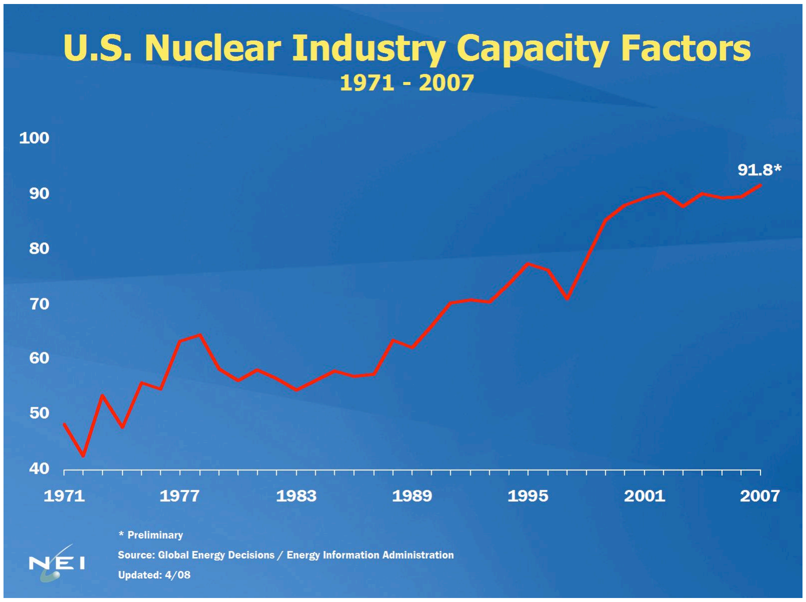


Figure 4.10: US Nuclear Industry Capacity Factors. [33]

actions these reactors have increased their original energy production rates and the operating-life of the plant. Also the efficiency of the plants can be increased if the length of refueling outage of the reactor is decreased. "In 1990 the average refueling outage time was 107 days but dropped to 40 days by 2000. The fastest refueling outage time is 15 days." [33]

4.2 Wind Energy

In order for a grid-connected wind power plant to be effective the average wind speed needs to be at least 5 m/s, though 3 to 4 m/s wind speeds can be used for battery charging and water pumping, small scale energy production on a business or home scale. The main problem with wind power is that wind speed is seldom steady or constant. Wind speed varies with time of day, season, height above the ground, and the surrounding terrain. To see whether an area is useful as a wind resource, wind power density is calculated. It is measured in watts per meter squared. The wind power density is broken up into classes (similar to hurricane and tornado classes). The classes vary with wind speed and height above the ground, see table 4.11. For most grid-connected wind power plants, a power class rating of a 4 or higher is preferred. With more advances in wind technology, power plants may be able to be built in a class 3 area and have a good energy output.

Classes of Wind Power Density at 10 m and 50 m [(a)]

	10 m (33 ft)		50 m (164 ft)	
Wind Power Class	Wind Power Density (W/m^2)	Speed[(b)] m/s (mph)	Wind Power Density (W/m^2)	Speed[(b)] m/s (mph)
	<100	<4.4 (9.8)	<200	<5.6 (12.5)
	100 - 150	4.4 (9.8)/5.1 (11.5)	200 - 300	5.6 (12.5)/6.4 (14.3)
	150 - 200	5.1 (11.5)/5.6 (12.5)	300 - 400	6.4 (14.3)/7.0 (15.7)
	200 - 250	5.6 (12.5)/6.0 (13.4)	400 - 500	7.0 (15.7)/7.5 (16.8)
	250 - 300	6.0 (13.4)/6.4 (14.3)	500 - 600	7.5 (16.8)/8.0 (17.9)
	300 - 400	6.4 (14.3)/7.0 (15.7)	600 - 800	8.0 (17.9)/8.8 (19.7)
	>400	>7.0 (15.7)	>800	>8.8 (19.7)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) Mean wind speed is based on the Rayleigh speed distribution of equivalent wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3(from the Battelle Wind Energy Resource Atlas)

Figure 4.11: Classes of Wind Power Density at 10m and 50m. [2]

You can calculate the power of a wind turbine. The interesting thing about the power is that it is proportional to the cub of the velocity of the wind, so if the wind seed is doubled the power output is eight times larger. The equation is as follows:

$$P = 0.5 \times \rho \times A \times Cp \times V^3 \times Ng \times Nb \tag{4.5}$$

Where P is the power, ρ is the air density, A is the rotor swept area (the area that the rotors cover that are exposed to the wind), Cp is the Coefficient of

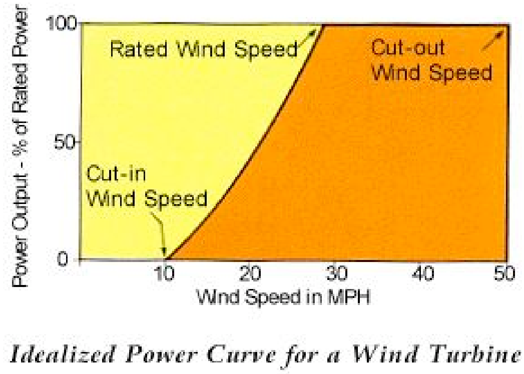


Figure 4.12: Wind turbine power. [2]

performance (.59 Betz limit is the maximum theoretically possible, .35 for a good design),V is the wind speed, Ng is the generator efficiency (50% for car alternator, 80% or more for a permanent magnet generator or grid-connected induction generator), and Nb is the gearbox and bearings efficiency (could be as high as 95%). This is a good way to compare wind turbines but what really matters is the annual energy output of the turbine. It is more important to get a consistent energy output then a high energy output for a brief period of time. The larger the swept area the slower the speed of the wind needs to be for the wind turbine to operate correctly, cut-in wind speed. If the average annual wind speed of an area is known, one can calculate the capacity factor for the turbine, Cf.

$$Cf = \frac{(average\ energy\ output\ for\ 1\ year)}{(operation\ at\ the\ rated\ power\ output\ for\ 1\ year)} \tag{4.6}$$

Most capacity factors are between .25 and .30. If an area is very windy the energy output would probably be higher than the calculated energy output since the relation of power to wind speed is nonlinear. More accurate results can be obtained if there are distributions of wind speeds at a given site are available. Other factors that can affect the power output of a wind turbine are blade airfoil shape and geometry, cut-out wind speed (max operational wind speed), and high wind stalling. [2]

The cost of electricity from wind power is relatively close to the cost of electricity from coal, 1.051 x coals. 20 years ago it was 5 times more expensive than it is now, 5 cents/kWh, since larger plants are being built and that wind technology is improving. Wind power can compete with coal as a low costing renewable energy source. It hasn't yet because coal has instillations ready built while there are not very many wind power plants around but they have been growing. In 1999 the installed wind power capacity was about $21.9 * 10^9$ kWh. Now the installed wind power capacity is about $198 * 10^9$ kWh. In just under a decade the installed wind power capacity has increased by about 800%, see Fig:4.13. Wind is a very abundant, green, renewable energy source for most of the United States, see Fig:4.14. It is estimated that the entire United States

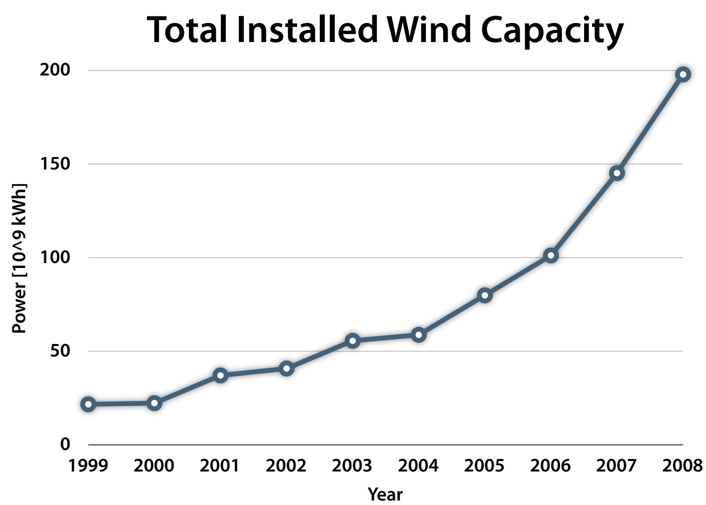


Figure 4.13: The total installed wind capacity. [55]

can produce $3590 * 10^9$ kWh of power from on-land wind, using only 33% of the land of the wind potential areas, and $7950 * 10^9$ kWh of power from off-shore wind, using only 33% of the water area between 5 and 20 nautical miles and 67% of the water area between 20 and 50 nautical miles from shore. Adding these two together you get $11540 * 10^9$ kWh of power, at 100% capacity factor, and this is about 3 times the amount of the current electricity use of the United States. Wind can and is rapidly becoming a major energy producer for the United States.

By 2030 it is estimated that the energy consumption of the world will increase by 50%. Going off this and thus saying that the United States energy consumption would also increase by 50%. The projected energy consumption of the United States will be $4.427 * 10^{13}$ kWh per year, and the worlds projected energy consumption will be $2.037 * 10^{14}$ kWh per year. It is estimated that the wind could supply $1.7 * 10^{15}$ kWh of energy for the World, at 100% capacity, (from the U.S. Department of Energy). The US Department of Energy has proposed to increase the energy input from wind power in 2030 by 20% in the United States. This is a large increase, since only 2% of the energy for electricity was generated by wind power ($8.02 * 10^{10}$ kWh out of $4.02 * 10^{12}$ kWh). Though, it is probable that this will occur if the current trend of increasing wind power generation continues. By 2030 the projected amount of electricity energy generated in the United States would be about $7.4 * 10^{12}$ kWh, 20% of that is $1.48 * 10^{12}$ kWh. If wind energy was added to supply the increase in electricity demand instead of coal the emissions from coal would only increase by 10

The cost of wind power electricity can be reduced even more if the wind

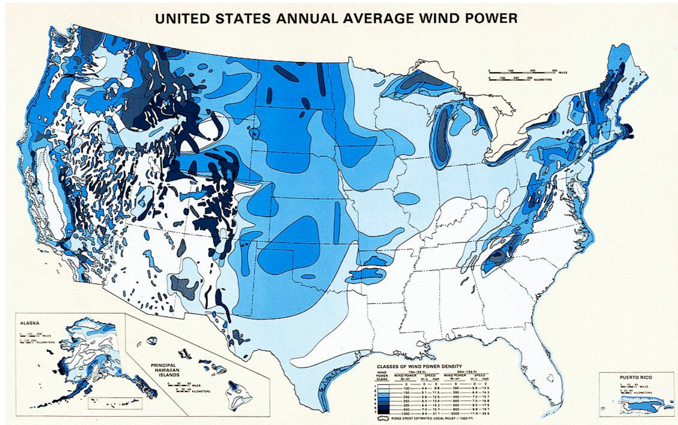


Figure 4.14: The darker the blue the more powerful the wind. All areas shaded blue can produce wind power except for the lightest color blue. [17]

project is an investor-owned utility, currently being done with gas power plants. It has been estimated that a typical 50-MW wind farm with an installed cost of $ 1,000/kW, a 30% capacity factor, and operations and maintenance (O&M) expenses of 0.65 cents/kWh could generate electricity at a cost reduction of about 30%. Internally-financed public utility ownership is estimated to reduce overall costs by approximately 10-40%. Financing for wind power is more restrictive than financing for gas-fired energy sources, and thus cost more to qualify for the financing terms. If the financing terms for wind were more similar to gas-fired energy sources, the cost could drop by 25%. If all cost reductions are taken into account, the cost for wind energy could be maybe as low as 2.90 cents/kWh.

Financing Type	including PTC (first 2) including REPI (last 2)	without PTC (first 2) without REPI (last 2)
Private ownership, project financing	4.95 cents/kWh	6.56 cents/kWh
IOU ownership, corporate financing	3.53 cents/kWh	5.9 cents/kWh
Public utility ownership, internal financing	2.88 cents/kWh	4.35 cents/kWh
Public utility ownership, project financing	3.43 cents/kWh	4.89 cents/kWh

Figure 4.15: Wind Plant Financing.[2]

State	2008 Installed Capacity (10^9 kWh)	Potential Wind Power (10^9 kWh)
California	22.22412	59.3052
Colorado	9.35568	480.924
Idaho	1.20888	72.6204
Illinois	8.0154	61.1448
Iowa	14.4978	551.004
Kansas	4.4676	1067.844
Maine	0.37668	55.9764
Michigan	0.5256	65.3496
Missouri	1.42788	52.2096
Montana	2.38272	1016.16
Nebraska	1.02492	868.116
Nevada	0	50.2824
New Mexico	4.34496	435.372
New York	9.42576	62.0208
North Dakota	4.18728	1212.384
Oklahoma	6.03564	724.452
South Dakota	1.63812	1026.672
Texas	58.67448	1192.236
Wisconsin	2.86452	56.4144
Wyoming	4.02084	746.352
Rest of the US	41.42602	921.1504
Total	**198.1249**	**10777.99**

Figure 4.16: Potential of Wind Power Plants in the US by State.[54]

	5 to 20 Nautical Miles			20 to 50 Nautical Miles			5 to 50
Region	< 30 m deep	=> 30 m deep	% Exclusion	< 30 m	=> 30 m	% Exclusion	
New England	9,900	41,600	67	2,700	166,300	33	220,500
Mid-Atlantic States	46,500	8,500	67	35,500	170,000	33	260,500
California	2,650	57,250	67	0	238,300	33	298,200
Pacific Northwest	725	34,075	67	0	93,700	33	128,500
Total	59,775	141,425	67	38,200	668,300	33	907,700

Figure 4.17: Offshore Resource Estimates (MW).[32]

4.3 Solar Energy

Solar Energy is an abundant, reliable, and green energy source. It has been used since ancient Roman times. They used it to heat their homes in the winter. They used lenses and mirrors to ignite fires, distill and weld metal. Solar cells are a device the can collect this energy and transform it into electricity. "Solar cells are semiconductor devices that exploit the photovoltaic effect to directly create electric current and voltage from the collection of photons (quanta of light)." [8] They do this silently with no moving parts and the materials in them are reliable, thus requiring little maintenance. Solar cells have been used for powering anything from calculators and watches to satellites and exploration vehicles. "Using only 0.1% of the Earth's land space with solar collectors that operate with a collection efficiency of merely 20%, one could gather more than enough energy to supply the current yearly energy needs of all inhabitants of the planet ($1.2x10^{14}$ kWh)." [47] Solar cells are still expensive relative to fossil fuels, nuclear energy and wind energy. [8, 37]

There are three main generations of solar cells. The first is "wafer" cells which are made from layers of semiconductor material and are usually thick enough to support themselves, up to .5 mm. This is the most common solar cell and the main types of "wafer" solar cells are single and multi-crystalline silicon cells and commercial production cells. These cells have efficiency from 10 to 15%. The cost of these cells can only be reduced to the cost of the silicon wafers. These cells are mechanically and electrically connected together to form weatherproof solar modules that produce convenient voltages and currents since each cell is produced individually.

The second generation of solar cells aims to reduce the cost of solar cells by reducing the thickness of the active material and thus decreasing the efficiency of them. The object of this method is to deposit the semiconductor over a substrate or superstrate, which provides mechanical support, rapidly. This method hopes that the majority of the cost will be defined by the cost of the substrate or superstrate since they are the most likely material to decrease in cost. These solar cells are made over large areas of substrate or superstrate by having the semiconductor deposited in a pattern to form the cells, thus forming the entire module in one step rather then in multiple steps like the first generation cells. The four main thin-film solar cell types are amorphous silicon, polycrystalline silicon, cadmium telluride, and copper indium diselenide. The efficiency of these cell types are from 4 to 9%. Since these cells had a much lower cost, it was believed that this type would become the dominant solar cell, but it failed to do so because the main manufacturer stopped production late in 2002.

The third generation hopes to eventually combine both high efficency and affordability. They are called tandem cells. These cells range from a low cost, low efficienct amorphous silicon-germanium to an ultra high efficienct III-V (cells made from elements of Groups III and V of the Periodic Table) cells. There are two major ways to compare solar cells are by their efficiencies and by their cost per peak Watt. There has been a rapid increase in both the production of and energy production from solar cells in recent years, Fig: 4.18 and 4.19 show these increases, trying to find a reliable green energy source.

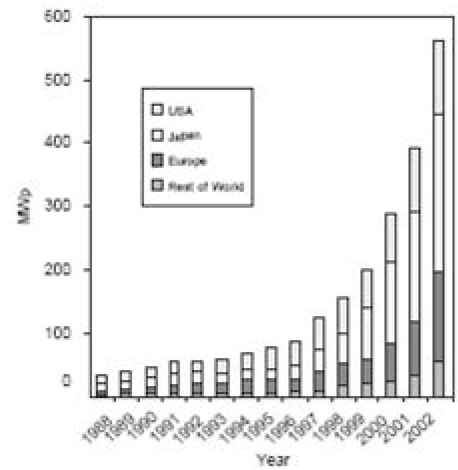


Figure 4.18: World solar cell production, 19882002, for the three main production zones and for the rest of the world (ROW). Data from Photon International and Renewable Energy World. [8]

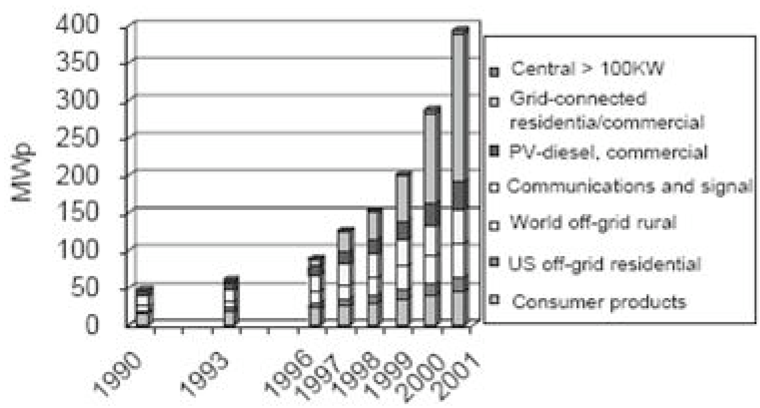


Figure 4.19: World PV market by application, 1990-2001. Data from Renewable EnergyWorld. [8]

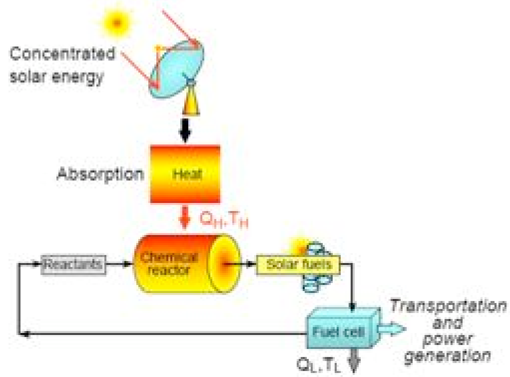


Figure 4.20: Schematic of solar energy conversion into solar fuels. Concentrated solar radiation is used as the energy source for high-temperature process heat to drive endothermic chemical reactions toward the production of storable and transportable fuels. [47]

There are three basic ways to make solar fuels from solar energy, solar electrochemical, solar photochemical, and solar thermochemical. Solar thermochemical path offers some thermodynamic advantages. This process uses mirrors to concentrate solar energy on a reactor and receiver, which then convert that energy into a transportable fuel source by carrying out an endothermic chemical reaction. The solar energy is stores in the chemical bonds of the product from the reactor, Fig: 4.20. The efficiency of the reactor increases with temperature, but so does the radiation from the receiver and reactor back into the environment. The three main optical configurations of mirrors and receivers are the trough system, the tower system, and the dish system, see Fig: 4.21. [47]

The mean flux concentration ratio, $\tilde{C}$, is the ability of the collection systems to concentrate solar energy. It is calculated by the equation

$$\tilde{C} = \frac{Q_{solar}}{IA} \tag{4.7}$$

Where A is the target area at the focal plane, I is the incident normal beam insolation, and Qsolar is the solar power input into the target. The average values of the mean flux concentration ratio are between 30 and 100 suns for trough systems, between 500 and 5,000 suns for tower systems, and between 1,000 and 10,000 suns for dish systems, where 1 sun is equal to 1kW/m2. This heat is concentrated on a working fluid (typically air, water, helium, sodium, or molten salt) and further used in traditional Rankine, Brayton, and Stirling cycles to produce solar fuels. The heated chemical reactor allows the reactants to form solar fuels because of the equilibrium constant changes to favor the products. The equilibrium constant changes to favor the products because the reaction forming the solar fuels is an endothermic reaction, thus the reaction requires heat to proceed forward.

The most common solar fuel that is produced is hydrogen. This reaction

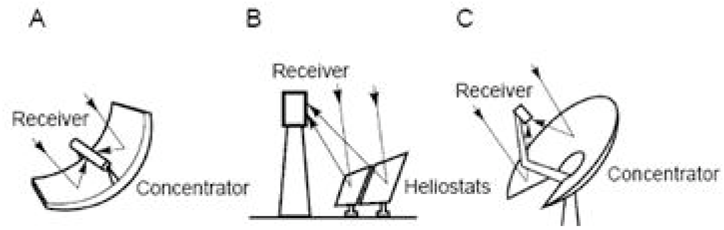


Figure 4.21: Schematic of the three main optical configurations for large-scale collection and concentration of solar energy: (A) the trough system, (B) the tower system, and (C) the dish system. [47]

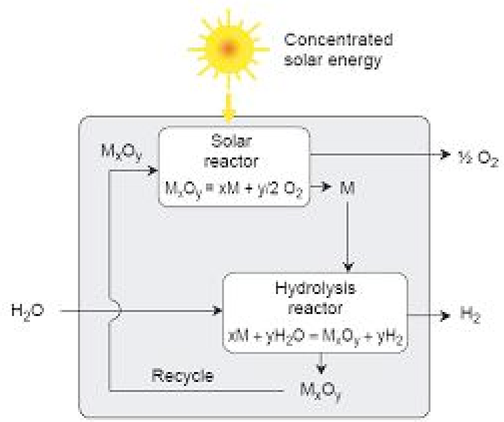


Figure 4.22: Representation of a two-step water-splitting thermochemical cycle using metal oxide redox reactions. [47]

requires a metal oxide, a catalyst, and water. This reaction produces hydrogen and oxygen. The two step reaction that occurs is

$$M_xO_y \rightarrow xM + \frac{Y}{2}O_2 \tag{4.8}$$

$$xM + yH_2O \rightarrow M_xO_y + yH_2 \tag{4.9}$$

where M is the metal participation in the reaction and MxOy is its metal oxide. In order for the first reaction step to occur the reactor must have an internal temperature of at least 2000 K. Since the hydrogen and oxygen are formed in different steps there is no need to have a high-temperature gas separator, thus eliminating a step in the process. The hydrogen is then stored for transportation or for latter use.

The solar electrochemical path is solar-made electricity, from photovoltaic or solar thermal systems, followed by an electrolytic process. This process uses "semiconducting materials to achieve the absorption of light energy to generate free charge carriers within the material and the separation of the negative and positive charge carriers to produce unidirectional electrical current through

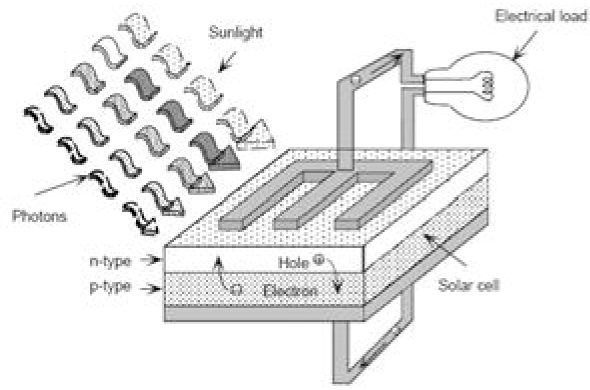


Figure 4.23: Solar cell operation. [8]

terminals that have a voltage difference between them, a solar cell." The main process for a photovoltaic cell is that photons enter the cell volume through the front surface. Higher energy photons, blue or violet, are absorbed first and proceed down the visible spectrum to low energy photons, red, are absorbed last, thus penetrating more into the cell. The photons are absorbed by electrons and this excites the electron and frees it from the semiconductor leaving behind a positive hole in the semiconductor. This difference in charge creates a flow of electrons, current, that produce a potential, voltage, and creates a source of energy. [8]

The price of solar electricity would need to decrease by a significant amount for it to be competitive with coal or any other electricity generation source. The Department of Energy states that for a plant coming on-line in 2015 the price for solar energy would be about 30 cents per kwh, about 5.65 times the cost per kwh for coal, see Fig: 4.24.[10] In order for the price per kwh to decrease the efficiency of the solar cells needs to increase, cost of materials needs to decrease, cost of production of the solar cells needs to decrease, amount of material used needs to decrease and efficiency of storing solar energy needs to increase. Maintenance costs for solar energy plants are very low compared to other energy plants. The maintenance costs are for replacing motors that move the mirrors or solar cells with the sun and keeping the mirrors and solar cells clean from dust and other particles. Most of the components for the solar plants have lifetimes of 10 years or more, except for the fuel cells and batteries which have lifetimes of 5 and 4 years, respectively.[31]

One way that solar energy can be competitive is through nanostructured thin films for solar cells. This new technology is currently being researched at the University of California. They hope to develop a solar cell that uses this material that is more efficient and cost effective. This thin film is made up of titanium oxide doped with nitrogen that absorb a broad range of light energy and nanocrystals of quantum dots made of cadmium selenide that aid in energy conversion and absorption of visible light. The combining of these two types of nanomaterials increased the efficiency three fold compared to each nanomaterial separately. This advance in solar cell technology could make solar energy more cost effective and thus more competitive. [59]

Type of Energy Source	Cost per kwh	Cost Comparison to Coal
Coal	$0.0531	--
Wind	$0.0558	1.051x coal
Natural Gas	$0.0525 (before subsidies)	.98x coal
Nuclear	$0.0593	1.12x coal
Solar	$0.30	5.65x coal
Biomass	$0.075	1.41x coal
Geothermal	$0.075	1.41x coal

Figure 4.24: Cost per kwh for Different Energy Sources [10]

Chapter 5

Energy Policy Research

5.1 Matlab Model

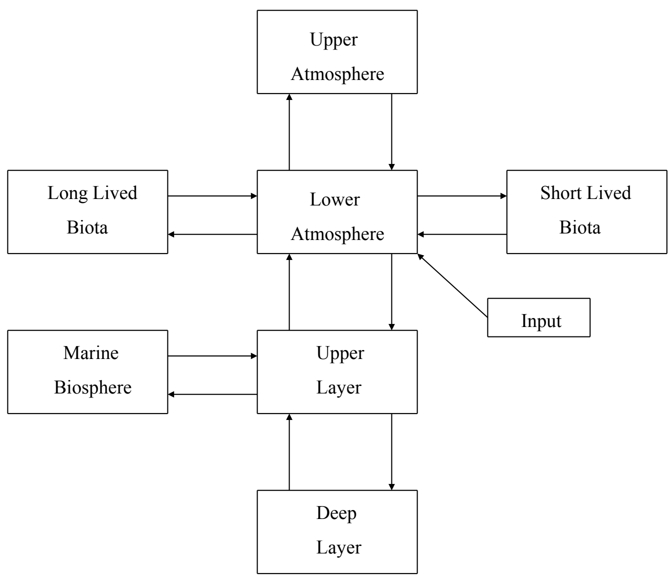


Figure 5.1: Layout of the CO_2 climate model. [5]

Presented here is a global model of the CO_2 concentrations in the Earth's lower atmosphere based on a seven reservoir system. The reservoirs which will be dealt with in this model include the upper and lower atmosphere, the short and long lived biota, the marine biosphere, and the upper and deep ocean layers all linked together as shown in Figure 5.1. These reservoirs are represented mathematically as shown in Table 5.1 where t denotes the time in years with the initial time taken to be the year 1850 ($t_0 = 1850$). The model was constructed so as to match the observed CO_2 concentration from the Mauna Loa Observatory in Hawaii which recorded a value of 384 ppm in 2007. [5]

Name	Reservoir
$c_{ua}(t)$	Upper atmosphere
$c_{la}(t)$	Lower atmosphere
$c_{sb}(t)$	Short lived biota
$c_{lb}(t)$	Long lived biota
$c_{ul}(t)$	Upper ocean layer
$c_{dl}(t)$	Deep ocean later
$c_{mb}(t)$	Marine biosphere

Table 5.1: Reservoir concentrations. [5]

One of the assumptions which have been made in this model include uniform concentrations of CO_2 in each of the reservoirs which breaks down the differential equations from partial differential equations into ordinary differential equations (ODEs) of time only. The concentrations in each of the reservoirs will have the dimensionless form of the following

$$c(t) = \frac{c_{dim}(t) - c_{dim}(t = 1850)}{c_{dim}(t = 1850)} \tag{5.1}$$

which gives the concentrations in all the reservoirs in the same "units" (all having dimensionless units). The ODE for the upper atmosphere of the climate model presented in Figure 5.1 takes the following form

$$\frac{dc_{ua}}{dt} = \frac{1}{\theta_{ua-la}}(c_{la} - c_{ua}),\ c_{ua}(1850) = 0 \tag{5.2}$$

where θ_{ua-la} is the "mean residence time" or mixing time for a CO_2 molecule to travel from the lower atmosphere to the upper atmosphere. To obtain the concentrations of CO_2 in each of the reservoirs we have to first construct the ODE that governs the CO_2 concentration for a given reservoir similar to the ODE constructed for the upper atmosphere in Equation 5.2 and then integrate from the initial time ($t_0 = 1850$) to the desired time which we will take as $t = 2030$. In the case of the upper atmosphere this will take the form of

$$c_{ua} = \int_{t=1850}^{t} \frac{1}{\theta_{ua-la}}(c_{la} - c_{ua})\, dt. \tag{5.3}$$

The ODE for the lower atmosphere follows similarly as

$$\frac{dc_{la}}{dt} = \frac{1}{\theta_{la-ua}}(c_{ua} - c_{la}) + \frac{1}{\theta_{la-sb}}(c_{sb} - c_{la}) + \dots \tag{5.4}$$

$$\dots + \frac{1}{\theta_{la-lb}}(c_{lb} - c_{la}) + \frac{1}{\theta_{la-ul}}(c_{ul} - c_{la}) + Q_c(t). \tag{5.5}$$

Here, the ODE is slightly more complex due to the linking of the lower atmosphere with the upper atmosphere, long and short lived biota, and upper ocean layer. The term $Q_c(t)$ is the CO_2 contribution from humans, the so-called anthropogenic emission rate and is defined as

$$Q_c(t) = c_1 e^{r_1 t} \tag{5.6}$$

where r_1 is determined by the equation

$$r_1 = r_1 b + r_1 c\left(\frac{t - 2005}{2030 - 2005}\right). \tag{5.7}$$

The anthropogenic emissions rate is currently set to 1% and increases linearly to the sum r_1. When exploring different energy policies in Section 2, $r_1 c$ will be defined as to give the value of the CO_2 concentration in the lower atmosphere projected by each of the energy policies in the year 2030, also known as the fractional increase in emissions by 2030. Similarly, the differential equation which governs the upper ocean layer is shown in Equation 5.9. [5]

$$\frac{dc_{ul}}{dt} = \frac{1}{\theta_{ul-la}}(c_{la} - c_{ul}) + \frac{1}{\theta_{ul-dl}}(c_{dl} - c_{ul}) + \dots \tag{5.8}$$

$$\dots + \frac{1}{\theta_{ul-mb}}(c_{mb} - c_{ul}). \tag{5.9}$$

The differential equations which governs the carbon dioxide concentrations in the short and long lived biota, marine biosphere, and deep ocean layer reservoirs are given by Equations 5.10, 5.11, 5.12, and 5.13, respectively. [5]

$$\frac{dc_{sb}}{dt} = \frac{1}{\theta_{sb-la}}(c_{la} - c_{sb}),\ c_{sb}(1850) = 0 \tag{5.10}$$

$$\frac{dc_{lb}}{dt} = \frac{1}{\theta_{lb-la}}(c_{la} - c_{lb}),\ c_{lb}(1850) = 0 \tag{5.11}$$

$$\frac{dc_{mb}}{dt} = \frac{1}{\theta_{mb-ul}}(c_{ul} - c_{mb}),\ c_{mb}(1850) = 0 \tag{5.12}$$

$$\frac{dc_{dl}}{dt} = \frac{1}{\theta_{dl-ul}}(c_{ul} - c_{dl}),\ c_{dl}(1850) = 0 \tag{5.13}$$

5.2 Energy Trends & Consumption

World energy consumption of all energy sources is presently projected to rise approximately 50% in 2030 from the levels seen in 2005 by the Energy Information Administration (EIA), the statistical department headed under the Department of Energy (DoE) in the United States. Shown in Figure 5.2 is the predicted world energy consumption of all energy sources in quadrillion btu starting from the year 2005 to 2030. From this apparent trend of increasing use of energy fuels detrimental to the current climate status, it is clear that the energy policies of all countries must change to meet the increasing trend of greenhouse gases in the lower atmosphere.

5.3 Exploring Branching Energy Policies

For our IQP Project, we explored the effects of different electricity energy policies throughout the world on carbon dioxide concentrations in the lower atmosphere. Shown in Figure 5.3 is the electricity generation in 2005 with predictions

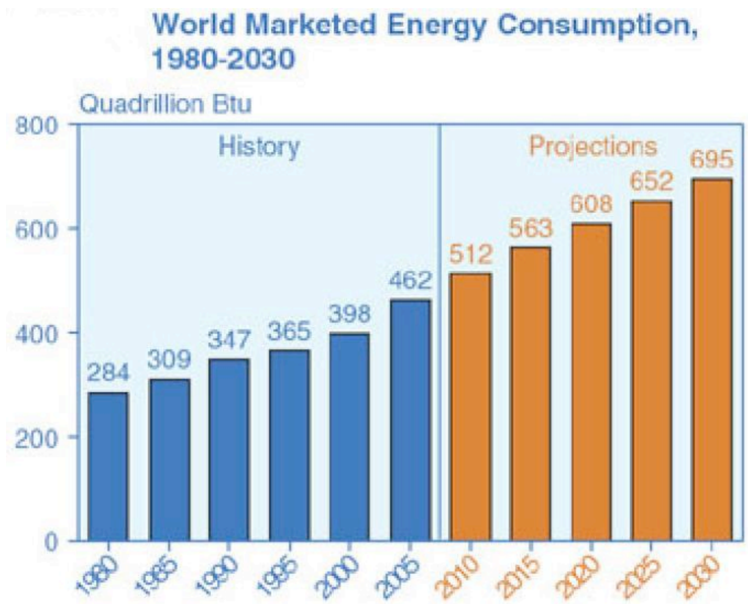


Figure 5.2: Projected energy consumption of the entire world from 2005 to 2030 by the EIA. [16]

of future electric energy use to the year 2030 by the EIA. Figure 5.3 shows the distrubtion of energy fuel use from 2005 with projections to 2030 with fossil fuels being the most widely used energy source by far. Renewables came in a surprising 18% with hydropower constituting more than 90% of the renewables. The two major points that this graphs shows is our dependence on fossil fuels for obtaining the majority of our electrical energy needs and also our unwillingness to quickly adopt alternative energy sources, particularly in renewable energy.

Before continuing on with out energy policy research, a note must be made on the fact that electricity generation only contributes roughly 17% of the world's carbon dioxide emissions. This, of course, leaves out carbon dioxide emissions from vehicles, another major source of emissions. This decision was made primarily due to the lack of information for carbon dioxide emission values for different vehicle types per distance traveled throughout the world. The values used for each of the different energy sources is shown in Table 5.2 for the amount of carbon dioxide released per kWh of energy consumed in grams. One thing to notice is that solar energy wasn't experimented with simply due to the high costs still attached to the energy source. Most of the energy sources experimented here have either been developed for a while or are at a point that is economically feasible for various countries to pursue.

Table 5.2 shows the average amount of CO_2 released in grams per kWh for each type of electricity generation plant. Due to the wide variations in reported numbers for CO_2 emissions, we took the highest reported number for a conservative approach.

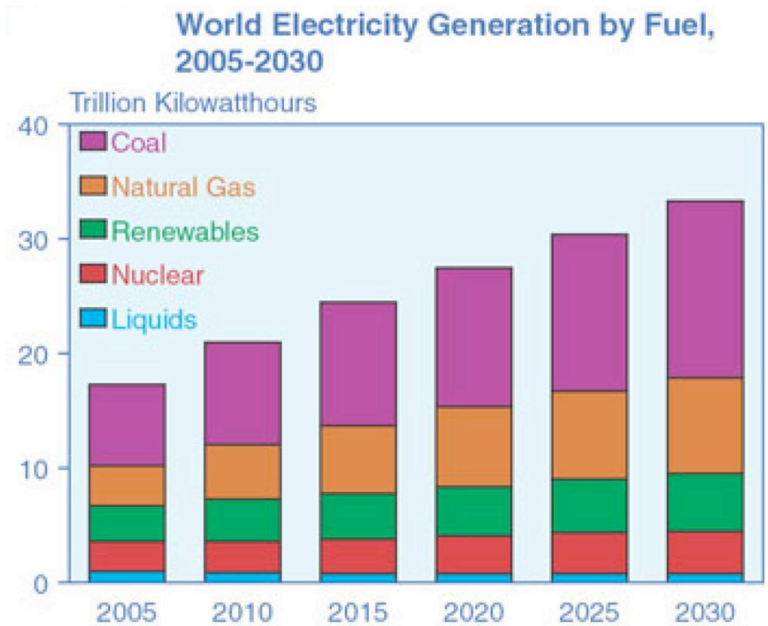


Figure 5.3: Projected energy consumption of the entire world from 2005 to 2030 by the EIA. [16]

Energy		CO_2 Emissions per kWh $[g/kWh]$
Coal	-	960
Liquid	-	740
Natural Gas	-	443
Nuclear	-	66
Hydro	Renewable	18
Wind	Renewable	10

Table 5.2: Grams of CO_2 released per kWh for each type of electricity generation plant. [29] [14] [27]

5.3.1 Carbon Dioxide Unit Conversion

Before proceeding to explore different energy policies, we must first understand how to convert from grams of CO_2 to CO_2 in ppm for the lower atmosphere. This can be done by using Equation 5.14

$$CO_2\ [ppm] = \frac{CO_2\,[g]}{V_{Lower\ Atmosphere}\,[L]} \times \frac{22.4\,[L]}{[mol]} \times \frac{[mol]}{44\,[g]} \times \frac{[ppm]}{10^{-6}} \tag{5.14}$$

where 22.4 $\left[\frac{L}{mol}\right]$ is the volume taken by an ideal gas at STP and 44 $\left[\frac{g}{mol}\right]$ is the molar mass of CO_2. The volume of the lower atmosphere is taken to start from sea level to the boundary which separates the troposphere from the stratosphere, the tropopause, as shown in Figure 5.4. To calculate this volume, we first need the height of the lower atmosphere which is taken to be 14.5 $[km]$ from NASA. [7] By subtracting the volume of the Earth from the volume obtained from combining the troposphere with the Earth itself, a rough estimate of the volume of the lower atmosphere can be calculated as shown in Equation 5.17.

$$V_{la} = \frac{4}{3}\pi(R^3_{Earth\ Radius\ \&\ Troposphere} - R^3_{Earth\ Radius}) \tag{5.15}$$

$$= \frac{4}{3}\pi(6385.5^3 - 6371^3) \tag{5.16}$$

$$V_{la} = 7.41 \times 10^9\ km^3 = 7.41 \times 10^{21}\ L \tag{5.17}$$

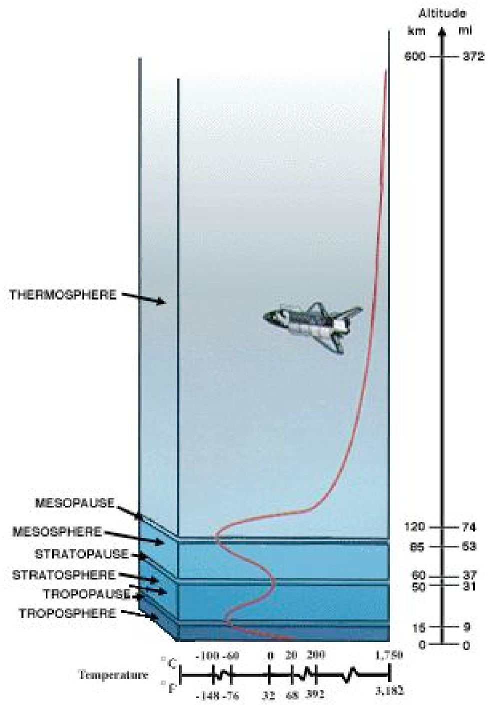


Figure 5.4: The Earth's atmosphere is divided into multiple regions with the lower atmosphere constituing the region from sea level to the upper troposphere. [7]

5.3.2 CO_2 Concentration Calculation

The CO_2 emissions in 2030 were calculated for each policy using the equations

$$CO_{2,\,E,\,2030} = E_{non-elec,\,2030} + E_{elec,\,2030} + \Delta E_{elec,\,2030} \tag{5.18}$$

$$E_{non-elec,\,2030} = E_{elec,\,2030} \times 5.0730 \tag{5.19}$$

where $CO_{2,\,E,\,2030}$ is the total emissions in 2030, $E_{non-elec,\,2030}$ is the non-electric generation emissions in 2030, $E_{elec,\,2030}$ is the electric generation emissions in 2030, and $\Delta\ E_{elec,\,2030}$ is the change in electric generation emissions for each policy in 2030. We assumed that the ratio of non-electric generated emissions to electric generated emissions, 5.0730:1, would stay about the same in 2030 and used this ratio to separate the electric from non-electric emissions if the current policies don't change.

The Matlab model needs to have the fractional increase in 2030 in order for it to calculate the CO_2 concentration for each year. This fractional increase can be found by using a standard numerical convergence method with a set tolerance value. The fractional increase in emissions by 2030, $r1c$, is first calculated using the equation

$$r1c = \frac{CO_{2,\,E,\,2030}}{[X]} - \frac{CO_{2,\,E,\,2005}}{[CO_{2,\,2005}]} \tag{5.20}$$

where $CO_{2,\,E,\,2030}$ is the CO_2 emissions for 2030 in ppm, X is the guessed value of the CO_2 concentration in 2030 in ppm, $CO_{2,\,E,\,2005}$ is the CO_2 emissions for 2005 in ppm and $[CO_{2,\,2005}]$ is the CO_2 concentration in 2005 in ppm. This $r1c$ value is run through the model and a CO_2 concentration in 2030 is predicted. If this value is approximately equal to the guessed value then that is the correct concentration for 2030. Otherwise, this value is set as the new value for X. $r1c$ is recalculated and the model is executed again with this new value and a new predicted CO_2 concentration in 2030 is obtained. This method is repeated until the most recent value of X is within a tolerance of $0.1\,[ppm]$ to the latest value of the CO_2 concentration in 2030 predicted by the model. This X value is the actual predicted CO_2 concentration in 2030 for the policy under research. Table 5.3 shows a summary of the calculated $r1c$ and CO_2 values in 2030 for all of the energy policies we investigated. (See 9.1.1 in the appendix)

$$\frac{CO_{2,\,E,\,2030}}{[X]} - \frac{CO_{2,\,E,\,2005}}{[CO_{2,\,2005}]} = r1c \rightarrow Run\ Model \rightarrow X_{new} \tag{5.21}$$

$$\begin{aligned}
&If\ |X_{new} - X| > 0.1\\
&Then\ X = X_{new},\ REPEAT\\
&End
\end{aligned}$$

$$\begin{aligned}
&If\ |X_{new} - X| \leq 0.1\\
&Then\ X\ is\ the\ CO_2\ concentration\ in\ 2030\\
&End
\end{aligned}$$

Policy	CO_2 2030 [ppm]	$r1c$	$CO_{2,\,E,\,2030}$ [ppm]	$\Delta E_{elec,\,2030}$ [ppm]
Same Energy Policy	461.84	0.0060438	7.4672	0
Predicted by the EIA	463.73	0.0061948	7.5680	0.101
World Switches to 49% Renewable and Nuclear	457.38	0.0056330	7.2074	-0.25984
US Switches to 20% Wind	460.40	0.0059161	7.3853	-0.081868
World Switches to 20% Hydro	458.75	0.0057608	7.2876	-0.17961
World Switches from Coal to Natural Gas	460.09	0.0058927	7.3696	-.097578
World Embraces Nulcear just like France	444.41	0.0043378	6.4275	-1.0397

$CO_{2,\,E,\,2005} = 3.8881$ ppm, $CO_{2,\,2005} = 379.78$ ppm, $E_{non-elec,\,2030} = 6.2376$ ppm, $E_{elec,\,2030} = 1.2296$ ppm.

Table 5.3: Calculated Values for each Policy.

5.3.3 Energy Policy From 2005

If we assume that the distribution of electric energy generation is constant for each of the energy sources until 2030, then the calculated CO_2 concentration in 2030 is projected to be 461.84 [ppm] if the same energy policy is pursued in 2030. This value will be used as a base for the world's "current energy policy" for this report (an energy policy based on current electricity consumption percentages for each of the energy sources). Different energy policies will be explored by modifying the contribution of each of the different energy sources in the year 2030 while still fulfilling the total projected electric energy needs of the future generation as projected in Figure 5.3.

Shown in Figures 5.6, 5.7, and 5.8 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the world following the same energy policy it had in 2005 until 2030. For this energy policy, a value of 0.0060438 for $r1c$ is reached which means that the anthropogenic emissions rate increases by 92.05% by the year 2030.

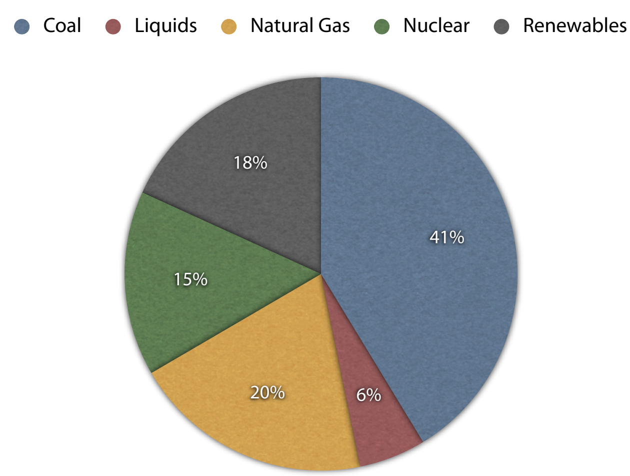


Figure 5.5: Current electricity generation by fuel type in 2005 from the EIA.

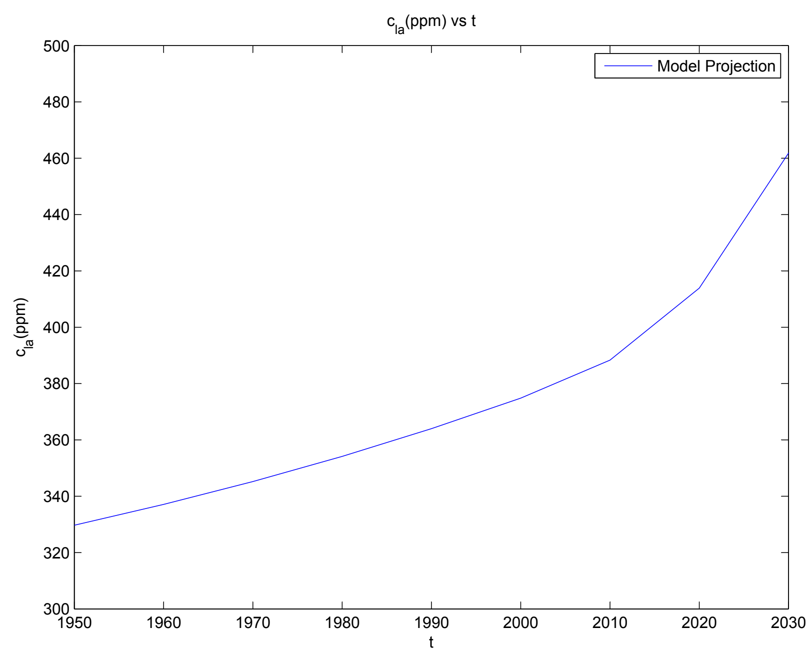


Figure 5.6: Projected CO_2 increase from 2005 to 2030 based on a 92.05% increase in CO_2 emissions rate as a result of the world following the same energy policy in 2005.

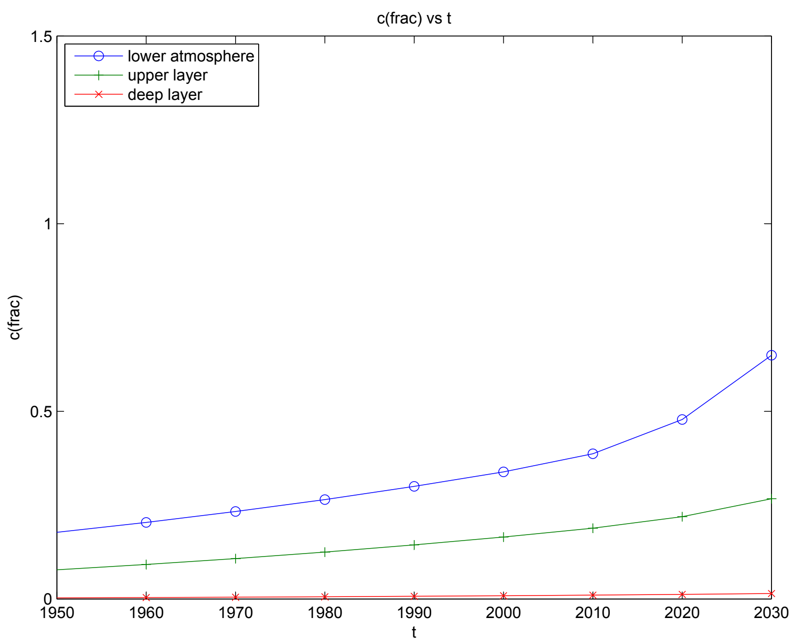


Figure 5.7: Projected fractional increases from 2005 to 2030 based on a 92.05% increase in CO_2 emissions rate as a result of the world following the same energy policy in 2005.

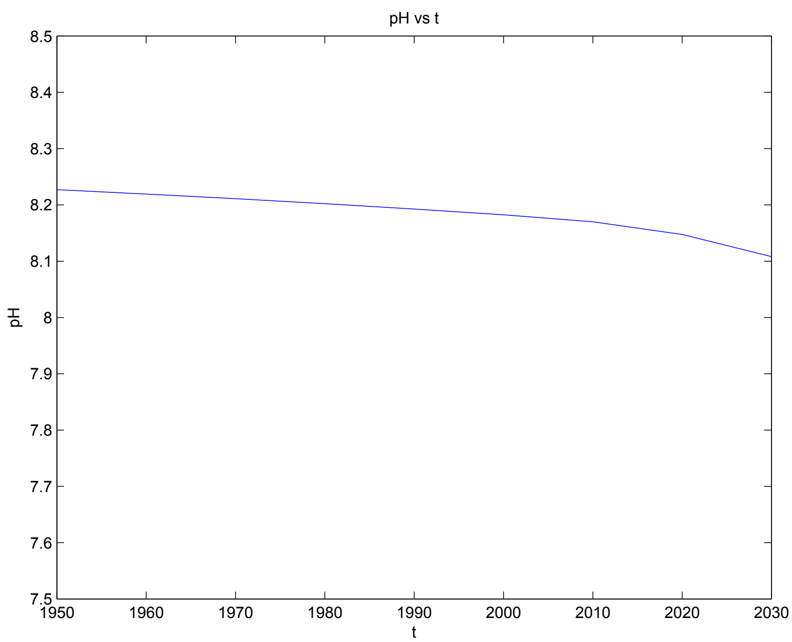


Figure 5.8: Projected pH level increase from 2005 to 2030 based on a projected 92.05% increase in CO_2 emissions rate as a result of the world following the same energy policy in 2005.

5.3.4 Wind Energy In the US

Electricity generation from wind farms are becoming not only a popular alternative energy source, but, also one of the most realistic approaches for renewable energy sources at the present moment and near term future. Studies performed by scientists have found this to be the case and should become an integral part of any major energy policy to be proposed in the future. This is mainly attributed to the fact that wind energy technologies have matured to the point of being economically feasible compared to other green technologies such as solar energy (both photovoltaic and thermoelectric) which is still too expensive. To see the benefits of switching to wind power, let's assume that the United States alone switched 20% of its electricity generation to wind farms and that any increase in electricity generation is again offsetted by decreasing the amount of electricity generation contributed by coal, the major contributor of carbon dioxide emissions. The percentage increase and decrease for each energy source is shown in Table 5.4. What we find is that a reduction of 1.44 *ppm* of CO_2 concentration is achieved by 2030 assuming that our energy policy is switched immediately. [3]

Shown in Figures 5.9, 5.10, and 5.11 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the United States pursuing wind energy for 20% of its electricity generation in 2005 until 2030. For this energy policy, a value of 0.0059161 for $r1c$ is reached.

Table 5.4 shows the percentage increase/decrease for each energy source to form the "wind energy policy" for the United States.

Energy Source	% Change	% Energy Distribution
Coal	-30.5	35.5
Liquids	-80.3	0.6
Natural Gas	0	19.1
Nuclear	0	19.3
Hydro	0	6.5
Wind	713.6	20.0
$\Delta\, CO_2$ Projections in 2030	-1.44 ppm	

Table 5.4: Projected increase and decrease in each of the energy sources in 2030 if the United States increases its wind power generation to 20% of its total electricity generation.

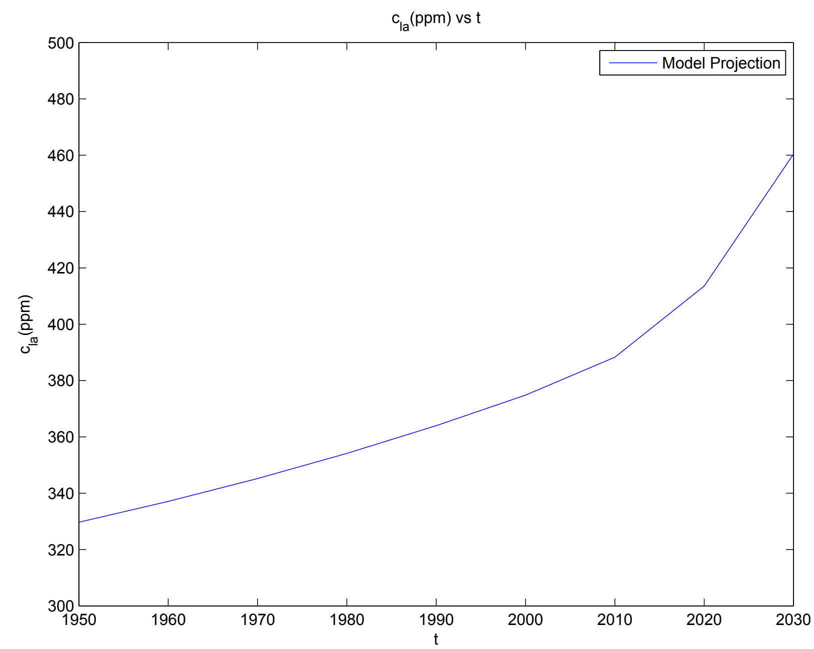


Figure 5.9: Projected CO_2 increase from 2005 to 2030 based on a 89.9% increase in CO_2 emissions rate as a result of the United States increasing its electricity consumption to 20% wind energy.

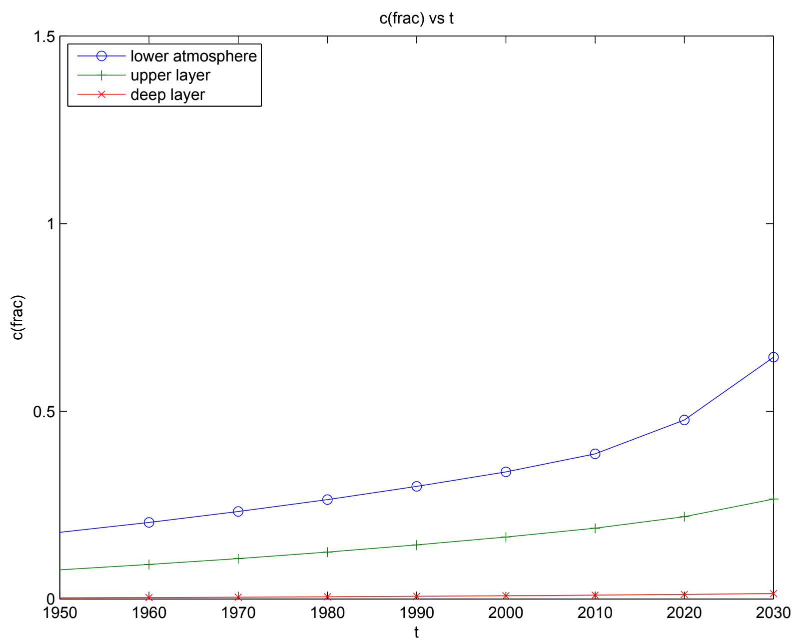


Figure 5.10: Projected fractional increase from 2005 to 2030 based on a 89.9% increase in CO_2 emissions rate as a result of the United States increasing its electricity consumption to 20% wind energy.

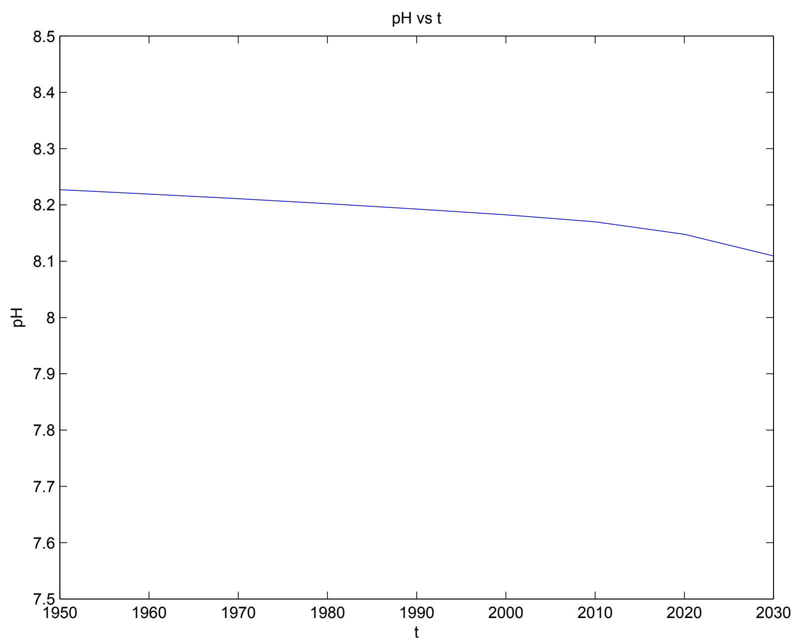


Figure 5.11: Projected pH level increase from 2005 to 2030 based on a projected 89.9% increase in CO_2 emissions rate as a result of the United States increasing its electricity consumption to 20% wind energy.

5.3.5 Hydroelectric Energy

Another viable renewable energy source includes hydroelectric energy. Hydroelectricity, however, also has some notable disadvantages going against it which includes finding the necessary space and ideal location to build the dams for generating the electricity. This often can lead to political issues due to the need to relocate residents who are presently occupying that region. Also, the building of such a large structure almost always necessitates the destruction of the environment around that local region.

Shown in Table 5.5 are the percentage increases and decreases for each energy source for employing this energy policy for hydroelectric energy. What we find is that an emissions rate increase of 87.4% is achieved which results in a reduction of 3.09 *ppm* of CO_2 by 2030 and an r1c value of .0057608. Shown in Figures 5.12, 5.13, and 5.14 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the world pursuing hydroelectric energy for 24.9% of its electricity generation in 2005 until 2030.

Energy Source	% Change	% Energy Distribution
Coal	-20.2	32.8
Liquids	0	5.5
Natural Gas	0	19.6
Nuclear	0	15.1
Hydro	50.0	24.9
Wind	0	2.1
$\Delta\, CO_2$ Projections in 2030	-3.09 ppm	

Table 5.5: Projected increase and decrease in each of the energy sources by in 2030 with the world pushing hydropower.

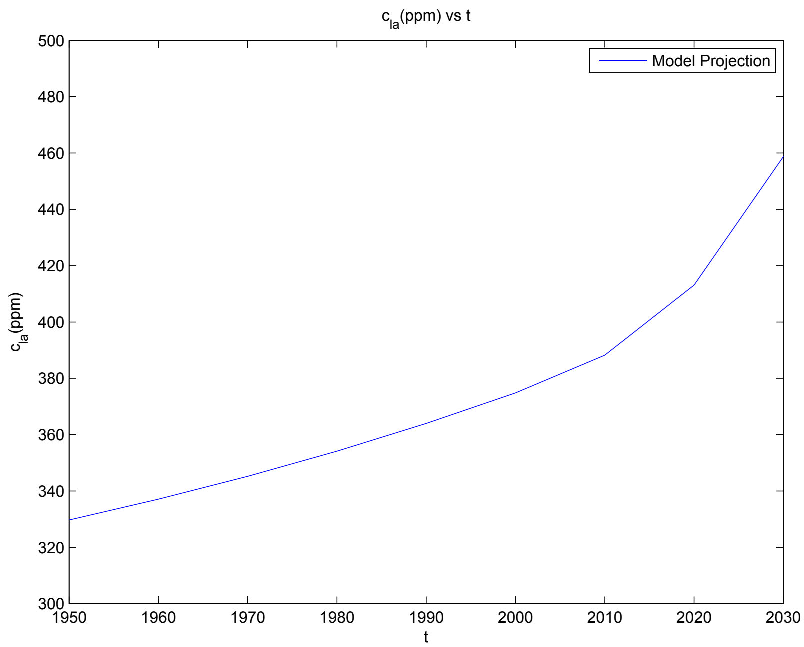


Figure 5.12: Projected CO_2 increase from 2005 to 2030 based on a 87.4% increase in CO_2 emissions rate as a result of the world increasing its electricity consumption to 24% hydroelectric energy.

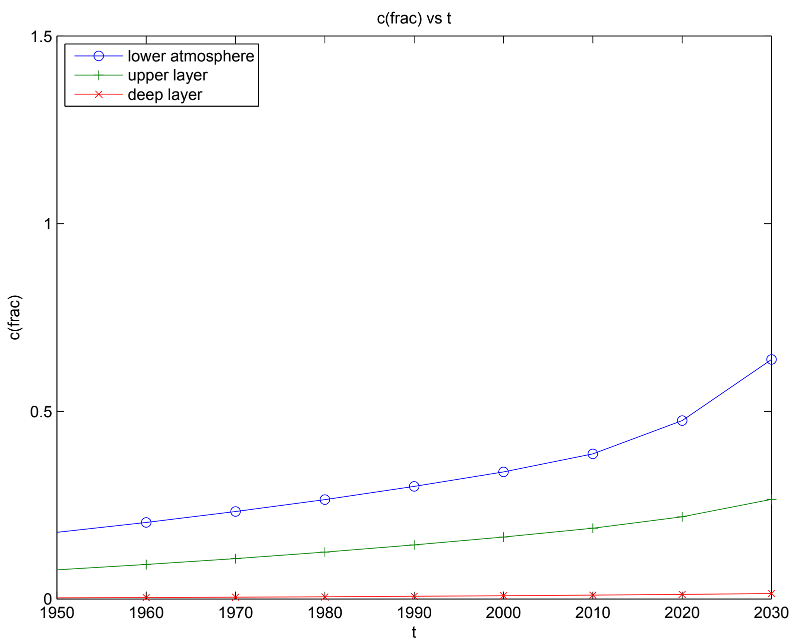


Figure 5.13: Projected fractional increase from 2005 to 2030 based on a 87.4% increase in CO_2 emissions rate as a result of the world increasing its electricity consumption to 24% hydroelectric energy.

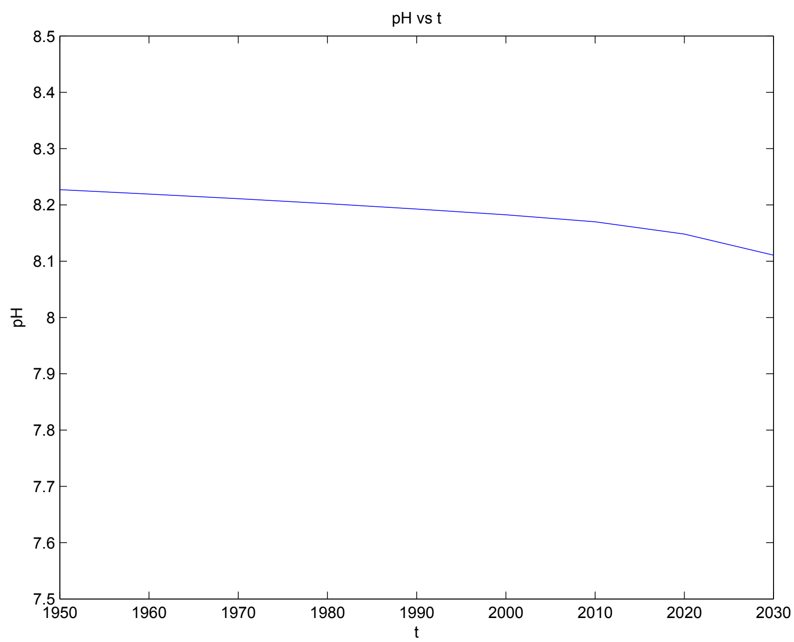


Figure 5.14: Projected pH level increase from 2005 to 2030 based on a projected 87.4% increase in CO_2 emissions rate as a result of the world increasing its electricity consumption to 24% hydroelectric energy.

5.3.6 Renewable & Nuclear Energy

An interesting energy policy would be to increase the electricity contribution for both renewable and nuclear energy at the same time. Table 5.6 shows the percentage increase and decrease of each energy source for this policy. We decided on increasing the contribution from nuclear by 31.7% and hydroelectric and wind energy by 31.8% and 227.0%, respectively for a total contribution of 19.9%, 21.9%, and 7.0% in 2030.

What this leads to is a concentration of 457.38 *ppm* of CO_2 in 2030, a reduction of 4.46 *ppm* of CO_2, with an $r1c$ value of 0.0056330 and an emissions rate increase of 85.4%. Shown in Figures 5.15, 5.16, and 5.17 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the world pursuing a combination of nuclear, hydroelectric, and wind energy for 49% of its electricity generation in 2005 until 2030.

Energy Source	% Change	% Energy Distribution
Coal	-23.0	31.6
Liquids	-17.3	4.5
Natural Gas	-22.9	15.1
Nuclear	31.7	19.9
Hydro	31.8	21.9
Wind	227.0	7.0
$\Delta\, CO_2$ Projections in 2030	-4.46 ppm	

Table 5.6: Projected increase and decrease in each of the energy sources in 2030 with 49% renwables and nuclear energy.

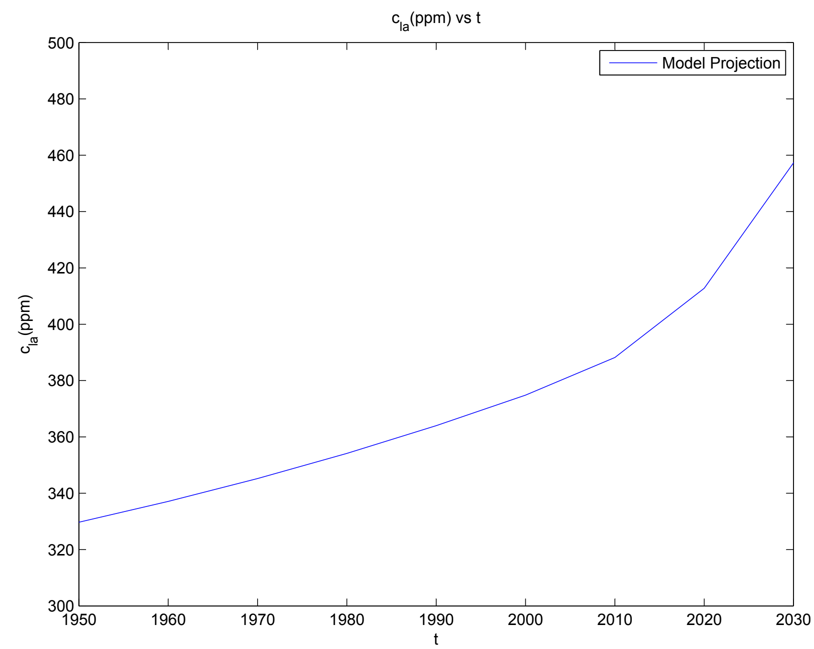


Figure 5.15: Projected CO_2 increase from 2005 to 2030 based on a 85.4% increase in CO_2 emissions rate as a result of the world increasing its electricity consumption to a combination of 28.9% renewable and 21.1% nuclear energy.

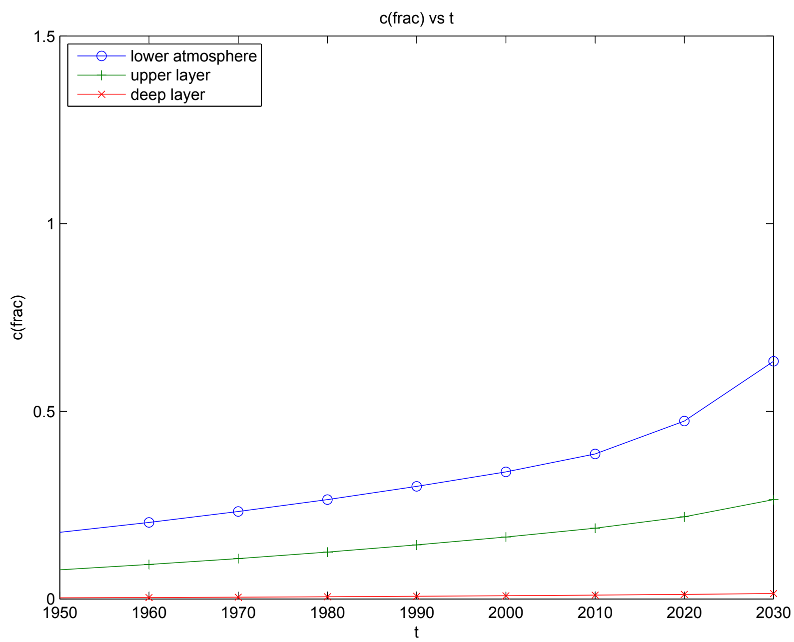


Figure 5.16: Projected fractional increase from 2005 to 2030 based on a 85.4% increase in CO_2 emissions rate as a result of the world increasing its electricity consumption to a combination of 28.9% renewable and 21.1% nuclear energy.

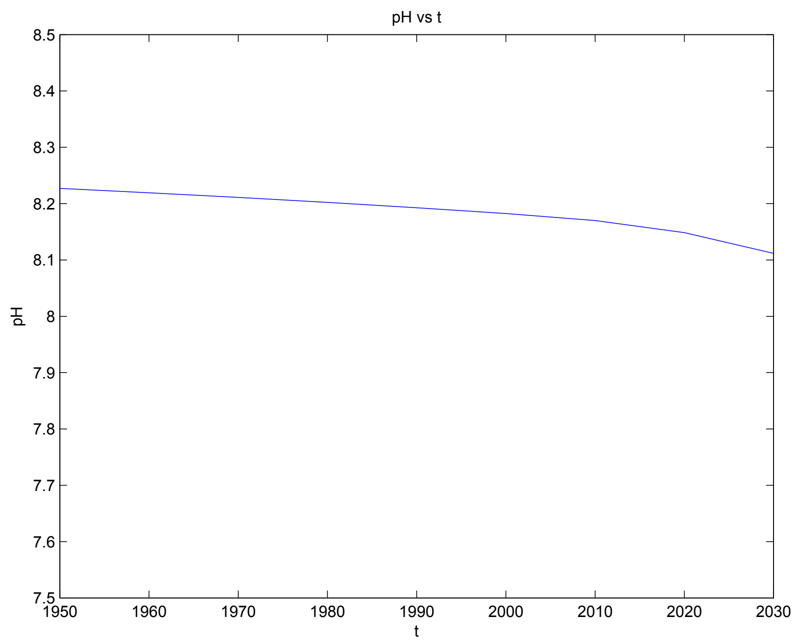


Figure 5.17: Projected pH level increase from 2005 to 2030 based on a projected 85.4% increase in CO_2 emissions rate as a result of the world increasing its electricity consumption to a combination of 28.9% renewable and 21.1% nuclear energy.

5.3.7 Nuclear Energy Policy From France

One energy policy that we're curious about is that of France. France employs nuclear reactors for 78% of its electricity generation, more than the usual for any country (the US in comparison obtains only roughly 19% of its electricity generation from nuclear reactors). Table 5.7 shows the percentage increase and decrease of each energy source for this policy that the world would pursue. What this leads to is a concentration of 444.41 *ppm* of CO_2, a reduction of 17.43 *ppm* of CO_2. This is the largest reduction of CO_2 compared to the other energy policies we've explored thus far which isn't that much of a surprised.

The $r1c$ value for this energy policy is 0.0043378, an emissions rate increase of 65.3%. Shown in Figures 5.18, 5.19, and 5.20 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the world pursuing nuclear energy for 78% of its electricity generation in 2005 until 2030.

Energy Source	% Change	% Energy Distribution
Coal	-94.5	2.3
Liquids	-95.0	0.3
Natural Gas	-95.0	1.0
Nuclear	415.1	77.8
Hydro	0	16.6
Wind	0	2.1
$\Delta\, CO_2$ Projections in 2030	-17.43 ppm	

Table 5.7: Projected increase and decrease in each of the energy sources in 2030 following France's approach to nuclear energy.

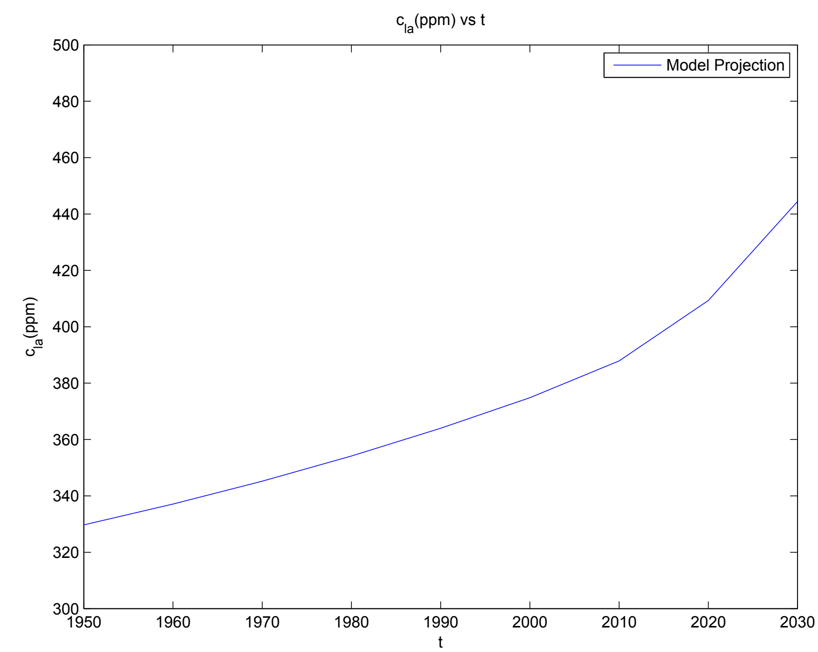


Figure 5.18: Projected CO_2 increase from 2005 to 2030 based on a 65.3% increase in CO_2 emissions rate as a result of the world following the energy policy of France in 2005 (78% nuclear).

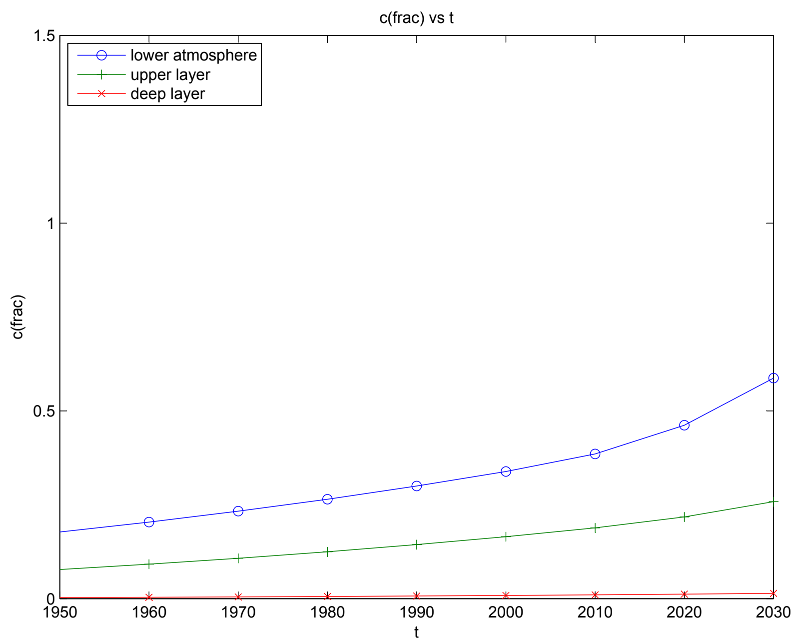


Figure 5.19: Projected fractional increase from 2005 to 2030 based on a 65.3% increase in CO_2 emissions rate as a result of the world following the energy policy of France in 2005 (78% nuclear).

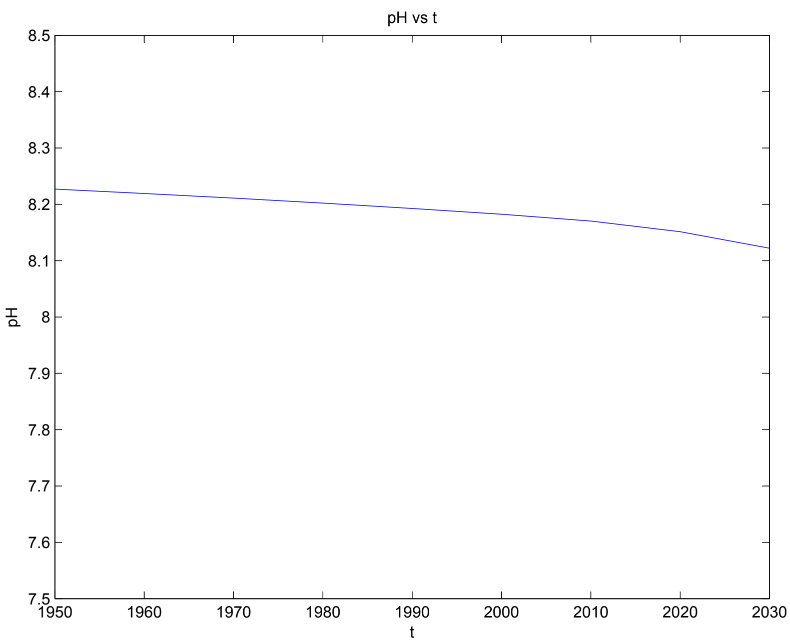


Figure 5.20: Projected pH level increase from 2005 to 2030 based on a projected 65.3% increase in CO_2 emissions rate as a result of the world following the energy policy of France in 2005 (78% nuclear).

5.3.8 Energy Policy Projected By EIA

Once we use the values for the percentage increase and decrease of each energy source as projected by the EIA in 2030 as shown in Table 5.8, we calculate that an increase in 1.89 *ppm* is achieved. This can be attributed primarily to the continuing increase use of coal which is the worse greenhouse gas emitter in this energy group. Also, the combination of reducing renewable energy use as well as increasing natural gas use does not help with the situation.

The $r1c$ value for this energy policy is 0.0061948, an emissions rate increase of 94.6%. Shown in Figures 5.21, 5.22, and 5.23 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the world pursuing the projected energy policy from the EIA for its electricity generation in 2005 until 2030.

Energy Source	% Change	% Energy Distribution
Coal	11.8	46.2
Liquids	-58.4	2.3
Natural Gas	27.6	25.2
Nuclear	-25.7	11.3
Renewables	-17.7	15.0
$\Delta\, CO_2$ Projections in 2030	1.89 ppm	

Table 5.8: Projected increase and decrease in each of the energy sources by the EIA in 2030.

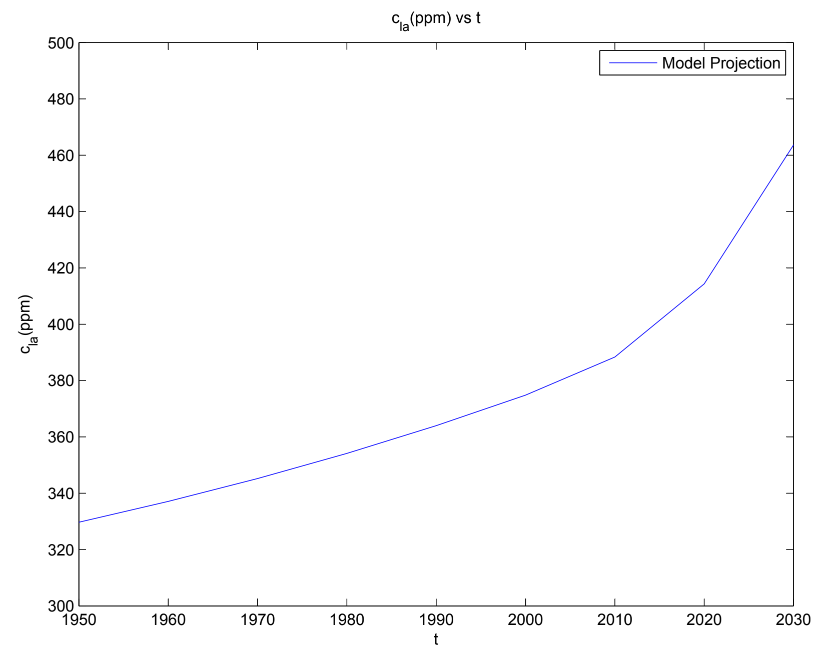


Figure 5.21: Projected CO_2 increase from 2005 to 2030 based on a 94.6% increase in CO_2 emissions rate as a result of the world following the energy policy predicted by the EIA in 2030.

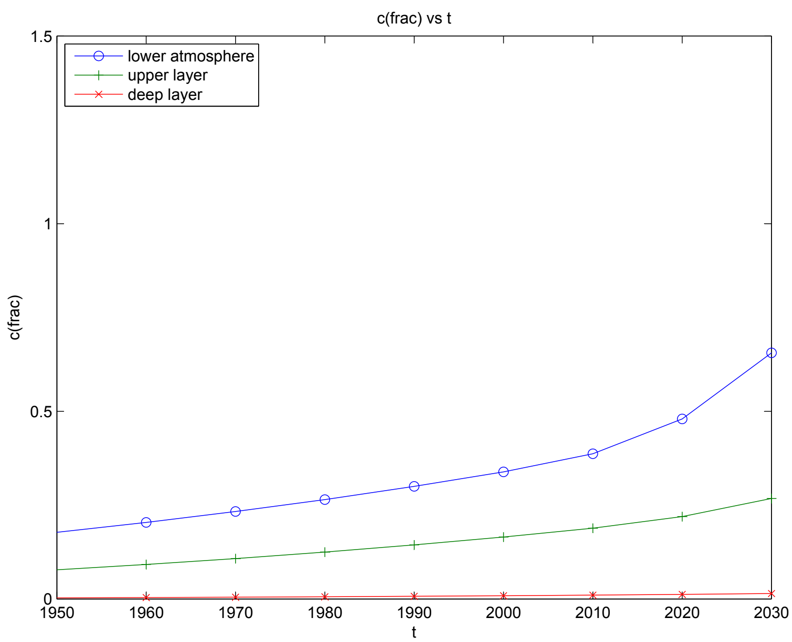


Figure 5.22: Projected fractional increase from 2005 to 2030 based on a 94.6% increase in CO_2 emissions rate as a result of the world following the energy policy predicted by the EIA in 2030.

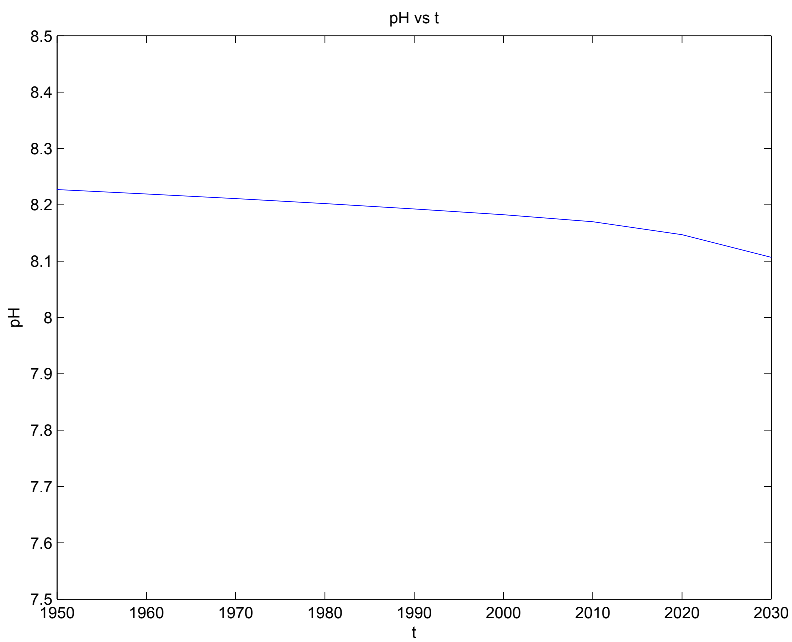


Figure 5.23: Projected pH level increase from 2005 to 2030 based on a projected 94.6% increase in CO_2 emissions rate as a result of the world following the energy policy predicted by the EIA in 2030.

5.3.9 Decreasing Coal Consumption for Natural Gas

Even though natural gas is not a popular choice, its availibility at the present moment means that it can be used immediately. Also, since its carbon emissions rate is still lower than coal, it also means that redistributing some of the electricity contribution from coal to natural gas should decrease the amount of carbon dioxide released into the atmosphere. We based this energy policy on having coal contribute 32.8% and natural gas contributing 27.9% of the electricity generation in 2030, a decrease of 20.0% and an increase of 41.8%, respectively, as shown in Table 5.9. Basec on this energy policy, we calculate that an increase in 1.75 *ppm* is achieved which is still lower than the energy policy predicted by the EIA.

The $r1c$ value for this energy policy is 0.0058927, an emissions rate increase of 89.5%. Shown in Figures 5.24, 5.25, and 5.26 are the plots from the model for the CO_2 concentration in the lower atmosphere, fractional increase of CO_2 in the lower and upper atmosphere and deep ocean layer, and average pH level of the ocean waters, respectively, as a result of the world decreasing coal by 20.0% and increasing natural gas by 41.8% for its electricity generation in 2005 until 2030.

Energy Source	% Change	% Energy Distribution
Coal	-20.0	32.8
Liquids	0	5.5
Natural Gas	41.8	27.9
Nuclear	0	15.1
Hydro	0	16.6
Wind	0	2.1
ΔCO_2 Projections in 2030	-1.75 ppm	

Table 5.9: Projected increase and decrease in each of the energy sources in 2030 aimed at reducing coal use to natural gas use.

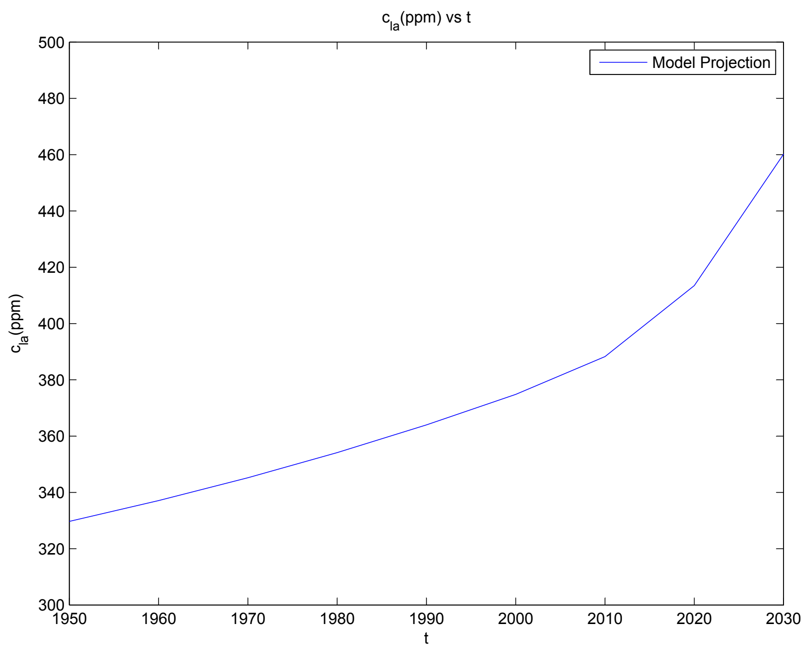


Figure 5.24: Projected CO_2 increase from 2005 to 2030 based on a 89.5% increase in CO_2 emissions rate as a result of the world decreasing coal by 20% and increasing natural gas by 41.8% for a contribution of 32.8% coal and 27.9% natural gas.

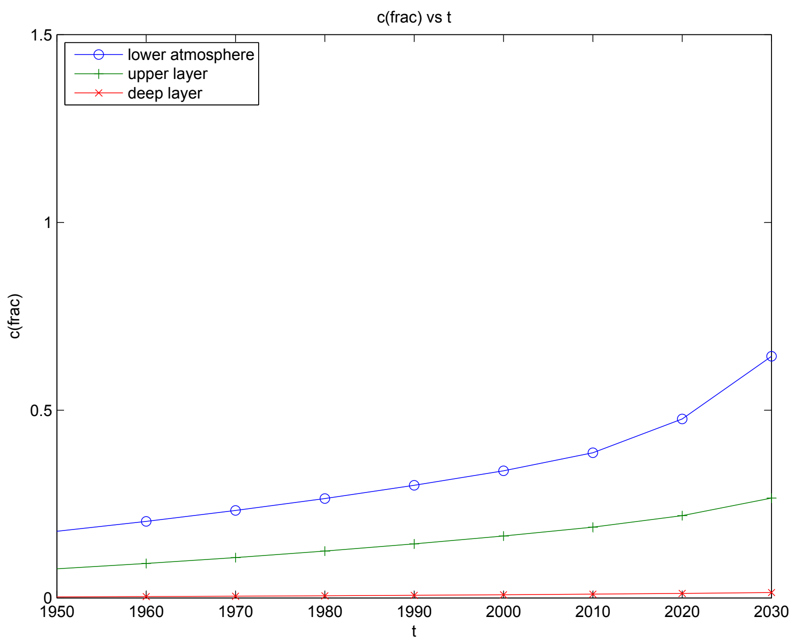


Figure 5.25: Projected fractional increase from 2005 to 2030 based on a 89.5% increase in CO_2 emissions rate as a result of the world decreasing coal by 20% and increasing natural gas by 41.8% for a contribution of 32.8% coal and 27.9% natural gas.

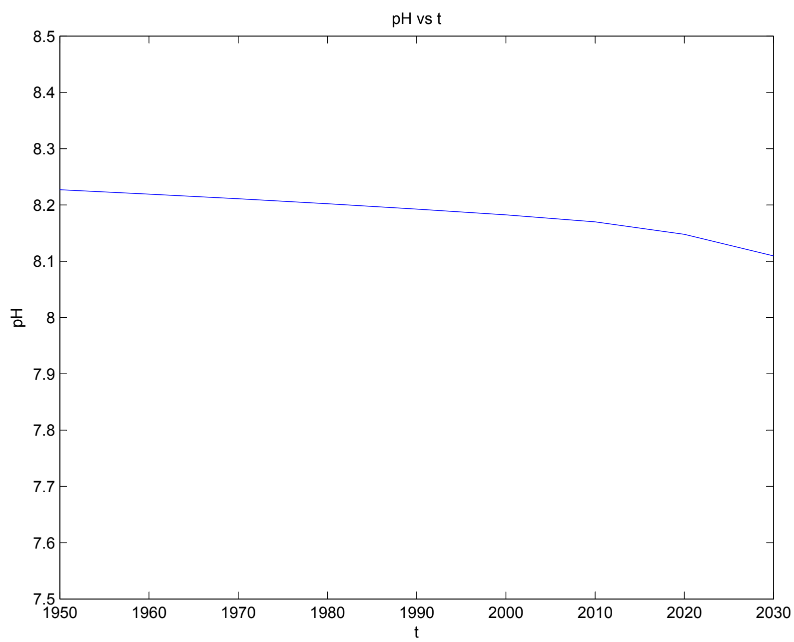


Figure 5.26: Projected pH level increase from 2005 to 2030 based on a projected 89.5% increase in CO_2 emissions rate as a result of the world decreasing coal by 20% and increasing natural gas by 41.8% for a contribution of 32.8% coal and 27.9% natural gas.

5.4 Summary of Energy Policies

What we found was that for future energy policies, wind power will need to play a crucial role due to its maturity and likelihood of providing electricity at a lower cost while not sacrificing carbon dioxide emissions compared to other green technologies. In addition, we have found that a combination of wind and nuclear energy is an enticing option due to nuclear, wind, and hydroelectric energy's low carbon dioxide emission rates. However, this energy policy would most likely prove to be controversial due to concerns surrounding nuclear reactors such as waste disposal and the decommissioning of reactors. As for wind and hydroelectric energy, they each require a constant wind velocity and the necessary space for placement of dams, respectively.

Since electricity comprises only about one sixth of the total CO_2 emissions per year, the change in emissions from 2005 to 2030 aren't as drastic compared to other sources such as vehicles for example. But, over a longer period of time, the effect on future CO_2 concentrations in the lower atmosphere will become much more significant. The percent reduction in CO_2 emissions from electricity sources range from 6.6% to 21.1% for the policies where only the US switches 20% of its electricity generation to wind energy and where the world switches its electricity generation to a combination of about 29% renewable and 20% nuclear energy, respectively. The most drastic, but also most uneconomical, policy is the one in which the world embraces nuclear energy for 79% of its electricity generation similar to France. This would result in emissions being reduced by 85%. On average the percentage of CO_2 emissions reduction from our policies is about 13%, which is a considerable reduction in emissions just from electricity generation alone.

In order for the emissions to be reduced even more, a reduction in non-electric CO_2 emissions needs to be researched on. Since the non-electric emissions accounts for about five sixths of the total carbon dioxide emissions, there will be a greater impact on the lower atmospheric CO_2 concentrations if these sources of emissions are reduced in particular. These emissions are mostly made up of exhaust from vehicles, industrial processes, boilers, and engines. Alternative technologies and also innovations on current technologies need to be further researched and implemented for a significant reduction in the future CO_2 emissions rate.

Chapter 6

Mitigating Proposals

One method to mitigate climate change is through geoengineering. This is done by reducing the solar radiation flux received by the Earth in the lower atmosphere and on its surface as well. Radiative forcing due to anthropogenic emissions of CO2 in 1998 was 2.43 $\left[\frac{W}{m^2}\right]$ ± 10% with 60% of originating from the burning of fossil fuels. This radiative forcing has recently increased to 2.50 $\left[\frac{W}{m^2}\right]$ with 62% of it being contributed from the burning of fossil fuels. In a recent study, reducing the radiation from the sun by 1.8% could counterbalance a doubling of the concentration of CO_2 in the atmosphere. With current emission targets, the CO_2 concentration would reach a stabilization concentration of 550 [*ppmv*] at best. This is almost double the concentration of CO_2 in 1750, 278 [*ppmv*]. So, if we're serious about reducing the rate of climate change in the future, we need to have multiple approaches to this problem and geoengineering is a promising way to accomplish this task.

Early geoengineering methods were very expensive and could only be carried out on a macro-level by governments. These methods attempted to increase the size of carbon sinks and reduce the amount of sunlight infiltrating the Earth's atmosphere with examples such as injecting aerosols into the lower atmosphere, putting metallic balloons into the upper atmosphere, and putting giant mirrors into orbit around the Earth. While these methods would work, they were fairly expensive, relatively difficult to accomplish, and are heavily technology based. There is a new method that aims to increase the albedo of the Earths surface, instead of reducing the solar radiation flux arriving to the Earth. This new method is called Terrestrial Albedo Amplification through land surface modification and can be accomplished easily on a local scale with relatively low technological required. [23]

One of the new methods for Terrestrial Albedo Amplification is to increase the albedo of human settlements. The average artificial surface area per capita was recorded to be 46 m^2, 260000 km^2 in total world wide, through global land surface imagery, though this value only applies for urban surface areas. The actual artificial surface area is much greater in value which include all residential, recreational, industrial, commercial, transportation-related and institutional land, but not agricultural land. Global estimates of all artificial surface areas are given to range from 440 to 500 m^2 of artificial surface area per capita. A typical albedo value for human settlements is about 0.15. If we are able to double the albedo of human settlements, the overall albedo of the Earth would increase by 0.000875 from a value of 0.140804 and the albedo of urban areas would increase from 0.12-0.16 to 0.20-0.37. This increase would decrease the average radiative forcing by 0.17 $\left[\frac{W}{m^2}\right]$. This can be done by using Titanium Oxide (TiO_2) based paints on roofs and facades since these paints are more reflective, the cost is about $\frac{\$15}{m^2} - \frac{\$30}{m^2}$. Another approach is to use high albedo cement, white cement, for paved surfaces and would cost about $\frac{\$15}{m^2} - \frac{\$25}{m^2}$. The albedo for roofing and paved surfaces would increase from 0.1 to 0.7 and 0.1 to 0.4 respectively.

A different method is to increase the albedo of the worlds grasslands. This would include open shrublands, grasslands and savannahs. Because these land types cover about 30% of the worlds land surface, the resulting change in radiative forcing should be significant if we are able to change the albedo of these lands. Since the temporal variations in cloud cover, mean solar zenith angles, precipitation and phase offsets of annual vegetation growth cycles are different for all grasslands around the world, the surface albedo of each 1 degree latitude zone band with a grassland fraction of 80% or more were calculated for each month. From this data the global average annual grassland surface albedo was calculated to be 0.17. If the albedo of each grassland area was increased by 25% for each month the global average annual grassland surface albedo would increase by 0.002626. This would cause a decrease in the average radiative forcing by 0.59 $\left[\frac{W}{m^2}\right]$, which is a significantly greater value than increasing the albedo of human settlements.

Plants with white, light-green and light-yellow colored leaves have a higher reflectiveness of visible light relative to green colored plants. This is usually because of lower pigmentations of chlorophyll or other pigments in the leaves and stems. Another factor that affects the reflectiveness of plants is the presence of trichomes and waxes that efficiently reflect visible light on plants leaves with some plants already showing this property. These plants are Carex hachijoensis and Chlorophytum comosum, which are grasses, and Alpinia zerumbet, Euonymus europaeus, Ficus aspera, Cerastium biebersteinii and Senecio, which are shrubs. Cineraria are current plants that have more reflective leaf surfaces and have lighter colored leaves. These plants are usually hardy plants that can live in almost any environment. However, transplanting these plants around the worlds' grasslands could and probably would have averse affects on the ecosystems of those grasslands.

Implications of these albedo changes must be thought out and modeled carefully, since changing the albedo of a given area could change the climate significantly. Modeling of modern surface albedo changes from 0.02 to 0.06 in the temperate United States indicate no significant change in seasonally averaged precipitation, but have a net cooling effect. On the other hand, models of the tropics imply a quite different effect. There is a net warming effect and drier hydrological conditions are expected to occur. Changing the albedo of human settlements is readily available, but changing the albedo of vegetation needs to be looked into more extensively. The effects of geoengineering can significantly decrease radiative forcing, but they also have to be careful about how it will affect the local climate and to determine if the advantages outweigh the cons.

6.1 Simple Global Warming Calculations

Global warming has been increasing since the previous ice age. It is most likely caused by the changes in the ocean temperature which would cause changes in the currents and CO_2 emissions from the oceans. The change in the concentrations of CO_2 is believed to be the major contributor to temperature changes due to the greenhouse effect. The prehistoric CO_2 concentrations in the ice sheets are well correlated to temperature, which means that changes in the temperature of the oceans caused an increase in the concentration of CO_2. Increases in CO_2 concentrations since 1940 have been mainly contributed from fossil fuel burning. Also volcanic eruptions can cause transitions from glacial climates to interglacial climates.

The radiation power of the Sun per square perpendicular meter is $1368W/m^2$. The average radiation of the Sun per square meter of the Earth is one-fourth of the previous value due to the surface geometry relation of a disk to a sphere, thus $342W/m^2$. This radiation power is then partially reflected back into space due to the reflectiveness of the Earth, the albedo of the Earth. 31% of the radiation is reflected back into space, 21% from clouds, 6% from air, dust and water vapor, and 4% from the ground. This means that 69%, $236W/m^2$, of the incoming radiation is absorbed b the Earth. 37.4% is absorbed by clouds, 53.6% is absorbed by water vapor and CO_2, and 9% is absorbed by the Earths surface, these values are based on average cloud cover. This absorbed radiation is then reemitted into space as infrared radiation. There are satellites that are able to record how much radiation is reemitted into space from the Earth and the average recorded infrared radiation of the Earth to space is $235W/m^2$. This is very close to the amount of radiation absorbed, which means that the Earth balances incoming and outgoing energy to a very high accuracy. If there was no cloud cover instead of average cloud cover, the amount of radiation absorbed would increase to $286W/m^2$ from $236W/m^2$ and the amount of radiation remitted into space would be $266W/m^2$, thus the Earth would heat up when there is no cloud cover. This means that clouds have an important roll in the climate of the Earth. [19]

To begin the calculations, there is an equation that represents the absorption and radiation of a body. For the Earth this equation becomes

$$\frac{1}{4}\varepsilon_v I_{sun} = \varepsilon_{IR}\sigma T^4 \tag{6.1}$$

where I_{sun} is the solar radiation power of the sun, ε_v is the emissivity of he Earth in the visible spectra, ε_{IR} is the emissivity of the Earth in the infrared spectra, $\sigma = 5.67x10^{-8}W/m^2K^4$ is the Stefan-Boltzmann constant, and T is the temperature of the surface of the Earth. For this model the equilibrium temperature is 279 K, this is when $\varepsilon_v = \varepsilon_{IR}$. $\varepsilon_v \approx .69$ and $\varepsilon_{IR} \approx .605$ for the Earth. 6.1 shows the emissivites of the Earth and each of its parts compared to

	Infrared	Visible	T for 100 % Cover
Black Body	1.00	1.00	279 K
Cloudless Ground	≈ 0.69	0.90	298 K
Clouds	≈ 0.56	0.55	278 K
Snow	≈ 0.30	0.10 (0.20)	212 K (252 K)
Whole Earth	0.605	0.69	288 K

Table 6.1: Effective emissivities for infrared and visible radiation. The last column shows the temperature corresponding to a 100% cover of black body, cloudless ground, cloud or snow. The last row corresponds to 50% cloud cover, 5% snow cover, leaving 45% clear ground. The measured average temperature is 288 K. [19]

a black body, an object that completely absorbs and emits radiation.

A more complicated model that separates the atmosphere into two parts, the upper atmosphere and lower atmosphere and the Earths surface, can be used to better describe the radiation of the atmosphere and the surface. The equation for total radiation into space for this model is

$$\sigma T^4 - \varepsilon\sigma(T^4 - T_2^4) \tag{6.2}$$

where σT^4 is the surface radiation, $1-\varepsilon$ is the fraction of the radiation that gets through to the upper atmosphere, and $\varepsilon\sigma T_2^4$ is the amount the upper atmosphere radiates into space. The remaining fraction ε is absorbed by greenhouse gases and aerosols in the atmosphere and the upper atmosphere also radiates $\varepsilon\sigma T_2^4$ back to the lower atmosphere. T_2 reduces the amount of radiation that escapes into space since it is colder than T, the upper atmosphere is colder than the lower atmosphere and the surface. To account for the greenhouse effect, the effective emissivity is

$$\varepsilon_{IR} = 1 - \varepsilon[1 - (\frac{T_2}{T}^4] \tag{6.3}$$

where ε is estimated to be about 0.813. If T = 288 K then $T_2 \approx 244K$.

The next step to increase the complexity of the model is to separate the surface and lower atmosphere. $168W/m^2$ is to be absorbed by the surface, $67W/m^2$ is to be absorbed by the atmosphere, and $102W/m^2$ is transported by thermals, evaporation and transpiration. The emissivity of the Earth in the infrared is defined as 1 and the fraction absorbed by the atmosphere is ε. This model breaks for $\varepsilon \leq 0.5$ because the absorbed sun power and power of thermals, evaporation and transpiration are assumed to be constant and independent of the concentration of CO_2. The temperature of the surface with no atmosphere should be 253.72 K since the surface would absorb all of the solar radiation, but this model breaks down before then and thus shows an incorrect value, 6.2. Doubling the concentration of CO_2 in the atmosphere would increase ε to 0.833 since it would decrease the radiation to space by about $3.75W/m^2$. From this

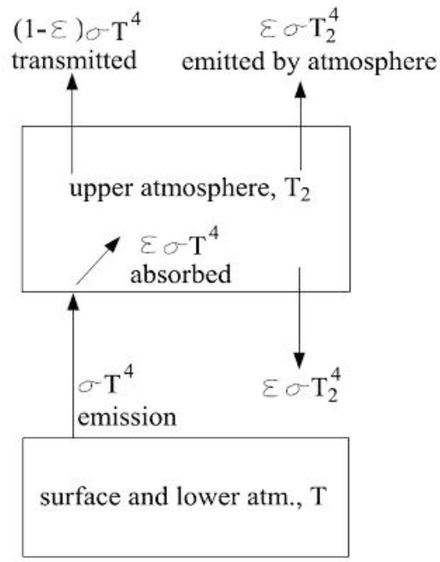


Figure 6.1: Two-box model of the greenhouse effect. [19]

model, the temperature of the surface should then be 2.1 K higher then it is now, but this might not be accurate since the temperature of the upper atmosphere might change with changes in CO_2 concentrations due to fluxes and absorptions not taken into account and also that thermals, evaporation and transpiration are assumed to be constant and independent of the concentration of CO_2 but in reality are in someway related to the concentration of CO_2. [19]

For the current emissivities of the Earth, if any change occurs in the temperature of the Earth will cause an increase in infrared radiation and thus stabilizes the temperature back down to the original temperature. The only way to change the equilibrium temperature is to change the emissivities of the Earth. This could happen if a world-wide snow storm occurs, thus changing the emissivity of the surface of the Earth and cool the Earth and maybe cause an ice age if the Earth cools enough so the snow wouldnt melt. Standard deviation fluctuations of the Earths temperature from year to year are about 0.22 K for the 20th century. It has been seen that typical inter-glacial periods last for about 50 thousand years. In this time frame there is a 50% probability that there will be a fluctuation of at least 4.2 standard deviations, about 1 K. Can this small change in world-wide temperature cause an ice age or does something else in conjunction with it need to occur to cause one.

It is speculated that in order to get out of an ice age, there would need to also be a change in emissivities, like covering the snow with ash or dirt from a volcanic eruption or maybe a meteorite impact. An explosion that ejects $210^{15}kg$ deposits an average of $4kg/m^2$ of ash over the Earth, which is a sizable amount to change the albedo of the Earth. In 6.3 there is a list of major volcanic eruptions and they are put on a time scale with temperatures of that time.

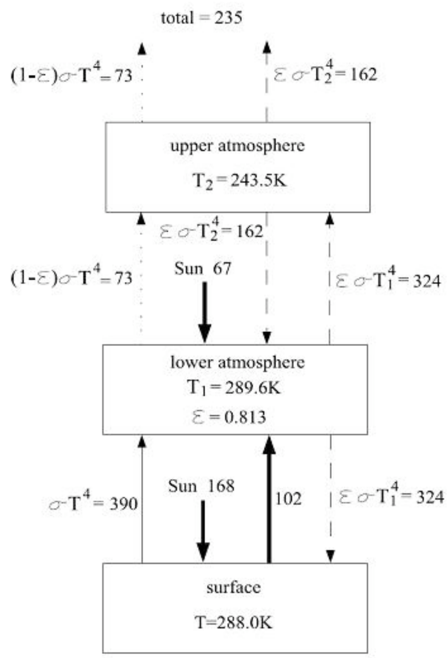


Figure 6.2: Three-box model of the greenhouse effect. The numbers are in units of W/m^2. Dotted lines correspond to the infrared window, while dashed lines correspond to frequencies absorbed or emitted by greenhouse gases in the atmosphere (mainly H_2O, CO_2 and ozone). Thermals, evaporation and transpiration are estimated to transport $102W/m^2$. [19]

You see that the temperature increases after a major eruption after a relatively short period of time and causes an inter-glacial period, though eruptions have a short-term cooling effect. [19]

I ploted the points of 6.2 a found that for the relevent section of the data, the points fit a linear curve. Thus I was able to use this rough model of the atmosphere to linearly interpolated between the two given concentrations and their corresponding temperaures. Using this linear interpolation, the lower atmspheric CO_2 concentration of each policy can be used to calculate a rough estimate of the world's average lower atmospheric temperature with the corresponding policy, see Table: 6.4. The increase in temperature ranges from about 0.48 K to about 0.62 K. This is an average of about 0.023 K per year, compaired to the past 48 years where the temperature increased by approximately 0.017 K per year, this is a significant change in the rate of temperature increase. [1]

ε	T	T_1	T_2	Comment
0.0	253.72 K	n.a.	n.a.	$235W/m^2$ radiation, no atmosphere
0.05	238.94 K	452.5 K	380.5K	
0.3	250.51 K	310.1 K	260.8 K	
0.5	262.20 K	290.5 K	244.3 K	model breaks down for ε ¡ 0.5
0.6	269.20 K	287.3 K	241.3 K	
0.7	277.24 K	286.9 K	241.3 K	
0.8	286.65 K	289.1 K	243.1 K	
0.813	288.00 K	289.6 K	243.5 K	$290ppmCO_2$
0.833	290.14 K	290.4 K	244.2 K	$580ppmCO_2$
0.9	297.91 K	293.9 K	247.1 K	
1.0	311.81 K	301.7 K	253.7 K	opaque atmosphere

Table 6.2: Temperatures of the surface (T), lower atmosphere (T_1), and upper atmosphere (T_2) in the three box model as a function of the emissivity of the atmosphere in the infrared (Q). The absorbed Sun power and power of thermals, evaporation and transpiration are assumed to be constant (independent of the concentration of CO_2). [19]

Caldera Name	Ejected Mass [$10^{15}kg$]	Date [10^3 years ago]
Toba (Indonesia)	6.9	74
Yellowstone (Wyoming, USA)	2.2	600
Porsea (Toba, Indonesia)	2.0	790
Taupo (New Zealand)	1.3	26.5
Long Valley (California, USA)	1.2	700

Table 6.3: Large explosive volcanic eruptions in the last million years. [19]

Policy	CO_2 concentration (X) [ppm]	T [K]	ΔT
Current (2005)	379.78	288.66	0
World Embraces Nuclear just like France	444.41	289.14	0.4769
World Switches to 49% Renewable and Nuclear	457.38	289.24	0.5726
World Switches from Coal to Natural Gas	458.75	289.25	0.5827
World Switches to 20% Hydro	460.09	289.26	0.5926
US Switches to 20% Wind	460.40	289.26	0.5949
Same Energy Policy	461.84	289.27	0.6055
Predicted by the EIA	463.73	289.28	0.6195

Table 6.4: Rough calcultions of the average world temperature using the different policies and their CO_2 conentrations. $T = \frac{290.14-288}{580-290}X + 285.86$.

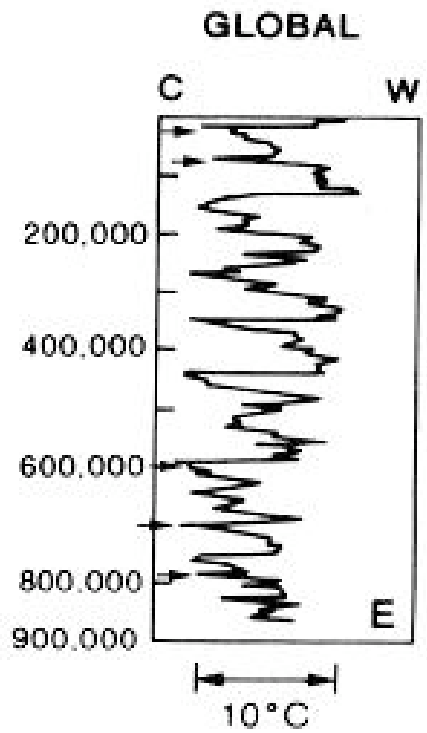


Figure 6.3: Ice-core temperature data of the last 900 thousand years, compared with the largest known volcanic explosions in that period (arrows). [19]

Chapter 7

Conclusions

As stated in the Introduction, the goal of an IQP is to research an issue or topic area that links together science, technology, and society. This IQP on trace gases certainly fulfills that criteria as it is still an ongoing issue with a fair amount of critics and proponents on both sides of the aisle and will have a major impact on society and future generations as a whole as demonstrated by some of the issues that was brought up in the report such as human migration and crop production.

At the beginning of the project, we both stated some goals that we wanted to achieve such as researching the current issues related to climate change, such as the issue of crop production related to an increase in CO_2 concentrations and increases in temperature, and electricity generation in addition to others. We also wanted to provide an easy explanation for people who are not in the scientific fields, while at the same time providing enough detail for others wanting a deeper understanding of the science and mathematics related to our research.

We not only accomplished our goal of understanding the basic science behind climate change, but we also learned about the possible effects it can have on the world. David was able to use his knowledge in the chemical sciences to understand the processes involved with the increase in CO_2 concentration and relate it to the effects on different chemical concentrations in the soil and the ocean. Long was able to use his skills in the mathematical sciences to understand the differential equations behind the Matlab model. By working together, we were both able to obtain a greater knowledge in this field by collaborating together on the project and learning from each others research as opposed to working on the project individually.

What we have seen from our analysis of different energy policies is that we are still currently on a path of releasing more carbon dioxide emissions by relying too much on coal plants for electricity generation. Although natural gas contributes significantly less than coal, its emissions per kWh value is still not where we want to be in order to mitigate climate change. Emerging technologies which have already proven to be reliable include both wind and hydroelectric energy. The United States in particular has numerous locations that have great potential for generating electricity though wind farms throughout its land, most notably in the West Mountain region, along the coastlines, and also the Great Lakes. Countries which have already shown wind energy to be a reliable energy source include Germany and Denmark where it makes up 7% and 17%, respectively. [15]

Although nuclear energy is still a controversial energy option in certain parts of the world such as the United States, some countries have taken the initiative to make it their number one energy source, most notably by France. Aside from the politics that comes with nuclear energy, in terms of the efficiency of energy generated per carbon dioxide emission released nuclear is still one of the top choices. In terms of the amount of CO_2 which can be prevented from being emitted back into the lower atmosphere, nuclear energy is more reliable than wind energy due to fluctuations in the weather of a particular region in which the wind farms are positioned. Nuclear power plants can provide continuous energy for longer sustained periods of time. Solar energy could be a reliable energy source, but, first it needs to be more cost effective. It is costly and the efficiency of the solar cells isn't very high, but, once the technology progresses to a point were this is no longer true, solar energy can potentially be a widely used renewable energy source. One possible option would be to use a combination of both nuclear and renewable energy sources as explored in our report.

We both enjoyed working on this project as it required us to not only learn about new topics, but, also about the ramifications of a dangerous increase in CO_2 concentrations in the lower atmosphere. It also taught us how to effectively manage our time while working on a team project and taking classes at the same time. We have not only increased our understanding of the subject, we've also taken some interests in areas we weren't so familiar with such as the migrational paths taken by our earliest human ancestors thousands of years ago.

Chapter 8

Recommendations for Future IQPs

During the course of this IQP research project, several topics and analysis were omitted due to the decision to delve deeper into certain topics, such as crop production and human migration, while also researching the current situation in the solar, wind, and nuclear energy fields. In particular, a cost analysis between the different energy sources and their effects on reducing CO_2 emissions would have been very desirable and would also have given a rough idea on the feasibility of pursuing those alternative energy sources, such as ethanol, geothermal, and hydrogen energy.

In addition to picking up from where we left off in terms of the effects of pursuing different energy policies on CO_2 concentrations in the lower atmosphere, what we would recommend for future students performing their IQP in this research area would be to include emissions from different vehicle types such as hybrids, diesels, and other variations. Furthermore, improving on the basic Matlab model that was used to compute future CO_2 concentrations and also looking at different computer models would be helpful in enhancing the accuracy of the CO_2 projections.

Engineering students should perform research into different engine and energy technologies and possibly research specific technological innovation possibilities. Based on how developed these technologies are, they should predict to the best of their abilities the timeframe that these technological innovations could be introduced into the market. Someone could also analyze the production of this innovation to see if the cost of production is economically feasible. In addition, one could see how this innovation would affect the CO_2 emissions if it was introduced into the market.

One topic which we didn't delve into as much as we would have liked to is how climate change will affect the economy and the world's economic market. Student with an interest in economics should look into this and reference the Stern Review to point them in the right direction (they should also make an effort to research the reports that try to discount the Review as well). They could create different economic energy policies to see which policies are economically feasible. Also they could look further into the effects of decreasing crop yields and their effect on the world's populous while providing a deeper analysis into the effects it will have on different regions and countries.

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Chapter 9

Appendix

9.1 Matlab Codes

9.1.1 co2_script.m

```
global guess
global Δ_co2
global x
global r1c
K=1
guess=400      %initial guess value (arbitrary) if the model
               %does not converge set guess to a different value
guess1 = guess;
x = Δ_co2/guess;    %calculating the initial r1c value
model_1_main;           %run model
while abs(pm(1,19)−guess1)≥0.1; % Checks for tolerance condition
        x = Δ_co2/guess; % Sets r1c to new value
        model_1_main; % Reruns model
        guess1 = guess;
        guess=pm(1,19) % Sets guess value to CO2 concentration
                        %determined by model
end
display('Value is within tolerance')
return
```

9.1.2 co2_rate.m

```
  function [c1,r1]=CO2_rate(t)
%
% Function CO2_rate returns the constants c1, r1 in the CO2
% source term
%
%   CO2_rate = c1*exp(r1*(t−1850))
%
% for the case ncase.
%
  global ncase
  global r1c
  global x
```

```
%
% c1 sets the CO2 ppm at 2007
  c1=4.33e-03;
%2.2e-3 1.8
% Base CO2 rate
  r1b=0.010125;
  r1=r1b;
%.01
% Change the base rate for t > 2010
  if(t>2005)
    if(ncase==1)r1c= .0060438; end
    %if(ncase==1)r1c= x-.010125; end
    if(ncase==2)r1c= 0.0025; end
    if(ncase==3)r1c= 0.0000; end
    if(ncase==4)r1c=-0.0100; end
%
%   Linear interpolation in t between 2010 and 2100
    r1=r1b+r1c*(t-2005)/(2030-2005);
  end
```

9.1.3 model_1_main.m

```
%
% Clear previous files
 %clear all
  clc
%
% Parameters shared with other routines
  global ncall ncase
%
% Spline coefficient arrays
  global epss hions Tcs pHs
%
% Equilibrium constants
  global k0 k1 k2 kb kw
%
% Initial condition
  n=7;
  y0=zeros(1,n);
%
% Independent variable for ODE integration
  t0=1850;
  tf=2100;
  tout=[t0:10:tf]';
  nout=26;
  ncall=0;
  ncase=1;
%
% Set up spline interpolation
  nouts=0;
  [epss,hions,Tcs,pHs]=splines(nouts);
%
% ODE itegration
  reltol=1.0e-06; abstol=1.0e-06;
  options=odeset('RelTol',reltol,'AbsTol',abstol);
  mf=2;
  if(mf==1) % explicit integration
    [t,y]=ode45 (@model_1,tout,y0,options); end
  if(mf==2) % implicit integration
```

```
    [t,y]=ode15s(@model_1,tout,y0,options); end
%
% Display selected output
  fprintf('\n mf = %2d   abstol = %8.1e   reltol = %8.1e\n\n',...
          mf,abstol,reltol);
  fprintf('\n     t     cla      cul     pm      eps     pH      r1\n')
  for it=1:nout
%
%   CO2 emissions rate (in lower atmosphere)
    [c1,r1]=CO2_rate(t(it));
%
%   CO2 ppm (in lower atmosphere)
    pm(it)=280*(1+y(it,1));
%
%   Evasion factor
    eps(it)=ppval(epss,pm(it));
%
%   pH
    pH(it)=ppval(pHs,pm(it));
%
%   Total carbon
    Tc(it)=ppval(Tcs,pm(it));
%
%   Hydrogen ion
    hion(it)=ppval(hions,pm(it));
%
%   CO2 (CO2 + H2CO3 in upper layer)
    co2(it)=k0*pm(it);
%
%   Bicarbonate
    hco3(it)=k0*k1*pm(it)/hion(it);
%
%   Carbonate
    co3(it)=k0*k1*k2*pm(it)/hion(it)^2;
%
%   Boron
    B=0.409;
    boh4(it)=B/(1+hion(it)/kb);
%
%   Selected output
    fprintf(' %5.0f%10.4f%10.4f%10.1f%10.3f%10.3f%10.4f\n',...
              t(it),y(it,1),y(it,5),pm(it),eps(it),pH(it),r1);
  end
%
% ppm at 2007 (linear interpolation between 2000 and 2010)
  p2007=pm(16)+(pm(17)-pm(16))*(2007-2000)/(2010-2000);
  fprintf('\n ncase = 1, ppm(2007) = %6.1f\n',p2007);
  fprintf('\n ncall = %4d\n',ncall);
%
% Plot numerical solution
%
% vs t
  figure(1);
  plot(t,y(:,1),'o-',t,y(:,5),'+-',t,y(:,6),'x-')
  title('c(frac) vs t'); xlabel('t'); ylabel('c(frac)')
  legend('lower atmosphere','upper layer','deep layer','Location',...
  'NorthWest')
  axis([1950 2030 0 1.5])
  figure(2);
  plot(t,pm,'-')%, timemauna, concentrationmauna,'o')%, realtime,
  %realconcentration, '+')
  title('c_{la}(ppm) vs t'); xlabel('t'); ylabel('c_{la}(ppm)')
  legend('Model Projection')%,'Exponential Fit Mauna Loa Data',
```

```
  %'Location','NorthWest')
  axis([1950 2030 300 500])
  %figure(3);
  %plot(t,eps,'-')
  %title('eps vs t'); xlabel('t'); ylabel('eps')
  figure(4);
  plot(t,pH,'-')
  title('pH vs t'); xlabel('t'); ylabel('pH')
  axis([1950 2030 7.5 8.5])
  pause;
%
% vs pH
  figure(5);
  plot(pm,co2,'-')
  axis tight
  title('CO_2 + H_2CO_3 (millimols/liter) vs pm (ppm)'); ...
  xlabel('pm (ppm)'); ylabel('CO_2 + H_2CO_3')
  figure(6);
  plot(pm,hco3,'-')
  axis tight
  title('HCO_3^- - bicarbonate (millimols/liter) vs pm (ppm)'); ...
  xlabel('pm (ppm)'); ylabel('HCO_3^-')
  figure(7);
  plot(pm,co3,'-')
  axis tight
  title('CO_3^{-2} - carbonate (millimols/liter) vs pm (ppm)'); ...
  xlabel('pm (ppm)'); ylabel('CO_3^{-2}')
  figure(8);
  plot(pm,boh4,'-')
  axis tight
  title('B(OH)^-_4 (millimols/liter) vs pm (ppm)'); ...
  xlabel('pm (ppm)'); ylabel('B(OH)^-_4')
  figure(9);
  plot(pm,co2/co2(1),'o-',pm,hco3/hco3(1),'+-',pm,co3/co3(1),'x-')
  axis tight
  title('c(frac) vs ppm'); xlabel('ppm'); ylabel('c(frac)')
  legend('CO_2+H_2CO_3','HCO_3','CO_3','Location','NorthWest')
% print -deps ode.eps; print -dps ode.ps
```

9.1.4 model_1.m

```
  function yt=model_1(t,y)
%
% Function model_1 computes the temporal derivatives of the seven
% dependent variables
%
% Parameters shared with other routines
  global ncall
%
% Model dependent variables
  cla=y(1);
  cua=y(2);
  csb=y(3);
  clb=y(4);
  cul=y(5);
  cdl=y(6);
  cmb=y(7);
%
% ODEs
```

```
  [c1,r1]=CO2_rate(t);
  dcla=     1/5*(cua-cla)+...
            1/1*(csb-cla)+...
          1/100*(clb-cla)+...
           1/30*(cul-cla)+...
          c1*exp(r1*(t-1850));
  dcua=     1/5*(cla-cua);
  dcsb=     1/1*(cla-csb);
  dclb=   1/100*(cla-clb);
  dcul=    1/30*(cla-cul)+...
          1/100*(cdl-cul)+...
           1/10*(cmb-cul);
  dcdl=  1/1000*(cul-cdl);
  dcmb=    1/10*(cul-cmb);
%
% Derivative vector
  yt(1)=dcla;
  yt(2)=dcua;
  yt(3)=dcsb;
  yt(4)=dclb;
  yt(5)=dcul;
  yt(6)=dcdl;
  yt(7)=dcmb;
  yt=yt';
%
% Increment calls to model_1
  ncall=ncall+1;
```

9.1.5 epsilon.m

```
  function [eps,hion,Tc,pm,pH,iter]=epsilon(max,pm0,dpm)
%
% Equilibrium constants
  global k0 k1 k2 kb kw
%
% First computation (of eps, hion, Tc, pm, pH)
  k=1;
%
% Equilibrium constants (in millimoles/lt units)
  k0=0.03347*1.0e-03;
  k1=9.747e-7*1.0e+03;
  k2=8.501e-10*1.0e+03;
  kb=1.881e-9*1.0e+03;
  kw=6.46e-15*1.0e+06;
%
% Alkalinity
  A=2.435;
%
% Boron concentration
  B=0.409;
%
% Initial parameters
%
%   pm
    pm(1)=pm0;
%
%   Evasion factor
    eps(1)=8.8;
%
```

```
%   Total carbon in upper layer
    Tc0=2.057;
    Tc(1)=Tc0;
%
%   hi (in millimoles/lt units)
    xhi=5.4e-9*1.0e+03;
%
% while loop in k
  while(k≤max)
%
% while loop in hi
  dif=1.0;
  niter=25;
  iter=0;
%
% Polynomial coefficients
  c0=2.0*k0*k1*k2*kb*pm(k);
  c1=k0*k1*kb*pm(k)+2.0*k0*k1*k2*pm(k)+kw*kb;
  c2=k0*k1*pm(k)+B*kb+kw-A*kb;
  c3=-kb-A;;
  c4=-1;
%
  while(dif>1.0e-12)
%
%   Next Newton iteration; test for convergence failure
    iter=iter+1;
    if(iter>niter)
      fprintf('\n iter = %3d, iter exceeds niter for k = %3d\n',...
      iter,k);
      break;
    end
    hi=xhi;
%
%   Polynomial
    f=c0+c1*hi+c2*hi^2+c3*hi^3+c4*hi^4;
%
%   Derivative of polynomial
    df=c1+2*c2*hi+3*c3*hi^2+4*c4*hi^3;
%
%   Newton's method (for new hi)
    xhi=hi-f/df;
%
%   Change in hi (Newton correction)
    dif=abs(xhi-hi);
%
% End of while loop for Newton iteration
  end
%
% h ion array
  hion(k)=xhi;
%
% pH array
  pH(k)=3-log10(hion(k));
%
% Total carbon
  Tc(k)=k0*pm(k)*(1.0+k1/hion(k)+k1*k2/hion(k)^2);
%
% Evasion factor
  if(k≠1)
    eps(k)=((pm(k)-pm(1))/pm(1))/((Tc(k)-Tc(1))/Tc(1));
  end
%
% End of while loop in k
```

```
k=k+1;
if(k>max)break; end
pm(k)=pm(k-1)+dpm;
end
```