Guide to the Science of Climate Change in the 21st Century

Chapter 5
Carbon Cycle

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5.1 Introduction

The carbon cycle describes how carbon circulates through the atmosphere, biosphere, oceans and is influenced by human activities. A schematic of the carbon cycle for entire Earth is shown in Figure 5.1. (There are several other schematics of the carbon cycle such as shown in https://scied.ucar.edu/image/carbon-cycle-diagram-nasa).

5.2 Units

The mass of carbon, in any form, is measured in tonnes or metric tons equal to 1000 kilograms. The calculation of the mass of carbon excludes oxygen and any other elements – only the carbon. The carbon cycle shown is for the whole planet. The masses of carbon are very large so the measurement units are gigatons of carbon or GtC. One gigaton equals 1,000,000,000 tons. Stored carbon is measured in GtC and is shown in Figure 5.1 in the numbers in parentheses. The flow of carbon (area of the entire Earth) is called the carbon flux. It is measured in gigatons per year or GtC/yr.

5.3 Carbon in the atmosphere

Most of the carbon in the atmosphere is in the form of carbon dioxide gas or CO_2 though there are small amounts of numerous other gases such as methane and other hydrocarbons and substances used in cooling systems (refrigerators, freezers and air conditioners) that also contain carbon. The atmosphere contains 800 GtC. Atmospheric carbon in the form of carbon dioxide is the most important of the greenhouse gases or GHG. (See Figure 4.1.) Atmospheric circulation results in a more-or-less uniform concentration of carbon dioxide in the atmosphere over the entire surface of the Earth. NASA provides thorough discussion on carbon dioxide in the atmosphere that may be found in https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/#:~:text=Carbon%20dioxide%20is%20a%20different,timescale%20of%20many%20human%20lives. It is important to know that the life of carbon dioxide in the atmosphere varies between 300 to 1000 years.

Other greenhouse gases in the atmosphere are measured in terms of carbon dioxide equivalent (CO_2e or CO_2eq or CO_2-e). This is calculated from the global warming potential (GWP) of the gas and can be measured in terms of weight or concentration. GWP is the heat absorbed by any greenhouse gas in the atmosphere as a multiple of the heat that would be absorbed by the same mass of carbon dioxide, (CO_2). GWP is 1 for CO_2. Carbon dioxide equivalent is the amount of CO_2 which would warm the Earth as much as that amount of gas and so provides a common scale for measuring the climate effects of different gases. Carbon dioxide equivalent equals the GWP times the amount of the other gas. E.g., if a gas has a GWP of 100, two tons of the gas have a carbon dioxide equivalent of 200 tons. One part per million of the same gas in the atmosphere has a carbon dioxide equivalent of 200 parts per million (https://en.wikipedia.org/wiki/Global_warming_potential).

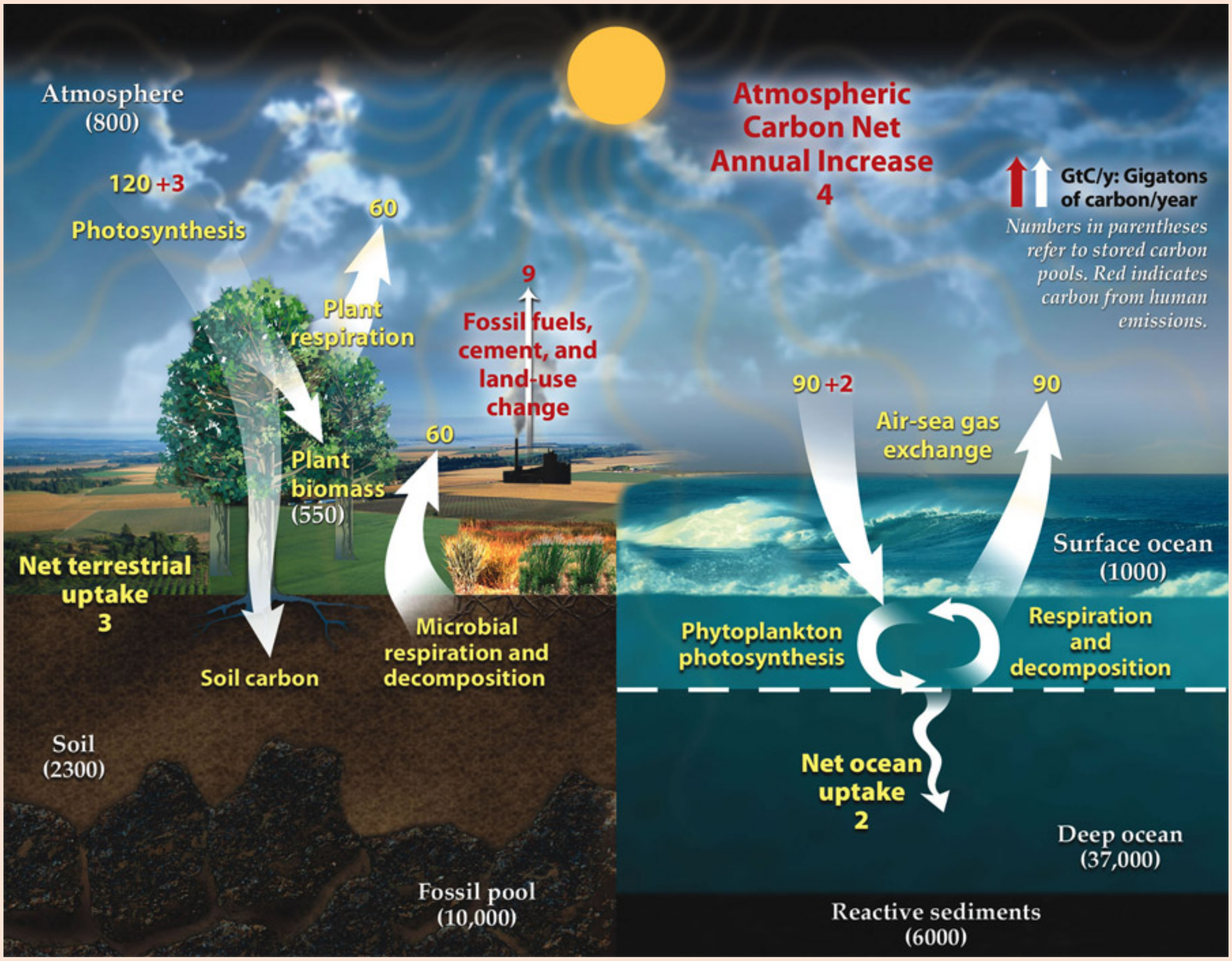

Figure 5.1 Carbon Cycle. (Office of Biological and Environmental Research of the U.S. Department of Energy Office of Science https://www.energy.gov/science/doe-explainsthe-carbon-cycle)

5.4 Plant biomass (terrestrial)

The terrestrial plant biomass stores 550 GtC. Plants that use photosynthesis will extract carbon dioxide from the atmosphere, 123 GtC/y, to produce chemical energy (e. g. glucose and other carbohydrates) and will release carbon dioxide back into the atmosphere when consuming chemical energy, plant respiration, 60 GtC/y. This is illustrated in Figure 5.2. Chlorophyll, shown in green, receives radiant energy from the sun which supplies the energy to use carbon dioxide from the atmosphere through openings in leaves and stems known as stomata to produce glucose, the photosynthesis process. In the process of transforming the glucose into a variety of other organic forms plants will also absorb oxygen and transpire carbon dioxide back into the atmosphere. Much of the carbon dioxide will remain as plant biomass until such time as the plant dies and its organic tissue is consumed by organisms and return the stored carbon dioxide back to the atmosphere. (The global distribution of vegetative biomass capable of converting carbon dioxide to plant tissue is shown in Figure 5.3. A similar amount will move into the soil system to become soil carbon and returned to the atmosphere through microbial respiration and decomposition. The soil stores 2300 GtC (plus whatever is stored in peat bogs and permafrost). The net terrestrial uptake is 3 GtC/y.

The carbon stored in plant biomass, all forms, will ultimately be returned to the atmosphere in the form of carbon dioxide or methane (natural decay or burning). Exceptions are the biomass which formed coal and hydrocarbons such as oil, natural gas and methane in which the carbon would be permanently stored were it not for human mining and burning of these carbon stores.

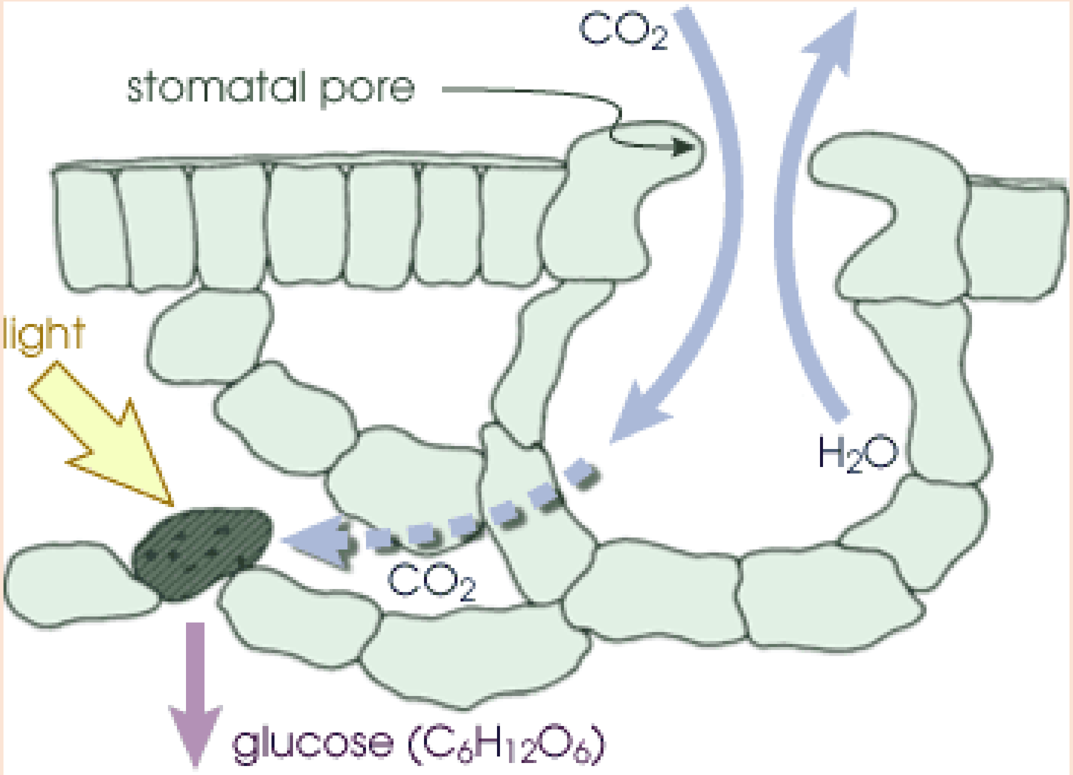

Figure 5.2 Photosynthesis and respiration in plants.

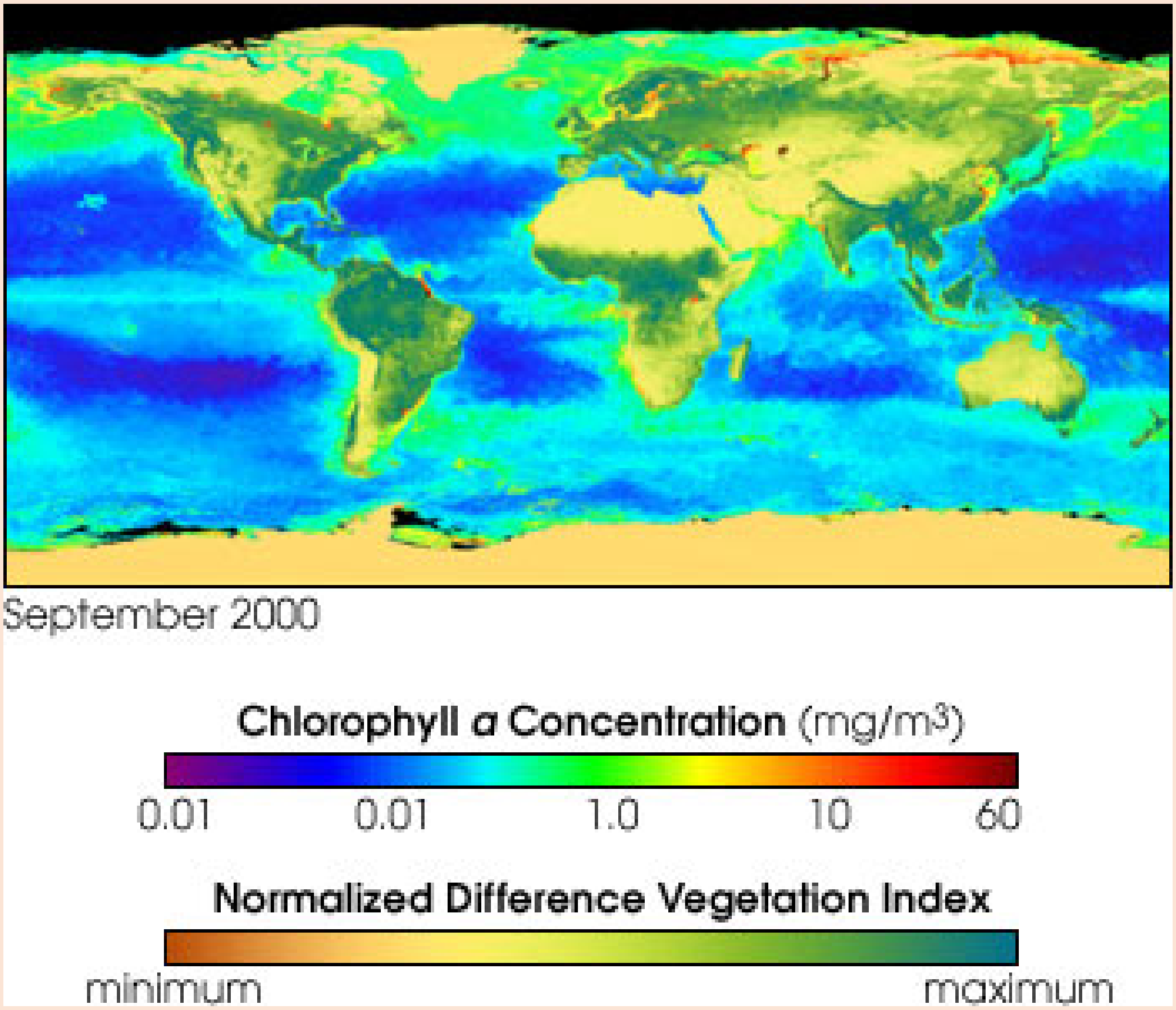

Figure 5.3 Vegetative biomass capable of converting CO_2 to plant tissue.

5.5 Oceans

Oceans will absorb 92 GtC/y from the atmosphere and release 90 GtC/y back into the atmosphere in the air-sea gas exchange process. (See NASA video, https://svs.gsfc.nasa.gov/4873). The temperature of the water determines the maximum amount of carbon dioxide the water can hold in the dissolved form. The colder the water the more carbon dioxide can be dissolved. As the concentration of dissolved carbon dioxide increases the water becomes more acidic, a process known as acidification.

The water is divided into two zones, surface ocean and deep ocean which includes the intermediate zone. See Figure 5.4. The surface ocean receives sufficient sunlight to support plant growth, such as algae. The maximum depth of this zone is considered to be 200 m though it could be much less depending on the clarity of the water. The surface ocean stores 1000 GtC and the deep ocean stores 37000 GtC.

The reactive sediments primarily refer to calcium carbonate that is included in the skeletal remains of marine life and the deposits of these remains on the ocean floor. Carbon dioxide is removed from the atmosphere by a chain of biological activity starting with photosynthesis by plants such as algae which are then consumed by organisms which use the various forms of organic carbon in the plants together with calcium and magnesium that is already dissolved in the ocean water or the plants to form their skeletons. This process is the most important mechanism that allows for permanent removal carbon dioxide from the atmosphere and its permanent storage.

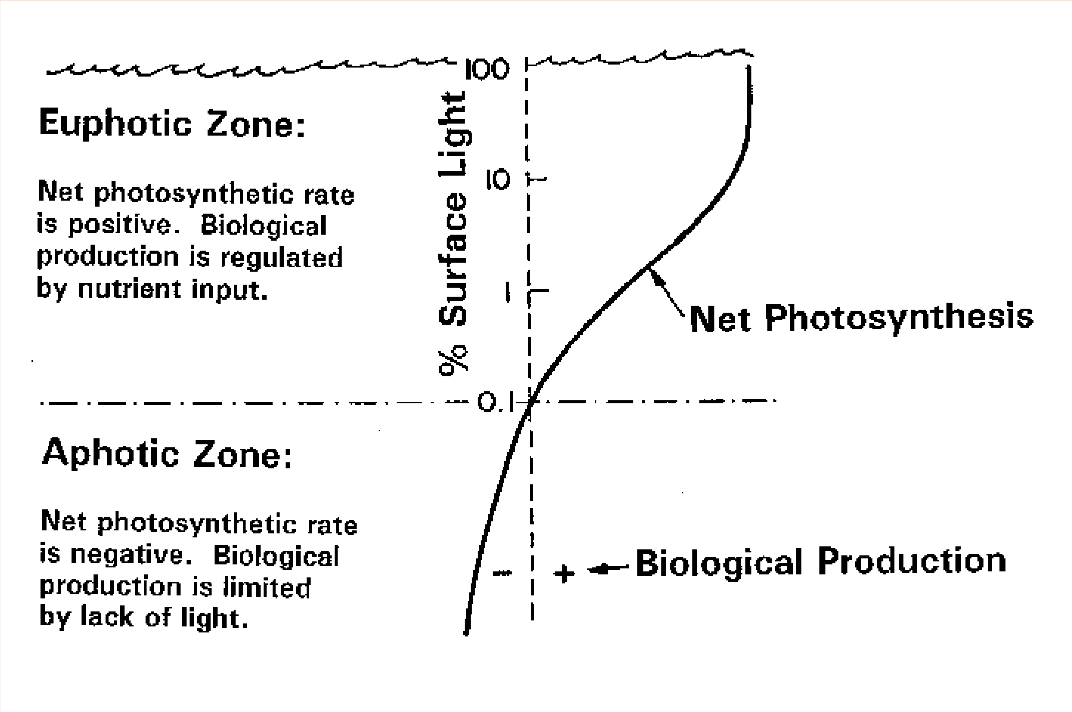

Figure 5.4 Depth zones in the ocean where photosynthesis can and cannot occur.

The increase in the amount of carbon dissolved in the ocean and amount of carbon leaving in the form of sediments represent approximately 2 GtC/y of the carbon that was initially absorbed at the ocean surface.

A paper titled, ‘Quantifying the carbon export and sequestration pathways of the ocean’s biological carbon pump’ https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GB007083 describes how some of the atmospheric carbon dioxide absorbed by phytoplankton may be transferred to deep ocean where it can be stored for hundreds of years.

Ocean acidification occurs when the carbon dioxide absorbed by the ocean reacts with the water to form carbonic acid as shown in the figure 5.5. Carbon dioxide is ultimately removed when the carbonate solids are sequestered in the sediment; however, the water will still become more acidic.

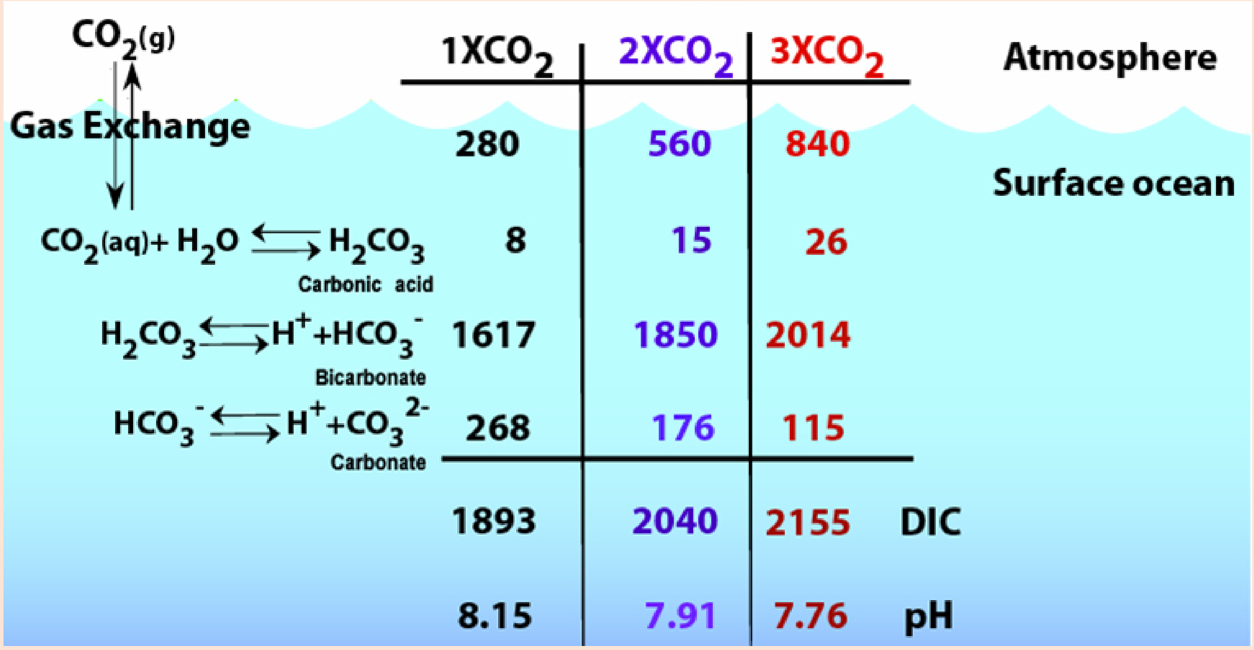

Figure 5.5 A detailed discussion of ocean acidification, carbon uptake and carbon storage may be found in https://www.pmel.noaa.gov/co2 .

5.6   Fossil pool

This is the carbon stored in the Earth’s crust in the form of coal, oil and natural gas and is estimated to be 10,000 GtC. This carbon would remain stored were it not for human extraction and burning.

Though not shown in Figure 5.1 methane hydrates, ice-like form of methane and water, on the bottom of the deep ocean and permafrost are estimated to store up to 5000 GtC.   The occurrence and break down of methyl hydrates is illustrated in Figure 5.6.   Break down of methyl hydrates is considered a far smaller contributor to atmospheric GHG’s than emission of greenhouse gases from human activities.

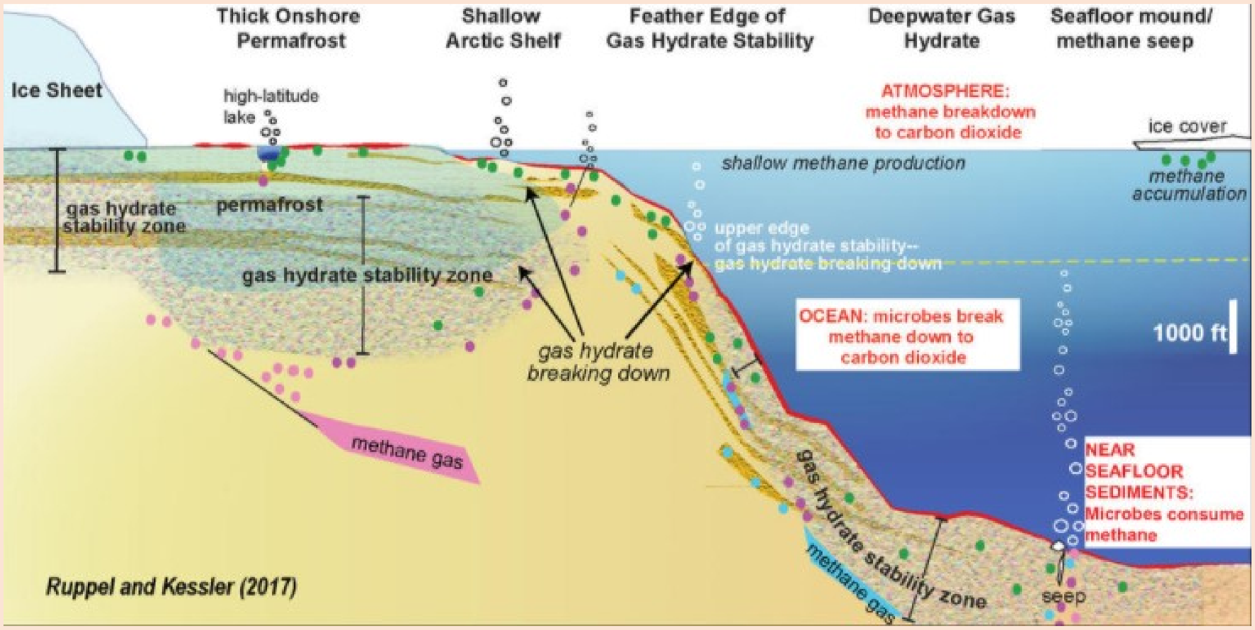

Figure 5.6 Occurrence of methyl hydrate beneath the sea floor, in permafrost areas and beneath some ice sheets and the processes that destroy methane sinks in the sediments, ocean and atmosphere. (https://www.usgs.gov/news/gas-hydrate-breakdown-unlikely-cause-massive-greenhouse-gas-release)

5.7 Fossil fuels, cement and land use change

The industrial revolution was only possible with the exploitation of available fossil fuels. Initially, coal was burned to energize the steam power generation and later to produce electricity, iron and cement. Today, fossil fuels are used to power all forms of transportation and heating and cooling of buildings.

Cement production involves the heating of calcium and magnesium carbonates (ancient marine deposits of limestone and dolomite) by burning some form of fossil fuel. Carbon dioxide is released as part of a chemical reaction and burning of fossil fuel.

Land use change includes the conversion of natural ecosystems, grassland and forest, to cultivation for production of crops. This process releases much of the carbon stored in the soil and the carbon stored in the vegetation.

The combined release of carbon into the atmosphere from the burning of fossil fuels, cement production and changes in land use is 9 GtC/y. This is new carbon that will be taken up by photosynthesis at the rate of 3 GtC/y and absorption in the surface of the ocean at the rate of 2 GtC/y. The remaining amount of carbon will be stored in the atmosphere at the rate of 4 GtC/y.

5.8 Weathering

Igneous and sedimentary rocks are lifted to form mountains as a result of the collision of the plates they are part of that float and move on the viscous upper layers of the Earth's surface immediately below called the mantel. The rock is exposed to chemical weathering processes. Weathering is not illustrated in Figure 5.1 because natural weathering occurs on geologic time scales (millions of years). However, it is a very important process that is thought to have reduced the concentrations of carbon dioxide in the atmosphere, resulting from volcanic eruptions, to levels suitable for life. Carbon dioxide that is consumed by the weathering reactions is permanently removed from the atmosphere via carbonate precipitation in the oceans. file:///C:/Users/David%20Manz/Downloads/geosciences-09-00258%20(1).pdf . This process is illustrated in Figure 5.7.

Acceleration of the weathering reactions of minerals that consume carbon dioxide when they dissolve and drain into the ocean is considered a potentially viable option for removing carbon dioxide from the atmosphere. The process is known as enhanced weathering and is a subject of considerable research. https://www.frontiersin.org/articles/10.3389/fclim.2019.00007/full

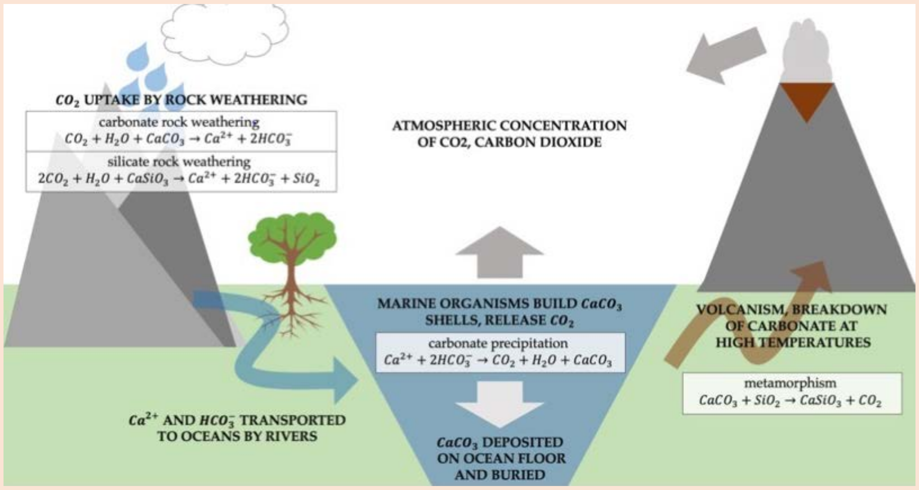

Figure 5.7 The geologic carbonate-silicate cycle taken from https://en.wikipedia.org/wiki/Enhanced_weathering#:~:text=When%20silicate%20or%20carbonate%20minerals,2%20%E2%86%92%20H2CO

5.9 Carbon waste

Carbon waste is the by-product of human activities including the use of fossil fuels for the production of plastics and wasted bio-carbon such as plant and animal material (solid carbon waste). Carbon waste might be distributed on the land or ocean where it is hoped that it will decompose, disappear with the resulting greenhouse gases emitted to the atmosphere. Carbon waste is often stored in land-based storage facilities (land-fills) where it might ultimately decompose and release greenhouse gases such as carbon dioxide and methane to the atmosphere or be burned (incinerated) with the same release of greenhouse gases from the waste itself plus the energy that is used to consume it (typically a fossil fuel). Carbon waste that enters the oceans in the form of plastics will also decompose or settle to the ocean floor but while this is happening the plastic has serious deleterious impacts on the ocean biosphere.

Ultimately, carbon waste will be part of the carbon cycle as shown in Figure 5.1. Carbon waste that is already in a gas form is emitted directly into the atmosphere and is already included in the carbon cycle.

Carbon waste is pollution, a waste of energy, potentially harmful to human health and is considered a significant and unnecessary contributor to global warming.

5.10 Information support

Key web sites:

1. U.S. Department of Energy explains the Carbon Cycle. https://www.energy.gov/science/doe-explainsthe-carbon-cycle

2. UCAR carbon cycle diagram from NASA. https://scied.ucar.edu/image/carbon-cycle-diagram-nasa

3. The carbon cycle NASA. https://earthobservatory.nasa.gov/features/CarbonCycle

4. The carbon cycle NASA. https://www.nasa.gov/centers/langley/news/researchernews/rn_carboncycle.html

5. NASA, The Atmosphere: Getting a Handle on Carbon Dioxide, October 19, 2019. https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/#:~:text=Carbon%20dioxide%20is%20a%20different,timescale%20of%20many%20human%20lives.

6. Movement of carbon dioxide between the air and sea, NASA. https://svs.gsfc.nasa.gov/4873 .

7. U.S. Carbon cycle science program. https://www.carboncyclescience.us/what-is-carbon-cycle

8. NOAA ocean acidification. https://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F

9. Photosynthesis. https://en.wikipedia.org/wiki/Photosynthesis.

10. Methane hydrates. https://worldoceanreview.com/en/wor-1/ocean-chemistry/climate-change-and-methane-hydrates/

11. Methane clathrate. https://en.wikipedia.org/wiki/Methane_clathrate

12. Methane hydrates and contemporary climate change. https://www.nature.com/scitable/knowledge/library/methane-hydrates-and-contemporary-climate-change-24314790/

13. Gas hydrate breakdown unlikely to cause massive GHG release. https://www.usgs.gov/news/gas-hydrate-breakdown-unlikely-cause-massive-greenhouse-gas-release

14. Carbon dioxide equivalent. https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Carbon_dioxide_equivalent

15. Global warming potential. https://en.wikipedia.org/wiki/Global_warming_potential

16. Refrigerants. https://en.wikipedia.org/wiki/List_of_refrigerants

17. Global carbon dioxide emissions from cement production. https://essd.copernicus.org/articles/11/1675/2019/essd-11-1675-2019.pdf

18. Carbon concrete. https://en.wikipedia.org/wiki/Environmental_impact_of_concrete#Carbon_Concrete

19. Carbon dioxide emissions from cement production. https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_1_Cement_Production.pdf

20. Cement producers reduce carbon dioxide emissions. https://www.scientificamerican.com/article/cement-producers-are-developing-a-plan-to-reduce-co2-emissions/

21. Carbon dioxide emissions from global cement industry. https://www.annualreviews.org/doi/pdf/10.1146/annurev.energy.26.1.303

22. Cement emissions matter for climate change. https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change

23. Climate change and land. https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf

24. Land use, land-use change and forestry. https://unfccc.int/topics/land-use/workstreams/land-use—land-use-change-and-forestry-lulucf/land-use—land-use-change-and-forestry

25. Land use, land-use change and forestry. https://en.wikipedia.org/wiki/Land_use,_land-

use_change,_and_forestry#:~:text=Land%2Duse%20change%20can%20be,per%20year%20to%20the%20atmosphere.

26. Consumption of atmospheric carbon dioxide through weathering of ultramafic rock in the Voltri Massif (Italy): Quantification of the process and global implications, Fondini, F, Vaselli, O, and Zuccolini, M. V. in Geosciences. file:///C:/Users/David%20Manz/Downloads/geosciences-09-00258.pdf

27. CO_2 removal with enhanced weathering and ocean alkalinity enhancement: Potential risks and co-benefits for marine pelagic ecosystems, Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, Sarah and Renforth, Phil, 2011. Research paper in the journal, Frontiers in Climate. https://www.frontiersin.org/articles/10.3389/fclim.2019.00007/full

28. Enhanced weathering. https://en.wikipedia.org/wiki/Enhanced_weathering#:~:text=When%20silicate%20or%20carbonate%20minerals,2%20%E2%86%92%20H2CO

29. Quantifying the carbon export and sequestration pathways of the ocean's biological carbon pump, Nowicki, Michael, DeVries, Tim, and Siegel, David A., in the journal of the American Geophysical Union, 31, January 2022, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GB007083

30. Ocean carbon acidification, uptake and storage NOAA, https://www.pmel.noaa.gov/co2 .