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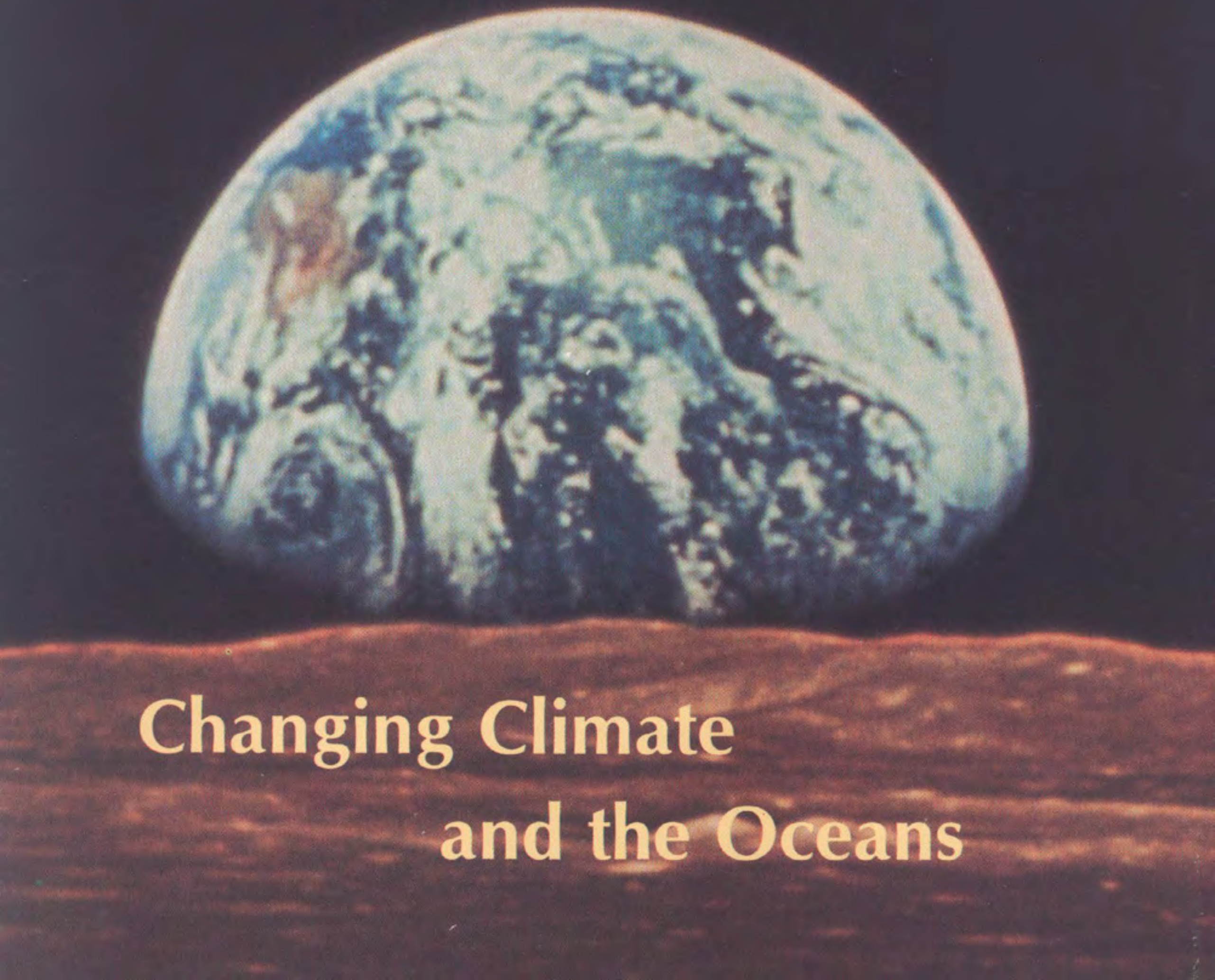


Changing Climate and the Oceans

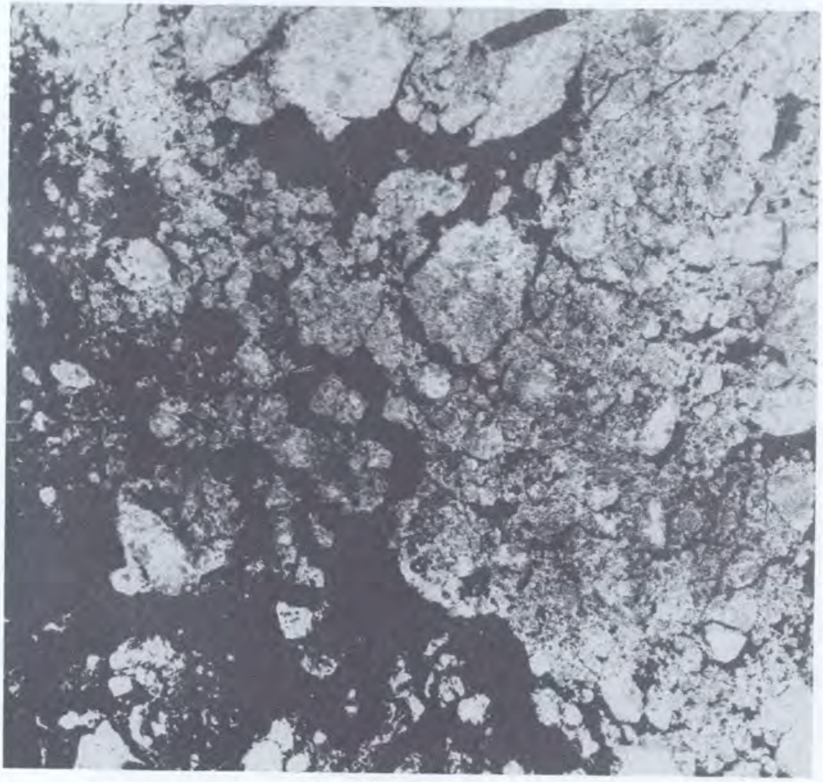
Global Ocean Flux

by James J. McCarthy, Peter G. Brewer, and Gene Feldman

The trend of increasing concentrations of carbon dioxide in the atmosphere, which is now firmly documented at several monitoring stations around the globe, builds on the data base initiated nearly 30 years ago at Mauna Loa, Hawaii, by Professor C. David Keeling of the Scripps Institution of Oceanography. Today, with help from the National Oceanic and Atmospheric Administration (NOAA) (see Figure 1, page 9, previous article), these data constitute one of the most important bodies of evidence linking the actions of humankind to global scale change in biogeochemical cycles.

At present only a few of the effects of this change are known; many are predicted. Climate models predict that the increasing concentrations of "greenhouse" gases in the Earth's atmosphere will result in a global warming by as much as 2 to 3 degrees Celsius in the next half century. There has been evidence, however, to indicate atmospheric warming since early in the 20th century, and recent analyses of long time series for ocean surface temperature indicate a trend of ocean warming during the last 120 years (Jones and others, 1986, *Nature* 322:430–34).

Change in responses to local shifts in weather and climate will probably influence agricultural productivity for some regions, yet the extent of this is, at present, impossible to predict. It is apparent that the largest changes in air temperature will be at high latitudes and the associated melting of polar ice predicted with climate models could raise sea level by about 1 meter. It should be noted, however, that melting of sea ice, such as that covering the Arctic Ocean, will have no direct effect on sea level, any more than melting ice will overflow a cocktail glass. It is the melting of ice accumulated on land, such as in Antarctica or Greenland that is at issue. Models used to predict such effects are becoming more refined through an improved understanding of the distribution of heat and momentum in the world's oceans.



The central Arctic Ocean is covered in summer by 8 million square kilometers (3 million square miles) of ice. But melting of this sea ice has no direct affect on sea level any more than melting ice cubes effect the level of liquid in a glass of scotch and soda. SAR image of Arctic pack-ice motion here obtained by NASA's Seasat satellite.

Marine Biogeochemical Exchange Processes

During the last few years, the role of marine biogeochemical processes in the long term natural cycle of change in atmospheric CO_2 content and its relationship to the periodic ice age cycles in climate has become more obvious. During the last ice age, about 18,000 years ago, the atmospheric CO_2 content was strongly lowered, with a rapid rebound at the end of the glacial cycle. We know that the ocean must have played a dominant role in forcing the atmosphere, but we do not understand exactly how. However, the manner in which this coupling between biogeochemical cycles and climate might be affected by anthropogenic alteration might provide an important research focus in oceanography.

It is no longer thought to be a simple coincidence that planet Earth, the "blue" planet, sometimes affectionately referred to as the "water-cooled" planet, has very different atmospheric composition from those of her sister planets. The great abundance of oxygen in the atmosphere of Earth (21 percent), which was a prerequisite to the evolution of animal life, and likewise the extremely low concentration of carbon dioxide (0.03 percent), are consequences of the photosynthetic activity by plants. In contrast, the atmospheres of Venus and Mars are nearly devoid of oxygen and contain 90 and 50 percent carbon dioxide, respectively. Water, even water vapor, is very scarce in the atmospheres of Venus (0.01 percent), and Mars (0.1 percent). A tempting scenario for the evolution of Earth's current atmosphere attributes not only the high levels of oxygen, but also the low levels of carbon dioxide to the great success of plants on our planet. It is obvious that it is not enough simply for plants to flourish. For each molecule of CO_2 removed from the air by growing plants one is put back on decay of the tissue. We only see a net draw down if we squirrel away some of the fixed carbon by burial, and thus prevent the backflow to the atmosphere. Nature has done this for millions of years. Modern man is now reversing the process in a century or two.

Plants on land and in the sea function similarly in their interaction with the atmosphere via the processes of photosynthesis and respiration. Animals and bacteria consume oxygen, and release carbon dioxide via the oxidation of assimilated organic material, originally synthesized by plants. These processes in the terrestrial system involve direct exchange between the organism and the atmosphere. In the marine system, and similarly in fresh water, the biologically mediated exchange is between the organisms and reservoirs of oxygen and carbon dioxide dissolved in water.

Exchange of these gases between the atmosphere and the hydrosphere is controlled by physical and chemical processes. Since photosynthetic activity in oceanic waters can only occur at depths shallower than about 100 meters, while respiration occurs all the way to the seafloor, ocean mixing is key among the physical processes responsible for the air/sea exchanges of biologically active gases. It is the mixing of deep water to the ocean surface that permits carbon dioxide

The Mauna Loa Observatory on the Island of Hawaii. Key data obtained over the years at this station by Professor C. David Keeling of the Scripps Institution of Oceanography on the rising level of carbon dioxide in the atmosphere have served as benchmark observations in the field of climate studies. (Photo courtesy of David Moss, Scripps Institution of Oceanography)

produced by respiration to escape and the oxygen depleted by this same process to be replenished. Within the terrestrial realm, the accumulation of carbon and depletion of oxygen occurs somewhat analogously in soils, but the long residence time of deep ocean waters and sediments results in much greater significance for the vast marine biogenic reservoirs in controlling the global carbon budget.

The atmosphere of Venus, above, is nearly devoid of oxygen, but is made up mainly of carbon dioxide (90 percent). (Photo courtesy of NASA)

Each species of plant has its own optimum set of conditions for growth and storage of carbon. The reverse process of decay is also regulated, with the time constants for the deep ocean being especially long. Thus, the accumulation of oxygen in the Earth's atmosphere partially reflects the different time constants for the processes of photosynthesis and oxidation of organic matter in terrestrial and marine ecosystems.

Differences in Land, Sea Carbon Cycles

Some of these key differences between the marine and terrestrial components of the carbon cycle are evident in Table 1. Whereas the biomass of terrestrial and marine organisms, which is predominantly plant material, differ by two orders of magnitude, the rates of photosynthetic activity or primary productivity for the two domains are rather similar. The values selected for these two rates are currently the subject of great debate, and many experts on this subject will argue that we know neither value to within a factor of two uncertainty.

Explanation for the fact that the two rates can be similar while the quantities of biomass are so different lies in the contrast between the allocation of carbon in tissues of terrestrial and marine plants. Terrestrial plants contain large quantities of cellulose as structural material to support leaves, stems, and roots. In marked contrast, the dominant marine plants, unicellular phytoplankton, allocate only minor quantities of carbon to cellulose-like structural components, investing the bulk of their carbon in proteins, simple sugars, and lipids. This relatively small investment in organic structural materials allows for fast specific growth rates, with doubling times as short as one or two days for many of the marine phytoplankton.

Many animals in the sea make shells of calcium carbonate, including those constructing vast coral reefs. However, only one group of phytoplankton, the coccolithophorids, use carbon

Table 1. Major carbon reservoirs and fluxes. (Units in gigatons of carbon, where 1 Gt = 1 billion metric tons)

RESERVOIRS	GT C
Atmosphere	700
Oceans:	
Total inorganic	35,000
Particulate organic	3
Land biota	600
Soil humus	3,000
Marine sediments (Organic)	10,000,000
(Calcium carbonate)	50,000,000
Fossil fuels	5,000
FLUXES	**GT C·YR^{-1}**
Atmosphere — marine biota	45
Atmosphere — land biota	70
Deposition in oceans	1–10
Fossil fuel combustion	5

dioxide dissolved in seawater to form calcium carbonate plates, known as coccoliths, that armor the cells' exterior (see page 13).

While the biological processes contributing directly or indirectly to the flux of carbon dioxide from the atmosphere to the biosphere give rise to a roughly equal partitioning of the organic product between the marine and terrestrial realms, its fate, once organically fixed, differs greatly between the two. The greatest contrast between analogous components of these systems is in the reservoirs of remains for dead plants and animals, which consist mostly of remnants of structural materials. Whereas the quantity of carbon stored in soils is large compared to the standing stock of plants on land, the ratio of masses for the analogous reservoirs in the ocean is, by comparison, absolutely enormous.

More than 99 percent of the carbon contained in the reservoirs influenced by biological processes now resides in marine sediments (Table 1, page 18). Although the calcium carbonate component of deep sea sediments is larger than the organic carbon component by a factor of five, even the ratio between the smaller of these two and the standing stock of ocean biota is immense relative to the analogous ratio for the terrestrial system. The rate at which carbon is now entering the deep ocean sediment reservoir, either as organisms or their calcium carbonate skeletons, is not known with great precision.

Interestingly, the effect of adding CO_2 from our atmosphere to the ocean is to make the naturally alkaline seawater very slightly more acidic. The effect is hard to measure, but can be predicted with some certainty. As this "CO_2-labelled" water sinks to the ocean floor in polar regions and becomes entrained in the deep ocean flows, it will eventually encounter a boundary where the calcium carbonate on the ocean floor is very sensitive to such chemical attack. The carbonate layers on the ocean floor will begin to dissolve. Since this signal will remain locked in the deep sea for hundreds of years, it is not an urgent human concern, but is a fascinating scientific phenomenon.

Compared with the total quantity of buried remains of organisms, the fossil fuel reservoir on which our modern industrial economy depends is a small subcomponent. It is, however, large compared to the reservoir of carbon dioxide in the atmosphere. The human acceleration of the rate at which fossil fuel carbon is burned and returned to the atmosphere is generally accepted as the major cause of the well-documented increase in atmospheric carbon dioxide content during the last century.

Only about half of all the CO_2 that has been produced by the burning of fossil fuels now remains in the atmosphere. The CO_2 "missing" from the atmosphere is the subject of an important debate—since the pathways and fates are at the heart of the questions about the damage man is doing to the environment. The great majority of the missing CO_2 has invaded the ocean, for this system naturally acts as a giant chemical regulator of the atmosphere. Those engaged in the debate over the details of this process—atmospheric, terrestrial, and ocean scientists—argue over whether the ocean has taken up 40 percent or 50 percent of the emitted CO_2. One vexing problem is that the changes are very hard to measure: we can calculate a theoretical result; we can provide "proof" by measuring tracers of carbon—and other chemicals also added to our world by man; but the challenge of producing a record of the changing ocean to match that of the atmosphere still lies ahead.

It is clear, however, that ocean processes have a major role in the regulation of the carbon dioxide content of the Earth's atmosphere. From analysis of gas bubbles trapped in ancient ice, it is apparent that the carbon dioxide concentration has varied by about a factor of two during the last few hundred thousand years, and that this cycle is highly correlated with the ice age cycle of the Quaternary Period (from 2 million to 10,000 years ago). To provide quantitative answers to questions relating to the ocean's role in the natural cycle of climate, and to know how ocean properties and processes might change in response to anthropogenic modification of this cycle, observations and models must focus on key aspects of the ocean's biogeochemistry. Much consideration has been given to this.

Marine Primary Productivity

A major uncertainty in global ocean data is the rate of photosynthetic activity, or primary production, for marine phytoplankton. Although these plants are capable of population doublings every few days, loss terms, such as grazing by zooplankton and sinking deeper than the sunlit layer, typically prevent the size of the plankton population from increasing perceptibly over this period.

Since it is usually not possible to determine the rates of production with time series measurements of population size, the alternatives are to measure either the rate at which carbon dioxide is consumed or the rate at which oxygen is produced. The former became possible with the introduction of the carbon-14 tracer technique in plankton production studies early in the 1950s, and its use in the following two decades permitted the first comprehensive global estimates of the rate for marine primary production (Figure 1). This general global view of marine primary productivity is probably reasonably correct, but we now believe that a more accurate representation is both needed and possible.

It is evident that the highest rates of production occur in regions that are periodically cooled and enriched by vertical mixing which brings nutrients from the deep ocean to the surface. There is an abundance of carbon dioxide dissolved in seawater, and except at very high latitudes, it is the availability of other nutrients, particularly nitrate and phosphate, that limits the rate of primary production in the sun-lit surface waters. High latitude phytoplankton can grow at temperatures close to the freezing point of seawater, and in polar regions, it is light that seasonally exerts the most effective control on production processes. At temperate latitudes,

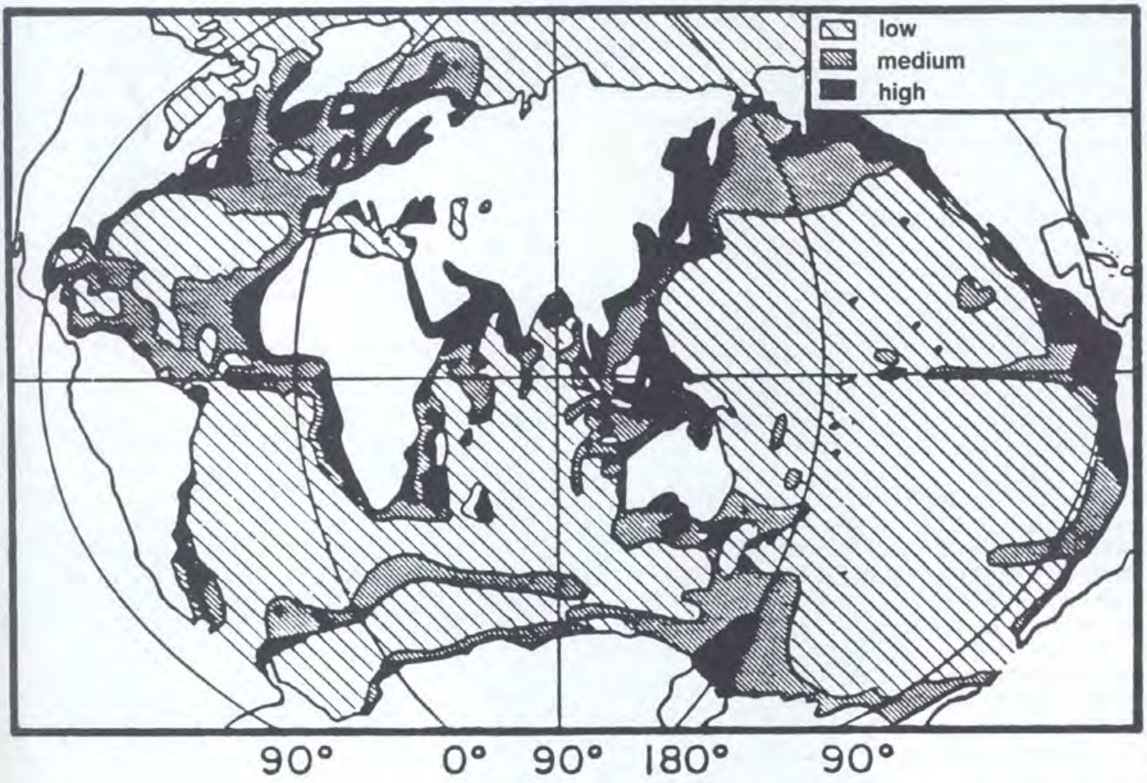


Figure 1. Distribution of primary plant production in the world ocean, average values per square meter of ocean surface per year. (From Broecker and Peng (1982), adapted from a map in Koblentz-Mishke and others, 1970)

primary production has an annual cycle, which is influenced both by light and by seasonal convection or storm-induced mixing of nutrients upward from depths of several tens to a few hundred meters.

The combined effects of winds and ocean currents result in pronounced upwelling of some eastern boundary currents, along the equator, and in the Southern Ocean, and this upwelling of nutrient rich water also stimulates plankton growth. In general then, both the seasonal mixing in temperate regions and the upwelling at particular localities over a wide range of latitudes are responsible for stimulating production and giving rise to a similarity in patterns for cool surface ocean temperatures and primary production. With time these upwelled waters warm, phytoplankton consume the nutrients, and, as the nutrients become depleted, the rates of primary production decline.

Techniques suitable for assessing rates of primary production from changes in oxygen concentration with high precision, and others for tracing the photosynthetic production of oxygen with isotopic techniques are available, but have yet to receive wide application. Indirect approaches involving oxygen have, however, had a significant impact on research related to plankton production. In some ocean regions, the oxygen produced by plankton can be trapped below the immediate warm surface waters for several months by a strong density gradient. The annual cycle is completed when strong winter-time mixing "ventilates" the water column to the depth of the main thermocline and permits accumulated oxygen to escape to the atmosphere. Estimates for rates of primary production necessary to create these seasonal surpluses of oxygen seem to be higher than those typically arising from studies using the carbon-14 tracer technique, forcing ocean scientists to struggle to balance their chemical budgets.

An independent assessment of the rate of primary production can be attained from the rate at which organic material sinks from the photosynthetic region, or euphotic zone, of the water column. Containers known as sediment traps can be suspended at fixed depths to collect sinking particles, which consist of intact phytoplankton cells and remains of plants and animals. These data can be used in conjunction with measurements of the respiratory consumption of organic matter within the waters shallower than the trap in order to estimate the rate of primary production.

Within the last few years, considerable progress has been made in reconciling disparate estimates of marine primary production. Notable among these are improved applications of the carbon-14 techniques, which now yield higher estimates of production than have been reported in the past. Moreover, investigators have begun to combine multiple approaches in studies addressing the rates of plankton production and consumption, and success with these has contributed to the consensus that oceanographers are now ready to address these issues on a global scale. However, the technology to accomplish this is not yet in place. The need, at this point in time, is for scientists to design and build sensors and instruments to measure these processes. It represents a difficult technical challenge.

While the highest rates of primary production occur in coastal regions, and these systems can be studied effectively with ships and moored arrays, the most challenging region is the oceanic province lying beyond the continental shelves. Although the brilliant blue waters of the open ocean are often thought to be relatively unproductive, on a per area and per year basis, their rates of primary production average about half those for coastal waters and about a third those for upwelling regions. In part, this is because the coastal regions have greater amplitude in the annual cycle of nutrient supply and primary production, giving rise to seasonal "plankton blooms." However, as a consequence of the great areal extent of the oceanic province, which amounts to 90 percent of the total ocean area, as much as 80 percent of the oceans' primary production occurs in these central ocean regions.

Details regarding both the spatial and temporal distribution of primary production in oceanic waters remain poorly known. Whereas global computations include substantial data sets for some regions of the Northern Hemisphere ocean basins, coverage for the more extensive oceanic regions of the Southern Hemisphere is very sparse. Moreover, data for a complete annual cycle are rare even for the northern regions. One notable demonstration of the seasonal variability in oceanic production is a three-year time series in the Sargasso Sea near the island of Bermuda (Figure 2). Although a brief and intense seasonal bloom is evident in these data, its magnitude is variable over the period of the study.

Such plankton blooms, whether in coastal or oceanic regions take on particular significance in the study of marine biogeochemical cycles. These represent periods when plants are produced at rates in excess of herbivores' ability to graze. In the last decade, it has become evident that the flux of biogenic particles to the deep sea is also highly seasonal. This confirmed the supposition that seasonal blooms in the open ocean, although poorly documented, are common and that these blooms are important in terms of export of biogenic particles, including associated skeletal materials to the deep sea. The study of plankton blooms is hindered by their ephemeral nature—they can peak and dissipate in a few weeks time—and by the near impossibility for ship-bound oceanographers to sample synoptically for other than very small regions.

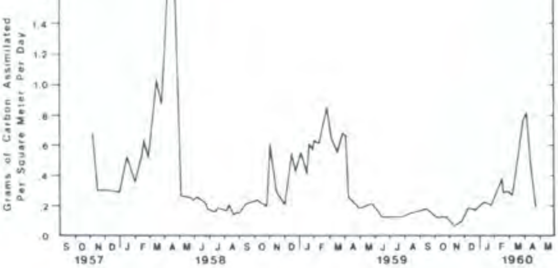


Figure 2. Gross primary production at Station 'S' in the Sargasso Sea off Bermuda (After Menzel and Ryther, 1961)

The Role for Satellites

This temporal and spatial variability is a regular feature of marine ecosystems and occurs over a broad spectrum of time and space scales. To span the range from kilometer scale to global features, and from the short-term, ephemeral events to the interannual, global climate and circulation driven changes in the ocean biota, is the role of satellite remote sensing. Whereas local studies are essential for refining our understanding of certain critical physical/chemical/biological processes, satellite observations provide the best opportunity for extrapolating these local observations to regional, basin, or global scales.

For a study of the biogeochemistry of the oceans from space, the changes in ocean color that can be detected by a sensor such as the Coastal Zone Color Scanner (CZCS) have been shown to provide a quantitative measure of near-surface phytoplankton pigment concentrations. These concentrations, which for remote sensing applications represent the sum of chlorophyll-*a* and phaeophytin-*a*, are an index of phytoplankton biomass and may be empirically related to primary production. In addition to providing information about the distribution and abundances of phytoplankton, one of the most important features of these measurements lies in their role as a link between the major physical and chemical processes that take place in the ocean and the first step in the system of biological production. As stated in the National Research Council report entitled "A Strategy for Earth Science from Space in the 1980s and 1990s," the first priority is to measure the concentration of chlorophyll-a in the world's oceans.

This is also the priority of a CZCS processing effort being undertaken at NASA's Goddard Space Flight Center. The major objective of this program is to produce global scale maps of the time and space distribution of phytoplankton biomass and primary productivity in the world's oceans. To do this, approximately 65,000 individual 2-minute CZCS scenes, each covering an area roughly 1,500 by 800 kilometers, which were acquired between November 1978 and June 1986, will be processed over the next few years. This global data set will allow us to begin to address more effectively questions concerning the interrelationships among climate, the oceans, and their biology.

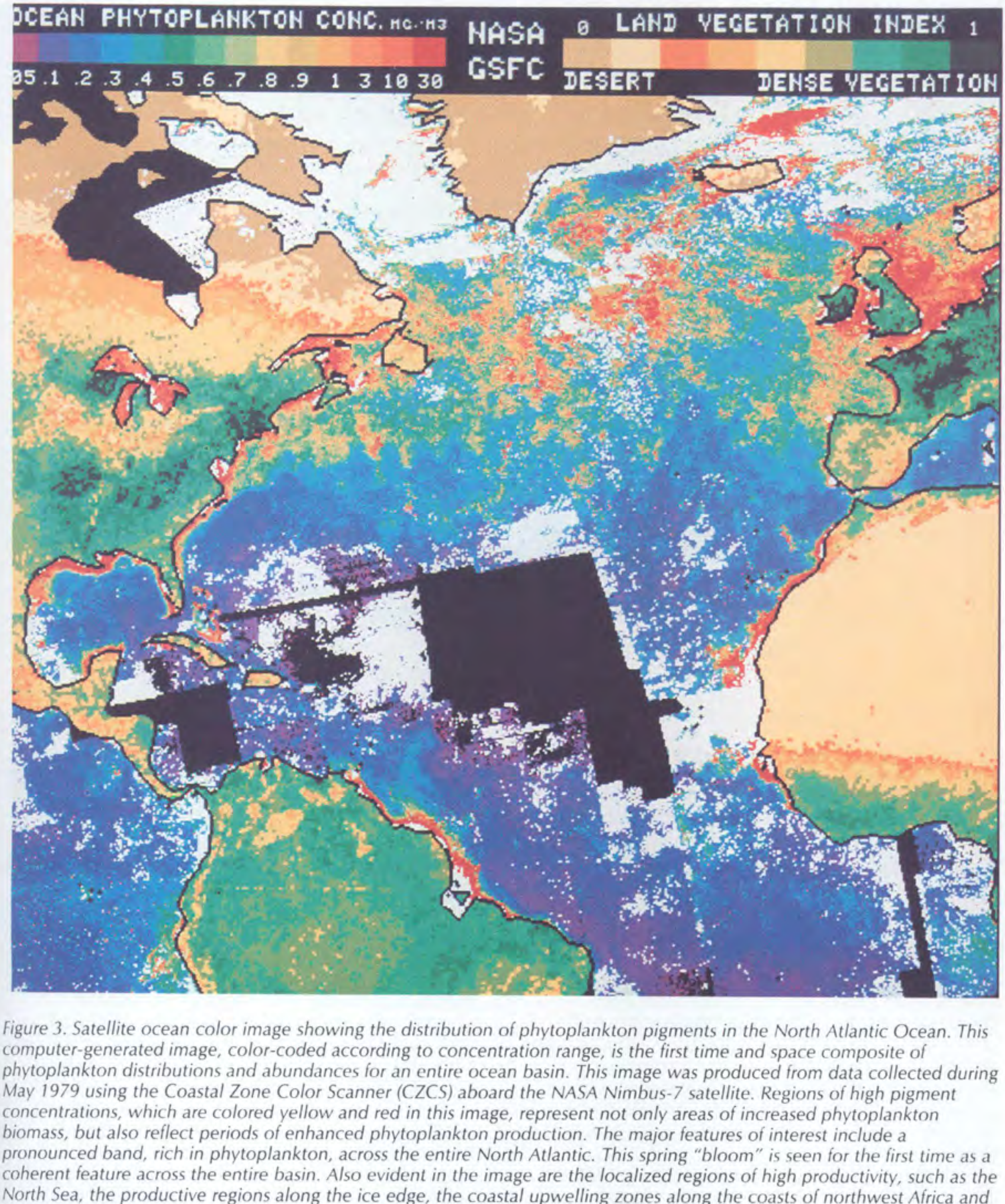


Figure 3. Satellite ocean color image showing the distribution of phytoplankton pigments in the North Atlantic Ocean. This computer-generated image, color-coded according to concentration range, is the first time and space composite of phytoplankton distributions and abundances for an entire ocean basin. This image was produced from data collected during May 1979 using the Coastal Zone Color Scanner (CZCS) aboard the NASA Nimbus-7 satellite. Regions of high pigment concentrations, which are colored yellow and red in this image, represent not only areas of increased phytoplankton biomass, but also reflect periods of enhanced phytoplankton production. The major features of interest include a pronounced band, rich in phytoplankton, across the entire North Atlantic. This spring "bloom" is seen for the first time as a coherent feature across the entire basin. Also evident in the image are the localized regions of high productivity, such as the North Sea, the productive regions along the ice edge, the coastal upwelling zones along the coasts of northwest Africa and South America, and the outflows of the Amazon, Orinoco, and Mississippi Rivers. The number of days in the composite vary from 0 (black area) to 14. White indicates cloud cover.

Before the full-scale processing effort begins (January, 1987), a pilot system was established so that the procedures, methodologies, and products could be refined. This pilot system produced the first space/time composite of phytoplankton concentrations for an entire ocean basin (Figure 3).

The North Atlantic ocean basin was selected as the test case during May 1979 because of the density of CZCS coverage.

A total of 450 CZCS scenes were processed, and the resulting satellite-derived chlorophyll images were remapped into the predefined North Atlantic sampling grid (100W-10E Longitude, 80N-20S Latitude) to produce 31 individual daily

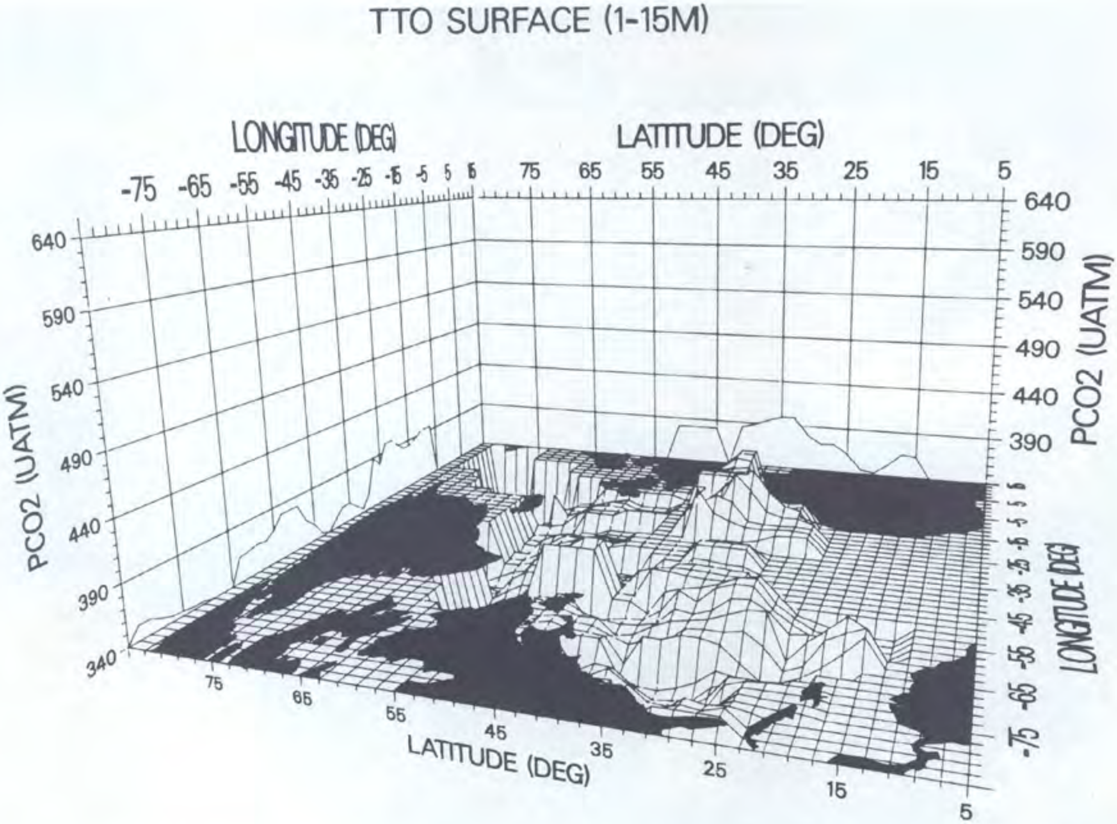


Figure 4. The partial pressure of CO_2 gas in surface seawater expressed as a departure from atmospheric equilibrium. Units are parts per million in volume terms, expressed as microatmospheres. Negative values, or "holes" imply a CO_2 flux from the atmosphere to the ocean, and "peaks" imply a CO_2 flux from the ocean to the atmosphere. (Courtesy Dr. Peter Brewer, WHOI)

mosaics, which showed the CZCS coverage for each particular day. These mosaics were then composited over weekly and monthly time scales.

Each picture element (pixel) in the composited images represents the average chlorophyll concentration within a 24 × 24 kilometer area of ocean surface. The number of pigment retrievals at each sampling point varied, with the densest sampling along the coastal margins and the fewest number of points in the open ocean. In fact, the large black region in the center of the monthly composite shows that no CZCS data were collected at all over this area during May 1979.

Although significant mesoscale variability was observed over short time scales (daily to weekly), monthly CZCS composites appear to retain the major mesoscale structures and dominant features of the region and will be the best means for quantifying the large-scale, interannual variability in global ocean primary production.

Global Ocean Flux Study

In the last two years, groups of oceanographers from several countries have begun to define a program known as the Global Ocean Flux Study. Its primary aim is to observe and understand the biogeochemical cycles of the ocean sufficently well to predict the interaction between the oceanic, atmospheric, and sedimentary cycle for carbon and associated elements, such as nitrogen, oxygen, and sulfur. It is envisioned that this program will be phased with other major ocean programs that are scheduled for early in the 1990s as part of the new National Science Foundation focus in Global Geosciences.

For one example of the value of such a program, we refer the reader to Figure 1, page 9, of the Moore and Bolin article showing the atmospheric CO_2 record. Carbon dioxide in the atmosphere has no active chemistry; that is, it is not created or destroyed by any chemical reactions whatsoever. It is simply mixed around the globe by winds. The peaks and valleys in this record result from the atmosphere being fed by waves of CO_2 put into, and pulled out of, the air by land and sea. The land fluxes are more rapid and produce the dominant short-term signals. The ocean fluxes are smaller (Figure 4), but have immense capacity. An ability to observe and predict these changing fluxes would be of enormous value to those who are concerned with global change.

A change in climate can be expected to alter the productivity and food chain relationships of the world's ocean. (Wilson North © 1985)

The key elements of the Global Flux Study are:

1). The use of satellite sensed ocean color data to estimate plankton distribution on the necessary space and time scales;

2) The correlation of this signal with direct observations of upper ocean chemistry and biology; and

3) Measurements of the rain rate of organisms and their remains to the ocean floor and its relationship to the sediment accumulation flux.

Essential complementary data on the physical template of ocean heating, cooling, mixing, and transport processes will be provided by programs like the World Ocean Circulation Experiment (WOCE), described in the box on page 25, and the Tropical Ocean Global Atmosphere Program (TOGA).

The translation of these observations into the first comprehensive global view of ocean primary productivity, carbon flux to the deep ocean, and other variables of critical importance to our understanding of the coupling of marine biogeochemical cycles and the physical climate system will involve a novel mix of measurements and models on the largest scale. A change in climate like that predicted for the next century in response to increasing atmospheric concentrations of CO_2 and other greenhouse gases can be expected to alter the upper ocean conditions that influence oceanic plankton blooms.

Because of the enhanced downward flux of particulate carbon associated with blooms, a change in bloom conditions can have feedback to climate. The time scale for this may, in general, be long, but recent models have shown a particular sensitivity in high latitude regions where this feedback may have global consequences on much shorter time scales.

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