The Joint Global Ocean Flux Study

- J G O F S -

SCIENCE PLAN

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH

International Council on Scientific Unions
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Foreword

This Science Plan sets out the core scientific problems and goals of the Joint Global Ocean Flux Study (JGOFS) and puts forward plans for the research required to advance our understanding of these problems. The plan is also intended to provide a framework within which the Committee for JGOFS can develop the international cooperation and collaboration which will be essential if such a large set of research problems are to be solved.

The plan had its genesis at JGOFS-1 (the first meeting of the Committee for JGOFS) in Miami in January 1988, but the necessity for devoting a large amount of effort to planning the JGOFS North Atlantic Pilot Study meant that the writing of the plan was delayed until late 1989. In the intervening period a number of countries produced their own national JGOFS plans, which provided invaluable source material.

The basic outline of the plan was developed at the meeting of JGOFS-3 in Hawaii in September 1989 and a small group of willing writers were recruited under the editorial leadership of M.J.R. Fasham. The contributors were W.H. Berger, P.G. Brewer, K.H. Denman, H.W. Ducklow, G.T. Evans, H. Elderfield, M.R. Lewis, T. Platt, D. Turner, G. Wefer, and B. Zeitzeschel. Other members of the JGOFS Committee made many valuable comments on the first draft. The second draft was reviewed at JGOFS-4 in Kiel in March 1990. The final version is the result of suggestions for improved presentation made at that meeting.
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1 The Scientific Problem

1.1 Introduction

There is a growing consensus and alarm that the earth will experience a global climate change over the next 50 to 100 years in response to the increase in atmospheric greenhouse gases caused by human activities. Carbon dioxide (CO$_2$) now accounts for about half the atmospheric greenhouse effect (Ramanathan et al., 1985) and is expected to be more dominant in the future. Hence, CO$_2$ has been the focus of concern. Since 1955, the concentration of CO$_2$ in the atmosphere has increased from 315 ppm to about 350 ppm (Keeling et al., 1989), due primarily to the burning of fossil fuels and, to a lesser degree, changing land use. Studies of ice cores show that the pre-industrial atmospheric CO$_2$ varied between 180 and 300 ppm over the last 165,000 years. Thus, current human activity has perturbed the atmospheric CO$_2$ burden beyond what has occurred at any time during this period. While much can be learnt about past climatic fluctuations from the palaeo-historical records, it will be necessary to extrapolate beyond these records, by documenting the change through direct observation and by predicting change with computer models, in order to assess and to prepare for the climate-induced impact on the Earth.

Of the estimated anthropogenic input of carbon dioxide, 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 Gt/yr (1 Gt=10$^9$ tonnes); but we do not know how this capacity is regulated. The ocean stores some 50 times more CO$_2$ than the atmosphere, and a relatively small change in the oceanic carbon cycle (for example, in response to climatic change) can have large atmospheric consequences. Moreover, the ocean has a more complicated carbon cycle than the atmosphere, involving many inorganic and organic forms. Various sophisticated models of the atmosphere and ocean give different estimates of how much CO$_2$ is exchanged and where. Clearly we must improve the observational and conceptual bases of our estimates and predictions. JGOFS has therefore been designed to increase our understanding of the ocean carbon cycle, its sensitivity to change, and the regulation of the atmosphere-ocean CO$_2$ balance. More formally, it has two goals (SCOR 1987a):

1: To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.

2: To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

The entry of anthropogenic CO$_2$ into the ocean is a net result of much larger carbon fluxes between the ocean and atmosphere and within the ocean. Any attempt at prediction has to consider likely changes in fluxes throughout this network. A reasonable target for JGOFS would be to reduce the uncertainties in the fluxes to the level of 2 Gt/yr, the size of the anthropogenic input. For
some of the important fluxes, this means improving precision by a factor of 10 over current knowledge.

1.2 The History of JGOFS

The role of the ocean in controlling climate change through the storage and transport of heat (and liquid water) was recognised early on by the World Climate Research Programme (WCRP) and led to the planning of the Tropical Ocean - Global Atmosphere (TOGA) study and the World Ocean Circulation Experiment (WOCE, 1988a & b). In parallel to this initiative, the Joint SCOR/IOC Committee on Climatic Change and the Ocean (CCCO) proposed a global survey of the oceanic CO$_2$ field and WOCE agreed to make berths available on ships taking part in the WOCE Hydrographic Programme (WHP). Geochemists and biologists were concerned that a physical transport model with an upper boundary condition would be inadequate to determine the ocean’s role in the atmospheric CO$_2$ budget, and hence the prediction of climate change in response to the atmospheric build-up of greenhouse gases would not be possible. These concerns were articulated at a NATO meeting in 1982 on the chemistry of the upper ocean (Burton et al. (eds.), 1986) and at a workshop in the USA in 1984 (GOFS, 1984). The proceedings of these meetings provided the initial scientific focus for the formulations of the various national programmes now underway or planned.

The formal organisation of JGOFS commenced in February 1987 when the Scientific Committee on Oceanic Research (SCOR) of ICES, sponsored a meeting of experts in Paris (SCOR, 1987a). There, the goals, scientific elements, topics of emphasis and organisational structure of JGOFS were agreed upon. In October 1987 the SCOR Executive Committee established an international planning Committee for JGOFS which met for the first time in January 1988 (SCOR, 1988). Links were to be established with other SCOR global programmes - WOCE and TOGA. In 1988, JGOFS assumed responsibility for the CCCO CO$_2$ measurement programme and a Joint JGOFS-CCCO Panel on Carbon Dioxide was established, replacing a similar CCCO panel. In 1989, a formal agreement was reached between SCOR and the ICSU Special Committee for the International Geosphere-Biosphere Programme for global change (IGBP) making JGOFS a core programme of IGBP but responsible directly to SCOR.

As early as 1987, several European countries were planning ocean flux field studies; in particular FRG was planning for 1989 an extensive cruise by the research vessel “Meteor” to commemorate the centennial of Hensen’s Plankton Expedition. JGOFS seized this opportunity to organise its first regional process study, which led to the 1989 JGOFS North Atlantic Pilot Study. The participating countries were FRG, UK, Netherlands, USA and Canada.

1.3 The Oceanic and Atmospheric Carbon Cycles

1.3.1 Summary of present knowledge

The oceanic carbon cycle is one of the most complex planetary phenomena. Although recognised for its importance in regulating the atmospheric CO$_2$ level more than 50 years ago (Callendar, 1938), it was not until 1957 that the first formal calculations (Revelle & Suess, 1957) were made. Even then technical problems in observing and understanding the ocean were substantial and it is only in the last 20 years or so that any significant body of useful information has accumulated.

The most familiar example of our present perturbation of the global carbon cycle is the atmospheric record (fig. 1). CO$_2$ has no active chemistry in the atmosphere, being neither created nor destroyed, and we may regard the well studied atmospheric reservoir as being fed by two complex black boxes, the oceans and the land, plus a well documented fossil fuel source of some 5.5 GtC/year. Should even one of these black boxes be well constrained, our
ability to describe the contemporary carbon cycle would be greatly enhanced (Brewer, 1986). For prediction the problem is harder, and knowledge of the fundamental principles is then required.

On land, elevated CO₂ levels cause a small stimulation in the growth of plants, but this small effect is dwarfed by the large-scale changes taking place as a result of land deforestation and reforestation (Detwiler & Hall, 1988). It is possible, though debatable, that tropical deforestation is currently matched by temperate zone forest growth (Pearman & Hyson, 1981; Tans et al., 1990).

While the annual productivity of plants in the ocean is as great as that on land, their instantaneous effect on the atmosphere is greatly damped due to the slowness of gas exchange between air and sea. The half-time for the air-sea exchange and water chemistry equations to approach equilibrium is about 5 months (Broecker & Peng, 1982). Thus the visual signal presented by the atmospheric CO₂ record, in which the annual oscillations are principally driven by exchanges with terrestrial plants, greatly underestimates the important role of the ocean. Fig. 2 illustrates this problem. It shows the greatly reduced atmospheric oscillations in the ocean-dominated southern hemisphere (Komhyr et al., 1985). In contrast to land, the addition of CO₂ to the ocean does not fertilise plants, for sea water already contains some 2 millimoles of carbon dioxide per litre.

The flow of carbon dioxide between atmosphere and ocean is dominated by ocean upwelling and downwelling. High latitude
water cools and dissolves more CO₂ before it sinks; water upwelling at the equator warms and releases CO₂. The rate of carbon entering the oceans at high latitudes and leaving at low by this route is about 40 (±10) Gt/yr (Moore & Bolin, 1986). The gas flux across the sea surface at a point is a product of the partial pressure difference and a surface transfer coefficient (piston velocity) that increases with wind speed in a known way. Global wind speed data are available from satellite measurements. Surface measurements of the partial pressure of CO₂ (pCO₂) in the ocean are sparse, and therefore global estimates of net air-sea exchange must now depend on averages over large areas of ocean and over seasonal or even annual time scales; this is what contributes most of the uncertainty in our estimates of the net CO₂ flux. Much of JGOFS will therefore be devoted to determining how the key processes vary in space and time, to improve the accuracy of interpolations.

Surface transfer is closely related to vertical mixing in the water column, which determines the gradient of CO₂ concentration with depth and hence helps determine the surface pCO₂. Chemical and biological processes determine pCO₂ away from the region of direct atmospheric exchange. Dissolved inorganic carbon (DIC) is divided between CO₂ and the much larger pool of bicarbonate and carbonate: the balance is determined by the reversible reaction

\[
\text{CO}_3^- + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons 2\text{HCO}_3^- \quad (1)
\]

Simulation of this chemical system requires knowledge of the apparent dissociation constants \(K_a\) and \(K_b\) of carbonic acid and boric acid \(K_b\) in sea water, the gas solubility, and equations linking the variables pH, pCO₂, total CO₂ (TCO₂), and alkalinity.

The interplay of chemistry (buffer capacity) and ocean and atmosphere reservoir sizes leads to a fundamental number, the Revelle factor, controlling air-sea exchanges. This, the ratio of the fractional change in the oceanic property to that of the atmospheric property, i.e.

\[
\frac{\text{dpCO}_2/\text{pCO}_2}{\text{ocean}} \div \frac{\text{dpCO}_2/\text{pCO}_2}{\text{air}}
\]

is presently about 10:1, varying with temperature and alkalinity. As we gradually enrich the upper ocean in CO₂ we perturb the system and, by Le Chatelier’s principle, the ocean will resist change, reducing its uptake of fossil fuel CO₂. Balanced against this is the exposure to the air of new, uncontaminated, deep water with its lower pCO₂. In general, after long (10³ years) exposure to an atmospheric CO₂ perturbation, the ocean will take up some 85% of the signal.

Another important process affecting pCO₂ is plant photosynthesis in the well-lit surface layer. At some times of the year the resulting uptake of CO₂ is so fast that CO₂ is driven far from its physical-chemical equilibrium and so an inverse correlation can be observed between

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**Fig. 3.** Transect made during the JGOFS 1989 Pilot Study showing the inverse correlation of surface pCO₂ and chlorophyll concentration (from Watson et al., unpublished manuscript).
surface pCO₂ and surface chlorophyll (fig. 3). The amount of carbon taken up depends on inorganic nutrients like nitrogen. In low-latitude regions basically all the nutrients are used up in the summer and therefore as much carbon as possible is taken up. At high latitudes, for example the Southern Ocean, large amounts of nutrient remain in the water all year round. If they were taken up then pCO₂(ocean), and therefore pCO₂(air), could be drawn down further. There is evidence that this happened during glacial periods. Ice core records show that changes as large as (though much slower than) the anthropogenic input occurred between glacial and inter-glacial periods (Barnola et al., 1987).

Much of the biological production is quickly recycled back to CO₂ through plant and animal respiration, and therefore does not represent a net removal. Total primary production in the ocean is perhaps 40 Gt/yr, of which, depending on the geographical location, between 10 and 40% sinks out of surface waters as particles (plant cells, faecal particles, etc.). The recycling of production through respiration can be difficult to estimate (Platt et al., 1989). There is no way to distinguish “new” or “recycled” CO₂ in primary production - and only the “new” production has any net effect on reducing pCO₂. However, nitrogen is taken up as well in an almost constant proportion of 1 nitrogen atom for every 7 carbon; and we can distinguish “new” nitrogen (primarily nitrate) from “locally regenerated” nitrogen (primarily ammonia or urea). So new and regenerated production, defined operationally by the kind of nitrogen taken up, are equated to exported and recycled carbon uptake (Eppley & Peterson, 1979; Eppley, 1989). Measurements of the “f-ratio”, the ratio of new to total production, have been made in many places and related to many features of the water (e.g. nitrate concentration), but the relations are at best tentative and empirical (Harrison et al., 1987).

Interesting questions have also been raised by recent measurements (Sugimura & Suzuki, 1988) that suggest that a large amount of carbon is locked up in high molecular weight, non-volatile organic molecules, that are broken down only very slowly. These measurements imply a downward net dissolved organic carbon (DOC) flux of 4 ±2 Gt/yr that may be important in supplying carbon to the deep ocean ecosystem. For example, Smith (1987) observed that along a transect of stations away from the continental shelf, the organic carbon demand of the sediment community exceeded the concurrent downward flux of POC, especially at two near-shelf stations. If these results can be generalised to large areas of the ocean, they raise at least two questions: Do DOC fluxes supply the remainder of the carbon required by the sediment community, and/or does the continental shelf export more carbon to the deep ocean than usually believed?

The calcium carbonate components of some phytoplankton and zooplankton also contribute to the downward flux of carbon. When organic carbon sinks, it is typically dissolved and regenerated as CO₂ in the top few hundred metres; when calcareous shells sink, they are dissolved and regenerated much deeper. As carbonate is removed from the water, reaction (1) must move to restore carbonate and therefore increase CO₂, leading to a potential reduction in the oceanic drawdown of atmospheric CO₂. It is therefore important to be able to predict the temporal and spatial succession of calcareous phytoplankton.

1.3.2 Quantifying the major pathways

JGOFS has been developed on the premise that our knowledge of the natural cycles of biogenic elements is inadequate on global and climate scales, either to predict or to detect biogeochemical change in the ocean associated with human activity. To sharpen the objectives of JGOFS and to provide a scale by which we can measure our progress, we can ask the questions: how well do we presently understand these cycles, and how well do we need to know them to achieve our goals? As already discussed, the ocean is believed to be
moderating the increase of CO$_2$ in the atmosphere by taking up the equivalent of about 45% of the new CO$_2$ being introduced into the atmosphere from human activity, i.e. about 2 Gt/yr. Although we know from models (Oeschger et al., 1975) that this oceanic uptake occurs, direct observation of the carbon cycle proves to be difficult (Brewer, 1978).

In an equilibrium ocean-atmosphere system, the globally averaged CO$_2$ exchange between ocean and atmosphere must equal zero, and the net exchange of CO$_2$ between the ocean surface and ocean interior must also equal zero. Otherwise, the pCO$_2$ in the surface ocean would on average be either greater or less than the surface atmosphere causing a net flux between the atmosphere and the ocean. In the present perturbed state, there must be a net flux of carbon from the ocean surface layer to the ocean interior to maintain a net pCO$_2$ difference at the air-sea interface; otherwise the ocean could not continue to receive an apparent net flux of 2 Gt/yr of CO$_2$ from the atmosphere. However, it is assumed that this perturbation is small and that the ocean carbon cycle is largely in balance, even though surface waters today are enriched in CO$_2$ by more than 40 micromoles/kg over those of a century ago. Volk & Bacastow (1989) conclude that “today’s major ocean sources and sinks of CO$_2$ were also major sources and sinks in the pre-anthropogenic ocean”.

Consider first the three main pathways for removal of carbon from the ocean surface layer to the ocean interior. In an ocean carbon cycle in equilibrium, the fluxes returning carbon from the ocean interior to the ocean surface layer will balance the downward fluxes:

(a) The biological pump.

A fraction of the photosynthetic fixation of carbon by marine phytoplankton sinks out of the surface ocean as detritus or the fecal pellets of marine zooplankton. This so-called “export” production must be supported by a flux of nutrients into the surface layer, mainly as nitrate from the ocean interior. The downward flux of carbon via this pathway is believed to be about 5 Gt/yr (Moore & Bolin, 1986; Martin et al., 1987, Berger et al., 1987; Garcon & Minster, 1988; Berger, 1989), but may be as high as 20 Gt/yr (Packard et al., 1988). The high uncertainty reflects the current lack of consensus within the scientific community.

(b) High latitude convection of dissolved inorganic carbon (DIC).

High latitude winter convective sinking of surface waters is thought to transport about 40 (±10) Gt/yr of DIC from contact with the atmosphere (Moore & Bolin, 1986). For typical surface total CO$_2$ concentrations, this flux requires a downward volume flux of about 50 x 10$^3$ m$^3$ s$^{-1}$ (Sverdrups) of water. The error bars are arbitrary, based on model and CTD section estimates of the southward flux of North Atlantic Deep Water of only 15-30 Sverdrups (e.g. Gordon, 1986). The doubling apparently comes from the formation of Antarctic Bottom Water (AABW) in the Weddell and Ross Seas, although recent studies (Poisson & Chen, 1987) indicate that much of the AABW forms under ice, so that the waters would not be in equilibrium with atmospheric CO$_2$.

(c) High latitude convection of dissolved organic carbon (DOC).

Until recently DOC concentrations were considered to be relatively uniform over the ocean at a concentration of order 1 gC m$^{-3}$ (about 0.08 millimole), suggesting a downward (and equal upward) flux of about 2 Gt/yr. However, the recent work of Sugimura & Suzuki (1988) yields surface concentrations in the North Pacific of order 3 gC m$^{-3}$ (about 0.25 millimole) and deep concentrations of order 1 gC m$^{-3}$. If their methodology gains widespread acceptance and if similar concentrations are typical in the North Atlantic, then 5 Gt/yr of DOC could be carried downwards by high latitude convection to where the concentrations would be much lower. We thus take our estimate of the downward flux of DOC
via this pathway to be about 4 (±2) Gt/yr.

Collectively, these three pathways could remove downwards from the ocean surface layer an amount of carbon 30 times the amount believed to be the net input from the atmosphere to the ocean due to anthropogenic activities, but the present uncertainty in our knowledge of this total is probably about 100%. The anthropogenic invasion, obeying the rules of gas exchange, and responsive to surface area, is distributed somewhat differently from the natural carbon distribution, and cannot be considered to be in steady state. Some 80% of the anthropogenic signal now resides in the upper 750 m of the great subtropical gyres (Stuiver, 1978).

Knowledge of the sensitivity of these pathways to change is the ultimate goal of JGOFS. However, one criterion for the success of JGOFS could be to determine each of these pathways to a precision comparable with the size of the anthropogenic perturbation (about 2 Gt/yr believed to be sequestered by the oceans). For the two larger pathways, that is a reduction in uncertainty of a factor of 10. That is the minimum level of knowledge required if we are to detect the expected perturbation from an equilibrium ocean carbon cycle. It is problematic to predict whether JGOFS can achieve this level of precision by the year 2000, since our knowledge and understanding in this area is evolving so rapidly.

1.3.3 Models

Early box models of the ocean CO₂ system contained an approximately correct chemical characterisation, but a greatly inadequate physical response time. Oeschger et al. (1975) provided the first calibrated diffusive ocean uptake model. They devised a single box ocean responding to a perturbed atmospheric through a 75 m thick surface layer overlying a series of diffusive sub-layers, so that the response time was much longer compared with that of a single large box of great depth. They showed that this system could correctly account for the response to the CO₂ perturbation and, by formally incorporating the differing responses to ¹⁴C and ¹³C, were able to calibrate the model against the observed tracer ¹⁴C signal.

Such models, describing fossil fuel uptake alone, were abiological, and reduced all of ocean physics to a single vertical diffusion coefficient. In order to make progress we must move far beyond this for several critical reasons:

- The ice core record shows that during the last glaciation the atmospheric CO₂ level was lowered by about 70 ppm (thus enhancing glacial cooling), and increased rapidly to pre-industrial levels at the end of the glaciation (Neftel et al., 1982). The shift dominantly involved the ocean carbon reservoir (Sarmiento & Toggweiler, 1984). Such massive reorganisations of ocean-atmosphere cycles (Broecker & Denton, 1989) jolt our complacency about climate change.

- The rapidity of greenhouse gas forcing today will probably induce ocean circulation changes, with biological feedbacks to the cycle of carbon and related biogenic elements that are poorly understood (we are not even certain of their sign), and are possibly large. Abiological models, such as those above, cannot simulate such changes.

- We must match observations of the earth-ocean-atmosphere system with the basic laws of chemistry, physics and biology if we are to gauge the effects of human intrusion.

1.3.4 Observations

Observations of the oceanic carbon system have now matured so as to make the goals of JGOFS achievable. For total CO₂ the technical problems of achieving measurement accuracy to near plus or minus 1 micromole/kg have been solved with the advent of gas extraction/coulometry techniques. Early data sets, such as those from GEosecs, relying principally upon titrations, contain a number of problems (Bradshaw et al., 1981). Discrepancies in K₂¹ and K₂¹ are close to
resolution (Goyet & Poisson, 1989). Alkalinity measurements precise to ±1 microequivalent/kg are achievable (Bradshaw & Brewer, 1988). Measurement of pCO₂ to ±1 microatmosphere is routinely achieved. For ¹⁴C the advances in accelerator mass spectrometry have made possible determinations to ±6 parts per million.

Fig. 4. Variations of TCO₂ concentration observed from April 25 to May 31, 1989 at 47°N, 20°W in the North Atlantic Ocean (solid line). The dashed line indicates the variation of TCO₂ expected due to CO₂ exchange at the ocean-atmosphere interface; diamonds indicate TCO₂ expected for CO₂ exchange across the ocean-atmosphere interface during time intervals between two measurements. The difference between a diamond and the measured value directly above or below it shows the net influence of biological activity and water mixing. The primary productivity data, provided by John Martin, permit determination of variations in TCO₂ concentration associated with biological activity.

These measurement capabilities must be set in the context of ocean variability and secular change. The annual change in surface seawater TCO₂ today, in response to fossil fuel input, is a little more than 1 micromole/kg. The seasonal change at an oligotrophic site such as Bermuda is about 30 micromoles/kg; at the JGOFS North Atlantic Pilot Study site at 47°N, 20°W a change of 50 micromoles/kg occurred in just 6 weeks (fig. 4). Plainly, if we are to observe and understand the changing carbon cycle of the ocean, these signals must be described with considerable sophistication, and their expression in different oceanic regions objectively analyzed through dedicated experiments.

The ocean we observe today is, as a result of fossil fuel CO₂ invasion, strongly contaminated. Surface seawater today contains close to 40 micromoles/kg more CO₂ than it did a century ago. Recognition of this signal is possible (Brewer, 1978) but the coefficients required for the calculation are still poorly known. The effect of this contaminant signal is to bias our estimate of ocean-atmosphere fluxes. For instance, Brewer et al. (1989) used the calculated mass transports of Hall & Bryden (1982) and Roemmich & Wunsch (1985) to estimate the net CO₂ flux across 25°N in the Atlantic Ocean. They computed a flux of 0.7x10⁹ moles CO₂/sec southward. However, by stripping the fossil fuel component from the upper layers and repeating the calculation the flux was 1.1x10⁹ mole CO₂/sec, a result some 40% larger and more consistent with the requirements of atmospheric models. JGOFS must learn to deal with an already rapidly evolving signal.

1.3.5 Predictions

Predicting the future course of invasion of a passive inert tracer signal in the ocean would be difficult enough. The characteristics of a perturbation of the ocean’s carbon cycle, which could yield significant feedbacks, are at present virtually impossible to predict. By the end of JGOFS we should be much closer to this goal. In general a warmer ocean should lead to reduced penetration of the particle flux with depth, decomposition of dissolved organic carbon and nitrogen, and more rapid nutrient cycling. At present it is believed that this would tend to elevate atmospheric CO₂ levels, but we simply do not have the scientific facts to give a realistic answer.
The JGOFS Goals and Scientific Strategy

2.1 Introduction

The Committee for JGOFS has set two goals for the programme during the 1990s (SCOR, 1987a). For planning purposes each of these goals has been broken down into a number of objectives as follows:

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**Goal 1:** To determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.

**Specific objectives within Goal 1:**

1.1 To characterize the present geographical distribution of key biogeochemical properties and rate processes pertinent to the oceanic carbon system, as a necessary prerequisite to predicting change in the system.

1.2 To quantify factors that control how carbon moves with and through the water, via ocean currents, mixing, diffusion and particle sinking.

1.3 To determine the response of the ocean carbon system to physical and chemical forcing from sub-seasonal events to decadal changes.

1.4 To estimate the exchange at ocean boundaries. These include air-sea exchanges (those most directly related to the rationale for JGOFS), exchanges at the bottom (with both benthic communities and buried sediments), and exchanges at continental margins.

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**Goal 2:** To develop a capability to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change.

**Specific objectives within Goal 2:**

2.1 To determine the role of the ocean in modifying the atmospheric increase in anthropogenic CO₂ and other gases affecting climate.

2.2 To develop coupled physical and biogeochemical models of the ocean for the purposes of testing our understanding and improving our ability to predict future climate-related change.

2.3 To establish strategies for detecting, above the background of natural seasonal and event-scale variability, longer term changes in ocean biogeochemical cycles in relation to climate change.

2.4 To examine the late Quaternary palaeoceanographic record to determine the relationship between ocean circulation, palaeoproductivity, and CO₂ content in the atmosphere, to aid in the prediction of future CO₂-related climate change.

There is a tension in ocean science between providing good, large scale descriptions of oceanic conditions and understanding the fundamental processes that cause them to be as observed. Successful attainment of the JGOFS goals requires a dual track pursuit of a large scale global survey and an understanding of pertinent biogeochemical
processes by site-specific process studies. Although basin and global surveys and satellite data provide an inventory of relevant variables at specific spatial and temporal locations in the ocean, they do not provide information on the rates of transformations of matter and energy at these sites nor on how those rates are influenced by physical forcing and ecosystem dynamics. Moreover, such inventories do not provide an understanding of what causes and maintains the patterns of material distributions, fluxes and biogeochemical cycling, or the mechanisms whereby matter is altered in the ocean. Detailed, process-oriented studies are required at numerous sites in the ocean with the goal of providing an understanding of ocean processes in sufficient detail that can be incorporated into models for the simulation and prediction of biogeochemical fluxes. Since we neither have good large scale descriptions of many biogeochemical variables, nor understand how the many processes that relate these variables operate on either the meso- or basin-scale, a variety of model studies are required to identify critical processes and parameters, and to act both as an assimilation mechanism for the observed data sets to produce basin-scale fields, and to predict the future state of the ocean.

Therefore JGOFS proposes a strategy which braids five strands:

- A number of process studies to elucidate the mechanisms controlling the carbon cycle in different parts of the world ocean,

- A large scale, global survey activity using remote sensing, ship observations on a global set of transects, and a long time series observation programme at key sites, to improve basic descriptions of biogeochemical variability,

- Model studies to identify critical processes and variables, to assimilate observed parameters into basin and global scale fields, and to predict the future state of the ocean,

- A study of the past climatic record by means of geochemical sampling of deep-sea and continental shelf sediments, and,

- An international data archiving effort to assimilate and use effectively the vast amount of high quality data that will be obtained during the JGOFS observational period.

These components are not mutually exclusive scientific activities but interact with each other in various ways (fig. 5). In later chapters the five strands of the JGOFS strategy will be discussed in more detail, but in the remainder of this chapter we will highlight how each of them contributes to the JGOFS objectives.

![Fig. 5. The interactions between the various components of JGOFS.](image)

### 2.2 Attaining the JGOFS objectives

**Objective 1.1: To characterize the present geographical distribution of key biogeochemical properties and rate processes pertinent to the oceanic carbon system, as a necessary prerequisite to predicting change in the system.**

This objective will be achieved by a mixture of global surveys and process studies. Few large scale surveys of biogeochemical variables have been carried out in the ocean.
The GEOSECS and TTO programmes generated a number of long transects of geochemical parameters in the central ocean basins, which provided a one-time picture of the deep ocean state. However, the JGOFS emphasis on carbon cycling gives rise to the need for new global data sets that were not envisaged when these earlier programmes were designed.

A composite, large scale biogeochemical view of the ocean surface, mid-depth, and deep waters is necessary for achieving this objective. We cannot develop models to identify critical processes, validate existing and future models, nor understand the ocean's role in the carbon cycle without such data.

It is proposed that the JGOFS global survey should be achieved by:

- Using satellite data of ocean colour and other remotely-sensed data to provide a global, time-varying picture of phytoplankton pigment and primary production,
- Measuring CO₂, nutrients and, when possible, phytoplankton pigments on the transects of the WOCE Hydrographic Programme (WHIP),
- Implementing, wherever possible, key JGOFS sections to acquire further data essential for describing the biogeochemical cycling in different oceanic zones,
- Conducting an internationally coordinated global array of sediment traps and benthic flux measurements.

More details of these plans are given in chapters 5 and 6.

A global survey, desirable though it is, cannot alone enable us to achieve objective 1.1. Our knowledge of the ocean carbon cycle is still far from complete and so carefully designed process studies are required to increase our basic understanding of the underlying mechanisms. Each process study will have some unique objectives that reflect the characteristics of the site being investigated. However, in order to achieve the objective, all process studies in JGOFS should have the following generic aims:

- To assess the rates of, and controls on, vertically distributed primary production, and the degree to which they can be inferred from remotely sensed quantities such as near-surface pigment, diffuse attenuation, and solar irradiance,
- To assess the processes controlling atmosphere/ocean gas exchange,
- To define the dynamics and fluxes of particulate and dissolved organic matter as functions of physical forcing, primary production, and trophic interactions in the euphotic zone,
- To understand the mechanisms governing the distribution, transformation, and sedimentation of particulate matter throughout the water column and to measure the significant rates,
- To define the nature, rates, and controls of material transfer at the sediment-water interface,
- To develop, to the extent possible, algorithms that relate biogeochemical fluxes and transformations occurring throughout the water column to a limited suite of variables available from remote sensing platforms or ocean ship surveys.

From oceanographic studies carried out in the past twenty years it is clear that the mechanisms controlling the carbon cycle are not uniform throughout the world ocean. There are obvious latitudinal differences in physical surface forcing, and the ocean current system has as yet poorly understood effects on ecosystem structure. It is therefore necessary to plan a series of process studies at a number of sites that will give a sufficient representation
of the diversity of the ocean biogeochemical system. This topic is discussed more fully in chapter 3, and further details on the aims and planning of process studies are given in chapter 4.

**Objective 1.2:** To quantify factors that control how carbon moves with, and through the water, via ocean currents, mixing, diffusion and particle sinking.

This objective concentrates on the role of transport processes in the carbon cycle. Many small space-scale transport processes can be studied as part of a process study. For example, vertical mixing can be determined from property profiles, always assuming vertical eddy diffusivities can be estimated. Similarly the particulate sinking flux can be estimated from floating sediment traps. However, it is often difficult to distinguish vertical and horizontal advective processes when carrying out process studies. One approach is to minimise the effect of horizontal transport by a Lagrangian sampling technique. One or more drogued buoys are deployed and the process experiment is positioned relative to the drogues. There are, however, a number of practical problems associated with this method, such as deciding the depth of the drogues and how best to determine the average position of a set of drogues moving in different directions. This approach is being employed during the 1990 U.K. JGOFS cruises in the N.E. Atlantic and so some answers to these problems may be forthcoming. Another approach involves the concept of control volumes (Dickey & Siegel, 1988) in which one ship is deployed to carry out, say, a triangular survey with the aim of quantifying the horizontal transport, while a second ship measures the time rate of change of the biogeochemical fields at the centre of the triangle.

The larger scale transport of carbon and nutrients within the ocean can at present only be inferred from traditional oceanographic transect surveys and modelling studies. The information on ocean currents obtained from the WHP and the WOCE modelling programme, coupled with the distribution of biogeochemical properties obtained from past and future surveys, will be a key factor in the attainment of this objective.

**Objective 1.3:** To determine the response of the ocean carbon system to physical and chemical forcing from sub-seasonal events to decadal changes.

The response of the ocean carbon system to sub-seasonal events can be studied by well planned multinational, multi-platform, process studies. An example was given by the 1989 JGOFS North Atlantic Pilot Study, which involved ships from five nations deployed in the north-eastern Atlantic from March until October (fig. 6; see chapter 6 for further details). This exercise yielded a unique, highly resolved, data set on the changes in a temperate ecosystem over the period from late winter, through spring and summer and into autumn. More such long duration process studies are planned between 1991 and 1997.

Turning to the longer time-scales, valuable long time series of physical and biological observations exist for weather stations ("Papa" in the Pacific and "India" in the Atlantic) and the Bermuda site (station "S"). Further data of this sort would be invaluable and the US JGOFS programme has initiated two time-series stations close to Bermuda and Hawaii. However, until NASA began to produce the global pigment maps derived from the NIMBUS-7 Coastal Zone Colour Scanner (CZCS), there were no time-varying descriptions of global oceanic fields of a biological variable. These maps (fig. 7) have already greatly influenced our perception of the biogeochemical processes in the ocean and have provided data for testing models. The satellite observations show an ocean that is heterogeneous on many scales, with the largest part of the variance at low spatial and temporal frequencies. These large time and space scales are at present most poorly
observed in the ocean and therefore a satellite-based observing programme is an essential component of JGOFS.

In summary JGOFS proposes studying the time-response of the ocean carbon system by:

- Mounting long-duration process studies in selected ocean areas.
- Using satellite data to observe the large-scale response of the phytoplankton system to seasonal and other events.
- Supporting a number of long-term time series sites in diverse regimes in order to address inter-annual variability.
- Cooperating with other international programmes (WOCE, TOGA, IGAC) to produce large scale seasonal descriptions by augmenting the observing system as required.

More details of these plans are given in chapters 5 and 6.

Fig. 6. Ship coverage during the JGOFS 1989 North Atlantic Pilot Study.
Fig. 7. World pigment map produced by NASA Goddard Space Flight Centre and the University of Miami from CZCS satellite data. This composite image of the ocean chlorophyll concentration was produced from 31.352 4-km resolution CZCS scenes from November 1978 through June 1981. The scale indicates increasing concentrations of pigment concentrations ranging from <.05 mg/m² (violet at left) to 30 mg/m² (red-brown at right).
Objective 1.4: To estimate the exchange at ocean boundaries. These include air-sea exchanges (those most directly related to the rationale for JGOFS), exchanges at the bottom (between both benthic communities and buried sediments), and exchange at continental margins.

(a) Air-sea exchanges

The air-sea exchange of most interest to JGOFS is the flux of CO₂ between the ocean and the atmosphere. As discussed in section 1.3.1 this flux can be estimated from the pCO₂ difference between air and ocean and the piston velocity, itself a function of wind speed. Global estimates of the latter quantity can be obtained from satellite data (Etcheto & Merlivat, 1988), but there are insufficient data on the spatial and temporal distribution of sea surface pCO₂, especially at high latitudes, which may cast doubt on our present estimates of this flux. JGOFS proposes to meet this need by implementing seasonal surveys of pCO₂ (see section 6.4).

(b) Exchanges with benthic sediments

The benthic ecosystem is a lower boundary condition for the ocean carbon cycle; any model we construct must provide sufficient carbon to support the community metabolism plus the small fraction of carbon that remains permanently buried in the sediments, thereby contributing to the sedimentary record. JGOFS will therefore encourage the measurement of appropriate benthic fluxes, either as an element of process studies (see section 4.4.3 and chapter 8) or, as previously discussed, as part of a global survey.

(c) Exchanges with coastal seas and shelves.

In the late 1980s an extensive US programme (SEEP) was carried out to try and quantify the interchange of organic matter and nutrients across the US eastern shelf edge (Walsh, 1988). Despite this activity, the extent to which continental shelf ecosystems export organic matter to the open ocean is still a matter of some debate (Rowe et al., 1986). However, there is much geochemical evidence for the interchange of certain elements and a US-JGOFS workshop on this subject (GOFS, 1987) recommended that a further observational programme was required in order to meet JGOFS goals. JGOFS has not, as yet, planned a process study of the ocean-shelf margin. At the JGOFS Pacific Planning Meeting in Tokyo in April 1990 it was pointed out that Chinese rivers inject close to a quarter of the total sediment from land to the ocean margins, and it is not clear how much of this material is exported to the ocean interior. Many countries strongly supported a JGOFS process study of the Western Pacific marginal seas. The IGBP core project on "Land Ocean Interactions in the Coastal Zone" (LOICZ) also has an interest in the ocean-shelf interface as an outer boundary condition for its own studies of coastal seas. It is clear that objective 1.4c can best be achieved by organising one, or more, cooperative JGOFS-LOICZ programmes at selected ocean margin sites.

Objective 2.1: To determine the role of the ocean in modifying the atmospheric increase in anthropogenic CO₂ and other gases affecting climate.

The part of this objective relating to CO₂ will be achieved by the gradual synthesis into models of the information obtained by the programmes designed to achieve goal 1. It is impossible to predict at this stage how successful JGOFS will be in achieving this objective. To a great extent success will depend on the resources that can be deployed by the oceanographic countries of the world. This objective should be clearly kept in mind during the first few years of the implementation phase of JGOFS, so that the objectives associated with goal 1 can be modified if it would make the successful achievement of objective 2.1 more likely.

Other atmospheric trace gases such as
methane, nitrous oxide, chlorofluorocarbons, and dimethyl sulphide are also implicated in future climate change scenarios and, unlike CO₂, they are reactive in the atmosphere. The study of these gases is the focus of the IGBP core project “The International Global Atmospheric Chemistry Programme” (IGAC). One of the IGAC foci (Galbally, 1989) is “Natural variability and anthropogenic perturbations of the marine atmosphere”, which clearly overlaps with our JGOFS objective. Bearing in mind the global ship coverage implied by the JGOFS plans in the 1990s, a close cooperation with IGAC to achieve our common goals is obviously imperative.

**Objective 2.2: To develop coupled physical and biogeochemical models of the ocean for the purposes of testing our understanding and improving our ability to predict future climate-related change.**

This objective, the overall goal of the JGOFS modelling programme, will be achieved by developing comprehensive global models of the oceanic carbon cycle, and associated elements, that will be used to diagnose the present and predict the future response of the oceanic biogeochemical system to climatic change.

Within this goal we can identify three specific objectives:

- The development of local or regional biogeochemical models to provide a context for specific JGOFS field programmes, and to determine critical quantities, flows, or parameters that need to be measured to achieve the overall goal.

- The development of models that will estimate phytoplankton surface chlorophyll concentrations, total primary production, and new production from satellite ocean colour and other remotely sensed data. and,

- The development of global models capable of predicting the biogeochemical fluxes of carbon, and associated elements, both within the ocean and across the ocean-atmosphere interface.

These objectives can only be met if operational ocean circulation models are available. Such models are being actively developed by the WOCE community and a close linkage with these groups will be developed.

Further details of the modelling plans are given in Chapter 7.

**Objective 2.3: To establish strategies for detecting, above the background of natural seasonal and event-scale variability, longer term changes in ocean biogeochemical cycles in relation to climate change.**

Two aspects of the JGOFS programme are directed towards this objective. The first is the detection of an increase in the anthropogenic CO₂ content of the ocean by repeating, some years later, the global survey of CO₂ being carried out as part of the WOCE Hydrographic Programme. The accuracy of CO₂ measurements has now increased sufficiently that this would be possible after a period of about ten years (see section 6.2.2). The second is the detection of changes in global primary production using satellite ocean colour observations (see chapter 5). Both of these approaches would be stretching our present technology and resources to the limit. However, it is possible that as a result of the accumulated research of the JGOFS programme other strategies may be discovered.
Objective 2.4: To examine the late Quaternary palaeoceanographic record to determine the relationship between ocean circulation, palaeoproductivity, and CO$_2$ content in the atmosphere, to aid in the prediction of future CO$_2$-related climate change.

This objective will be achieved by palaeoceanographic studies that will focus on the central themes of the programme, namely the transformation and transport of carbon in the ocean, as well as the subsequent deposition in sediments. Carbon that is fixed in the phytoplankton and zooplankton (both as tissue carbon and as skeletal carbonate) of the surface layer is incorporated in rhythmic sequences and is in part also recycled within this zone. This component alone contains the signal for the condition of the entire system at a time-scale of hundreds to thousands of years. However, even if all the processes operating at the present time were precisely known, the extrapolation of the information contained within the sediments to a time sequence and the prediction of reactions to disturbances is difficult. In order to improve our interpretation of the sedimentary record it is important that the JGOFS process studies should measure other biogenic components, in addition to the carbon flux, for the comparison of contemporary benthic fluxes with the sedimentary record. Further details of JGOFS plans to study the sedimentary record are given in Chapter 8. These activities will be coordinated with the IGBP project on "Past Global Changes", which includes efforts to recover palaeo-data dealing with past carbon cycles.
Fig. 8. Currents and temperature deviations at the surface of the world ocean. “Temperature variation” represents the deviation from the average temperature over the whole southern hemisphere ocean at the corresponding latitude (from Dietrich et al., 1980).
3

Definition of Biogeochemical Provinces

3.1 Introduction

This chapter addresses the amount of spatial detail that JGOFS sampling will need, by dividing the oceans into a set of provinces within which the biogeochemical cycle can be considered structurally homogeneous. Ideally, the inventory of provinces should be made as economical as possible. Completeness can always be achieved using dense grids and long time-scale studies, but economy demands a choice of “crucial” stations which will yield similar information at a much reduced cost. We need to focus our investigations so that the effort expended in different areas of the ocean reflects a weighting in terms of additional information gained. Such weighting must include both the size of the new area represented by an additional study and the new qualities in the pattern observed.

The ocean can be seen as a set of interconnected subsystems, each of which generates its own typical flux patterns. Once these subsystems are defined, the whole ocean can be modelled with some confidence by the integration of its parts. The problem is that the subsystems are unlikely to be well-defined. There are no biogeochemical provinces that, like countries in a global community, can be delineated by geographic boundaries and the particular (biogeochemical) language spoken within. Instead, there are regions with more or less similar patterns of background conditions and processes, that are separated from other such regions by more or less distinct transition zones. Within a transition zone, patterns may be quite different from either region and may not necessarily be depicted as a combination of the patterns which it separates. The position of these transition zones may also vary seasonally.

The identification of a “province”, then, will depend upon a specific definition of “similarity” in terms of physical, chemical, and biological properties and processes.

3.2 Similarity, Gradients, and Oceanographic Tradition

Physical and biological oceanographers have long attempted to provide an identification of typical regions as “water masses” or “biogeographic provinces” (McGowan, 1974; Backus et al., 1977; Fasham & Foxton, 1979). Their observations (temperature, salinity, oxygen content of subsurface waters, and faunal/floral compositions) are quite numerous and global, providing useful guidelines for subdivision. As an example, the surface water temperatures (deviations from the normal distribution) and the surface water currents during the northern hemisphere winter are shown in fig. 8. One highly useful means of drawing boundaries, in the present context, is the distribution of primary productivity (fig. 9). It is quite closely tied to physical parameters, and integrates information about nutrient content of subsurface waters, seasonal mixing and upwelling, and solar irradiation. More recently, Platt & Sathyendranath (1988) have put forward a scheme for subdividing the oceans into a finite set of provinces based on a parameterisation of primary productivity.

Another approach is to overlay global maps showing average annual temperature, seasonal temperature variation, and average productivity (Koblentz-Mishke et al., 1970; Berger et al., 1987) in order to find regions with a “similar” pattern. Such regions would function as “biogeochemical provinces”, with their own typical export production patterns.
They would show a close association with the traditional geographic subdivisions based on surficial current systems for the obvious reason that circulation drives both chemistry and biology. The zones separating the provinces, with their strong gradients, would be worthy of study in their own right.

### 3.3 Province Types and Nutrient Supply

Oceanic provinces can be characterized by the physical forcing functions determining the extent to which primary production (or new production) is supported by the import of new nutrients. On a global scale this includes the formation of bottom water in high latitudes and the upwelling of nutrient rich water (Chavez & Barber, 1987). On seasonal and regional scales, provinces will emerge via mapping of the depth of the winter mixed layer, upwelling, mesoscale eddies, horizontal advection in the transition zones between coastal and shelf waters, as well as between shelf and oceanic waters, and short-term advection and mixing induced by local wind events.

High nutrient supply, from strong vertical exchange processes, serves to establish large oceanic provinces in which seasonal or yearly production and the related particle fluxes are high. Polar regions, temperate areas, coastal and equatorial upwelling regions are examples of such provinces. These provinces are likely to play a considerable role in the oceanic carbon cycle: the polar and upwelling regions are sinks and sources, respectively, for atmospheric carbon dioxide (Broecker & Peng, 1982). In comparison, the sub-tropical gyres, in which the upward transport of nutrients is impeded by a shallow thermocline, have lower production and export fluxes per unit surface area. Due to their vast extent, however, they nevertheless contribute significantly to the
ocean carbon cycle. An important feature of these regions is the nutrient entrainment into the lower part of the euphotic zone, that fuels new production and vertical particle flux on the event scale (Goldman, 1988). These patterns of new production and particle export are generally reflected in the composition and amount of biological residues in the underlying sediments, especially in their organic carbon contents (fig. 10).

Episodic events of nutrient enrichment in surface waters associated with mesoscale eddies (Nelson et al., 1985, 1989; Woods, 1988), or sporadic nutrient pulses caused by local wind events (Klein & Coste, 1984; Eppley & Renger, 1988), may support a large proportion of the annual new production, even in the central gyre regions (Platt & Harrison, 1985). Satellite images of pigment data have been successfully used to record such events (Lohrenz et al., 1988). Algorithms to convert such images to primary production are available (Platt & Sathyendranath, 1988; Platt et al., 1989), and the definition of oceanic provinces is further refined by mapping the frequency of such events from satellite data (fig. 11). That these events are generally of a seasonal nature can be seen in the particle flux measurements (e.g. Deuser, 1987; Honjo, 1984; Wefer et al., 1988).

3.4 Ecosystem Structures

Neither the quality nor the quantity of the biologically controlled or influenced carbon export has a “linear” relationship to the nutrient input (fig. 12). As a result, the provinces must be defined on the basis of characteristic biological “system structures” in addition to the physical forcing functions. Whereas physical forcing is decisive for the overall magnitude of export fluxes, ecosystem structures will influence the character of the export, i.e. fast sinking particles, fine suspended particles with low (if any) sinking rates, and dissolved organic matter. Regions and seasons with different ecosystem structure are found within each of the provinces described by physical forcing functions, mediating the physical constraints on food web structures. The abundance, size distribution, and depth of primary producers and consumers reflect differences in physical adaptations and life cycle strategies (Margalef, 1978; Smetacek, 1985; Legendre & Le Fèvre 1989). The size distribution of phytoplankton and size and trophic position of the consumers determine the magnitude and composition of particulate and dissolved export rates (Michaels & Silver, 1988).

![Fig. 12. Variation of f-ratio (the ratio of new production to total production) with the ambient concentration of nitrate (from Eppley, 1989).](image)

The differences in the biologically mediated flux are reflected in the time lag between physical supply and photosynthetic assimilation of new nutrients on the one hand, and vertical loss rates of organic matter on the other (Parsons & Lalli, 1988). These macroscopic properties can be expressed as seasonal and regional differences in the ratio of new to total production (the f-ratio), which may serve for the further refinement of provinces.

On coastal shelves, temperate seas, and polar regions, particularly near the seasonally receding ice edge, there are provinces where
large phytoplankton cells (commonly diatoms) dominate the annual spring blooms and sink as cells or aggregates to the seafloor without undergoing significant remineralisation (v. Bodungen et al., 1987). Such vertical export of freshly-assimilated new nutrients is also important in provinces where episodic and sporadic nutrient entrainment into the euphotic zone fuels a large part of the annual new production (Platt & Harrison, 1985; Platt et al., 1989).

Species compositions that result from adaptation and tropho-dynamic interaction will also influence the inorganic composition of export fluxes (Peinert et al., 1989). Of special interest are ratios in the fluxes of organic material to siliceous and calcareous skeletons of primary producers and heterotrophic organisms such as diatoms, cocolithophorids, radiolarians, foraminifera and pteropods.

Flux patterns and composition are altered in provinces where the primary product is channelled into the pelagic food web and oxidised to various degrees in the different depth strata. Generalist feeders such as the Antarctic krill or salps in the North Atlantic considerably accelerate particle flux to great depth via their fast-sinking faecal pellets, regardless of whether these organisms feed on new or regenerated production (v. Bodungen et al., 1987; Michaels & Silver, 1988). This also applies to the short foodwebs that develop during coastal upwelling events.

Seasonally migrating copepods and surface layer over-wintering mesozooplankton populations may prevent outbursts of new production and, despite their potentially fast sinking faecal pellets, may conserve matter in the upper layers, as has been reported from the North Pacific and the Norwegian Sea (Frost et al., 1983; Peinert et al., 1989). In such ecosystems, annual maxima of particle flux occur later in the season, as they are influenced by life cycles and/or shifts in the major grazer populations (Peinert et al., 1989). Vertical migration of organisms that feed in the euphotic zone and excrete faeces and dissolved substances in deeper layers will also change the pattern of export flux, as does the activity of bathypelagic communities (Longhurst & Harrison, 1988). The various trophodynamic interactions in all depth strata in the biological provinces of the ocean will influence the proportion of new production reaching the seafloor and contribute to the benthic and burial fluxes. Likewise, these interactions determine what proportion will be exported as fine particulate and organic matter, contributing to oxygen utilisation within the oceanic thermocline.

3.5 Sedimentation Regimes

Differences between physico-biological provinces translate into differences in sediment delivery, as mentioned above. Thus, an excellent way to determine major biogeochemical provinces is to map the content of organic carbon (fig. 10) in sediments. The result is that once again, the great dichotomy between the "green" and the "blue" ocean emerges. Dissolved silicate tends to be removed efficiently closer to shore. Nitrate is used up somewhat less rapidly, presumably because nitrogen is more readily recycled. A small residual of phosphate tends to remain after the initial extraction of nutrients.

The sea floor below an upwelling plume experiencing differential stripping of nutrients receives the corresponding materials: first silica and then organic carbon, with increasing distance away from an upwelling area. Organic matter, when supplied in sufficient amounts, leads to oxygen deficiency in the bottom water and can cause anaerobic sedimentation. If conditions fall short of the extreme of immediate sulphate reduction at the sediment surface, carbonate tends to be dissolved because of the low pH of interstitial waters due to a high concentration of carbonic acid.

The definition of provinces by these criteria would be based on (1) sulphate reduction, (2) organic matter burial, (3) silica burial, and (4) preservation of carbonate
corrected for saturation of bottom water). Over
large areas of the deep sea, especially in the
Pacific, this method would not work well
because little is known about the red clay
provinces in terms of subtle difference in silica
and organic carbon content. However, the
major role of the continental margins would
clearly emerge.

3.6 Selection of observational sites for
Process Studies

It is obvious from the above description of
the different approaches to defining criteria for
biogeochemical provinces that only a
combination of them will yield a suitable
compromise for the selection of observational
sites for the Joint Global Ocean Flux Study. A
detailed set of observations that could serve as
an objective basis for choosing sites does not
yet exist. Pelagic observations reflect particular
events as much as long-term averages. The
intuition of experienced oceanographers is
needed to help in the selection, and is reflected
in the following list of suggested sites. One of
the legacies of JGOFS will be better data and
concepts for defining provinces. More detailed
physical and biogeochemical characterisations
of these sites are given in the U.S. JGOFS
Science Plan (U.S. JGOFS, 1990)

1. The North Atlantic

The factors controlling the seasonal cycle
of production in North Atlantic were the focus
of the successful international JGOFS Pilot
Study in 1989 (see section 4.4.1). A number of
European nations will be carrying out further
studies in the north-east Atlantic in the early
1990s and a comparative study with the north-
east Pacific has been proposed for 1995.

2. The Equatorial Pacific

The Equatorial Pacific will be the site of
the second major JGOFS Process Study
beginning in the fall of 1991. The major
objective of this experiment will be the physical
and biogeochemical mechanisms regulating
primary production and vertical fluxes driven
by equatorial upwelling. The Western Pacific
undergoes strong interannual variability
caused by El Niño-Southern Oscillation
(ENSO) events, and their effect on productivity
and biogeochemical cycling is at present
largely unknown. This variability creates the
need for a longer term sampling programme
and the involvement of the East Asian
countries, Australia, and New Caledonia will be
essential. The Equatorial Pacific was the
subject of international planning meetings at
Honolulu in 1989 and Tokyo in 1990.

3. The Southern Ocean

A site in the Southern Ocean will
probably be the focus of the next JGOFS
process study. The main subjects of this study,
 provisionally planned to begin in 1992, will
concern the role of the Southern Ocean in the
global CO₂ balance, the reasons for spatial
variability in production, the persistence of
high nitrate levels in the surface waters, and
the possible role of iron as a limiting nutrient
(Martin & Gordon, 1988). The study may be
located in the Weddell Sea, an important region
of bottom water formation. Another area of
interest is the west-wind drift along the
Antarctic Convergence, a region characterized
by intense mesoscale variability. The CZCS
data show a band of higher phytoplankton
pigment concentrations associated with the
convergence. The JGOFS study in the
Southern Ocean will be discussed at the
"Biogeochemistry of the Southern Ocean" meeting in Brest in July, 1990.

4. The Northwest Indian Ocean

This study, which is planned to begin in
1994, will address the variations in primary
and new production and export fluxes that
arise from the seasonally reversing monsoonal
circulation. Other influences on the region
include episodic dust input from the Arabian
Peninsula. An international planning meeting
for the Indian Ocean is now under discussion.

The following process studies have been
suggested by the JGOFS Scientific Steering
Committee or by national JGOFS Committees,
but the final decision on whether, or when,
they will take place will be made during the formulation of the JGOFS Implementation Plan.

5. The Gulf Stream

A process study focussing on the exchange of particles between this energetic western boundary current and the continental margin, and on the sharp productivity gradients across the current, would be located along a transect between Cape Hatteras and the Sargasso Sea. This study should be timed to coincide with any future U.S. studies of shelf-ocean exchanges.

6. The Kuroshio and Western Pacific Margin

The Kuroshio is a major source of heat and nutrients for the Northwest Pacific. It interacts strongly with marginal seas into which several major rivers input large amounts of freshwater and other materials. The area also experiences sediment input from atmospheric dust transport from Asia. Materials could be transported from the seas to the ocean interior by the Kuroshio itself or through branches of the Kuroshio, i.e. induced shelf currents, by way of the Japan Sea. The East China Sea is an ideal place to study fluxes between coastal seas and the open ocean.

7. The Polar Ice Margin

The Southern Ocean is now recognised as a region of very low primary production. The exception, once thought to characterize the entire ocean, is the productive zone near the ice edge, which exhibits extreme variations in sedimentation. Similar zones are associated with the ice edges in the Arctic. A process study located in the Bellinghausen Sea, planned by the British Antarctic Survey (BOFS, 1990), will emphasise the paradigmatic diatom-krill food chains of the ice edge zone and the physical and geochemical dynamics supporting that production.

8. Central Gyres

The persistently nutrient-depleted expanses of the central gyres have possibly the lowest primary production, but also cover vast areas. The annual averages for primary and new production and export fluxes remain poorly characterized, as do the mechanisms driving vertical nitrate supplies that support the production system. A JGOFS process study could be located in the Atlantic, along the Cape Hatteras-Sargasso Sea transect, or in the Pacific along a transect between Hawaii and the Oyashio Current. Both of these transects would include observations at the two US JGOFS time series stations.

9. Eastern Boundary Upwelling

The major upwelling areas in the Atlantic and Pacific have been extensively studied in the past. However, a coordinated study of one of these areas using the whole suite of JGOFS measurement techniques may be warranted. Possible candidates are the Peru or Benguela upwelling regions.

10. The Subarctic North Pacific Gyre

In contrast to the North Atlantic, winter mixing in the North Pacific is limited to 150m by a strong halocline and this has implications for the timing and magnitude of the spring bloom, gas exchange, and the oceanic distribution of dissolved gases and nutrients. This area has already been the subject of an extensive multi-disciplinary programme (SUPER) and the information derived from this exercise will be invaluable for planning a JGOFS process study.

11. The Northern North Atlantic

This area, comprising the Greenland and Norwegian Seas, plays an important role in the draw-down of atmospheric carbon due to the formation of Atlantic Deep Water in the Greenland and Barents Seas. The biologically mediated carbon flux is regulated by a series of seasonally changing complex ecosystem structures. Information is required on the seasonal regulation of the carbon cycle, particularly the relative proportions of organic flux to those of siliceous and calcareous skeletons.
4 Process Studies

4.1 Introduction

Process studies lie at the heart of JGOFS, providing detailed observations of key oceanographic phenomena including annual and shorter term events, experimental tests of hypotheses, and measurements of fluxes and parameters. They aim to elucidate in a mechanistic way the processes controlling biogeochemical fluxes on scales of hours to months as they operate in particular ocean regions. The JGOFS North Atlantic Pilot Study, a year-long, international, multi-platform investigation of the spring phytoplankton bloom in the eastern North Atlantic Ocean, provides a model for the design, planning and execution of future process studies. In this section, the objectives, scientific components, and experimental design considerations of JGOFS process studies will be discussed.

4.2 Justification

Process studies address questions about oceanographic events, properties and processes that cannot be approached adequately by time series or large scale operations. The central aim of these studies is to provide models of short-term biogeochemical processes that can be used to explain and predict global scale patterns of element cycling between the atmosphere, ocean and sediments. To accomplish this goal, process studies must yield information on the rates and interactions of a wide array of biogeochemical and physical processes, using a correspondingly large range of observational techniques. In particular, methods that are too time-consuming or technically demanding to be employed in other JGOFS operations are required to define the rates and mechanisms controlling biogeochemical fluxes. Furthermore, most processes controlling such fluxes are Lagrangian in nature, residing in mesoscale or smaller water masses that move and evolve in time and space. Thus, with a few key exceptions, observations of key processes cannot be carried out at fixed sites or along basin-wide sections without aliasing.

In order to fill the observational and conceptual gaps between the time series and large scale components of the JGOFS Programme, and to provide formulations of specific biogeochemical processes for models, a series of multi-platform, international cooperative process studies have been proposed (see section 3.6).

4.3 Aims

The principal aims of the process studies component of JGOFS are:

4.3.1 Inventory of key fluxes.

One goal of JGOFS is a better understanding of the processes controlling the air-sea-sediment fluxes and phase transitions of carbon and other biologically regulated elements. A modern series of measurements of the rates of key processes (e.g., new production, vertical transport, air-sea gas exchanges) in the major biogeochemical provinces of the global ocean is required for this purpose.

4.3.2 Definition of control mechanisms

The rates, timing, and spatial organisation of the major flux processes vary in different regions due to regional variations in physical
driving forces (e.g., convective overturning, solar irradiance, upwelling, storm frequency), and differences in the ecological structure of foodwebs and the taxonomic composition of biological communities (see Chapter 3). The physical and biological mechanisms leading to spatial variations in geochemical fluxes will be explained by properly designed studies tailored to each particular situation.

4.3.3 Description of events.

Biogeochemical fluxes occur during various oceanographic events, ranging from the weekly to monthly passage of synoptic storms, through mesoscale phenomena like eddy evolution and annual occurrences such as spring blooms and ice edge migration, to large scale interannual oscillations like El Niño. Because biogeochemical flux variability is concentrated in events at a range of scales, rather than proceeding steadily and inexorably over large regions, an important goal of the process studies is to provide careful descriptions of the temporal progression and geographic extent of such events.

4.3.4 Model calibration and parameter evaluation.

The ultimate goal of JGOFS is the construction and application of hybrid biogeochemical process/general circulation models that can define the current biogeochemical state of the ocean, and predict its future evolution in response to global warming and other externally imposed changes. These models require a large number of parameters, many of which are presently poorly defined or difficult to evaluate. Examples include physiological parameters characterising the photosynthesis-irradiance and nutrient uptake-concentration relationships in phytoplankton, physical parameters such as particle adsorption-desorption and gas exchange coefficients, and geochemical rate constants governing diffusion of solutes in sediments. Such parameters may best be evaluated through experimental studies carried out during process studies. It is particularly important to define the variability of each in space and time, and characterize the factors regulating that variability.

4.4 Description of a process study.

While the principal biogeochemical processes occur in all ocean basins, their relative magnitudes, controlling mechanisms and variability differ from one region to the next. Each area may have unique problems about which JGOFS will ask particular questions. Therefore, each process study will be designed to address the critical events, processes and scales of variability in each region to be studied, and the various studies will differ somewhat in their organisation, duration, overall scope, size, and composition. Nonetheless, there will be common elements to all process studies that are as important as the differences. Some of the key similarities and differences are discussed below, as a step towards describing a process study.

4.4.1 The JGOFS Pilot Study

In 1987, the SCOR Committee for JGOFS resolved to carry out a pilot process study as a means of laying the operational foundation for international cooperation in multidisciplinary studies of biogeochemical fluxes. A predictable, easily detectable event of clear significance to JGOFS aims was desired. Spring phytoplankton blooms are predictable annual events during which a large fraction of the primary production is exported from the surface layer, and they typically exhibit large chemical and biological signals in response to the vernal restratification of the upper ocean. Analysis of CZCS imagery of surface pigment fields showed that the bloom in the North Atlantic is one of the largest (area x duration x amplitude) seasonal events in the global colour field. Previous observations suggested that this was a consequence of the intensive deep mixing driven by convection in the North Atlantic. A study of the spring phytoplankton bloom in the eastern North Atlantic Ocean, already in independent planning stages in several countries, was chosen as the subject
for the pilot study at an international planning meeting held in Paris in 1987 (SCOR, 1987b).

The scientific objective of the Pilot Study was to gain a new understanding of the temporal evolution of the spring bloom, the mechanisms responsible for its generation, maintenance and decay, and the biogeochemical consequences emanating from it. The main elements of the study included observations of the hypothetical northward progression of the bloom in the vicinity of 20°W longitude, and an intensive study of its development from initiation to decay near the German 'BioTrans' station at 47°N, 20°W. The seagoing components of the study had a large number of scientific elements, including an consensus list of core measurements, which all participants agreed to include in as many of their cruises as possible. The study included participation by scientific parties on vessels from Canada, the Federal Republic of Germany, The Netherlands, the United Kingdom, and the United States; 12 deep ocean sediment trap moorings, remote sensing overflights by the US NASA WA-P3 aircraft, and analysis of AVHRR and GEOSAT satellite imagery. An extensive series of technical intercalibration exercises was carried out among the vessels, moorings and aircraft. Coordinated, multi-ship exercises were performed at several locations along 20°W, and at several times near 47°N, 20°W.

The Pilot Study had few precedents of a process-oriented, international nature in the biogeochemical disciplines. Therefore planning and organisation of the study received great attention. A logistics coordinator was appointed to facilitate cooperation and communications among the study participants during the field programme. The chief scientists or national coordinators met several times in the year preceding the field programme. In addition to holding national meetings of their own scientists. Particular attention was also paid to joint analysis and dissemination of the data arising from the study. National database managers were appointed, and both individual national and international data management workshops were held to ensure timely submission of all data, and establishment of internationally accessible databases by all interested parties. A workshop for cooperative analyses of the data was held at Kiel in March 1990 and the formal presentation of the results of the study will be made at a conference to be held in Washington in November 1990.

Communications among the vessels, between the vessels and home laboratories, and between aircraft, satellites and ships proved to be a task larger than anticipated. A new system integrating electronic mail, Inmarsat voice and digital communications, satellite down-links and telex and fax linkages is now being planned for the next process studies.

4.4.2 Sampling design and logistics.

Biogeochemical processes are driven by physical forcing that occurs over a wide variety of scales. Although JGOFS will address variability ranging from diel to, in some cases, geological time periods, process studies are limited by logistic considerations to the shorter term variations that can be studied during research vessel cruises. JGOFS process studies will be designed to observe behaviour of the biogeochemical system over diel to event scales. These short term observations will be extended to furnish coverage of seasonal cycles with suitably scheduled programmes of multiple cruises and mooring deployments. Ideally each observational programme will allow extended periods of observation at each site, enabling studies of processes to be carried out over at least 3-10 days. This will permit observations of responses to event-scale forcing, or at least provide several realisations of diel processes. An example of this approach is the FRG cruise programme during the Pilot Study which consisted of a series of 10-14 day drifter studies extending over 5 months between 18°N and 72°N.

Process study observations require some combination of regional scale Eulerian and
Lagrangian observational strategies, because biogeochemical processes move and evolve within advecting water masses. The Lagrangian behaviour of the biogeochemical system, particularly in the surface layer, cannot be properly studied by observations at fixed sites. Observations of upper layer processes should be made while following drifters and using remotely sensed information on surface fields to supply the larger scale context in which individual sampling operations are embedded. In some cases, studies can be located within mesoscale water bodies as they move and change over time. For example in the French "Meditlante" Programme, couplings between surface productivity and midwater fluxes were observed within eddies emanating from the Straits of Gibraltar. In other cases, cooperative cruise programmes can combine the Eulerian regional survey approach with the Lagrangian drifting studies. In the UK-JGOFS programme for 1990, one vessel will follow a suite of ARGOS drifters making time series observations while a second vessel will survey the surrounding physical and biogeochemical fields with Seasat, a towed undulating sensor package (Fasham et al., 1985). Thus, process studies, while tied to specific regions, are not fixed at particular sites like the time series stations.

Process studies will be planned to last about three years. In some cases, 2 or more studies may be carried out simultaneously. However, the basic strategy is to start a new study each year, beginning with the Pacific Equatorial Study in 1991. Each JGOFS Process Study will follow a cycle in which the main field programme will be carried out in year 2, after a year of planning and preliminary studies. A year or more of sample and data analysis will complete each study.

4.4.3 Required measurements

During the planning of the 1989 Pilot Study, JGOFS scientists compiled a list of core measurements and defined protocols in an attempt to standardise the observational programme, and facilitate intercalibration and comparison of data. The core measurement list for future JGOFS studies will change as new methods are developed and as new areas of investigation are discovered. The kinds of measurements currently believed to be of greatest importance to JGOFS process studies are described briefly below. Details of specific measurement protocols may be found in the SCOR/JGOFS Report on Core Measurement Protocols (SCOR, 1989).

(a) Meteorological measurements

Shipboard measurements of meteorological variables should be made automatically at the greatest possible frequency. In particular, measurements of variables relating to air-sea fluxes of heat, light, and dissolved gases should be made to the highest possible standards.

(b) Water Column Measurements

A large suite of observations in the upper water column is required. These include measurements of:

- **Physical Properties** specifying the structure of the vertical and horizontal fields in which biogeochemical measurements are made.

- **Optical Properties** chosen primarily to define the time and space-dependent variations in photosynthetically active solar radiation, profiles of plant pigments and light absorption by particulate matter.

- **Biological Standing Stocks.** The emphasis will be on the principal groups of organisms regulating the cycling of carbon, nitrogen and other elements. The degree to which taxonomic identity, size and chemical composition will be resolved for different groups will vary according to the needs of each study. Current modeling efforts suggest that the principal groups may be limited to phytoplankton (2-3 size classes, plus separation of diatom and coccolithophorid groups); zooplankton (2-3
size classes and possibly separation of the migratory fraction) and bacteria (possibly including distinction of attached versus free cells). Detailed taxonomic descriptions will in most cases not be required.

- **Chemical Stocks.** Here also, the main emphasis is on the elements and compounds of greatest importance to the carbon cycle and the linked biogeochemical cycles that drive it. Thus the principal forms or phases of carbon to be measured include CO₂ and total dissolved inorganic carbon, dissolved and particulate organic matter (DOC, DON, POC and PON). In some cases much more chemical detail may be needed. Other important chemical species include the plant nutrients nitrate, ammonium, urea, reactive inorganic phosphorus, silicate, and trace metals (particularly, in view of its possible role in limiting phytoplankton growth, iron). Dissolved oxygen and certain other dissolved gases will be measured primarily to specify important fluxes (photosynthesis, respiration, denitrification). Additional chemical species will be important in different studies primarily as tracers of fluxes and other biogeochemical processes. These include, but are not limited to, thorium (²³³Th,²³⁰Th), uranium (²³⁴U), lead (²¹⁰Pb), polonium (²¹⁰Po), and protoactinium (²³¹Pa), and organic biomarkers such as individual pigments, lipids, and structural polymers.

- **Biological And Chemical Fluxes.** Here again, current models provide a means of choosing from a multitude of rate processes the principal transports and transformations of greatest interest for JGOFS (Ducklow et al., 1989). Biologically mediated fluxes define the rates of transformation of carbon and nitrogen among different physical, chemical, living and nonliving forms. The following processes all ideally require several independent, redundant measurements: primary production (total and new production), zooplankton grazing, bacterial production, nitrogen regeneration. Vertical transport of the major classes of chemical substances noted above will be measured by moored and floating sediment traps.

- **Benthic Fluxes.** Only a small proportion of the material reaching the sea floor is “permanently” lost from the marine environment and incorporated into the geological record, the remainder being recycled in dissolved form. Important aims are:

  (i) To investigate the early diagenesis of organic carbon and associated trace elements and its relationship to the biotic community;

  (ii) To examine the processes controlling the dissolution of calcium carbonate;

  (iii) To relate benthic processes to the supply of material from the overlying water column;

  (iv) To relate contemporary benthic processes and the current supply of material to the interpretation of the geological history of carbon burial.

This last activity cross links with the study of the sedimentary record discussed in Chapter 8.

4.4.4 Link with modelling, development of process sub-models.

There needs to be a close tie between the modelling and process study components of JGOFS. Current basin scale modelling efforts can aid in planning process studies by suggesting in a quantitative way which measurements are most critical for understanding, and where they should be made. A preliminary list of critical JGOFS measurements was compiled at the first meeting of the JGOFS Modelling Working Group. They are:

(a) Seasonal cycles of phytoplankton,
zooplankton, and bacterial biomass. DOC, DON, nutrient concentrations, and f-ratio.

(b) Photosynthetic parameters of the P-I curve and phytoplankton specific respiration coefficients.

(c) Microbial loop rate processes. In this respect, it was recognised that it was important to measure size fractionated chlorophyll, detrital concentrations, primary production, and zooplankton biomass and rate processes, both in and below the euphotic zone.

(d) More information is needed on the rates of remineralisation below the euphotic zone and their vertical structure. It is especially important to distinguish the rates of carbon and nitrogen metabolism and this requires some characterisation of the types of organic/inorganic carbon making up the detrital material.

(e) More data are required on the state of the biogeochemical system in temperate zone winters. The seasonal dynamics of most models are highly sensitive to the "pre-bloom" concentrations of, for example, nutrient, chlorophyll, and zooplankton.

(f) Observational programmes leading to a better understanding of physical mixing process in the top 1000m of the water column were regarded as essential prerequisites to developing successful JGOFS models. In particular, the role of mesoscale variability in facilitating the vertical mixing of nutrients needs to be elucidated.

By distinguishing the roles of horizontal from vertical transports in supplying nitrate to the production system in a given study area, models can help in the design of sampling strategies.
5 Remote Sensing

5.1 Introduction

The objectives of JGOFS are ambitious: never before have oceanographers attempted to understand the biogeochemical cycles of the world’s oceans on such scales. To address them will require synoptic observations on global scales over decades, with sufficient spatial and temporal resolution to resolve the dominant frequencies and wave numbers of variation. These measurements can now be made using untended observational platforms in space, in the air and in the sea; it is only through the use of such remote observations that the objectives of JGOFS on the global scale can be achieved.

The remote observations cannot stand alone; they require for their interpretation a rigorous parameterisation of small-scale physics and biology. This parameterisation is dependent on critical field observations and experiments, and on the development of appropriate models of the upper ocean. The models in turn will depend on the remotely sensed observations for initialisation and constraints based on advanced data assimilation techniques. Therefore, the satellite data is an integral part of an iterative coupling between remote observations, in situ experimentation, and modelling efforts. Any of these in isolation will prove insufficient.

The advanced sensors now in orbit above the earth’s surface, and planned flights in the JGOFS era, provide strong motivation and justification for timely implementation of the JGOFS programme. For the first time, it will be possible to estimate wind speed and direction, the fluxes of heat, momentum and material, including carbon dioxide, at the sea surface, the biological production of organic matter and the variability of the surface currents at the requisite scales. These observations can in turn be used to understand, and ultimately predict, the role of the ocean in global biogeochemical cycles. The technological challenges remain large, not the least the need to reduce and use the volume of data, which will be forthcoming at an unprecedented rate. Nonetheless, the ready availability of these data on an international basis will permit answers to questions that have to date been impossible to address. Some of the remote measurements that will be critical to JGOFS follow.

5.2 Air-sea fluxes of heat, momentum and mass

Models of biogeochemical cycles in the upper ocean rely on appropriately parameterised mixed layer physics. The boundary conditions for these mixed layer models include the net fluxes of heat and momentum at the sea-surface; these fluxes also directly influence the transport and transformation of carbon and other biologically important elements in the upper ocean. For example, solar radiation incident on the sea surface warms and stabilises the upper ocean. It is also responsible for driving photosynthetic production of organic matter. Transfer of momentum from wind to sea mixes the upper ocean and is responsible for generating turbulence that mixes nutrients and other dissolved and particulate constituents in the vertical. Excess latent heat losses drive the convective motions responsible for deep water formation and the transport of both organic and inorganic carbon to the deep sea.
Estimation of these fluxes from remote observation is now within reach. Statistics of cloud distributions, from remote observations of visible radiances, can be used to estimate the solar radiation flux at the sea surface with considerable skill. Both passive and active microwave radiometers can be used to estimate wind stress and sea-state. Accurate measurement of sea-surface temperature from passive radiometers permits acceptable estimation of latent heat fluxes. Much work remains, but the possibility now exists for the ready availability of sea-surface heat and momentum fluxes in a form and on scales appropriate for JGOFS.

Estimation of the net flux of carbon dioxide and other gases such as dimethyl sulphide (DMS) across the air sea interface is a high priority for JGOFS. This flux depends on the difference in partial pressure between air and sea, and on the gas exchange coefficient. Both the regional and temporal variability in the partial pressure differential, and in particular the gas exchange coefficient, are poorly known at present (see Chapter 6). The mechanisms of carbon dioxide exchange at the molecular level and the role of entrained bubbles are uncertain, but some success has been found in the laboratory in relating the carbon dioxide flux to wind speed. This relationship has recently been used in conjunction with satellite scatterometer-derived winds to produce a global map of net carbon dioxide exchange over the oceans (Etcheto & Merlivat, 1988). Uncertainties in scaling up from the laboratory to the ocean remain, but initial progress is encouraging for future remote assessment of the rate of carbon dioxide exchange between atmosphere and ocean.

An area of some recent concern involves the flux of materials from land to ocean via aeolian transport. Dust from the Asian desert can be detected in the marine atmosphere; it has been suggested that this flux is a significant source of trace metals to the upper ocean that may stimulate primary production (Martin & Gordon, 1988). Observation of the marine atmosphere in the visible bands may permit quantification of this flux.

5.3 Exchanges between coastal and open ocean

The exchange of nutrients and carbon between the coast and the open sea sets boundary conditions for both coastal models and those dealing with ocean basins. The cross-margin exchange is a key, but little understood process (GOFs, 1987). The parameterisation of the various physical processes, such as transport by mesoscale eddies and coastal upwelling, in terms of remote observations of variability in sea-surface elevation and sea-surface temperature is in its infancy. It is likely that an understanding of the processes controlling cross-shelf exchange will require intensive in situ observations with satellite observations providing the larger scale context (Walsh et al., 1988). Future satellite altimetric measurements, such as TOPEX/Poseidon coupled with ocean colour and ongoing SST observations could potentially be useful in attaining the required understanding.

5.4 Biological production of the ocean

5.4.1 Phytoplankton pigments

The remote measurement that has caused the greatest excitement within JGOFS is the estimation of basin and global scale variability in the concentration of plant pigment in the upper ocean. These pigments are responsible for the absorption of solar radiation in the primary reduction of inorganic carbon, a first step in the oceanic removal of atmospheric carbon dioxide. The images of the global distribution of these pigments (fig. 7, chapter 2), derived from the now-defunct Coastal Zone Colour Scanner (CZCS), have revolutionised the way biological oceanographers view the oceans (NASA, 1989). For the first time, the blooming of the ocean basins in the spring has been observed as has the extent of the enriched areas associated with the coastal ocean (fig. 11, chapter 3).
5.4.2 Total Primary Production

Satellite-based ocean colour monitors can also be used to estimate the global distribution of primary production. The general approach will be: first, to establish a procedure for estimating total primary production at a particular station (the local algorithm) using remotely sensed data on chlorophyll; next, to work out procedures for extending the local results to estimate total production at large horizontal scale; and finally, to enquire whether equivalent statements can be made about the new primary production.

A number of methods, using either empirical transfer functions or more mechanistic physiological models, have been proposed for estimation of total primary production from remotely sensed data (Smith et al., 1982; Eppley et al., 1985; Collins et al., 1986; Platt, 1986; Platt et al., 1988; Morel & Berthon, 1989; Balch et al., 1989 a, b; Sathyendranath et al., 1989). The same general issues have to be faced, regardless of the method chosen. These arise because of fundamental limitations on the remote sensing process and because of unavoidable parameterisations of the underlying physiology.

It is required to estimate the primary production per unit area of ocean surface. On the other hand, the signal received by the colour scanner contains information from only the upper one fifth or so of the photic zone. Hence consideration has to be given to the local structure of the vertical pigment profile, since the possibility exists that high concentrations of chlorophyll (deep chlorophyll maximum, DCM), located below the depth of penetration of the colour scanner signal, could bias the local estimates of primary production. Using a parameterisation of a generalised pigment profile, Platt et al. (1988) examined this issue in detail. It was shown that, provided independent information is available on the local vertical structure of the pelagic ecosystem (in particular the shape of the pigment profile), any bias in the estimate of primary production introduced as a consequence of the incomplete penetration of the colour scanner could be easily removed.

It will also be necessary to parameterise the response of the pigment biomass to available light. In most empirical regression methods, this parameterisation is buried in the regression coefficients connecting biomass and production. One advantage of using a more mechanistic formulation is that such coefficients can be interpreted directly in terms of known physiological variables, such as the quantum yield of photosynthesis. Moreover, these physiological properties can be made the subject of direct measurement at sea during occupation of the intensive stations.

Recommended Protocol:

The estimates of primary production will be made using algorithms based, as far as possible, on first principles. The following steps are based on Platt & Sathyendranath (1988) and Sathyendranath & Platt (1988; 1989 a, b). However, it may be noted that, as long as the algorithms are based on photosynthesis-light relationships, the data requirements and the problems to be solved are likely to remain the same, even when improved algorithms become available in the future.

1. Estimate the surface irradiance for the particular location and time, including a correction for cloud cover.

2. Given the surface weighted pigment from satellite observations, and given independent knowledge of the shape of the vertical pigment profile at that location, estimate the absolute vertical pigment profile.

3. Use the pigment profile to compute optical attenuation coefficients and thus compute the submarine light field as a function of depth, wavelength and zenith angle.

4. Given independent knowledge of the
local parameters of the photosynthesis-light curve, compute the depth profile of primary production.

5. Integrate over depth and time to find daily rate of water column production.

6. Integrate over area for which that location may be considered representative.

7. Integrate over seasons and years as required.

5.4.3 Implications for JGOFS Field Programmes

The protocol outlined above presupposes that the ocean can be partitioned into a limited number of zones within which the essential biological properties (shape of pigment profile, photosynthesis parameters) can be considered as uniform in space within seasons. There is considerable evidence that this is so (see chapter 3). A major initial task is to delineate these zones (biogeographic provinces), based on oceanographic knowledge and intuition. It is probable that one of the best guides to fixing these zones will be the large scale satellite images themselves. Their boundaries will be revised and refined as JGOFS progresses.

An important implication for JGOFS is that the stations chosen for the process studies should coincide with the suite of zones selected for parameterisation of the remote sensing models. This should not be difficult to arrange since the process study stations ought to be chosen to represent as broad a range of oceanographic conditions as possible. For each biogeographic province it will be essential to establish an archive of the parameters of the biomass profile and of the response of photosynthetic biomass to available light.

It may be noted that the protocol described in the previous section automatically defines the sea truth requirements, which calls for vertically resolved data on pigments and physiological parameters and for spectrally resolved irradiance at the surface and in the interior of the sea.

5.4.4 New Production

Although the measurement of new production is a high priority objective of JGOFS, there is no direct method for its estimation by remote sensing. Generally speaking, within each of the biogeographic provinces, an f-ratio could be assigned a typical value for a given season, based on independent knowledge (the result of intensive station work) of the local structure of the pelagic ecosystem. Multiplying the total production by this f-ratio will give an estimate of new production.

Eventually, however, one would hope to do better than this; that is, to account for local and transient variations in the f-ratio within biogeographic provinces. An essential requirement will be simultaneous remotely-sensed data of an oceanographic property field other than ocean colour (e.g. temperature) that could serve as a proxy index of local perturbation in water column structure leading to local change in nitrate supply and, therefore, in f-ratio. Regional and annual estimates of new production would then be calculated as weighted integrals of the local results. Another possibility is offered by some recent global or basin-scale biogeochemical cycling models (Sarmiento et al., in press). Such models could combine satellite data on the biomass field with model-derived data on nitrate supply and f-ratio to calculate new production (Platt et al., 1989).

5.4.5 Algorithm development

Concurrently with the application of satellite data in process studies as described above, algorithm development will also have to be undertaken, to ensure optimum utilisation of the data. Well-established algorithms exist for estimating the biomass field from the Coastal Zone Colour Scanner (CZCS) data, and processed data are now available on a routine basis from NASA. New algorithms are now emerging for estimation of primary production
using remotely-sensed data, and there is a need for further testing and improvements to these algorithms as well. However, the next generation sensors will have improved capabilities, and there will be a need for the development of new biomass algorithms to capitalise on the better quality data. No algorithms currently exist for new production calculations. However, some possibilities (indirect) exist as discussed earlier, and need to be followed up. An important element of the JGOFS field programme will be to provide sea truth data for verification of algorithms relating to pigment concentration, total primary production and new production.

5.5 Aircraft surveys

Airborne lidars now available offer three major advantages over the satellite sensors: (a) higher spectral resolution and therefore scope for more rigorous algorithms and for retrieval of more variables; (b) capability of obtaining depth-resolved data; and (c) operation under dense cloud conditions. In addition, when available concurrently, the fluorescence technique of the lidars can be used to check or validate the ocean-colour algorithms applied to satellite data. The depth-resolved signals from aircraft lidars will be a valuable tool for extending local ship observations, and for parameterising the biomass profiles of a given biogeographic zone. Major JGOFS field studies would therefore benefit from concurrent lidar overflights. In the JGOFS North Atlantic Pilot Study for example, aircraft data proved extremely useful in identifying bloom areas, and, therefore, in effecting mid-course cruise corrections for the research vessels in the ocean.

5.6 The Future

Of particular interest to JGOFS is a new ocean colour sensor planned for 1992/1993, the Sea-viewing Wide Field of View Sensor (SeaWiFS). It will produce images of global distributions of plant pigment and productivity with a temporal and spatial resolution of two days and 4 km respectively. In addition, higher spatial resolution will be available for selected coastal regions. These data will be a cornerstone to the JGOFS effort and will drive new modelling efforts serving as a base upon which the success of models can be evaluated. Key to this use is a data distribution programme that will provide timely raw data to specialists for algorithm development but which would also deliver reduced data to oceanographers interested in addressing scientific questions using advanced personal computers.

The space-faring nations of the world have an impressive agenda of new Earth observing satellites planned for the JGOFS era. Most of the above mentioned processes will be accessible to remote observation; our primary recommendation is to support this development, and encourage wide-spread use of the new observational capability particularly by scientists with more traditional oceanographic backgrounds.

It is clear that satellite oceanography has matured to the point where data from remote sensors is an acceptable, and integral part of research programmes such as JGOFS. Challenges in the field still exist, but will be overcome. We can look forward to the day in the very near future where satellite oceanography ceases to exist as a separate sub-discipline and joins the CTD and Secchi disk in the arsenal of tools that can be brought to bear on outstanding oceanographic problems of the day.
Large Space/Time Scale Surveys

6.1 Introduction

The global survey of key oceanic properties is the most basic and traditional form of gaining knowledge of the ocean. Modern large scale ocean geochemistry was shaped by the GEOSECS programme in the 1970s. For the first time a comprehensive survey of the ocean carbon system was conducted from the far North Atlantic to the far North Pacific. The results were far-reaching and, while they yielded the time scale for the deep ocean circulation, they also posed new problems that gave rise to new programmes such as the Transient Tracers in the Ocean (ITTO).

One of the main motivations for JGOFS has been the growing realisation of the interconnectedness of biological and geochemical processes in the ocean giving rise to the need for new global data sets that were not envisaged when GEOSECS and TTO were designed. For example, models of plankton food web dynamics demonstrate the importance of processes controlling nutrient dynamics and the ratio of new to total primary production for our understanding of the relationship between primary production (which can, in principle, be estimated from satellite ocean colour data) and the export of carbon from the euphotic zone (Vezina & Platt, 1987; Ducklow et al., 1989; Peinert et al., 1989; Fasham et al., 1990). In order to understand these processes information is required on the large- and small-scale distributions of microorganisms and zooplankton, and of their waste products (ammonium and dissolved organic nitrogen) that are the key currency of nitrogen cycling. Our ignorance about the distribution of these quantities in space and time severely limits our ability to model the carbon cycle. Ideally we also require the further constraints on the carbon cycles that could be provided by a global network of sediment traps and benthic community respiration measurements (Smith, 1987).

6.2 The Global Survey

6.2.1 The JGOFS contribution

All these considerations suggest the need for a new global survey, with at least the same spatial coverage as GEOSECS, in which a new suite of biogeochemical variables is measured. Some of these requirements will be met by the WOCE Hydrographic Programme as discussed in the next section and it is important to realise that the WOCE programme will be using a large slice of the international research ship survey time over the next ten years. During this same period JGOFS will also require ship resources to carry out its research programme of process studies as outlined in Chapters 3 and 4 and so the extent of the ship resources available for the global survey will need to be carefully evaluated when the implementation plan is prepared. With this caveat, the global survey component of JGOFS will comprise the following:

- An agreed suite of well-defined, intercalibrated, biogeochemical core measurements will be made throughout the water column at a regular spacing along a world-wide series of JGOFS transects. Such a suite will include pigments, nutrients, biomass components, gases, dissolved organic species, particulate organic carbon and nitrogen, and radionuclides.
• The same suite will be measured, wherever possible, on ship-of-opportunity transects, either when on passage to JGOFS transects or process studies, or in cooperation with other national or international programmes.

• A global array of sediment traps will be deployed to estimate the vertical particle flux. Ideally these traps would be in close proximity to the JGOFS transects.

• A global set of benthic measurements will be made to provide boundary constraints.

• Along track observations of surface pigments, nutrients, CO$_2$, and O$_2$ will be made on all JGOFS cruises.

Provided that suitable intercalibrations are carried out and the data are collected into a unified JGOFS data base, these results will provide a basis both for extrapolating the global satellite data to other property fields and for testing and validating the computer models.

6.2.2 Cooperation with the WOCE Hydrographic Programme

The joint CCCO-JGOFS panel on carbon dioxide has identified the need for a major global study of oceanic carbon chemistry in order to constrain and improve current models of the global carbon cycle (CCCO, 1988). It has been recognised that both JGOFS and WOCE have a part to play in this study, with JGOFS activities focusing primarily on process studies, while the WOCE Hydrographic Programme provides extensive spatial and temporal coverage. However, it was decided at an early stage in the planning of WOCE that the required measurements of the CO$_2$ system should be the responsibility of JGOFS who, jointly with CCCO, agreed to coordinate the provision of the necessary skilled manpower for measuring CO$_2$ on the WOCE WHP cruises. The specification for these measurements, as set out by the CCCO/JGOFS panel, is to measure full depth profiles of total CO$_2$, alkalinity, and pCO$_2$ to within 1 µMol/kg, 1 µeq/kg, and 1 µatm respectively, and it is the responsibility of this panel to facilitate the intercalibration required to achieve these standards.

The result of this agreement is that for the first time a fully documented and internally consistent description of the oceanic carbon dioxide system will be produced, with standards and experimental protocols common to both programmes and the results fully integrated through the JGOFS data archive. Furthermore, if such a survey could be repeated in the late 1990s the anthropogenic increase in oceanic CO$_2$ could in principle be detected.

In May 1990 agreement was reached with the WOCE Scientific Steering Group that, on WHP cruises where spare berths were available, a third berth could be made available to JGOFS scientists for the purpose of making measurements of the underwater optical field and phytoplankton pigment distribution. These data will be critical for using satellite ocean colour data to calculate primary production (see Chapter 5). Finally, the accumulation of the WOCE nutrient data set throughout the 1990s will also be of great significance for JGOFS. Such data provide a powerful check on modelling the ocean's biogeochemical cycles.

6.3 Long Time Series Observations

Much of the data obtained during the JGOFS programme will be made during cruises of fairly short duration. Such studies cannot characterize and explain longer period changes in oceanic biogeochemical and ecological variables. Examination of the few long term data sets shows the importance of understanding the variability of marine ecosystems at time scales ranging from seasonal to interannual periods (Wiebe et al., 1987). Therefore JGOFS requires a network of Time Series Stations at which regular measurements of key properties and processes are made at biweekly to monthly intervals, or continuously, for those properties measurable by untended, automated sensors (Dickey, 1988).
• The same suite will be measured, wherever possible, on ship-of-opportunity transects, either when on passage to JGOFS transects or process studies, or in cooperation with other national or international programmes.

• A global array of sediment traps will be deployed to estimate the vertical particle flux. Ideally these traps would be in close proximity to the JGOFS transects.

• A global set of benthic measurements will be made to provide boundary constraints.

• Along track observations of surface pigments, nutrients, CO$_2$, and O$_2$ will be made on all JGOFS cruises.

Provided that suitable intercalibrations are carried out and the data are collected into a unified JGOFS data base, these results will provide a basis both for extrapolating the global satellite data to other property fields and for testing and validating the computer models.

6.2.2 Cooperation with the WOCE Hydrographic Programme

The joint CCCO-JGOFS panel on carbon dioxide has identified the need for a major global study of oceanic carbon chemistry in order to constrain and improve current models of the global carbon cycle (CCCO, 1988). It has been recognised that both JGOFS and WOCE have a part to play in this study, with JGOFS activities focusing primarily on process studies, while the WOCE Hydrographic Programme provides extensive spatial and temporal coverage. However, it was decided at an early stage in the planning of WOCE that the required measurements of the CO$_2$ system should be the responsibility of JGOFS who, jointly with CCCO, agreed to coordinate the provision of the necessary skilled manpower for measuring CO$_2$ on the WOCE WHP cruises. The specification for these measurements, as set out by the CCCO/JGOFS panel, is to measure full depth profiles of total CO$_2$, alkalinity, and pCO$_2$ to within 1 μmol/kg, 1 μeq/kg, and 1 μatm respectively, and it is the responsibility of this panel to facilitate the intercalibration required to achieve these standards.

The result of this agreement is that for the first time a fully documented and internally consistent description of the oceanic carbon dioxide system will be produced, with standards and experimental protocols common to both programmes and the results fully integrated through the JGOFS data archive. Furthermore, if such a survey could be repeated in the late 1990s the anthropogenic increase in oceanic CO$_2$ could in principle be detected.

In May 1990 agreement was reached with the WOCE Scientific Steering Group that, on WHP cruises where spare berths were available, a third berth could be made available to JGOFS scientists for the purpose of making measurements of the underwater optical field and phytoplankton pigment distribution. These data will be critical for using satellite ocean colour data to calculate primary production (see Chapter 5). Finally, the accumulation of the WOCE nutrient data set throughout the 1990s will also be of great significance for JGOFS. Such data provide a powerful check on modelling the ocean’s biogeochemical cycles.

6.3 Long Time Series Observations

Much of the data obtained during the JGOFS programme will be made during cruises of fairly short duration. Such studies cannot characterize and explain longer period changes in oceanic biogeochemical and ecological variables. Examination of the few long term data sets shows the importance of understanding the variability of marine ecosystems at time scales ranging from seasonal to interannual periods (Wiebe et al., 1987). Therefore JGOFS requires a network of Time Series Stations at which regular measurements of key properties and processes are made at biweekly to monthly intervals, or continuously, for those properties measurable by untended, automated sensors (Dickey, 1988).
There are a few examples of longer series of data collected from some oceanic sites. Perhaps the best known is the 3 year series of regular primary production measurements made at Station "S" near Bermuda (Menzel & Ryther, 1960). Station "S" is also the site of the longer series of observations of hydrography (cf. Jenkins & Goldman, 1985) and of a continuous deployment of deep ocean sediment traps (Deuser, 1987). These data demonstrate the strong seasonal variations in primary production and vertical transit fluxes (sensu Berger et al., 1989) forced by annual episodes of convective mixing and vernal restratification (Deuser, 1987). The US JGOFS Programme has recently established new time series stations at Bermuda and in the central North Pacific off Hawaii. These initiatives will identify the biogeochemical consequences of periodic ecological events and, if continued over the longer term, may detect changes in the ecological and chemical state of the ocean brought about by global climate change.

There are several other series of observations made at fixed locations, notably at the Ocean Weather Stations Papa and India (Parsons & Lalli, 1988), and two examples of long term measurement programmes made over regional areas. The CalCOFI Programme at the Scripps Institute of Oceanography has been collecting data on plankton properties in the California Current since 1950. Analyses of these data show that much of the variability in macrozooplankton abundance, and perhaps other properties, is concentrated at interannual periods, with little, if any contributed by seasonality (Chelton et al., 1982). The Continuous Plankton Recorder Survey was begun by Sir Alistair Hardy in 1931, with the aim of "...attempting to apply methods similar to those employed in meteorology to a study of the changing plankton distribution, its causes and effects." (Hardy, 1967). At times extending monthly cruises across the entire North Atlantic Basin, the survey has demonstrated a long term decline in plankton abundance, which may have reversed in the mid 80's (Dickson et al., 1988). The causes of these trends and cycles are not well understood, and the consequences for the global cycles of carbon and other elements are completely unknown.

For logistic reasons, most ocean observatories need to be located near islands or coastal nations with well-equipped marine laboratories and research vessels capable of performing modern, high precision measurements of chemical, biological and physical variables. At present, both JGOFS observatories are located in tropical, oligotrophic waters. Additional stations are needed in higher latitude, coastal, upwelling and boundary current regimes. Once established, these sites will provide the means to define the time-varying behaviour and spectral properties of the physical, ecological and biogeochemical system in each area. These data sets will also provide invaluable material for calibration and validation of biogeochemical models (Sarmiento et al., 1990; Fasham et al., 1990). Furthermore these sites will attract many other short and longer term investigations that can draw on the resources and historical database collected at each place (e.g. Fuhrman et al., 1989). Time series observatories also provide useful centres for the development and testing of new instruments. Each site requires a dedicated team of 5-10 individuals to make measurements, collect, process, and analyse samples, tend instruments and interpret and report data.

6.4 Seasonal Survey of pCO₂

Recently there has been a growing controversy over the size of the oceanic sink for anthropogenic CO₂ in the oceans. Ocean models suggest that the sink must amount to 2 Gt/yr, with approximately 1.2 Gt/yr and 0.8 Gt/yr going into the southern and northern hemisphere oceans respectively. However, atmospheric modelling based on the known geographical distribution of fossil fuel burning, the observed gradient in atmospheric pCO₂ between the Northern and Southern Hemispheres, and the time constant for gas exchanges between the two hemispheres, show
that the southern hemisphere ocean most likely has no net uptake or loss to the atmosphere (Tans et al., 1990). This suggests that the northern hemisphere oceans must be absorbing the entire 2 Gt/yr. However, the best estimates of oceanic CO$_2$ uptake, based on pCO$_2$ data, are only around 1 Gt/yr. Since the conclusions drawn from the atmospheric models appear to be fairly robust, it is important to assess the accuracy of the lower sink estimate based on oceanic data.

The flux of CO$_2$ between the atmosphere and the ocean is estimated from a bulk formula that takes the product of the piston velocity (which parameterises the physical driving force) and the partial pressure difference between the two phases (the chemical driving force). In order to integrate this flux over an ocean basin, it is necessary to estimate the values of the piston velocity and partial pressure difference over large areas. The piston velocity is related to windspeed using a set of empirical linear relationships derived from wind tunnel and lake measurements, which are now being confirmed by measurements made in the North Sea under more realistic conditions. Global windspeed will be available from satellite measurements in the near future (see Chapter 5). The partial pressure difference is obtained from surface water measurements of pCO$_2$, which are then averaged over large areas of ocean and over seasonal or even annual time scales. It is this integration of an often sparse pCO$_2$ dataset that contributes the greatest uncertainty to the estimates of CO$_2$ flux.

In the North Atlantic, deep water forms close to major sites of fossil fuel burning. In spring and summer it is known that pCO$_2$ in surface waters is reduced sharply, leading to a flux from the atmosphere to the ocean. Recent results from the JGOFS North Atlantic Pilot Study have shown that pCO$_2$ is extremely patchy at this time of year, correlating strongly with chlorophyll (fig. 3, chapter 1), and shows strong latitudinal gradients (Turner et al., 1989). This patchiness is a new feature revealed by underway CO$_2$ analysis methods, and casts doubt on the accuracy of a basin-wide integration of pCO$_2$ based largely on data from bottle samples, particularly since comparable data from other seasons are not available.

It is therefore possible that the mismatch in CO$_2$ sink estimates noted above results not from an error in the basic assumption (that fossil fuel CO$_2$, not remaining in the atmosphere is lost to the ocean), but from a large uncertainty in the estimate of oceanic CO$_2$ uptake arising from a pCO$_2$ database which is inadequate for this purpose. Similar uncertainties exist about the CO$_2$ uptake in the Southern Ocean (Volk & Liu, 1989).

There is thus an urgent requirement to document more accurately the seasonal cycle of pCO$_2$ in the North Atlantic and North Pacific, and if possible the Southern Ocean, in order to constrain more closely the estimate of net annual flux of CO$_2$. Logistically, seasonal surveys of the North Atlantic would be the easiest to achieve. The minimum requirements would be underway measurements of pCO$_2$ and total CO$_2$ along the cruise track, backed up by measurements of chlorophyll. Use of satellite ocean colour data would then allow the effective integration of pCO$_2$ in areas and seasons where pCO$_2$ and chlorophyll are correlated (and most likely show patchy distributions).

In view of the critical importance of these measurements for quantifying the fate of anthropogenic CO$_2$, this project is regarded as a high priority for JGOFS.
7

Modelling

7.1 The modelling requirements of the JGOFS programme

The ultimate aim of the modelling component of JGOFS is to produce a model that can predict the evolution of carbon, and other biologically important elements, throughout the world ocean decades to centuries ahead. There are three reasons why this goal, which has obvious practical benefits in devising strategies to cope with the problem of greenhouse gases, is at present beyond our capability. First, although the present generation of computers is powerful enough to model the complex and detailed equations involved, the time taken to carry out simulations is excessively long. For example, a model of the North Atlantic capable of resolving mesoscale eddies reaches equilibrium with the atmosphere after 80 days of processor time on the most powerful computer available. An even longer run would be necessary to model the oceanic biogeochemical transformations. Secondly, we lack a firm conceptual understanding of many key processes in the ocean biogeochemical system. Thirdly, we lack data with which to test the models. We can expect the computer problem to be solved for us by the turn of the century, and JGOFS has been planned to tackle the other two problems. The time is therefore ripe to embark on an ambitious modelling programme with some reasonable expectation that both the computer tools and the underpinning data base will be available to achieve success.

The distributions of bio-active compounds in the ocean have fascinated oceanographers for decades and many attempts have been made to describe the processes that produce these patterns using simple mathematical models. Until very recently, however, the global models were not biologically realistic, while good biological models were applied to only local space scales. Despite this, simple chemical models, in which the role of the biota was either ignored or parameterised by simple linear models, have proved very useful in trying to understand the role of the ocean in modifying the atmospheric CO$_2$ concentration in the geological past (Sarmiento et al., 1988) and in understanding the controls on CO$_2$ uptake in the present world ocean (Volk & Liu, 1988). Biological models have from their earliest development used more realistic nonlinear functions to describe the interactions between organisms, but the global perspective of the geochemists has, until recently, been lacking. Furthermore, the oceanic circulation and mixing processes used in most models were often highly simplified. Now, however, considerable progress is being made in modelling the oceanic circulation on both basin and global scales. It is therefore feasible to attempt to combine these parallel developments in modelling to achieve the JGOFS modelling goals.

The legacy of JGOFS will be an understanding of the system, as encoded in algorithms and models, that will enable us to monitor the state of the ocean in real-time and to predict its future course in the era of climate change.

7.2 Local and Regional Models

Marine ecosystems are extremely complex and no scientific programme can hope to sample them in any complete sense. However some subset of the total possible observation set may be sufficient for the achievement of a
given objective. A major component of the JGOFS strategy is the process studies carried out in key areas of the world ocean over time scales of a few months. Few areas will see more than one such study during the JGOFS programme. It is therefore imperative that these studies be designed specifically to obtain the information required by the global models discussed below. Furthermore, the local hydrography of each area will present specific sampling problems. Ideally each process study should be preceded by a modelling exercise in which the present level of understanding of the biogeochemical and physical processes is incorporated in a model to provide a theoretical underpinning for designing and interpreting the observational programme. Sensitivity analysis techniques should be used to identify the critical variables and parameters (Fasham et al., 1990). For example, recent models (Evans & Parslow, 1985) have indicated that, in temperate latitudes, the winter values of primary production and zooplankton biomass have a critical effect on the development of the spring phytoplankton bloom, and so this identifies the need for a winter sampling programme. Also, modelling has highlighted the potentially important role played by DOM in the ocean and, therefore, the importance of obtaining accurate estimates of this quantity (Toggweiler, 1989). A modelling-based approach to designing experiments has been proposed in the past but rarely practised. It is extremely important that the JGOFS implementation plan for the process studies should include modelling as a key factor.

The process studies will also provide a feedback into the JGOFS modelling programme at a number of levels. At the lowest level they can provide estimates of parameters required for process sub-models, such as photosynthesis, zooplankton grazing, or particle sinking. Secondly they can provide data with which to test the validity of these sub-model parameterisations, and finally they can provide time series of biological stocks, chemical concentrations, and biogeochemical flux measurements with which to test both local and global models. An example of the latter use has been the many recent models that have been tested using the historical data sets from Bermuda Station “S” (Jenkins & Goldman, 1985; Musgrave et al., 1988; Fasham et al., 1990).

7.3 Models for assimilating satellite data

Satellites provide us with a world-wide coverage of certain variables, such as ocean colour or wind speed, that are essential to the JGOFS programme. Algorithms for estimating phytoplankton surface chlorophyll concentrations from the Coastal Zone Colour Scanner (CZCS) satellite observations have undergone considerable development over the last few years and have resulted in the highly illuminating global maps produced at the NASA Goddard Space Flight Centre (NASA, 1989). It is also possible to use the ocean colour data to predict primary production using algorithms based on the theory of the photosynthetic process (see Chapter 5). One of the major tasks of JGOFS will be to determine, by means of a global, ship-based verification programme, the generality of these algorithms and their regional specificity. These techniques will then provide a global, partially synoptic picture of phytoplankton biomass and primary production; one of the key biogeochemical fluxes required to achieve the goals of the JGOFS programme.

It would be highly desirable to be able to extend the utility of the satellite data by attempting to predict the global distribution of the fraction of primary production exported from the euphotic zone (the new or export production). Such a data set could be extremely valuable for interpreting the results of the JGOFS sediment trapping programme and for providing a source function for models of the carbon cycle of the deep ocean. However the calculation of export from total primary production may not be a straightforward affair. The results from a model of nitrogen cycling in the North Atlantic developed by Sarmiento et al. (in prep) have shown that there is no simple mathematical equation relating new to total primary production. If this proves to be true
then the only way of estimating export production may be to use the satellite-derived estimates of primary production as an input to the sort of ecosystem model discussed in the next section.

7.4 Global Ocean Models

The ultimate aim of the JGOFS modelling programme is to develop global primitive equation models of the biogeochemical fluxes in the ocean that can predict the time evolution of these fluxes from given starting conditions. Such models will use state-of-the-art General Circulation Models (GCMs) driven by monthly-averaged boundary conditions to predict the fields of advection, convection, and mixing in the ocean. When combined with tracers representing nutrients, dissolved inorganic carbon, and some depiction of the biogeochemical transformations near the ocean’s surface and in the interior, these models will be able to predict full threedimensional concentrations fields for comparison with JGOFS observations. A number of models of this type are currently operational and have been used with some success to predict the observed distribution of bomb-produced tritium and $^{14}$C distributions (Maier-Reimer & Hasselmann, 1987; Toggweiler et al., 1989b; Kagan et al., 1986; Fokin, 1989).

Until recently global, biogeochemical models have not explicitly modelled the surface water biological production, or this production has been rather simply parameterised by restoring the surface nutrient concentrations to the observed values (Maier-Reimer & Hasselmann, 1987; Sarmiento et al., 1989). Sarmiento et al. (1989; in press) have made a first attempt at explicitly modelling the biological nitrogen cycle in the eutrophic zone of the North Atlantic. Although the results are encouraging there is great scope for improving the agreement with data. Other attempts to model the seasonal progression of primary production are also being made by Ryabchenko (1990) with a world ocean model.

The results from the Sarmiento et al. model have shown that one cause of the discrepancy between model and data is that the present generation of GCMs do not adequately model some of the key physical processes such as equatorial upwelling. To this extent we are therefore dependent on progress being made on the next generation of GCMs. Furthermore, Woods (1988) has suggested that upwelling associated with mesoscale currents may be a key process in providing nutrients to the eutrophic zone. If this proves to be the case then it will be necessary to use eddy-resolving models with their attendant computational demands.

Parallel to work with GCMs, a set of simple global models should be developed. Such models have the virtue of being able to reproduce many large scale features of ocean biogeochemistry with a very small number of free parameters. When constrained by tracer data, simple global models yield useful information on the strength and distribution of biogeochemical sources and sinks in the ocean. Such information can help to guide theoretical formulations for modelling biogeochemical processes, in particular below the euphotic zone. Since such models lend themselves to a large number of sensitivity studies, they can be very useful for setting planning priorities. For example, results from a recent model (Shaffer & Sarmiento, 1990) suggest that even large changes in circulation, mixing and ecosystem structure at low and mid latitudes, where primary production is limited by nutrient availability, only have a small effect on atmospheric pCO$_2$. However, large changes at high latitude can have a large impact on pCO$_2$ (ibid; Sarmiento & Toggweiler, 1984). Thus it is vital to JGOFS goals to learn more about controls on primary production in regions with no apparent nutrient limitation.

Recent biological research has demonstrated the potential importance of small organisms, such as bacteria and protozoa, in the recycling of dissolved and particulate organic material (Pomeroy, 1974; Williams, 1981; Ducklow, 1983), and a number
of recent models have tried to incorporate these new ideas (Pace et al., 1984; Moloney et al., 1986; Frost, 1987). Modelling the oceanic ecosystem will of necessity be a compromise between the need for a parsimonious model for incorporation in a GCM, and the requirement to capture the complexity of the actual biological interactions that is valid in all geological regions. At the present time we do not know how much of the biological size spectrum needs to be resolved in order to attain the predictive goals of JGOFS. Research into the effect of different levels of physical and taxonomic detail will be an important component of JGOFS modelling.

Another area where more development is required is in modelling the remineralisation of organic material and dissolution of CaCO$_3$ casts below the euphotic zone. The fitting of models to deep ocean observations of nutrients, oxygen, and trace metal distributions may provide some insights into this problem (Bacon et al., 1985; Nosaki et al., 1987). In the absence of an accepted biogeochemical model, many recent GCM-based models have parameterised this process by using a depth-related function empirically derived from sediment trap data (Martin et al., 1987). To gain a better predictive understanding, concrete questions, such as "How does decomposition rate depend on temperature and zooplankton detrital grazing?" and "What determines vertical gradients of the degree of fractionation of nutrients versus inorganic carbon?", need to be addressed. One of the principal aims of the JGOFS programme should be to provide a firmer understanding of the biogeochemistry of the deep ocean so that better models of remineralisation can be developed.

Furthermore, some organisms have requirements for specific elements or compounds, like diatoms for silicon or coccolithophorids for calcium carbonate. The uptake of calcium carbonate has a direct effect on alkalinity and thereby the partial pressure of carbon dioxide. Such considerations lead to a requirement for multi-element models that can predict the spatial and temporal evolution of these specific components of the phytoplankton. This modelling objective has implications for the sampling programme as suitable data will be required to validate these models. Palaeoceanographic information may also prove useful in this respect.

The interaction of the biological and chemical processes at the ocean’s margins with processes in the open ocean looms as one of the most difficult issues in JGOFS. Direct measurements of off-shore and onshore fluxes are extremely difficult, if not impossible, to make. GCMs run with current levels of resolution do not resolve the shallow water regimes near the margins. The best hope for progress in this field lies with nested high-resolution models of particular ocean margins within basin-scale GCMs (Wroblewski and Hofmann, 1989). The two models would use the same physics and algorithms for transformation at much different levels of resolution. Key predictions of coupled margin-basin models involve the on-shore and off-shore transport of nutrients, dissolved organic matter, and particulate organic matter. The sea truth provided by JGOFS data includes the margin-basin contrast and seasonal changes in phytoplankton biomass and nutrient fields.

Finally, because we intend these models to make predictions for the coming decades and centuries, it is important that they be constructed using expressions that we believe will continue to be true after the climate changes. Modelling tricks, such as restoring the surface temperature, salinity, or nutrient fields to observed values, or introducing empirically determined geographical variations in biological rate parameters, may be valuable during the learning process but are not suitable for long-term climate prediction models.
8

Benthic Processes and the Sedimentary Record

8.1 Introduction

Processes at the sea bed play a crucial role in the cycling of carbon and associated biogenic elements within the ocean. The sediments are the largest and longest-term store of carbon and act as the flywheel governing the global response of the carbon cycle to climatic variation. Organic matter introduced to the benthic boundary layer is processed and transformed by physical, chemical and biological processes on various time scales leading to the release of certain constituents to the water column (the "benthic flux") and the permanent burial of others. Effects on the water column can be highly significant, especially for nutrient species. A full description of the modification of material added to the seafloor is vital in order to link modern processes with the sedimentary record. The establishment of this link makes the sediments of the seafloor ideal to resolve climate-related changes in biogeochemical cycling.

The flux of carbon in the oceans varies over time scales ranging from days to tens of millions of years. Fluxes on very long time scales are of only indirect interest to JGOFS since they define the framework of earth processes upon which shorter-term fluctuations are imposed. However, fluxes on time scales within the Quaternary are of crucial importance to the broad objectives of JGOFS because they represent a period when large shifts in atmospheric carbon dioxide concentrations have occurred and are associated with periods of major climatic change.

Ice-core studies have established that atmospheric carbon dioxide is about 80 parts per million by volume lower during cold glacial climates than it is during warm interglacial times (Barnola et al., 1987; fig. 13) and explanations for such changes have been extremely influential in the development of theories of the oceanic CO₂ cycle. The seafloor is the ultimate sediment trap: the historical variations in atmospheric CO₂ are recorded in sediment cores (Shackleton et al., 1983; fig. 14) and examination of the sedimentary record provides a major (perhaps the only) means by which models of carbon fluxes, nutrient balances, ocean circulation and climate can be integrated.

Fig. 13. CO₂ concentration in ppm plotted against age in the Vostok record (upper curve) and atmospheric temperature change derived from the isotopic profile (lower curve). (from Barnola et al. 1987). Reprinted by permission from Nature vol. 322, pp. 408-414, copyright © 1987 MacMillan Magazines Ltd.)
8.2 Objectives

- To determine and understand the controls on and rates of transfer of carbon and associated biogenic materials and elements between the water column and bottom sediments and the relation to the sedimentary record;

- To examine the Quaternary palaeoceanographic record to determine the relationship of ocean circulation, palaeoproduction and the atmosphere, to aid in the prediction of CO₂-related climatic change.

8.3 Techniques

For studies of benthic processes, measurements are needed to characterize benthic fluxes using benthic chambers, pore-water gradients, in situ electrode measurements, coupled with high-resolution studies of sediment composition. Radiochemical measurements, field observations and modelling are needed to resolve problems of bioturbation. Studies of sedimentary geochemistry should also emphasise microbiologically mediated transformation reactions since these also affect sedimentary redox reactions. Emphasis must also be placed on the fate of inorganic carbon. Studies are also needed of the fate of calcite and aragonite at the sea bed and the coupling of organic-inorganic carbon cycles such as through sedimentary carbonate dissolution by metabolically produced CO₂. Studies of carbon isotopes in sediments and pore waters will be vital.

For studies of the Sedimentary Record, there are two complementary approaches to be used. One is to estimate fluxes of substances (organic and carbonate carbon, opal, aeolian dust etc.) from their rates of accumulation in the sedimentary record. The other is to use proxy indicators (O and C isotopes, microfossils, Cd/Ca and other palaeochemical tracers, organic biomarkers etc.) to reconstruct the temperature, chemical composition and
circulation of past oceans and atmospheric composition. Central to both approaches is the requirement for precise chronology and for this there is a need to supplement classical oxygen isotope stratigraphy and conventional radiocarbon dating with radiocarbon dating of foraminiferal species by accelerator mass spectrometry. It will be important that the link between these two areas of study is strengthened. As new palaeochemical tracers are explored and old ones used more extensively, their calibration should be firmly established, comparing water column properties with their record in foraminiferal calcite, in opal, in sediment geochemistry.

8.4 Approaches

To have global relevance, benthic data are needed from each of the major biogeochemical provinces and it is essential that benthic flux and process studies are fully integrated into the main JGOFS Process Studies. Evaluations must be made to permit global extrapolations from a limited data set. It is likely that studies complementary to the major JGOFS effort in the deep sea need to be carried out on continental margins, emphasising metabolic rate measurements such that the effect of global warming on benthic fluxes of CO$_2$, methane and nutrients can be evaluated.

Palaeoceanographic investigations cannot resolve events at the highest frequency end of the temporal range of carbon fluxes but can be used for changes at frequencies of the order of one year (in varved sediments) up to longer intervals in hemipelagic and pelagic sediments. It will be important to document changes in the fluxes of the relevant JGOFS core properties for comparison of contemporary benthic fluxes with the sedimentary record. It will be necessary to evaluate glacial-interglacial differences in carbon fluxes and their regional variability, and to resolve controversies about how well they reflect productivity changes or changes in carbon preservation, possibly through the development of low-oxygen bottom waters. There is a need for a palaeoceanographic variation of the GEOSECS approach whereby property distributions for critical parameters (CO$_2$, nutrients, hydrography) are obtained for crucial oceanic sections. The time variability of carbon fluxes should be determined at key sites within different oceanographic provinces as defined in Chapter 3. Other approaches include high-resolution studies of the transition from the last glacial maximum to the present; a history of low- and mid-latitude upwelling as related to the accumulation of organic matter in sediments in order to deduce relationships between atmospheric CO$_2$ variations and productivity changes; and detailed studies of the North Atlantic Ocean, which during the past 25,000 years experienced the largest climatic change of the world ocean, thereby providing an excellent case study of the effects of migration of the polar front on productivity, particulate matter fluxes and atmospheric carbon dioxide concentrations.

Work in these areas must be integrated with other IGBP programmes. For example, JGOFS work on the Sedimentary Record will be linked to work in the IGBP programme "Past Global Changes" and will result in mutual strengthening of scientific understanding.
Data Management

The success of JGOFS critically depends on the establishment of international data exchange and management activities for biogeochemical observations. Historically these data have not been either catalogued or exchanged easily due to factors associated with the labour intensive nature of the analysis process, differences in analysis protocols, lack of confidence in the data product, etc. The JGOFS observational and analysis framework, which is based on a distributed international approach to the observing system, explicitly assumes rapid, easy sharing of data, models, analyses, and observation systems for its success.

The present hierarchical model assumes international data exchange will occur through interactions between the various national oceanographic data centres. Each national data centre will have a JGOFS focus through a JGOFS data coordinator. This coordinator will be responsible for acquiring national data sets, analyses, etc., for the extra-national use, acquiring extra-national data sets for national use, ensuring conformation with agreed international data exchange modes and formats, making inventories of national holdings, and interacting with the JGOFS Data Management Task Team as needed. Individual scientists will interact with their respective national JGOFS data coordinator as specified by their national programme.

Standards have already been promulgated by the JGOFS Data Management Working Group for data access and portability. These standards include a common self-describing data format for data archiving and exchange and use of modern object oriented data management approaches for retrieval, merging and analysis. Development of portable accession software and network based distributed data accession models should provide scientists with direct paths to observations, model results, and related products as they become available.

As a trial of the proposed data exchange formats, the Data Management Working Group focused on the needs of the JGOFS North Atlantic Pilot Study that was successfully completed during the 1989 field season. A set of twenty core measurements to be conducted during the Pilot Study was defined early in the planning stages. For each of these, agreement was reached on a standard measurement protocol and level of accuracy to be attained. The utility of the proposed formats was discussed at the JGOFS Pilot Study Data Analysis Workshop in Kiel in March 1990. Cruise participants from all nations involved brought their data to Kiel for a week-long "hands on" session at which various data sets were merged and preliminary scientific findings discussed.

As part of the implementation plan JGOFS will be defining up to 12 process studies (Chapter 3). At each site upwards of twenty core measurements will be made. Thus, the minimum data management requirements of JGOFS can be appreciated. There will also be large amounts of remotely sensed data-most importantly ocean colour data, which it is hoped will come from the SeaWiFS instrument to be launched in 1993.

The JGOFS Committee considers that free exchange of information is essential for the success of JGOFS, and at its 1989 meeting in Hawaii the following policy regarding data
access and submission was formally adopted.

- Recognising that science is best served by free and open communication of findings, including data in raw form; and,

- In view of the enormous value of uncorrupted data sets as input to models useful in the design of field projects and in hypothesis testing; and,

- Noting that JGOFS will produce, at public expense, high quality data sets of extreme value to ocean biogeochemistry;

- The JGOFS Committee believes that READING ACCESS to this JGOFS Data Base(s) should be without restriction for any interested user. The information in the Data Base(s) will be labelled as to its originator and it is EXPECTED that readers would obey the normal scientific obligation to contact the originator for permission to make further use of those elements of interest to them.

- The JGOFS Committee hopes that each and every national committee for JGOFS would endorse this policy on data access.

- Ensuring that JGOFS investigators submit their data to the JGOFS data base in a timely manner (as defined in the core measurement protocols) falls within the responsibility of the various national committees.
The Next Steps

This document is intended to set out the scientific problems that are the particular concern of the JGOFS project, define aims and objectives whereby these problems can be solved, and provide a framework within which the international cooperation - the prime asset of JGOFS - can be planned. Many participating nations are already actively involved in JGOFS activities, for example the 1989 Pilot Study, and are planning future activities. It is therefore essential that a JGOFS Implementation Plan be formulated as soon as possible. A JGOFS International Planning Office (IPO) has been set up at the Institut für Meereskunde at Kiel University, and a Scientific Secretary has been appointed to run it. The IPO will provide the focus for developing the Implementation Plan and it is important that this plan should be formulated as soon as possible.

Some of the issues that must be resolved are:

- A time-scale must be set for the whole programme. This time-scale must bear in mind that projects of this scope require some years before their results are assimilated, and that national legislators and planners will increasingly be asking for guidance for policies for climate change. At the present time JGOFS is envisaged as a ten-year programme starting in 1989, with the aim of finishing the main cruise programmes by 1997-98, to allow for the data assimilation and modelling activities to be completed by the end of the decade.

- The extent and nature of the global survey and the siting of process study sites must be finalised. This will involve a trade-off between scientific criteria, logistical considerations, and the willingness of national JGOFS programmes to adopt particular transects and sites. Cooperation with other programmes such as WOCE is obviously essential.

- Agreement must be reached on a set of core measurements that will be measured during JGOFS process studies. Experimental protocols and calibration procedures must be defined for each of these measurements. A foundation has already been laid for this exercise by the Cruise Coordinating Committee for the JGOFS 1989 Pilot Study.

- The methods whereby data are to be assimilated into a JGOFS data archive must be agreed internationally. This will involve cooperation with international and national data centres.

- The various national modelling activities need to be encouraged to cooperate in order to achieve the JGOFS goals.

In order to resolve these issues, the JGOFS Committee at its meeting in Kiel in March 1990 set up a number of Task Teams. The topics to be covered by these Teams are:

1. Design of the Global Survey
2. General Specification of a JGOFS Process Study
3. Modelling Coordination
4. Planning of Time Series Stations
5. Benthic Flux Studies
6. Studies of the Sedimentary Record
7. Data Management

These teams will be given a set of objectives designed to develop the JGOFS Implementation Plan by early 1991.
References


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