Global ocean studies, the greenhouse effect, and climate change: Investigating interconnections

Scientists are using new tools and approaches to understand the importance of the ocean for the Earth's climate system

by K. Rozanski, S.W. Fowler, and E.M. Scott

The world ocean consists of 1.3 billion cubic kilometers of salty water covering 71% of the Earth's surface. This enormous body of water exerts a powerful influence on the global ecosystem. It supplies water for the hydrological cycle on the continents, acts as a global thermostat smoothing thermal gradients resulting from temporal and spatial variations of the incoming solar radiation, regulates atmospheric composition of some trace gases, and acts as a dumping site for many anthropogenic contaminants.

Climate fluctuations are commonly identified with changes in the atmosphere. However, one cannot examine the atmosphere alone. Processes in the atmosphere are strongly coupled to the land, to the oceans, and to the ice-covered parts of the Earth's surface (known as the cryosphere). There is also a strong coupling to the biosphere comprising the living systems on land and in the ocean. Atmosphere, land, ocean, cryosphere, and biosphere together form the basic structure of the climate system. *(See schematic, page 27.*

Understanding the climate system requires, among other things, a knowledge of how the ocean and the atmosphere exchange heat, water, and greenhouse gases. For instance, one has to understand what the major circulation patterns of the global ocean are; how rapidly the deep ocean interior responds to atmospheric changes; and what processes are responsible for the formation and decay of sea ice.

The concentrations of several major greenhouse gases in the atmosphere (carbon dioxide (CO_2), methane, nitrous oxide) have changed naturally on ice-age time scales, and have been increasing since pre-industrial times due to human activities. The ocean plays an important role in the rate of greenhouse warming. It does so by absorbing excess greenhouse gases from the atmosphere and some of the greenhouse-induced heat. Both processes tend to slow down the rate of greenhouse warming. Without the buffering effect of the ocean, the global ground-level temperature of the atmosphere would now be probably one to two degrees Celsius higher.

The question arises whether the ocean will continue to slow down this warming, and whether the rate of this influence will be reduced

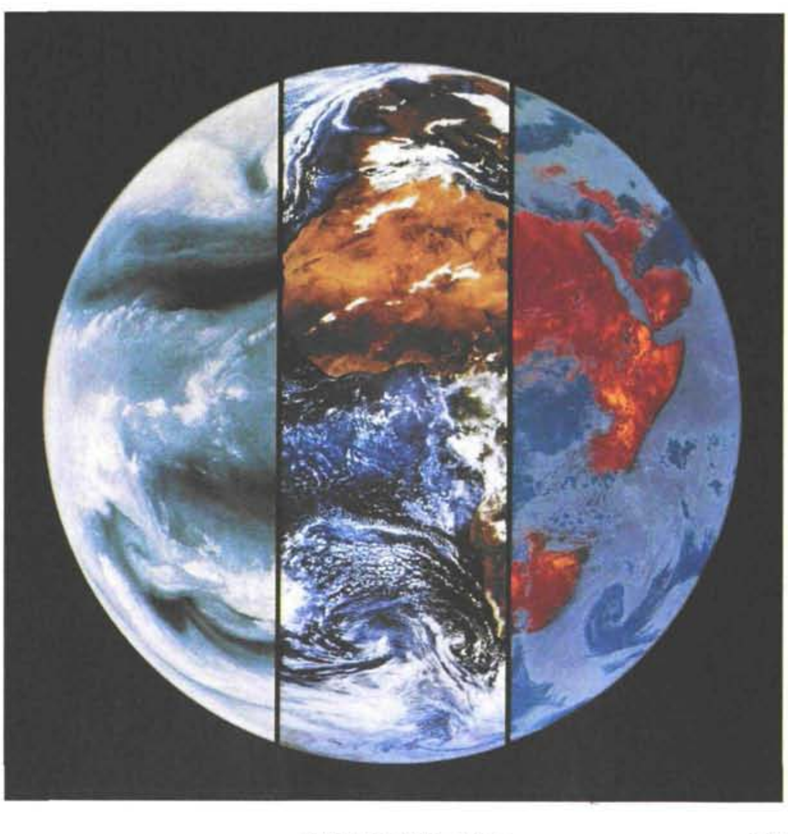

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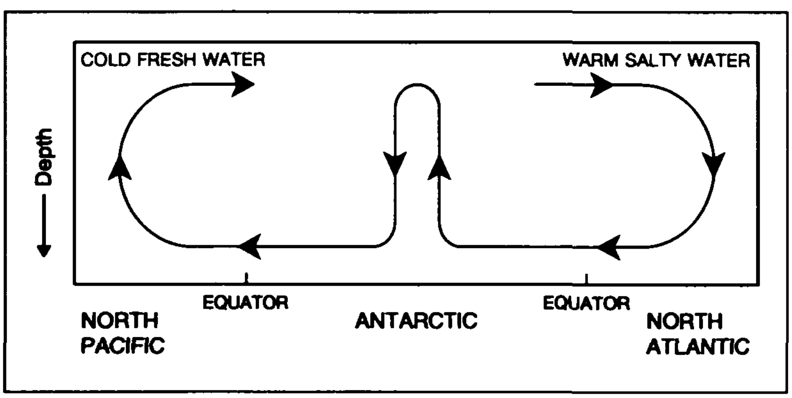
Photo credit: European Space Agency.

or accelerated as the process continues. These questions must be answered with real confidence before we can predict the full extent of global climate change. Therefore, a much better understanding is required with regard to (1) the gas exchange processes at the air-sea interface, with emphasis on CO_2, (2) the transport pathways of greenhouse gases from the surface to the deep layers of the ocean and to the sediments, and (3) the factors controlling ocean circulation.

The ocean in motion

Wind-driven, surface circulation of the ocean essentially moves heat and water on horizontal planes only. Much slower is thermohaline circulation: cooling and/or increased salt content induced by excessive evaporation on the sea surface from dense water, which sinks into the ocean's interior. This process, on the one hand, forces deeper layers of the ocean to interact with the atmosphere and, on the other hand, "opens" the enormous volume of the deep ocean to store heat and CO_2, among other properties.

This sinking of dense surface water presently occurs in a few restricted regions of the ocean. The deepest convection occurs in the northern North Atlantic (Norwegian and Greenland Seas) and around Antarctica (Weddell Sea). In the North Atlantic, the warm surface water, which has a long history of contact with the atmosphere, is cooled and dissolves more CO_2 before it sinks as relatively salty water into the deep ocean. In the Southern Hemisphere, upwelled deep water, having been cut-off from direct contact with the atmosphere for a relatively long time, is quickly converted to cold denser water with a high content of CO_2 and re-enters the deep and bottom layers of the ocean. These two water masses, each with their own characteristic properties, spread throughout the ocean and force a slow but steady upwelling of the "resident" deep ocean water.



A simplified representation of global ocean circulation, often referred to as a "conveyor belt".

This resident deep water is composed of older water that has been modified by vertical mixing processes, by organic material descending from the sea surface, and by contact with the seafloor sediments. Eventually, upwelled water migrates back to the sinking regions to complete a circulation loop often referred to as a "conveyor belt". *(See diagram.)*

The rate and mode of deep water formation in the North Atlantic and of oceanic heat transfer to high latitude continental areas are a function of the surface water circulation in the region. Excess salinity (with accompanying heat flux that depends on the rate of the surface water's flow into the Atlantic) creates strong oceanic fronts, defines the boundaries between ice-covered and open ocean areas, and heats the adjacent northern European region. The entire system has been shown to be highly unstable on decadal, historical, and geologic time scales. For instance, it is known from historical records that even minor perturbations of the sea-ice limit, and of the salinity, temperature, and volume of inflowing surface waters, can seriously affect the European climate, economy, and living conditions. This happened, for instance, between the 15th and 18th centuries during the so-called Little Ice Age.

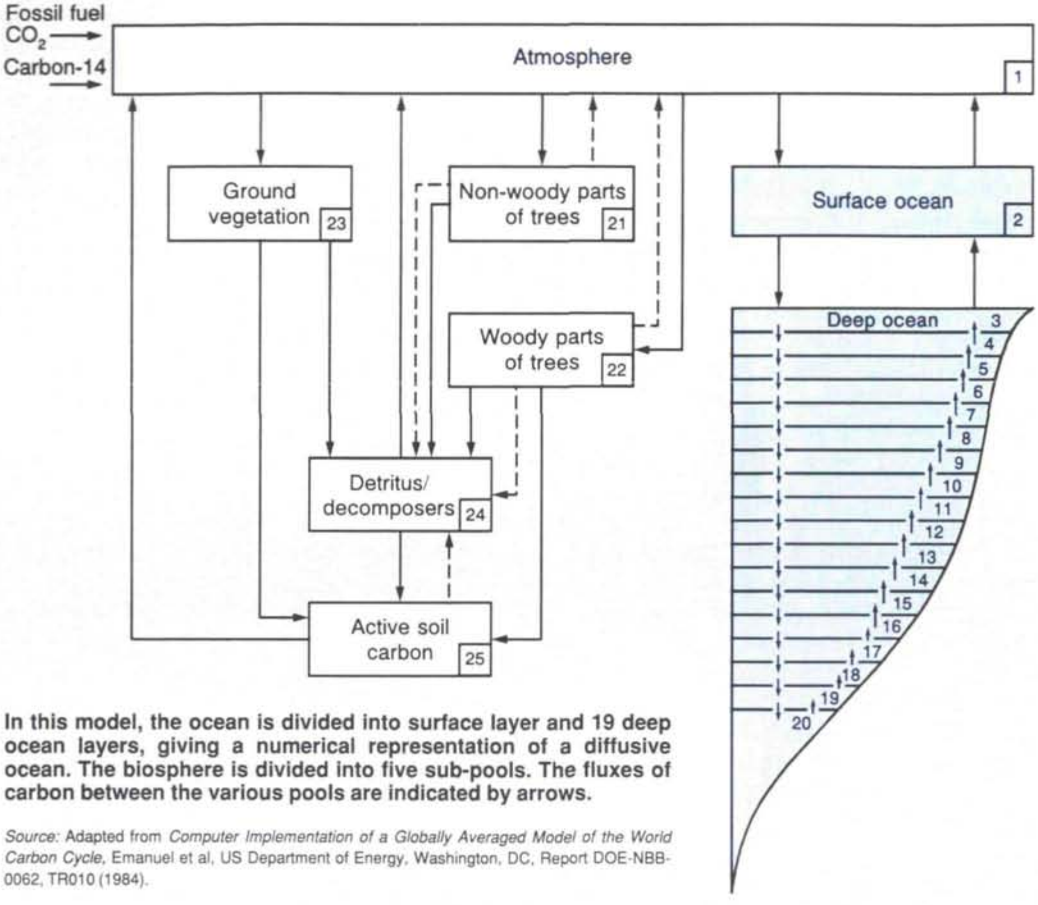
Modelling the ocean's dynamics

Our understanding of ocean dynamics and its role in the global carbon cycle is, in general, being increased through two related activities: mathematical modelling of the system and detailed experimental and observational studies.

Models and modelling projects contribute to our understanding by synthesizing knowledge gained from specialized bio-geochemical projects and by presenting a picture of the overall structure and patterns of interaction of the system under study. The carbon cycle is complex, and the processes to be incorporated in any model may have time scales varying over years to centuries. Thus, the synthesis of available knowledge is an important activity.

Any model, even the most complex one, always represents a simplification of the real world. It is an empirical description of the system and may only describe processes that are of importance for some particular space and time scales. The model results are subject to uncertainty due to the limited number of physical, chemical, and biological processes which can be included and because of the inadequacy with which the processes are treated, in particular our lack of quantitative knowledge concerning the rates with which the processes occur.

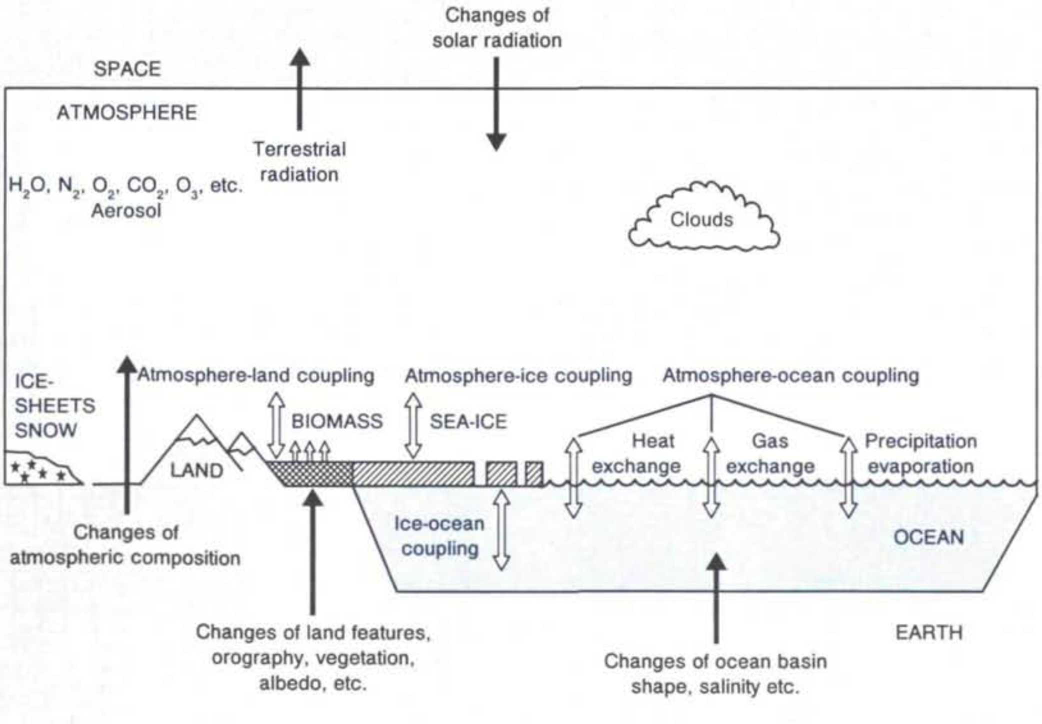
Model for evaluating global carbon cycle



In this model, the ocean is divided into surface layer and 19 deep ocean layers, giving a numerical representation of a diffusive ocean. The biosphere is divided into five sub-pools. The fluxes of carbon between the various pools are indicated by arrows.

Source: Adapted from *Computer Implementation of a Globally Averaged Model of the World Carbon Cycle*, Emanuel et al, US Department of Energy, Washington, DC, Report DOE-NBB-0062, TR010 (1984).

Structure and interactions of global climate system



The modelling process is linked to the experimental work through the need for data to calibrate and validate the model. The data requirements for each model are dependent on the processes incorporated and may range from ocean-wide observations to very specialized series of measurements at a limited number of locations.

With these reservations in mind, a hierarchy of models for the global carbon cycle can be developed. At the first and simplest level, only the most important processes, such as air-sea exchange, are considered. Generally such models take the form of box models, with the boxes representing specific carbon reservoirs. At the next level, one- or two-dimensional models are developed, describing selected, steady-state characteristics of the cycle. On top of the hierarchy are three-dimensional, time-dependent models. These provide the most realistic description of the structure and dynamics of the global carbon cycle. They are, however, still at a very early stage of development.

At the IAEA's Marine Environment Laboratory (IAEA-MEL) in Monaco, preliminary carbon cycle modelling work has been based on a number of box models of varying complexity. The carbon cycle is conceptualized as a series of interconnected pools. The four main pools are the atmosphere, the terrestrial biosphere, the hydrosphere, and the litosphere. Each of these in turn may be further sub-divided into constituent sub-pools. For instance, if we consider the hydrosphere, this comprises both fresh water and oceanic systems. However, as far as the carbon cycle is concerned, it is sufficient to focus on the ocean alone.

For modelling purposes, the ocean is commonly divided into functional layers: (1) the surface ocean, heated by the sun and agitated by the wind, (2) an intermediate region, and finally, (3) the deep ocean. In the surface layer, biological processes are most active and the timescale of processes is short, while in the deep ocean the rate of change is much slower. *(See diagram, page 27.)* Given a conceptual model, the next step is to quantify the large number of parameters which the model requires, specifically the exchange rates between the various pools. A commonly used approach is to consider the distribution of a tracer substance in the ocean and how it has changed over time.

Isotopes as tracers in ocean studies

Both anthropogenic and naturally produced radioisotopes constitute the most powerful tools available for studying the dynamics of ocean circulation on different time scales. Through a knowledge of the patterns and time histories of the input of these radioisotopes to the sea surface and a knowledge of the evolution of their distributions within the sea, one can gain better insight into the rates of deep water formation and its distribution in the deep ocean, the rates of vertical mixing in the upwelling zones, and the patterns and rates of circulation of water in the ocean's interior.

Among the most widely applied radioisotopes are tritium and carbon-14. Tritium, which was produced from past nuclear weapons testing, is part of a water molecule and thus constitutes an ideal tracer of water movement. Its relatively short half-life (12.4 years) makes it especially useful to investigate oceanic processes with characteristic time scales on the order of a few. decades. Radiocarbon has a half-life of 5730 years and is produced by cosmic-ray interactions in the upper atmosphere. It enters the ocean by molecular diffusion of carbon-14 dioxide through the stagnant boundary layer at the sea surface and is incorporated in the carbon cycle of the ocean. Its half-life is long enough to investigate processes with time scales on the order of 1000 to 10 000 years, comparable with the average residence time of water in the entire ocean (approximately 1000 years). However, radiocarbon also has been produced as a result of nuclear weapons testing in the 1950s and 1960s and more recently as a result of nuclear power generation and fuel reprocessing. This anthropogenic carbon signal which first appeared in the atmosphere is a key to the study of various aspects of the global carbon cycle.

Scientists at IAEA-MEL, in collaboration with other groups, have been involved in using this anthropogenic tracer to study ocean biogeochemical pools and exchanges between particulate and dissolved organic and inorganic carbon. This very detailed work requires use of new techniques for the characterization of organic carbon and state-of-the-art measurement techniques, such as accelerator mass spectrometry (AMS), appropriate to the measurement of radiocarbon in very small samples.

Recently, two radioisotopes of noble gases were used to investigate the dynamics of ocean circulation. Krypton-85, produced in nuclear reactors and released to the atmosphere during reprocessing of nuclear fuel, has a similar half-life to tritium (10.7 years). Its history in the atmosphere is well known. Krypton-85 is considered an attractive potential tracer replacing bomb-produced tritium, which has already been transferred to the ocean from the atmosphere via precipitation and molecular exchange. The second radioisotope, argon-39, has only natural sources (cosmic-ray production in the atmosphere). It is a useful tracer for oceanographic studies because it is chemically inert and because its half-life (269 years) lies between those of tritium, krypton-85, and carbon-14. The main disadvantage of these two tracers is the relatively complex analytical procedure necessary to determine their activities in the ocean water.

The use of radioactive tracers such as radiocarbon provides important new data in understanding the bio-geochemical processing of carbon in the oceans. Moreover, it ensures that new models which may be developed have the data required for calibration and validation.

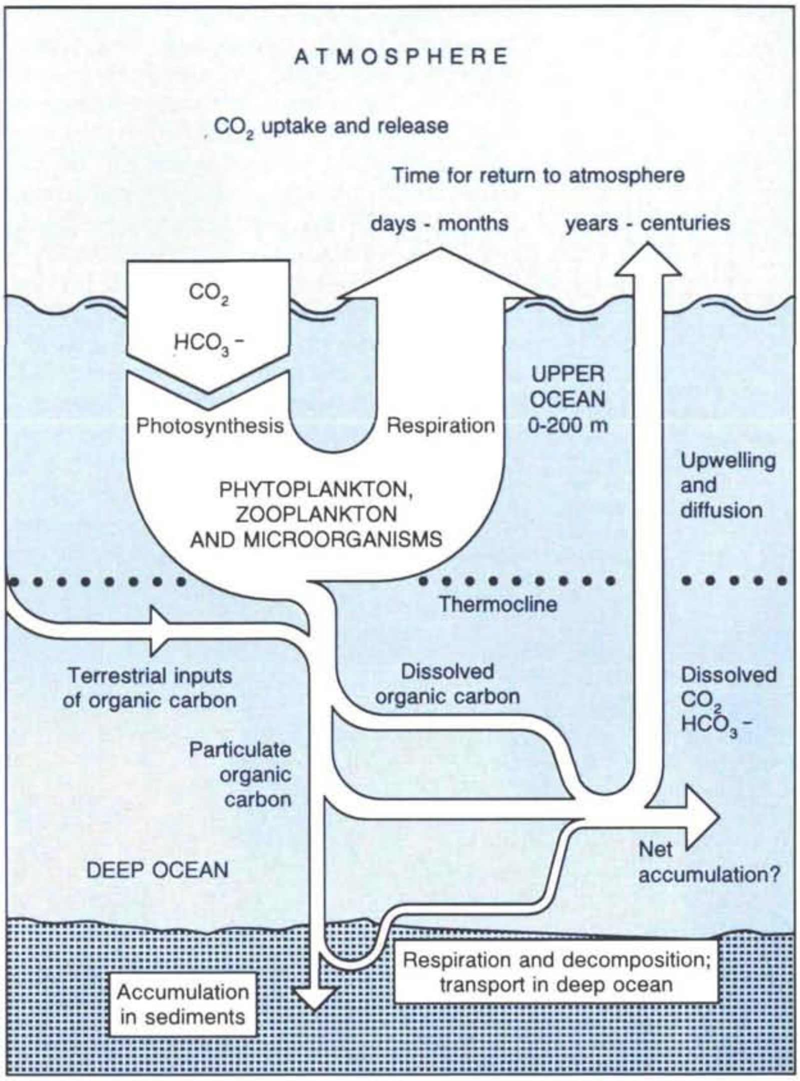
Carbon cycle in the ocean

Of the estimated input of CO_2 due to fossil-fuel burning and changing land use, less than 60% is now present in the atmosphere. The ocean is believed to be taking up much of the remainder, at a rate of about 2 gigatons per year (one gigaton of CO_2 equals 10^{15} grams of carbon). Because the ocean stores approximately 50 times more carbon than is present in the atmosphere, a relatively small change in the oceanic carbon cycle — in response to climate change and/or changes in oceanic circulation — may induce large changes in atmospheric CO_2 concentration.

For instance, it has been estimated that the uptake of anthropogenic CO_2 from the atmosphere by a completely stagnant ocean would be reduced fourfold compared to the present value. Enhanced circulation, on the other hand, would increase absorption of all current anthropogenic CO_2 emissions to nearly 90%. This is, however, only a rough estimate and in fact little is known about how the capacity of the ocean to absorb CO_2 is regulated on different time scales.

These problems are presently being addressed by the Joint Global Ocean Flux Study (JGOFS), one of the established core projects of the International Geosphere-Biosphere Programme (IGBP). The project focuses on CO_2 dynamics, and the oceanic carbon cycle and its sensitivity to environmental changes.

Carbon cycling within the ocean is governed by a set of reversible oxidation-reduction reactions between dissolved CO_2 and organic matter in which marine organisms are the principal catalysts. Biogenic carbon (organic and carbonate particles) is produced in the upper 100 meters or so (termed the "euphotic zone") by the sun-driven process of photosynthesis. These small biogenic particles created by the process of "primary production" enter the food chain. The result is that carbon is either incorporated into organisms as growth; metabolically respired as CO_2; or transformed into organic detritus which is exported from the surface layers via gravitational sinking. This continuous downward rain of biogenic particles, the so-called "biological pump", is the main component of all marine biogeochemical cycling studies focused on global environmental change. *(See figure.)*

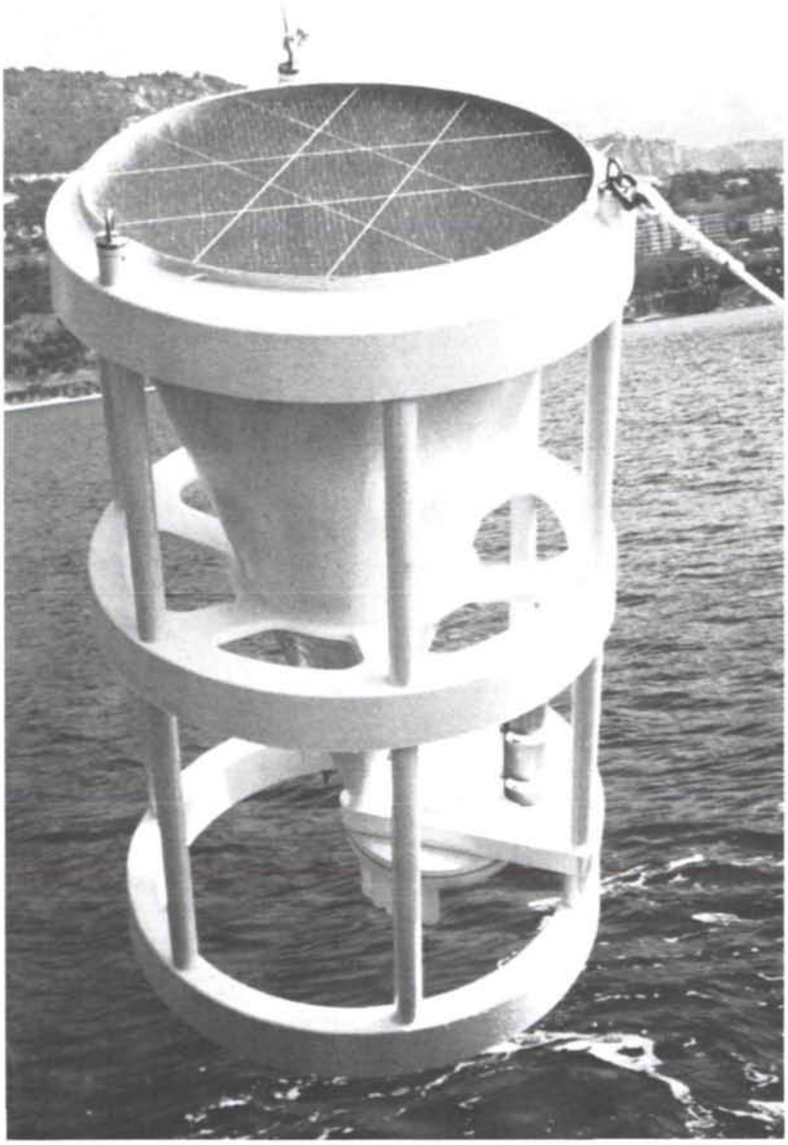


Main elements of the ocean's "biological pump"

Recent evaluations suggest that the oceanic biological pump can export approximately 7.4 gigatons of particulate organic carbon (POC) per year from the euphotic zone. This value is roughly 15% of global primary production estimates and approximately equivalent to the annual input of CO_2 to the atmosphere by combustion of fossil fuels.

As the biogenic detritial particles sink slowly through the deeper waters, more than 90% of the exported organic carbon is recycled to dissolved inorganic carbon through combined activities of bacteria, animal ingestion, and mechanical remineralization. Thus, normally less than 1% of the organic carbon produced in the euphotic zone ever enters the deep ocean and only a small fraction of that is permanently incorporated in deep sea sediments. Despite the overriding importance of the biological pump and its associated recycling pathways in the global carbon cycle, relatively little is known about the structure, mechanisms, and rates of these processes.

In recent years sediment traps — which can be viewed as marine particle "rain gauges" — have been increasingly used by oceanographers to quantify the downward flux of carbon and other elements associated with sinking particulate matter. Despite several problems inherent in their use in moving water bodies like the ocean, sediment traps remain the only available tool for directly measuring in a fairly accurate way the downward flux of marine particles.



Serving as a "rain gauge" of marine particles, an automated time-series sediment trap is used by the IAEA's Marine Environmental Laboratory.

Since 1987 the IAEA-MEL has been collaborating with French scientists by deploying sediment traps beneath the euphotic zone in the northwestern Mediterranean (Ligurian Sea). The aim is to follow the interannual variation in carbon removal from the ocean surface layers in this region. Preliminary results suggest that export of particulate carbon from ocean surface waters cannot be viewed simply as a slow, uniform sedimentation process; rather it occurs as "pulses" of particles linked to biological productivity patterns in the overlying waters.

Scientists are interested in the downward flux of organic carbon from the euphotic zone since it is believed to be proportional to "new production". In its simplest terms, this is defined as the fraction of primary production derived from external sources of nitrogen brought in from outside the euphotic zone, under the assumption that over the long-term, the export of nitrogen and carbon must be balanced by the quantities imported into the euphotic zone. Therefore, if new production can be considered proportional to carbon exported from the euphotic zone, then removal of CO_2 from the surface to deep ocean can be calculated. Because of the important ramifications of the new production concept, scientists have been searching for other ways to estimate rates of this process.

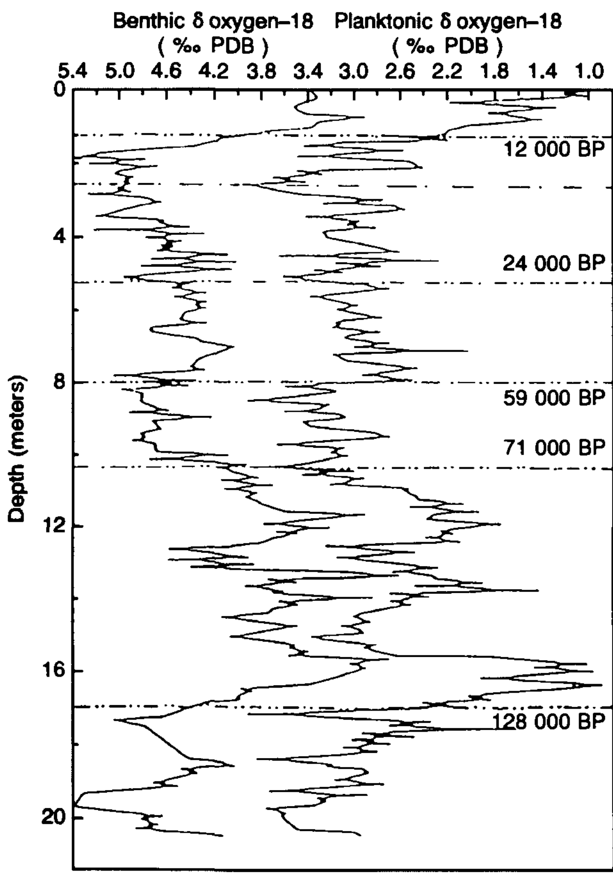
One such method receiving wide attention involves the use of the natural radionuclide thorium-234 as an appropriate tracer for quantifying particle formation and export rates in surface waters. Thorium-234, unlike its soluble parent uranium-238, is particle reactive and, owing to its relatively short half-life (24.1 days), can be used to delineate biogeochemical processes which operate on time scales of days to a few months. Recent studies have found that, because of its strong association with biogenic particles, there is an inverse relationship between the residence time of dissolved thorium-234 in sea water and the rate of primary production. If the particles to which thorium adsorbs are biogenic, then thorium-234 coupled with particulate carbon data could be used to estimate carbon export or new production. In most of the open ocean regions, the majority of the suspended particles are biogenic; thus the thorium-234 technique has great potential for use particularly in these areas.

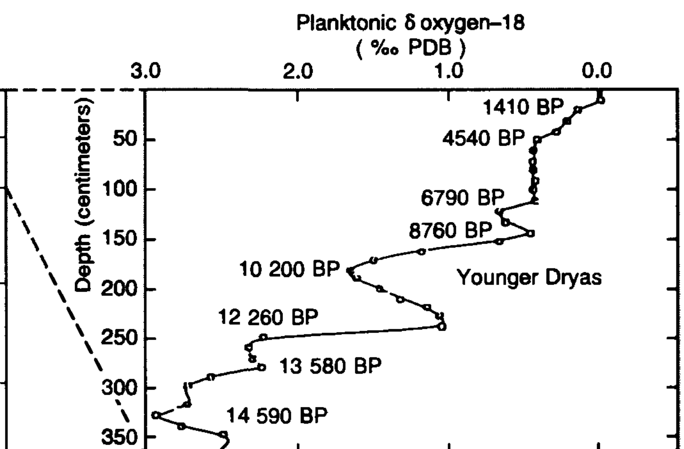
In the collaborative study in the Ligurian Sea, IAEA-MEL has begun examining the relationship between the flux of particulate thorium-234 and that of carbon. Results so far suggest that an overall coupling between particulate thorium-234 flux and carbon export from the euphotic zone exists, although some significant variations, particularly in the thorium-234/carbon ratio, tend to blur the correlation. Work is under way to clarify the origin of these variations.

Another approach to quantify uptake of anthropogenic CO_2 by the ocean is based on estimates of the net global CO_2 flux across the air-sea interface. To calculate this flux one has to properly assess mean global values of two variables: (2) the difference of the partial pressure of CO_2 between the surface ocean and the atmosphere, and (2) the gas transfer coefficient for CO_2. Since both parameters vary strongly with the season and the region of the ocean, this method is plagued by a rather large uncertainty of the estimated CO_2 uptake. Radioisotopes, mainly bomb-produced carbon-14 and natural radon-222, were used to derive the gas transfer coefficient for CO_2. Research is being done to obtain better coverage of large regions of the ocean and to elaborate ways of monitoring of the variables via remote sensing.

Still another way to quantify the present role of the ocean in the global carbon cycle is to model the observed spatial and temporal variations of CO_2 concentration in the Earth's atmosphere. Typically, three-dimensional transport models are used to simulate the global distribution of CO_2 in response to specific assumptions about the strength and location of surface fluxes of CO_2, including oceanic regions. The atmosphere integrates the fluxes from all sources and sinks. Thus, it contains the large-scale signatures of CO_2 source and sink areas that are highly variable, and therefore difficult to measure on smaller scales.

Data from the present international network of CO_2 monitoring stations, located almost exclusively in oceanic areas, cannot be used to resolve longitudinal gradients of CO_2 concentration. Consequently, the identification of the important source/sink areas with sufficient accuracy using this approach is still difficult. Because carbon-13/carbon-12 isotope ratios of CO_2 being released by the ocean and the terrestrial biosphere differ considerably, it is hoped that high-precision measurements of its large-scale variations will help in quantifying the contribution of the land and the ocean in the global carbon balance. The IAEA is actively involved in this field of research through a co-ordinated research programme on "Isotope Variations of Carbon Dioxide and Other Trace Gases in the Atmosphere". The programme focuses on





At left: An example of oxygen-18 variations in foraminifera shells extracted from the deep-sea sediment core off New Zealand's South Island. Shown are the variations covering the last glacial/interglacial cycle. ***Above:*** An example of high-resolution analysis of oceanic sediment cores. Shown are variations of oxygen-18 in planktonic foraminifera during the last 15 000 years, extracted from sediment core off the coast of Portugal. The Younger Dryas cold phase is clearly seen in the profile. A technique known as accelerator mass spectrometry, when applied to radiocarbon dating, makes possible the establishment of a high-resolution chronology such as the one presented here.

Notes: Ages indicated in the graph are defined as conventional radiocarbon ages (BP means Before Present, defined as 1950). Variations are given as per mille deviations from the standard (which is PDB for oxygen-18 in carbonates and V-SMOW for oxygen-18 in water). *Sources:* Adaped from *Geochimica et Cosmochimica Acta*, 53, W.S. Broecker and G.H. Denton, (1989); and *Nature*, 342, R.G. Fairbanks (1989).

providing high-quality, intercomparable time series of isotopic composition of atmospheric trace gases in carefully selected locations.

Global environmental archive

The oceanic record of the past global changes constitutes the backdrop against which human modifications of the state of the Earth can be evaluated. It is essential to distinguish between human impact and natural variation, the latter being deduced from the record of a broad spectrum of time scales. Of all records bearing on the history of the oceanic and atmospheric climate, the ocean record is the most continuous one available. It is also rich in information about key elements of the chemical and biological interactions in the system.

Because the ocean system is so large, the oceanic record carries a strong global signal. It informs us also about such regional events as the El Niño-Southern Oscillation (ENSO) or ice front movements. In marginal seas and along the edges of continents, it documents continental events — for instance, changes in aridity or the input of riverborne particulate and dissolved matter into the oceans.

The oceanic record can be considered on three time scales. On a long time scale of 10 000 to 100 000 years, the oceanic sediments preserve the signature of major changes of climate, i.e. glacial-interglacial cycles driven mainly by the cyclic variations of the orbital parameters of the Earth system originally postulated by Milankovitch. On an intermediate time scale of 1000 to 10 000 years, aperiodic events of significant amplitude but with shorter duration — such as the Younger Dryas cold phase in Europe or the Little Ice Age — are superimposed on the Milankovitch cycles. Finally, on a short time scale of 10 to 1000 years — which is accessible mainly in sediments deposited in coastal regions and via analysis of reef corals — one can address the nature and frequency of the occurrence of rare events such as major floods, periods of regional drought, or volcanic eruptions. It is also the time scale characteristic for major human interferences in the global environment.

An extensive and well-established methodology exists today to collect sediment samples and to analyze many of the properties that provide a wide range of palaeoceanographic proxies. The isotope techniques, based on stable and radioactive isotopes, have proved to be most useful in this respect.

The oxygen-18/oxygen-16 ratio of the carbonate shells of marine protozoans called foraminifera, which are present in marine sediments, is a function of the oxygen-18/oxygen-16 ratio of sea water and of its temperature. These two factors act in the same direction during the glacial/interglacial climatic fluctuations, enhancing the isotopic variations preserved in the calcium carbonate formed. *(See graphs.)* Whereas the oxygen-18/oxygen-16 ratio obtained from deep-water benthic foraminifers primarily measures isotope changes of sea water controlled by changes of global ice volume (growth and retreat of continental ice sheets), the oxygen-18/oxygen-16 ratio of planktonic species of foraminifera living close to the sea surface mainly responds to changes of the temperature of the surface ocean.

Radioactive isotopes present in the marine environment provide a unique opportunity to establish the proper time scale for past climatic events preserved in oceanic sediments. Among the most widely used are radiocarbon, the uranium series disequilibrium, and potassium-argon methods. With the onset of accelerator mass spectrometry and more recently thermal ionization mass spectrometry applied to radiocarbon and uranium series dating, respectively, it has been possible to establish a detailed chronology of the last glacial/interglacial climatic cycle.

Future directions

At the present time, the principal motivation for research on global change is public concern about anthropogenic environmental change (particularly climatic change) during the next century. The postulated global warming induced by excessive emissions of greenhouse gases may have serious socio-economic consequences for the entire human population. There are good reasons to believe that the anticipated changes of global and/or regional climate may proceed relatively fast, leaving little room to undertake effective countermeasures or to launch proper adaptation programmes.

There is no doubt that the global ocean is a key element of the Earth's ecosystem. Paradoxically, so far it is also the least known one. Concentrated, international effort is therefore needed to investigate different aspects of this vast, extremely complex system and its role in controlling the climate. Among the most urgent tasks is an advancement of our understanding of the varying rates of uptake and release of CO_2 by the ocean under changing environmental conditions. The isotope techniques based on both stable and radioactive isotopes have an important role to play in this ambitious endeavour. ❐