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Chapter 12

Ocean Biogeochemistry: A Sea of Change

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12.1 Introduction

A comprehensive understanding of the global carbon cycle is required to address contemporary scientific issues related to the atmospheric accumulation of greenhouse gases and their cumulative effects on global environmental change. Consequently, detailed *in situ* investigations of terrestrial and marine ecosystems are necessary prerequisites for developing a predictive capability for environmental variability and the effects of human-induced perturbations. These investigations need to address the interdisciplinary connections between physics, chemistry and biology, and in each ecosystem, address broad questions regarding the distribution, abundance, diversity, and control of key plant, animal and microbe populations and their interactions with their habitats. Ideally, these field studies should be conducted at strategic sites that are representative of large biomes or in regions that are likely to exhibit substantial interannual variability over large areas. Furthermore, these field investigations should be conducted for at least several decades, in order to distinguish natural variability from that induced by human activities.

In spite of their recognised importance, systematic, long-term biogeochemical observations of oceanic habitats are rare. In response to a growing awareness of the ocean's role in climate and global change research, and the need for comprehensive oceanic time-series measurements, the International Geosphere-Biosphere Programme (IGBP) was established in 1986. One of the essential core components of IGBP, the Joint Global Ocean Flux Study (JGOFS) project, was established in 1987 to improve our understanding of the oceanic carbon cycle and to quantify the exchange of carbon with the atmosphere, the seafloor and the continental boundaries.

One of the enduring legacies of JGOFS will be the long-term time-series stations that were established during the programme and that will continue into this millennium. These stations fulfil a crucial goal within JGOFS. They study the changes in the ocean carbon and nutrient cycles on interannual and, soon, decadal time scales. Each year, nature presents a unique set of physical forcings and biological initial conditions. Each year, the oceans respond in a unique way. By studying the variations between years, we gain a greater understanding of how these ecosystems function. By using natural variability as our guide, we can gain insight into the relationship between biogeochemistry and climate, an insight that will prove invaluable as we try to predict the future fate of the carbon cycle and the climate.

12.2 The Oceanic Carbon Cycle

The large and dynamic oceanic reservoir of carbon, approximately 4×10^{19} g distributed unequally among dissolved and particulate constituents with various redox states (reduction-oxidation), plays an important role in global biogeochemical cycles. The two largest pools are dissolved inorganic carbon and the less oxidised pool of mostly uncharacterised dissolved organic carbon. A chemical disequilibrium between DIC and organic matter is produced and maintained by numerous biological processes. The reversible, usually biologically-mediated interconversions between dissolved and particulate carbon pools in the sea collectively define the oceanic carbon cycle.

Primary conversion of inorganic carbon to organic matter is generally restricted to the euphotic zone of the world's ocean through the process of photosynthesis. The supply of reduced carbon and energy required to support deep water metabolic processes is ultimately derived from the upper ocean and is transported down by advection and diffusion of dissolved organic matter, gravitational settling of particulate matter and by the vertical migrations of pelagic animals and phytoplankton. Each of these individual processes, collectively termed the "biological pump", is controlled by a distinct set of environmental factors, and therefore, the relative contribution of each process may be expected to vary with changes in habitat or with water depth for a given habitat.

Each year, the biological pump removes an estimated 10 Gt C (1 Gt = 10^{15} g) from the surface waters of the world ocean, a value that is equivalent to ~15% of the annual global ocean primary production. This export of organic matter is sustained by a continuous reflux of major nutrients; over broad time and space scales the supply of nutrients from below is balanced by the downward flux of particulate matter. These coupled delivery and removal processes control the ability of the ocean to sequester atmospheric carbon.

12.3 Ocean Time-Series Programmes

When designing a time-series field programme, care must be given to the uncompromised collection of complementary data, including dissolved substrates, dissolved gases, particulate matter, and other parameters. In addition to the availability of numerous sampling devices, there is also a variety of potential sampling platforms, including research vessels, towed and towed-undulating vehicles, submersibles, remotely operated vehicles, autonomous underwater vehicles, moorings, drifters, and Earth-orbiting satellites. Each platform has its own unique capabilities and limitations. Integrated measurement systems including multiple sampling platforms and fast response sensors are likely to emerge as the method of choice in future investigations of biogeochemical processes in the sea (Fig. 12.1).

In 1988, we began a systematic examination of microbial and biogeochemical processes in what was, at that time, considered to be a temporally stable habitat – the North Pacific subtropical gyre (Fig. 12.2). After the first decade of approximately monthly research cruises, it was concluded that this sampling frequency was too

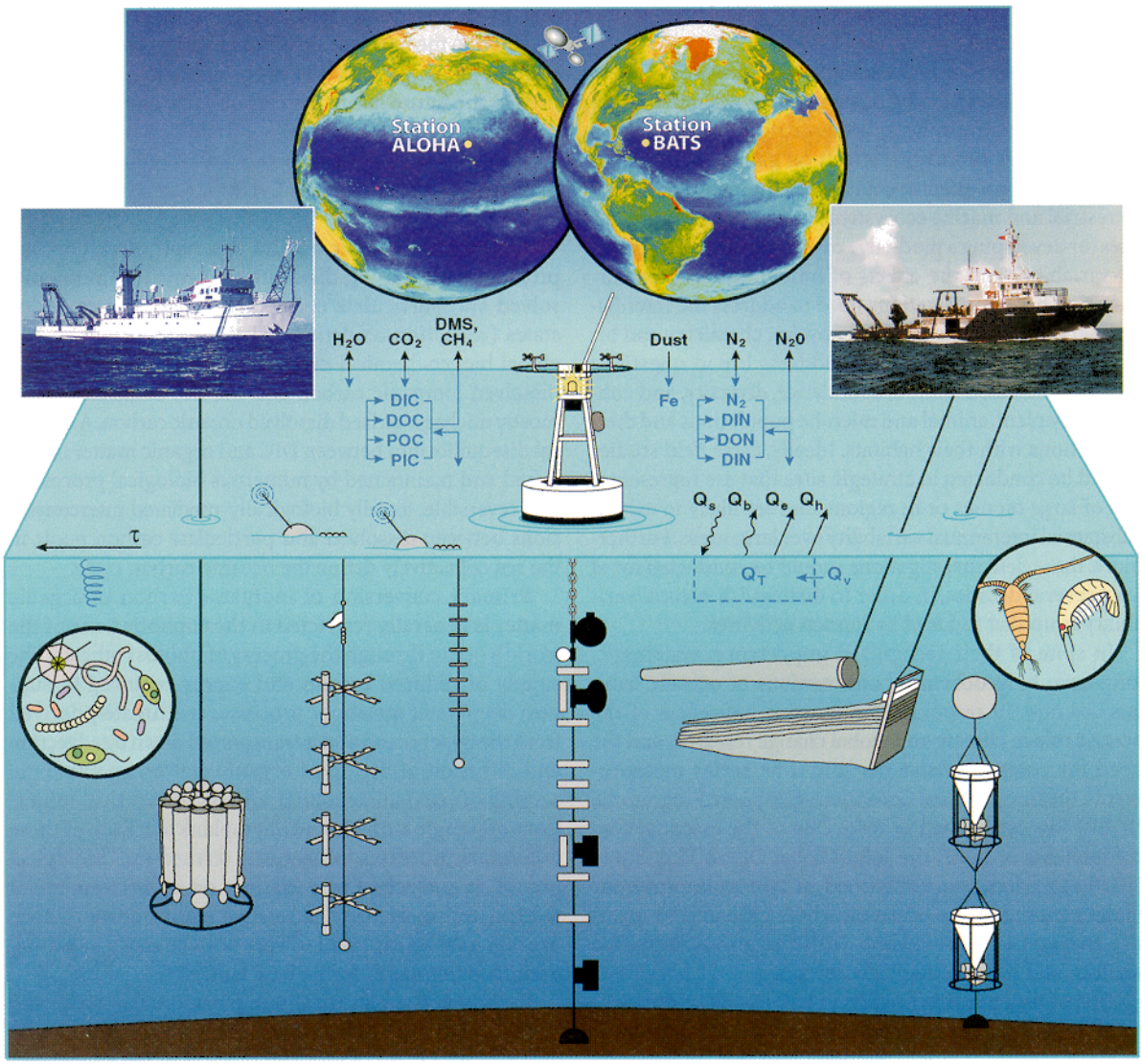


Fig. 12.1. From the macroscope to the microscope, investigations of ocean biogeochemistry at the U.S. JGOFS time-series programs. *Top:* Satellite view of the global biosphere based on observations from the SeaWiFS mission (September 1997–August 1998); imagery courtesy of NASA-Goddard Space Flight Center and the Orbital Sciences corporation (Gene Feldman; see *http://seawifs.gsfc.nasa.gov/SEAWIFS.html*). *Left-centre* and *right-centre:* The research vessels Moana Wave and Weatherbird II at work in the North Pacific and North Atlantic Oceans. *Bottom:* Examples of the variety of ship-based and remote sampling techniques used in the two time-series programs to obtain relevant information on the cycles of carbon and associated bioelement cycles in the sea. Several important components of these cycles, including dissolved and particulate inorganic and organic pools are shown at centre along with selected air-sea exchange processes. Shown in the *enclosed circles* are microscopic images of nanoplankton (*left*) and mesozooplankton (*right*) (reproduced with permission from the Oceanography Society 2001)

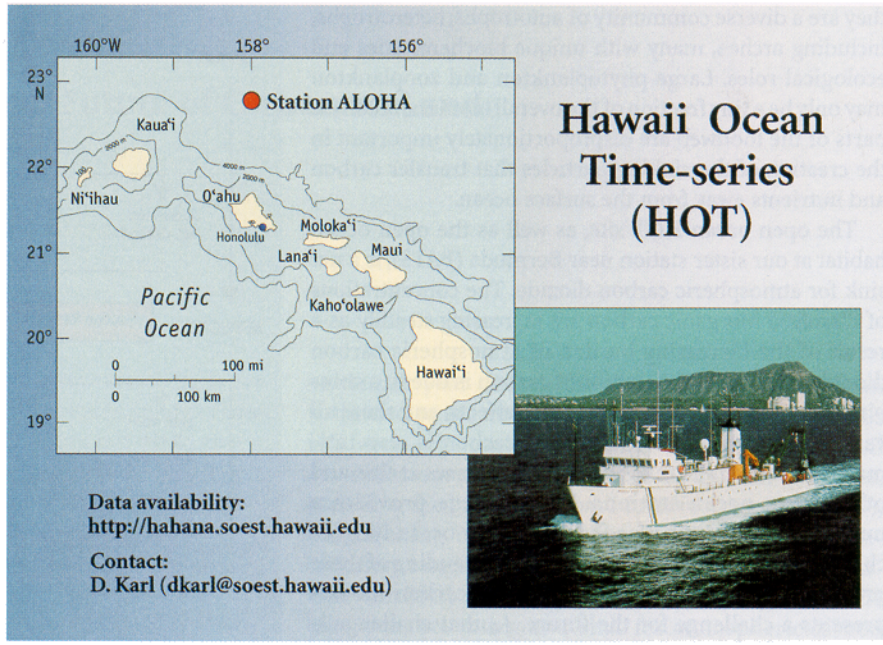


Fig. 12.2.
Vital HOT statistics including sea map, key contacts and photo of the now retired R/V Moana Wave returning to port after a successful HOT cruise

coarse in time to fully resolve even the most important physical-biological interactions (Karl 1999). The greater the number of time periods and space scales that are involved, the greater the measurement intensity to achieve even a basic understanding. As Stommel (1963) cautioned, "Where so much is known, we dare not proceed blindly – the risk of obtaining insignificant results is too great." Undersampling is, unfortunately, a sobering fact of life in oceanography.

The Hawaii Ocean Time-series (HOT) programme has provided unique insight into the functioning of Earth's largest biome (Karl et al. 2001). The knowledge gained challenges some of the most closely held assumptions in ocean biogeochemistry and provides clues to the mechanisms through which ocean biology may influence global climate. The physical and biological processes at HOT show strong interannual and decadal variability. The El Niño Southern Oscillation (ENSO) has a strong influence on mixing and stratification, and both sites show signs of decadal variations in mixing and biogeochemistry. Nitrogen fixation is an unexpectedly strong component of the major nutrient cycles (Karl et al. 1977). The rate of nitrogen fixation is probably strongly linked to the supply of iron, a critical micronutrient for the enzyme nitrogenase. In the Pacific, the reorganisation of the ecosystem that accompanies the rise of nitrogen fixation appears to occur on decadal time scales as a shift between nitrogen and phosphate limitation.

Finally, ecosystem structure matters. The simple characterisation of biogeochemistry as the flow of nutrients and energy through simplified foodwebs hides a massive complexity of organisms and processes. Changes in the composition of the biological community have a strong effect on how it functions. The "bacteria" are no longer a homogeneous mix of heterotrophic consumers;

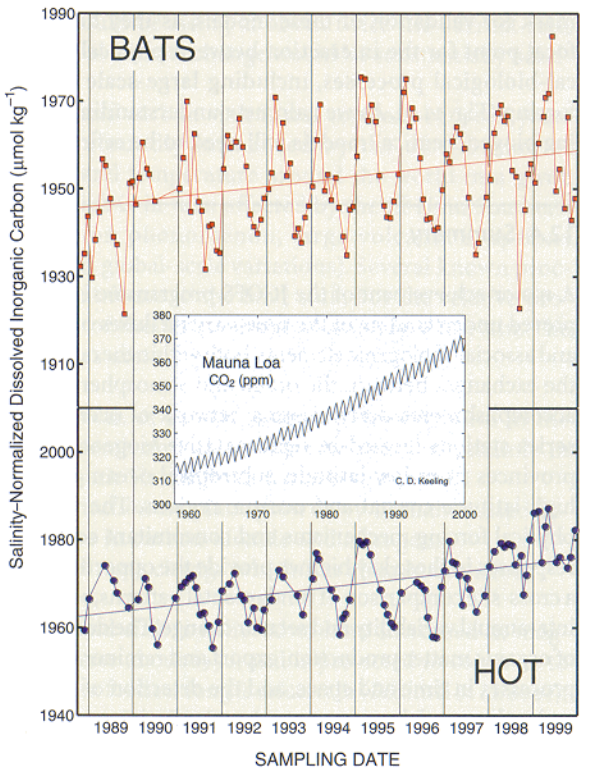


Fig. 12.3. The initial 11-year record of mixed-layer dissolved inorganic carbon (DIC), normalised to a salinity of 35.0 (N-DIC), for the BATS (*upper curve*) and HOT (*lower curve*) open ocean time-series sites. The larger annual amplitude at *BATS* is a manifestation of the greater seasonal temperature range and seasonal variation in the magnitude of greater organic matter production, both of which contribute to N-DIC dynamics. The significant increasing N-DIC trend with time over the 11-yr period (BATS = +1.23 µmol kg^{-1} yr^{-1}, HOT = +1.18 µmol kg^{-1} yr^{-1}) is the ocean's response to the increasing burden of atmospheric carbon dioxide as shown by the centre inset using the C. D. Keeling atmospheric data set from Mauna Loa, Hawaii

they are a diverse community of autotrophs, heterotrophs, including archea, many with unique biochemistries and ecological roles. Large phytoplankton and zooplankton may only be a tiny fraction of the overall biomass, but these parts of the foodweb are disproportionately important in the creation of the sinking particles that transfer carbon and nutrients away from the surface ocean.

The open ocean HOT site, as well as the open ocean habitat at our sister station near Bermuda (BATS), is a net sink for atmospheric carbon dioxide. The concentrations of dissolved inorganic carbon are increasing steadily as a result of the increasing burden of atmospheric carbon dioxide (Fig. 12.3). The uptake of carbon is due to a combination of biological and solubility effects, and these all vary through time. The uptake of carbon is also intimately linked to the mix of unique processes at this and other open ocean stations. This linkage provides a number of clues to the feedback between ocean biogeochemistry and global climate. The understanding of these processes and their inclusion in global carbon models presents a challenge for the future. As that challenge is met, the time-series stations will provide a crucial benchmark for validation of these models, as they become a focal point for the interaction between physical-chemical-biological processes, including large-scale climate forcing (Fig. 12.4). As we gain new understanding, existing biogeochemical models will need to be refined.

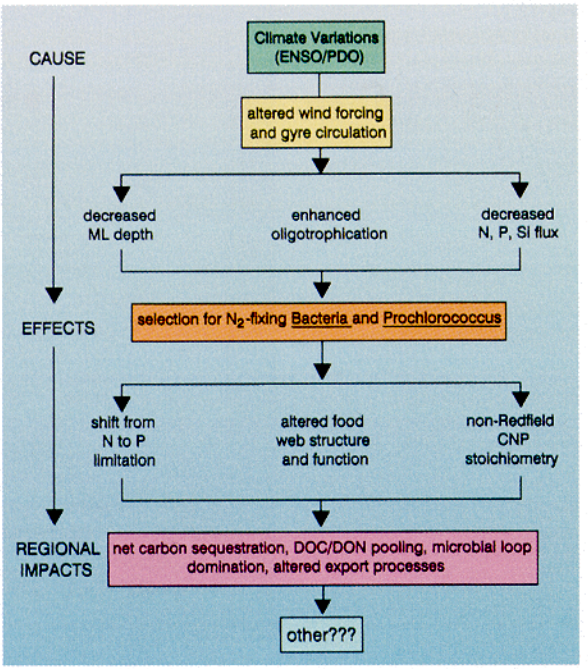


Fig. 12.4. Hypothetical view of the effects of climate variability on ecosystem structure and function in the North Pacific Subtropical Gyre based, in part, on results obtained during the decade-long HOT research programme. Changes in the stratification of the surface ocean has affected nutrient and trace element budgets and has selected for N_2-fixing bacteria and *Prochlorococcus*, resulting in a domain shift from predominantly Eucarya to predominantly Bacteria. This has resulted in numerous observed and potential biogeochemical consequences, including non-Redfield CNP stoichiometry and, therefore, a net sequestration of atmospheric carbon dioxide (redrawn from Karl 1999)

12.4 Summary

A major achievement of the JGOFS programme is an improved understanding of the time-varying fluxes of carbon and associated biogenic elements, both within the ocean and the exchanges between the ocean and atmosphere. These accomplishments derive from a network of ocean time-series stations located in representative biogeochemical provinces from low-latitude, subtropical ocean gyres to high latitude coastal and oceanic regions. The variable physical forcing mechanisms and concomitant ecological responses in these key biomes provide the opportunity for a cross-site comparison of fundamental patterns, seasonal/interannual variability and secular change. The decoupling of organic matter production, export and remineralisation processes in time and space, and the detection of decade-scale, climate-driven ecosystem perturbations and feedbacks combine to reveal a time-varying, biogeochemi-cal complexity that is just now becoming evident in our independent and collective ocean time-series data sets.

Ultimately, oceanic productivity, fishery yields and the net marine sequestration of atmospheric greenhouse gases are all controlled by the structure and function of planktonic communities. Detailed palaeoceanographic studies have documented abrupt changes in these processes over time scales ranging from centuries to millennia. Most of these major shifts in oceanic productivity and biodiversity are attributable to changes in Earth's climate, manifested through large-scale ocean-atmosphere interactions. By comparison, contemporary biodiversity and plankton community dynamics are generally considered to be "static", in part due to the lack of a suitable time frame of reference, and the absence of oceanic data to document ecosystem change over relatively short time scales (decades to centuries). The establishment of a global network of ocean time-series stations for repeated physical and biogeochemical measurements represents one mechanism for the ecosystem surveillance that is necessary to record and eventually understand these complex oceanic processes.

References

Karl DM (1999) A sea of change: Biogeochemical variability in the North Pacific subtropical gyre. Ecosystems 2:181–214

Karl DM, Letelier R, Tupas L, Dore J, Christian J, Hebel D (1977) The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean. Nature 388:533–538

Karl DM, Dore JE, Lukas R, Michaels AF, Bates NR, Knap A (2001) Building the long-term picture: The U.S. JGOFS Time-series programs. Oceanography 14:6–17

Stommel H (1963) Varieties of oceanographic experience. Science 139:572–576