**Intergovernmental Oceanographic Commission**
*Reports of Meetings of Experts and Equivalent Bodies*

International Council for Science
Scientific Committee on Oceanic Research

# IOC-SCOR
# OCEAN $CO_2$ ADVISORY PANEL

## First Session
Paris, France
4-6 September, 2000

**UNESCO**

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## 1. OPENING

The Chair, Dr. Douglas Wallace from IfM-Kiel, opened the meeting and welcomed the panel members to the 1st session of the SCOR-IOC $CO_2$ panel. A full list of panel members is given in Annex II. The Executive Secretary of the IOC, Dr. Patricio Bernal, welcomed the members and outlined the history of IOC's previous $CO_2$ panels, highlighting the role of intergovernmental scientific advisory groups in advocating basic research and data collection programmes. He encouraged the panel to coordinate its efforts and share recommendations with other international science groups focusing on ocean carbon issues.

## 2. ADOPTION OF THE AGENDA

The Chair introduced the Agenda and modifications were suggested to the order of some talks. The adopted Agenda is given in Annex I.

## 3. REVIEW OF THE TERMS OF REFERENCE

The Panel reviewed the Terms of Reference and made several modifications to emphasize the focus on the total carbon system rather than just $CO_2$. The adopted Terms of Reference are given in Annex III.

## 4. GOALS AND PRODUCTS OF THE PANEL

The Chair stated that the Panel should serve as a communication forum for carbon observations, collecting and disseminating information on the range of activities going on in ocean carbon science and working to co-ordinate international efforts on technology development, data and information sources, and research programmes. The Panel should identify key people and programmes working within each ocean basin to provide information on new developments and programmes. Several programmes mentioned as possible collaborators in this effort included the CARINA programme for the North Atlantic, PICES in the Pacific, a group from CSIRO to co-ordinate South Ocean activities, and POGO. The $CO_2$ Panel will develop a web-site to serve as a communication forum for the ocean carbon community and to begin linking these regional information systems. One of the major products of this Panel will be recommendations and strategy development for an ocean carbon observation system. The Panel should liase with other international groups in this effort.

## 5. CURRENT STATUS OF CARBON CYCLE SCIENCE ACTIVITIES

The Panel members gave reports on a number of ocean carbon science programmes with which they are involved. The members discussed these programmes and made recommendations where necessary for actions or interactions that would move the programmes forward.

### 5.1 $CO_2$ SEQUESTRATION RESEARCH

Dr. Ken Caldeira, from the University of California / Lawrence Livermore National Laboratory, reported on this item. Ocean carbon sequestration is the deliberate storage of anthropogenic carbon in the oceans, above that amount that would be stored through natural physical or biological processes. Two basic strategies have been proposed to increase ocean carbon storage. (See **Figure 1**)

Relatively pure streams of compressed $CO_2$ can be directly injected into the ocean interior. After injection, the $CO_2$ droplets would dissolve into the oceanic dissolved inorganic carbon pool, and would eventually degas to the atmosphere or interact with carbonate sediments. Research into the biological consequences of direct $CO_2$ injection is at a highly preliminary stage. Direct pH effects are expected to be the primary agent of biologic impact, although there could be significant direct $CO_2$ effects as well. It has been suggested that the dissolution of carbonate minerals could mitigate the pH effects of direct $CO_2$ injection on the ocean environment. Additionally, there are many relevant issues in hydrate chemistry and physics, plume physics, ocean transport, and sediment interactions that are just beginning to be addressed. A consensus seems to be developing, largely based on the work in OCMIP (see below) and in other fora, that direct $CO_2$ injection at 3 km depth or deeper is quite effective at retaining $CO_2$ in the oceans. The associated engineering issues generally appear to be tractable.

Another proposed strategy involves fertilization of the surface ocean with iron or other nutrients. Iron has been shown to stimulate primary production in several areas of the global ocean, including large regions of the Southern Ocean and equatorial upwelling areas. Research needs to be conducted to understand how changes in primary production relate to changes in carbon fluxes to the oceanic interior, and ultimately increased ocean carbon storage. Model results indicate that fertilization of large expanses of the ocean could result in additional storage of about 1 PgC / yr in the ocean, but this number is highly uncertain. There is extremely little information on how ocean fertilization, if practiced on a large scale, would affect marine biota and biogeochemistry.

There is considerable concern that these ocean sequestration strategies might produce more environmental problems than they solve. Furthermore, there are questions regarding the ethical, political, and legal questions surrounding exploiting the ocean commons in this new way. Guidance from the Panel could be helpful in devising ways to address these complicated issues.

The Panel discussed these issues and suggested that smaller, regional models, rather than global models, should be used to examine $CO_2$ injections / sequestration. The Panel should maintain a watching brief on $CO_2$ sequestration technology and activities (field experiments, modeling, etc.) When necessary, the Panel should form a specialize sub-group of experts in the field to provide advice on programmes and policy.

## 5.2 CERTIFIED REFERENCE MATERIALS PROGRAMME

Dr. Andrew Dickson, from the Scripps Institution of Oceanography, reported on reference materials for oceanic $CO_2$ analyses. As the scientific study of the Global Carbon Cycle becomes an ever more international enterprise, there is a growing need for extensive, reliable, oceanic $CO_2$ measurements which, though made at different times by different scientists from different laboratories (in the US and abroad), must be comparable and correct. The need for such measurements was articulated in the long-range plan of the Division of Ocean Sciences of the US National Science Foundation (NSF, 1987). Since then, high-quality oceanic $CO_2$ measurements have been an integral part of the Joint Global Ocean Flux Study (SCOR, 1992), which has been going on since 1989 and will play an important role in future observing systems (Merlivat and Vézina, 1992; Wallace, 1995; Carbon and Climate Working Group, 1999).

Unfortunately, in the past, oceanic $CO_2$ measurements made by different groups have rarely been comparable. Whenever it has been necessary to bring together such data, ad hoc adjustments have been necessary (e.g., Gruber et al., 1996), and even for the GEOSECS data there is a history of such adjustments and calibration corrections (Bradshaw et al., 1981). Early in the JGOFS era, the US National Science Foundation (NSF) Division of Chemical Oceanography (then directed by Dr. N. Andersen) thus recognized the need for reference materials (RMs) for oceanic $CO_2$ analyses (see also UNESCO, 1991). In 1989, NSF funded Dr. A. G. Dickson's laboratory at the Scripps Institution of Oceanography — working in collaboration with Dr. C. D. Keeling's group — to devise a strategy to prepare RMs for total dissolved inorganic carbon ($C_T$) and total alkalinity ($A_T$) measurements. This work is described in Dickson et al. (2001).

In 1990, the first batch of RMs was analyzed for $C_T$ over a period of some months and shown to be stable. Once it had been demonstrated that such materials could be produced and distributed, the

US Department of Energy paid for the preparation and distribution of RMs for use on the US Global $CO_2$ Survey, carried out in conjunction with the WOCE Hydrographic Program one-time survey (1991–1997). Furthermore, Dr. M. Riches (of the US Department of Energy) agreed to fund the distribution of RMs to other non-US labs that were carrying out similar $CO_2$ surveys. These surveys provided a unique opportunity to combine high-quality $CO_2$ data together with state-of-the-art hydrographic measurements. Reference materials were analyzed regularly on board ship to confirm that the shipboard analytical systems were working correctly and to provide assurance of the quality of the results obtained (DOE, 1994; Johnson et al., 1998; Millero et al., 1998; Feely et al., 1999; Lamb et al., in press).

Over the past 11 years (1990–2000), Dr. Dickson's laboratory has distributed suitable certified RMs world-wide for total dissolved inorganic carbon and total alkalinity in sea water. About 24,000 bottles of RM have been distributed to more than 50 laboratories, in more than 20 countries, for use in the quality control of their measurements. They have been used extensively to confirm that instruments are performing properly and to ensure measurement compatibility. Over half of the RMs distributed to date were employed by US scientists. The remaining ones have been used to support $CO_2$-measurement activities in other countries. Many of the major non-US users — Australia, Bermuda, Canada, France, Germany, the Netherlands, and the United Kingdom — were also heavily involved in JGOFS-related measurements. The current distribution level is still well over 2,000 bottles per year and is growing. Work is in progress at Scripps to extend the certification of the RMs to $^{13}C$ and pH.

Since 1998, NSF alone has funded this program and a nominal charge of $25 per bottle has been levied on users (in addition to charges for shipping and handling). This cost was estimated as the marginal cost of producing a single bottle of CRM — recognizing that the bulk of the costs of maintaining the laboratory are borne as a contribution by NSF. NSF recognizes the importance of this work, and its present director of Chemical Oceanography, Dr D. Rice has indicated that he expects to continue funding this program, provided that there is broad community support for such an activity. Dr. Dickson's laboratory Nevertheless it is essential for the Panel to investigate additional mechanisms for support of such key activities so as to ensure the long-term existence of RMs for use in future internationally coordinated observing programs.

The Panel discussed this issue and recognized that a potentially serious problem exists because at present, there is only a single source of reference materials. Other groups make their own CRMs, but these are only secondary standards calibrated by the original source. This one programme is insufficient to handle the large, international observation programmes now being planned. The Panel suggested that a stronger link should be established between the CRM programme at Scripps and Dr. Pieter Tan's group for measurements. The Panel also noted that in order to provide the necessary volume of quality standards for future observation programmes, another independent source of CRMs should be established, perhaps within the European Community.

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## 5.3 OCEAN CARBON CYCLE MODELING INTERCOMPARISON PROJECT (OCMIP)

Dr. Corinne Le Quéré reported on the OCMIP programme. The objective of OCMIP is to improve ocean carbon-cycle modeling by comparing models amongst each other, and with independent observations. Model-model and model -data differences and similarities are highlighted and related to specific physical, chemical, and biological processes. Four groups participated in the first phase of OCMIP (1995-1997), which focused on natural and anthropogenic $CO_2$. The general conclusions drawn from OCMIP-1 are as follows (Orr et al., 2000; Sarmiento et al., 2000). Although the global uptake of anthropogenic $CO_2$ is similar in all models, ranging from 1.5 to 2.2 PgC/yr, regional differences are large. The Southern Ocean South of 30º S is the region of greatest disagreement. A comparison with anthropogenic $CO_2$ inventories in the Atlantic (Gruber 1998) and Indian (Sabine et al., 1999) oceans suggests that most models underestimate the inventory of anthropogenic $CO_2$ between 50º S and 50º N and overestimate it poleward of these latitudes (**Figure 2**). Thus, the global inventory is in the right ball park, but regional discrepancies exist. Differences amongst models grow in the future. In spite of these differences however, the current inter-hemispheric transport of carbon is nearly zero in all models. An analysis of the relationship between bomb $^{14}C$ and anthropogenic $CO_2$ in OCMIP models suggests that $^{14}C$ is a better proxy for $CO_2$ now than it was during GEOSECS, mostly because of the increasing similarity of their atmospheric history.

Thirteen groups participated in the second OCMIP phase (1998-2000). In addition to natural and anthropogenic $CO_2$ simulations, OCMIP-2 included simulations of CFCs (Orr and Dutay 1999). Such simulations highlight model differences caused by ocean physics (**Figure 3**).

Preliminary conclusions of OCMIP-2 suggest that the diagnostic model of the Alfred Wagner institute reproduces best the observed profiles of CFCs. Prognostic models including lateral mixing along density surfaces and dynamic sea-ice generally perform better than simpler models. OCMIP-2 results generally support the conclusions of OCMIP-1. In particular, ocean $CO_2$ uptake for the 1980s is between 1.6 and 2.2, with the range amongst models widening in the future because of differences in ocean physics (**Figure 4**).

A third phase of model comparison is being planned, with special focus on marine biology. Extensive model-data comparisons will be continued in the future, and part of the funding may be required to building appropriate data-bases for model comparisons. It is also realized that more diversity in the models being compared should be emphasized.

The Panel noted that there were large regional differences between the models of $CO_2$ sink and source strength and location. The models diverge even further when spun forward in the future. These problems result from different dynamics of mixing used in the models. The third phase of the OCMIP programme will incorporate biological components into the models. The Panel expressed concern over the lack of agreement in the appropriate dynamics used in the models, and suggested that the programme focus on resolving these questions before moving on to the even more complicated issue of including biology in the models. The Panel recommended that the OCMIP-3 planners focus on this issue and form stronger collaborations with physical oceanographers to improve the dynamics and resolution of the models.

OCMIP Modeling Groups

1. AWI (Alfred Wegener Institute for Polar and Marine Research), Bremerhaven, Germany
2. CSIRO, Hobart, Australia
3. IGCR/CCSR, Tokyo, Japan
4. IPSL, (Institute Pierre Simon LaPlace), Paris, France (OCMIP1 and 2)
5. LLNL, Livermore, California, USA
6. MIT, Boston, MA, USA
7. MPIM, (Max Planck Institut fuer Meteorologie - Hamburg) Germany (OCMIP 1 and 2)
8. NCAR, (National Center for Atmospheric Research), Boulder, Colorado, USA
9. NERSC, (Nansen Environmental and Remote Sensing Center), Bergen, Norway
10. PIUB, (Physics Institute, University of Bern), Switzerland
11. PRINCETON (Princeton University [AOS, OTL] / GFDL), Princeton NJ, USA (OCMIP1&2)
12. SOC (Southampton Oceanography Centre) / SUDO / Hadley Center, England (OCMIP1&2)
13. UL (University of Liege) /UCL (University Catholique de Louvain), Belgium

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## 5.4 LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)

Dr. Michel Frankignoulle reported on this item. The LOICZ Project (http://www.nioz.nl/loicz/) is one of eleven Programme Elements of the IGBP and focuses on the area of the earth's surface where land, ocean and atmosphere meet and interact. The overall goal of this project is to determine at regional and global scales:

- the nature of that dynamic interaction;
- how changes in various components of the Earth system are affecting coastal zones and altering their role in global cycles;
- how future changes in these areas will affect their use by people; and,
- a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

LOICZ approves three classes of research projects:

- Core
- Regional
- Relevant

The project types are distinguished on the basis of geographic extent, scientific contribution to LOICZ global research, and commitment to the Project.

### 5.4.1 LOICZ Core Research Projects

Core Research as defined by the IGBP is research that directly addresses the Science Plan goals of IGBP Projects. Such research addresses global issues, either through the production and testing of widely applicable models of change in coastal zones or through providing wide geographic syntheses of information on coastal properties, coastal flux rates or coastal processes and their rates of change. At present there are five core projects approved:

- Coastal Typology Development; Bob Buddemeier
One of the most important initial tasks for LOICZ is to establish a global coastal zone typology based upon available scientific information, both descriptive and dynamic – the Typology Data Set. Such a system will allow grouping of the World's coastal zone into clusters of discrete, scientifically valid units based on both natural and socio-economic features and processes.

- Continental Margins Task Team (CMTT); Assoc/Prof. Talaue-McManus and Dr Kon-Kee Liu
The overall goal is to assess the contribution of continental margins and seas to $CO_2$ sequestration and horizontal flux of carbon, nitrogen and phosphorus across the ocean continental margin boundary.

- Biogeochemical Budgeting Modeling; Prof. Smith and Prof. Wulff (Supported by UNEP and GEF)
The goal of this Project is to compile regional carbon/nitrogen/phosphorus data and budget models for numerous coastal areas of the world that can be used to produce global syntheses models of their flux in the coastal zone.

- Deltaic Processes; Prof. Sanchez-Arcilla
This project is establishing a global network of "deltaic specialist". It will take the lead in providing guidance and assistance to the wider LOICZ network in developing data-related protocols and methodologies for deltaic studies.

- SARCS/WOTRO/LOICZ Southeast Asia Research; Prof. Ong Jin-Eong
The project aims to integrate natural - social science assessment of changes in coastal zones (Indonesia, Malaysia, the Philippines, Thailand and Vietnam). All involve the modeling and synthesis of both biogeochemical and socio-economic data that will be useful not only in characterising the coastal zone processes in the region, but also as test cases for the necessary conceptual and operational development for scaling up to global analysis.

### 5.4.2 LOICZ Regional Research

LOICZ Regional research is as defined by the IGBP but in addition, contributes to global issues, within a regional framework, either through the production and testing of widely applicable models of change in coastal zones or through providing regional syntheses of information on coastal properties, coastal flux rates or coastal processes and their rates of change. At present the following regional projects have been approved:

- Australian Great Barrier Reef, Terry Done, Australia;
- Land-Ocean Interactions in southern South America (PARAT), J.-L. Probst, EU;
- Sustainable use of coastal ecosystems: EUROBASIN, Wim Salomons, Germany;
- Ecology of tropical coastal systems: Mangrove dynamics and management (MADAM), Ulrich Saint-Paul, Germany;
- Lower Volta Mangrove Project: Phase I -Assessment of environmental, economic and social factors, Christopher Gordon, Ghana;
- Integrated Coastal Zone Management in Banten Bay, A. Nontji, Indonesia;
- Carbon and Nutrient Fluxes and Socio-Economic Studies of the Merbok Mangrove Ecosystem, ONG Jin-Eong, Malaysia;
- Etude multidisciplinaire d'Aide à la Gestion Intégrée des Zones Côtières, M. Snoussi, Morocco;
- Impact of Nematodes on physical properties of sediments, Carlo H.R. Heip, Netherlands;
- Economic and technological aspects of internationally coordinated strategies, H. Verbruggen, Netherlands;
- BOA research theme on tidal areas, Herman Ridderinkhof, Netherlands;
- EROS 2000 Black Sea, Peter Herman, Netherlands;
- Sustainable use of international river basins: definitions, criteria & assessment, W.P. Cofino, Netherlands;
- Sustainable management of the coastal area of SW Sulawesi (WOTRO-Programme), Pieter G.E.F. Augustinus, Netherlands, Indonesia;
- Economic Evaluation and Biophysical Modeling of the Marine Environment of Bolinao in Support of Management for Sustainable Use, Liana Talaue-McManus, The Philippines;
- Study on key processes of ocean flux in the East China Sea (POFLECS), Dunxin Hu, China;
- Land-ocean interactions in China seas and their impacts on coastal marine environments, ecosystem and living resources, Dunxin Hu, China;
- Land-Ocean Interaction in the Russian Arctic (LOIRA), V. Gordeev, Russia;
- Economic Evaluation and Biophysical Modeling of the Impact of Shrimp Farming on the Mangrove Systems of Ban Don Bay, Thailand; Gullaya Wattayakorn, Thailand;
- Land-Ocean Interaction Study (LOIS), Anthony Stebbing, United Kingdom;
- Synthesis and upscaling of sea-level rise vulnerability assessment studies (SURVAS global project), United Kingdom;
- Economic Evaluation Studies of Mangrove Conservation and Rehabilitation in Nam Ha Province, NGUYEN Hoang Tri, Vietnam;

### 5.4.3 LOICZ Relevant Research

LOICZ relevant research is, as defined by the IGBP, research which makes an indirect contribution to the project, without formal affiliation. This research addresses issues identified as of priority in the Implementation Plan of LOICZ, either through the production and testing of models of change in coastal zones, or through providing information on flux rates, or coastal processes and their rates of change and thus contributing to national and/or regional level synthesis. At present there are a number of relevant projects (more than 50) that have been adopted within the framework of LOICZ from participating scientists. Some of these projects are funded by the EU in the framework of the ELOISE projects network (*European Land Ocean Interactions studies*)

## 5.5 SURFACE OCEAN-LOWER ATMOSPHERE STUDY (SOLAS)

Dr. Doug Wallace presented an update of the SOLAS status. He stated that the science plan has been completed and is available at http://www.ifm.uni-kiel.de/ch/solas/main.html. He noted that the carbon cycle issues to be covered by SOLAS were carefully chosen to be consistent with the overall goals of SOLAS and that as a result SOLAS cannot be considered to be a comprehensive ocean carbon science programme. Rather, with JGOFS ending, there remains a very obvious and urgent need for new international activities to address overall cycling of carbon and related elements within the ocean. SOLAS would establish firm links with such new activities, possibly in a manner analogous to JGOFS-LOICZ interactions.

SOLAS-related issues relevant to ocean carbon cycle science include: air-sea gas exchange parameterization, temporal and spatial variability of $pCO_2$ in surface waters in relation to mixed-layer physical and biological variability, assessments of the capability for remote sensing of key carbon variables, modeling of ocean carbon and air-sea $CO_2$ fluxes, the effect of carbon system speciation changes (e.g., biocalcification rates) on air-sea $CO_2$ flux and upper ocean carbon cycling resulting from increased $pCO_2$, and macronutrient effects on productivity and carbon sequestration. SOLAS science planning took place in the clear awareness of the importance of the sub-surface ocean for carbon cycling.

The Panel reiterated the point made by Dr. Wallace that with JGOFS ending, there was a need for new international ocean carbon research activities. The Panel decided to closely follow the development of the SOLAS science plan and outline what carbon issues SOLAS will not be addressing, and provide input about issues that could be addressed within the framework of the programme. In addition, the Panel will investigate ways in which ocean carbon science may be integrated into other oceanographic programmes such as CLIVAR.

## 5.6 OCEAN OBSERVATIONS PANEL FOR CLIMATE

Dr. Maria Hood reported on this activity. The Ocean Observation Panel for Climate (OOPC) met at the Institute of Marine Research in Bergen, Norway on 20-23 June. The Terms of Reference for the OOPC and the membership of the panel were presented to the $CO_2$ panel to provide an idea of the mandate and expertise of the OOPC.

At the OOPC meeting, the panel was informed of the reformation of the $CO_2$ advisory panel, and that the panel will undertake specific tasks, such as writing discussion papers and briefings, convening special workshops and international ocean $CO_2$ conferences, and providing ready expertise as needed to IOC, OOPC, and SCOR. The Chair of the OOPC, Neville Smith, noted that $CO_2$ be an important part of the long-term observing strategy for climate, and that together with the Ocean Colour Panel, GOOS will work to establish both in situ and satellite monitoring programmes for carbon. He also stressed that OOPC was depending on this $CO_2$ panel for guidance in developing the larger Ocean Observing System for Climate.

At the OOPC meeting, Dr. Peter Haugan (Geophysical Institute, University of Bergen) discussed some of the imminent needs for a carbon component to the global observing system, noting that:

- The field work phases of both JGOFS and WOCE have come to an end;
- SOLAS, which is seen as the successor programme to JGOFS for carbon studies is not yet operational. In addition, this programme will only focus on upper ocean processes;
- The Kyoto Protocol requires nations to monitor their "national" carbon sources and sinks, and that interannual and seasonal resolution is required to constrain both oceanic and terrestrial budgets versus emissions;

- The issue of deep-ocean storage of carbon has gained much attention in the last few years and this is a development that the OOPC and new $CO_2$ panel must watch.

In terms of observation requirements, Dr. Haugan stated that the overall need is for improvement in measurement methods for the various components of the oceanic $CO_2$ system. He noted that there is a strong need to characterize the seasonal and interannual variability of $CO_2$, and that methods must be developed further to determine pre-industrial and anthropogenic components of the $CO_2$ flux. The role of biological processes in regulating the distribution and flux of $CO_2$ is also a major focus of research.

Dr. Haugan stated that the most important needs for the $CO_2$ panel are:

- to advise on the measurement and observation strategy;
- to advise on the issue of deep-ocean carbon storage;
- develop an overall strategy for the carbon observing system, combining surface $pCO_2$ and related observations from the VOS programme, carbon component measurements from repeat hydrographic sections, and time series of vertical profiles at key locations.

The Panel expressed frustration at the lack of inclusion of carbon monitoring in the framework of the OOPC climate monitoring system recommendations, and suggested that there should be dual membership between the OOPC and the $CO_2$ panel.

Dr. Hood further reported on the Integrated Global Observing Strategy (IGOS), which unites the major satellite and surface-based systems for global environmental observations of the atmosphere, oceans and land. (http://www.unep.ch/earthw/igos.htm). IGOS is a strategic planning process involving a number of partners, which links research, long-term monitoring and operational programmes, as well as data producers and users, in a structure that helps determine observation gaps and identify the resources to fill observation needs. IGOS focuses primarily on the observing aspects of the process of providing environmental information for decision-making, and provides a framework for decisions and resource allocation. The Partnership includes CEOS, the G3OS, WMO, UNESCO - IOC, FAO, UNEP, ICSU, IGFA, and IGBP.

Dr. Hood pointed out that there are strong links between IGOS Partners and ocean carbon cycle science activity through a new initiative of the IGOS Partners to develop an integrated strategy for monitoring the global carbon cycle. This integrated strategy will involve the atmospheric, terrestrial, and ocean carbon communities in developing a strategy and plan for an "Earth System" based approach to monitoring the global carbon cycle. For the ocean section, GOOS has been asked to form a small working group to develop a document outlining the initial observing system for ocean carbon. D.r Scott Doney (UCAR / NCAR) will head the group. Working Group members have been identified and invitations sent. The IOC secretariat and Dr. Doney have outlined a first draft of an inventory of the existing ocean carbon monitoring programmes, as well as some of the planned and suggested network elements proposed by various national and international groups. This group would like the $CO_2$ panel to serve as a partner in the development of this observation system by providing input and guidance to the Working Group.

## 5.7 NEW MEASUREMENT TECHNOLOGY – Leif Anderson

Dr. Leif Anderson presented this report. Analytical methods for the determination of the marine carbonate system have been developed since the 1960s. Below is a list of the most frequently used techniques, indicating their specific characteristics. This list primarily refers to field studies, and not autonomous sensors.

| | *Method* | *Precision* | *Accuracy* | *Speed* |
|---|---|---|---|---|
| **pH** | Glass electrode and buffer calibration | Moderate | Moderate | Medium |
| | Spectrophotometry using indicator | Very good | Determined by indicator $pK_a$ | Fast |
| ***f*$CO_2$** | Gas equilibrium and IR detection | | Determined by standard gas | |
| | Gas membrane and spectrophotometric detection | | Determined by indicator $pK_a$ and equilibrium computations | |
| **$A_T$** | Titrations in closed cells | Medium/good | Medium/good | Slow |
| | Titrations in open cells | Very good | Determined by CRM | Fast |
| | Spectrophotometry with indicator and acid | Not yet developed enough? | | Fast |
| **$C_T$** | Titration in closed cells | Not in action any longer(?) | | Slow |
| | Gas extraction on acidified samples with coulometric detection | Extremely good | Determined by standard gas and CRM control | Slow |
| | Gas extraction on acidified samples with IR detection | Very good | Determined by CRM | Slow |

Potential future developments are:

- to further develop the spectrophotometric technique for determination of pH as well as total alkalinity titration;
- to develop the membranes for the determination of *f*$CO_2$;
- to develop faster techniques for high precision/accuracy determination of total dissolved inorganic carbon.

The Panel discussed reasons for the slow development of chemical sensors, including the expense of using the relatively few, existing test moorings, the various degrees of success attained by some sensors, and budget competition with technology development of physical oceanographic sensors for use on drifters. Despite these constraints, there is considerable activity in development of buoy-mounted and ship-mounted sensors. The Panel suggested that information and status about technique / sensor development be put on the $CO_2$ Panel web-site to share information and co-ordinate efforts.

## 5.8 CURRENT STATUS OF ATMOSPHERIC OBSERVATIONAL NETWORK

Dr. Roger Francey reported on this item.

*Data availability:* The most comprehensive and up-to-date compilation of observations of the global levels of atmospheric $CO_2$ is available on the World Wide Web at [http://www.cmdl.noaa.gov/ccgg/globalview/co2]. GLOBALVIEW $CO_2$ is a Cooperative Atmospheric Data Integration Project, updated annually, currently with 141 data-records (effectively sites) contributed by 23 laboratories from 17 nations.

A smaller number of laboratories (but perhaps 75% of sites) are contributing $CO_2$ stable isotope data to GLOBALVIEW. GLOBALVIEW is a data assimilation product, where monthly average data are constructed for each site, using interpolation and extrapolation techniques to ensure uniform spatial representation. For $CO_2$, a limited selection of data is made based on inter-laboratory comparisons of World Meteorological Organization (WMO) initiated "round-robin" comparisons of measurements on circulation high pressure cylinders of air standards spanning a range of $CO_2$ concentrations. $CO_2$ (and some $\delta^{13}C$) data are also contributed to the World Data Centre for Greenhouse (Gases Japan, [http://gaw.kishou.go.jp/wdcgg.html]) and CDIAC (Oak Ridge, USA, [http://cdiac.esd.ornl.gov/]). Other potentially relevant data on atmospheric $\Delta^{14}C$ and $\delta\ ^{18}O$ in atmospheric $CO_2$ are being collected by individual laboratories but are not yet routinely archived in accessible databases. This is also the case for a small, but growing number of laboratories that are conducting measurements of $O_2/N_2$ at 10-20 sites in the background atmosphere.

*Calibration:* $CO_2$ mixing ratios are reported on the WMO Mole Fraction Scale which is determined as a result of repeat manometric determinations of the $CO_2$ in a suite of high pressure cylinders of air at the WMO Central $CO_2$ Laboratory at NOAA/CMDL in Boulder Colorado (Zhao et al., 1997). A target precision for merging data from different networks has been set by 2-yearly WMO convened expert forums over the last 20 years. Recent precision targets are 0.1 ppm and 0.05 ppm for Northern and Southern Hemispheres, respectively. The relatively poor precision of a manometric determination (at best 0.1 ppm) complicates the absolute calibration. Three high-pressure cylinder WMO "round-robins" conducted throughout the 1990s have shown that more than 40% of laboratories fail to reach even the 0.1 ppm target in measured differences with respect to NOAA. One contributing factor is the poor compliance with WMO guidelines for linking to the CCL primary scales, which in turn is associated with the cost of not only purchasing and regularly recalibrating CCL standards, but of purchasing and maintaining the large number of secondary, transfer and reference cylinders necessary to maintain these links.

Even more seriously, recent comparisons between long-term records of continuous in situ analysers versus flasks collected and analysed in a central laboratory within one network, or between flasks between different networks exhibit differences at the 0.2-0.3 ppm level (Masarie et al., in review). A similar unsatisfactory situation emerges from International Atomic Energy Agency sponsored comparisons of $\delta\ ^{13}C$ data between the four major networks (Allison et al., in press). Intercalibration of other relevant tracers such as $O_2/N_2$ is even less developed.

GLOBALHUBS is a strategy to address these problems and has been endorsed by recent. WMO and IAEA Expert forums, and promoted by international science planning forums (e.g. IGOS, IGBP). It establishes four internationally distributed HUB laboratories which use redundant techniques to maintain very frequent high-precision comparisons of measurements for a range of long-lived atmospheric trace gases, and which play a lead role in providing well-characterised air at low cost, and diagnostic tools, to other laboratories within their region. Prompt, transparent reporting of all measurements on the World Wide Web is a key feature. GLOBALHUBS provides a convenient framework with which to improve and propagate links to primary standards. While international funding to establish GLOBALHUBS has not yet been identified, the basic principles are currently being incorporated and tested in regional initiatives such as CARBOEUROPE.

*Network Design:* Existing sampling networks have been established largely based on the constraints of measurement techniques and the intuition of experimentalists. For example, one result is a heavy bias of $CO_2$ sampling sites towards sampling of the marine boundary layer. A number of improved techniques are emerging, including the use of aircraft and tall towers, improved $CO_2$ analyser systems (higher precision, and lower flows implying greatly reduced logistic overheads), possible satellite-borne remote $CO_2$ sensing, all aimed at improving the sampling over more heterogeneous (terrestrial) regions. For example, reducing uncertainties in flux estimates over continental regions is currently one of the more effective ways of improving ocean exchange estimates using atmospheric techniques. The use of inversion models that permit treatment of uncertainties, are increasingly being called on to assess the effectiveness of sampling networks and to optimise the development and deployment of sampling instrumentation, prior to deployment. The need to coordinate the sampling of the atmosphere and the ocean (or terrestrial) flux estimates using inversion-modelling techniques is also clearly advisable.

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## 6. REVIEW OF UNFINISHED BUSINESS FROM THE PREVIOUS $CO_2$ PANEL

The Panel remarked that the community needs to fund the continued development and assembly of the ocean $CO_2$ database. It was suggested that several members of the panel outline the current efforts in data collection / compilation in various nations and regions and advocate and/or actively seek support to continue and co-ordinate these programmes.

The Panel also discussed the need to raise the issue / awareness of data availability, and that the community must establish a pattern of making data available at some reasonable time after the programme.

## 7. THE NEED FOR AN OCEAN CARBON OBSERVING SYSTEM

The Panel discussed several key issues / arguments for the need for an observing system. One of the central questions is, "how are things changing ?", and it is clear from previous oceanographic programmes that these questions can only be fully addressed with decadal timescale sampling programmes supported by a dedicated observing sytsem. The Panel discussed the necessary timescales for observations of the carbon system, and it was stated that the necessary time and space resolutions are coarser than previously thought, making a carbon observation programme more feasible. The Panel also suggested that stronger links should be made with the carbon modeling community to best plan sampling strategies required. Discussions were continued on this issue under Agenda Item 10. The Panel will also participate in the development of this subject further in the GOOS Technical Document, 'A Global Ocean Carbon Observation System—A Background Report', being edited by Dr. Scott Doney (National Center for Atmospheric Research) and Panel technical secretary, Maria Hood.

## 8. REGIONAL AND GLOBAL OBSERVATIONS

### 8.1 NORTH PACIFIC

Dr. Yukihiro Nojiri first detailed monthly maps of $pCO_2$ constructed for the North Pacific with the data collected from the Japanese-Canadian collaboration using the cargo ship Skaugran 1995-1997. These data provide the capability of evaluating the monthly air-sea fluxes north of 30ºN. The results are relatively close to those extrapolated by Takahashi et al. (perhaps because Takahashi et al. used part of the same data set).

Dr. Nojiri then detailed recent results obtained in June 2000: during this season there is a strong correlation between $pCO_2$ and chlorophyll in the Northwest Pacific: values as low as 200 ppm for $pCO_2$ were observed in areas where Chl-a was higher than 4 µg/l. Dr. Nojiri pointed out that for observing such meso-scale structures, high resolution data are needed for both $pCO_2$ and chlorophyll. Combining the two instruments has been done on the Alligator Hope Monitoring that started in 1999 in the North Pacific (The cost is estimated to be about 5 M$ for the first equipment, and 8 M$ for the pair of instruments).

Dr. Nojiri presented a map of the North Pacific and detailed the different surveys (past and future):

1. Mirai / JAMSTEC:
    - Sub Arctic 1997-2003;
    - Tropical 1998-2002.

2. SAGE (SubArctic Gyre Experiment): 1997-2001.

3. NIES
    - Skaugran: 1995-1999 (Japanese/Canadian collaboration; mid to high latitude in the North Pacific);
    - Alligator Hope monitoring (1999- present): Tokyo-Seattle-Vancouver;
    - Alligator Liberty : Japan-Mexico: 1999-2001.

4. Station KNOT - occupied in 1998 (13 visits), 1999 (12 visits) and 2000 (9 visits).

Dr. Nojiri presented two future project goals, far from the North Pacific. One concerns a South Pacific survey project that may be organized in collaboration with US and Australian groups. Strong recommendations from the panel are highly needed to present and defend such a project. The second project is the opportunity of using Japanese cargo vessels sailing from Argentina to South Africa and then to Japan. This cruise would explore the South Atlantic and North Indian oceans.

## 8.2 NORTH ATLANTIC

Dr. Andrew Watson, from the University of East Anglia, provided an overview of ocean carbon activities in the North Atlantic.

1. Historical data base: CARINA: At the initiative of the $CO_2$ group at IFM, Kiel, a workshop was held in June 1999 with the aim of bringing together as much $CO_2$ data from the North Atlantic as possible. This data is currently available to all members of the CARINA partnership, but not to others. Membership is open to all those who contribute data to CARINA. Data from about 150 cruises have been gathered to date, much of which but not all is public domain data. Even where the data is publicly available, it is considered very worthwhile to bring it together in a single resource.

2. CAVASSOO: ("Carbon variability studies from ships of opportunity" ) This is an EU project funded between 2001 and end 2003, the purpose of which is to collect underway $pCO_2$ and supporting data from ships of opportunity crossing the N. Atlantic on a regular basis (monthly or bimonthly). The objective is to gain sufficient synoptic data on the N. Atlantic to enable calculation of the sink for $CO_2$ and its variability with season and inter-annually. **Figure 5** shows the planned routes to be covered in the project. Each of four partners (Universities of Kiel, East Anglia, Bergen and the Instituto de Investicagiones Marinas, Vigo), is responsible for one route. It is hoped that the data will be combined with, and be complementary to, efforts from the US to run similar Ship of Opportunity lines. First data from CAVASSOO should be available in 2002.

## 8.3 SOUTHERN OCEAN

Dr. Nicolas Metzl, from the Université Pierre et Marie Curie, reported on ocean carbon activities in this region. In the far, windy and glacial Southern Ocean, $pCO_2$, DIC, TA and $\delta^{13}C$ observations were obtained during the recent WOCE/JGOFS era (1990-2000). The analyses of these data in different basins (Atlantic, Indian, Pacific sector) showed clearly that the spatio-temporal $pCO_2$ distribution is regional and follows the main hydrological and biogeochemical zonations: the sub-Antarctic Zone (SAZ), the Polar Front Zone (PFZ), the Permanent Open Ocean Zone (POOZ), the Seasonal Ice Zone (SIZ), and coastal zones, including Weddell and Ross seas. For a complete understanding of processes that control the variability of the carbon cycle in the Southern Ocean, studies need first to focus on each of these sectors: this includes detailed analysis of the observed $CO_2$ distribution, the coupling of inorganic chemistry with dynamics and biological studies (with the help of satellite observations, e.g. altimetry, ocean colour, etc) and modelling to test hypotheses (iron limitations, formation of intermediate, deep and bottom waters, etc.) that could be used in large-scale models to predict the coupling between carbon cycle and climate.

Despite the large number of data obtained during the nineties, cold waters of the Southern Ocean still contain mysteries for biogeochemistry, paleoclimatology and climate change studies. One of these concerns the air-sea $CO_2$ flux estimate: the sign of the flux ($CO_2$ source or sink?) generally differs when using ocean data (or ocean models) or atmospheric inverse approaches (**Figure 6**).

Other uncertainties are related to the anthropogenic $CO_2$ inventory in the ocean: the differences between indirect methods based on data collection and ocean models reach a factor of 3 at high latitudes in the southern hemisphere. Reducing these uncertainties is important not only for the present knowledge of the global carbon budget but also because it has been suggested that the Southern Ocean would be highly sensitive to climate change; the "C5" studies (Climate Change/Carbon-Cycle Coupling) includes changes in dynamics, biological communities, export production. The primary productivity in the Southern Ocean is also presented as a dominant factor for explaining the glacial/interglacial greenhouse gas variations. For all these studies, data synthesis is an important step towards a better description of the processes that control the spatio-temporal variabilities of the oceanic carbon cycle, including validations of C5 models.

There have been recent attempts to merge Southern Ocean $CO_2$ data sets from different groups for air-sea flux calculations at large-scale, processes studies and/or to validate models (e.g.; Louanchi et al., 1999; Metzl et al., 1999; Takahashi et al., 1999); there is also a clear need, expressed by our community (e.g. 2nd JGOFS Int. Symposium), to progress and communicate for many reasons:

- The large-scale seasonal sea surface $pCO_2$ (and DIC) distribution of the Southern Ocean (here taken from Polar Front to the Pack Ice) is not known;
- Therefore, integrated air-sea $CO_2$ fluxes in the S.O. is not well known; numbers exist but associated errors are generally not fully estimated;
- Concerning the air-sea fluxes, there are large differences between oceanic views (observations and OGCM) and atmospheric inverse calculations (e.g. **Figure 1**); there are also large differences when comparing different inverse calculations or different OGCM and we don't know exactly why (but there is progress, e.g., OCMIP and TRANSCOM projects);
- Interannual variability ($pCO_2$/DIC) is not known (there are some identified variability but at local scale and mostly summer); therefore, the role of the S.O. with regard to the variations of the rate of increasing atmospheric $CO_2$ is not known (it may be low compared to EqPAC/ENSO region, but we need to know). This is particularly important for the SAZ, which represents an annual sink of about 1 GTC/yr (e.g. **Figure 7**), a region where intermediate and mode waters are formed;
- On decadal to century timescales, the sensitivity of the Southern Ocean with regard to climate change could be large (e.g. Sarmiento et al., 1998; Bopp et al., 2000); these "C5" studies

(Climate Change/Carbon-Cycle Coupling) include changes in dynamics, biological community, export production, but C5 models need more complete validations;

- Data synthesis activity is an important step toward validation of models and better understanding the model's stories;
- Validation is crucial to check and correct both simple and complex parameterizations because processes that control the carbon spatio-temporal variabilities in the S.O. are identified and quantified but not clearly understood and verified (but JGOFS offers new ideas and results);
- Anthropogenic $CO_2$ inventory in the S.O. is not known: the differences between methods, indirect and OGCM, reach a factor of 3 (see results from Gruber, 1998 and Sabine et al., 1999);
- Published data and/or merged data products, are not easily available but projects are underway (e.g. A. Dickson, 2000) to create global $pCO_2$ dataset (including standardization); this will take time and I am sure everyone would agree that the year 2000 is a good time to start sharing and merging data from the last century (this is also our responsibility for present and future research, including the definition of new observational strategies, where and when?).

The list above is incomplete. This is just an introduction to give a flavour of what the S.O. waters are still hiding; the list does not included what has been learned since the beginning of WOCE/JGOFS era. The list also does not included what is still not understood about the dynamics (rate of deep and bottom water formations, role of sea-ice coupling, etc.), the biology (export production, C/N/Si/Fe coupling), or the paleoclimatology (Vostok records, climate and paleo-productivity) etc. Many of these questions are addressed in the framework of CLIVAR, SOLAS and other international projects.

Data synthesis: reality and dreams - The starting point for any $CO_2$ data synthesis will be to have a list of the cruises, noting when and where the cruise was organized. A large portion of this information, could certainly be obtained from 5 main sources:

- The CDIAC (contact A.Kozyr);
- The JGOFS cruises inventory (contact B.Balino) and links to national JGOFS data base;
- The Joint IOC-JGOFS $CO_2$ Panel report (Poisson et al, 1995);
- The Data set assembled at Lamont (Takahashi et al., 1999);
- The Data set under construction at Scripps (A.Dickson, 2000).

These reports and archives include global $CO_2$ data. In order to compile the list of the cruises and to identify the projects for the next 5 years, an inquiry has been addressed to about 50 colleagues.

Since May 2000, we have received about 15 answers with relevant information. **Figures 8** and **9** detail the period of the cruises.

It is clear that most of the data have been obtained during austral summer, some in spring and autumn. In most of the circumpolar zones (SAZ, PFZ, POOZ, SIZ) between 5 to 15 % of the cruises represent winter data. During summer, all basins (Atlantic, Indian, Pacific, Ross and Weddell) have been explored (**Figure 10**) but we recognized, at that stage, more than half of the cruises listed (information obtained directly from contributors) have been organized in the Indian sector. The list needs clearly to be completed.

Projects concerning $CO_2$ observations in the S.O. are presented below. The table presents a list of cruises that are planned by different groups (the list includes projects accepted or recommended but not yet accepted). The information was obtained directly from contributors in May-June 2000. Note that few cruises are planned for winter season.

**Table 1**. Planned Cruises for the Southern Ocean

| Origine | Countr | Institut | Cruise | Year | Mont | Month | Ocea | Frontal SAZ / | POO | SIZ | Surf | DIC | TA | pH | d13C- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bakker/Wats | PB/U | NIOZ/UE | CARUS | 2000 | 11 | | ATL | Yes | Yes | Yes | Yes | Yes | | | |
| Hoppem | Germ | | Polarster | 2003 | X | | AT WED- | Yes | Yes | | Yes | Yes | | | |
| Ishii | Japa | MRI | Umitaka- | 2001 | 11 | | PAC | | Yes | Yes | | Yes | | Yes | |
| Ishii | Japa | MRI | Hakuho- | 2001 | 12 | janv- | PAC | Yes | Yes | Yes | Yes | Yes | | Yes | |
| Ishii | Japa | MRI | Polar | 2002 | 2 | | PAC | | Yes | Yes | | Yes | | Yes | |
| Ishii | Japa | MRI | Shirase/JARE | 2002 | 3 | | PAC | | Yes | Yes | | Yes | | Yes | |
| Metzl | Fr | LPCM/IPS | OISO | 2001 | 1 | 2 | IND | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| Metzl | Fr | LPCM/IPS | OISO | 2001 | 7 | 2 | IND | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| Metzl | Fr | LPCM/IPS | OISO | 200X | 1 | Rep | IND | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| Metzl | Fr | LPCM/IPS | OISO | 200X | 7 | Rep | IND | Yes | Yes | Yes | Yes | Yes | Yes | | Yes |
| Poisso | Fr/Arge | LPCM/IPS | ARGA | 200X | | Rep. | AT | Yes | Yes | Yes | Yes | | | | |
| Tilbrook/Tru | Aust | CSIR | WOCE/SR | 2001 | 11 | | IND | Yes | Yes | Yes | Yes | | | | |
| Tilbroo | Aust | CSIR | Supply | 200X | | | IND | Yes | Yes | Yes | Yes | | | | |
| Tilbroo | Aust | CSIR | Time | 200X | | | IND | Yes | | | | | | | |

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## 8.4 ARCTIC OCEAN AND NORDIC SEAS

Dr. Leif Anderson, from the University of Göteborg and Chalmers University of Technology, reported on these activities. Air – sea exchange of carbon dioxide is driven by, together with the wind field, the difference in partial pressure ($pCO_2$) between the two media. The spatial and temporal variability in $pCO_2$ over the year is significantly larger in the surface water relative to the atmosphere. The solubility of $CO_2$ increases with decreasing temperature, favouring a flux from the atmosphere into the surface water in oceanic regions losing heat to the atmosphere, like the North Atlantic [*Watson et al.,* 1995] and the Nordic Seas [*Anderson et al.,* 2000b].

The carbon cycle in the Arctic Mediterranean Seas is of extra importance because of extended vertical ventilation that occurs here during the winter season. This ventilation penetrates regularly down to about 1000 m in the Greenland Sea [*Bönisch et al.,* 1997], and in some years has reached several kilometres depth in some areas. The effects of this ventilation on the carbon cycle are at least twofold: it serves as an effective conveyor of dissolved carbon from the surface water to the deep, and as a means of extensive vertical mixing of nutrients (and dissolved inorganic carbon) up into the surface water. The former is a means of sequestering anthropogenic carbon dioxide on time scales of several hundred years, while the latter fosters primary production.

Prior to the 1990s, work within the carbon cycle of the Nordic Seas was limited to the study of the Transient Tracers in the Ocean (TTO) project and a winter expedition in 1982 by the Bedford Institute of Oceanography [*Chen et al.*, 1990]. Cruises in which carbon system parameters have been determined within the Arctic Mediterranean Seas are given in Tables 2 – 4. The air-sea carbon flux has been estimated from budget computations to be $110 \times 10^{12}$ g C $yr^{-1}$ in the Arctic Mediterranean Seas [*Lundberg and Haugan,* 1996] and $24 \times 10^{12}$ g C $yr^{-1}$ in the Arctic Ocean, including the shelf seas [*Anderson et al.,* 1998a]. The difference, $86 \times 10^{12}$ g C $yr^{-1}$, is hence assigned to uptake by the Nordic Seas. These estimates have significant uncertainties, but they point to the significance of the Nordic Seas in uptake of $CO_2$ from the atmosphere. For the Arctic Ocean, the shelf seas are the most important, with the uptake from the atmosphere being 9 x$10^{12}$ g C $yr^{-1}$ in Barents Sea [*Fransson et al.,* 2001].

Data from the European funded European Sub-Polar Ocean Project (ESOP) was used to compute the air-sea flux in the three sub-seas of the Nordic Seas and in different seasons, shown in Table 5 [*Skjelvan et al.,* 1999]. It was further shown that the uptake of atmospheric $CO_2$ in the Greenland Sea is positive all year around and in the order of 20 ± 4 x $10^{12}$ g C $yr^{-1}$ when integrated over the ice free part [*Hood et al.,* 1999; *Anderson et al.,* 2000b]. The air – sea flux is about 10 times higher than the sequestering of anthropogenic carbon, 2.4 ± 0.7x$10^{12}$ g C $y^{-1}$, by deep water production below 1500 m [*Anderson et al.,* 2000a]. On the other hand there is a significant production of intermediate waters, 200 – 1500 m, that also contributes to the overflow into the North Atlantic Ocean. Of the reported overflow estimated to be about 5 Sv, around one-third is driven by deep and intermediate water formation in the Arctic Ocean [*Mauritzen,* 1996; *Anderson et al.,* 1998b, 1999] and the rest is likely more or less equally divided between the Greenland and Iceland Seas. Thus, anthropogenic carbon corresponding to a ventilation of close to 2 Sv will be sequestered in the Greenland Sea, increasing the estimate by a factor 10 and making it about the same as the atmospheric uptake.

The organic matter formed during primary production, which drives about half of the atmospheric uptake in the Greenland Sea, is to a very high degree mineralized in the upper few hundred meters during the non-productive seasons. Only on the order of a few per cent of the new production is found in sediment traps as shallow as 300 m. It is also seen in the distribution of decay products, nutrients and dissolved inorganic carbon that no significant mineralization occurs in the deep Greenland Sea. Hence, in a longer time perspective it is only through the production of waters that are dense enough to contribute to the overflow into the deep North Atlantic that atmospheric carbon dioxide will be sequestered. This is under the assumption that the ecosystem will not change in a way that increases the biological pump of carbon from the surface water to the deep ocean.

A natural question is then, how sensitive is the sequestering of carbon to a climate change? Will processes in the Arctic Mediterranean Seas make a positive feedback to the atmospheric $CO_2$ concentration, with direct or indirect consequences the climate change?

**Table 2**. Cruises during which data relevant to the carbon cycle were measured in the Greenland Sea within ESOP projects. UW$pCO_2$ equals underway measurements of the $CO_2$ partial pressure in the surface water.

| Expedition | Month | $C_T$ | $A_T$ | $p$H | UW$pCO_2$ | *DOC* |
|---|---|---|---|---|---|---|
| Håkon Mosby, 1994 | February | √ | √ | | | |
| Håkon Mosby, 1995 | February | √ | √ | | √ | √ |
| Håkon Mosby, 1997 | March | √ | | | √ | |
| Håkon Mosby, 1994 | March | √ | √ | | | |
| Johan Hjort, 1997 | April | √ | √ | √ | √ | |
| Johan Hjort, 1995 | May | √ | | | √ | |
| Johan Hjort, 1994 | May | √ | | | | |
| James Clark Ross, 1996 | June-July | √ | | | √ | |
| Johan Hjort, 1996 | July-August | | | | | √ |
| Johan Hjort, 1993 | August | √ | | | | |
| Johan Hjort, 1998 | August | √ | √ | √ | | |
| Johan Hjort, 1995 | November | √ | | | | |
| Håkon Mosby, 1996 | November | √ | | | √ | |

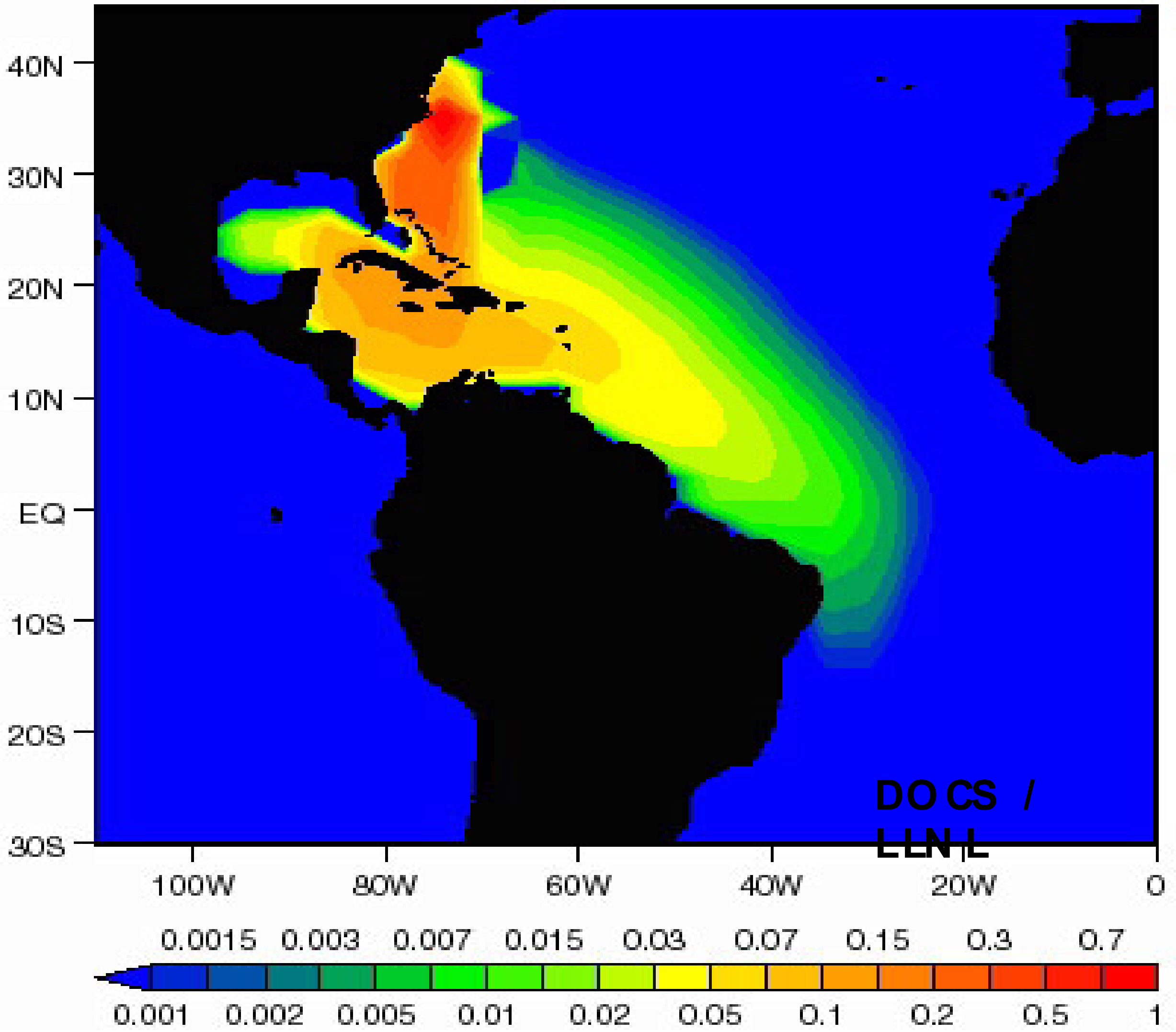
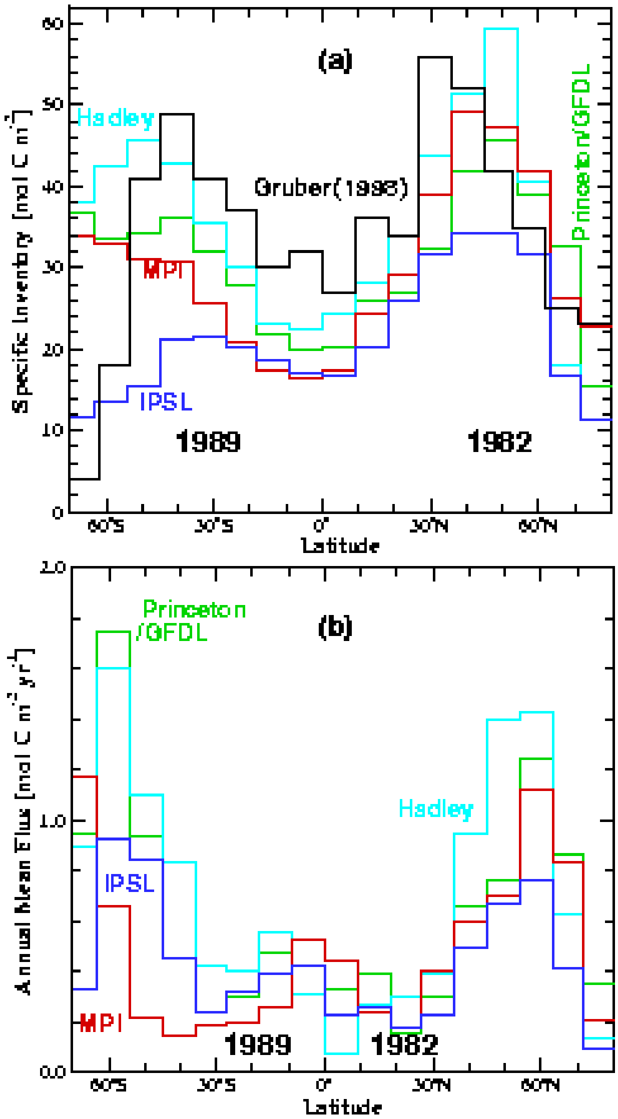


**Figure 1.** Simulations of direct injection performed at Lawrence Livermore National Laboratory indicating predicted distribution of $CO_2$ deliberately injected into the oceans. Such simulations can be used to estimate the effectiveness of this strategy at sequestering carbon away from the atmosphere, and to indicate the distribution of pH and DIC changes that could be expected from such an injection.

**Figure 2** (from Orr et al., 2000)



J. Orr, LSCE/CEA-CNRS, Saclay
OCMIP 10 February 200

**Figure 2** (a) Specific inventory of anthropogenic $CO_2$ in the Atlantic Ocean [in mol C $m^{-2}$] according to the data-based estimates of *Gruber* [1998] (black) and the model estimates from Princeton/GFDL (green), MPI (red), Hadley (cyan), and IPSL (blue). (b) Annual mean air-sea $CO_2$ flux [in mol C $m^{-2}yr^{-r}$] simulated by the same four models. North of the equator inventories and fluxes are given for 1982 (TTO/NAS etc); south of the equator they are given for 1989 (SAVE etc).

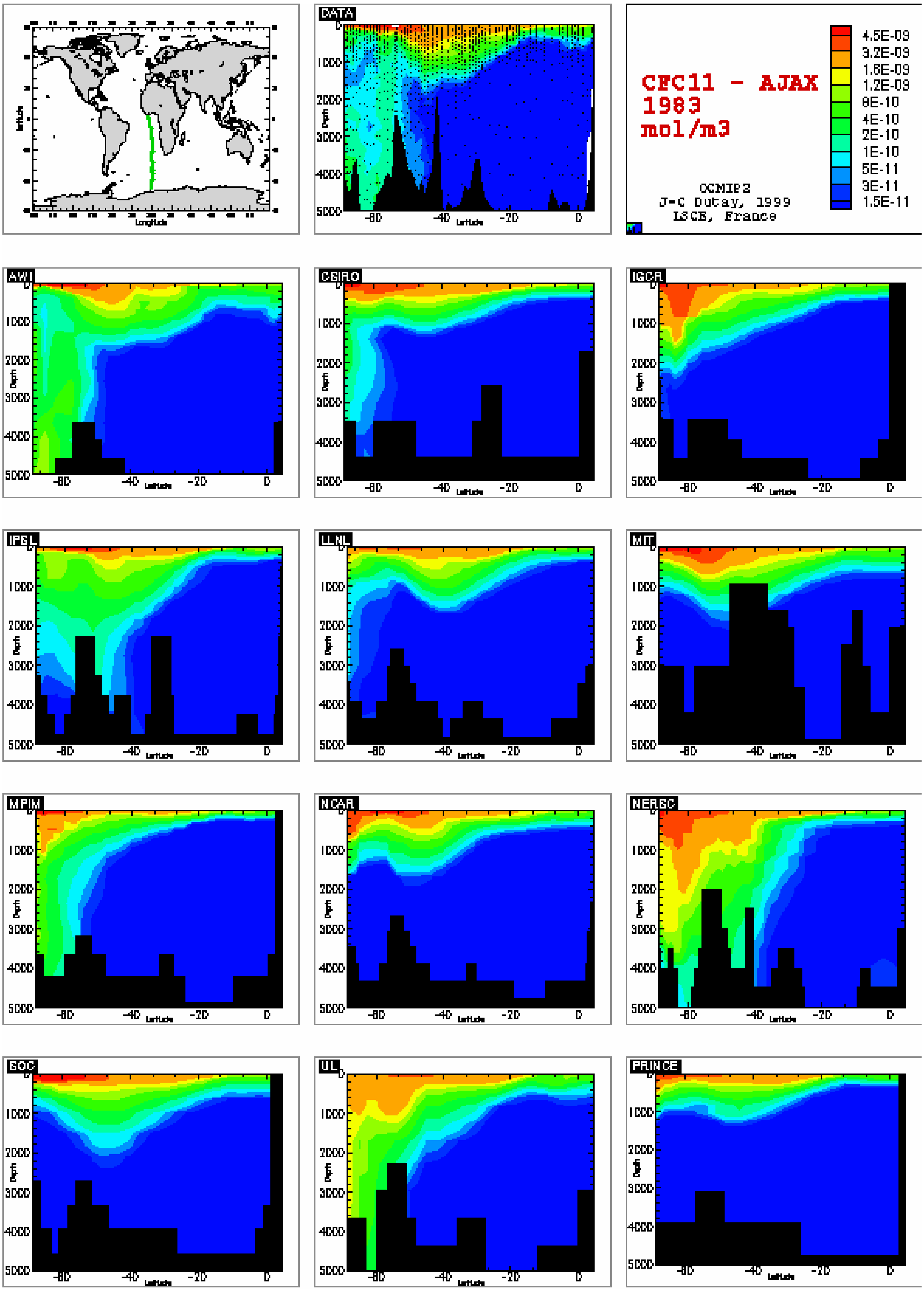
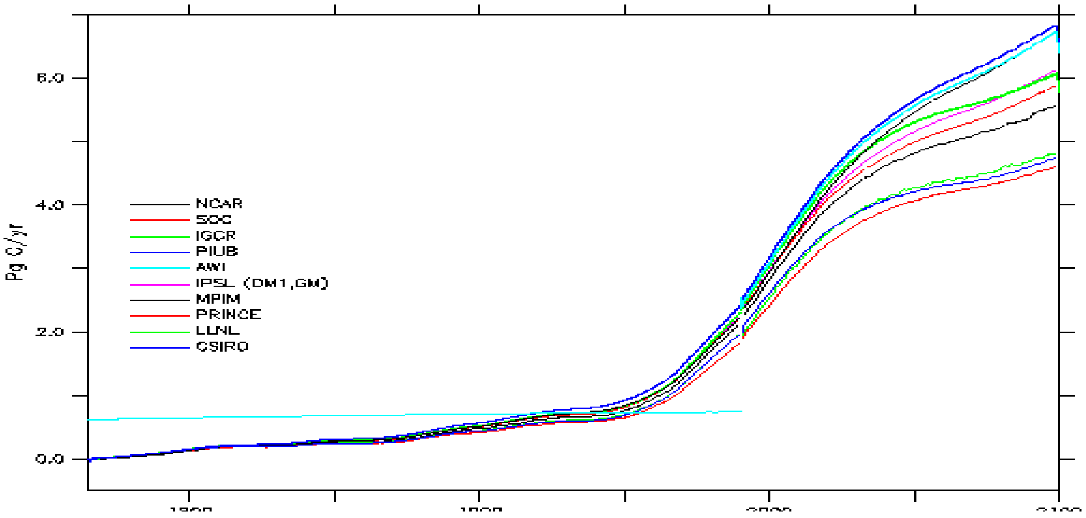


**Figure 3** (from Orr and Dutay, 1999).

**Figure 4**. OCMIP-2: Global mean air-sea flux estimates (Historical + CIS92A



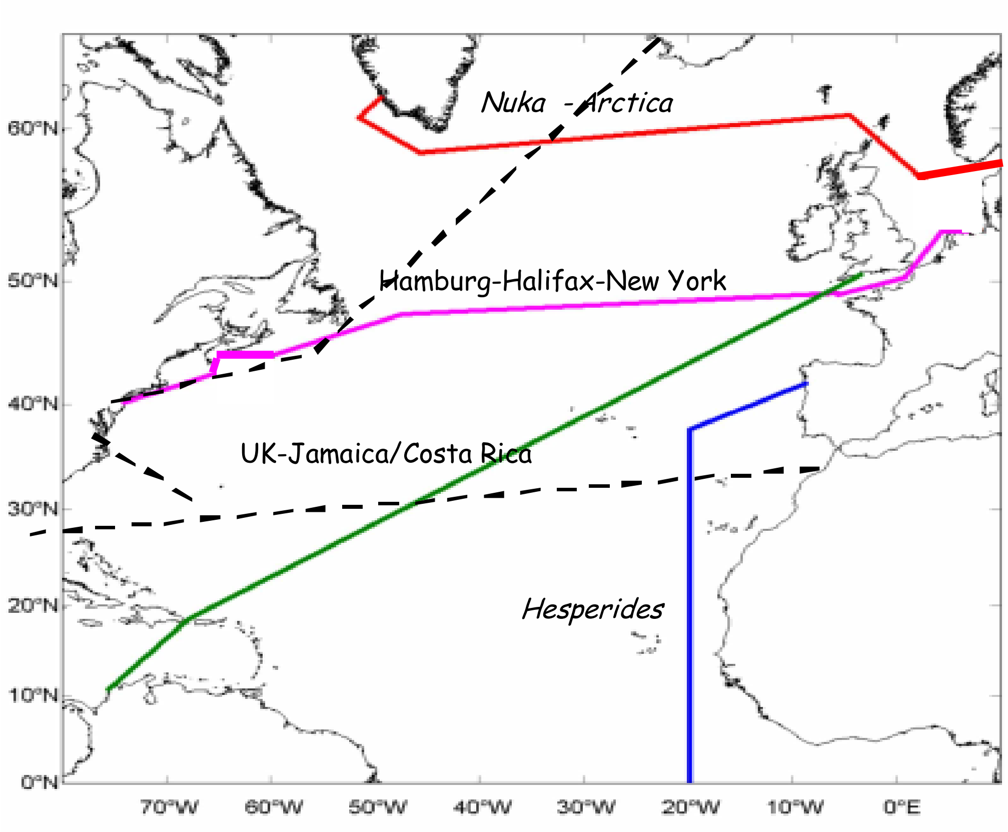


**Figure 5**: Proposed ship of opportunity routes for $pCO_2$ measurements in CAVASSOO (solid lines). Also shown are proposed lines for $CO_2$ measurements to be run by US and Canadian colleagues.

**Figure 6**. Air-sea CO$_2$ fluxes in the Southern Ocean (from Metzl, 2000).

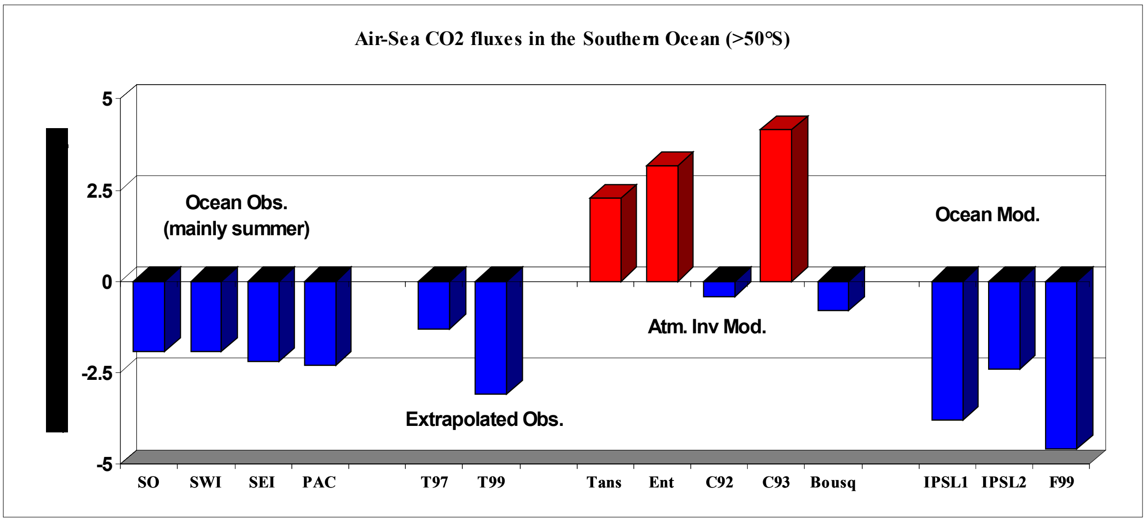


**Figure 6** presents the Air-sea CO$_2$ fluxes in the Southern Ocean (Metzl, 2000) deduced from observations and models (blue bars indicates ocean sinks, red bars indicate sources). All estimates, derived from published calculations (generally presented in different units and periods for the region south of 50°S), are reported here in common unit (mmol/m$^2$/d) and calculated or corrected to a standard gas transfer coefficient (Wanninkhof, 1992). For fluxes based on observations we show the results from Tans et al., 1990 (noted **S.O**. for the whole Southern Ocean), from Metzl et al., 1995; ( **SWI**) for the south-western Indian sector, from Tilbrook, 1995; (**SEI**) in the south-eastern Indian sector; and from Murphy et al.,1991 (**PAC**) in the South Pacific. Flux estimates from extrapolations are those from Takahashi et al (1997, 1999) (noted **T97**, **T99**); T97 refers to year 1990; T99 version refers to year 1995 and includes new data mostly in the Indian Ocean (MINERVE data from Poisson et al., 1993; Metzl et al. 1995, 98 and US/JGOFS from Sabine et al., 2000). Estimates obtained with atmospheric inverse methods are those from Tans et al., 1990; Enting et al., 1995; Ciais et al., 1995 (two years 1992 and 1993) and Bousquet, 1997. Estimates from ocean models are two versions of the IPSL model (IPSL 1 with HAMOCC3 and IPSL2 with P3ZD biogeochemical scheme) developed by Aumont (1997); and finally, the modelling approach developed by Louanchi et al (1996) applied on the Southern Ocean by Louanchi et al (1999). In all Southern Ocean sectors, observations suggest that the southern ocean is a sink during summer, around 2 mmol/m$^2$/d. However, most results from atmospheric models suggest the region is a source or close to equilibrium whereas large scale ocean models clearly suggest that austral region acts as a strong sink (maybe too strong); although "large scale" average model calculations seems reasonable compared to observed fluxes, it is worth noting that models sometimes show incoherent distribution at "regional scale"; the simulated puzzle of sources and sinks is not the same as the observed puzzle. One priority should be to validate more rigorously the simulated puzzle of sources and sinks and to document *in-situ* pCO$_2$ distribution during winter season. The oceanic view should then be used to constraint atmospheric models that are unable to capture the air-sea CO$_2$ fluxes in the Southern Ocean, mostly because meridional gradient of atmospheric CO$_2$ concentration are small in the sub-polar and high latitudes of the southern hemisphere, a region where atmospheric GCM does not assimilate a lot of *in-situ* data.

**Figure 7**. Monthly fCO$_2$ in the Indian Ocean Sub-Antartic Zone

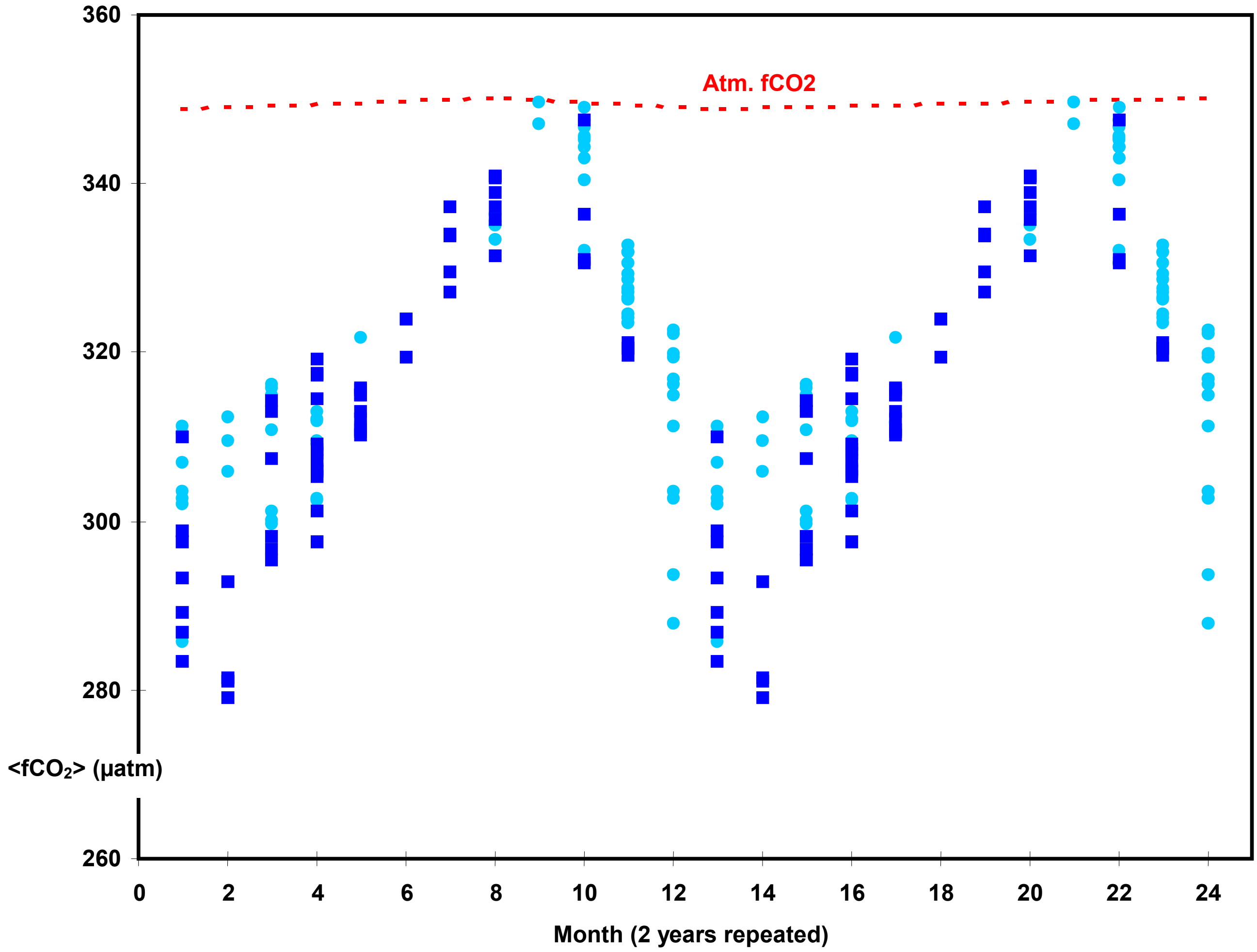


**Figure 7**. Synthesis of fCO$_2$ data in the Southern Ocean. Figure 7 shows the synthesis of fCO$_2$ data is very useful to improve our understanding of spatial and temporal (at least seasonal) variability of the oceanic CO$_2$ cycle and air-sea fluxes calculations. As an example, this figure shows the annual sea surface fCO$_2$ cycle composed in the Indian Ocean Sub-Antarctic Zone (Metzl et al., 1999): circles and squares represent average monthly fCO$_2$ data observed respectively in the eastern (by CSIRO/Australia) and western (LPCM/France) Indian Ocean. In summer, low fCO$_2$ (CO$_2$ sink) are dominated by primary production; near equilibrium concentrations in austral winter are associated to deep mixed layers occurring in the SAZ. Such an observed cycle can be used to validate ocean carbon models (e.g. OCMIP runs), to constrain atmospheric models, or to calculate large scale air-sea CO$_2$ fluxes. Extrapolation of the fCO$_2$ cycle couple with wind speed data, suggest the SAZ represent a sink around 1 gTC/yr for the circumpolar region 40-50° S.

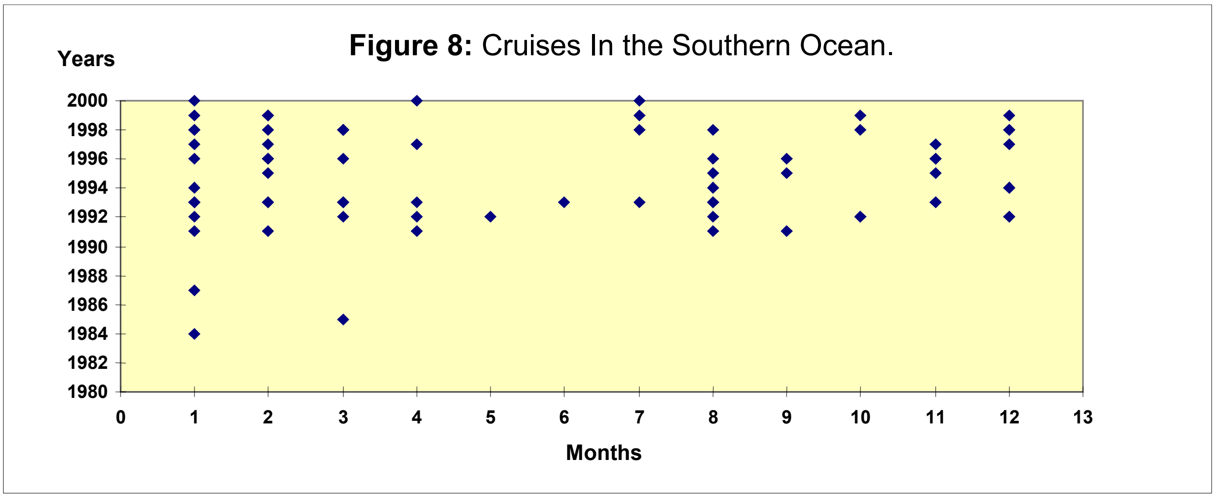


**Figure 8**: Period (Yr/month) of cruises with pCO$_2$ observations in the Southern Ocean (all sectors). Note in Figure 8 that there are few cruises during winter season. This figure is based on information obtained directly from contributors. It should be completed with list of cruises detailed in other archives (e.g. CDIAC).

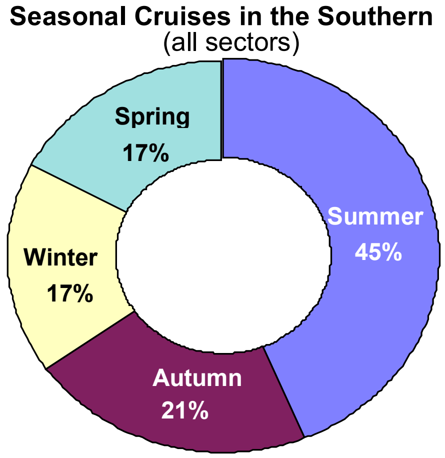


**Figure 9:** Percentage of cruises for different seasonal (years 1982-2000). This figure is based on information obtained directly from contributors.

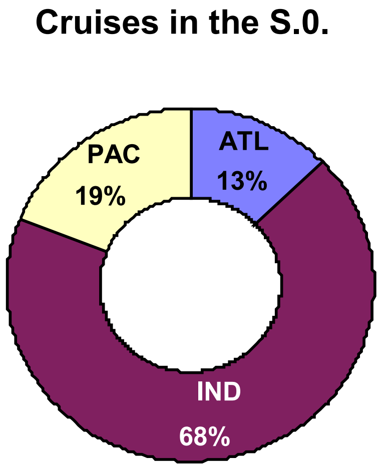
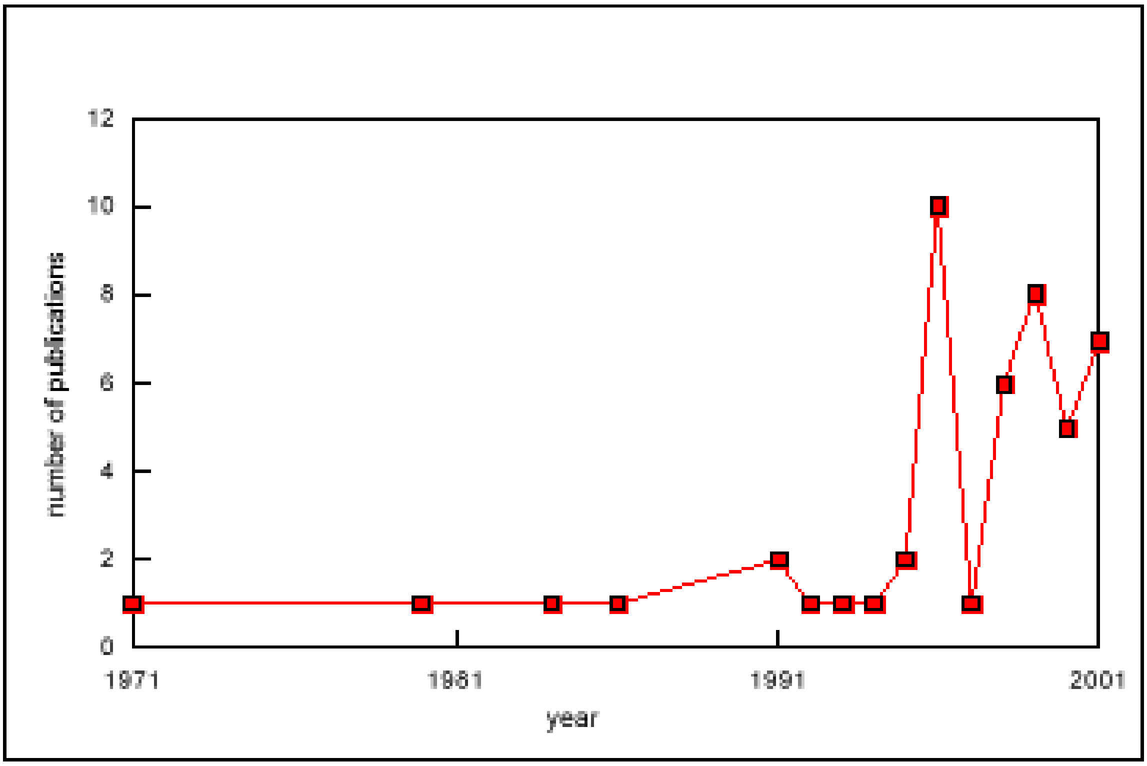


**Figure 10**: Percentage of cruises for different basin (Ross included in PAC, Weddell in ATL). This figure is based on information obtained directly from contributors.

**Figure 11**: Publications on air-sea exchanges in coastal ecosystems



| Expedition | Month | $C_T$ | $A_T$ | $p$H | $f$$CO_2$ | UW$p$$CO_2$ |
|---|---|---|---|---|---|---|
| B05-1996 | May | √ | | √ | √ | |
| B09-1996 | September | √ | | | √ | |
| B12-1996 | November | √ | | | √ | |
| B03-1997 | February | √ | | | √ | |
| B06-1997 | May | √ | | √ | √ | |
| B10-1997 | September | √ | | | √ | |
| B15-1997 | Nov.-Dec. | √ | | | √ | |
| B02-1998 | Feb.-March | √ | | | √ | √ |
| B06-1998 | May-June | √ | | | √ | √ |
| B09-1998 | September | √ | | | √ | √ |
| B12-1998 | November | √ | | | √ | √ |

**Table 3**. Cruises of R/V Bjarni Saemundsson to the Denmark Strait and Iceland Sea during which data relevant to the carbon cycle were measured within ESOP 2. $f$$CO_2$ equals batch measurements of the $CO_2$ fugacity.

**Table 4**. Cruises during which data relevant to the carbon cycle were measured in the Arctic Ocean.

| Expedition | Month | $C_T$ | $A_T$ | $p$H | *DOC* |
|---|---|---|---|---|---|
| YMER-80 | August-September | √ | √ | | |
| CESAR (83) | April-May | √ | √ | | |
| MIZEX-84 | June-July | √ | √ | √ | |
| Canadian Ice Island (85) | June | √ | √ | | |
| Polarstern-87 | July-August | √ | √ | | |
| Oden 91 | August-September | √ | √ | | √ |
| Polarstern 93 | August-September | √ | | | |
| Arctic Ocean Section-94 | August | √ | √ | | √ |
| Laptev and East Siberian Seas (94) | August | √ | √ | | √ |
| Polarstern 96 | August-September | √ | √ | √ | √ |
| JOIS 97 | May-June | √ | √ | | |

**Table 5.** Air-sea flux estimates of $CO_2$ (g C $m^{-2}$ $yr^{-1}$) in central areas of the Greenland Sea, Norwegian Sea and Iceland Sea, as estimated by *Skjelvan et al.* (1999).

| Area | Season | | | |
|---|---|---|---|---|
| | Winter | Summer | Fall | Average |
| Greenland Sea | 120 | 65 | 94 | 93 |
| Norwegian Sea | 53 | 56 | 32 | 47 |
| Iceland Sea | 69 | 53 | 85 | 69 |

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## 8.5 INDIAN OCEAN

Dr. Dileep Kumar, from the National Institute of Oceanography of India, reported on ocean carbon activities in the Indian Ocean. The realization of human interference with the climate has paved way for undertaking global ocean exercises under the International Geosphere Biosphere programme (IGBP). The observations made as a part of the Indian national and international projects related to this programme threw new light into the processes of carbon dioxide cycling in the North Indian ocean. The Bay of Bengal is found to be a seasonal sink of atmospheric carbon dioxide (Kumar et al., 1996, Sarma et al., 1998) while the Arabian Sea is confirmed to be a source (George et al., 1994). The latter is in accordance with Takahashi (1989) but the former was different. The absorption by the Bay of Bengal surface waters is facilitated by strong surface stratification that curtailed effective upward pumping of pCO$_2$ laden sub-thermocline waters to the surface. In addition, nutrient loading from atmosphere and heavy river discharge facilitates higher biological production thus reducing the surface pCO$_2$ levels. Its levels decreased with salinity decrease, which is found to be lower closer to the coast and in winter monsoon season (Kumar et al., 1996). The removal of particulate carbon from upper layers of the Bay of Bengal appears to be more (Ittekkot et al., 1991) than in the Arabian Sea (Nair et al., 1989). The reduced remineralization of organic carbon in the former than in the latter region (Naqvi et al., 1996) could also have contributed to the reduced pCO$_2$ levels in surface waters of the bay. In contrast the remineralization is intense even in sub-oxic intermediate waters of the Arabian Sea where occurrence of nepheloid layers have been found (Naqvi et al., 1993).

Launching of Arabian Sea process Study as a part of the Joint Global Ocean Flux study (JGOFS) revealed a large variability in physico-chemical forcings and biological components that strongly influence the carbon dioxide cycling (Krishnaswami and Nair, 1996; Smith et al., 1998; Burkill, 1999). One of the important aspects established is the role of convection, driven by winter cooling, in promoting biological production (Banse, 1984; Madhupratap et al., 1996; Smith et al., 1998). It appears that the winter production might dominate that driven by monsoonal upwelling in summer. The Arabian Sea is also found to perennially emit carbon dioxide to atmosphere (Sarma et al., 1998; Goyet et al., 1999) with stronger emissions during southwest monsoon when the surface pCO$_2$ reached 680-700 µatm (Kortiginzer et al., 1997; Sarma, 1999). The sinking fluxes of organic carbon have been found to be insufficient to support the estimated respiration rates in intermediate layers. (Ducklow, 1993; Naqvi et al., 1993; Banse, 1984). A recent study on transparent exopolymer particles (TEP) indicated the occurrence of easily degradable polysaccharide materials in sub-oxic layers that could support the respiratory demands (Kumar et al., 1998). This study also revealed strong association of TEP with mineral particles that facilitate faster removal of organic carbon from the water column of the Bay of Bengal.

The information on carbon dioxide system in the southern subtropical Indian ocean and sub-antarctic regions is largely contributed by French researchers (Metzl et al., 1998; 1999) in addition to that by the World Ocean Circulation Experiment (WOCE; Goyet et al, 1999; Sabine et al., 1999). A strong seasonality in $pCO_2$ levels has been observed. While the sub-antarctic is found to be a sink of atmospheric carbon dioxide in austral summer (Metzl et al., 1999) the southern subtropical Indian Ocean is a sink in winter (Metzl et al., 1998). The seasonal amplitude in these regions is about 50-60 μatm. The amplitude in the Indian Ocean appears to be greater in the north in view of the extreme physical and biological regimes. While the variability in the bay is brought about by freshwater discharge that in the Arabian Sea is by combined effects of circulation and biological production.

A modeling study of Louanchi et al. (1996) clearly established net absorption to emission trends as one progresses from sub-antarctic region to the North Indian Ocean. While the Indian Ocean north of $10^oN$ can release carbon dioxide to atmosphere throughout the year that between $20^oS$ and $10^oS$ emits during December-May. However, the modeling results do not appear to support the seasonal trends noted by Metzl et al. (1998, 1999) between sub-antarctic and subtropical waters. The Indian Ocean is estimated to absorb 0.5 Gt C $y^{-1}$ (Lounchi et al., 1996). Results from the WOCE programme (Sabine et al., 1999) substantiate the trends observed by Takahashi (1989) and Louanchi et al. (1996), in general. The most significant outcome of the WOCE results is the estimation of anthropogenic fraction of the carbon dioxide in the Indian Ocean. While the anthropogenic carbon is higher in the Bay of Bengal surface waters it penetrated deeper in the Red Sea followed by the Arabian Sea (Goyet et al., 1999). From the inventory made by Sabine et al. (1999) it would seem that much of the impinged carbon enters the deep Indian Ocean near the subtropical convergence zone. The water column inventory indicates an annual invasion of 0.24 Gt C in to the Indian Ocean. This invasion might result both from air-sea exchange and lateral transport. The dominant process is yet to be established.

What next? With the current knowledge it is difficult to find the carbon turnover and construct budgets in the Indian Ocean. The following points need to be addressed in this connection to improve upon our understanding of the carbon dynamics in the Indian Ocean.

- Carbon turnover in surface waters - from organic matter synthesis to Regeneration;
- Impact of continental connections – effect of materials transported from atmosphere and rivers in carbon fixation and removal from water column;
- Effects of turbulent conditions – on promoting biological production and intensifying the air-sea exchange processes;
- Effect of African dust deposition on southern ocean productivity;
- Mapping of winter production in the Arabian Sea;
- Quantification of river inputs of anthropogenic carbon dioxide;
- Effect of stratification on carbon draw down in the Bay of Bengal;
- Initiate short and long term measurements.

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## 8.6 COASTAL OCEAN OBSERVATIONS

Dr. Michel Frankignoulle, from the Université de Liège, reported on ocean carbon activities in the coastal ocean. Human activities presently release about 7.7 Gigatons of carbon per year (Gt C year $^{-1}$ ) to the atmosphere, by fossil fuel burning and change in land use (*e.g.* deforestation). It is well established that 3.3 GtC /yr remain in the atmosphere. The ocean behaves as a sink estimated to be 2.0 GtC /yr and the terrestrial biosphere is often assumed to trap the remaining 2.4 GtC /yr. However, this budget does not consider explicitly the fluxes in the coastal ocean because it is difficult to include this region in global circulation models and because of the lack of field data on the spatial distribution and temporal variability of $pCO_2$. The coastal ocean is the site of intense physical and biological processes from which important air-sea gradients of $CO_2$ can be expected, but the air-sea $CO_2$ exchanges are still poorly known. The causes of these uncertainties are many. First, these regions show high variability in time and in space that is usually not adequately monitored by sparse or incomplete data sets. Second, the budgets proposed in literature are based on indirect calculations and use different approaches and a variety of experimentally determined processes that yield different conclusions from one author to another, even within the same research programme [SEEP I and II projects]. Thirdly, the biological diversity of coastal ecosystems make difficult to establish global budget for the coastal ocean. For these reasons, very little literature is available on air-sea $CO_2$ in the coastal ocean. To illustrate this point, Figure 12 gives the number of papers published over the last 30 years and related to air-sea $CO_2$ exchange in coastal ecosystems and it shows that the number of publication only started to be significant in the second part of the 90's.

Among the various coastal ecosystems, the continental shelf is of particular importance, due to its relative surface area (82% of the coastal ocean). The shelf is known to house a large fraction of the oceanic primary production, a contribution by far larger than its surface area fraction (7%) of the total ocean. The role of continental shelves in the global carbon cycle has been the subject of a few major national and international research programmes (*e.g.* KEEP, KUSTOS, OMEX, SEEP, SES, TROPICS) but it is not yet clear if these regions act as a sink or as a source of atmospheric $CO_2$. The role of the shelves in the inorganic carbon cycle is uncertain because it results from the integration of production/degradation/export of organic carbon, burial/dissolution of carbonates in the shallow sediment and input of inorganic carbon from rivers and coastal upwelling. Table 1 gives a tentative summary of data available so far for the proximal and distal shelf. The lack of data is obvious from this table but a recent work carried out during five cruises in the East China Sea suggests that continental shelves constitute a significant sink for atmospheric $CO_2$ and led the authors to formulate the “continental shelf pump” hypothesis that could accounts for a sink in the range 0.5 to 1.0 GtC /yr. Some other coastal ecosystems have been studied in terms of atmospheric interactions. Estuaries are known to be most often strongly over-saturated with $pCO_2$ which may reach several thousands µatm. Coral reefs are usually recognized to act as a source of $CO_2$ due to the low net production and the net release of $CO_2$ by calcification. Seagrass meadows are net autotrophic and should act as net sinks for atmospheric $CO_2$. The relative importance of these sinks and sources have still to be determined in the global context. An additional complication is due to the temporal variability, which is different for most coastal ecosystems, and the sampling strategy has to be adapted for each of them. Seasonal variability can be influenced by nutrients or light availability, by upwelling/downwelling and relaxation, river water flow, and monsoons. Daily variability may be either small (shelf) or intense (estuaries, reefs, seagrass meadows).

| Ecosystem | Region | Authors | Year | pCO2 range | annual coverage | net annual flux (mmol/m².day) | Remarks |
|---|---|---|---|---|---|---|---|
| Upwelling | Peruvian coast | Kelly and Hood | 1971 | 140 - 1200 | poor | none | |
| | | Simpson and Zirino | 1980 | | | | |
| | | Copin-Montégut and Raimbault | 1994 | | | | |
| | Mauritanian coast | Copin-Montégut and Avril | 1995 | 300-450 | poor | none | |
| | | Lefèvre et al. | 1998 | | | | |
| | | Bakker et al. | 1999 | | | | |
| | Omani coast | Körtzinger et al. | 1997 | 365 - 750 | good | | |
| | | Goyet et al. | 1998 | | | **+ 2.5** | W92 |
| | Californian coast | Simpson | 1984 | 130-690 | poor | none | |
| | | Friederich et al. | 1995 | | | | |
| | | van Green et al. | 2000 | | | | |
| | Portuguese-Galician coast | Pérez et al. | 1999 | 320 - 460 | fair | calculated but not annually integrated | L&M86 |
| | | Borges and Frankignoulle | submitted | 265 - 415 | fair | in preparation | L&M86, T90, W92 |
| River plumes | Yantze and Yellow river | Tsunogai et al. | 1999 | 278 - 360 | good | not computed specifically for plumes | based on a 70% reduction of 14C global mean K |
| (Salinities < 34) | - | Wang et al. | 2000 | 200 - 370 | good | not computed specifically for plumes | L&M86, T90 |
| | Weser and Elbe | Brasse et al. | 1999 | 400 - 427 | poor | none | |
| | - | Brasse et al. | submitted | 110 - 550 | good | none | |
| | - | Frankignoulle et al. | 1998 | 340-580 | fair | measured but not annually integrated | floating bell method |
| | Douro, Gironde, Sado | Frankignoulle et al. | 1998 | 385-1330 | poor | measured but not annually integrated | floating bell method |
| | Rhine | Hoppema | 1991 | 150 - 450 | fair | none | |
| | - | Bakker et al. | 1996 | 300 - 800 | poor | none | |
| | - | Frankignoulle et al. | 1998 | 385-585 | fair | measured but not annually integrated | floating bell method |
| | Scheldt | Borges and Frankignoulle | 1999 | 90 - 778 | good | none | |
| | - | Frankignoulle et al. | 1998 | 240-640 | fair | measured but not annually integrated | floating bell method |
| | - | Frankignoulle et al. | 1996 | 150 - 550 | fair | none | |
| | - | Frankignoulle et al. | 1996 | 117 - 658 | good | calculated but not annually integrated | L&M86 |
| | - | Borges and Frankignoulle | submitted | 88 - 677 | good | **+2.0 to +4.7** | L&M86, T90, W92 |
| | Fly, Purari, Kikori (Papoua New Guinea) | Brunskill et al. | 2000 | **none** | fair | **+33** | from P/R balance, no CO2 measurements |
| | Ganges, Mahanadi, Godavari and Krishna (Bay of Bengal) | Kumar et al. | 1996 | 240-370 | good | **-0.6** | W92 |
| | Amazon | Ternon et al. | 2000 | 150 - 370 | fair | not specifically | ???? |
| | Congo | Bakker et al. | 1999 | 352 - 409 | poor | none | river plumes that extend into open ocean behond shelf break |
| Open shelves | Bering Sea | Codispoti et al. | 1986 | 130 - 440 | good | none | |
| | Noth Sea | Frankignoulle and Borges | in press | 150 - 550 | good | calculated but not annually integrated | L&M 86 |
| | - | Kempe and Pengler | 1991 | 100 - 450 | poor | calculated but not annually integrated | K= 11.9 cm/h based on Broecker and Peng (1982) |
| | - | Schneider et al. | 1992 | 340 - 220 | poor | none | |
| | New Jersey coast | Boehme et al. | 1996 | 211 - 658 | good | **-1.17 to -2.30** | L&M86, T90, W92 |
| | East China Sea | Tsunogai et al. | 1999 | 278 - 390 | good | **-8.00** | based on a 70% reduction of 14C global mean K |
| | - | Wang et al. | 2000 | 200 - 400 | good | **-3.3 to -7.7** | L&M86, T90 |
| | Gulf of Biscay | Frankignoulle and Borges | in press | 260-440 | good | **-4.8 to -7.6** | L&M86, T90, W92 |
| | Southern Bight of the North Sea (mixed waters) | Borges and Frankignoulle | submitted | 162-423 | good | **-1.4 to -2.9** | L&M86, T90, W92 |
| | English Channel | Frankignoulle et al. | 1996 | 180 - 480 | fair | none | |
| | | Frankignoulle et al. | 1996 | 220 - 500 | fair | calculated but not annually integrated | L&M 86 |
| | | Borges and Frankignoulle | submitted | 320 - 443 | good | **+0.6 to +1.1** | L&M 86, T90 and W92 |
| | Baltic Sea | Thomas and Schneider | 1999 | 200 - 500 | fair | **-2.5** | biogeochemical model calibrated & 2 cuises & W92 |

poor = one cruise
fair = more than 2 cruises

good = covering seasonnality

seasonnality pour d'autres systèmes est due
à des processus physiques/météo tels que
mousson ou cycle annuel
upwelling/donwelling
seasonnality pour d'autres systèmes est due
à la limitation classique lumière/nutriments

de la production primaire
seasonnality pour d'autres systèmes est due
débit d'eau douce (certaines plumes, Mer Baltique)

Cyclicité à relativement courte échelle du style cycle
upwelling/relaxation d'upwelling de l'ordre de 15 jours

Variabilté à échelle diurnes est soit faible (open shelf)
soit très forte (récifs, herbiers)
Bref, stratégie d'échantillonnage dans chaque zone doit
être spécifique

Recommendations for research in the coastal ocean:

- Continental shelves: a better coverage at highest latitudes (Northern Hemisphere);
- All ecosystems: a better coverage in Africa;
- Estuaries: data from Asian and African rivers;
- Air-sea exchange coefficient: some ecosystems need a specific algorithm because turbulence is also generated by interactions with the bottom (estuaries, coral reefs);
- Coupling oceanic and continental shelf models;
- Evaluating the response of coastal ecosystems to global change (sea level rise, carbonate chemistry…).

The Panel discussed the results of the compilation of coastal carbon flux research, and expressed surprise and concern over the potential 1 Gigaton uncertainty incurred by ignoring the coastal areas. The current $CO_2$ climatology (Takahashi) does not include the coastal zone. The Panel recommended support for further investigations of carbon fluxes in the coastal zone and inclusion of these results in global estimates and models (when resolution will permit).

## 8.7 REMOTE SENSING

Dr Jaqueline Boutin, from the Université Pierre et Marie Curie, reported on remote sensing activities in relation to ocean carbon research and monitoring. Remote sensing data are used to support *in situ* data for air-sea $CO_2$ flux studies in the following ways:

### $CO_2$ exchange coefficient:

Owing to the multiplication of remote sensing sensors measuring the sea surface wind speed, U, (altimeters, microwave radiometers, scatterometers), data from 1985 are now available to study the space and time variability of the $CO_2$ exchange coefficient, K, at regional and global scales. The main drawback is that the exact relation between K and U is still a very debated question.

Nevertheless, whatever the K-U relationship is used, a large part of the variability of the air-sea $CO_2$ flux at short term (weekly to seasonal) and at regional scale is driven by K; this has been shown for several regions. Moreover, using global wind fields, it is possible to estimate the consequences of using various K-U relationships on the global K fields variability and associated flux as well as the wind speed range, which is of importance for air-sea $CO_2$ flux studies: when looking at global flux, about 90% of the flux is obtained for wind speed between 4 and 17m/s. When looking at regional fluxes, an accuracy of about 0.1GtC/yr is obtained for a wind speed range between 2 and 17m/s [Boutin et al., 2000].

In the future, the monitoring of K should continue with new planned remote sensors (Seawinds on ADEOS2, ASCAT on METOP, etc.). A better knowledge of the K-U relationship could emerge from new in situ experiments. The use of other parameter than U could also be envisaged (friction velocity, $u_*$, mean square slope) to monitor K [Frew et al., 2000], the main difficulty being to establish their relation to K; new methods to derive global fields of $u_*$ from altimetry [Elfouhaily et al., 1998] and from scatterometry [*Weissman and Graber*, 1999] have recently been developed.

### Ocean $CO_2$ partial pressure and air-sea $CO_2$ flux:

Remote sensing data help to describe in space and time the physical and biogeochemical context in which in situ data are collected. For instance, Robertson et al. [1994] showed on an AVHRR image that their measurements were made in a coccolithophore bloom; Boutin et al. [1999] identified variability in $pCO_2$ measurements in the tropical Pacific Ocean due to tropical instability waves. Once the physical, biological and chemical mechanisms driving the $pCO_2$ variability are identified, criteria derived from remotely sensed parameters must be found to approximate them, and to define the boundary of the province where the identified mechanisms are valid. Then, these criteria must be applied to remote sensing data to monitor the space and time variability of $pCO_2$ over a ‘province’. Such a method has been successfully applied over the equatorial Pacific Ocean [*Boutin et al.*, 1999] (see Figure 12, below). It is noticeable that, in some cases, better results were obtained when SST derived parameters (monthly anomalies, gradients, etc) are used instead of SST alone.

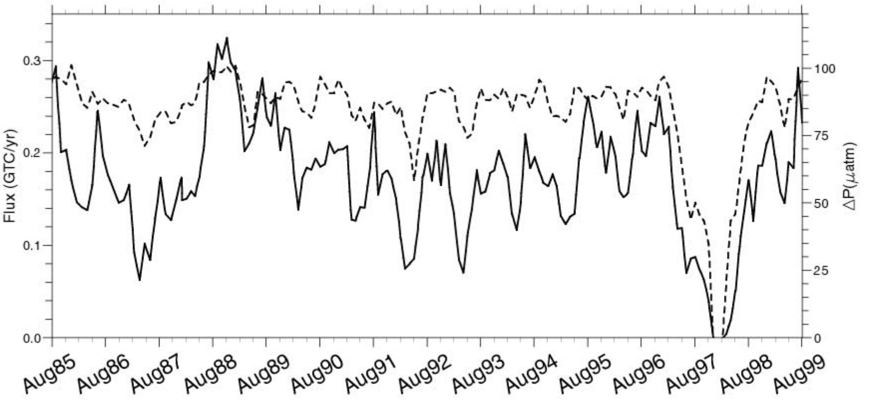
At present, these studies are limited to regions where criteria on remote sensing data have been developed. In these regions, the monitoring of $pCO_2$ and associated $CO_2$ flux obtained from remote sensing are useful to validate large scale estimates derived from 3D biogeochemical ocean models, or from atmospheric inversions.

Improvements are expected from the joint use of several remotely sensed parameters (e.g. SST and chlorophyll, altimetry). However, the development of empirical relationships between in situ data and remote sensing data requires numerous in situ data: up to now, the limited availability of simultaneous ocean color and in situ data has hampered the joint use of ocean color and SST. Chlorophyll is an indicator of the biological activity but also complements the SST information related to the ocean circulation. Moreover, new biological parameters (e.g. coccoliphorids , trichodesmium distributions) are now derived routinely from SEAWIFS data by NASA and could also help. Finally, sea surface salinity fields measured from satellite should become available: SMOS/ESA instrument is foreseen in ~2005.

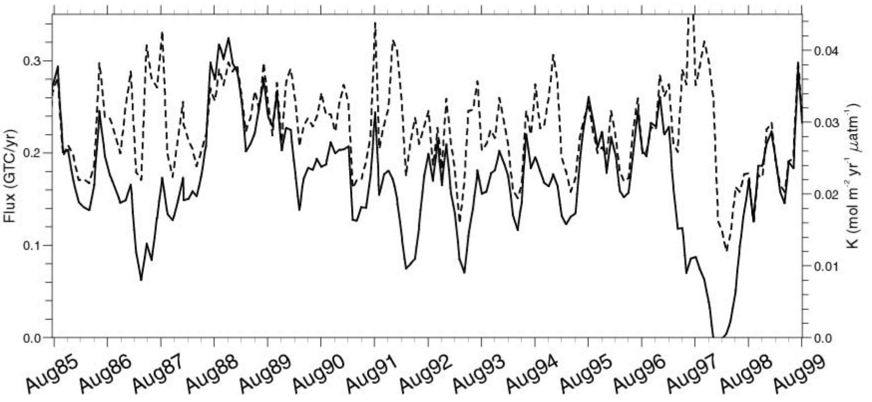
*(next page)* Figure 12. Air-sea $CO_2$ flux over the Equatorial Pacific Ocean

AIR-SEA CO2 FLUX over the EQUATORIAL PACIFIC OCEAN

Extrapolated ΔP average over the equatorial upwelling



K average over the equatorial upwelling



Equatorial Upwelling extension

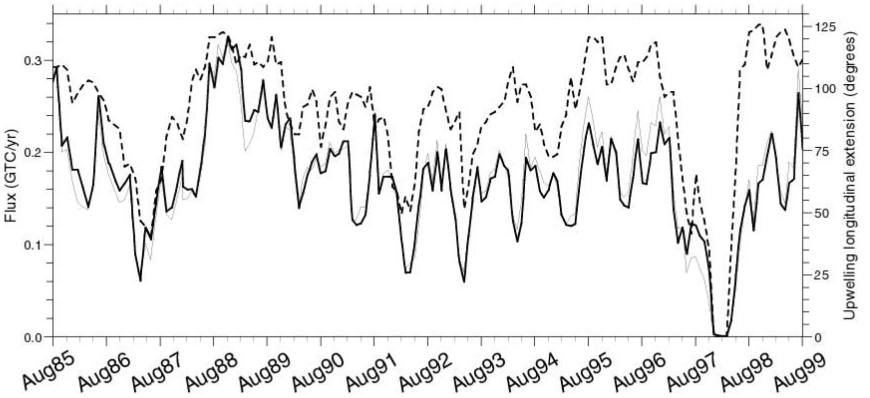


**Figure 12**. Air-sea CO$_2$ flux (continuous line) , DP (dashed line, top), K(dashed line, middle), Surface of upwelling (dashed line, bottom), as derived from SST in the equatorial Pacific Ocean between 0N and 5S. SST and monthly SST anomalies were used to fit the pCO$_2$ measurements in the equatorial upwelling ; the SST latitudinal gradient was used to track the presence of upwelling water at the equator and to derive the boundary between equatorial upwelled waters and warm pool water. Short term variability is primarily derived by K whereas large interannual variability is primarily driven by DP and surface of the upwelling variability.

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## 9. FUTURE DIRECTIONS IN OCEAN CARBON MODELING

Dr. Corinne Le Quéré, from the Max-Plank-Institut für Biogeochemie, reported on future directions for including marine biogeochemistry in ocean carbon modeling. Ocean carbon-cycle modeling requires the parameterization of physical, chemical, and biological processes. Biological processes are currently modeled following three methods: (1) nutrient based models where the export of carbon is a function of surface nutrient, (2) nutrient restoring models where carbon fluxes are calculated to be the rates required to maintain observed nutrient concentration, and (3) models that represent the food chain between nutrients, phytoplankton, zooplankton, detritus (NPZD). All models reproduce roughly the spatial patterns of DIC, $pCO_2$ and phosphate. NPZD models which include DOC cycling can also reproduce roughly the seasonality of $pCO_2$ and atmospheric potential oxygen (APO) (Six et al., 1996).

The remaining problems are first that marine productivity is generally overestimated in high nutrients-low chlorophyll (HNLC) regions and underestimated in sub-tropical gyres. The overestimation is probably due to the absence of the limiting nutrient iron, which is being included in several models (Archer and Johnson 2000). The underestimation is partly due to the absence of eddies in global models (McGillicuddy and Robinson 1997; Oschlies and Garcon 1998). The remaining discrepancy may be caused by the absence of nitrogen fixers (Karl et al., 1997), or by deficiencies in the parameterization of the remineralization of organic matter, which can be a source of nutrients to the sub-tropics. Second, the formation and dissolution of $CaCO_3$, which control alkalinity, is generally weakly parameterized because there are conflicting evidence for the ratio of $CaCO_3$ versus soft production. Third, none of the global models currently include the coastal zone and the influence of this region is unclear, particularly concerning the transport of organic carbon from land to the open ocean. Finally, models impose a tight coupling between nutrients and carbon, although many hypothesis for marine biological feedbacks to climate are based on their decoupling (for example Redfield ratios, nitrogen fixers, species competition).

More generally, there is often a gap between biological observations which are regional and species-dependent, and global models which require global parameters. This gap could be filled if global or basin-scale parameters are deduced from observations, or if global models are modified to incorporate directly regional information at the species level.

The Panel discussed several of the problems inherent in ocean carbon models, reiterating the need for better dynamics / physics in the models. The models have problems reproducing alkalinity, and over-estimate productivity at high latitudes and underestimate productivity in the subtropics. The models also rely on a tight coupling between nutrients and carbon ratios, which is very questionable since past carbon changes may result from carbon-nutrient cycle decoupling. The Panel suggested that there should be stronger interactions between the modeling community and the research / observation community to address these questions and inconsistencies.

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## 10. GENERAL DISCUSSION ON OCEAN CARBON OBSERVING SYSTEM PLANNING

The Chair outlined the socio-economic, political, and scientific justifications for an ocean carbon observing system, and highlighted some of the successes from previous programmes and remaining questions and problems. The group then outlined the necessary elements of an ocean carbon observing system, and made significant progress towards defining specific locations and timescales for these observations. The outline / draft report of the Ocean Carbon Observing System Strategy prepared by the group is given in Annex IV. The work will continue during the intersessional period and in collaboration with other groups (eg, IGOS, IGBP).

## 11. REVIEW OF SCHEDULED ACTIONS

The Panel outlined a number of action items to be addressed in the next year. Several of these actions still need to be more completely formulated and discussed by the group. The draft list of action items is given in Appendix V.

# ANNEX I

## AGENDA

1. **OPENING AND WELCOME**

2. **REVIEW AND ADOPTION OF THE AGENDA**

3. **REVIEW OF THE TERMS OF REFERENCE**

4. **GOALS AND PRODUCTS OF THE PANEL**

5. **CURRENT STATUS OF CARBON CYCLE SCIENCE ACTIVITIES**
    5.1 $CO_2$ SEQUESTRATION RESEARCH: CALDEIRA
    5.2 REFERENCE MATERIALS PROGRAM: DICKSON
    5.3 OCMIP: LE QUERE
    5.4 LOICZ: FRANKIGNOULLE
        **5.4.1 LOICZ Core Research Projects**
        **5.4.3 LOICZ Regional Research**
        **5.4.3 LOICZ Relevant Research**
    5.5 SOLAS: WALLACE
    5.6 OOPC AND IGOS: MARIA HOOD
    5.7 NEW MEASUREMENT TECHNIQUES: ANDERSON
    5.8 CURRENT STATUS OF ATMOSPHERIC OBSERVATIONAL NETWORK

6. **REVIEW OF UNFINISHED BUSINESS FROM THE PREVIOUS $CO_2$ PANEL**

7. **THE NEED FOR AN OCEAN CARBON OBSERVING SYSTEM**

8. **REGIONAL AND GLOBAL OBSERVATIONS**
    8.1 NORTH PACIFIC – YUKIHIRO NOJIRI
    8.2 NORTH ATLANTIC – ANDREW WATSON
    8.2 SOUTHERN OCEAN – NICOLAS METZL
    8.4 ARCTIC OCEAN – LEIF ANDERSON
    8.5 INDIAN OCEAN – DILEEP KUMAR
    8.6 COASTAL OBSERVATIONS – MICHELE FRANKIGNOULLE
    8.7 REMOTE SENSING – JAQUELINE BOUTIN

9. **FUTURE DIRECTIONS IN OCEAN CARBON MODELING**

10. **GENERAL DISCUSSION ON OCEAN CARBON OBSERVING SYSTEM PLANNING**

11. **REVIEW OF SCHEDULED ACTIONS**

## ANNEX II

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# ANNEX III

## TERMS OF REFERENCE

SCOR – IOC Advisory Panel on Ocean $CO_2$

- IOC provides financing with SCOR, in-kind assistance, and stewardship for the Panel;
- The Panel undertakes specific tasks (eg, white papers, special workshops, international ocean $CO_2$ conferences) and provides ready expertise to IOC and SCOR as needed.

General Terms of Reference

i. Advise SCOR / JGOFS, GOOS, LOICZ, and OOPC on observations, data management and modeling needed for studies of the global carbon cycle;

ii. Provide an international forum for initiatives to promote high-quality observations of $CO_2$ in the oceans;

Specific Terms of Reference

i. To identify gaps and weak links in the present carbon cycle observation system that compromise the ability to understand and predict global change;

ii. To identify opportunities that can be used to further develop such an observing system (eg, collaboration with other global observing systems);

iii. To aid the synthesis of JGOFS and IGBP results with respect to marine $CO_2$ observations, data management and modeling by:

    a. Initiating and facilitating the assembly of $CO_2$ data bases
    b. Interacting with ocean modelers to identify the weaknesses and encourage appropriate uses of $CO_2$ data
    c. Encouraging and facilitating the collaborative analysis of $CO_2$ data sets and supporting data

iv. To maintain a watching brief to advise IOC and SCOR on $CO_2$ sequestration in the ocean;

v. To advise GOOS and OOPC on technology development needed to improve future capacity for carbon cycle monitoring;

vi. To advise GOOS and OOPC on the observational strategies needed to assess, model, and predict global ocean $CO_2$ fluxes;

# ANNEX IV

## Ocean Carbon Observing System Strategy – DRAFT

### *Why Do We Need an Ocean Carbon Observing System?*

### 1. Background

$CO_2$ that is stored in the ocean does not affect the Earth's radiation balance, so the oceanic uptake of excess $CO_2$ mitigates the potential for global warming. In order to predict the magnitude of future climate change resulting from greenhouse gas emissions, a requirement is the prediction of future atmospheric $CO_2$ levels for given emissions scenarios. There is also an immediate socio-political requirement for better understanding of the global carbon cycle as a consequence of the endorsement of the Kyoto Protocol in 1997. Attempts to limit the future growth of atmospheric $CO_2$ concentration, however modest, will involve major, and potentially costly, changes in energy and technology policy. The proposed inclusion of certain terrestrial carbon sinks in carbon emission budgeting increases the need to better define global carbon sinks and sources. Further, future assessment of the effectiveness of measures taken to reduce carbon emissions will ultimately be judged by their long-term effect on atmospheric $CO_2$ levels which in turn requires an understanding of long-term storage changes in all key carbon reservoirs (atmosphere, oceans and the terrestrial biosphere).

Public awareness of human impacts on the local, regional and global environment is very high. The interest of the public in having access to accurate information concerning changes to their environment is also very high. One of the major foci of such interest and also concern at the global scale is the effect of human activity and climate on the carbon cycle.

- **Given the major potential economic and technological implications of any attempt to control or redirect global energy policy through global "carbon management", it is essential that predictions, assessments and models of future behaviour of the carbon cycle are based on sound scientific data and understanding.**

There are at least three key scientific questions of relevance to global carbon cycle science arising from current policy-related issues:

1. How large are present-day oceanic and terrestrial carbon sources and sinks, where do they operate, and what processes are responsible?
2. How will terrestrial and, particularly, oceanic carbon sources and sinks behave in the future under higher $CO_2$ and a possibly altered climate and ocean circulation?
3. How will we monitor and assess the effectiveness of emissions controls and sequestration activities on global atmospheric $CO_2$ levels (including checking our forecasts of sink behaviour)?

The answers to most of these questions, including those dealing specifically with the behaviour of the terrestrial biosphere, will rely on a combination of carbon-cycle models that are coupled and checked against global data sets covering the behaviour of the oceanic and atmospheric carbon reservoirs. The complexity and variability of carbon storage and uptake on land means that the long-standing approach of separately determining storage and fluxes in the ocean and atmosphere and evaluating regional and global behaviour of the terrestrial biosphere by difference will likely be required well into the future. Increasingly inverse modelling techniques utilizing constraints imposed by atmospheric, oceanic and terrestrial measurements are being developed and applied. Both approaches rely on access to a set of relevant and high-quality observations covering regional and global scales.

There is a certain perception in the global carbon cycle science community that the present characterization of ocean behaviour with respect to these issues is relatively robust and that we are in possession of a set of observations and models that we can use to reliably assess the key questions given above. This unfortunately is not the case, although it should be recognised that a great deal is known.

### CHANGE IN BUFFER CAPACITY NEXT 100 YEARS

*figure and text*

The potential currently exists to greatly improve our understanding of ocean behaviour in the carbon cycle is high based on coordinated use of existing measurement technologies and modelling techniques. Here we highlight some examples of problems related to the key questions given above.

## 2. The Oceanic Sink

### Present-Day Sink

A major success of the past decade of ocean carbon cycle research has been the development and testing of a wide variety of models suited to assessing past and future uptake of excess $CO_2$. These models generally show good agreement concerning the global magnitude of the oceanic sink for the present day. This estimate also agrees with a completely independent estimate based on $O_2/N_2$ time-series in the atmosphere.

The models however show much less agreement with respect to where such Excess $CO_2$ is being stored in the ocean:

- *viz. OCMIP figure*

This lack of agreement on regional scales points to major discrepancies in the representation of ocean circulation and mixing between the various models.

The model results also tend to diverge from Excess $CO_2$ estimates derived from observations

- *viz. Sabine et al figure*
- Section on Coastal Fluxes needed (M. Frankignoulle)

### Future Oceanic Sink

Most importantly, the differences in model physics suggested by these comparisons have major implications for the future behaviour of the oceanic sink. While showing reasonably good agreement for the present-day, the models diverge dramatically in their predictions of uptake strength over the next 100 years.

- *viz. OCMIP 2 figure*

This divergence of future uptake has nothing to do with the representation of complex climate-ocean feedbacks or ocean biology in the models. It is purely a function of the representation of steady-state ocean physics and chemistry. This is a worrying result suggesting that we understand much less about ocean behaviour than our apparent success at predicting present-day global ocean uptake may have led us to believe.

## 3. Inverse modelling and the air-sea flux constraint.

### Regional fluxes: what locations and processes are responsible?

- *Rayner figure*
- *Fan et al. figure*
- *Metzl bar chart, air-sea flux in Southern Ocean estimated from measurements vs inversions*

- *Need similar figure, Northern Hemisphere…*

**Interannual variability: climate sensitivity**

What is the climate sensitivity of these large-scale processes?

- *Keeling, Francey 1, Francey 2, Battle et al figures – divergent estimates of Terrestrial vs Oceanic processes*
- *Feeley El Nino compilation / flux change*
- *models*
- *air-sea flux estimates from satellites (Boutin and LeQuerre figure) – model vs climatology*

**air-sea flux climatologies**

**Takahashi Climatology**

There exists only 1 air-sea flux climatology. Built into this are a set of important assumptions and limitations (*A.Watson will list and evaluate assumptions*) – very sparse data, over 40 yr period, poor seasonal coverage.

- *Takahashi flux map.*
- *Spatial coverage*
- *Temporal Coverage*

Coastal Ocean

The coastal ocean is potentially an area of large and important net fluxes of carbon to the atmosphere. No climatology exists for coastal areas, and these areas are not included in the Takahashi climatology. The uncertainties from ignoring this region could be on the order of 1 Gt C / yr.

- *Frankignoulle tables / figure*

***What Sort of Carbon Observing System do we Need?***

**Basin Scale Surface Observations.**

*Quantify variability in space and time.*

| | |
|---|---|
| PLATFORM: | VOS and Drifters |
| LOCATION / SCALE: | Basin scale coverage |
| HIGHEST SAMPLING FREQUENCY: | Monthly |
| PRODUCTS: | • $\Delta pCO_2$ and air-sea flux estimates with known uncertainties on regional scales<br>• atmospheric observations and data for atmospheric inverse model community<br>• data for ground-truthing satellite observations of atmospheric $CO_2$ |

**Upper Ocean time-series observations (including Coastal flux studies)**

*High-frequency, fixed location; complement VOS programmes and provide depth information.*

| | |
|---|---|
| PLATFORM: | Time-series sites and moorings – especially instrumented biogeochemical moorings |
| LOCATION / SCALE: | Representative, significant sites |
| HIGHEST SAMPLING FREQUENCY: | Hours to weeks |
| PRODUCTS: | • definition of processes affecting surface $pCO_2$<br>• relative influence of biological, solubility and alkalinity pumps<br>• functioning of biological pump<br>• particle flux and remineralization<br>• required to link air-sea flux estimates to carbon cycle model depictions of processes<br>• provides context for experimental campaigns and process studies<br>• Ground-truthing satellite information |

**Hydrographic sections.**

*Reduce signal to noise in previous data, assessment of how the transport fields and fluxes change over time.*

| | |
|---|---|
| PLATFORM: | research vessels |
| LOCATION / SCALE: | whole basin scale. Repeat surveys |
| HIGHEST SAMPLING FREQUENCY: | Seasonal. (Usually longer) |
| PRODUCTS: | • Constraints on inventories and time-rate-of-change of carbon<br>• Constraints on lateral and interhemispheric transports of carbon<br>• Regional budgets<br>• Model physics refinement<br>• Long-term changes in ocean behaviour |

***Existing Elements of an Observing System – What does it look like ?***

**I. Observations**

**Relevant Global Observations**

### 1. Satellites monitoring ocean colour, SST, wind, atmospheric $CO_2$, and surface roughness :

| Operational | Planned |
|---|---|
| POLDER on ADEOS | †MODIS sensor on EOS Terra and EOS Aqua |
| SeaWiFS | †MERIS on ENVISAT |
| CEOS / SCOR Ocean Biology Project | †OCM on IRS-P4 |
| NASA SIMBIOS Project | †GLI on ADEOS-2 |
| TOPEX / Poseidon ERS (mesoscale variability and physical circulation) | †NPOESS Preparatory Programme to develop a visible and infrared sensor (VIIRS) |
| Pathfinder AVHRR (sst) | †SGLI on GCOM |
| NSCAT, QuickScat (wind speed) | |

### 2. The atmospheric observation network

### 3. Argo (ancillary data – no carbon as yet)

**Regional Observations**

- *Map of Uwe Send*

The map represents ongoing programmes and where we believe it would be reasonable / possible to get funding. This is not an optimized system, but rather the systems in place or planned that could constitute an initial observation system.

## II. Model Utilization/Interaction with the Observing System

atmospheric inverse models
ocean prognostic models
ocean data assimilation models

## III. General Challenges

- Data handling
- Data assimilation – compilations of basin scale and global data sets, interpolation with models
- System calibration, QC / QA
- System optimization
- Instrument development
- Synergy with other programmes – CLIVAR, SOLAS, DEOS, GODAE, GOOS, GCOS, LOICZ, etc.
- Filling in the gaps

# ANNEX V

## ACTION ITEMS – *DRAFT*

1. Communication Forum on Ocean Carbon Science Activity (section 4)
Actions: Form collaborations with regional data and information groups; develop web-site ($CO_2$ Panel site) to collect and disseminate information about ongoing and planned programmes, technology development, and data availability.

2. $CO_2$ Sequestration
Actions: Maintain a watching-brief on activities in this area; form an expert group as needed to advise on future directions for research, public awareness / policy, etc.

3. Certified Reference Materials Programme
Actions: Advocate for development of additional CRM programmes in support of future observation network needs.

4. Coastal Carbon Cycle Science
Actions: Advocate increased inclusion / focus on the coastal ocean carbon cycle; develop a new climatology that includes the coastal zone.

5. Measurement Technology
Actions: Information and status about technique / sensor development to be put on the $CO_2$ Panel web-site to share information and co-ordinate efforts.

6. Data Set Compilation / Assembly
Actions: Continue development of an ocean carbon data base (A. Dicksen, SIO); search for funding support for data collection / assimilation programmes.

7. Observation System Planning
Actions: Continue developing observing system strategy and plans during the intersessional period; Collaborate with other groups (eg, IGOS, IGBP).