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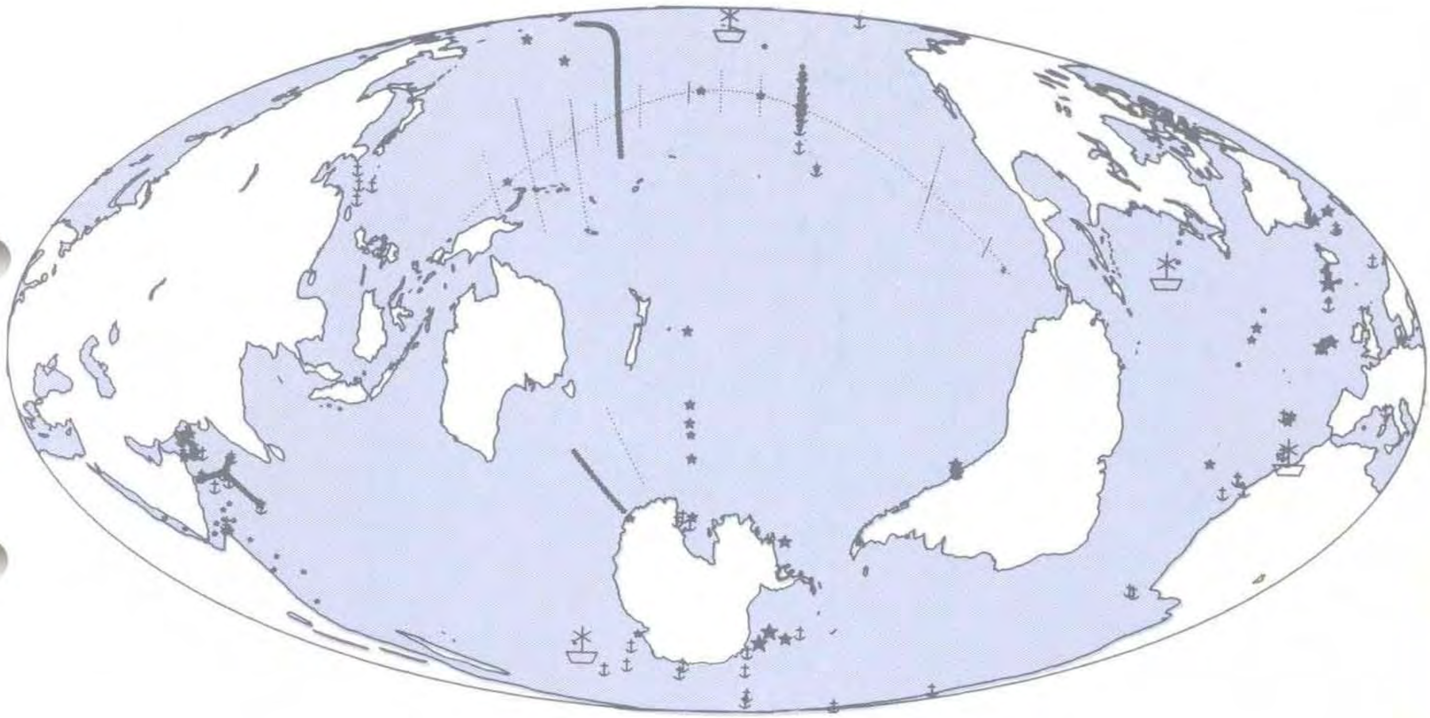

Joint Global Ocean Flux Study
Implementation Plan

JGOFS REPORT NO. 9

SCIENTIFIC COMMITTEE ON OCEANIC RESEARCH
INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

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Executive Summary

The oceans contain some 50 times as much carbon dioxide as the atmosphere, and small changes in the ocean carbon cycle can therefore have large atmospheric consequences. Such changes are believed to have had important feedback effects on climate during the transitions to and from ice ages; they may also have important consequences during the climate changes that are predicted to occur in the next 50 - 100 years, as a result of rapidly rising levels of atmospheric CO_2 and other greenhouse gases.

Models indicate that the oceans are currently taking up at least a third of the anthropogenic CO_2, by dissolving it in water that then loses contact with the atmosphere because of sinking or vertical mixing. Biological processes complicate the oceanic carbon cycle; although they probably do not affect the present uptake of *anthropogenic* CO_2, they are important (1) as a determinant of the natural background distribution of carbon; (2) because seasonal variation in biological processes complicates the effort to measure the background distribution; and (3) because biological feedbacks have the potential to amplify chemical and physical effects.

Many scientists worldwide are addressing aspects of the ocean carbon cycle, but to determine overall net fluxes and the processes controlling them is beyond the capability of any one nation. Therefore the Joint Global Ocean Flux Study (JGOFS) has been established, under the auspices of the Scientific Committee on Oceanic Research and as a Core Project of the International Geosphere-Biosphere Programme. Its purpose is to plan and execute the research that requires international cooperation. Close to 20 countries are already contributing to JGOFS planning or field work. The scientific goals of JGOFS were published in its Science Plan (SCOR 1990):

- 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.

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

The JGOFS Science Plan describes how the goals can be attained through a combination of large-scale surveys from satellites and ships; studies of key processes to help interpret and interpolate between surveyed quantities; series of monthly measurements for many years to determine how fluxes and processes vary; and studies of the record of oceanic and climatic conditions preserved in Quaternary sediments. An overarching programme of synthesis and modelling will ensure that observations are planned and interpreted with JGOFS goals in mind. JGOFS will create a high-quality data set by specifying measurement protocols and providing training in their use; it will also institute a data management system to make the data easily available to the scientific community.

Field work began in 1989, and will continue until about 1997, with a peak in 1994-95 as results from the next generation of satellite ocean colour sensors become available. Analysis and data synthesis will continue for the rest of the decade.

This Implementation Plan describes how the internationally coordinated part of JGOFS will be accomplished, and what resources are needed. Planning is a continuous process, and revisions to this document will be published to provide updated information as JGOFS develops. The Plan mentions some possible activities that are not scheduled yet, although this Executive Summary refers only to research for which firm commitments have been made. The Implementation Plan also refers to scientific thought that has developed since the Science Plan was published, and can thus be regarded, in part, as a Science Plan update.

JGOFS will restrict itself to the most important tasks consistent with its lifetime and resources. Carbon exchange between the atmosphere and ocean is its main focus; however, for periods longer than a year, the main factors limiting this flux may be associated with the exchange of carbon between the upper ocean and the ocean interior. JGOFS has therefore adopted the following "operational goal" for evaluating components of the programme:

> To assess more accurately, and understand better the processes controlling, regional to global and seasonal to interannual fluxes of carbon between the atmosphere, surface ocean and ocean interior, and their sensitivity to climate changes.

This goal is expressed in more detail in the following objectives:

- an assessment of large-scale carbon fluxes, obtained from a greatly increased network of observations
- a set of models that express our understanding of the processes controlling large-scale carbon fluxes
- a procedure for observing the ocean in a routine, synoptic manner to detect possible changes in the ocean carbon cycle in response to climate change
- a well-cared-for data set, comprising observations made according to standard protocols and a system for making subsets of these data easily available to researchers
- knowledge and understanding of fluxes across the continental margins, to provide reliable boundary conditions for global models
- an increased number of countries with an interest and skill in planning JGOFS-type activities and making the appropriate measurements and global-scale inferences.

The global synthesis will be carried out with the aid of a variety of models. These include concept-driven models of the underlying processes, tuned to the data collected during JGOFS, and data-driven models designed to interpolate and extrapolate as best we can between and beyond JGOFS observations.

Large-scale surveys will lead to maps of fluxes which can be integrated to produce global flux estimates. Surveys so far planned include ocean colour from satellites and carbon system measurements made on cruises of the World Ocean Circulation Experiment (WOCE).

Some ocean regions need to be studied in greater detail, either (1) because the resolution of large-scale surveys may be too coarse to adequately describe the processes occurring there; or (2) because that part of the ocean is known to be particularly sensitive to climate change; or (3) because the magnitude of the regional carbon flux is a high proportion of the global total, and therefore needs to be well determined. Four regions have been chosen for detailed study, on the basis of their likely contribution to reducing uncertainties in understanding the ocean carbon cycle.

The North Atlantic is a major area of deep water formation where dissolved CO_2 is carried away from the surface ocean, where a large seasonal biogenic signal complicates the interpretation of surveys, and where the sedimentary record indicates a large sensitivity to past changes in climate. The Equatorial Pacific has a large area and a large pool of unused nutrients (representing a potential uptake of carbon that is not occurring); interannual variability connected with El Niño effects complicates the interpretation of surveys. The Southern Ocean is a complicated region of large fluxes, which appear to be in approximate balance now but may get out of balance in a changed climate. It also has a large pool of unused nutrients, and the influence of changes in sea ice cover needs special attention. The Arabian Sea is an area of very high average chlorophyll, and of extreme seasonal variation driven by monsoonal reversals; it also offers a wide range of physical forcing in an area where light does not vary much, i.e. a region of instructive contrasts.

Process studies are ongoing or planned for all of these regions. They are designed to provide the sort of understanding that can be extended over a large area and used to make syntheses, especially understanding expressed in improved models and parameters for the key processes. They will provide an inventory of key fluxes, a definition of control mechanisms, and an understanding of forcing at time scales ranging from a week to several years.

Time series stations will be maintained for several years to observe and interpret seasonal and interannual variability of fluxes and processes over the whole water column, using a combination of shipboard observations at specific sites, made monthly or more often, and sediment trap moorings. Stations currently operate near Bermuda and Hawaii; others are planned for Kerguelen Island and the Canary Islands.

Sedimentary record studies are underway in many ocean basins to determine the relationships between ocean circulation, biological production, atmospheric CO_2, and climate over a wide range of past conditions.

A special effort will be made to determine horizontal boundary fluxes across continental margins. This work, which offers the opportunity for participation of many coastal states in JGOFS research, will be coordinated jointly with the IGBP proposed Core Project on Land-Ocean Interactions in the Coastal Zone.

Updated protocols will be published for measuring the most important variables. To encourage the use of these protocols by all investigators in all regions of the ocean, training workshops will be held in conjunction with JGOFS process studies. An international data management system, linking small topical (e.g. national) JGOFS data centres, will make it possible for researchers to find out about and access the data collected during JGOFS.

Although this Implementation Plan concentrates on the parts of JGOFS that demand international coordination, it recognizes the essential information contributed by associated activities of individual nations. Those relevant national activities that are known to the JGOFS Project Office at the time of preparation of this first version are described here.

Annexes provide information on the organization of JGOFS, including the planning groups that have contributed or are now contributing to the design of the study; addresses of people to contact for further information on its different parts; and brief descriptions of other closely-related international programmes.

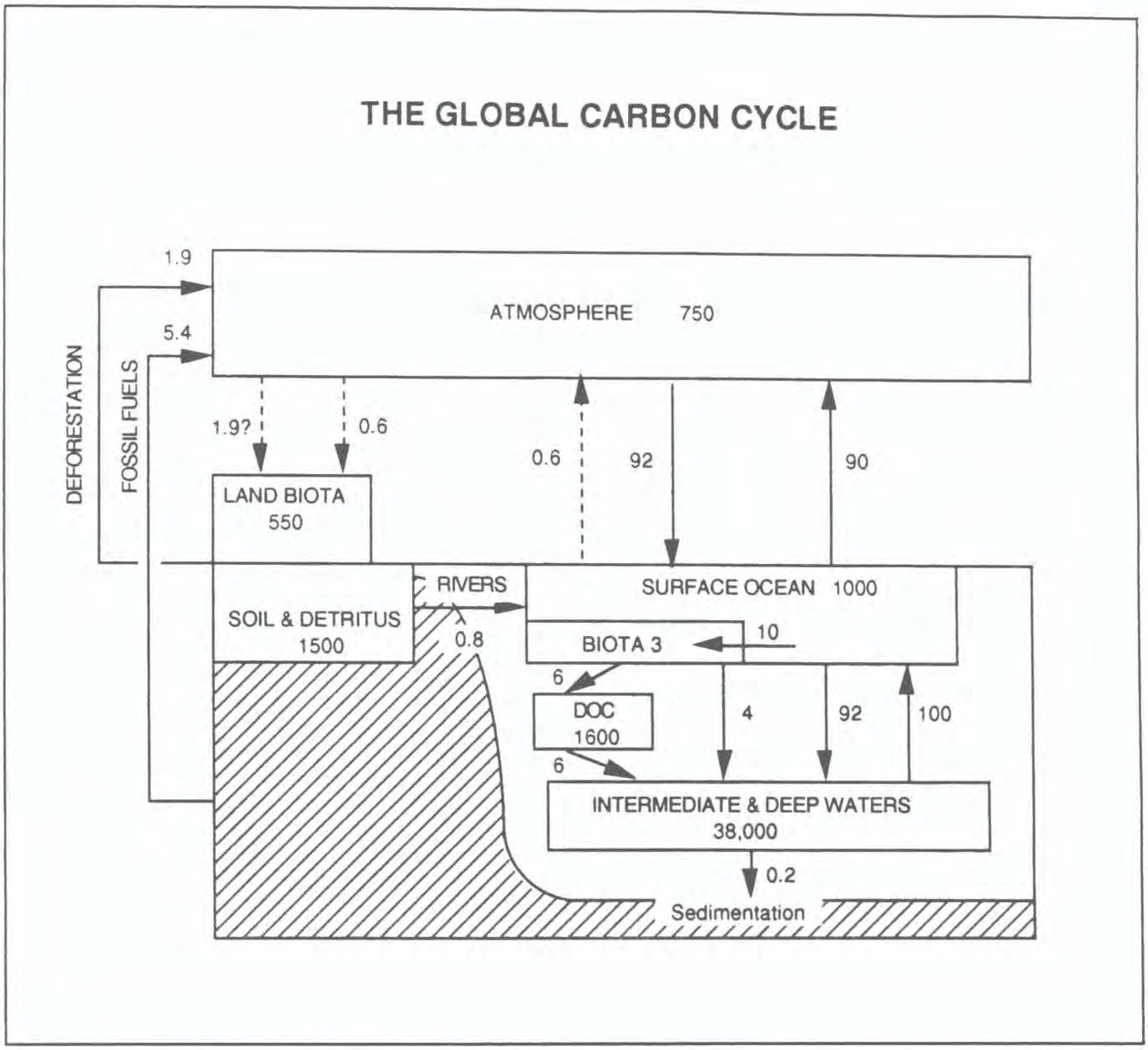

Figure 1. Major global carbon pools and fluxes

Values are estimates for the decade 1980-1989 in GtC yr^{-1} for fluxes and GtC for reservoirs (after Houghton *et al.*, 1992). The difference in the main exchange fluxes between atmosphere and ocean (solid arrows) corresponds to the oceanic uptake of anthropogenic CO_2, i.e. 2.0±0.5 GtC yr^{-1}. The export production of carbon from the upper ocean is not well known; published estimates range between 4 and 20 GtC yr^{-1}. The amount of dissolved organic carbon (DOC) in the ocean is currently under debate. The values of the gross fluxes between surface and deep waters (92 and 100 GtC yr^{-1}) depend on the two levels between which the exchange is assumed to take place; very different values can therefore be chosen. The difference between these two fluxes is the net upward transport that balanced, in pre-industrial time, the downward flux by particles and DOC; today, this difference is smaller, corresponding to the net downward transport of anthropogenic CO_2. For the land biosphere, only net exchange fluxes are shown. The dashed arrows of 0.6 GtC yr^{-1} from the ocean to the atmosphere, and from the atmosphere to the land biota, denote the fluxes required to balance the difference between carbon input into the ocean by rivers and continental rocks. The dashed arrow of 1.9 GtC yr^{-1} from the atmosphere to the land biota represents the flux required to balance the budget of atmospheric CO_2 perturbations.

1. Introduction

Scientific interest in the global carbon cycle has grown during the last decade, in response to two main developments. Firstly, analysis of polar ice cores has shown that atmospheric carbon dioxide has previously varied in parallel with the Earth's glacial-interglacial cycles. Secondly, atmospheric CO_2 is now rapidly increasing due to human activities, and this threatens to cause major changes in the global climate. Both ocean circulation and marine biogeochemical processes play a large role in regulating the atmospheric concentration of CO_2, mediated through air-sea exchange. Ocean uptake has undoubtedly slowed the build-up of anthropogenic CO_2 in the atmosphere; however, the strength of that effect, and its future behaviour, are uncertain.

The Joint Global Ocean Flux Study is based on the premise that, by making the right measurements for a decade and synthesizing the results, it can deliver a greatly improved understanding of the processes that govern carbon flow in the ocean and its coupling with other components of the global carbon cycle. As a result, we will have much more realistic predictions of how the ocean system will react to climate change. The JGOFS Science Plan (SCOR 1990) laid out the goals of JGOFS and described the scientific tools that are available to pursue them. The goals are:

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

This Implementation Plan develops a structure for achieving JGOFS goals, outlines the necessary activities, and estimates the resources that will be required to carry out this work. Planning JGOFS is an ongoing process, and much thinking that would logically fit into the Science Plan has developed only since that plan was published. Therefore the Implementation Plan also contains some updated scientific planning, where appropriate. However, for the full scientific context it should be read in conjunction with the Science Plan.

JGOFS implementation can be considered as building a bridge between, on the near side, what we currently understand about the magnitudes and causes of carbon flow in the ocean, and, on the far side, what we want to understand when JGOFS is over. The remainder of this introduction contains a description of the near and far sides, and a brief argument that the bridge can indeed be built.

1.1 An overview of carbon fluxes

The Earth's major carbon pools and our current estimates of the fluxes between them are shown in Figure 1. Carbon mostly enters and leaves the ocean as CO_2, via gas exchange at the sea surface. The local flux is proportional to ΔpCO_2, the difference between the partial pressures of CO_2 in air and seawater. Physical and biological processes produce large spatial and temporal variations in pCO_2 in the surface ocean, and therefore direct determination of net global air-sea exchange is difficult. CO_2 and other forms of carbon are transported to deep water by both physical and biological processes: convection, advection, convection and small-scale turbulence are responsible for the transport of dissolved inorganic and organic carbon, whilst biological processes are responsible for the formation of particulate carbon, with its more rapid transport, by sinking, from the upper ocean.

Under natural steady-state conditions (during periods of climatic stability), the gross downward flux of carbon out of the upper ocean is compensated by an upward transport of dissolved carbon of closely similar magnitude. As a result, the net flux of CO_2 between atmosphere and ocean was near-zero, and atmospheric CO_2 levels were stable, for at least a thousand years before the onset of industrial activities.

Dissolved inorganic carbon (DIC) concentrations are lower in surface water than in deep water. One reason for this is that surface water is generally warmer than deep water, and CO_2 is less soluble in warm than in cold water. Another reason is biological uptake of carbon, due to photosynthesis. Of the total primary production in the ocean, between 10 - 40% sinks out of the surface as particles, and an unknown further fraction (possibly as much again) is transported downwards as dissolved organic carbon. The total amount of production exported to deep water is estimated to be between 4 - 20 GtC yr^{-1} (1 Gt, gigatonne, is 10^{15} grams), with the rest recycled in the photic zone.

Since the Industrial Revolution, human activities have introduced significant additional amounts of CO_2 into the atmosphere, creating an imbalance between the different global subsystems. The ocean contains much more carbon than the atmosphere, and over a time scale of centuries it will contain most of the anthropogenic CO_2. On this time scale, the uptake is mainly controlled by the rate at which carbon is transported to the deep ocean. Current carbon cycle models estimate the global net air-sea flux of anthropogenic CO_2 to be about 2 GtC yr^{-1}. Whilst most of the CO_2 emissions due to use of fossil fuel occur in the northern hemisphere, more than half of the world ocean is in the southern hemisphere. It might therefore be expected that at least half the CO_2 uptake by the ocean occurs there, but that does not seem to be the case.

Atmospheric circulation models indicate that the southward flux of airborne CO_2 across the equator (caused by the interhemispheric concentration difference) is just large enough to explain the annual CO_2 increase in the southern-hemisphere atmosphere. However, model data do not match the estimated CO_2 flux into the southern ocean. This finding led Tans *et al.* (1990) to conclude that the ocean takes up less CO_2 than predicted by carbon cycle models; instead, they postulated a large CO_2 sink in northern temperate land biota. Their model does not take account of any net oceanic transfer of carbon between hemispheres, nor the probable role of the pre-industrial ocean as a net source of CO_2 (due to oxidation of organic matter carried in by rivers). The details of these processes are not yet well understood, but it is clear that in order to reconcile the atmospheric and oceanic CO_2 observations, natural processes as well as the anthropogenic perturbation must be carefully studied.

Changes in biologically-mediated vertical transport within the ocean have the potential to cause atmospheric CO_2 variations. Thus several hypotheses on the cause of the glacial-interglacial CO_2 variations have invoked changes in the biological pump. However, many components of these models are at present over-simplified. For example, the rate of remineralization of sinking organic particles: this is usually described as an empirical function of depth, but is now known to be affected by particle size and composition, as well as by temperature and oxygen concentration. Quantitative knowledge of such relationships is required for tackling the question of how future climate change would affect the ocean carbon cycle.

Marine biological processes are usually not considered to be limited by the availability of CO_2. It is therefore unlikely that marine ecosystems have yet been directly affected by, or represent a net sink for, the anthropogenic CO_2 increase. However, the feedback role of marine biology in a changed climate is unknown. Significant environmental changes (in particular, different ocean circulation patterns) can be expected to lead to changes in ecosystem structure and composition, which in turn could have a global-scale impact on ocean carbon transport.

The carbon cycle is closely linked to cycles of other elements, in particular nutrients and oxygen. On a large scale, the relative amounts of the main elements involved in biological transformations (Redfield ratios) are roughly constant, but detailed studies show systematic regional and depth variations in these ratios. This finding has important implications for modelling the ocean carbon cycle. In equatorial and polar regions, particularly the Southern Ocean, phytoplankton biomass and primary production are often low – even when the main nutrients (nitrogen and phosphorus) are abundantly available. It is not clear what factors limit biological productivity in these nutrient-rich areas: possible candidates include grazing, temperature, light and vertical mixing, and/or the lack of a trace nutrient such as iron.

1.2 Operational goal and objectives

JGOFS cannot study every aspect of carbon flux, and must therefore decide upon and restrict itself to the most important tasks consistent with its lifetime and resources. Exchange between the atmosphere and ocean is a major pathway connecting the ocean with the rest of the global carbon cycle. However, gas exchange between the surface ocean and the atmosphere generally proceeds more quickly than the flux of carbon between the upper ocean and ocean interior, so that the rate limiting factors for surface-to-deep transport processes may have greater long term importance. High frequency variability is smoothed by this slower flux; nevertheless, there could be significant low frequency variability, with trends operating over large areas for several years. The detection and analysis of such effects, if occurring, would be of great interest to JGOFS.

With these ideas in mind, the JGOFS Scientific Steering Committee adopted an "operational goal" for JGOFS, to provide a practical guide for assessing the relevance and success of individual components of the programme:

> To assess more accurately, and understand better the processes controlling, regional to global and seasonal to interannual fluxes of carbon between the atmosphere, surface ocean and ocean interior, and their sensitivity to climate changes.

This goal will be achieved through the following products, that serve as JGOFS objectives:

- an assessment of large-scale carbon fluxes, obtained from a greatly increased network of observations
- a set of models that express our understanding of the processes controlling large-scale carbon fluxes
- a procedure for observing the ocean in a routine, synoptic manner to detect possible changes in the ocean carbon cycle in response to climate change
- a well-cared-for data set, comprising observations made according to standard protocols and a system for making subsets of these data easily available to researchers
- knowledge and understanding of fluxes across the continental margins, to provide reliable boundary conditions for global models
- an increased number of countries with an interest and skill in planning JGOFS-type activities and making the appropriate measurements and global-scale inferences.

1.3 Operating strategy

The different types of JGOFS activity were identified in the Science Plan; this document describes how they fit together to make the structure that JGOFS needs.

1.3.1 Synthesis of global fluxes

JGOFS will develop a plan for synthesizing the observations into a picture of large-scale fluxes. This will not happen automatically, and the mathematical techniques that exist, or must be invented, are described in Section 2. Two kinds of activity are involved here, although the boundaries between them are not clearcut. Firstly, interpolation between all the data that are collected will provide a simple assessment of fluxes. Secondly, understanding and prediction will be obtained from the development 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" (Science Plan, p 28).

1.3.2 Observations

Large-scale surveys

JGOFS will carry out large-scale surveys through a combination of sea surface observations from satellites, continuous shipboard measurements along transects, and more detailed point measurements collected at a network of ship stations and moorings. The surveys will provide global inventories of carbon in various forms; and a network of local concentration gradients and exchange rates will provide a basis for estimating large-scale fluxes. Particular attention will be paid to resolving seasonal variations at mid and high latitudes. The surveys that are planned are described in Section 3.

Regional studies

A global flux study must go beyond large-scale surveys. That is because a survey of the present-day state is unlikely to show the rules by which it operates, and therefore how it might react to change. Furthermore, a survey from a ship at a particular time of year may be misleading in regions of strong seasonal variablility, and understanding the variability can help us to correct for it and interpret the survey results better. For example, surface water pCO_2 can change greatly over 100 km or a week, and existing ΔpCO_2 observations do not cover the ocean densely enough in space and in time to permit a reliable determination of mean regional or global net fluxes. Principles for choosing regions of importance to JGOFS, and the regions chosen, are discussed in Section 4.

Regions will be studied in several ways. Process studies (Section 5) will investigate in detail the key variables controlling carbon fluxes. Such studies are designed to provide the sort of understanding that can be extended over a large area and used to make syntheses, especially understanding expressed in refined models and improved estimates of model parameters. Time series studies (Section 6) will make measurements and estimate fluxes over the seasonal to interannual time scales of interest to JGOFS, and will provide records of long-term behaviour as a constraint on models.

The operational goal implies an emphasis on pelagic studies. However, JGOFS also includes studies of ocean sediments, since they provide the main sink for carbon on geological time-scales and also contain important benthic indicators of upper ocean processes. Thus records left in the sediment can be seen as a time series that contains information about much larger changes in the ocean than those that will occur in the next decade. Interpretation of the sedimentary record (Section 7) not only requires analyses of geochemical composition, but also studies of how sediment is formed in the benthic boundary layer. That is because compositional changes within and between sediment samples (e.g. in the abundance of organic carbon) may be due to changes either in export production or in the benthic conditions that control preservation (see Section 5.1.6)

Continental margin studies

JGOFS will assess and quantify carbon fluxes across continental margins as a boundary condition for the open ocean (Section 8). Coastal seas are more heterogeneous than the open ocean, with physical conditions affected by additional variations in topography and water depth, adjacent landforms and salinity. Furthermore, the biogeochemical processes that operate there are also more complex, so that whatever understanding we gain cannot be as easily extrapolated as for open ocean studies.

However, the study of coastal processes is facilitated because many more countries are willing and able to carry out oceanographic research on their continental margins, and several large programmes relevant to JGOFS are already active or planned.

Collection and management of data

The synthesis of JGOFS will require a high quality data set, with trustworthy observations from around the world freely accessible for scientists to analyse. This will be achieved during data collection, by defining core variables to be measured and protocols for measuring them (Section 9.1); by running intercalibration experiments at sea to make sure that all measurements are comparable; and by offering training in making the measurements according to the protocols (Section 9.2); and, after data collection, through archiving, quality control, and mechanisms for exchange and distribution of data and data catalogues (Section 9.3).

The JGOFS data set will also be a valuable resource for other projects; for example, by providing the oceanographic component for Earth system models, and as a baseline for future global change studies.

1.3.3 Organization

Internationally coordinated activities

JGOFS is sponsored by the Scientific Committee on Oceanic Research (SCOR), and is an established Core Project of the International Geosphere-Biosphere Programme (IGBP). The JGOFS Scientific Steering Committee (SSC), appointed by SCOR, has overall responsibility for the design, implementation, execution and synthesis of each internationally coordinated activity. This involves decisions on: the most informative measurements to be made; the most effective use of resources; and the best ways to interact with other large-scale programmes. Initially, such decisions will be largely based on the accumulated experience of the participants, but as skill in modelling and synthesis grows, they will be supplemented by model-based assessments of how informative different possible measurements and strategies would be for particular questions. The SSC, supported by the JGOFS Project Office, will define the questions, form planning and coordinating committees, coordinate observational elements and set the timetables for each study.

The SSC has created a number of task teams and planning groups to consider scientific and logistic questions and make recommendations to the SSC. These groups will identify the most important processes and variables to study; the regions in which such studies will provide the greatest insight and most useful data; and the best experimental design for the studies. They will then identify the sequence of events necessary to complete specific tasks, the resources required for the tasks and the level of international coordination that is required. Some task teams disband after delivering their reports; others (e.g. data management, and synthesis and modelling) are expected to last throughout JGOFS. Reports have already been received from task teams on pelagic and benthic process studies, time series studies, large scale surveys, and sedimentary record studies. A task team for ocean margin studies was formed in 1992, and a team for remote sensing is being formed.

National activities

Much of JGOFS takes place at the national level, with national committees planning and funding their own programmes which contribute to JGOFS aims, without putting demands on the international planning process. However, it is highly desirable for national committees to take full account of the international context, to maximize the scientific contribution of their own research to global flux questions.

Coordination between national and international studies is achieved as follows. National JGOFS groups will formulate plans for their activities, based on the JGOFS Science Plan and Implementation Plan. The chairs of these groups will take part in JGOFS SSC meetings, during which they report how national plans and activities are contributing to the international goals. The SSC will provide advice and comments that allow the national groups to refine their plans in the light of JGOFS scientific and operational goals. This process will also allow the SSC to identify gaps in the overall programme.

Given the magnitude of the task, there is a need to increase the number of countries interested in ocean carbon flux – and that are able to make relevant measurements, interpret results and share data worldwide. Training in making flux measurements according to JGOFS standard protocols will be offered, and links with internationally available databases will be fostered.

Timing

JGOFS is not an open-ended project. Field work planned in detail lasts past 1994 (Table 1). By this time, experience with the ocean colour satellite SeaWiFS should be sufficent so that another three years of field work, guided by this sensor, can be sensibly planned. Such satellite-based work will be necessary to obtain the global context that forms the distinguishing part of JGOFS. The main field phase of JGOFS will end in 1997, and the next three years will be devoted to the final synthesis and filling in gaps in the global survey. A process study, including planning and analysis, will take 5 - 6 years to complete (see Section 5.2.2) and a time series study will take three years longer than the actual period during which observations are made.

Table 1. Provisional schedule of main JGOFS field activities 1989 - 1998.

● denotes times of intensive, internationally coordinated activity
○ denotes times of extra, national contributions

Year / Quarter	89	90	91	92	93	94	95	96	97	98
Process studies										
North Atlantic	●●	○○	○○	○○			●●●●	●●●●		
Equatorial Pacific		○ ○	○ ○	●●●●	●●●●	● ○				
Southern Ocean				●● ●	● ●	● ○	○ ○	○ ●	● ●	●
Arabian Sea				○○○○	○○○○	●●●●	●●●●			
Time series										
Bermuda	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Hawaii	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
ANTARFIX					---	-----	-----	-----	-----	-----
Canary Islands					--	-----	-----	-----	-----	-----
Surveys										
WHP	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
JGOFS Survey							-----	-----	-----	-----
SeaWiFS					--	-----	-----	-----	-----	-----

2. Global synthesis

An ideal strategy for synthesis and experimental design would use a model of oceanic carbon flux that described the relevant physics, chemistry and biology with high spatial resolution, into which all the observations, not only of JGOFS but of all relevant field and laboratory studies, were assimilated. From this one would produce the best estimates of carbon flux that the data allow, and also design the data set that would lead to the greatest possible improvement in such estimates. The different practical strategies used in JGOFS will fall short of this ideal, but should begin to converge toward it during the study.

There are four obstacles to attaining the ideal. First, models at fine spatial scales are so sensitive to initial conditions and atmospheric forcing that their detailed predictions contain an effectively random component at small scales. Secondly, even if it were possible to smooth such models or their output to make trustworthy predictions at large scales, the data that we wish to compare with model output would have similarly random components. Thirdly, we will always have imperfect equations for the ecological part, especially for the terms that determine community composition and hence Redfield ratios. Fourthly, it is mathematically difficult to assimilate a large and unsystematic collection of data into a large and nonlinear system of equations.

2.1 General principles

The overall plan is to infer, mostly from very sparse local measurements, quantities that can be extended to large areas of the ocean and used as a basis for regional or global flux calculations. Such quantities will always be based on a model: for example, one justifies averaging a set of observations by invoking a model that states there is no systematic variation in the quantity observed. No model is perfect, but it is worth the effort making global flux assessments even from plausible but inadequate models, provided we state their assumptions as clearly and openly as possible.

For any but the simplest model, it will be necessary to determine or choose the values of several models parameters (quantities that are constant within any one model run, but which may change between runs). This can be done in different ways. Data from the North Atlantic Bloom Experiment and the Bermuda and Hawaii time series stations consist of concentration and flux measurements. In principle, it is possible to use these measurements to estimate the parameters of a model, by finding that parameter set for which the model predictions most resemble the observations.

In practice, the mathematics of finding this best fitting set is difficult, computer-intensive, and unreliable. Unreliable both in the sense that the numerical approximation techniques may fail to find the minimizing parameter set, and in the sense that this set may not be stably determined; i.e., that small changes in the measurements, or in the measure of deviation we choose, may lead to large changes in the estimated values of some of the parameters. This general problem of ill-conditioning, and some of the remedies, are discussed in more detail in Seber and Wild (1989).

One of the reasons why the mathematics is so difficult is that the model output corresponding to a measurement is influenced by, and therefore contains a little bit of information about, every parameter of the model. The process of estimation can be made quicker and more reliable if measurements in the ocean can be supplemented by measurements under laboratory conditions that are manipulated so that the competing effects of different parameters can be distinguished. Future JGOFS process studies will concentrate on just this sort of experiment to determine parameter values.

One can take two different attitudes to the relationship between parameters and data. One attitude regards parameters as convenient summaries of sets of data, but less important than the data themselves; the other regards parameters as facts in their own right, and the purpose of data collection as being to obtain estimates of parameter values. The appropriate attitude depends on our circumstances and needs. Let us suppose, for example, that a time series station has measured, monthly for a year, the JGOFS core variables and the fluxes of carbon between atmosphere and surface ocean, and between surface ocean and ocean interior. It may happen that all these data are not sufficient to determine well the parameters of some model of water column ecology. It may also happen that the model's behaviour is very sensitive to the values of poorly determined parameters, if those parameters are changed one at a time. For flux assessments, however, one is more concerned with the sensitivity of flux estimates to observations, regardless of the parameter values. Different sets of parameters that fit observed fluxes equally well are unlikely to differ much in the way they interpolate between observations (although this assertion must be checked and not taken for granted).

For flux prediction, the parameter values themselves and how they might change become more important. This is because parameter *values* can change independently whereas parameter *estimates* will be dependent, tied together by the observations. Experiments and other studies that probe beyond contemporary conditions have a key role here.

JGOFS should perform many alternative syntheses, and determine how they change as more data become available for them to work on. This activity should defend against the danger of relying too much on the results of any one method. The opposite danger, of dropping a model as soon as its inadequacies are identified, could lead to JGOFS never making global estimates at all. All the synthesis techniques should be applied continually as information comes in.

It is important that the estimates of fluxes come with estimates of errors. Perhaps the only objective way to track the progress of JGOFS towards its goals will be by how flux estimates using different techniques converge, and how their error estimates decrease. We must remember that we can estimate only the errors we know about, which are almost certain to be less than the errors we do not suspect. But, even if the error estimate is wrong, it will be informative to watch it decrease as JGOFS progresses.

2.2 Low-detail models

These are exemplified by the HILDA model which Shaffer, Siegenthaler, Sarmiento, and others have used to study air-sea CO_2 fluxes and their sensitivity to changes in the working of the ocean carbon system (e.g. Shaffer 1992). It has a very simple physical structure, has few parameters, and is tuned to a few well-known data, namely the globally averaged vertical profiles of temperature, ^{14}C, phosphate, oxygen, alkalinity, salinity and DIC. The tuning provides global estimates of important quantities like the Redfield ratio and the depth distribution of subsurface remineralization. The model is so aggregated that its parameters correspond to nothing physical and therefore cannot be estimated from first principles. Sensitivity of the model to its parameters has been calculated.

2.3 High-detail GCM-based models

These are exemplified by the work of Sarmiento, Fasham and others on inserting ecological equations into a physical general circulation model (GCM) and calculating the fluxes that result. Results for a nitrogen cycle model (the simplest model for which questions about new production and its relation to total primary production can be posed) in the North Atlantic will soon be published; results for the Equatorial Pacific and Indian Ocean are being analysed. A joint model of carbon and nitrogen flow is currently under investigation, for incorporation in a Southern Ocean GCM.

It is very difficult to assimilate data into these models to estimate their parameter values directly. Therefore other aspects of JGOFS must be devoted to obtaining the needed parameters. Planning for process studies has recognized this point, and there will be increased emphasis on determining parameters in future process study cruises.

2.4 Models designed for data assimilation

Much effort in JGOFS will be devoted to collecting data, and so it is important to develop models that are easy to assimilate data into. Examples include models that are linear in their parameters, or models constructed so that a datum can in principle affect only a few parameters – like linear interpolation. For example, Brewer *et al.* (1989) performed a data-based assimilation to assess carbon transport across 25°N in the North Atlantic. A workshop will be held to construct such models, and to examine the necessary compromises.

Achieving a global synthesis entails performing a numerical integration: measuring a variable field at a sparse set of points and interpolating to estimate the values of the field at every point in the domain. Large-scale surveys are devoted to measuring the variables; process studies to determining and improving the rules for interpolation. The better one can interpolate, the fewer observations are needed to achieve the same accuracy in the integral. As a corollary, integrals derived from quantities that vary slowly in space and time will be particularly accurate. Such quantities are most likely to be found below the ocean surface layer, including the near-bottom and in sediments. The hypothesis that there is a manageable number of ocean biogeochemical provinces, within each of which an important set of quantities can be considered constant (Science Plan, p 19-26), can be seen as a hypothesis about the most appropriate interpolation rule – favouring piecewise-constant interpolation over continuous functions.

2.5 Experimental design

Once we know how we will use observations to make assessments of carbon flux, we can start to ask which observations would be the most influential. One possible route is to have a detailed ecological GCM running, and 'sample' the output from it in the way that field studies sample the real ocean. It will be important to sample with error – both measurement error (which can be large for variables like zooplankton grazing rates) – and natural variability (e.g. from an eddy-resolving model, by assuming that samples from nearby times and places give an idea of the ensemble variability at the time and place in question). We can apply one of the JGOFS synthesis techniques to the model-derived samples, and compare data generated from different sampling schemes according to how they reduce uncertainty in flow estimates. As well as asking where and when to sample, we can ask questions about what to sample. Is there a good set of complementary variables, which constrain flux estimates in different ways and therefore provide stronger constraints together than they would separately? Is there a good set of low-variablility variables? What would be the gains from more accurate measurement techniques, especially compared to the losses if they were more time-consuming? Success may come slowly (if at all), but the expense of ship-based fieldwork is so great that even small successes are valuable.

Models have already influenced some of the planning of JGOFS measurements. Thus, the emphasis on DOC measurements stems in part from model studies of 'nutrient trapping' (Najjar *et al.* 1992). For the equatorial Pacific, results of ecological CGMs have already contributed to the experimental design of the process study in that region: for example, some cruise tracks were shifted to sample model-predicted increases in autumn nitrate and CO_2 in surface waters near Peru. The Indian Ocean planning group is also using model results to assist in scheduling fieldwork for that region.

The HILDA model can be used similarly. Shaffer (1992) has analysed how sensitive its flux predictions are to its parameters; one might also analyse how sensitive the flux estimates and their precision are to the data on which the parameter estimates were based, and also to JGOFS data set.

2.6 Task team

A synthesis and modelling task team has been formed to make detailed recommendations, and to coordinate work along these lines. It may be necessary for international JGOFS to commission some of the needed modelling work. The task team will also cooperate with the regional planning groups on experimental design.

Contact: John Parslow

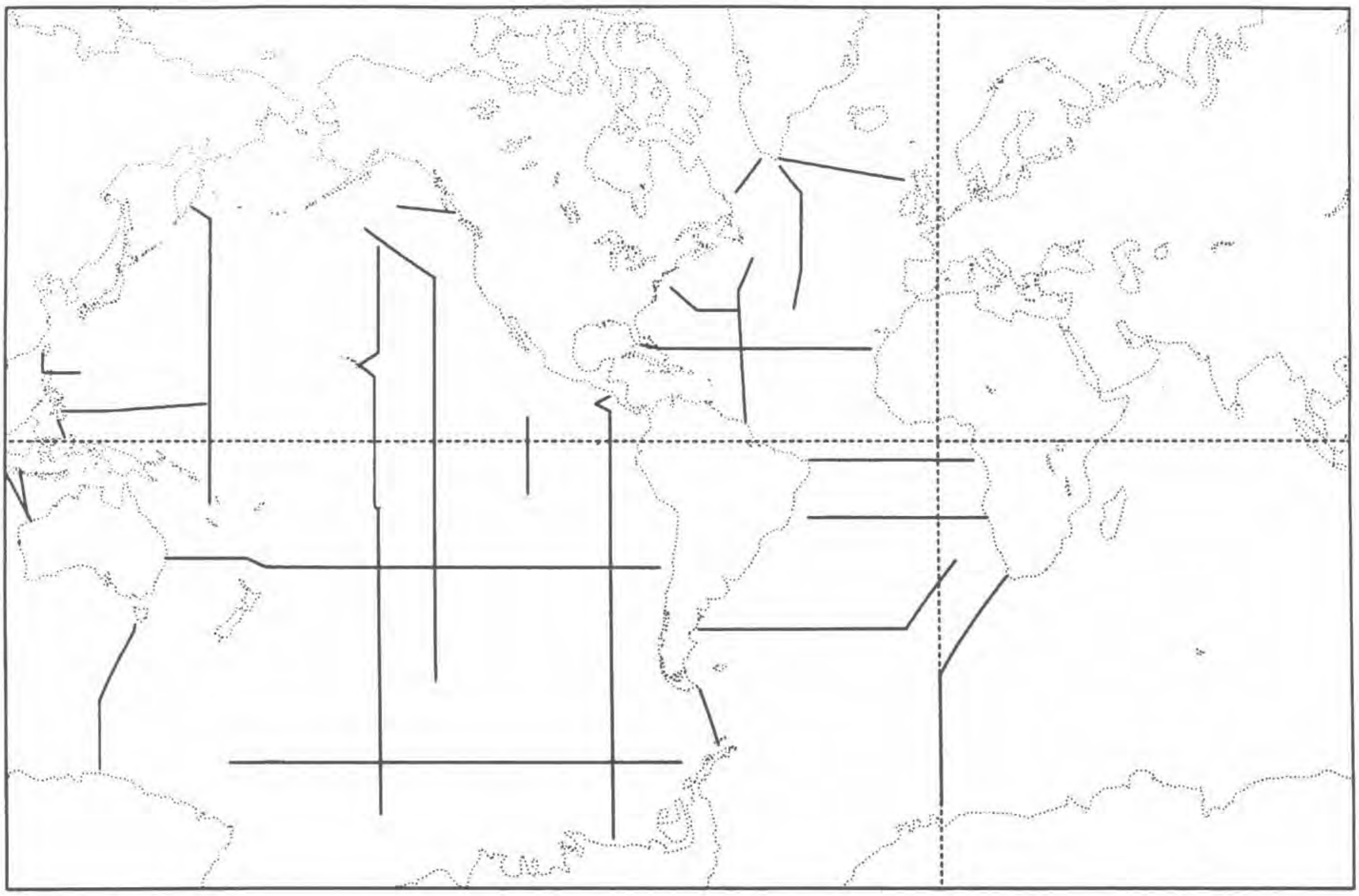

Figure 2. The carbon dioxide survey.

Transects along which CO_2 has already been measured (either in JGOFS cruises or on cruises of the WOCE Hydrographic Programme) or will be measured by the end of 1992. WHP transects in subsequent years will cover at least as much again.

3. Large scale surveys

The most direct way to assess global fluxes is to integrate measurements from large-scale surveys of relevant properties. This entails making a map of the quantity to be integrated, through a combination of a set of measurements and a method for interpolating between them. It will be possible to measure only a few properties, and JGOFS will choose those that can be measured quickly or are especially informative. There is a tradeoff between speed and information: it can be worthwhile surveying a property that takes a long time to measure if the measurement is highly accurate, or if the information complements other JGOFS data in a useful way.

Aspects of regional studies, especially underway measurements *en route* to a study site, can contribute to the goal of global coverage. Ships in transit to the time-series stations or the process study sites should make underway measurements that will contribute to the global survey. Surveys from other 'ships of opportunity' will be encouraged. However, the modelling and statistics of such unsystematic coverage will need attention, and it is important that inter-calibrations be done regularly among the different components of JGOFS, and between JGOFS and WOCE (especially for nutrients).

3.1 The JGOFS survey

Some of the activities listed below (3.2 - 3.5) are already being carried out or scheduled on existing platforms; the rest would require dedicated JGOFS survey cruises. Dedicated survey work will be a necessary step in realizing JGOFS objectives, as stated in the Science Plan, but large commitments are now being made to the process studies and to the current global survey that is being done in collaboration with WOCE (Figure 2). Consequently the survey envisioned in the Science Plan will not start immediately, but planning should begin now for a survey following the WOCE World Hydrographic Programme (WHP) survey. JGOFS will promote the timely assimilation of data from the current global survey and its use in the planning of the next survey. It may also be possible to realize the stated objective of detecting long-term change in the oceanic carbon inventory.

The JGOFS survey will consist of repeat occupations of selected WHP sections. Station spacing would be less close, but a much larger number of properties would be measured, possibly including the entire suite of core measurements, radionuclides, stable isotopes, and other tracers. A joint JGOFS/ WOCE group will be formed to develop the new global survey plan. High priority is being given to reaching a consensus on measurement protocols for DOC and DON, so that the complete inventory of carbon and nitrogen can be measured. JGOFS will encourage the development of new instruments for use in future global surveys (e.g. sensors, towed profilers).

Contact: Mike Bacon

3.2 Carbon dioxide

DIC and pCO_2 are important quantities for JGOFS to survey. Combined with physical transport models they give the fluxes of DIC following water movements; combined with atmospheric concentrations and gas exchange coefficients they give the net air-sea exchange of CO_2. The total inventory of excess CO_2 in the water column over presumed pre-industrial levels indicates the integrated anthropogenic invasion to date.

Berths are provided on all WHP cruises, as a cooperative project between JGOFS and WOCE, for the measurement of pCO_2, total CO_2 (DIC), pH, and alkalinity. At a minimum, JGOFS carbonate system measurements will include DIC and pCO_2. Every effort will be made to equip all JGOFS ships and ships of opportunity with continuous pCO_2 systems to get the maximum global coverage. The JGOFS casts will measure CO_2 variables every 10 m in the top 100 m, as well as at standard, deeper WOCE depths.

The measurements have been coordinated internationally by an Advisory Panel on Carbon Dioxide jointly sponsored by JGOFS and the SCOR/IOC Committee on Climate Change and the Ocean (CCCO). Details can be found in CCCO (1991). JGOFS will promote the training of more groups able to make reliable CO_2 measurements in the global survey, and will encourage the establishment of additional CO_2 standards laboratories.

JGOFS should appoint a global survey coordinator to arrange full JGOFS participation in all WHP cruises. Such an individual could also ensure that the JGOFS measurement protocols are followed, and could provide quality checks on the data prior to archiving.

The seasonal survey of CO_2 (Science Plan p. 13) is not yet scheduled.

Contact: Liliane Merlivat

3.3 Other chemical variables

The measurement of dissolved and particulate carbon, in both its organic and inorganic forms, has an obvious primary place in any JGOFS survey. A survey of DOC with the most modern methods is especially important, because ideas about the amount of DOC in surface water have recently changed very rapidly. As soon as a consensus on measurement protocols is reached, DOC (and dissolved organic nitrogen, DON) measurements will be added on WHP cruises. JGOFS will also survey other biologically important elements, like nutrients. Additional continuous measurements will be included as capabilities are developed (e.g. for O_2 /Ar and pH, and using flow-injection techniques for the measurement of nutrients).

3.4 Ocean colour from satellites

For JGOFS to be successful at the scale of ocean basins, *in situ* measurements need to be related to variables that can be sensed from satellites. This decade will bring much-improved satellite measurements of ocean colour, surface winds, the surface wave field, sea-surface temperature and sea ice. Ocean colour fields offer the only chance to get detailed and synoptic global coverage of a property, chlorophyll, which gives some indication of surface POC. The SeaWiFS mission should begin to produce data in late 1993, by which time JGOFS will have in place plans for validation, interpretation, and useful data products.

The direct measurement of primary production (i.e. the flux from DIC to POC) is impractical for large-scale surveys of the ocean. However, the combination of the pigment and optics survey, and colour imagery from satellites, will go far towards providing JGOFS with a global view of this flux. Formulae for the daily rate of primary production have recently been devised; they require knowledge of photosynthesis parameters, chlorophyll, and optical properties of the water column. This explains the need for surveys of pigments and optical properties (see below): satellite colour imagery, to be properly interpreted in terms of plant biomass, requires such sea truth data from a wide variety of places in the ocean. Process studies will give better understanding of variability in photosynthetic parameters; such information, together with modelling efforts, should greatly improve estimates of primary production at the basin-scale in the near future.

It may be that other relevant parameters vary more slowly than ocean colour and light, in which case the procedure for estimating global primary production would separate into two components – one of which varies slowly enough that shipboard work can map it reasonably; the other varying quickly, but measurable by remote sensing.

Contact: Graham Harris

3.5 Pigments and optics in surface water

In the open ocean, optical properties are closely tied to the pigment and biogenic particles suspended in the water. Algorithms for interpreting satellite ocean colour images depend on the relationship between chlorophyll and optical properties of the water column. The relationship between total phytoplankton and what a satellite senses depends on the vertical distribution of chlorophyll in the water column. Primary production and optical properties depend on the distribution of plant pigments and particles. To make proper use of the global coverage provided by ocean satellite imagery, JGOFS needs the sea truth provided by ship-board studies.

JGOFS will make a large-scale survey of photosynthetic pigment profiles and optical properties. Space is guaranteed on cruises of the US WOCE Hydrographic Program for a scientist to measure pigments and optical properties, and on other international cruises of the WHP such work is top priority for any available berth. Every effort will be made to fill these berths, when available.

Contact: John Marra

3.6 Radioactive isotopes

Radionuclides in the ^{238}U series can help to determine export production and organic matter fluxes through the water column. For example, ^{234}Th is continuously produced throughout the water, at a nearly uniform rate, by the radioactive decay of ^{238}U. Because thorium is adsorbed onto particles and is removed from the upper water column as particles sink, there is less ^{234}Th than would be expected from the equilibrium between its radioactive production and decay rates. The deficit in the euphotic zone is strongly correlated with export production. Thus ^{234}Th concentration in the euphotic zone offers an independent estimate of export production, and is a fast supplement to methods that must wait for a sediment trap to accumulate a significant amount of material. For more details, see US JGOFS (1990).

Radiocarbon measurements are an important tool for determining oceanic circulation rates and for validating circulation models. They are not part of JGOFS activities, but are included in the WOCE programme whose results JGOFS will use for its own inferences.

3.7 Isotope ratios

There is a fractionation of the isotopes ^{13}C and ^{12}C during photosynthetic uptake of carbon, so that the $^{13}C/^{12}C$ ratios in DIC primarily reflect the action of the biological pump. The large-scale distribution of $^{13}C/^{12}C$ ratios represents an integrated result of biology, water circulation and gas exchange. Observations of this isotope ratio are therefore a valuable tool, in combination with data on DIC and nutrients, for validating carbon cycle models. The anthropogenic CO_2 increase is accompanied by a decrease of $^{13}C/^{12}C$ ratios, which can yield an additional constraint for simulations of the fate of anthropogenic CO_2. Quay *et al.* (1992) combine oceanic and atmospheric $^{13}C/^{12}C$ measurements to estimate the uptake of anthropogenic CO_2 by the ocean. Valuable information would also come from isotopic measurements in POC, DOC and calcium carbonate. These measurements should be made on JGOFS and WHP cruises at every opportunity.

3.8 Sinking flux of particles

Deep flux measurements with sediment traps, benthic flux measurements, and determinations of burial rate should also be included in the JGOFS survey as needed to complete the global picture. However, additional cruises, separate from those dedicated to the survey of water-column properties, are likely to be required for such deep flux measurements. Opportunities for other activities on station (e.g. large-volume pumping, and biological rate measurements) should be provided while benthic flux measurements are in progress. JGOFS will promote the development of instruments that will increase the speed and reduce the cost of these measurements (e.g., microelectrodes, *in situ* whole-core squeezers, and inexpensive sediment traps).

Sediment traps provide a direct measure of the downward flux of particulate carbon from the surface to the sea floor. They integrate activity over (vertical) space and time, thus estimating quantities at time scales appropriate to JGOFS. Long-term arrays are presently included at the Bermuda, Hawaii and Kerguelen time series stations (see Sections 6.5, 6.6 and 6.8); at the BIOTRANS site (47°N 20°W); and at other mooring sites in the Southern Ocean, the polar Atlantic Ocean (10.1.3), the Arabian Sea (5.7), the eastern boundary current off Chile (10.4.1), and the equatorial Atlantic Ocean.

3.9 Benthic flux measurements

The role of the benthic boundary zone (BBZ) in carbon recycling varies markedly with oceanographic setting. For example, in continental margins much of the particulate carbon that sinks below intermediate waters is recycled in the BBZ, and is easily mixed back into the euphotic zone. In oligotrophic regions, only a small part of the carbon rain reaches the BBZ – and what is recycled there takes perhaps centuries to return to the surface. To extrapolate these preliminary findings to the global scale, it will be necessary to determine the spatial variability of benthic fluxes on basin scales, and for this purpose a set of widely-distributed measurements is required. This will entail the short-term deployment (2 - 3 days) of benthic chambers and/or the collection of box cores on transects of stations during other JGOFS activities (transits to process study sites, servicing of time series stations, etc.), as well as during the other large space-scale surveys that are planned.

4. Regional structure of JGOFS

JGOFS should study a region in greater detail if a large-scale survey cannot resolve particularly important processes operating there. Possible reasons include the following: (1) the region is a large source or sink of CO_2 and it is especially important to get the numbers right (this might simply require a more detailed survey); (2) large seasonal variability implies that the answers from a survey with poor seasonal coverage would be misleading; (3) the region is particularly sensitive to climate change, and therefore needs to be understood and not simply surveyed; and (4) the region is especially simple, and therefore provides a good opportunity for increasing our understanding.

The general aims of a regional study are the same whatever combination of pelagic and benthic process studies, time series stations and sediment core studies is adopted:

- to assess fluxes of carbon between the atmosphere and the ocean interior, and determine their variability on seasonal to interannual time scales.
- to understand the structure and functioning of the system that determines these fluxes, and incorporate this understanding in improved models and parameter values.
- to assess and understand how carbon fluxes respond to physical forcing on time scales from days to years.

The importance of benthic processes as tracers makes it appropriate to add a specific aim:

- to understand the settling flux to the benthic boundary zone, the recycling of materials within it, and burial of material below it.

This section describes the features of different oceanographic regions that have importance for carbon flow. One point to address is the size of a region, and how fine a spatial scale JGOFS must consider: would we learn more from five very detailed process studies or fifty less detailed ones? Regions are in general one or a few 'biogeochemical provinces' as discussed in the Science Plan (p. 19-26). JGOFS will do a range of studies from a few large-scale to many smaller scale. This section discusses the currently planned large-scale efforts. It should be understood that the plan assumes the existence of many smaller scale studies that address the boundaries of these regions and exchanges between them.

4.1 North Atlantic

Atmospheric data and models (Tans *et al.*, 1990) suggest strongly that the principal net global CO_2 sink must be in the northern hemisphere. The most likely marine sink of sufficient magnitude is the North Atlantic, one of the main regions where deep water is formed.

Cruises during the JGOFS North Atlantic Bloom Experiment (NABE) showed that there is a large seasonal variation (≈100 ppm) in surface pCO_2. A decrease of 60-75 ppm occurred within a month, associated with the development of the spring phytoplankton bloom. There is also evidence of strong sensitivity of this ocean region to environmental changes on longer time scales.

The North Atlantic is not a uniform region – the Gulf Stream provides a large lateral transport of carbon and nutrients, and there are strong latitudinal gradients in the depth of winter mixing as well as the seasonal light cycle. There are therefore gradients in the magnitude and seasonality of primary production, almost certainly affecting the amount of carbon lost from the upper ocean. A station with strong seasonality and weak lateral motion is a good place to study intensively, whether with time series, process studies or a combination of such methods: for example, 47°N 20°W, a site that has already received intensive study and where detailed physical information is available.

Future process studies in the North Atlantic will be directed at improving our knowledge of the seasonal cycle of pCO_2, how it varies geographically, and the factors controlling the pCO_2 cycle. The far northern region (Arctic Ocean, Norwegian and Greenland Seas) should be included as both model studies and the sedimentary record indicate that that part of the North Atlantic may be strongly affected by, and contribute to, global climate change.

4.2 Equatorial regimes

These regions are the largest source of CO_2 from the ocean to the atmosphere. They include very large areas of high primary productivity with large gradients in both production and fluxes associated with the strong zonal circulation patterns.

The equatorial Pacific is important because of its size, and because it appears to be nutrient-replete. Interannual variability associated with the El Niño - Southern Oscillation exceeds the seasonal variability in production and settling fluxes. The burial of organic carbon can be very large, and approximates the distribution of high production in the overlying waters. Thus the bottom sediments of the equatorial Pacific have significantly larger organic carbon contents than those below the oligotrophic gyres of higher latitudes. Even higher carbon burial rates occurred in the eastern equatorial Pacific during each of the last six glacial maxima (extending back some 450,000 yr), presumably related to higher export of organic material from surface waters.

Equatorial regions may also present meridional gradients of iron limitation. A comparative study of iron-enriched and iron-depleted regions could be part of future studies (also see Section 10.2.1).

4.3 The Southern Ocean

Carbon fluxes in the Southern Ocean represent a quantitatively significant component of the global carbon cycle. They are likely to be highly susceptible to climate change, but are less well understood than the carbon fluxes in more accessible ocean regions. In particular, the presence of continually high nutrient concentrations remains enigmatic (and has important consequences for atmospheric CO_2 concentrations), and the extent of sea ice is expected to be one of the features most sensitive to climate change. Some subsystems within the Southern Ocean act as sources of CO_2 to the atmosphere, others as sinks. Each independently represents a large term in the global budget for air-sea exchange of carbon. However, observations in Southern Ocean waters are so restricted, both in space and in time, that it is not yet known whether the region as a whole acts as a net source or sink for atmospheric CO_2.

Biological productivity, and the processes that transport fixed carbon and nutrients to the deep sea, are spatially and temporally variable in the Southern Ocean. To gain a quantitative understanding of these fluxes, we not only need to improve our basic knowledge of the factors that limit biological productivity where nutrients are abundant, but also of the coupling between grazers and primary producers, and of the efficiency of the microbial loop.

Air-sea exchange of CO_2, biological productivity, the annual advance and retreat of sea ice, and ventilation of deep water masses are all influenced by the stability of the upper water column. Stratification of surface water is generally weak and is largely determined by salinity; this could be affected by a reorganization of the freshwater balance of the region. Our ability to predict the response of biological processes and of chemical fluxes to a perturbation of water column stability is hindered by a lack of a basic knowledge of the magnitude of the fluxes and of the factors which regulate biological processes.

JGOFS-supported measurements will expand the data base describing the magnitude and variability of carbon fluxes in the Southern Ocean. Process studies will improve our ability to predict the response of these fluxes to perturbation, by identifying the factors which regulate carbon fluxes and by gaining a mechanistic understanding of how these factors operate.

4.4 Monsoonal regimes

The advantages of studying a monsoonally driven oscillation are as follows: (1) there is a very strong seasonal signal in chlorophyll concentration and primary production; (2) because the timing is very predictable, it is possible to plan cruises to determine pre-monsoon initial conditions; and (3) because the monsoon is local, it is possible to study adjacent ecosystems with the same light conditions but greatly different physical forcing. The possibilities for increases in understanding are therefore high.

The North Indian Ocean is important to JGOFS because of its high and seasonally variable chlorophyll concentration. It contains about half as much total chlorophyll as the whole North Atlantic, and its seasonal variability is greater because of the monsoon-driven circulation in the Arabian Sea. Under present conditions, it is not known whether this region is a sink for atmospheric CO_2 (because of its high rates of primary productivity and large concentrations of sedimentary carbon), or a source (because of outgassing of CO_2 brought to the surface during upwelling). The wide range of climatic variability in the Arabian Sea makes it an excellent place to study the interactions of past climates – and possible future climates – with ocean biogeochemistry.

Northward of 10°S, the basin contains a zone of low oxygen at water depths between about 150 and 1500 m. This low-oxygen zone needs to be studied for its potential influence on the food web, the transformation of sinking material, denitrification and the release of nitrous oxide, and the degradation of organic matter on the sea floor.

The planktonic food chain of the Arabian Sea is unusual. During oligotrophic periods, bacterial production is high and the biomass of zooplankton is a much higher fraction of observed primary production than in other comparable waters (e.g. the Sargasso Sea). During the July-September monsoon period, one species of zooplankton, absent in oligotrophic periods, dominates the biomass and supplies intense grazing pressure on phytoplankton. Biomass of fish appears to be dominated by mesopelagic myctophids (lantern fish). A short and well coupled food chain could accelerate the flux and cycling of carbon and nitrogen.

4.5 Eastern and western boundary regimes

Eastern boundary currents are sites of intense and persistent coastal upwelling of carbon-rich water, leading to surface layer pCO_2 values of 600-700 ppm and hence probably the strongest local CO_2 outgassing from the ocean. The effect is moderated by high primary production and strong biotic sinks of carbon from the surface layer. Such regions occcupy only 1-2% of the ocean surface, they are not resolved in current GCM models, and their importance for global carbon cycling is unknown.

Among such currents, the Peru-Chile current system has the longest N-S extent, the most persistent upwelling, and the largest biological production. Through El Niño - Southern Oscillation dynamics, it is tightly coupled to the equatorial Pacific Ocean, the site of a major JGOFS process study. The eastern South Pacific showed the largest data gap in a recent compilation of ^{14}C primary production in the global ocean (Berger 1989), and the GEOSECS expedition did not visit this part of the ocean.

Western boundary currents, such as the Gulf Stream in the North Atlantic and the Kuroshio in the Pacific, are major vehicles transporting heat and nutrients northwards; and fluxes of upwelled nitrate may help to initiate spring blooms in high latitude regions. These currents receive lateral input of both particulate and dissolved carbon and nitrogen through offshore export. Major rivers transport terrigenous materials to the western margin areas. Prevailing winds carry dust from the continents to the west.

Seasonality of transports in and to western boundary currents may be important. For example, changes in the offshore transport of nitrogen and carbon may be associated with the collapse of the spring bloom (Walsh *et al.* 1988).

4.6 Central gyres

Oligotrophic gyres occupy large fractions of the area of the open ocean. They generally have low primary productivity, and low seasonal and interannual variability. Extrapolation from the limited data set presently available can therefore be done with greater confidence than for any other ocean regime. A significant proportion of new production may now be fertilized by anthropogenic inputs of nitrate (via the atmosphere), providing one of the first major oceanic responses to human activities.

5. Process studies

The carbon system in the surface ocean is so complicated, and so rapidly varying in space and time, that global averages inferred by interpolation from shipboard surveys are unreliable. Only if there is some underlying order that varies much more slowly, will JGOFS goals be attainable.

Process studies are conceived to seek this underlying order. They consist of large, generally multi-ship exercises making a detailed suite of measurements with high resolution in time for several months. As well as observations of carbon variables and fluxes, they include experiments to describe and parameterize the way these variables and fluxes interact. They address fundamental problems of carbon and associated fluxes in strategically-chosen ocean basins, in particular by improving process models, estimating their parameters, and suggesting new models. They should allow the determination of balanced carbon budgets, because variables are measured frequently enough, and for long enough, that accumulation in pools as well as fluxes between them can be assessed. Each individual study has its own specific objectives pertinent to scientific problems in that region or biogeochemical province, but all can be subsumed under the general aims for regional studies (Section 4), and require a closely-similar approach.

5.1 Main scientific components

A full understanding of pelagic and benthic carbon cycling, export and burial and their relationship to global change requires that the issues described below (5.1.1 - 5.1.7) should be addressed. These focus the work of JGOFS on establishing the nature of the carbon balance in water column and sediments across a wide range of environments, so that we may understand how the balance has changed due to past perturbations in climate and how it may be altered in the future.

5.1.1 Inventory of key fluxes

Observations of seasonal-to-interannual as well as shorter-term variations in surface pCO_2, water column DIC, POC, DOC, oxygen and associated nutrients, and benthic carbon fluxes in each region will be assembled and analyzed to provide information on the transport and transformation of carbon within the ocean, and its exchange with the atmosphere.

5.1.2 Definition of control mechanisms

Quantitative descriptions of planktonic and benthic foodweb structure, trophic dynamics and related biogeochemical fluxes will be sought at levels of detail pertinent to different modelling activities. These will be used to make new mathematical formulations for models.

5.1.3 Temporal forcing at scales less than a year

Biogeochemical and trophic exchanges are forced and regulated by the physical environment of the atmosphere-ocean system. One way to improve our understanding of the links between the physical climate system and the biogeochemical machinery of the ocean is to structure our observational programmes to monitor mesoscale and larger events that affect fluxes. Examples of such events that will be addressed in different process studies include seasonal transitions (e.g. spring blooms, deepwater formation and seasonal changes in ice cover), and frontal passages (atmospheric storms, monsoons, oceanic eddies and rings).

5.1.4 Interannual variability

Seasonal cycles in different basins are not repeated exactly each year. In some regions, the cause of the interannual variability can be identified (e.g. ENSO events). In other regions, more subtle environmental influences can produce significant changes in the amplitude and timing of annual events (e.g. North Atlantic bloom) or longer-term variability (e.g. decadal changes in polar sea ice). A mechanistic understanding of such longer term variation is needed to advance JGOFS process models toward a predictive capability.

5.1.5 Model calibration and parameter evaluation

Observations of individual flux processes (e.g. primary production, sedimentation, and DOC decomposition) and events will be used to adjust and calibrate models. Observational and experimental programmes will be designed (in collaboration with the synthesis and modelling task team) to evaluate the parameters controlling key processes – such as the effect of wind on gas exchange rate; of irradiance on photosynthesis rate; of nutrient concentration on uptake rate; and of food availability on ingestion rate.

5.1.6 Benthic carbon fluxes, recycling and burial

The main role of benthic process studies in JGOFS is to provide time-integrated indicators of carbon fluxes between the surface ocean and ocean interior. Thus the amount of particulate carbon reaching the seafloor is determined by all production, mineralization and transport processes occurring in the overlying water column; its subsequent fate is determined by a further suite of biological, geochemical and physical processes occurring above, at and below the sediment-water interface. JGOFS benthic studies will address the key fluxes and transformations occurring in the bottom nepheloid layer, at the interface, and in that part of the sediment where organic carbon is actively recycled. Together, these reactive environments constitute the benthic boundary zone (BBZ).

Processes occurring within the BBZ will be investigated in a wide range of depositional regimes. Particular attention will be given to the relative importance of shelf, continental margin and deep ocean benthic fluxes; the temporal variability of biogeochemical activity in these regimes; and the processes occurring within the different parts of the BBZ.

Palaeoproduction estimates cannot be determined from the sedimentary record unless we know the proportion of production that is permanently buried. This information will be obtained by measuring and modelling the delivery of carbon and other elements to the BBZ, and the recycling and burial processess occurring there. In addition to providing the basis for a quantitative interpretation of sediment cores, JGOFS benthic studies will assist in: (1) assessing the wider significance of benthic fluxes for the ocean carbon cycle, at both regional and global scales; and (2) developing an ability to predict the response of benthic processes to anthropogenic impacts.

5.2 Guidance and planning

The first JGOFS Process Study was the pilot study of a spring phytoplankton bloom, the North Atlantic Bloom Experiment (NABE), which took place in 1989, mostly along 20°W . NABE was coordinated by the JGOFS SSC through a Coordinating Committee made up of the national coordinators of the participating nations. The study itself was collaborative, international and multi-disciplinary. Research vessels from five nations (Canada, Germany, Netherlands, UK and USA), a NASA P-3 aircraft, and many moorings were deployed. Satellite-derived data on eddy dynamics (using the GEOSAT altimeter), sea surface temperature and a limited range of optical properties (using AVHRR) were relayed to the research vessels.

Guided by this experience, JGOFS has set up a number of mechanisms to ensure efficient and proper planning, execution and synthesis of process studies. The various groups and activities are described briefly below, and the individual elements for each study are given in the sections on each study. The principal criterion for selection of regions for intensive process studies is the amount by which a study in a given region could be expected to reduce uncertainties in our understanding of present and future carbon fluxes, for a given level of effort. Using this criterion, JGOFS will conduct process studies in the Equatorial Pacific, Southern Ocean, North Atlantic and Arabian Sea.

5.2.1 Regional Planning Groups; Coordinating Committee

Regional planning groups define the scientific rationale, and plan and guide each JGOFS process study. They contain members from nations participating in the study, with a Chair appointed by the SSC. The planning groups convene the series of meetings and other activities shown in Table 2. The Chairs of the regional planning groups form a Coordinating Committee responsible for coordinating the process studies as and when needed, and establishing a liaison among the groups, and between the groups and the SSC.

5.2.2 Schedule

Much of the work for a process study is carried out before and after the period of the main field activity. The full schedule for planning, implementing and interpreting a typical process study is expected to take about 5 years (Table 2).

5.3 Resources required

Process studies require a large and diverse array of observing systems and analytical resources to meet their goals. The major types of resources are listed here, so that individual countries can estimate costs according to national accounting procedures.

Research vessels JGOFS process studies are focussed primarily on open ocean problems. Some 500 days of shiptime is required per year of main field study, spread over perhaps five research vessels. To accommodate the scientists and technicians required to measure the core variables, vessels capable of housing 20-40 scientists are desirable, with up to 40-50 days endurance. Smaller research vessels may also be needed, for ancillary investigations and mooring deployment/recovery.

Satellites In addition to their primary role in data collection for the global synthesis (Section 3.4), remote sensing satellites are needed for real-time guidance of sampling operations and interpretation of shipboard operations. The sensors of greatest utility are ocean colour instruments, sea-surface temperature radiometers, and altimeters.

Table 2. Schedule for a 'typical' JGOFS Process Study

Year 1	• Formation and initial meeting(s) of a planning group with at least one scientist from each participating country • National and international planning workshops open to all interested scientists • Announcements to inform the scientific community of the study and invite participation
Year 2	• Planning group meeting(s) • Modelling workshop • Completion of scientific design of experimental programme • Identify need for ships
Year 3	• Planning group meeting(s) • Define individual science components • Earliest start of field programme
Year 4	• Field programme (could last into year 5)
Year 5	• National and international data workshop(s) where the cruise participants meet for informal discussions and exchange of prelimenary results • National and international scientific conference(s) • Second modelling workshop

Provision of ground stations, and data processing capabilities during field operations, are also essential for JGOFS.

Aircraft Remote-sensing aircraft equipped with LIDARs (light detection and ranging sensors) and radiometers for sea surface temperature and ocean colour provide high-resolution viewing of process study areas – and are less vulnerable to cloud cover interference than satellites. The NASA P-3 equipped with LIDAR was used in NABE and a similar aircraft will be flown in the Equatorial Pacific study.

Moorings Ships can make observations for only a limited time, and satellites view only the ocean surface. For greater temporal coverage, depth-dependent observations and relative independence from weather, a variety of moorings have been and will be used in JGOFS. These include upper ocean physical/meteorological moorings and bio-optical moorings, and deep ocean sediment trap moorings. Moorings carrying equipment capable of sensing dissolved gases and nutrients are under development, and will be deployed as soon as available.

Free vehicles Unattended measurements of benthic fluxes need to be made in a wide range of oceanic environments, to provide data on transport processes in the benthic boundary zone. This will require the extensive use of bottom landers capable of operating for periods of up to a month. A larger number of shorter deployments (2 - 3 days) will also be needed, to map the regional variability in short-term fluxes.

5.4 North Atlantic

Planning group leader: Richard Lampitt

5.4.1 Time frame

The main initial field phase was in 1989, with follow-on national cruises in 1990, 1991 and 1992. The next major concentration of field work is planned to cover three winter periods and two summer periods from the beginning of 1996 to the end of 1997.

5.4.2 Aims

The aims of the North Atlantic process study are:

- to measure the seasonal and geographic variability of CO_2 exchange between surface water and the atmosphere
- to estimate the transport of carbon and associated compounds due to the Gulf Stream system
- to characterize the biological component of the drawdown of carbon from the atmosphere to the ocean, and from the surface of the ocean to its interior
- to develop basin-wide models that describe and predict the major biogeochemical cycles.

5.4.3 General operating plan

A basin-wide survey of surface pCO_2, with seasonal coverage and 3° spatial resolution would be ideal. Should this prove impracticable, the design work for a less intensive survey that will provide as much information as possible needs to be done. A control volume experiment involving four sections across the Gulf Stream is also planned, to determine the transport of dissolved and particulate material by this current.

Future process studies at several sites will address the seasonal cycle of biogeochemical processes. The Bermuda (Section 6.5) and EUMELI (10.1.1) stations are already studying oligotrophic processes. Seasonal studies should also be carried out at a mesotrophic deep mixing site, such as BIOTRANS (47°N 20°W), or one slightly to the northeast where bottom topography is simpler. A characteristic site of deep water formation should also be studied, perhaps around 76°N 5°W.

Modelling studies indicate that the abundance of overwintering micro- and mesozooplankton has a large influence on carbon flow in the North Atlantic; the factors that determine their population size need to be investigated. Further modelling studies are expected to suggest other key measurements for inclusion in the 1996-97 field programme.

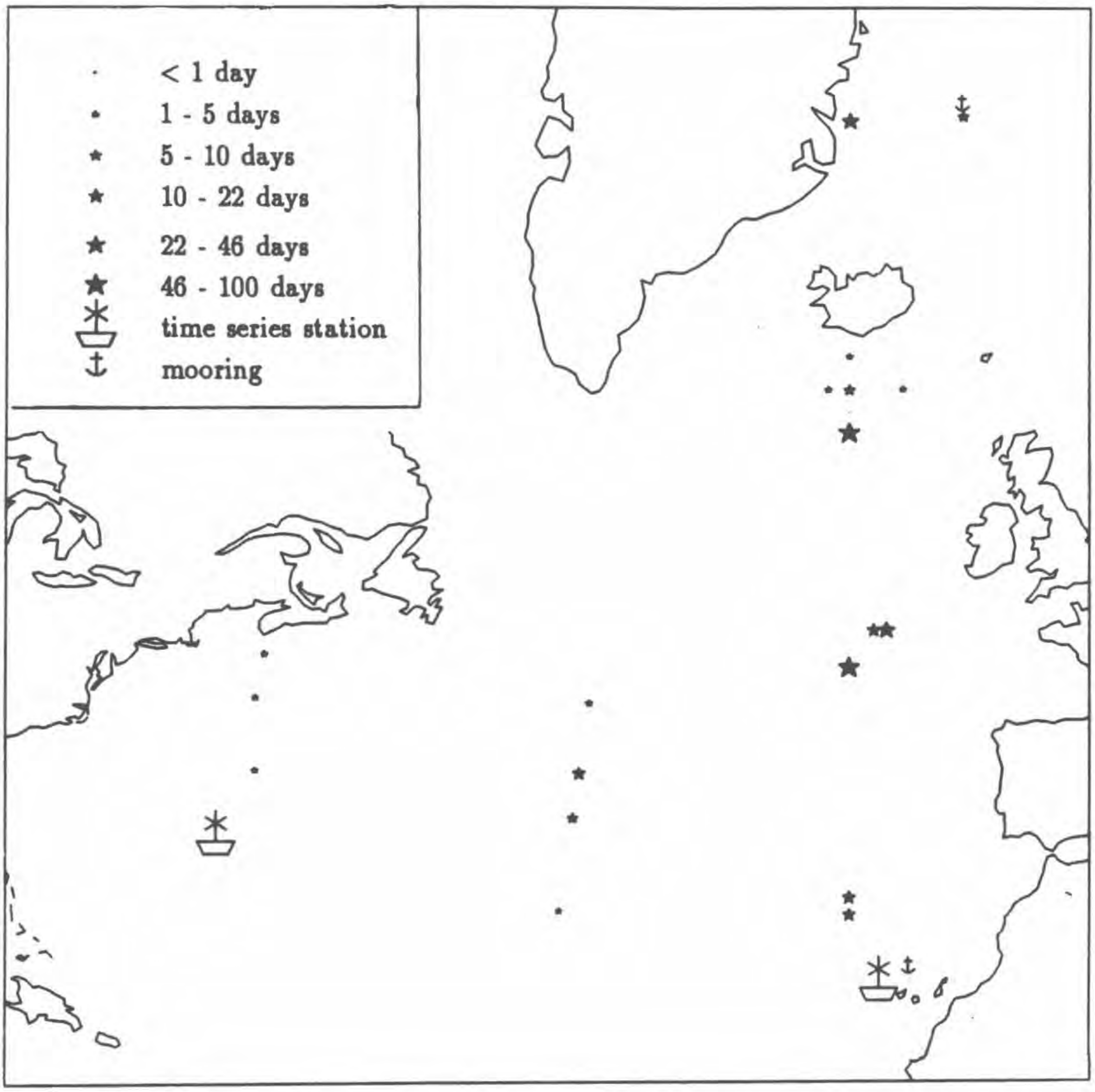

Figure 3. North Atlantic process studies; Phase I, 1989-1992.

This includes all the 1989 NABE work, all the Canadian western North Atlantic work, the 1990 and 1991 BOFS cruises, the 1992 Meteor cruise, SFB313 work in the Norwegian and Greenland Seas, and EUMELI.

5.4.4 Participating nations

Canada, Germany, the Netherlands, UK, USA and France participated in the North Atlantic Bloom Experiment (NABE) and associated studies. Most of these nations have continued to be active in the area, and are expected to participate in the next internationally coordinated phase.

5.4.5 Planning meetings and reports

Plans for North Atlantic GOFS Pilot Program (US GOFS, 1986); JGOFS North Atlantic Planning Workshop, Paris, September 1987 (SCOR, 1987); NABE Data Workshop, Kiel, March 1990 (SCOR, 1990a); NABE International Scientific Symposium, Washington, November 1990 (SCOR, 1990d).

5.4.6 Resources

The 1989 NABE involved about 400 days of ship time and a NASA P-3 aircraft. A similar resource requirement is expected for the next internationally coordinated phase. The SeaWiFS sensor should then be a proven instrument, available for routine use.

5.5 Equatorial Pacific

Planning group leader: Margaret Leinen

5.5.1 Time frame

Field studies cover the period 1991-1995.

5.5.2 Aims

The aims of the equatorial Pacific process study are to assess:

- how large a role the equatorial Pacific plays in global biogeochemical cycling
- how efficiently the carbon pump operates in the equatorial Pacific
- how midwater, deepwater, and benthic processes modify or control fluxes in this region
- how equatorial Pacific biogeochemical cycling is affected by El Niño conditions.

5.5.3 General operating plan

The aims will be achieved through: (1) measurements of important carbon system variables in a survey mode; (2) measurements of rates coupled with studies of processes and mechanisms; (3) measurements of benthic and midwater variables and processes at a scale similar to that of surface ocean studies; and (4) measurements and process studies during El Niño and non-El Niño conditions.

5.5.4 Participating nations

Australia Survey cruises will be carried out by CSIRO in 1992 from 1.5°S to 10°N along 147°E, and 10°N to 10°S along 155°E; longer stations will be occupied at two locations to be determined on the survey cruise.

Canada There will be a benthic survey and processes cruise along 115-120°W.

France A survey of physics, pCO_2, pigments, microscopy and nutrients from 90°W to 165°E was carried out along the equator in early 1991. Similar surveys have been performed along 165°E from 20°S to 10°N every January and July since 1984. In November 1993, there will be a pelagic process study along 155°E from 15°S to 20°N, and at two stations along 150°E (one at the equator and one in water drifting away from the equator); this work is coordinated with SeaWiFS validation, as part of OLIPAC (Oligotrophic Pacific Study). There will also be a pelagic process study at 0°N 165°E in April 1994, as part of FLUPAC (Flux dans l'ouest du Pacifique Equatorial). OLIPAC and FLUPAC are both within the France-JGOFS project EPOPE (Etude de Processes dans l'Ocean Pacifique Equatorial). Contact: Yves Dandonneau.

Japan Survey transects of physics, optics, pigments, nutrients and microscopy (down to 300 m depth) from 45°N to 10°S along 175°E take place late each year in the period 1990 - 1994. In late 1990, there were also biogeochemical surveys across the equator at 150°W, 160°W, 180°E, 179°E and 160°E. Other work includes a trans-Pacific (90° to 140°E) survey of physics, optics, pigments and nutrients along the equator in 1992, and a trans-equator process study (at 160°W or 170°W) in late 1993.

USA Several NSF and NOAA cruises are scheduled for 1992, with emphasis on 140°W. These include surveys, process studies, air/sea interaction studies, time series, and benthic work. There is also an ONR-funded study of iron-enrichment of productivity in this area. The process study cruises are complemented by seven moorings along 140°W, and by NASA P-3B LIDAR over-flights, looking for fronts and resolving their zonal structure.

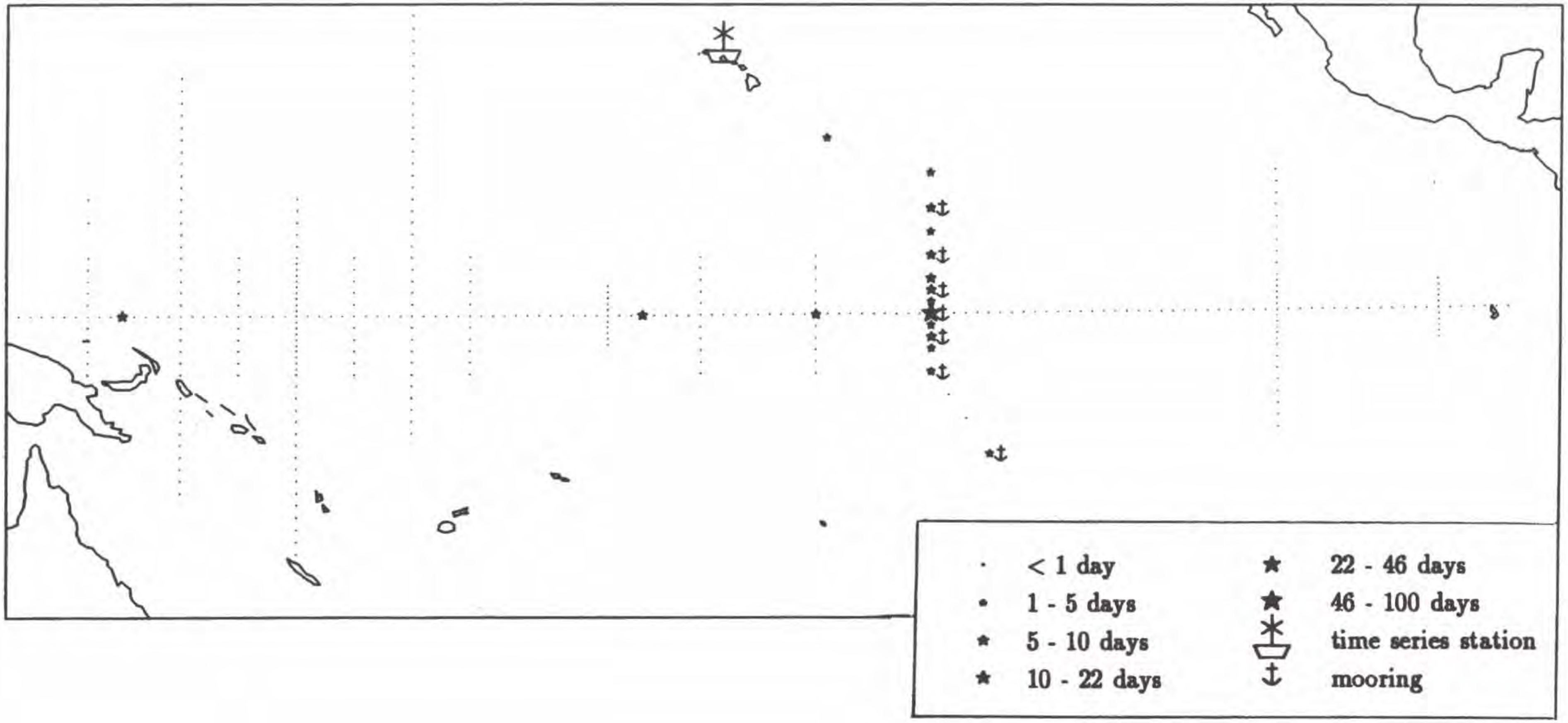

Figure 4.

Equatorial Pacific Process Study. This includes accomplished or planned work by the USA, France, Japan and Australia.

5.5.5 Planning meetings and reports

US JGOFS Pacific Planning Report (US JGOFS, 1989); JGOFS Pacific Planning Workshop, Honolulu, September 1989 (SCOR, 1989); International Workshop on Equatorial Pacific Process Studies, Tokyo, April 1990 (SCOR, 1990e); Pacific Modelling Workshop: Princeton USA, September 1990 (unpublished).

5.5.6 Resources

Research vessels Several hundred days of shiptime are already scheduled, with research vessels including *Atalante, Franklin, Thompson* and *Wecoma.*

Satellites The USA will collect, process and supply AVHRR data to vessels during its 1992 field season.

Aircraft The NASA P-3B will fly four missions during the late-1992 survey. It will be equipped with an Airborne Oceanographic LIDAR with two lasers.

Moorings The US will have seven moorings along 140°W from January to December, 1992.

5.6 Southern Ocean

Planning group leader: Julian Priddle

Plans for JGOFS research in the Southern Ocean divide into two phases. For Phase 1, there is a wide geographic spread, and an emphasis on large-scale mapping as well as detailed process studies. Component cruises were mostly at an advanced planning stage before their inclusion in the JGOFS Southern Ocean study. The Southern Ocean Planning Group has assisted in the coordination of these cruises, and in the development of a uniform approach.

Phase 1 is expected to provide a biogeochemical definition of the main subsystems of the Southern Ocean, with a one-dimensional model that couples biological and biogeochemical cycling of carbon and nutrients to the physical environment. The study will also map significant areas of the Southern Ocean, providing spatial and temporal information on air-sea CO_2 exchange and the effects of sea ice on carbon transport processes.

In Phase 2, this work will be scaled up to allow the use of models to describe the fluxes within and between subsystems, and thus produce descriptive models for the subsystems as regions and for the Southern Ocean as a component of a global ocean model. Phase 2 will also address further aspects such as bottom water formation.

In order to estimate the exchanges between subsystems during Phase 2 studies, it seems likely that a more-or-less meridional array of study sites will be used to provide the coverage of all subsystems in a geographically related region. Suitable sites could be linked to the WOCE section A12, SW from South Africa, which will be worked regularly during Phase 2 and is adjacent to the site of the AWI 400 mooring. A second study region between 150°E and 180° may also be desirable.

5.6.1 Time frame

The first phase of the Southern Ocean study is protracted, with some cruises having already taken place, and further cruises and mooring deployments planned up to 1996. However, it is anticipated that sufficient field work will have been undertaken by the end of the 1994-95 austral summer for this to represent a practical review point. Phase 2 is planned for 1996-98.

5.6.2 Aims

There are six objectives for the Southern Ocean investigation as a whole. The interpretation and emphasis of these objectives will differ in the different regions of the Southern Ocean selected for study. The objectives are to answer the questions:

- What role does the Southern Ocean play in the present day global carbon flux? What is the spatial and temporal pattern of the major processes that determine the net flux in the whole Southern Ocean, and within selected subregions?

- What controls the magnitude and variability of primary production and particle fate? (For the open water zone within the Polar Front, this addresses the problem of high nutrients and low production; for the seasonal ice zone, the physical conditions which determine the development and cycle of ice-edge blooms).

- What are the major features of spatial and temporal variability in the physical and chemical environment, and in key biotic systems? (There is a need for special emphasis on variability, as an integral part of the interpretation of measurements which will of necessity be more limited in scope and coverage than for other areas of the world ocean).

- What is the effect of sea ice on carbon fluxes in the Southern Ocean?

- How has the role of the Southern Ocean changed in the past?

- How might the role of the Southern Ocean change in the future? (The aim is to construct a modelling framework which would be capable of addressing this question).

5.6.3 General operating plan

The first phase of the study is based on a number of cruises that were not initially planned together. Although certain modifications and additions have been introduced, the spatial and temporal coverage is determined to a large extent by various 'outside' factors, including logistical considerations. For the second phase, the aim is to focus cruise effort on one or two regions.

The existing cruise plans for Phase 1 are summarized below. For all subsystems, the spatial coverage is wide, although the sector 90°W to 180° is not covered.

Planned studies on the permanently open ocean within the Polar Front show predominantly summertime coverage. Particular attention is paid to the area south of Australia, around Kerguelen and south of South Africa. In addition to dedicated cruises, underway sampling during supply runs to Australian and Japanese bases will enhance spatial coverage.

Temporal and spatial coverage in the ice-associated region of the Southern Ocean are better coordinated. Much work will be undertaken in the Antarctic Peninsula region, with particular emphasis on the Weddell Sea where a suite of cruises will provide coverage throughout the sequence of ice-formation and ice-melt.

A number of studies of frontal systems will be undertaken. These dynamic structures demand different experimental approaches from those envisaged for the regional studies. Again the cruises planned to cover these systems represent a broad circumcontinental coverage. Seasonal coverage is good.

The study of the productive regions associated with the Subtropical Convergence (STC) falls within this group. Plans for this remain tentative, but it appears that comparative studies of the STC at pairs of sites where eastern and western boundary currents interact would be a profitable approach. Areas near South Africa and Australia present the most likely sites.

Extra core measurements related to ice-associated variables have been defined, and measurement protocols agreed. Silicate will be an important nutrient core measurement.

5.6.4 Participating nations

Australia Five cruises will be carried out on *Aurora Australis* in 1991-95, concentrating on fronts and on the seasonal-ice zone in transit between Australia and Antarctic research stations in the sector 137-155°E. Smaller-scale process studies in the seasonal ice zone near 137°E and at 70°E are envisaged as part of the Australian programme.

France The aim of the ANTARES programme is to model the cycles of carbon, nitrogen, silicon and sulphur in the Indian sector of the Southern Ocean. Three instrument moorings will be deployed from March 1993 to March 1996, west of Kerguelen Island, south of 50°S. Five cruises are scheduled during austral spring and summer periods, devoted to

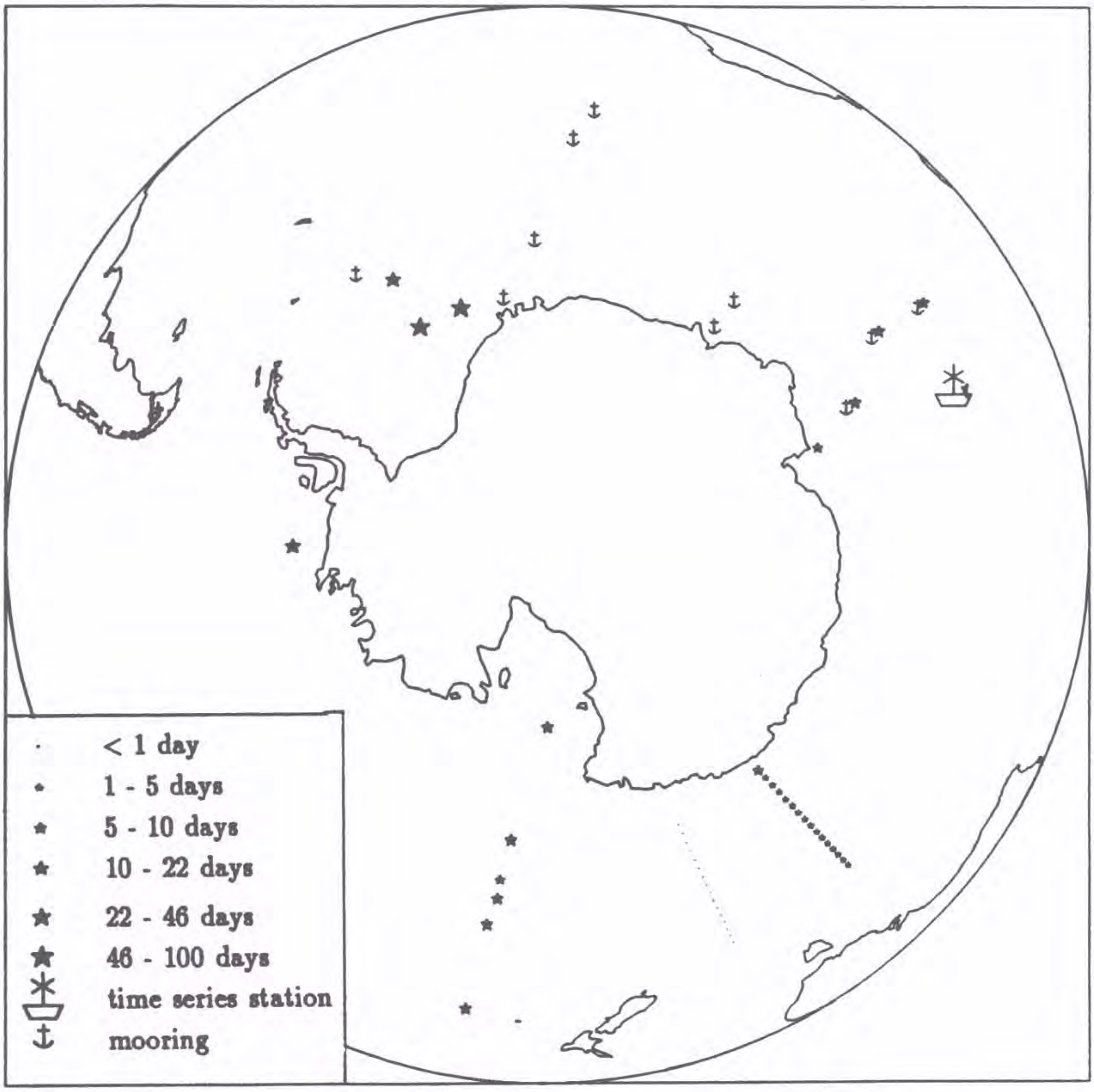

Figure 5. Southern Ocean process study.

This include planned work by the USA, UK, France, Germany, Japan and Australia. Positions are approximate: they will depend on the positions of the ice edge and polar front at the time of the cruises.

process studies and to matter flux in the surface layer, the water column, and the water-sediment interface. These cruises will cover the permanently open-ocean zone, the seasonal ice zone, and the polar front/ subtropical convergence zone. ANTARES also includes palaeoceanographic components. Contact: Paul Tréguer.

Germany A series of cruises on *Polarstern* took place in 1991-92, investigating the seasonal pattern of biogeochemical cycling in the seasonal ice zone in the Weddell Sea. These cruises link with long-term sediment trap deployments and WOCE stations. They include collaborative programmes with the Netherlands and South Africa.

Japan JGOFS measurements are being made at stations along a series of cruise tracks between Australia and the Antarctic coast 40-150°E, using *Shirase* in the Antarctic summer seasons 1991-92, 1992-93 and 1993-94. A multidisciplinary cruise by the *Hokuho Maru* will include work in Prydz Bay in 1994-95.

South Africa Seven cruises will be carried out in the ocean between South Africa and Antarctica, concentrating on fronts and the open ocean zone.

UK A two-ship cruise, using *James Clark Ross* and *Discovery*, will investigate the biogeochemistry of the marginal ice zone of the Bellingshausen Sea in late 1992, with associated open-ocean surveys of pCO_2 and other properties. The British Antarctic Survey will conduct subsequent cruises.

USA Eight cruises on *Nathaniel B. Palmer* will be carried out on a transect along 180° in 1994-96. The first five cruises contain over 90 days of scientific operations; the last three are less definite but of similar duration.

Underway measurements on passage to and from Antarctic research stations will yield further information.

5.6.5 Planning meetings and reports

JGOFS Southern Ocean Workshop, Brest, June 1990; JGOFS Southern Ocean Planning Group meetings in Cambridge UK, December 1990, and Bremerhaven, May 1991; modelling workshop, Cambridge UK, October 1991. Informal reports of these meetings are available from J. Priddle, pending the publication of the JGOFS Southern Ocean Planning Report (SCOR, in prep).

Also see: US JGOFS Southern Ocean Process Study (US JGOFS, 1992b).

5.6.6 Resources

Research vessels A total of 38 cruises are planned to date, of which 22 study the permanently open ocean area within the Polar Front, 24 study ice-associated systems and 30 study frontal areas. It should be noted that very few research vessels can work in or near ice.

Satellites Ocean colour will be measured by SeaWiFS; there are activities planned in conjunction with several cruises to validate and calibrate SeaWiFS specifically for ice-affected regions. A number of Antarctic satellite receiving stations are planned. These will give circumcontinental coverage for SeaWiFS, providing data northward to the Subtropical Convergence. AVHRR will measure temperature; AVHRR, SMM/I and SMMR will measure sea ice. ADEOS will contain a scatterometer to measure winds after 1995. Many platforms will measure surface irradiance and cloud cover.

Aircraft Ocean colour sensors on aircraft will provide valuable additional information in an area where cruise coverage is patchy and spatial heterogeneity important at small scales. An extended-range P3 will fly from Christchurch, mapping the region where the US JGOFS transect crosses the polar front, and, if possible, the northern limit of sea ice. Flights will support cruises in four seasons in 1994-95. Ocean colour sensors will also be flown on logistics aircraft.

Moorings There are five US subsurface moorings, each with four sediment traps, along 170°W at 45°, 57°, 60°, 66° and 76°S. The three northernmost also have surface moorings with bio-optics, meteorology and chemical sensors.

The French ANTARFIX station near Kerguelen is attended and fulfils the JGOFS time-series criteria. See Section 6.8 for more details.

Other long-term mooring sites are at Kapp Norwegica, in Lützow-Holm Bay, in Prydz Bay, and at locations 50°S 57°E, 57°S 57°E, 63°S 65°E, and 55°S 4°E.

5.7 Arabian Sea

Planning group leader: Bernt Zeitzschel

The unique and intensive processes that make the Arabian Sea important to JGOFS are described briefly in Section 4, and in more detail in US JGOFS (1991) and in the US Implementation Plan for the Arabian Sea (US JGOFS, 1992c). Knowledge gained from the JGOFS studies will also foster the rational use of natural resources in the region.

5.7.1 Time frame

There was one cruise in 1991; five cruises are scheduled in 1992, seven in 1994 and 14 in 1995. The main JGOFS thrust will be in 1994 and 1995.

5.7.2 Aims

The aims of the Arabian Sea process study are:

- to investigate the seasonality and magnitude of biogeochemical responses to intense and regularly oscillating physical forcing
- to quantify the role of the region in the global cycles of carbon and biologically associated elements, including its role as a net source or sink of atmospheric CO_2 and other gases relevant to climate change
- to quantify primary production and the transformation, flux and fate of carbon
- to quantify the role of the oxygen minimum at 300 - 1500 m in biogeochemical cycling
- to quantify Quaternary monsoon variability in relation to fluctuations in ocean palaeocirculation and palaeoproductivity.

5.7.3 General operating plan

The aims will be achieved by carrying out intensive shipboard process studies, extensive surveys, time series studies, remote sensing, and modelling. Fieldwork will be required during each of the five monsoonal periods: SW monsoon (June - September), autumn transition (October - November), NE monsoon (December - February), spring transition (March - April), and baseline period (May).

Time-series stations operating for 5 - 10 years will be needed to determine system variability and trends. Stations are currently proposed off India, Kenya, Oman and Pakistan; others are needed.

Remote sensing data will be obtained from satellites via local receiving stations, and from aircraft. This study will provide one of the earliest opportunities to use data from the SeaWiFS colour sensor. Data will be processed online to guide ship operations and assess biogeochemical processes and fluxes.

Modelling will be used to integrate observations and processes in order to develop predictive capabilities within a biogeochemical synthesis. Modelling will be carried out over a range of space and time scales from specific processes to the basin scale. This will involve interaction and integration of intensive and extensive studies.

To obtain a wide participation of scientists from countries bordering the northwestern Indian Ocean, as well as to guarantee data quality, several workshops and training courses (in particular for JGOFS core measurement protocols) are scheduled or are in preparation:

Bangalore, India; 24-26 August 1992. Indian Ocean Circulation, CCCO Indian Ocean Panel.

Mombasa, Kenya; August 1992. JGOFS training course, The Netherlands Research Foundation.

Muscat, Oman; 7-10 January 1993. Living Resources in the Northern Arabian Sea, Intergovernmental Oceanographic Commission (IOC).

Mombasa, Kenya; Autumn 1993. JGOFS training course, The German Ministry for Research and Technology, in cooperation with IOC. Contact: B. Zeitzschel.

Karachi, Pakistan; 1993. JGOFS training course, US proposed.

5.7.4 Participating nations

Germany Several cruises by *Meteor* in 1994.

Netherlands Two cruises by *Tyro* in 1992.

Pakistan The NASEER (North Arabian Sea Environment and Ecosystem Research) study started in January 1992, and is making quarterly measurements of the JGOFS core measurements at 19 stations along a track from the Pakistan and eastern Oman coasts out to 500 km offshore.

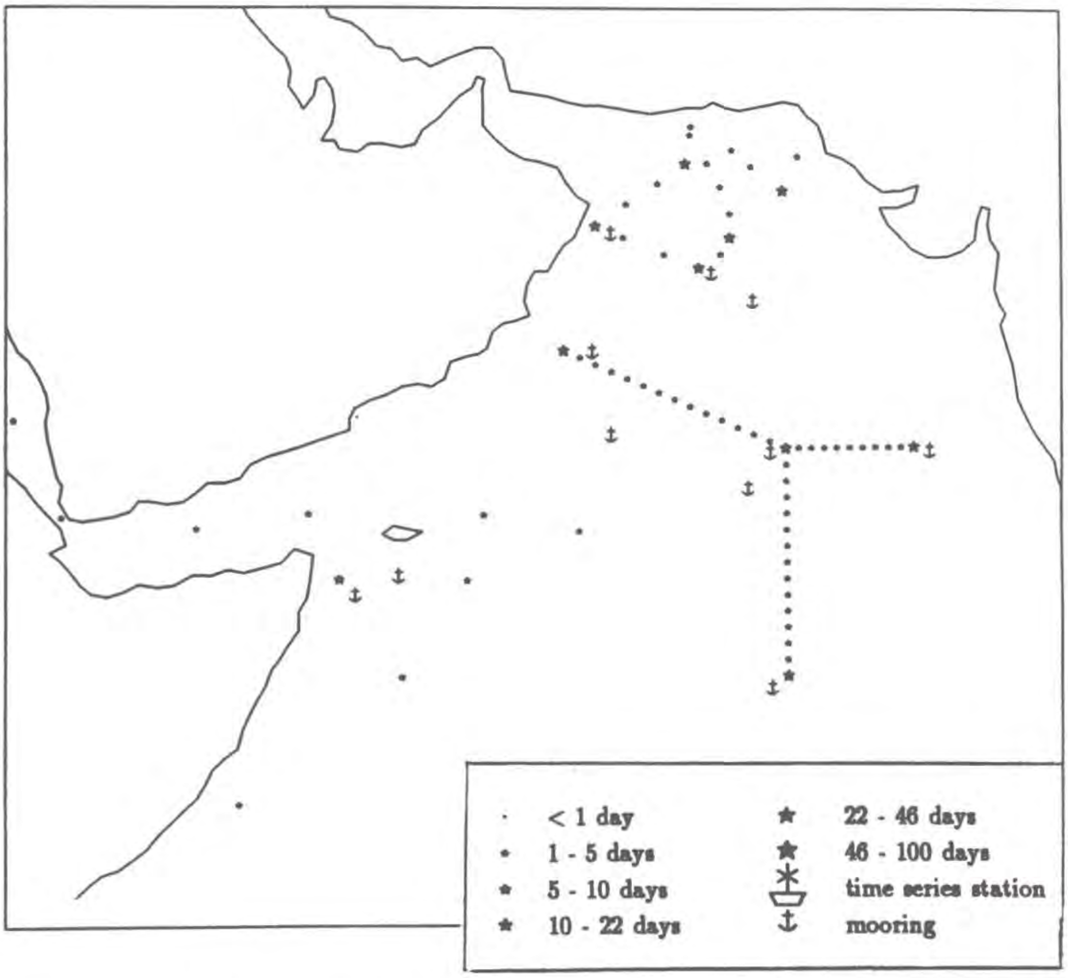

Figure 6. Arabian Sea process study.

This includes accomplished or planned work by Pakistan, the Netherlands, Germany, USA and India. Work by other countries bordering the region, and by the UK, is being planned.

UK Cruises are planned for 1994, but not yet funded.

USA Ten NSF cruises and five ONR cruises (480 ship days) in 1994-95 are planned on *Thompson*, including at least four moorings and NASA P-3 LIDAR overflights. A NASA HRPT Ground station for SeaWiFS reception will be set up to provide ocean color data for cruises during 1994-95.

Canada, Kenya, Oman will also collaborate.

5.7.5 Planning meetings and reports

Indian Ocean Planning Group meetings have been held at Goa, India (Jan 1991); Bermuda (Oct 1991); and on *Tyro* (at sea in the Mediterranean, May 1992). Reports of these meetings are available from the JGOFS Project Office.

Also see: US JGOFS Arabian Sea Process Study (US JGOFS, 1991); US JGOFS Arabian Sea Process Study Implementation Plan (US JGOFS, 1992c); and Netherlands Indian Ocean Programme 1990/1995 (Netherlands Marine Research Foundation, 1991).

5.7.6 Resources

Satellites During the project, the European Remote Sensing Satellite ERS-2 will provide information on sea surface temperature, sea surface topography and winds. SeaWiFS and, from early 1995, ADEOS will provide ocean colour data.

Moorings The US plans four moorings with two instrument strings each. One string is a surface mooring with mixed layer instruments, the other is subsurface with sediment traps. See US JGOFS (1992c) for details.

6. Time series

JGOFS seeks understanding in terms of models that will simulate several years and correctly describe events in all seasons. The detailed experiments of process studies cannot usually be carried out for more than a few weeks or months; thus time series studies, with observations made regularly over very much longer periods, are also necessary for constraining parameter values. Year-round observations should provide flux estimates free of seasonal bias; they should also reveal some of the variability that limits our ability to understand and predict from a few years of data.

JGOFS will run a network of time series stations at which regular measurements of key properties and processes (mostly the same measurements that are made in process studies) are made at biweekly to monthly intervals, or continuously for those properties measurable by unattended, automated sensors. Time series stations will generally be close to a marine laboratory, to facilitate frequent, quick access. Although this limits the number of possible sites, it enables much complementary work to be planned taking advantage of backgound knowledge and facilities.

6.1 Aims

In addition to the fundamental aims for regional studies (Section 4), time series stations have the following specific objectives:

- to observe and interpret the seasonal and interannual variability in the rates of particle flux and remineralization over the entire water column
- to provide data on global trends of selected variables related to oceanic carbon during a decade.

Moreover, the existence of the facilities and the long series of data will attract other researchers for other purposes; e.g., the development and testing of new techniques and instruments, especially mooring techniques; performing other carbon flux studies; educational activities and intercomparison exercises; surface truth for satellites; and ocean-atmosphere interaction experiments.

6.2 Guidance and planning

A time series advisory committee has been formed to provide oversight for the quality of measurements and observations, and for the comparability of data sets from different stations. Advice on these matters is available upon request.

The proximity of time series sites to research centres will largely determine how often they are visited by research vessels. All sites should have moored instruments recording as many relevant variables as possible; however, if research vessel visits can be frequent a much wider range of data can be obtained. At all time series sites, a study should be carried out to determine how well the site represents its surrounding area. This study will vary in scope and time depending on the province to be evaluated.

As new technologies emerge, it will be possible to collect more data. In order to improve temporal resolution, from months to days or hours, it is necessary to develop new mooring and sensor technologies for autonomous recording of key variables (e.g. CTD, O_2, fluorescence, transmission, and currents).

Time series advisory committee: Anthony Knap, David Karl and Bodo von Bodungen.

6.2.1 Temporal resolution and duration

Time scales of interest in time series studies range from diel to decadal. It is appropriate here to consider the temporal resolution and duration of observation which would be required at a particular site in order to obtain results of acceptable accuracy. The accuracy required will depend on the variable under consideration and probably the province, and should in the first instance be determined from modelling studies. The strong intuition of all scientists involved is that monthly sampling is the minimum that is useful, and biweekly sampling is much preferable. The sampling strategy needs to be re-evaluated after 1.5 - 2 years of experience at a site.

Limitations in resources demand that a particular site should be studied only for as long as is neccessary, after which effort may need to be redirected to another unstudied province. Decadal changes can only be examined at a very small number of sites (perhaps one or two) and in any case this is beyond the current JGOFS time period. Interannual variation should be examined at a larger number of sites taking advantage of *in situ* instruments, such as sediment traps.

6.3 Recommended measurements

All the JGOFS core measurements (Section 9.1) should be made at frequently visited stations. Sediment cores should also be taken. Autonomous recording stations (e.g. on buoys and moorings) should measure at least temperature, salinity, pressure, current speed and direction, vertical particle flux, meteorological observations, bio-optical and acoustic variables.

The potential of Yo-Yo systems and autonomous submarines with instrumentation packages is currently under investigation.

6.4 Resources required

The estimated resources required for a frequently-visited JGOFS time series site, and for one with moored equipment, are given below, based on the levels of effort at the Bermuda and Hawaii stations.

6.4.1 Frequently visited stations

Facilities 100 m^2 laboratory space; 40 m^3 storage space; 100 m^2 preparation space.

Personnel Two scientists, two technicians.

Shiptime Monthly cruises each of 5 days, (allowing 12 extra days per year for bad weather); verification cruises 20 days.

Shipboard equipment To include: hydro winch with conducting cable, CTD, Rosette, Niskin bottles, Go Flo bottles, fluorometer for CTD, transmissometer, spare sensors, computer, current meters, drifting sediment trap array, spare array, drifting productivity array, spare array, Argos transmitters, spare Argos transmitters, and PAR sensor.

Laboratory equipment To include: Autoanalyser, fluorometer, salinometer, liquid scintillation counter, CHN analyser, DOC analyser, HPLC, Coulometer, alkalinity equipment, and computers.

6.4.2 Moored equipment

Station facilities staging area 60 m^2; laboratory 90 m^2.

Personnel Half-time scientist, half-time technician.

Shiptime 12 days plus 3 weather days per year.

Shipboard equipment To include: sediment traps (3), current meters (3), releases (2), floats (40), surface unit, surface transmitter, thermistor chain, Doppler current meter, meteorological package, biospherical optical package (3), surface float, telemetering equipment, miscellaneous sensors, mooring equipment.

6.5 Bermuda Atlantic Time Series

The Bermuda Atlantic time-series station (BATS) was established in 1988. The station is located 80 km SE of Bermuda (31°50 N, 64°10 W). Regular monthly sampling started in October 1988. BATS builds on a long tradition of time-series resarch in this part of the ocean, including deep sediment traps and a 37-year series of biweekly hydrographic samplings. In addition to the major monthly cruises, starting in the spring of 1990, additional cruises have been added of shorter duration in order to document the yearly overturn and bloom period. In 1990 and 1991 five of these cruises were made.

The standard JGOFS core measurements (with the exception of zooplankton) are made, by researchers at the Bermuda Biological Station (BBSR). In addition, a number of other individuals have been funded to carry out complementary measurements at the site.

There is currently 100% replication of DOC, and replication of nutrients and salinity has been increased to 20 - 30%. This high degree of replication ensures that a direct estimate of precision will always be available for these samples. Current precision of oxygen, salinity and nutrient methods is less than 0.1 - 2% (depending on the methods), with the goal of achieving 0.1 - 1%. BBSR personnel are actively involved in intercalibration exercises for salinity, oxygen, nutrients, DOC, and particulate matter.

Cruise results are initially sent to the US JGOFS office at Woods Hole; they are then forwarded to the US National Oceanographic Data Center (NODC) where they are available to the community as a whole. Data reports have been published covering the period October 1988 - September 1989.

Contact: Anthony Knap

6.6 Hawaii Ocean Time Series

In October 1988, a JGOFS time-series site was established at Station ALOHA (A Long-term Oligotrophic Habitat Assessment), approximately 100 km north of Oahu at 22°45 N, 158°0 W. It is also a WOCE station, is directly on a proposed TOPEX/Poseidon satellite groundtrack, and is 50 km away from the steep topography associated with the Hawaiian Ridge. The water depth is 4750 m, the seafloor is without relief and the sediments are predominantly composed of pelagic red clay. Station KAHE, located off Kahe Point at 1000 m water depth is also routinely occupied during monthly cruise operations.

It is believed that Station ALOHA is far enough from the Hawaiian Archipelago that the physical, chemical and biological conditions at the time-series station will be representative of the central North Pacific gyre. These waters are characterized by relatively high and uniform surface temperatures (23-28°C), a broad thermocline and a seasonally variable mixed layer (40 - 100 m). The conditions anticipated within the water column include low nutrient concentrations in the euphotic zone, with concomitant low planktonic biomass, low rates of new primary production and low rates of particle flux. Investigations to date support these expectations.

The standard JGOFS core measurements are made, with the exception of zooplankton. Taken together, these data will adequately characterize the physical, chemical and biological conditions of the water column which ultimately determine the rates of organic matter production and particle flux from the surface layers of the ocean (i.e., the biological pump). In the near future, it is hoped that several of the most important variables (temperature, salinity, currents, oxygen, nutrients, pigments and optical properties) will be monitored using remotely-operated instruments deployed from permanent bottom-moored platforms or surface buoys.

Data reports are published annually. Those currently available cover October 1988 to December 1990. The Hawaii Ocean time series (HOT) data are also available using the worldwide Internet system. The data reside on a workstation at the University of Hawaii in ASCII files which may be copied to DOS-based machines without ambiguity. The workstation's Internet address is: hokulea.soest.hawaii.edu or 128.171.151.47. The data are in a subdirectory called /pub/hot. Additional information about the data base is given in several files called Readme.* at this level. The file "Readme.first" gives general information; the user is encouraged to read it first.

Contact: David Karl

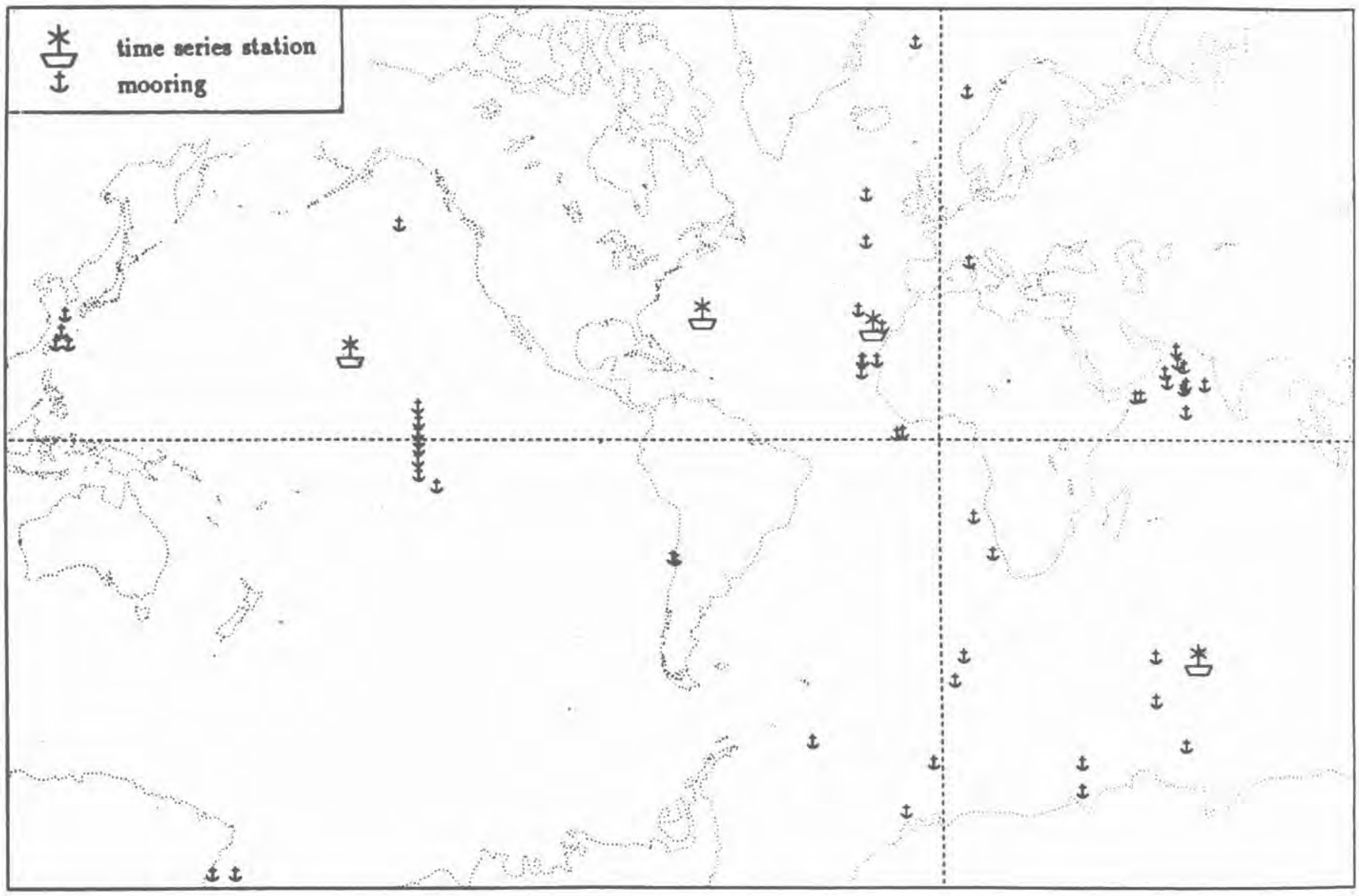

Figure 7.

Time series and long-term sediment trap moorings. The list of moorings comprises those that have been reported to the JGOFS Project Office.

6.7 Canary Islands

The site of the station has been selected in collaboration with WOCE. The station is to be located in the Canary Current, 100 km north of the island of Gran Canaria (at 29°10 N 13°0 W), in water depth of about 3600 m.

The Canary Islands area is part of the recirculation regime in the upper ocean North Atlantic subtropical gyre, which extends from the Gulf Stream via the Azores and Canary Currents to the North Equatorial Current. One branch of the gyre is found to the west of the Canary Islands, whilst another branch approaches Madeira, crosses the Canary archipelago, and merges with the Canary Current flowing southward along the west African coast. The oceanography of this area is strongly influenced by the periodicity of the trade winds, which drive coastal upwelling along the West African coast.

The seasonal and interannual variability of the flow pattern and strength of the Canary Current will affect nutrient supply, and hence primary production and flux of organic carbon through the water column. The area is also highly influenced by windblown dust from West Africa. The station off Gran Canaria, in an area with moderate primary production (60 – 90 gC m^{-2} yr^{-1}, Berger *et al.* 1989), is a particularly good site to study seasonal and interannual changes in particle flux, productivity and biogeochemical cycling through the water column in a transition zone between the eutrophic coastal upwelling waters and the open ocean oligotrophic waters.

The permanent station will be occupied once every month. The cruises will last between 3 - 5 days. Most of the JGOFS core measurements except zooplankton will be made. Once or twice a year, a mooring with sediment traps, bio-optical instruments and current meters will be recovered and redeployed.

Contact: Gerold Wefer or Javier Aristegui

6.8 ANTARFIX: South Indian Ocean

The time series station ANTARFIX is located at 50°40 S, 68°25 E, 100 km southwest of Kerguelen island. The aims of ANTARFIX are:

- to monitor the ocean-atmosphere CO_2 and O_2 exchanges, in order to understand the processes that govern these exchanges and the role of primary production in the water column of the Polar Front Zone of the Indian Ocean
- to observe and interpret the seasonal and interannual variabilities of the production, flux, decomposition and dissolution of carbon and associated elements at the same location.

This is also the site of the KERFIX station for physical oceanographic measurements. The WOCE CP2 working group has agreed to include KERFIX in the WOCE implementation plan as SRS1 (South Routine Station 1). In addition, sediment cores will provide further information on flux dynamics in this oceanic area.

The JGOFS core variables will be measured during the ANTARFIX/KERFIX joint programmes. The permanent station consists of two sediment traps (1 m^2 section, 24 cups), at 300 m (just below the mixed layer) and 1000 m depth and of continous measurement instruments, below each trap and in the mixed layer. The recovery of the mooring, the trap sample collection and checking of the probes is planned twice yearly, with *Marion Dufresne*. Sediment cores will be taken and large volumes of seawater (to allow more detailed analyses of the suspended material) will be filtered during these cruises. *La Curieuse*, based at Kerguelen will visit the time series station monthly and collect dissolved, planktonic and suspended matter from 30 litre volumes of seawater. Observatories and laboratories are established on Kerguelen island, providing a continous monitoring of meteorological data and allowing analysis of S, O_2, pCO_2, DIC, nutrients, biomass, primary production (^{14}C), photosynthesis vs light curves, chlorophyll and ammonium.

KERFIX monitoring with *La Curieuse* started in January 1990. The first ANTARFIX mooring was deployed in April 1992. The whole programme is planned for at least three years, and is closely coupled to the French ANTARES programme (1993 - 1996).

Contact: Catherine Jeandel

7. Sedimentary record

For JGOFS, the main reason for studying the sedimentary record is "to determine the relationship of ocean circulation, palaeoproductivity and CO_2 content of the atmosphere, to aid in the prediction of CO_2-related climatic change" (Science Plan, p. 47). Studies of the sedimentary record are particularly useful for JGOFS where the processes involved change with time scales of hundreds to thousands of years, such as the dynamics of thermohaline circulation and their effects upon ocean chemistry. Relationships have been established in recent years between historical variations in the CO_2 content of the atmosphere and changes in the spatial structure and chemistry of water masses in the ocean, more at the level of well-informed guesses than proven theories. The provision of high-resolution records of past atmospheric CO_2 levels, coupled with an understanding of the role played by the ocean in controlling past variations, can constrain models in a broad enough range of situations to let us evaluate the future more confidently.

The advantage of having high-resolution sedimentary records is that unique constraints can be established for narrow time bands. Thus, models which may be developed to clarify feedbacks induced by rapid CO_2 variations during periods of abrupt climate change, must do so within the boundaries of oceanic variability recorded by sediments at such specific times. Clearly, such models must be able to give realistic simulations of past CO_2 variations if they are to have credibility in predicting future scenarios.

A wide range of geochemical tracers is now being applied to the assessment of circulation and productivity history. These include the measurement of: (1) stable isotope ratios ($\delta^{13}C$, $\delta^{18}O$), Cd/Ca and Ba/Ca ratios and radiocarbon in foraminiferal calcite; (2) opal, $CaCO_3$ and C_{org} contents and U-series radioisotopes in sediments; and (3) concentrations of minor elements and organic biomarkers. In addition, microfossil assemblages (radiolaria, foraminifera, diatoms and coccoliths) are used to estimate past temperature and salinity characteristics of water masses. Acoustic sensing techniques are also being refined and used to assess $CaCO_3$ dissolution history and palaeocirculation on longer time scales. A comprehensive analytical approach to sedimentary record studies within JGOFS is required, in the same way that process studies benefit enormously from the application of a comprehensive range of core measurements.

The study of a sediment core consists both of flux estimates, based on accumulation rate calculations, and of chemical and isotopic tracers. The joint objective is to reconstruct the temperature, chemical composition and circulation of past oceans and atmospheric composition. It is important to derive precise chronology in such studies; for example, by using accelerator mass spectrometry (AMS) for radiocarbon measurements. A timescale for periods longer than about 40 kyr is obtained from the variations in oxygen isotope ratios (driven by the extent of global ice volume) in foraminifera, linked by other studies to precisely timed changes in the Earth's orbital parameters (the Specmap timescale).

Attainment of this objective will require extensive international collaboration between laboratories. Phase relationships and the timing of specific events, such as the Younger Dryas, are critical with respect to understanding ocean-atmosphere-climate-sediment linkages.

Samples collected by sediment traps used to study present-day fluxes will be extremely valuable for calibration of the currently-used palaeoceanographic tracers and development of new ones. Collection of biweekly to monthly time series of as many palaeoceanographic tracers as possible in sediment trap material will greatly improve our ability to understand their variations in the sediments. Dedicated traps on JGOFS moorings will probably be needed to supply adequate amounts of material for these calibration studies.

Contact: Tom Pedersen

7.1 Samples for sedimentary record studies

The retrieval of high-quality cores is of critical importance to the planned work. Ideally, a long core should be recovered, with minimal disturbance and distortion, of a volume sufficient to supply all the needed samples from the working half of the core. Only large volume corers will provide the resolution needed. In addition, it is necessary to capture the sediment-water interface intact, so that surface samples can be obtained to provide calibration of sedimentary proxies to the modern ocean. Wherever possible the following approach should be adopted by JGOFS in the collection of sediment cores.

The use of large-diameter piston corers such as the LCF (Long Coring Facility, of the Bedford Institute of Oceanography), the Stacor (used by France and the UK), or the long Kastenlot (used by Germany) is highly recommended, in preference to conventional narrow-diameter piston cores. Newly designed large-volume standard piston corers (up to 20 m in length) like that built recently by J. Broda at Woods Hole, should also be used whenever possible.

At least one high-quality box core or set of multicores (i.e. cores with the sediment-water interface intact) should be collected at each site where piston cores are raised. The careful collection and storage of the top centimetre of such cores (in addition to regular vertical subsampling) is of great importance for subsequent tracer calibration studies. Depending on the performance of the large corers, an intermediate-length large diameter gravity core should also be collected at each location.

7.1.1 Recommended measurements

δ^{18}O and δ^{13}C in paired benthic and planktonic foraminifera Comparisons should be made between near-surface dwelling planktonic species, particularly *Globigerinoides ruber* and epifaunal benthic genera, particularly *Cibicidoides*.

Organic carbon and $CaCO_3$ Both are critical; measurement of the former is not trivial in commonly found carbonate-rich deposits. The use of techniques such as that of Weliky *et al.* (1983) is highly recommended for carbonate rich samples, as is the measurement of $CaCO_3$ by coulometry.

Opal The method of strong alkali dissolution and molybdate blue analysis, carefully calibrated with respect to dissolution time, is recommended (see Demaster, 1981).

^{14}C by AMS As noted earlier, provision of high quality chronology is of paramount importance. AMS radiocarbon dating of monospecific foraminifera samples is therefore considered to be a core measurement.

Samples for bulk density measurements To be collected routinely from cores, preferably by the careful insertion of pre-weighed thin-walled hollow cubes of known volume into split core faces. The availability of accurate wet and dry bulk density measurements is critical for subsequent calculation of accumulation rates.

It would be extremely useful to have a wide range of other analyses carried out (e.g. Cd/Ca and Ba/Ca ratio measurements in foraminifera, nitrogen determinations, δ^{13}C and δ^{15}N in organic matter, organic biomarker analyses, major and minor element chemistry, U-series isotopes and others), but these cannot be listed as core measurements given analytical limitations and capabilities which vary widely amongst different laboratories. JGOFS participants carrying out sedimentary record studies will collaborate as widely as possible with other laboratories to make a comprehensive range of measurements.

The fluxes of ^{210}Pb and organic matter in sediment traps are correlated (Moore and Dymond 1988). Therefore the amount of ^{210}Pb in sediment cores could serve as a tracer to infer the flux of organic matter arriving at the sediment surface.

7.2 Resources required

7.2.1 Sampling platforms

Only a few research vessels are large enough to handle the large-volume corers (e.g. *Hudson, Marion Dufresne, Meteor, Polarstern, James Clark Ross, Discovery*). Wherever possible, JGOFS cruises that include sedimentary record studies should be on ships large enough to allow use of large-diameter corers. The JGOFS SSC will facilitate access to such ships.

7.2.2 Analysis

Sedimentary record studies are by nature analytically (and thus, labour) intensive, and therefore take longer to complete than other studies. Long time frames for provision of support need to be established at the outset of studies of the sedimentary record. The studies should commence, where practicable, early in JGOFS, so that as many data as possible will be available for the final synthesis.

7.2.3 Sediment traps

Calibration and refinement of palaeoceanographic tracers are strongly limited by our understanding of how such tracers respond in the modern ocean. Time series sediment trap studies are important to improve understanding of the sedimentary record. In addition to routine sediment trap analyses, other analyses are important for calibrating tracers: for example, knowledge of the water depth and season in which foraminifera lay down their tests is needed for correct interpretation of compositional changes recorded by tests buried in sediments. Because such palaeoceanographic calibrations need relatively large samples, dedicated sediment traps for palaeoceanographic studies should be placed on as many of the annual or multiyear JGOFS sediment trap arrays as possible.

7.2.4 Curation of cores

It is important that cores collected under the JGOFS programme be well curated and stored. They will thereby provide a valuable international resource - particularly since many of the last generation of important cores held in major archives have been depleted, and there are no good collections of surface sediments available.

8. Continental margin boundary fluxes

Although less than 20% of the total sea surface lies over continental shelves and slopes, the coastal oceans are important in the global carbon cycle. They are the transit zone between the land and the open ocean, where much terrigenous and anthropogenic material is received, transformed and transported to the open ocean. Their productivity is high due to nutrient input from river runoff and coastal circulation, mixing and upwelling, and this may cause net drawdown of atmospheric CO_2. The shelves and slopes are sites of rapid carbon deposition and active benthic processes, which exchange materials with the open ocean by lateral transport.

A good understanding of the processes occurring on continental margins and the associated fluxes is needed for realistic boundary conditions for global models of the marine carbon cycle. Furthermore, rapid sedimentation rates in coastal areas may provide high resolution sedimentary records.

However, this part of the ocean varies greatly in space and time, making it difficult to choose typical areas for a particular study. The intensity of lateral mixing mechanisms such as frontal mixing, eddy transport and turbidity currents are especially variable.

JGOFS will carry out continental margin studies in collaboration with the proposed IGBP project on Land-Ocean Interactions in the Coastal Zone (LOICZ). Mechanisms for developing liaison between JGOFS and LOICZ, including joint planning teams, will be instituted as required. Continental margin studies enable many more nations to be involved in JGOFS. Such collaboration will be mutually beneficial in several ways: the researchers of participating countries will share in the technical and scientific development of JGOFS (including the calibration of satellite data for shelf seas), whilst JGOFS will have facilitated access to territorial waters, and to the extensive database for the coastal ocean.

JGOFS will also encourage and support other initiatives to make measurements relevant to carbon and nutrient flux in continental margins, whether organised by individual countries or by other internationally coordinated programmes.

8.1 Aims

The aims of continental margin studies within JGOFS are:

- to quantify the exchange of carbon between given marginal zones and the open ocean
- to understand the seasonal and inter-annual fluctuation of carbon fluxes and nutrient cycles due to physical and biological variation
- to estimate the exchanges between shelves, slopes and the open ocean by lateral transport
- to evaluate the importance of carbon deposition on the continental slope
- to determine the air-sea CO_2 exchange rates in strong upwelling areas
- to characterize those features of continental margins that enable extrapolation to the global scale.

8.2 Study areas

There are many different types of continental margin. Study areas will be selected according to their importance for global carbon flow and the possibility of generalizing the results obtained from local studies. Continental margins that would seem important include:

Areas with large input of river sediment, such as the East China Sea and the Bay of Bengal. The river sediment may carry very large amounts of terrigenous organic matter and nutrient elements to the ocean.

Areas of strong coastal upwelling, such as the Chile and Peru coast, NW Africa coast, Namibian and South African west coast, and Somali basin. The upwelling induces locally intense primary production.

Areas of cyclonic eddy upwelling in western boundary currents, such as the southeastern coast of USA. Although their productivity is moderate, the strong boundary current favours rapid exchange with the open ocean and thus may produce a significant carbon flux.

The shelf area around the SE Asia Archipelago, where the productivity is high and the sediment production is voluminous. The flow of water from the Pacific to the Indian Ocean may carry large amounts of carbon to the deep ocean from this region.

8.3 Ongoing and proposed regional programmes

Many nations have already formulated comprehensive research projects to study transport processes and biogeochemical fluxes across the continental margin. Several of these involve international participation and are already linked to JGOFS. Brief descriptions of some relevant studies follow:

KEEP (Kuroshio Edge Exchange Processes) is a multidisciplinary study of the China (Taipei) JGOFS programme with participation from Canada, France, Russia and USA. KEEP is scheduled for 1989 - 1994; its aims are to study the exchange of water between the Kuroshio and the East China Sea northeast of Taiwan, and to estimate the related biogeochemical fluxes. KEEP-MASS will extend fieldwork to shelf regions of the Yellow Sea, Sea of Japan, and possibly Okhotsk Sea. Contact: Chen-Tung (Arthur) Chen

The Japan Marine Science and Technology Center will start a five year project on flux studies in ocean margins. The main objectives are to quantify the cycle of biogenic elements in the marginal seas of the Pacific through extensive field surveys, and to evaluate the role of marginal seas in global climate change. The first target of the field survey is the East China Sea, which receives large amounts of dissolved and suspended materials from the Changjiang River and Yellow River. Extensive colloboration with other nations, especially China, is expected.

ECOMARGE (Ecosystems of continental margins), part of France-JGOFS, is a multidisciplinary programme with participation from Spain, Switzerland and USA. Using time series observations and seasonal survey cruises, ECOMARGE aims to determine the origin, composition and transport mechanisms of particulate matter on continental margins. Benthic studies are included, and sites in the NW Mediterranean and the Bay of Biscay are currently under investigation. Contact: André Monaco

EROS-2000 and OMEX are EC programmes on biogeochemical fluxes, with emphasis on lateral transport and transformation processes. EROS-2000 (European River-Ocean Systems) addresses riverine sources and the coastal fate of material, with current work in the NW Mediterranean and planned studies on the Danube and Black Sea. OMEX (Ocean Margin Exchanges study) will, from 1993, extend this work to continental margin fluxes, particularly those between the NW European shelf and the NE Atlantic.

CoOP (Coastal Ocean Processes) is a US project addressing not only the transformation and fate of material on continental margins, but also cross-margin transport processes. It includes studies of air-sea interactions, terrestrial inputs and benthic-pelagic coupling, with emphasis on features that can be extrapolated via process studies and modelling.

Other projects that involve research on continental margin processes include a Benguela Current study, by South Africa and Namibia, and the Chilean eastern boundary current study (Section 10.2.1).

8.4 Task team

JGOFS and LOICZ have recently established a joint Continental Margins Task Team. Its term of operation is three years, after which its achievements, membership and terms of reference will be reviewed.

Task team leader: Chen-Tung (Arthur) Chen

9. Data quality and availability

The success of JGOFS, especially its synthesis function, depends on having observations of high quality, readily available to the scientific community. The Science Plan (p. 51) states the data access and submission policy of JGOFS: basically that investigators submit their data in a timely manner and that there should be reading access to the data without restriction to anyone interested. Those who wish to use the data are expected to obey the normal scientific obligation to contact the originator for permission. Data collection and management are closely linked, because part of the task of managing the data set is determining how reliable its elements are.

9.1 Core measurements and protocols

An important aspect of the JGOFS observational strategy is the development of standard, high-quality methods for core measurements, to facilitate data comparisons between different research groups and to improve confidence in the JGOFS data set as a whole. A preliminary version of these protocols was prepared for the North Atlantic Bloom Experiment (SCOR, 1990c), and a more detailed version will be published in late 1992.

The list of core measurements was developed in consultation with modellers; it addresses the variables and rate processes, and their hydrographic background, that need to be quantified for the development of JGOFS biogeochemical process models. An important goal of the programme is to build the capability to perform each measurement to JGOFS standards, following the accepted protocol, on each process study cruise. The core measurements adopted for the NABE study included meteorology and positioning; CTD, O_2 probes and fluorometry; oxygen titrations; nutrients; optics; pCO_2, DIC, alkalinity and pH; POC and PON; DOC; pigments and chlorophyll; bacteria and cyanobacteria; mesoplankton abundance and grazing; microzooplankton abundance and grazing; primary production by ^{14}C; primary production by O_2; new production by ^{15}N; and floating and moored sediment traps.

Protocols for additional core measurements particular to the Southern Ocean have been prepared by the Southern Ocean planning group. These include silicon cycle components; ice-associated optical measurements; ice physical structure and cover; satellite observations of ice; and ice biota.

Further protocols have been developed for the following benthic flux and concentration measurements: the permanent burial flux below the biologically mixed layer; the solute flux across the sediment/water interface; biological carbon oxidation, including aerobic and anaerobic processes that result in significant chemical fluxes; biological mixing of sediments and pore water exchange (e.g. bioturbation, irrigation and resuspension); benthic primary production; biological transformations of carbon and other sedimentary components; chemical transformations in the BBZ; and physical processes that govern the exchange of particles and solutes between the sediment and the overlying water.

Contact: Anthony Knap

9.2 Training

Given the importance of involving as many nations as possible in JGOFS, the SSC will continue to promote opportunities for training in making high quality measurements according to the JGOFS protocols. This is being done with the assistance of the Intergovernmental Oceanographic Commission (IOC), in particular in preparation for the Arabian Sea process study. Support from the IOC, Netherlands and Germany has been obtained for JGOFS training workshops in Mombasa and Goa (see Section 5.7.3). More such workshops are needed, as are similar training workshops on data analysis, use of remotely sensed data and the establishment and maintenance of time series stations.

Quality assurance, intercalibration and data comparability are important subjects for all components of JGOFS. JGOFS looks to the IOC for assistance in identifying the requirements of scientists in the regions, mobilization of resources and coordination of the training activity. Collaboration with the IGBP System for Analysis, Research and Training (START) activity is also appropriate.

National JGOFS committees in developed countries are expected to contribute to the training effort. For example, wherever possible, provision should be made for scientists from developing countries to participate on cruises.

Contact: Neil Andersen.

9.3 Data management

The JGOFS data management system aims to provide all interested scientists with complete and convenient access to the international JGOFS data set. When the system is fully established, the information available should include: data from current experiments, as up-to-date as possible, regardless of country of origin; extensive documentation and "metadata", including indications of data quality (variance); historical data collections; inferred quantities; processed and remapped fields; and model output. Transfer of this information or selected subsets should be as smooth as possible.

The proposed model for data management sees the leading role taken by small topical data centres, each responsible for assembling an online database from a clearly defined subset of the data. Often, but not inevitably, the subset will consist of the data collected by investigators from a single country. This system is more centralized than one in which responsibility is distributed to the data originators: experience has shown that the active involvement of professional data managers is needed to overcome problems of data quality, documentation and permanent availability. However, such arrangements are less centralized than a single world data centre – on the basis that the data subsets should be small enough for the data managers to have easy access to all the originators. There could also be problems with a single JGOFS data centre if scientists in the host country were perceived as having privileged access to that data centre.

The US National Oceanographic Data Center (NODC) and the British Oceanographic Data Centre (BODC) are working examples of the sort of centre envisaged. Each national JGOFS programme will either establish one or more topical data centres in their country, or arrange for an existing centre, possibly in another country, to be responsible for managing their data. In either case, the national programme will inform individual investigators of their obligations to submit data to the appropriate topical centre and satisfy the centre's requirements for quality control and documentation.

Each topical centre will establish data exchange formats to be used by investigators submitting data to the centre. It will also: (1) establish flexible procedures for retrieving and working with the data; (2) arrange training in using the procedures; (3) provide remote access to the extent practicable; and (4) arrange exchange with other centres so that the complete JGOFS data set is available from each centre, accessible according to that centre's procedures. NODC and BODC have already completed these steps for North Atlantic Bloom Experiment data. See also Section 6.6 for access to Hawaii Ocean time series data via Internet.

The data centres together will create a data inventory containing summary information about all the available data. This inventory will be published periodically, and in between published editions an up-to-date version will be made widely available from at least each topical data centre and the JGOFS Project Office in Kiel, and possibly on an electronic bulletin board. If there is a need, centres may also publish other, more specialized data products.

A Data Management Task Team will work throughout the life of JGOFS to coordinate the activities of the data centres, monitor compliance with data management requirements, and periodically reassess the needs and performance of the system.

Contact: Glenn Flierl or Roy Lowry

10. Associated national activities

This chapter briefly describes some of the main JGOFS-relevant national activities known to the JGOFS Project Office, that are not internationally coordinated through the SSC. Their benefit to the programme as a whole is greatly enhanced if measurements are made in accordance with JGOFS protocols, and if data are made available through recognized JGOFS data centres.

10.1 The North Atlantic and adjacent seas

10.1.1 French activities

EUMELI in the tropical Atlantic is a programme of France-JGOFS (1990-93) that aims to understand and assess particle fluxes from the ocean-atmosphere interface to the burial in sediments, by means of process studies at three sites (EUtrophic, MEsotrophic and oLIgotrophic) where deep sediment traps have been deployed for nearly two years.
Contact: André Morel

FRONTAL, part of France-JGOFS, aims at the study of mesoscale processes at frontal zones, which appear to play a dominant role during the spring bloom at mid latitude. At least until 1996, the main activity will be the study of the Almeria-Oran frontal system (SW Mediterranean Sea).
Contact: Alain Sournia

DYFAMED in the Mediterranean Sea, part of France-JGOFS, is developing into a time series station where JGOFS core variables will be measured on a monthly basis and deep sediment traps will be maintained.
Contact: Patrick Buat-Ménard

France-JGOFS activities are coordinated with the French PNEDC (Programme National d'Etude de la Dynamique du Climat); the PNEDC is developing a global ocean-atmosphere model into which biogeochemical models will be incorporated, and also includes a programme for assessing and modelling air-sea carbon dioxide exchanges. This modelling effort will also be applied to other ocean basins.

10.1.2 UK: PRIME

PRIME (Plankton Reactivity in the Marine Environment) is a five year proposal for a comprehensive study of plankton community structure and function. It has close links to JGOFS, and will provide a framework for research on the biogeochemical role of plankton, including novel techniques and modelling studies. The programme will bring together a diverse community of scientists, including many who were involved in the UK Biogeochemical Ocean Flux Study (BOFS). Cruises are planned in 1995 and 1996.
Contact: Peter Williams

10.1.3 UK: sediment studies

Sediment analyses will continue on a suite of Kasten cores collected in 1989 - 1991 along 20°W (from 60°N to 18°N) as part of BOFS. Objectives include using isotopic and chemical measurements of foraminiferal calcite to identify variations in time of the bottom-water circulation and nutrient distributions and budgets; identification of regional lysocline shifts through time and their relationship to circulation; and establishing historical fluxes and mass balances for $CaCO_3$ and terrigenous and organic matter inputs through the last glacial-interglacial cycle. Further sediment studies are proposed along a continental margin transect from the BIOTRANS site (47°N 20°W) to the shelf break southwest of Ireland.

10.1.4 Germany: Arctic Ocean

The Sonderforschungsbereich (SFB) 313 at Kiel University is investigating the history of environmental changes in the northern North Atlantic in relation to global climatic variations during the past 300 kyr. Field studies are carried out in the Norwegian and

East Greenland Seas, and on the Rockall Plateau south of the Iceland-Faeroes Ridge. The region in the Greenland Sea has been proposed as a JGOFS time series station. Research within SFB 313 addresses changes in surface and deep water circulation and chemistry; modifications of planktonic microfossil assemblages in relation to ecological factors; and variations in organic matter productivity. The variables studied in this work include stable isotopes and trace metals in foraminifera, AMS ^{14}C and U-series isotopes, all relevant groups of planktonic organisms, organic C and N and their isotopic compositions, and various organic components.

Benthic components include near-bottom transport, sediment accumulation and biogeochemistry. The overall goals of the study are to assess biogenic fluxes of elements and their export to the sediment in the contemporary northern North Atlantic, and to use such results in interpreting palaeoceanographic data and in developing palaeoclimate models.

From 1986-1988 sediment trap moorings were deployed on the Voering Plateau, a 1200 m deep plateau off the Norwegian continental shelf. Since summer 1986, vertical particle export has been recorded year round at a station in the Norwegian Basin (3300 m water depth; 70°N 0°W). Since November 1987, a second station in the Jan Mayen Current has been studied (2700 m water depth; 73°N 5°W), where annual moorings of sediment traps are also deployed. This station is ice covered for several months. In the vicinity of mooring stations, pelagic process studies have been carried out in different seasons of the year, including drifting sediment traps and short-term moorings. Cruises will continue at least until 1993, and for a further three years if funding is provided.

Contact: Bodo von Bodungen

10.2 Equatorial regimes

10.2.1 US: iron enrichment experiment

A mesoscale (10-100 km^2) iron enrichment experiment in a high nutrient, low chlorophyll area of the ocean is proposed. Such an experiment must be large enough to analyze planktonic food web dynamics, but small enough to avoid any long-term environmental impact. A suitable place for an initial experiment is in the equatorial Pacific, where high temperature and light conditions should result in the creation of a phytoplankton bloom in 3-7 days, well before the iron patch disperses and ceases to be trackable.

Preliminary experiments are planned for the autumn of 1993 in the eastern equatorial Pacific study area (4-6°S, 90-100°W), to investigate possible problems with mixing and iron solubility. Inorganic iron will be spread in the ship's wake (maximum initial concentration = 0.1 μmol Fe per litre) in long (5-10 km) streaks. The streaks will be marked with drogued buoys and labeled with SF6, an inert tracer. The speed at which the SF6 disperses will be determined, as well as the amount of inorganic iron remaining in solution. If the inorganic iron precipitates immediately, a form of chelated iron will have to be used. With these initial findings, a full experiment will be planned and performed in 1994. The study will be timed to take advantage of remote sensing of chlorophyll concentrations via the SeaWiFS satellite.

For further details, see US JGOFS (1992a).

10.2.2 Canada: productivity and upwelling records

Research is planned on the productivity and upwelling history in the eastern equatorial Pacific. Isotopic, organic carbon and nitrogen, major and minor element, AMS ^{14}C and U-series isotope measurements will be made in this collaborative project. The aim is to determine temporal and spatial variability and cyclicity in the accumulation of organic matter and other biogenic components across the equatorial divergence and as a function of depth. One cruise is planned to collect a suite of cores from the equatorial region west of the Galapagos Islands to complement cores already available collected from the Panama Basin region.

10.2.3 Japan: sediment studies

Fifteen Japanese scientists will participate in JGOFS sedimentary record studies during the period 1991 - 1995. The main objectives are: to clarify the relationships between the fluxes collected in sediment traps and those determined from the study of nearby sediments; and to investigate the time-varying nature of fluxes and their relationship to palaeoclimate, using measurements made on box and piston cores from the western equatorial and northwestern Pacific.

Sediment traps will be deployed at four depths between 500 m and 9 km in the Japan Trench, and at 1.5 and 4 km depths at two sites in the western equatorial Pacific and a further location some 20° to the north (18.5°N 143.5°E). The traps will be serviced regularly and will remain in place for several years. Box and piston cores will be collected from the vicinity of each sediment trap.

Measurements to be made on these cores, and where appropriate on the trap samples, include: magnetic susceptibility; determination of $CaCO_3$, opal and C_{org} contents; ^{14}C and U-series activities for dating purposes; compositional variations of organic matter, particularly those resulting from diagenesis; distributions of a wide range of microfossils including diatoms, radiolaria, pollen, silicoflagellates and benthic and planktonic foraminifera; $\delta^{13}C$, $\delta^{18}O$ and Cd/Ca ratios in foraminifera tests; and $\delta^{13}C$ and $\delta^{15}N$ in organic matter.

The initial phase of the programme is expected to be completed by 1996.

10.2.4 Germany: vertical flux studies

Vertical flux studies using sediment traps and other particle collecting instruments have been or will be conducted in the Equatorial Atlantic at about 10°W, near Cape Verde Islands and off Cape Blanc. These stations extend the JGOFS work in the North Atlantic along 10-20°W (Fig. 3) further south to an area influenced by trade winds (coastal and equatorial upwelling) and atmospheric dust.

Contact: Gerold Wefer

10.3 The Southern Ocean

10.3.1 UK: sediment studies

In the Southern Ocean, the work centres on the Bellingshausen Basin, west of the Antarctic Peninsula. Objectives include: assessing the ability of Holocene sediment to provide a record of new production, and to locate the mean position of the ice front; to correlate and investigate the phase relationships among production and the CO_2, CH_4 and aerosol records derived from terrestrial ice cores; to determine the limits of time resolution of the sedimentary record and the ability of fine-scale sampling to resolve features such as the Younger Dryas and Little Ice Age; and to investigate through the sedimentary record the operation of processes not seen today which may have influenced the carbon budget during the glacial maximum (e.g. Pacific polynyas).

10.3.2 Germany: sediment studies

The Sonderforschungsbereich (SFB) 261 in Bremen is working in the South Atlantic Ocean and its Antarctic sector. The transects planned for the next five years will cover the major surface current systems in this ocean including the central gyre. The goals of the sedimentary record studies are to reconstruct: the dynamics of the trans-equatorial heat transport in relation to North Atlantic deep water formation; productivity variations in relation to intermediate water formation and nutrient utilization in the Antarctic; and variations in Antarctic bottom water formation in relation to shelf ice formation and other factors. The temporal frame is the Late Quaternary, particularly periods of rapid climatic changes. To assess temperature and productivity variations for the past, various proxy parameters will be analysed, including the basic chemical and isotopic measurements defined above, microfossil assemblages, and specific organic biomarkers.

Contact: Gerold Wefer

10.4 Boundary currents

10.4.1 Chilean eastern boundary current

The overall goal of the studies off Chile is to understand carbon cycling in the Peru-Chile current. The results will be used to assess the role of eastern boundary currents in the global carbon cycle. These studies will also contribute to the oceanographic exploration of the eastern South Pacific Ocean and to a better understanding of the upwelling ecosystem off Chile.

This is a cooperative project among research groups from Chile, Sweden, Denmark and Germany. The field work began in November 1991 and will continue until 1997, with four cruises per year of 6-11 days duration each, at several locations on a transect out from the coast. The observations should thus resolve seasonal and El Niño-related variations.

Time series observations are made at an offshore station (30°S, 73°12 W), and a slope station (30°19 S, 71°47 W) at which moorings were deployed in November 1991. The offshore station is located 200 km from the coast, seaward of the Peru-Chile Trench, at a water depth of 4200 m. The mooring has three sediment traps (0.5m^2 section, 20 cups) and 5 current meters; in future it will be supplemented by a meteorological buoy. The slope station is 12 km from the coast at a depth of 800 m and has three current meters. The moorings are recovered and redeployed twice a year. Most of the JGOFS core measurements are made at both stations, although not yet new production, DIC and alkalinity. Twice a year, about 15 additional stations are made with a CTD/Rosette and a fine scale CTD/current/fluorescence/PAR profiler to study local spatial structure.

Contact: Gary Shaffer or Tarsicio Antezana

10.5 Central gyres

10.5.1 Canada: calcium carbonate dissolution

This project will study the history of calcium carbonate dissolution in the eastern, central and western Pacific. $CaCO_3$ solubility on the seafloor is highly sensitive to changes in circulation and bottom-water CO_2 content, and is known to have varied markedly on glacial-interglacial timescales. This project will employ high-resolution acoustic techniques to determine, synoptically, the extent and cyclicity of carbonate dissolution in the central Pacific over long time scales. The acoustic information will be calibrated initially by reference to carbonate analyses made on long cores.

10.6 North Pacific

10.6.1 Canada: Station P time-series programme

Detritus fluxes of carbon, calcium carbonate, nitrogen and silica have been measured at 50°N 145°W since 1982. Automated sequential sediment traps moored at 3800 m are used; since 1989, traps have been added at 200 and 1000 m. Floating sediment traps are deployed and primary productivity measurements made on 2 - 4 cruises per year. This work builds on a long history (over 30 years for many variables) of oceanic research at the site.

Contact: C.S. Wong

10.6.2 Japan: North Pacific carbon cycle study

The main objectives of this project are to monitor carbon-related substances and their flux in the north Pacific, and to develop a carbon cycle model in this area. This study focusses on the influence of biological processes on the carbonate chemistry and fluxes of particles in the upper ocean. The field survey covers major domains of the North Pacific: sub-arctic boundary, sub-tropical gyre and tropical regions.

In 1990 and 1991, two detailed transect surveys along the 175°E line from 45-48°N to 8-15°S were conducted during August to October using the research vessel *Hakurei-Maru*. Hydrographic observations (down to 300 m depth) including CTD plus several additional sensors, carbonate system, nutrients, size fractionated chlorophyll and other biological sampling were carried out. Surface pCO_2, temperature, salinity, and chlorophyll were monitored continuously. Deep sea sediment traps were moored at 48°N, 30°N, 13°N, and 0°N in 1991. The first phase of this monitoring programme will last 5 years.

10.7 Continental margins

10.7.1 Canada: carbon burial on century time scales

The annual accumulation of organic carbon over the last 200 years will be studied in Saanich Inlet, an anoxic fjord on the Canadian west coast, by using diatom, dinoflagellate, pollen and organic carbon distributions in the varved sediments of the basin. Varves provide a high resolution time-scale which should allow definition of annual and decadal cycles or events. Thus, climatic and oceanographic variability and anthropogenic influences in the area over the last few to several centuries will be assessed.

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A. JGOFS planning groups

Membership of many of these groups has changed since their establishment; the people listed are the members on 1 September 1992 or when the group completed its task and disbanded. Reports of the meetings are available from the group leader, or from Elizabeth Gross or Geoffrey Evans.

Scientific Steering Committee

Trevor Platt (Canada, chair), Otis Brown (USA), Patrick Buat-Ménard (France), Chen-Tung (Arthur) Chen (China - Taipei), Yves Dandonneau (France), Kenneth Denman (Canada), Hugh Ducklow (USA), John Field (South Africa, vice-chair), S. Krishnaswami (India), Margaret Leinen (USA), Alexander Lisitzin (Russia), Liliane Merlivat (France), Julian Priddle (UK), Gary Shaffer (Denmark), Ulrich Siegenthaler (Switzerland), Victor Smetacek (Germany), Gerold Wefer (Germany)

Support staff

Geoffrey Evans, executive scientist; Elizabeth Gross, executive secretary and SCOR liaison; Phillip Williamson, IGBP liaison.

Council of National Chairs

Australia, Graham Harris; Canada, Louis Legendre; Chile, Tarsicio Antezana; China (Beijing), Dunxin Hu; China (Taipei), Wen-Ssn Chuang; France, Guy Jacques; Germany, Jan Duinker; India, S. Krishnaswami; Italy, Vincenzo Damiani; Japan, Isao Koike; Netherlands, Hein de Baar; New Zealand, Barrie Peake; Russia, Alexander Lisitzin; South Africa, John Field; UK, Peter Williams; USA, Otis Brown.

Process Studies Task Team

Hugh Ducklow (USA, leader), Guy Jacques (France), David Turner (UK), Marlon Lewis (Canada), Christian Stienen (Germany), Alain Dinet (France), Marcel Veldhuis (Netherlands)

The team met in Washington, DC in November 1990, and in Banyuls-sur-Mer, France, in May 1991.

Benthic Studies Task Team

Stephen Calvert (Canada, leader), Olaf Pfannkuche (Germany), Willem Helder (Netherlands), Richard Jahnke (USA), Bernard Boudreau (Canada), John Parkes (UK)

The team met in Bermuda in April 1991.

Time Series Task Team

Gerold Wefer (Germany, leader), David Karl (USA), Anthony Knap (USA), Steve Emerson (USA), Javier Aristegui (Spain), Richard Lampitt (UK), Catherine Jeandel (France)

The team met in Bremen in May 1991.

Sedimentary Record Task Team

Tom Pedersen (Canada, leader), M. Lyle (USA), Graham Shimmield (UK), Peter Müller (Germany)

The team worked by correspondence and submitted a report in June 1991.

Global Survey Task Team

Mike Bacon (USA, leader), Reiner Schlitzer (Germany), Tom Dickey (USA), Richard Jahnke (USA), Frank Millero (USA)

The team met in Miami in February 1992.

Pigments and Optics Task Team

John Marra (USA, leader), Marcel Wernand (Netherlands), Howard Gordon (USA), James Mueller (USA), Jim Aiken (UK)

The team met in Palisades, NY in March 1991.

Data Management Task Team

Glenn Flierl (USA, leader), Roy Lowry (UK), Uli Wolf (Germany), Hugh Ducklow (USA), George Heimerdinger (USA), Joop Rommets (Netherlands), Kai Jahnke (Germany)

The team met in Cambridge, MA in June 1991, and at the Goddard Space Flight Center in Maryland in February 1992.

Synthesis and Modelling Task Team

John Parslow (Australia, leader), Mike Fasham (UK), Véronique Garcon (France), Jorge Sarmiento (USA), Fred Wulff (Sweden), Geoff Evans (Germany/Canada)

The team met in March 1990 in London, and informally in May 1992 in Bonas, France.

Continental Margins Task Team

Chen-Tung (Arthur) Chen (China - Taipei, leader), Patrick Holligan (UK), James Yoder (USA), Hong Huasheng (China - Beijing), S. Krishnaswami (India), K. Iseki (Japan)

The team will meet in October, 1992 in Taipei.

JGOFS-CCCO Panel on Carbon Dioxide

Liliane Merlivat (France, leader), Peter Brewer (USA), Otis Brown (USA), Andrew Dickson (USA), Ernst Maier-Reimer (Germany), Frank Millero (USA), Graeme Pearman (Australia), Trevor Platt (Canada), Alain Poisson (France), Ulrich Siegenthaler (Switzerland), Taro Takahashi (USA), Shizuo Tsunogai (Japan), Andrew Watson (UK), C.S. Wong (Canada)

The team held its second session in April 1991 in Paris; the proceedings have been published (CCCO 1991). The third session took place in Monterey, California in April 1992. This Panel will continue after CCCO ceases to operate.

Indian Ocean Planning Group

Bernt Zeitzschel (Germany, leader), Sharon Smith (USA), Otis Brown (USA), Alain Poisson (France), Martien Baars (Netherlands), Trevor Platt (Canada), R.R. Nair (India), Peter Burkill (UK), Thabit Al-Abdessalaam (Oman), G.S. Quraishee (Pakistan), Ezekiel Okemwa (Kenya)

The group met in Goa in January 1991, in Bermuda in October 1991, and on board the Netherlands research vessel *Tyro* in the Mediterranean in May 1992.

Equatorial Pacific Planning Group

Margaret Leinen (USA, leader), Yves Dandonneau (France), Denis Mackey (Australia), Marlon Lewis (Canada), Makoto Terazaki (Japan)

The group met in Tokyo in April 1990.

Southern Ocean Planning Group

Julian Priddle (UK, leader), Robert Anderson (USA), Hein de Baar (Netherlands), Ulrich Bathmann (Germany), Mitsuo Fukuchi (Japan), Christiane Lancelot (Belgium), Mike Lucas (South Africa), Denis Mackey (Australia), Paul Tréguer (France), Cornelis Veth (Netherlands)

The group met in Cambridge, UK in December 1990, and in Bremerhaven in May 1991; in addition a modelling meeting was held in Cambridge in October 1991.

North Atlantic Planning Group

Richard Lampitt (UK, leader), Hugh Ducklow (USA), John Marra (USA), Alain Dinet (France), Bodo von Bodungen (Germany), Glen Harrison (Canada), Catherine Goyet (USA)

The group met in January 1992 in Wormley, UK.

Process Studies Coordinating Committee

Hugh Ducklow (USA, leader), Margaret Leinen (USA), Bernt Zeitzschel (Germany), Richard Lampitt (UK), Julian Priddle (UK)

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C. Implications of national participation in JGOFS

JGOFS provides the opportunity for national participation in an important multidisciplinary programme of oceanographic research. Global questions can be addressed only if national contributions are developed in concert, so that results can be integrated and extrapolated. National participation in JGOFS brings both benefits and responsibilities. These notes are provided for guidance at the current stage of development of the JGOFS programme; they are not intended as a formal constitution.

Benefits

Among the ways in which the international JGOFS programme benefits its component national studies are that it:

- facilitates the planning of national programmes addressing the ocean carbon cycle, its boundary exchanges and associated biogeochemical processes by providing a soundly-based intellectual and organisational framework for such research, with overall aims, approach and implementation developed and endorsed by the international science community
- adds to the scientific value of national field work, and assists in its interpretation, by providing complementary information; for example, by widening the range of studies and extending their temporal and spatial coverage
- promotes the rapid communication of scientific ideas and results at the frontiers of knowledge, through meetings and publications, and by encouraging disciplinary and interdisciplinary liaison at the international level between individuals and research groups
- develops, and tests the applicability of, standard methods and protocols for measuring key variables, thereby facilitating national and international quality control, intercalibration studies, and subsequent data exchange, synthesis and interpretation
- assists in the cost-effective deployment of major capital equipment and facilities, by encouraging their collaborative use and promoting the international transfer of technological expertise
- makes available the data sets collected by its component studies, and assists in developing a common data management strategy in liaison with national and international data centres
- provides a unique opportunity to develop national training in marine biogeochemistry within an international, interdisciplinary context
- ensures that close working links are developed with other relevant international programmes and studies, particularly those of SCOR/IGBP/ICSU, WOCE/WCRP and IOC
- promotes the concepts of JGOFS science, and the results obtained from the programme, to ensure their wider recognition, and hence indirectly assists in obtaining funds for its national components.

Responsibilities

National participation in JGOFS requires a commitment to:

- form an appropriate organisational structure for the national coordination of JGOFS activities, with an agreed representative for international liaison, in accordance with national arrangements for participation in SCOR, IGBP or ICSU activities
- develop a national programme to address JGOFS goals and objectives (as stated in

the JGOFS Science Plan), keeping the JGOFS Scientific Steering Committee informed of national plans and giving due consideration to any advice or guidance from the JGOFS SSC

- carry out that programme in accordance with relevant aspects of the JGOFS Implementation Plan, wherever possible using JGOFS-recommended protocols and providing the opportunity for international collaboration

- participate in the activities of the JGOFS SSC, by assisting in the planning and development of the programme as a whole, and reporting on national progress

- make national JGOFS data available to the wider JGOFS community, in accordance with JGOFS protocols for international data exchange

- seek, through national funding sources, a national contribution to the staff and resources required to coordinate the programme as a whole and to provide central services; for example, data management and the work of the JGOFS central offices.

D. International activities related to JGOFS

The boundary exchanges of interest to JGOFS, and global scale responses to climate change, are affected by non-oceanic systems that are beyond the scope of JGOFS to study in any detail. Furthermore, there is no intention to investigate (and model) the complex hydrodynamic properties of the ocean in a comprehensive manner: consideration of ocean circulation and mixing is limited to their effects on nutrients, biological production and carbon transport processes.

JGOFS has already improved our understanding of ocean biogeochemical processes, and will undoubtedly continue to do so. Yet the wider, long-term value of its results will be within the context of research on other aspects of global systems and cycles. To achieve that, JGOFS researchers must not only be familiar with scientific progress in other fields, but also be involved in relevant collaborative studies - both to ensure scientific liaison and complementarity, and to make the most effective use of limited resources (finance, manpower, ships and other research facilities). Opportunities for such collaboration, and for JGOFS to contribute to wider scientific objectives, are enhanced by the status of JGOFS within two ICSU bodies, SCOR and IGBP, promoting contact with other international projects and programmes addressing ocean function and its role in global change.

Several of these related studies have already been mentioned in the preceding sections, and only an outline of selected activities is presented here. For a more comprehensive account of the role of international organisations in marine science, see Laughton (1990).

D.1 International Geosphere-Biosphere Programme

IGBP provides a coherent, integrated programme for research on the interactive physical, chemical and biological processes that regulate the Earth's ability to support life. The scientific synthesis of IGBP is achieved through the linked development and implementation of a suite of Core Projects, addressing the key research issues related to global change (IGBP, 1990). JGOFS was designated a Core Project of IGBP in 1989; it plays an essential role in the overall programme. Several other IGBP Core Projects and framework activities are very closely related to JGOFS, with opportunities for mutually beneficial collaborations (see below).

IGBP does not directly fund research. However, it works closely with national IGBP Committees, science academies and research councils to secure support for IGBP projects and their international coordination.

Contact: Phillip Williamson.

D.1.1 LOICZ - Land Ocean Interactions in the Coastal Zone

LOICZ addresses the global aspects of human impacts on coastal land and shelf seas, and the role of land-ocean coupling in biogeochemical cycles. There is emphasis on the riverine transport of sediment, nutrients and carbon, and the fate of such materials in estuaries and shelf seas. Processes at the shelf break are also included. Status: Science Plan in preparation, for IGBP review in 1992. Main study regions not yet decided, but likely to include shelf sea areas around SE Asia, Europe and North America.

Contact: Patrick Holligan.

D.1.2 IGAC - International Global Atmospheric Chemistry project

IGAC is concerned with chemical, biological and anthropogenic processes determining atmospheric composition, and their climatic interactions. The marine atmosphere, and the air-sea exchange of biogenic gases, are of special interest: the scope for joint work with JGOFS on these topics was discussed at the NATO Advanced Research Workshop (BOAT: Biogeochemical Ocean Atmosphere Transfers) at Bermuda, January 1992. Status: underway, with implementation including studies in the Pacific, Atlantic and Southern Oceans.

D.1.3 GOEZS - Global Ocean Euphotic Zone Study

GOEZS is a potential IGBP project, with early planning activities receiving joint IGBP/SCOR support. Preliminary ideas are that it should aim to integrate and develop the JGOFS and WOCE data sets, in order to significantly upgrade the treatment of ocean-atmosphere coupling within GCMs. There would also be a major data acquisition component (with emphasis on the upper ocean), based on anticipated improvements in sampling methodologies and the new research questions arising from current studies. Plans for GOEZS will be developed during 1992/93, with strong JGOFS involvement.

D.1.4 PAGES - Past Global Changes

PAGES has two themes: the fine detail of global climate changes in the past 2,000 years; and the role of biospheric processes in the Quaternary ice-age cycle, especially during periods of rapid change (IGBP, 1992). The oceanic component of the latter theme will focus on continental margins, and the collection of sediment cores covering the last few hundred thousand years for micropal-aeontological and isotopic analysis. The field phase starts in 1993. Oceanic study regions are not yet identified. The PAGES studies of multi-proxy mapping will develop methods of data analysis that may also be applicable to JGOFS.

D.1.5 GAIM - Global Analysis, Interpretation and Modelling

GAIM is directed at the development of global biogeochemical models, for coupling with GCMs. There is particular interest in the carbon cycle, and scaling-up techniques for valid integration and data synthesis. Status: Science Plan in preparation, for IGBP review in 1992 and implementation 1993 onwards.

D.1.6 IGBP-DIS - Data and Information System

IGBP-DIS addresses the development, dissemination and coordination of global data sets to meet the needs of IGBP projects. IGBP-DIS works closely with national and international data centres: it is not directly responsible for data management and archiving. Main emphasis to date has been on improving the availability and inter-pretation of remote-sensing data (AVHRR) for terrestrial studies. Existing oceanographic links are mostly with IOC and GCOS.

D.1.7 START - System for Analysis, Research and Training

START is developing networks for regional collaboration within IGBP, to increase the capacity for regional assessment of the causes and consequences of global change (IGBP, 1991). The START regional divisions are land-based, but include coastal areas. START could therefore assist JGOFS in the involve-ment of developing countries in continental margin studies, linked to LOICZ activities in shelf seas.

D.2 Scientific Committee on Oceanic Research (SCOR)

D.2.1 SCOR Committees, Panels and Working Groups

The JGOFS Scientific Steering Committee was established by, and is responsible to, SCOR. Its progress is reviewed by SCOR at biennial General Meetings.

SCOR Working Groups that are currently active and relevant to JGOFS include WG 86, Ecology of Sea Ice (with SCAR and AOSB); WG 92, Ocean/Atmosphere Palaeochemistry;

WG 93, Pelagic Biogeography; and WG 95, Sediment Suspension and Sea Bed Properties.

Contact: Elizabeth Gross.

D.2.2 GLOBEC - Global Ocean Ecosystems Dynamics

GLOBEC is currently being established as a SCOR/IOC research programme. Its aims are to understand the effects of physical processes on predator-prey interactions and population dynamics of zooplankton, and their relation to ocean ecosystems in the context of the global climate system and anthropogenic change. Close collaboration with JGOFS is expected.

D.3 Scientific Committee on Antarctic Research (SCAR)

SCAR has proposed a multidisciplinary programme on the Ecology of the Antarctic Sea Ice Zone (EASIZ), as part of a regional component of IGBP. It is likely that the implementation of EASIZ will primarily be achieved through collaboration with the JGOFS Southern Ocean programme and other studies (e.g. the Southern Ocean component of GLOBEC). Joint coordination of Southern Ocean JGOFS activities was recently recommended by a SCAR/SCOR Workshop (Bremerhaven, September 1991).

D.4 World Climate Research Programme (WCRP)

WCRP is jointly coordinated by ICSU and the World Meteorological Organisation (WMO) of the UN. It has two major oceanographic research projects, WOCE and TOGA, with their scientific guidance provided by the WCRP Joint Scientific Committee (that includes SCOR and IOC representation).

D.4.1 WOCE - World Ocean Circulation Experiment

The goal of WOCE is to develop global models of ocean circulation for the prediction of climate change (WOCE, 1988). This will be achieved by a comprehensive survey (the "global description", including the WOCE Hydrographic Programme, WHP), together with studies of the Southern Ocean and gyre dynamics. WOCE field activities began in 1990 and collaborations with JGOFS are well-established, at both the national and international level (see Sections 3.4 and 3.5).

D.4.2 TOGA - Tropical Ocean and Global Atmosphere

TOGA is directed at improving the physical description of ocean-atmosphere interactions in tropical regions, with particular interest in El Niño events in the Pacific. The observational systems and data sets developed by TOGA have been of great value in planning JGOFS studies in the Equatorial Pacific and Indian Ocean, and these collaborations will be further developed.

D.5 Intergovernmental Oceanographic Commission (IOC)

The IOC provides the intergovernmental framework to assist in the implementation of JGOFS. Aside from the specific actions identified in Section 9.2, IOC Member States are being encouraged to provide the necessary resources to permit the meaningful involvement of scientists from developing countries in JGOFS. Technical expertise is provided as part of the IOC/UNEP joint programme on the Investigation of Pollution in the Marine Environment (GIPME), by Groups of Experts on Methods, Standards and Intercalibration (GEMSI); the Effects of Pollution (GEEP); and Standard Reference Materials (GESREM).

Since 1979, IOC has supported, jointly with SCOR, the Committee on Climatic Changes and the Ocean (CCCO). CCCO has served to promote discussion of interdisciplinary oceanographic problems related to climate change and to recommend actions to its sponsoring bodies and to the WCRP; TOGA and WOCE originated with the CCCO. The work of the JGOFS/CCCO Advisory Panel on

Carbon Dioxide (see Annex A) includes the CO_2 survey described in Section 3.2.

As a result of organizational changes relating to WCRP, IOC and SCOR have agreed that CCCO should be disbanded. The CO_2 Panel will continue as a jointly sponsored body. The details of these arrangements are under discussion.

Contact: Neil Andersen.

D.6 GOOS - Global Ocean Observing System

GOOS is being developed as a component of the proposed Global Climate Observing System (GCOS) under WMO, ICSU, UNEP and IOC, to meet the long-term needs for climate system monitoring and change detection. A GCOS Joint Scientific and Technical Advisory Committee has been established, and it is expected that JGOFS and SCOR will be involved in the detailed consideration of the GOOS component of GCOS.

D.7 Ocean Drilling Program

The ODP serves a wide constituency within the geological community: a diverse set of objectives of the programme are met by drilling on the sea-floor. In most cases the drilling objectives differ fundamentally from proposed work within JGOFS, but this is not always the case. A small JGOFS-ODP liaison group has been established to enhance communication between the programmes. It may be possible for individual JGOFS scientists occasionally to use the drill ship as a sampling platform for certain limited studies that will not interfere with the day-to-day drilling operations.

E. Acronyms

ADEOS	Advanced Earth Observing System
ALOHA	A Long-term Oligotrophic Habitat Assessment
AMS	accelerator mass spectrometry
ANTARES	Antarctic research (France-JGOFS)
ANTARFIX	Antarctic fixed station (France-JGOFS and WOCE)
AOSB	Arctic Ocean Sciences Board
AVHRR	Advanced Very-High Resolution Radiometer
BATS	Bermuda Atlantic Time Series
BBL	benthic boundary layer
BBSR	Bermuda Biological Station for Research
BBZ	benthic boundary zone
BIOTRANS	biological transformations (site at 47°N 20°W)
BODC	British Oceanographic Data Centre (Bidston)
BOFS	Biogeochemical Ocean Flux Study (UK)
CCCO	SCOR/IOC Committee on Climatic Changes and the Ocean
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
CTD	conductivity, temperature and depth sensor
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
DYFAMED	atmospheric dynamics and fluxes in the Mediterranean Sea (France-JGOFS)
EASIZ	Ecology of the Antarctic Sea Ice Zone
ECOMARGE	ecology of the continental margins (France-JGOFS)
EEC	European Economic Community
ENSO	El Niño - Southern Oscillation
EPOPE	Étude de Processes dans l'Ocean Pacifique Équatorial
EROS	European River Ocean System (EEC)
EUMELI	eutrophic, mesotrophic and oligotrophic sites (France-JGOFS)
FLUPAC	flux dans l'ouest du Pacifique équatorial (France-JGOFS)
FRONTAL	frontal process studies (France-JGOFS)
GCOS	Global Climate Observing System
GCM	general circulation model
GEOSECS	Geochemical Ocean Sections
GLOBEC	Global Ocean Ecosystems Dynamics
GOOS	Global Ocean Observing System
HILDA	high-latitude diffusive-advective model
HOT	Hawaii ocean time series
HPLC	high-precision liquid chromatography
ICSU	International Council of Scientific Unions
IGBP	International Geosphere-Biosphere Programme
IOC	Intergovernmental Oceanographic Commission
KAHE	time series station off Kahe Point, Hawaii
KEEP	Kuroshio Edge Exchange Processes
KERFIX	Kerguelen fixed station (France-JGOFS)
LIDAR	light detection and ranging
LOICZ	Land-Ocean Interactions in the Coastal Zone
MAST	Marine Science and Technology (EEC)
NABE	North Atlantic Bloom Experiment of JGOFS
NASA	National Aeronautics and Space Administration (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)

NODC	National Ocean Data Center (Woods Hole, USA)
NSF	National Science Foundation (USA)
ODP	Ocean Drilling Program
OLIPAC	Oligotrophic Pacific (France-JGOFS)
OMEX	Ocean Margin Exchanges
ONR	Office of Naval Research (USA)
PAR	photosynthetically available radiation
PNEDC	Programme Nationale d'Etude de la Dynamique du Climat (France)
POC	particulate organic carbon
PON	particulate organic nitrogen
SCAR	Scientific Committee on Antarctic Research
SCOR	Scientific Committee on Oceanic Research
SMM	Solar Maximum Mission
SMMR	Scanning Multichannel Microwave Radiometer
SRS1	South Research Station 1 (WOCE)
SSC	Scientific Steering Committee of JGOFS
TOPEX	topography experiment
WBC	Western Boundary Current
WHP	World Hydrographic Programme of WOCE
WOCE	World Ocean Circulation Experiment

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