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A New Look at the Long-term Carbon Cycle

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ABSTRACT

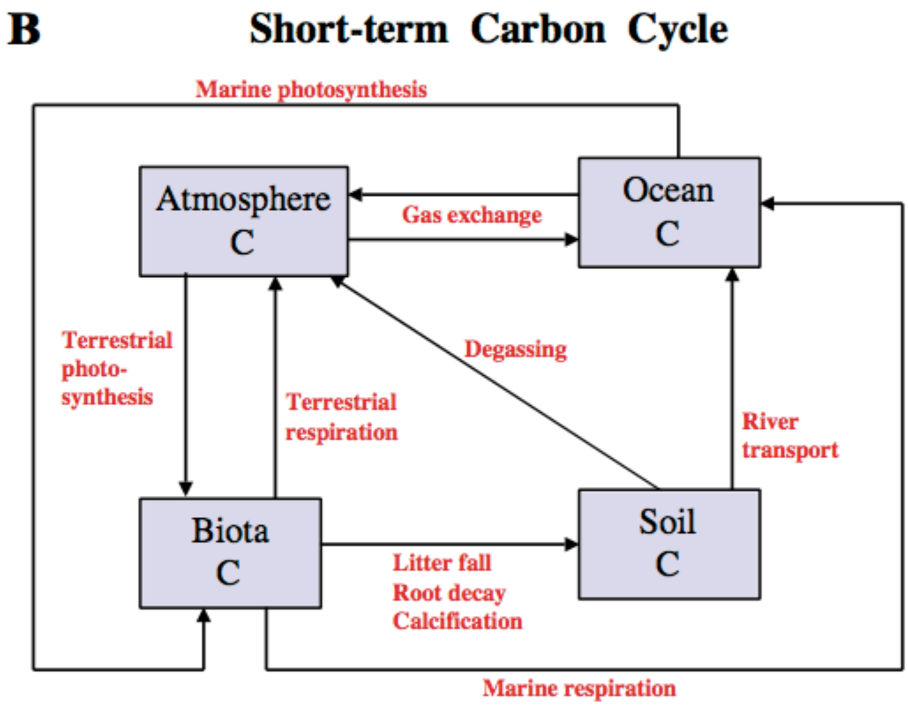
The long-term carbon cycle is the cycle that operates over millions of years and that involves the slow exchange of carbon between

- rocks
- and the surficial system consisting of the ocean, atmosphere, biota, and soils.

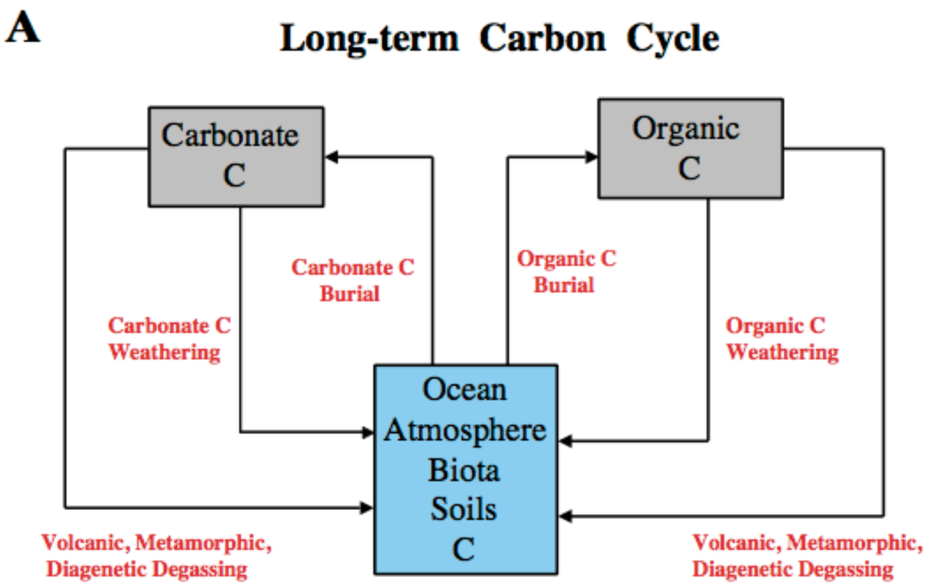
It is distinguished from the short-term carbon cycle, in which carbon is rapidly exchanged only within the surficial system (Short-term Carbon Cycle, B). A new type of diagram illustrates the cause-effect relations involved in the long-term carbon cycle and how these processes affect the levels of atmospheric O2 and CO2. The diagram also includes the cycle of phosphorus as it affects the burial of organic matter in sediments. The diagram is distinctly different from, and is here compared to, the more traditional representation of geochemical cycles in terms of box models. By following paths leading from causes to effects, one can trace complex loops that demonstrate positive and negative feedback, and this allows discovery of new subcycles that deserve further study. This type of diagram should be applicable in general to other geological and geochemical processes.

INTRODUCTION

The term “carbon cycle” means many things to many people.



- For those concerned with the present growth of CO2 in the atmosphere, due to deforestation and the burning of fossil fuels, the carbon cycle consists of those sources and sinks that exchange carbon with the *atmosphere* on a human time scale. This includes the *biosphere, oceans, and soils*, and I refer to it here as the *short-term carbon cycle (Atmosphere C, Ocean C, Biota C, Soil C)*. This cycle is also the dominant control on atmospheric CO2 over longer periods, including the glacial-interglacial stages of the Quaternary.



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- However, as one goes back further in geologic time, one must take into account the exchange of carbon between rocks and the *combined biosphere-hydrosphere-atmosphere-soil system*. This gives rise to the concept of the long-term carbon cycle
  - (GEOCARB III: A REVISED MODEL OF ATMOSPHERIC CO2 OVER PHANEROZOIC TIME (2001)
    - cache: file:///Users/msteenken/Jochen/Contents/Webs-/acamedia.info/sciences/sciliterature/globalw/reference/aeg-ag/literatur/geocarb/Geocarb_III-Berner.pdf),
    - C and G in GEOCARB are the amounts of carbonate and organic C in rocks, respectively (two top compartments in diagram A)
  - and it is this cycle that is the dominant influence on the levels of atmospheric oxygen and carbon dioxide over millions of years (Holland, 1978). (Humans have accelerated this cycle by the burning of organic carbon in sedimentary rocks that otherwise would oxidize only very slowly by weathering.)

A cause-effect–type diagram, previously used in modeling physiology (Grodins, 1963; Riggs, 1970), climate (Saltzman and Moritz, 1980; Saltzman and Maasch, 1991), and ocean nutrients and oxygen (Lenton, 1998) can be used also to illustrate the various kinds of feedbacks that control CO2 and O2 in the long-term (multimillion-year) carbon cycle.

LONG-TERM CARBON CYCLE
Summaries of the processes that affect carbon transfer as part of the long-term carbon cycle (Fig. 1), and how they affect atmospheric CO2 and O2 can be found in a variety of sources (e.g., Garrels and Perry, 1974; Walker, 1977; Holland, 1978, 1984; Berner, 1989, 1998).

The processes affecting CO2 can be divided into two subcycles.

1. The first, the silicate-carbonate subcycle (A, see above), involves the uptake of atmospheric CO2 (processed mostly by photosynthesis and respiration to form soil CO2 and organic acids) during the weathering of Ca and Mg silicate minerals. A representative generalized reaction for Ca is:

$2CO2 + H2O + CaSiO3 \ -> \ Ca^{++} + 2HCO3 + SiO2$. (1)

The dissolved Ca ++ and HCO3 are carried by rivers to the sea, where they are precipitated (almost always by means of a biological process) as CaCO 3 in sediments:

$Ca^{++} + 2HCO3- \ -> CaCO3 + CO2 + H2O$. (2)

(Mg is removed from the oceans by dolomite formation or by exchange for Ca with ridge basalts, the Ca being subsequently precipitated as CaCO3).

The net overall reaction (Ebelmen, 1845; Urey, 1952) is:

CO2 + CaSiO3 -> CaCO3 + SiO2. (3) (weathering)

In this way CO2 is removed from the atmosphere and buried as limestone. The weathering of Ca and Mg carbonates, by comparison, does not result in net loss of CO2 to the rock record because the weathering reaction for carbonates is simply the reverse of reaction 2 or its dolomite [MgCa(CO3)2] analogue.

To replace the CO2 lost to the rock record, degassing occurs as a result of the thermal breakdown of carbonates at depth by volcanism, metamorphism, or deep diagenesis. This process completes the silicate-carbonate subcycle and can be represented for Ca simply by:

$CaCO_3 + SiO_2 \rightarrow CO_2 + CaSiO_3$, (4) (metamorphosis)

which is the reverse of reaction 3.

2. The other carbon subcycle is that for organic matter (see A, above). This subcycle affects both CO_2 and O_2. The burial of organic matter in sediments represents a net excess of photosynthesis over respiration and can be represented by the reaction normally applied to photosynthesis:

$CO_2 + H_2O \rightarrow CH_2O + O_2$. (5) (photosynthesis)

This reaction explains how organic matter burial results in the production of atmospheric O_2.

To complete the organic subcycle, O_2 is consumed and CO_2 produced by the oxidation of organic matter in old sediments exposed to weathering on land:

$CH_2O + O_2 \rightarrow CO_2 + H_2O$. (6)

This reaction also represents the overall process of the thermal breakdown of organic matter, followed by the degassing to the surface of reduced carbon-containing gases (exemplified by CH_4 in Fig. 1) and their rapid oxidation to CO_2 by atmospheric O_2.

In sum, reactions 3–6 constitute the long-term carbon cycle and are one way of representing it.

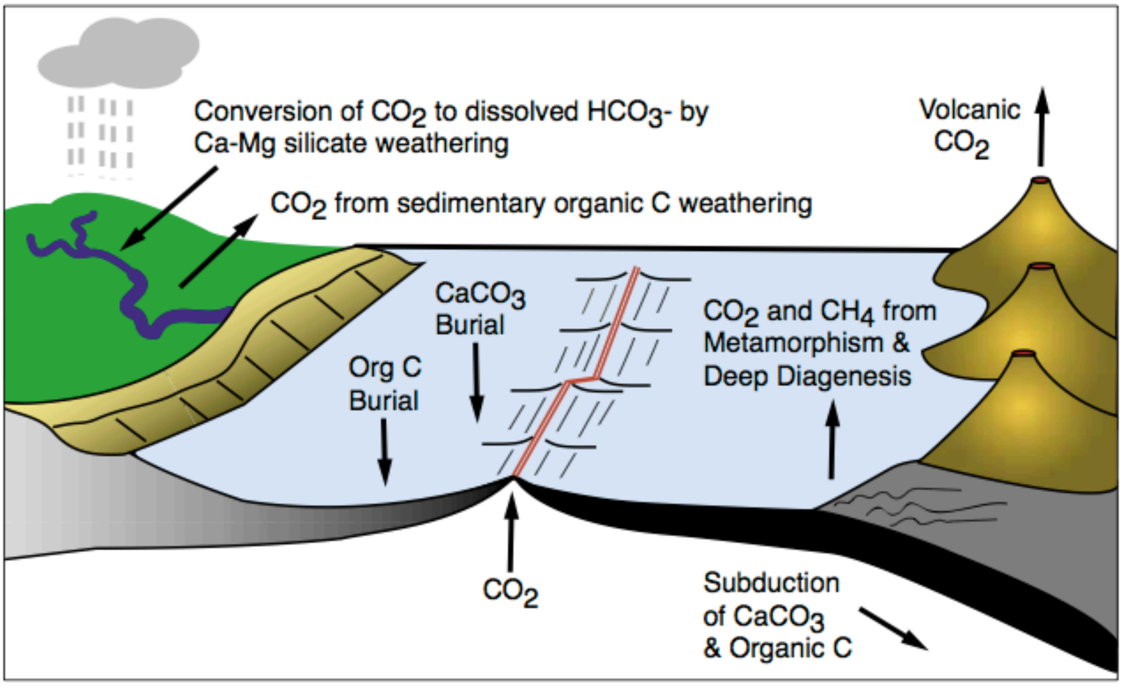

Figure1 is another means of representation, which can be simplified in the form of the box model diagram (see A, above).

However, there is another way of looking at the long-term carbon cycle that does not simply show sinks, sources, and fluxes, as do cartoons like Figure 1 or box model diagrams (see above). Instead of focusing on fluxes and reservoirs, one can look at causes and effects.

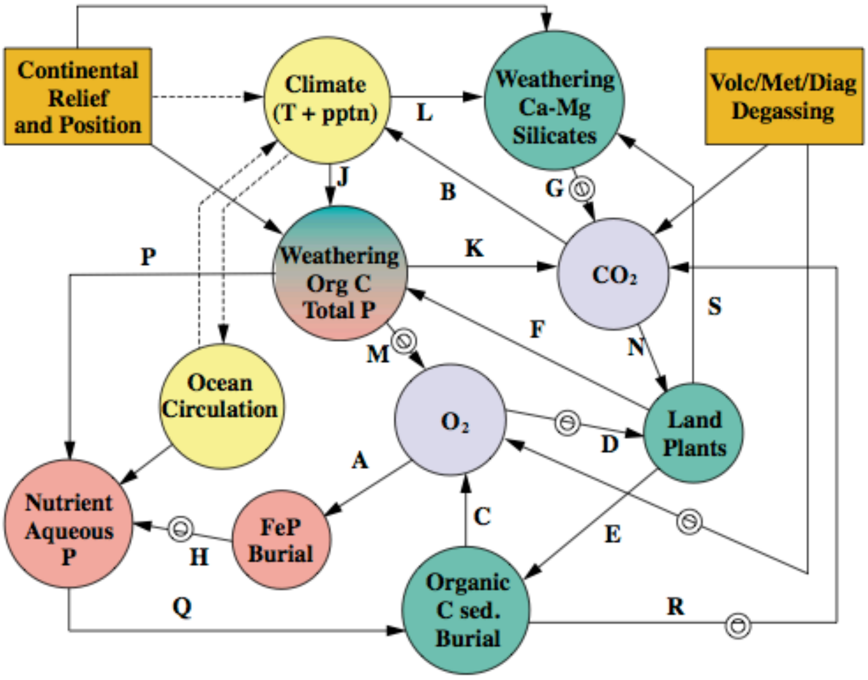

Figure 2. Cause-effect feedback diagram for the long- term carbon cycle.

- Arrows originate at causes and end at effects. The arrows do not simply represent fluxes from one reservoir to another.
  - Arrows with small concentric circles represent inverse responses; e.g., as *Ca-Mg silicate weathering* increases, *CO2 decreases*.
  - Arrows without concentric circles represent direct responses; e.g., as *organic C burial* goes up, *O2* goes up.
- Letters adjacent to arrows designate paths followed by feedback loops.
- The blue regions marked *O2* and *CO2* refer to atmospheric gases.
- Surficial processes involving
  - carbon are in green (*Organic C sed. Burial, Land Plants, Weathering Ca-Mg Silicates, Weathering Org C*),
  - phosphorus in pink (*Org C Total P, Nutrient Aqueous P, FeP Burial*), and
  - those not directly involving either C or P in yellow (*Climate (T + pptn)*, with T being temperature; pptn being precipitation, *Ocean Circulation*).
- Tectonic processes (*volcanic, metamorphic, diagenetic degassing*; *continental relief and position*) are in orange boxes.
- Dashed lines between climate and tectonics or ocean circulation refer to complex combinations of physical processes not discussed in this paper.
- *Nutrient aqueous P* is phosphorus dissolved in natural waters that is available for uptake via photosynthesis, both continental and marine;
- *FeP* represents phosphate adsorbed on hydrous ferric oxides.
- *Organic C* and *P burial* includes that on the continents and in marine sediments.
- For diagrammatic clarity, arrows from *organic carbon burial* to *organic weathering* or *degassing* (i.e., recycling of carbon) are not shown (see text).
- There is no arrow going directly from *O2* to the *weathering of organic carbon* because of evidence that changes in atmospheric O2 probably do not affect organic carbon weathering rate (see text).

How to use Fig.2
Negative feedback results when an increase (or decrease) of a variable results, at the end of a cycle, in a *dampening* of this increase (or decrease).
Positive feedback results in *amplification* of an initial increase (or decrease).

Discerning negative from positive feedback is the major advantage of using diagrams like this.

- If during a cycle, the sum of small concentric circles is an odd number, the cycle leads to negative feedback.
- If the sum of small circles is even, including zero, the feedback is positive.

As an example, follow the path marked by arrows B, L, and G. Because only one small circle is encountered, this cycle should result in negative feedback.

- Increased atmospheric CO2 should lead to a warmer and wetter Earth, via the atmospheric greenhouse effect, which
- should lead in turn to enhanced weathering of Ca-Mg silicates and uptake of CO2.

This negative feedback loop has been emphasized in several studies as an important control on atmospheric CO2 over geologic time (see discussion in Berner and Caldeira, 1997)

more feedbacks explained

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