Curriculum Units by Fellows of the Yale-New Haven Teachers Institute
2021 Volume IV: The Earth's Greenhouse and Global Warming

The role of carbon dioxide in our changing climate

Curriculum Unit 21.04.04
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Introduction

The changing climate is a phenomenon that will affect us all in the future - with a global increase of 2.1 degrees Fahrenheit over the last century[1] ,decreasing sea ice in the arctic, rising sea levels, and an increase in the frequency of severe weather events, high school students are sure to feel the effects of climate change. While many students may have heard the terms "climate change" and "global warming" in the news, this unit aims to help students develop a scientific understanding as to what is causing these changes. Through a deeper understanding of the scientific basis of climate change, specifically the role of carbon dioxide in climate change, students will be better equipped to explain the changes that they are observing in real time. It is my hope that through this investigation students will become voices of change in their schools and communities, helping to educate others and get involved in climate action.

Rationale

This unit is written to be used in the 9th grade Phy-chem course at a large public high school in New Haven. Wilbur Cross, the largest high school in New Haven, serves about 1,600 students. 75% of students are eligible for free or reduced-price lunch and 88% are minorities. Most students are coming to Wilbur Cross from public middle schools in New Haven, where they have had an introduction to weather and weather systems, as well as earth science.

As an introductory high school science class, all 9th grade students in New Haven take the Phy-Chem course. In this course students begin the year by learning about weather and climate, including a focus on how the climate is changing and what evidence we have for these changes. Students then investigate the natural resources on Earth, how these resources cycle through the Earth system, and what impacts humans have on the availability of natural resources. Finally, the third and fourth quarter focus on waves and energy and how these technologies can be used to mitigate climate change. This unit is designed to be taught in the first quarter of the Phy-chem course as an introduction to the scientific principles that cause climate change. The state of New Haven has adopted the NGSS, so this unit is designed with these standards in mind.

Before this unit begins, students in Phy-chem will have learned about weather concepts, such as temperature, humidity, wind patterns, global currents, and pressure. Before beginning the unit, students will investigate evidence that the climate is changing by looking at pictures of locations in Greenland in the 1920s and 2015, analyzing graphs that show temperature changes over the last 200 years, and examining the frequency of extreme weather events.

Objectives

The unit aims to address three essential questions:

- How does carbon naturally cycle through the Earth's system?
- How do humans alter the natural carbon cycle?
- How does carbon dioxide increase the temperature? (climate sensitivity)

This unit will take place over six 80-minute periods, covering the following topics:

- Day 1 - Modeling the carbon cycle
- Day 2 - Human impact on the carbon cycle
- Day 3 - Analyzing graphs
- Day 4- Lab - how does carbon dioxide affect the temperature of the atmosphere
- Day 5 - Climate sensitivity
- Day 6 - Creating a model

Content Background

Carbon is a nonmetallic element that is incredibly important to many processes on earth, as it serves as the backbone for many living organisms and has the ability to store energy in its bonds. Carbon has 6 protons, and has isotopes with 6, 7, and 8 neutrons. A neutral carbon atom has 6 electrons, 2 in the inner shell and 4 in the outermost shell. It can lose 4 electrons to have a charge of +4 (oxidized cation) or gain 4 electrons to have a charge of -4 (reduced anion). Because of its ability to both lose and gain electrons, carbon can form bonds with many other elements, making it extremely important to many biological and geological processes.

There are four types of carbon molecules that are found on Earth. Organic carbon, like hydrocarbons and carbohydrates, is formed by photosynthesis and makes up living and dead material. It is in a reduced state, so therefore it stores energy. Bicarbonates and carbonates are forms of inorganic carbon that are present as dissolved ions, particularly in the oceans. Carbonate can also be found as a solid inorganic compound in soils, ocean sediments, and glacial flour, finely ground sediment. Finally, carbon dioxide (CO_2) is a gaseous form of inorganic carbon that can be found in the atmosphere, water, and soil. Oxidized carbon, such as carbon dioxide and calcium carbonate are the most stable forms of carbon.

Carbon cycle - pre anthropogenic

Carbon naturally cycles through organic and inorganic forms. There are four main reservoirs where carbon is stored. Carbon is measured in gigatons, which is equivalent to one billion metric tons. The atmosphere holds 700 Gigatons (Gt) of carbon in the gaseous form of carbon dioxide. Carbon dioxide makes up a very small percentage of the gases in the atmosphere, only 0.039%. Ocean waters hold 38,000 Gton of oxidized inorganic carbon, 600 Gt of dissolved organic carbon, and 1 Gton of carbon in living organisms. The land holds 500 Gt of carbon in living organisms as well as 1500 Gt of dead carbon in the soil from the decomposition of plants and animals. Most of this carbon (about 1000 Gt) is stored in the permafrost. The concentration of organic carbon in soil in a specific location varies widely depending on the climate and land use. Finally, sedimentary rock holds 1.2 million Gt of carbon in the form of rock carbonates (mainly $CaCO_3$) and 5000 Gton in the form of fossil fuels.[2]

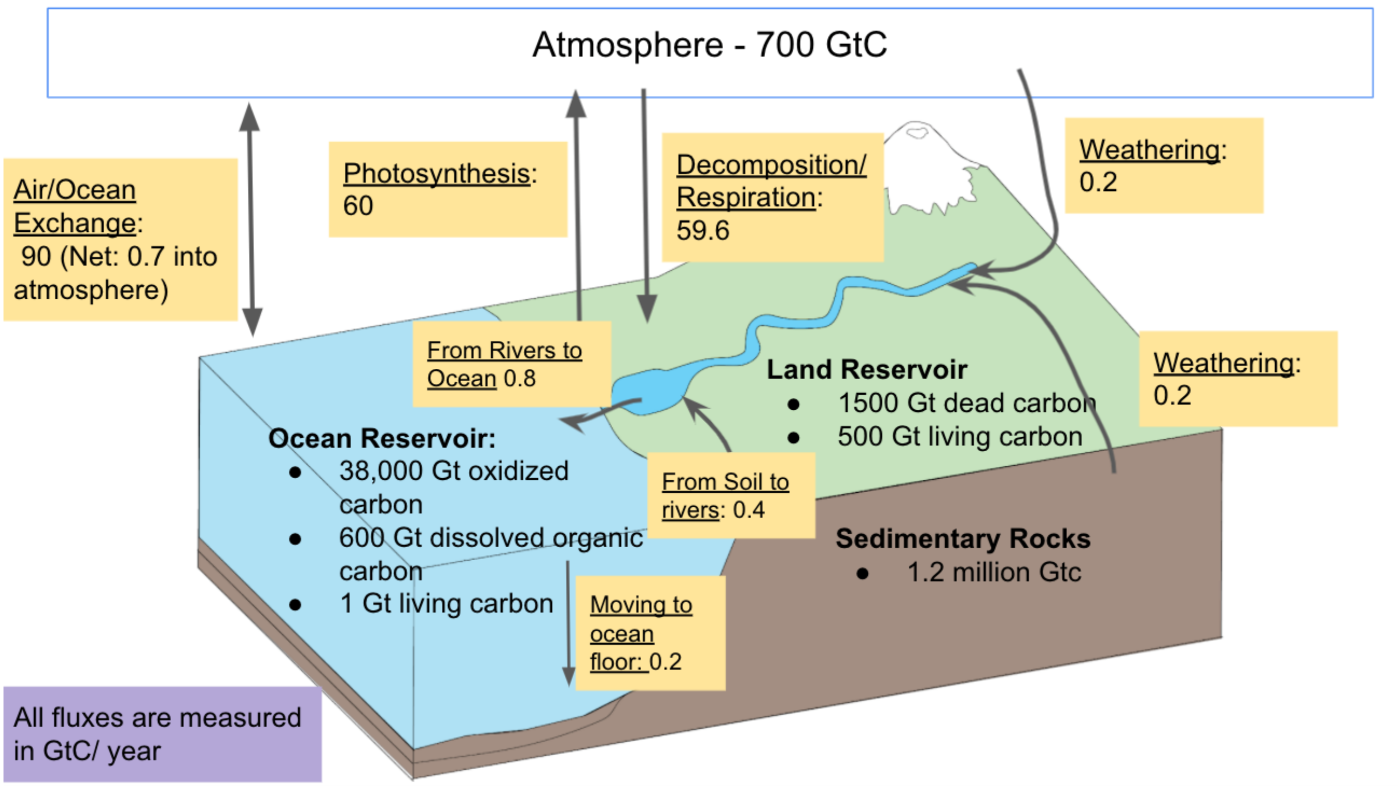

Figure 1: This figure shows the carbon held in each of four reservoirs: atmospheric, ocean, land, and sedimentary rock. It shows the movement of carbon between reservoirs in the preanthropogenic era.

Carbon moves through these reservoirs through three major chemical reactions. The first is that of photosynthesis/ cellular respiration: carbon dioxide reacts with water and energy to produce CH_2O and oxygen. In this reversible reaction, oxidized carbon (CO_2) is reduced using energy from the sun to create organic carbon. This organic carbon is produced by plants and some autotrophic bacteria on land and in the sea. In the reverse direction, organic carbon is oxidized using O_2 in order to produce energy. The by-products of this reaction are carbon dioxide and water vapor. Because of the nature of this reversible reaction, the amount of carbon dioxide in the atmosphere increases and decreases on a yearly cycle. During the growing season, the plants in the terrestrial biosphere use a greater amount of carbon dioxide, causing the atmospheric level to decrease. In the winter, however, the respiration reaction dominates, causing the level of carbon dioxide to increase.

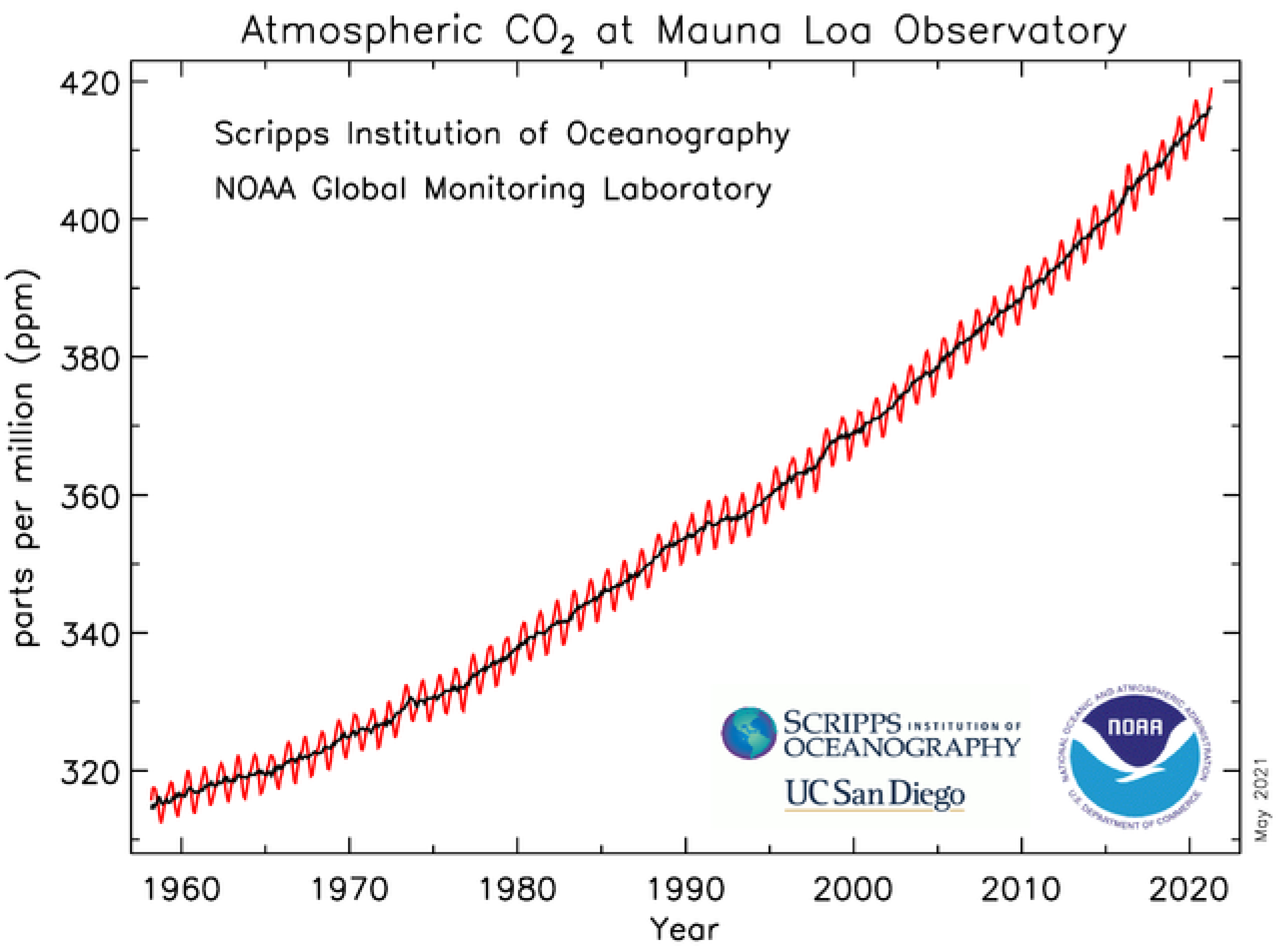

Figure 2: This graph shows carbon dioxide levels measured at the Moauna Loa Observatory in Hawaii. Each year the CO2 decreases in the summer and increases in the winter, causing a cyclical pattern (Source: https://gml.noaa.gov/ccgg/trends/)

On average, 60 Gt is taken out of the atmosphere every year through terrestrial net primary production (reaction 1) and 59.6 Gt is put back in by decomposing organisms on land (reaction 1 reverse).[3]

The second reaction that moves carbon through the three main reservoirs is a chemical weathering reaction. The chemical reaction for carbonate weathering is calcium carbonate reacts with carbon dioxide and water to form calcium ion and hydrogen carbonate. In carbonate weathering, carbon dioxide from the atmosphere reacts with water to form carbonic acid (H_2CO_3). The carbonic acid dissociates, allowing hydrogen ions to move freely in the water. These hydrogen ions then react with minerals, such as calcium carbonate ($CaCO_3$) forming clays and soluble ions. The dissolved sedimentary rocks are converted into solids by shell building organisms, like coral and plankton, which form shells from the material. Over time, when the organisms die, they sink to the ocean floor and form sedimentary rock. This is a reversible reaction, so when organisms form calcium carbonate shells, they release carbon dioxide.

The forward reaction is favored in warm, wet conditions on the Earth's surface. It also occurs faster when the level of $CO_2$is higher. The reverse reaction occurs in the high temperature and high pressure environment of the Earth's interior and is called metamorphic decarbonation. The CO_2 produced by the metamorphic decarbonation is eventually released back into the atmosphere through volcanic degassing. Unlike the photosynthesis/cellular respiration reaction, these reactions are both very slow, and occur over the time period of billions of years. Weathering and metamorphism account for the movement of about 0.1 Gtons of carbon in the global carbon cycle .[4]

The third reaction present in the cycling of carbon is air water exchange. In this reaction, carbon dioxide gas dissolves at the surface of the atmosphere, and in the reverse direction, carbon dioxide gas is released from ocean into the atmosphere. The rate of the reaction is governed by differences in gas concentration in the ocean and the atmosphere and the exchange coefficient. The exchange coefficient determines how quickly a gas molecule can move from the ocean to the atmosphere and vice versa.

It takes hundreds of years for the carbon dioxide to reach equilibrium between the atmosphere and the ocean because of the amount of time that it takes for deep ocean water to reach the surface ocean, where it can exchange CO_2 with the atmosphere. Once CO_2 dissolves in the ocean, it undergoes a reaction to form carbonic acid, which then dissociates and increases the concentration of hydrogen ions in the water, making the water more acidic. This reaction allows the ocean water to act as a buffer, stabilizing the concentrations of CO_2 in the water.

Carbon cycle - anthropogenic (fossil fuels)

The carbon in the atmosphere has increased by 133 ppm since 1750. Initially, the rise in carbon dioxide in the atmosphere was caused by land use changes and deforestation, which decreased the amount of photosynthesis that was removing carbon dioxide from the atmosphere. The clearing of land also took stored organic carbon and converted it to carbon dioxide, further increasing the CO_2 in the atmosphere.

After the industrial revolution, the amount of carbon dioxide continued to increase due to the burning of fossil fuels. Fossil fuels include coal, oil, and natural gas.

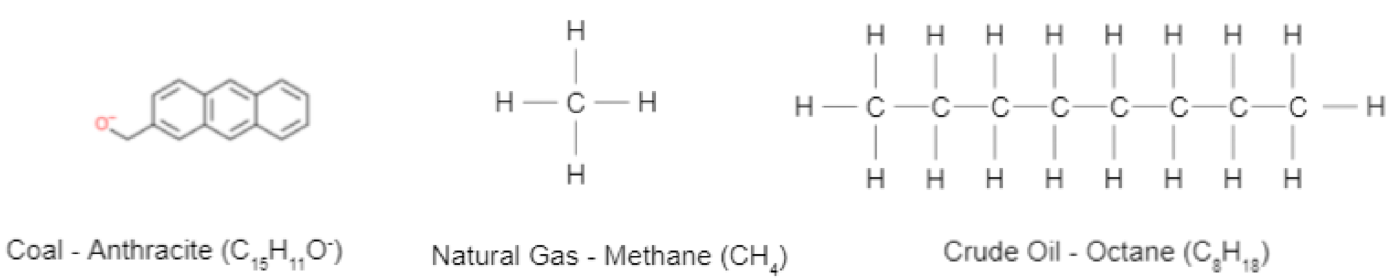

Figure 3: The chemical structures of coal, natural gas, and crude oil.

Coal is made up of organic carbon preserved in the land plants found in swamps and other organic rich soils and sediments, where the water keeps the carbon from becoming oxidized. The carbon accumulates into thick layers of peat. As the organic matter gets buried deeper in the ground, both the temperature and pressure increase. After a few million years under high temperature and high pressure, coal is formed. While the estimates of the amount of carbon contained in coal reserves differ, the low estimates assume that there are 1,000 Gtons of carbon currently stored in the coal reserves[5] . Oil is a hydrocarbon, made of hydrogen and carbon atoms. Petroleum (oil and natural gas) is mainly formed when dead plankton and algae sink to the ocean floor and mixes with the clay material that is deposited in the ocean by rivers and streams. If this occurs in an anoxic (without oxygen) environment, the organic material is converted into sedimentary rock called organic shale which is made of kerogen, which then continues to be buried in the Earth's interior. The temperature and pressure increases, and the kerogen is converted into oil hydrocarbons, and at an even higher temperature, natural gas, mostly in the form of methane (CH_4). Because the oil and natural gas are less dense than water, they migrate up towards the surface of the sedimentary rock where they are trapped by an impermeable layer of rock. This forms oil and natural gas reservoirs into which people can drill to release the oil and gas.

These materials are great sources of energy because they undergo combustion reactions, producing carbon dioxide, water, and large amounts of energy, in the reverse of the reaction described above. When one kilogram of coal is burned, it produces 25,000,000 joules (25 MJ) of energy. One kilogram of crude oil produces 42-47 MJ of energy. Natural gas has the highest energy production potential, producing 42-55 MJ of energy for every one kilogram of natural gas. Using the ratio of the molecular weight of carbon dioxide (MW= 44.01 g/mol) and the molecular weight of carbon (MW=12.01 g/mol), the amount of CO_2 produced by the combustion of one kilogram of coal, oil, and natural gas can be calculated[6] . Anthracite coal is made of 90% carbon. The amount of carbon dioxide produced from one kilogram of coal is equal to (44.01/12.01)x 0.9 which equals 3.3 kg of CO_2 released. Crude oil, or octane (C_8H_{18}) is composed of 84% carbon and therefore one kilogram of octane burned produces 3.1 kg of carbon dioxide. Methane (CH_4), (natural gas) is composed of 75% carbon, so one kilogram of methane burned produces 2.75 kg of CO_2.

These two major changes (deforestation and burning of fossil fuels) have significantly altered the carbon cycle, causing an imbalance. Deforestation increases the amount of CO_2 in the atmosphere by decreasing the amount of photosynthesis occurring, as well as decomposing the organic carbon stored in plants and soils. Today, deforestation mostly occurs in the tropics. It is responsible for a 1.6 Gt increase of carbon per year. The burning of fossil fuels adds 9.4 Gt of carbon to the atmosphere per year. This leads to a total increase of 11.0 Gt of carbon.

Some of this carbon is removed by changes in the carbon sinks. Land uptake has increased by 3.4 GtC, having doubled over the last 50 years. There are several possible reasons for why land uptake has increased in the anthropogenic carbon cycle. One possibility is that with the warming atmosphere throughout the globe, the growing season has lengthened, which allows for a longer "inhale" in the breathing of the land. Another possible reason for the increase in carbon uptake on land is because of CO_2 fertilization, which causes plants to grow faster. This occurs because when there is an increase of carbon dioxide in the atmosphere, the amount of time that the plant stomata has to be open decreases, which leads to higher rates of photosynthesis. It remains, however, unclear how much of an effect this will have on future carbon levels[7] . As the world continues to warm, it is possible that the increasing temperature of the soil will inhibit the soil from storing carbon, therefore decreasing the amount of carbon that is held in the land reservoir.

In the anthropogenic era, carbon uptake by the ocean has increased by 2.5 GtC. This is mainly due to the equilibrium shift in the air water exchange reaction. When the concentration of carbon dioxide in the water increases, the reaction is shifted to the right, consuming more CO_2, and producing more HCO_3^- . This reaction acts as a buffer for the water, and allows the seawater to take up a large amount of carbon dioxide. The amount of CO_2 being taken up by the ocean has also increased due to the reversed concentration gradient where the concentration of carbon dioxide in the atmosphere is much larger than the concentration of carbon dioxide in the ocean. Carbon dioxide, therefore, moves into the ocean through diffusion in order to try and reach a new equilibrium state.

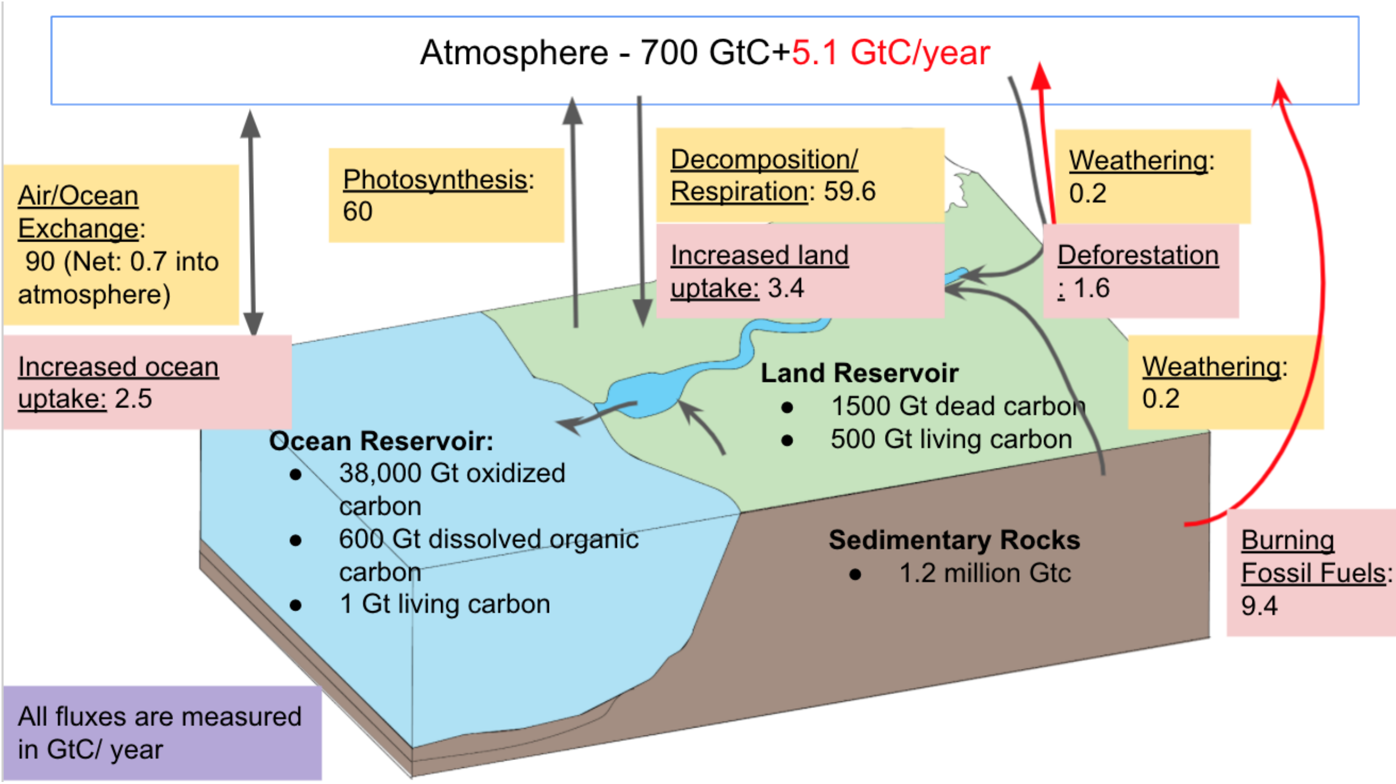

Figure 4: The anthropogenic carbon cycle includes changes in the carbon reservoirs due to the burning of fossil fuels and land use changes

The total increase in carbon in the atmosphere (11.0 Gt) is partially balanced by the 3.4 Gt decrease due to land sinks and 2.5 Gt decrease due to ocean sink, for a total decrease of 5.9 Gt. This leads to an overall increase of 5.1 Gt of carbon dioxide in the atmosphere[8] . This can be represented by the equation for the global carbon budget: $E_f+E_{luc}=G_{atm}+S_{ocean}+Ss_{land}+B_{im}$ where E_f is fossil fuel emissions, E_{luc} is the land use changes, G_{atm} is the carbon growth in the atmosphere, S_{ocean} is the carbon stored in the atmosphere, $S_{land}$is the carbon stored on land, and B_{im} is equal to the carbon imbalance.

How carbon dioxide affects temperature

As can be seen in the graph below, the global temperature has steadily increased throughout the last century.

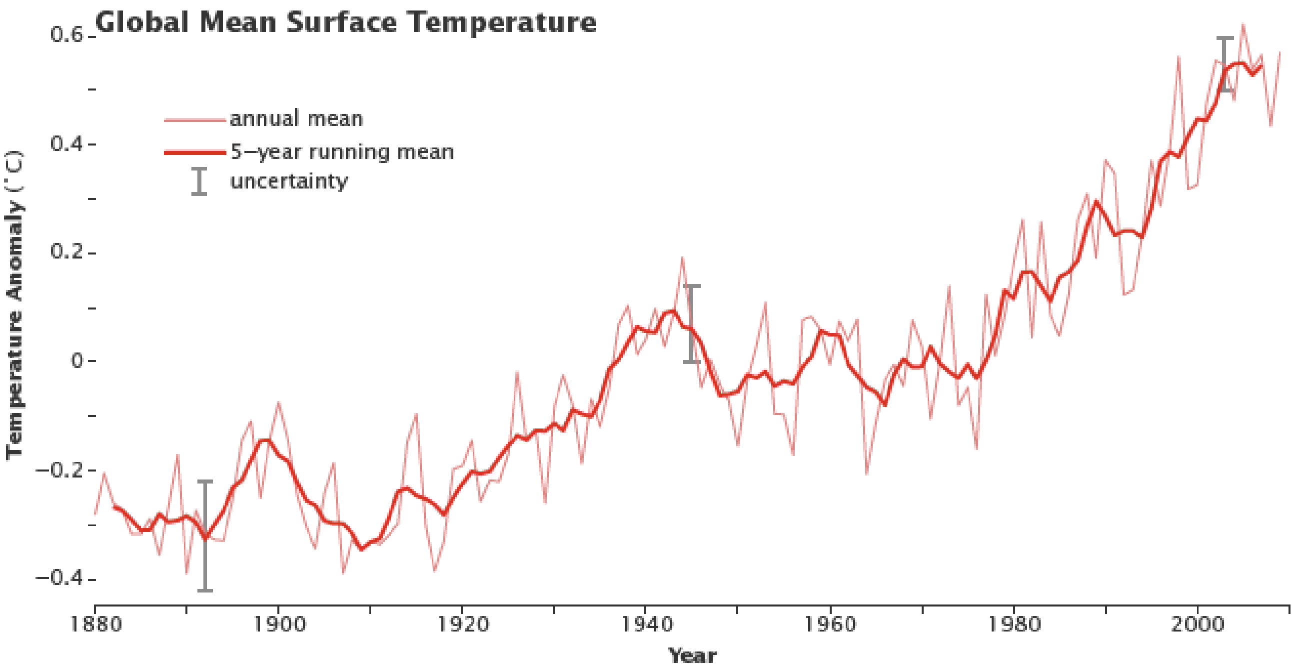

Figure 5: Figure 4: This graph shows the temperature anomaly from 1880 to the present. In 2010, the 5 year mean is 0.5 degrees celsius, meaning that the average temperature is 0.5 degrees higher than the average temperature. (Source: NASA)

The main cause of this increase is due to increased greenhouse gases in the atmosphere. The dominant greenhouse gases are carbon dioxide, water vapor, methane, nitrous oxide, and hydrofluorocarbons. Between 1990 and 2015, it is estimated that greenhouse gas emissions have increased by 43%, with more than 50% of the greenhouse gases emissions coming from carbon dioxide. The amount of carbon dioxide in the atmosphere is currently 409.8 ppm, which is 100 ppm higher than the highest point it has been in the last 800,000 years.

The Greenhouse effect is the process by which greenhouse gases trap heat in the atmosphere. Without the greenhouse effect, the temperature of the Earth would be too low to be habitable. The implications of the greenhouse effect can be seen when comparing Earth to other planets. Mars, which has very low CO_2 in the atmosphere, has an average temperature of -50 ℃. On the other hand, Venus, with its atmosphere made up of 96 % CO_2, has an average temperature of 420℃. Earth is found in the middle of these extremes, with an atmosphere that contains 0.03% carbon dioxide and an average temperature of 15℃.

Greenhouse gases absorb and emit thermal radiation from the sun. Much of the radiation emitted from the sun is short wavelength radiation which includes visible light and portions of infrared (IR) radiation. When IR radiation hits a CO_2 molecule, it causes the bonds to vibrate. The CO_2 molecule can then emit the extra energy as an infrared photon or transfer it to another molecule when they collide. This causes the motion of the surrounding molecules to increase, which increases the average kinetic energy, or temperature of the molecules. When this process occurs naturally (without the human added greenhouse gas emissions), the radiation entering the atmosphere is equal to the radiation emitted back out into space. This is called the equilibrium climate.

When the amount of carbon dioxide in the atmosphere increases, more heat is trapped, disrupting the climate equilibrium. Radiative forcing is a measure of how much the Earth’s energy system is out of balance, measured in Watts per meter squared (W/m^2). It can be found by measuring the amount of energy going in and subtracting the amount of energy reflecting back into space, and usually considers the energy at the top of the atmosphere, at the boundary between the troposphere and stratosphere. The current level of radiative forcing is 2.3 W/m^2 from 1750 to 2011 according to the IPCC (Intergovernmental Panel on Climate Change) report. This is 43% higher in 2011 than it was in 2005. Carbon dioxide accounts for the largest percentage of the radiative forcing, when compared to other greenhouse gases. While carbon dioxide absorbs less heat than methane or nitrous oxide, it has a much higher concentration in the atmosphere and stays in the atmosphere for a longer period of time.

Climate sensitivity models

Climate sensitivity is a measure of how much the Earth's temperature will change due to the human caused increase in carbon dioxide. Because the climate system is a complicated system with many different inputs and feedback cycles, there is not an easy answer to this question - scientists have come up with many different models to explain how the rise in carbon dioxide will affect the Earth's temperature. In a simple model that does not include any feedback systems, the temperature is predicted to increase by one degree Celsius when the concentration of carbon dioxide in the atmosphere doubles. However, there are several feedbacks in the climate system that alter this prediction. Positive feedback amplifies the effects warming to further increase the temperature, and negative feedback diminishes the effect of warming. Some of the main feedbacks that affect the climate sensitivity are water vapor concentrations, clouds, and surface albedo (reflectiveness of the earth's surface).

Air can hold more water vapor when warmed. Therefore, when the temperature increases, the amount of water vapor in the atmosphere increases. This, in turn, increases the greenhouse effect by trapping more heat. The effect of clouds on warming is more complicated. Clouds at low altitude reflect some sunlight back into space and decrease the temperature. High altitude clouds trap more heat in the atmosphere. Additionally, clouds that have more liquid water molecules are more effective at blocking sunlight than clouds composed of ice. The third main input is albedo, the measure of reflectiveness of the Sun on the Earth. As snow and ice cover decrease with increasing temperature, the albedo will also decrease because there is less reflective material. Given these inputs, estimates of climate sensitivity range from an increase of 1.5 degrees Celsius to 4.5 degrees Celsius when the carbon dioxide in the atmosphere doubles, with an average estimate of 3 degrees.

There are several different methods used to estimate climate sensitivity, all of which provide different estimates as to how much the temperature will increase when carbon dioxide doubles. The physics based method uses fundamental physics equations and models to predict how the temperature will increase. For example, the first law of thermodynamics, which describes the flow of energy in the Earth's system and states that energy cannot be created or destroyed, only transformed. Another example is the Clasius Clapeyron Equation which describes the relationship between temperature and water vapor pressure. These (and other) classical physics equations are imputed into a model, which then predicts the temperature increase if the carbon dioxide is doubled. A second method to estimate climate sensitivity uses direct observations and records of surface temperature and ocean heat. This method typically yields lower temperatures than the other methods. This is partially because of uncertainty in the heat of the ocean due to incomplete records, especially in places like the Artic where the temperature is rapidly increasing. The lower estimates can also be accounted for by the fact that these estimates do not take into account the effect that modern feedback loops play in the changing temperature[9] . These estimates are also affected because the role of aerosols in warming is not yet fully understood. Some aerosols lead to cooling while others lead to warming, and the aerosols also interact with clouds in a way that may increase cooling. A third method of estimating climate sensitivity is by looking at paleoclimate changes. In order to do this, scientists look at fossils and other natural records such as tree rings in order to learn about "climate proxies" from thousands to millions of years ago. Through this method, researchers can learn about how the climate has changed in different temperature periods. Because of the different time periods stressed in each of these models, the different models yield slightly different results for the climate sensitivity of the Earth. They all, however, agree that the Earth is warming at a dangerous rate and will continue to warm unless drastic actions are taken.

Teaching strategies

This unit will take place over six 80-minute periods, covering the following topics:

Lesson 1 - Modeling the carbon cycle

Students will be able to:

- Describe the reservoirs where carbon is stored
- Describe how carbon moves between the reservoirs in the pre-anthropogenic carbon cycle
- Determine how plants and animals convert carbon from one form to another

Students will first learn about the reservoirs where carbon is stored (land, ocean, atmosphere, sedimentary rock. They will then model how carbon moves through the carbon cycle by playing the carbon cycle game. In the first version of this game, fossil fuels will be left out. After playing 10 rounds of the game, students will reflect on where the carbon molecules spent the most time and how quickly they were able to move from one reservoir to another. Students will also conduct a mini-lab in which they will determine whether plants and animals produce carbon dioxide. They will first perform a control test in which they mix baking soda and vinegar and observe the color change of bromothymol blue when exposed to the carbon dioxide gas. They will then determine whether animals produce carbon dioxide by blowing through a straw into a solution with bromothymol blue. The color change will indicate that carbon dioxide is produced. For a third test, students will place a sprig of elodea into a covered test tube with bromothymol blue, and observe if there is a color change after 24 hours.

Lesson 2 - Human impact on the carbon cycle

Students will be able to:

- Identify 6 greenhouse gases
- Explain how fossil fuels produce carbon dioxide
- Create a model of the anthropogenic carbon cycle

During this lesson, students will use the Greenhouse Gas Cards[10] to learn about the 6 main greenhouse gases (carbon dioxide, water vapor, methane, ozone, and chlorofluorocarbon). Students will then play the carbon cycle game again, adding in the fossil fuels station. They will then reflect on how the fossil fuels change the way that carbon moves through the cycle. Finally, students will create a model of the carbon cycle based on what they learned in lesson 1 and 2. Their model can include pictures and/or descriptions to show how carbon flows through the different reservoirs in the anthropogenic era. As a homework assignment, students will use an online carbon footprint calculator to determine how much carbon they produce in their daily life in order to make this concept more relevant.

Day 3 - Analyzing graphs

Students will be able to:

- Analyze a graph of carbon dioxide and temperature emissions over time
- Determine patterns in temperature and carbon dioxide data
- Write a claim, evidence, reasoning paragraph that describes how industrialization has increased carbon dioxide levels

To begin this lesson, students will observe one graph that shows temperature vs time and one graph that shows carbon dioxide levels vs time over the last 300 years. Students will write down three things that they notice from these graphs and three things that they wonder. They will then discuss their observations and questions in small groups. Next, students will examine graphs that show carbon dioxide levels over the last 100, 500, and 800,000 years through looking at data from the ice cores. Based on these graphs, students will write a claim as to how industrialization has affected the amount of carbon dioxide in the atmosphere.

Day 4- Lab - how does carbon dioxide affect the temperature of the atmosphere

Students will be able to:

- Collect data to measure temperature over time
- Create a graph of temperature vs. time for three different scenarios
- Write a claim for how the presence of carbon dioxide affects the temperature

Students will conduct an experiment that models how carbon dioxide acts as a greenhouse gas and increases the temperature of earth. Students will set up three bottles, equidistant from a heat lamp. In one bottle, they will add a given amount of water and leave the top open. In a second bottle, they will close the top of the bottle. In the third bottle, they will add alka seltzer in order to release carbon dioxide into the bottle. They will then measure the temperature of each of the bottles every 5 minutes for a 60 minute lab period. At the end of the lab, they will create graphs of temperature vs. time for each of the three bottles and analyze the graphs to determine how the presence of carbon dioxide affects the temperature in the bottle.

Day 5 - Climate sensitivity

Students will be able to:

- Use a model to predict how increasing carbon dioxide will affect the global temperature
- Explain the benefits and challenges of climate models

To begin this lesson, students will use the EN-ROADS climate change simulator (https://en-roads.climateinteractive.org/scenario.html?v=21.6.0) to examine how various factors affect the temperature. Using the “Net CO_2 Emissions”, they will first observe the predicted temperature increase under current conditions. They will then choose at least three different factors to change and examine how those factors affect the predicted temperature increase. Next, students will watch Kate Marvel’s Ted Talk: https://www.ted.com/talks/kate_marvel_can_clouds_buy_us_more_time_to_solve_climate_change. This Ted

Talk introduces the idea of climate models and explains some of the challenges that models face in predicting how the temperature will change in the future. The video specifically focuses on clouds, discussing how clouds both increase and decrease the temperature. Finally, students will read a short article on climate sensitivity[11], which will explain what climate sensitivity is and how different models contribute to the estimate of temperature change.

Day 6 - Creating a model

Students will be able to:

- Create a model of how carbon dioxide contributes to climate change
- Make a recommendation to reduce climate change based off of the role of carbon dioxide in rising temperature

As a concluding project, students will develop their own models of the role that carbon dioxide plays in climate change. Using what they have learned about the carbon cycle, the effect of fossil fuels on the carbon cycle, and the various models of climate sensitivity, students will be able to design a model and make a prediction as to how they think the levels of carbon dioxide will continue to change and how that will affect the temperature. As a final extension, students can make a recommendation for how to reduce climate change and describe how that change will affect their model.

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This site has a graph that shows the carbon dioxide levels over the last 800,000 years.

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"Climate Change: Vital Signs of the Planet." NASA. May 27, 2021. Accessed April & May 2021. https://climate.nasa.gov/.

"Coal Formation." Miners. Accessed May 23, 2021. http://www.minersmuseum.com/history-of-mining/coal-formation/.

This site addresses how coal is formed over millions of years.

"Explainer: How Scientists Estimate Climate Sensitivity." Carbon Brief. October 05, 2020. Accessed July 02, 2021. https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity.

I used this site to learn about different climate sensitivity models, and how each of the models provides a different estimate as to how much the temperature will increase.

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"Geology and Climate." American Chemical Society. Accessed May 19, 2021. https://www.acs.org/content/acs/en/climatescience/oceansicerocks/geologyandclimate.html.

This site describes the process of weathering and its role in the carbon cycle. It includes a helpful diagram that shows how carbon flows from the land to the ocean

"Heat Values of Various Fuels." World Nuclear Association. Accessed May 23, 2021. https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various- fuels.aspx.

This site contains a table that includes the heat values of fossil fuels (coal, oil, and natural gas), which can be used to calculate the amount of energy produced from the combustion of each type of fuel.

"How the Oceans Absorb Carbon Dioxide Is Critical for Predicting Climate Change." Ocean Carbon Uptake. Accessed May 02, 2021. https://www.pmel.noaa.gov/co2/story/Ocean Carbon Uptake.

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IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

The IPCC report provided information on the current measure of radiative forcing.

Johnson, Charles. Carbon Dioxide Emission Factors for Coal. Accessed May 18, 2021. https://www.eia.gov/coal/production/quarterly/co2_article/co2.html.

I used this site to determine how much carbon dioxide is emitted from the combustion of coal.

"Ocean - Atmospheric Exchange." Ocean - Atmospheric Exchange | EARTH 103: Earth in the Future. Accessed May 23, 2021. https://www.e-education.psu.edu/earth103/node/676.

This site discusses the air-water exchange of carbon dioxide.

Ocean Carbon Uptake. Accessed July 02, 2021. https://www.pmel.noaa.gov/co2/story/Ocean Carbon Uptake.

"Oil Formation." Oil Formation - Energy Education. Accessed May 23, 2021. https://energyeducation.ca/encyclopedia/Oil_formation.

This site describes how oil is formed over time.

Sarmiento, Jorge L., and Nicolas Gruber. "Sinks for Anthropogenic Carbon." *Physics Today* 55, no. 8 (2002): 30-36. doi:10.1063/1.1510279.

"The Carbon Cycle." NASA. Accessed April & May 2021. https://earthobservatory.nasa.gov/features/CarbonCycle.

This site is an excellent resource to learn about the basics of the carbon cycle. It includes many visuals to help represent what happens to the carbon throughout the cycle.

"The Earth's Radiation Budget." NASA. Accessed June 02, 2021. https://science.nasa.gov/ems/13_radiationbudget.

"What a Three-million Year Fossil Record Tells Us about Climate Sensitivity." Carbon Brief. February 04, 2016. Accessed June 01, 2021. https://www.carbonbrief.org/what-a-three-million-year-fossil-record-tells-us-about-climate-sensitivity.

This site describes the different methods of estimating climate sensitivity and investigates the estimates made by different models

Student Reading List

Krulwich, Robert. "The Earth Has Lungs. Watch Them Breathe." Science. May 04, 2021. Accessed May & June 2021. https://www.nationalgeographic.com/science/article/the-earth-has-lungs-watch-them-breathe .

This website contains a graphic that shows how the concentration of carbon dioxide changes seasonally. In the visualization, students can see that the concentration of carbon dioxide is low during the summer months, but increases significantly in the fall and winter.

"SVS: Global Temperature Anomalies from 1880 to 2020." NASA. Accessed May & June 2021 https://svs.gsfc.nasa.gov/4882#30730 .

This visualization shows how temperature anomalies have increased over the last century. It offers an easy way for students to see the changing temperature over time.

"What Is the Greenhouse Effect?" NASA. May 10, 2021. Accessed April & May 2021. https://climatekids.nasa.gov/greenhouse-effect/ .

This site offers a simple explanation of how the greenhouse effect increases the temperature of the earth.

"Meet the Greenhouse Gases!" NASA. Accessed July 02, 2021. https://climatekids.nasa.gov/greenhouse-cards/.

These cards explain the six main greenhouse gases, including why they are needed in our atmosphere and what the hazards of having too many are. They are used in lesson 2 to introduce the greenhouse gases to students.

Notes

[1] "Climate Change: Vital Signs of the Planet," NASA|, accessed April 02, 2021, https://climate.nasa.gov/

[2] David Archer, Global Warming: Understanding the Forecast (Hoboken, NJ: Wiley, 2012), 92

[3] Jorge L. Sarmiento and Nicolas Gruber, "Sinks for Anthropogenic Carbon," Physics Today 55, no. 8 (2002): doi:10.1063/1.1510279

[4] David Archer, Global Warming: Understanding the Forecast (Hoboken, NJ: Wiley, 2012), 92

[5] David Archer, Global Warming: Understanding the Forecast (Hoboken, NJ: Wiley, 2012), 104

[6] "Heat Values of Various Fuels," Heat Values of Various Fuels - World Nuclear Association, accessed July 02, 2021, https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

[7] David Archer, Global Warming: Understanding the Forecast (Hoboken, NJ: Wiley, 2012), 125

[8] Pierre Friedlingstein, "Human Induced Changes on the Global Carbon Cycle over the Last 60 Years," 2020, doi:10.5194/egusphere-egu2020-4822

[9] "Explainer: How Scientists Estimate Climate Sensitivity," Carbon Brief, October 05, 2020, accessed July 02, 2021, https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity

[10] "Meet the Greenhouse Gases!" NASA, accessed July 02, 2021, https://climatekids.nasa.gov/greenhouse-cards/

[11] "Making Sense of 'Climate Sensitivity' – Climate Change: Vital Signs of the Planet," NASA, March 16, 2021, accessed July 02, 2021, https://climate.nasa.gov/blog/3017/making-sense-of-climate-sensitivity/

Appendix on Implementing District Standards

This unit addresses the following Next Generation Science Standards:

HS-PE-ESS2-6: Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere.

HS-PE-ESS3-5: Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.

HS-PE-ESS2-2: Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems.

HS-PE-ETS1-1: Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants

This unit also addresses the following Crosscutting Concepts from the NGSS:

Patterns

- Cause and Effect
- Systems and system models
- Energy and Matter
- Stability and change

This unit also addresses the following Science and Engineering Practices from the NGSS:

- Asking questions
- Developing and using models
- Analyzing and interpreting data
- Constructing explanations
- Engaging in argument from evidence