3 The Carbon Cycle

Introduction

Carbon, the fourth most abundant element in our galaxy, is essential to life on earth. Virtually everything contains some form of carbon. Plants use carbon dioxide to produce energy for growth, and the human body is about 20% carbon by weight.

Carbon can be measured in various forms, including carbon dioxide (CO_2), methane (CH_4), and calcium carbonate ($CaCO_3$), which is found in rocks and aquatic shells. We can also measure organic carbon, which is found in organisms.

The carbon cycle is the movement of carbon in its different forms among various "pools." These pools include the atmosphere, the oceans, the terrestrial biosphere (vegetation and soils), and the geosphere (mineral soils, sediments, rock layers of earth's crust, and fossil fuels).

The total amount of carbon on earth and in the atmosphere is *constant*. However, the amount of carbon in the various pools and the time it takes for carbon to move from one pool to another varies widely.

Carbon is exchanged daily between the atmosphere and the biosphere, for example, when plants absorb CO_2 for photosynthesis. But it can take millions of years for carbon to move from the biosphere into the geosphere, a transfer that occurs during the formation of fossil fuels.

Pools that accumulate more carbon than they emit are referred to as carbon "sinks." For example, the oceans, the biosphere, and the atmosphere are carbon sinks because the total amount of carbon in each increases annually.

It has been hypothesized that increased levels of carbon in the atmosphere may be triggering warmer temperatures. To better understand why the atmosphere accumulates carbon, scientists focus on the exchanges or "flows" of carbon between the atmosphere and other pools.

The oceans both absorb and emit the largest amounts of carbon on an annual basis. The oceans currently store an estimated 39 trillion metric tons of carbon. Each year, they release 90.6 billion metric tons of carbon while absorbing 92.2 billion metric tons. Thus, the net "sink" of the oceans is about 1.6 billion metric tons annually. [1] (For a sense of scale, Canada emits roughly 177 million metric tons of carbon annually from the combustion of fossil fuels.) [2]

The terrestrial biosphere is also a carbon sink. Forests and plants absorb carbon dioxide from the air during photosynthesis. Along with water and sunlight, plants convert CO_2 into sugars for energy and the production of leaves, bark, roots, and other forms of growth. Over time, carbon accumulates in plant tissues and soils.

Plants, trees, and soils are also sources of carbon emissions. Like humans and animals, plants release carbon (CO_2) into the atmosphere when they break down sugars for energy. Carbon is also released during plant decomposition. On average, the terrestrial biosphere (vegetation, soil, and detritus) absorbs 120 billion metric tons of carbon and emits 119.6 billion metric tons annually. [3]

Other important sources of carbon include the combustion of fossil fuels, volcanic activity, and wildfires. Land use changes, such as timber harvests and landscape clearing, are responsible for the emission of about 1.6 billion metric tons of carbon each year. The burning of fossil fuels creates another 6.4 billion metric tons of carbon emissions annually. Overall, human activities are responsible for about 1% of total carbon emissions into the atmosphere each year. [4]

The amount of carbon that remains in the atmosphere is primarily a function of total emissions less the amount absorbed by other pools. When the amount of carbon emitted into the atmosphere is greater than the amount absorbed, carbon levels in the atmosphere increase.

However, recent studies have found that these numbers do not add up as one would expect. The sum of all of the carbon emitted into the atmosphere minus the amount absorbed by the various pools is *not* equal to the amount of carbon that remains in the atmosphere; the amount of carbon remaining in the atmosphere is less than the difference between emissions and absorptions. Recent studies estimate that an amount equal to about 33% of human emissions of carbon is unaccounted for. [5]

Despite decades of research, our understanding of the global carbon cycle is incomplete. It is particularly challenging for scientists to quantify the amount of carbon exchanged between the various pools over time. Extensive use of computer modeling, satellite imagery, and ground measurements have improved our understanding, but precise measurements of carbon flows remain elusive.

This lack of understanding affects climate models and forecasts, resulting in inaccurate and unreliable predictions. Despite their unreliability, these same analyses and models are being used by governments to make policy decisions.

The limitations of climate models

The most complex climate models attempt to simulate various climate components such as the atmosphere, oceans, land, and ice. At the moment, climate models are the most comprehensive tool available for studying and simulating the interaction of diverse climate components and processes.

Though they are useful, climate models have important limitations. Even the most complex models cannot calculate every process in the climate, including many that are known to play important roles. Consequently, climate modelers must find ways to simplify and approximate many real-world physical relationships.

Evaluating the accuracy of climate models

Weather forecasts can be tested against actual observations to see if the model was accurate, but climate models often make predictions that span decades or longer, making it more difficult to confirm their accuracy. As a result, climate models are often tested by observing how closely they can simulate known past and present climate changes. The Intergovernmental Panel on Climate Change (IPCC) notes that since its last report in 2001, model performance has improved overall, but errors and biases remain. [6]

Temperature

Models can only simulate annual average temperatures in most regions of the world to within approximately 3° C of observations. [7] Averaging simulations across all models produces slightly better results, but errors in simulations involving polar regions are larger.

In addition, most models predict that increasing the atmospheric concentration of greenhouse gases will result in a strong warming in the troposphere around the tropics, and that the warming there will be greater than at the surface. However, since 1979, all but one weather balloon and satellite record have shown *less* warming in the tropical troposphere than at the surface. [8]

Precipitation

Models can simulate some large precipitation patterns on a regional scale, but individual models show substantial biases, especially in tropical regions.

Sea ice

When averaged across models, the simulation of observed sea ice coverage in the polar regions is reasonably similar to observations. However, the range of estimates among models exceeds 50% of the observed mean, and projections into the future remain uncertain. [9] Evaluations of the accuracy of the models are also limited by a shortage of real-world data for comparison.

Climate sensitivity

"Climate sensitivity" is the expected increase in global average temperature if the amount of carbon dioxide in the atmosphere were to double. Climate sensitivity is mostly influenced by feedback processes in the climate, which are difficult to estimate. Without the feedback process, a doubling of greenhouse gases would only raise average global temperatures in a climate model by about 1° C. [10] But because of the expected positive feedback processes, mainly from water vapor, most models project that global average temperatures would increase between 2° C and 4.5° C, with approximately 3° C being the most common estimate. [11]

Despite much research, the range of climate sensitivity estimates has not changed much over the past few decades. A major source of uncertainty is the difficulty of predicting the response of clouds to temperature increases.

Summary

Climate models are important for understanding and predicting possible climate changes, but the challenges of representing small-scale climate and weather processes, as well as the ongoing discrepancies between projected climate conditions and observations, are important limitations. Since models are used not only for making projections, but also for analyzing human influence on the current climate, it is important to understand their inherent uncertainties.

References

1 Intergovernmental Panel on Climate Change [IPCC] (2007). *Climate Change 2007: The Physical Science Basis*. Intergovernmental Panel on Climate Change. <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>.

2 Marland, G., T.A. Boden, and R.J. Andres (2008). *Global, Regional, and National Fossil-Fuel CO_2 Emissions*. Carbon Dioxide Information Analysis Center. <http://cdiac.ornl.gov/trends/emis/overview.html>.

3 IPCC (2007).

4 IPCC (2007).

5 Houghton, J. T., G. J. Jenkins, and J.J. Ephraums (eds.) (1990). *Climate Change: The IPCC Scientific Assessment*. Cambridge University Press.

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8 IPCC (2007).

9 IPCC (2007).

10 Rahmstorf, Stefan (2008). Anthropogenic Climate Change: Revisiting the Facts. In E. Zedillo, *Global Warming: Looking Beyond Kyoto* (Brookings Institution): 34–53. <http://www.pik-potsdam.de/~stefan/Publications/Book_chapters/Rahmstorf_Zedillo_2008.pdf>.

11 Rahmstorf (2008).

Lesson 3-A

The missing sink

Theme

Nearly everything on earth contains at least some carbon. Although there is a fixed amount of carbon in the earth and atmosphere, it is continuously cycled from one pool to another. Our ability to track flows of carbon between the various pools is limited by the complexity of the carbon cycle.

Purpose

To demonstrate that our lack of understanding concerning the carbon cycle diminishes the reliability of carbon tracking and climate modeling.

Description

Students will gain a basic understanding of carbon sources and exchanges. Using estimates of carbon stocks and flows, students will analyze data regarding various stocks and flows, and learn about the "missing sink" of carbon.

Procedure

1 Open a carbonated beverage in class. Ask students if they know what causes the bubbles.

> *Carbonation is the result of carbon dioxide dissolved in liquid under pressure. When the pressure is reduced (by opening the can or bottle), the carbon dioxide can no longer remain dissolved in the liquid and is released, creating bubbles of gas (CO_2).*

2 Show *Visual 3.1: The global carbon cycle* to demonstrate that carbon is everywhere and is always cycling from pool to pool.

3 Using *Visual 3.2: Forms of carbon*, explain that there are three forms of carbon: carbon dioxide (CO_2), methane (CH_4), and calcium carbonate ($CaCO_3$).

4 *Visual 3.3: The carbon cycle* describes the various attributes of the cycle. "Flows" refer to the movement of carbon between various pools. Some flows (also called "fluxes") are slow; for example, when carbon is held in the lower layers of the ocean and used in the formation of fossil fuels. Other flows are fast; for example, when carbon is exchanged between plants or animals and the atmosphere. Carbon is continuously moving between the oceans and the atmosphere. Explain that "sinks" are pools that absorb more carbon than they emit.

5 Refer again to *Visual 3.1: The global carbon cycle*. Review the different pools, sinks, and flows. Both carbon pools and flows are measured in billion metric tons (gigatons) of carbon. The arrows show how carbon flows between pools.

6 Hand out *Worksheet 3.1: Understanding the carbon cycle*. Review the description of the exercise using *Visual 3.4: Global carbon stocks and flows*. Have students complete the exercise in small groups.

7 Discuss the answers to each question. Explain the concept of the "missing sink." Tell students that the sum of all of the carbon emitted into the atmosphere minus the carbon absorbed by the various pools is not equal to the amount of carbon that remains in the atmosphere. The amount of carbon remaining in the atmosphere is *less* than the difference between emissions and absorptions. This difference is the missing sink. Emphasize that the missing sink is a scientific unknown, and is not a math or data error.

8 What does the missing sink reveal about current models of climate change?

> *Climate models are important for understanding and predicting possible climate changes, but they have a number of limitations. Scientists have used climate models to estimate the amount of carbon emitted into the atmosphere and the changing carbon levels in the atmosphere, oceans, and biosphere. However, the missing sink is still debated as our knowledge of it is uncertain.*

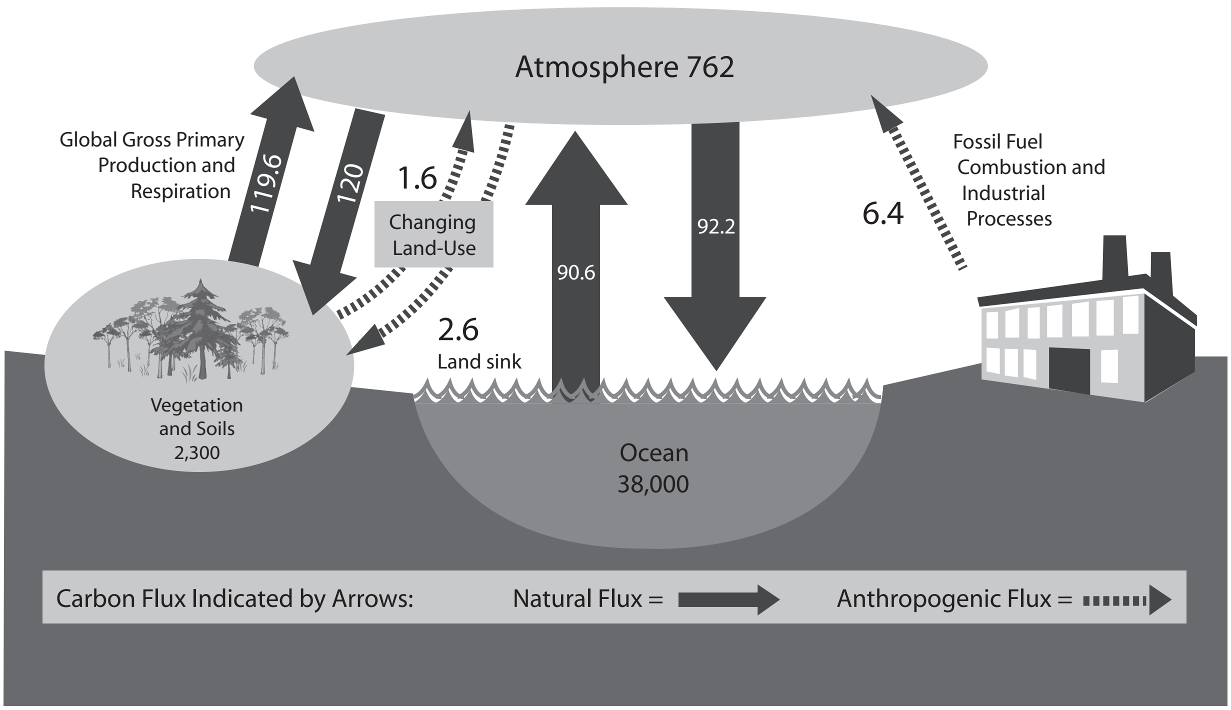
Final Thought

Remind students that science is a process of learning. The natural world may seem hopelessly complex, but that same complexity is what inspires scientists to develop and test new hypotheses. Each hypothesis advances our understanding of the world. Science is neither flawless nor absolute; it is simply the best knowledge we have at a given time. What we think we know today is susceptible to change in the future.

Visual 3.1

The global carbon cycle

The global carbon cycle



*Carbon fluxes are measured in billions of metric tons of carbon (GtC).
Source: Adapted from Intergovernmental Panel on Climate Change [IPCC] (2007). *Climate Change 2007: The Physical Science Basis*. Intergovernmental Panel on Climate Change. <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>.

Visual 3.2
Forms of carbon

All carbon falls under 2 categories

Organic carbon

Found in living and dead organisms.

Hydrocarbons

Organic compounds made up of hydrogen and carbon, such as coal, natural gas, oil, and various fuels.

There are 3 forms of carbon

Carbon dioxide CO_2

Released through fossil fuel combustion, cement production, volcanic activity, respiration, decay of organic material, weathering, and certain changes in land use.

Absorbed by oceans and plants.

Methane CH_4

Mostly anthropogenic; sources include fossil fuel production, livestock, and waste management.

Calcium carbonate $CaCO_3$

Compounds made up of hydrogen and carbon, including coal, natural gas, and various fuels.

Visual 3.3

The carbon cycle

The carbon cycle

Carbon pools

Carbon reservoirs

- The atmosphere
- The oceans
- Terrestrial biosphere: living and dead vegetation and organic soils
- The geosphere: mineral soils, sediments, and rock layers of earth's crust; includes fossil fuels

Carbon sinks

Carbon reservoirs that absorb more than they emit

- Oceans, terrestrial biosphere, and the atmosphere

Carbon flows

The movement of carbon between various pools

Visual 3.4
Global carbon stocks and flows

Carbon stocks (storage) in billions of metric tons of carbon (GtC)

Carbonate rocks	65,000,000
Fossil fuels	3,700
Soils	~1,600
Vegetation and detritus	~700
Oceans	38,000
Atmosphere	762

Carbon flows (flux) in GtC

	Emissions	Absorption	Net
Oceans	90.6	92.2	- 1.6
Vegetation, soil, and detritus	119.6	120	- 0.4
Weathering		0.2	- 0.2
Fossil fuels	6.4		6.4
Land use changes	1.6		1.6
Missing sink		2.6	- 2.6
Net flux to the atmosphere			3.2

Sources: Oelkers, E. H., and D. R. Cole (2008). Carbon Dioxide Sequestration: A Solution to a Global Problem. *Elements* 4: 305–10.
Intergovernmental Panel on Climate Change [IPCC] (2007). *Climate Change 2007: The Physical Science Basis*. Intergovernmental Panel on Climate Change. <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>.

Worksheet 3.1

Understanding the carbon cycle

Different types of carbon move through the earth and the atmosphere; some move rapidly, others very slowly. The total amount of carbon remains constant.

Inorganic carbon, such as bicarbonate and carbonate, is found in rocks and shells. Organic carbon is found in plants and animals. Carbon gases include carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO).

The carbon cycle is the movement of carbon from one form to another. Carbon emissions are absorbed by the atmosphere, the oceans, and the biosphere.

Using the tables below, answer the questions on the following page. You may need a calculator for this exercise.

Carbon stocks (storage) in billions of metric tons of carbon (GtC)

Carbonate rocks	65,000,000
Fossil fuels	3,700
Soils	~1,600
Vegetation and detritus	~700
Oceans	38,000
Atmosphere	762

Carbon flows (flux) in GtC

	Emissions	Absorption	Net
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Weathering		0.2	- 0.2
Fossil fuels	6.4		6.4
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Missing sink		2.6	- 2.6
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Worksheet 3.1

Understanding the carbon cycle

1 Which of the carbon stocks is the largest?

2 What percentage of carbon stocks is held in oceans (approximately)?

3 Which of the carbon emissions sources is the largest? Which is the smallest?

4 Which carbon flow has the greatest net emissions? The greatest net absorption?

5 Which of the carbon flows are caused by human activity?

6 What is the sum of the net emissions of carbon that are caused by human activity?

7 What is the “missing sink”?

Worksheet 3.1 Answer Key

Understanding the carbon cycle

1 Which of the carbon stocks is the largest?

Carbonate rocks store 65,000,000 billion metric tons of carbon.

2 What percentage of carbon stocks is held in oceans (approximately)?

0.06 %. Total carbon storage is approximately 65,044,762 billion metric tons.

3 Which of the carbon emissions sources is the largest? Which is the smallest?

Largest: Land. Smallest: Land use changes.

4 Which carbon flow has the greatest net emissions? The greatest net absorption?

Greatest net emissions: Fossil fuels. Greatest net absorption: Missing sink.

5 Which of the carbon flows are caused by human activity?

Fossil fuels and land use changes.

6 What is the sum of the net emissions of carbon that are caused by human activity?

8 billion metric tons. (Fossil fuels, 6.4, plus land use changes, 1.6, equals 8 billion metric tons.)

7 What is the "missing sink"?

Carbon that has been released into the atmosphere is absorbed by the oceans, the biosphere, and the geosphere. However, the sum of all of the carbon emitted into the atmosphere minus the carbon absorbed by the various pools is not equal to the amount of carbon that remains in the atmosphere. The amount of carbon remaining in the atmosphere is less than the difference between emissions and absorptions. Recent studies estimate that an amount equal to about 33% of human emissions of carbon is unaccounted for.

Lesson 3-B

Weather forecasting

Theme

As much as scientists do know about weather and climate, weather forecasting still involves a lot of uncertainty and guesswork. Meteorologists analyze past and current atmospheric conditions to try to predict future weather. Using satellite data and computer models, they forecast future conditions. Changing forecasts and the proportion of inaccurate predictions are evidence that weather forecasting is imprecise.

Purpose

This lesson will demonstrate the challenges faced by meteorologists and climatologists when modeling and forecasting local weather and global climate conditions.

Description

Students will track weather forecasts for one week and examine the reliability of those forecasts. Measuring the rate of weather forecast errors can help students put complex climate change computer models in context with relatively simple weather prediction models. Compared to weather forecast models, climate change models, which are much more complex, have a much higher likelihood of error because far more variables are involved.

Procedure

1 Have students read *Student Reading 3: The limitations of climate models*. This will help students understand the difficulties surrounding climate modeling.

2 Hand out *Worksheet 3.2: Weather forecasts*. Using the worksheet, students will track weather forecasts for one week and examine the reliability of one-day predictions, three-day predictions, and weekly predictions. As the week progresses, students will compare the actual weather on each day to the forecast at the beginning of the week.

3 At the end of the week, have a class discussion about the accuracy of the weather forecasts. Have students compare forecasts from the different sources that were used by students to complete the assignment.

Final Thought

It is important for students to understand that predictions will never be 100% accurate. Although scientists know a lot about weather and forecasting, there are still many areas of uncertainty. Similarly, there is still a great deal of uncertainty about climate change.

Student Reading 3

The limitations of climate models

The most complex climate models attempt to simulate various climate components such as the atmosphere, oceans, land, and ice. At the moment, climate models are the most comprehensive tool available for studying and simulating the interaction of diverse climate components and processes.

Though they are useful, climate models have important limitations. Even the most complex models cannot calculate every process in the climate, including many that are known to play important roles. Consequently, climate modelers must find ways to simplify and approximate many real-world physical relationships.

Evaluating the accuracy of climate models

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Temperature

Models can only simulate annual average temperatures in most regions of the world to within approximately 3° C of observations. [2] Averaging simulations across all models produces slightly better results, but errors in simulations involving polar regions are larger.

In addition, most models predict that increasing the atmospheric concentration of greenhouse gases will result in a strong warming in the troposphere around the tropics, and that the warming there will be greater than at the surface. However, since 1979, all but one weather balloon and satellite record have shown *less* warming in the tropical troposphere than at the surface. [3]

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Climate sensitivity

"Climate sensitivity" is the expected increase in global average temperature if the amount of carbon dioxide in the atmosphere were to double. Climate sensitivity is mostly influenced by feedback processes in the climate, which are difficult to estimate. Without the feedback process, a doubling of greenhouse gases would only raise average global temperatures in a climate model by about 1° C. [5] But because of the expected positive feedback processes, mainly from water vapor, most models project that global average temperatures would increase between 2° C and 4.5° C, with approximately 3° C being the most common estimate. [6]

Despite much research, the range of climate sensitivity estimates has not changed much over the past few decades. A major source of uncertainty is the difficulty of predicting the response of clouds to temperature increases.

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References

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6 Rahmstorf (2008).

Worksheet 3.2
Weather forecasts

Using the form below, track weather forecasts for the coming week. You may use the weather forecasts from a TV newscast, radio station, newspaper, or website, but be consistent, i.e., use the same source throughout the assignment. Then answer the questions on the following page.

Weekly forecast on Monday **Date:**

	Monday (predicted)	Tuesday (predicted)	Wednesday (predicted)	Thursday (predicted)	Friday (predicted)
Temperature High					
Temperature Low					

Weekly forecast on Tuesday **Date:**

	Monday (actual)	Tuesday (predicted)	Wednesday (predicted)	Thursday (predicted)	Friday (predicted)
Temperature High					
Temperature Low					

Weekly forecast on Wednesday **Date:**

	Monday (actual)	**Tuesday (actual)**	Wednesday (predicted)	Thursday (predicted)	Friday (predicted)
Temperature High					
Temperature Low					

Weekly forecast on Thursday **Date:**

	Monday (actual)	**Tuesday (actual)**	**Wednesday (actual)**	Thursday (predicted)	Friday (predicted)
Temperature High					
Temperature Low					

Weekly forecast on Friday **Date:**

	Monday (actual)	**Tuesday (actual)**	**Wednesday (actual)**	**Thursday (actual)**	Friday (predicted)
Temperature High					
Temperature Low					

Worksheet 3.2

Weather forecasts

How accurate was Monday's weather prediction for each day of the week?

Monday:

Tuesday:

Wednesday:

Thursday:

Friday:

How did the weather predictions change over the course of the week compared to Monday's forecast?