Class 7: The Carbon Cycle

- How is carbon circulated through the atmosphere and the Earth?
- How are humans interfering with the carbon cycle?

Learning Objectives

1. Identify Earth’s carbon sinks, sources, and reservoirs. (1)
2. Explain why atmospheric carbon dioxide concentrations fluctuate in a consistent manner throughout the year. (2)
3. Identify and explain some of the feedback systems inherent in the carbon cycle due to climate change (2,3)
4. Diagram the interactions over time between various stocks and flows of carbon cycle (4)
Climate Forcing:

Something that ‘pushes’ the climate system in one direction
Climate Forcing:

Example: explosive volcanoes reduce incoming solar radiation
Climate Forcing:

Example: Earth’s orbital cycles... affect how much solar radiation is received at different latitudes.
Orbital cycles:

Do not affect how much radiation is hitting Earth, but where and when that radiation is focused
Review: Forcings and Feedbacks

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Example:
• More axial tilt = more intense seasons
Review: Forcings and Feedbacks

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Example:
• More axial tilt = more intense seasons (and vice versa)
Review: Forcings and Feedbacks

Orbital cycles:

For reconstructing climate, we look at solar radiation received during summer at 65°N.

This is where big ice sheets form!
Review: Forcings and Feedbacks

Feedbacks:

Internal dynamics that amplify (positive) or diminish (negative) a forcing
Review: Forcings and Feedbacks

Positive feedback example - Greenland Ice Sheet lowering, exposed to more warm air, further melting

Adiabatic Processes

Dry adiabatic lapse rate describes the expansional cooling of ascending unsaturated air parcels

Illustration of dry and moist adiabatic lapse rates
Review: Forcings and Feedbacks

Feedbacks:

Positive feedback example – West Antarctic ice retreat, allowing more ocean water under ice, enhanced melting

Image from Pattyn (2018), *Nature Communications*
Feedbacks:

Negative feedback example – Mountain glaciers retreating, end up at higher elevations where it is colder.
Today’s Class

Quick Lesson on Units:

Gigaton = 1 billion tons (~140 million bull elephants)

Gigatons of Carbon vs. Gigatons of Carbon Dioxide

GtC vs. GtCO$_2$

\[
\frac{12}{12+16+16 = 44}
\]

\[
\text{carbon: } \frac{6}{12.011} = 0.5\text{C}
\]

\[
\text{Oxygen: } \frac{8}{15.999} = 0.5\text{O}
\]

3.7X
Carbon Cycle: Reservoirs
Carbon is present on Earth in many forms!

Atmosphere: CO$_2$, CH$_4$

Oceans: Dissolved CO$_2$, H$_2$CO$_3$

Plants/Soils: C$_6$H$_{12}$O$_6$ (organic tissue)

Rocks and Sediments: Limestone, Shale, Coal, Oil
Carbon Reservoirs (GtC)

Atmosphere (600, Preindustrial)

Surface Ocean (1,000)

Plants/Soils (2,000)

Deep Ocean (40,000)

Rocks and Sediments (66,000,000)
Check In

Big Picture: Carbon Observations

Carbon Cycle: Reservoirs

Carbon Cycle: Exchanges

Human Impacts on Carbon Cycle

Carbon Cycle Feedbacks in a Warming World
Carbon Cycle: Exchanges
Mauna Loa Observatory

Atmospheric CO₂ at Mauna Loa Observatory

Scripps Institution of Oceanography
NOAA Earth System Research Laboratory

The Mauna Loa observatory is a gas measuring station located high up on the Mauna Loa volcano (11,140 feet above sea level). Its location in the middle of the Pacific and high above local emission sources makes it ideal for sampling ‘global average’ air. It has been continually recording since 1958!
Think, Pair, Share

This plot of atmospheric CO$_2$ shows a pattern of annually increasing and decreasing concentration on top of the overall rising trend. What process(es) do you think could be responsible for this pattern?
Dave Keeling was a chemist and physicist who developed a method to accurately measure gas concentrations in air. He began monitoring atmospheric CO$_2$ levels around the world and eventually secured funding to set up long-term monitoring stations in strategic locations. His Mauna Loa observatory has continually recorded CO$_2$ concentrations since 1958 and was the first warning sign that humans were increasing greenhouse gas concentrations.
Plants take CO$_2$ out of the atmosphere and emit oxygen and water vapor

- **Photosynthesis**: Absorbing CO$_2$ and solar radiation, creating ‘food’
- **Respiration**: Plant breaks down ‘food’ for energy, releasing CO$_2$
Global-Scale Photosynthesis

Figure from NASA
Carbon Exchanges

Atmosphere

Respiration

Photosynthesis

Surface Ocean

Plants/Soils

Deep Ocean

Rocks and Sediments
Carbon Exchanges

Atmosphere

Surface Ocean
- Photosynthesis: CO₂ dissolving in
- Respiration: CO₂ dissolving out

Plants/Soils
- Photosynthesis
- Respiration

Deep Ocean

Rocks and Sediments
Carbon Exchanges

\[ \text{CO}_2 + \text{H}_2\text{O} = \text{weakly acidic rain} \]

\[ \rightarrow \text{weathers rocks} \]

Weathering products reform as seafloor limestone

Subducted limestone outgasses from volcanoes

Volcanism

CO$_2$

Subduction

Melting

CO$_2$

Weathering products reform as seafloor limestone

Rock weathering
Carbon Exchanges

Atmosphere (600, Preindustrial)

Surface Ocean (1,000)
- Photosynthesis
- CO₂ dissolving in
- Respiration
- CO₂ dissolving out
- Dead things sinking
- Upwelling
- Downwelling

Plants/Soils (2,000)
- Photosynthesis
- Respiration
- Volcanoes
- Buried organic matter

Deep Ocean (40,000)

Rocks and Sediments (66,000,000)
- Limestone formation
Carbon Exchanges (GtC/year)

Atmosphere (600, Preindustrial)

Surface Ocean (1,000) 100 100

Deep Ocean (40,000) 37 37

Plants/Soils (2,000) 0.1

Rocks and Sediments (66,000,000) 0.1 0.1
Carbon Exchanges

In general...

The bigger a carbon reservoir, the slower it exchanges carbon

In a stable climate, the carbon cycle is balanced
Today’s Class

Humans are acting like an extra carbon exchange to the natural carbon cycle. From which reservoirs do you think we are removing carbon, and where are we adding it?
Human Impacts on the Carbon Cycle
Carbon Exchanges (GtC/year)

Atmosphere (600, Preindustrial)

Surface Ocean (1,000)

Plants/Soils (2,000)

Deep Ocean (40,000)

Rocks and Sediments (66,000,000)
<table>
<thead>
<tr>
<th>Carbon Exchanges (GtC/year)</th>
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<tbody>
<tr>
<td><strong>Atmosphere (600, Preindustrial)</strong></td>
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<td>Surface Ocean (1,000)</td>
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<td>Deep Ocean (40,000)</td>
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<tr>
<td>Plants/Soils (2,000)</td>
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<td>100</td>
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<td>Fossil Fuels (5,000)</td>
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<td>0.2</td>
<td>0.1</td>
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<td>Rocks and Sediments (65,995,000)</td>
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Human Carbon Emissions

**Burning Fossil Fuels**

$9.9 \pm 0.5 \text{ GtC/y}$

Data from World Meteorological Organization

**Land Use Change**

$1.3 \pm 0.5 \text{ GtC/y}$
Atmosphere (600, Preindustrial)

Surface Ocean (1,000)

Deep Ocean (40,000)

Plants/Soils (2,000)

Fossil Fuels (5,000)

Rocks and Sediments (65,995,000)

Human Carbon Emissions
2015:

Emissions:
~11.2 GtC

Atm: 6.2 ± 0.2
Ocean: 3.0 ± 0.5
Land: 2.0 ± 0.9

Data from WMO Annual Carbon Budget
Human Carbon Emissions

Atmosphere (750) + 6.2

Surface Ocean (1,000)

Deep Ocean (40,000)

Plants/Soils (2,000)

Fossil Fuels (5,000)

Rocks and Sediments (65,995,000)

100 100 100

3.0 100 100

37 37

9.9

100 0.2 0.1

0.1

0.1

2.0 1.3 1.0
Human Carbon Emissions

We are disrupting a balanced system

Carbon dioxide concentrations over the holocene

- EPICA Dome C high res (E. Monnin, 2006)
- Law dome ice core (D. Etheridge, 7/2010)
- Cape Grim measurements (CGBAPS, 2/2017)
Today’s Class

- Carbon Cycle: Reservoirs
- Carbon Cycle: Exchanges
- Human Impacts on Carbon Cycle
- Carbon Cycle Feedbacks in a Warming World
Roughly what percentage of human-caused carbon emissions remain in the atmosphere?

A. 90 - 100%
B. 70 - 80%
C. 50 – 60%
D. 30 – 40%
E. 10 – 20%
Carbon Cycle Feedbacks in a Warming World
1. (Negative Feedback)
Will more carbon in atmosphere lead to more carbon uptake by plants?

Figure from Kirschbaum, 2011, *Plant Physiology*
Yes! This feedback should slow carbon increase in atmosphere... if we were not cutting down our forests
Carbon Cycle Feedbacks in a Warming World

Atmosphere (750) + 6.2

Surface Ocean (1,000)

Deep Ocean (40,000)

Plants/Soils (2,000)

Fossil Fuels (5,000)

Rocks and Sediments (65,995,000)

3.0 100 100 100 1.3 2.0

37 37 9.9 0.2 0.1 0.1

100

0.1

2. (Positive Feedback)
Melting permafrost will increase carbon flux into atmosphere
Carbon Cycle Feedbacks in a Warming World

Atmosphere (750) + 6.2

Surface Ocean (1,000)

Deep Ocean (40,000)

Plants/Soils (2,000)

Fossil Fuels (5,000)

Rocks and Sediments (65,995,000)
3. (Positive Feedback)
Less atmospheric carbon dissolves in warmer water
Carbon Cycle Feedbacks in a Warming World

Atmosphere (750) + 6.2

Surface Ocean (1,000)

Deep Ocean (40,000)

Plants/Soils (2,000)

Fossil Fuels (5,000)

Rocks and Sediments (65,995,000)
4. (Long Term Negative Feedback)
More chemical weathering (CO₂ removal from atmosphere) in a warmer climate
Carbon Cycle Feedbacks in a Warming World

In Summary:

• Feedbacks in carbon cycle will amplify (positive feedback) or diminish (negative feedback) the amount of carbon increase in the atmosphere

• Negative feedbacks:
  • Increased plant photosynthesis with increasing atmospheric CO$_2$
  • Increased chemical weathering (long-term)

• Positive feedbacks:
  • Melting permafrost adding more carbon to atmosphere
  • Decreasing ocean uptake of carbon with increasing temperature