SUMMARY REPORT for the WOCE /JGOFS CARBON TRANSPORT WORKSHOP (Southampton, UK, 25-29 June 2001)

(re-edited by Bernard Avril (JGOFS IPO), in August 2003, after the original report available at: ftp://ftp.soc.soton.ac.uk/pub/woceipo/transport_wkshop.pdf)

General Introduction

The WCRP World Ocean Circulation Experiment (WOCE) carried out an unprecedented survey of the global ocean between 1990 and 1998. One objective of this effort was, through observations, models and data assimilation, to make new and improved estimates of the oceanic transports of heat and freshwater (and of other physical and chemical properties). See King, Firing and Joyce, in: "Ocean Circulation and Climate", p. 99-122, Academic Press, 2001. The IGBP / SCOR Joint Global Ocean Flux Study (JGOFS) collaborated with WOCE to provide the additional measurements that would enable new estimates of the storage and transport of carbon to be made. See e.g., Wallace, in: "Ocean Circulation and Climate", p. 489-521, Academic Press, 2001.

As both WOCE and JGOFS approached their final phases, a need was perceived to assess (on both basin and global scales) the progress made towards finalising these estimates. Consequently a "Carbon Transport Workshop" was approved by the Scientific Steering Committee of WOCE as the last in a series of regional and subject-based workshops. In parallel, the JGOFS Scientific Steering Committee planned a workshop with very similar aims. Since the physical measurements (and some of the modelling activities) of WOCE underpinned the JGOFS carbon issues it was agreed in mid-2000 that both workshops be held together.

Accordingly the WOCE/JGOFS Carbon Transport Workshop was held at the Southampton Oceanography Centre, Southampton, UK, 25-29 June 2001. The organising committee for the WOCE component part was chaired by Carl Wunsch with members Harry Bryden, Simon Josey, Jochem Marotzke, Herle Mercier, Kevin Speer, Peter Saunders, Masao Fukasawa, Susan Wijffels and Jürgen Willebrand. The organising committee for the JGOFS component part was co-chaired by Paul Robbins and Rik Wanninkhof with members Alison Macdonald, Molly Baringer and Doug Wallace. Local support was provided by Jean Haynes and Sandy Grapes at the WOCE International Project Office and by Roberta Lusic at the Atlantic Meteorological Laboratory of NOAA.

For both WOCE and JGOFS, the workshop was expected to make progress towards:

- reaching a consensus on the values of the transports and their error bars,
- assessing the extent to which the oceanic transport divergences are consistent with and/or constrain air-sea flux estimates,
- evaluating the strengths and weaknesses of ocean only and coupled model estimates,
- documenting the key conclusions that can be passed to WCRP and IGBP/SCOR and to future climate change programmes.

For the week long meeting the WOCE workshop was planned for the first 2.5 days with the third day providing an overlap with the first half day of the JGOFS workshop. Participants were invited to one or the other workshop sessions, but advised that they were welcome to both. There were plenary sessions throughout the meeting with both invited speakers and assigned commentators: there were also poster sessions. In all 45 posters were submitted from a total attendance of 94 scientists from Australia, Bermuda, Canada, France, Germany, Italy, Japan, Norway, Russia, Spain, UK and USA. Participants were provided with a meeting document, which contained the agenda, list of participants and poster abstracts. Financial support was provided by International JGOFS, IOC, US WOCE, US JGOFS, US NOAA, WCRP, SOC and the UK Global Environmental Research Committee. Their assistance is gratefully acknowledged.

Summary of the WOCE workshop

The meeting agenda reveals that estimating the ocean transports of heat and freshwater were approached in several ways, namely from:

- inverse calculations performed on individual and groups of WOCE transoceanic sections,
- unconstrained ocean and coupled General Circulation Models (GCMs), and
- ocean state estimation (OGCM with data assimilation).

Because virtually all of these approaches rely extensively on air-sea exchange fluxes, considerable attention was given to this topic too.

All of the subjects above were presented by invited speakers backed by assigned commentators. The speakers were invited to review their chosen topic rather than present results solely from their own research. Selected items from this material are presented in the following paragraphs.

As indicated above the air-sea exchanges of mass, heat, freshwater and momentum exercise a key role in many analyses of ocean transports, so the programme began with a review of the work of the WCRP/SCOR Working Group on Air-Sea Fluxes (WGASF, www.jhu.edu/~scor/wg110front.htm, www.wmo.ch/web/wcrp/airsea.htm and www.soc.soton.ac.uk/JRD/MET/WGASF/) by its co-chair, Peter Taylor. This group had over a 3 year period met, agreed on a report and held a workshop at which were identified issues regarding the needs, amongst others, for new instrumentation, field validation and error estimates. Accordingly, no single flux product could be unqualifiedly recommended. All products, including the widely used reanalysis products, had identifiable deficiencies, and the documentation of these was one important result of the committee's work. The WCRP Joint Science Committee (JSC) had decided that such a committee should continue, i.e., becoming a standing committee, in order to pursue its numerous problems.

In a later plenary talk, Simon Josey described the various methods of determining air-sea heat exchange and indicated their imperfections. For example, ship-based estimates, which did best in validation exercises, suffered from sampling problems and failure to close the global budget. One such climatology (SOC), which he had co-authored, had been modified in the Atlantic by combining the ship-based values with ocean transport divergences derived from WOCE section heat fluxes. The method showed promise and would be pursued as more WOCE results with attendant errors became available. Finally he commented on the new ocean heat flux data set by Trenberth and Caron (2001) that a number of plenary speakers had employed as a basis for comparison with their own results.

The application of inverse modelling to hydrographic sections revealed differences in approach. One school argued that this process should build on the analysis of individual sections, then regional studies and finally on a global analysis. This seems rational but was not the step that the community had taken. Alex Ganachaud presented the results of a global analysis of all available WOCE hydrographic data, and Steve Rintoul, of an analysis of data from the Southern Ocean. The sheer volume of information in both is daunting and although both authors were able to reveal agreements and disagreements with previous research, neither would claim that a detailed and independent analysis of their results had yet been made. The issue of time dependence, e.g., the lapse of time over which data was gathered, was raised, and in discussion, it was argued that its presence severely impaired the quality of the results despite attempts to exclude the upper ocean (the principle region of time dependence) from direct consideration. It was proposed that repeat section data be employed to illuminate this problem. It was also agreed that the way forward with virtually all analyses was to incorporate data from floats, drifters, altimetry and moored currentmeters, presently missing from most treatments. The question of how bias in the information in one location, say due to an incorrect estimate of the western boundary current transport there, would spread through a regional or global analysis was also not quantified although Jochem Marotzke's work described some aspects of this phenomenon in the North Atlantic.

During the decennium of WOCE, the realism of Ocean models (OGCMs) has improved enormously, and David Webb presented the results of heat and freshwater transports from them. The impact of resolution on heat transport estimates has been well documented and these were described. Although eddy activity increases and becomes more realistic as the resolution is increased, say from 1° to 0.1°, the increase in heat transport is primarily due to the improved western boundary current representation and physics, although northern and southern boundary conditions may also play a role in the limited area models currently available at the very high resolutions. The strength of the Ekman transport is important in determining the heat transport in tropical regions and reflects directly on the forcing employed. Mixing in the overflow regions, handled better in isopycnal models than in level models, is also a crucial issue along with high latitude convection. Most of these issues were being considered by the WCRP/CLIVAR Ocean Model Development Working Group (www.clivar.org/publications/other_pubs/clivar_transp/pdf_files/wgomd_members.pdf).

Yanli Jia presented heat transport results employing property fields archived during the Coupled Model Intercomparison Project (CMIP, www-pcmdi.llnl.gov/cmip/) which began in 1995. Initial experiments had shown a very wide range of results, some quite at variance with reality especially in the southern hemisphere. In the North Atlantic Ocean, many of the models developed a weak meridional overturning cell with deep water too warm, thus yielding low heat transports. A second set of more recent experiments produced more realistic results, reflecting improved model physics.

Detlef Stammer presented the case for ocean-state estimation, a method which combines the dynamical consistency of ocean models with the realism of ocean data and allows temporal variability through time-dependent forcing. As admitted in the WOCE AIMS report of 1997, this method represents the way forward for the ultimate synthesis of WOCE data. However the method required massive computing resources and the development of data assimilation techniques unfamiliar and unique to the ocean community. Such activities were being carried out in a handful of locations around the world, mostly with an operational emphasis. In the USA, a consortium called Estimation of the Circulation and Climate of the Ocean (ECCO, www.ecco-group.org/) had been set up between MIT, SIO and JPL, and Stammer described how various data types (satellite altimetry, sea surface temperature, reanalysis fluxes and wind stress, all time varying) had been assimilated into a low resolution (2°) global ocean model. To date, Levitus hydrographic climatology had been used to describe the ocean, but future plans include the use of WOCE hydrographic sections and other WOCE data types and, as computing power increases, of increased model resolution. Results obtained to date reveal the inconsistency of prior surface fluxes with model and observations, a result which was shown to be unrealistic in Simon Josey's talk. However realistic heat transports were obtained in the Pacific and Southern Oceans but were underestimated in the Atlantic Ocean.

Conclusions and Recommendations of the WOCE workshop

Jürgen Willebrand led a discussion of the status of the research on heat and freshwater transports which focused heavily on problems remaining and requirements for future work. Below are some of the issues raised:

1) The 1990-1998 WOCE/JGOFS global survey has succeeded in providing new, very high quality data from which many new estimates of heat and freshwater transport had been derived by inverse modelling. This work need to be continued but increased attention need to be placed on temporal variability amongst groups of sections, considering, amongst other terms, oceanic heat storage. Other data from altimetry, drifters, floats, etc. should also be incorporated in these analyses.
2) Time-dependent global ocean state estimation has been performed at 2°-resolution based principally on the assimilation of upper ocean data. This work will continue with incorporation of other WOCE data types and, as computer power becomes available, at higher resolution. This line of research, together with that described in item 1 above, represent parallel ways forward for the synthesis of WOCE data.
3) The accuracy of air-sea exchanges is limited by a number of factors, such as the sparseness of measurements at high latitudes, errors in individual flux components (e.g., precipitation and solar radiation) and biases in meteorological measurements reported from ship. Progress can be made by addressing these errors and by using WOCE section transport estimates as constraints.
4) Neither data nor model errors, needed for ocean state estimation, were known sufficiently well. Alex Ganachaud coordinated the exchange of information and experience on these topics.
5) Due to the efforts of the WOCE Data Products Committee and the WOCE DAC managers for the most part the accessibility of WOCE data is no longer a significant issue. The same cannot be said of contemporary model outputs, whose relative inaccessibility (and daunting volume) has limited its potential for assisting observationalists and illuminating observational results.
6) It was evident that the collaboration between researchers, which WOCE had fostered and had proved so fruitful, needs to continue. How would this occur since WOCE end shortly and fewer opportunities would exist? One such initiative occurred at the transport workshop when an evening meeting to discuss future ocean hydrography and carbon measurements led to the formation of an informal group that will seek through CLIVAR to co-ordinate and set standards for the re-occupation of WOCE/JGOFS sections during the coming decennium (www.clivar.org/carbon_hydro/index.htm).

Oceanic Biogeochemical Fluxes

Beginning in the late 1980's and continuing through the decennium of the 1990's, the Joint Global Ocean Flux Study (JGOFS) conducted a comprehensive programme to extend our knowledge of the global ocean carbon cycle through the oceanic biogeochemistry. The main focus of JGOFS was to acquire both the quality and quantity of measurements necessary to identify and quantify biogeochemical processes within the ocean, their interactions with the atmosphere and their influences upon and responses to human-induced perturbations. This goal required international cooperation and collaboration among the physical, chemical and biological disciplines. The programme was comprised of six components: long-term time-series, process studies, CO_2 survey, ocean colour satellite survey, synthesis and modelling, and data management.

The purpose of the Southampton Workshop was to bring together representatives from both the physical and biogeochemical fields to:

1) allow a forum for an exchange of ideas among individuals from the different disciplines,
2) assess the present state of knowledge and
3) recommend a course for future collaborative study of biogeochemistry and circulation within the oceans.

There was a strong focus on the carbon cycle; however, it was not exclusive of the related cycles of freshwater, heat and nutrients.

The international group of attending experts arriving from eleven countries, included observationalists and modellers, physical oceanographers, biogeochemists and atmospheric scientists, senior scientists, post-docs and students. As the vast suite of JGOFS biogeochemical measurements related to the CO_2 survey has been performed in cooperation with the World Ocean Circulation Experiment (WOCE) cruises, this workshop met along with the WOCE scientists investigating ocean fluxes. This gave all those attending a unique opportunity to discuss the global ocean carbon cycle within a truly interdisciplinary approach.

The JGOFS portion of the meeting was held as a set of invited plenary talks, working group sessions and poster presentations. In the two and half days which the meeting devoted to JGOFS, eight plenary talks were given on a wide range of topics which centred not on the individuals' latest results, but rather on the state of the field in the speakers' area of expertise. There were 25 JGOFS posters and although these posters were presented by their authors on only two days, the posters themselves were displayed for the entire week. The JGOFS and WOCE posters were interspersed, creating an atmosphere which naturally brought the two communities together.

Three working groups were focusing on carbon transport, regional budgets and variability, and modelling. These working groups produced statements summarizing the status of knowledge after the JGOFS fieldwork programme, issues still considered crucial for study and recommendations for future collaborative efforts to address these issues. The summary and list of recommendations which follow are offered as representing an interdisciplinary and international consensus of the communities seeking to better understand and quantify ocean biogeochemical fluxes and their influence upon the global carbon system.

Summary of the JGOFS workshop

The study of the carbon cycle within the ocean is following in the steps of heat and freshwater studies, but because of air-sea exchange, and carbon biological and chemical components it is a far more complex problem. This workshop report summarizes our present state of knowledge of the ocean carbon system and recommends future directions for research.

Pre-industrially the atmospheric concentration of CO_2 was about 280 µatm. At present it is 370 µatm and rising. The release of carbon into the atmosphere through fossil fuel emissions has averaged about 6.2 PgC a^{-1} over the last decennium. Meanwhile atmospheric CO_2 content has increased at a rate of 2.8 PgC a^{-1}. Both modelling and pCO_2 studies indicate that the amount of carbon stored in the ocean is increasing by about 2 PgC a^{-1}. Estimates of land storage remain uncertain. The questions at hand are about the location of the oceanic sinks of anthropogenic carbon, their size and their control mechanisms.

The oceanic and atmospheric carbon budgets are intimately related. Atmospheric carbon isotope inversions are used to identify possible sources and sinks by applying a model-created atmospheric transport field to measured distributions of trace gases. Usually, the total atmospheric carbon and ^{13}C budgets are used and the unknowns which are solved for, are the net fluxes of carbon from the ocean and the terrestrial biosphere to the atmosphere. From an oceanic perspectives such inversions are useful as they provide an independent estimate of the net carbon entering the ocean.

The coordinated efforts of WOCE, JGOFS and US Ocean Atmosphere Carbon Exchange Study (OACES, www.aoml.noaa.gov/ocd/oaces/, now US NOAA GCP) have provided thousands of direct estimates of carbon and carbon-related properties over the last decennium. To make these measurements available to the scientific community, an initiative has been organized to synthesize these data into a consistent dataset. Twenty thousand individual water samples from the Indian Basin collected between 1994 and 1996 provide TCO_2 and TA estimates with an accuracy of ±2 and ±4 $\mu mol\ kg^{-1}$, respectively. In the Pacific Ocean, 24 cruises provide estimates of TCO_2 and TA with an accuracy of ±3 $\mu mol\ kg^{-1}$ and ±5 $\mu mol\ kg^{-1}$, respectively. The Atlantic Ocean synthesis is nearly complete. This synthesized dataset is now being used to examine ocean transport and global inventories of anthropogenic CO_2. It has been found that the deepest penetration of anthropogenic CO_2 occurs in regions of water mass formation, while the shallowest penetrations occur in upwelling regions. Thermocline ventilation rates can be studied through a comparison of anthropogenic tracers that have different atmospheric histories and equilibration times. When complete, the global carbon dataset will contain nearly 100,000 samples.

Direct measurements of meridional oceanic carbon fluxes were first attempted a dozen years ago at 24°N in the Atlantic with only nine stations across the entire breadth of the transect, each containing only a few samples. Now, as described above the efforts of WOCE, JGOFS, OACES and other programmes have made such estimates more accurate, better resolved and if not commonplace, at least more abundant. As the physical and biogeochemical communities have begun to work together on understanding the ocean carbon system, a new clarity in research techniques is being developed. For example, after years of confusion between carbon transport calculations which included freshwater flux estimates *versus* those which used salinity normalizations, a clear picture has now evolved as to how the freshwater cycle affects oceanic carbon transport estimates. Another interesting issue which has arisen out of the comparison between results from the modelling and observational communities is an apparent disagreement between models and data as to where the oceanic uptake of anthropogenic carbon is occurring. The reason for the discrepancy is not yet clear, but when understood will greatly enhance our ability to believe the predictive capabilities of GCMs.

The state of global coarse-resolution carbon cycle models is being researched through the JGOFS/GAIM Ocean Carbon Model Intercomparison Project (OCMIP, www.ipsl.jussieu.fr/OCMIP/). These models are one of the few tools available for exploring carbon as it relates to climate change. Comparing the models to each other as well as to the WOCE/JGOFS survey affords an excellent opportunity for understanding the large-scale predictive skill they provide and points to a number of issues which remain such as: poor ocean circulation representation (e.g., shallow North Atlantic Deep Water penetration), lack of riverine input, through flow transports and natural boundaries for freshwater exchange. Not all the models display all problems, but not one is problem-free. Nevertheless, these models provide a way to explore how processes which vary regionally work together to produce integrated property fluxes.

As the global carbon survey works provide a “snapshot’’ of the oceanic carbon concentrations, a few individual locations (e.g., BATS & HOT) are providing detailed time series of the ocean carbon cycle. During the 1990’s surface seawater total CO_2 increased at a rate of 2.2±6.9 $\mu mol\ kg^{-1}\ a^{-1}$, while the partial pressure of CO_2 increased at a rate of 1.4±10.7 $\mu atm\ a^{-1}$. These increases are attributed to the uptake of anthropogenic CO_2 combined with interannual variations in hydrographic properties within the subtropical gyres. Some of this variability can be linked to large-scale climate variations such as the North Atlantic Oscillation and the El Niño Southern Oscillation through a comparison of temporal anomalies. As BATS and HOT and other time-series stations continue to collect data, and as new time-series stations are begun, our understanding of how biogeochemistry is influenced by climate variability will improve, as will our ability to predict future changes.

The first day of JGOFS sessions overlapped with the last day of WOCE sessions. Carl Wunsch's wrap up of the WOCE sessions which focused on physical oceanography served well to highlight some of the most immediate tasks facing the biogeochemists as well as the direction of future research for both communities.

For example, large-scale transports and divergences of mass, heat and freshwater have been determined and will asymptotically improve as efforts are still underway to estimate large-scale transports and divergences of total carbon, anthropogenic carbon and carbon-related properties. A number of posters illustrating Atlantic Ocean results were presented.

A recurring theme of the WOCE portion of the workshop the end of the simple concept which consider the ocean as a steady system. Both the JGOFS talks and posters indicated that the oceanic carbon community is already beginning to focus on issues of temporal variability even as the steady-state problem is being considered.

In his introduction to the JGOFS portion of the workshop, Rik Wanninkhof suggested that to make the most out of this meeting of both the biogeochemical and physical communities, scientists should:
1) summarize the current state of knowledge,
2) determine the remaining overarching questions and
3) make recommendations for the future.

The plenary talks provided for the first suggestion as they covered a wide range of topics and were presented by scientists from the biogeochemical, physical oceanographic and atmospheric communities. The discussants for these talks were chosen to come from a different camp of the speakers. Rik Wanninkhof presented a tutorial on CO_2 uptake designed to supply physical oceanographers with basic concepts. Harry Bryden in turn gave a presentation of the fundamentals of ocean mass and property transport calculation. The working groups focused on the latter two of Wanninkhof's suggestions. A summary of the recommendations is given in the next section.

Conclusions and Recommendations of the JGOFS workshop

The working group reports provide detailed lists of specific issues which need to be addressed in the future to ensure that the knowledge gained over the JGOFS years continues to improve. The goal is a detailed and quantitative understanding of biogeochemical cycles within the ocean (with the focus here on the carbon cycle), how they are affected by and how they might cause change in the physical circulation, and ultimately, how they relate to global balances and climate change. The following list represents a condensed abridged version of the particular topics which, the working groups suggest, should be pursued or addressed:

- Measurement of carbon and carbon related properties within the Indian, Pacific, Southern Oceans and Arctic Basin should be brought up to par with those presently available in the Atlantic Ocean,

- Measurement of both spatial and temporal variabilities in the ocean carbon budget. Exploration of such variability on inter-decennial time-scales,
- Measurement of dissolved organic matter, iron, micronutrients and new transient tracers,
- Standard reference materials for nutrients and metals, other than DIC and DOC,
- To improve experiment design and use of resources, fine resolution, regional model simulations in the spirit of the coarse resolution, adjoint, sensitivity studies would be extremely useful,
- New technology for measuring biogeochemical properties to take advantage of float, ship of opportunity and other time-series programmes should be developed,
- Further study of the processes which set stoichiometric ratios and study of how the interplay among functional groups affects biogeochemical budgets,
- Research into the processes governing the physical and biogeochemical interactions among the interior circulation, the surface mixed layer, frontal regions, topography and the coastal margins,
- The effects of wind and rivers also require further study,
- Variability/prediction of biogeochemical transports, in sea surface pCO_2 and other greenhouse gases,
- Further exploration of mixing, diffusion and entrainment of biogeochemical properties and of the parameterization of these effects for models,
- Creation of hybrid-coordinate models, earth system models (atmos/ocean/biogeo) and inversion tool boxes, extension of biogeochemical models beyond carbon, and assimilation of biogeochemical data into various types of models,
- Intercomparison efforts (model/model and model/data) should be continued and new methods for testing biogeochemical models should be developed,
- Further research into the uptake and transport of anthropogenic CO_2 both regionally and globally,
- Uncertainty in anthropogenic carbon estimates needs to be better understood,
- Continued and improved access to both observed datasets and model outputs.

An additional point raised is the need to overcome the fact that transport variations caused by climate change can still (and seem to) create globally consistent circulation schemes. WOCE/JGOFS provide a single "snapshot" of ocean circulation. To understand this system in the context of a changing climate, this single point is not adequate. There remains the need to design an observation system which can resolve temporal changes in circulation and biogeochemical transports.

There is a strong recommendation for collaboration among CLIVAR and international carbon communities and other biogeochemical study programmes. Collaborations should immediately begin between the physical and biogeochemical communities for experiment design (including survey lines) and among the biogeochemical physical and atmospheric communities for the development of atmosphere/ocean biogeochemical coupled models. If questions are phrased to take advantage of the capabilities of all groups (ocean physicists, biogeochemists and atmospheric scientists) the coordinated effort would be beneficial not only to those involved, but also to the international effort to understand and control anthropogenically caused climate variations.

Acknowledgments

We wish to thank the supporting cast which made this meeting possible, enjoyable and productive. On the U.S. side, we thank Roberta Lusic for her tremendous patience in dealing with the JGOFS abstracts, as well as the many versions of emails going out the interested parties. On the U.K. side, we thank Sandy Grapes and Jean Haynes for their invaluable organizational help during the planning stages and throughout the course of the workshop. We also thank the SOC Research Divisions for the use of their facilities. Support for the workshop was no less interdisciplinary or international than the attendees as funding was provided by International JGOFS, US JGOFS, US WOCE, International WOCE, US National Science Foundation in collaboration with the US National Oceanic and Atmospheric Administration, US National Aeronautics and Space Administration, US Department of Energy and US Office of Naval Research.

Working Group Reports

There were three working groups for the JGOFS portion of the meeting. These groups were given the following charges:

- Focus on the interaction/intersection of circulation and biogeochemistry
- What are the advances and discoveries made during WOCE/JGOFS?
- What crucial problems remain?
- Future Strategy
    - Where do we go from here?
    - What advances can/should be made over the next 10 years?
- How do the results/uncertainties of mass, heat, freshwater etc. transports impact out ability to examine biogeochemical fluxes?
- What opportunities are there for circulation and biogeochemical studies to overlap in the future?

Report from the Working Group on Carbon and Nutrient Transport

Working Group Leaders:
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Working Group Participants:
Marta Alvarez-Rodriquez, Dorothee Bakker, Stuart Cunningham, Richard Feely, Alex Ganachaud, Andy Jacobson, Truls Johannessen, Greg Johnson, Alicia Lavin, Alison Macdonald, Alberto Naveira-Garabato, Tsung-Hung Peng, Kelvin Richards, Jorge Sarmiento, Denise Smythe-Wright, Iris Solar, Bronte Tilbrook, Michal Vanicek.

This working group was made up of scientists from both the physical and biogeochemical communities, and included both observationalists and modellers. In answer to the questions put forth as charges to the working groups and keeping in mind the focus on the interaction/intersection of circulation an biogeochemistry, the following ideas were suggested:

I. What advances/discoveries were made during the WOCE/JGOFS era?

The most obvious thought which came to mind immediately within our group is the tremendous progress made in determining a quantitative view of ocean circulation, that is, improved estimates and more estimates in more regions of mass and heat transports and their associated uncertainties. These advances are the base from which we can go forward to viewing the oceans as a variable system rather than the steady-state view necessitated by our knowledge, understanding and capabilities prior to WOCE and JGOFS. The great improvement in the quantity, quality and consistency of the WOCE/JGOFS datasets cannot be understated.

During WOCE/JGOFS there was a wider range of participants (including both international and interdisciplinary collaborations) than has ever been achieved previously. These collaborations have allowed great progress to be made in the biogeochemical transport estimates and in the application of these estimates to air/sea flux and budget studies. There have also been advances in separating biogeochemical tracers into components which represent different processes. There has been tremendous improvement made in modelling the ocean circulation and in combining model physics with observed datasets.

II. What crucial problems remain?

In spite of these improvements in our ability to observe and model the oceans, issues remain which should be addressed:

There are some obvious inconsistencies among disciplines, e.g., oceanic divergence estimates in the Atlantic Ocean and globally are not consistent with atmospheric (CO_2 and O_2) model estimates. From the mostly observationally oriented perspective of our group we felt that observed divergence estimates are hindered by inconsistent methods and unknown uncertainties in some of the data.

There needs to be improvement still in model physics (particularly in terms of inverse models), tn the combining of data from different sources (floats, altimetry, current meters), not necessarily speaking of assimilation, and in the use of available tracers in inverse models (^{13}C, ^{14}C, DIC, ^{3}H, ^{3}He, SF_6, CFCs and nutrients). There remains a need for collaboration between biogeochemists and those performing inverse studies to make this happen.

Work remains to be done to advance the understanding of the circulation system in the Atlantic Ocean to the same degree in the Indian, Pacific, Southern Oceans and Arctic Basin.

Although access to datasets was greatly improved during the WOCE/JGOFS era, the situation must continue to improve, as it is still not necessarily a simple task to obtain datasets and to obtain them in a format which is straight forward to use. These comments apply particularly to DIC, DOC, alkalinity, CFC's, ^{14}C data.

An additional point made is the need to overcome the fact that transport variations caused by climate change can still (and seem to) create globally consistent circulation schemes. WOCE/JGOFS gave us a single "snapshot" of ocean circulation. To understand this system in the context of a changing climate this single point is not adequate. There remains the need to design a system of observation which can resolve temporal changes in circulation and biogeochemical transports.

Specific topics which need further study include:

- storage estimates for heat, carbon and nutrients
- riverine input estimates of carbon and freshwater
- precipitation, evaporation and freshwater fluxes
- Indonesian Passage throughflow
- Observations to study seasonal, annual or interannual variations in biogeochemical processes and resulting fluxes and flux divergences
- Uncertainty estimates on anthropogenic carbon not adequately understood.

III. How do the results/uncertainties of mass, heat and freshwater transports impact our ability to examine biogeochemical processes?

While uncertainties in net mass flux affect out ability to accurately estimate carbon transports, uncertainties in divergence estimates have less impact. To aid in avoiding such large uncertainties, it is recommended that anomaly constraints be used in box inverse model estimates. Regional studies would be more appropriate than long lines for looking at localized biogeochemical processes, particularly for those in which the gradients occur in the upper portion of the water column.

IV. What advances can be made in the next ten years?

Although estimates made from global inverse models have been tremendously useful, it is now time to take a different tack in which the emphasis is on combining regional inverse results to produce globally consistent quantitative solutions. The reasoning behind this statement is that often regional studies made in a particular geographical area have been necessarily formulated and scrutinized in greater detail than the large global models. The techniques to perform such a synthesis currently exist, but they require co-variances to be part of all individual solutions. Such a synthesis would also demand that consistent methods be used in the calculation of quantities such as anthropogenic carbon.

There is now a need to resolve nutrient variability (inventory transport) which requires continued observations.

There is a need for long-term time-series surveys (including, but not exclusively, long-line repeat transects) to address variability of many properties, in particular anthropogenic carbon.

Regionally, such surveys should resolve annual as well as interannual variations. Fine resolution, regional model simulations could be used to improve experiment design and use of resources (in the spirit of the coarse resolution, adjoint sensitivity studies presented by Detlef Stammer).

Throughout the last decennial, advances have been made in coupled ocean/atmosphere modelling. The next ten years should also address improvements in coupled atmosphere/ocean biogeochemical modelling. Along the same line, there is a need to develop more methods / tools for testing biogeochemical models.

Another question which was brought up and which should be answered quantitatively is: How well can models predict CO_2 changes in the next ten years and can we measure that change in the ocean? The latter requires a physical and biogeochemical study of uncertainties in the carbon budget.

V. Where do we go from here?

Collaboration among the groups brought together at this meeting is paramount to bring about the biogeochemical measurements modelling necessary to the advances suggested above. The measurements need to happen not just on long line transects, but also in other ways. That is, taking advantage of the high resolution repeated XBT lines, float programmes, moored time-series and regional studies.

VI. What opportunities are there for circulation and biogeochemical studies to overlap in the future?

There is a strong recommendation for collaboration among CLIVAR and with international carbon communities and other biogeochemical programmes.

We recommend the immediate beginnings of collaboration between the physical and biogeochemical communities for experiment design (including survey lines) and collaboration among the biogeochemical physical and atmospheric communities in the development of atmosphere/ocean biogeochemical coupled models.

Collaboration between the communities would supply the necessary basis for testing fundamental hypotheses crucial for understanding the interactions between ocean circulation and biogeochemical cycles. It will also go far in determining fluxes and flux divergences in particular regions such the Indonesian Passages, the Southern Ocean and the Arctic Ocean.

Report from the Working Group on Regional Budgets and Variability

Working Group Leaders:
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The working group met to discuss and list 1) the important biogeochemical advances made over the last decennium as a part of the JGOFS/WOCE efforts, 2) the remaining questions, 3) future strategies, 4) opportunities for linking biogeochemical and hydrographic studies, and 5) impacts of hydrographic knowledge and uncertainties on understanding of biogeochemical processes.

The working group recognized that it could not be exhaustive in its considerations, but sought instead to gain insights from some of the major successes to date. A sample list (Table 1) of the locations and types of budgets providing significant advances demonstrates the important role of data from the JGOFS process studies and time series stations, as well as from the WOCE sections, to those budgets. The equatorial Pacific Ocean and the Southern Ocean, both of which have received particularly strong attention internationally, have perhaps the best coverage for spatially and temporally resolved budgets. Basin and global budgets are developing, and will continue to do so, with ongoing use of the WOCE sections data.

Table 1: A Sampling of Where and What Kinds of Budgets have been made

- Atlantic carbon transport/divergences (e.g., Holfort/Wallace)
- North Pacific (>30°N) carbon on Japanese VOS
- Indian Ocean and North Pacific silica (e.g., P. Robbins)
- Equatorial Pacific (e.g., R. Feely, P. Quay, etc.)
- JGOFS Regional Studies (Ross Sea, Arabian Sea, HOT, BATS)
- Southern Ocean nitrate/mixed layer analysis
- Southern Ocean (Australian seasonal nitrate/carbon drawdown)
- Subpolar Western North Pacific Japanese time series
- Global inversion of nitrate (e.g., R. Schlitzer)
- Southern Indian Ocean CO_2 (French Kerguelen occupations)
- Global ocean climatologies (oxygen/nitrate; Najjar/Lee)

I. Important biogeochemical advances/discoveries during WOCE/JGOFS

Several advances have been achieved during the WOCE/JGOFS years, but much work can still be done using the existing data sets. The following is a list of the achievements suggested by the working group:

1. The importance and role of iron in ocean biogeochemistry were identified.
2. The modulation of air/sea gas exchanges in the Equatorial Pacific as controlled by ENSO was elucidated.
3. During WOCE, many transoceanic sections were occupied on which a full suite of biogeochemical measurements were collected simultaneously with high quality physical measurements such as temperature, salinity and velocity. These unique datasets are allowing

the first attempts at using mass-balanced circulation budgets to quantify large-scale biogeochemical flux divergences.

4. The paradigm of elemental cycles has been challenged, particularly with regard to dissolved organic matter (DOM).
5. The improved spatial and temporal resolutions in the measurement of delta pCO_2 has advanced our understanding of the location and strength of the air/sea CO_2exchange. Advances have come about largely as a result of improved air/sea gas exchange parameterizations.
6. The role of nitrogen fixation in marine elemental cycles has been re-evaluated (e.g., N* issues).
7. One of the most important advances to come out of WOCE/JGOFS is the estimation of anthropogenic CO_2 inventories and distributions. Biogeochemical rate estimates have resulted from the large-scale mapping of nutrients and tracers.
8. During the intensive JGOFS regional studies, scientists have begun to observe and understand the links between variability in biogeochemical fluxes and cycles and variability in the physical system.
9. Foodweb variability, in response to forcing, impacts carbon dynamics (e.g., monsoons, stability and iron in the Southern Ocean, the nitrogen cycle at Station ALOHA).
10. Biogeochemical budgets vary in response to decennial forcing (e.g. ENSO)

II. Crucial Remaining Problems

The remaining problems largely centre on what was not measured over the past decennium, whether it was inadequate/poorly resolved coverage of a region, a flux or a state variable. There remain many more ocean regions with poor or no coverage than regions with adequate coverage. The exchanges between the continental margins and the open ocean, in particular, were not sufficiently resolved. Important variables/fluxes need improved parameterization (e.g., anthropogenic CO_2, air/sea gas exchange), while most require improved validation (using reference materials, etc.). Crucial issues suggested by the working group are as follows:

1. There are few measures of variability in carbon budgets beyond the equatorial Pacific region and the time-series sites. Improved carbon budgets are required in the Southern Ocean (all oceans?). Moreover, the fate of river carbon (DIC, organic matter) discharges remains largely unknown. Anthropogenic carbon algorithms need validation/improvement.
2. Very few measurements were made of dissolved organic matter (C, N, P) or trace metals on the WOCE sections. As such, we have only a superficial idea of the role of these variables in ocean biogeochemistry.
3. Bulk parameterizations of mixing, air/sea gas exchange and wind stress have improved but require further and substantial refinement.
4. Most of the WOCE sections were not suited to the study of exchanges between the coastal and open ocean. In addition, time-series sites and process studies were isolated from the large-scale WOCE survey lines. Hence, there is a gap in our knowledge of the processes governing margin-to-open-ocean interactions. Focused regional studies are needed with a coordinated suite of measurements to address the link between local and large-scale processes.
5. How can we detect the changes and variability in biogeochemical processes that are due to climate change? This problem remains a central challenge.
6. Standard biogeochemical reference materials are not available (they exist for carbon, i.e. DIC & DOC, but not for others such as nutrients and metals). We need to establish standards to ensure that in the future variables are measured in a consistent way, and thereby making the measurements from various laboratories directly comparable. (Note: the U.S. National Research Council has formed a committee to address this issue. They will meet in Florida, 10-12 September 2001).

7. With the new ARGO programme, there is an opportunity to greatly increase the number of biogeochemical measurements. However, to take advantage of the float array, rapid technological advances are required in the development of sensors for autonomous deployments.

III. Future strategy? Where do we go from here? What advances can be anticipated?

An important problem to overcome in the next phase of field effort is the present disconnection between the WOCE sections and the JGOFS efforts. The differential locations and timing of these, one relative to the other, does not favour direct support or sharing of data/interpretation between the projects. A strategy to overcome the lack of connectivity is to design activities that accommodate the strengths and needs of both the hydrographic and biogeochemical programmes. Coordinating sampling at time and space scales appropriate to both approaches should be done. Specific suggestions are as follows:

1. A closed volume experiment should be planned in which a time-dependent regional budget of C, Fe, N, and Si can be attempted. Can we close the budget? The chosen site should exhibit large biogeochemical signals/variability, such as a coastal upwelling region (e.g. Arabian Sea), or a region with strong riverine input (e.g., Bay of Bengal).
2. An important and thus far neglected strategy identified is the need to sample physical variables at time and space scales appropriate to biogeochemical processes in future integrated experiments.
3. In the immediate future, there is a need for the development of autonomous instrumentation that will measure nutrients and pCO_2 from floats and ships of opportunity.
4. We can anticipate the continued analysis of the global set of WOCE measurements of carbon, nutrients, O_2, silica, etc, which will yield estimates of biogeochemical fluxes across WOCE sections and their associated divergences within enclosed regions/basins. Estimates of flux divergences will allow biogeochemical rate estimates (using nutrients, ^{14}C).
5. A step towards further improvement and validation of parameterizations would be to create more air-sea flux time-series using meteorological buoys and ships of opportunity.
6. We suggest that evolving techniques for determining air/sea CO_2 flux measurements (e.g. eddy correlation) should be standardized for general and regular use.
7. The GEOSECS and WOCE/JGOFS nutrient datasets should be compared to estimate temporal changes.
8. If biogeochemical experiments are to be carried out in the future, analytical (laboratory) capacities will need to be rebuild. Many hydrographic and carbon teams, for example, have suffered major loss of personnel or complete closure over the last five or ten years.

IV. What opportunities are there for combining circulation and biogeochemistry efforts in future observations?

There are opportunities for better coordinating hydrographic and biogeochemical problems and approaches (see list below). The ARGO programme presents opportunity for remote sensing of key biogeochemical variables in the context of hydrographic variables if the technical obstacles could be overcome. Advances in data assimilation capabilities must extend coverage over both the hydrographic and biogeochemical variables. The linkage between specific biogeochemical and hydrographic processes offers a great deal of advance. Examples include interpretation of biogeochemical variable gradients along neutral density surfaces, the contribution and interpretation of vertical mixing processes, horizontal transport and subduction of both hydrographic and biogeochemical variables, etc.:

1. CLIVAR is focused on decennial (and longer) variability; but biogeochemistry, in the first instance, requires studies on intra-annual scales. The opportunity to link to ARGO should not be missed; new technical advances in autonomous sensors will be required.
2. It may be possible to gain understanding of the variability in sea surface pCO_2 through its covariance with heat content/variability, as indicated by ARGO.
3. Mixing and entrainment/detrainment of biogeochemical properties to/from the mixed layer is poorly understood and crudely parameterized. Investigations of mixing and diffusion processes should be combined with biogeochemical measurements to lead to better parameterizations.
4. Assimilation of biogeochemical data into models (technological problems? e.g., biology into data streams) will serve to integrate physical/biogeochemical variables at various time/space scales and improve simulations and predictions of important processes.
5. Linkage of wind- driven circulation and organic nutrient transport is being considered in models. It should be addressed experimentally. The question here is the potential contribution of nutrients in DOM to export in oligotrophic waters.
6. Biogeochemical processes (remineralization, oxygen utilization, export) should be elucidated on specific density surfaces (AAIW; NPIW, etc.). This can be done initially with WOCE/JGOFS datasets, and with future sampling directed at the question.
7. The physical controls on uptake and transport of anthropogenic CO_2 need to be studied.
8. Cooperation between physical programmes and the air/sea (N, DMS, CO_2) exchange studies (SOLAS) will greatly advance the goals of the latter programmes.
9. There is an opportunity to increase remote sensing applications to surface biogeochemistry in the study of interactions with fronts and currents etc.
10. We must combine biogeochemical efforts/interpretations with existing high-temporal frequency, physical sampling

V. How do results/uncertainties of mass/heat/fresh water transports impact our ability to examine biogeochemical processes/rates?

1. We have not quantified the uncertainties in physical transports; need to quantify and reduce uncertainty. Highest uncertainty in lowest latitudes.
2. We should identify regions that are more/less variable/uncertain, then exploit the stable regions for study. The highly variable systems should be a lower priority for now, if we decide the firm understanding would be difficult to achieve over the near term.

Conclusion of the Working Group

Every effort should be made to bring the physical and biogeochemical groups together early, before field studies are planned and conducted, to identify the questions that can be supported and answered together.

The biogeochemical community should not continue the trend of asking for support from the physicists after the fact. Questions should be phrased to take advantage of the capabilities of both physicists and biogeochemists. It is beneficial to both groups, regarding rationale and achievements, to work in a coordinated way.

Report from the Working Group on Model Development and Data Assimilation

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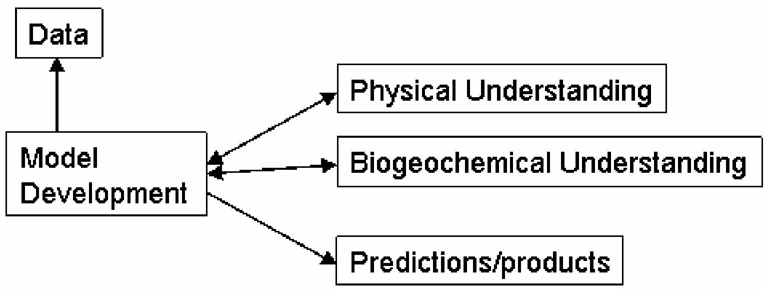
This working group was tasked with evaluating achievements during WOCE and JGOFS projects and opportunities for future research in the areas of model development and data assimilation. The panel focused its discussions around the schematic shown in Figure 1, indicating that model development depends on increasing physical and biogeochemical understanding as well as the provision of high quality data. In its turn, well-constructed models result in increasing physical and biogeochemical understanding as well as producing useful predictions and products for users outside the field of oceanography. Achievements and opportunities were organized into each of the areas in Figure 1.



Products

By products we mean results which are important to people outside of the oceanographic community. WOCE and JGOFS have produced at least two such results.

<u>Anthropogenic CO_2</u>: An important accomplishment of the WOCE/JGOFS datasets was to quantify the oceanic uptake of anthropogenic CO_2. The global uptake of CO_2 (accounting for almost 1/3 of global emissions) is far better known that the terrestrial uptake at present and indeed serves as an important constraint on the net terrestrial uptake. This result is of great importance not only to the scientific community, but to policymakers worldwide.

<u>Heat fluxes</u>: WOCE/JGOFS provide global-scale estimates of the flux of heat carried by the oceans. This estimate too is of importance to the general community as it affects climate in many parts of the globe.

Key opportunities, challenges: The working group identified a number of areas where the WOCE/JGOFS community has an opportunity to contribute:

- Radiatively active gases: Can we monitor/predict variability of CO_2 fluxes and trace gas production on basin scales? This will become increasingly relevant as the world moves towards a control regime for greenhouse gases.
- Climate variability: Can we monitor/predict coupled modes of climate variability (both physical climate and ecosystems on decennial-centennial scales? This is also of great relevance to a number of resource management issues around the globe.

Physical understanding

Mixing, potential vorticity and topography: A major step forward in physical understanding during WOCE/JGOFS, especially from the modelling point of view, was the recognition that away from a few regions (rough topography, straits and gaps) diapycnal mixing is relatively weak. Weak interior mixing implies that potential vorticity is conserved following the flow, an implication substantially verified during the "subduction experiment". Potential vorticity conservation also implies that topography should play an important role in regulating deep flows.

Key opportunities and challenges: More work needs to be done understanding the implications of heterogeneous mixing for the large-scale circulation, especially in the deep ocean, and the interactions of the interior circulation with boundaries (surface mixed layer, topographic features, shelves).

Ocean eddies: Another significant development during WOCE was the development of a framework for representing the effects of mesoscale eddies within the ocean on the large-scale circulation, recognizing that eddies can produce residual flows and producing several possible representations for such flows.

Key opportunities and challenges: While there is an overall theoretical framework, it has not been validated or calibrated observationally, and its impacts on the circulation are only beginning to become understood.

Role of the Southern Ocean: Theoretical, modelling, and observational studies have all implicated the Southern Ocean as a key region for the thermohaline circulation. The role of Antarctic Intermediate Water and mode waters is emerging as quite important.

Key opportunities and challenges: What sets the mean stratification in the Southern Ocean? What regions other than deep water formation regions are important for driving the thermohaline circulation?

Variability: There has been increasing recognition during the WOCE/JGOFS period that the ocean circulation varies, not only on interannual time scales but on inter-decennial time scales associated with such patterns as the Pacific Decennial Anomaly, the Arctic and Antarctic Oscillation, the North Atlantic Oscillation and potentially others.

Key opportunities and challenges: What are the coupled modes of variability involving the high- and mid-latitudes and tropics? What are the fundamental physical processes important for representing these modes? Are these modes predictable? How do they impact our ability to monitor/detect long-term climate change?

Biogeochemical understanding

Biological cycling of carbon: JGOFS field experiments provided a baseline for evaluating biological carbon cycling in key ecosystems especially within the mixed layer.

Key opportunities and challenges: Although preliminary syntheses have been done, there is still much work to be done in extending these results to the regional scale. The coastal ocean remains a challenge as well. How the coastal and deep oceans connect biogeochemically is not well understood. A key question for future modelling is the nutrient mineralization process from the surface to depth, as proposed in the Ocean Carbon Transport, Exchanges and Transformations (OCTET, www.msrc.sunysb.edu/octet/) programme.

Micronutrients: A key development during the JGOFS period was the validation of the hypothesis that iron acts as a limiting nutrient for several key ecosystems.

Key opportunities and challenges: What is the iron budget in the ocean? The large-scale distribution of iron is not well known, and the cycling of iron within the water column is not well known either.

Functional groups: The JGOFS works have demonstrated the importance of "functional groups" (diatoms, calcifiers, nitrogen fixers) for biogeochemical cycling. Switches between functional groups are thought to be important for governing stoichiometric ratios, remineralization profiles, the alkalinity cycle, the response of ecosystems to climate change and changes in micronutrient supply.

Key opportunities and challenges: What are the fundamental (physical, chemical, biological) processes that set stoichiometric ratios? How does the interplay among functional groups affect important biogeochemical budgets (Alk, N, Fe, Si)? This question could be a key one for the proposed Ecological Determinants of Ocean Carbon Cycling (EDOCC; picasso.oce.orst.edu/ORSOO/EDOCC/EDOCC.html) project.

Variability:
Over the last decennium, observational syntheses have clarified the fact that decennial scale variability is a pervasive feature in the atmosphere. The observation that ecosystems such as that at the HOT station can shift between different modes of operation, possibly as a result of this variability has important implications for biological and chemical oceanography.

Key opportunities, challenges: What sort of ecosystem scale variability occurs on regional/basin scales? How does this link to physical variability in climate?

Data

Climatologies: WOCE and JGOFS provided the modelling community with several important climatologies, namely:
(a) large, 3-dimensional gridded datasets based on high quality data of key biogeochemical tracers (nutrients, radiocarbon, alkalinity),
(b) a baseline dataset of high-quality hydrographic sections for inversions and studies of climate change,
(c) Gridded climatologies of surface fluxes,
(d) Two-dimensional climatologies of surface pCO_2,
(e) Float-based estimates of the intermediate circulation.

Key opportunities and challenges: Continued access to these datasets through public access data centres must be a priority. Additionally, it should be recognized that while these datasets represent an important first cut at climatologies, significant holes remain to be filled for certain tracers, in particular, nutrients, radiocarbon, and transient tracers, and regional uncertainties about the climatologies need to be quantified. While the distribution of mixing in the deep ocean is emerging as an important player in the circulation, direct measurements of this quantity are relatively sparse. Finally, micronutrients (in particular iron) and dissolved organic matter may play an important role in global biogeochemical cycling, yet relatively few measurements have been taken of these fields to date. Extending measurement programmes to include micronutrients, DOM, and dissipation is a major recommendation of this working group.

<u>Transient tracers</u>: WOCE and JGOFS provided a large dataset of transient tracer measurements (CFCs, bomb radiocarbon, He-Tritium). Transient tracers are important because they contain important information about the rate at which processes occur.

Key opportunities and challenges: The use of this data in validating and calibrating circulation models and in estimating carbon uptake is just beginning. A key problem for this type of work is that many of the most widely measured transient tracers now have falling concentrations in the atmosphere. Attention needs to be paid to developing new transient tracers that can be used to estimate rates of processes in the ocean interior.

<u>Carbon uptake</u>: Data-based estimates of anthropogenic carbon uptake were developed by several groups during WOCE and JGOFS era using the high-quality dataset as a variable: The JGOFS time series stations, satellite measurements of ocean colour, atmospheric measurements of oxygen and carbon isotopes all revealed that significant changes in global biogeochemical cycles occur on interannual to inter-decennial time scales. The WOCE dataset shows variability in water mass formation and in heat transport on the same time scales.

Key opportunities and challenges: The time-series stations in particular are invaluable tools for detecting long-term modes of variability and testing mechanistic models of how this variability occurs. Existing time-series stations should be extended, both in time and in the kinds of measurements which are made. If possible, additional time-series stations should be started in biogeochemically important regions. These efforts should be linked to remote-sensing programmes which attempt to estimate ecosystem-scale variability. Developing systems to monitor large-scale climate variability, both with floats and long-lines will be extremely important. A key challenge for this effort on the physical side will be the monitoring of boundary currents. A key challenge on the biological side will be the development of sensors for floats which can measure biologically relevant fields. For modellers, an important product of this work will be the compilation of high-quality flux datasets which capture variability and can be used to drive forward models.

Model development

<u>Community models</u>: One of the great successes during the WOCE/JGOFS period was the development of community models which enabled numerous groups around the world to begin realistic simulations of ocean circulation without having to start from scratch. Examples include the Regional Ocean Modelling System (ROMS, quercus.igpp.ucla.edu/research/projects/roms/), the Miami Isopycnic Coordinate Model (MICOM, oceanmodeling.rsmas.miami.edu/micom/) and the Modular Ocean Model (MOM, www.gfdl.gov/~smg/MOM/MOM.html).

Key opportunities and challenges: The group identified four areas where there are significant needs for community models: (1) Hybrid coordinate models that take advantage of the best features of isopycnal-, level- and sigma-coordinate models,
(2) Adjoint models for use in data assimilation, parameter estimation in biogeochemical codes,
(3) Earth System Models which include a variety of atmospheric and ocean models,
(4) Inversion toolboxes. Development of such community codes is analogous to the development of off-the shelf instrumentation. As the latter is vital for making it easier for multiple groups to collect high-quality data, the former is important to allow multiple groups to synthesize coherent modelled pictures of the ocean.

<u>New classes and uses of models</u>: The WOCE/JGOFS era saw a blossoming of the use of inverse models using multiple data sources and adjoint techniques for data assimilation. Global high-resolution models (Principal Oscillation Pattern, POP, www.oc.nps.navy.mil/navypop/; Ocean Circulation and Climate Advanced Modelling project, OCCAM, http://www.soc.soton.ac.uk/JRD/OCCAM/) were run and analyzed in detail. Multiple groups around the world began to use general circulation models to simulate the carbon cycle. One-dimensional test-beds were developed for biogeochemical modelling, providing groups with a solid framework within which to test ideas about biogeochemical cycles.

Key opportunities and challenges: Biogeochemical analysis in inverse models is just beginning and will require continued support in years to come. While many groups are beginning to extend biogeochemical models past C (to look at ecosystem structure, trace gases, nitrogen cycling, iron cycling, etc.) this work is still in an early stage.

<u>Model numerics</u>: One of the main accomplishments in the WOCE/JGOFS period was to bring to the fore the issue of model numerics as a determiner of the solutions produced by numerical models. The Dynamics of North Atlantic Models (DYNAMO, www.ifm.uni-kiel.de/fb/fb1/tm/research/dynamo/dyn_m.html) intercomparison project was particularly important in this regard. There is now a widespread recognition that the details of advection schemes, vertical coordinate system, entrainment, and lateral diffusion schemes can play a major role in model solutions- especially with respect to diapycnal fluxes which are vitally important for biogeochemical applications.

Key opportunities and challenges: A key task in years to come will be to extend intercomparison projects to look at the details of circulation and the physics responsible for them, isolating those differences that are due to differences in boundary conditions from those that are due to differences in numerics. The representation of flow near topography (boundary currents, straits and gaps, overflows) remains a major numerical challenge for physical models.

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ACRONYMS

AIMS – WOCE Analysis, Interpretation, Modelling and Synthesis – www.woce.org/organization/aims/aims.html

ARGO – Array for Real-time Geostrophic Oceanography – argo.jcommops.org/

BATS – Bermuda Atlantic Time-series Study – www.bbsr.edu/cintoo/bats/bats.html

CLIVAR – Programme on Climate Variability and Predictability – www.clivar.org/

CMIP – CLIVAR Coupled Model Intercomparison – www.clivar.org/publications/other_pubs/iplan/iip/pa1.htm#A1054

DYNAMO – Dynamics of North Atlantic Models – www.ifm.uni-kiel.de/fb/fb1/tm/research/dynamo/dyn_m.html

ECCO – Estimation of the Circulation and Climate of the Ocean – www.ecco-group.org/

EDOCC – Ecological Determinants of Ocean Carbon Cycling project – picasso.oce.orst.edu/ORSOO/EDOCC/EDOCC.html

GEOSECS – Geochemical Ocean Sections Study – ingrid.ldgo.columbia.edu/SOURCES/.GEOSECS/

HOT – Hawaii Ocean Time series station – hahana.soest.hawaii.edu/hot/hot.html

IGBP – International Geosphere Biosphere Programme – http://www.igbp.kva.se/

IPO – JGOFS International Project Office – www.uib.no/jgofs/IPO_descript.html

JGOFS – Joint Global Ocean Flux Study – www.uib.no/jgofs/jgofs.html

MICOM – Miami Isopycnic Coordinate Model – oceanmodeling.rsmas.miami.edu/micom/

MOM – GFDL Modular Ocean Model – www.gfdl.gov/~smg/MOM/MOM.html

OACES – NOAA Ocean-Atmosphere Carbon Exchange Study – www.aoml.noaa.gov/ocd/oaces/index.html

OCCAM – Ocean Circulation and Climate Advanced Modelling project – www.soc.soton.ac.uk/JRD/OCCAM/

OCMIP – Ocean Carbon Modelling Intercomparison Project – www.ipsl.jussieu.fr/OCMIP/

OCTET – Ocean Carbon Transport, Exchanges and Transformations – www.msrc.sunysb.edu/octet/

OMDWG – WCRP/CLIVAR Ocean Model Development Working Group – www.clivar.org/publications/other_pubs/clivar_transp/pdf_files/wgomd_members.pdf

POP – Principal Oscillation Pattern – www.oc.nps.navy.mil/navypop/

ROMS – Regional Ocean Modelling System – quercus.igpp.ucla.edu/research/projects/roms/

SCOR – Scientific Council of Oceanic Research – www.jhu.edu/~scor/

SOC – Southampton Oceanography Centre – www.soc.soton.ac.uk/

SOLAS – Surface Ocean and Lower Atmosphere Study – www.uea.ac.uk/env/solas/

WCRP – World Climate Research Programme – www.wmo.ch/web/wcrp/wcrp-home.html

WGASF – WCRP/SCOR Working Group on Air-Sea Fluxes – www.soc.soton.ac.uk/JRD/MET/WGASF/

WOCE – WCRP World Ocean Circulation Experiment – www.woce.org/