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Carbon is the basic building block of life. Through the process of photosynthesis, plants on land, or algae living in lakes and oceans, take up carbon dioxide (CO_2) and convert this gaseous form of carbon into living organic products (such as carbohydrates, proteins, fats, etc.). Through the process of respiration, organisms break down these organic compounds for energy, metabolizing them into various forms of chemical compounds and regenerating the CO_2.

Figure 1.

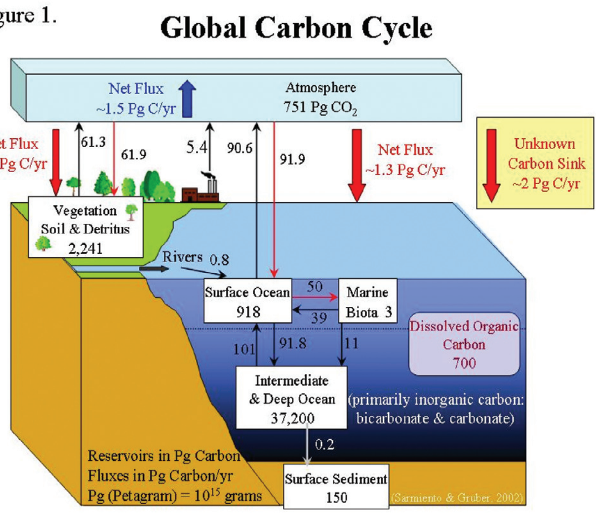

Figure 1: The global carbon cycle (values from the 1990s shown and schematic developed from [5] (Sabine et al. 2004), and [6] (Field et al. 2006). The figure does not show the vast amount of carbon that resides within rocks and deep ocean sediments. The values inside the reservoir boxes (for example, vegetation or atmosphere) represent the amount of carbon within the reservoir. The values next to the arrows represent the fluxes (or flow) of carbon from one reservoir to another. The wide red and blue arrows denote the net flux of carbon from the atmosphere (red) and to the atmosphere (blue). Values in parentheses represent the percentage of carbon derived from human activities. The biological processes of photosynthesis for the ocean is shown as a red arrow from DIC (dissolved inorganic carbon, primarily as bicarbonate and carbonate), to the sum of marine biota and DOC (dissolved organic carbon); respiration is the black arrow pointed towards DIC.

Carbon-derived materials such as oil, coal, and wood are important sources of energy and are materials that advance human civilization. Coal, natural gas, and petroleum are collectively called fossil fuels, because they are derived from the buried remains of plants, animals, and algae that are exposed to high heat and pressure over millions of years. The combustion (or burning) of fossil fuels (for electricity, heating, transportation, etc.) and wood (from forest fires and home heating) returns these stored organic materials to carbon dioxide. Thus, the carbon in fossil fuels that has been buried beneath Earth's surface for millions of years is being rapidly released into Earth's atmosphere as carbon dioxide. Current levels of carbon dioxide in Earth's atmosphere (380 parts per million—ppm; [1]) are much higher than at any time in the past 650,000 years for which we have scientific data (<300 ppm; [2]), and have increased significantly since the industrial revolution of the 1750s (from 280 ppm; [3]).

The level of carbon dioxide in the atmosphere plays an important role in earth's climate through the "greenhouse effect." Carbon dioxide in Earth's atmosphere is considered a greenhouse gas because it is transparent to much of the Sun's radiation, but blocks long-wave infrared radiation (primarily as heat) re-emitted by Earth rather than allowing the heat to escape into space. As levels of carbon dioxide increase in earth's atmosphere, more heat is trapped, resulting in higher temperatures on a global scale. These temperatures are only slightly higher than usual, but promote longer growing seasons, redistribution of vegetation, melting of glaciers, sea-level rise, and other environmental impacts.

As a result, understanding the global carbon cycle provides insight about life on Earth, as well as its role in climate change. The impact of global industrialization over the past few centuries to Earth's carbon cycle is the subject of much scientific research. A significant amount of carbon is released every year from the burning of fossil fuels [4]. Of the carbon released, ~50% remains in the atmosphere (resulting in higher CO_2 concentrations), ~28% is taken up by vegetation on land (includes CO_2 emissions from land due to deforestation and other land use changes), and ~26.6% dissolves into the ocean surface [5, 6]. The previous values exceed 100% because of uncertainties associated with carbon flux estimates. One of the current mysteries is the allocation of the 466 petagrams (Pg = 10^{15} grams) of CO_2 emissions generated from human activity since 1850 [6]. Current estimates suggest that the atmosphere retains 187 Pg of this CO_2, and the ocean contains 118 Pg [6]. The remainder, 161 Pg, is assumed to be stored on land as vegetation through re-growth of forests and in soils [5]. However, a portion of this carbon could also be stored in ocean waters or sediments. Solving the mystery of the "missing" (unaccounted) carbon is critical to understanding how increasing emissions of CO_2 impact the global carbon cycle and climate change.

Figure 2.

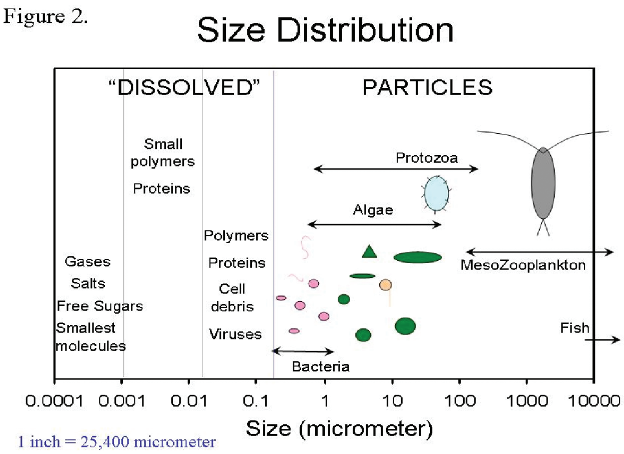

Figure 2: Schematic of the size distribution of dissolved materials and particles in the ocean.

Dissolved Organic Carbon

Carbon in the ocean is categorized as dissolved inorganic carbon (e.g., CO_2, bicarbonate, carbonate), particulate inorganic carbon (ex. calcium carbonate present in seashells), particulate organic carbon (POC; composed of living and dead organisms), and dissolved organic carbon (DOC). Particles and dissolved materials are operationally defined as matter larger or smaller than 0.2 μm, respectively (Figure 2). Approximate size ranges of marine biota and dissolved matter are given in Figure 2. Hence, DOC is defined as the organic carbon content in seawater which passes through a 0.2 μm pore-sized filter. It is primarily composed of small polymers of carbohydrates and proteins released into the water.

Although dissolved organic carbon represents <2% of the total carbon in the ocean, it comprises nearly all (>97%) of the organic carbon in the ocean [3]. Because DOC represents an important component of the global carbon cycle (equivalent in magnitude to carbon in atmospheric CO_2), investigating the sources and removal of DOC within the ocean is vital to understanding the carbon cycle. Photosynthesis is the principal source of DOC to aquatic ecosystems [7]. DOC is either released directly by phytoplankton as they grow or can be indirectly released as they are fed upon by small crustacean animals, from viral-induced breakage of phytoplankton or through break down of detritus (dead material) by microbial communities, primarily bacteria.

The potentially large fluxes of carbon in the coastal ocean underscore the significance of the coastal ocean to the global carbon cycle. The coastal ocean accounts for ~20% of the ocean's photosynthesis [8]. Rivers transport ~0.3 Pg of DOC per year to the ocean (and 0.2 Pg POC per year) [5], yet the terrigenous contribution (land-derived carbon, primarily from vegetation and soils) to this overall flux is not well known [9]. Because terrestrial ecosystems are highly productive, their contributions to coastal ocean DOC could be significant. While particles from terrestrial ecosystems are primarily deposited in the coastal region [10], DOC is considered the main conduit for transporting terrestrial organic carbon into the deep ocean. An important research question is whether terrestrial carbon inputs to the ocean have increased over the past 150 years and account for some of the missing carbon.

Historically, coastal ocean waters have been a source of CO_2 to the atmosphere because of river contributions of dissolved inorganic carbon (DIC; currently 0.4 Pg per year) and land-derived organic carbon that is subsequently degraded to CO_2 by microbes in the coastal ocean [5]. However, human population growth, agriculture, and other activities along coastal regions have resulted in the export of higher levels of nutrients to the ocean, which support more extensive phytoplankton blooms in coastal waters. The enhanced photosynthesis in the surface ocean removes more CO_2 from seawater enhancing the solubility of atmospheric CO_2 into the ocean due to the reduced CO_2 concentration in the surface ocean with respect to the atmosphere. Burial of the organic carbon from phytoplankton blooms into coastal sediments would sequester this carbon from the atmosphere. Furthermore, recent evidence demonstrates the importance of CO_2 outgassing from rivers to the atmosphere (Figure 1) with tropical rivers of greatest significance due to microbial degradation of large inputs of land vegetation and soil derived organic matter into these rivers [5].

DOC can be converted to CO_2 when it is broken down by microbial communities or by sunlight. Microbial communities in the ocean are the primary recyclers of organic materials, accomplishing most of the decomposition of particles and DOC to CO_2. An increase in the conversion of the total DOC reservoir in the ocean to CO_2 of 1% annually would exceed the amount of CO_2 released from fossil fuel combustion [11]. Higher rates of conversion, due to increasing microbial respiration from higher ocean temperatures, or from increasing ultraviolet radiation to the ocean surface could have profound effects to atmospheric CO_2 levels and possibly to climate change. The potential impact of DOC on atmospheric CO_2 and climate change is rather minor compared to other factors that impact the concentration of atmospheric greenhouse gases such as CO_2 and methane. For example, vast reservoirs of methane trapped within frozen Arctic soils may be released as the soils thaw due to global warming. As the Arctic perma-frost warms, microbial respiration of organic matter within these soils could also release significant amounts of CO_2 to the atmosphere.

Chromophoric Dissolved Organic Matter

Chromophoric dissolved organic matter (CDOM) represents the colored fraction of DOC. CDOM is colored because it absorbs light at certain regions of the visible spectrum more intensely (violet and blue light). The wavelengths of light that are not absorbed can be scattered, and thus, the CDOM will be perceived as the color of the scattered light (from a faint yellow to brown). The substance that leaches from tea bags placed in water is an example of CDOM.

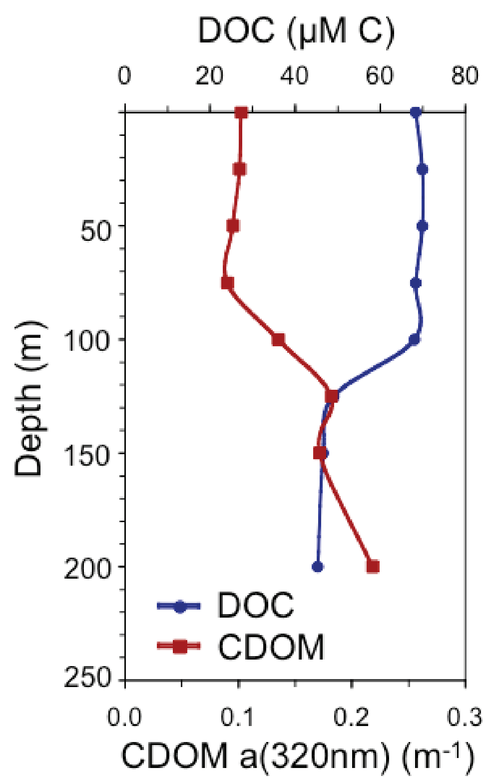

Figure 3: DOC and CDOM absorption distributions in the tropical North Atlantic Ocean. Higher DOC at the surface reflects biological production and release of DOC by phytoplankton, bacteria, and zooplankton. The lower CDOM values within the surface ocean layer compared to deeper waters demonstrate the impact of the photochemical oxidation by sunlight in surface ocean waters.

CDOM levels can vary both spatially and temporally. In coastal waters, CDOM can dominate the absorption of sunlight, particularly in the ultraviolet and blue regions of the light spectrum. Physical processes that promote vertical mixing of the coastal ocean such as winter seasonal mixing (due to storms) can introduce CDOM to the surface ocean. As sunlight intensity increases in spring and summer, the water at the ocean's surface warms making it less dense than water at depth, which is colder. This difference in density causes stratification between surface and deep ocean water, essentially forming a barrier that reduces the exchange of dissolved materials between the surface and deeper water. Sunlight can lead to the loss of CDOM and DOC in a process called photochemical oxidation, or photobleaching. A small portion of the absorbed sunlight can convert CDOM to CO_2 or cause a structural transformation of CDOM [12, 13, 14, 15]. Seasonal vertical stratification isolates DOM at depth from sunlight, resulting in DOC with greater color at depth than at the surface (Figure 3).

At regional and global scales, satellite observations combined with field observations have provided new insights into seasonal and interannual changes in photosynthesis on land and in the ocean [16, 17]. Satellite instruments used to study ocean color do not measure ocean constituents directly, but rather measure light leaving the ocean at multiple wavelengths (blue, green, red, etc.), which can be used to derive the concentration of ocean constituents, including not only chlorophyll, but also CDOM. Discharge of DOC from terrestrial sources and particles (detritus and minerals) into coastal waters by rivers and the presence of intense phytoplankton blooms in coastal waters complicate the optical properties of the coastal ocean. Thus, this work focuses on trying to resolve and separate the optical signals of CDOM, chlorophyll (which represents algal biomass), and non-living particles in the coastal ocean and linking them to DOC concentrations in order to apply satellite observations to study coastal waters (Figures 4a and 4b). Measurements collected by satellites offers the capability to study the carbon cycle at much greater spatial and temporal scales than otherwise possible.

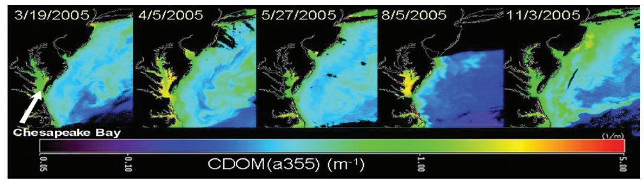

Figure 4a: Prototype satellite-derived CDOM absorption for the U.S. Mid-Atlantic coast from NASA's MODIS sensor on the Aqua satellite platform. Substantial changes in CDOM occur along the coastal ocean from spring to summer and summer to fall. CDOM absorption decreases from spring to summer, due to photochemical oxidation by sunlight. From summer to fall, storm events will vertically mix the water column and introduce CDOM from depth into surface waters.

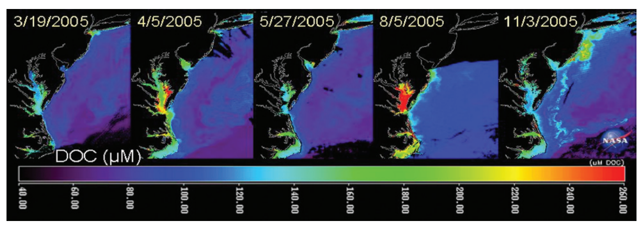

Figure 4b: Protoype DOC satellite image for the U.S. Mid-Atlantic coast from NASA's MODIS sensor on the Aqua satellite platform. The higher DOC concentrations along the coast are primarily due to land contributions of organic carbon to the ocean through rivers, bays and groundwater. The greatest seasonal change in DOC along the coastal ocean occurs from spring to summer. Much higher DOC concentrations are observed in summer compared to early spring due to direct and indirect release of DOC by marine organisms and accumulation of DOC resistant to bacterial degradation on the scale of weeks to months. A storm front that passed through the region on April 2 appears to have had a major impact on DOC between March 19 and April 5 from the influx of DOC from Chesapeake Bay into the nearby ocean.

Additional Reading

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Web Sites

http://www.usgcrp.gov/

The US Global Change Research Program Web site describes many ongoing scientific investigations of the Earth’s changing climate. This Web site also includes recent news releases.

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Glossary

Crustacean—any of a large class of mostly aquatic organisms that have an exoskeleton; examples lobsters, shrimps, crabs, wood lice, water fleas, and barnacles.

Detritus —dead material that is starting to disintegrate.

Inorganic—class of compounds not having a carbon basis; not from a living organism.

Microbial —caused by a microscopic organism, often bacteria.

Organic—class of compounds having a carbon basis; being or derived from a living organism.

Polymer—a naturally occurring or synthetic compound consisting of large molecules made up of a linked series of repeated simple units.

Terrigenous —produced on land.

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Discussion Questions

1. What problem does this article discuss?
2. Draw your own conclusions as to the solution(s) to this problem.
3. Design an experiment to support your solution(s).
4. What scientific laws may possibly be challenged as a result of the solution to this problem?
5. Why is it important to know the answer to this problem?