

MARINE BIOGEOCHEMICAL CYCLES: EFFECTS ON CLIMATE AND RESPONSE TO CLIMATE CHANGE

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Summary

Biogeochemical cycling involves the various reservoirs that store elements, the fluxes between these reservoirs and the physical, chemical and biological parameters that regulate these fluxes. Additionally, the cycles of many elements, such as carbon, nitrogen, phosphorus and sulfur, are coupled via numerous feedback mechanisms. Changes in the composition of the biosphere and in elemental fluxes occur at all time scales due to environmental forcings. However, the rates of changes that have occurred during the past 200 years and those that are predicted for the next 100 years are unprecedented. Understanding and predicting the response of the biosphere and of the biogeochemical cycling of elements to these changes is a formidable scientific challenge.

The oceans, due to their extent and properties, play a major role in elemental biogeochemical cycling. For example, oceanic processes drive the atmospheric carbon concentration and climate at glacial-interglacial time scales. The oceans are also a resource for food, transportation and recreation, and contribute to 60% of the total economic value of the biosphere.

The understanding of the oceanic biogeochemical cycles progressed a lot in the past 30 years. Nevertheless, several aspects remain unclear and, more importantly, their response to climate change is poorly understood. This chapter essentially addresses these cycles at the global scale and the impacts of human perturbation upon these cycles. It is mostly concerned with the carbon and carbonate cycles but the interactions with the cycles of other nutrients, mostly nitrogen, phosphorus and iron, are addressed briefly.

1. Introduction

A biogeochemical cycle is the circulation of an element in the Earth system. It involves various reservoirs that store the element, fluxes between reservoirs as well as the physical, chemical and biological parameters that regulate the fluxes. Additionally, the cycles of many elements are intimately tied via numerous feedback mechanisms. It can therefore be readily appreciated that the study of a biogeochemical cycle is a formidable undertaking that involves chemists, biologists, physicists, geologists and modelers (see also *Chemistry of the Oceans*).

Global change encompasses, in its broadest sense, both global climatic changes (e.g., $p\text{CO}_2$ and temperature) and environmental changes occurring at the regional or local scale (e.g., eutrophication). It must be emphasized that it has two components: a natural component resulting from the variability of the Earth system and a human-induced component that became significant less than 300 years ago and that is related to agricultural, industrial and urbanization activities. These activities release gases or substances that interfere with the natural functioning of the Earth system by modifying the atmospheric and aquatic chemistry and, in turn, biological processes. One of the major endeavors of biogeochemical research is to discriminate between these two components of global change. The assessment of the present and future perturbations of the biogeochemical cycling of elements therefore requires a good knowledge of past geological cycles. This chapter essentially addresses the global scale and the human perturbation. It is mostly concerned with the oceanic carbon and carbonate cycles but the interactions with the cycles of other nutrients, mostly nitrogen and phosphorus, will also be addressed briefly.

2. Carbon and Carbonate Cycles

The carbon and carbonate cycles are closely linked for two reasons. First, inorganic carbon is both a component and an end product of calcium carbonate (CaCO_3) deposition (i.e., calcification) (Appendix 2). Second, precipitation of CaCO_3 requires energy that is supplied directly (photosynthetic calcifiers) or indirectly (non-photosynthetic calcifiers) by primary production. The carbon and carbonate cycles are addressed separately, for convenience, in the following two sections but their interactions will be outlined.

2.1. Carbon Cycle

The global carbon cycle comprises four major carbon reservoirs: rocks, ocean, continental (land biota, soil and detritus) and atmosphere (Figure 1). The ocean is a major component of the global carbon cycle. It is the second largest carbon reservoir,

after the rock reservoir, with about 39 000 Pg C. By contrast, the land biota, soil and detritus contain 2 150 Pg C and the pre-industrial atmosphere 600 Pg C, mostly in the form of carbon dioxide.

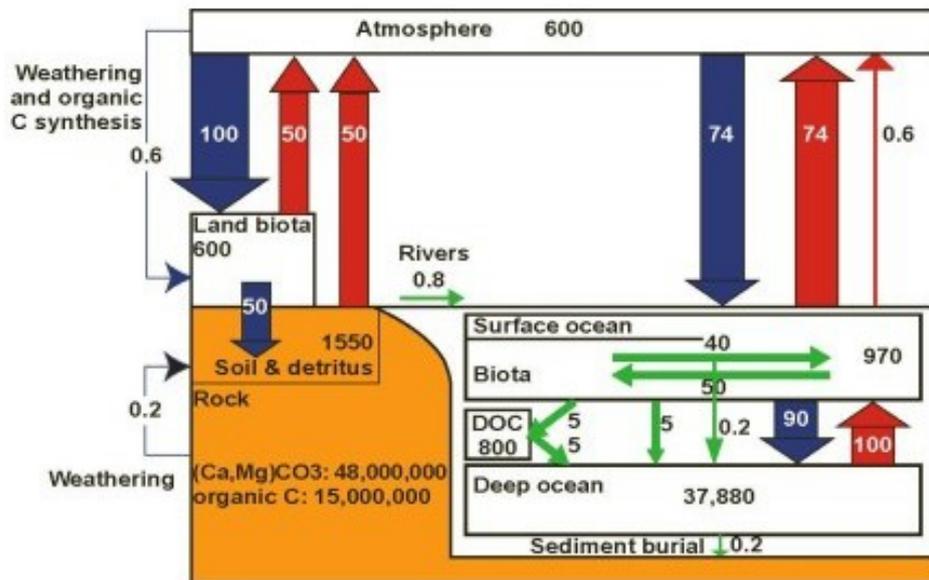


Figure 1. Pre-industrial carbon cycle. The amount of inorganic carbon in the reservoirs and the magnitude of fluxes are in Pg C and Pg C yr⁻¹, respectively. The atmospheric, surface and deep ocean reservoirs are presently increasing at a rate of, respectively, 3.4, 0.4 and 1.6 Pg C yr⁻¹ due to the anthropogenic perturbation (not shown).

The ocean receives 0.8 Pg C from river input and terrestrial run off but it mostly exchanges carbon with the atmosphere as a result of changes in the carbon content of surface water driven by physical, chemical and biological processes. These processes are commonly referred to as "pumps" because they transfer carbon against concentration gradients: they reduce the dissolved inorganic carbon (DIC) concentration of surface water (and the atmosphere) and increase it in the deep ocean. The DIC concentration is about 12% higher below 1 km depth than at the surface.

The solubility pump enables chemical exchange of CO₂ between seawater and the atmosphere. CO₂ dissolves as a function of the difference of its partial pressure (*p*CO₂) between the atmosphere and seawater in order to establish equilibrium (equal *p*CO₂) in both reservoirs. Temperature is a strong control of the equilibration, together with salinity and wind. CO₂ is more soluble in cold than in warm water. The physical pump, which is closely related to the solubility pump, is the process through which DIC is transferred to the ocean interior when surface water sinks to the deep ocean. It mostly operates in high latitude areas as part of the conveyor belt or thermohaline circulation (THC). The water budget is closed by the transport of warm and salty surface water (1500 m thick) to the North Atlantic where it cools, stores CO₂, and sinks (Figure 2).

Deep currents bring the water mass to the South, where it merges with the deep water generated around the Southern Ocean, and on to the North Indian and Pacific Oceans where it warms, upwells, and releases CO₂ to the atmosphere. The downward water flux is of the order of 50 Sv (1 Sverdrup = 10⁶ m³ s⁻¹), divided almost equally between the

North Atlantic and Southern Oceans. Coastal and equatorial upwellings, as well as mixing and convection are other mechanisms returning deep CO₂-rich water to the surface. This large-scale flow stores carbon in deep water, which is further enriched with carbon during its journey through biological processes as will be seen later. The storage time is about 1 000 years, the time lag between sinking in the North Atlantic and upwelling in the North Indian and Pacific Oceans.

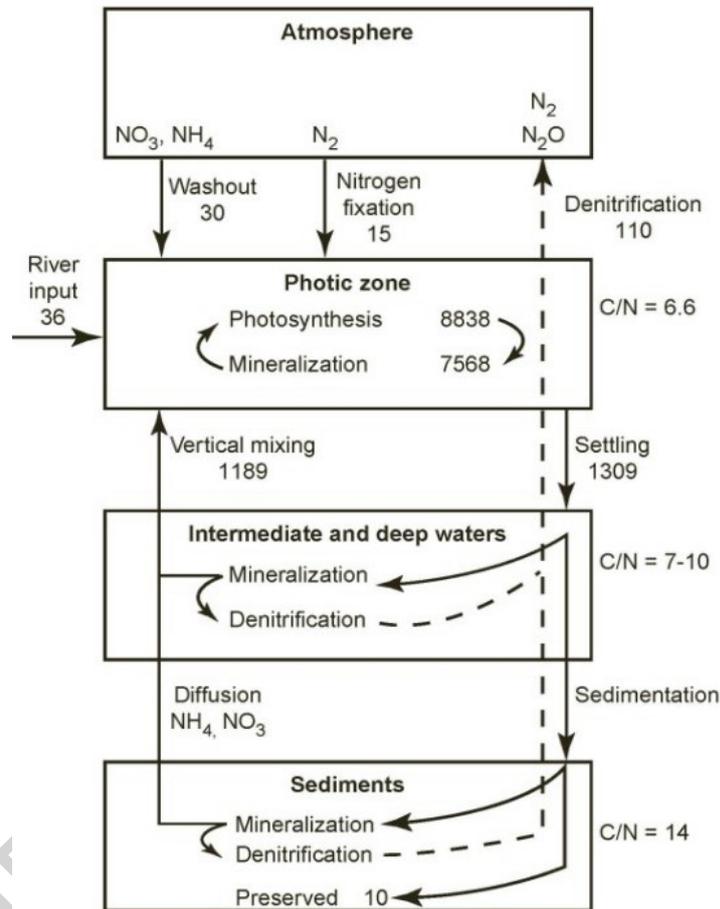


Figure 2. Simplified diagram of the thermohaline circulation.

Biological processes affecting the oceanic carbon cycle are the metabolism of organic (photosynthesis and respiration) and inorganic (precipitation and dissolution of CaCO_3) carbon (Appendix 1). Photosynthetic phytoplankton fixes CO_2 in the upper, illuminated, surface ocean. The organic carbon produced is mostly remineralized to CO_2 , but a small portion escapes respiration and is exported in the form of particulate and dissolved organic matter (biological pump) to the deep ocean, where another portion is mineralized by bacteria. The global oceanic photosynthesis fixes approximately 50 Pg C yr^{-1} , 80% is mineralized in the upper ocean, nearly 20% is mineralized in the deep water column and sediment (storage time of hundreds of years), and less than 1% is buried in the sediment (storage time of millions of years). The biological pump is responsible for about 9% of the 12% difference in inorganic carbon between the surface and deep ocean. It must be pointed out that these figures, especially the amount of organic matter mineralized in surface water vs exported, are subject to intense discussion. Also, the

export production strongly depends on the community composition. Small photosynthetic cells have a competitive advantage for the use of the small amount of nutrients available in oligotrophic areas where they dominate the community. A large portion of the primary production is utilized by microbial heterotrophs that efficiently cycle carbon through a microbial loop and leave little carbon for export. The situation is very different in areas where nutrients are more abundant because larger phytoplankton can successfully compete with smaller cells for nutrient utilization and are therefore much more abundant. Since nutrients are usually delivered as pulses, the grazers that feed on phytoplankton cannot efficiently use the carbon produced because they have a reproductive delay of several days. A larger portion is therefore available for export compared to oligotrophic areas.

The atmospheric partial pressure of CO₂ ($p\text{CO}_2$) was relatively stable at about 280 μatm for several centuries prior to the industrial revolution, suggesting that the carbon cycle was in steady state. The carbon cycle has however, been subject to anthropogenic perturbation since the mid 1800s. The use of fossil fuel is effectively returning carbon to the atmosphere that was stored in the rock reservoir; the average release was 5.4 Pg C yr⁻¹ in the 1980s. Changes in land use practices released an additional 1.6 Pg C yr⁻¹ during the same period. This excess carbon is approximately partitioned as follows: 46% remains in the atmosphere, increasing $p\text{CO}_2$ to a present value of 367 μatm and at an annual rate of 0.4%, 29% is taken up by the ocean, with the remaining possibly being stored by an unidentified continental sink. It must be pointed out that this partitioning is plagued with considerable uncertainty and subject to intense debate and research. The effect of the biological pump on atmospheric $p\text{CO}_2$ has been explored through modeling studies. It was shown that the pre-industrial atmospheric $p\text{CO}_2$ would have been 450 μatm in an ocean without marine biota whereas a fully functional biological pump, that would have used all available nutrients, would have led to an atmospheric $p\text{CO}_2$ of 160 μatm . The contribution of the ocean is therefore very substantial but is insufficient, as will be seen later, to mitigate the present and future CO₂ emissions ($p\text{CO}_2$ is predicted to reach 706 μatm by the year 2100). Note, however, that the contribution of the carbonate pump was not included in the model used to make these predictions.

Primary production exhibits large seasonal changes due to changes in the supply of light, the depth of the mixed layer, and in the supply of nutrients by upwelling, mixing and advection. In many areas, the winter cooling of surface water induces a strong convection and a deepening of the mixed layer. This has several consequences. First, some of the primary producers sink to light-limited depths, decreasing photosynthesis, which is already low due to the lower temperature. Second, deep mixing brings a supply of carbon, favoring a short-term CO₂ degassing to the atmosphere, and nutrient which result in a delayed stimulation of photosynthesis in spring and summer, when the mixed layer stabilizes and becomes thinner. The contribution of the coastal ocean to the global carbon cycle is another matter of intense debate. It plays a major role in the burial of organic carbon either imported from land or locally produced but it is controversial whether it is a carbon sink or source. The reason is the very limited amount of data available on net ecosystem production of the open coastal ocean. This is not a trivial issue because, as will be seen later, coastal ecosystems are those that are and will be the most significantly perturbed by human activities.

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Biographical Sketch

Jean-Pierre Gattuso is a CNRS Senior Research Scientist and has 18 years of experience in the study of coastal marine organisms and ecosystems, both in European waters and overseas. He has held positions in

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