Seasonal SAWTOOTH PATTERNS in the CARBON CYCLE

A Phenology and Climate Lesson for 9th-12th Grade Students

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CURRICULUM DEVELOPMENT
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CONTRIBUTORS
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DESIGN AND LAYOUT
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A Phenology and **SEASONAL SAWTOOTH PATTERNS IN THE CARBON CYCLE** *Climate Lesson*

Seasonal Sawtooth Patterns in the Carbon Cycle

DESCRIPTION

Students compare atmospheric carbon dioxide levels and plant phenology (or seasonal "greenness") data to determine why atmospheric carbon dioxide levels follow a sawtooth trend and how that contributes to a feedback loop.

PHENOMENON

What causes the sawtooth pattern in the carbon dioxide graph?

GRADE LEVEL

9-12

OBJECTIVES

Students will:

- identify the correlation between seasonal cycles in atmospheric carbon levels and photosynthetic activity.

TIME

45 MINUTES

NEXT GENERATION SCIENCE STANDARDS

HS-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.

Science & Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Analyzing and Interpreting Data Engaging in Argument from Evidence Constructing Explanations and Designing Solutions	ESS2.A: Earth Materials and Systems ESS2.D: Weather and Climate ESS2.E: Biogeology	Scale, Proportion, and Quantity Stability and Change

BACKGROUND

Since the Industrial Revolution, average atmospheric carbon dioxide (CO_2) levels have steadily increased. However, if you look closely at the data, you'll notice a repeating annual pattern: CO_2 levels drop slightly during the spring and summer, then rise sharply in the fall and winter. This "sawtooth" pattern appears in measurements from around the world, but it is especially clear in long-term data collected at the Mauna Loa Observatory in Hawaii (NOAA).

This seasonal pattern is mostly due to photosynthesis in the Northern Hemisphere, which has most of Earth's landmass. Plants in the Northern Hemisphere absorb large amounts of CO_2 during their growing season in spring and summer. As plants grow leaves and actively photosynthesize, they take in CO_2 from the atmosphere. In the fall and winter, when many plants lose their leaves and photosynthesis slows down, CO_2 levels begin to rise again.

Phenology is the study of seasonal changes in plants and animals, such as when trees grow leaves, flowers bloom, or birds migrate. These changes are triggered by environmental factors such as temperature, rainfall, and daylight hours.

Tracking these changes over time helps scientists understand how ecosystems respond to climate and weather patterns. For example, researchers monitor plants using regular observations or time-lapse photography, sometimes over many years. A network of cameras called Phenocams does this automatically by taking repeated images of the same plants or landscapes. The cameras calculate a "greenness" index from each image, which reflects how actively plants are photosynthesizing. You can explore live Phenocam data and images here: Phenocam Network

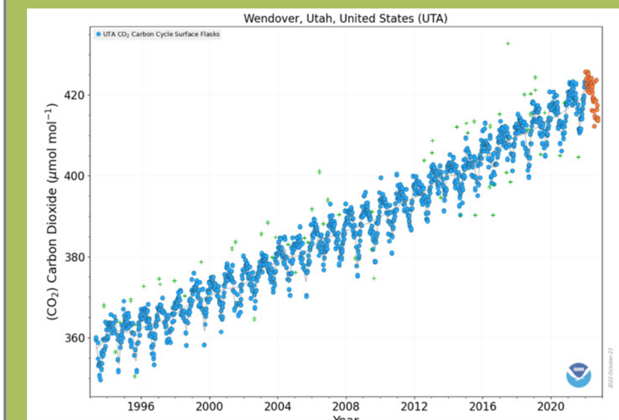
By comparing Phenocam and CO_2 data, you can see a correlation between carbon dioxide levels and photosynthesis. When Phenocam images show greener vegetation, it indicates that plants are photosynthesizing and removing CO_2 from the atmosphere, and the evidence of this can be seen in the CO_2 data. In contrast, browner images suggest less photosynthesis and higher CO_2 buildup in the atmosphere. Examining this connection between plant activity and CO_2 levels will help students visualize how Earth's natural systems influence atmospheric gases.

PREPARATION

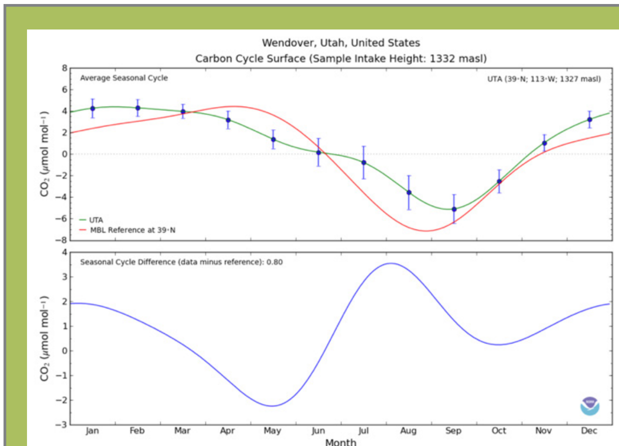
1. Optional: If you would like to use data from a site closer to you, replace the graph on Slides 4 and 5 with data from a local site. Use this NOAA site to find a nearby atmospheric carbon monitoring station and pull up the data, using the instructions below. Save the graph and use it to replace the graph on slide 4.
2. Optional: Replace the graph on Slide 3 of atmospheric CO_2 recorded at Mauna Loa with the most recent graph found here. These graphs are updated weekly and will always show the data from the previous year. The graph in the slides is from January 2024 to January 2025.
3. If your students do not have access to computers or you have limited time, you can skip the instructions on slides 11-14 and instead show students graphs of your choosing. If using the provided graphs on Slides 4 and 5 from Wendover, Utah, use the phenology graph on Slide 21 from Onaqui, Utah. Slides 22-24 have graphs from other locations you can use.

PROCEDURES

1. **Slide 2:** Show students the atmospheric carbon dioxide (CO_2) graph from Mauna Loa, Hawaii. The National Oceanic and Atmospheric Administration (NOAA) measures the amount of carbon dioxide in the atmosphere from the top of the Mauna Loa volcano in Hawaii. Because Mauna Loa is in the middle of the Pacific Ocean, away from large cities, the carbon dioxide levels there give a clear picture of changes in the atmosphere. NOAA releases updated graphs frequently; visit https://gml.noaa.gov/ccgg/trends/mlo.html for the most recent graph.
   a. Ask students to summarize the trends in the graph.
      i. CO_2 in the atmosphere is increasing. This is largely due to the burning of fossil fuels. CO_2 is one of the most common greenhouse gasses contributing to climate change. You can explore this phenomenon in other lessons in Climate Change and the Carbon Cycle, and Insulating You, Insulating Earth.
      ii. CO_2 goes up and down every year. When we see this pattern on a graph, we call it a sawtooth pattern.
   b. Point out the sawtooth pattern and brainstorm ideas about what might cause it.
2. **Slide 3:** Zoom in on one year. We hear a lot about rising CO_2 levels, but why does atmospheric CO_2 vary in such a predictable pattern during one year? Why does atmospheric CO_2 decrease between June and September? Note: You can visit https://gml.noaa.gov/ccgg/trends/weekly.html for the most recent graph.



3. **Slide 4:** Show students a CO_2 graph from a local CO_2 monitoring station; the instructions for finding these graphs are below. Or you can use the example from Wendover, Utah, which is already in the slides. Note the sawtooth pattern is still present in a more local dataset, and it looks a lot like the graph from Mauna Loa.

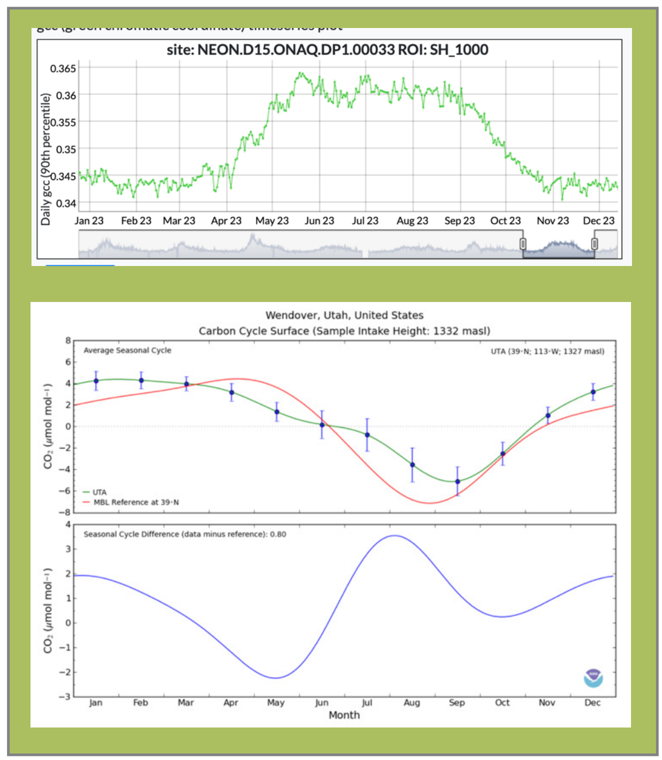


4. **Slide 5:** Use the seasonal patterns graph to determine which months have maximum and minimum CO_2. The green line is the CO_2 level for the location you choose. The key identifies the green line with the points and error bars with a 3-letter code associated with that site (UTA= Utah). The red line (with no points and error bars) is the Marine Boundary Layer (MLB), a reference line from an ocean site at the same latitude. Marine sites are

generally far from major carbon sources and sinks, so therefore serve as a more globalized reference. The bottom graph shows the difference between the red and green lines and can be ignored for the sake of this activity. Use the months along the bottom axis to help answer questions using the green line with the points on it from the top graph.

a. As a class, answer question 1 on the worksheet and have students sketch the seasonal cycle graph on question 2 using the points on the green line on the graph for both questions.

5. **Slide 6:** Show students this diagram of the carbon reservoirs and discuss where carbon goes when it leaves the atmosphere.
   a. Ocean via gas exchange and photosynthesis by phytoplankton
   b. Biosphere via photosynthesis by plants
   c. Ask students if either of these could be responsible for the drop in CO_2 in the summer? [More photosynthesis is happening during summer months than during winter months.]
6. **Slide 7:** Remind students what is happening during photosynthesis. Plants break apart CO_2 removed from the air and water to create glucose and oxygen.
7. **Slide 8:** The biosphere is doing a lot more photosynthesis in the summer than in the winter, as you can see in these photos taken between March and November 2022 near Sedona, Arizona (shown in the map on the upper right of the slide). Therefore, plants are pulling more CO_2 out of the air during summer months. Note that the southern hemisphere summer is during the northern hemisphere winter. However, the seasonal pattern is visible in the global data because the majority of land covered in plants is in the northern hemisphere. **Phenology is the study of seasonal patterns in living things.**
8. **Slide 9:** A Phenocam is an internet-connected camera that scientists use to monitor plant greenness over time. Phenocams are operated by a network of scientists around the world and coordinated by scientists at Northern Arizona University. A Phenocam takes images on a regular basis, and each image is analyzed to calculate the number and intensity of green pixels in the photo. The graph shows the greenness of images from the Phenocam near Sedona, Arizona. Note the seasonal rise and fall of greenness. Remind students that plants are green because they are full of chloroplasts, which is where the plant converts CO_2 to glucose.
9. **Slide 10:** The graph in the previous slide is showing a value called Green Chromatic Coordinate (GCC) for each picture taken by the Phenocam. This value is calculated based on how green each pixel in the image is. We are using the GCC as a proxy for when plants have more or less photosynthetic capacity
10. **Slide 11:** Show students the Phenocam webpage (https://phenocam.nau.edu).
    a. Click on the map menu at the top of the page.
    b. Click the layer button to add state borders.
    c. Green dots represent active Phenocams. Click on a dot to see the most recent picture.
    d. Click on a picture to access all data from the camera.
11. **Slide 12:** Once on the camera's page, use the ROI button to see the graph of the GCC or "greenness" data. You can also use the Browse Images button to see all the images from the Phenocam.
12. **Slide 13:** Use the slider at the bottom of the graph to zoom in on one year, as demonstrated in the video. Move the first slider to Jan (year) and the second slider to Dec (same year). This will probably be the hardest part for students so demonstrate carefully. Note that the number after the month is the year, not the day.



13. **Slide 14:** Give students time to explore the Phenocam website to look for nearby Phenocams. Instructions are on the worksheet. Students will use the local CO_2 graph you showed them earlier and nearby Phenocams, and then answer questions 3-6. If students don't have computers, or time is limited, the teacher can pull up local Phenocam data to examine in groups or as a class. For advanced classes or classes with ample time, see the extension below in which students choose their own CO_2 monitoring site also.

14. **Slide 15:** Climate change will have many impacts, and they will vary across the globe. In the Southwest, climate change is expected to cause more frequent and extreme droughts and more forest fires because as temperatures rise, evapotranspiration (the combined effect of evaporation and transpiration in plants) increases, drying out the air and soil, all of which could limit plant growth and photosynthesis. Using what you know about phenology and carbon dioxide, how will higher temperatures affect carbon dioxide levels in the atmosphere?
    a. More CO_2 will lead to increasing temperatures.
15. **Slide 16:** Increasing CO_2 leads to higher global temperatures.
16. **Slide 17:** This leads to higher evapotranspiration. Unless precipitation also increases, this will lead to drier air and soil.
17. **Slide 18:** Drier air and soil can lead to plant stress, reducing plants' ability to photosynthesize, which leads to even more CO_2 in the atmosphere because less is taken up by plants. Rising carbon dioxide levels can create a positive feedback loop, leading to even higher CO_2 levels in the future.
    a. A positive feedback loop is a scenario in which cascading events lead to a less stable system, as opposed to a negative feedback loop, which reinforces a stable system.
    b. In this case, the higher CO_2 levels lead to a series of events that continue to increase CO_2 levels, creating instability and change in the system. A positive feedback loop does not necessarily lead to a positive outcome.
    c. Have students answer question 7 on their worksheet.
18. **Slide 19:** Give students time to discuss and answer questions 8 and 9 on their worksheets. If time allows, ask groups to share their answers and reasoning.
    a. Question 8: A wildfire that kills a large number of plants will increase atmospheric carbon dioxide in two ways. The first is all the carbon dioxide released as the plants burn. After the fire, the lack of plants means that carbon dioxide is not being removed from the atmosphere through photosynthesis. So local CO_2 levels will be higher until the plant life recovers.
    b. Question 9: Students may argue that 100 trees will be a large increase in local photosynthesis, especially over the life of the trees. They may also argue that 100 trees will have only a small impact globally.
19. **Slide 20:** This graph shows Phenocam data from a research station in Sweden, close to the Arctic Circle. Note that 2021 and 2022 had higher peak greenness than usual. What could be causing this? Warmer temperatures in the far north are leading to more plant growth, when cold temperatures were a limiting factor in the past.
    a. How could this impact photosynthesis and atmospheric CO_2 levels? Have students answer question 10 on their worksheet and discuss.
    b. Places that were too cold for much plant growth could become more vegetated, increasing photosynthesis in those regions. These regions could turn from a carbon source, emitting more CO_2 than they take in, to a carbon sink, absorbing more CO_2 through photosynthesis than they emit.
    c. In this location, we MAY actually see rising CO_2 trigger a LOCAL negative feedback loop, because higher CO_2 levels lead to more photosynthesis, which could actually lower CO_2 locally. However, at some point, continuous increasing CO_2 would reach a tipping point and start having negative effects on photosynthesis. We would need local CO_2 data to back this up.

EXTENSIONS

1. Rather than having students find Phenocams near the CO_2 monitor you show, you can have students choose their own monitoring station and Phenocam to answer questions 1-7.
2. Look at the extra graphs on slides 22-24 and discuss the differences in these graphs and others you have viewed.

INSTRUCTIONS FOR FINDING LOCAL CARBON DIOXIDE LEVELS
NOAA INTERACTIVE ATMOSPHERIC DATA VISUALIZATION (IADV)

1. Open this website if it is not already open: https://gml.noaa.gov/dv/iadv/
2. Use the "+" symbol to zoom in on the area.
3. Hover over and then click on the **red** dot that is closest to where you live. Red dots indicate active sites.
   a. Ensure that the name of the sampling location that you would like to use (closest to where you live) is listed in the first drop down menu at the top of the page.
4. In the drop down menus near the top of the page:
   a. Find programs, and choose "Carbon Cycle Gases."
   b. Leave the other two drop down menus on their default settings.
      i. Popup detail: "Full"
      ii. Active Sites: "All Sites"
5. In the right side bar, click on the "Carbon Cycle Gases" button.
   a. Two or more plot types will appear.
      i. Click on "Time Series."
      ii. Save this graph and use it to replace the graph on slide 4.
6. In the right side bar, click on the "Seasonal Patterns" button.
   a. Hit Submit.
   b. Save this graph and use it to replace the graph on slide 5.

Name: ______________________ Date: ______________________ Period: ______________

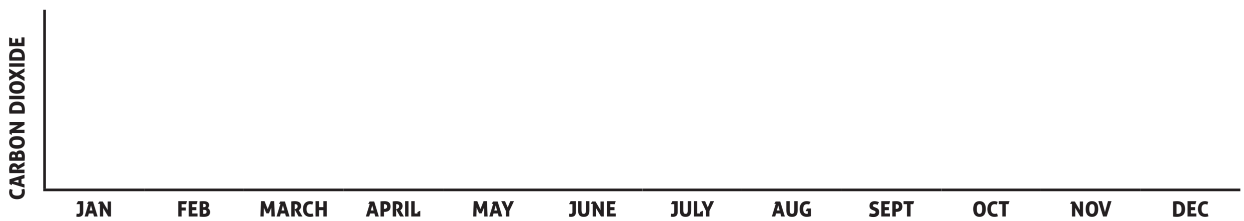
SEASONAL SAWTOOTH PATTERNS
IN THE CARBON CYCLE

1. CO_2 Monitoring Station Location: ______________________

   Month(s) with **highest** CO_2 levels: ______________________

   Month(s) with **lowest** CO_2 levels: ______________________

2. Sketch the pattern of one year of CO_2 levels in the atmosphere in the graph below.



ON YOUR COMPUTER:

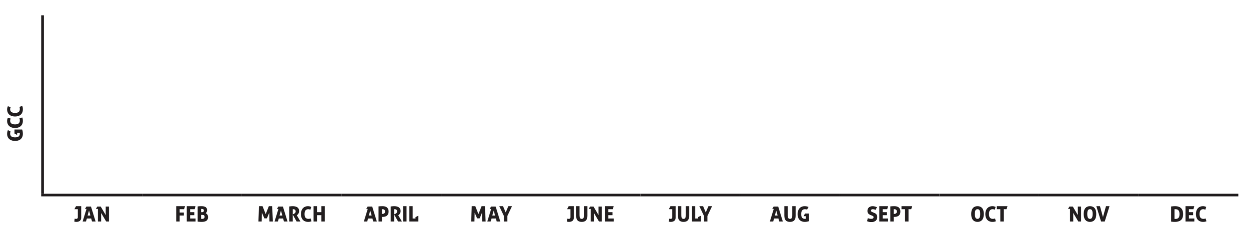
1. Go to phenocam.nau.edu.
2. Click Map in the top menu.
3. Choose the Streets layer to add states and cities to the map.
4. Zoom in to find Phenocams and click on a green dot in a location near the CO_2 monitoring station you used above.
5. Click on the picture to go to the camera's page.
6. Click the button below the words "ROI Timeseries" on right side of the large picture.
7. Examine the greenness graph. Use the sliders under the graph to change the dates shown on the graph.
8. Hover your mouse over points on the graph to see the date of each data point.

3. Phenocam Location: ______________________

   Month(s) with **highest** GCC levels: ______________________

   Month(s) with **lowest** GCC levels: ______________________

4. Sketch the pattern of one year of Green Chromatic Coordinate (GCC) levels in the graph below.



5. Compare the two graphs you sketched:

   a. When the local GCC (greenness) is high, CO_2 levels are ______________.
   HIGH / LOW

   b. When the local GCC (greenness) is low, CO_2 levels are ______________.
   HIGH / LOW

6. Based on your graphs, what is causing the seasonal decrease in CO_2 levels? Explain your reasoning.

7. As people produce CO_2, the greenhouse effect traps heat energy inside the atmosphere and leads to climate change. One of the impacts of climate change is ______________ (HIGHER / LOWER) air temperatures. The change in temperature leads to a/an ___________________ (INCREASE / DECREASE) in evaporation and transpiration, which means that there is less water available to plants. Plants will be ____________ (MORE / LESS) green, which means they take up ____________ (MORE / LESS) CO_2 through photosynthesis. When photosynthesis ____________________ (INCREASES / DECREASES) because of higher temperatures there is _____________ (MORE / LESS) CO_2 in the air. This ____________________ (INCREASES / DECREASES) the greenhouse effect, which will lead to _______________ (HIGHER / LOWER) temperatures.

8. How would a wildfire affect the local CO_2 data? Explain your reasoning.

9. If your hometown decided to plant 100 new trees downtown, how would that affect climate change? Explain your reasoning.

10. The Phenocam graph from Vindeln, Sweden shows higher-than-normal GCC in the most recent years. This may be because warmer temperatures allow for more plant growth in places where cold used to limit plant growth. How could this impact global CO_2 levels?