Project Number:
IQP MH-0405 – 11135
IQP MH-0405 – 11134
IQP MH-0405 – 21004

Carbon Dioxide Emissions and Their Impacts

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:

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Jacqueline Cormier

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Maryanne Plunkett

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Professor Mayor Humi

Department of Mathematics

Abstract

The objective of this project was to research global warming and its effect on earth and society. We focused on the impacts of fossil fuels and the resulting increase of carbon dioxide emissions. The global climate models we used demonstrated a large increase in carbon dioxide concentrations due to anthropogenic sources. To mitigate the adverse effects of carbon dioxide in the atmosphere we considered geosequestration, metabolites and enzymes for plants, and the addition of carbonate ions into oceanic sinks.

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Executive Summary

The topic of this Interdisciplinary Qualifying Project is to research global warming and the effects it is having on the Earth. Global warming is the increase in the Earth's mean atmospheric and oceanic temperatures over time. Carbon dioxide emissions are the focus of this project, because they are a major contributor to the global warming situation. The amount of carbon dioxide present in the atmosphere today is approximately 365 ppm. Before the industrial revolution, the concentration of carbon dioxide in the atmosphere was 280ppm. This difference can be attributed to human activity. The length of time that carbon dioxide remains in the atmosphere is another important factor, when considering its global effect.

The objectives for this project are to research and analyze the carbon cycle, climate models, social impacts and possible solutions. The first goal for this project is to analyze the Earth's carbon cycle and find out how much of the emitted carbon dioxide remains in the atmosphere. Another objective is to model the carbon dioxide emissions and global climate. These models project future changes in the climate including changes in the atmosphere, the ocean, and specific regions of the world. The models also illustrate the current and projected impact on human life and the environment. These impacts are considered in five sections; human health, hydrological cycle, agriculture, habitats and species. The final goal of this project is to suggest solutions to global warming.

The results of the carbon cycle analysis show that approximately 70% of all emitted carbon dioxide remains in the atmosphere, while the rest resides mostly in the ocean. The Global CO_2 Model shows the vast difference between the rising CO_2

concentrations when humans are a part of this cycle, and CO_2 concentrations when humans have no input into it. This simplistic model shows that reservoirs had 1026% higher concentrations by the year 2000, when humans contribute to the carbon dioxide concentrations in the atmosphere reservoir. The one-dimensional Global-Average Model of Energy Balance shows how carbon dioxide concentrations affect the climate by 3°C. The Hadley Centre models project a variety of results concerning the growing carbon dioxide levels. The results from these models include how the carbon dioxide concentrations could be 250 ppm less if humans were not influencing the cycle. The Massachusetts Institute of Technology's Integrated Global System Model shows economic costs of stabilizing the current carbon dioxide concentrations in 2005 to be $2.5 trillion dollars.

The increased occurrence of heat waves, disease outbreaks and respiratory agitators, are the major health effects caused by global warming. The heat wave that struck Western Europe last year claimed over 30,000 lives. The northern spread of malaria and West Nile virus can be attributed to the increasing global temperature. The production of ragweed pollen has increase drastically due to excess carbon dioxide in the atmosphere. This pollen can bind with air pollution and can be a serious respiratory agitator.

The different components of the hydrologic cycle that are affected by global warming are the ocean, global weather patterns, and ground water. The sea level of the ocean is rising due to thermal expansion and an increase in melting of sea ice and glaciers. Over the past 100 years, the sea level has changed approximately 1 – 2 mm/yr, by 2100 the estimated rise is .94 m. The thermohaline circulation of the ocean may also be affected by the change in the formation of sea ice. The global weather patterns are affected not only by the rising temperatures, but also by changes in the thermohaline circulation. The US has already had a 20% increase in precipitation, along with four destructive hurricanes in 2004.

This increase in precipitation is not uniform, areas of the country that are struggling to meet their water demand will receive less average rainfall, while areas with large water resources will receive more precipitation. Areas that experience less rainfall will also suffer from lower moisture content in their soils.

The changes in global weather affect agriculture by increasing pest populations and weather variability. The increased pest populations are estimated to decrease plant tissue mass by 30%. Chaotic storms and general precipitation changes are projected to put 55-70 million people at risk of hunger by 2080.

Global habitats are also impacted by climate change. The main habitats that are affected are forests, coastal areas and marine ecosystems. Global warming causes forests to become more vulnerable to disease, pests and forest fires, while providing an environment that will encourage the onset of these threats. Impacts on coastal areas include an increase in the coastal flood plain area. This increase will put 600 million people at risk by 2100.

The effects of climate change on these various habitats also affect the species that inhabit them. These affects include breeding times, growth rate, migration, population, life expectancy and food source.

Solutions to the rising concentrations of carbon dioxide and other greenhouse gases include the Kyoto Protocol, energy efficiency, natural energy resources, sequestration of carbon dioxide, carbon dioxide absorption by plants and soils, and carbonate ion addition to oceans. Each of these solutions helps regulate carbon dioxide emissions, yet progress needs to be made on all of them before they are feasibly effective.

1. Introduction

We selected this Interactive Qualifying Project for many reasons. We felt that there are many aspects of global warming that require further investigation such as global, environmental, economic and social impacts before accurate conclusions can be drawn. The many aspects of this field that have not been fully researched give us the opportunity to make a genuine contribution. Studying global warming is also personally rewarding because we are attempting to make a positive contribution to society in an area that our society has overlooked. It is also personally fulfilling because this projects outcome will affect all countries. We both share an interest in this subject and a desire to expand our current knowledge of global warming and ways to prevent it.

Our goals for this project are to gain a detailed understanding of the entire global warming process with specific focus on carbon dioxide emissions and their impacts. We will research the social effects that global warming is having on our global society now and in the future. Possible solutions to the expanding global warming problems will also be researched.

We each have our own personal reasons why we were interested in this particular project. Jacqueline Cormier is currently studying to become a chemical engineer with an environmental concentration. This project will assist her in completing her concentration and is also a crucial part of her future employment plans. After graduating, she hopes to get a job that has a positive affect on the environment like a job at the Environmental Protection Agency or as an environmental consultant. The other group member, Maryanne Plunkett, is considering getting an environmental concentration and would like to find a job where she feels that she is impacting the world in a positive way.

Global warming is an issue easily overlooked by our short-sighted society. There needs to be more emphasis on the affects of global warming today and in the future. The results of our research will contribute to the many voices insisting that as a society, we need to adopt a more sustainable life style.

Global warming is the process by which the Earth's atmospheric and oceanic temperatures increase over time. This change can be attributed to gases in the atmosphere called greenhouse gases. Greenhouse gases are naturally present in our atmosphere. The three major natural greenhouse gases are water vapor $(H_2O)_v$, carbon dioxide (CO_2), and ozone (O_3). Water vapor is responsible for about 60% of the natural warming process; carbon dioxide is responsible for about 26%, and ozone is responsible for the majority of the remaining effects. Greenhouse gases that have minor natural impacts are methane (CH_4), nitrous oxide (N_2O), sulfurhexafluoride (SF_6), and halocarbons such as perfluoromethane (CF_4). Although all of these gases are present naturally, they are also products of human activity. When a temperature change is caused by natural gases, it is referred to as a climate change. When the change is caused by human activity, then it can be considered global warming or anthropogenic climate change. Humans have begun to produce more and more greenhouse gases since the industrial revolution.

	CO_2 (Carbon Dioxide)	**O_3 (Tropospheric ozone)**	**CH_4 (Methane)**	**N_2O (Nitrous Oxide)**	**CFC-11 (Chlorofluoro-carbon-11)**	**CF_4 (Perfluoro-methane)**
Pre-industrial concentration	about 280 ppm	25 ppt	about 700 ppb	about 270 ppb	zero	40 ppt
Concentration in 1998	365 ppm	34 ppt	1745 ppb	314 ppb	268 ppt	80 ppt

Table 1: Concentrations of Greenhouse Gases that are affected by Human Activity (C.1 Observed Changes in Globally Well-Mixed Greenhouse Gas Concentrations and Radiative Forcing.)

Table 1 demonstrates that large portions of the greenhouse gases that exist in our environment today are anthropogenic gases. This large output of unnatural gases is raising concerns about global warming.

Anthropogenic gases are products of a variety of human activity. Carbon dioxide is a byproduct of fossil fuel combustion and of cement manufacturing. Methane is emitted from landfills, coal mining, leaky natural gas lines, increasing ruminant population, rice cultivation, and anaerobic waste management lagoons. (Can we diffuse the Global Warming Time Bomb)

Ozone is not directly emitted into the atmosphere; it is formed in the atmosphere by the photochemical smog reaction shown below.

$$N_2(g) + O_2\,(g) \text{ -----> } 2NO(g)$$

$$NO(g) + O_2\,(g) \text{ -----> } 2NO_2\,(g)$$

$$NO_2\,(g) + \text{sunlight ----> } NO(g) + O(g)$$

$$O + O_2 \text{ -----> } O_3$$

(The Chemistry of Photochemical Smog)

Approximately 75% of anthropogenic nitrogen dioxide is produced through fossil fuel combustion. The remaining percentage is a result of biomass burning, agriculture and industrial activities. Perfluoromethane is a by-product of aluminum and semiconductor production. (Emissions of Greenhouse Gases in the United States 2003)

Chlorofluorocarbons or CFCs have been used since the 1920s as propellants in aerosol cans, as refrigerants in refrigerators and air conditioners, as degreasing agents, and in the manufacturing of foam packaging. Although their use is now prohibited, CFCs can remain in the atmosphere for over one hundred years. (Chlorofluorocarbon)

Before discussing global warming and its social implications, it is important to understand the Earth's heating process and the role that greenhouse gases play in this process. The Earth is warmed by electromagnetic radiation from the sun. Visible radiation is absorbed by the Earth's surface and is then re-emitted in the form of infrared radiation (IR), as shown in figure 1. (Greenhouse Gases Absorb Infrared Radiation)

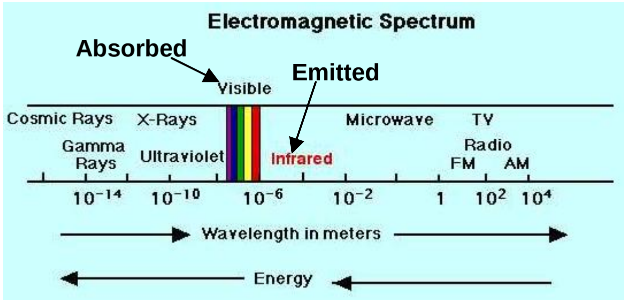


Figure 1: Electromagnetic Spectrum (Greenhouse Gases Absorb Infrared Radiation)

The frequency range for infrared radiation is similar to the vibrational frequency range found in greenhouse gas molecules. This correspondence allows the gas molecules to absorb the radiation. The radiation is absorbed by the bonds in the molecule and causes the bonds to bend and stretch as shown in Figure 2. (The Power of Infrared Spectroscopy and Spectral Comparison)

Molecular Vibrations

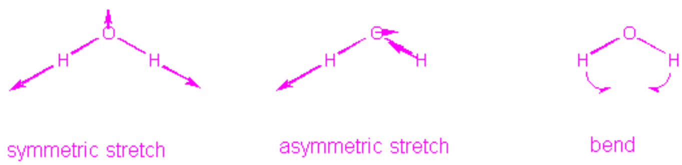
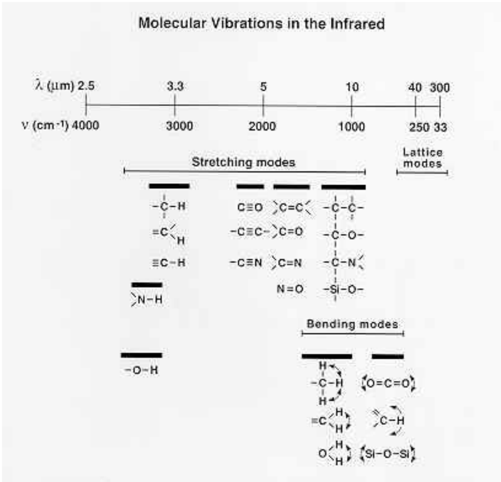


Figure 2: Molecular Vibrations (Infrared Spectroscopy)

Different molecular bonds absorb different IR frequencies; Figures 3 and 4 outline the IR absorbance of some common molecular bonds.



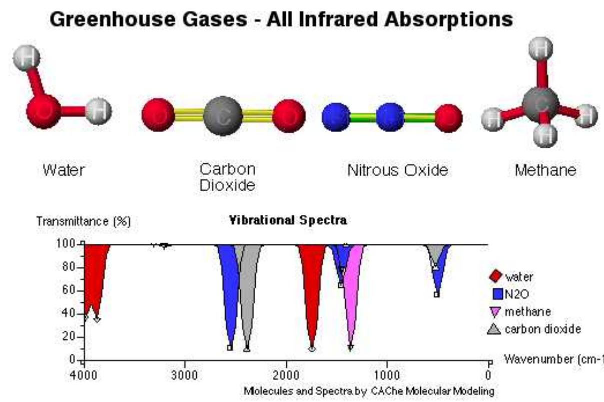


Figure 3: Infrared Absorption Frequencies (The Power of Infrared Spectroscopy and Spectral Comparison)

Figure 4: Infrared Absorption Frequencies (The Power of Infrared Spectroscopy and Spectral Comparison)

Once the molecules have absorbed the radiation, they are in an excited, yet unstable state. The molecules emit the radiation in the form of thermal energy to stabilize themselves. This thermal energy is responsible for heating the Earth.

It is important to note that not all anthropogenic gases are greenhouse gases. Other main industrial gases, such as aerosols actually have a cooling effect on the Earth. Aerosols cool the earth in two ways. First, they are highly reflective, which causes more solar heat to be directed back into space. Secondly, they alter the properties of water droplets in clouds, resulting in clouds that are more reflective. The drops are altered by the presence of more nuclei. The drops condense around the nuclei, which makes the average drop size smaller. The smaller drops are more reflective and also impede rain production, allowing the cloud to have a longer lifespan. Another human activity that results in a cooling effect is the replacement of forests with croplands. Forests absorb solar heat; their removal reduces the amount of heat absorbed by the Earth.

Although human activity results in both warming and cooling process, not enough cooling agents are produced to counterbalance the greenhouse gases. The net anthropogenic effect is still positive, resulting in a heating force.

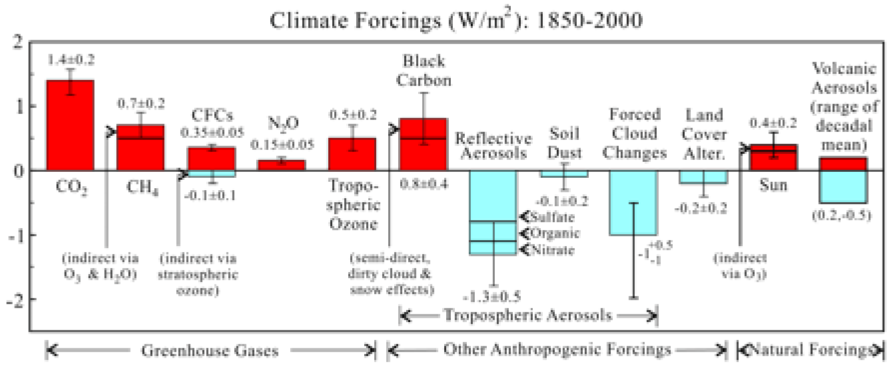


Figure 5: Climate Forcings (Geophysics Trends of Measured Climate Forcing Agents)

Figure 5 illustrates that out of the many greenhouse gases that contribute to global warming; carbon dioxide is the gas that influences global warming the most. With the general knowledge of all anthropogenic gases, including their sources, chemical and physical reactions and their impact on the earth's warming and cooling processes, the effects of carbon dioxide can now be discussed.

2. The Carbon Cycle

It has been established that the presence of excess carbon dioxide molecules in the atmosphere contributes drastically to the greenhouse effect. To further grasp how carbon dioxide contributes to global warming the amount of carbon dioxide and its duration in the atmosphere must be known. Two main research facilities in Mauna Loa, Hawaii and the South Pole have been monitoring atmospheric concentrations of carbon dioxide since 1985. These facilities estimate the current concentration of carbon dioxide to be approximately 365 ppm. The length of time that the excess carbon dioxide remains in the atmosphere is dependent upon the Earth's natural carbon cycle. This cycle outlines the flow of carbon through the Earth's sinks. Areas of the planet that absorb carbon are called sinks; processes that emit carbon are called sources. This cycle is call the carbon cycle. For analytic purposes, the carbon cycle is divided into four sections; the atmosphere, the biosphere (plants), soils and the ocean. The carbon cycle, its various sections and the affects of anthropogenic carbon production will now be discussed.

2.1 Natural Carbon Cycle

The four sections of the carbon cycle; the atmosphere, the biosphere, soils and the ocean, are called carbon sinks. Sinks can be broken down into smaller units call reservoirs. Before analyzing the affects that anthropogenic carbon sources have on these sinks and on the Earth as a whole, the natural interactions that occur within and between each sink should be understood.

Carbon enters the atmospheric sink through the respiration of animals, plants and volcanic eruptions. Respiration occurs when carbohydrates and oxygen react to form carbon dioxide, water and energy.

$$CH_2O + O_2 \rightarrow CO_2 + H_2O + \text{energy}$$

The reversal of this process is called photosynthesis, which occurs when solar energy (hυ), water and carbon dioxide are absorbed by plant life, to produce carbohydrates and oxygen.

$$h\upsilon + CO_2 + H_2O \rightarrow CH_2O + O_2$$

Since plants undergo both photosynthesis and respiration, it is important to consider the net photosynthesis, instead of the gross photosynthesis, when analyzing how much carbon plants remove. Another source of carbon dioxide is volcanic activity, more specifically the gaseous portion of magma. Approximately, 1-5% of magma is gaseous by weight and about 80% of that gas is water vapor. The remaining gas is composed of sulfur dioxide and carbon dioxide.(Volcanic Gases) Volcanic activity currently releases about 130–230 million metric tons of carbon dioxide each year, this amount is equivalent to approximately 1% of human carbon dioxide emissions. (Carbon dioxide)

The next carbon sink to consider is the biosphere. The biosphere is composed of three reservoirs; ground vegetation, non-woody parts of trees, and woody parts of trees. This plant life contains large quantities of carbon in the form of carbohydrates, as illustrated in the previous section.

Consideration is now given to the soil sink, which is composed of two reservoirs; the decomposition reservoir and the active soil reservoir. The decomposition reservoir is located at surface of the soil sink. It is in this reservoir that microorganisms break down detritus and convert it to soil. Detritus is composed of shed tissues, dead bodies and waste products of organisms. The lower reservoir is called the active soils reservoir.

Figure 6 displays the interactions between the atmosphere, the biosphere and the soil sink. The combination of these three sinks is called the terrestrial portion of the carbon cycle. Figure 6 outlines the amount of carbon contained in each of the sink's individual reservoirs, the rate at which the carbon is transferred between reservoirs and the residence time for each sink. The residence time is the amount of time the average carbon atom spends in each reservoir. The carbon amounts are indicated in units of 10^9 tons of carbon, the times are in years and the transfer rates are in units of 10^9 tons per year. The diagram represents a pre-industrial environment, which means that steady-state assumptions can be made.

Terrestrial Portion of the Carbon Cycle

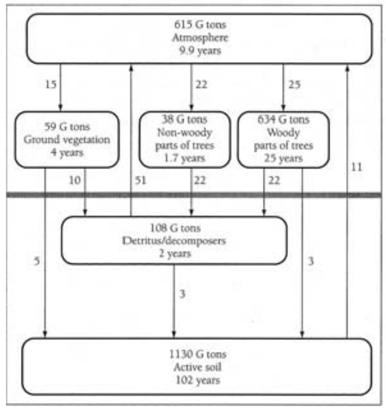


Figure 6: Terrestrial Portion of the Carbon Cycle (McElroy)

The last sink to be considered is the ocean sink. The ocean is divided into four reservoirs; warm surface water, cold surface water, intermediate water and deep ocean. The ocean carbon cycle is not a closed cycle, like that of the terrestrial carbon cycle; carbon is lost to the sediment section of the ocean cycle. Carbon can move in two directions once it is in the sedimentary stage. The carbon can either be returned to the surface, by way of the biosphere, over a long period of time, or it can be withdrawn into the mantle of the Earth. Once in the mantle, it reemerges through hot springs or volcanic activity. Carbon movement through this sink is outlined in Figure 7. The given information and units are similar to the data displayed on the previous diagram. The dashed lines indicate carbon transfer due to the falling of fecal matter. This diagram also represents a pre-industrial environment, so the carbon flows are assumed to be steady state.

The Ocean Sink

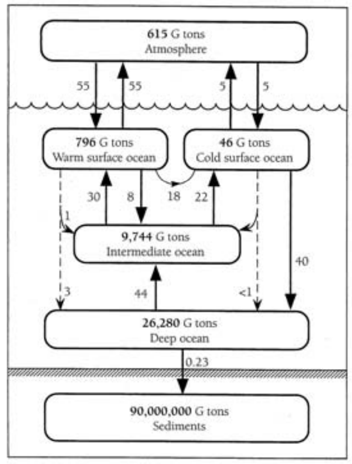


Figure 7: The Ocean Sink (McElroy)

With an overview of each of the individual sinks, the entire natural carbon cycle can be seen as a whole. Figure 8 is the composite model for the global carbon cycle.

Global Carbon Cycle

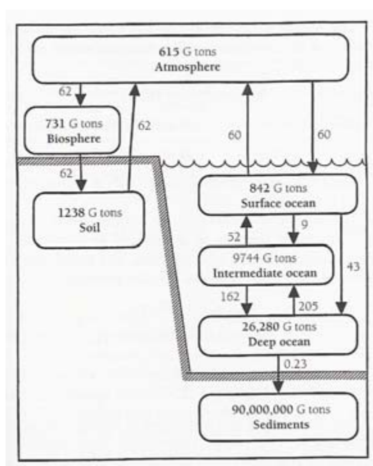


Figure 8: Global Carbon Cycle (McElroy)

From the given data, the residence time of carbon in the ocean sink is approximately equal to 612 years. The probability that the carbon will move to the sediments rather than the atmosphere is equal to $0.23x10^9$ tons C per year divided by $60.23x10^9$ tons C per year, or 0.0038. From this probability, it is possible to calculate that a carbon atom has visited the ocean 263 times. Multiplying the number of times the average carbon atom visits the ocean sink by the residence time of the carbon atom in the ocean, produces the total amount of time the average carbon atom has spent in the ocean sink. The average carbon atom has spent a total time of approximately 160,930 years in the ocean sink. The combined residence time for the atmosphere-ocean-biosphere-soil cycle is 171,087 years. When comparing the residence time of total cycle to that of the ocean's residence time, it is evident that the average carbon atom spends most of its time in the ocean sink. Repeating the calculations for the sediment reservoir, it is found that its residence time for carbon is approximately 390 million years. Considering life has existed for 4 billion years, it can be estimated that the average carbon atom has cycled through the sediment section of the Earth about ten times. The amount of carbon contained in the ocean is almost 60 times larger that that of the atmosphere and exceeds the amount of carbon in the atmosphere-biosphere-soil sinks by a factor of fourteen. These calculations demonstrate that the ocean's capacity to absorb carbon will drastically affect the redistribution of anthropogenic carbon.

2.2 Anthropogenic Effects on the Carbon Cycle

Once the natural flow of carbon though the Earth's sinks is understood, it is possible to study how the addition of excess anthropogenic carbon affects the carbon cycle. Carbon dioxide makes up 76% of all anthropogenic green house gases. Most of the anthropogenic carbon is produced by combusting fossil fuels. The combustion of gasoline in car engines is one of the main contributors to carbon dioxide pollution. Gasoline is a very complex mixture; it contains over 500 hydrocarbons that may have between 3 to 12 carbon atoms. The majority of gasoline is made up of saturated hydrocarbons or alkanes. Figure 9 shows a few examples of common alkanes found in gasoline. (Gasoline FAQ)

Common Saturated Hydrocarbons in Gasoline

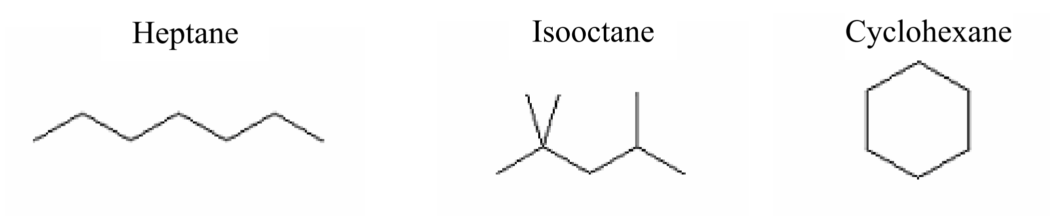


Figure 9: Common Saturated Hydrocarbons in Gasoline (Chemfinder.com)

The remaining hydrocarbons in gasoline are unsaturated.

Common Unsaturated Hydrocarbons in Gasoline

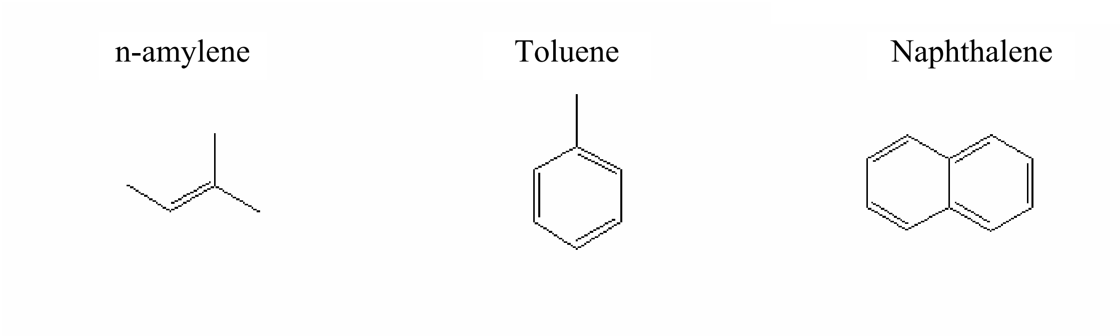


Figure 10: Common Unsaturated Hydrocarbons in Gasoline (Chemfinder.com)

Due to the complexities of gasoline, methane is usually used to demonstrate a combustion reaction.

$$CH_4[g] + 2\ O_2[g] \rightarrow CO_2[g] + 2\ H_2O[g] + \text{ENERGY}$$

In this reaction, chemical bonds are both broken and formed, this process results in a positive net energy, or an exothermic reaction. Initially, energy is required to break the bonds in both the methane and oxygen molecule. Once these bonds are broken, new bonds are formed, giving off energy. Figure 11 illustrates that more energy is emitted, in the form of heat, than is required to initiate the reaction.

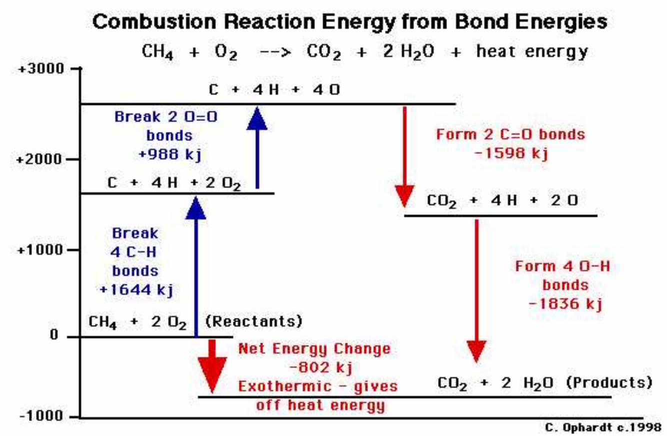


Figure 11: Combustions Reaction Energies (Energy of Combustion)

The energy stored in fossil fuels is a result of decomposition of organic matter under extreme temperatures, pressure and other unknown factors, for approximately 300 million years.

The process of combusting these fossil fuels and the process of removing them from the earth, have serious affects on the natural carbon cycle. This process essentially removes carbon from the sediment sink and releases it into the atmosphere sink. Unnaturally redistributing the Earth's carbon upsets the carbon cycles inherent equilibrium. When the chemical equilibrium of a system, even one as large as the earth, is disturbed, Le Chatelier's Principle states that the equilibrium position will shift in the direction which tends to counteract the effect of the disturbance. Based on this fundamental chemical theory, the disturbed carbon cycle will attempt to shift carbon back into the sediment sink, in order to restore equilibrium. Unfortunately, as discussed in the previous section, the average carbon atom spends most of its time in the ocean and makes several visits to the atmosphere, terrestrial biosphere and soil before it is withdrawn into the sediments. Hence, the rate at which the earth can reestablish equilibrium is dependent on the ocean's capacity to absorb excess carbon.

The ocean's absorption capacity is affected by its ion concentrations. The ocean's most common cations, positively charged ions, are sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}); the most common anions, negatively charged ions, are chloride (Cl^-), sulfate (SO_4^{2-}) and bromide (Br^-). Table 2 shows the average oceanic concentrations of each of these ions. There is a net positive charge equal to 0.002 charge equivalents per liter.

Concentrations of the Major Cations and Anions in the Ocean

Positive Charge		
Cation	*mol l^{-1}*	*charge eq l^{-1}*
Na^+	0.470	0.470
K^+	0.010	0.010
Mg^{2+}	0.053	0.106
Ca^{2+}	0.010	0.020
Sum		0.606
Negative Charge		
Anion	*mol l^{-1}*	*charge eq l^{-1}*
Cl^-	0.547	0.547
SO_4^{2-}	0.028	0.056
Br^-	0.001	0.001
Partial Sum		0.604
$HCO_3^- + 2CO_3^{2-}$		0.002
Sum		0.606

NOTE: A pH of 8 gives a concentration of H^+ equal to 10^{-8} mol l^{-1}, which is less by a factor of 10^5 than any of the values on the table.

Table 2: Concentrations of Major Ions in the Ocean (McElroy)

This positive charge is offset by the negative charge of the dominant forms of dissolved carbon. The majority of the dissolved carbon is contained in two compounds, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. The amount of dissolved carbon needed to counterbalance the net positive charge can be determined by the ocean's alkalinity. Alkalinity is the measure of the ability of a solution to neutralize hydrogen ions (H+); it is usually expressed as the equivalent concentration of calcium carbonate ($CaCO_3$) required to make this neutralization. Carbonate alkalinity is the sum of the concentration of bicarbonate ions plus two times the concentration of the carbonate ions.

$$[Alk] = [HCO_3^-] + 2[CO32^-]$$

$$[Alk] = [Na^+] + [K^+] + 2[Mg^+] + 2[Ca^{2+}] – [Cl^-] – 2[SO_4^{2-}] – [Br^-]$$

Carbon dioxide is a weak acid in solution, the reaction through which carbon is absorbed or dissolved into the ocean can be written as seen below.

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+$$

The loose proton can then react with carbonate to form bicarbonate.

$$H^+ + CO_3^{2-} \rightarrow HCO_3^-$$

The sum of these two reactions produces the net reaction below.

$$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$$

Upon examining the net reaction, it is evident that the carbonate ion is the limiting reactant. Therefore, the amount of excess carbon dioxide absorbed by the ocean will be limited by the ocean's concentration of carbonate ions.

It is important to understand that the three reactions above do not proceed to completion, but that the products and reactants remain in a state of constant equilibrium. To gauge how much carbon dioxide can actually be absorbed, the equilibrium constants of the reactions must be known.

$$CO_2\,(g) \leftrightarrow CO_2\,(aq)$$

$$CO_2\,(a) + H_2O \leftrightarrow HCO_3^- + H^+$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$$

From the reactions above, we can derive an equilibrium relationship. The equilibrium constants for the reactions above will be labeled, α, K_1 and K_2, respectively. The partial pressure of gaseous carbon dioxide will be labeled pCO_2.

$$\alpha = \frac{[CO_2\ (aq)]}{pCO_2}$$

$$K_1 = \frac{[H^+]\ [HCO_3^-]}{[CO_2\ (aq)]}$$

$$K_2 = \frac{[H^+]\ [CO_3^{2-}]}{[HCO_3^{\ -}]}$$

Rearranging the K_1 equation to equal $[H^+]$ and substituting it into the K_2 equation provides us with the equation below.

$$K_2 = \frac{K_1\ [CO_2\ (aq)]\ [CO_3^{2-}]}{[HCO_3^{\ -}]^2}$$

Then rearranging the α equation to equal $[CO_2\ (aq)]$ and substituting it into the equation gives us the following equation.

$$\frac{\alpha\ K_1}{K_2} = \frac{[HCO_3^{\ -}]^2}{pCO_2\ [CO_3^{2-}]}$$

Setting the equilibrium values α, K_1, and K_2 equal to $K^{'}$ results in the final equilibrium equation. Table 3 outlines the equilibrium constants as a function of temperature.

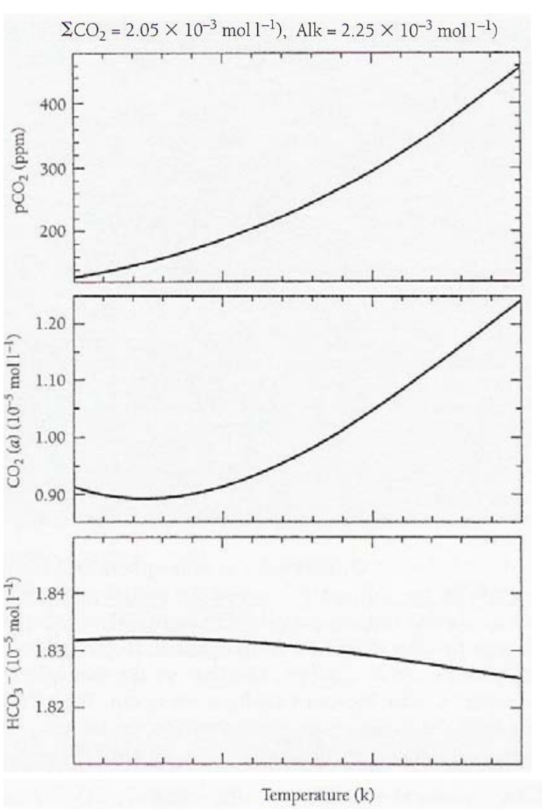
Values of Dissociation Constants as a Function of Temperature				
T	α	K_1	K_2	K'
(°C)	10^{-2} mol (l atm)$^{-1}$	10^{-7} mol l^{-1}	10^{-10} mol l^{-1}	mol (l atm)$^{-1}$
0	6.33	6.28	3.50	113.8
5	5.25	7.12	3.99	93.6
10	4.42	7.93	4.67	75.0
15	3.77	8.68	5.52	59.3
20	3.26	9.36	6.52	46.8
25	2.85	9.95	7.60	37.4

Table 3: Values of Dissociation Constants as a Function of Temperature (McElroy)

It is now clear how alkalinity and the concentrations of carbonate and bicarbonate ions affect the ocean's absorption of carbon dioxide. The partial pressure of the carbon dioxide is also present in the equilibrium equation and therefore must also affect the ocean's ability to absorb carbon dioxide. The exchange of carbon dioxide between the atmosphere and the ocean is dependant on the difference of the partial pressure of carbon dioxide in the atmosphere and the partial pressure of carbon dioxide in the air just above the ocean's surface. The air just above the ocean's surface is in equilibrium with the ocean; whereas the air in the atmosphere is not. If the partial pressure of carbon dioxide in the ocean is greater than that of the atmosphere then carbon dioxide will be released from the ocean into the atmosphere. If the partial pressure of the atmosphere is greater, carbon will be released in the opposite direction.

The equilibrium constants show how the partial pressure is also affected by temperature. As the water temperature increases, the partial pressure of dissolved carbon dioxide also increases. This increase in the partial pressure in the water causes carbon dioxide to be released into the atmosphere so that the partial pressures of the ocean and the atmosphere will be in equilibrium. Figure 14a and 14b show how the partial pressure of the ocean, the pH, the concentration of dissolved carbon dioxide and the concentration of carbonate, bicarbonate and hydrogen ions vary as a function of temperature. The figures assume a constant alkalinity of 2.25 x 10 $^{-3}$ charge equivalents per liter and a constant concentration of total dissolved inorganic carbon ($\sum CO_2 = CO_2\,(aq) + HCO_3^- + CO_3^{2-}$) of 2.05 x 10^{-3} moles per liter. The figures show how an increase in temperature shifts the reaction $CO_2 + CO_3^{2-} + H_2O \leftrightarrow 2HCO_3^-$ to the left. Bicarbonate ions are converted to carbonate and hydrogen ions and carbon dioxide. As the aqueous carbon dioxide is increased, the partial pressure of the carbon dioxide increases also. The excess hydrogen ions lead to a drop in the ocean's pH.

Changes is Partial Pressure, pH, and Ions Concentrations as a Function of Temperature



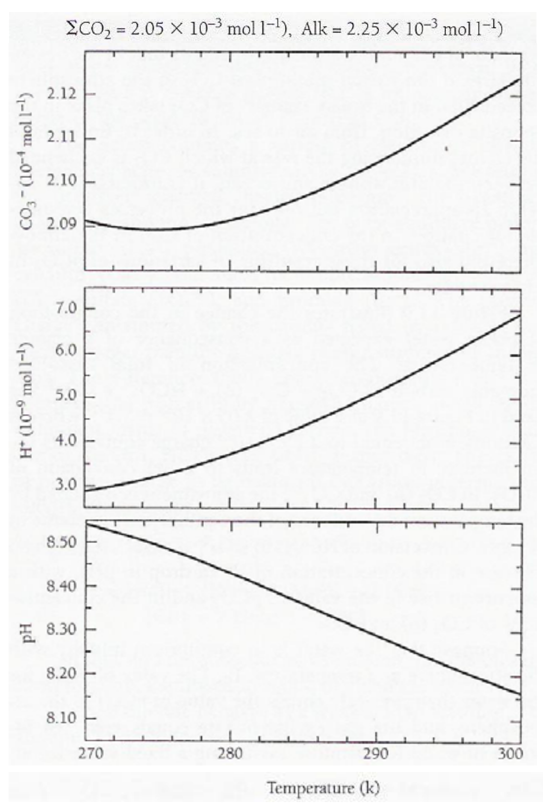


Figure 12a: Changes is Partial Pressure, pH, and Ions Concentrations as a Function of Temperature(McElroy)

Figure 12b: Changes is Partial Pressure, pH, and Ions Concentrations as a Function of Temperature(McElroy)

Assuming a constant temperature of 293K and a constant alkalinity of 2.25×10^{-3} charge equivalents per liter, how will the ocean react when the concentration of carbon dioxide in the atmosphere is increased? Figures 15a and 15b demonstrate that as the partial pressure of carbon dioxide in the ocean increases, the concentration of aqueous carbon dioxide increases. From the given reaction, $CO_2 + CO_3^{2-} + H_2O \leftrightarrow 2HCO_3^-$, when the amount of carbon dioxide increases, the equation shifts right. Therefore, the concentration of carbonate ions decreases and the concentration of bicarbonate ions increases. The total dissolved inorganic carbon $\sum CO_2 = CO_2\,(aq) + HCO_3^- + CO_3^{2-}$ increases as well. Since dissolved carbon dioxide also acts as a weak acid, the pH decreases and the H^+ concentration increases.

Changes in Ion Concentrations and pH as a Function of Partial Pressure

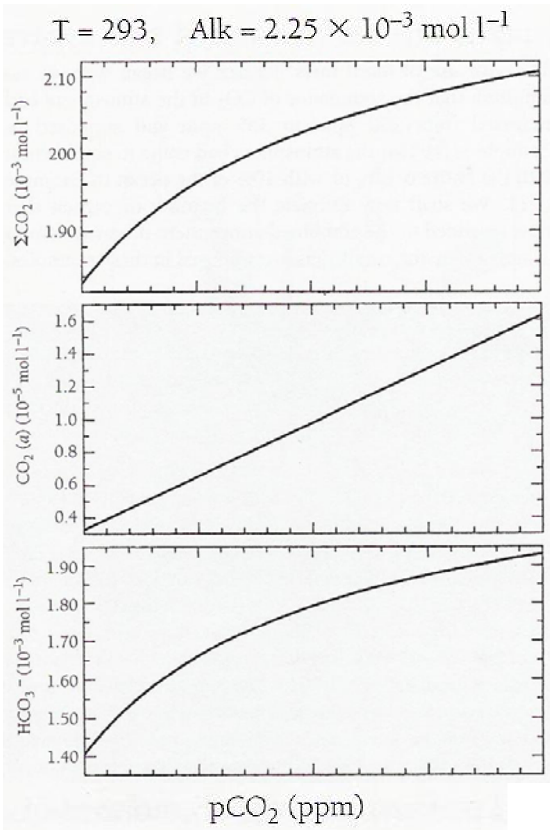


Figure 13a: Changes in Ion Concentrations and pH as a Function of Partial Pressure (McElroy)

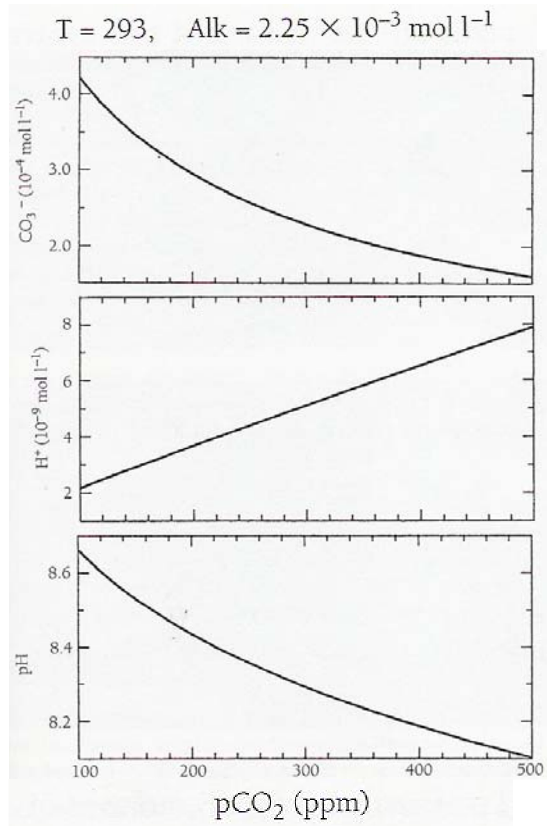


Figure 13b: Changes in Ion Concentrations and pH as a Function of Partial Pressure (McElroy)

The graph of total dissolved inorganic carbon as a function of the partial pressure of carbon dioxide is of particular interest. Roger Revelle (1909-1991), an oceanographer, studied this relationship extensively. The ratio of total dissolved carbon to the partial pressure of carbon dioxide is known as the Revelle factor. In this particular example, the Revelle factor is approximately 10%.

Now that the primary factors, which affect the ocean's ability to take up carbon dioxide, have been discussed, calculations can be made to figure out how much anthropogenic carbon dioxide can be redistributed to the ocean sink and at what rate the redistribution will occur. Assume for the sake of calculation that the concentration of carbonate ions is uniform throughout the ocean. The concentration of carbonate ions before the industrial revolution will be labeled $[CO_3^{2-}]_0$ and the carbonate concentration today is $[CO_3^{2-}]$. From the given reaction, $CO_2 + CO_3^{2-} + H_2O \leftrightarrow 2HCO_3^-$, it can be seen that every mole of carbon dioxide requires one mole of carbonate in order to react. Therefore, the increase in carbon absorbed by the ocean per unit volume can be written as seen below.

$$(\Delta C)_{ocean} = ([CO_3^{2-}]_0 - [CO_3^{2-}])$$

Assuming that the entire volume of the ocean has had the ability to interact with the atmosphere since the industrial revolution, the entire volume of the ocean (V) can be factored into the equation.

$$(\Delta C)_{ocean} = V\,([CO_3^{2-}]_0 - [CO_3^{2-}])$$

Since any decrease in $[CO_3^{2-}]$ caused by the absorption of carbon dioxide is offset proportionally by a rise in the partial pressure of carbon dioxide pCO_2, if the pre-industrial partial pressure is $(pCO_2)_0$ and the current value is pCO_2, then the following can be equated.

$$(pCO_2)_0 * [CO_3^{2-}]_0 = pCO_2 * [CO_3^{2-}]$$

Rearranging this equation and substituting it into the previous equation, the following equation is produced.

$$(\Delta C)_{ocean} = \frac{V\,[CO_3^{2-}]_0\,(pCO_2 - (pCO_2)_0)}{pCO_2}$$

Next, the pre-industrial mass of carbon in the atmosphere M_0 will be factored into the equation, assuming the mass of carbon in the atmosphere will always be proportional to the partial pressure of carbon dioxide in the atmosphere.

$$(\Delta C)_{atmos} = \frac{M_0\,(pCO_2 - (pCO_2)_0)}{(pCO_2)_0}$$

The fraction of excess carbon remaining in the atmosphere can be assumed to equal to the change of carbon in the atmosphere divided by the change of carbon in the atmosphere and the ocean.

$$f_{atmos} = \frac{(\Delta C)_{atmos}}{(\Delta C)_{atmos} + (\Delta C)_{ocean}}$$

Using the previous equations for $(\Delta C)_{atmos}$ and $(\Delta C)_{ocean}$, we find that f_{atmos} equals the following.

$$f_{atmos} = \left[1 + \frac{V\,(pCO_2)_0}{M_0\;\;pCO_2} * [CO_3^{2-}]_0 \right]^{-1}$$

Using this relationship, the fraction of total carbon remaining in the atmosphere can be determined. To calculate this value, the mixing ratio of carbon dioxide must be known. The estimated present day value of the mixing rate has risen to 355ppm, hence this value will be used for the calculation. The theoretical value for the initial amount of carbon dioxide in the atmosphere is 280ppm, the initial concentration of carbonate ions is 200 x 10^{-6} moles per liter and the volume of the ocean is estimated at 1.33 x 10^{21} liters. The result is, 19% of the fossil fuel carbon would remain in the atmosphere and the rest would be inducted into the ocean. However, this equation assumes that the entire ocean had the ability to come to equilibrium with the atmosphere. Unfortunately, only the water on the surface of the ocean is in equilibrium with the atmosphere. The water in the ocean overturns very slowly, in fact, only about 10% of the ocean has been in contact with the atmosphere since the industrial revolution. Using 10% of the original volume from the equation above, it can be calculated to show that 70% of the fossil fuel carbon would remain in the atmosphere.

The mathematical relationships discussed in the previous sections are just a few of the many equations required to accurately predict the impact of carbon dioxide emissions. There are hundreds of variables and interactions between each sink, especially when human emissions are included, because certain assumptions, like steady state assumptions, can no longer be made. In order to combine all of these variables and mathematical relationships, scientist use computer models to simulate the environment's complex cycles and systems. Various models, of different degrees of complexity, were utilized over the course of this project. The sections below assess these models, the systems they simulate, the required input, the simplification that are assumed in order to run the model, and the results that the models produced.

3. Global Climate Models

Global and climate modeling is designed to track and predict possible environmental changes caused by anthropogenic and other natural inputs into this delicate system. These models are based on hundreds of inputs and on different feedback loops in and between the atmosphere, the ocean, the carbon cycle, the terrestrial ecosystem and human inputs into these environments. Realistically, no model could ever achieve the complexity needed to properly predict the future climate. If such a computer model did exist, there would not be a computer with the ability to evaluate the model within a realistic amount of time. Climate organizations around the world continue to create new models in an effort to predict the future climate more realistically. Newer models have fewer uncertainties and errors, which allows scientists to predict the repercussions of humans' environmentally harmful actions more accurately.

Global climate models are separated into two main classifications which are determined by the degree of simplification that is implemented when simulating the climate and by the type of data that is inputted into the system. One such classification is the complexity of the world that the model diagrams or the number of dimensions that are considered. The other classification is dependant on the type of scientific input used in the model in terms of their basic physical principles. The type of model used for a simulation is contingent on the principles of a particular assessment and the speed and time needed to receive the results.

The complexity of the simulated world is divided into four different levels: zero-dimensional model, one-dimensional model, two-dimensional model, and three-dimensional model.

The zero-dimensional models look at the earth as one single consistent object without any changes in temperature, elevation, longitude, or latitude. The one-dimensional models look at the earth with one type of variation, usually longitude or latitude, but elevation is also used. Two-dimensional models allow variations in two directions. For example, many simple ocean temperature models are two-dimensional, which look at the temperatures of the ocean longitudinally and latitudinally while assuming the ocean is of constant depth. The most complex type of model is the three-dimensional model. Most air and ocean circulation models are three-dimensional because they look at the earth as it actually is; made up of longitudes, latitudes and elevation or depth. (Myneni)

Models are also separated by the types of input data the model uses and the physical principles this data emulates. These different types of inputs are separated into four categories: energy balance models, radiative convective models, general circulation climate models and coupled general circulation models. The energy balance models assess the amount of radiation the earth absorbs and emits in order to find the temperatures that result from the planet's energy balance. Radiative convective models require more complex form of input information and they usually model the temperature changes up through the atmosphere in regard to the energy transport from radiative and convective sources. The general circulation climate models are the most complete but also the most complex. These general circulation models are usually described with three-dimensional models and have the potential to accurately reflect the atmosphere. The coupled general circulation models include data about the circulation of the atmosphere coupled with the ocean's circulation. (Myneni)

Hundreds of climate models have been created, using different variations of the types of climate models, which have been described along with other models not mentioned. Several of global climate models were used and researched during this project. The zero-dimensional model, Global CO_2 Model, describes the different levels of carbon dioxide in the seven different reservoirs of the world given human input of carbon dioxide. A one-dimensional Global-Average Model of Energy Balance calculates the resulting temperature changes in the top and bottom of the atmosphere given a matrix of atmospheric data. The Hadley Centre Climate models were also researched. Their models include general circulation models of the atmosphere and the ocean, an atmosphere circulation model with a 'slab' of ocean, an atmospheric chemistry model, a coupled atmosphere-ocean general circulation model, a regional climate model and a carbon dioxide cycle model. The Massachusetts Institute of Technology's Integrated Global System Model, which takes several models and combines them to form a more accurate representation of the global climate, was also included in the study of global climate modeling. These four models will show the different types of models that can be created based off the type of input and type of results that an organization may desire.

3.1 Global CO_2 Seven Reservoir Model

The Global CO_2 Model is a model that replicates the accumulating concentrations of carbon dioxide that exist in the seven reservoirs. This model does not include the affects that the different carbon dioxide levels, in each of the seven reservoirs, have on the climate. The results of this model could easily be extended or used for input to another climate model. The seven reservoirs that this model splits the world into are: the Upper Atmosphere, the Lower Atmosphere, the Long-Lived Biota (world's forests), the Short-Lived Biota (plants with short life spans), the Mixed Ocean Layer, the Deep Sea, and the Marine Biosphere. The relationship between the reservoirs and the human input is shown in Figure 14. The variable, Input, shown in Figure 14 is the human influence on this system. (McHugh)

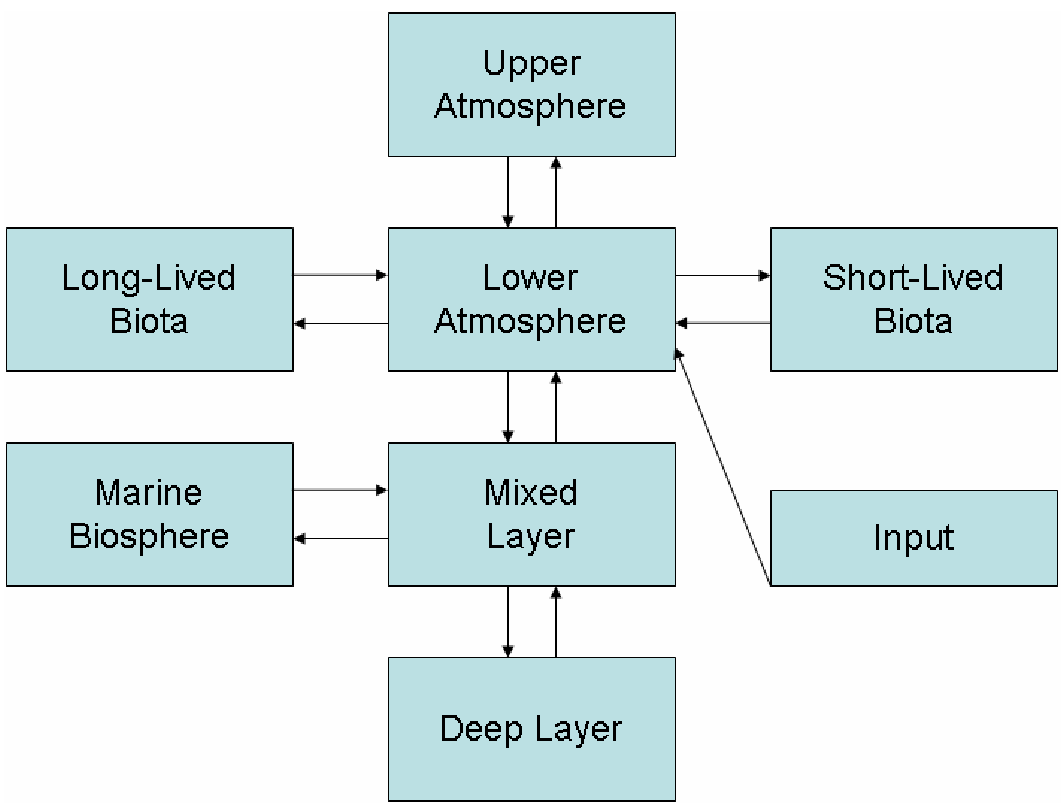


Figure 14: Seven Reservoir of Global CO_2 Model (McHugh)

The Global CO_2 Model has seven ordinary differential equations of the carbon mass balances which correspond to the seven reservoirs. The relative concentration of carbon in the derivative of these seven equations for each reservoir *i* is,

$$C_{ir}(t)=(C_i(t)-C_i(1700))/\ C_{ta}(1700)$$

Where, $C_{ir}(t)$ is the relative concentration of carbon in the *i*th reservoir, $C_i(t)$ is the carbon in the *i*th reservoir at time t (grams), $C_i(1700)$ is the carbon in the *i*th reservoir at time 1700, the base time for the model (grams), $C_{ta}(1700)$ is the carbon in the total atmosphere at time 1700 (grams). The initial conditions for the derivative equations, $C_{ta}(1700)$, is equal to zero. There are also six fluxes on the right hand sides which can be simplified to five equations. The fossil fuel consumption rate, $\gamma(t)= \gamma_o e^{rt}$ where t is the calendar year, γ_o is 2.3937 x 10^{-29} (1/yr), r is .03077 (1/yr).The carbon added to the lower atmosphere in tone/years, $T_{py}(t)$, is given by $T_{py}(t)= \gamma(t)N_{ao}/((453.6)2000.0))$, where N_{ao} is 6.156 x 10^{17} grams. (McHugh)

When the Global CO_2 Model is run with the human input constants that are stated above, the resulting carbon dioxide concentration distributions for the seven reservoirs are displayed in Figure 15. When this simulation is run without the human input constants the resulting graph is shown in Figure 16. The graphs display less rapid increase in the rate of change for each reservoir and many of the reservoirs now look closer to linear equations than the exponential equations they displayed when human input was a part of the model. The Deep Ocean Layer concentrations of CO_2 in both simulations still increase exponentially, but when there is no human input the concentration of CO_2 it is 10^{26} times less in the year 2000. This significant concentration difference is shown in Figures 17a and 17b.

The Deep Ocean Layer also still absorbs the most CO_2 compared to any of the other reservoirs in both scenarios.

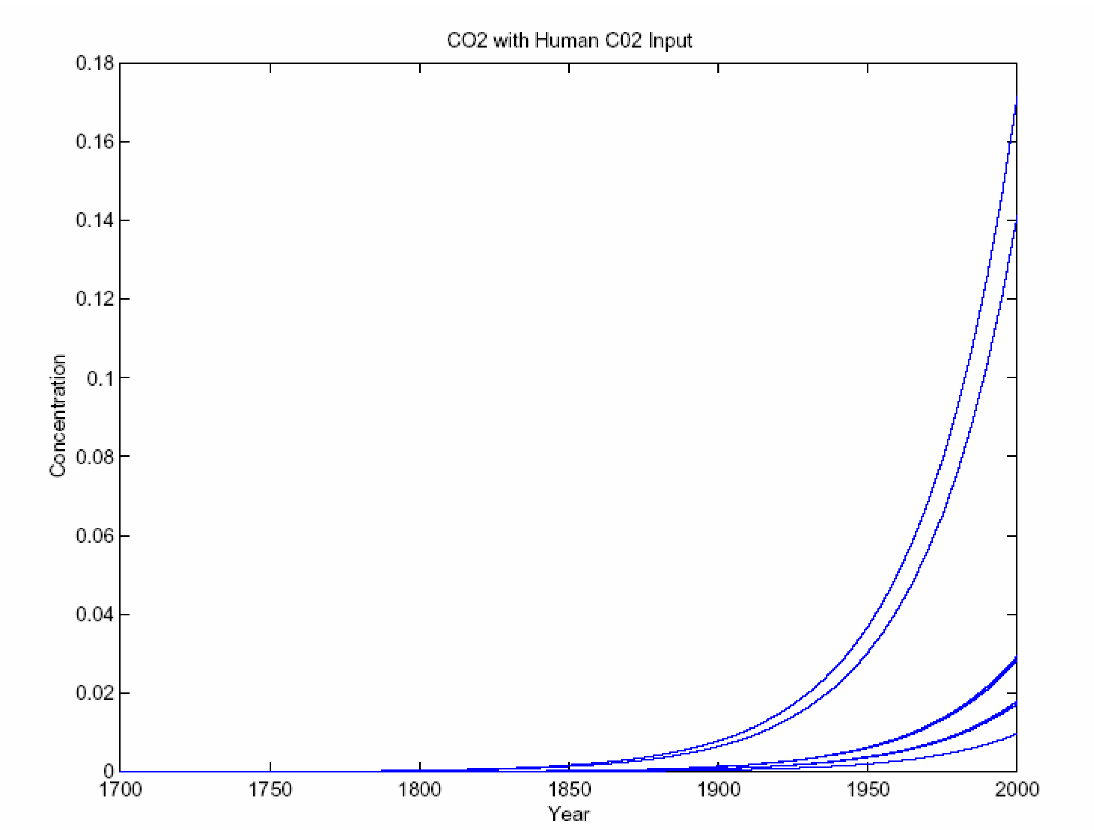


Figure 15: All the reservoirs

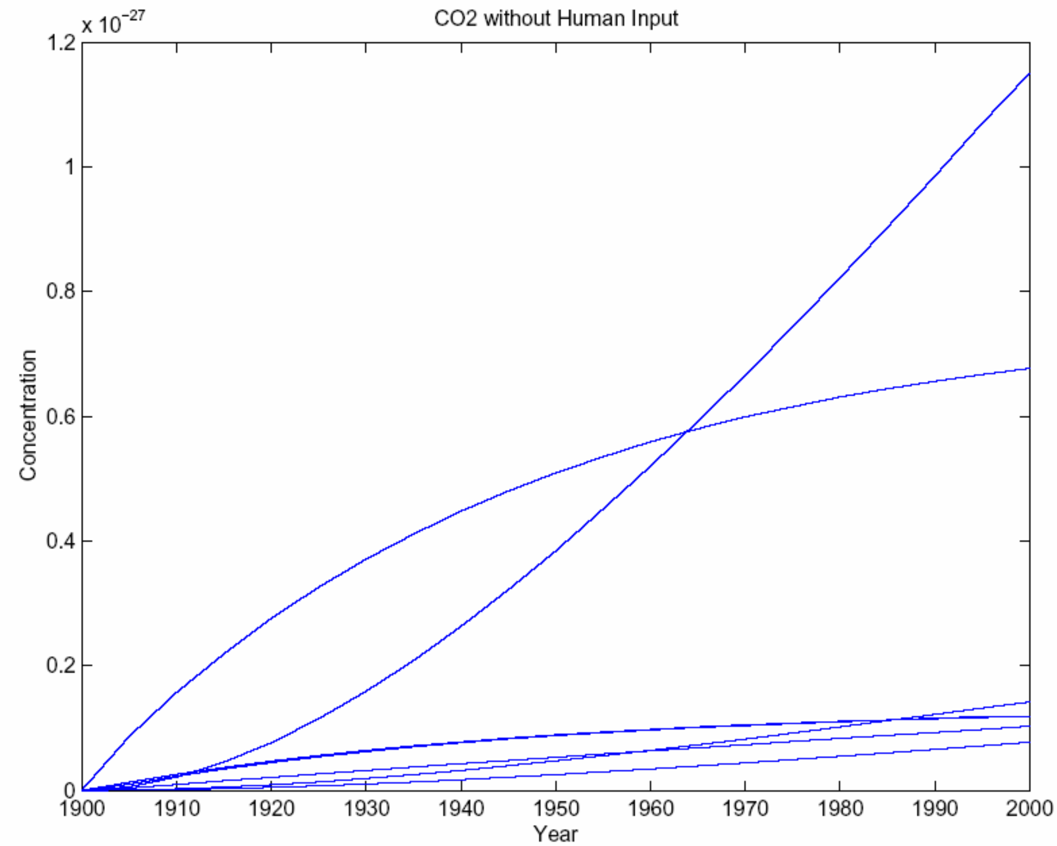
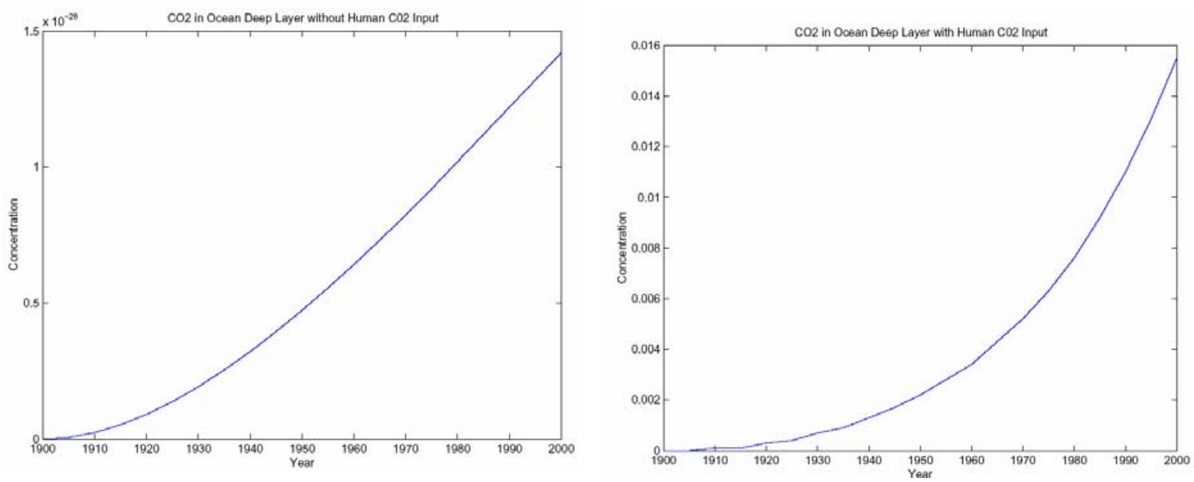


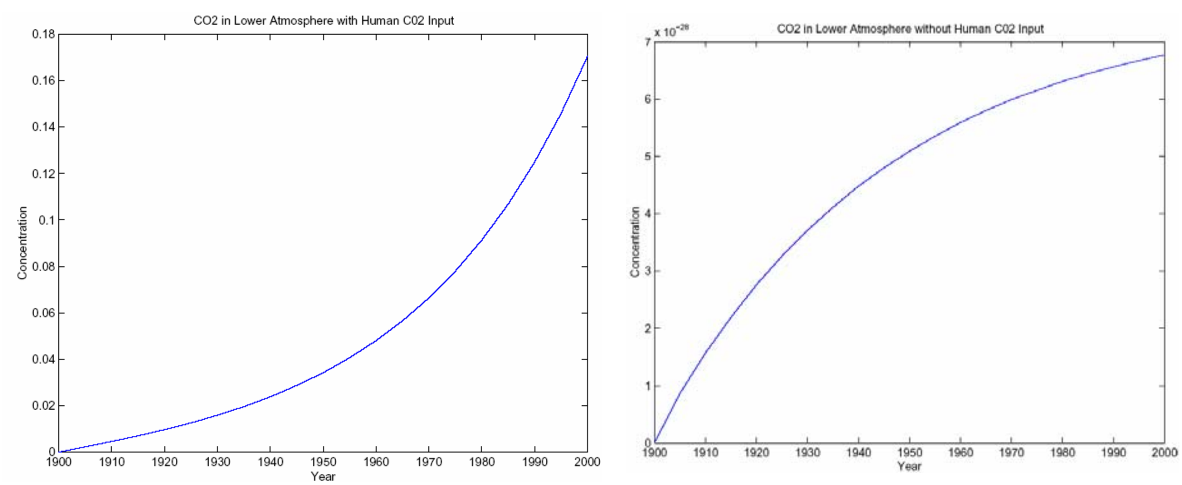
Figure 16: The CO_2 concentrations without human input into the model



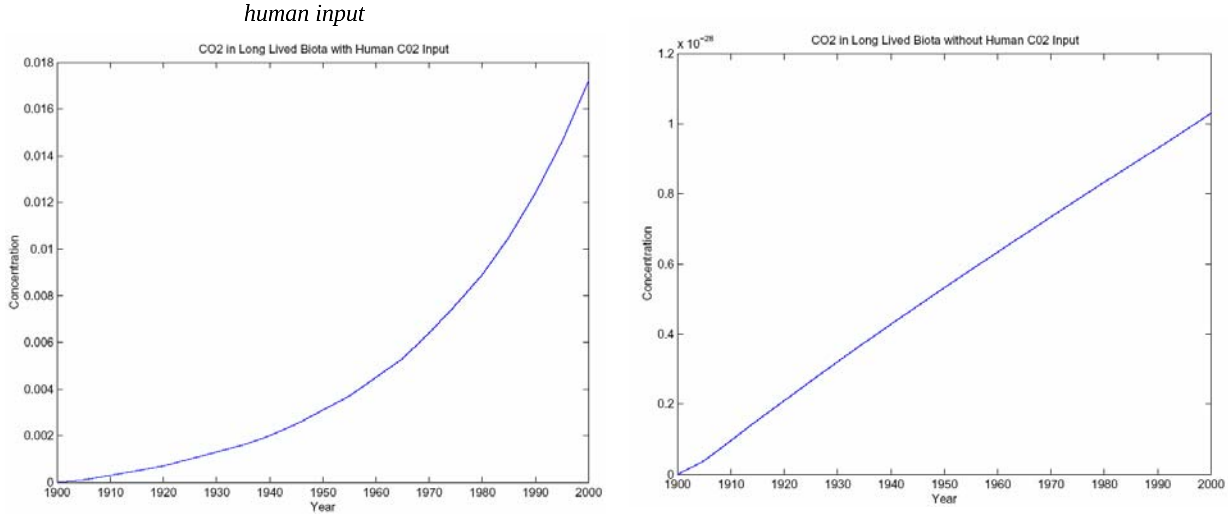
Figures 17a (left) and 17b (right): CO_2 concentrations in the Ocean Deep Layer with (17a) and without (17b) human input

In Figures 18a and 18b, the curves of the concentration of CO_2 in the Lower Atmosphere have changed greatly. When human CO_2 input is used in the model, the Lower Atmosphere concentration increases exponentially, but when the model does not receive human CO_2 input the Lower Atmosphere's CO_2 concentration growth changes from an exponential function to a logarithmic function.

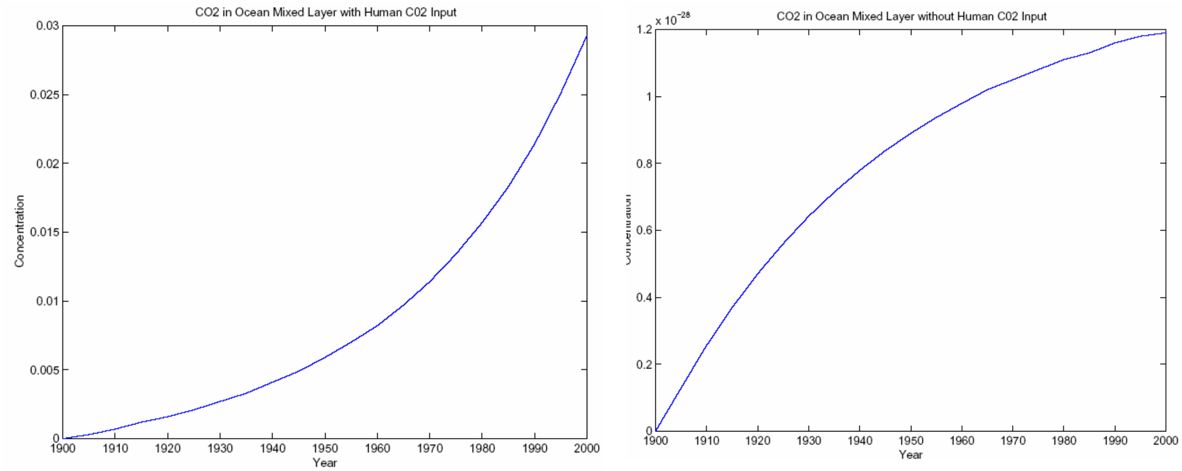
The Long Lived Biota also becomes almost linear without human CO_2 input; Figures 19a and 19b compares the two different simulations. The Mixed Ocean Layer, Figures 20a and 20b, and the Upper Atmosphere, Figures 21a and 21b, become logarithmic functions when there is no human input of carbon dioxide; opposed to the exponentially growing functions shown when there is human CO_2 input. Short-Lived Biota and the Marine Biosphere are still exponential, shown in Figures 22a and 22b and Figures 23a and 23b correspondingly, but when there is human input by the year 2000 the CO_2 levels are 10^{26} times higher.



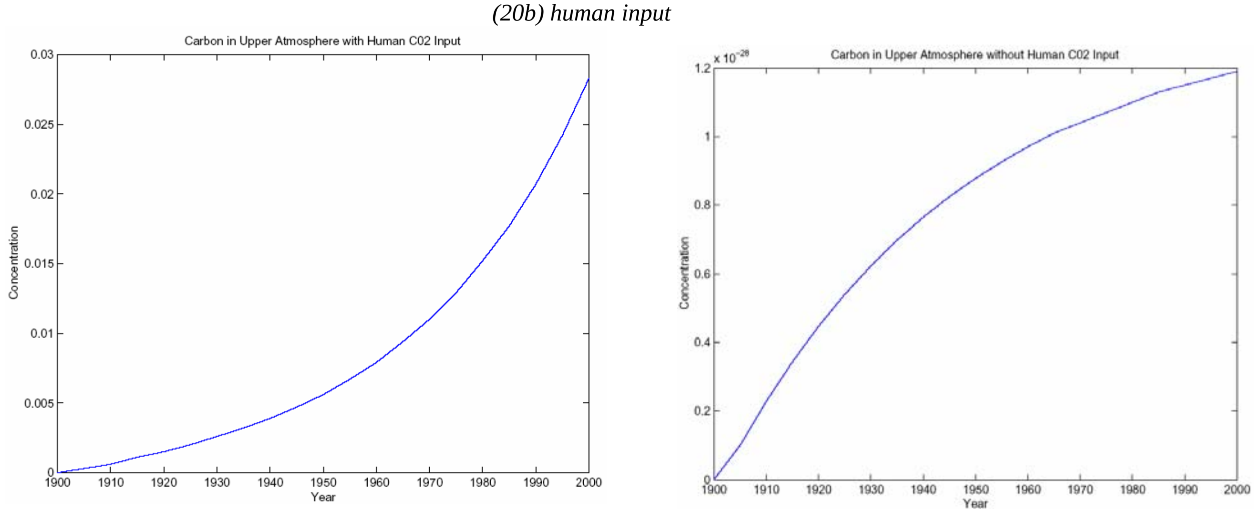
Figures 18a (left) and 18b (right): the concentration levels in the Lower Atmosphere with (18a) and without (18b) human input



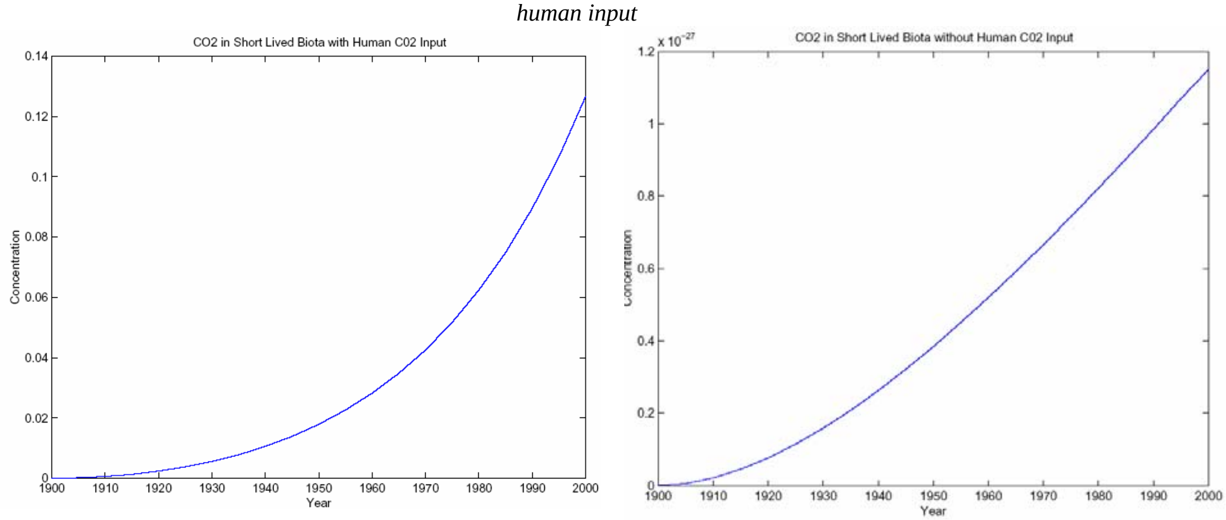
Figures 19a and 19b: the concentrations of CO_2 in the Long Lived Biota with (19a) and without (19b) human input



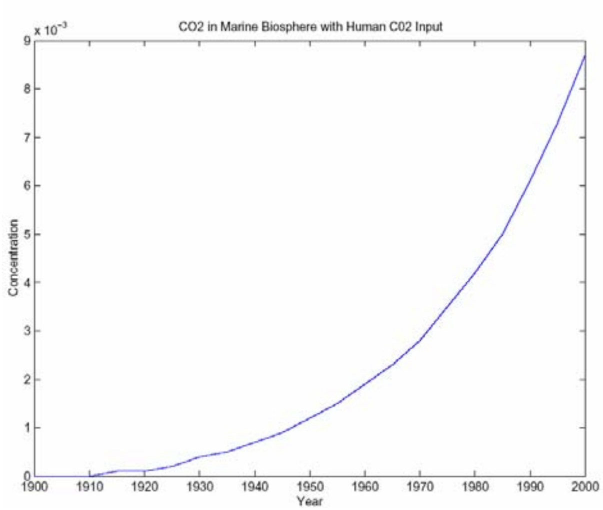
Figures 20a (left) and 20b (right): show the concentrations of CO_2 in the Ocean Mixed Layer with (20a) and without (20b) human input

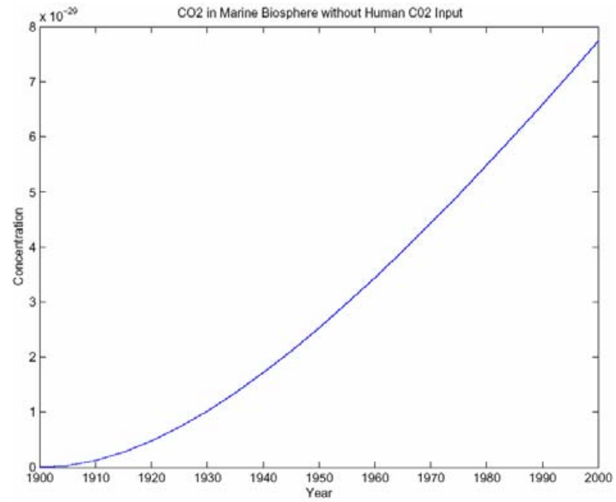


Figures 21a (left) and 21b (right): show the CO_2 concentrations in the Upper Atmosphere with (21a) and without (21b) human input



Figures 22a (left) and 22b (right) show the CO_2 concentrations in the Short Lived Biota with (22a) and without (22b) human input





Figures 23a (left) and 23b (right) show the CO2 concentrations in the Marine Biosphere with human input (23a) and without human input (23b)

This global climate model is a very simplified version of the carbon dioxide concentration changes resulting from human's impact on the environment. One of the simplifications in this particular model is the initial carbon dioxide concentrations. These initial concentrations for the seven reservoirs in 1700 are zero. This value does not reflect the true concentrations of the reservoirs at that time and is the main source of inaccuracies within this model.

3.2 One-Dimensional Energy Balance Climate Model

The One-Dimensional Energy Balance Climate Model is of the global-average, which models of the energy balance at the top and bottom of the atmosphere as it is affected by various parameters the modeler enters. The input for this global model is a matrix that has eight columns of data: one column of row numbers, four columns with actual data on spectral absorption, mixed gas, ozone and water, and three dummy columns all with 145 rows. The program also takes into consideration the following variables: the solar constant, initial surface temperature, initial temperature lapse rate, stratospheric temperature, flux factor, surface pressure, CO_2 mixing ratio, ozone column amount, precipitable water amount, land surface albedo, clear-sky atmospheric reflectance, clear-sky atmospheric transmittance, low layer cloud amount, cirrus cloud (and volcanic aerosol), low layer cloud albedo, low layer SW cloud transmittance, cirrus cloud albedo, cirrus SW cloud transmittance, cirrus long wave emittance, low layer cloud top height, low layer cloud base height, and cirrus height above tropopause. The values for all of these variables can be entered in by the user or a default value for each can be used. (Justus)

The results from the model when using the default values for each of the input variables include the values for the clear sky albedo, clear sky total transmittance, planetary albedo, equilibrium temperature, number of iterations, flux factor, new surface temperature, new atmospheric lapse rate, tropopause, and a couple of variables that helped calculate these values. Given the standard values and data, the resulting values are shown in Results 1.

Results 1	
Clear-sky planetary albedo	0.11121
Clear-sky total transmittance	0.704
Planetary albedo	0.30545
Equilibrium temperature	254.36 K
Number of iterations	5
(S0/4)*(1-alpha),Eir (W/m**2)	237.4 237.4
Eclr,Ecld,Ecir,Eboth (W/m**2)	251.7 227.0 240.0 216.6
Ednclr,Edncld,Edncir (W/m**2)	281.3 363.9 283.5
SWnet,LWnet,Els (W/m**2)	136.5 -63.6 72.9
G	148.2 W/m**2
g	0.3845
Eepsilon(eff)	0.6155
Flux factor (W km m**-2 K**-1)	-11.53
New Surface temperature	287.17 K (= 385.6 W/m**2)
New atmospheric lapse rate	6.33 K/km
Tropopause	11.144 km

The resulting data shows the atmospheric conditions resulting from the input values. The most important of these values is the new surface temperature, 287.17 K. Given the standard input the real average global temperature is about 14˚C (57.5˚F). When the default variable for clear-sky atmospheric reflectance is changed from 0.05 to .01 the resulting data is shown in Results2. A similar change in the atmosphere given higher concentrations of CO_2 would decrease this variable. The new average temperature is raised to 290.25 K (17˚C). A difference of 3˚ is a substantial temperature change given only a one variable change; albeit an important one.

Results 2	
Clear-sky planetary albedo	0.05905
Clear-sky total transmittance	0.701
Planetary albedo	0.27979
Equilibrium temperature	256.68 K
Number of iterations	1
(S0/4)*(1-alpha),Eir (W/m**2)	246.1 246.1
Eclr,Ecld,Ecir,Eboth (W/m**2)	260.7 235.7 248.5 224.7
Ednclr,Edncld,Edncir (W/m**2)	293.5 380.0 295.7
SWnet,LWnet,Els (W/m**2)	139.2 -66.3 72.9
G	156.3 W/m**2
g	0.3884
epsilon(eff)	0.6116
Flux factor (W km m**-2 K**-1)	-11.53
New Surface temperature	290.25 K(= 402.4 W/m**2)
New atmospheric lapse rate	6.32 K/km
Tropopause	11.639 km

3.3 Hadley Centre for Climate Prediction and Research

Another group of climate models that were also examined are the Hadley Centre for Climate Prediction and Research's climate models. The Hadley Centre provides a focus in the United Kingdom for the scientific issues associated with climate change. They have engineered several different types of models that simulate the earth's climate, which depends on the atmosphere, the land's surface, and the ocean and the ocean's surface. Some of the models they have developed are: the three dimensional atmosphere model, a three dimensional atmosphere model with a 'slab' of ocean, a three dimensional ocean model, an atmosphere chemistry model, a coupled atmosphere and ocean model, a regional climate model and a carbon cycle model. (Jorkens)

The general circulation model for the atmosphere simulates the land's surface and cryosphere. This is similar to the weather forecasting models but it is more generalized because it is usually predicting for a longer time period. The atmosphere circulation model is provided with sea surface temperatures as well as data of the sea ice coverage, because it does not have any predicting mechanisms for conditions over the ocean. The model cannot predict how conditions over the ocean will change given the results it formulates. This atmosphere circulation model is used to study atmospheric processes, variability of climate and the climate's response to changes in sea-surface temperature. (Jorkens)

The next type of model is the atmospheric general circulation model with a 'slab' of ocean. This model extends the atmospheric general circulation model and it has the ability to predict sea-surface temperatures.

However, the atmospheric general circulation model with a ‘slab’ of ocean does not deal with the depth of the ocean though; it deals with the ocean as an entity of a constant depth. The atmospheric circulation with an ocean ‘slab’ model is used for predicting what the climate would be like for a constant level of carbon dioxide and it is not used for predicting the rate of change in the climate because the rate of change is largely affected by the ocean and its circulation. (Jorkens)

The ocean general circulation model is a counterpart to the atmosphere general circulation model. Both models are three dimensional, but do not have the ability to simulate in their counter part’s area. The ocean circulation model has to be supplied with atmospheric data including the air temperature and other properties. This model can be used only when studying ocean circulation, interior processes and variability. (Jorkens)

The atmospheric chemistry model simulates the chemical processes in the atmosphere that change concentration of gases not relating to CO_2. Examples of these gases are the ozone, methane, CFC replacements, nitrogen oxides, hydrocarbons, and carbon monoxides. The atmospheric chemistry model considers the emission of these gases from both natural and human sources. The model also determines the rate of formation and decomposition of these gases. Figure 24 shows the concentrations of ozone in the troposphere today estimated from human and natural emissions (top), and estimates concentrations in pre-industrial times. (Jorkens)

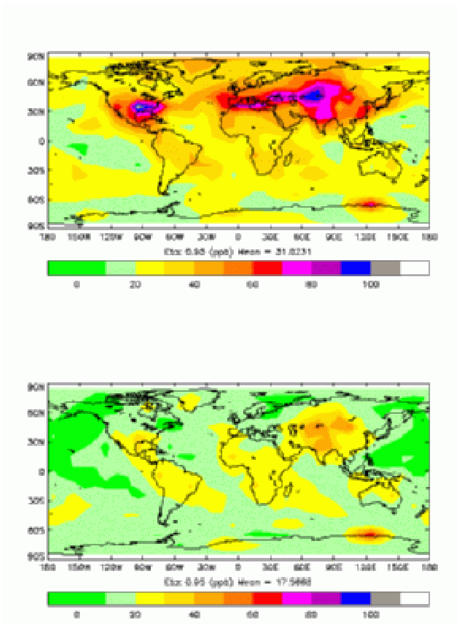


Figure 24: *Modeled concentrations of tropospheric ozone today (top), and (bottom) those estimated for pre-industrial times (Atmospheric Chemistry)*

The coupled atmosphere-ocean general circulation model is one of the most complex models of the Hadley Centre. The atmosphere-ocean circulation model combines the atmosphere general circulation model and the ocean general circulation model into one highly complex model. This model is used for predicting the rate of change for the future climate. The atmosphere-ocean general circulation model can be used alone, but concentrations of various gases have to be specified. This model can also be used with either the carbon dioxide cycle or the atmospheric chemistry model. When the model is used with the carbon cycle model, it is able to predict changes in the carbon dioxide concentrations given the CO_2 emissions as input. If the atmosphere-ocean general circulation model is used with the atmospheric chemistry model, the model can then predict changes in other atmospheric gases in response to climate changes and emission changes. Other extensions are also being developed, such as a more complex "eddy-permitting ocean" model called the HadCEM. One feature of this model's output data is displayed in Figure 25 of the global heat transport.

The figure shows the heat transport split into the time-mean and time-varying flow components. The difference between the time-varying component (yellow) and the coarser resolution (red) shows how the eddies have a large impact on the heat transport. (Jorkens)

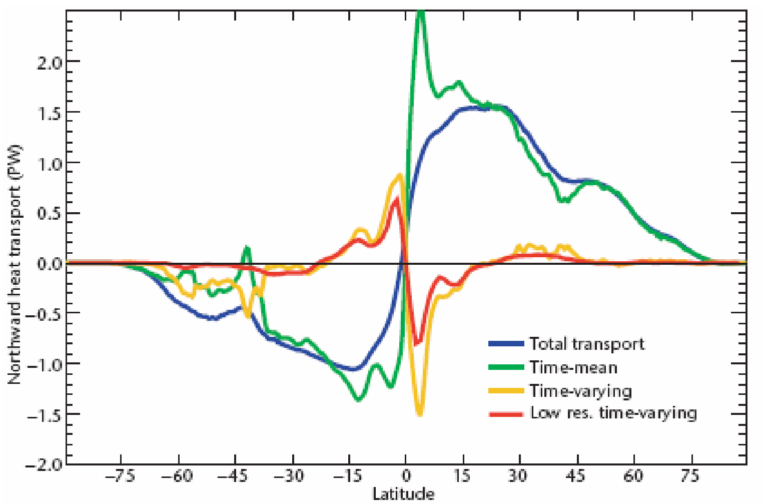


Figure 25:
Northward ocean heat transport from HadCEM
(HadCEM: A Climate Model with Eddy-Permitting Ocean)

The regional climate model is designed for smaller areas so that distinctive land structures like mountains or bodies of water, which affect the climate, can be represented. The regional model is usually run under shorter time constraints than any of the other models, typically around 20 years due to the complexity and refinement of the model. Using such a regional model centered over Europe, the change in summer precipitation is shown in Figure 26, given a doubling in CO_2 concentrations in the year 2020. (Jorkens)

Projected change in summer precipitation by the year 2020 in Europe

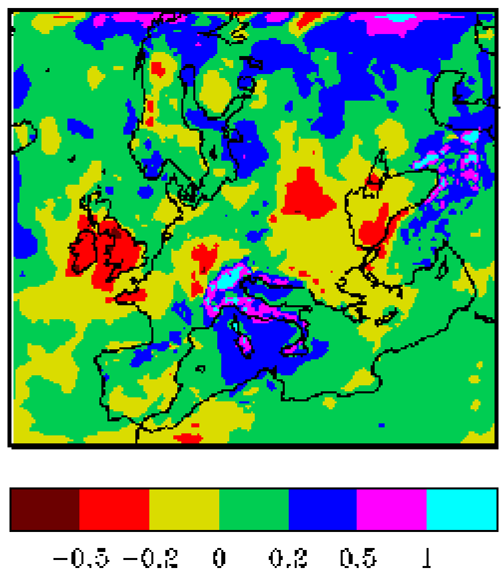


Figure 26: Changes in precipitation in mm/day (RegionalClimate Predictions)

The carbon cycle is modeled with respect to both the ocean general circulation model and the atmosphere general circulation model. The carbon cycle is a very important part of the atmosphere and the ocean cycles and it includes three subsets, an ocean carbon cycle model, a terrestrial carbon cycle model, and a coupled climate-carbon model. (Jorkens)

The ocean carbon cycle model keeps track of the chemical reaction of carbon dioxide in the surface waters. The mechanisms controlling how the carbon dioxide is transferred to the deep ocean water, the physics of the ocean, and the ocean's biology all have to work together to accurately represent the ocean's carbon cycle. The current model, used by the Hadley Centre to represent this cycle, is run at a low resolution in order to accurately represent the physics of the ocean. This method allows for less computing resources and provides the option of more testing. The ocean's biology represented by Figure 27, shows how the phytoplankton needs sunlight and nutrients, while the zooplankton preys on phytoplankton and on themselves. Dead materials form detritus, which breaks down to form nutrients. (Jorkens)

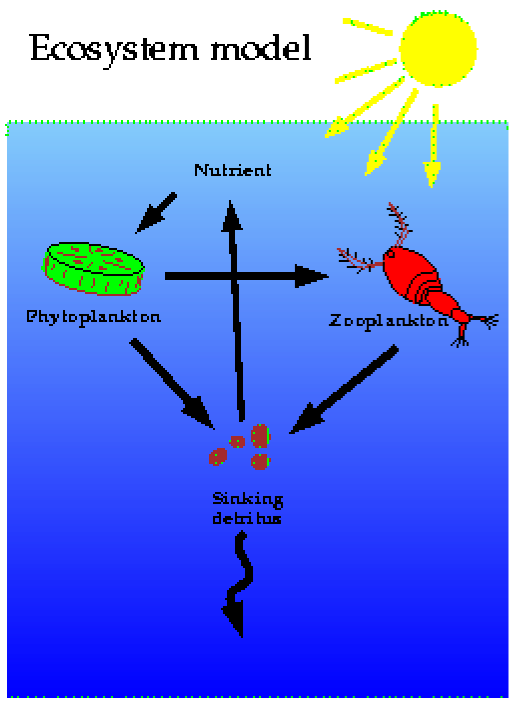


Figure 27: Ocean Biology (Carbon Cycle)

Dissolved inorganic carbon and alkalinity represent the remaining carbon in the ocean. The dissolved inorganic carbon is absorbed by phytoplankton, and emitted back into the ocean when it is broken down. The alkalinity is used for calculations to determine the proportion of dissolved inorganic carbon in the surface, in the form of CO_2, which is then used to calculate the air-sea flux of CO_2. The physics of the ocean moves all of these different components around.

The results of the zonally integrated air-sea flux of CO_2 are then compared to data collected from the environment. As shown in Figure 28, the simulation values are very similar to the data collected on air-sea flux of CO2, the main difference that the simulation does not account for, is the changes around the equator in the Pacific. (Jorkens)

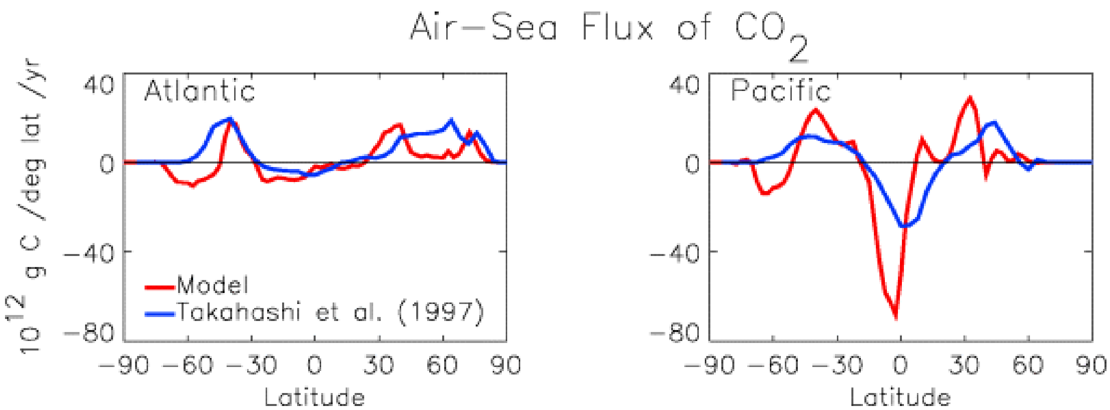


Figure 28(Carbon Cycle)

The amount of carbon absorbed during phytoplankton growth can also be simulated by this carbon dioxide model. The main difference between the projected values from the model and data collected is the subtropics, which are known to behave differently then the rest of the world in this respect. The two graphs in Figure 29 demonstrate this behavior deviation. (Jorkens)

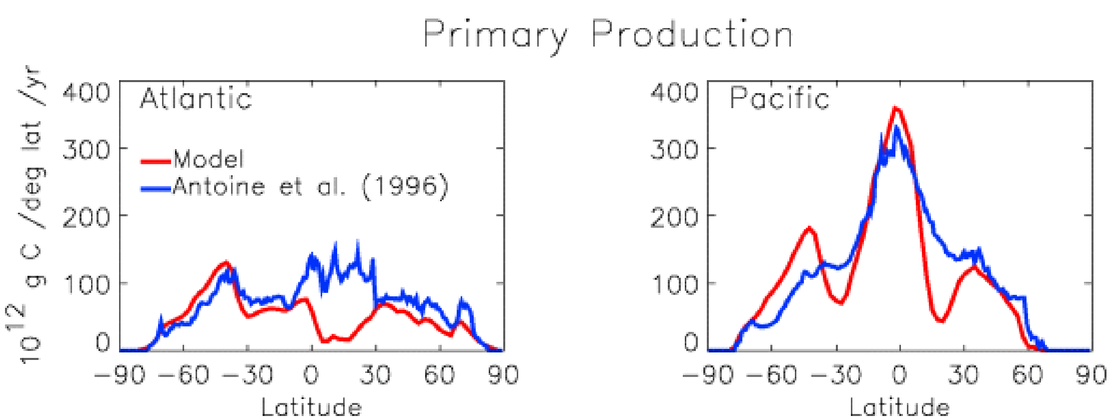


Figure 29: Amount of carbon taken up during phytoplankton growth (Carbon Cycle)

The terrestrial carbon cycle model is a global model of the vegetation, which consists of five types of vegetation: broadleaf tree, needle leaf tree, C3 grass, C4 grass, and shrub. A model of the interaction of the types of vegetation with the climate and atmosphere that was used in the carbon cycle model is show in Figure 30. (Jorkens)

Types of Environmental Affects caused by Vegetation

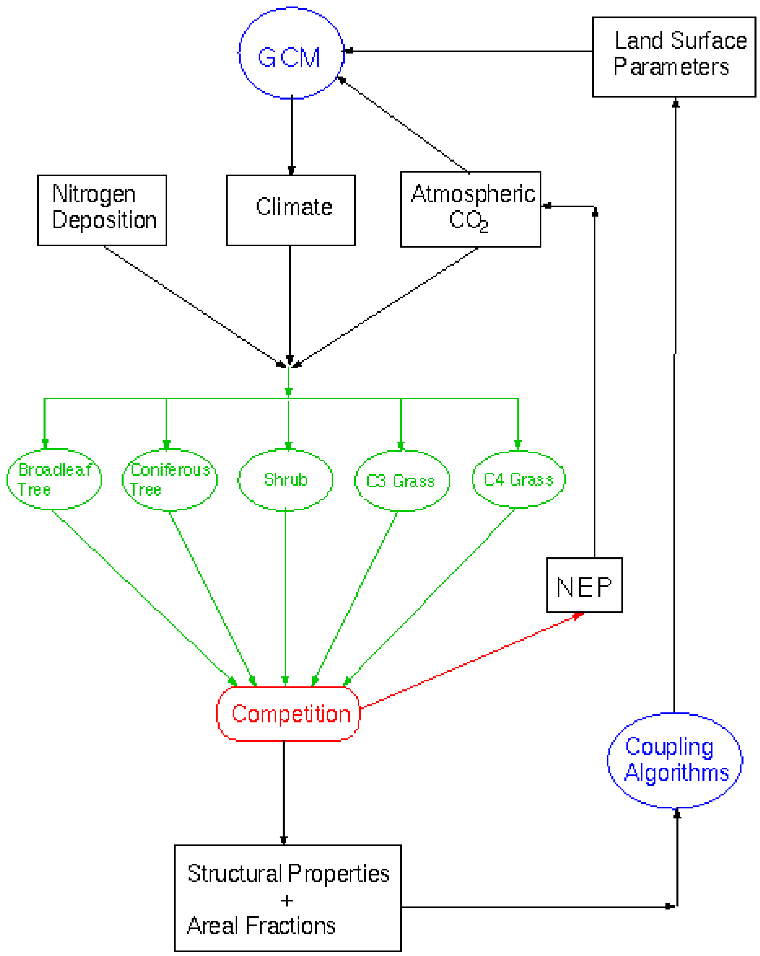


Figure 30 (Carbon Cycle)

Each type of vegetation has growth and respiration, both of which are dependant on climate conditions like temperature and soil moisture. The net primary productivity is the difference between a plant's photosynthesis and its respiration.

Carbon is used by the plant for leaf, stem, or root mass, and then reverted back into the soil and broken down. This process of breaking down the carbon and releasing it back into the atmosphere it is referred to as soil respiration and is demonstrated in Figure 31. (Jorkens)

Plant Cycle

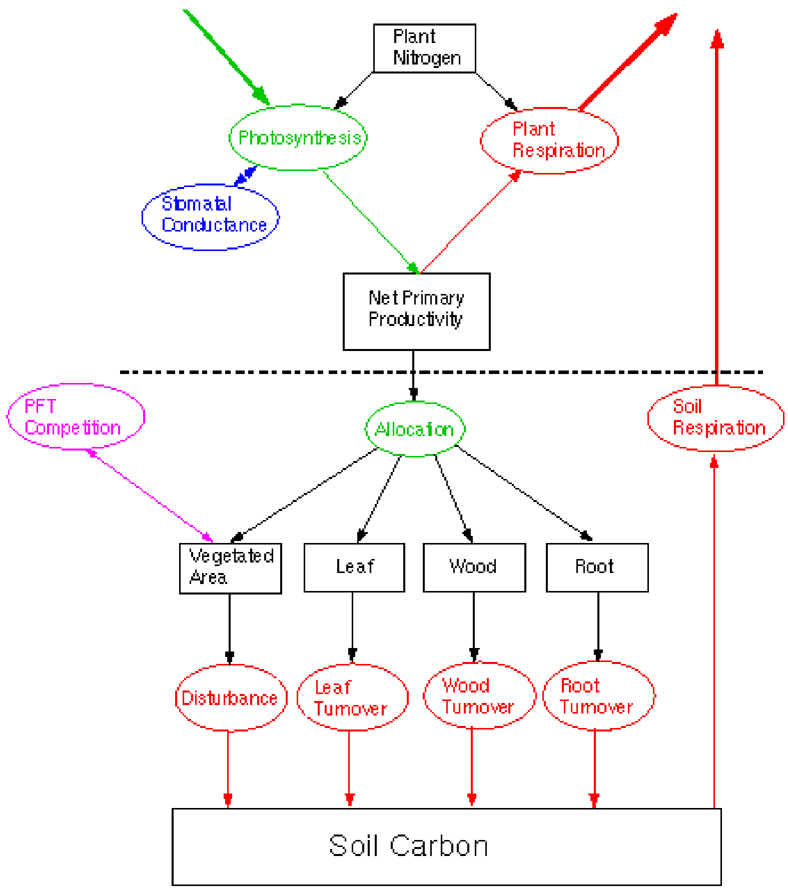


Figure 31 (Carbon Cycle)

If the Carbon Cycle Model is run without any other considerations with regard to environmental changes that would affect the carbon dioxide concentrations, the CO_2 concentrations are shown in Figure 32.

The red line in Figure 32 represents the rising concentrations of carbon dioxide when the concentration affects the temperature and the temperature affects the carbon dioxide concentrations. The blue line represents the rising concentrations without the link between the climate and carbon dioxide. (Jorkens)

Rising CO_2 Concentrations

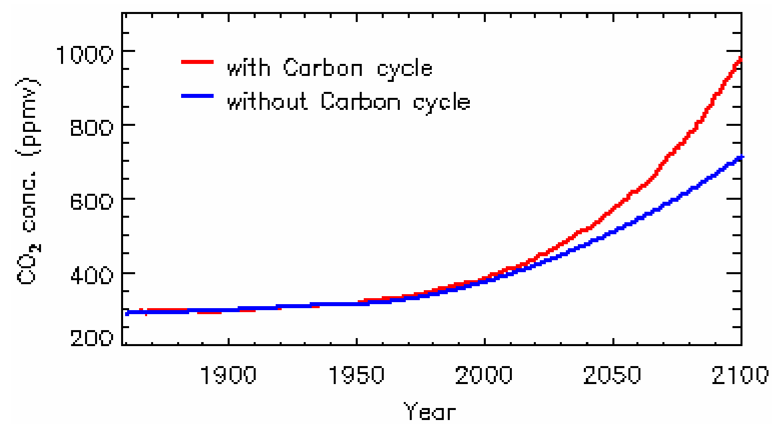


Figure 32(Carbon Cycle)

When the carbon cycle and its resulting CO_2 concentrations are used to plot the rising global temperatures given the rising concentrations in Figure 34, the mean temperatures are shown in Figure 33. The same relationship between the CO_2 concentrations and the temperature is used in this figure in red and omitted in blue like in Figure 32. (Jorkens)

Global Mean Temperature

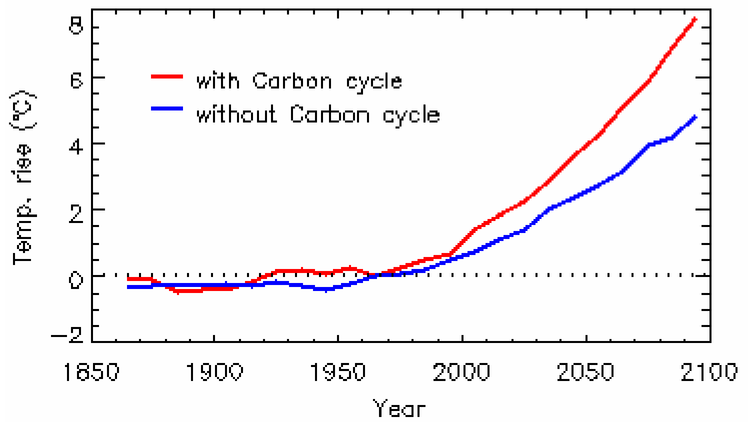


Figure 33(Carbon Cycle)

Figure 33 shows an increase of 3˚C in 2100, when the link between the carbon concentrations and the temperature is used. The rate of global average temperature change and the values from Figure 33 can be used to compute the changes that will take place in the vegetation and soil, as shown in Figure 34. Figure 36 shows the increasing CO_2 concentrations and temperatures. The soil carbon content drops from the increased soil respiration as a consequence of the more rapid break down of carbon. The carbon levels of the vegetation eventually start to decrease exponentially due to the dying out of the forests because of changes in temperature and precipitation. (Jorkens)

Soil and Vegetation Carbon Levels

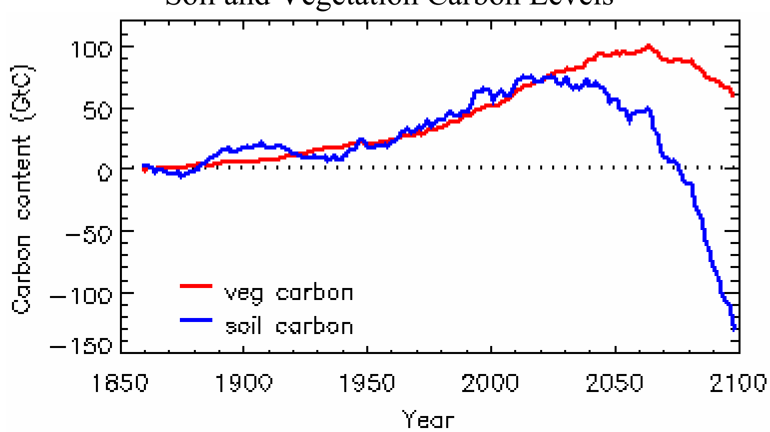


Figure 34(Carbon Cycle)

The total amounts of carbon held in the vegetation and soil after a long run of the model under pre-industrial conditions are 495 GtC and 1170 GtC respectively. The International Panel on Climate Control estimates of real-world values are 600 and 1600 respectively, but there are no direct, global measurements and the modeled values are within the possible range of values. Typically in the model, GPP is about 120-125 GtC/yr, plant respiration is about 62 GtC/yr and soil respiration is about 60-61 GtC/yr. For a single year, NEP can be as large as 3-4 GtC (either uptake or release), but in the long term it is very close to zero. This indicates that the model is in a state of balance.

All of the models from the Hadley Centre show the many of the different aspects of the global climate that can be modeled, and also how the complex models can actually be. Some models further clarify circulation of the atmosphere and ocean, and how these might change in the future; while other models give values for the possible temperature changes from the increasing concentrations of gases. Both types of climate models are very important to this type of modeling because both types of models are dependant on each other. Many of the models from the Hadley Centre were initially created to stand alone, but have been integrated into other more general models of the global climate. More general models are of the entire climate system are also created, like the Massachusetts Institute's Integrated Global System Model. MIT's model takes a much more general view of all of the atmospheric and oceanic interactions in order to produce general data on climate changes. The purpose of generating this data is to determine the economic stress given the rising gas concentrations and rising global temperatures.

3.4 Massachusetts Institute of Technology's Integrated Global System Model

The Massachusetts Institute of Technology's Integrated Global System Model is designed to simulate environmental changes in response to the anthropogenic forces. The current model includes an economic model, a coupled model of atmospheric chemistry and climate, and models of terrestrial ecosystems. Figure 35 shows the feedback loops in the atmosphere. These models attempt to be more regional specific than many other more general models. Figure 36 shows how the entire model breaks down into its components and shows the different feedbacks in the model and ones that will be implemented in the future. (Prinn)

Chemistry in Troposphere

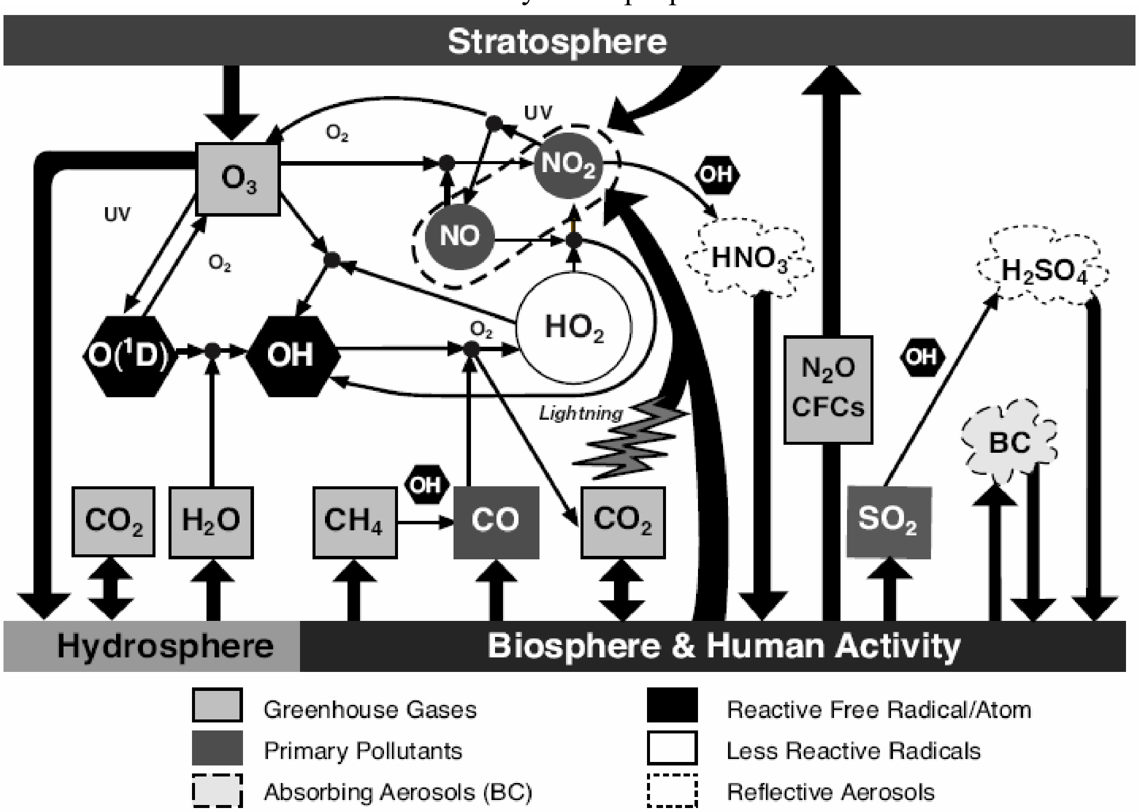


Figure 35: Shows linkage between urban air pollution and climate (Prinn 3)

MIT Integrated System Model

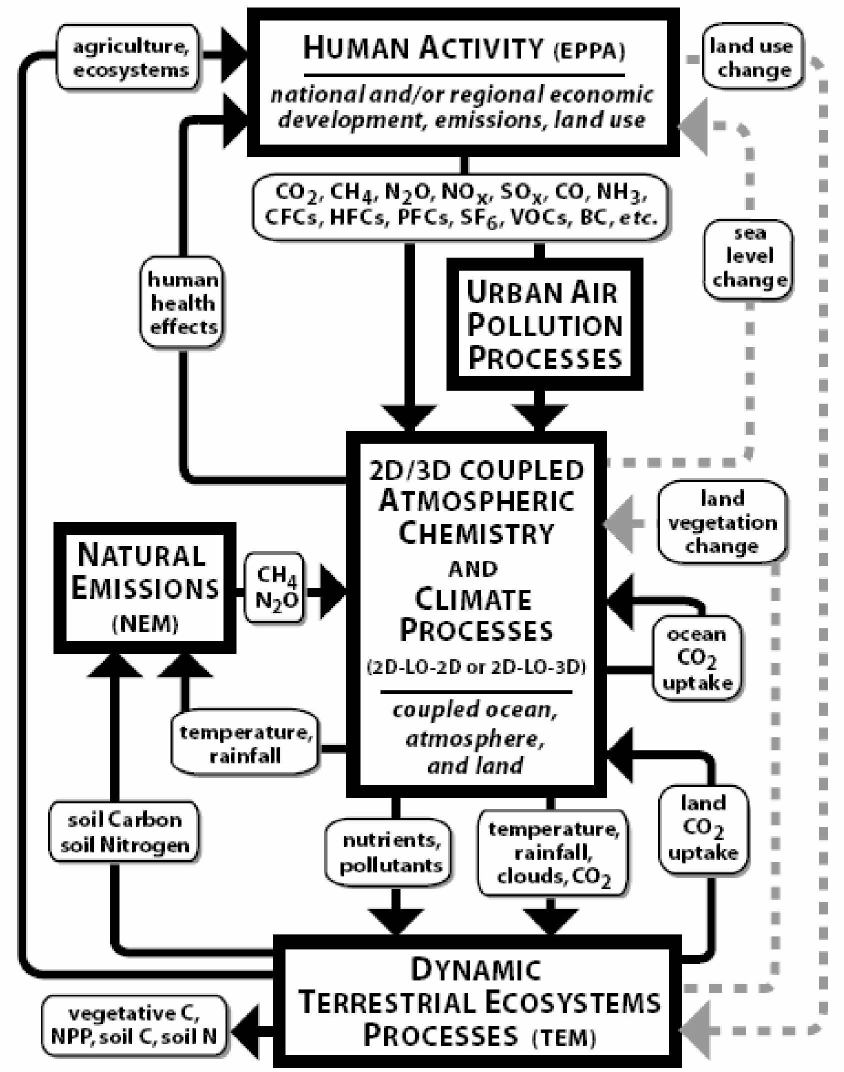


Figure 36: framework, sub-models, and processes, feedbacks that will be implemented are dashed lines (Prinn 5)

The outputs from the coupled atmospheric chemistry and climate model drive the Terrestrial Ecosystems Model. The output from this model feeds into the coupled atmospheric chemistry and climate model, and also feeds the soil nutrient contents to the Natural Emissions Model. (Prinn)

The economics sub-model accounts for the world's economy and energy usage when estimating the anthropogenic emissions. Analysis of different policies is also possible using this model; therefore it can provide nations with the estimated costs of changing international trade policies.

The atmospheric chemistry model analyzes the concentrations of gases and aerosols in an urban environment and estimates their affect. This model is used in conjunction with a model that processes exported pollutants from urban areas including emissions from non-urban areas. This model produces conditions for the polluted areas, and the background areas (rural) as well. There is also a climate component, which is constructed from a two dimensional land model and a three dimensional ocean circulation model. A simplified version of earth's atmospheric chemistry is also used to connect the climate and the chemistry models. These models then enable predictions for climate and air composition over land and over the ocean. A mass-balance model of the ice sheets in Greenland and Antarctic is incorporated, while a mass-balance model of the mountain glaciers is currently being designed. These two mass-balance models will make simulations that will include sea level changes. A terrestrial ecosystem model is also included, which can predict ecosystem states and support other feedbacks in the model. A natural emissions model is used to simulate natural carbon emissions from the land to the atmosphere. This model is used primarily in reference to policy making. The model helps predict how economics and population growth are integrated and how they affect the climate and human's emissions. (Prinn)

Results from this model are described in Figures 37-40. In Figure 37, it shows the predicted emissions for 2100, as well as the emissions for 2100 if they were capped in 2005.

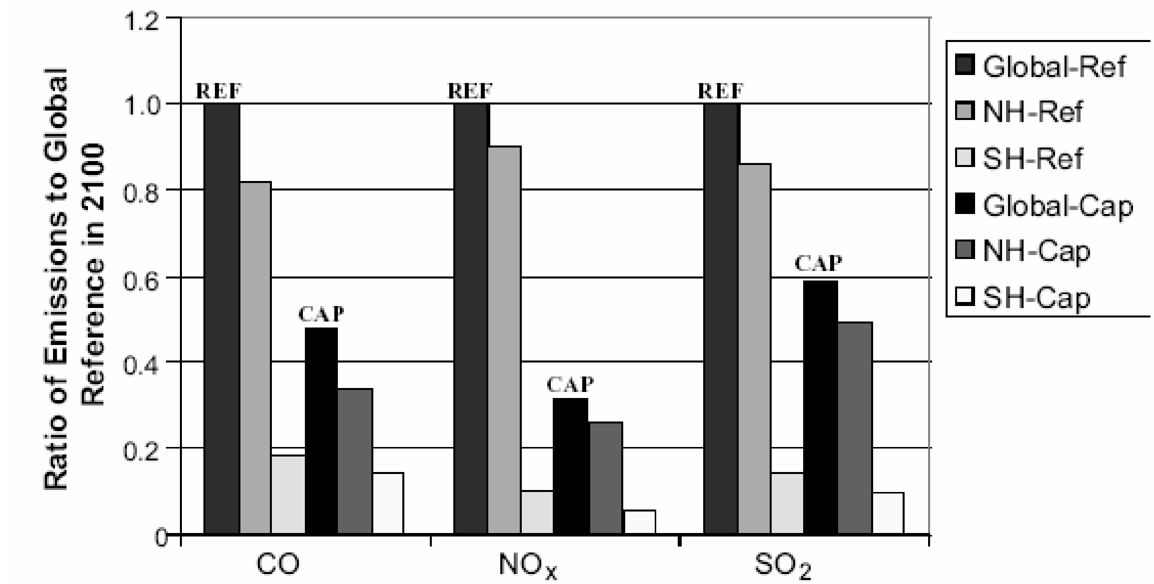


Figure 37: The 2005 emissions cap is shown as a ratio of the emissions projected for 2100 (Prinn 7)

In Figure 38, shows the effects of concentrations of other gases on CO, NO_x, SO_x if capped in five different ways. Also the effects if they are all capped, if only CO, NO_x, and SO_x are capped, and then if each CO, NO_x, or SO_x are capped by themselves. The differences in the concentrations of CH4, O3, aerosols, and OH from their capped values to the projected values in 2100 are also shown in Figure 38.

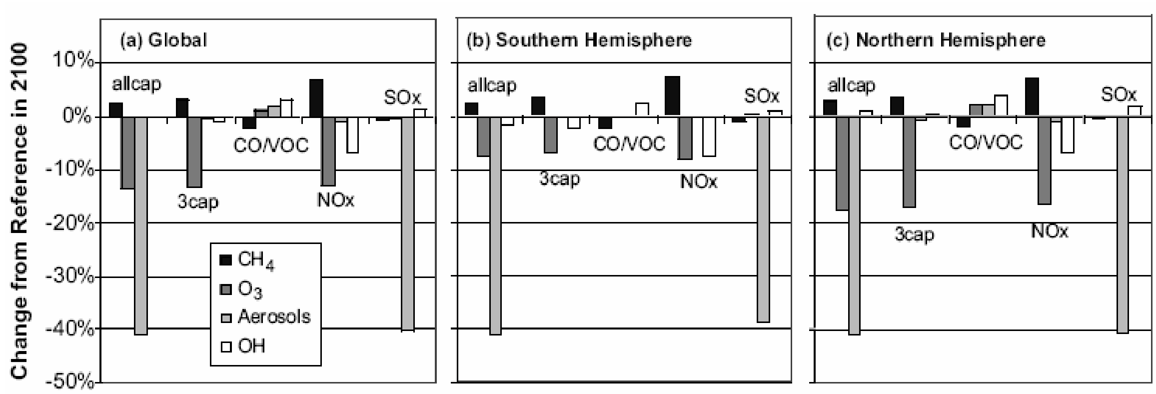


Figure 38: Emissions capped at 2005, uncapped emissions referenced up to 2100 (Prinn 8)

Figure 39 shows the net primary production, carbon intake of vegetation only, and the net ecosystem production, vegetation with soil respiration and decay. This model shows how both net values increase as ozone decreases. Figure 40 shows the data produced if forests receive fertilizer or the nitrogen they needed for more productive photosynthesis.

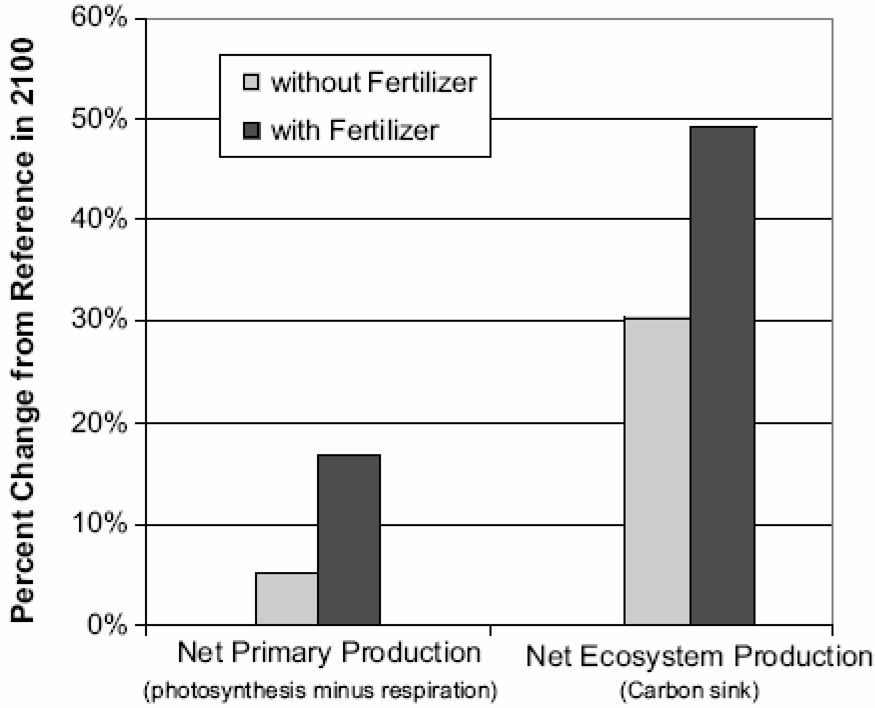


Figure 39: The uptake of carbon is shown in Net Primary Production and Net Ecosystem Production as percent change (Prinn 9)

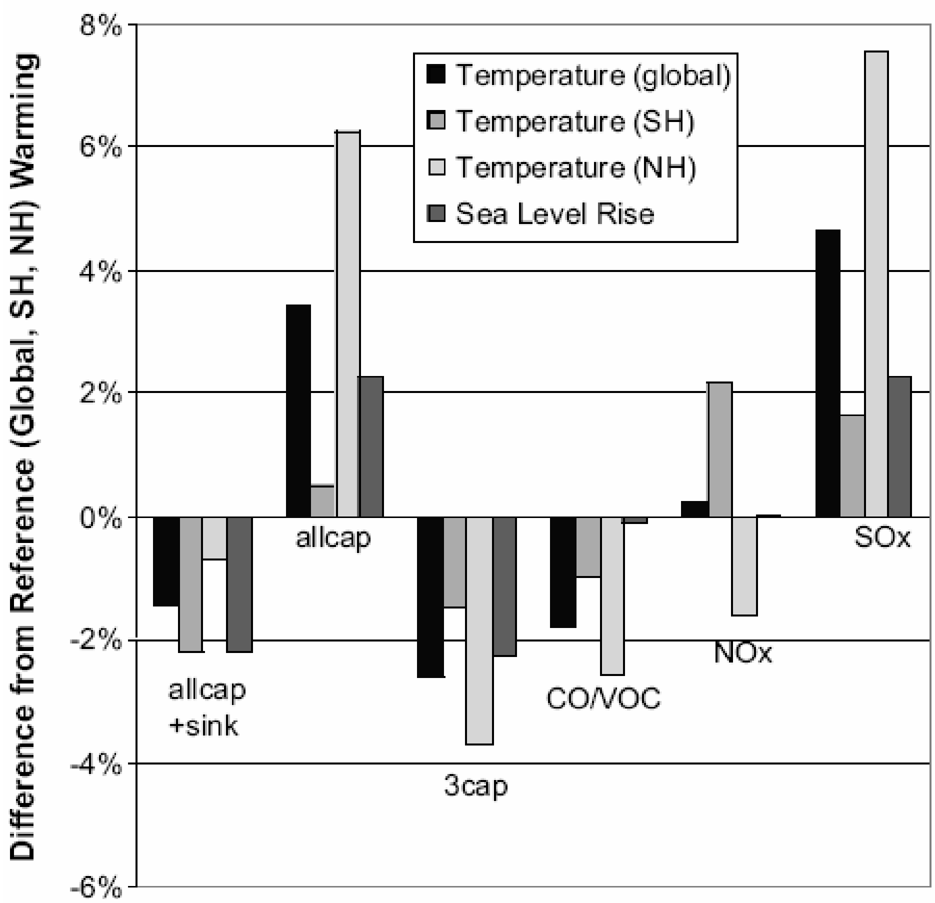


Figure 40: Effects capping has on the temperature and sea level (Prinn 11)

The effects the gas concentrations have on the global temperatures and the sea level and are shown as percentages of the global-average reference case changes of 2.7°C and .4 meters respectively. The largest change shown is when SO_x is capped, due to its reflective nature it helps cool the affects of other gases.

Economic affects of all of these environmental changes are considerable. One such policy created is done by capping the gas concentrations at 2005 or 550 parts per million (ppm) of CO_2. The estimated saving of this policy, including a 5% discount, are $2.5 trillion dollars (for 'without fertilizer' figures) and $4.7 trillion dollars (for 'with fertilizer' figures). The cost of a stabilization policy would still more, much more. It is estimated that these figures are only 12 to 22% of the total stabilization policy.

Although all of the models discussed are vastly different, they all lead to the same conclusion regarding the carbon dioxide emissions that are being put into the atmosphere by humans. The Global CO_2 Model results showed the vast difference between the rising CO_2 concentrations when humans are part of the cycle, many reservoirs had 10^{26} times higher concentrations by the year 2000 than when humans were not adding any CO_2 to the cycle. The One-Dimensional Global-Average Model of Energy Balance showed the rising temperature that would occur when CO_2 concentrations would reduce the reflectance rate. The Hadley Centre Models projected a variety of values about the changing temperatures and environment. The atmospheric chemistry models showed how the ozone levels from humans during pre-industrial times, so that they can be compared to the ozone concentrations from today. The coupled atmosphere-ocean general circulation model allowed the Hadley Centre scientists to graph the ocean heat transport more precisely in order to show the large affect the eddies actually have on ocean circulation; with this knowledge they can make more accurate ocean circulation and global climate models. The Hadley Centre's regional model also showed how the precipitation in Europe will decrease around 73 mm/year in 20 years. The carbon dioxide cycle also showed, just like previous carbon dioxide models how the carbon dioxide levels will increase exponentially. However, this model also showed how the increase of CO_2 concentrations will affect temperature, and how this affects soil respiration and vegetation globally. The Massachusetts Institute of Technology's Integrated Global System Model gave results for the increasing levels of CO_2, but also demonstrated the large economic costs of stabilizing the carbon dioxide levels in the year 2005, \$2.5 trillion dollars (\$4.7 trillion if fertilizer is included). This projected cost was estimated to be only 12-22% of the projected cost of stabilizing the climate when the carbon dioxide concentrations get too high. But these increasing levels of CO_2 are already affecting the environment. Climate changes have been recorded and weather patterns are changing due to the poisonous levels of carbon dioxide that humans are pumping into the environment. The current affects of the rising carbon dioxide levels along with the projected affects are discussed in the next section.

4. Social Impacts

The projected changes to the climate have social and economic implications. These impacts include alterations to human health, hydrological cycle, agriculture, habitat, and species. The major health affects include heat waves, respiratory agitators and an increase in disease outbreaks. Changes to the hydrological cycle are comprised of changes in the sea level, the thermohaline circulation, weather patterns, and water resources. The agricultural impacts from the warming climate and changes in the hydrological cycle include crop losses and increased pest populations. Various habitats including forests, coastal areas, and marine life are also impacted by these changes. Changes also affect migrations, lifespan, reproductive cycles, population, growth rate, and food sources of wildlife. All of these impacts illustrate the negative affects caused by global warming.

4.1 Health Affects

One of the many negative impacts that global warming will have and is currently having on our society is the increase in health problems. Three of the main health problems that our society is now facing are unexpected heat waves, increase of diseases and respiratory aliments.

Examples of current heat wave problems occurred last summer over Western Europe and in Chicago in 1995. In Western Europe, during the summer of 2004, a region of high atmospheric pressure hung over the area for several weeks. This high-pressure area prohibited any flow of rain bearing, low-pressure systems that typically arrive from the Atlantic Ocean. As a result, most of Western Europe experienced an extended period of unusually hot, dry weather. Switzerland saw the hottest June in over 250 years, with a temperature 5.9^{o}C above normal. In France, the temperature remained around 104^{o}F consecutively for many weeks. France's National Institute of Health and Medical Research estimated that there were close to 15,000 heat related deaths in France that August. Scientists calculate that this heat wave may have claimed over 30,000 European lives that summer. These numbers would make it Europe's largest disaster in over 50 years.

Similar problems occurred in Chicago in 1995, where 739 people died of heat related problems. Another heat wave hit Chicago in 1999. Death tolls were not as staggering this time, as the city made the proper alterations to living conditions after the 1995 heat wave. They found that many of the victims were elderly, poor or lived in the heart of the city. Most of them did not have air conditioning units, or if they did, they could not afford to turn them on. After 1995, the city made a huge effort to provide affordable air conditioning and initiated a program to check on elderly people and people who lived alone. As a result, only 110 people died in the heat wave of 1999. This demonstrates that with the appropriate preparation sudden heat waves will be less dangerous, but still deadly.

The increase in diseases is directly related to the increase in global temperature. Diseases that once existed only in tropical areas, can now survive and flourish in more northern areas. Diseases like malaria and West Nile virus are becoming more of a problem in northern areas. Additionally, seasonal diseases are able to remain in some areas for longer periods of time, due to the increase in the area's average temperature.

Diseases can be spread directly from person to person, or they can be transmitted to people through a host organism, such as a mosquito, tick or rat. These host organisms are referred to as the vector organism. The area must have hospitable conditions for both the microorganism that causes the disease, and for the vector organism. Table 4 outlines some of the vector borne diseases that affect populations. It details the size of the population effected, the type of organism that hosts the disease, and the area of land that is subject to the disease.

Main Vector-Borne Diseases: Populations at Risk and Burden of Disease

Disease	Vector	Population at Risk	Number of People Currently Infected or New Cases per Year	Disability-Adjusted Life Years Lost[a]	Present Distribution
Malaria	Mosquito	2400 million (40% world population)	272,925,000	39,300,000	Tropics/subtropics
Schistosomiasis	Water Snail	500–600 million	120 million	1,700,000	Tropics/subtropics
Lymphatic filariasis	Mosquito	1,000 million	120 million	4,700,000	Tropics/subtropics
African trypanosomiasis (sleeping sickness)	Tsetse Fly	55 million	300,000–500,000 cases yr^{-1}	1,200,000	Tropical Africa
Leishmaniasis	Sandfly	350 million	1.5–2 million new cases yr^{-1}	1,700,000	Asia/Africa/ southern Europe/ Americas
Onchocerciasis (river blindness)	Black Fly	120 million	18 million	1,100,000	Africa/Latin America/ Yemen
American trypanosomiasis (Chagas'disease)	Triatomine Bug	100 million	16–18 million	600,000	Central and South America
Dengue	Mosquito	3,000 million	Tens of millions cases yr^{-1}	1,800,000[b]	All tropical countries
Yellow fever	Mosquito	468 million in Africa	200,000 cases yr^{-1}	Not available	Tropical South America and Africa
Japanese encephalitis	Mosquito	300 million	50,000 cases yr^{-1}	500,000	Asia

[a] Disability-Adjusted Life Year (DALY) = a measurement of population health deficit that combines chronic illness or disability and premature death (see Murray, 1994; Murray and Lopez, 1996). Numbers are rounded to nearest 100,000.
[b] Data from Gubler and Metzer (1999).

Table 4: Main vector-borne diseases: populations at risk and burden of disease (Climate Change 2001: Working Group II: Impacts, Adaptations and Vulnerability)

As can be seen in Table 4, most of the areas affected run along the equator, and are tropical or subtropical areas. If the planet's average temperature is allowed to rise, the areas of land that are considered tropical will increase. Table 5 discusses the effects that temperature increase has on the vector organism and on the disease itself.

Effect of Increased Temperature on Vector- and Rodent-Borne Disease Transmission

Climate Factor	Vector	Pathogen	Vertebrate Host and Rodents
Increased temperature	– Decreased survival, e.g., *Culex. tarsalis* (Reeves *et al*., 1994) – Change in susceptibility to some pathogens (Grimstad and Haramis, 1984; Reisen, 1995); seasonal effects (Hardy *et al*., 1990) – Increased population growth (Reisen, 1995) – Increased feeding rate to combat dehydration, therefore increased vector–human contact – Expanded distribution seasonally and spatially	– Increased rate of extrinsic incubation in vector (Kramer *et al*., 1983; Watts *et al*., 1987) – Extended transmission season (Reisen *et al*., 1993, 1995) – Expanded distribution (Hess *et al*., 1963)	– Warmer winters favor rodent survival

Table 5: Effect of Increased Temperature on Vector- and Rodent-Borne Disease Transmission (Climate Change 2001: Working Group II: Impacts, Adaptations and Vulnerability)

Research is currently being conducted to see if changes in precipitation affect the incidence of disease. This data is valuable because global warming also affects precipitation patterns and frequencies, as will be discussed in a later section.

The third major health issue is respiratory aliments. There has been a significant increase of lung disease, asthma and other respiratory problems, especially among inner city youths. The presence of excess carbon dioxide in the air causes plants to produce more mold spores and pollen. Experimental research shows that doubling concentrations of carbon dioxide in the atmosphere from 300ppm to 600ppm induces approximately a four-fold increase in the production of ragweed pollen. (Climate Change 2001: Working Group II: Impacts, Adaptations and Vulnerability, Aeroallergens) Although pollen and mold spores don’t cause asthma directly, they do agitate the condition. Furthermore, pollen and spores can readily pick up air pollutants, such as diesel exhaust, which further agitates the lung tissue and makes it even more sensitive to pollens and spores. Additionally, climate changes may increase the length of plants’ pollen production season.

4.2 Hydrological Cycle

The temperature increases that affect humans and our health also cause changes in the hydrological cycle. This cycle outlines how water perpetually moves around the Earth and its atmosphere. Approximately 496 * 10^3 km^3 ("The Effects of Global Warming on the Hydrologic Cycle.") of water is moved through this cycle yearly, out of a total volume of 1,386,000,000 km^3. The volumes of water stored in the different water sinks are shown in Table 6. (Perlman)

Water Volume Distribution

Water source	Water volume, in cubic kilometers	Percent of total water
Oceans, Seas, & Bays	1,338,000,000	96.5
Ice caps, Glaciers, & Permanent Snow	24,064,000	1.74
Groundwater	23,400,000	1.7
Soil Moisture	16,500	0.001
Ground Ice & Permafrost	300,000	0.022
Lakes	176,400	0.013
Atmosphere	12,900	0.001
Swamp Water	11,470	0.0008
Rivers	2,120	0.0002
Biological Water	1,120	0.0001
Total	1,386,000,000	100

Table 6 (1 km^3 is equal to 10^6 liters) (Perlman)

The estimated distribution of these water sources is shown in Figure 41 by their percentages of the total amount of water on Earth.

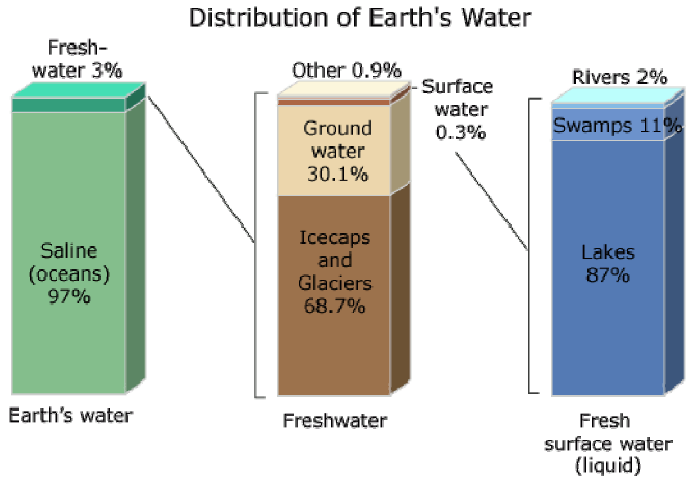


Figure 41 (Perlman)

The mean residence time for the atmosphere and ocean are currently 10 days as a water vapor and 3,000 years in liquid forms respectively. The complete hydrologic cycle is shown in Figure 42 and includes evaporation, transpiration, condensation, precipitation and runoffs. The cycle's residence time in each water source determines the distribution of Earth's water to Earth's water sinks. This fragile balance will be altered by climate changes that are occur from global warming. ("The Effects of Global Warming on the Hydrologic Cycle.")

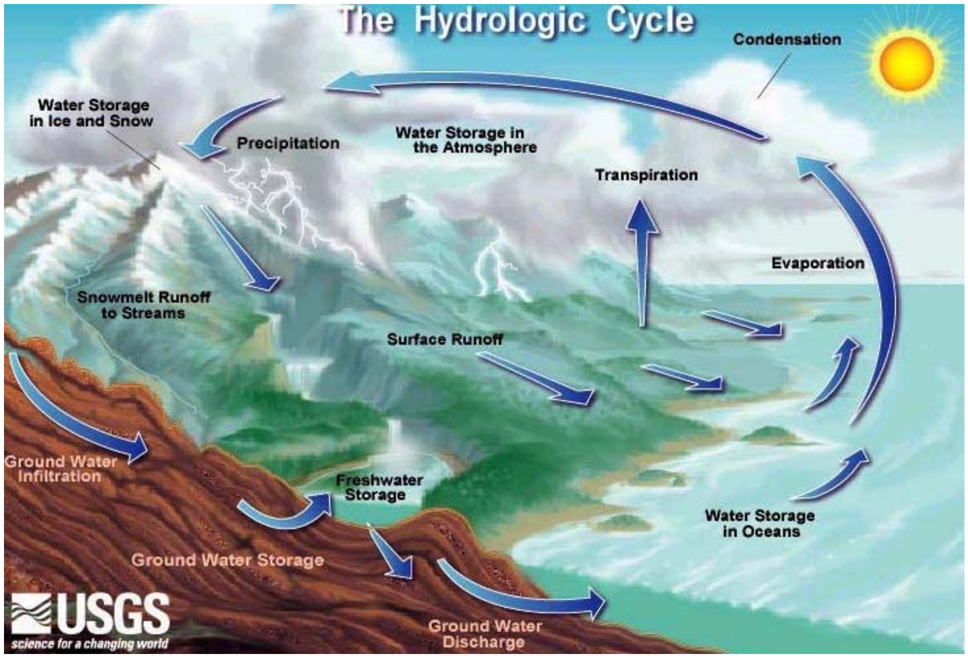


Figure 42 (Perlman)

The different components of the hydrologic cycle that will be affected are the ocean, global weather patterns, and ground water. The ocean will be affected because of the rising sea level, which may in turn affect the thermohaline circulation of the ocean. The global weather patterns are affected not only by the rising temperature but also changes in the thermohaline circulation. The temperature changes and the other resulting changes will affect ground water quality and availability. All of these are part of the changes to earth's climate that may occur from alterations in the global hydrologic cycle.

4.2.1 Ocean's Sea Level

The rising global temperatures will affect the world's oceans in a variety of ways. The rising sea level and the thermohaline circulation are all part of the slight changes that will be occurring as the global temperatures slowly rise. Over the past 3,000 years the global mean sea level rise has been 0.1-0.2 mm/yr. Since 1990 the sea level rise has been 1 – 2 mm/yr. By 2100, the rise is estimated to be up to .94 m when comparing it with the sea level in 1990. (McLean) The sea level rise is caused by thermal expansion of the ocean and by glacier melting from the increases in the global temperature.

These higher temperatures cause the ocean to be in the presence of higher levels of solar heat. Given the relatively high boiling point of water, it can absorb this energy without changing to a vapor. But the energy it absorbs is expressed through kinetic energy. This kinetic energy causes the water molecules to expand. The expansion of water molecules leads to sea level rise. The sea level rise will vary from region to region due to the fact that expansion is dependent on the warmth of the ocean in that area. Even if the greenhouse gas emissions are stabilized, the sea level is projected to keep expanding for hundreds of years. This possible future expansion is due to the current increase in global temperatures and the ocean's large heat capacity. (Perlman)

The thermal expansion is not the only thing that affects the sea level. Higher temperatures will cause melting and loss of sea ice, fast ice, glaciers and icebergs. Also, the increasing temperature causes a smaller snow season, which does not allow for the renewal of these lost and depleted ice structures. Snow cover itself has declined 10% the past 30 years and will decrease another 10-20% by 2100. (Hassol)

Over the past 30 years, there has also been an overall 8% depletion of sea ice; which means that approximately 1 million square kilometers have melted away. The decline since 1900 up until 2003 in sea ice per square kilometer is shown in Figure 43. The figure shows how the decline started about 50 years ago and how drastic the sea ice melting is during the summer season.

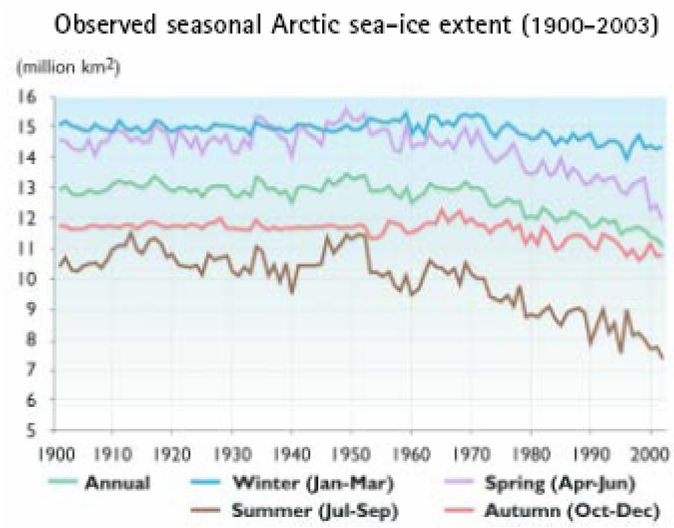


Figure 43(Hassol, 31)

The projected levels of sea ice melting show a worsening of this trend. By 2100, sea ice areas are estimated to be 10-50% smaller than that of today. During the summer season, the sea ice masses are projected to decrease by more than 50% within the the next century. Projected decreases in sea ice areas are shown in Figure 44 as well as the current area that sea ice covers in the Artic. (Hassol)

Projected Changes in Sea Ice

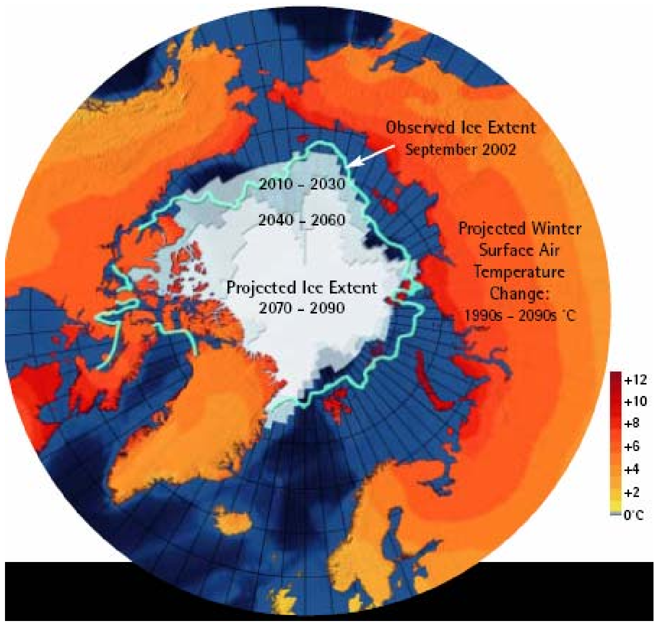


Figure 44(Hassol, 36)

While the projected decline in sea ice levels causes an increase in the sea level, it will not come close to the affect that the melting glaciers will have on the sea level. The estimated land based ice in the Artic is 3,100,000 km^3, which if melted is the equivalent of eight meters of water. Sixteen percent of the Greenland Ice Sheet has already melted since 1979, and Alaska's contribution to the sea level rise is at least double that of Greenland. Figure 45 shows the changes in regional glacier volumes since 1960. The glacier that has been affected the mostly by the change in temperature is the North American Artic as shown in Figure 45.

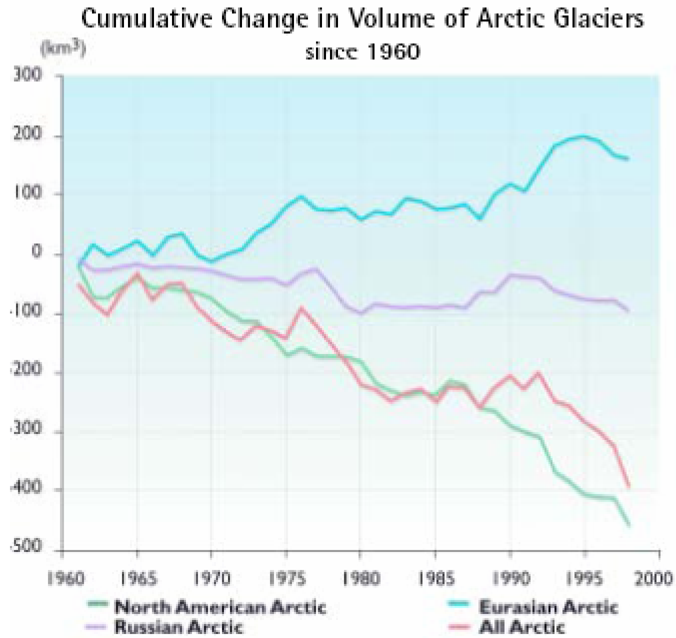


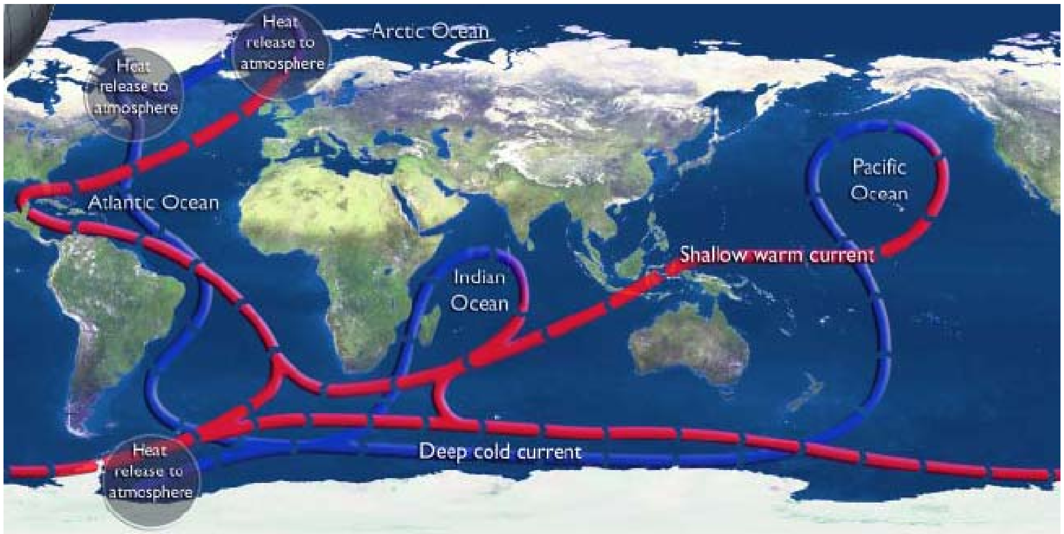
Figure 45 (Hassol, 47)

The substantial loss began in the 1960s and has been increasing more rapidly since the 1980s. By 2100, the projected rise in the global sea level is approximately 4-6 cm due to the melting glaciers and sea ice. (Hassol)

The loss of reflexivity from the melted snow and ice will be one of the most harmful reactions to the warming temperatures. The melted snow reveals soil and the melted sea ice reveals ocean, both of which absorb more sunlight than snow. Snow reflects approximately 85-90% of the sun's rays, while soil and vegetation reflect only 20% of the sun's rays, and the ocean reflects the least, only 10%. These higher absorption rates will only increase global warming and the rise in sea level. The oceanic changes that are occurring could change or completely shut down the thermohaline circulation of the ocean.

4.2.2 Ocean's Thermohaline Circulation

The Thermohaline Circulation is a powerful force on the world's climate system. When sea ice is formed higher salt densities occur near the coast. The heavier salt water sinks to the ocean floor and flows down to the deep ocean basin and then upwelling in lower altitudes. The water from the north then cools the tropics. The cooler water now in the tropics absorbs the sun's heat and travels up the Gulf Stream into the North Atlantic. This allows for heat to be brought pole-ward and for the heat to be vented into the atmosphere. The current Thermohaline Circulation is shown in Figure 46. (Hassol) This cycle is estimated to transport 1PW (10^{15} Watts) of heat northward across 24º N in the Atlantic Ocean. (Thorpe) The melting of ice sheets, glaciers, and sea ice may negatively affect the ocean circulation. The increased melting of sea ice, combined with the slowing of its formation, causes the density of the coastal salt water to lessen. The result is a reduction in quantities of water with high enough densities to be able to sink to the deep ocean basin, therefore slowing the Thermohaline Circulation. (Hassol) This slowing of the circulations also affects the climate, because much of the tropical heat that is no longer brought northward in the ocean and lost to the atmosphere. (Thorpe)



Ocean's Thermohaline Circulation

Figure 46 (Hassol, 38)

The Hadley Centre, HadCM3, shows that if the Thermohaline Circulation were to shut down, it would take about 120 years for the climate to stabilize and the ocean circulation to restart. During this time, the Northern Hemisphere would significantly cool off while the Southern Hemisphere would heat up. The most drastic cooling period for the Northern Hemisphere is projected to be within the first decade of the circulation shutdown. Within this time frame, the projected average temperature change is 3-5ºC. Cooling does continue throughout the Northern Hemisphere after this period, but to a lesser degree. Similar temperature changes have occurred in the past. During the 'Little Ice Age' in Europe the average temperature change was 0.5ºC and the coldest year, 1740, had an anomaly of -2.5ºC. If over double the temperature cooling of the 'Little Ice Age' occurs given a thermohaline circulation failure, the affects on human and animal life would be drastic. Temperature changes similar to these would cause agricultural reductions of about 12% in the Northern Hemisphere, particularly in Central America.

These temperatures would not be able to sustain any of the vegetation types that are currently grown there. (Thorpe)

Even if the thermohaline circulation does not completely shut down due to the reduction in the formation of sea ice; the slowing of it will cause cooler temperatures in the Northern Hemisphere. Europe particularly will have to sustain much colder temperatures, whereas the Southern Hemisphere will continue to heat up from global warming. Other general affects from the slowing or stopping of the thermohaline circulation are the ocean's carbon dioxide intake, thermal expansion, and the transport of nutrients and carbon within the ocean. The ocean will also absorb less carbon dioxide because less of the oceans will be exposed to the atmosphere and therefore will be less able to absorb carbon dioxide. The decrease in ocean movement will also mean that the warmer waters will not be carried up to colder regions; this water will just continue to absorb heat and continue to expand. This expansion will cause a greater rise in sea level. The circulation of the ocean also allows for the transport of nutrients to the surface and the transport of carbon to the deep ocean. Without this transport of nutrients, surface marine life will die out and carbon from dying animals and plants will not be moved into deeper waters. (Thorpe)

The thermohaline circulation of the ocean has a large affect on the climate of the world, especially the Northern Hemisphere. Changes in this cycle and changes in the sea level have their own affects on the global balance. Weather patterns, costal areas, and water resources can all be affected by these changes and the global changes that are occurring from the rising temperatures.

4.2.3 Weather Patterns

Global warming has been disrupting the weather patterns for years and these disruptions are only projected to worsen. Global warming causes evaporation rates to increase and also supplies more energy for storm systems to use. Global precipitation levels increased 2% over the course of the twentieth century. These precipitation increases are not evenly distributed throughout the globe. The northern hemisphere has a higher net precipitation increase of 10% that is related in, “The Effects of Global Warming on the Hydrologic Cycle”, while Mark Lynas in “Warning On the Winds” says the US alone will have a 20% increase in precipitation. Increases in rainfall result in more damage to the surrounding area, which is also projected to increase by 10% percent. While the US and the Northern Hemisphere are getting more rainfall, the subtropics have had a decrease in precipitation of around 0.3% per decade. Rainfall and disastrous storm systems like hurricanes, typhoons, monsoons, floods, and droughts have also been increasing in frequency, because of added kinetic energy in the waters due to rising temperatures. (“The Effects of Global Warming on the Hydrologic Cycle”)

One such semiannual storm system is El Niño, which has been super charged by the increases in ocean surface temperatures. The El Niño inter-annual phenomenon occurs because of shifts in pressure above the Pacific Ocean. The pressure changes include high pressure in the Southern Pacific Ocean and low pressure in the central Pacific Ocean. These pressures result in changes in wind patterns and ocean currents. Since this weather trend began in the 1700s, it has been escalating. El Niño shifts weather patterns and causes droughts in Africa, Australia, India, Indonesia, and the Philippines.

Other affects include flooding in Peru and Ecuador, while California suffers devastating storms. This increasingly harmful trend caused record-breaking temperatures for 16 months in 1997, and brought unusual floods, cyclones and droughts.

Figure 47 shows the changes in weather patterns when El Niño occurs and also shows the Pacific Ocean pressures that do not allow for an El Niño. ("The Effects of Global Warming on the Hydrologic Cycle")

El Niño Weather Changes

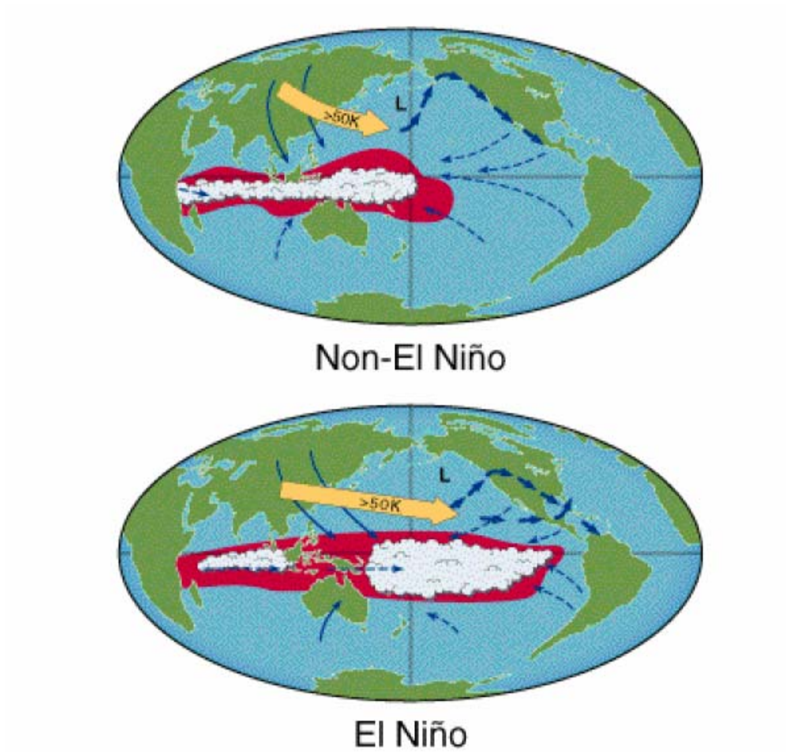


Figure 47

A more severe El Niño is not the only changes to the weather patterns caused by global warming. Rising global temperatures are causing higher frequency and intensity of other storms as well. Changes in storm intensity like that of hurricane Mitch in 1998, which produced a total of six feet of rain or the five feet of rain in Haiti over 36 hours in May 2004. Europe was also affected directly by rising temperatures when they endured the heat wave of 2003. (Eilperin)

In 2004 alone, there have been eight tropical cyclones that have reached tropical storm and hurricane strength, which set a new record that year. Brazil was also hit by its first hurricane ever recorded, which included 90 mile per hour winds generated from the South Atlantic. Japan has also endured typhoon after typhoon hitting the region at a rate of one per week. (Lynas) The US alone spent $11.6 billion in emergency relief funding for the four hurricanes that hit Florida in 2004's hurricane season. ("Hurricane losses may reach 10bn") Although storms of this nature have always occurred, the frequency with which they have been occurring in 2004, show the affect that global warming is having on the weather patterns.

All of these extreme storms are not just a fluke of nature; they are from the rising global temperatures, and the resulting rising ocean surface temperatures. The changes in precipitation, El Niño, hurricanes, typhoons, and heat waves are all aspects of the resulting climate caused by the warming trend. This trend influences not only the climate and the ocean but land and water resources.

4.2.4 Water Resources

Studies show that the effects of global warming will cause an overall increase in the discharge of fresh water from rivers around the world; this increase could be as high at 15%. Net precipitation in the US alone has increased by 5-10% during the 20th century. Unfortunately, the increase will not be evenly dispersed. The extra precipitation will fall in areas with large water sources, and less precipitation will fall in areas that are already struggling to meet their water demands. The Colorado River, for example, may experience a runoff decline of 15-20%, with a 10% reduction in deliveries to water users. This decline could cost water users in the Colorado Basin about $200-300 million per year. (Water Supply and Demand) Many mid-latitude rivers are expected to experience flow reductions due to climate change, especially those that run through heavily populated regions. Examples of these rivers include the Mississippi, Mekong and especially the Nile. The Nile is one of the world's most heavily used and politically contested rivers; the Manabe model predicts an 18% fall in flow by the end of the 23rd century. In contrast to these examples, the Ob River, in Siberia, will experience the opposite result, with a projected flow increase of 42% by the end of the 23rd century. The Yukon River is also predicted to have a flow increase of as much as 47% by the end of the 23rd century. (Climate change heralds thirsty times ahead)

Climate changes will also cause already semi arid areas to experience a drop in the moisture content of soils. These areas include northeast China, the grasslands of Africa, the Mediterranean and the southern and western coasts of Australia. Soil moisture will fall by up to 40% in southern states of the US. This drop in moisture content will increase the demand and the cost of irrigation.

In preparation for this demand, countries have begun to explore the costs of diverting rivers with predicted increases in flow, to areas that may experience moisture decrease in their soils. For example, Russia is exploring plans to divert Siberian Rivers to irrigate the deserts around the Aral Sea (New Scientist, 9 February 2004). Diversion of Pacific rivers to the western United States is also a possibility. (Water Supply and Demand)

Water quality will also be affected by climate change. Areas that experience more frequent heavy precipitation events will very likely flush more contaminants and sediments into lakes and rivers. However, these areas will also experience an increase in the flow volume of their rivers, which may help to dilute the non-point source pollution. Areas that experience a reduction in precipitation may experience an increase in salinity in their river systems. Contamination of rivers may also increase due to the increased risk of flooding events. Flooding can cause overloading of storm and wastewater systems, as well as damage to water and sewage treatment facilities, mine tailing impoundments, and landfills, thereby increasing the risks of contamination. There is also an increased incidence of water-borne diseases after flood events. (Climate Change Impacts on the United States The Potential Consequences of Climate Variability and Change)

4.3 Agriculture

Since global warming sets off a chain reaction, all of the systems interrelating to the climate are severely affected. Climate changes produce alterations in the hydrological cycle. Reactions from these changes are increases in chaotic weather systems and general water cycle changes, along with regional precipitation changes. These precipitation changes will affect pest control farmers all over the world. Larger populations of plant eating organisms will infest many areas due to the increases in temperature. The extra cost of pest control will inevitably increase produce prices worldwide. The higher prices can be attributed to sudden destructive weather systems, which are already affecting crop yields. The affects on the agricultural trade can cause economical problems on the regional, business, and household levels.

Climate changes, specifically precipitation, will cause many farmers to have larger populations of pests due to the higher temperatures and better breeding grounds. The ranges of pests like the soybean cyst nematode and the corn gray leaf blight have been expanding in the US since the 1970's. This expansion is directly proportional to the enabling climate trend. Future temperature estimations will continue to allow pests to flourish. The raised carbon dioxide levels cause a higher crop yields, since the plants will be able to photosynthesize faster, thus enabling them to develop more nitrogen tissue mass. Problems with pests will be slightly offset by this projected increase in nitrogen tissue mass, but not enough to make the net production changes positive. Fifteen different experiments have been done to establish this fact. All of the experiments indicated that when plants were treated with higher levels of carbon dioxide their tissue mass decreased by 30%.

Eighty percent of this decrease was due to the pest increases that occurred in the experiment. The studies also showed that pests like aphids (suckers) would thrive in the future hotter climate, whereas the populations of the lepidopteras (leaf chewers) performed poorly under the new conditions. The current trend of growing populations of pests and the experimental data which shows how pests will thrive under future conditions means that many farmers and consumers will have to deal with yet another problem when growing and buying produce. (Brown)

Pests are not the only issue that will affect crop yields; chaotic weather and dangerous storms can destroy a farmer's entire harvest. Two such examples of the increasing chaotic weather trends in 2004 have been the typhoons in Japan and the four hurricanes that hit the United States. Both of these reoccurring natural disasters severely affected the prices of produce in each country.

Tokage, the twenty-third typhoon that Japan has dealt with in 2004, wreaked havoc on an already damaged land. Most of the crops were either swept way or flooded, which caused them to rot. Lettuce prices increased, the 10-kilogram box went from 1,575 yen ($14.50) to 12,600 yen ($115.60). These high vegetable prices are not a slight jump in produce pricing, and they will continue because Tokage also destroyed the soybean and rice crops along with the apple and tangerine orchards. This created not only high prices for the consumers, but also no profit for farmers who lost their whole crop during these disasters. The situation puts a strain on the whole country's economy. ("Typhoon Score direct hit on farmers, consumers")

Another example of the inflated costs of vegetables and produce caused by the treacherous storm systems is when the four hurricanes hit Florida and the surrounding coastal states. Even though these states can rebuild, the effects of the hurricanes are being felt throughout the country by the raised costs of produce. The harvest of oranges will drop 29% and grapefruits will drop 63%. Peanuts, whose production usually stems from Georgia, Alabama and Florida (all of which got hit by hurricanes), will also have a drastic increase in price because of a bad crop. (Quick) Price increases were not initially visible to consumers because many companies were taking a loss. However, tomato prices have increased immediately. This is because torrential rains and pests damaged the California tomato crop, while Florida's tomato harvest was destroyed by the hurricanes. ("CA Rain Contributes to Tomato Shortage") Tomatoes that were sold wholesale at 50 to 60 ¢ per pound are now at $1.20 to 1.50 a pound. (Boone) For the average consumer, this has meant a doubling in price for hothouse or roman tomatoes; paying up to $3 per pound. ("CA Rain Contributes to Tomato Shortage") Cotton from Alabama plantations, shrimp, and building supplies will also be going up because the cost of rebuilding many damaged houses and businesses. ("Florida's Hurricanes To Hit Texans In The Wallet") Although each price change is relatively small, many households have felt the affects of the hurricanes financially whether or not they were directly hit by them.

By the end of 2004, both Japan and the United States were still feeling the affects that the chaotic weather had on their agriculture and their economies. Between the money spent by the government in assistance funding and the rising in prices, natural disasters can put a large toll on the economy of an area or a nation.

Natural disasters are increasing with the changing climate. If storms like these continue, the agricultural business will slowly be ruined in many areas of the world.

The projected climate changes that will occur, including mainly precipitation changes, show that vulnerability of agricultural trade is dependent on the region, business size, and on a population's prosperity. The most vulnerable region of the world will be the tropical areas. The tropical agricultural businesses will have to deal with more drastic effects on their agriculture industry because even slight temperature changes will cause their plants to die. In these dry lands, the increasing temperatures facilitate the burning and dehydration of plants. Small businesses and rural farmers will be seriously affected by these temperature changes. Larger businesses have the ability to absorb the cost of a bad harvest, whereas small rural farmers can be destroyed in one year if their whole crop is ruined. The public will also be affected by these agricultural changes. The loss of crops leads to higher prices for produce and many people or regions that do not have the available funds could starve. Regions with tropical climates and third world standing like Africa will be substantially hurt by changes in climate. Africa is projected to have 55-70 million people at risk of hunger by 2080 due to changes in the agriculture industry. Many other countries will experience similar effects because of the climate changes, and the rising costs of produce. Even in prospering countries, the higher prices could lead to a much higher percentage of the population starving than ever before. (Brown)

The climate changes, in the form of sudden storms or steady temperature increases will have an adverse affect on the crop yields and their prices.

Many regions' agriculture industry will suffer from being over run by pests or having their crops die from lack or excessive precipitation. The changes in climate do not just affect human's food sources; they affect animals' food supplies and their habitats as well.

4.4 Habitat

Habitats all over the world will be affected by global warming and its various side effects. The primary habitats that will be affected are forests, coastal areas, and marine ecosystems. These habitats are essential parts of the world ecosystem and changes to these systems will cause irreparable damage to all species and to humans' way of life.

4.4.1 Forests

Global warming will affect the world's forests. Temperature increases will cause forests to migrate northward and upwards in elevation. Climate change will also affect forest's vulnerability to disease, pests and forest fires, while providing an environment that will encourage the onset of these threats. Temperature changes will also affect; the structure of trees, their growth rates, photosynthesis and total leaf area.

As temperatures increase, forests migrate north to remain in a suitable climate. Unfortunately, the projected global temperature increase for the next 100 years is 2^{o}C. This drastic increase would require some species of trees to migrate approximately 2 miles every year. This migration rate may be feasible for trees whose seeds are distributed by birds. Trees that rely on the wind or procreate by bearing nuts cannot migrate more than a few hundred feet per year. The limitations on some species of trees will cause less biodiversity in the developing forest areas. The presents of bad soil on the northern boarder of the forest area will also deter its migration. If the climate change is more gradual, trees will be able to fill in northern areas at approximately the same rate as southern areas become too hot and dry to support the forest. Global warming will also change seasonal patterns such as freezing and thawing. These changes may cause shifts in forest areas.

Rainfall variation is another side effect of global warming. Precipitation is predicted to increase drastically in some areas and at the same time decrease drastically in others. Changes in precipitation will also affect forest populations. A decrease in rainfall will produce drier soil, which will make it more difficult for small trees and saplings to survive.

Dry soil does not affect older trees as severely, because they have stronger more developed root systems. A drier climate will also cause forests to give way to rangelands. Wetter climates will cause forests to expand into rangelands.

Areas that experience a decrease in precipitation will be much more vulnerable to forest fires. Forest fires are part of a forest's natural life cycle, altering this part of the cycle will affect the rest of the cycle.

Changes in temperature and precipitation can alter the likelihood of outbreaks of diseases and insects. Many forests are already experiencing longer and more frequent outbreaks than they have experienced in previous years. Poplar trees and other tree species are battling with an increased incidence of canker diseases. Trees seem to experience especially severe cases of some canker diseases when there is low moisture content in their bark. This drop in moisture content is caused by an unusually dry climate.

The armillaria root disease is also predicted to occur more frequently and grow at a faster rate, due to temperature increase and drier climate. This disease is one of the largest threats to the regeneration and productivity of forests in North America's Pacific Northwest. Two to three million m^3 of forest per year are lost to armillaria disease in this area. Studies have found that lodgepole pines are experiencing a 43% decrease in volume and a 23% decrease in height in that area.

Dry climates also encourage the outbreak of eastern spruce budworm. The eastern spruce budworm is estimated to defoliate approximately 2.3 Mha in the United States and affect 51 million m^3 of Canadian forests. During periodic outbreaks, budworm populations can reach over 22 million larvae per hectare. These outbreaks can affect up to 72 Mha and can last for 5-15 years.

Increasing temperatures are directly related to the number of spruce budworm eggs laid. It has been found that 50% more eggs are laid at temperatures of 25°C than at temperatures of 15°C. The increasing temperature also shifts the timing of the budworm's reproduction season. This shift allows reproduction to occur when the populations of the budworm's natural parasitoid predators are low. Climate change will also alter the structure of trees, changes such as the moisture content in their bark and leaf coverage area. Changes in the tree's growing season and nutritional feedback may also occur. The boreal forests have shown an increase in their growing season length, this increase correlates directly to the climates temperature.

Extreme weather events, such as hurricanes, tornadoes, heavy rainstorms and flooding can cause serious destruction and alteration in forests. The increasing frequency and severity of these storms is directly connected to global warming.

Climate changes affect many aspects of forest habitat, from decreased biodiversity, fires, pest infestations to disease. Forests will become more venerable to these problems at the global temperature increases.

4.4.2 Costal Ecosystems

The coastal zones are greatly affected by global warming and the resulting temperature fluctuation. Within the past one hundred years, 70% of the world's sandy beaches have been retreating, 20% have been stable and only 10% have been increasing. One of the most significant impacts of global warming on the costal ecosystems is the rising of the sea level. Global warming and sea level will cause currently eroding shorelines to erode quicker and further. Even stable and increasing shorelines are projected to begin eroding. (McLean)

The rise in sea level will cause not only shoreline erosion, but it will cause lowlands to be flooded, the displacement of wetlands, higher storm flooding, sea intrusion into estuaries and aquifers, changes in surface water quality and groundwater, and changes in pathogen distribution. This affects not only marine life but also humans, since approximately 20% of the human population lives within 30 km of the sea. According to the current projection, 600 million people will occupy costal flood plains by 2100, due to the estimated 0.94 meter rise in sea level. The tie between global warming and the rising sea level is obvious when considering the history of the global sea level rise in comparison to the rate at which the sea level is rising today. Over the past 3,000 years, the global mean sea level rise has been 0.1-0.2 mm/yr. Since 1990, the sea level rise has been 1 – 2 mm/yr. By 2100, the rise is estimated to be up to 0.94 m from the 1990 sea level. The cumulative economic costs of this sea level rise by 2100 are estimated to be $20 billion to $150 billion US dollars. This figure includes the cost of protecting the endangered coastal lands, damages from the changing sea level, loss of tourism and the loss of land. (McLean)

Specific coastal areas at risk are deltas, wetlands, and coral reefs. The risks to deltas include deterioration from sediment starvation, subsidence, and other stresses. These stresses caused by environmental changes and other human impacts lead to accelerated inundation, shoreline recession, and wetland deterioration. The projected sea level rise is estimated to contribute to the loss of 22% of the world's coastal wetlands. Another coastal area that may be affected by sea level changes and general temperature changes are coral reefs. Many healthy coral reefs are expected to be able to adapt to the changing water temperatures and the rising sea level. Unfortunately, many coral reefs that have been degraded by other human activities will be heavily impacted. About 58% of reefs are currently considered to be at risk due to human activities. Adding the stress from temperature changes and the increasing sea level, could be disastrous to these coral reefs. These extensive changes in the ocean will also affect the aquatic life. (McLean)

4.4.3 Marine Ecosystems

Marine life is perhaps more vulnerable to climate changes than their counter parts on land. Global warming affects marine life populations by changing the nutrients that they receive from coastal areas and ocean circulation and by changes in the sea surface temperature. Most importantly, these affects influence the locations of marine life's breeding grounds. Any marine life changes in a given area will also result in population changes in marine mammals and the sea birds. Other changes in marine life may also be compounded by disease and changes in costal systems.

These ecosystems have already begun to change. Over the course of 1976 and 1977, a fluctuation similar to future fluctuation from global warming occurred. A climate ocean regime shift caused a reduction of nutrients in shallow mixing layer. This shift caused a decrease in the productivity of zooplankton, which in turn affected the kelp and sea bird populations. The affects of this shift on animal populations is shown in Figure 48. This figure shows how the catches of salmon and sardines are synchronized with the climate and ocean shifts that were happening in the North Pacific at that time. These shifts show how the changes in ocean climate will impact marine fish, mammal, and bird populations. (McLean)

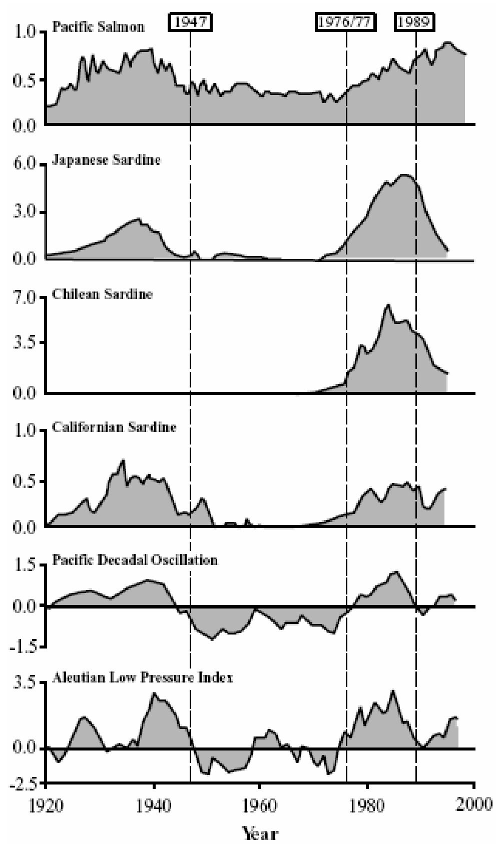


Figure 48 (McLean, 10)

Marine aquaculture is also being affected by the warming temperatures. It has more than doubled from 1990 when it was 4.96 catches (Mt), to 1997 when it was at 11.14Mt. Similar trends are reflected in the fresh water aquacultures. The aquacultures increase while the fishing yields remain constant. This may create consequences if natural declines in fish populations have a sudden drop and fisheries are still harvesting as they were before the decline. The varying populations of fish affect the marine mammals too. In California from 1987 to 1994, there was a 40% decline in sea birds resulting from the decline in fish populations in that region. (McLean)

4.5 Species

The decline or alteration of the habitats considered in the previous section is having serious impacts on the wildlife that inhabit these areas. The biodiversity of this planet is already in serious jeopardy due to human encroachment on habitat. Further alteration of the remaining habitat due to temperature fluctuation only compounds this ever-growing problem.

Animal populations are effective indicators of climate fluctuation, because they are physiologically constrained by temperature and moisture. Presently, many different species are showing migration poleward and upwards in elevation, in attempts to remain in their preferred thermal climate. These habitat shifts affect various aspects of species' life, such as; breeding times, growth rate, migration, population, life expectancy and food source. Scientists have ruled out the possibility that these habitat shifts can be attributed to human incursion, since such incursion do not occur less frequently along the poleward sides of the animal's habitat, than they do along the equatorial side of the animal's habitat.

Unfortunately, many species do not have the ability to migrate poleward or elevation wise, because those areas of land may be blocked off by human population. The Bengal tiger is at risk of extinction because human populations deter its migration to a more suitable climate. The Bengal tiger is projected to lose 18% of its land and habitat to rising sea levels, caused by global warming. Elevation migration may also be insufficient, if mountain ranges are not high enough to provide the desired climate.

Invertebrates, such as butterflies, have begun to show shifts both poleward and upwards in elevation as global temperatures increase.

Amphibians are especially susceptible to shifts in climate because they occupy more than one habitat in a lifetime and they have moist permeable skin. The Monteverde Cloud Reserve, in Costa Rico, found that Golden Toad and Harlequin Frog populations vanished after periods of extremely dry weather. These periods of extremely hot, dry weather cause a reduction in the frequency of dry season mist. The mist reduction also correlates to serious declines in four other frog populations and two lizard populations.

The habitat ranges for birds are also moving; increasing polewards as global temperatures increase. Penguins, especially the Chinstrap and Adelie penguin, have been seriously affected by climate changes in the Arctic. These two populations of penguins have changed drastically over the past twenty-five years; in correlation with a 4-5°C temperature increase that has occurred in the past fifty years. Both species of penguins have similar diets and breeding ranges, but their winter habitats differ greatly. The Adelie penguin only inhabits packed ice, while the Chinstrap penguin cannot tolerate ice and remains near the open water. These habitat requirements are a crucial aspect of each species' survival. An increase in temperature has caused the Adelie penguin population to decrease by 22% and the Chinstrap penguin population to increase by 400%. These population fluctuations are the result of the melting of packed ice. As the packed ice melts, it provides more open water area for the Chinstrap, while eliminating the habitat area of the Adelie penguin.

Increase global temperatures do not just cause shifts or reduction in the habitat of wildlife. Temperature increases also affect the reproductive cycles of many animals. Studies have found that spittlebugs hatch earlier when seasonal temperature is 3^{o}C above normal. Two species of frog, found in the northern region of their habitat range in the

UK, were found to spawn 2-3 weeks earlier in 1994 than they did in 1978. There was a direct correlation found between the increase in their habitat's temperature and the occurrence of early spawning. Scientists have observed earlier breeding times for birds in Europe, North America, and Latin America. A change in the migratory patterns of birds has been noted in Europe. Birds in the US are departing later for their fall migration and returning to the area earlier than in pervious years. Higher temperatures affect the sex of unborn reptiles. In warmer years, painted turtles are found to grow to larger sizes and reach sexual maturity faster. The eggs of the Pied Flycatcher bird were found to increase in volume as the temperature increased.

Temperature changes can also effect how susceptible an animal is to disease. The Australian Quokka differs in susceptibility to salmonella infections depending on the state of the climate.

Extreme weather events, caused by global warming, can also lead to serious declines in wildlife population. Hurricanes can lead to the direct death of large quantities of a species. These hurricanes also destroy breeding and foraging grounds, leading to population decreases long after the event has occurred.

It is obvious that rising temperatures can cause fluctuations in wildlife populations in several different ways. In the future, biodiversity will become a more serious problem as global warming continues to affect our planet. (Ecosystems and Their Goods and Services)

These impacts demonstrate how global warming affects all aspects of human and animal life. The all-encompassing affects of climate change prove the seriousness of this global dilemma. These severe impacts show the need for alternate energy sources and economic solutions to reduce the carbon dioxide concentrations.

5. Solutions

Given various social and economical impacts of global warming, governments and researchers have suggested potential solutions. After considerable research, we have developed our own a carbon dioxide reducing hypothesis. Government solutions to global warming include global policies like that of the Kyoto Protocol. The Kyoto Protocol provides reduction of emissions of greenhouse gases. Other government policies include energy efficiency restrictions. Cleaner energy resources are also being implemented to reduce emissions and the cost of energy. Natural energy resources that are currently being implemented include; solar, wind and wave power plants. Carbon sequestration is also being implemented. This process involves collecting the carbon dioxide from coal burning power plants and then pumping it into faults in the ground or the ocean floor. To further reduce carbon dioxide concentrations, research and experimentation is conducted on plants and soils to increase carbon absorption.

After considerable research, we have developed our own carbon dioxide reduction hypothesis. Our theoretical solution is to better utilize the ocean as a carbon sink. Addition of the carbonate ions would allow greater absorption of carbon dioxide by the ocean because these ions are the limiting reactant in the absorption process. The implementation of a variety of the solutions should allow for reduction in greenhouse gas concentrations and the resulting global warming.

5.1 Kyoto Protocol

The previous section discuses the various affects that global warming is having on the Earth and society. Now that these problems have been evaluated, solutions to these problems are needed. The Kyoto Protocol is the global solution to the problem of global warming. The Kyoto Protocol is an amendment to the United Nations Framework Convention on Climate Change (UNFCCC). It is an international treaty devoted to the reduction of global warming. This treaty was negotiated by more than 160 nations on December 1997. Its major goal is to reduce net emissions of certain greenhouse gases, primary carbon dioxide. If all participating countries meet their emission reduction quotas, the reduction in average global temperature is predicted to be between 0.02°C and 0.28°C by the year 2050. The participating countries are responsible for developing their own techniques to meet their five-year reduction goals.

Human energy consumption attributes to 80% of the United States greenhouse gas emissions. For our country to meet their reduction goals, the Energy Information Administration (EIA), estimates that 18% to 77% less coal will be utilized. The reduction of coal use will affect primarily electricity generation. Additionally, 2% to 13% less petroleum will be used, affecting transportation. To compensate for this loss, the operating life of existing nuclear units will need to be extended, and energy consumers will need to use 2% to 16% more renewable energy and between 2% and 12% more natural gas. This shift in energy use must occur by the year 2010. These energy changes will cause the average delivery costs of energy to be 17% to 83% higher, than was originally projected for the year 2010.

If this plan is implemented, economic performance is likely to fall, while the price of energy rises, and consumption and employment decrease. Economically, the coal mining industry would be hit the hardest by these energy transitions. Over the last two decades, the number of coal miners employed in this country has been declining by approximately 6%. Without considering the Kyoto Protocol, this number is expected to increase to 15%. When including the coal energy reduction scenario, between 10,000 and 43,000 (or more) jobs could be lost. (Economic Effects of a Complex Agreement Depend on Many Assumptions)

As of November 2004, 127 countries have ratified the protocol. These countries include Canada, People's Republic of China, India, Japan, New Zealand, Russia, Romania and Bulgaria. Unfortunately, the United States has neither ratified nor withdrawn from the protocol. Before the Protocol was negotiated, the senate passed a 95-0 vote saying that the United States should not sign any protocol that "would result in serious harm to the economy of the United States". Aware of the Senate's views, Vice President Al Gore defiantly signed the Kyoto Protocol. However, the Clinton Administration never submitted the protocol for ratification, knowing it would not pass. President George W. Bush says that he also does not intend to submit the treaty for ratification. Since the United States emits 5,410 million metric tons of carbon dioxide per year, our failure to ratify the treaty, will significantly reduce its global success. (Kyoto Protocol)

5.2 Energy Efficiency

The US energy needs have changed drastically since the 1970s. Over the years, the utilization of energy may have been more dependent on the actual costs of energy than on the actual need of energy. Through consumer demand to cut energy cost and research and development the energy efficiency of products such as refrigerators has been improved. In 1974, refrigerators were responsible for 1800 kWh per yr, but by 2001 that energy usage has been reduced to 450 kWh per yr. But consumer demands on certain products are not entirely centered on energy efficiency. The energy efficiency of cars has not progressed like other items because consumer's demands for cars are not energy centered but design centered. In 1975, a new passenger car's fuel efficiency was 14 miles per gallon, whereas in 1999 a new car averages 28.3 miles per gallon. The difference between the changes in energy efficiency of cars and refrigerators has been regulated by the energy efficiency changes since the 1970s. The efficiency of refrigerators has progressed greatly through the years and now refrigerators use one quarter of the energy they used in 1974. This has mainly been accomplished because of regulations and policies set by the government. But, cars progress has been much more constrained because of the Corporate Average Fuel Economy (CAFÉ), which set goals for fuel efficiency of new vehicles sold in the USA. The CAFÉ standards have been frozen since 1990; the mpg (miles per gallon) has also been frozen during this time frame. The main problem is that the cost of the energy in the US needs to rise, along with the regulations on energy usage. If the cost of energy is higher, then companies will have to make more efficient products and find ways create their products more efficiently in order to sell them at competitive prices in the US.

5.3 Renewable Energy

The most commonly known way to fight global warming and reduce carbon dioxide emissions is to utilize renewable energy. Unfortunately, renewable energy is the least implemented solution. Renewable energy delivers safe and clean energy with no apparent health hazards and minimal environmental ones. Countries have been lax in changing over to solar, wind and wave power because their current energy sources have already been established. But, many countries are now updating their energy sources to include natural resources.

The United States has implemented several different renewable resource programs involving solar, wind and hydro electricity. The US has solar plants like the Solar Two located in California, which has 2,000 giant mirrors that it uses to reflect sunlight onto its 300 ft receiver. The receiver heats the salt that flows through it. The salt is heated to 1,065°F and is then stored in a tank. When energy is needed, the molten liquid is used to move a steam generator thus generating electricity. ("Solar thermal technology deemed a success") Another natural energy source that the US is implementing is wind farms. The Storm Lake General Facility in the Midwest provides electricity to 200,000 people in Michigan. This facility saves an estimated 300,000 tons of coal and 500,000 tons of carbon dioxide emissions per year. (Stenger) Even off the coast of Massachusetts, the installation of approximately130 turbines is scheduled to begin construction in 2005. These turbines are projected to provide about a total of 420 megawatts of electricity, totally to over 75% of the energy required for the Cape Cod area and its surrounding islands. ("New Mass. Boundary may thwart wind farm")

Hydroelectricity is also being used throughout the country, and new turbines are scheduled to be implemented in New York City's East River. Verdant Power Company will be putting 200 or 300 turbines in the river, which is projected to provide five to ten megawatts of electricity. The initial cost of the turbines is over $20 million, but Verdant is hopeful that this project will allow them to install turbines throughout New York. They have estimated the possible hydropower of the state at about 1,000 megawatts, or power for about 1 million homes. Many other projects are underway, including many European projects. ("Harnessing Power of the Waves")

The United Kingdom is also trying also to change some misconceptions about renewable resources with their offshore wind turbines, which produce power cheaper than their newest nuclear power plant. They are also looking to make an offshore wind park off the coast of East Anglia, which would theoretically produce 25% of the current UK energy consumption. The jobs taken from oil and gas industries will be easily utilized by the jobs needed for the engineering and building of these wind structures. Countries like Germany are also creating massive wind parks to stave off the amount of carbon dioxide going into the atmosphere. ("Renewable energy: the way forward")

Countries around the globe are trying to lessen their dependence on oil and coal because of the immanent dangers to the environment. One of the many ways of reducing this dependency is through the use of wind, water, and solar power. Other ways of reducing oil and coal emissions are also being researched including carbon dioxide sequestration.

5.4 Carbon Dioxide Sequestration

Creating solutions to the ever growing global warming problem is not hard, but having them actually be economically conceivable and embraced by all nations is more than difficult. The easiest and cleanest way of reducing carbon dioxide emissions is by using renewable energy like wind, wave and solar power. Many countries do not want to change their energy source, so they have decided that sequestering the carbon dioxide from their power plants is the answer. This sequestering includes geosequestration, ocean sequestration, and allowing the carbon dioxide to bond with minerals to make a harmless but bulky rock. The carbon dioxide power plants normally pump into the atmosphere will now be pumped into the earth. Another sequestration technique could be deep-sea storage; pumping the CO_2 down to the bottom of the ocean. Ocean dumping laws would have to be changed in order for this process to take place, but the natural pressure of the ocean would prevent the carbon dioxide from escaping back into the atmosphere. Although the effects of carbon dioxide on fish populations and coral is unknown, the ocean would be able to store between 1,000 and 27,000 gigatons of CO_2. Both the deep-sea storage and the geosequestration pose serious health risks. If the carbon dioxide were ever released through seismic activity or a leak, it could result in many health problems for all living things in that area. There is also another, safer way of putting carbon dioxide back into the environment without the possible health risks. When carbon dioxide is mixed with serpentine, a mineral, and water it creates a safe and stable but very bulky rock. Space to put these carbon dioxide boulders would become problematic, but the cost of monitoring the liquid CO_2 that was pumped into the ground or ocean would not be needed. (Yeomans)

Although much higher in cost the technique used to trap and separate out the carbon dioxide at power plants could theoretically be applied to cars and other types of transportation, which contributes one fifth of the world's carbon dioxide emissions. If the vehicles were to have a filtering device built in with a storage unit, much of the emissions of carbon dioxide could be eliminated.

The sequestration of carbon dioxide is done by separating the gas chemically or physically with the use of solvents, membranes and cryogenics from power plants. Only new coal burning power plants with this technology can separate out the carbon dioxide, unfortunately old power plants cannot be modified to perform this task. The carbon dioxide that is collected from the power plants is then compressed until it forms a liquid. This liquid can then be sequestered into the earth or ocean, or even changed into the bulky carbon rock.

The most popular sequestering technique is currently geosequestration, the burying of carbon dioxide back into the earth. This burying is done by pumping the compressed carbon dioxide liquid into faults or folds in the earth. The most economically feasible way to use this technique is to pump the CO_2 into oil or gas wells. The liquid carbon dioxide is used in this technique to pump any remaining oil or gas out of old wells. This technique is being developed all over the world including the United States, Canada, and Australia. (Catchpole)

Geosequestration has been successfully used on the Weyburn Oil Field in Saskatchewan, Canada. Scientists from the United States brought the liquid carbon dioxide from the US and then pumped it into this well.

One hundred and thirty million barrels of oil have been recovered from the Weyburn field that would not have been able to be pumped out without the use of the liquid CO_2. More than 1.9 billion cubic meters of CO_2 have been injected into this field already. All of the carbon dioxide would have been emitted into the atmosphere. (Dey) The life of expectancy of this particular oil field has been extended by more than 25 years. (Yeomans)

The Australian government is investing $500 million dollars into the development of geosequestration. The large size of this investment reflects the countries refusal to transfer to more environmentally safe energy sources. This hesitation to change to more environmentally friendly energy sources can be attributed to the fact that Australia has enough coal to last over 200 years. Australia also emits more CO_2 per person than any other country in the world, due to their reliance on coal burning power plants. Even with the largest geosequestrian project worldwide, it is estimated their reduction in carbon dioxide emissions will be by only 7% by the year 2020. The estimated reduction in the year 2020 is only seven percent, while Australia's estimated increase of emissions is 40%. (Catchpole)

The United States is working toward the first near zero-emissions fossil-fuel plant with the Carbon Sequestration Leadership Forum. This one billion dollar project and organization was established in 2003 and includes many countries around the globe. (Yeomans)

Many scientists argue about the safety of pumping carbon dioxide into the ground or ocean. Seismic activity or unexpected instability of the carbon dioxide might cause it to leak out of the ground rapidly.

There are currently no methods to stop the leaking process should it occur. Depending on the size of the leak, the environmental impacts could be astronomical.

5.5 Plant and Soil Carbon Dioxide Regulators

Plants and soils are responsible for regulating all of the carbon dioxide on the planet. Many scientists are researching for ways to increase plants' and soils' absorption of carbon dioxide. Research on plant absorption of carbon dioxide includes metabolites, bioengineering, conditions where plants absorb the most carbon dioxide and how much carbon dioxide they will be able to absorb in future CO_2 conditions. Soil research is also being conducted to determine a way to allow soil to absorb all the carbon that it has lost through tilling, agriculture and other affects. Scientists are also searching for a carbon dioxide feeding microbe. Other research being performed is the artificial replication of the photosynthesis processes in order to produce a carbon dioxide converter.

The metabolite that was discovered by Patrick Unkefer and his team is a topical application that tricks the plant into operating as if it has more nitrogen in its system. The metabolic trigger affects the plants perception of nitrogen because nitrogen is an element that usually limits a plants' intake of carbon dioxide. Plants that are subjected to this metabolite grow faster and have a greater mass of protein. Bioengineers are also trying to recreate this affect without the topical application by breeding different traits in plants. This approach has already been applied to tobacco, and is currently being experimented using other types of plants. (Unkefer) Another bioengineering technique is to breed plants so that they have more numerous pores; the greater number of pores allows the plants to absorb more carbon dioxide. The greater absorption from the pores provides a similar effect as the metabolite. Plants would grow faster and create larger masses of protein.

Other non-chemical causes for plants to take in more carbon dioxide have been identified. Findings from the volcanic eruption of Mount Pinatubo showed a significant change in the area's concentration of carbon dioxide. The plants of that area were actually absorbing at a higher rate than normal after the eruption. Plants and soil are very sensitive to temperature changes, but the atmospheric decrease in the growth rate of carbon dioxide concentration is not explainable by mere temperature changes. Data from the eruption showed a 5% drop in solar radiation and 30% drop in direct radiation. The plants in the area of the eruption were getting a lot less direct sunlight and more diffused sunlight, which caused an increase in the carbon dioxide intake. The tops of plants become saturated when they are in the presence of direct sunlight. The diffusion of sunlight from the haze created by the eruption, caused plants to be more efficient and take in double the amount of carbon dioxide. This photosynthetic increase is not just true for the plants in that area; all types of plants are affects in a similar way. Aspen forests, mixed deciduous forests, Scott pine forests, tall grass prairies, and winter wheat all reacted similarly under these conditions during testing. Although volcanic eruptions do not happen often, this eruption did lead to scientific experimentation that showed that plants max carbon dioxide intake is when the cloud cover is at 50%. (Tawney)

Although the cloud cover affects the amount of carbon dioxide intake of plants, the amount of carbon dioxide in the atmosphere also affects how much carbon dioxide a plant takes in. Experiments performed by the University of Illinois showed that exposing plants to the expected CO_2 concentrations for 2050, 560 ppm, increased their intake by 12%. The length of time that plants can sustain this dramatic increase in their intake is limited by the nutrients in the soil. The capacity of the soil to sustain this type of growth is estimated to be only ten years without adding fertilizers into the system. (Barlow)

Plants are not the only life form in the ecosystem that absorbs carbon dioxide; soil also soaks up carbon dioxide. Like plants, if soil is given the appropriate conditions it can also take in more carbon dioxide. The soil can absorb much more carbon dioxide because most agriculture soils have lost one-third of their carbon from tilling. The humification process is when soil incorporates carbon from decomposing animals and plants, and converts it into stable organic matter, humus. The rate of this process is controlled by enzyme stability, moisture, alkalinity, oxygen, microbe population, and physical properties of different soils. An experiment by the Department of Energy's Pacific Northwest National Laboratory showed that an alkaline called "fly-ash" speeds up normal humification, but frequent cycles of wetting and drying the soil is very important to the process. If soils are replenished to their carbon capacity, many carbon dioxide problems could be solved.

Plants and soils may not be the only natural ways of converting carbon dioxide, microbes and artificial photosynthesis are also being researched. In 2001, Keith Cooksey and his team received a one million dollar grant to look for ways of lowering CO_2 levels. Most of his team is working with algae, and how to implement it in relation to cleaning the gases from power plants before the gases are vented into the atmosphere. But, Keith is also looking for a thermo tolerant microbe in Yellowstone National Park that would do much the same thing as the algae. Such microbes could be widely used and fewer changes to the current plants would have to be made. (Trinity-Stevens)

Another process being heavily researched is artificial photosynthesis, especially the conversion from carbon dioxide to carbon monoxide. When chlorophyll alone is removed from plants, it decomposes quickly, so scientists have to mimic photosynthesis using catalysts from rhenium complexes. This catalyst transfers electrons when it absorbs solar energy. Currently this catalyst causes the reaction to proceed too slowly, and experimentation is still being done to create a more efficient catalyst. (Walsh)

All of these processes from metabolites, soil re-saturation and artificial photosynthesis are being heavily researched and experimented, in hopes of using them to globally reduce carbon dioxide concentrations in the atmosphere.

5.6 Carbonate Ion Addition

Since global warming is caused by excess greenhouse gases in the atmosphere, especially carbon dioxide, a logical solution would be to find a way of removing carbon dioxide from the atmosphere. The anthropogenic section of the carbon cycle discussed the use of the ocean as a sink for carbon dioxide. It was found that through natural processes the ocean absorbs 30% of anthropogenic carbon dioxide. Carbon dioxide is absorbed by the ocean through the following chemical process:

$$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$$

The equilibrium constant for this reaction is given by this equation:

$$K' = \frac{[HCO_3^-]^2}{pCO_2\,[CO_3^{2-}]}$$

As was discussed, the absorbance of carbon dioxide by the ocean is dependant on temperature, the partial pressure of carbon dioxide, and on the concentration of carbonate ions. When these three variables are in their natural state, the ocean can absorb a decent quantity of anthropogenic carbon dioxide. If humans were able to adjust these variables, to favor the absorption of more carbon dioxide, how much more carbon dioxide could be removed from the atmosphere? How would these adjustments affect the ocean and its wildlife?

In reality, it would be impossible to alter the ocean's temperature or the partial pressure of carbon dioxide. The only variable that could be changed is the concentration of carbonate ions. The equation shows that, if carbonate ions are added, more carbon dioxide will react and more bicarbonate ions will be produced.

Assuming a constant temperature and partial pressure, we can find the amount of excess carbon dioxide that will be absorbed when more carbonate ions are added. (McElroy)

The byproduct of this reaction is bicarbonate ions. Increasing the concentration of bicarbonate will increase the alkalinity of the ocean. Water having a high alkalinity will have a more stabilized pH. Aquatic life can be very sensitive to changes in pH; the additional stabilization of the pH can be considered a positive side effect. However, large increases in alkalinity will cause some increases in pH. High concentrations of bicarbonate can cause the pH of a body of water to rise above 8.5. (Irrigation Water Quality Criteria) The average pH of seawater is approximately 8.2, although this is not a large difference, even minor changes in pH may have side affects.

The effects of increasing the ocean's concentration of carbonate ions are still uncertain. Attempting to alter any concentrations in a body of water as large as the ocean is somewhat impractical. Soda ash, or sodium carbonate, is the substance commonly used to increase the concentrations of carbonate ions in bodies of water. The cost of a 50-pound bag of soda ash is approximately fifteen dollars. The total volume of the ocean is approximately 1.33×10^{21} liters. The amount of soda ash required to have even the slightest impact on the concentration of carbonate ions in a body of water that size, would probably not be cost effective. More data should be collected, before accurate conclusions about the feasibility of this solution can be made.

Although each of these solutions can help to reduce atmospheric concentrations of carbon dioxide, none of them can effectively complete this goal on their own. The Kyoto Protocol will not be ratified by the United States, one of the major greenhouse gas producers. This protocol also does not provide suggested methods of reduction, merely required standards. Energy efficiency is another solution that does not provide procedures and only provides restrictions. The efficiency is also dependant on government standards, which may not be restrictive enough for efficiencies to increase. Natural energy resources, although environmentally friendly, damages ecosystems and changes wind and water circulation. Although sequestration removes carbon dioxide from the environment, this process allows governments to further their dependency on oil and coal. Sequestration techniques also have to possibility of allowing carbon dioxide to escaping back into the atmosphere. This release would not only reverse any positive affects, but the drastic release do to serious damage to the environment and be a serious health risk to anyone in the area. Plant and soil experiments on carbon dioxide intake may allow for carbon to be put back into the earth, but forest fires and other natural processes could also invalidate these processes. The addition of carbonate ions in to the ocean is economically unrealistic. This solution is also relatively undeveloped, their may be other unknown complications or side effects that will not be discovered until actual lab simulations are conducted. Due to these various drawbacks, implementing an assortment of these solutions would be the appropriate course of action.

6. Conclusion

In this IQP, we discovered detailed information about the effects of anthropogenic carbon dioxide on the carbon cycle. We used various models to analyze the global effect of carbon emissions. We studied a long list of side effects of global warming, and how these side effects are getting increasingly worse as this problem remains unchecked. Some of the current side effects include an increase in disease, the largest natural disaster to occur in Europe in over 50 years, sea level increase, more frequent and more intense storm systems, extinction of wildlife, the slowing of oceanic circulation and amplified El Niño; just to name a few. If current trends continue, by the year 2100, six hundred million people will live in costal flood plain areas and the sea level will have risen almost a meter. The slowing of thermohaline circulation could cause the northern hemisphere to be drastically colder, while the southern hemisphere will be much warmer.

We attempted to provide our own solutions along with the solutions of governments and scientists. Governments are attempting to regulate emissions, while gradually integrating environmentally conscientious technologies into the main stream. Scientists are working with metabolites, bioengineering, soil re-saturation and artificial photosynthesis in attempts to discover new carbon dioxide reducing technologies. We hypothesized the carbon dioxide reducing effects of increasing concentrations of carbonate ions in the ocean. While all of these ideas have the potential to reduce carbon dioxide concentrations in the atmosphere, without full global implementation they will be ineffective.

We suggest that future researchers expand upon one of the many solutions previously discussed. Further experimentation and lab simulation would provide specific data and a clearer understanding of the benefits and limitations of these concepts.

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