Project Number: MH-0505

TRACE GASES IN THE ATMOSPHERE

An Interactive Qualifying Project Report

submitted to the Faculty of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Soufiane El Beqqali

Daniel J. Czarnecki

Charles Petano

Ann M. Troy

Date: 21 April 2006

Professor Mayer Humi, Major Advisor

Abstract

This Interactive Qualifying Project evaluates and discusses the issues surrounding Global Warming and suggests strategies for mitigating the many negative effects that society will encounter. Global Warming is the direct result of greenhouse gases such as carbon dioxide, methane gas, nitrous oxide, and above all, water vapor. This project uses computer modeling to project future levels of carbon dioxide concentrations through a seven carbon reservoir model. Ultimately, emissions must be reduced and a form of carbon storage should be implemented.

Table of Contents

List of Tables and Figures

Figures

Section 3.1

Section 3.2

Section 3.3

Section 3.4

Section 3.6

Section 3.7

Tables

Section 3.6

Section 3.7

1 Executive Summary

This IQP explores the issues and mechanisms involved in the process of Global Warming, as well as the various climatic and socioeconomic implications thereof. Additionally, this project offers several viable solutions to mitigate the effects of Global Warming.

The project starts with an explanation of the Greenhouse Effect. This includes the role of various atmospheric gases trapping infrared radiation from the Earth. Next we discuss the different motions within the atmosphere and how they affect the diffusion of greenhouse gases among reservoirs. In the next section we look at the Carbon Cycle, focusing on the different forms of carbon and the interactions between carbon reservoirs. We also utilized MATLab to create a 7-resevoir, 0-dimensional model for carbon concentrations in the atmosphere. The following section looks at the role of Solar Flux Variability in global climate changes. The project also examines the socioeconomic implications of Global Warming including possible health effects as well as costs associated with damage due to Global Warming. We then look at recent developments in new fuel reserves such as methane hydrates and tar sands. The next section presents possible solutions to mitigate Global Warming, such as geo-sequestration, scrubbers, ocean fertilization, and others. Finally we present our conclusions based on our research and make suggestions for future IQP's covering this topic.

2 Introduction

Every year more and more carbon dioxide and other greenhouse gases are released into the atmosphere. These gases cause the well known “greenhouse effect”; a process whereby infrared radiation emitted by earth is trapped by the atmosphere. This has a number of possibly adverse effects, such as rising sea levels, changes to local and global climate systems, and increased storm severity. Over the past 30 years, researchers have used Global Climate Models (GCM’s) to attempt to make predictions about the effects of these gases on the Earth’s climate. This is a difficult task however, since the Earth’s atmosphere is a complex dynamic system which behaves chaotically.

The authors believe the subject matter contained in this report is quite appropriate for an IQP at WPI; with so many engineers leaving the school going on to design systems which utilize fossil fuels, it is important to understand the possible repercussions of carbon emissions. For instance, the authors hope engineers who plan to work in the automotive field will gain a new perspective as to the importance of fuel efficiency. Some power plants (especially coal fired plants) release large quantities of CO_2 into the atmosphere. Mechanical engineers with a focus in thermo-fluids can go on to careers where they design these large scale plants. We hope these designers would be mindful of the potentially harmful effects of coal and other fossil fuel power plants and use this awareness to design more eco-friendly systems.

The reasons each author has chosen to be involved with this project vary. Since human made greenhouse gases are dramatically changing our climate, it is important to understand how this change is taking place and how it will affect future generations. It is important to understand the intensity of the climate change and the effects this change will have on humanity. This will help us make insightful decisions in the future, whether in our career or simply in our daily lives. We hope this project will enrich our careers as we will be able to speak to other engineers from different fields of study on the importance of environmental awareness.

3.1 The Greenhouse Effect

3.1.1 A Description of the Greenhouse Effect

The sun emits radiations at different frequencies, but only some of these radiations are absorbed by the earth, resulting in the increase of the average temperature of earth. However, without the greenhouse effect, the temperature would not be high enough for humans and other forms of life to survive on the planet. The greenhouse effect is a natural process related to the existence of a variety of gases in the atmosphere such as water vapor, carbon dioxide, and methane that makes life on earth possible. These gases trap the energy coming from the sun and act like a blanket that keeps our environment warm and conducive to all forms of life. However, too many greenhouse gases may increase the temperature too much leading to a climate change and introducing severe weather conditions that affect all kinds of life on the planet. Recently, there has been a dramatic increase in the concentration of different greenhouse gases in the atmosphere as a result of the activities of humans especially after the industrial revolution.

The earth receives energy from the sun in the form of short and visible wavelength radiations. If there were no atmosphere, the earth would act as a “grey body”, which means that it would reflect a portion of the incoming radiation, absorb the rest, and emit some of the absorbed energy back to space (Humi). The emitted energy is in the form of infrared or long wavelength radiation, which is not perceived by the human eye. Furthermore, the amount of the emitted energy increases as the temperature of the earth increases, and it is proportional to the fourth power of the earth’s temperature. It is given by the Black-Body Stefan-Boltzmann law $B=\sigma T^4$, where T is the surface temperature of a given body. Researchers have shown that if we assume earth is not surrounded by the atmosphere, equilibrium would be reached when the temperature is equal to only about $-25\ ^{o}C$. This extremely low temperature would make life on earth impossible (Humi).

The greenhouse effect is what keeps the temperature on earth at a level where life can be sustained. Some of the energy emitted from the earth is trapped in the atmosphere as a result of the greenhouse effect causing a further increase in the average temperature of the earth. The greenhouse gases in the atmosphere absorb some of the energy emitted from the earth's surface, which is in the form of long wavelength radiation. This energy is then released in all directions causing a portion of the absorbed energy to go back toward the surface of the earth. In order to understand how energy is absorbed by greenhouse gases in the atmosphere, we need to use the photon model of light. Photons coming from the sun have an energy that is equal to hv where h is the Planck constant and v is the frequency. These photons can be absorbed by an atom only if the atom has two energy levels E_1 and E_2 such that $E_2 - E_1 = hv$. The atom becomes excited to the higher energy level E_2 before it goes back to the initial energy level E_1 releasing the absorbed energy (Humi).

The atmosphere contains many gases that can absorb the photons emitted from the earth's surface. There are many molecules that can absorb the emitted photons including water vapor, carbon dioxide, and methane. The atmosphere has large amounts of water vapor and carbon dioxide along with other greenhouse gases such as ozone. The greenhouse gases in the atmosphere are mostly from natural sources, and they keep the temperature of the earth at a reasonable average temperature of about $15^{0}C$ (Houghton 15). In addition to the greenhouse gases from natural sources, humans also contribute to the greenhouse effect by adding additional amounts of the existing greenhouse gases such as carbon dioxide and methane, and introducing new ones such as Chlorofluorocarbons. Since the industrial revolution, carbon dioxide and other greenhouse gases in the atmosphere have been increasing significantly. This increase is due to the burning of fossil fusels, deforestation, the manufacturing and use of fertilizers, and other human activities. The importance of the greenhouse gas does not depend only on the concentration of the greenhouse gas but also on the amount of infrared radiation that it absorbs (Houghton 28).

The human made greenhouse gases result in a rise in temperature which impacts the climate and the environment on our planet. Unfortunately, the concentrations of greenhouse gases in the atmosphere have been increasing dramatically in the last hundred years. When more greenhouse gases are injected into the atmosphere, more infrared radiation emitted by the earth is absorbed. After that, the absorbed energy is released into the atmosphere causing a temperature rise at the surface of the earth, which may have many effects on our environment. For example, the increase in temperature may affect the climate causing some areas to experience frequent severe storms or floods, while other regions may experience severe droughts. The temperature of the ocean will also rise causing the expansion of the ocean waters and the melting of the ice glaciers, which may lead to the rise of sea level affecting many coastal communities. It will also have many effects on agriculture and will affect the balance of many ecosystems and even the health of people as will be discussed later in the report.

3.1.2 The Greenhouse Gases

Carbon Dioxide

Carbon dioxide is the most important human made greenhouse gas, whose atmospheric concentration has been increasing dramatically as a result of human activities. Before the industrial revolution, the mixing ratio of carbon dioxide in the atmosphere was almost constant for several thousand years with a mean value of 280 parts per million (Houghton 29-42). After the industrial revolution, the concentration of carbon dioxide has been increasing due to the burning of fossil fuels and other human activities. The human activities have added about 600 Gigatonnes of carbon dioxide to the atmosphere starting from the 1700s, which results in a present mixing ratio of over 370ppm (Humi).

Figure 4.1.1 - Carbon Concentration over Last 10,000 Years from Taylor Dome (Houghton 32)

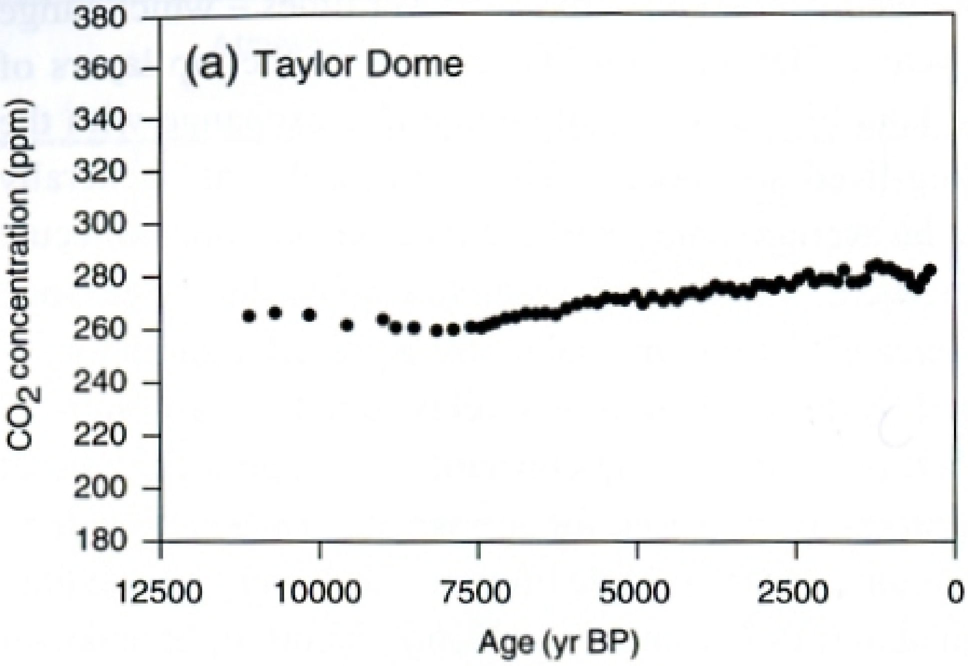
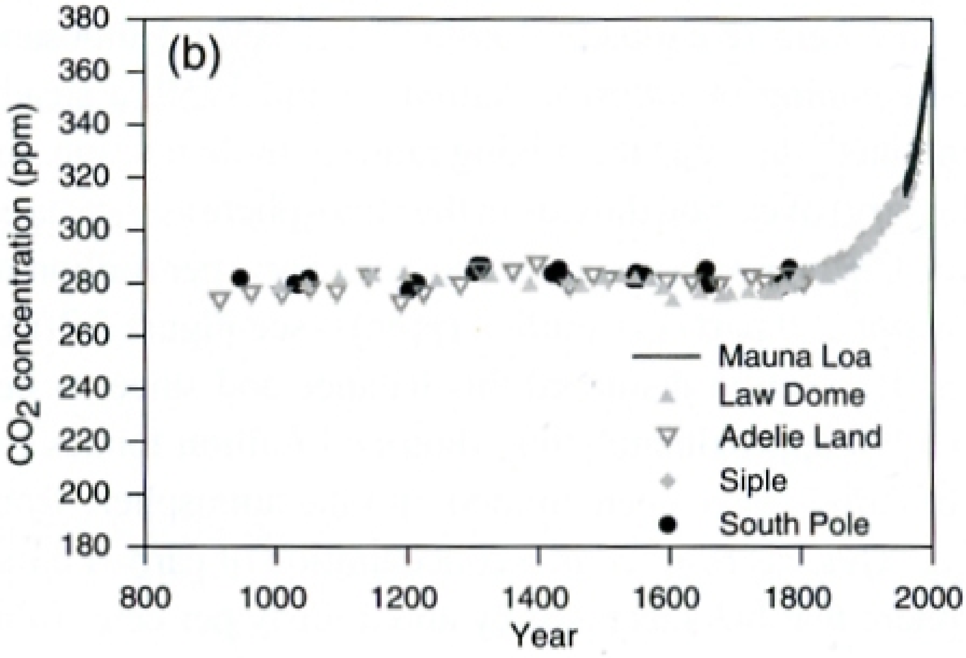


Figure 4.1.2 - Carbon Concentration over Past Millennium from Antarctic Ice Cores (Houghton)



Figures 4.1.1 and **4.1.2** illustrate the amounts of carbon dioxide in the atmosphere during the last 10,000 and 1000 years respectively. In addition to fossil fuel burning, carbon dioxide emission can result from the burning and decay of forests in some regions of the world as more land is used for agriculture and because of the expansion of cities due to population growth. However, this may be balanced by the re-growth of forests in other regions, which makes it difficult to determine whether the change in land use adds more carbon dioxide to the atmosphere or represents a sink (McElroy). The ocean takes up some of the carbon dioxide added to the atmosphere. However, most of the carbon added to the ocean stays in the top levels for a long time because it takes hundreds of years for the upper level water to mix with the lower level water (Humi).

There are both positive and negative feedbacks related to the increase in the concentration of carbon dioxide and other greenhouse gases (Houghton). One example of negative feedback is the carbon dioxide fertilization effect. As more carbon dioxide is added to the atmosphere, more carbon is absorbed by plants causing a reduction of the atmospheric concentration of carbon dioxide (Humi). In addition, the manufacturing and use of fertilizers may cause an increase in other greenhouse gases. However, the increased use of fertilizers may possibly result in an enhancement of the uptake of carbon dioxide by forests and plants through photosynthesis, which is the process by which plants change carbon dioxide, light, and water to organic matter. This is also a negative feedback because it actually reduces the concentration of carbon dioxide in the atmosphere.

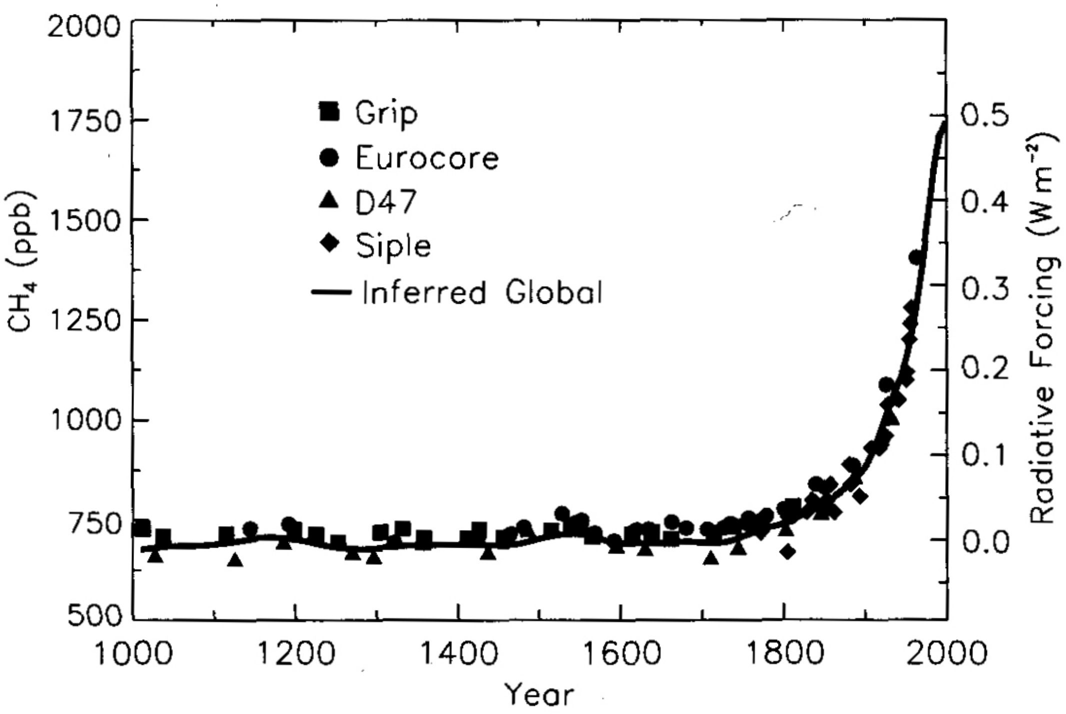
On the other hand, there are many positive feedbacks related to global warming and carbon emissions. Positive feedbacks are more important because an increase in a certain process leads to an enhancement of the process and a faster increase. An example of positive feedback is an increase in respiration rates and carbon dioxide emissions as temperature increases due to human made greenhouse gases, especially by microbes in soil. However, although studies have demonstrated that this is true for temperature rise during a short time such as during the El Nino, there is no evidence that this holds for temperature rise over prolonged amounts of time (Humi). There is also another positive feedback due to the effect of temperature rise and climate change on the growth of forests. As a result of harsh weather conditions due to global warming, more forests and vegetation may die and decay releasing more carbon dioxide into the atmosphere (Houghton).

It is important to predict the effects the increase in the concentrations of different greenhouse gases may have on the climate in the future. In order to achieve this, the amounts of carbon dioxide emissions in the future need to be approximated. Unfortunately, not only the concentration of carbon dioxide in the atmosphere is increasing; even the rates of CO_2 emissions are increasing. Even if the carbon dioxide emissions are halted, the carbon dioxide that already exists in the atmosphere will diffuse out slowly and will stay for a long time. One reason for this is the sink of carbon to the ocean takes hundreds of years because of the slow mixing rate of the upper levels of the ocean with the lower levels, as was mentioned before. It is quite difficult to estimate future emissions of carbon dioxide because this depends on the activities of the whole population of the world. Many assumptions need to be made with relation to population growth, economic growth, energy needs, the development of new energy sources, and the possible effects due to concerns about global warming. Since we cannot predict exactly how human activities in the future will be, different possibilities are considered to produce different graphs or scenarios of carbon dioxide emissions (Humi).

Methane

Methane is also an important greenhouse gas that exists in the atmosphere due to both natural and human sources. Like carbon dioxide, the concentration of methane in the atmosphere was constant for at least two thousand years before 1800, and was approximately 700 parts per billion (Houghton 42-44). However, after 1800, the atmospheric methane concentration has increased rapidly to reach about 1750 part per billion by the year 2000, which is more than double that of the pre-industrial value (Humi). **Figure 4.1.3** is a plot of the concentration of methane over the past millennium.

Figure 4.1.3 - Change in Methane Concentration over the Past Millennium (Houghton 42)



Although the concentrations of methane appear relatively small compared to the concentrations of carbon dioxide, the contribution of a methane molecule to the greenhouse effect is eight times that of a carbon dioxide molecule. However, methane has a very short life time, only about twelve years (Humi).

The natural sources of methane in the atmosphere include wetlands, termites, and oceans, with the wetlands being the most important source. The human portion of the methane is due to leakage from natural gas pipelines and oil wells, generation from rice paddies, and enteric fermentation (Humi)**Error! Bookmark not defined.**. It is also due to waste treatment, landfills, and biomass burning (Houghton). It is very difficult to estimate the amount of methane produced by wetlands, rice paddies, and animals because of the variations from season to season and the variations between regions of the world

(Humi). However, the portion that results from fossil fuel sources can be estimated by looking at the different isotopes of carbon in atmospheric methane**Error! Bookmark not defined.**. The removal of methane occurs mainly in the atmosphere by chemical destruction as it reacts with hydroxyl radicals OH produced by light, oxygen, ozone, and water vapor (Humi)**Error! Bookmark not defined.**.

Nitrous oxide

Nitrous oxide is one of the minor greenhouse gases; a chemical used as an anesthetic and often called laughing gas. Its concentration in the atmosphere is approximately 0.3 parts per million, which is about 16 % more than the pre-industrial concentration. However, it is characterized by an atmospheric life time of about 115 years, which is relatively long since it is much longer than the life time of Methane. The Nitrous oxide results from natural and agricultural ecosystems. In addition, it also results from the increasing use of fertilizers, the burning of biomass, and the production of chemicals such as nylon (Humi). The Nitrous oxide is destroyed by photo-dissociation in the stratosphere and also through the reaction with electrically excited Oxygen atoms (Houghton 44).

Chlorofluorocarbons (CFCs) and Ozone

CFCs are human made chemicals that are used in refrigerators and the manufacturing of insulation and aerosol spray cans (Houghton 44-47). Although they have been used widely since they are non-toxic and non-flammable, they can add to the greenhouse gases and cause serious environmental issues. CFCs are themselves greenhouse gases and they are very powerful compared to other greenhouse gases. In addition, the presence of these gases in the upper levels of the atmosphere can cause destructive effects.

Ozone is a greenhouse gas that can result from aircrafts and also adds to global warming. Ozone is very reactive, consisting of three atoms of oxygen and it exists in small amounts in the stratosphere. Ozone molecules are formed from oxygen molecules through the action of ultra violet radiation coming from the sun (Houghton 28). The advantage of ozone is the molecules are destroyed as they absorb a form of ultra violet radiation having a slightly longer wavelength, which can be very harmful to humans and other forms of life on earth. However, CFCs evaporate at very low temperatures and move toward the upper levels of the atmosphere where the chlorine in them is disassociated as a result of ultraviolet radiation. The resulting chlorine acts as a catalyst that destroys ozone and changes it back to oxygen molecules. The destruction of ozone is very dangerous since it allows some of the harmful ultraviolet radiation to reach the earth, and it is known as the ozone hole (Houghton).

Fortunately, the Montreal protocol in 1987 and the amendments agreed in London in 1991 and in Copenhagen in 1992 required that the manufacturing of CFCs should be aborted completely by 1996 in industrial countries and by 2006 in developing countries. However, CFCs are characterized by a long lifetime that will allow them to stay in the atmosphere for hundreds of years to come. In addition, both Ozone and CFCs are greenhouse gases. Although the concentration of CFCs is only about 1 part per billion, a CFC molecule has a greenhouse effect that is five to ten thousand times greater than a molecule of carbon dioxide and has a lifetime of hundreds of years as was mentioned above. CFCs account for approximately 20% of the greenhouse effect. Because the increase in CFCs results in decreasing the ozone, some of the greenhouse effect resulting from the CFCs is compensated by the decrease in ozone (Houghton).

CFCs are being replaced by other halocarbons such as the hydrochloro-fluorocarbons (HCFCs), which will also be banned by 2030, and the hydro-fluorocarbons (HFCs). The HCFCs and the HFCs are also greenhouse gases, but they have a shorter lifetime than CFCs and it is in the range of tens of years. On the other hand, the rates of manufacturing of these chemicals may increase in the future and thereby contribute more to the greenhouse effect. Therefore, they should be taken into consideration and should be included into the studies of climate change (Houghton).

Other important greenhouse gases are perfluorocarbons such as CF_4 and C_2F_6 and sulfur hexafluoride SF_6, which result from some industrial processes. Theses gases are important because they have a long lifetime in the atmosphere which extends to probably more than a thousand years. Ozone, which is a greenhouse gas itself, can also move to the stratosphere from the troposphere. It can also be produced by chemical reactions involving sunlight and the nitrogen oxides emitted from aircraft exhaust at the upper level of the troposphere. Studies in the northern hemisphere suggest that ozone concentrations in the troposphere have doubled since the industrial revolution (Houghton).

Water Vapor

We have seen that carbon dioxide is the most important human made greenhouse gas and that the most imperative step in reducing global warming is to reduce carbon dioxide emissions. On the other hand, water vapor is more powerful than all other greenhouse gases, and it contributes to the greenhouse effect more than any other greenhouse gas including carbon dioxide. In addition, although most of the water vapor in the atmosphere is due to natural processes, it may present a positive feedback to global warming. As temperatures rise due to global warming, more water is evaporated leading to a higher atmospheric concentration of the gas. This adds an additional amount of greenhouse gas to the atmosphere, which in turn leads to increased temperatures. In addition, water vapor played an important role in the temperature rise in Europe.

Studies done by Dr. Wallace Broecker illustrate the importance of water vapor as a greenhouse gas (Houghton). In order to determine the contribution of a given greenhouse gas to the greenhouse effect, we may multiply the actual concentration with the Global Warming Potential (GWP) of each gas relative to carbon dioxide (Hieb). If water vapor is not taken into consideration, the total contribution of carbon dioxide to the greenhouse effect is about 72.37% and that of the human made portion is about 2.33%. Also, the contribution of the total anthropogenic greenhouse gases is approximately 5.53% (Houghton). These percentages seem to be high because the greenhouse effect of water vapor is not taken into consideration.

If on the other hand, we include the greenhouse effect of water vapor, the greenhouse effect due to carbon dioxide and all other gases will be small compared to the effect due to water vapor. Water vapor is responsible for about 95% of the greenhouse effect. It is estimated that both natural and human made carbon dioxide contributes about 3.618% to the greenhouse effect if we include water vapor. Furthermore, only about 0.117% of the greenhouse effect is due to the anthropogenic carbon dioxide. These percentages are very small compared to the values we obtained without water vapor. Furthermore, if we sum all the human made greenhouse gases, the total human contribution to the greenhouse effect is about 0.28%, which is very small compared to the

5.53% which we obtained when water vapor is not taken into account. These numbers illustrate how important water vapor is as a greenhouse gas. The reason why many studies do not incorporate water vapor might be because most of it is naturally induced. In fact only about 0.001% of the total water vapor is human made (Houghton).

In addition, studies have shown that water vapor played an important role in the recent temperature increase in central Europe. Central Europe experienced an increase in temperature that is three times as fast as the temperature increase in the northern hemisphere (Appel). The temperature increase in countries like Germany and Poland was due to the greater amount of water vapor released into the atmosphere by forests and crops (Houghton 28). Scientists claim that 70% of the recent increase in temperature in central Europe was caused by water vapor while the rest is caused by other greenhouse gases (Houghton).

3.2 Atmospheric Structure and Dynamics

3.2.1 - Vertical Structure of the Atmosphere

The Atmosphere has several local temperature minima as a function of increasing altitude, as seen in **Figure 3.2.1**.

Figure 3.2.1 – Temperature Variation with Altitude

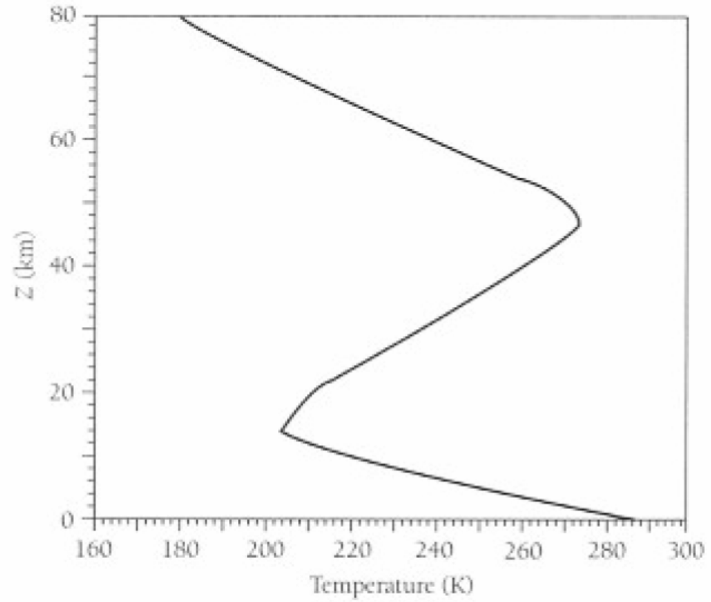


Figure 7.5 Temperature versus altitude in the atmosphere. Temperatures were taken from measurements made by the Atmospheric Trace Molecule Spectroscopy (ATMOS) Experiment flown on the space shuttle in May 1985 (Farmer et al., 1987). Data refer to 30°N. Temperatures shown here were used to construct the pressure profile shown in Figure 7.4. Source: Farmer et al. 1987.

The first minimum is at an altitude near 11 km, with a temperature of about 216 K. The temperature then increases with height to a local maximum of about 270 K at 50 km.

A secondary minimum of about 180 K and is located around 85 km. The lowest region of the atmosphere, up to the first temperature minimum, is called the troposphere. The troposphere is relatively unstable, a consequence of the decrease of temperature with altitude. (McElroy)

The upper boundary of the troposphere, the altitude corresponding to the temperature minimum, is known as the tropopause. Above this lies the stratosphere. Vertical motions are strongly inhibited in the stratosphere as a result of the increasing temperature with altitude. Most of the world’s ozone is contained in the stratosphere. The temperature maximum near 50 km marks the upper boundary of the stratosphere, known as the stratopause. (McElroy)

The region of decreasing temperature above the stratopause is the mesosphere. The upper boundary of this region, the mesopause, is defined by the temperature minimum near 85 km. Above this is a region of increasing temperature called the thermosphere. Here are the highest temperatures anywhere in the atmosphere. The density of air is low at this location to allow satellites to orbit earth for extended periods of time. (McElroy)

The atmosphere experiences vertical motions as a result of several mechanisms. The simplest is when air encounters an obstruction, such as a mountain range. The air is forced up the slope of the mountain. As it rises, it cools. If the moisture content is sufficient, the temperature drops to the dew point and clouds form. Then, as the air crosses the mountain it sinks, and if conditions allow mountain lee waves can form. This is when the air oscillates in altitude, much like dropping a stone in a pond. (McElroy)

Vertical motion can also occur as a result of converging air in a low pressure system. Air tends to spiral inward toward the center of a low pressure system. Needing somewhere to go, the converging air rises, its temperature often decreasing to the dew point. For this reason low pressure systems are often accompanied by bad weather. (McElroy)

Weather fronts can also cause vertical motions in the atmosphere. An advance of warm air, a warm front, will tend to slowly ride over the cold air underneath. This is a function of the differing densities of air in the warm and cold regions. Warm fronts are frequently delineated by bands of clouds accompanied by widespread precipitation. Similarly a cold front will tend to drive warm air up and over the cold front. The boundary on a cold front is typically steeper than on a warm front. (McElroy)

3.2.2 - Horizontal Motions of the Atmosphere

Motions in the horizontal plane (motions along the surface of the Earth) are determined primarily by the horizontal pressure gradient and by the Coriolis force, with a contribution near the surface from a frictional force (McElroy). The Coriolis force includes two parts, a west-east Coriolis force and a north-south Coriolis force.

Air moving northward from the equator will tend to acquire an eastward component of velocity. Air moving southward toward the equator will begin to move westward. This is a result of the west-east Coriolis force. It acts to the right of the direction of motion in the Northern Hemisphere. The Coriolis force is derived by conserving the angular momentum of a control volume of air as it moves with respect to the equator. The volume of air will have the greatest angular velocity at the equator and zero angular velocity at the poles. Conserving angular momentum requires the control volume of air to develop a velocity with respect to the earth. Newton's law says that a change in velocity is caused by a force. Thus we have the Coriolis force to accomplish this (McElroy).

Geostrophic wind is the wind that results from a balance between the pressure gradient and the Coriolis force. The geostrophic wind provides a good approximation to the real wind at mid to high latitudes, assuming a large spatial scale. However, near the Earth's surface, friction will have an influence. For instance, air circling around a high pressure system in the Northern hemisphere would describe a clockwise path in the absence of friction. Friction serves to decrease the wind speed, with an associated reduction in the magnitude of the Coriolis force. This causes a disruption in the geostrophic balance. The air tends to be pushed by the pressure force and away from the center of the high. (McElroy)

3.3 The Carbon Cycle

Carbon exists in the atmosphere, the ocean, the biosphere and the soil. There is an ongoing transfer of carbon between the biosphere-soil system and the atmosphere, between the atmosphere and the ocean, and between the ocean and the sediments at bottom of the ocean. In addition, carbon in the form of carbon dioxide is added to the atmosphere as a result of burning fossil fuels and deforestation. In this section we will discuss the most important ways by which carbon is transferred between different reservoirs. We will focus more on the transfer between the atmosphere and the ocean because the ocean represents one of the most important sinks of carbon dioxide. The most abundant form of inorganic carbon in the ocean is the bicarbonate HCO_3^- and the carbonate ions CO_3^{2-}. Both of these compounds account for more than 99% of the carbon in the ocean (McElroy 154). Also, the ocean contains many ions other than the bicarbonate and the carbonate ions but the positive charge contributed by the cations is slightly larger than the negative charge contributed by the anions. The positive charge in the ocean is compensated mainly by the negative charge carried by the bicarbonate and the carbonate ions (McElroy 148).

The transfer of carbon between the atmosphere and the ocean depends on the partial pressure of carbon dioxide in the atmosphere and in the ocean (McElroy 149). As more human made carbon dioxide is added to the atmosphere, the partial pressure of carbon dioxide in the atmosphere increases, which causes some of the carbon dioxide to sink into the ocean. The increase in the concentration of the CO_2 at the surface of the ocean results in a decrease in the concentration of the carbonate ion CO_3^{2-} and an increase in the concentrations of the bicarbonate HCO_3^- and the hydrogen ion H^+ (McElroy 148-149). First, a molecule of carbon dioxide reacts with a water molecule to produce a bicarbonate ion and a hydrogen ion as illustrated by **Equation 3.3.1.** (McElroy 148-149)

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \qquad \textbf{Equation 3.3.1}$$

The production of the hydrogen ion results in an increase in the acidity of the ocean water. However, some of the hydrogen ions react with the carbonate ions to produce more bicarbonate ions which is illustrated by **Equation 3.3.2** (McElroy 148-149).

$$H^+ + CO_3^{2-} \rightarrow HCO_3^- \qquad \textbf{Equation 3.3.2}$$

Combining the two reaction equations gives us Equation **4.3.3.** (McElroy 148-149)

$$CO_2 + H_2O + CO_3^{2-} \rightarrow 2HCO_3^- \qquad \textbf{Equation 3.3.3}$$

As can be seen from **Equation 3.3.3**, the ability of the ocean to absorb excess carbon dioxide from the atmosphere is limited by the availability of the CO_3^{2-} in the ocean. In addition, the concentration of CO_3^{2-} in the ocean declines at a rate that is proportional to the increase of the partial pressure of carbon dioxide pCO_2 (McElroy 148-149). The ratio of the fractional change in partial pressure of carbon dioxide pCO_2 and the fractional change in the total dissolved carbon is a measure of the ability of the ocean to take up additional CO_2 and is called the Revelle factor (McElroy 150).

Changes of temperature over the year also affect the concentration of carbon dioxide in the ocean and the atmosphere. There is a release of CO_2 to the atmosphere during the summer and spring and a compensatory uptake in the autumn and winter (McElroy 142). When the temperature of the ocean increases, the pressure of CO_2 in the ocean is more than its pressure in the atmosphere, which results in a flow of CO_2 from the ocean to the atmosphere (McElroy 150). Therefore, when studying the greenhouse effect of carbon dioxide, we are mostly concerned about the yearly average of the carbon dioxide concentration.

As a result of the burning of fossil fuels and deforestation, the concentration of carbon dioxide in the atmosphere increases. Although a fraction of the added carbon dioxide sinks into the ocean, most of the added greenhouse gas remains in the atmosphere. The fraction of the added carbon that is taken up by the ocean is called the Keeling factor which is given by **Equation 3.3.4** assuming a uniform chemical composition of the ocean (McElroy 151-152).

$$\mathrm{f}_{\mathrm{atm}} = \left[1 + \frac{(pCO_2)_0}{pCO_2}[CO_3^{2-}]_0 \frac{V}{M_0}\right]^{-1} \qquad \textbf{Equation 3.3.4}$$

V is the volume of water that had the opportunity to interact with the atmosphere; M_o is the mass of carbon in the atmosphere; $[CO_3^{2-}]_0$ is the initial concentration of the carbonate ion; and $(pCO_2)_0$ and pCO_2 are the initial and final pressure of carbon dioxide in the atmosphere respectively. If the ocean is to reach equilibrium with the atmosphere, only about 19% of the carbon dioxide resulting from fossil fuel burning since the industrial revolution will stay in the atmosphere and 81 % would sink into the ocean. However, the equilibrium is not reached yet leaving the atmosphere with about 70 % of the added CO_2. This is due to the small concentration of CO_3^{2-} and the slow vertical circulation of the ocean (McElroy 151-152).

In order to understand why most of the added carbon remains in the atmosphere, we need to examine the processes responsible for the transfer of the carbon between the atmosphere and the upper water and between the upper water and the deep sea. The net downward flux of chemical species resulting from the vertical movement of water is given by **Equation 3.3.5** (McElroy 162).

$$F = -K\frac{dc}{dz}$$ **Equation 3.3.5**

$c(z)$ is the concentration of the chemical at the level z. $K = V\Delta Z$ is called the eddy diffusion coefficient where V is the bulk vertical motion of water and ΔZ is the mixing length, which is usually given as an average value. The vertical movement in the upper levels of the ocean causes the carbon to sink. However, the vertical movement of water at the immediate vicinity of the surface is equal to zero (McElroy 163). Therefore, the movement of chemicals from the surface into the fluid's bulk is interrupted by collisions with water molecules because there is no vertical movement of the water. The downward flux through this stagnant boundary layer is given by **Equation 3.3.6** (McElroy 163).

$$F = vc(0) - vc(\lambda)$$ **Equation 3.3.6**

$c(\lambda)$ and $c(0)$ are the concentrations of the chemical species at the bottom and at the top of the stagnant boundary layer. $v = \frac{D}{\lambda}$ is the piston velocity where D is the coefficient of molecular diffusion. The carbon is transferred rapidly to the base of the stagnant boundary layer and the concentration of all dissolved carbon adjusts to the higher level of CO_2 following the chemical reactions that we discussed earlier. However, the transfer to deeper levels of the ocean proceeds at a rate determined by the strength of eddy mixing (McElroy 163). Tracing the C^{14} produced by the testing of nuclear weapons or measurement of the CFCs can be used to find values for these coefficients (McElroy 163).

The carbon absorbed by the ocean spreads rapidly over the upper levels of the ocean, within a few hundred meters from the top, enabling part of the human generated carbon dioxide to be taken up rapidly by the ocean. However, the spread of the carbon into lower levels of the ocean takes a long time. The reason for this is that it takes up to several hundred years for the upper levels of the ocean to mix with intermediate levels, and it takes over a thousand years for the upper levels of the ocean to mix with the lower levels (Houghton 34). Most of the carbon absorbed by the ocean stays in the upper levels, which makes the ocean unable to take up a high amount of carbon dioxide. This is the reason why most of the added carbon dioxide stays in the atmosphere instead of sinking into the ocean. After the carbon sinks into the deep sea, it is transferred into the sediments where it remains almost forever. After a very long time, these sediments are transported by the crustal plates and it may rise to the surface and undergo erosion. Also, the carbon may be vented to the atmosphere when there is a volcano eruption or a through a hot spring (McElroy 147).

In addition, marine life has an effect on the budget of carbon in the ocean and in the whole ocean-atmosphere-biosphere-soil system. The growth and decay of organisms in the ocean affects the abundance of both organic and inorganic carbon, and also varies the alkalinity of the ocean (McElroy 154-155). First, a portion of the carbon dioxide absorbed by the ocean is taken up by photosynthesis in the ocean (McElroy 154-155). Alkalinity is defined as the net positive charge contributed by all species in the ocean except the carbon (McElroy 148-149). Alkalinity is important because changing the alkalinity of the ocean may result in a release or an uptake of carbon dioxide by the ocean to balance the positive or negative charge. There is a change in alkalinity as a result of the production of calcite from Ca^{2+} and CO_3^{2-} and also from the conversion of nitrate NO_3^- to organic matter by marine organisms (McElroy 154-155). The decrease of CO_2 and NO_3^- as a result of the growth of organisms leaves the water less acidic because the concentration of the hydrogen ion decreases. This requires a net conversion of the bicarbonate ion HCO_3^- to the carbonate ion CO_3^{2-} to maintain equilibrium. This leads to further uptake of carbon dioxide from the atmosphere (McElroy 154-155). In addition, The carbon may be transferred to the deep ocean when planktons decay and sink into the ocean where it undergoes decomposition. This process, which is called "the biological pump", is important because it results in a sink of carbon to the deep sea (Houghton 35).

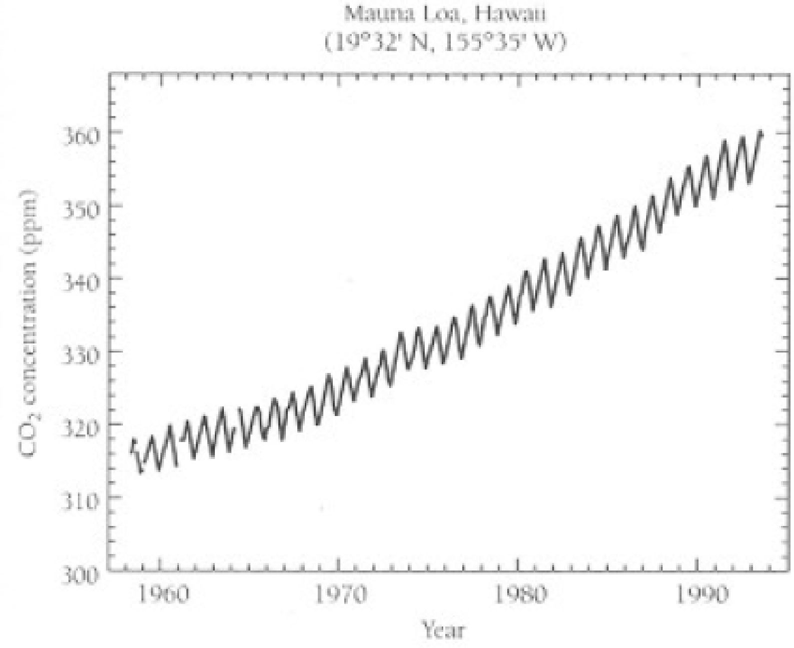
The transfer of carbon between the atmosphere and the biosphere-soil system can also be important and affect the concentration of carbon dioxide in the atmosphere. However, the direction of the transfer of carbon between the atmosphere and the biosphere-soil system depends on the spread of vegetation and forests and also on land use by humans (Houghton 39-41). The biosphere-soil system could represent either a source or a sink in the global scale. It could provide a source in one region and a sink in another depending on the extent of vegetation. In regions where forests are expanding, there is a sink of carbon dioxide because of photosynthesis. On the other hand, in regions with extensive deforestation, there is a source of carbon dioxide because of the decay of vegetation and because reducing the vegetation results in a reduction of the amount of CO_2 taken up by photosynthesis. In addition, burning forests in order to use land for agriculture or expanding a city may also result in a release of carbon dioxide. Deforestation in the tropics represents a source of carbon dioxide while re-growth of forests in previously defrosted forests in mid-latitudes of the Northern hemisphere represents a sink (McElroy 143).

Estimating the contribution of the biosphere-soil system to the carbon dioxide budget can be done in different ways. One method uses the fact that there is a difference between the amount of oxygen used when burning fossil fuels and the amount of oxygen used or produced by the biosphere. The combustion of fossil fuels results in the removal, on average, of about 1.39 mole of O_2 for each mole of CO_2 produced. On the other hand, the uptake of 1mol of CO_2 by the biosphere is associated with a release of 1.1 mol of O_2 and verse versa (McElroy 143). The resulting carbon dioxide will be distributed between the ocean and the biosphere, while the oxygen will stay in the atmosphere because of its low solubility in water. Since we can measure the change of oxygen in the atmosphere and since we know the contribution of the combustion of fossil fuels, we can determine the contribution of the biosphere-soil system (McElroy 143).

Another method of estimating the contribution of the biosphere-soil system is to study the different carbon isotopes. When carbon dioxide is taken up by plants and other living creatures, less ^{13}C is taken up in proportion to ^{12}C. Fossil fuel such as coal and oil contains less ^{13}C and no ^{14}C at all because it was originally living matter and has been stored in Earth for much longer than the half-life of ^{14}C (5,730 years) (Houghton 37). By studying the ratio of the different carbon isotopes in the atmosphere, the oceans, and the gas trapped in ice cores and in tree rings, it is possible to determine where the additional carbon dioxide in the atmosphere came from and also what amount has been transferred to the ocean (Houghton 37)**Error! Bookmark not defined.**.

The concentration of carbon dioxide in the atmosphere varies along the course of the year.

Figure 3.3.1 - Variation of the CO_2 concentration in Mauna Loa, Hawaii (McElroy 148)



The graph in **Figure 3.3.1** illustrates the increase in the CO_2 concentration in Mauna Loa, Hawaii as a result of the human generated carbon dioxide as well as the increase and decrease in the CO_2 concentration during a one year period. Analysis of these graphs shows that the CO_2 concentration decreases during spring and summer and increases during autumn and winter. This is due to the uptake of CO_2 by plants and trees during the spring and summer as a result of photosynthesis and the balancing effect of respiration and decay during autumn and winter (McElroy 141). The graph also illustrates the importance of the photosynthesis in the budget of carbon dioxide in the atmosphere.

3.4 Model for CO_2 Levels in the Atmosphere

3.4.1 - The Original Model[*]

As part of this project, we explored the use of computer models to predict CO_2 concentrations. We did this by utilizing and modifying a model originally created by Professor A. J. McHugh of Lehigh University's Department of Chemical Engineering. The model was run using MATLab and was input into MATLab with the help of Professor Mayer Humi of Worcester Polytechnic Institute's Department of Mathematical Sciences.

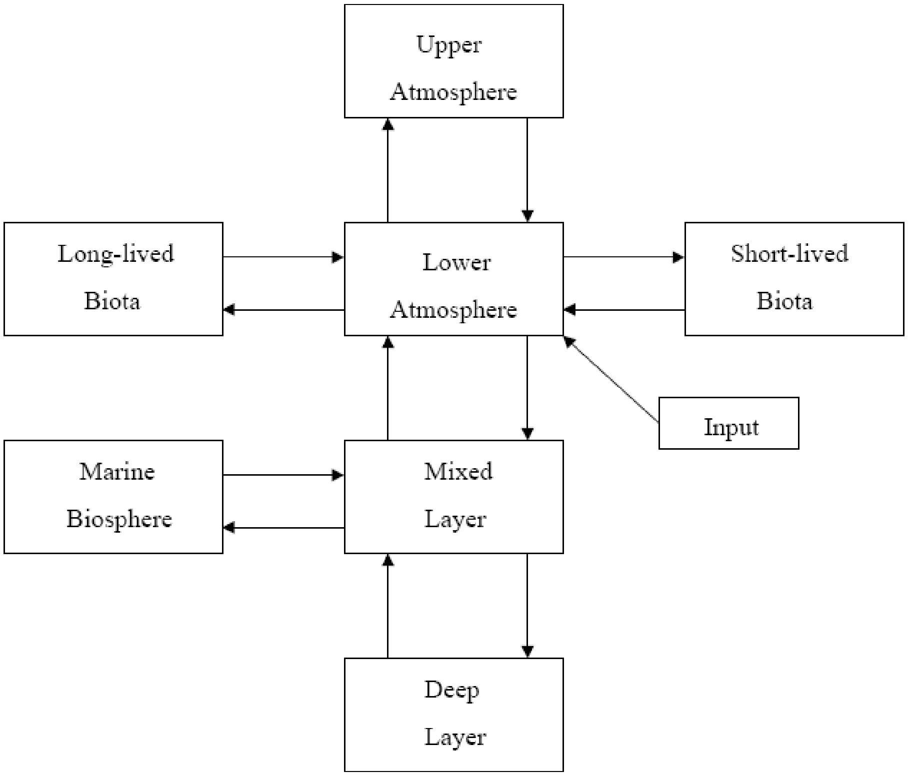
This carbon model divides the earth-atmosphere system into seven reservoirs (McHugh). Each reservoir is assumed to be "perfectly mixed" which means there are no spatial differences in the concentration of carbon in each one of them. The atmosphere is divided into two reservoirs: the upper atmosphere and the lower atmosphere. The carbon dioxide resulting from the burning of fossil fuels is first injected into the lower atmosphere. It then transfers from the lower atmosphere to the upper atmosphere and other reservoirs from there. The third reservoir is the long lived biota, which represents the world's forests. On the other hand, the plants with a short life cycle of about a year represent another reservoir called the short lived biota. Since the ocean plays an important role in the carbon cycle, it consists of three reservoirs. The ocean itself is divided into two reservoirs called the mixed ocean layer and the deep sea. The last reservoir is the marine biosphere, which represents the various planktons that exchange

---

[*] **Note:** The original model as well as our modified versions can be found in **Appendix A** of this report.

carbon with the ocean and other reservoirs. **Figure 3.4.1** illustrates the seven reservoirs with a set of arrows showing the exchange of carbon between adjacent reservoirs.

Figure 3.4.1 - Reservoirs with Arrows Showing Fluxes between Reservoirs (McHugh)



The carbon cycle is modeled using seven initial value first order ordinary differential equations with time as the independent variable, and many assumptions were made to simplify the analysis (McHugh). As was mentioned before, the carbon is assumed to be uniformly distributed over each reservoir in order to simplify the model and deal only with one independent variable. In addition, the climate change resulting from the carbon dioxide in the atmosphere may also affect the carbon cycle. For example, increased temperature may affect the transfer of carbon between different reservoirs.

However, we assume that the change of climate does not interact directly with the process and, therefore, the model does not contain a climate component. The flux of carbon into and out of each of the seven reservoirs is represented by a differential equation. This will result in seven differential equations which will be introduced in the following paragraphs.

Now, we are ready to introduce the differential equations and parameters which the original model uses (McHugh). These are the same equations that we are going to use in our MATLab program in the next section. In this model, the concentration is normalized and it is presented as a dimensionless quantity. For example, the concentration $C_{ir}(t)$ of carbon in the ith reservoir at time *t* is given by **Equation 3.4.1**. (McHugh)

$$C_{ir}(t) = \frac{C_i(t) - C_i(1700)}{C_{ta(1700)}} \qquad \textbf{Equation 3.4.1}$$

Where,

$C_i(t)$ The amount of carbon in the ith reservoir at time t in grams

$C_i(1700)$ The amount of carbon in the ith reservoir at time t = 1700 in grams

$C_{ta}(1700)$ The amount of carbon in the total atmosphere at time t = 1700 in grams

The rate of change in the concentration of carbon in each reservoir is equal to the sum of the fluxes into and out of the reservoir, as presented by **Equations 3.4.2** through **3.4.8.** (McHugh)

$$\frac{dC_{ua}}{dt} = D_{lu}$$ **Equation 3.4.2**

$$\frac{dC_{lb}}{dt} = D_{lb}$$ **Equation 3.4.3**

$$\frac{dC_{sb}}{dt} = D_{sb}$$ **Equation 3.4.4**

$$\frac{dC_{la}}{dt} = -D_{lu} - D_{sb} - D_{lb} + D_{ml} + \gamma(t)$$ **Equation 3.4.5**

$$\frac{dC_{ml}}{dt} = -D_{ml} - D_{md} - D_{mb}$$ **Equation 3.4.6**

$$\frac{dC_{mb}}{dt} = D_{mb}$$ **Equation 3.4.7**

$$\frac{dC_{ds}}{dt} = D_{md}$$ **Equation 3.4.8**

Where,

C_{ua}	Carbon concentration in the upper atmosphere
C_{lb}	Carbon concentration in the long-lived biota
C_{sb}	Carbon concentration in the short-lived biota
C_{la}	Carbon concentration in the lower atmosphere
C_{ml}	Carbon concentration in the ocean mixed layer
C_{mb}	Carbon concentration in the marine biosphere
C_{ds}	Carbon concentration in the deep sea

The terms D_{lu}, D_{lb}, D_{sb}, D_{ml}, D_{md}, and D_{mb} represent the fluxes from one reservoir to the other and have units of year^{-1}.

The term $\gamma(t)$ represents the input of carbon resulting from human activities such as burning fossil fuels and has units of year^{-1}. This term takes into account the increase in carbon dioxide emissions as a function of time. It can be obtained by taking into consideration different factors that affect the carbon dioxide emissions such as increasing energy needs and population growth. The human made carbon dioxide input in this model is expressed as an exponential function, and it is given by **Equation 3.4.9.** (McHugh)

$$\gamma(t) = \gamma_0 e^{rt}$$ **Equation 3.4.9**

Where,

$\gamma_0 = (2.3937)(10^{-29})$ year^{-1}

$r = 0.03077$ year^{-1}

If we multiply the right side of the equation by the amount of carbon in the atmosphere at the year 1700 (t=1700) and convert from grams to tons, we can compute the amount of carbon added in tons per year, which is given by **Equation 3.4.10.** (McHugh)

$$T_{py}(t) = \frac{\gamma(t) N_{a0}}{(453.6)(2000)}$$ **Equation 3.4.10**

$N_{a0} = (6.156)(10^{17})grams$ is the total carbon in the atmosphere in grams (in base year), which is the same as the $C_{ta}(1700)$ we defined before.

The flux of carbon from one reservoir to the other depends on the concentration of carbon in the reservoir and in other reservoirs depending on the process involved. For example, the flux from the lower atmosphere to the upper atmosphere depends on the concentration of carbon in the lower atmosphere and in the upper atmosphere. The original model uses equations that present each flux as a function of carbon concentrations in different reservoirs as well as some constants, which were provided to us. The equations that relate the fluxes and the carbon concentrations can be developed from **Equations 3.4.2** through **3.4.8** and they are given by **Equations 3.4.11** through **3.4.16.** (McHugh)

$$D_{lu} = \left(\frac{1}{T_{ul}}\right)\left(\frac{P_1}{1-P_1}C_{la} - C_{ua}\right)$$ **Equation 3.4.11**

$$D_{lb} = \beta\left(\frac{F_{lb0}}{N_{a0}}\right)C_{la}$$ **Equation 3.4.12**

$$D_{sb} = \left(\frac{1}{N_{a0}}\right)F_{sb0}\left(\beta C_{la} + \frac{C_{lb}}{P_2} - \frac{C_{sb}}{P_3}\right)$$ **Equation 3.4.13**

$$D_{ml} = \left(\frac{1}{T_{am}}\right)\left(\frac{1+\frac{C_{org}}{C_{mt}}}{P_4}\varepsilon C_{ml} - \frac{1}{1-P_1}C_{la}\right)$$ **Equation 3.4.14**

$$D_{mb} = \left(\frac{F_{mb0}}{N_{a0}}\right)\left(1+\frac{C_{mb}}{P_5}\right)\left(\frac{\beta C_{ml}}{P_4}\right)$$ **Equation 3.4.15**

$$D_{md} = \left(\frac{1}{T_{dm}}\right)\left[\left(\frac{W_s}{W_m} - 1\right)C_{ml-}C_{ds}\right]$$ **Equation 3.4.16**

Where,

$C_{org} = 0.001\, grams/liter$	The organic carbon concentration in the ocean mixed layer
$C_{mt} = (12.011)(0.002057)\, grams/liter$	The inorganic carbon concentration in the ocean mixed layer
$\beta = 0.6$	The biota growth rate factor
$T_{am} = 5.8\, years$	Exchange time from lower atmosphere to mixed layer
$T_{ul} = 2.0\, years$	Exchange time from upper to lower atmosphere
$T_{dm} = 1500\, years$	Exchange time from mixed layer to deep sea
N_{ua}	The total carbon in the upper atmosphere in grams (in base year)
N_{lb}	The total carbon in the long lived biota in grams (in base year)
N_{sb}	The total carbon in the short lived biota in grams (in base year)
N_{ml}	The total carbon in the mixed layer in grams (in base year)
N_{mb}	The total carbon in the marine biosphere in grams (in base year)
$P_1 = \frac{N_{ua}}{N_{a0}} = 0.15$	Normalized concentration in Upper Atmosphere
$P_2 = \frac{N_{lb}}{N_{a0}} = 2.534$	Normalized concentration in Long Lived Biota
$P_3 = \frac{N_{sb}}{N_{a0}} = 0.122$	Normalized concentration in Short Lived Biota

$P_4 = \frac{N_{ml}}{N_{a0}} = 2.0$ Normalized concentration in Ocean Mixed Layer

$P_5 = \frac{N_{mb}}{N_{a0}} = 0.1$ Normalized concentration in Marine Biota

$F_{lb0} = (2.6)(10^{16})\,grams/year$ Initial flux from lower atmosphere to long lived biota

$F_{sb0} = (3.0)(10^{16})\,grams/year$ Initial flux from lower atmosphere to short lived biota

$F_{mb0} = (2.0)(10^{16})\,grams/year$ Initial flux from mixed layer to marine biosphere

$\varepsilon = 12.5$ Ocean evasion factor

$W_s = (1.370)(10^{21})\,liters$ The total volume of the ocean

$W_m = \frac{P_4 N_{a0}}{C_{mt} + C_{org}}$ The volume of the ocean mixed layer in liters

In order to solve the differential equations for carbon concentrations, we need the initial conditions at *t* = 1700. Since, as we have already seen in the above discussion, the concentration at each of the reservoirs is given by the equation below.

$$C_{ir}(t) = \frac{C_i(t) - C_i(1700)}{C_{ta(1700)}}$$ **Equation 3.4.16**

The initial carbon concentration in each of the reservoirs is zero (McHugh).

$$C_{ua}(1700) = C_{lb}(1700) = C_{sb}(1700) = C_{la}(1700) = C_{ml}(1700) = C_{mb}(1700) = C_{ds}(1700) = 0$$

Since all the constants in the differential equations are known and since the initial conditions are also given, we can use a computer program to solve them in any interval of the form [1700,t_f]. In the next section, we will use MATLab to solve the differential equations and plot the carbon concentrations in each reservoir as a function of time.

The first order carbon model that we just discussed is not very accurate because many assumptions were used in order to simplify the analysis. The entire earth-atmosphere system cannot be modeled by only seven reservoirs. In addition, the model ignores the difference in carbon concentration from one region to the other. For example, the biota may represent a sink of carbon in one region and a source in another region. The model did not include a climate component to account for the effect of the temperature increase and the climate change on the carbon cycle. However, the model provides us with good understanding of how we can predict carbon dioxide concentration in the atmosphere, which is crucial for the study of climate change.

3.4.2 – Determination of New Initial Conditions

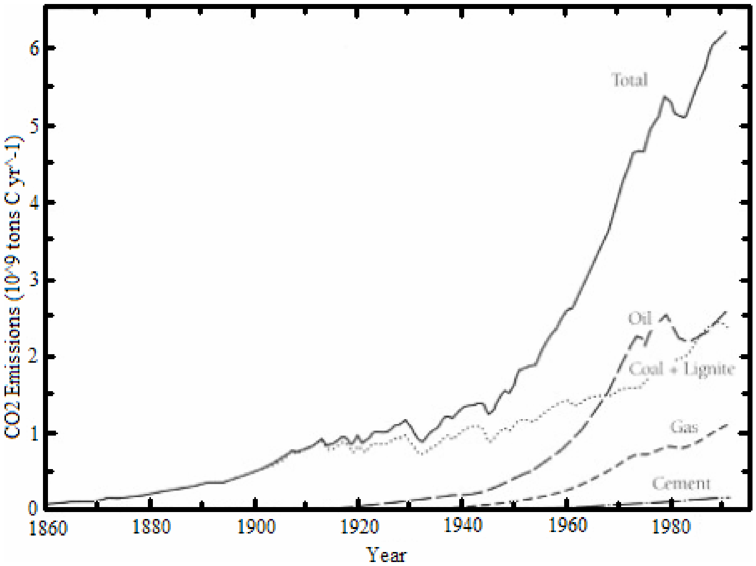
Using the model discussed in the previous section, we attempted to predict a couple of scenarios in which the human input to the system is different than the original models. In the first scenario, the human input takes the form of a linear function and the second scenario takes the form of a logarithmic function. For both cases, new initial conditions needed to be determined for the year 2000.

To find new initial conditions for this model, we started by running the original model from the year 1700 to the year 2000. This gave us the percent increase of CO_2 in each of the seven reservoirs. Using this information we found the new concentration constants for the seven reservoirs. For the two atmospheric reservoirs, this meant simply multiplying the initial amounts by the percent increase. For the other five reservoirs, the process was a little more involved. We started by using the original amount of CO_2 in the two atmospheric reservoirs, *Na0*, to de-normalize the concentration constants in the seven reservoirs. This was done by dividing the *P* constants for each reservoir by *Na0*. Then we multiplied each of the de-normalized values by their corresponding percent increases. Next we renormalized these values to get our new *P* constants. To do this we added the new concentrations for the two atmospheric reservoirs together to get a new *Na0*. We then divided the new concentrations for each of the five other reservoirs by this new *Na0*, resulting in our new *P* constants. The final step in this process was replacing the starting date of 1700 with 2000 in the interval for integration. With the new initial conditions set we moved on to trying our different forcing scenarios.

3.4.3 – Model with Linear Forcing Function

The first scenario we tried is one where the input of CO_2 into the atmosphere by humans follows a linear trend. To model this, we simply changed the forcing function in the differential model to one that is of a linear form. Originally the function was **gam = gam0 * exp(r * t)**. We changed this to **gam = (t - 2000) * ((9.07d14 / Na0) * (t - 2000) + (5.44d15 / Na0)).** One thing to note about this equation is the times have the starting year subtracted from them. This is because for the equation to give the correct values, it needs to start with a time of zero, while the integration range needs to start from the year 2000. The other important thing to notice is that the slope and intercept values from this equation had to come from somewhere. We got these amounts from a plot of human output of CO_2 from 1860 to 1990. See **Figure 3.4.2**.

Figure 3.4.2 – Global CO_2 Emissions from Fossil Fuel - Burning and Cement Production (McElroy)



From this plot we approximated an intercept value by linearly extrapolating a value for the year 2000. We then approximated the slope of the line between the years 1980 and 1990 to find the slope of our equation. Then we converted their units to match those of the computer model. The values we ended up with are 9.07×10^{14} grams/year^2 for the slope and 5.44×10^{15} grams/year for the initial value. Finally we normalized both values by *Na0* to match the rest of the model. It's important to note that we used these fairly imprecise methods to find initial conditions and constant values because we were not primarily concerned with the values we got from the model. Instead, our primary concern was the shape of the output. This was because current data tends to vary depending on the source, as well as we were trying to predict the future. Therefore, we focused on the shape of the output and drew conclusions based on that data. The predicted concentration increases for the two atmospheric reservoirs are presented in **Figures 3.4.3** and **3.4.4.**

Figure 3.4.3 - CO$_2$ Concentration in Upper Atmosphere

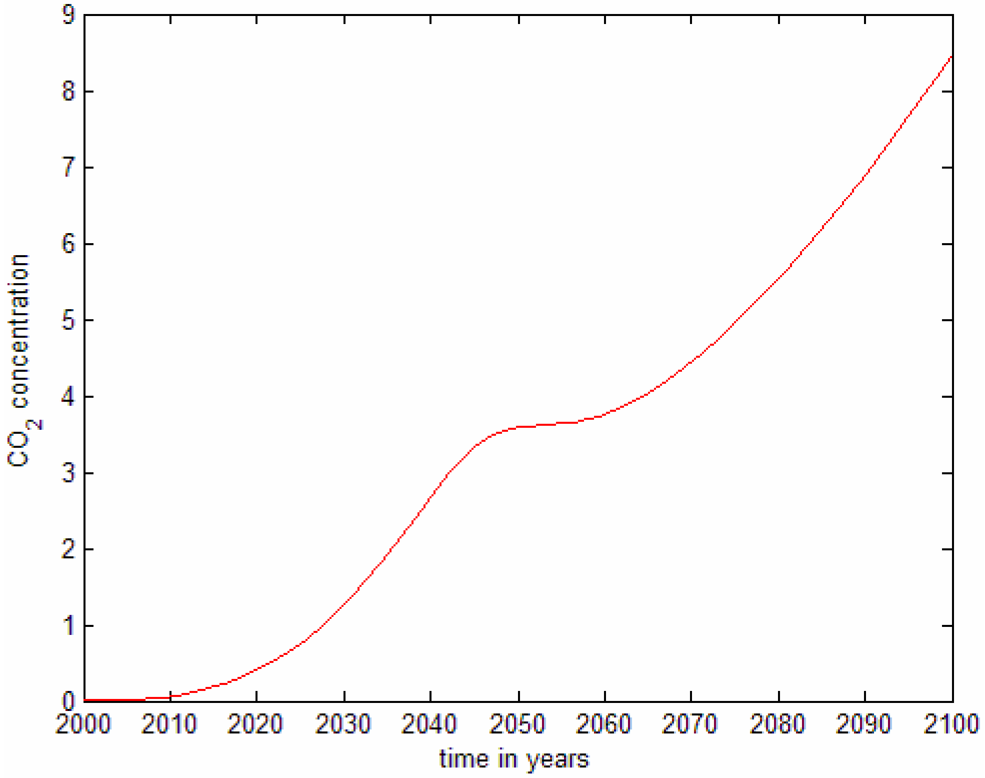
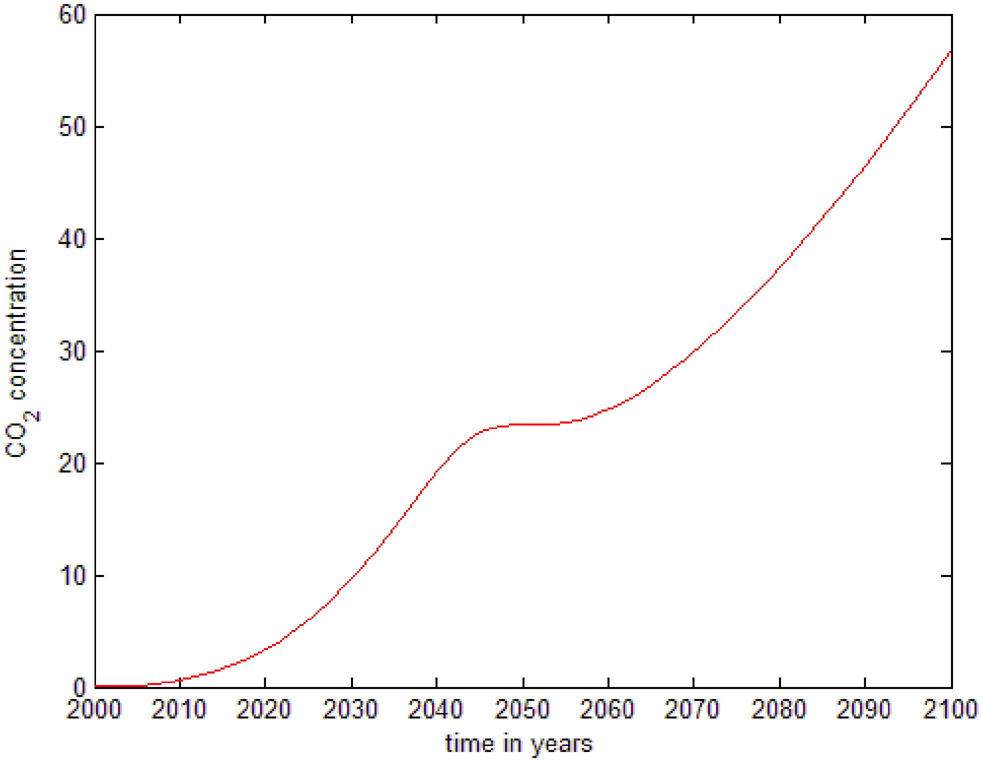


Figure 3.4.4 - CO_2 Concentration in Lower Atmosphere



We can see from these plots with a linear forcing function, the CO_2 concentrations in the atmosphere will continue to rise at a fairly steady rate. The "hump" is an interesting feature of this plot and is most likely the result of the particular system of differential equations used in this model. This suggests that to get any sort of reduction in concentrations of CO_2, or at least a slowing of increase, we will need to curb CO_2 more than just going from an exponential to a linear output function.

3.4.4 – Model with Logarithmic Forcing Function

For the scenario using a logarithmic forcing function we used essentially the same methods as the linear scenario except that we used an equation with a log function. For this scenario we attempted to give this function the same initial conditions as the linear scenario. However, for the other constants we used arbitrary values as we had no real data from which to generate these values. This is acceptable though, because again, we are primarily concerned with the shape of the output data. The forcing function in this case is now **gam = (t - 2000) * ((5.44d15 / Na0) + (t * (9.0718474d13 / Na0) * 1 * log(t - 1999)))**. Again we had to adjust the time parameters to allow for the correct initial conditions. The results of this forcing function are presented in **Figures 3.4.5** and **3.4.6.**

Figure 3.4.5 - CO_2 Concentration in Upper Atmosphere

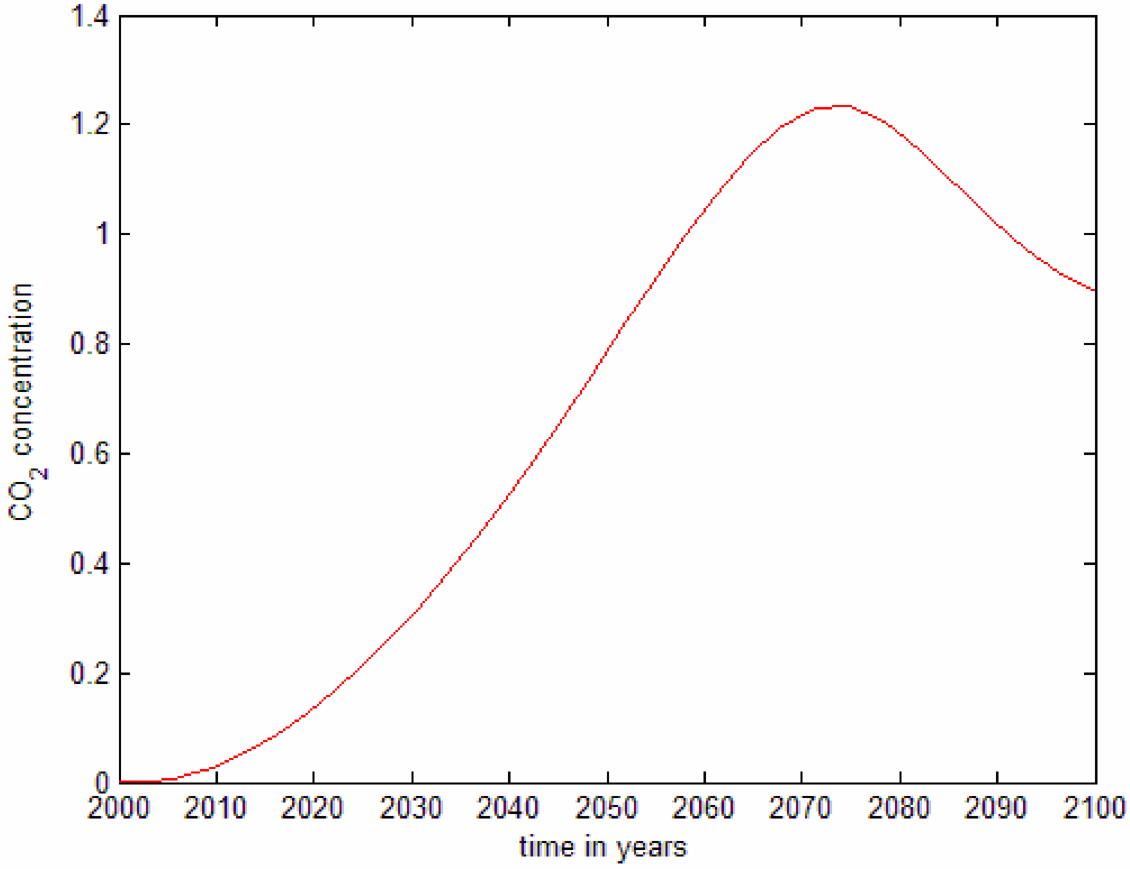
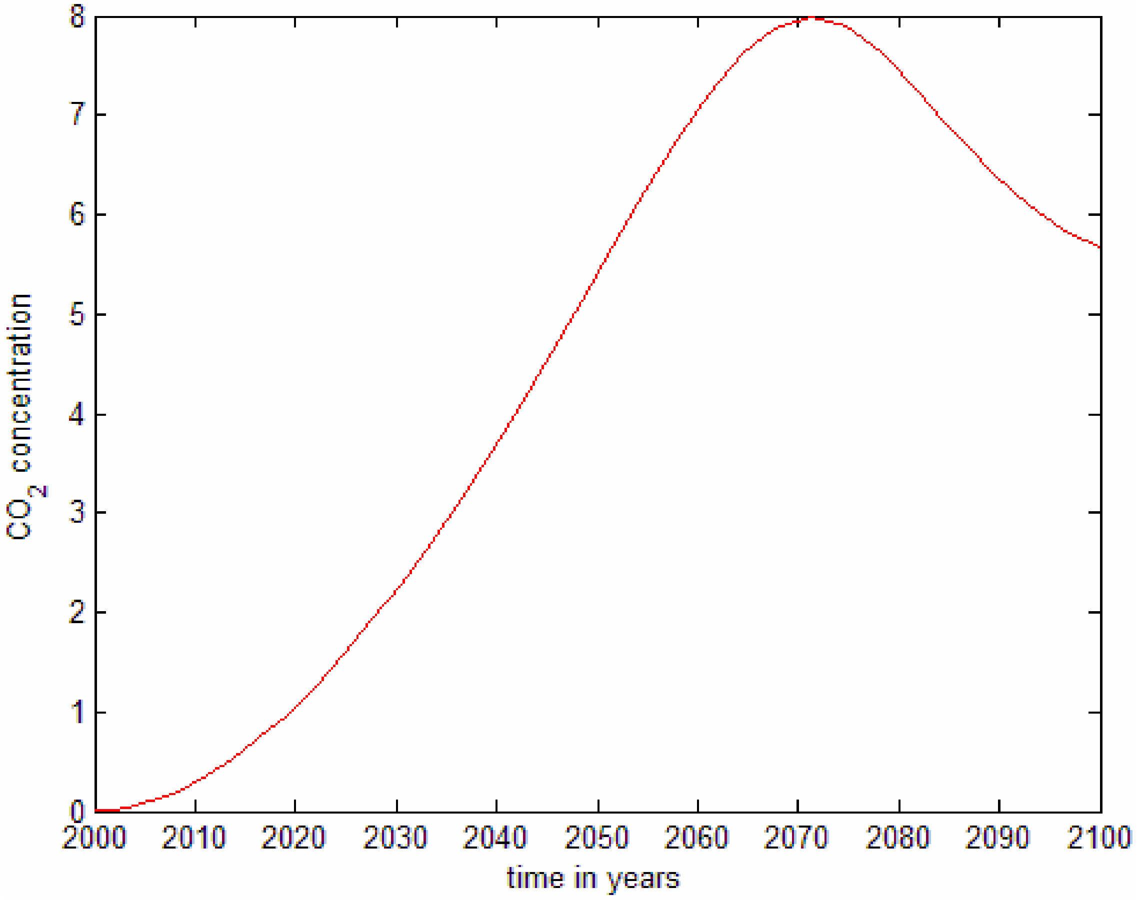


Figure 3.4.6 - CO_2 Concentration in Lower Atmosphere



As we can see, this scenario has a much more interesting result. Based on this, if we start to reach a cap on our CO_2 output, the atmosphere will be able to recover to a certain degree on its own. However, it appears the final amount would still be greater than the initial amount.

We can see that based on what our CO_2 output is in the future, we can have some drastically different results. However, in both cases it appears there will still be an increase in concentration. This implies that if we want to decrease concentrations then we will need to work to actually decrease the total CO_2 output. By what means this can occur is discussed later in this report.

3.5 Solar Flux Variability

The Sun plays an uncertain role in the variation of earth's climate. Like many topics in climate variation, there are a wide range of opinions. However, there are typically two camps involved in the issue. Either the Sun is responsible in a dominant way for climate variation or it is of little or no consequence whatsoever (Rind). As is often the case, reality probably lies somewhere in the middle. The Earth's atmosphere, surface, and oceans form a complex system of nonlinear feedbacks, and thus it is very difficult to determine the Sun's exact role in climate variation.

Humans have already seen evidence of solar variation. For example, in 1859 a solar eruption induced ground currents that destroyed US telegraph wires, and another in 1989 when a solar eruption again induced ground currents causing a blackout in the Northeast and disrupting spacecraft orbits and operations. The Sun's approximate radiative output is 1365 W/m^2, which delivers an average of 341 W/m^2 to Earth. Of this net radiation that reaches Earth, about 31% is reflected while the remaining radiation is absorbed. Greenhouse gases trap additional energy making the global average surface temperature 288 K. (Lean)

Photon energy at wavelengths shorter than 300 nm constitutes only about 1.5% of the Sun's total radiative output, yet that energy is the primary source of heating for the entire terrestrial atmosphere at altitudes above 10 km. Photons with wavelengths between 170 and 300 nm are emitted from the Sun's photosphere (high altitude) and absorbed in Earth's stratosphere and mesosphere (high altitude). Likewise emissions from the Sun's corona are absorbed by lower altitude areas such as the thermosphere. The author also notes the process by which ozone is created. Molecular oxygen absorbs photons with energies greater than 5 eV, causing the molecules to dissociate. The individual atoms then form ozone at altitudes between 15 and 50 km. Ozone absorbs wavelengths between 200 to 300 nm heating the atmosphere and driving dynamical processes that couple the middle and lower atmosphere (Lean).

A wind mainly of protons emanates from the Sun with a velocity of about 450 km/s. These winds exit large dark “holes” in the Sun’s corona, and are eventually deflected by Earth’s magnetic field. The magnetosphere receives hundreds of billions of watts daily, even though the solar wind typically transports less than one-millionth of the Sun’s electromagnetic energy. Solar and magnetospheric particles can transfer energy to gases in Earth’s atmosphere via collisions, mostly in the 100 - 400 km area. Energetic particles can penetrate Earth’s lower atmosphere where they can deplete ozone and produce various isotopes, or they can produce ^{14}C and ^{10}Be isotopes if they reach Earth’s surface (Lean).

Fluctuations in the Sun’s energy output are nearly periodic, occurring about every 11 years. These fluctuations are driven by a dynamo near the bottom of the outer one-third of the Sun’s interior. The rate at which these gases rotate varies with latitude and radius, and this differential rotation causes strong magnetic fields. Turbulent convection and meridional flow combine to move the active-field region pole ward, which leads to a reversal of the polar fields. Magnetic flux is not evenly distributed over the Sun’s surface. Therefore, where it is concentrated it modifies the local temperature and density, causing changes in the Sun’s radiative output. Increases of 0.1% in total brightness have been recorded during activity maxima, the result of a 1 W/m^2 reduction by dark spots and a 2 W/m^2 increase due to faculae (Lean).

Terrestrial responses to these increases are greatest at high altitudes. The temperature near Earth's surface increases by less than .1 K in response to a 1 W/m^2 increase in total solar brightness. An order-of-magnitude increase in UV radiation will cause a 1 K change at 50 km. Near 500 km, the temperature changes 500 K in response to fluctuations of a factor of two or more in EUV and x-ray radiation (Lean).

However, there are many difficulties in determining the Sun's exact role in climate variation. Natural modes of climate variability are important to consider, since their effects must be "filtered out" of the overall climate data to narrow in on the forcings from the sun. Over the Atlantic in winter, the average sea level pressure near 25^o to 45^o N is higher than around 50^o to 70^o N. If this pressure gradient is enhanced, stronger than average westerly winds can occur across the Atlantic, cold winters occur over the northwest Atlantic, warmer winters in Europe, Siberia, and East Asia, and so on. This pattern is referred to as the North Atlantic Oscillation (NAO). Some authors treat the NAO as part of a larger pattern between the North Polar Region and the mid-latitudes in both the Atlantic and Pacific, called the Artic Oscillation (AO) (Haigh).

Observational records of pressure, temperature and precipitation have shown large inter-annual variability in the NAO index. However over the past two decades the NAO has been strongly biased toward a positive, westerly phase. Some suggest this might be a response to global warming. Some GCMs corroborate this increasing index, but some others do not, suggesting the NAO pattern may not be accurately described by the use of simple indices (Haigh).

There are also uncertainties with coupling sea surface temperatures and the state of the middle atmosphere. Planetary scale waves produced in the lower atmosphere by longitudinal variations in topography propagate upward in winter high latitudes through the stratosphere and transfer momentum and heat, which feed the general atmospheric circulation. The location of where this wave absorption takes place depends on the ambient temperature and wind structure; any changes induced in the mean temperature structure of the stratosphere may result in a feedback effect on lower atmosphere climate (Haigh).

A further example of uncertainty of solar forcing is the so called "faint sun paradox". The Sun is believed to have been 25 to 30% less luminous 4.5 billion years ago, which should have produced a completely ice covered Earth for about 2 billion years. Yet free flowing water and the beginnings of life were apparent 3.5 or more billion years ago. It is presumed that greenhouse gases were present to offset the solar deficit. However the Sun's UV radiation would destroy reducing gases such as CH_4 or NH_3 in short order. In this case what would have been expected from solar forcings alone was not reflected in the climate, due possibly to multiple feedbacks (Rind).

Solar irradiance has been monitored for the past two decades, and shows peak-to-peak changes on the order of 0.1%. A total irradiance change of such magnitude used to force GCMs produces a global average climate change of about 0.5 °C. This suggests a climate dominated by solar variations in pre-industrial times. However, observations indicate the climate system has been much more variable than implied by the global mean temperature. There is little consistency in the growth of mountain glaciers during the "little ice age" with ice advances at different times that do not necessarily coincide with the reconstructed solar irradiance reductions. Natural variations or other forcings can override the climate's response to solar forcing. In addition solar forcing will have less short term effect on oceans as compared to land, which can lead to wind changes. Thus some regions warm even when the globe as a whole cools (Rind).

Geological records, such as ^{14}C and ^{10}Be levels, provide information concerning Sun variability. Reconstructions of climate forcings and surface temperatures in the past millennium suggest that solar and volcanic activity were responsible for temperature changes of a few tenths of a Kelvin and account for significant pre-industrial global surface temperature variance. The author cites the "little ice age" as the most recent example. During this period temperatures were 0.3 - 1 K cooler than at present. This cooling coincided with low solar activity. However, there are uncertainties that cloud the influence of the sun during the Little Ice Age. The actual reduction of total solar output is unknown; it was perhaps as small as .05%. Also the large modulation of ^{10}Be levels do not agree with solar activity changes during this period (Lean).

3.6 Health Effects Related to Rising CO_2 Levels

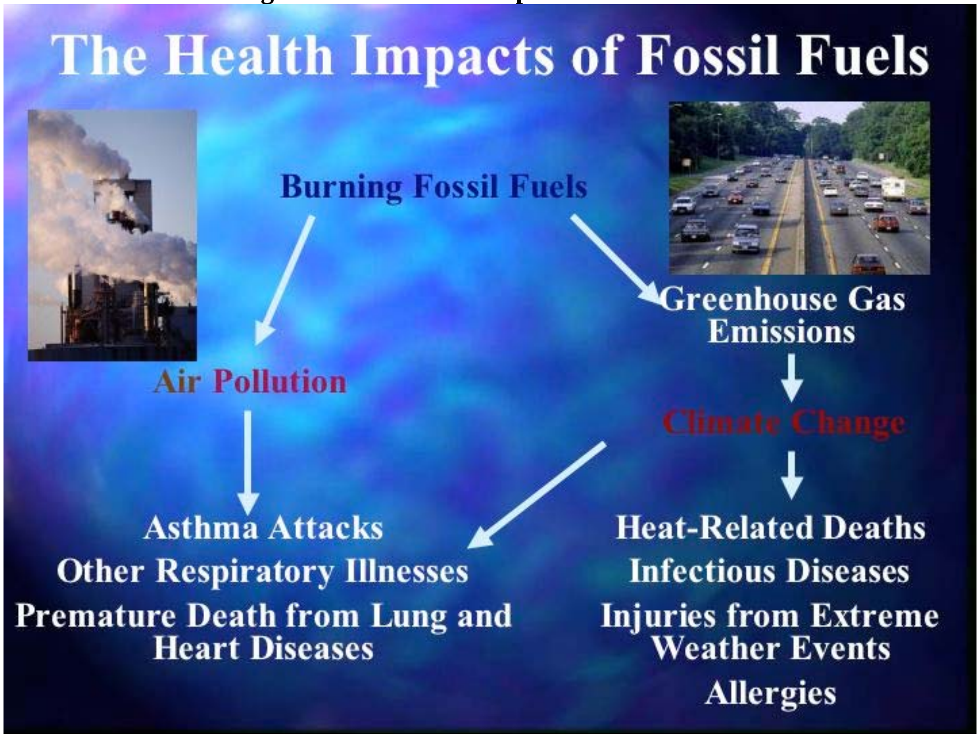
Today, the atmospheric concentrations of carbon dioxide are now 379ppm, though the earth hasn't seen more than 280ppm for the past 400,000 years. These higher concentrations must have some adverse affect on humans whether it is directly or indirectly.

Studies have shown that CO_2 can have an indirect effect on humans by increasing levels of pollen. When weeds and other carbon dioxide breathing plants have been exposed to higher concentrations of CO_2 they respond by increased proliferation. With approximately 40 million Americans suffering from some form of allergies, this is one potentially unpleasant effect of global warming. Opportunistic weeds such as ragweed and many trees produce 40% to 61% more pollen when grown in conditions with twice the normal concentration of CO_2. Parts of Europe, after much monitoring, have already shown an increase in pollen in the open environment. Global warming brings also the threat of droughts. With these comes the possibility that weeds, like the ragweed, will be able to take over areas normally inhabited by grass and other vegetation that produces less pollen.

Today, an estimated cost of $3.2 billion a year is paid out for asthma treatment of people younger than 18 years old. From 1980 to 1994, the incidence of asthma in adults has increased 75%. However, sadly, the largest increase has been among children at the preschool age. Asthma for this age has increased 160%. This could result from the fact that developing organs such as the lungs are more susceptible to pollutants. Below, in

Figure 3.6.1, is a visualization of how fossil fuels create deadly cycle to impact human health.

Figure 3.6.1 – Health Impacts of Fossil Fuels



The Health Impacts of Fossil Fuels

Burning Fossil Fuels

Air Pollution

Greenhouse Gas Emissions

Climate Change

Asthma Attacks
Other Respiratory Illnesses
Premature Death from Lung and Heart Diseases

Heat-Related Deaths
Infectious Diseases
Injuries from Extreme Weather Events
Allergies

Plants are not the only organism that can thrive in a CO_2 rich environment. Molds also grow abundantly with the conditions common to global warming. “Long-term field experiments with elevated CO_2 show that some fungi in arbuscular mycorrhizal associations with trees have enhanced growth and sporulation” (Epstein and Rogers 9). This increase in mold will cause a higher dependence on indoor air circulation. Mold spores will be better transported by increased numbers of hurricanes and flooding incidents. Many families cannot afford air conditioning to prevent the mold spores from entering their homes. Therefore, the people most affected by higher mold levels will be those in the lower income echelon.

As fungal growth increases, insurance policy costs will increase. Also, getting home coverage will become more difficult, especially for lower income families. Already insurance does not usually cover water damage, and the brokerage firms will work fungal damage into that category.

In the twenty years spanning from 1979 to 1999, 8,015 people died in the United States from excessive heat exposure. That's a number larger than any combined death toll taken by hurricanes, tornadoes, floods, and earthquakes. If the climate change continues to progress as it has, it is expected that by 2050, this number will have doubled. When nighttime minimum temperatures fail to drop low enough, areas of high concrete concentration cannot cool properly. This causes intense heat indexes for places such as cities where buildings and streets absorb the visible light during the day and then give off heat during the night. Unfortunately, the city is also where a large number of elderly live without proper air conditioning (Epstein and Rogers).

Lastly, erratic snowstorms, ice storms, and extremely dense fog, all caused by the changing Gulf Stream pattern, will become a great threat to motorists and pedestrians alike. If the scenario becomes severe enough and the Gulf Stream is completely turned around, then North America will become more like a tundra. That itself is deadly to the majority of Americans. Asthma and pollen will no longer be an issue.

In addition to the adverse effects caused by global warming, CO_2 itself, in high enough concentrations, can cause damage to the human body. Data is compiled below to show the effects of various levels of CO_2 concentrations and the resulting physiological symptoms.

Table 3.6.1 – Physical Manifestations of Increased CO_2 Concentrations

Headaches	7.5% CO_2
Dizziness	7.5% CO_2
Restlessness	7.5% CO_2
Shortness of Breath	7.5% CO_2
Sweating	7.5% CO_2
Feeling of Discomfort	7.5% CO_2
Elevated Heart Rate	7.5% CO_2
Increased Blood Pressure	7.5% CO_2
Visual Distortion	7.5% CO_2
Nausea/Vomiting	10% CO_2
Impaired Hearing	10% CO_2
Unconscious	10% CO_2
Coma	30% CO_2
Convulsions	30% CO_2

Death from asphyxiation usually occurs around 30%, however, there have been several deaths reported to have occurred at concentrations in the range of 20%. Asphyxiation causes the body cells to not get the oxygen they need to live (Indoor Air Quality). Another source says that CO_2 levels ranging from as low as 2% to 8% can cause "nausea, dizziness, headache, mental confusion, increased blood pressure and [increased] respiratory rate" (Material Safety). Although it is highly unlikely that the atmosphere will ever reach levels of CO_2 high enough to cause sever damage in a short time period to the human body, it is obvious that as levels increase the body cannot get as much oxygen as it normally would. For a healthy individual, exposure to 1.5% CO_2 concentrations will cause mild problems. At the current rate of CO_2 emissions, the atmosphere is only 100 years from that level.

Carbon dioxide content in fresh air is approximately 0.04%, and in exhaled air approximately 4.5%. However, that is a figure for fresh air. As cities and urban areas continue to grow, fresh air is becoming heavily polluted and highly concentrated in CO_2.

When inhaled in high concentrations (about 5% by volume), it is toxic to humans and other animals. This is sometimes known as choke damp, an old mining industry term, and was the cause of death at Lake Nyos in Cameroon, where an “upwelling of CO_2-laden lake water in 1986 covered a wide area in a blanket of gas, killing nearly 2000” (Carbon Dioxide from Wikipedia).

Hemoglobin, the main oxygen-carrying molecule in red blood cells, can carry both oxygen and carbon dioxide, although in quite different ways. As CO_2 levels increase within the blood stream, less oxygen can be carried. The decreased binding to oxygen in the blood due to increased carbon dioxide levels is known as the Haldane Effect, and is important in the transport of carbon dioxide from the tissues to the lungs. Conversely, a rise in the partial pressure of CO_2 or a lower pH will cause offloading of oxygen from hemoglobin. This is known as the Bohr Effect (Carbon Dioxide from Wikipedia).

CO_2 is carried throughout the blood in three different ways. Most of it (about 80%–90%) is converted to bicarbonate ions HCO_3^- by the enzyme carbonic anhydrase in the red blood cells. Of that, 5%–10% is dissolved in the plasma and 5%–10% is bound to hemoglobin as carbamino compounds. The exact percentages vary depending on whether is arterial or venous blood.

The CO_2 bound to hemoglobin does not bind to the same site as oxygen; rather it combines with the N-terminal groups on the four globin chains. However, because of allosteric effects on the hemoglobin molecule, the binding of CO_2 does decrease the amount of oxygen that is bound for a given partial pressure of oxygen (Carbon Dioxide from Wikipedia). People with ailments such as lung disease, asthma, and bronchitis will feel an increase in atmospheric CO_2 much more than a healthy individual (Indoor Air Quality).

3.7 Socioeconomic Implications

3.7.1 - Economic Implications

Global warming will cause major impacts on the human body, but those impacts will also cause a strain on the economy. As health problems increase due to global warming, more medications and professional health care services are needed. Pollen especially will cause an increase in healthcare expenses per capita.

Table 3.7.1 – Average Expenses for Respiratory Ailments

Condition status	Total all services	Hospital stays	Physician visits	Non-physician visits	ER visits	Prescriptions filled	Home health care services	Other	Total $ (in billions)
All respiratory conditions	3,753	1,679 (45)	658 (18)	255 (7)	102 (3)	653 (17)	292 (8)	115 (3)	45.5
Respiratory conditions only	843	#365 (43)	176 (21)	32 (4)	53 (6)	#198 (24)	2 (0)	#17 (2)	2
Respiratory and other chronic conditions	4,465	2,001 (45)	776 (17)	310 (7)	114 (3)	764 (17)	362 (8)	139 (3)	43.5
Asthma	2,973	1,207 (41)	597 (20)	228 (8)	96 (3)	586 (20)	173 (6)	85 (3%)	30.8
All Non-respiratory conditions	2,624	1,126 (43)	600 (23)	210 (8)	77 (3)	372 (14)	188 (7)	51 (2)	428.9
One Non-respiratory condition	1,321	741 (56)	278 (21)	83 (6)	61 (5)	114 (9)	29 (2)	15 (1%)	83.4
Two or more Non-respiratory conditions	3,443	1,368 (40)	801 (23)	290 (8)	87 (3)	535 (16)	289 (8)	73 (2)	345.6
No chronic conditions	365	137 (38)	113 (31)	34 (9)	33 (9)	26 (7)	#11 (3)	#9 (3)	34
Total	1,891	808 (43)	433 (23)	151 (8)	63 (3)	265 (14)	132 (7)	39 (2)	508.5

The above table shows the average expenses paid by individuals today on respiratory ailments. “The per capita increment in total expenditures attributable to respiratory conditions ranged from $1,003–2,588, from a national total ranging from $12.1–31.3 billion”(Blanc). “Overall, persons with respiratory conditions accounted for $45.5 billion in annual expenditures, representing the equivalent of ~0.6% of the Gross Domestic Product for the USA in 1996” (Blanc).

As temperatures increase, various sectors of society will be affected economically by global warming. The global temperature has increased approximately 0.83 degrees °C and, although this will decrease the amount of fuel needed during the winter, it will greatly increase the time period of air conditioning usage. Air conditioners function by extracting heat from a residence and pumping it into the atmosphere. This only creates a warmer atmosphere and therefore air conditioner usage increases. Following is a representation of electricity usage for one year:

Figure 3.7.1 – Power Production for Various Fuels

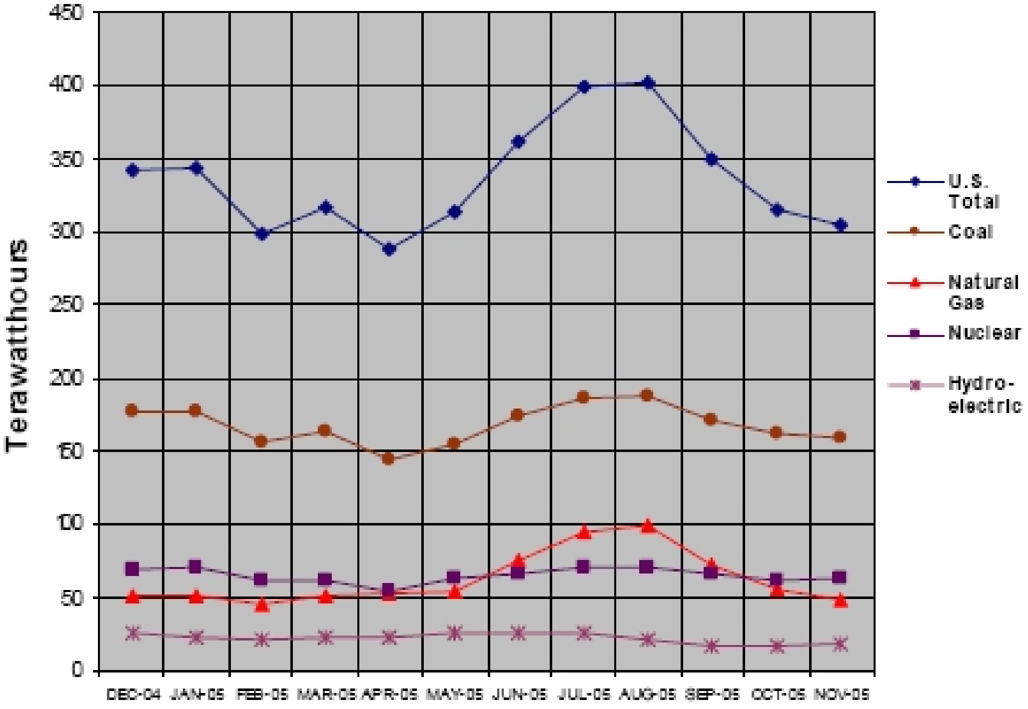


Figure 3.7.1 shows the usage of fuels for electricity in the 2005 fiscal year. A spike occurs during the months of June, July, August, and September, the four hottest months of the year. This is when electricity is most heavily used for air conditioning. “Year-to-date through October 2005, the average price paid for natural gas by electricity generators was $7.85 per MBtu, an increase of 34.4% from the same period in 2004”(Johnson).

Figure 3.7.2 – Increase in Electricity costs from 2004-2005

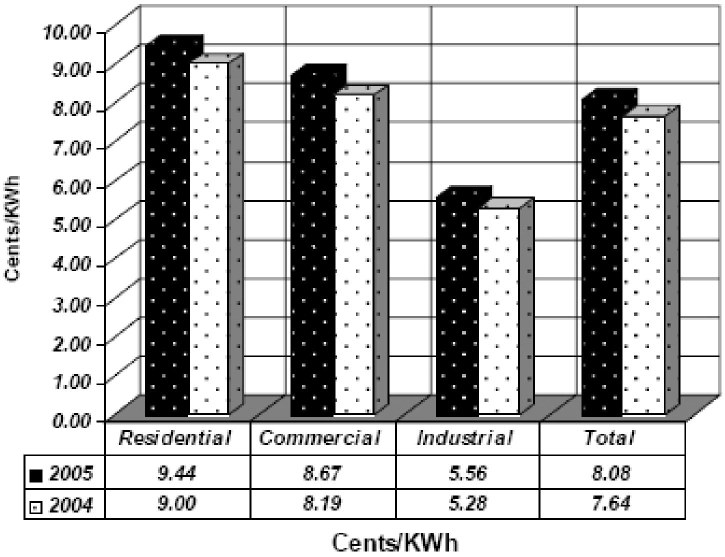
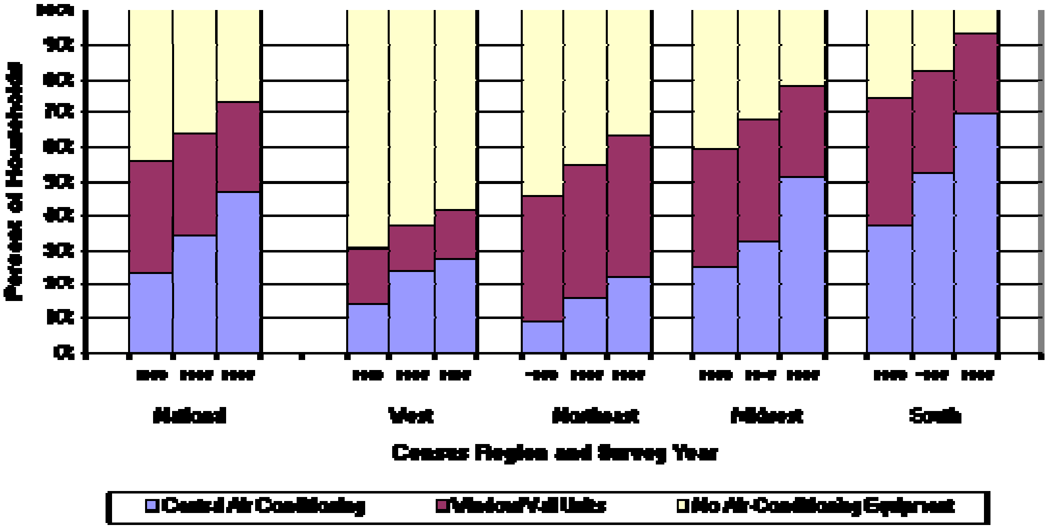


Figure 3.7.2 shows the increase in electricity cost between two years among the various sectors. Electricity can be a difficult thing to monitor in terms of global warming because so many factors affect it.

“During the first half of the century, the national average price of electricity decreased as more efficient generating units were brought into service. This general trend has continued. The average real price of electricity to all sectors in 1999 (that is, the price adjusted to reflect the purchasing power of the dollar) was 22 percent below the price in 1960. However, the apparent stability in electricity prices masked fluctuations that occurred throughout the period. For example, following the oil embargo in 1973 and 1974, electricity prices increased rapidly because of escalation in the costs of fuel, labor, materials, capital, and services to electric utilities"(Eynon).

It is difficult to use air conditioner usage to judge the influence of Global Warming on the economy. Air conditioning units have become more efficient and thus use less energy. Therefore, the increase in energy consumption is not directly proportional to the increase in air conditioner usage. Meanwhile, politics influence oil prices, resulting in further complexity. However, the increase in air conditioner use is adequate evidence that global warming is having a small effect on the world's economy.

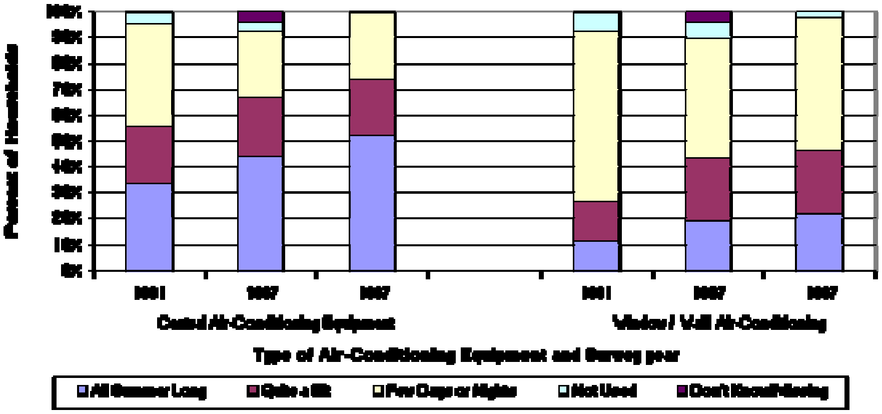
Figure 3.7.3 – Increase in Air Conditioning Use 1981-1997



Sources: Energy Information Administration; 1978, 1987, and 1997 Residential Energy Consumption Surveys.

Figures 3.7.3 and **3.7.4** verify the amount of air conditioning increase from 1981 to 1997. The most important detail to be noted is the increase in percentage of "all-summer" usage from households. Obviously populations increase, but with the percentage increasing, it says that the summers are becoming longer, hotter, and generally more difficult to deal with. (Battles)

Figure 3.7.4 – Central Air vs. Window Unit Air Conditioning 1981-1997



Sources: Energy Information Administration; 1981, 1987, and 1997 Residential Energy Consumption Surveys.

Electricity used by the residential sector increased from 2.47 quadrillion Btu in 1978 to 3.54 quadrillion Btu in 1997. This is not an accurate representation of air conditioning usage because of increased efficiency of the actual air conditioning units. **Table 3.7.2** represents the electricity use as compared to the average number of cooling degree-days (Battles).

Table 3.7.2 – Electricity Usage 1978-1997

Survey Year	Household Electricity Consumption for Air-Conditioning (Quadrillion Btu)	Number of Households with Central Air-Conditioning (million)	Number of Households with Room Air-Conditioning (million)	Average Number of Cooling Degree-Days	Average SEER of Central Air-Conditioning Units Sold During the Year
1978	0.31	17.6	25.1	1.109	7.34
1980	0.32	22.2	24.5	1.200	7.55
1981	0.33	22.4	26	1.108	7.78
1982	0.3	23.4	25.3	1.011	8.31
1984	0.32	25.7	25.8	1.101	8.66
1987	0.44	30.7	26.9	1.139	8.97
1990	0.48	36.6	27.1	1.124	9.31
1993	0.46	42.1	24.1	1.085	10.56
1997	0.42	47.8	25.8	1.056	10.66

Sources: Energy Information Administration, 1978-1982, 1984, 1987, 1990, 1993, and 1997 Residential Energy Consumption Surveys; National Oceanic and Atmospheric Administration; Air-Conditioning and Refrigeration Institute.

In 2004, Toronto experienced a massive heat wave. This is a result of global warming accumulating over the past twenty years, and it gives an excellent picture of how global warming could affect the world by causing heat waves.

"The Greater Toronto Area alone experienced a total of 57 smog days as of September 16, 2005 compared with 34 smog days for all of 2004, and higher electricity demand helped drive up the price of electricity by approximately 74% between May and August 2005. In August this year (2005), the average weighted price during peak hours was 12.60¢/kWh. However, during times of lower demand, the average weighted price was 7.31¢/kWh" (Evans). 0.126 CAD = 0.109190 USD, and 0.731 CAD = 0.633520 USD.

On a broader scale, Klaus Tòpfer of the United Nations Environment Programme, stated that "Losses due to more frequent tropical cyclones, loss of land as a result of rising sea levels and damage to fishing stocks, agriculture and water supplies, could annually cost around 304.2 billion dollars" (Impact of Climate Change). The water industry world-wide will be facing $47 billion of extra costs annually by 2050. Flood defense schemes to protect homes, factories and power stations from rising sea levels and storm surges may cost on average one billion dollars per year. It is estimated that in low lying countries like the Deltas of Bangladesh and in small island States, the cost could be significantly higher. Eco-system losses, including mangrove swamps, coral reefs and coastal lagoons, could run at over $70 billion by 2050. "Europe's biggest climate related losses will be in respect to higher levels of mortality and health costs. These may, annually, be running at $21.9 billion" (Impact of Climate Change). In the United States the extra costs of health related measures and more intensive water management may reach nearly $30 billion a year by 2050.

In May of 2005, the Environmental Resources Management of the UK government estimated that global warming would cost the UK at least 1.7 billion United States Dollars. Costs would include strengthening sea and river defense as well as improving housing to adapt to climate change.

If no political figure is willing to make change today for the benefit of mankind, eventually there will be many who are willing to change for the benefit of the all-mighty dollar. Hopefully, new technologies will be pursued before it comes down to simply a Price Tag.

3.7.2 - Social Implications

One of the consequences of global warming is sea level rise (SLR). Among all the effects of global warming, sea level rise will have the greatest impact on human life as we know it today. Economies have always flourished near the shore and, hence, eleven of the world's 15 largest cities lie on the coast or estuaries. In the United States alone, 53% of the population lives near the ocean (Gornitz).

Not only will the sea level itself rise, but also storm surges will become more rampant and destructive. In two model scenarios, it has been concluded that the sea level will increase anywhere in the range of 40 to 50 cm over the next 100 years. This will be a direct result of the same trends today that are raising the sea level. As the Earth gets warmer, the water expands and increases in volume. A second reason is that as temperatures rise in the polar caps the melting ice adds to the volume of ocean waters. A worrisome detail is the knowledge that the polar regions are warming at a rate 5 times faster than the Earth on average.

Approximately 400 million people live within 20 meters of the current sea level. This figure is difficult to back because data has not yet been developed to accurately say just how many people live within a certain elevation above the sea level (Gornitz). On a more practical scale for this discussion, it has been estimated that 8 to 10 million people live within 1 meter of high tide on the river deltas of Bangladesh, Egypt and Vietnam alone. Half a million people live in archipelagos and coral atoll nations that lie almost entirely within 3 meters of sea level, such as the Maldives, the Marshall Islands, Tuvalu, Kiribati and Tokelau (IPCC). An increase of 1 meter in sea level would practically eliminate these islands.

Figure 3.7.5 – World Population Distribution

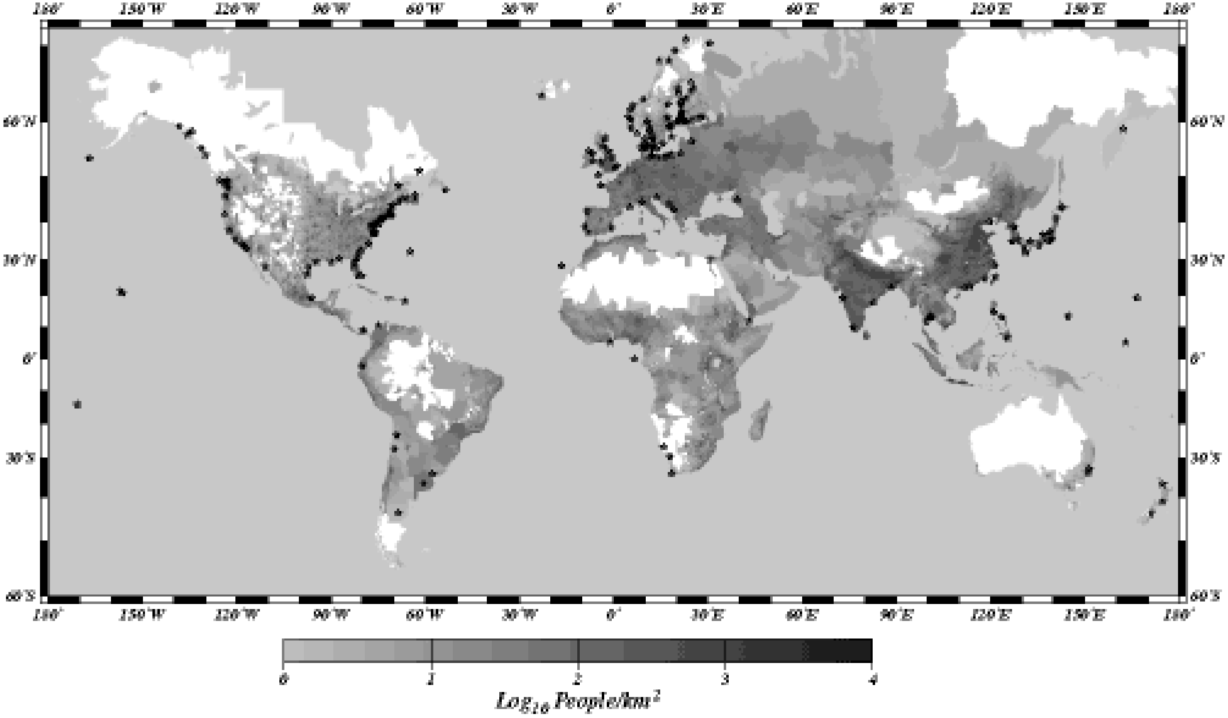
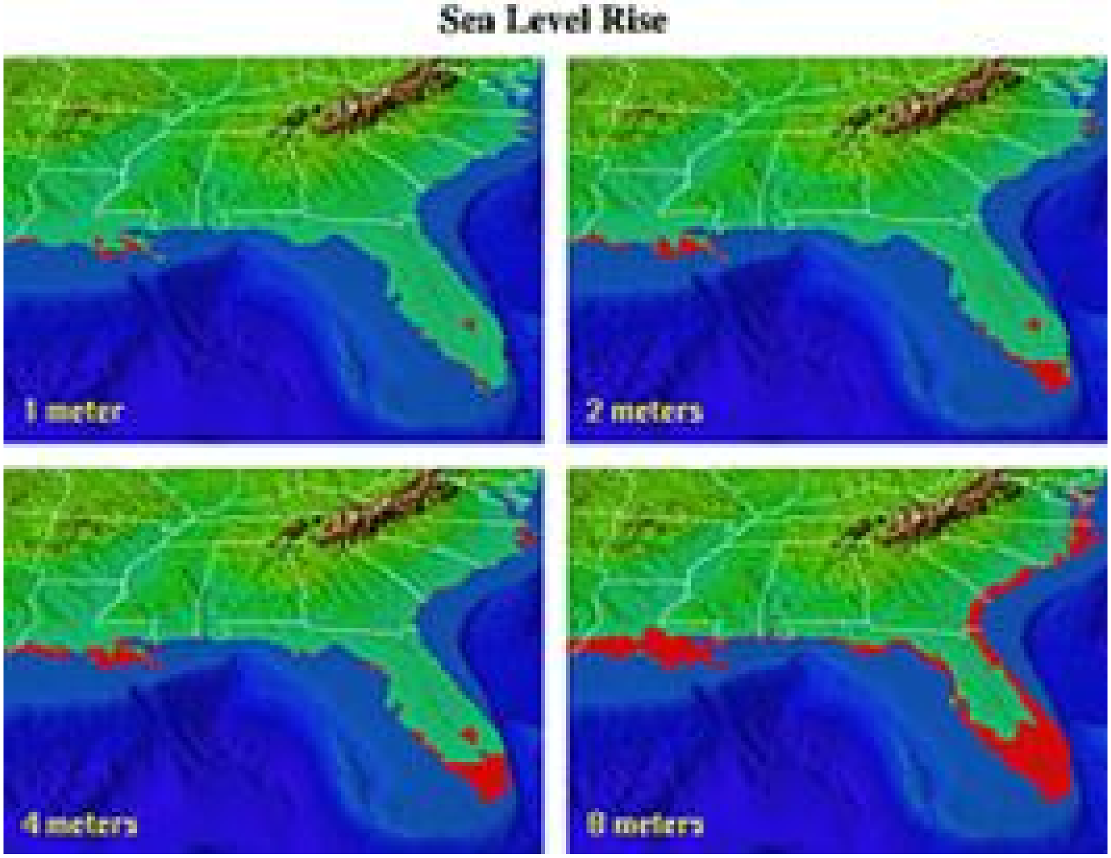


Figure 3.7.5 is a figure of approximate population density along the world's coastlines. High concentrations lie on the western and eastern sea boards of the United States and in the northern European regions.

Figure 3.7.6 – Sea Level Rise Effects on Southeastern US



Here is an extremely enlightening visualization of how sea level rise will affect low lying areas. The top left corner shows the south eastern United States with a 1m rise in sea level. The top right corner shows the same region with 2m of rise. The bottom left corner shows it with 4m and the bottom right corner shows it with 8m. Practically the entire eastern seaboard is submerged by 8m. However it is not expected for the sea to rise 8m, surges are the key concern. Hurricanes already take a huge toll on the south, with an added sea level rise, the results will be devastating (IPCC).

A country such as America will somehow manage with the increasing sea level by building levies and evacuating certain regions. However, small island nations such as the Maldives and the Pacific atolls lie within only a few meters of sea level (IPCC). These locations would not be able to front the finances to face such dangerous waters. This will lead to political strife and massive loss of life. Societies that already have existing social, economic and climatic stresses will be affected the most.

As water levels increase, response options fall broadly into three categories: retreat, accommodation, and protection. Retreat is simply that, no efforts would be made to fight the waters. Instead of fighting the water, humans would evacuate areas as they slowly become inhabitable. Accommodation involves dealing with an increased sea level. Putting buildings on piles, increasing the number of flood shelters, converting land use into ocean farming, and growing other plants that are flood and salt water resistant would be used as part of an accommodation plan. Protection would mean levies. New Orleans is a prime example of levies. However, New Orleans is also a prime example of what can go wrong and the magnitude of the devastation when things do go wrong. Protection would fortify the coastline to physically preserve the dry land as we know it today.

The cost of implementing such reinforcements on the coastline is enormous. For one meter of sea level rise, approximately 360,000 kilometers would be needed at a cost of 500 billion dollars spread out over the next one hundred years. This number can only go up as inflation drives prices higher. This number also does not include the cost of real estate that would be lost due to water rise.

As people try to relocate away from the coastal areas, social tensions will increase. Many large cities lie near the coast and with large cities comes a wide variety of ethnicities, religions and other differences cause for tensions to swell among the areas being settled. People moving away from the shore would be faced with difficulties and frustration in finding new places to live, many of them would not even be able to afford a move, leaving their destiny in the hands of fate.

3.7.3 - Politics of Global Warming

Global warming is just that, global. However, controlling it is in the hands of the powerful. The Kyoto Protocol focused on the powerful nations in attempts to control CO_2 emissions. Currently, the Bush administration has withdrawn America from the Kyoto Protocol. In just America, with the democratic government, an issue like global warming could possibly be the next major deciding factor in elections. Issues like abortion and gun control are key differences between Republic and Democratic political parties and global warming could be the next big difference. If one party supports scientific research and more control on emissions and the other does not, there could be a major shift in voter support.

If countries come together to unite against this major global problem, political differences and issues could be resolved on a “need-to-cooperate” basis. Fossil fuels will eventually become obsolete and the power that the Middle East now holds today will be taken away.

Currently, senators like McCain are taking action in Congress to fire more political awareness of global warming. So many Americans believe they can go about their business without feeling any repercussions and global warming will never affect them. Senator Frank Lautenberg said, “If we ignore 30 years of scientific data, we are putting ourselves in jeopardy.” Unfortunately, “It is politics - not science - that is prohibiting action on global warming, said Senator Frank Lautenberg, a New Jersey Democrat” (Pegg). McCain proposed a bill that would require CO_2 emissions to be capped at year 2000 levels. The bill was defeated in the Senate last October by a vote of 53 to 44, but “supporters of the legislation said the vote was a watershed moment in the U.S. debate over the issue of global warming.” (Pegg)

Other issues come up when politicians are believed to be advocating new technologies to combat global warming. President Bush provided extensive funding for research in physical sciences. At first glance one would think that President Bush was pushing for new technologies to fight global warming. However, his underlying motives are merely to compete with China as the new rising power. Oil will not last indefinitely and it will run out especially quickly while supporting two major powers. America needs to develop new technologies other than fossil fuels in order to maintain its stance as a major world power. This research for alternative energy sources is based entirely off the importance of political domination (Aldous).

3.8 New Fuel Reserves and Implications

3.8.1 - Mining Methane Hydrates

One possible solution to reducing emissions from the burning of fossil fuels is to use fuels that burn more cleanly than coal and oil. One such fuel is methane. Methane is more favorable than coal and oil because it has a higher ratio of hydrogen to carbon atoms than other fuels. Currently, methane is used in a number of applications such as home heating and appliances in the form of natural gas. Natural gas is comprised mostly of methane with small amounts of other gases such as propane and butane. However, the current supply of methane is limited (Arabe).

Scientists and engineers have been looking at large methane deposits that exist around the world in the form of methane hydrates on the ocean floor. The deposits around the world have been estimated to contain as much as 200 quadrillion ft^3 of methane, though these estimates vary by a couple orders of magnitude. This equates to enough methane to supply the US's current energy usage for 2,000 years. Even at the most conservative end, the amount of methane available in these deposits is ten times that of all current sources of natural gas. From these estimates we can see that this energy source is of enormous importance (Arabe).

Methane hydrates are simply a solid form of methane that can exist in high-pressure, low-temperature environments. It is similar to a sponge, except in this case the sponge material is actually water, and the methane is the material absorbed. Because it is solid, a small quantity of the hydrates contains a large volume of the methane gas. From 1 ft^3 of the hydrates, approximately 180 ft^3 of methane can be extracted. However, due to the nature of this material, there are a number of difficulties in the development of this as a viable energy source (Arabe).

These hydrates are often difficult to study. While the existence of these deposits has been known for a number of years, not until recently has it been possible to study them in detail. One reason is the deposits exist in the deep-ocean environment and also in regions of permafrost. The deep-ocean region provides very low temperatures and high pressures. To study the material, it is necessary to simulate these conditions, which requires specialized machinery. This material also requires sophisticated measuring equipment, such as computed tomography X-ray scanning and nuclear magnetic resonance imaging (Arabe).

Another issue lies in the large scale mining of this resource. The hydrates are located in areas that require specialized equipment and in environments that make the extraction process difficult. Along with the fact that the mining process is difficult, there are also the environmental risks involved. Methane is 100 times more effective as a greenhouse gas than CO_2. Should large quantities of methane be released, the effects would be widespread and possibly devastating. Also, in locations where deposits exist near various life-forms, an accident could be devastating to that local ecosystem (Arabe).

Though there are a number of difficulties involved with the use of methane hydrates, it is nonetheless a very promising energy source. First, if the US were to switch to the use of primarily methane in place of coal and oil, the CO_2 emission of the country would be significantly lower. Also, the US’s dependence on foreign fuel sources would be reduced, thus it would have a significant effect on the political landscape. This could also mean a reduction in oil prices as a result of increased competition. Then there is always the fact that, even with conservative estimates, this energy source is enormously vast, allowing for more time to develop better, renewable, and even cleaner energy sources (Arabe).

As it stands now, the use of this resource is still up in the air. Scientists and engineers are still developing ways to economically mine the methane hydrates as well as process them. They are also trying to determine the possible consequences should this resource be mined; both in normal operation and if some sort of accident were to occur. So as of now, don’t expect to see any methane hydrate at your local gas station in the near future, though it may be a possibility farther down the road (Arabe).

3.8.2 - Recovery of Bitumen from Tar Sand

Oil sand (tar sand) deposits are composed of sand, silt, clay, water and about 10%-12% bitumen. Bitumen is the technical term for the crude oil extracted from the sands; it is defined as viscous oil that will not flow to a well in its natural state. Therefore the sands are either heated so the bitumen can be pumped, or the sands are surface mined (also known as strip mining). The crude bitumen is then extracted from the sands by essentially mixing the material with hot water to wash the bitumen from the sand (Raynolds).

Often oil sands are deep enough where the only viable method to recover them is “in situ” recovery. The process is similar to conventional drilling for oil, but has several complications due to the thick nature of the bitumen. Usually high pressure steam is injected via a pipe extending down to the reserve in order to separate the bitumen from the sand. The heat from the steam also serves to reduce the viscosity of the bitumen so it can be pumped to the surface. This is the predominant method know as Steam Assisted Gravity Drainage (SAGD) (Raynolds).

After being separated from the sand, the bitumen must be “upgraded” before it can be refined into gasoline, diesel, and other hydrocarbon products. Upgrading converts the bitumen from a molasses-like product into lighter, higher quality synthetic crude oil that can then be sent to refineries. The process involves adding hydrogen to the bitumen.

One of the drawbacks of utilizing tar sands is the extra processing involved. It is, in fact, an energy intensive endeavor. Natural gas is used to generate the heat and steam necessary in the SAGD extraction process and it is also used as a source of hydrogen in the upgrading process. It takes about 750 ft^3 of natural gas to process one barrel of bitumen start to finish via surface mining, and about 1500 ft^3 per barrel if the reserve is SAGD mined. Some argue this is unacceptable, since a clean energy source (natural gas) is being used to produce a non-clean energy source (gasoline, diesel, etc.) (Raynolds).

Most of the world's oil (more than 5 trillion barrels) is in the form of tar sands, although it is not all recoverable. While tar sands are found in many places worldwide, the largest deposits in the world are found in Canada (Alberta) and Venezuela, each of which have about one-third of the world's total tar sands resources, and much of the rest is found in various countries in the Middle East. In the United States, tar sands resources are primarily concentrated in Eastern Utah, mostly on public lands. The in-place tar sands oil resources in Utah are estimated at 12 to 20 billion barrels (Tar Sands).

3.8.3 – Clean Coal

Clean coal technology will hopefully be a fast growing field of research and development. Although it is not a renewable energy source, it will last much longer than oil reserves and promises many advantages. Currently it is one of the dirtiest sources of energy used. It produces approximately 9 billion tones of carbon dioxide each year, of which most is from power generation.

Currently there are systems called Integrated Gasification Combined Cycle (IGCC) and "the [power plants] use coal and steam to produce hydrogen and carbon monoxide which are then burned in a gas turbine with a secondary steam turbine to produce electricity" ("Clean Coal" Technologies). If oxygen instead of air is used to feed the combustion, then the carbon dioxide concentrations are much higher and can be easily captured. Today there are ten oxygen-fired gasifiers in use in the United States. A shift reactor oxidizes the CO with water to form steam that is basically hydrogen gas and carbon dioxide. These are separated and the hydrogen gas then acts as the fuel for the electricity generation. These IGCC plants have a thermal efficiency of 45% (thermal efficiency is the ratio of work being produced to the energy being put it).

The gasification process involves a couple reactions between hydrogen, oxygen, and coal. The first step is to put the coal through pyrolysis with temperatures above 400 degrees Celsius. This leaves char and a hydrogen-rich volatile. The char is then gasified above 700 degrees Celsius. This gives a gas and ash. All these take place in an oxygen deprived environment. Pure hydrogen gas gives 121 MJ/kg, a value five times that of straight coal. The water-shift reaction is not in use, but eventually it will be. Carbon and oxygen combine to form CO, and carbon and water (H_2O) combine to give CO and hydrogen gas. Finally the CO and H_2O react to form CO_2 and hydrogen gas (this last step in the water-step reaction). After this, CO_2 is highly concentrated and easily collected ("Clean Coal" Technologies).

There is also research going into geosequestration, or the storage of carbon dioxide deep underground. Norway's Sleipner gas field in the North Sea is capable of long-term safe storage of about 600 billion tones of CO_2. The gas is injected about one kilometer below the sea bed into the rock and remains there. In these deep saline aquifers, the CO_2 is expected to remain for thousands of years with only a little of it dissolving. Since one of the problems with geosequestration is collecting the CO_2, this clean coal technology can and will provide an efficient way of getting high concentrations of CO_2 for storage.

3.9 Possible Solutions to Global Warming

So far, global warming has been broken down into its various components, discussed in detail, and the various scenarios it will cause within society. An understanding of global warming is about as far as scientists have gotten on the subject. International acts, like the Kyoto Protocol, are attempting to control CO_2 emissions, but nothing is being done to reverse some of the damage already done. Getting international cooperation has proven difficult, seeing as America has already been removed from the Kyoto Protocol by the Bush Administration. Many sources provide creative and intuitive ways to remove CO_2 from the atmosphere, but unfortunately it will take a major natural disaster before society will fully accept and act on these methods to save the atmosphere.

For the past 400,000 years the concentration of CO_2 in the atmosphere has not exceeded 280 parts per million (ppm). However, in the past 100 years, it has increased to 380 ppm, a number of unprecedented records. In 2001, the White House held a round-table discussion on the subject of global warming. President Bush had pulled the United States out of the Kyoto Protocol (designed to limit CO_2 emissions) and instead wanted to pursue other options to mitigate global warming. The discussion was dubbed, “Response Options to Rapid or Severe Climate Change.” This discussion presented six main ideas regarding global warming and how to deal with it. Michael Behar published an article evaluating these six ideas on global warming mitigation. He assigned a rating system for these various solutions including feasibility, cost, and risk. He used feasibility (1 to 10), cost ($ to $$$$) and risk (1 to 10) factors in discussing the solutions.

3.9.1 – Geosequestration

The first option to control CO_2 levels is already underway. It is geosequestration, or storing CO_2 underground. It has a feasibility of 10, a cost of $$ and a risk of 4. All these factors are in favor of this method. Its feasibility and cost are both good and the risk is not very high relatively speaking.

Geosequestration is a form of carbon sequestration in which the carbon dioxide is stored in cavities underground, as opposed to being dissolved in the deep-ocean waters. The Weyburn Project, located in the Saskatchewan province in Canada, has been on going for 6 years and has already stored six million tons of CO_2. It has done this with thirteen million dollars in funding (Behar). Australia is increasingly investigating geosequestration since rock is a vast resource on the continent. Scientists in Australia are calling possible sites ESSCI, or "Environmentally Sustainable Site for CO_2 Injection." There is much controversy because many of these sites fall in nature reserves and if something went wrong the results would be devastating. Research is underway in rural areas that would not affect either nature or man (Quinion).

One of the pitfalls of this solution is that CO_2 is not readily available in concentrated form. It is free floating throughout the atmosphere and would need to be captured before it could be pumped underground. Also, as of yet, there are no laws requiring CO_2 capture from power plants; the most prevalent source of CO_2. In addition to these problems, with CO_2 being stored underground it is always a possibility that, while drilling for oil or natural gas, a reservoir of CO_2 could be punctured, resulting in the depressurization of the reservoir. This and other natural leaks could result in poisoning of residential basements. CO_2 is extremely dangerous if encountered in high concentrations; it is an odorless gas and therefore difficult to detect.

The Weyburn Project alone is supposed to store 25 million tons of CO_2 by 2033, an equivalent of 6.8 million cars being on the roadway for one year. With humans producing 28 gigatons of CO_2 each year, a vast storage reservoir is vital. It has been estimated that the underground reservoirs currently available could hold as much as 200,000 gigatons of CO_2.

Another related form of sequestration is to increase the ability of soil to hold carbon dioxide. Studies have been performed on this field of soil sequestration. Dirt is one of the larger CO_2 sinks and it is possible to increase its ability to absorb CO_2 from the atmosphere through crop management. This would only take hold in places where farm lands are prevalent; however, farm lands do cover a large amount of the terrestrial soil. As populations grow, they require more and more cultivated food substances. Farm lands are necessary to keep the populations healthy and thriving. Tilling the soil decreases the soil's ability to hold organic carbon matter and, also, different crops deplete different nutrients. One study shows that on average, "a change from conventional tillage (CT) to no-till (NT) can sequester 57 ± 14 g C m^{-2} yr^{-1}" (Post). Crop rotation can also change how the soil takes in and holds carbon. Some plants deplete CO_2 from the soil, while others contribute to storing CO_2 within the ground. By alternating crops it is possible to "sequester an average [of] 14 ± 11 g C m^{-2} yr^{-1}" (Post). As promising as these findings are, they would be extremely difficult to implement. The majority of farmers do not have a higher education; it would be difficult for them to understand the reasons behind a new farming technique.

3.9.2 - Scrubbers

The second option was to filter the CO_2 from the air. It was tagged with a feasibility of 4, a cost of $$$, and a risk factor of 4. These are not the best numbers in this rating system for reason that will follow. It was proposed that giant filters will act like flypaper, catching the CO_2 molecules from the air as they drift past. NaOH or $Ca(OH)_2$, both chemicals that bind with CO_2, are purposed to be pumped through the filtering screen where they bind with the CO_2 then carry it to a secondary chemical reaction to the two reactants to their original states. The CO_2 would then be stored and the binding agent would be pumped back through the filter to capture more CO_2. A scrubber 200 feet high and 165 feet wide would collect about 90,000 tons of CO_2 per year. It has been estimated that a complete system of these filter scrubbers is at least two years away.

There are problems with these scrubbers. First, CO_2 is not highly concentrated in the atmosphere and to scrub it would require high amounts of energy, defeating the purpose of the scrubber. Second, in order to make an impact on the CO_2 concentrations in the atmosphere, an area the size of Arizona would need to be covered with scrubber towers.

3.9.3 – Ocean Fertilization

The third option is to fertilize the ocean. It would be quite feasible and very cost effective; however, it has a risk factor of 10. John Martin, an oceanographer, had a hunch that the ocean was anemic, in other words, it was iron deficient. Regions high in nutrients and minerals were empty of life forms. Blooms of plankton occurred when a small area was tested with powdered iron. Plankton consume CO_2 and increasing their numbers would throw off the homeostasis status of the carbon cycle. The ocean would represent an imbalanced carbon give and take ratio. More carbon would be entering the ocean that would be exiting.

This process looks extremely promising. However, the ripple effect of this alteration in the food chain could be devastating. If plankton populations boom then the essential nutrients and minerals needed by fish populations would be rapidly depleted. According to one scientist, "A fertilization event to take care of atmospheric CO_2 could have the unintended consequence of turning the oceans sterile. Oops." (Behar)

3.9.4 – Turn CO_2 to Stone

The next solution method is to turn CO_2 to stone. It has a feasibility of 7, a moderate cost and a low risk. All three of these rankings give it a good standing among the other methods. An example of CO_2 being turned to stone naturally is the Grand Canyon. However, this took millions of years. Researchers at the Arizona State University are working on a way to speed up this process. Serpentine and olivine are used as a feedstock to turn the CO_2 into magnesium carbonate. Sodium bicarbonate is used as a catalyst to initiate the reactions, which take place under high pressure and high heat. The draw backs to this solution are cost and energy efficiency. It costs roughly seventy dollars to turn one ton of CO_2 into stone and then consumes more fossil fuels to initiate the reactions.

3.9.5 – Alter Earth's Albedo

The next solution, although not highly impressive or realistic, is using artificial clouds to alter the earth's albedo. It is thought that if cloud cover is increased it will decrease the amount incoming solar energy, or at least filter it a little. The marine stratocumulus clouds around the tropics would be increased their already 1/3 coverage of the oceans. The clouds would be formed by drifting wind propelled boats that seed clouds with salt water droplets. They have smokestack-like appearance and within the stacks would be Flettner rotors. It is estimated that the ocean would need between 5,000 and 30,000 of these cloud forming boats in order to do anything of significance. The down side of these cloud forming boats is that they could make rain harder to form. If an area was having a drought, such a climate alteration would be detrimental. On a slightly more critical note, adding more H_2O to the atmosphere seems to be adding to a more serious problem. CO_2 is problematic, but H_2O in the atmosphere has been the key greenhouse gas and adding to the H_2O levels could only make it worse, not better (Behar).

3.9.6 – Space Based Mirrors

Finally, it has been proposed that humans send giant mirrors to outer space in order to deflect a portion of the incoming solar energy. This is the least likely solution to global warming, but has been suggested, and should only be looked at as a last resort. It has the lowest feasibility and by far the highest cost of any other proposed solution. The mirrors would be placed in orbit as satellites and would only appear as tiny sun spot on Earth, but could significantly reduce the amount of incoming energy. The mirrors would need to cover a span of 600,000 square miles, an astronomical number to be taken as a whole mirror to space and would therefore have to be taken in pieces, an extremely costly procedure. This proposed solution is ultimately outlandish and considered no more than a creative thought process.

3.9.7 – Reduce CO_2 Emissions

Aside from these drastic CO_2 eliminating procedures, there is a simpler method to combat global warming. Vehicles account for 20 percent of America's CO_2 output. Increasing vehicle efficiency is an easy way to reduce CO_2 emissions. Ultimately an alternative energy source would be the best vehicle solution, however, that will take many years of research and development before that is a reality. The next relatively feasible solution is to conserve our rain forests. They represent one of the largest CO_2 sinks, and they are rapidly being depleted for farm lands and grazing lands. Above all, the most common sense solution is to find renewable energy sources. Another proposed solution is to tax carbon dioxide emissions (Massey).

A group of scientists have developed a Clean Energy Transition plan. It is a proposed way of cutting back on emissions and also aiding third-world nations, by stimulating a world energy modernization movement. It would provide economic advantages to industrial world leading nations and also give third world nations a platform from which to build a stable economy. It is composed of five major parts. The first part states that all subsidies for fossil fuels will be eliminated and equivalent subsidies will be provided to train displaced workers in the fields of renewable energy sources and deploy worldwide energy efficient technologies. The second part requires an international acceptance of stringent fossil fuel regulations. The third aspect eliminates any monopolies currently held by low efficiency fossil fuel consuming energy production and stimulates competition for more efficient energy sources. In other words, it would require the de-privatization of power companies. This will allow for free competition and a faster transition to more efficient energy means (Detwyler). The fourth part would place a tax on an item like international currency transactions to help fund third world countries so as they might transition to a high-efficiency, lower-carbon energy system. Finally, the fifth part calls for the creation of an agency under the Kyoto Protocol to aid in the transfer of old technology to newer more efficient tools throughout the world (Epstein).

4 Conclusions

This project has brought to the group members' attentions just how pertinent global warming is. The research and computer modeling done over the course of this project have enlightened the members on topics ranging from heat fluxes to ways of reducing emissions. Global warming is a current issue and despite what many skeptics say, it will continue to be an eminent danger to life as man knows it. Society will undoubtedly be affected by global warming, in one way or another. Either society will feel the effects of a changed lifestyle in mitigating carbon dioxide emissions, or it will feel the direct negative effects of global warming. If nothing is done to halt or reverse global warming then temperatures will increase, sea levels will rise, medical expenditures will climb, and pollution will run rampant. Our basic computer model, which utilizes ordinary differential equations to represent the increase in carbon dioxide concentration throughout the seven reservoirs, shows a definite rise in CO_2 concentrations under different future scenarios. The atmosphere maintains a delicate balance between two extremes. One extreme is a warm tropical environment, much like the one today, and the other is an ice-age. There is a fine line between these two extremes. The point of most concern from this project is determining how far the current situation is from the next ice-age.

5 Recommendations for Future IQP's

As this project came to its conclusion, our project group thought about different things that future projects on this subject might want to cover or investigate. This section presents those recommendations.

5.1 – More Extensive Computer Modeling

One of the areas that we covered in our project was the use of computer models in predicting various phenomena related to global warming. In particular we used a basic zero dimensional, seven reservoir differential model to predict CO^2 levels in the atmosphere. Future projects could expand upon our work by looking into models that focus on other related phenomenon. These models could be temperature models based on latitude or CO^2 levels based on parameters other than just time. Another avenue future projects could focus on is a more advanced CO^2 concentration model. Instead of having a simple zero dimensional model as part of the report, the primary focus of the project could be a more complex model. For instance a one dimensional model that takes into account time and latitude. Future projects could even go so far as to work at developing a three dimensional model for their entire project. This would be the entire project essentially due to the complexities of developing such a model.

5.2 – Hands on Experimentation

One of the things that our project group did not get a chance to do is any hands on work. The work we did was all research oriented. Future IQP groups could expand upon this topic by performing various data gathering. One such example would be to measure CO^2 levels in the Worcester area over the duration of their project to observe the seasonal fluctuation of carbon dioxide levels. Another example would be to measure solar flux over the duration of their project to observe variations in solar flux at ground level. This data could then be used to support arguments about the importance or non-importance of variations in these quantities. Performing these hands-on experiments could serve to increase the interactivity of this project. It would also make for a more interesting final report where the groups findings would be presented.

These two areas are the things that we feel future IQP groups should focus on or add into their project with the end result of creating a better final report.

6 Works Cited

Aldhous, Peter. "Insight: Has President Bush turned green?." New Scientist 2538 11 Feb. 2006: 12. 04 Apr. 2006. <http://www.newscientist.com/channel/earth/climate-change/mg18925384.200-insight-has-president-bush-turned-green.html>

Appel, Arianne. "Global Warming Supercharged by Water Vapor?" NationalGeographic.com November 2005. <http://news.nationalgeographic.com/news/2005/11/1110_051110_warming.htm>

Arabe, Katrina C. "Mining the Ocean's Natural Gas" iGreenBuild.com. April 2005. <http://www.igreenbuild.com/cd_1424.aspx>

Battles, Stephanie J. Trends in Residential Air-Conditioning Usage from 1978 to 1997. 24 July 2000. Energy Information Administration. 02 Feb. 2006. <http://www.eia.doe.gov/emeu/consumptionbriefs/recs/actrends/recs_ac_trends.html>.

Behar, Michael. "Now You CO2, Now You Don't." Popular Science Aug. 2005: 53-58.

Blanc, P., M. Cisternas, M. Eisner, et al. A national study of medical care expenditures for respiratory conditions. 19 Sept. 2001. European Respiratory Journals. 12 Feb. 2006. <http://erj.ersjournals.com/cgi/content/full/19/3/414>.

Carbon Dioxide from Wikipedia, the free encyclopedia. 30 Mar. 2006. Wikipedia the Free Encyclopedia. 30 Mar. 2006. <http://en.wikipedia.org/wiki/Carbon_dioxide>.

Detwyler, Thomas. Some Solutions to Global Warming. 19 Feb. 2001. 01 Dec. 2005. <http://www.uwsp.edu/geo/courses/geog100/GlobWarm-Solns.htm>.

Epstein, Paul and Ross Gelbspan. The Heat is Online. n.d. 29 Nov. 2005. <http://www.heatisonline.org/contentserver/objecthandlers/index.cfm?id=3138&method=full#4>

Epstein, Paul R and Christine Rogers. ed. Inside the Greenhouse:The Impacts of CO2 and Climage Change. Boston: Harvard Medical School, 2004.

Evans, Ken and Ellen Leesti. Record Heat Waves Call for Immediate Action. 29 Sept. 2005. Power Wise. 13 Feb. 2005. <http://www.cannontech.com/news/powerWISEPressReleaseSept29.pdf>.

Eynon, Robert T. Electricity Prices. n.d. The Electricity Forum. 14 Feb. 2006. <http://www.electricityforum.com/electricity-prices.html>

Gornits, Vivien. “Coastal Populations, Topography, and Sea Level Rise.” March 2000. <http://www.giss.nasa.gov/research/briefs/gornitz_04/>

Haigh, Joanna D. “Climate Variability and the Influence of the Sun” Science V.294 (2001): 2109-2111

Hieb, Monte. “Water Vapor Rules the Greenhouse System” January 2003. <http://www.clearlight.com/~mhieb/WVFossils/greenhouse_data.html>

Houghton, J.T. "Global Warming: The complete briefing." Port Chester, NY: Cambridge University Press, 1997.

Humi, Mayer. Modeling Geophysical Flow

Impact Of Climate Change To Cost The World 300 Billion $US A Year. 03 Feb. 2001. United Nations Environment Programme. 12 Feb. 2006. <http://www.solcomhouse.com/Impact.htm>.

Indoor Air Quality Resource Center. n.d. AERIA. 09 Feb. 2006. <http://www.aerias.org/kview.asp?DocId=138&spaceid=2&subid=13>

IPCC, Response Strategies Working Group. “Strategies for Adaption to Sea Level Rise.” November 1990. <http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsSLRAdaption.html>

Johnson, Melvin. ed. Electric Power Monthly. Feb. 2006. Energy Information Administration. 15 Feb. 2006. <http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html>.

Lean, Judith. “Living with a Variable Sun” Physics Today June 2005: 32-38

Massey, Rachel. Global Warming Opportunity. 21 Dec. 2000. Environment Research Foundation. 01 Dec. 2005. <http://rachel.org/bulletin/bulletin.cfm?Issue_ID=1923>.

Material Safety Data Sheet: Gaseous CO2. Feb. 2006. Universal Industrial Gases, Inc. 07 Feb. 2006. <http://www.uigi.com/MSDS_gaseous_CO2.html>.

McElroy, Michael B. The Atmospheric environment: effects of human activity. Princeton: Princeton University Press, 2002.

McHugh, A.J. "Global CO2 Model (GCM)." Spring 1997. Lehigh University. <http://www.lehigh.edu/~wes1/co2/co2mod.pdf>

Oil Shale & Tar Sands Leasing Programmatic. 2006. <http://ostseis.anl.gov/guide/tarsands/index.cfm>

Pegg, J.R. “Senators Grapple with Politics of Global Warming.” Environment News Science. March 2004. <http://forests.org/articles/reader.asp?linkid=29956>

Post, Wilfred M and Tristram O. West. “Soil Organic Carbon Sequestration by Tillage and Crop Rotation: A Global Data Analysis.” Soil Science Society of America Journal 66. Sep. 2002: N. pag. U.S. Department of Energy’s Office of Science, Biological and Environmental Research Program. 02 Feb. 2006 <http://cdiac.ornl.gov/programs/CSEQ/terrestrial/westpost2002/westpost2002.html>.

Quinion, Michael. World Wide Words. 08 Mar. 2003. 01 Dec. 2005. <http://www.worldwidewords.org/turnsofphrase/tp-geo2.htm>.

Raynolds, Mario. Severson-Baker, Chris, Woynillowicz, Dan. “Oil Sands Fever: The Environmental Implications of Canada’s Oil Sands Rush.” November 2005.

Rind, D. “The Sun’s Role in Climate Variations” Science V.296 (2002): 673-677

7 Appendix A – Computer Model Data Files

Presented here are the .m files for the MATLab models discussed in Section IX.D of this report. The original model is presented first followed by the linear forcing function and then the logarithmic forcing function. Only the lines that are different are presented for the edited versions.

co2sys.m – Original Model

```
1 - %file co2sys.m

2 -

3 - function dx =co2sys(t,x)

4 - global Na0 Tam Tul Tdm betta Flb0 Fsb0 Fmb0 Cmt Corg ...

5 - eps P1 P2 P3 P4 P5 Ws Wm gam0 r

6 -

7 - Cua=x(1);

8 - Clb=x(2);

9 - Csb=x(3);

10 - Cla=x(4);

11 - Cml=x(5);

12 - Cmb=x(6);

13 - Cds=x(7);

14 -

15 - %Dlu=-Kul*Cua+Kul*(Nua/Nla)*Cla;

16 - Dlu=1/Tul*(P1/(1-P1)*Cla-Cua);

17 -
```

```
%Dlb=betta*(Flb0/Nla)*Cla;
Dlb=betta*(Flb0/Na0)*Cla;

%Dsb=-(Fsb0/Nsb)*Csb+(Fsb0/Nlb)*Clb+betta*(Fsb0/Nla)*CLa;
Dsb=1/Na0*Fsb0*(betta*Cla+Clb/P2-Csb/P3);

%Dml=-Kam*(Na0/Nla)*Cla +Kam*Na0/(Cmt*Wm)*eps*Cml;
Dml=1/Tam*((1+Corg/Cmt)/P4*eps*Cml-1/(1-P1)*Cla);

%Dmb=betta*(Fmb0/Na0)*(1+Cmb*Na0/Nmb)*Cml*Na0/Nml;
Dmb=Fmb0/Na0*(1+Cmb/P5)*betta*Cml/P4;

%Dmd= -Kdm*Cds+((Ws-Wm)/Wm)*kdm*Cml
Dmd=1/Tdm*((Ws/Wm-1)*Cml-Cds);

gam= gam0*exp(r*t);
Tpy=gam*Na0/(2000*453.6);
dx=[Dlu;Dlb;Dsb;-Dlu-Dsb-Dlb+Dml+Tpy;-Dml-Dmd-Dmb;Dmb;Dmd];
%------------------------------------------------------
```

co2sim.m – Original Model

```
% help command prints help on the command

% define some global constants that will be valid
% when you call a function or a subroutine.
```

```
% cof is the cofficient matrix for the interaction between the reserviours
global Na0 Tam Tul Tdm betta Flb0 Fsb0 Fmb0 Cmt Corg ...
eps P1 P2 P3 P4 P5 Ws Wm gam0 r

%request high accuracy
format long

% give values to the global constants
Na0=6.156d17;
Tam=5.8;
Tul=2.;
Tdm=1500.;
betta=0.6;
Flb0=2.6d16;
Fsb0=3.d16;
Fmb0=2.d16;
Cmt=(12.011)*0.002057;
Corg=0.001;
eps=12.5;
P1=0.15;
P2=2.534;
P3=0.122;
P4=2.;
P5=0.1;
Ws=1.370d21;
```

```
Wm=(P4*Na0)/(Cmt+Corg);
gam0=2.3937d-29;
r=0.03077;

% set error tolerance and method for the numerical
%integrator of the differential equations.
odeset('maxstep',1.,'reltol',1.e-3,'bdf','on')

%perform the integration 'lorsys' is a file that defines the system
%[0,100] time interval for the integration
%[5,5,5] define the initial conditions
[t,x]=ode15s('co2sys',[0,100],[0.;0.;0.;0.;0.;0.;0.]);

%plot x=x(:,1) vs. time(t0=1700) in red
plot(t,x(:,1),'r')

%title for the plot
title('CO_2 Concentration In the Upper Atmosphere')
xlabel('time in years')
ylabel('CO_2 concentration')

%save the plot to a postscript file
print -dpsc2 -r600 CO2sim.ps


```

```
55 - %plot x=x(:,4) vs. time(t0=1700) in red
56 - plot(t,x(:,4),'r')
57 -
58 - %title for the plot
59 - title('CO_2 Concentration In the Lower Atmosphere')
60 - xlabel('time in years')
61 - ylabel('CO_2 concentration')
62 -
63 - %save the plot to a postscript file
64 - print -dpsc2 -r600 -append CO2sim.ps
65 - %to get out of matlab type 'quit' and return.
66 - %-----------------------------------------------------
```

co2sys.m – Linear Forcing Function

```
33 - gam = (t - 2000) * ((9.07d14 / Na0) * (t - 2000) + (5.44d15 /
      Na0));
```

co2sim.m – Linear Forcing Function

```
13 – Na0=7.07703d17;
24 - P1=0.134188;
25 - P2=2.515232;
26 - P3=0.108025;
27 - P4=1.790826;
28 - P5=0.087829;
41 - [t,x]=ode15s('co2sys',[2000,2100],[0.;0.;0.;0.;0.;0.;0.]);
```

co2sys.m – Logarithmic Forcing Function

```
33 - gam = (t - 2000) * ((5.44d15 / Na0) + ((9.0718474d13 / Na0) * 1 * log(t - 1999)));
```

co2sim.m – Linear Forcing Function

```
13 – Na0=7.07703d17;
24 - P1=0.134188;
25 - P2=2.515232;
26 - P3=0.108025;
27 - P4=1.790826;
28 - P5=0.087829;
41 - [t,x]=ode15s('co2sys',[2000,2100],[0.;0.;0.;0.;0.;0.;0.]);
```