Intergovernmental Oceanographic Commission
Reports of Meetings of Experts and Equivalent Bodies

Second International Meeting of Scientific and Technical Experts on Climate Change and the Oceans

Valletta, Malta
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UNESCO

In this Series, entitled

Reports of Meetings of Experts and Equivalent Bodies, which was initiated in 1984 and which is published in English only, unless otherwise specified, the reports of the following meetings have already been issued:

1. Third Meeting of the Central Editorial Board for the Geological/Geophysical Atlases of the Atlantic and Pacific Oceans
2. Fourth Meeting of the Central Editorial Board for the Geological/Geophysical Atlases of the Atlantic and Pacific Oceans
3. Fourth Session of the Joint IOC-WMO-CPPS Working Group on the Investigations of 'El Niño' *(Also printed in Spanish)*
4. First Session of the IOC-FAO Guiding Group of Experts on the Programme of Ocean Science in Relation to Living Resources
5. First Session of the IOC-UN(OETB) Guiding Group of Experts on the Programme of Ocean Science in Relation to Non-Living Resources
6. First Session of the Editorial Board for the International Bathymetric Chart of the Mediterranean and Overlay Sheets
7. First Session of the Joint CCOP(SOPAC)-IOC Working Group on South Pacific Tectonics and Resources
8. First Session of the IODE Group of Experts on Marine Information Management
9. Tenth Session of the Joint CCOP-IOC Working Group on Post-IDOE Studies in East Asian Tectonics and Resources
10. Sixth Session of the IOC-UNEP Group of Experts on Methods, Standards and Intercalibration
11. First Session of the IOC Consultative Group on Ocean Mapping *(Also printed in French and Spanish)*
12. Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ships-of-Opportunity Programmes
13. Second Session of the Joint CCOP/SOPAC-IOC Working Group on South Pacific Tectonics and Resources
14. Third Session of the Group of Experts on Format Development
15. Eleventh Session of the Joint CCOP-IOC Working Group on Post-IDOE Studies of South-East Asian Tectonics and Resources
16. Second Session of the IOC Editorial Board for the International Bathymetric Chart of the Mediterranean and Overlay Sheets
17. Seventh Session of the IOC-UNEP Group of Experts on Methods, Standards and Intercalibration
18. Second Session of the IOC Group of Experts on Effects of Pollutants
19. Primera Reunión del Comité Editorial de la COI para la Carta Batimétrica Internacional del Mar Caribe y Parte del Océano Pacífico frente a Centroamérica *(Spanish only)*
20. Third Session of the Joint CCOP/SOPAC-IOC Working Group on South Pacific Tectonics and Resources
21. Twelfth Session of the Joint CCOP-IOC Working Group on Post-IDOE Studies of South-East Asian Tectonics and Resources
22. Second Session of the IODE Group of Experts on Marine Information Management
23. First Session of the IOC Group of Experts on Marine Geology and Geophysics in the Western Pacific
24. Second Session of the IOC-UN(OETB) Guiding Group of Experts on the Programme of Ocean Science in Relation to Non-Living Resources *(Also printed in French and Spanish)*
25. Third Session of the IOC Group of Experts on Effects of Pollutants
26. Eighth Session of the IOC-UNEP Group of Experts on Methods, Standards and Intercalibration
27. Eleventh Session of the Joint IOC-IHO Guiding Committee for the General Bathymetric Chart of the Oceans *(Also printed in French)*
28. Second Session of the IOC-FAO Guiding Group of Experts on the Programme of Ocean Science in Relation to Living Resources
29. First Session of the IOC-IAEA-UNEP Group of Experts on Standards and Reference Materials
30. First Session of the IOCARIBE Group of Experts on Recruitment in Tropical Coastal Demersal Communities *(Also printed in Spanish)*
31. Second IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes
32. Thirteenth Session of the Joint CCOP-IOC Working Group on Post-IDOE Studies of East Asia Tectonics and Resources
33. Second Session of the IOC Task Team on the Global Sea-Level Observing System
34. Third Session of the IOC Editorial Board for the International Bathymetric Chart of the Mediterranean and Overlay Sheets
35. Fourth Session of the IOC-UNEP-IMO Group of Experts on Effects of Pollutants
36. First Consultative Meeting on RNODCs and Climate Data Services
37. Second Joint IOC-WMO Meeting of Experts on IGOSS-IODE Data Flow
38. Fourth Session of the Joint CCOP/SOPAC-IOC Working Group on South Pacific Tectonics and Resources
39. Fourth Session of the IODE Group of Experts on Technical Aspects of Data Exchange
40. Fourteenth Session of the Joint CCOP-IOC Working Group on Post-IDOE Studies of East Asian Tectonics and Resources
41. Third Session of the IOC Consultative Group on Ocean Mapping
42. Sixth Session of the Joint IOC-WMO-CCPS Working Group on the Investigations of 'El Niño' *(Also printed in Spanish)*
43. First Session of the IOC Editorial Board for the International Bathymetric Chart of the Western Indian Ocean
44. Third Session of the IOC-UN(OALOS) Guiding Group of Experts on the Programme of Ocean Science in Relation to Non-Living Resources
45. Ninth Session of the IOC-UNEP Group of Experts on Methods, Standards and Intercalibration
46. Second Session of the IOC Editorial Board for the International Bathymetric Chart of the Caribbean Sea and the Gulf of Mexico
47. First Session of the IOC Editorial Board for the International Bathymetric Chart of the Western Indian Ocean
48. Twelfth Session of the Joint IOC-IHO Guiding Committee for the General Bathymetric Chart of the Oceans
49. Fifteenth Session of the Joint CCOP-IOC Working Group on Post-IDOE Studies of East Asian Tectonics and Resources
50. Third Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes
51. First Session of the IOC Group of Experts on the Global Sea-Level Observing System
52. Fourth Session of the IOC Editorial Board for the International Bathymetric Chart of the Mediterranean
53. First Session of the IOC Editorial Board for the International Chart of the Central Eastern Atlantic *(Also printed in French)*
54. Third Session of the IOC Editorial Board for the International Bathymetric Chart of the Caribbean Sea and the Gulf of Mexico *(Also printed in Spanish)*
55. Fifth Session of the IOC-UNEP-IMO Group of Experts on Effects of Pollutants
56. Second Session of the IOC Editorial Board for the International Bathymetric Chart of the Western Indian Ocean
57. First Meeting of the IOC *ad hoc* Group of Experts on Ocean Mapping in the WESTPAC Area
58. Fourth Session of the IOC Consultative Group on Ocean Mapping
59. Second Session of the IOC-WMO/IGOSS Group of Experts on Operations and Technical Applications
60. Second Session of the IOC Group of Experts on the Global Sea-Level Observing System
61. UNEP-IOC-WMO Meeting of Experts on Long-Term Global Monitoring System of Coastal and Near-Shore Phenomena Related to Climate Change
62. Third Session of the IOC-FAO Group of Experts on the Programme of Ocean Science in Relation to Living Resources
63. Second Session of the IOC-IAEA-UNEP Group of Experts on Standards and Reference Materials
64. Joint Meeting of the Group of Experts on Pollutants and the Group of Experts on Methods, Standards and Intercalibration
65. First Meeting of the Working Group on Oceanographic Co-operation in the ROPME Sea Area
66. Fifth Session of the Editorial Board for the International Bathymetric and its Geological/Geophysical Series
67. Thirteenth Session of the IOC-IHO Joint Guiding Committee for the General Bathymetric Chart of the Oceans *(Also printed in French)*
68. International Meeting of Scientific and Technical Experts on Climate Change and Oceans
69. UNEP-IOC-WMO-IUCN Meeting of Experts on a Long-Term Global Monitoring System
70. Fourth Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes
71. ROPME-IOC Meeting of the Steering Committee on Oceanographic Co-operation in the ROPME Sea Area
72. Seventh Session of the Joint IOC-WMO-CPPS Working Group on the Investigations of 'El Niño' *(Spanish only)*
73. Fourth Session of the IOC Editorial Board for the International Bathymetric Chart of the Caribbean Sea and the Gulf of Mexico *(Also printed in Spanish)*
74. UNEP-IOC-ASPEI Global Task Team on the Implications of Climate Change on Coral Reefs
75. Third Session of the IODE Group of Experts on Marine Information Management
76. Fifth Session of the IODE Group of Experts on Technical Aspects of Data Exchange
77. ROPME-IOC Meeting of the Steering Committee for the Integrated Project Plan for the Coastal and Marine Environment of the ROPME Sea Area
78. Third Session of the IOC Group of Experts on the Global Sea-level Observing System
79. Third Session of the IOC-IAEA-UNEP Group of Experts on Standards and Reference Materials
80. Fourteenth Session of the Joint IOC-IHO Guiding Committee for the General Bathymetric Chart of the Oceans
81. Fifth Joint IOC-WMO Meeting for Implementation of IGOSS XBT Ship-of-Opportunity Programmes

CONTINUED ON INSIDE OF BACK COVER

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TABLE OF CONTENTS

SUMMARY REPORT

PREAMBLE

The Second Meeting of scientific and technical experts on oceans and climate in Malta was organized by IOC in co-operation with the Foundation for International Studies, in response to Chapter 17 of the Agenda 21 provisions adopted in Rio. This Meeting was a natural sequence to the first one, held in Malta in 1991, the main focus of which was dedicated to questions of ocean dynamics (heat exchange) in relation to climate change.

The distinctive feature of the Second Meeting was its orientation to problem of oceans and carbon dioxide, and consideration of the ocean capacity as a CO_2 sink. This task was defined in the first instance by applied interests of the progress of the FCCC negotiating process.

A summary paper "CO_2 and the Ocean: the State of Knowledge", was used as a basis for discussion. A number of interesting points were expressed by participants, such as:

(i) a comparison of different assessments of annual anthropogenic carbon uptake by the ocean, obtained by various methods and the related character of errors and limits of reliability;

(ii) the considered opinion that the missing CO_2 is absorbed equally by ocean and terrestrial biosphere;

(iii) the burial of CO_2 in ocean sediments is possible by active injections and long-term CO_2 burial (in subduction zones) - may be one way to achieve the necessary CO_2 balance in the atmosphere;

(iv) the "ship of opportunity" method of continuous observations for partial CO_2 pressure in the sub-surface layer of the ocean, and in the surface layer of the atmosphere, represents a new technology of the systematic gathering of actual data;

(v) analysis of satellite images of the ocean's surface allows evaluation of total CO_2 absorption by the ocean, but still does not permit the assessment of uptake of the anthropogenic component and its regional distribution;

(vi) the increase of the ocean surface temperature results in the increase of CO_2 absorption, as confirmed by the studies of El Niño events, so that the ocean could be considered in a certain sense, as a self-regulator of changes of the average temperature of the atmosphere.

Naturally, several gaps and uncertainties in knowledge were identified which require attention.

1. OPENING

The Second Meeting of Scientific and Technical Experts on Climate Change and the Oceans, 6-8 October 1994, was hosted by the Foundation for International Studies in Valletta, Malta. Proceedings were opened by Professor S. Busuttil, Director-General of the Foundation for International Studies, University of Malta, Professor David Attard, University of Malta and Director of the International and Maritime Law Institute, and Dr. Gunnar Kullenberg, Secretary, Intergovernmental Oceanographic Commission (IOC). Professor Busuttil stressed that the meeting should help to identify further actions in relation to the oceans to be undertaken by States as part of the process of mitigating the adverse effects of potential climate change.

Professor David Attard, University of Malta, emphasized the importance of interaction between the political and scientific communities with respect to Climate Change. The role of the oceans must be an important element in the process, focusing not only on one but several areas, e.g., biological, chemical and physical aspects. He recalled the international concern of anthropogenic influences with respect to potential Climate Change, specifically referring to the United Nations Framework Convention on Climate Change (FCCC) and the efforts of Malta in raising the awareness of the climate change issue at the intergovernmental level. The scientific knowledge is inadequate and generally speaking, the weaker the scientific knowledge is, the weaker the decision-making approach. Science and politics should not be divorced, and in this context, he stressed the importance of this meeting to update the scientific basis and further needs. A great deal of good scientific work has been and is being done and should be presented to politicians so that they can understand the implications and adjust their priorities and policy accordingly.

The Secretary IOC welcomed all participants and expressed appreciation for the willingness of the experts to share their time and knowledge. He said that the Intergovernmental Oceanographic Commission of UNESCO with the local assistance of the European Centre on Insular Costal Dynamics (ICOD) of the Foundation for International Studies was convening this meeting of experts on climate change and the oceans.

He recalled that the first in this series of small IOC workshops on Climate Change and the Oceans took place in Malta in 1991. Then the physical and dynamic aspects of the subject were primarily dealt with. It resulted in the production of a report entitled "International Meeting of Scientific and Technical Experts on Climate Change and the Oceans" (IOC Reports of Meeting of Experts and Equivalent Bodies No. 68 and IOC Technical Series No.38).

This second meeting was held in response to recommendations made at the United Nations Conference on Environment and Development (UNCED) and in particular in its Agenda 21 (Chapter 17). In paragraph 17.102 it states "Recognizing the important role that oceans and all seas play in attenuating potential climate change, IOC and other relevant competent United Nations bodies, with the support of countries having the resources and expertise, should carry out analyses, assessments and systematic observation of the role of oceans as a carbon sink."

The Secretary IOC summarized the relevant decisions of the IOC Governing Bodies for the implementation of the United Nations Conference on Environment and Development (UNCED) adopted at the Seventeenth Session of the IOC Assembly (Paris, March 1993). The goal of the meeting was highlighted together with the Terms of Reference and the objectives. He summarized the importance of socio-economic aspects and referred to IOC Technical Series No. 38 "The Oceans and Climate: A Guide to Present Needs", and in particular the working document "CO_2 and the Ocean: A Review of the State of Knowledge", edited by Dr. A. Alexiou, on the basis of inputs from the Scientific Committee for JGOFS, for the present meeting, as important reports to build upon. The working document for the meeting is given in Annex III.

He recalled that the First International Meeting of Scientific and Technical Experts on Climate Change and Oceans in 1991, Malta, was held to establish the fundamental role of oceans in the climate system. This second meeting was also organized to follow up what has been done and how far we have advanced

scientifically. He noted that new elements have arisen and that it is important to bring these new elements, e.g., modelling, biochemical aspects and interactions, into the overview of CO_2 and the ocean. He emphasized the importance of using the intergovernmental mechanism of IOC to bring to the attention of Governments the need to address the research underpinning their policy. He stressed that this meeting was not meant to compete with the Intergovernmental Panel on Climate Change (IPCC) process, but to supplement the scientific overview on CO_2 and the oceans and other associated matters related to Climate Change.

The meeting reviewed the update on the oceans and CO_2 issue (Annex III). It discussed new elements of the greenhouse gas problem, including emphasis on the biology and biochemistry involved in gas exchange between the oceans and the atmosphere. Participants addressed the interdisciplinarity of the problem and agreed to produce a brief but concise report on the most recent findings of research in this field and their implications and to provide recommendations for future application.

2. ADMINISTRATIVE ARRANGEMENTS

Professor James O'Brien and Professor Ulf Lie were invited to co-chair the meeting, and their willingness to do so was greatly appreciated.

The meeting adopted the Agenda (Annex I); the list of participants is given in Annex II. The agenda and schedule were introduced by the Secretary IOC who also informed the meeting about the documentation and noted with regret that some of the invited experts were not able to attend due to last minute changes.

3. BASIC SCIENTIFIC RESULTS AND ISSUES WITH RESPECT TO OCEANS AND CO_2

The participants presented their recent scientific findings with respect to oceans and CO_2. This provided an overview of the present scientific mainstream as a basis for the evaluation of the role of the oceans in the greenhouse gas balance and, in particular, the CO_2 content of the atmosphere. The overview identified a series of questions and uncertainties which need to be addressed further by a series of process studies, modelling experiments and systematic ocean observations. Each presentation generated considerable discussion, elucidating un-resolved problems, questions and uncertainties. There was general agreement that the review of existing knowledge up to approximately 1992/93 provided in the background paper "CO_2 and the Ocean: a Review of the State of Knowledge" (Annex III), was complete and well done.

Dr. P. Quay began by presenting the global CO_2 budget and the application of coupled atmospheric and oceanic carbon isotope (13C/12C) measurements to determine the oceanic uptake of CO_2 (see also section 4.2 in background paper Annex III and Annex IV.1). He illustrated the calculation of the net oceanic and terrestrial biospheric uptake rates, including an error analysis, from atmospheric $12CO_2$ and $13CO_2$ mass balances. The net oceanic CO_2 uptake rate, calculated from the measured change in oceanic and atmospheric 13C/12C over the last 20 years, is 1.8 ± 0.9 GtC/yr and the net biospheric uptake rate is 0.4 ± 1 GtC/yr. The error in the uptake rate depends primarily on the uncertainty in the measured change in the oceanic inventory of 13C/12C, and to a lesser extent, on the assumed reservoir time for carbon in the terrestrial biosphere. He estimated that the uncertainty likely will not decrease below ± 0.6 GtC/yr using this method. An oceanic CO_2 uptake rate can also be determined by determining the magnitude of the 13C/12C disequilibrium between the atmosphere and ocean. With the few oceanic 13C/12C data available currently, however, this disequilibrium is poorly known. There is a critical need for more oceanic 13C/12C data and a seawater 13C/12C standard that can be distributed between laboratories in order to achieve adequate quality control of the data.

A review of modelling results focusing on physical processes was presented by E. Maier-Reimer, which brought out the importance of the need for a better knowledge of thermocline ventilation processes, the significance of the main thermocline depth and related processes (see also Section 3.1 in background paper, Annex III, (1992) and Annex IV.2). The ocean description is based on the ocean climatology prepared by S. Levitus (1992), and an improved data base is clearly most important. This is gradually being obtained through the World Ocean Circulation Experiment (WOCE). It is also required that observation efforts focus on some

specialized regions in the ocean where the mixing and ventilation rates may play particular roles, e.g., areas of deep water formation and main thermocline ventilation (including such matters as 18°C water formation in the Atlantic). The oceanic uptake of anthropogenic CO_2 at the main thermocline level is given by model experiments as 1.54 GtC per year. The range of uptake (anthropogenic) is 1.0-2.5 with an average of 1.54 GtC/yr. From CFC and 14C, Maier-Reimer presented indications that this value is too low. A revised model version with higher resolution yields 1.95 GtC/yr. There is, unfortunately, no measurable tracer that could be used as a perfect analogue for CO_2, and currently models are optimized using 14C as a tracer. Additional data on other tracers is being obtained through WOCE. This will certainly help narrow down the range of model results and help define the surface-layer response time to CO_2. The model points out that a single tracer cannot be relied upon (e.g., 14C) for calibration, but that several tracers must be used in order to tune the models. Modellers are currently working to include biological processes in the models.

Professor J. O'Brien reviewed the present knowledge of the role of the El Niño phenomenon emphasizing the release of CO_2 from the Pacific Ocean during the El Niño years (see also section 6.2 in the background paper, Annex III, and Annex IV.3). The 1992 anomaly was suggested to represent an increased sink of CO_2, which could be due to increased moisture in the northern latitudes resulting from the extended El Niño period. The interannual variability of atmospheric CO_2 content and ocean variability correlate well, as demonstrated by the El Niño-CO_2 correlation. The change in terrestrial CO_2 uptake also correlates well with ocean variability. The size of the fluctuations of the biosphere uptake was also shown. The presentation generated considerable discussion.

Professor R. Barber showed an analysis of the Mauna Loa CO_2 data that brought out the year to year trends in the monthly CO_2 uptake or release. An increasing trend for the month of June over the last decade or so is evident, and might be due to a terrestrial fertilization through increased atmospheric CO_2. Alternatively, it could be due to an increase in atmospheric moisture from the ocean - an example of how the ocean influences the terrestrial biosphere, and also an example of a potentially very important feedback mechanism. We cannot as yet distinguish oceanic and terrestrial events, in the sense that they cannot be decoupled since the ocean possibly drives both mechanisms. Professor Barber also presented the results of the ocean iron fertilization experiment (see also section 7.2 in the background paper, Annex III and Annex IV.4).. He pointed out that three conditions are required for the fertilization to be useful as a tool to increase the medium to long-term oceanic uptake of anthropogenic CO_2, namely:

(i) the hypothesis that iron is a limiting factor must be true; the one experiment suggested that this is the case, but more conclusive evidence is required;

(ii) the oceanic biological pump must function so that the increased planktonic production is exported to the deep ocean sink; the experiment showed that this was not the case; the bio-chemical recycling was far too efficient in this case;

(iii) the exported carbon needs to be maintained in the deep ocean sink without being mixed or re-circulated to the surface; model experiments show that mixing and recirculation are particularly strong in the Southern Ocean with only 15 to 30% of the carbon being partitioned into the sink.

The equatorial Iron Ex experiment suggested that iron fertilization would not result in an increased net oceanic uptake of CO_2. However, a Southern Ocean experiment is required for a conclusive test of the effect of iron fertilization. Presently, the scientific evidence shows that there is no lasting effect on the atmospheric CO_2 content resulting from such an experiment - there would only be a transient signal.

Dr. T. Packard presented some calculations of global new production and deep ocean CO_2 sequestering based on measurements of respiratory electron transport system (ETS) activity in microbial populations in the water columns of the open Atlantic and Pacific Oceans (see Annex III, Section 5 and Annex IV.5). A global new production rate of 22 GtC per year and a global gross CO_2-sequestering rate of 8 GtC per year for the water column below 1000m were calculated. The data base consisted of only 9 ETS profiles from each of the Atlantic and the Pacific oceans and does not include benthic metabolism. Nevertheless, the calculations

represent rare examples of global geochemical rate determinations from process studies. These rates help to quantify the biological part of the ocean's gross CO_2 uptake rate, but the physico-chemical part still needs to be quantified. These results, as with the results of all ocean process studies, should be considered for inclusion in carbon cycling models. Sensitivity analysis should be made to determine how and where to include them.

Dr. D. Cooper presented a recent effort to increase the oceanic data on partial pressure of CO_2 in the ocean surface layer and the atmosphere above by using ships of opportunity. Two lines (UK-Jamaica and UK-Cape Town) were in operation, and results showed the large variability as well as expected fractionations relating to the various ocean zones (shelf seas, transitions, open ocean, ocean gyres). The observations of the pCO_2 and $DpCO_2$ between the ocean and atmosphere are indispensable for the calculation of the gas exchange using the bulk formula approach (Section 3.2 in background paper, Annex III). The meeting agreed that this method of obtaining an increased data base was recommendable.

4. IMPLICATIONS OF THE PRESENT STATE OF KNOWLEDGE FOR THE CO_2 ISSUE

Dr. A. Metalnikov and Professor U. Lie briefly reviewed the requirements for information on the CO_2 balance in relation to the UN Framework Convention on Climate Change. They stressed the fact that the carbon and CO_2 budgets are not yet closed and that there are missing parts. They then brought up the possibility of increasing the oceanic uptake of anthropogenic CO_2 through various actions.

The Secretary IOC drew attention to the work of the IPCC and, in particular, referred to a recent article "The IPCC Initiates New Assessments of the Climate Change Issue", by the Chairman IPCC, Professor B. Bolin, to appear in NATURE. The Secretary IOC also presented some results of the study carried out by the World Energy Council's Commission "Energy for Tomorrow's World - The Realities, the Real Options and the Agenda for Achievement" which were presented in a recent article by the WEC Secretary-General ("Global Climate Change: Some Views from the WEC", Bulletin UATI, No. 1, 1994). The Secretary IOC also referred to some major problems facing our goal to achieve sustainable development, the population increase, global food production, energy consumption, and shifts in the development of markets for industrial productions. There is a need to relate the CO_2 problem to problems facing development. In the subsequent discussion, several points were made and summarized as follows:

(i) quantifying the fate of CO_2 is difficult since the net uptake of anthropogenic CO_2 is a small proportion (2%) of the total CO_2 fluxes;

(ii) ocean models, isotopic carbon and atmospheric O_2 measurements indicate that the oceanic uptake of anthropogenic CO_2 is about 2 GtC per year (by isotopic 1.1-2.7 GtC and by models 1.0-2.5 GtC);

(iii) the missing anthropogenic CO_2 has likely been taken up equally by the oceanic and terrestrial biospheres;

(iv) model results indicate that most (65-85%) of the initial oceanic anthropogenic CO_2 uptake occurs in the main thermocline, the ventilation of which may be of the order of 20 years (decades);

(v) thermocline ventilation (mixing) and not CO_2 gas exchange is the most important factor affecting the oceanic uptake of CO_2 and occurs on decadal and shorter time-scales;

(vi) the seasonal gains and losses of atmospheric CO_2 are large and the territorial biosphere is the driving force;

(vii) until oceanwide measurements of carbon inventory changes are made, global ocean-atmosphere models will provide the best estimates of where anthropogenic CO_2 resides in the ocean;

(viii) the ocean is not in a steady state, and hence, interannual variations must be expected;

(ix) an oceanic carbon systematic observation strategy should be based more on model results than has been the case so far;

(x) carbon cycling and ocean climate models should be modified to include and test the significance of more oceanographic processes.

Furthermore, the following points were noted:

(i) certain specific areas of the marine system need dedicated evaluations as to their roles not yet carried out, e.g., marshes, mangroves, wetlands, shelves, estuaries, coral reefs;

(ii) model studies suggest that over long time scales (100-1000 years) the oceans will efficiently recycle the CO_2, but less CO_2 will be returned than originally sequestered;

(iii) sequestration of CO_2 in the ocean may be achieved on engineering principles, but the consequences are unknown;

(iv) burial of CO_2 in ocean sediments can only be achieved through blanketing by sedimentation or active injection into the sediments; a delay of CO_2 release could be obtained by inorganic or organic carbon burial in the deep sea sediments;

(v) currently, neither models nor observations allow us to adequately quantify uptakes of anthropogenic CO_2 in different zones of the ocean, e.g., in shelf sea areas or EEZs:

(vi) long-term burial of CO_2 (e.g., in subduction zones) is possibly the only way to permanently solve the CO_2 build-up process.

5. SUMMARY STATEMENT

On the basis of the presentations and discussions of implications, and with reference to the overall problem of potential climate change, the meeting formulated and agreed upon a number of statements which are scientifically justified. These are presented here as individual statements and are the main conclusions of the meeting. In some cases, they are formulated as recommendations for further actions by the community at large.

(i) Currently, four approaches for estimations of ocean CO_2 uptake have been shown to yield consistent net oceanic uptake rates of about 2 GtC (anthropogenic) per year. Two of these approaches rely on mass balances of atmospheric $13CO_2/12CO_2$ and oxygen and the other two rely on either atmosphere or ocean models. The uncertainty range is 0.1 to 1.5 GtC per year.

(ii) Biochemical studies, focused on boundary regions of the oceanic water column would be useful in improving current understanding of the role of mid-water column metabolism and remineralization on oceanic CO_2 uptake and carbon recycling. The most important regimes are the waters between the surface mixed layer and the intermediate water (i.e., the water column between 50 and 300m depth) and the waters of the benthic boundary layer. In particular, these studies would help to quantify the remineralization rates at the bottom of the euphotic zone and the upper thermocline region of the ocean which are critical in quantifying the temporal and spatial variability of the biological pump. Furthermore, such studies provide an opportunity to integrate biochemical, ecological and biological oceanographic processes into carbon-cycle models. Through sensitivity analysis, the relative impacts of these processes on the role of the ocean in sequestering anthropogenically derived CO_2 could be elucidated and evaluated. By this activity, research on CO_2-related processes can be better focused and prioritized.

(iii) Living systems are inherently characterized by variability. Determination of the causes of this variability and the temporal/spatial scales may significantly increase our current understanding of global carbon cycling.

(iv) The recent episodic slowdown in the global atmospheric CO_2 increase rate may be due to "large scale" oceanic processes and short-term variability of the ocean. Carbon isotope and atmospheric oxygen measurements should help determine the roles of the ocean and terrestrial biosphere.

(v) The CO_2 modelling community is encouraged to make sensitivity analyses to better determine model uncertainties, e.g., effect of model predictions using ECMWF vs WOCE/FSU wind fields in interdecadal (5-10 years) forcing variations of CO_2 uptake.

(vi) Time series of surface pCO_2 data on basin-wide scales will provide information on seasonal, regional and interannual variability of air-sea CO_2 exchange. "Ship of opportunity" sections should be encouraged and extended to include supplementary measurements aimed at process studies.

(vii) The large interannual changes in atmospheric CO_2 accumulation rates which are significantly correlated to ENSO events, indicate that the equatorial ocean has a substantial effect on CO_2 sequestration.

(viii) Model predictions indicate that most (65-85%) of the anthropogenic CO_2 accumulation occurs in the sub-tropical gyres, closely related to the main thermocline ventilation processes. An improved understanding of these ventilation processes is of great importance.

(ix) A coastal zone sink for CO_2 will have to be related to high sedimentation rates, and thus a sediment burial and a geological process. High biological production rates alone in coastal zones are insufficient conditions for a coastal zone CO_2 sink.

(x) There is a strong need to quantify the uncertainties in the CO_2 budgets e.g., source and sink rates in terms of the +- 1SD or +- 2SD error in the mean and whether the errors represent primarily natural variability, measurement variability or insufficient data. The following table provides an indication (for references, please refer to Annex III).

Process	CO_2 flux in GtC/yr	Uncertainty source
Fossil fuel combustion	5.4 +/- 0.5	Fuel production data
Deforestation and land use	1.8 +/- 1	Extrapolation errors
Atmospheric accumulation	3.2 +/- 0.2	Sampling sites and frequency
Missing CO_2	4 +/- 1.2	Sum of errors
Ocean uptake	2 +/- 0.6	Model inaccuracies and lack of data
Implied terrestrial uptake	2 +/- 1.3	sum of errors

(i) Iron Fertilization: The present evidence based on one experiment is that this would not have any long-term effect on CO_2 withdrawal from the atmosphere. However, an experiment concerning the Southern Ocean would help further clarify this matter. Moreover, fertilization of the ocean may be important in relation to increase of food production. The biology of the ocean may have an influence on interannual variability of atmospheric CO_2 content, but the important biological processes are unknown.

(ii) The basic state of the ocean is strongly influenced by biology. The anthropogenic perturbation is superimposed on this basic state with strong inherent variability, and the anthropogenic perturbation is independent of the natural state, as long as the biology has not changed.,

(iii) Model results should be better used to improve design of field experiments and identify critical sampling needs and areas.

(iv) Additional scientific groups should be encouraged to do ocean modelling activities provided adequate concentration of resources can be achieved, including computer power.

(v) Sensitivity of model predictions needs to be further investigated, e.g., with respect to ocean circulation changes, thermocline ventilation changes, Ekman pumping rates, and biochemical processes. Long-term changes of ocean uptake have been inferred from changes in gas exchange (e.g., Southern Ocean, equatorial area). Model responses to wind fields obtained in alternative ways than those from ECMWF also need to be investigated.

6. CLOSURE

The meeting was closed by the co-chairs and Professor Busuttil expressed appreciation to all participants for their work and contribution. The Secretary of IOC thanked the host organization for all the help and hospitality.

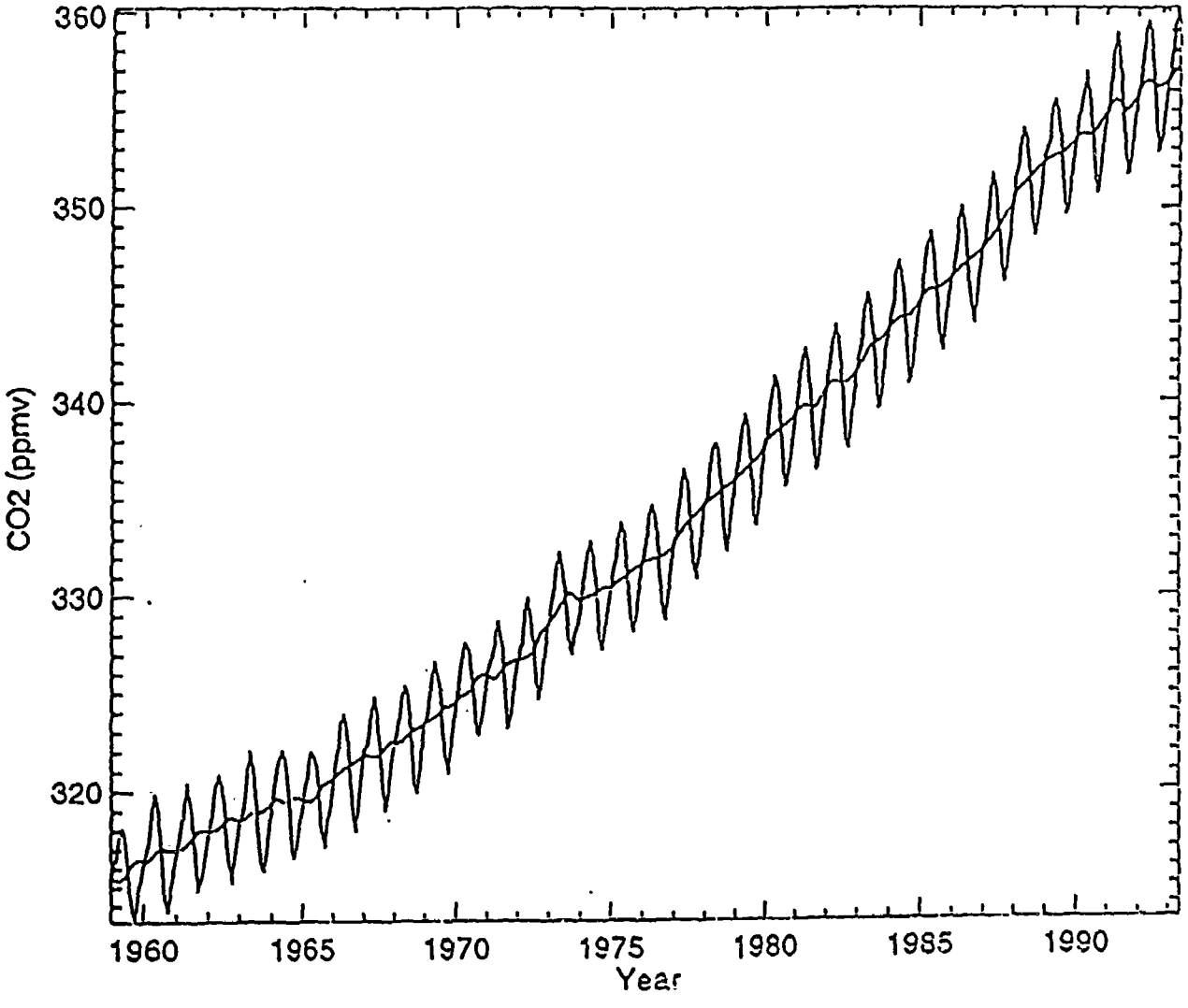

Fig.1 The Mauna Loa CO_2 concentration in parts per million. The thin line is the concentration with the seasonal and semi-annual signals removed.

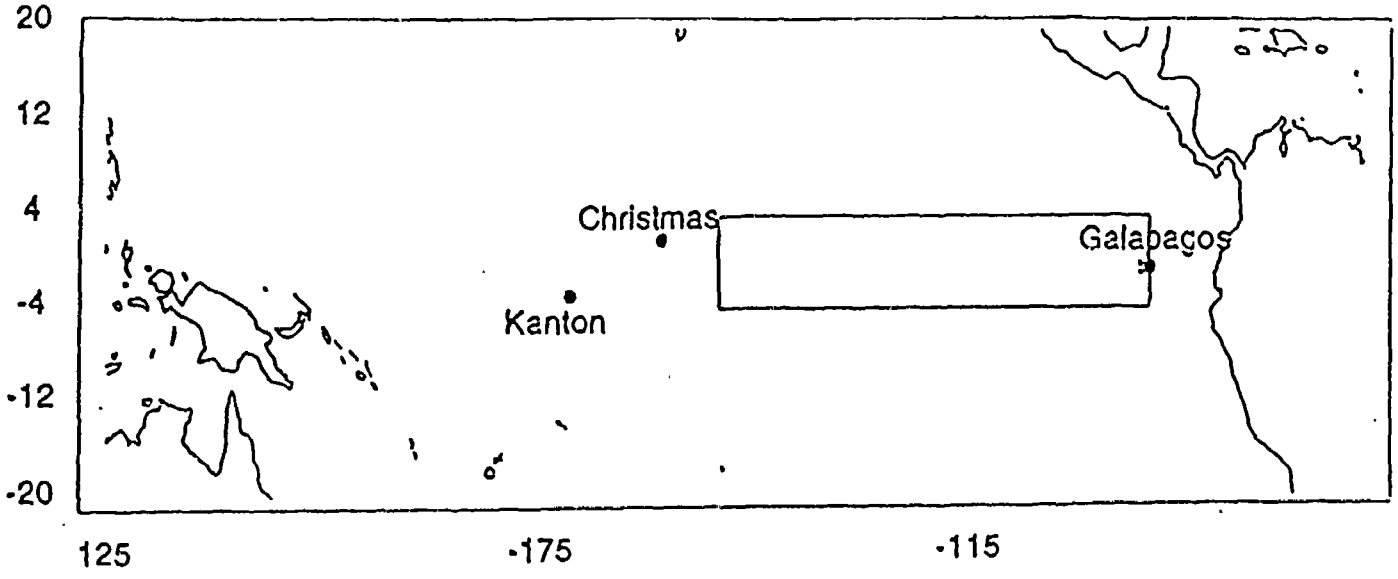

Fig.2 Map of the equatorial Pacific Ocean. The JMA region between 4°N-4°S and 150°W 90°W, outlined by the box. The three islands whose sea-level measurements are examined, are indicated.

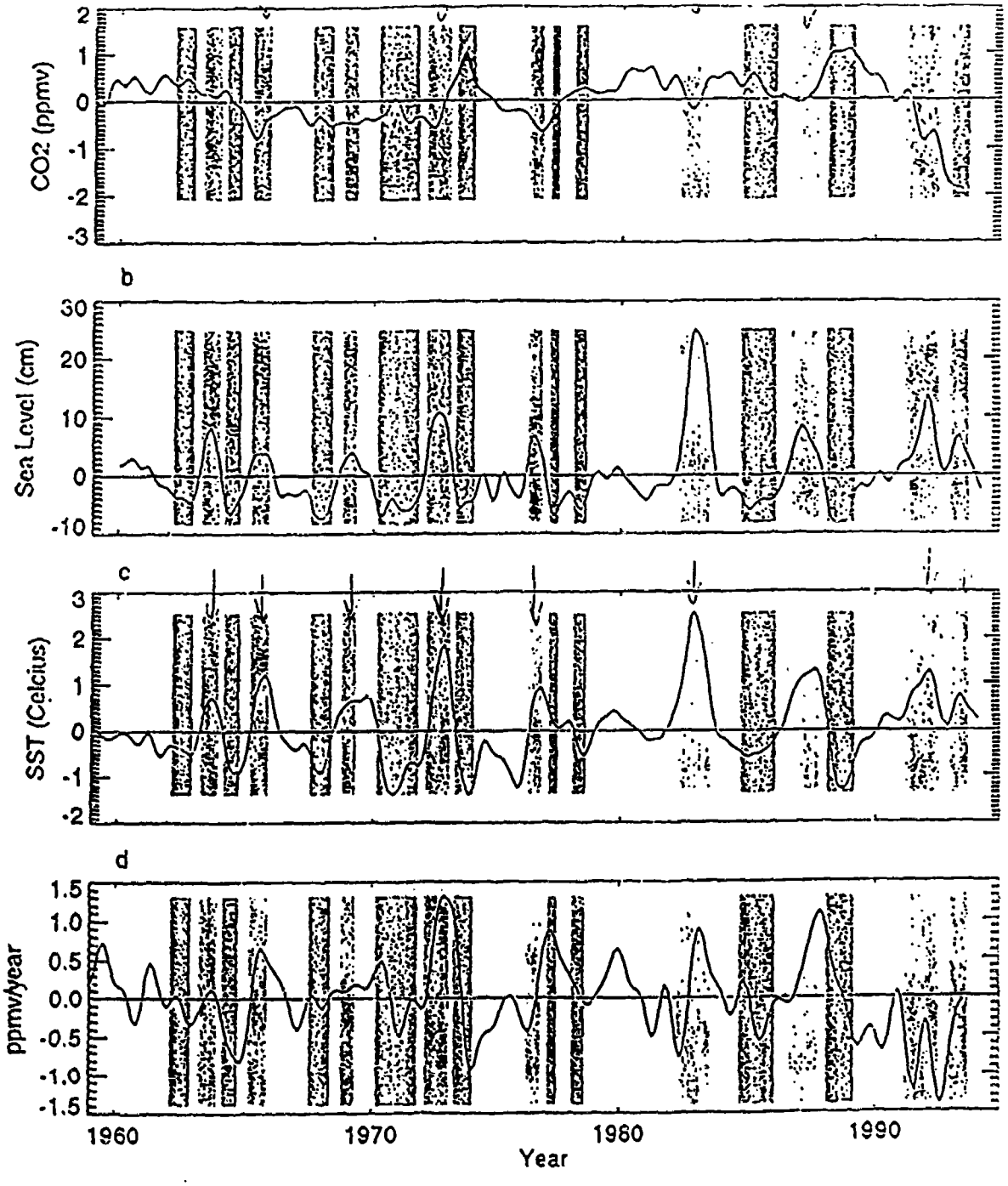

Fig.3 Obervational records and the occurrence of ENSO events. The light-shaded regions indicate El Niño and the dark-shaded regions indicate El Viejo, both being designated by Galapagos sea-level as described in the text; (a) The atmospheric carbon dioxide concentration anomaly from Mauna Loa, Hawaii after removing the trend and seasonal signal. The long-term increase is found by fitting the measurements to a quadratic in time. The seasonal and semi-annual signals are removed using a least-squares fit to the detrended signal. Ten forward and backward passes of a 1-2-1 Hanning filters are used to sonooth the data; (b) The sea level anomaly from the Galapagos Islands located at 0°N, 90°W. The annual signal was removed and the same filter as in (a) was used; (c) the five-month running mean of monthly SST anomaly in the Pacific from JMA. The same filter as in (a) was used; (d) the time derivative of (a). The time derivative of (a). Before differentiation, twenty forward and backward passes of the Hanning filter were used.

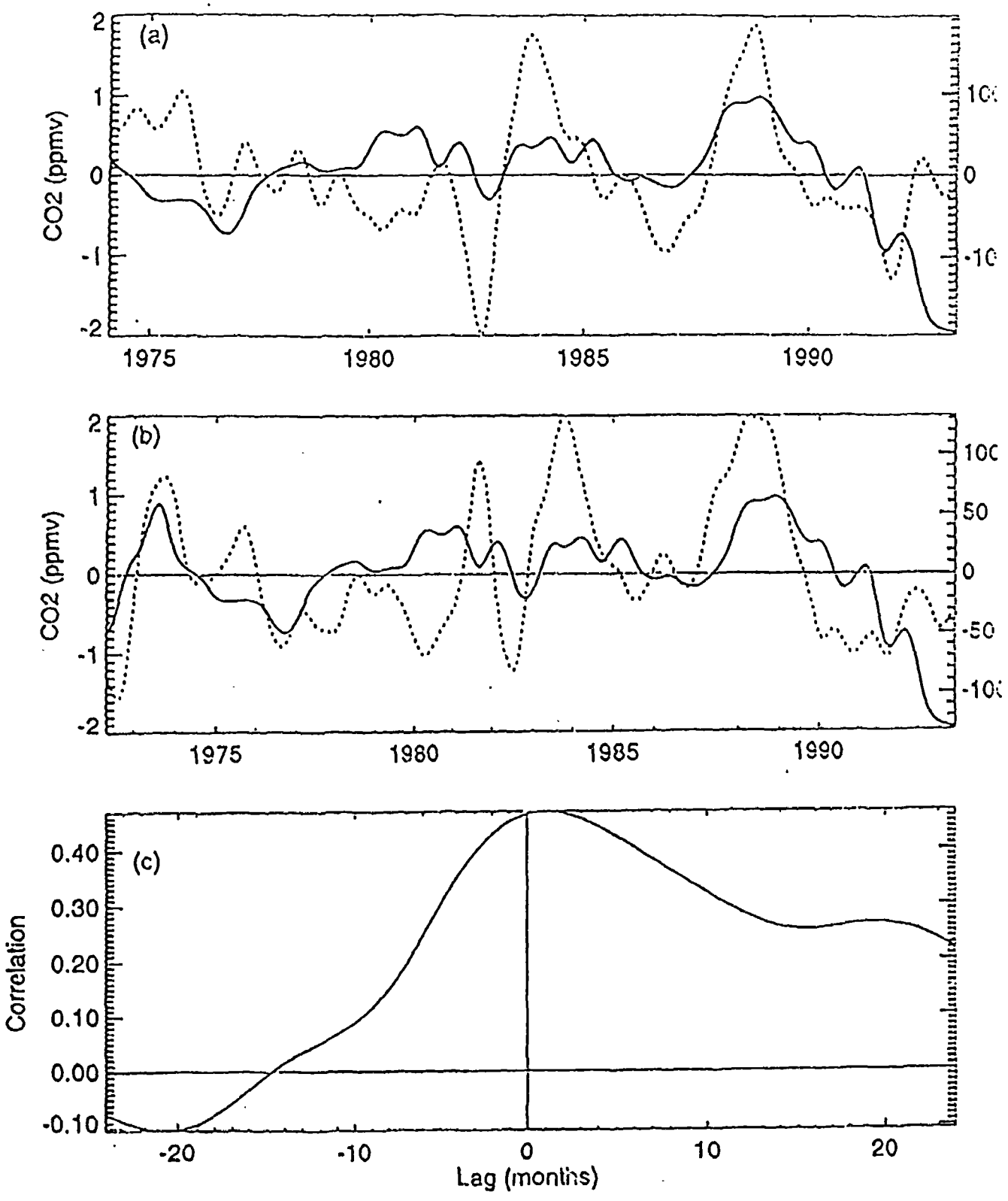

Fig.4 Overlays of CO_2 anomalies (solid line) with flipped SL anomalies (dashed line) from (a) Christmas Island (157.5W,2N); (b) Kanton Island (171.7W,2.8S). The annual and semi-annual signals have been removed. The smoothing for all data is the same as in Fig.3(a); (c) The correlation for the data in (b).

ANNEX I

AGENDA

1. OPENING

2. ADMINISTRATIVE ARRANGEMENTS

3. BASIC SCIENTIFIC RESULTS AND ISSUES WITH RESPECT TO OCEANS AND CO_2

4. IMPLICATIONS OF THE PRESENT STATE OF KNOWLEDGE FOR THE CO_2 ISSUE

5. SUMMARY STATEMENT

6. CLOSURE

ANNEX II

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ANNEX III

CO_2 AND THE OCEAN: A REVIEW OF THE STATE OF KNOWLEDGE

Edited By
Arthur G. Alexiou

This paper was prepared as a background document in anticipation of a meeting of ocean CO_2 experts to be hosted by the Government of Malta on behalf of the Intergovernmental Oceanographic Commission, 6-8 October 1994. The meeting is in response to IOC responsibilities regarding the ocean's role in the carbon budget, identified by the UN Conference on Environment and Development in Rio de Janeiro, June 1992. It is a product of the Joint IOC-JGOFS Panel on Carbon Dioxide whose members are activley involved in CO_2 laboratory and field programs. It also draws on published literature by other experts, in particular on a review article by Siegenthaler and Sarmiento (1993) that addressed exceedingly well, many areas intended to be covered in this background paper.

1. INTRODUCTION

Concern over the effects of the inexorable rise in the partial pressure of CO_2 and other greenhouse gases in the atmosphere was one of the principle reasons for convening the United Nations Conference on Environment and Development (UNCED) in Rio De Janeiro in 1992. Climate and the carbon cycle appear to have been so tightly interdependent in the historical record that they must be considered together in accounting for global environmental changes. The oceans as a whole constitute a large reservoir of carbon - the upper 75-100 meters alone contain as much carbon as the entire atmosphere. Less than half of the CO_2 generated from fossil fuel combustion and land use practices, i.e., the so-called anthropogenic CO_2, is retained in the atmosphere. The remainder is taken up by the ocean and by the land biosphere. It is believed that the oceanic and terrestrial sinks for this CO_2 are of comparable magnitudes with the ocean sink the larger. The future evolution of the atmospheric CO_2 is therefore crucially dependent on the net exchange of carbon between the ocean and the atmosphere - which in turn depends on the ocean processes that affect the distribution of carbon in the ocean.

At UNCED, the international community recognized the need for improved understanding of the important role that the oceans and seas play in attenuating potential climate change. The Conference produced a set of agreements on environment and development that were embodied in AGENDA 21. Section 17.106 calls for the IOC and other relevant competent United Nations bodies, with the support of the countries having the resources and expertise, to carry out analyses, assessments and systematic observations of the role of the oceans as a carbon sink. As part of its response, the IOC requested the IOC-JGOFS CO_2 Advisory Panel to prepare this state of knowledge review as a background document for a meeting of experts to devise approaches to accomplish these ends and to consider the consequences of potential changes in ocean circulation, nutrient distribution and temperature, due to global warming, on the carbon cycle as we know it today.

The IOC has played a leading role, in cooperation with SCOR, in stimulating research along these lines since the mid 1980s. The late Roger Revelle saw the greenhouse potential of CO_2 early on and realized that the available ocean CO_2 data base was woefully inadequate for quantifying the carbon fluxes between the ocean and the atmosphere. He was largely responsible for generating efforts through the World Climate Research Program (WCRP) and the Joint Global Ocean Fluxes Study (JGOFS) to undertake this task, initially under the aegis of the IOC and SCOR.

It was not seen as achievable, however, to determine the magnitude and variability from global integrals of directly observed flux changes. Rather, the aim of the global field programs from the beginning was to obtain the first accurate data sets on concentrations and, through model calculations, compute present day fluxes. It is reasonable to expect, that in some cases the data will contain signals that can be shown to have varied with time. While measurement techniques are now adequate to detect these signals, it is not reasonable to expect that the net CO_2 flux can actually be measured over the world ocean, let alone the changing of this flux with time. We are forced, therefore to rely on models. Estimates obtained from observations will put severe constraints on the models and force them to be more realistic.

As more data and new techniques have become available, the major modelling centres have been able to reach closer agreement on their attempts to quantify the various components of the global carbon budget. But the magnitude of the uncertainties in their results is still too large to reliably partition between the land and the ocean, the fate of that fraction of the anthropogenic CO_2 that is known to have been injected into the atmosphere, but not present there now. This document covers the current state of knowledge concerning the ocean carbon cycle and the means available for its study. As such, it provides a basis for developing a strategy for the further analyses, assessments and observations called for in AGENDA 21.

2. GOALS OF OCEAN CARBON RESEARCH

Global ocean climate research is aimed at achieving a deeper understanding of the processes relevant to the global carbon cycle. This is an absolute prerequisite if the potential impacts of perturbations to the carbon system are to be predicted with a level of skill and with a long enough lead time that will allow governments to make scientifically and economically sound decisions for ameliorating those impacts. A first priority is movement toward the following objectives:

(i) to quantify the role of the ocean in CO_2 uptake over the last 30-year period for which we have reliable data for the atmospheric record and burning of fossil fuels;

(ii) to detect the change with time of the efficiency of the ocean sink.

(iii) to understand the time varying ocean processes sufficiently well to establish the bounds of natural CO_2 variability.

To attain these objectives requires narrowing the uncertainties in existing estimates of CO_2 fluxes and changes in oceanic storage through acquisition of high quality global data sets and improved modelling techniques.

3. RECENT BEST ESTIMATES OF THE CO_2 BUDGET

Estimates of the amount of carbon stored in the various components of the global carbon budget, the steady state fluxes between them and the perturbation of CO_2 imposed on the system since the beginning of the industrial age are provided in the table below. They serve to illustrate the carbon cycle problems that CO_2 researchers are grappling with in attempts to predict the impact on climate of increasing CO_2 in the atmosphere. These have been compiled principally from the 1992 Supplementary Report to the IPCC Scientific Assessment, and more recent updates of some of the estimates by Siegenthaler and Sarmiento (1993), Orr (1993) and Quay et al (1993).

<u>CO_2 atmospheric concentration</u>		
A.	pre-industrial time (measurements of ice core air bubbles)	280 ppm
B.	at present (1993) (direct air measurements at Mauna Loa and South Pole since 1958)	358 ppm
C.	increase to date since pre-industrial times (from A - B)	78 ppm

<u>C storage (in Gt)</u>		
D.	in atmosphere during pre-industrial times (reconstructed from A)	600
E.	in atmosphere now (1990, increasing 3.4 Gt/yr) (calculated from B)	765
F.	in ocean during pre-industrial times (reconstructed estimate)	39,700
G.	in ocean now (1990, increasing 2.0 Gt/yr) (calculated from ocean carbon data)	39,820
H.	on land before 1860 in biota and soils (reconstructed estimate)	2,170
I.	on land now (1990) rate of change near zero) (deforestation approximates new growth; see M and Q)	2,050

Anthropogenic C in the atmosphere (in Gt)		
J.	inserted during 1860 to 1989 (estimated from fossil fuels consumed and land practices)	345
K.	accumulated during 1860 to 1989 (computed from measured increases in air and ice core air bubbles)	138
Anthropogenic C during the 1980-89 decade (in GtC/yr)		
L.	inserted into the atmosphere (estimated from fossil fuels consumed)	5.4 ± 0.5
M.	inserted into the atmosphere* (estimated from deforestation and land practices)	1.6 ± 1.0
N.	accumulated in the atmosphere (calculated from Mauna Loa - South Pole average)	3.2 ± 0.1
P.	added to ocean from atmosphere	
(P1)	based on ocean model calculations of downward transport of CO_2 constrained by bomb ^{14}C penetration (since 1960)	2.0 ± 0.5
(P2)	based on $^{13}C/^{12}C$ measured rates of atmospheric and oceanic change (since 1970)	1.8 ± 1.0
(P3)	based on available atmospheric and ocean pCO_2 data and an atmospheric model	2.0 ± 1.0
Q.	imbalance assumed to be taken up by land biosphere (from L + M - (N + P1))	1.8 ± 1.3

Major present day gross fluxes (in GtC/yr)		
R.	atmosphere to ocean	92
S.	ocean to atmosphere	90
T.	atmosphere to land (biota and soils)	102
U.	land to atmosphere (biota and soils)	100

Minor steady state fluxes (in GtC/yr, assumed unchanged since 1860)		
V.	added to ocean from rivers	0.8
W.	released from ocean to atmosphere	0.6
X.	deposited from ocean in sediments*	0.2
Y.	accumulated by soils from atmosphere	0.6

* Recent findings suggest the estimate of M is too high by 0.5 - 1.0 GtC because C density attributed to tropical forests is too high and continuing regrowth of forests in northern temperate latitudes has been neglected (Bolin, 1993). The figure of 0.2 GtC/yr for X is derived from an assumption of 1% detritus organic carbon from surface productivity of about 20 GtC/yr. There is also $CaCO_3$ deposition on the ocean floor. Estimates based on data from sediment traps indicate the total organic C flux, including the $CaCO_3$, averages about 0.4GtC/yr globally.

Scientists pursuing ocean CO_2 research have demonstrated remarkable ingenuity in arriving at the these estimates by exploiting unconventional data sources and making optimum use of conventional ones from many disciplines.

At present, the available hard data are insufficient to balance the global carbon budget within the accuracy required. The only relatively firm constraints are the figures on CO_2 released into the atmosphere by burning of fossil fuels plus those on the production of cement which is small (about 2%) and the records of atmospheric CO_2 monitoring stations at Mauna Loa and the South Pole since 1958. Though the record of deforestation was begun in 1850, figures for the situation on land, (e.g., deforestation plus land use changes and new growth) show large variations for the whole period and have large uncertainties, 40% or more, associated with them. The contribution of soil, the temporal fate of vegetation and wood products, as well as the uncertainties in the extent of deforestation and regrowth make the effects of human land use one of the most uncertain parts of the global carbon budget. Thus far, effort has been concentrated on estimating the ocean CO_2 uptake and assuming the remainder goes to the land. But the complexities of ocean carbon

distribution obscure the mechanisms underlying the CO_2 budget and prevent easy discrimination of the anthropogenic CO_2 signal from natural trends.

It is immediately clear from a quick look at the estimates in the table, that the net uptake of CO_2 by the ocean (P) is very small compared to estimates of the total CO_2 flux between the ocean and the atmosphere (R,S). Thus, trying to better quantify the net ocean uptake of CO_2 by subtracting two large numbers of nearly equal value is not promising. The research therefore has moved along other fronts: model development and acquisition of global data sets that make possible other approaches for calculating the anthropogenic CO_2 uptake by the ocean. Data on excess CO_2 based on CO_2 penetration depth and excess CO_2 concentrations at different depths, calibrated by freons, and fluxes of $CaCO_3$
and organic C into the deep ocean sediment would serve to constrain the "net approach.

3. ESTIMATING THE OCEANIC UPTAKE OF CO_2

In principle there are two basic ways that have been used to estimate CO_2 uptake by the ocean: (1) the use of carbon cycle models, and (2) calculations using global observations of the carbon system. Only with models, however can we hope to make reliable estimates of the future uptake of CO_2 by the ocean. On the other hand, model development depends on data and realistic parameterizations and new information derived from process research.

3.1 CARBON CYCLE MODELS

Models of the oceanic carbon cycle are being used for estimating the past, current and future ocean CO_2 uptake and to assess the influence of variations in biogeochemical processes, natural fluctuations as well as anthropogenic changes, on atmospheric CO_2. For both applications, a hierarchy of models of different complexity have been used and will be needed also in future.

Simple, box-type models are much easier to handle and much less expensive than 3-D-models regarding computing time and effort for programming and data evolution. They are valuable tools for understanding the role of different processes and for sensitivity studies. If calibrated by suitable tracer observations, they can yield realistic estimates of the oceanic uptake of anthropogenic CO_2 (e.g., Siegenthaler and Oeschger, 1987; Siegenthaler and Joos, 1992).

Information on the regional distribution of CO_2 sources and sinks and on the interaction between climate change, ocean circulation and the carbon cycle, can only be obtained using ocean general circulation models (OGCMs) (Maier-Reimer and Mikolajewicz, 1992; Sarmiento et al., 1992). In addition to 3-D OGCMs, dynamical 2-D (latitude-depth) models, which are less time consuming to run than 3-D schemes (Stocker, 1994), are being developed for study of the influence of the ocean circulation on the carbon cycle. This is particularly important for studies of the glacial-interglacial CO_2 variations, which require integrations over 10^4 to 10^5 years.

For all types of ocean carbon cycle and climate models, calibration or validation by means of oceanic tracer fields is crucial. The penetration of time-dependent tracers, notably natural and bomb-produced ^{14}C, CFCs and tritium are of particular interest as an analogue to invasion of anthropogenic CO_2 into the ocean. Observations of these tracers contain integrated information on rates of oceanic transport and mixing and on air-sea gas exchange fluxes which otherwise cannot be obtained. Also important, are ^{13}C data which contain natural markers of biological processes and burning of fossil fuels, because plants incorporate ^{12}C preferentially over ^{13}C. For the progress of ocean modelling it is important that observations of these tracers are made with global coverage.

Estimates of the oceanic CO_2 uptake made with bomb ^{14}C calibrated models, simple ones and OGCMs, agree relatively well. The best estimate for the period 1980-89 is 2.0 ± 0.6 Gt C/yr (Siegenthaler and Sarmiento, 1993). In order to further diminish the error on this estimate, higher resolution and

improvement on model physics are required. A critical intercomparison of different 3-D ocean carbon cycle models has still to be made. Nevertheless, comparison studies show that model results of CO_2 fluxes and inventories compare reasonably well with calculations based on observations.

For simulating the natural carbon cycle, biological processes must be included. This is a difficult task because of the lack of understanding, the non-linearity of biological processes and the large range of spatial and temporal scales involved. For global-scale simulations, it will be indispensable to represent biology in a highly parameterized way. JGOFS is contributing to this effort in an important way by furthering better understanding of the rate governing processes in the ocean in order to develop useful parameterizations.

The limitations of models are well understood by modelers themselves. These limitations are not always appreciated by those who would use their results. The historical CO_2 budget as revealed in sediment cores, corals, tree rings, ice cores, etc., represents a complexity of long-term behaviour that is a challenge to unravel. Current models used to forecast future CO_2 levels have a way to go before they are fully adequate to the task.

3.2 THE AIR-SEA pCO_2 DIFFERENCES APPROACH

3.2.1 Air-Sea Gas Exchange Coefficient

Atmospheric gases tend to become dissolved in the surface ocean and, vice versa, dissolved volatiles tend to escape to the atmosphere. This exchange across the surface of the ocean has been studied for many gases and a body of theory built up to describe the process. For the majority of gases, including CO_2, the flux (F) of a gas should be related to the difference in the partial pressures of gas in the atmosphere (pCO_{2atm}) and in equilibrium with surface ocean water (pCO_{2sur}) by the equation:

$$F = K_g [pCO_{2atm} - pCO_{2sur}] = K_g \Delta pCO2 \qquad (1)$$

The equation states that the flux is proportional to ΔpCO_2. This is true only when the flux is across an unbroken surface, and will require modification if a significant portion of the flux is carried by bubbles where $\Delta pCO_2 = pCO_{2atm} - pCO_{2sur}$. K_g is a parameter called the gas transfer coefficient, which accounts for the process of transport across the air-sea interface, and is also dependent on the solubility of the gas. produced by breaking waves.

In theory, this equation can be the basis for specifying not only the global net sink for atmospheric CO_2 in the ocean, but also how this is made up from individual source and sink regions around the world. In practice, the situation is not quite so clear-cut. While it remains a goal of oceanic CO_2 research to refine the estimates of CO_2 fluxes made in this way, there are shortcomings in the present data base and in the theory of gas exchange. These may make it impractical to obtain a value for the global uptake of CO_2 from equation (1) which can improve on the accuracy of the global uptake calculated from model simulations. However, there are good reasons besides obtaining the size of the global sink to be interested in the global distribution of the air-sea exchange flux.

The gas transfer coefficient, K_g, is dependent on local surface conditions. In particular, it increases rapidly and non-linearly with the wind speed as a result of the increasing turbulence in the water immediately adjacent to the surface. Several theoretical models have been formulated to predict the form of K_g, but the complexity of the process has meant that, in practice, empirical fits to observations have been more often used than derivations from theory. The most widely quoted such empirical fit is the "Liss-Merlivat" formulation (Liss and Merlivat, 1986).

Theory has been more successful in predicting how the gas transfer rates of different gases should relate to one another. For a roughened but not broken sea surface, K_g is proportional to $Sc^{-0.5}$, where Sc is a property of the gas termed the Schmidt number. This has the consequence that gas transfer rates observed at sea for one gas can be scaled to apply to any other. The $Sc^{-0.5}$ scaling has been extremely useful, as direct observation of gas transfer rates in the field has proved difficult. There are relatively few measurements therefore, and none where the gas measured was CO_2. Instead, most of the measurements were made with inert and sparingly soluble gases such as radon, helium and sulphur hexafluoride. The strategy for determining K_g in equation (1) has therefore been to scale the body of existing measurements using these gases to be appropriate for CO_2. The Liss-Merlivat relation was derived from such a scaling, and most of the measurements now in the literature tend to confirm it as a reasonably accurate representation of gas exchange. It should be kept in mind however, that the Liss-Merlivat formulation, the best currently available, is still unsatisfactory for the high wind regime in the winter, where breaking waves are important.

Though none of the available direct measurements were made with CO_2, there is an estimate of the overall, mean global CO_2 gas transfer coefficient, made from observations of the penetration into the ocean of the $^{14}CO_2$ derived from the nuclear atmospheric tests of the fifties and early sixties. This estimate provides the strongest constraint that we have on the global mean gas transfer coefficient. Unfortunately, the global ^{14}C-derived transfer coefficient is difficult to reconcile with the Liss-Merlivat relationship. Because of this discrepancy, our confidence in the absolute value of CO_2 fluxes obtained from equation (1) is weak; there appears to be some, as yet unidentified, reason why CO_2 exchange is faster than would be expected from existing knowledge and measurements using other gases.

In view of this uncertainty one might ask of what value is the "gas exchange" approach to determining ocean sources and sinks of CO_2. It is reasonable to assume that equation (1) gives, if not the absolute value of the flux, at least a way to obtain relative flux magnitudes between ocean regions. Such fluxes are valuable especially when used to constrain atmospheric "inverse" models used to deduce the distribution of sources and sinks compatible with the observed distribution of CO_2 in the atmosphere. The distribution of sources and sinks of atmospheric CO_2 is valuable in our attempts to understand how ocean circulation, chemistry and biology interact with climate and climate change as potential feedback mechanisms to affect atmospheric CO_2. The gas exchange method also provides an independent check on the model-derived estimates for the global oceanic uptake. Finally, CO_2 gas exchange is the subject of intense research in which it is hoped that the accuracy of our estimates will be considerably improved over the next few years.

3.2.3 Satellite Observations

Satellite observations offer the only cost effective way to obtain global synoptic coverage of ocean surface conditions. Current satellite systems permit observations of sea surface temperature, ocean color, surface wind and topography. Estimates of pCO_2 for surface waters can be derived from satellite observations of ocean color, temperature and surface wind. There are a hierarchy of empirical, statistically based approaches for the estimation of pCO_2, building from surface wind speed, to wind and temperature, to wind temperature and color. These methods are based on statistical correlations between pCO_2 and the particular parameters.

Another approach is to infer pCO_2 directly from ocean color using correlations derived from *in-situ* observations. However the physical relation between these two variables is very indirect. In certain regions, such as some upwelling zones where there is *a-priori* information on the association of nutrients with decreases in surface temperature, it is also possible to use ocean surface temperature observations to enable prediction of new production which, over a period of time, must constrain the carbon flux out of the water.

A more fundamental approach is to employ a model based system of the oceanic upper mixed layer to estimate pCO_2. Such a model would use photosynthetically active radiation (PAR), surface temperature, and winds as forcing inputs with ocean color as a constraint on model integrated biomass. The applicable caveat is that while chlorophyll in the upper layers may be a proxy for pCO_2, it is not always well-correlated

to satellite color data. Further studies are required to fully exploit satellite ocean color observations for the estimation of pCO_2.

3.2.4 Calculations Based on Spatial Distribution of CO_2 Concentrations

One particular study by Tans et al (1990) based on pCO_2 observations reported discomforting results in 1990. They calculated the ocean CO_2 uptake of about half of the generally accepted IPCC value of about 2 GtC/yr. Using a model of atmospheric circulation and data on the relative concentrations of CO_2 in the atmosphere and the ocean, Tans et al. made calculations to determine how much CO_2 could pass from the atmosphere to the ocean. From surface-water pCO_2 measurements in the Northern Hemisphere and the interhemispheric difference in atmospheric CO_2 concentrations, they estimated an oceanic uptake of less than 1 GtC/yr. This led Tans et al. to propose the existence of a large unaccounted for sink on land, the so-called "missing sink".

Subsequently, their results for the amount of carbon going into the ocean were revised upwards for the following reasons. Robertson and Watson (1992) calculated that if the ocean surface temperatures used to determine pCO_2 were corrected to account for the surface "skin effect" their result would have been higher by 0.44 GtC/yr. Another 0.4-0.7 GtC/yr was added to their estimate to account for that part of the river load of organic material entering the ocean that is remineralized there. The third correction is for the carbon transported north to south in the form of carbon monoxide which was not included by Tans et al. Properly accounted for, this adds another about 0.25 GtC/yr to the calculated ocean uptake. The revised estimate of 1.8 GtC/yr is entered in the table as P(3). Enting et al (1993), in a reassessment have been able to raise that figure to 2.0 ± 1.0 GtC/yr.

The estimates of CO_2 fluxes derived from direct observations are the sum of the natural and anthropogenic fluxes. Therefore, air-sea pCO_2 difference measurements do not indicate where anthropogenic CO_2 is mainly taken up as they yield only the total flux. There is no way, by direct measurement, to distinguish between regions where anthropogenic CO_2 is being mainly taken up.

4. RECOGNIZING THE ANTHROPOGENIC CO_2 SIGNAL IN THE OCEAN

Apart from employing models, the way that has usually been followed, the post-industrial CO_2 increase in the ocean can in principle be estimated in several different ways from observations:

i) By reconstructing the increase from measurements of the oceanic carbon system.

ii) By using the stable ^{13}C isotope

iii) By using transient tracers, like bomb-radiocarbon, tritium, or CFCs as analogs to anthropogenic CO_2 and trying to relate the two signals.

iv) By using O_2 observations

4.1 RECONSTRUCTING THE INCREASE FROM pCO_2 PROFILES

This approach was suggested by Brewer (1978) and, in a somewhat different way, used by Chen and Millero (1979). To determine the fossil CO_2 signal in a parcel of water, it is necessary to subtract the contributions to C_T and alkalinity due to biological activity, i.e., from respiration and calcium carbonate dissolution. The respiration contribution can be estimated from the apparent oxygen utilization, since the changes in C_T and O_2 are linked by a fixed ratio (Redfield ratio). The original (pre-formed) alkalinity of the water parcel can be calculated from salinity, since in a given ocean basin, the two properties are very well correlated. The alkalinity is also slightly affected by respiration (addition of NO_3); but this contribution can

also be obtained from the apparent oxygen utilization. In summary, the changes in C_T and in carbonate alkalinity due to biological activity can be estimated as:

$$\Delta C_T = 0.824\ \Delta O_2 + 0.5\ \Delta A_T \qquad (2)$$
$$\Delta A_{CaCO_3} = \Delta A_T - \Delta O_2/9 \qquad (3)$$

In this way, the pre-formed composition of the water parcel (i.e., its composition at the time when it was in contact with the atmosphere) can be reconstructed, and therefore the pre-formed pCO_2 determined.

The earlier studies using this (or a similar) approach were partly criticized because of uncertainties in the data and in the coefficients involved in the above equations. However, the signal is quite large by now -- surface water C_T is typically 40 μmol/kg higher than in pre-industrial time -- and the measurement accuracy has considerably improved to $\pm$ 1 μmol/kg for C_T. An exercise to reconstruct the oceanic CO_2 increase was done with November 1988 measurements in the Florida Straits by Goyet and Brewer (1991). Surface-water values were found to be near equilibrium with the 1988 atmospheric CO_2 concentration of about 350 ppm, and the reconstructed deep-water results near the pre-industrial atmospheric concentration of 280 ppm, which strengthens the confidence in the method.

With the prospect of obtaining large high-precision data sets of the oceanic CO_2 parameters during WOCE, it should be possible to reconstruct the oceanic CO_2 increase on a global scale.

4.2 THE $^{13}C/^{12}C$ APPROACH

Approximately 1% of the all the world's carbon is in the form of the stable isotope, ^{13}C. One part in a trillion is in the form of the radioisotope, ^{14}C. The rest is ^{12}C. Despite the huge disparity in these numbers, chemists are able to accurately measure the ratios of ^{13}C to ^{12}C to ^{14}C in the atmosphere, terrestrial biosphere and ocean. Man's activities result in changes in these ratios.

Scientists use the ratio of ^{13}C to ^{12}C as a means of tracing the fate of CO_2 released from combustion of fossil fuels and biomass. Since plants take up ^{12}C preferentially during photosynthesis, they contain a smaller proportion of ^{13}C than the atmosphere. Therefore the CO_2 emitted into the atmosphere from combustion is depleted in ^{13}C. The resultant change is a very small, but measurable signal in the $^{13}C/^{12}C$ ratio of the atmosphere's composition. This signal moves into the ocean as it exchanges CO_2 with the atmosphere.

Evidence exists showing this lowering of ^{13}C in the atmosphere and ocean has been occurring for some time. The ice core air bubbles show that the $^{13}C/^{12}C$ ratio has been decreasing steadily for the last 250 years. A decrease has also been detected in the carbon in ocean corals and in the surface waters of the Pacific and the southern Atlantic Ocean from measurements made during the past 20 years.

The rate of CO_2 uptake by the ocean can be calculated directly by comparing the measured change in the $^{13}C/^{12}C$ value of dissolved inorganic carbon since 1970 to the measured changes in the concentration and $^{13}C/^{12}C$ value of atmospheric CO_2 over the same period. Using this model-independent approach, Quay (1993) comes up with a figure of 1.8 ± 1.0 GtC/yr over the past twenty years using 17 depth profiles of $^{13}C/^{12}C$ from the Atlantic and Pacific Oceans. This compares with the 2.0 ± 0.5 GtC/yr obtained from averaging model simulations.

The differences in the $^{13}C/^{12}C$ ratios of dissolved inorganic carbon in the ocean has other useful interpretations. Their values in the surface ocean are controlled by three processes. Gas exchange drives the $^{13}C/^{12}C$ values toward equilibration with the atmosphere; upwelling lowers them; and net production of organic matter increases them. Thus their low values observed in the equatorial and subpolar Pacific indicate upwelling in those regions is more important than biological productivity and gas exchange.

Clearly, there is a strong case for increasing the global data set of high precision $^{13}C/^{12}C$ measurements. WOCE and JGOFS are attempting to do that. Not only do they provide a model-independent

method for tracing the fate of anthropogenic CO_2, they can be used with model-derived or measured upwelling rates to yield estimates of net production of organic carbon.

4.3 THE CO_2 APPROACH

As CO_2 is added to the atmosphere by oxidation and animal respiration, O_2 is depleted. The oceanic reservoir of C is significantly larger than that of the atmosphere. But even allowing for the buffering effect of the ocean carbonate system, the oceanic reservoir of CO_2 available for exchange on decadal time scales is similar to that of the atmosphere. Contrastingly, the atmospheric reservoir of O_2 is approximately 100 times larger than that of the oceans and about 1000 times larger than the reservoir of the ocean available for exchange with the atmosphere on time scales of decades. Thus, measurement of changes of the concentration of O_2 is a far more direct way of assessing the total oxidation taking place in the atmosphere, including the combustion of fossil fuels, loss of soil organic carbon and biomass burning. Though this fact has been appreciated for many years, techniques for the measurement at the necessary precision in a background of 21% O_2 have not been available until very recently.

Recent measurements of the decrease of atmospheric O_2 made possible by these new high-precision techniques, capable of measuring one in 10^6, show promise of yielding the total net flux of CO_2 from the land biota (land minus biospheric sink) and by difference, also the oceanic sink (R. Keeling and Shertz, 1992).

5. CO_2 SYSTEM MEASUREMENTS

5.1 SPATIAL AND TEMPORAL REQUIREMENTS FOR pCO_2

Internationally through WOCE and JGOFS, a considerable effort is now under way to document pCO_2 in the surface ocean, and its dependence on season, position, and interannual changes. There are now no major ocean regions in which there are not at least some measurements, and many areas are increasingly well covered.

How many such observations are needed before we have enough? If we lay aside the present difficulties stemming from the gas exchange rate uncertainties (hoping this will be resolved in the near future) we can calculate an order of magnitude figure for how many observations would be needed to define the global air-sea flux to a given accuracy. For example, in the North Atlantic (probably the ocean basin in which pCO_2 is most variable and best studied), it has been found that during the spring bloom the uncertainty at a given point is $\sim \pm 10$ μatm (Watson *et al.*, 1991). This suggests that ~ 100 independent observations would be required to define the mean value at a given point and season to within ± 1 μatm. Globally an error of 1 μatm in the mean would lead to an error in the flux into the ocean of order 0.2 GtC/yr (Tans *et al.*, 1990). In the ocean, the autocorrelation length and time scales are those appropriate to the passage of eddies, i.e., 1 month and 100 km. An adequate coverage might therefore require 100 observations for each 100 x 100 km box of ocean for each month of the year.

Such a coverage for every part of the global ocean is well beyond reach for the foreseeable future. However, the situation is not in reality so bleak as this. Most regions of the world appear to be more homogeneous in terms of surface pCO_2 than the North Atlantic. Furthermore, while such dense coverage cannot be obtained for every part of the ocean, it probably can be obtained along the routes that merchant ships frequent, and these observations may be interpolated with the help of models and satellite data to regions in which *in-situ* data are sparse.

5.2 THERMODYNAMICS OF THE OCEAN CO_2 SYSTEM

The most commonly measured quantities used to study the CO_2 system are pH, the total alkalinity (A_T), total CO_2 or total inorganic carbon (C_T), and the partial pressure of CO_2 (pCO_2). In principle, with

known values of any two of these, the remaining two can be calculated using thermodynamic relationships. In practice, however, when more than two are measured, discordant results are often obtained.

The most readily measured quantity is pCO_2 and its variability is large in space and time. It can currently be measured with a precision of ± 0.5 μatm and an accuracy of 1.0 μatm. However, it varies with temperature so a precise knowledge of the temperature dependence is important when pCO_2 in a seawater sample is measured at a temperature different from its *in-situ* temperature. This temperature dependence is also critically important for modelling the ocean-atmosphere CO_2 exchange.

At present, it is not clear what the best way is to correct for this temperature dependence. One option is that first used by T. Takahashi (1993) and his collaborators, and subsequently by a group headed by C.S. Wong. They each developed an exponential function, based on direct measurements, that fitted all the results of their measurements of the pCO_2 of various water samples at different temperatures. (The Wong function coefficient of .0413 (at S=35) turned out to be very close to the Takahashi value of .0423.) Another approach used by Copin-Montegut (1988, 1989) is to employ a formula for the effect of temperature and salinity on pCO_2 that is based on the relevant chemical equilibrium equations. The two approaches yield similar results.

There is also the problem that when using the equilibrium equations different results are obtained depending on the which set of constants is used. The most important constants are the carbonic acid dissociation constants K_1^* and K_2^*. Millero (1993) compared the results of calculations of the four carbon system parameters with five different sets of independently derived dissociation constants. Overall, the analyses were too limited to arrive at a clear choice and efforts are continuing at various laboratories to narrow the uncertainties. Nevertheless, these comparisons indicate that field measurements can now be made that are thermodynamically consistent with the present accuracy in measuring the various parameters of the system: ± 0.002 in pH, ± 4 μmol/kg in A_T, ± 2 μmol/kg in C_T, and ± 2 μatm in pCO_2.

6. NATURAL VARIABILITY

We are just beginning the large, long-term effort that will be necessary to adequately understand and quantify natural variability and the role of the present day ocean in modulating atmospheric CO_2. Within the next five years, the JGOFS-WOCE field programs will be completed. The data will provide a one-time snapshot of the pCO_2 of the world oceans but not how this picture varies with time. There are some non-WOCE, surface-only lines, however, that have been run long enough to give indications of the seasonal variations in pCO_2 in modern times. Spring warming increases and autumn cooling decreases pCO_2 in surface waters. Biological fixation of CO_2 in spring and regeneration in the fall also influences the pCO_2. Variations in the wind speed, the mixed layer thickness, upwelling and downwelling are also factors. Quantifying these processes and their contributions over time will depend on progress with model development and the acquisition of reliable long term observations beyond WOCE.

The industrial age anthropogenic CO_2 perturbations started around 1850. In the 100 years before that, fossil fuel burning was negligible. But even during that period it is estimated that land use changes added 30-50 GtC to the atmosphere, about half of which was taken up the ocean. On the 1000-years time scale, large natural long-term variations are evident in ice cores and ocean sediments all the way back to the last deglaciation. The Byrd ice core record indicates that the initial increase of atmospheric CO_2 to 280 ppm, 11,000 years ago, was followed by a reversal to perhaps 245 to 250 ppm 9000 years ago and then a return to 260 to 280 ppm 7000 years ago (Sundquist, 1993). It is against this kind of background of long response times of ocean-atmosphere-ice-land interaction that man's recent influence on the carbon cycle must be considered.

6.1 THE INFLUENCE OF THE BIOLOGICAL AND SOLUBILITY PUMPS

Carbon in the form of CO_2 is abundantly available in the surface waters of the ocean. It is absorbed from, or released to the atmosphere depending on the partial pressure differences. Several processes act to hold the equilibrium CO_2 concentration in surface waters below that of the ocean as a whole. Dissolved CO_2 is consumed in the euphotic zone by photosynthesis. Some of this assimilated carbon sinks as organic debris to the deep ocean where it is remineralized to dissolved inorganic carbon. The process of deep water formation in the polar regions also transfers dissolved CO_2 to the deep ocean because its solubility is higher in cold than in warm water. These downward biological and solubility pumps are balanced by upwelling and other forms of vertical mixing between the deep and surface waters. The carbon chemistry of the ocean, which also involves other inorganic carbon species (carbonic acid, bicarbonate and carbonate ions) as well as dissolved organic carbon, acts to diminish the capacity of the ocean to respond to increases in the CO_2 concentration of the atmosphere. For example, a 10% increase in atmospheric concentration of CO_2 requires only a 1% increase in the surface layer of the ocean to reach a new equilibrium (Bolin, 1993).

Data from the U.S. JGOFS year-long Equatorial Pacific field study reveal the important role of physical processes at various scales in determining chemical and biological variability. Resolving the relative effects of physics and biology will be important for understanding the controls on CO_2 exchange with the atmosphere.

6.2 THE INFLUENCE OF MAJOR ANOMALOUS EVENTS

The JGOFS equatorial Pacific springtime data indicate air-sea pCO_2 difference levels that are approximately 50% lower than normal during an El Niño year. Wong et al (1993) observed an 80% drop for the 1986/1987 El Niño in the Pacific equatorial region. When an El Niño event occurs, atmospheric CO_2 usually rises above its expected level. This has been attributed to reduced uptake by terrestrial vegetation resulting from a collapse of the Southeast Asian monsoon. The ocean actually reduces CO_2 from its expected level because of the collapse of upwelling of CO_2-rich waters in the equatorial Pacific. However, the terrestrial effect of opposite sign is generally larger.

There has been considerable speculation recently regarding the slowing of the growth rate of atmospheric CO_2, primarily in the northern hemisphere, just after the eruption of Mount Pinatubo in June 1991. It is unprecedented in the 35-year record of CO_2 measurements at Mauna Loa. This suggested causal relationship has spawned several possible explanations which have been examined by Sarmiento (1993). They range from the reduction of sunlight and the cooling caused by the eruption, to the iron fertilization of the ocean, the iron coming from the material ejected. Sarmiento's first-order calculated checks do not rule out these possibilities. He points out that had an ocean color imager in space been available at that time, such a carbon signal concentrated in the northern hemisphere almost certainly could have been detected.

Other anomalous events (such as the Great Salinity Anomaly in the North Atlantic which may have temporarily interrupted deep water formation, and the unprecedented recent three-year-long ENSO) almost certainly perturbed the CO_2 system balance for a time. As for the future, because the ocean record is so short, and since the anthropogenic CO_2 may itself be the cause of future anomalies, it will be difficult to assign cause or effect.

7. FERTILIZATION AND OCEAN PRODUCTIVITY

7.1 THE IRON HYPOTHESIS

Evidence exists in the historical record of the atmosphere preserved in the Antarctic ice cores that lends credence to the iron fertilization hypothesis. First posed by the late John H Martin, it suggests that plant growth in large areas of the ocean is limited by the availability of dissolved iron. Martin realized that changes in wind patterns could transport large amounts of iron as dust to the ocean and greatly stimulate ocean photosynthesis, thus drawing down atmospheric CO_2. The ice core records suggest this process has occurred

in the past; when dust and iron concentrations were high during the last two glacial cycles, atmospheric CO_2 was low.

Encouraged by the results of Martin's experiments on sea water samples, an international team of scientists recently tested the hypothesis in the open ocean. In October 1993, a controlled experiment was conducted by adding iron to a 64-square kilometer area of the equatorial Pacific replete with plant nutrients, such as nitrate and phosphate, but where phytoplankton concentration has been inexplicably low. Chlorophyl in the area of the fertilized patch went from 0.2 - 0.3 and reached values of 0.6 - 0.7 mg/m^3 on the second day, confirming the hypothesis. A large bloom was not detected - the NO_3, PO_4, and SIO_2 showed little changes. Interestingly, the increase in biomass appears to have been accompanied by a shift from a community dominated by organisms adapted to low iron to one dominated by organisms found in coastal areas. The iron was consumed in a about 3 days and ocean mixing erased traces of the patch within five days.

Model calculations indicate that iron fertilization could result in a modest draw down of CO_2 from the atmosphere but that when the iron input was stopped, CO_2 would escape again from the ocean. Thus iron fertilization cannot realistically be considered as a potential means for controlling the growth of atmospheric CO_2.

7.2 CO_2 FERTILIZATION

Since there is an abundance of carbon available in the ocean compared to other nutrients normally needed by plants to flourish, it has not been considered as a growth-limiting factor. It follows that the anthropogenic perturbation would not alter this condition. However, CO_2-limitation of the growth rate of algae has been found in the laboratory. The availability of CO_2 limits the rate of uptake in fast growing algal cells, and the conversion of bicarbonate (always plentiful in the ocean) is too slow to keep pace with CO_2 photosynthesis. Thus one can construct a CO_2-limitation hypothesis that is at least conceivable in the ocean.

Controlled tests on different species of land plants have shown that CO_2 enrichment of the atmosphere does have a detectable fertilization effect. It is not known how long lasting this effect is. The large scale potential biological significance of CO_2 enrichment in the air and in the ocean remains to be assessed. It is not considered in many model simulations at present.

8. CLIMATE FEEDBACK MECHANISMS

Predicting how the ocean would respond to global warming requires consideration of many complex interactive feedback mechanisms. Possible consequences of global warming, such as circulation changes, sea level rise and increased ocean temperatures, have potentially significant effects on both the biological and solubility pumps that maintain the state of the current carbon budget.

CO_2 being less soluble in a warmer ocean would lead to CO_2 outgassing. Warmer surface waters in the polar regions would serve to decrease deep water formation thus lessening the effectiveness of the solubility pump in transporting CO_2 to the deep ocean. Warmer surface water might also serve to increase the respiration of biological activity. That could affect the rate of primary production as well as the grazing rate by zooplankton with a consequent effect on the amount of organic carbon matter exported from the euphotic zone to the deep ocean. Another effect of warmer water would be to increase the average stability of the oceanic water column, making vertical mixing of nutrients across the thermocline more difficult. While the reduced import of nutrients would decrease biological productivity and thus the utilization of CO_2, the overall effect would be a lowering of pCO_2 because of the reduced upwelling of CO_2-rich waters,

Atmospheric particles affect the Earth's radiative balance directly through the backscatter of solar radiation and indirectly as cloud condensation nuclei. The global mean radiative forcing due to aerosol particles is calculated to be of the same order of magnitude (approximately 2 $watts/m^2$), but opposite in sign to the forcing due to CO_2 and the other greenhouse gases. Over the remote parts of the world's oceans, most

cloud condensation nuclei are composed of sulfates derived from the atmospheric oxidation of dimethylsulfide which is biologically produced in the ocean euphotic zone. Thus the biological productivity link to the overlying atmosphere also has a feedback potential on climate through albedo change.

Changes in metabolic rates and nutrient supply would also affect the rate of carbonate production, the primary material of corals and shells. The production and dissolution of carbonate significantly affect oceanic alkalinity as illustrated in the occurrence of both dissolved bicarbonate and calcium ions in the reaction:

$$CaCO_3 + H_2O + CO_2 \rightharpoonup Ca^{2+} + 2HCO_3$$

The production of carbonate in the surface layer decreases the alkalinity and thus has the same effect as adding dissolved CO_2, thus increasing the pCO_2, and thus leading to release of CO_2 to the atmosphere. The overall effect of carbonate production by corals and shelled organisms on the CO_2 budget also depends on the amount of $CaCO_3$ that dissolves in the deep sea because of its enhanced solubility there. A change in deep sea $CaCO_3$ dissolution will affect alkalinity. When mixed to the surface these alkalinity changes may act as positive or negative feedbacks in combination with other influences on atmospheric CO_2.

The marine sediment record suggests that a higher sea level could lead to increased $CaCO_3$ production on reefs and banks which could result in a release of CO_2 to the atmosphere. On the other hand, an accompanying decrease in oceanic alkalinity would enhance deep-sea dissolution of $CaCO_3$, a negative feedback. Circulation that would bring deep CO_2 to the ocean surface for release to the atmosphere, would attenuate deep-sea $CaCO_3$ dissolution, a positive feedback. The shifting balance between these processes gives the ocean the capacity to alter atmospheric CO_2 levels in response to changes in ocean circulation.

Finally, enormous amounts of methane, another greenhouse gas, are tied up in the ocean sediments as methane clathrates. Though a remote possibility, it is conceivable that climate changes could act in some way to release some of this methane to the atmosphere, thus producing a positive feedback.

9. CONCLUSION

Researchers have managed to piece together findings from a wide range of scientific disciplines that describe the carbon budget and illustrate the diversity in land-ocean-ice-atmosphere processes and feedback mechanisms that modulate atmospheric CO_2 over short and long time scales. One can conclude that these natural processes and feedbacks are responding now, and will continue to respond dynamically to the large anthropogenic CO_2 perturbation over time scales well beyond the period of foreseeable management policies. Sundquist (1993) makes the point, however, that the natural CO_2 variation is an interactive result, involving climate and the global carbon cycle in ensemble, whereas the anthropogenic perturbation is a unique top-down forcing mechanism. It is unlike anything we have learned about the oceanic CO_2 processes studied in the past. This intrinsically different downward forcing mode may lead to adjustments in the carbon cycle for which forecast models are not designed. As many decisions depend on what models tells us about the likely future, real long-term data from a well designed permanent ocean observing system are all the more crucial for keeping models honest.

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ANNEX IV

ABSTRACTS OF PRESENTATIONS

1. The 13 C/12C Approach
Paul Quay

The error in the 13C/12C approach is ±0.9 Gt C/yr (± 1 SD) and is dominated (>70%) by the uncertainty in the oceanic time change in 13C/12C. The minimum uncertainty in the net CO_2 uptake rate determined by this approach is +0.4 Gt C/yr and determined by assuming the oceanic change in 13C/12C which can estimated to ±0.006 o/oo, which is an estimate of the average agreement of the deep water del 13C measured in the 1970s and today. Considering all the errors, the uncertainty in this approach will likely not improve beyond ±0.6 Gt C/yr.

Tans *et al* (1993) used a similar atmospheric $13CO_2$ and $12CO_2$ budget approach to determine oceanic CO_2 uptake rates, with the modification that the air-sea $12CO_2$ and $13CO_2$ fluxes were substituted for the depth integrated ocean 13C/12C change. To use this approach they needed to estimate the air-sea 13C/12C disequilibrium. Based on oceanic 13C/12C measurements made during the 1970s, they concluded that the air-sea disequilibrium was 0.43 o/oo, which yielded a net oceanic CO_2 uptake rate of only 0.3 Gt C/yr. This rate calculation was very sensitive to the disequilibrium estimate, that is, a 0.2 o/oo error in disequilibrium yields a 1 Gt C/yr error in CO_2 uptake rate. Quay has recalculated the air-sea disequilibrium to be 0.63 o/oo, using surface data (-500 m measurements) from the Pacific and Atlantic oceans which corresponds to a net C°2 uptake of 1.1 Gt C/yr. One must add to this net air-sea flux a river CO_2 inflow rate of 0.6 Gt C/yr (Siegenthaler and Sarmiento, 1993) to calculate a change in the ocean CO_2 inventory of 1.7 Gt C/yr. The uncertainty in this net CO_2 uptake rate is ±1 Gt C/yr.

The 13C/12C approach is being used to determine the reason for the recent slow down in the growth rate of atmospheric CO_2 over the last few years (eg. Ciasis *et al*, J. Geo. Res., in press). Combining atmospheric 13C/12C and CO_2 concentration time series measurements with estimates of air-sea and atmosphere-biosphere 13C/12C disequilibrium allows one to distinguish between changes in terrestrial and oceanic CO_2 uptake effects.

What needs to be done?

a) 13C/12C measurements of dissolved inorganic carbon (DIC) in the ocean need to be recognized as a basic carbon system parameter (like TCO_2, pCO_2 and alkalinity) to be measured. Currently 13C/12C measurements are not being made as part of the WOCE or JGOFS programmes.

b) We need high quality (±0.03 o/oo) global measurements of the 13C/12C of DIC. Such a data set will be used by ocean modellers as constraints on their ocean CO_2 uptake predictions and to refine the 13C/12C budget results. The 13C/12C measurements made for WOCE AMS 14C determinations (made at Woods Hole), potentially, represent a global 13C/12C data set. The importance of these 13C/12C measurements should be recognized by the WOCE programme and the highest quality measurements should be encouraged.

c) We need 13C/12C-DIC standards that can be distributed to all scientists making these measurements, analogous to the DIC standards prepared by Andrew Dickson (Scripps) for the WOCE and JGOFS programmes. It is essential that inter-laboratory 13C/12C data is comparable to at least the current measurement precision of ±0.03 o/oo.

2. A review of modelling results focusing on physical processes
E. Maier-Reimer

3-D circulation models cannot be tuned with respect to transport rates, like box models. Traditionally, they were driven by restoring the surface values of temperature and salinity to the data from the X. Since the late 80s, evidence evolved to show that even small changes in boundary or initial conditions may yield a substantial change in the resulting circulation field of the model. In the Hamburg LSG model, from a series of five experiments with different plausible boundary conditions, one was chosen as the reference model that produced the most realistic simulation of natural radio carbon in the Atlantic. After that setting there was |nol nuch freedom of further X with respect to CO_2 uptake. To identify the reliability of the model we must therefore look at how it behaves with X against which it was not X.
?????

There is, unfortunately, no measurable tracer that could be taken as a perfect analoger for CO_2. They differ in time, history and spatial structure from CO_2 and penetration speed across the air sea interface (incidentally global warming could have the closest resemblance to CO_2, if the natural variability were better known).

The latter is in the order of 150m/y which is in most parts of the ocean, larger than the vertical displacement values of the water, it is not critical.

X 14C known in its time (more or less one big release) and space distribution. Its distribution in the ocean depends crucially on the gas transfer rate.

X has a similar time history line X 14C the spatial structure is poorly known. CFC's have a similar time and space distribution as CO_2. The gas exchange operates so quickly that almost everywhere it overrides the X circulation. They may be taken as an effective tracer to check the role of internal mixing processes in the model.

13C has a similar time and space history as CO_2 but a different penetration. Model circulations show however that it X well with CO_2 in the ocean; supposing that it were precisely measurable, it could serve as an almost perfect analogue for CO_2.

Princeton-Hamburg comparison

The published versions of the models predict an uptake of 1.54 Gt/y (Hamburg) and 1.9 Gt/y (Princeton) for the late 80s. The difference may be mainly attributed to the fact that the Princeton thermodine is twice as deep as that of the Hamburg LGG model. Efforts are X in Princeton to shallow it and in Hamburg to deepen it. As a result, the predictions for CO_2 will converge. Broecker has organized a systematic comparison and still holds the data.

Applications for models

Even if models do not perfectly reproduce nature they may be taken as a reliable tool for sensitivity studies, for instance: (i) Iron Fertilisation of the Southern Ocean; (ii) Effects of CO_2 fertilisation as on land; (iii) Deep sea disposal of CO_2; (iv) ENSO-related XX.

3. El Nino & El Viejo, An Atmospheric Climate Phenomena Driven by the Ocean
James O'Brien

In a paper submitted by Meyers and O'Brien a conjecture is made that the interdecadal variability of CO_2 on Mauna Loa, Hawaii is due to outgassing by CO_2 in the equatorial Pacific Ocean due to El Nino and El Viejo events. If one substracts the CO_2 rise and annual cycle, the residual signal is highly

correlated with indicators of El Nino such as the Japanese Meteorological Agency Sea Surface Temperature Index and sealevel on Pacific Island Stations. The following is the Meyer's & O'Brien (1994):

> Carbon dioxide (CO_2) in the terrestrial atmosphere has been rising since the late 1950s (Keeling et al., 1980). (See Fig. 1.) Departures from this nearly steady rise have been attributed to the El Nino/Southern Oscillation (ENSO) and its effects on terrestrial biomass (Bacastow, 1976; Gammon *et al.*, 1985; Sarmiento, 1993). An El Nino event is defined by the Japanese Meteorological Agency (JMA) as at least six consecutive months of sea-surface temperature (SST) anomalies greater than 0.5°C. This definition does not embrace the underlying physical mechanism of El Nino: a large downwelling Kelvin wave propagating eastward across the equatorial Pacific Ocean (Busalacchi and O'Brien, 1981).
>
> The Pacific Ocean is normally a large carbon source for the atmosphere (Tans *et al.*, 1990) due to the equatorial upwelling and outgassing of deep carbon rich waters. A downwelling wave (so called because it lowers the thermocline) inhibits the normal intrusion of deep waters towards the surface by reducing upwelling. This decreases the oceanic outgassinq of CO_2 (Feely *et al.*, 1987; Sarmiento 1993). SST anomalies increase because downwelling inhibits the deep cold waters from mixing with the upper warmer waters. Changes in CO_2 and SST are both the result of changes in thermocline depth. Sea level at the Kanton, Christmas and Galapagos Islands (Fig.2) are used as surrogate variables for thermocline depth (Busalacchi and O'Brien, 1981) at their respective locations.
>
> We designate an El Nino event (also called a warm event) to six or more consecutive months of smoothed Galapogos SL anomalies about 2 centimeters, corresponding to a thermocline downwelling of 40-60 meters. The Galapagos SL (in Fig. 3b) is selected because of its position in the far eastern Pacific and its proximity to the JMA SST region. The El Nino occurences defined using this SL are slightly different from those defined using SST (Table 1), but the yearls designated agree with all other lists of El Nino events. The direct influence of these events on CO_2 is revealed by correlating long-term observational records. It is shown that this influence is significant, with a lead time of 1-2 months in the central Pacific.

Atmospheric CO_2 anomaly vs. thermocline depth

The Mauna Loa atmospheric CO_2 (Keeling et al., 1989) is dominated by an increasing trend and an annual oscillation. After the trend and seasonal signals are removed the remaining CO2 anomalies (Fig. 3a) are the order 1 part per million by volume (ppmv). Most of the El Nino events (i.e., 1965, 1972, 1976, 1982-83 1991 and 1992) correspond to a local minimum in the anomaly. The initial CO2 decline most likely results from the suppression of CO_2 outgassing due to downwelling; the subsequent rise is attributed by others to the response of terrestrial vegetation (e.g. Keeling *et al.*, 1989). It is interesting to note that the major 1982-83 El Nino had little net effect on the total CO_2 concentration. However, roughly in phase with the SL changes there was a significant decrease of CO_2 from an anomalously high value to a lower value, followed by a return to the high value. This suggests a direct oceanic influence on the CO_2 anomaly.

Not all warm events result in diminished CO_2. The weak events of 1963 and 1969 had little effect, and the 1986/87 event coincides with steady and increasing CO_2. The reasons for these differences are uncertain but probably involve complicated interactions between the ocean, atmosphere and biosphere (Siegenthaler and Sarmiento, 1993). Similar differences are seen between El Viejo events.

El Viejo is the opposite aspect of the ENSO cycle. It is driven by an upwelling Kelvin wave triggered by increased trade winds. The Kelvin wave raises the thermocline, increases oceanic carbon outgassing and lowers SST anomalies. There is widespread disagreement on the designation of cold events (Bradley, 1987; Kilandis and Diaz, 1989; Van Loon and Maden, 1981); the SL defined Los Viejos to roughly concide with the ones defined by SST (Table 2). El Viejo events often correspond to local maxima in CO_2 anomalies. The largest CO_2 peaks of 1973 and 1988-89 occur during El Viejo events. Los Viejos of 1962, 1967-68, 1970-71 and 1985 correspond to weak maxima of CO_2, but those of 1964, 1977 and 1978 do not correspond to CO_2

maxima. There is a mean positive CO_2 anomaly from roughly 1977-86. It is possible that lingering upwelling conditions in the estratropics (Meyers *et al.*, 1994) are partly related to the high mean CO_2 from 1978-86, though further investigation is needed.

It has been known since Bacastow (1976) that ENSO, as represented by the Southern Oscillation Index (SOI), has a significant correlation with CO2 variations, but that CO_2 led SOI by a few months. SL at Galapagos also lags CO_2 by about two months. Examining SL at stations further west in the Pacific allows the comparison of CO_2 anomalies with the early stages of ENSO events (Fig. 4). Sea level at Kanton and Christmas Island lead the CO_2 anomaly by 1-2 months (Fig.4c), implying a rapid response that is probably too fast to result from indirect effects on the biosphere. The maximum correlation is 0.47 and 0.34 for Kanton and Christmas Island respectively. This is comparable to the values obtained by Bacastow (1976), suggesting that oceanic influences play a significant role in the SOI influence on variations in CO_2.

A rapid shift from one ENSO extreme to the other can have a significant impact on CO_2. Low CO_2 can quickly change to anomalously high CO_2 during or after an El Niño when an El Viejo quickly follows. This was the case in 197273, 1977 and 1983. Conversely, a rapid decline and change in the sign of the anomaly in atmospheric CO_2 occured in 1964 when an El Niño quickly followed an El Viejo event. The largest negative shift in 1960 to the present records occurred during 1991-1993 (cf., Figs. 3 and 4).

A Prediction

Since 1990 there has been a steady decline in the carbon anomaly (Sarmiento, 1993). Similar dropoffs in methane (Dlugokencky *et al.*, 1994; Rudolph, 1994) and carbon monoxide (Novelli *et al.*, 1994) have been reported. Neither of these has been directly attributed to ENSO, but to the eruption of Mount Pinatubo (Sarmiento, 1993; Kerr, 1994). We hypothesize that the continuing major decline in the CO2 anomaly is related to the lingering El Niño events in 1991 and 1992. (The second of these two events is considered to be a continuation of the first). The average SL anomaly at Galapagos from 1991 through the end of 1993 was five centimeters, suggesting a period of reduced oceanic outgassing. It is possible that this reduction in the oceanic carbon source is related to the reduction in atmospheric CO2.

The 1991-93 El Niño is over and the SL anomaly has changed again. If past relationships between SL and CO2 continue, a positive CO2 anomaly is expected to occur in 1994-95. This is very likely if SL continues to drop and El Veijo occurs in the next five months. At this time ENSO predictions are mixed. Most predict neither El Niño nor El Viejo, except for the NOAA-NMC forecast which forecasts a cold event.

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Tables

El Nino months by SL(SST)

Year	Initial		Duration
1963	4(6)		9(8)
1965	3(5)		10(10)
1968	11(11)	7(1G)	
1972	2(5)		12(11)
1976	4(6)		8(9)
1982	5(4)		17(17)
1986	9(9)		14(17)
1991	2(4)		18(16)
1992	12(3) *		10(G)

Table 1. Comparison of El Niño dates using definitions based on sea-level and sea surface temperature. The year, initial month and duration in months. Values in parentheses are based on SST. The starting year is 1993 for the SST-defined El Niño.

El Viejo months by SL(SST)

Year	Initial	Duration
1969	3	10
1964	3(4)	8(10)
1967	8(8)	11(9)
1970	3(5)	20(21)
1973	4(5)	10(11)
1974	(10)	(18)
1977 *	2	6
1978	2(5)	7(5)
1984	10(11)	17(10)
1988	2(4)	14(13)

Table 2. Same as Table 1 but for El Viejo defined as at least six continuous months of SL anomaly less than -3.5 centimeters. The SST defined events are from Sittel (personal communication).

* The 1977 event may be part of the 1978 event.

4. Iron Experiment: A Test of the Iron Hypothesis
R. Barber

Martin in 1990 hypothesized that phytoplankton growth in three highnutrient ocean regions (Southern Ocean, Equatorial Pacific and Northeast Pacific) is limited by the availability of iron. Martin designed an experimental test of this hypothesis by means of an *in situ* iron enrichment experiment. The hypothesis was advanced by Martin to explain the persistently high levels of inorganic nutrients in the Southern Ocean, but the first test of the hypothesis was carried out in the equatorial Pacific Ocean for tactical scientific reasons. The Southern Ocean (and north eastern Pacific) is an energetic ocean regime with frequent storms and, in particular, a lot of energy in the 5-day (or frontal) timescale. The phytoplankton response to an episode of nutrient injection is observed to be 5 to 10 days. It was clear that in the Southern Ocean one storm-driven mixing event could dispense the added iron before the biological response could be resolved, so early in the planning Martin picked a site at 5°S and 90°W where storms are rare and trade winds are relatively constant.

The experiment took place in October/November 1993 four months after Martin's death. Martin's test involved parallel and nearly identical studies of an experimental iron addition and the natural iron enrichment created as the South Equatorial current flows over the Galapagos platform and picks up iron from volcanic sediments.

The strategy of the experimental iron addition was to create a defined patch of water with iron concentrations 3 to 4 nmol.kg over background values and to compare phytoplankton activity, biomass and species composition in and out of the enriched water for several days. For thys-str< ~tegy to succeed, two real-time analytical procedures were necessary: (i) iron determinations with automated chemiluminescent flow injection; and (ii) determination of sulphur hexafluoride (SF_6) by electron capture gas chromatography. Iron and SF_6 were released in a stoichiometric mixture in a 64 Km^2 patch. Changes in SF_6 concentration enabled estimation of the dilution of the enriched water, and SF_6 provided a conservation tracer of the water that had been enriched with iron. Iron and SF_6 analyses established that a well-defined patch of water was created with iron enriched 3 to 4 nmol.kg over the background concentration and with 20 to 40 fmol.kg of SF_6. The added iron was not detectable after three days, but the SF_6 tracer enabled theRcontinual re-sampling of the enriched water layer for nine days in October/November 1993.

The strategy of the Galapagos leg of the IronEx cruise was to compare phytoplankton activity and biomass upstream of the islands along 89°W and downstream of the islands where chlorophyll plume and enhanced chlorophyll-specific productivity rates have been observed. The rationale of Martin's two part test of the iron hypothesis depended on the sediments of the Galapagos Islands enriching the SEC waters with a detectable concentration of iron. Analyses on IronEx found the downstream waters closest to the islands contained iron concentrations about 3 nmol.kg above background, but the concentrations rapidly fell to background levels in the downstream plume.

During IronEx, phytoplankton activity was assayed by a large number of procedures involving *in situ* and incubation analyses as well as aircraft remote sensing methods.

The phytoplankton response to the iron enrichment was fast and well defined. Chlorophyll increased from values of 0.2 to 0.3 $mg.m^{-3}$ to values of 0.6 to 0.7 $mg.m^{-3}$. Most of the increase occurred on Day 1; after Day 2, concentrations did not increase further but they remained at 0.6 to 0.7 $mg.m^{-3}$.
When the chlorophyll increase was partitioned to various taxa it showed that increases occurred in all the major taxanomic groups. In particular, the cyanophytes that were most abundant showed a string response to the added iron. Diatoms responded as well, but since they were numerically rare their response contributed little to increases in biomass and primary productivity that was seen during the nine days the patch was followed. The size spectrum of chlorophyll changes was relatively even across the size range.

Primary production increased from values of about 20 $mgC.m^{-3}.d^{-1}$ to about $1omgC.m^{-3}.d^{-1}$ and like chlorophyll, most of the increase was on Day 1. From day 3 to day 9 the productivity remained enhanced but did not increase. Size spectrum analyses showed that the enhancement was evenly distributed across the size spectrum from less than 1μm to 18μm. It is clear that there was not a differential enrichment or response of diatoms or relatively large cells. In this particular aspect, the response of phytoplankton in the iron-enriched patch was quite different from that in iron-enriched bottles.

A high biomass bloom did not develop, chlorophyll remained at a value of about 0.7 $mg.m^{-3}$. Without the accumulation of biomass, the impact on the abundant inorganic nutrients was very slight and there was a total inorganic drawdown of only about 5μmol.kg1 from an initial value of about 2000μmol.kg1.

The specific growth and carbon-specific productivity rates were very high, but phytoplankton losses through grazing apparently increased enough to prevent biomass from going higher than $O.7mychl.m^{-3}$. Net tows showed that mesozooplankton, especially cipepods, were dramatically more abundant in the patch and this increase was present within one day. It appears as though vertically-migrating zooplankton stayed in the enhanced phytoplankton patch after finding it on their regular diet migration pattern.

The first modest *in situ* test of iron fertilisation confirmed that the Iron Hypothesis is true for the equatorial Pacific, but equally interesting, the results showed that as rapid grazer response prevented a bloom, subsequent export of a significant amount of carbon produced a depletion of nutrients.

Enhancement of primary productivity rates did not lead to a proportional increase in export via the biological pump. The observation from IronEx is that the biological pump export enhancement is effectively cancelled out by grazing recycling. These two observations suggest that iron fertilisation of open ocean waters will not provide a means of intervening on the global carbon cycle.

Downstream of the Galapagos Islands, results were essentially identical to the iron patch. Rates and biomass increased, but nutrients were not depleted in the open waters downstream of the islands. About five days downstream, productivity rates and iron levels had fallen to background levels. At one location within the islands we observed a chlorophyll concentration at $>1Omychl.m^{-3}$, $400mgC.m^{-3}.d^{-1}$, nitrate depletion, and a massive drawdown of CO_2. The observations suggest that a shelf is required to prevent loss of iron from the water column support massive diatom bloom in tropical waters. Such shallow shelves are more or less iron-sufficient because of the sedimentary iron source, so purposeful iron addition on a large scale would not significantly increase their carbon burial.

The IronEx results suggest that iron fertilisation does not provide a means to engineer down atmospheric CO_2, despite the conclusion that the Iron Hypothesis is true.

5. Presentation Summary
T. Packard

New production in the sense of Eppley and Peterson and deep-sea CO_2 sequestering, in the sense of Sundquist, can be calculated from respiratory enzyme activity measurements made on deep sea water samples. The measurements yield instantaneous assessments of the potential respiration rate. Calculations of the *in situ* respiratory rate require a knowledge of bacterial physiology and the daily and seasonal variability of the enzyme activity. Rates of CO_2 production are calculated from respiratory CO_2 consumption by using the Redfield Ratio. The approach is amenable to time series studies and process studies. Furthermore, it has provided a calculation of 22 Gt per year for the global New Production and a value of 8 Gt per year for the deep-sea carbon sequestering rate in the ocean below 1000 meters. The calculations are unique because they are not based on isotope geochemistry, phytoplankton productivity, bulk water chemical analysis, or ocean modelling. Improvements in using this approach are appearing in the form of new electron acceptors, the use of fluorescence detection, the use of enzyme kinetics in interpreting the data, and laboratory studies of bacterial physiology. If these measurements could be made monthly over a period of 18 months in an area of deep water formation such as the North Atlantic, they would provide the first measurements of the seasonality of the deep-sea CO_2 production rate, they would show the influence of deep-water formation on the CO_2 production rate.

82. Second Meeting of the UNEP-IOC-ASPEI Global Task Team on the Implications of Climate Change on Coral Reefs
83. Seventh Session of the JSC Ocean Observing System Development Panel
84. Fourth Session of the IODE Group of Experts on Marine Information Management
85. Sixth Session of the IOC Editorial Board for the International Bathymetric Chart of the Mediterranean and its Geological/Geophysical Series
86. Fourth Session of the Joint IOC-JGOFS Panel on Carbon Dioxide
87. First Session of the IOC Editorial Board for the International Bathymetric Chart of the Western Pacific
88. Eighth Session of the JSC Ocean Observing System Development Panel
89. Ninth Session of the JSC Ocean Observing System Development Panel
90. Sixth Session of the IODE Group of Experts on Technical Aspects of Data Exchange
91. First Session of the IOC-FAO Group of Experts on OSLR for the IOCINCWIO Region
92. Fifth Session of the Joint IOC-JGOFS CO_2 Advisory Panel Meeting
93. Tenth Session of the JSC Ocean Observing System Development Panel
94. First Session of the Joint CMM-IGOSS-IODE Sub-group on Ocean Satellites and Remote Sensing
95. Third Session of the IOC Editorial Board for the International Chart of the Western Indian Ocean
96. Fourth Session of the IOC Group of Experts on the Global Sea Level Observing System
97. Joint Meeting of GEMSI and GEEP Core Groups
98. First Session of the Joint Scientific and Technical Committee for Global Ocean Observing System
99. Second International Meeting of Scientific and Technical Experts on Climate Change and the Oceans