INTERNATIONAL GEOSPHERE–BIOSPHERE PROGRAMME BOOK SERIES

The Changing Ocean Carbon Cycle

A midterm synthesis of the Joint Global Ocean Flux Study

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CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011–4211, USA www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain

First published 2000

Printed in the United Kingdom at the University Press, Cambridge

Typeface Ehrhardt 11/14pt [VN]

A cataogue record for this book is available from the British Library

ISBN 0 521 65199 9 hardback
ISBN 0 521 65603 6 paperback

Contents

1 The evolution of the Joint Global Ocean Flux Study project

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Keywords: ocean carbon cycle, carbon dioxide exchange, biogeochemical processes, greenhouse effect, primary production, SCOR, IGBP

Introduction

It is always interesting to note that numerous ancestors appear swelling with pride when the offspring is a great success. The Joint Global Ocean Flux Study (JGOFS) project is certainly such a success, and, not surprisingly, many recognise within JGOFS sequences of the genome of a favourite ancestral project or committee report. Since the editors of this volume have given me the liberty to inject personal views in this chapter, I should like to begin arranging the stage upon which JGOFS science has evolved, set as it was in the mid-1960s. (I will use the acronym JGOFS to refer to immediate precursors of this project and various national elements of it, many of which have other names.)

The ocean carbon cycle

Students beginning graduate studies in ocean sciences at the Scripps Institution of Oceanography three decades ago, as I did, received their first introduction to an oceanographic perspective of the carbon cycle with books such as Dietrich's 1963 text entitled *General Oceanography* (originally published in German in 1957). The schematic of the carbon cycle depicted by Dietrich is given in Fig. 1.1. It is essentially the same figure used earlier by Borchert (1951; in German as cited by Dietrich 1963) and even earlier by Kalle (1945; in German as cited by Dietrich 1963). By today's conventions, the dimensions for reservoirs and fluxes (mass C per unit area, and mass C per unit area $\times$ time) are both unusual and only awkwardly translated into dimensions that are more modern. One can see, however, that much of the cycle portrayed is in order. Dietrich summarises the wisdom of the time, that the terrestrial biological cycle is 'practically closed in itself' and the 'great geological cycle . . . is also balanced'. It is particularly

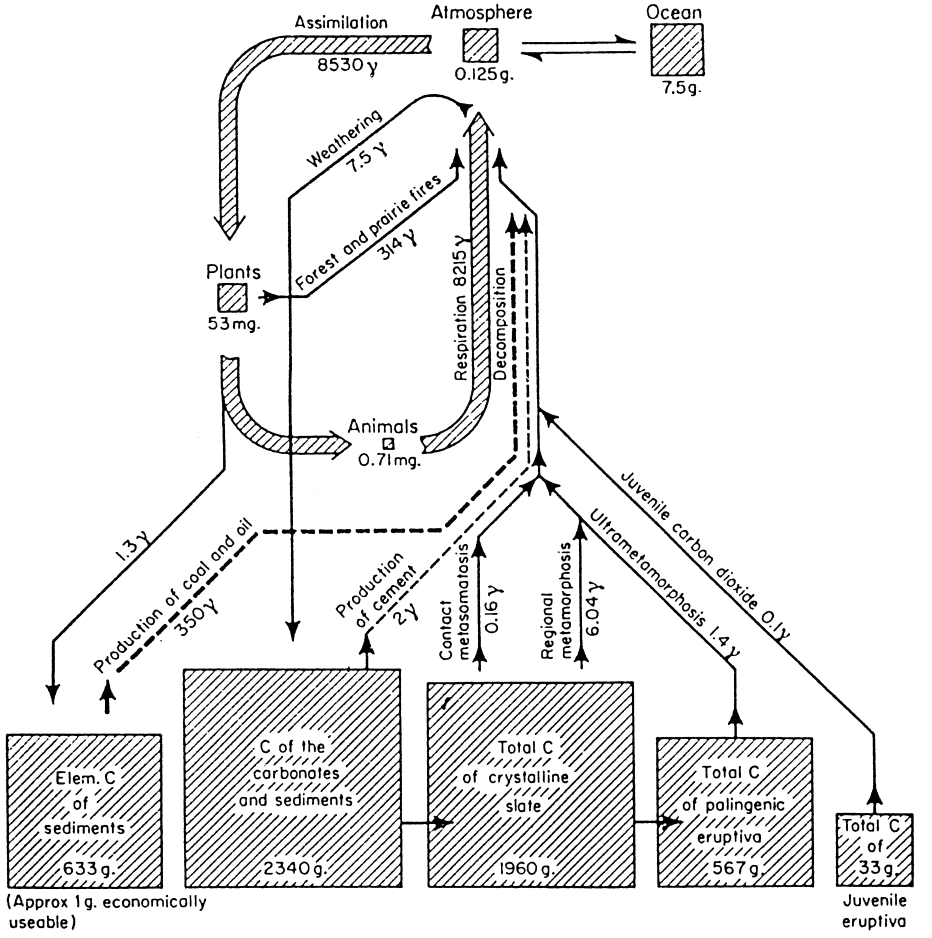

Figure 1.1 *Carbon cycle in nature (after K. Kalle, 1945; improved after H. Borchert, 1951). Dietrich, Copyright © (1963 Dietrich). Reprinted by permission of John Wiley & Sons, Inc.*

interesting to note how little was then known about the role of the ocean in the carbon cycle. Although the ocean reservoir of inorganic carbon is correctly indicated as being about sixty times larger than the atmospheric reservoir, there is no flux estimate for, or even an indication of, an exchange between the atmospheric and oceanic reservoirs. Implicit in this omission was an assumption that any such fluxes were either negligible or offsetting so as to yield zero net flux.

The understanding reflected in this diagram never could have been used to justify a project such as JGOFS. The ocean biota and associated sedimentation of organic and inorganic carbon are not even alluded to. Accompanying text acknowledges, however, that 'Although carbon stored in living substances . . .

represents a minute part of the total carbon content in the Earth's crust . . . it must be considered the actual motor which puts the geochemical carbon cycles in motion'. The importance of sedimentary burial of organic carbon in the evolution of Earth's atmosphere, and the stochiometric equivalence between this burial and Earth's atmospheric O_2 content, was not to be fully realised for another two decades (see Kasting, 1993).

Speculations regarding a potential increase in the so-called greenhouse effect of the Earth's atmosphere arising from release of CO_2 with fossil-fuel combustion were well known from the work of Callendar (1938) two decades before Dietrich, and even earlier, around the turn of the century, from the works of Arrhenius (1896) and Chamberlin (1899). Dietrich comments on the possibility of such a consequence of industrialisation by noting that the 'artificial supply of . . . carbon – (when) compared with the natural carbon dioxide production . . . is completely negligible – (and it could) have led to a doubling of the atmospheric carbon dioxide content since the start of industrialisation'. He then adds, 'This probably would have caused serious climatic consequences. It is doubtless a result of the great buffer capacity of the ocean that this increase in the carbon dioxide content of the atmosphere has remained so small as to be undetectable so far' (Dietrich 1963).

Skirrow, in the first volume of Riley & Skirrow's *Chemical Oceanography*, is himself the author of the chapter on carbon dioxide (1965). He uses exactly the carbon cycle schematic presented earlier by Dietrich, and in 105 pages on carbon dioxide in seawater, only with six lines does he treat the carbon cycle *per se*. He gives no more attention to the role of marine biogeochemical processes in this cycle than did Dietrich (1963).

The year 1957 is remembered by many in conjunction with the International Geophysical Year. This year was profoundly important for many aspects of Earth sciences, and the carbon cycle is no exception. In 1957, Roger Revelle and Charles David Keeling were preparing to implement the longest and most highly resolved time series that exists for global anthropogenic influence on atmospheric composition. Roger used to love to tell how difficult it was to sustain early funding for the Mauna Loa time series that Keeling began. Having demonstrated the seasonal cycle and slight upward trend at the end of the first few years was not, in the minds of some, sufficiently interesting to warrant additional support.

Another important piece of the ocean carbon cycle was also coming into focus at this same time. Sufficient data had been collected with the ^{14}C technique for assessing rates of primary productivity to make new global estimates of this process. Prior assessments based upon the oxygen light–dark bottle technique and various proxies had yielded estimates of global production as high as 130 Gt C yr^{-1} (Table 1.1). Steeman-Nielsen & Jensen (1957) presented the first

Table 1.1. *Estimates of global plankton production*

Year	Gt C yr^{-1}	Reference
1942	50–130	Sverdrup *et al.*
1946	126 ± 82	Riley
1957	20–25	Steeman-Nielsen & Jensen
1970	23	Koblentz-Mishke *et al.*
1971	44	Bruevich & Ivanenkov
1975	31	Platt & Subba Rao
1979	44	de Vooys
1987	42	Martin *et al.*
1995	45–50	Longhurst *et al.*

global composite of the ^{14}C data, and estimated a dramatically lower value of 20 Gt C yr^{-1}.

Estimates of global marine primary production of about 20 Gt C yr^{-1} prevailed for the next dozen years, culminating with the schematic for geographic distribution of primary production published by Koblentz-Mishke *et al.* (1970) (Fig. 1.2). Regardless of subsequent upward revisions of this estimate by 150–200% through the 1970s and 1980s, the original estimate and accompanying schematic of Koblentz-Mishke *et al.* remain popular choices in many overview and synthesis chapters and books, probably because of the power conveyed with the single global map. Interestingly, though, although derivative versions of this map are widely used, most delete detail in the original legend that indicated that, with the exception of the Indian Ocean, virtually no direct measurements were available to compute annual rates of primary production for the southern-hemisphere oceans.

The map of Koblentz-Mishke *et al.* helped to perpetuate the notion that offshore regions are without strong annual cycles in primary production. Indeed, in 1971, little was known about temporal variability in timing and magnitude of seasonal blooms. The three-year time series of Menzel & Ryther at Station 'S' southeast of Bermuda (Menzel & Ryther, 1961), which was truly exceptional documentation of such variability when published, remained exceptional in its detail and duration for oceanic waters until the advent of the JGOFS time-series stations near Bermuda and Hawaii in 1987. In fact the extent of temporal and spatial variability in primary productivity in many offshore as well as near-shore regions was only first known with the Earth orbiting Coastal Zone Color Scanner observations in the late 1970s.

By the early 1980s the well-established annually averaged secular trend in atmospheric CO_2 concentration permitted the determination that about half of human society's fossil-fuel CO_2 emissions currently remain in the atmosphere. Results of GEOSECS (Geochemical Ocean Sections) and other studies led to

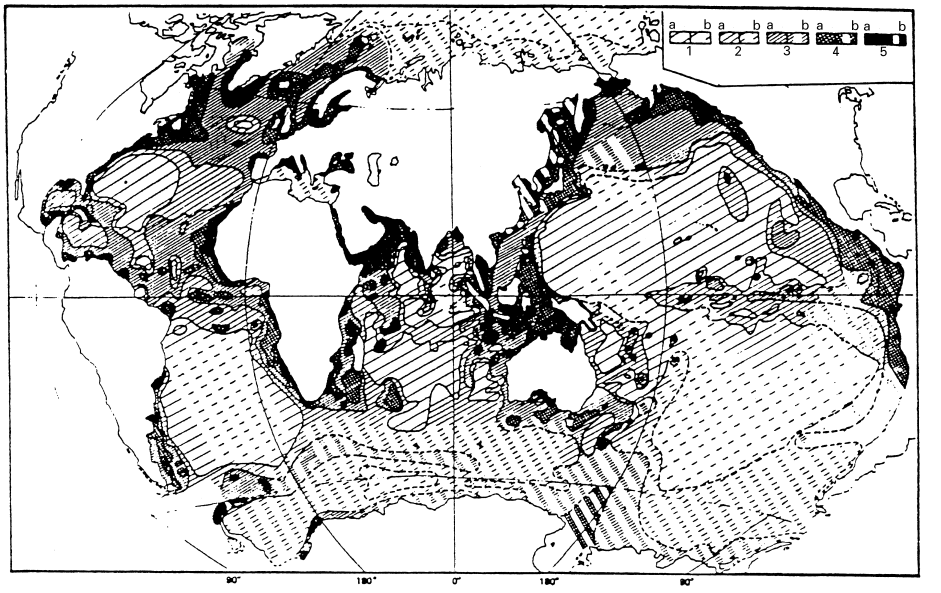

Figure 1.2 *Distribution of primary production in the World Ocean. Units are mg C m^{-2} d^{-1}: 1, less than 100; 2, 100–150; 3, 150–250; 4, 250–500; 5, over 500;* a, *data from direct ^{14}C measurements;* b, *data from phytoplankton biomass, hydrogen, or oxygen saturation. Reprinted with permission from* Scientific Exploration of the Southern Pacific. *Copyright © (1970 Koblentz-Mishke* et al.*) by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C.*

the strong arguments that the remaining portion, the so-called missing half, was being absorbed by the ocean. Then in 1982 came a most startling observation, the fact that polar ice samples contained evidence for a previously unknown oscillation in atmospheric CO_2, one of 80–100 ppm amplitude, which was in phase with temperature during the last glacial cycle (Neftel *et al.,* 1982) (Fig. 1.3). This finding stimulated much discussion and speculation as to which ocean processes could have contributed to such dramatic changes in the atmosphere. Certain marine biogeochemical responses and feedbacks were considered, and productivity and storage of organic carbon in the Southern Ocean were invoked by several groups (Knox & McElroy, 1984; Sarmiento & Toggweiler, 1984; Siegenthaler & Wenk, 1984).

At about the same time another discovery shattered a long-standing paradigm in ocean science. It had long been assumed that the deep ocean floor was without seasonality. The term 'rain of detritus' was coined by Alexander Agassiz (1888) to describe the slow continuous flux of fine particulate material from the upper ocean to deep benthic habitats. However, in the late 1960s it was noted that at depths of a few thousand metres certain marine invertebrates experience annual cycles in reproductive state (Schoener, 1968). Thus, in a habitat without

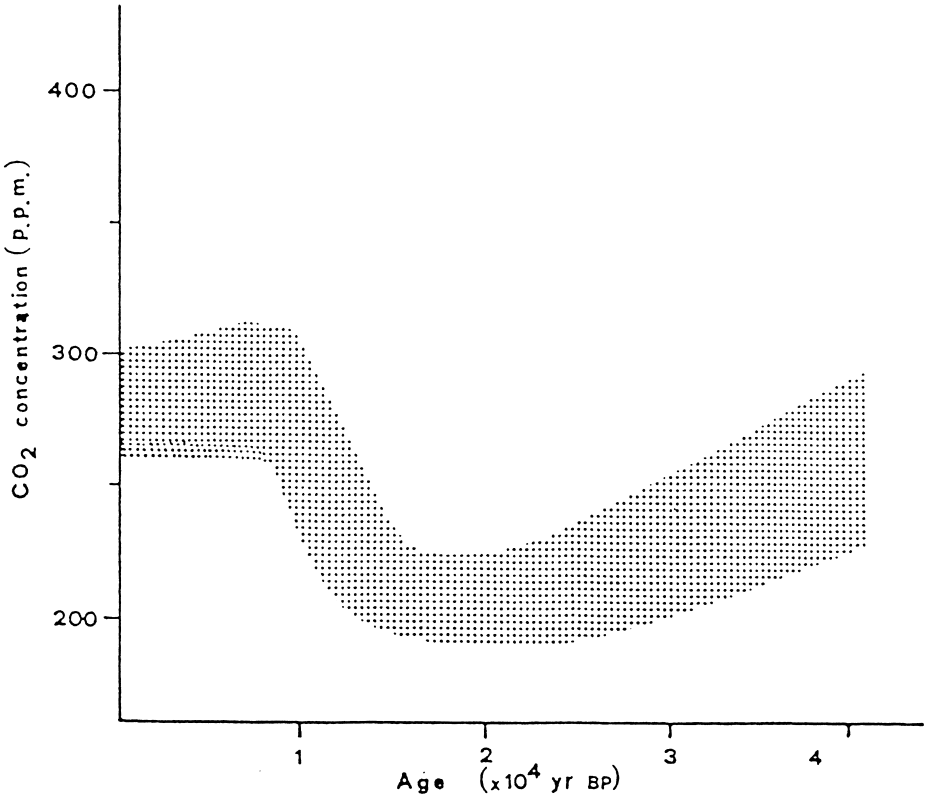

Figure 1.3 *Estimate range of atmospheric CO_2 during the past 40 000 yr. Reprinted with permission from* Nature *and the author. Copyright © (1982 Neftel* et al.*) by Macmillan Magazines Ltd.*

seasonal signals in either light or temperature, seasonality in the supply of sinking particulate material was a likely source of this effect. In the late 1970s, Werner Deuser began his time-series sediment-trap work southeast of Bermuda, and established (Deuser & Ross, 1980) that the seasonal cycle of organic flux to the deep ocean mimics the seasonal cycle of primary production in the overlying water (Fig. 1.4). Shortly thereafter, Honjo (1984), with higher temporal resolution, demonstrated pronounced interannual flux in organic matter to the deep ocean at Station 'P' in the North Pacific. The concept of seasonal and annual variability in vertical flux to great depth is now so well established that we tend to forget how recent these findings are.

The Earth system context

Another important development, and I shall argue a critical one, was to set the significance of these marine processes in a larger context. Although linkages

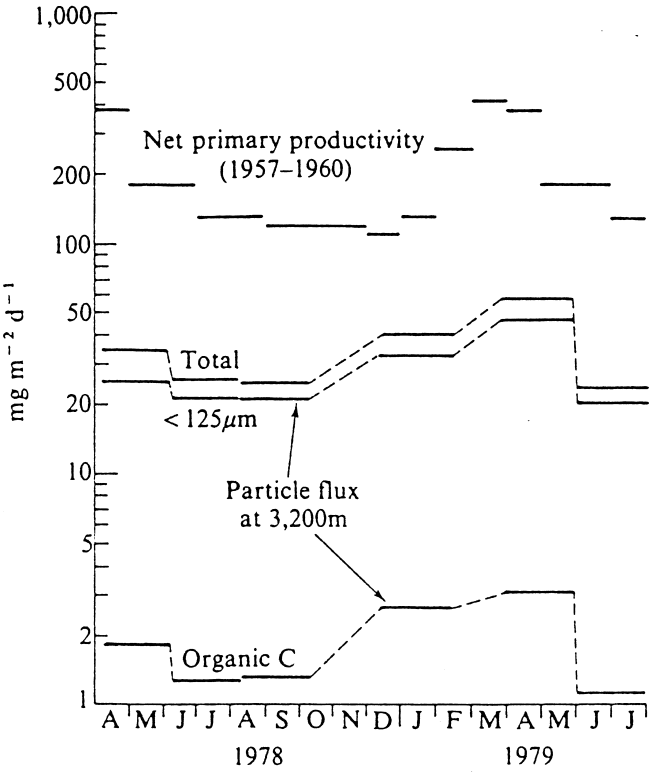

Figure 1.4 *Comparisons of monthly averages of daily net primary productivity (in terms of carbon) for the years 1957–60 with mean daily yields of total sediment (dry mass) and particulate organic carbon during six two-month sampling periods in 1978–79. Reprinted with permission from* Nature *and author. Copyright © (1980 Deuser & Ross) by Macmillan Magazines Ltd.*

between biogeochemical processes and climate had been inferred from polar ice-core data, a scientific plan that would permit the quantitative assessment of these and other relationships within the climate system was lacking.

The stage was set to do just this. The early 1980s were years of expansive and optimistic mood in ocean science. New satellite technology was providing information on ocean processes at temporal and spatial scales we had never before imagined possible, and priorities in ocean science shifted accordingly. Many moderate-scale oceanographic projects had been successfully completed, and several of these had been interdisciplinary. Within and between the marine, terrestrial, and atmospheric domains, research, and even new journals, were addressing questions relating to biogeochemical cycles. On a more general front, scientists in many disciplines were pondering potential consequences of the inexorable rise in atmospheric CO_2, as the words of Revelle & Suess (1957) that 'human beings are now carrying out a large scale experiment of a kind that could

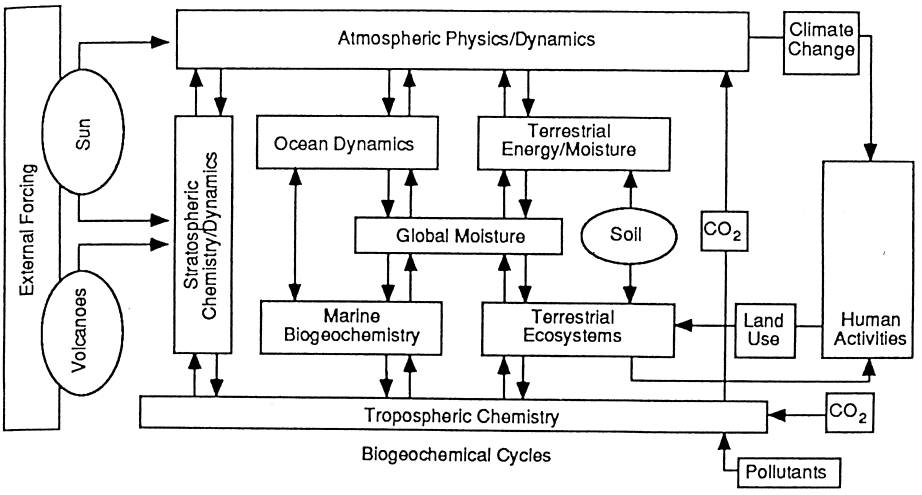

Figure 1.5 *Earth's climate system (ESSC, 1988).*

not have happened in the past nor be reproduced in the future' began to strike home.

One example of the larger context that was needed is evident in the schematic produced in the mid-1980s by the Earth System Science Committee in the USA. This committee began with a charge to report to the National Aeronautics and Space Administration (NASA) on research directions in Earth science, but its final report was embraced by the National Science Foundation (NSF) and the National Oceanic and Atmospheric Administration (NOAA) as well. This schematic (Fig. 1.5) (ESSC, 1988) was developed in various levels of detail and allowed scientists across the community of Earth sciences, broadly defined, to envision couplings among the various disciplinary segments in an overall union of physical dynamics and biology via biogeochemical cycles. In the USA, at least, the setting of any aspect of Earth science research in this larger context helped both to build the case for and allow access to new funds for large co-ordinated studies.

An important aspect of this approach was the design of effective observing capabilities and experiments, the results of which could be used to initialise and refine models of interactive ocean processes for the purpose of extrapolating to larger temporal and spatial scales, and to develop scenarios that could be tested by further observations. Needless to say, the role of models was and still is debated in this science. In early 1985 a distinguished geochemist involved in helping to organise US contributions to JGOFS stated that modelling is a 'buzz word', and argued that, although it is important, it must be kept in its proper place, which is in the design of data-gathering strategies. I believe this helped to set a tone that has been evident, at least in US JGOFS, until very recently.

By the early to mid-1980s, many pieces of the marine carbon cycle were falling into place. Considerable progress had been made in refining methodologies for measuring rates of primary production, new understanding had emerged regarding the role of the so-called 'biological pump' in the global carbon cycle, and strong inferences were being drawn about the interactions among ocean biogeochemical cycles and climate. The power of satellite observations for extending spatial distributions of certain physical and biological properties that historically were only measured *in situ*, and for inferring, with caution, rates of key biological processes on larger space and time scales, made a truly global study feasible. Products of the Coastal Zone Color Scanner enabled visualisation of spatial and temporal dimensions of plankton bloom cycles and episodes that were previously unknown owing to under-sampling with conventional methods. Moreover, as plans for the World Ocean Circulation Experiment (WOCE) were evolving, it was apparent that appending a JGOFS CO_2 sampling component to the World Hydrographic Program of WOCE would result in a very efficient use of resources.

Were there tensions within the scientific community regarding JGOFS objectives and plans for implementation? Of course there were, both within the community of supporting scientists and in adjacent fields as well. To accomplish the objectives of JGOFS, unprecedented international co-operation within the biological and chemical ocean science communities was required. No one nation had the resources necessary to undertake this task. Moreover, it was believed by some that individual national efforts designed to address JGOFS-related scientific questions would be difficult or impossible to co-ordinate within the structure of a single international project. In part, this perception was based upon understandable national differences in interest and programmatic emphasis, between coastal – open ocean, atmosphere–ocean, upper ocean – deep ocean, and deep ocean – sediment fluxes.

In addition to truly scientific differences, there were also issues relating to resources that attracted the attention of other segments of the ocean science community. Just as some scientists within JGOFS argued until recently that modelling should be given lower priority than observations and experiments, certain physical oceanographers argued in national and international meetings that JGOFS should be postponed until WOCE was completed. Nevertheless, momentum for a JGOFS study grew rapidly through the latter half of 1984. A pivotal meeting for US support was the National Research Council summer study convened by Kenneth Bruland in Woods Hole. About 60 scientists from 7 nations attended. The report from this meeting (NAS, 1984) provided a summary of the state of the science, and argued for a focused effort to understand biogeochemical cycles of the ocean sufficiently well to predict the interaction between the oceanic, atmospheric and sedimentary cycles of

biologically active elements.

In an effort to capitalise on this momentum and to effect the requisite international support for such a project, Roger Revelle thought there was a good chance of convincing the now defunct Committee on Climate Change and the Ocean (CCCO), which had been instrumental in launching the Tropical Ocean and Global Atmosphere programme (TOGA) and WOCE under the auspices of the World Climate Research Programme, to endorse this programmatic concept. Roger took Peter Brewer, Richard Gammon and me to CCCO VI in November 1984 to make this case. It was proposed that this new study would have two aspects: (1) measurement over time of the constituents of the carbon dioxide system in surface and subsurface ocean waters down to great depths, and the rates and locations of carbon dioxide exchange between the sea and the air; and (2) studies of the interaction between biological activity in the ocean and atmospheric and ocean carbon dioxide. This recommendation included determination of the flux of organic particles from the euphotic zone into deeper waters or onto the bottom and their chemical transformation, as well as estimates of the effects of biological production in surface waters on the air–sea carbon dioxide exchange.

Many participants in the CCCO meeting made complimentary remarks regarding the science, but several argued that there was no point in engaging in such a study until the physics of the ocean was better understood. In addition, some participants argued ardently that the ocean science community could never convince governments to support an altimeter and a new colour sensor at the same time. In the end, the CCCO rejected Roger's proposal, but the biogeochemical community did not heed their warnings.

National efforts related to JGOFS continued to emerge and flourish, and in early 1987 the Scientific Committee on Oceanic Research (SCOR) came to the rescue, by convening a meeting in Paris under the chairmanship of D. James Baker, Jr. The report of this meeting encouraged SCOR to provide the international home this project needed, and SCOR took this action. Subsequently, through an agreement of joint sponsorship with the International Geosphere–Biosphere Programme (IGBP), JGOFS became the first marine science project of this programme.

Much of the science that is revealed in the following chapters of this book would not have been possible without the architecture and infrastructure of JGOFS. The interdisciplinary and collaborative aspects of this project have been immensely productive, and for a young scientist just now entering this field it is probably difficult to imagine how tenuous the prospects for this type of research were only a decade ago. Those of us who have had the opportunity to pursue science of fundamental interest to ourselves in the context of this large project are indeed fortunate. For many of us in ocean science, the problems at

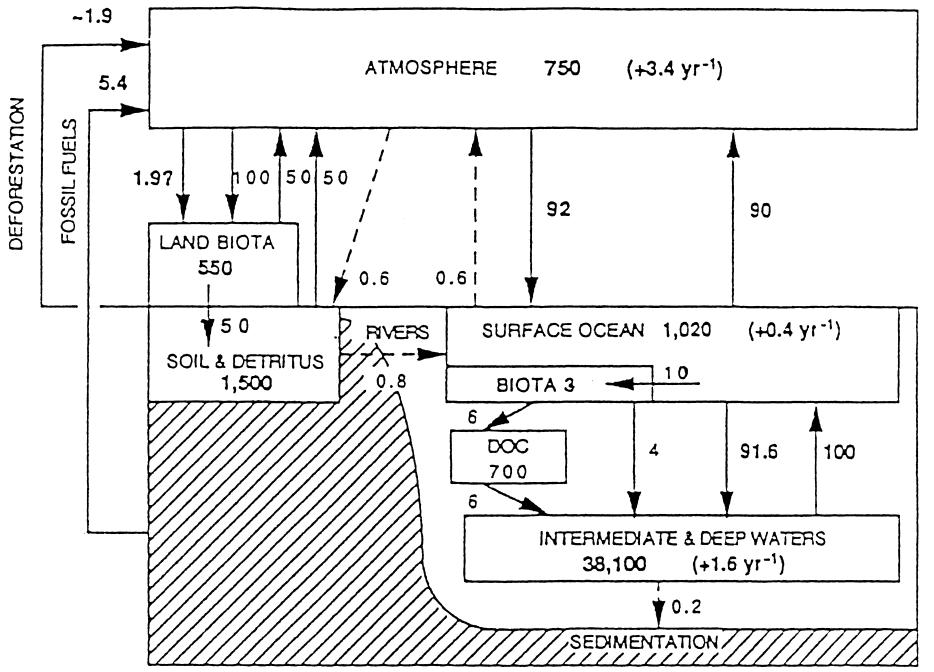

Figure 1.6 *Carbon cycle 1980–89. Units are Gt C and Gt C yr^{-1}. Reprinted with permission from* Nature *and author. Copyright © (1993 Siegenthaler & Sarmiento) by Macmillan Magazines Ltd.*

the interfaces of the traditional scientific disciplines have always had particular appeal. However, in this past decade the sense of societal relevance for aspects of these problems that relate to global and climate change has given both new purpose and a particular urgency to this science.

The future

Over the past three decades, knowledge and understanding of Earth's carbon cycle and the ocean's role in regulating atmospheric CO_2 content has grown substantially. This is abundantly evident in research papers (see, for example, Siegenthaler & Sarmiento, 1993) (Fig. 1.6) and in recent assessments of the Intergovernmental Panel on Climate Change (IPCC). It is necessary for us to improve the precision of estimates for essential reservoirs and fluxes. However, questions regarding the capacity of the ocean to sequester carbon in the future loom large. Model scenarios for future climate states typically presume that the ocean component of the carbon cycle will continue to function as it does at present. If under altered climate conditions, ocean circulation differs

substantially from its present state, then the ocean's capacity to absorb and retain CO_2 will certainly change as well.

History tells us that there were a couple of important periods in the evolution of the science that led to JGOFS, one in the late 1950s and another in the early 1980s. In both instances leaps in scientific understanding raised expectations and mobilised the ocean science community. I predict that the late 1990s will be another such moment, as the product of JGOFS propels a new wave of understanding as to how interaction among biogeochemical and physical processes determines Earth's climate.

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