Global Biogeochemical Cycles

Global biogeochemical cycles can be defined as any of the natural circulation pathways through the atmosphere, hydrosphere, geosphere, and biosphere of the essential elements of living matter. These elements in various forms flow from the nonliving (abiotic) to the living (biotic) components of the biosphere and back to the nonliving again. Research on the biogeochemical cycles focuses on seven of the major elements that make up more than 95% of all living species: hydrogen, carbon, sulfur, oxygen, and the major nutrients nitrogen, phosphorus and silicon. These elements combine in various ways. Here we focus on carbon and sulfur due to their importance for feedbacks with the climate and for environmental concerns.

Earth's life is linked to climate through a variety of interacting cycles and feedback loops. Human activities, such as deforestation and fossil fuel burning, have directly or indirectly modified the biogeochemical and physical processes involved in determining the Earth's climate over the last millennia and can disturb a variety of land and marine ecosystem interactions.

Climate System and Biogeochemical Cycles. The main driver for the climate system is the radiative balance at the top of the atmosphere. Incoming solar radiation is partly absorbed and reflected in the atmosphere. The remaining part is absorbed at the Earth's surface and re-emitted as long-wave radiation into the atmosphere. Greenhouse gases such as water vapor, carbon dioxide (CO_2), methane, and nitrogen oxides absorb the long-wave radiation and serve as a blanket for the lower atmosphere.

The potential for two-way interactions and feedbacks between the carbon cycle and the climate system comes from the radiative properties of CO_2, methane, and other greenhouse gases in the atmosphere. Changes of atmospheric CO_2 through anthropogenic emissions, for example, may lead to significant changes in atmospheric climate, ocean circulation, and magnitude and extent of continental ice sheets. Climate records indicate that large-scale abrupt climate changes have occurred repeatedly throughout the geological history, which are related to variations in the Earth's orbital parameters as well as to significant perturbations in the hydrological cycle. Coupled climate simulations suggest that CO_2-induced warming will lead to reduced marine and terrestrial carbon uptake. In the ocean, climate changes alter stratification, solubility, and nutrient supply to the euphotic zone, the zone in which sufficient light is available. These changes in the export of carbon into the deep sea feed back on the atmospheric carbon dioxide concentration.

Several studies indicate overall positive feedback processes due to global warming, but many of these processes are quantitatively not well known.

Global Carbon and Nutrient Cycles. The biogeochemical cycle of carbon and nutrients is of great importance to global climate change. The cycle includes four main reservoirs: the atmosphere, organic compounds in living or dead organisms, dissolved substances in the oceans and freshwater reservoirs, and storage in the geosphere (**Fig. 1**).

CO_2 in the Atmosphere. The primary forces that drive the long-term drifting of climate from extremes of ice-free poles to extremes of cold with massive continental ice sheets and polar ice caps are Earth's orbital geometry and plate tectonics. The orbitally-related climate oscillations vary about a climatic mean in response to changes such as continental geography and topography, seaways and bathymetry, and concentrations of greenhouse gases like CO_2 or methane. A recent review of the geologic records concluded that CO_2 and widespread continental glaciations are generally well-correlated through the Phanerozoic (the last 540 million years).

The atmospheric CO_2 concentration has significantly increased from about 280 parts per million (ppm) in 1800, the beginning of the industrial age, to 380 ppm today. New evidence suggests that concentrations of CO_2 started rising about 8,000 years ago, even though natural trends indicate they should have been dropping. Some 3,000 years later, the same thing happened to methane. Without these changes, current temperatures in northern parts of North America and Europe would be cooler by three to four degrees Celsius - enough to make agriculture difficult. Recent research has tried to estimate the sources and sinks of carbon from data and with computer simulations, which is fundamental for the understanding of the natural carbon cycle, and also significant for formulating global CO_2 emission strategies. According to these studies, the ocean acts as a major sink for anthropogenic CO_2.

Ocean Carbon Cycle. The marine carbon cycle is typically broken down into two components. The first is the solubility pump, with low solubility of CO_2 in warm waters, and the second is the biological pump, affecting the redistribution of biologically active elements like carbon, nitrogen, and silicon within the circulating waters of the ocean. The distributions of circulation patterns (e.g. eddies) and biomass are highly correlated (**Fig. 2**). The part of the biologically active elements which is exported to deeper layers and not recycled in the water column, is buried in sediments.

Planktonic organisms utilize carbon during photosynthesis, reducing the dissolved inorganic carbon in seawater. This change reduces the surface ocean pCO_2 and increases the uptake of CO_2 from the atmosphere. About 44% of the total gross primary production is used for the net primary production, while the remaining part is consumed by respiration. Nitrogen (N_2)-fixation can substantially change the inventory of nitrogen in the ocean, thereby stimulating marine productivity and atmospheric CO_2. Micronutrients like iron delivered to the ocean by river and dust input can promote the downward export of carbon from the euphotic zone. Moreover, particle size and particle aggregation, such as mineral ballasting, help to control the flux of organic material from the euphotic zone into the deep sea.

Climate change affects the intensity of the biological pump by altering limiting factors for productivity such as nutrient availability, light, or temperature. For example, analyses of computer simulations indicate that nutrients in polar surface waters may become depleted by stratification as a result of global warming. These water masses are transported subsurface to the equatorial region where a reduced nutrient supply causes a decrease in productivity.

Plankton species producing calcium carbonate skeletal material (e.g. coccolithophores) reduce the dissolved inorganic carbon concentration. The chemistry of calcium carbonate controls the pH of the ocean and, in turn, plays a large role in regulating the CO_2 concentration of the atmosphere on timescales of thousands of years and longer. For example, recent global warming simulations predict a significant decline of the pH value by about 0.4 or more over the next hundred years. Such a dramatic change can reduce the calcification of corals necessary for the build-up of reefs and promote the dissolution of calcareous shells and exoskeletons of marine organisms.

Land Biosphere Carbon Cycle. In contrast to the ocean, most carbon recycling through the land takes place locally within ecosystems. About half of the terrestrial gross primary production (120 Pg carbon per year) is respired by plants. The remainder (Net Primary Production; NPP) is approximately balanced by respiration with a smaller component of direct oxidation in fires (combustion). Most of the NPP is transformed to detritus through senescence of plant tissue (e.g. leaves). Some of the detritus decomposes and the carbon is returned quickly to the atmosphere as CO_2, while some is converted to soil carbon, which decomposes more slowly. Enhanced CO_2

levels in the atmosphere have a fertilization effect on short time scales but the long-term effects are still not well known. CO_2 uptake by the land carbon cycle may be reduced by global warming due to an increased carbon emission by soil microbes.

Carbon Cycle in the Geosphere. A long-term cycle on Earth involves the interaction of CO_2 with the Earth's crust. Atmospheric CO_2 dissolved in rain water forms carbonic acid which reacts with rocks, a process which is named weathering. On longer geological time-scales, the processes of sedimentation, chemical transformation, uplift, sea-floor spreading, and continental drift are involved in the carbon cycle.

Recently, massive methane gas hydrates (clathrates) which are buried in marine sediments have received attention as a possible energy source. They are not stable when the temperature of ocean waters rises, like during the Paleocene/Eocene thermal maximum (ca. 55 million years B.P.), or the pressure falls (e.g. due to sea level falls). These instabilities can generate undersea slumps which could result in tsunamis and sudden methane release to the environment which might induce a positive feedback on the climate.

Global Sulfur Cycles. The sulfur cycle in general, and acid rain and smog issues in particular, encompasses important climatic feedbacks and socioeconomic problems. Living organisms, including plants, assimilate sulfur while at the same time sulfur is released by organisms as an end product of metabolism. Sulfur can exist both as a gas and as sulfuric acid particles. The major sulfur gases include sulfur dioxide (SO_2), dimethyl sulfide (CH_3SCH_3 or DMS), carbonyl sulfide (OCS), and hydrogen sulfide (H_2S). The lifetime of most sulfur compounds in the air is relatively short (e.g. days). In its fully oxidized state, sulfur exists as sulfate and is the major cause of acidity in both natural and polluted rainwater. This link to acidity makes sulfur important to geochemical, atmospheric, and biological processes such as the natural weathering of rocks, acid precipitation, and rates of denitrification. Natural sulfur sources are SO_2 emissions from volcanoes and DMS emissions from the marine biosphere to the atmosphere. Similar to the carbon cycle, the sulfur cycle has been significantly perturbed by human influences. Today, global anthropogenic emissions constitute almost 75% of the total sulfur emissions, with 90% occurring in the northern hemisphere. These compounds mix with water vapor and form sulfuric acid smog. In addition to contributing to acid rain, the sulfuric acid droplets of smog form a haze layer that reflects solar radiation and can cause respiratory diseases or a cooling of the Earth's surface.

Plants take up some forms of these compounds and incorporate them into their tissues for growth. These organic sulfur compounds are recycled on land or in the water after the plants die or are consumed by animals. Bacteria are of importance as well since they can transform organic sulfur to hydrogen sulfide gas (H_2S). In the ocean, zones of H_2S (dead zones) can be found in areas with sluggish circulation and high nutrient supply like the northern Gulf of Mexico. Some of the sulfide is taken up by the lithosphere during the formation of rocks. Superimposed on the fast cycles of sulfur, the sedimentary cycle operates on long geological time-scales and includes processes such as erosion, sedimentation, and uplift of rocks containing sulfur.

Frontiers of future research on global biogeochemical cycles in the interdisciplinary field of Earth system science will seek to explore interactions among the major components of the Earth system (continents, oceans, atmosphere, ice, and life) by assimilating large data sets (like **Fig. 2**) into comprehensive climate models. These studies will be sophisticated to distinguish natural from human-induced causes of change and important to understand and predict the consequences of change.

For Background information see Climatic Change; Feedback; Greenhouse Effect; Orbital; Atmosphere; Hydrosphere, Geosphere; Photosynthesis; Respiration; Exoskeleton in the McGraw-Hill Encyclopedia of Science & Technology.

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National Ocean and Atmospheric Administration (NOAA): http://www.noaa.gov/
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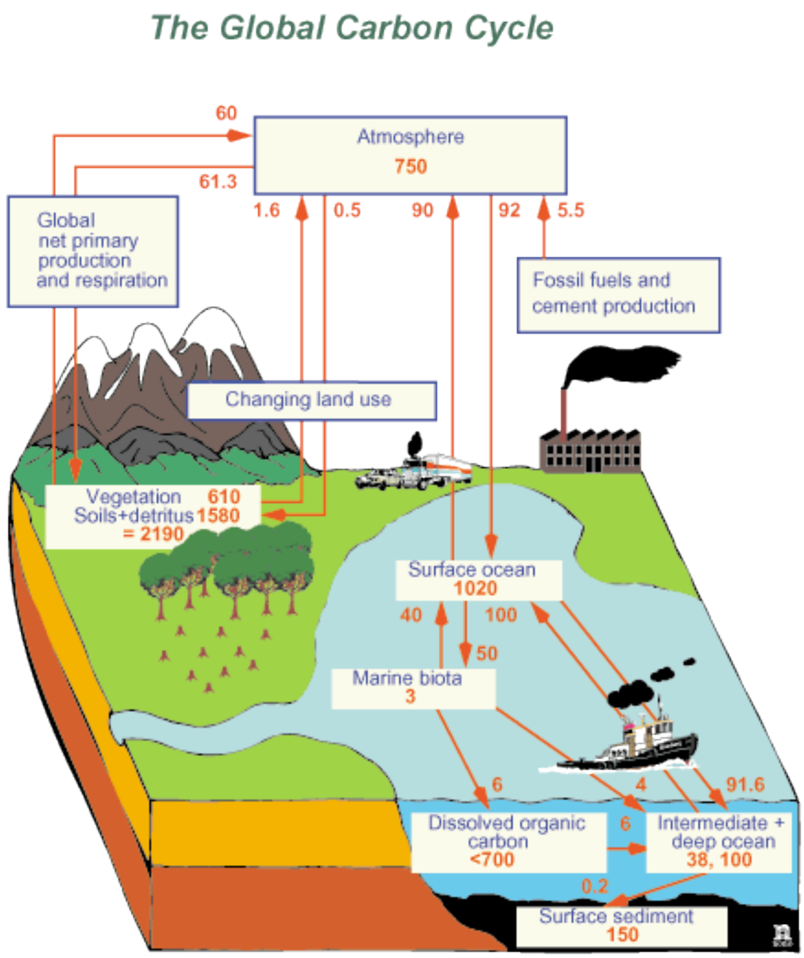
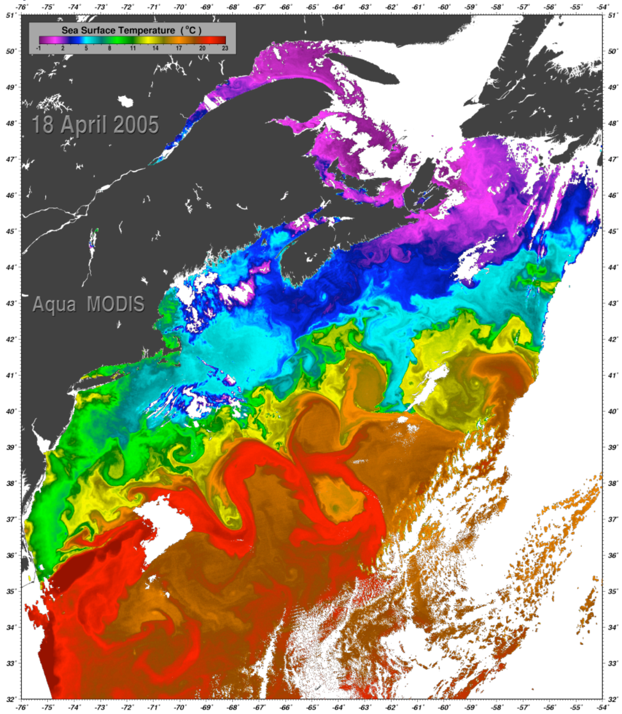


Fig 1. The global carbon cycle: storages (Pg Carbon; 1 Pg C=10^{15} g C) and fluxes (Pg C/yr) estimated from the 1980s. The numbers are similar to the recent international panel of climate change report (IPCC, 2001). Exact estimates of reservoirs and uptake of anthropogenic CO_2 are still controversial.

a)



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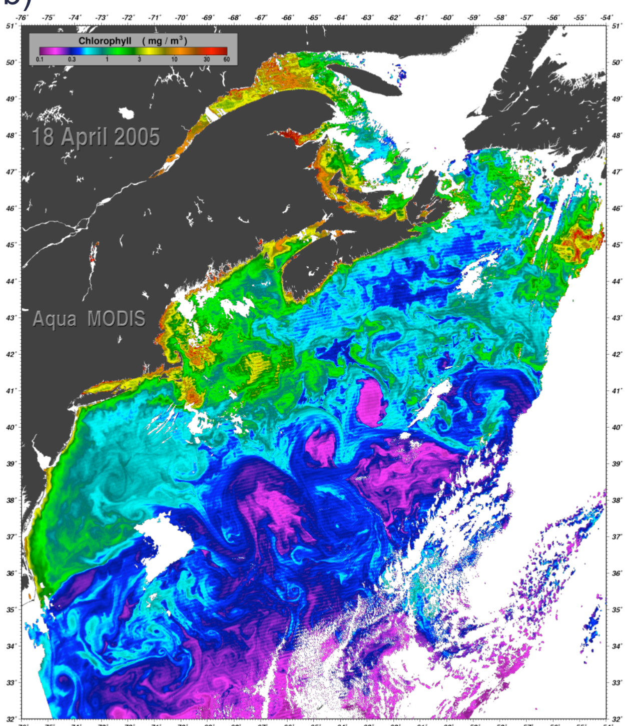

Figure 2: An example of spatial variability of the marine biota (Fig. 1.) as a result of the fluctuations in the ocean circulation. The warm heart of the Gulf Stream is readily apparent in the top sea surface temperature image. As the current flows toward the northeast it begins to

meander and pinch off eddies that transport warm water northward and cold water southward (a). The current also divides the local ocean into a low-biomass region to the south and a higher-biomass region to the north. This is evident in the bottom chlorophyll image (b). White areas are cloud coverage. The data were collected by MODIS aboard Aqua on April 18, 2005. (Courtesy of NASA Ocean Color Research Team http://oceancolor.gsfc.nasa.gov/).