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Earth's Dynamic Systems: The Carbon Cycle

Earth's Climate Engine

Aira Astralis

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Introduction

The carbon cycle is a part of the biogeochemical cycle where carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere of Earth. Other major biogeochemical cycles include the nitrogen cycle and the water cycle. Carbon is the main component of biological compounds as well as a major component of many rocks such as limestone. The carbon cycle comprises a sequence of events that are key to making Earth capable of sustaining life.

It describes the movement of carbon as it is recycled and reused throughout the biosphere, as well as long-term processes of carbon sequestration

(storage) to and release from carbon sinks. At 422.7 parts per million (ppm), the global average atmospheric carbon dioxide has set a new record high in 2024. To describe the dynamics of the carbon cycle, a distinction can be made between the fast and slow carbon cycle. The fast cycle is also referred to as the biological carbon cycle.

Fast cycles can complete within years, moving substances from atmosphere to biosphere, then back to the atmosphere. Slow or geological cycles (also called deep carbon cycle) can take millions of years to complete, moving substances through the Earth's crust between rocks, soil, ocean and atmosphere. Humans have disturbed the carbon cycle for many centuries. They have done so by modifying land use and by mining and burning carbon from ancient organic remains (coal, petroleum and gas).

Carbon dioxide in the atmosphere has increased nearly 52% over pre-industrial levels by 2020, resulting in global warming. The increased carbon dioxide has also caused a reduction in the ocean's pH value and is fundamentally altering marine chemistry. Carbon dioxide is critical for photosynthesis. The carbon cycle was first described by Antoine Lavoisier and Joseph Priestley, and popularised by Humphry Davy.

The natural flows of carbon between the atmosphere, ocean, terrestrial ecosystems, and sediments are fairly balanced; so carbon levels would be roughly stable without human influence. Carbon in the Earth's atmosphere exists in two main forms: carbon dioxide and methane. Both of these gases absorb and retain heat in the atmosphere and are partially responsible for the greenhouse effect.

That two-way traffic is the subject of this book. The chapters ahead follow carbon through its fast and slow circuits — the annual breathing of the biosphere and the multimillennial loop through rocks and ocean — and through

the instruments, discoveries, and arguments that made those circuits visible.

They also follow a subtler story: how a species learned, within a single lifetime, to see its own fingerprint written in the chemistry of the air, and what it has done with that knowledge. The carbon cycle is not only a natural system any more; it is the stage on which the century's biggest decisions are being made.

Chapter 1: The Discovery of The Carbon Cycle

The ocean contains the largest active pool of carbon near the surface of the Earth — a fact that took the science of the eighteenth and nineteenth centuries to establish, and that still anchors every modern budget of the element. Following carbon through its pools and pathways became possible only as chemistry itself matured: Lavoisier's balance-sheet thinking, the gas analyses of the nineteenth century, and the early carbon accounting of soils and seas gave the cycle its first quantitative skeleton. Each discovery recast an old intuition — that the world's materials circulate — into measurements that could be checked, argued over, and improved.

Methane produces a larger greenhouse effect per volume as compared to carbon dioxide, but it exists in much lower concentrations and is more short-lived than carbon dioxide. Thus, carbon dioxide contributes more to the global greenhouse effect than methane. Carbon dioxide is removed from the atmosphere primarily through photosynthesis and enters the terrestrial and oceanic biospheres.

Carbon dioxide also dissolves directly from the atmosphere into bodies of water (ocean, lakes, etc.), as well as dissolving in precipitation as raindrops fall through the atmosphere.

When dissolved in water, carbon dioxide reacts with water molecules and forms carbonic acid, which contributes to ocean acidity. It can then be absorbed by rocks through weathering. It also can acidify other surfaces it touches or be washed into the ocean.

Human activities over the past two centuries have increased the amount of carbon in the atmosphere by nearly 50% as of year 2020, mainly in the form of carbon dioxide, both by modifying ecosystems' ability to extract carbon dioxide from the atmosphere and by emitting it directly, e.g., by burning fossil fuels and manufacturing concrete.

In the far future (2 to 3 billion years), the rate at which carbon dioxide is absorbed into the soil via the carbonate-silicate cycle will likely increase due to expected changes in the Sun as it ages. The expected increased luminosity of the Sun will likely speed up the rate of surface weathering. This will eventually cause most of the carbon dioxide in the atmosphere to be squelched into the

Earth's crust as carbonate.

Once the concentration of carbon dioxide in the atmosphere falls below approximately 50 parts per million (tolerances vary among species), C3

photosynthesis will no longer be possible. This has been predicted to occur 600 million years from the present, though models vary. Once the oceans on the Earth evaporate in about 1.1 billion years from now, plate tectonics will very likely stop due to the lack of water to lubricate them.

The lack of volcanoes pumping out carbon dioxide will cause the carbon cycle to end between 1 billion and 2 billion years into the future. The terrestrial biosphere includes the organic carbon in all land-living organisms, both alive and dead, as well as carbon stored in soils. About 500 gigatons of carbon are stored above ground in plants and other living organisms, while soil holds approximately 1,500 gigatons of carbon.

Most carbon in the terrestrial biosphere is organic carbon, while about a third of soil carbon is stored in inorganic forms, such as calcium carbonate. Organic carbon is a major component of all organisms living on Earth. Autotrophs extract it from the air in the form of carbon dioxide, converting it to organic carbon, while heterotrophs receive carbon by consuming other organisms. Because carbon uptake in the terrestrial biosphere is dependent on biotic factors, it follows a diurnal and seasonal cycle.

In CO_2 measurements, this feature is apparent in the Keeling curve. It is strongest in the northern hemisphere because this hemisphere has more land mass than the southern hemisphere and thus more room for ecosystems to absorb and emit carbon. Carbon leaves the terrestrial biosphere in several ways and on different time scales. The combustion or respiration of organic carbon releases it rapidly into the atmosphere.

It can also be exported into the ocean through rivers or remain sequestered in soils in the form of inert carbon. Carbon stored in soil can remain there for up to thousands of years before being washed into rivers by erosion or released into the atmosphere through soil respiration. Between 1989 and 2008 soil respiration increased by about 0.1% per year.

In 2008, the global total of CO_2 released by soil respiration was roughly 98 billion tonnes, about 3 times more carbon than humans are now putting into the atmosphere each year by burning fossil fuel (this does not represent a net transfer of carbon from soil to atmosphere, as the respiration is largely offset by inputs to soil carbon).

There are a few plausible explanations for this trend, but the most likely explanation is that increasing temperatures have increased rates of decomposition of soil organic matter, which has increased the flow of CO_2. The length of carbon sequestering in soil is dependent on local climatic conditions and thus changes in the course of climate change.

The global carbon cycle is now usually divided into the following major reservoirs of carbon (also called carbon pools) interconnected by pathways of exchange:

Atmosphere

Terrestrial biosphere

Sediments, including fossil fuels, freshwater systems, and non-living organic material. Earth's interior (mantle and crust). These carbon stores interact with the other components through geological processes. The carbon exchanges between reservoirs occur as the result of various chemical, physical, geological, and biological processes.

The ocean can be conceptually divided into a surface layer within which water makes frequent (daily to annual) contact with the atmosphere, and a deep layer below the typical mixed layer depth of a few hundred meters or less, within which the time between consecutive contacts may be centuries. The dissolved inorganic carbon (DIC) in the surface layer is exchanged rapidly with the atmosphere, maintaining equilibrium.

Partly because its concentration of DIC is about 15% higher but mainly due to its larger volume, the deep ocean contains far more carbon—it is the largest pool of actively cycled carbon in the world, containing 50 times more than the atmosphere—but the timescale to reach equilibrium with the atmosphere is hundreds of years: the exchange of carbon between the two layers, driven by thermohaline circulation, is slow.

Carbon enters the ocean mainly through the dissolution of atmospheric carbon dioxide, a small fraction of which is converted into carbonate. It can also enter the ocean through rivers as dissolved organic carbon. It is converted by organisms into organic carbon through photosynthesis and can either be exchanged throughout the food chain or precipitated into the oceans' deeper, more carbon-rich layers as dead soft tissue or in shells as calcium carbonate.

It circulates in this layer for long periods of time before either being deposited as sediment or, eventually, returned to the surface waters through thermohaline circulation. Oceans are basic (with a current pH value of 8.1 to 8.2). The increase in atmospheric CO2 shifts the pH of the ocean towards neutral in a process called ocean acidification. Oceanic absorption of CO2 is one of the most important forms of carbon sequestering.

The projected rate of pH reduction could slow the biological precipitation of calcium carbonates, thus decreasing the ocean's capacity to absorb CO2. The geologic component of the carbon cycle operates slowly in comparison to the

other parts of the global carbon cycle. It is one of the most important determinants of the amount of carbon in the atmosphere, and thus of global temperatures. Most of the Earth's carbon is stored inertly in the Earth's lithosphere.

Much of the carbon stored in the Earth's mantle was stored there when the

Earth formed. Some of it was deposited in the form of organic carbon from the biosphere. Of the carbon stored in the geosphere, about 80% is limestone and its derivatives, which form from the sedimentation of calcium carbonate stored in the shells of marine organisms. The remaining 20% is stored as kerogens formed through the sedimentation and burial of terrestrial organisms under high heat and pressure.

Organic carbon stored in the geosphere can remain there for millions of years. Carbon can leave the geosphere in several ways. Carbon dioxide is released during the metamorphism of carbonate rocks when they are subducted into the Earth's mantle. This carbon dioxide can be released into the atmosphere and ocean through volcanoes and hotspots. It can also be removed by humans through the direct extraction of kerogens in the form of fossil fuels.

After extraction, fossil fuels are burned to release energy and emit the carbon they store into the atmosphere. The cycle in which that carbon travels has two tiers of speed: a fast biological circuit, closed within years, in which the element shuttles between the air and living things; and a slow geological circuit that grinds through rock on timescales no human lifetime can watch.

The geological limb reaches deep into the mantle, and a single round trip — burial, subduction, and return by volcanism — can consume millions of years, threading the element through crustal rock, soil, sea and air. The fast carbon cycle involves relatively short-term biogeochemical processes between the environment and living organisms in the biosphere (see diagram at start of article). It includes movements of carbon between the atmosphere and terrestrial and marine ecosystems, as well as soils and seafloor sediments.

The fast cycle includes annual cycles involving photosynthesis and decadal cycles involving vegetative growth and decomposition. The reactions of the fast carbon cycle to human activities will determine many of the more immediate impacts of climate change. The slow (or deep) carbon cycle involves medium to long-term geochemical processes belonging to the rock cycle (see diagram on the right). The exchange between the ocean and atmosphere can take centuries, and the weathering of rocks can take millions of years.

Carbon in the ocean precipitates to the ocean floor where it can form

sedimentary rock and be subducted into the Earth's mantle. Mountain building processes result in the return of this geologic carbon to the Earth's surface. There the rocks are weathered and carbon is returned to the atmosphere by degassing and to the ocean by rivers. Other geologic carbon returns to the ocean through the hydrothermal emission of calcium ions.

In a given year between 10 and 100 million tonnes of carbon moves around this slow cycle. This includes volcanoes returning geologic carbon directly to the atmosphere in the form of carbon dioxide. However, this is less than one percent of the carbon dioxide put into the atmosphere by burning fossil fuels. The movement of terrestrial carbon in the water cycle is shown in the diagram on the right and explained below: Atmospheric particles act as cloud condensation nuclei, promoting cloud formation.

Burning and volcanic eruptions produce highly condensed polycyclic aromatic molecules (i.e. Terrestrial plants fix atmospheric CO2 through photosynthesis, returning a fraction back to the atmosphere through respiration. Lignin and celluloses represent as much as 80% of the organic carbon in forests and 60% in pastures.

Litterfall and root organic carbon mix with sedimentary material to form organic soils where plant-derived and petrogenic organic carbon is both stored and transformed by microbial and fungal activity. Water absorbs plant and settled aerosol-derived dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) as it passes over forest canopies (i.e.

Biogeochemical transformations take place as water soaks into soil solution and groundwater reservoirs and overland flow occurs when soils are completely saturated, or rainfall occurs more rapidly than saturation into soils. Organic carbon derived from the terrestrial biosphere and in situ primary production is decomposed by microbial communities in rivers and streams along with physical decomposition (i.e.

Terrestrially-derived macromolecules such as lignin? and black carbon? are decomposed into smaller components and monomers, ultimately being converted to CO2, metabolic intermediates, or biomass.

Lakes, reservoirs, and floodplains typically store large amounts of organic carbon and sediments, but also experience net heterotrophy in the water column, resulting in a net flux of CO2 to the atmosphere that is roughly one order of magnitude less than rivers. Methane production is also typically high in the anoxic sediments of floodplains, lakes, and reservoirs. Primary production is typically enhanced in river plumes due to the export of fluvial nutrients.

Nevertheless, estuarine waters are a source of CO2 to the atmosphere, globally.

Coastal marshes both store and export blue carbon. Marshes and wetlands are suggested to have an equivalent flux of CO2 to the atmosphere as rivers, globally. Continental shelves and the open ocean typically absorb CO2 from the atmosphere. The marine biological pump sequesters a small but significant fraction of the absorbed CO2 as organic carbon in marine sediments (see below).

The chemical pathway is as follows: Two molecules of CO2 are required for silicate rock weathering; marine calcification releases one molecule back to the atmosphere. Biological carbon fixation, or carbon assimilation, is the process by which living organisms convert inorganic carbon (particularly carbon dioxide, CO2) to organic compounds. This pathway is cyclic due to the regeneration of the oxaloacetate.

The oceanic carbon cycle (or marine carbon cycle) is composed of processes that exchange carbon between various pools within the ocean as well as between the atmosphere, Earth interior, and the seafloor. The carbon cycle is a result of many interacting forces across multiple time and space scales that circulates carbon around the planet, ensuring that carbon is available globally. The Oceanic carbon cycle is a central process to the global carbon cycle and contains both inorganic carbon (carbon not bound to other carbon) and organic carbon (carbon that is incorporated into molecules with carbon-carbon bonds). Part of the marine carbon cycle transforms carbon between non-living and living matter.

End of free sample. The full book is available at putrabooks.github.io

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.