WORLD CLIMATE RESEARCH PROGRAMME

WORLD OCEAN CIRCULATION EXPERIMENT

JOINT GLOBAL OCEAN FLUX STUDY

WOCE/JGOFS OCEAN TRANSPORT WORKSHOP

Southampton Oceanography Centre, Southampton, UK.
25-29 June, 2001

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General Introduction

The WCRP's World Ocean Circulation Experiment (WOCE) carried out an unprecedented survey of the global ocean between 1990 and 1998. One objective of this was, through observations, models and data assimilation, to make new and improved estimates of the oceanic transports of heat and freshwater (and of other physical and chemical properties). See King, Firing and Joyce, p99-122 in' Ocean Circulation and Climate', Academic Press, 2001. The IGBP's Joint Global Ocean Flux Study (JGOFS) collaborated with WOCE to provide the additional measurements that would enable new estimates of the storage and transport of carbon to be made. See Wallace, p489-521 in 'Ocean Circulation and Climate', Academic Press, 2001.

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

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

For both WOCE and JGOFS the workshop was expected to make progress towards;-

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

For the week long meeting the WOCE workshop was planned for the first 2.5 days with the third day providing an overlap with the first half day of the JGOFS workshop. Participants were invited to one or the other workshop sessions, but advised that they were welcome to both. There were plenary sessions throughout the meeting with both invited speakers and assigned commentators: there were also poster sessions. In all 45 posters were submitted from a total attendance of 94 scientists from Australia, Bermuda, Canada, France, Germany, Italy, Japan, Norway, Russia, Spain, UK and USA. Participants were provided with a meeting document, which contained the agenda, (Appendix I) list of participants (Appendix IV) and poster abstracts (www.woce.org/news/transport_wkshop/).

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Summary of the WOCE workshop

The meeting agenda printed in Appendix I of this report reveals that estimating the ocean transports of heat and freshwater were approached in several ways, namely from

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

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

All of the subjects above were presented by invited speakers backed by assigned commentators. The speakers were invited to review their chosen topic rather than present results solely from their own research. Abstracts of these presentations are to be found in Appendix IIa and selected items from this material are presented in the following paragraphs.

As indicated above the air sea exchanges of heat, freshwater and momentum exercise a key role in many analyses of ocean transports, so the programme began with a review of the work of the WCRP/ SCOR Working Group on Air Sea Fluxes (WGASF) by its co-chair, Peter Taylor. This group had over a 3 year period met, agreed a report and held a workshop at which issues regarding the needs amongst others for new instrumentation, field validation, and error estimates were identified. The chairman's view was that no single flux product could be unqualifiedly recommended. All, and this included the widely used reanalysis products, had identifiable deficiencies, and the documentation of these was one important result of the committee's work. The WCRP Joint Science Committee (JSC) had decided that such a committee should continue, i.e. becoming a standing committee, in order to pursue its numerous problems. See pages 12-13 for Peter Taylor's extended abstract. Web pages for the working group can be found at www.soc.soton.ac.uk/JRD/MET/WGASF/.

In a later plenary talk Simon Josey described the various methods of determining air sea heat exchange and indicated their imperfections. For example ship based estimates, which did best in validation exercises, suffered from sampling problems and failure to close the global budget. One such climatology (SOC),which he had co-authored, had been modified in the Atlantic by combining the ship based values with ocean transport divergences derived from WOCE section heat fluxes. The method showed promise and would be pursued as more WOCE results with attendant errors became available. Finally he commented on a new ocean heat flux data set by Trenberth and Caron (2001) which a number of plenary speakers had employed as a basis for comparison of their own results. See pages 24-26 for an extended abstract.

The application of inverse modelling to hydrographic sections revealed differences in approach. One school argued that this process should build on the analysis of individual sections, then regional studies and finally on a global analysis. This seems rational but was not the step that the community had taken. Alex Ganachaud presented the results of a global analysis of all available WOCE hydrographic data, and Steve Rintoul of an analysis of data from the southern ocean. The sheer volume of information in both is daunting and although both authors were able to reveal agreements and disagreements with previous research, neither would claim that a detailed and independent analysis of their results had yet been made. The issue of time dependence, e.g. the lapse of time over which data was gathered, was raised and in discussion it was argued that its presence severely impaired the quality of the results despite attempts to exclude the upper ocean (the principle region of time dependence) from direct consideration. It was proposed that repeat section data be employed to illuminate this problem. It was also agreed that the way forward with virtually all analyses was to incorporate data from floats, drifters, altimetry and moored current meters, presently missing from most treatments. The question of how bias in the information in one location, say due to an incorrect estimate of the western boundary current transport there, would spread through a regional or global analysis was also not quantified although Jochem Marotzke's work described some aspects of this in the North Atlantic. See pages (14-16, 23, 27) for a description of these three presentations.

During the decade of WOCE the realism of Ocean models (OGCMs) has improved enormously to the extent that the committee invited David Webb to present the results of heat and freshwater transports from them. The impact of resolution on heat transport estimates has been well documented and these were described by the speaker. Although eddy activity increases and becomes more realistic as the resolution is increased, say from 1degree to 0.1 degree, the increase in heat transport is primarily due to the improved western boundary current representation and physics, although northern and southern boundary conditions may also play a role in the limited area models currently available at these very high resolutions. The strength of the Ekman transport is important in determining the heat transport in tropical regions and this reflects directly on the forcing employed. Mixing in the overflow regions, handled better in isopycnal models than level models, is also a crucial issue along with high latitude convection. Most of these issues were being considered by the WCRP/JSC/CLIVAR Ocean Model Development Working Group. Web pages can be found at www.ifremer.fr/lpo/OMDWG/.

Yanli Jia presented heat transport results employing property fields archived during the Coupled Model Intercomparison Project (CMIP) which was begun in 1995. Initial experiments had shown a very wide range of results, some quite at variance with reality especially in the southern hemisphere. In the North Atlantic many of the models developed a weak meridional overturning cell with deep water too warm, thus yielding low heat transports. A second tranche of more recent experiments produced more realistic results, reflecting improved model physics. See pages 28-29. Web pages for the project can be found at www-pcmdi.llnl.gov/cmip/.

Detlef Stammer presented the case for ocean state estimation, a method which combines the dynamical consistency of ocean models with the realism of ocean data and allows temporal variability through time dependent forcing. As admitted in the WOCE AIMS report of 1997, this method represents the way forward for the ultimate synthesis of WOCE data. However the method required massive computing resources and the development of techniques of data assimilation unfamiliar and unique to the ocean community. Such activities were being carried out in a handful of locations around the world, most with an operational emphasis. In the USA a consortium called ECCO (Estimation of the Circulation and Climate of the Ocean) had been set up between MIT, SIO, and JPL and Stammer described how various data types (satellite altimetry, sea surface temperature, reanalysis fluxes and wind stress, all time varying) had been assimilated into a low resolution (2°) global ocean model. To date Levitus hydrographic climatology had been used to describe the ocean but future plans include the use of WOCE hydrographic sections and other WOCE data types and, as computing power increases, increased model resolution. Results obtained to date reveal the inconsistency of prior surface fluxes with model and observations, a result which was shown to be unrealistic in Simon Josey’s plenary talk. However realistic heat transports were obtained in the Pacific and Southern Ocean but were underestimated in the Atlantic. See pages 18-22. Web pages can be found at www.ecco-group.org/.

Conclusions and Recommendations of the WOCE workshop

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

1) The 1990-1998 WOCE/JGOFS global survey has succeeded in providing new very high quality data from which many new estimates of heat and freshwater transport had been derived by inverse modelling. This work needed to be continued but increased attention needed to be placed on temporal variability amongst groups of sections, considering amongst other terms ocean heat storage. Other WOCE data, from altimetry, drifters, floats etc should also be incorporated in these analyses.

2) Time-dependent global ocean state estimation has been performed at 2° resolution based principally on the assimilation of upper ocean data. This work will continue with incorporation of other WOCE data types and, as computer power becomes available, at higher resolution. This line of research, together with that described in item 1 above, represent parallel ways forward for the synthesis of WOCE data.

3) The accuracy of air-sea exchanges is limited by a number of factors. These include the sparseness of measurements at high latitudes, errors in individual flux components (e.g. precipitation and solar radiation) and biases in meteorological measurements reported from ships. Progress can be made by addressing these errors and by using WOCE section transport estimates as constraints.

4). Neither data nor model errors, needed for ocean state estimation, was known sufficiently well. Alex Ganachaud was co-ordinating the exchange of information and experience on these topics.

5) Due to the efforts of the WOCE Data Products Committee and the WOCE DAC managers for the most part the accessibility of WOCE data is no longer a significant issue. The same cannot be said of contemporary model output, whose relative inaccessibility (and daunting volume) has limited its potential for assisting observationalists and illuminating observational results.

6) It was evident that the collaboration between researchers, which WOCE had fostered and had proved so fruitful, needed to continue. How would this occur since WOCE would end shortly and fewer opportunities would exist? One such initiative occurred at the transport workshop when an evening meeting to discuss future ocean hydrography and carbon measurements led to the formation of an

informal group that will seek through CLIVAR to co-ordinate and set standards for the re-occupation of WOCE/JGOFS sections during the coming decade. Web pages can be found at sprint.clivar.org/hydro/.

Oceanic Biogeochemical Fluxes

Beginning in the late 1980’s and continuing through the decade of the 1990’s the Joint Global Ocean Flux Study (JGOFS) conducted a comprehensive program to extend our knowledge of the global ocean carbon cycle through the biogeochemistry of the oceans. The main focus of the JGOFS program was to acquire both the quality and quantity of measurements necessary to identify and quantify biogeochemical processes within the ocean, their interaction with the atmosphere and their influence upon and response to human—induced perturbations. This goal required international cooperation and collaboration among the physical, chemical and biological disciplines. The program was comprised of six components: times series, process studies, CO_2 survey, ocean color satellite survey, synthesis and modeling, and data management.

The purpose of the Southampton Workshop was to bring together representatives from both the physical and biogeochemical fields to 1) to allow a forum for an exchange of ideas among individuals from the different disciplines, 2) assess the present state of knowledge and 3) to recommend a course for future collaborative study of biogeochemistry and circulation within the oceans. There was a strong focus on the carbon cycle, however, it was not exclusive of the related cycles of freshwater, heat and nutrients. The international group of attending experts arriving from eleven different countries, included observationalists and modelers, physical oceanographers, biogeochemists and atmospheric scientists, senior scientists, post-docs and students. As the vast suite of biogeochemical measurements which were the CO_2 survey had been performed in cooperation with the World Ocean Circulation Experiment (WOCE) cruises, so this workshop met along with the WOCE scientists investigating ocean fluxes. This gave all those attending a unique opportunity to discuss the global ocean carbon cycle within a truly interdisciplinary atmosphere.

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

The three working groups were divided as carbon transport, regional budgets and variability, and modeling. These working groups produced statements summarizing the status of knowledge after the JGOFS field program, issues still considered crucial for study and recommendations for future collaborative efforts to resolve these issues. The summary and list of recommendations which follow are offered as representing an interdisciplinary and international consensus of the communities seeking to better understand ocean biogeochemical fluxes and their influence upon the global carbon system in which we all live.

Summary of the JGOFS workshop

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

Pre-industrially the atmospheric concentration of CO_2 was about 280 µatm. At present it is 370µatm and rising. The release of carbon into the atmosphere through fossil fuel emissions has averaged about 6.2 PgCyr^{-1} over the last decade. Meanwhile atmospheric CO_2 concentrations have increased at a rate of 2.8 PgCyr^{-1}. Both modeling and pCO_2 studies indicate that the amount of carbon stored in the ocean is increasing by about 2 PgCyr^{-1}. Estimates of land storage remain uncertain. The questions at hand are where are the oceanic sinks of anthropogenic carbon, how big are they and what controls them.

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

The coordinated efforts of WOCE, JGOFS and OACES have provided thousands of direct estimates of carbon and carbon related properties over the last decade. To make these measurments available to scientific community there has been a organized program to synthesize these data into a consistent data set. Twenty thousand individual water samples from the Indian Basin collected between 1994 and 1996 provide TCO_2 and TA estimates with an an accuracy of ±2 and ±4µmol kg^{-1}, respectively. In the Pacific, 24 cruises provide estimates of TCO_2 with an accuracy of ±3µmol kg^{-1} and TA with an accuracy of ±5µmol kg^{-1}. The Atlantic synthesis is nearly complete. This synthesized data set is now being used to examine ocean transport and global inventories of anthropogenic CO_2. It has been found that the deepest penetration of anthropogenic CO_2 occurs in regions of water mass formation, while the shallowest penetrations occur in upwelling regions. Thermocline ventilation rates can be studied through a comparison of anthropogenic tracers which have different atmospheric histories and equilibration times. When complete the global carbon data set will contain nearly 100,000 samples.

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

The state of global coarse resolution carbon cycle models is being researched through the Ocean Carbon Model Intercomparison Project (OCMIP). These models are one of the few tools available for exploring carbon as it relates to climate change. Comparing the models to each other as well as to the WOCE/JGOFS survey affords an excellent opportunity for understanding the large scale predictive skill they provide and points to a number of issues which remain such as: poor ocean circulation representation (shallow North Atlantic Deep Water penetration), lack of riverine input, through flow transports and natural boundaries for freshwater exchange. Not all the models display all the problems, but neither is there one which is problem free. Nevertheless, these models are providing a way to explore how processes which vary regionally work together to produce integrated property fluxes.

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

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

For example, while large scale transports and divergences of mass, heat and fresh water have been determined and will asymptotically improve as efforts are still underway, efforts to estimate large scale transports and divergences of carbon, anthropogenic carbon and carbon related properties have just begun. A number of posters illustrating Atlantic results were presented (eg. Alvarez et al., Azetsu-Scott et al., Hansell et al., Haugan, Lumpkin and Speer, and Peng).

A recurring theme of the WOCE portion of the workshop was that we have probably reached the end of the road for thinking about the ocean as a steady system. Both the JGOFS plenary talks and the posters indicated that the carbon community is already beginning to focus on issues of temporal variability even as the steady state problem is being considered (eg. Bates, Doney and Lindsay, Macdonald et al., Haugan, Merlivat et al., Williams et al., and Wong et al.)

In his introduction to the JGOFS portion of the workshop, Rik Wanninkhof suggested that to make the most out of this meeting of scientists from both the biogeochemical and physical communities we should 1) summarize the current state of our knowledge, 2) determine the remaining overarching questions and 3) make recommendations for the future. The plenary talks provided for the first as they covered a wide range of topics (see Appendix IIb) and were presented by scientists from the biogeochemical, physical oceanographic and atmospheric communities. The discussants for these talks were chosen to come from a different camps from the speakers. Rik Wanninkhof presented a tutorial on CO_2 uptake designed to supply physical oceanographers with basic concepts. Harry Bryden in turn gave a discussion of the fundamentals of ocean mass and property transport calculation. The working groups focused on the latter two of Wanninkhof’s suggestions. A summary of the recommendations is given in the next section and details are presented in Appendix III.

Recommendations

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

- Measurement of carbon and carbon related properties within the Indian, Pacific, Southern Ocean and Arctic Basin should be brought up to par with those presentlyavailable in the Atlantic
- Measurement of both spatial and temporal variability in the ocean carbon budget. Exploration of such variability on interdecadaltime scales.
- Measurement of dissolved organic matter, iron, micronutrients and new transient tracers
- Standard reference materials for nutrients and metals other than DIC and DOC
- To improve experiment design and use of resources, fine resolution, regional model simulations in the spirit of the coarse resolution adjoint sensitivity studies would be extremely useful
- New technology for measuring biogeochemical properties to take advantage of float, ship of opportunity and other time series programs should continue to be developed.
- Further study of the processes which set stochiometric ratios and study of how the interplay among functional groups affect biogeochemical budgets
- Research into the processes governing the physical and biogeochemical interaction among the interior circulation, the surface mixed layer, frontal regions, topography and the coastal margin.
- The effects of wind and rivers also require further study.
- Variability/Prediction: of biogeochemical transports, in sea surface pCO_2 and other greenhouse gases
- Further exploration of mixing, diffusion and entrainment of biogeochemical properties and the parameterization of these effects for models
- Creation of hybrid coordinate models, earth system models (atmos/ocean/biogeo) and inversion tool boxes, extension of biogeochemical models beyond carbon, and assimilation of biogeochemical data into various types of models
- Intercomparison efforts (model/model and model/data) should be continued and new metrics for testing biogeochemical models should be developed.

- Further research into the uptake and transport of anthropogenic CO_2 both regionally and globally. The uncertainty in anthropogenic carbon estimates needs to be better understood.
- Continued and improved access to both observed data sets and model output.

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

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

Acknowledgments

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

WOCE/JGOFS Transport Workshop
AGENDA

Monday, 25 June (day 1)

Opening Session - *Lecture Theatre*

Welcome address - Howard Roe (SOC Director)	
Purpose of the Meeting and Introduction. Logistics.	Carl Wunsch John Gould
Purpose of the JGOFS Workshop.	Rik Wanninkhof Paul Robbins
Report of the Washington DC Flux Workshop.	Peter Taylor.

Science Session 1

Global and near-global inverse model estimates of heat/freshwater.	Alexandre Ganachaud *D/C Kevin Speer* *Susan Wijffels*
Discussion.	
Brief presentation of poster content.	
Poster session	
Transports in global unconstrained GCMs, high and low resolution.	David Webb. *D/C* Ric Williams.
Discussion	
Poster viewing and Icebreaker drinks	Hosted by SOC

Tuesday, 26 June (day 2)

Science Session 2

Constrained global GCMs (assimilated).	Detlef Stammer. *D/C Peter Killworth*
Brief talk, global GCM sensitivity.	Jochem Marotzke.
Direct estimates of surface heat flux fields:relationship of regional and global biases to constrained GCM flux adjustments and recent results from reanalyses/atmospheric residual methods.	Simon Josey *D/C Richard Wood*.
Poster presentation	
General discussion	

Science Session 3

Regional estimates of fluxes.	Steve Rintoul *D/C Harry Bryden*
Brief talk, CMIP results.	Yanli Jia.

Poster presentations.
Poster session

General discussion.

Wednesday, 27 June (day 3 transition)

Summary of WOCE workshop so far	Peter Saunders & Carl Wunsch
Opening remarks for JGOFS workshop participants	Rik Wanninkhof
The role of ocean transport in Global Carbon Cycle.	Doug Wallace *D/*C Greg Johnson.
Advances in ocean inverses for biogeochemical research questions.	Jorge Sarmiento *D/C Paul Robbins*.
WOCE workshop wrap-up: formulation of recommendations and status.	Jürgen Willebrand
Discussion on basics of transport	Harry Bryden
Discussion on uptake of CO_2	Rik Wanninkhof
JGOFS housekeeping	
Formation of working groups	
Charge to working groups	Rik Wanninkhof

Thursday, June 28 (day 4)

Unconstrained Ocean Carbon Cycle Models.	Scott Doney *D/C Peter Koltermann*
Atmospheric Inversions: Carbon isotopes	Ian Enting *D/C Kevin Speer*
Poster presentation (Chemical Transport)	
	Dorothee Bakker.
Working group sessions	
Anthropogenic Carbon Inventories.	Richard Feely.
	D/C Kumiko
Azetsu-Scott.	
Fresh water/salt transport:	Paul Robbins

Friday, June 29 (day 5)

Air-Sea fluxes and North-South Ocean Transport of CO_2 and O_2: Results from the Ocean Carbon-Cycle Model Intercomparison Project.	Jim Orr *D/C Liliane Merlivat*
Working group sessions	
Poster presentation (Biogeochemical Cycles)	Molly Baringer.
Regional Testbeds: Interannual Variability of the Oceanic Carbon Cycle at the U.S. JGOFS Bermuda atlantic Time-series Study (BATS) site	Nick Bates *D/C Bronte Tillbrook*
Working group sessions	
Working group reports, plans and summary of workshop	

REPORT ON THE WASHINGTON, DC
FLUX WORKSHOP

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Introduction

The during its three year lifetime the Joint WCRP/SCOR Working Group on Air Sea Fluxes (WGASF)[1] produced a major report (WGASF, 2000) and organised a Workshop on Air Sea Fluxes (May, 2001, near Washington DC). This talk will briefly introduce the Report and summarise the Workshop aims and conclusions.

The Report (WGASF, 2001)

The first nine chapters of the WGASF Report (WGASF, 2000) present a review of the present state of the art for air-sea fluxes including: the requirements of different scientific disciplines for surface flux data sets, the data sources available, direct flux measurements, parameterisations for radiative and turbulent fluxes, errors in flux fields, and methods of evaluation. The next two chapters occupy over half the report, being a summary of the availability and accuracy of estimates of the basic meteorological variables (temperature, humidity, etc.) and an evaluation of recently available flux field products, including the ECMWF 15 year reanalysis and the NCAR/NCEP1 and 2 reanalyses. The final chapter presents the discussion, conclusions and specific recommendations. Electronic copies of the report in PDF format (as a whole or in sections or individual chapters) can be accessed through the WGASF web site[2] where plain text contents lists can also be viewed. Hard copies are available on request from R. Newson, JPS/WCRP, WMO, Geneva (aclarke@wmo.ch).

This author's personal summary of the results of the WGASF are first that "there are no magic answers!". As is discussed in WGASF(2000), different flux fields will be better for different purposes and, unfortunately, a working group can not wave a magic wand and produce the definitive flux product. Secondly to "beware of false prophets!". Because a surface air-sea flux product appears to agree with transport estimates doesn't necessarily mean it is correct and that flux adjustment is not required does not confirm that a model has reproduced reality. However, progress has being made, as will be evident from WGASF(2000), the Air-Sea Flux Workshop proceedings[2], and later talks in the present Workshop.

The Workshop

The WCRP/SCOR Workshop on Intercomparison and Validation of Ocean-Atmosphere Flux Fields was held at the Bolger Center, Potomac, MD, (May 21 - 24, 2001). The aims included: fostering collaboration between the three central areas of endeavour in this work - modelling, remote sensing and verification, and providing a forum for flux evaluations complementary to those presented in the WGASF report. Three days of the Workshop were devoted to scientific presentations grouped as: Keynote Talks, Flux Products from Modelling and Data Assimilation, Validation of Flux products, Fields from Remote Sensing, and Measurements and Parameterisations. The fourth day was spent in Breakout Groups (see below). Reports from the Breakout Groups, and extended abstracts of the presentations will be published as a report in the WCRP series. Draft copies of the report sections, and PDF format versions of the extended abstracts, can be accessed through the WGASF web site. Preliminary agreement has been reached for the publication of a special issue of Journal of Climate based around the Workshop presentations (submission deadline is October 2001).

The recommendations of the Breakout Groups are available on the WGASF web site; they will be briefly summarised here. Breakout Group 1 on "Parameterisations and Measurement" suggested the need for an *Airflow Distortion* experiment comparing a Research Ship with suitable reference platforms; a *Technical Manual on Air-Sea Measurement Methods*; a *Radiation Measurement Comparison* experiment to compare ship-borne instrumentation with a platform that is fully instrumented to Baseline Surface Radiation Network standards; a marine *Flux-Profile experiment*; and *Coastal Ocean Case Study* experiments.

Breakout Group 2 on “Verification” stressed the need to validate air-sea flux data sets by *comparison to high-quality observations*; in which respect it supported the planned activities of *SURFA* to verify the near-surface fields from numerical weather prediction (NWP) centres using high-quality observations. *Error estimates are needed* for all air-sea flux data sets, these could be developed from the statistics compiled from data assimilation at NWP centres. An *extensive intercomparison of all flux fields* is still required; the *WGASF on-line catalogue of flux fields* should be expanded and include the evaluations. Indeed there is a outstanding need to *ensure the open distribution, preservation and availability of air-sea flux data sets and products*. Finally, new methods of *direct precipitation measurement* over the ocean are still desirable.

Breakout Group 3 considered “Flux Field Improvement In The Future”. There is a need: to *combine flux and meteorological products from different sources* including satellite data; to achieve *more timely delivery*; to provide *detailed error estimates*, particularly the space-time distribution of error covariances; and to provide all flux data sets with *metadata* (including a comprehensive buoy metadata catalogue). Needed improvements to flux products include *increased spatial and temporal resolution*; *parameterisations valid over a wider range of environmental conditions*; and *better radiative flux estimates*. The use of various flux fields as *forcing functions for atmospheric and oceanic general circulation models* would identify errors in the products and help validate the flux fields. Support was stated for the proposed *Global Precipitation Mission (GPM), reference site buoys*, development and maintenance of *in situ data archives accompanied by the collocated satellite data* (e.g. SEAFLUX), and efforts to *improve and qualify VOS observations* (e.g. VOSClim project). *Also to be supported were:* regional flux field synthesis and validation, analysis of large-scale heat and fresh water imbalances, validation and improvement of the wind stress fields, and improvement of the long-term space-time series of global sea-air flux anomalies.

The next Air-Sea Flux Working Group

The last meeting of the Joint Scientific Committee for the WCRP (Boulder, March, 2001) agreed that there should be a standing WCRP surface fluxes working group. The terms of reference should be developed at, and following the Washington Workshop and be finalised, together with the membership, at the March 2002 meeting of the JSC. The author has been asked to work with JSC officers and members, and the WCRP secretariat, in the preparations for the new working group. Now is the time to bring forward ideas, comments or criticism!

References:

WGASF (2000) Intercomparison and Validation of Ocean-Atmosphere Energy Flux Fields - Final report of the Joint WCRP/SCOR Working Group on Air-Sea Fluxes (P.K.Taylor, ed.) November 2000, WCRP-112 (WMO/TD-No. 1036), 306 pp. (available through http://www.soc.soton.ac.uk/JRD/MET/WGASF/)

(Footnotes)

[1] Co-Chairs: Dr. Sergey Gulev, P.P.Shirshov Inst. of Oceanology, RAS; Dr. Peter K. Taylor, Southampton Oceanography Centre, UK; Members: Dr. Bernard Barnier, Inst. de Mécanique de Grenoble, France; Dr. E. Frank Bradley, CSIRO, Australia; Dr. Tom Charlock, NASA Langley Research Center, USA; Dr. Peter Gleckler, Lawrence Livermore National Lab., USA; Prof. Masahisa Kubota / Dr. Kunio Kutsuwada, Tokai Univ, Japan; Dr. David Legler, COAPS, FSU, USA (now US CLIVAR); Dr. Ralf Lindau, Institut fuer Meereskunde, Kiel, Germany; Dr. Drew Rothrock, University of Washington, USA ; Dr. Joerg Schulz, DLR, Germany; Dr. Arlindo da Silva, Goddard Space Flight Center, USA; Dr. Andreas Sterl, KNMI, The Netherlands; Dr. Glenn White, National Center Environmental Prediction, USA.

[2] http://www.soc.soton.ac.uk/JRD/MET/WGASF/

LARGE-SCALE OCEANIC CIRCULATION AND FLUXES OF HEAT AND FRESHWATER FROM HYDROGRAPHIC DATA

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One time and repeat hydrographic measurements are the most accurate method for estimating large scale ocean heat transports (e.g., Bryden, 2001). The World Ocean Circulation Experiment (WOCE) observation program was in part aimed at determining basin scale oceanic heat transports and to provide calibration for, and test of ocean models and air-sea flux climatologies. Observations and analysis of transoceanic sections already produced a number of important results which we present, along with the global results of Ganachaud and Wunsch (2000; hereafter GW). GW provided a new estimate of the large scale circulation and associated heat (energy) and freshwater fluxes from selected transoceanic WOCE sections and the Franco-Indonesian JADE program. The method used by GW is that of hydrographic inverse box models (Wunsch, 1996). A geostrophic circulation overlain by a directly wind-driven (Ekman) layer is estimated across the hydrographic sections. Near-conservation of mass, top-to-bottom silica, and anomalies of salt, heat, and the phosphate/oxygen combination ("PO"=170[PO_4]+[O_2]) are required between sections. Figures 1 shows, for instance, estimates of oceanic heat transports in the Atlantic and Indo-Pacific oceans by GW and other authors from selected WOCE sections.

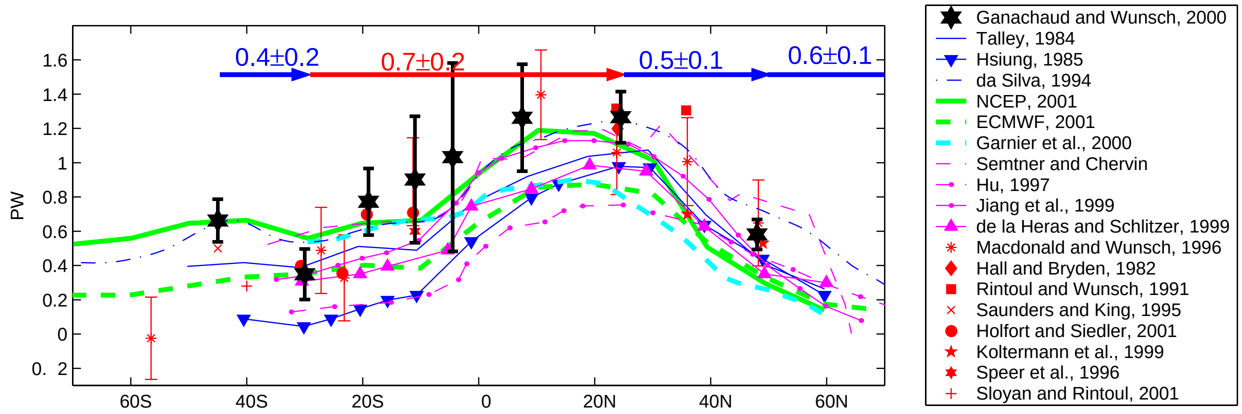

Fig 1.

Figure 1: Atlantic ocean heat transports from GW (black stars with thick error bars) and divergences between selected latitudes (numbers above the northward-pointing arrows, positive for heating). Heat, or energy transports are referred to 0°C. Error bars of hydrographic estimates (in red) are of ±0.3 PW for Hall and Bryden; ±0.2 PW for Rintoul and Wunsch; ±0.1 PW for Saunders and King; ±0.3 PW for Holfort and Siedler; ±0.15 PW for Koltermann et al.; ±0.17 PW for Speers et al.; and ±0.04 PW for Sloyan and Rintoul. Because of a high seasonal bias at 7.5°N, the transport was recalculated using the more reliable value at 24°N and substracting the mass-conserving heat residual between the two sections.

Heat transports. The corresponding air-sea heat fluxes from GW are indicated, with a warming of 0.7±0.2 PW (18±5 Wm^{-2}) in the tropics; and cooling of -1.1±0.14 PW in the North Atlantic and -0.4±0.2 PW in the South Atlantic between WOCE section A11 (approximately 45°S) and 30°S. Previous quantitative hydrographic estimates of heat transports are consistent with GW (in red: Macdonald and Wunsch, 1996, form a global model based on earlier data; Hall and Bryden, 1982; Rintoul and Wunsch, 1991; Saunders and King, 1995; Speers et al., 1996; Koltermann et al., 1999; Holfort and Siedler, 2001; Sloyan and Rintoul, 2001, regional models). Also indicated on Figure 2 are heat transport climatologies from air-sea fluxes (blue; Hastenrath, 1982; Talley, 1984; Hsiung 1985); atmospheric residuals (green: NCEP/ECMWF (Trenberth and Caron, 2001; hereafter TC); boundary conditions of atmospheric reanalyses (Garnier et al., 2001); and ocean general circulation /inverse models (magenta: Semtner and Chervin, 1992; Hu, 1997; Jiang et al., 1999; de las Heras and Schlitzer, 1999). Except for the NCEP and da Silva estimates, all produced a northward heat transport lower than those of hydrographic estimates in the Atlantic Ocean. Much of the difference is explained by differences in the air-sea fluxes north of 47°N. In the South Atlantic between A11 and 30°S, no climatology indicates the observed cooling. Part of the discrepancy may be due to the different area of flux integration because A11 is not zonal.

(TC do show a slight cooling in this region.) Overall in the Atlantic, the recent TC estimates are in good agreement with GW. Regional studies of heat transports in the Pacific and Indian Oceans produced less consistent results, in part because of the scarcer database, and in part because of the poorly determined heat transport across the Indonesian archipelago. For the summed Pacific and Indian oceans, climatologies show a strong heat gain in the tropical region, up to 3 PW while hydrographic estimates suggest a lower heating (GW obtain 1.6±0.4 PW), in better agreement with TC. The residual difference in tropical heating lies essentially in the Indian Ocean where little heating is found (Ganachaud et al., 2000). Globally, GW estimates a heating of 2.3±0.4 PW between 30°S and 24°N. Most cooling takes place in the northern hemisphere, with 1.7±0.2 PW north of 24°N versus 0.7±0.3 PW in the Southern Ocean.The different hydrographic estimates are consistent with this result. In contrast, the climatological estimates diverge, particularly in the Southern Hemisphere. The NCEP-ERBE estimate of TC is again in best agreement hydrography.

Freshwater: Despite the key role of moisture in climate regulation, freshwater transport estimates are highly uncertain. While evaporation rely on empirical formula based on in situ or radiometric satellite data, precipitation measurements are scarce and biased. Atmospheric models are hampered by both the lack of measurements over the ocean and the poor parameterization of cloud processes (Wijffels, Ocean circulation and Climate, 2001). Net ocean-atmosphere freshwater exchanges over large oceanic areas can be determined from the salt budget between hydrographic sections. Because freshwater exchanges are small fractions of the horizontal mass transports, uncertainties are still large. For instance, the GW model yield net evaporation between 30°S and 47°N, 1.2±0.5 Sv. This evaporation occurs essentially in the Atlantic and Indian oceans (Figure 2). Comparison with other flux estimates shows that reanalyses and climatologies agree with hydrography in both sign and magnitude while satellite data suggest more evaporation. The GW fluxes are compared in several oceanic regions with independent estimates from climatology, meteorological models and satellite data.

Hydrographic estimates of heat and freshwater fluxes from the WOCE program thus provided references and calibration to climatologies and ocean numerical models. WOCE estimates, of meridional, basin-wide transports, are consistent with most of the recent climatologies. Further regional analyses of the WOCE data will refine present estimates by using more meridional sections to increase the spatial resolution; by constraining with neutrally buoyant floats, ADCP and current meters (Wijffels et al., 2001) or by using repeat sections to lower the temporal bias present in one-time sections. Because hydrographic measurements suffer from seasonal biases, in particular for evaluation of nutrient transports, seasonal repeat measurements of the upper water column is potentially a necessary step before study of interannual variability of transports. The heat transport across the Indonesian archipelago, which is a major source of uncertainty, is being better measured (e.g., Vranes, 2001). But no monitoring is planned for its nutrient transport. Freshwater fluxes from hydrographic data are presently more uncertain than heat, but provide essential references to climatologies. Their uncertainties will be reduced as the variability of salt transports are better evaluated using repeat measurements and simulation in numerical ocean models. The geographical repartition of air-sea heat fluxes shows that the zonal sections that were used so far do capture the strongest signals. Future surveys from planning accordingly to the quantity to evaluate (e.g., a section between Florida and England would optimize the air-sea heat flux measurement in the North Atlantic).

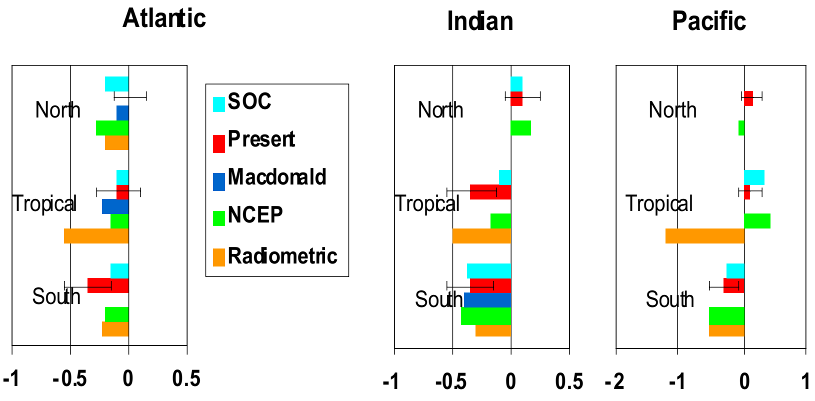

Figure 2: Ocean freshwater flux (E+R-P, 10^9kg s^{-1}). Overlain are, based on Wijffels (2001), the SOC climatology (Josey et al.,1999); Macdonald (1995); NCEP (Trenberth and Guillemot, 1998); and Radiometric estimates (Jourdan et al., 1997). Latitude bands are 47°N-24°N; 24°N-18°S; and 18°S-30°S (Atlantic and Pacific); 8°S-coast; 8°S-18°S and 18°S-32°S (Indian).

References

Bryden, H., and S. Imawaki, 2001,
Ocean Circulation and Climate, pp. 455—474. Academic Press.
de las Heras, M., and R. Schlitzer, 1999, *J. Geophys. Res.*, **104**, 15515—15536.
Ganachaud, A., and C. Wunsch, 2000, *Nature*, **408**, 453—457.
Ganachaud, A., et al., *J. Geophys. Res.*, **105**, 26,117—26,134.
Garnier, E., et al., 2000, *Int. J. of Climat.*, **20**, 1653—1673.
Hall, M. M., and H. L. Bryden, 1982, *Deep Sea Res.,* **29**, 339—359.
Hastenrath, S., *J. Phys. Oceanogr.*, **12**, 922—927, 1982.
Holfort, J., and G. Siedler, 2001, *J. Phys. Oceanogr.*, **31**, 5—29.
Hsiung, J., 1985, *J. Phys. Oceanogr.*, **15**, 1405-1413.
Hu, D. M., 1997, *J. Phys. Oceanogr.*, **27**, 96—120.
Imawaki, S., et al., 1997, *IWN*, **25**, 15—18, WOCE International Project Office.
Jiang, S., et al., 1999, *J. Geophys. Res.*, **104**, 25623—25645.
Josey, S. A., E. C. Kent, and P. K. Taylor, 1999, *J. Climate*, **9**, 2856—2880.
Jourdan, D., P. Peterson, and C. Gautier, 1997, *J. Phys. Oceanogr.*, **27**, 457—467.
Keith, D. W., 1995, Tellus, **47A**, 30—44.
Koltermann, P., et al., Deep-Sea Res., **46** (II), 109-138, 1999.
Macdonald, A., 1995, Oceanic fluxes of mass, heat and freshwater, Ph.D. thesis, *MIT/WHOI Jt. Program, Cambridge*.
Macdonald, A. M., and C. Wunsch, 1996, *Nature*, **382**, 436—439.
Rintoul, S. R., and C. Wunsch, 1991, *Deep Sea Res.*, **38**, Suppl., 355—377.
Saunders, P. M., and B. B. King, 1995, *J. Phys. Oceanogr.*, **25**, 1942—1958.
Semtner, A. J., Jr., and R. M. Chervin, 1992, *J. Geophys. Res.*, **97**, 5493—5550.
Sloyan, B., and S. Rintoul, J. Phys. Oceano., **31**, 143-173, 2001
Speers, K., et al., in The South Atlantic, Past and Present Circulation, pp. 105-120, Springer, 1996.
Talley, L., *J. Phys. Oceanogr.*, **14**, 231-241, 1984.
Trenberth, K. E., and J. M. Caron, 2001, Estimates of meridional atmosphere and ocean heat transports, *Submitted*.
Trenberth, K. E., and C. J. Guillemot, 1998, *Climate Dyn.*, **14**, 213—231.
Vranes, K., et al., 2001, The heat transport of the Indonesian throughflow and implications for the Indian Ocean heat budget, *Deep Sea Res.*, in press.
Wijffels, S. E., J. M. Toole, and R. Davis, 2001, *J. Geophys. Res.*, in press.
Wunsch, C., The Ocean Circulation Inverse Problem, 1996. 437 pp., Cambridge Univ. Press., New York.

TRANSPORT IN GLOBAL UNCONSTRAINED GCMS AT HIGH RESOLUTION

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Inverse and primitive equation models

It is noticeable at a meeting like the present one, that inverse and primitive equation models seem to have few points of contact so I would like to start by discussing one area where collaboration may be helpful.

Inverse models have many advantages, they are simple in concept, include an error analysis, handle hydrographic sections and produce easily understandable time independent solutions. Their disadvantage is that there is no internal check on dynamic realism so that there are hidden errors reflected in the large unconstrained null space. In such a situation the initial choice of the level of no motion becomes important.

In contrast the primitive equation models include the full physics and so explicitly show the effects of topographic control, non-linearities, westward intensification of current and vertical mixing. Their disadvantages are large complex data sets, model drift, known systematic errors, due to the numerics and poorly represented sub-gridscale processes, and a high cost. But when started from a good initial temperature and salinity field they rapidly produce barotropic and baroclinic solutions consistent with the dynamics and topography. They also soon sharpen up fronts and produce realistic features such as warm current cores and a meso-scale eddy field which are not in the initial data.

If there was no such thing as an inverse model, then the results from the leading high resolution ocean models would be our best guess at the state of the ocean. So when setting up an inverse model, this is probably the initial field that should be used. The inverse model will still be able to add the extra information coming from tracers and other data but the chance of having large dynamical errors in the final solution should be significantly reduced.

The effect of model resolution on oceanic transports

Low resolution models of the ocean often exhibit oceanic heat transports which are less than those estimated from hydrographic sections and current meter data. A number of reasons have been proposed for this, in particular a lack of a mesoscale eddy field and errors affecting western boundary currents. The latter include numerically induced upwelling (the Veronis effect) and the lack of a high temperature high velocity core at the centre of the modelled boundary current.

A study by Smith et al. (2000a), using an iso-pycnal model of the Atlantic, illustrates some of these effects. The model was run with a horizontal resolution of 0.9 and 0.33 degrees and used wide (4 degrees) and narrow (4/3 degrees) relaxation regions along the northern and southern open boundaries. (Being an iso-pycnal model it should not be affected by the Veronis effect).

The properties of the thermohaline circulation in such models is often best studied near 24 N where experimental studies have shown that it is responsible for almost all the heat transport. In the present case the increase in resolution increases the heat transport from approximately 1 PW to 1.2 PW.

It is tempting to attribute this all to the improved representation of the boundary current. Unfortunately the changes in the northern and southern boundary conditions produce changes in heat transport which are not much smaller. Webb (2001) showed that under a wide range of conditions the transport in a boundary current depended only on the north-south pressure gradient. It is thus possible that when resolution is changed, the change in thermohaline heat transport is primarily the effect of improved physics near the northern and southern boundaries of the model and not improvements in the boundary current itself.

A plot of the heat transport due to the gyre component of the circulation shows that between 40 and 55 degrees north the transport doubles in the high resolution run (to approximately 0.4 PW near 50 degrees north). This is almost certainly due to the improved representation of the western boundary current core. However as with the thermohaline circulation these ideas need to be tested further.

Smith et al. (2000b) report tests with a level model at resolutions of 0.4, 0.2 and 0.1 degree, the highest resolution being sufficient to resolve some of the eddy cascade as well as individual eddies. Because of the Veronis effect, level models without iso-pycnal mixing (as these were), usually produce a weaker thermohaline circulation especially at low resolution. Thus at 24 N, the 0.4 degree run produced a total heat transport of 0.7 PW, but in the 0.1 degree run this had increased to 1.1 PW. As with the iso-pycnal model, the level model also shows the increase in the gyre heat transport north of 40 N as the resolution is increased.

The models also have a well developed eddy field but this has little effect on the heat transport. Away from the equator, where other processes are involved, the largest eddy heat transports occur near 40 N near the altitude of the Gulf Stream extension region. In the 0.4 degree run the eddy heat transport is less than 0.1 PW and this barely doubles when the resolution is increased to 0.1 degrees.

Similar results are obtained in other models. In fact although for many years it was thought that eddies would be important in heat transport, the only place where their effect is significant is in the Southern Ocean at latitudes just south of Cape Town (i.e. the FRAM model, Thompson et al., 1997). Everywhere else their effect appears to be negligible.

Transports in the OCCAM model

At 24 N the heat transports in the OCCAM model, which has a resolution of 0.25 degrees, is 0.7 PW and the global heat transport is 1.1 PW (de Cuevas et al., 1999). In both cases the reduction compared with observations appears to be due primarily to the Veronis effect. In the N Atlantic, the effect of fluctuations (i.e. the meso-scale eddy field) is again small but in the Southern Ocean they dominate near 40 S. In the Southern Ocean the effect of the northwards surface Ekman transport is also important, the stronger winds of the OCCAM run giving a net northward transport at 40 S whereas the in the FRAM model, where the winds were weaker, the net heat transport is southwards.

The OCCAM model also allows study of the other major choke points of the ocean circulation. In the Bering Strait, the model shows a large amount of variability in transport due to the local winds acting on the extensive shallow continental shelf. However the mean transport is northwards, apparently because of the sea level drop from the Pacific to the

Atlantic. This possibly reflects the increased salinity of the Atlantic. Transports through the other Arctic straits are discussed by Aksenov and Coward (2001).

Between year 8 and 12 of the OCCAM run, the annually averaged Indonesian Throughflow has a value which is roughly 0.8 of that given by Godfrey's Island Rule (Godfrey 1989). At 1 cycle per year the amplitude is similar but the maximum is delayed by approximately 1 month. The relationship needs to investigated further but in both cases the discrepancy may be due to the time it takes Rossby waves to cross the Pacific. At higher frequencies there appears to be no connection between variations in the throughflow and Godfrey's Rule.

Although OCCAM was driven by an annually repeating monthly wind field, the transport variations of the Antarctic Circumpolar Current are irregular. The variations, which often occur over periods of a month or less, are strongly correlated with sea level changes on the Antarctic Continental shelf.

Concluding Remarks

The high resolution primitive equation models are good at generating velocity fields which are dynamically correct and which are consistent with both the density field and topography. The modelling community has most confidence in the horizontal fluxes obtained from the models. Detailed error estimates are not available but at 0.1 degree resolution the differences with observations are usually less than 20%.

References

Aksenov, Y., Coward, A.C., 2001: The Arctic Ocean Circulation as simulated in a very high resolution Global Ocean Model (OCCAM). Annals of Glaciology, 33 (in press).

de Cuevas, B.A., Webb, D.J., Coward, A.C., Richmond, C.S., Rourke, E., 1999: The UK Circulation and Advanced Modelling Project (OCCAM). Pp 325-335 in High Performance Computing, Ed Allan, R.J., Kluwer Academic/Plenum Publishers, New York, 584pp.

Godfrey, J.S., 1989: A Sverdrup model of the depth-integrated flow for the world ocean allowing for island circulation. Geophysical and Astrophysical Fluid Dynamics, 45, 89-112.

Smith, L.T., Chassignet, E.P., Bleck, R., 2000a: The impact of lateral boundary conditions and horizontal resolution on North Atlantic water mass transformations and pathways in an isopycnic coordinate ocean model. Journal of Physical Oceanography, 30(1), 137-159

Smith, R.D., Maltrud, M.E., Bryan, F.O., Hecht, M.W., 2000b: Numerical simulation of the North Atlantic at 1/10°, Journal of Physical oceanography, 30 (7), 1532-1561.

Thompson, S.R., Stevens, D.P., Doos, K., 1997: The importance of interocean exchange south of Africa in a numerical model. Journal of Geophysical Research, 102 (C2), 3303-3315.

OCEAN TRANSPORTS AND SURFACE FLUXES ESTIMATED FROM CONSTRAINED GCMS

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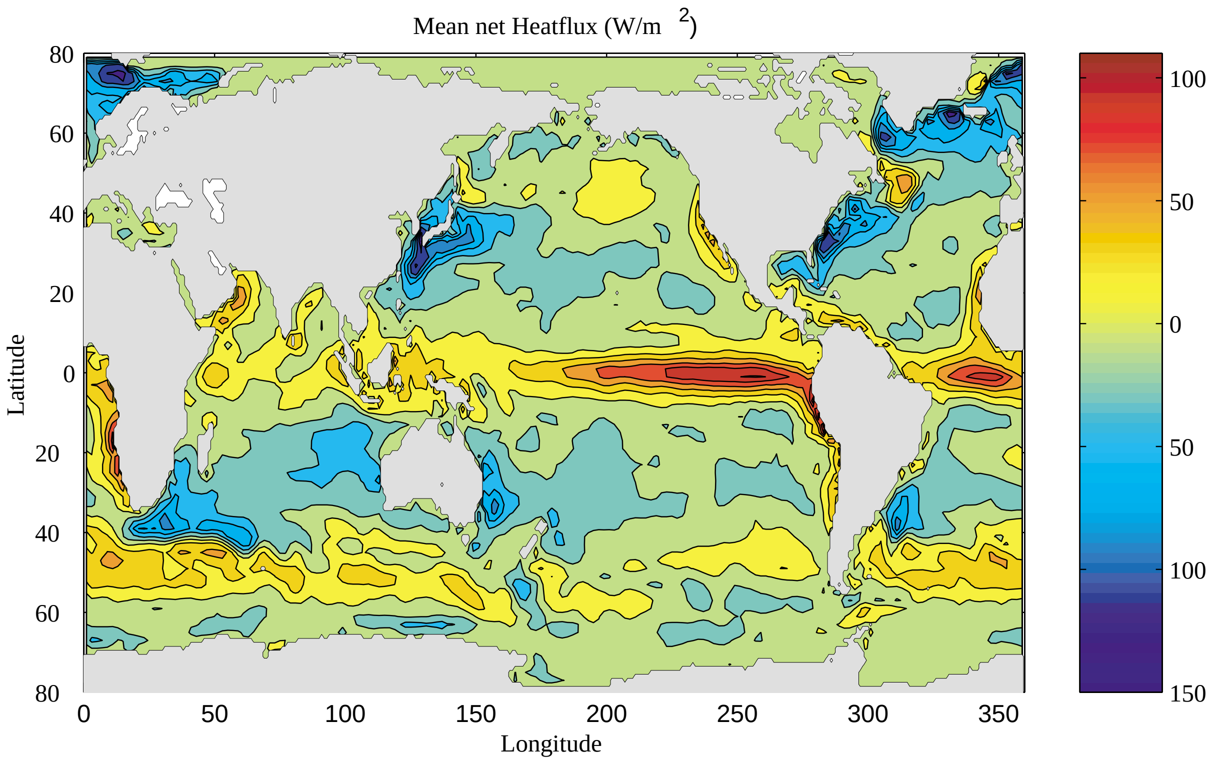

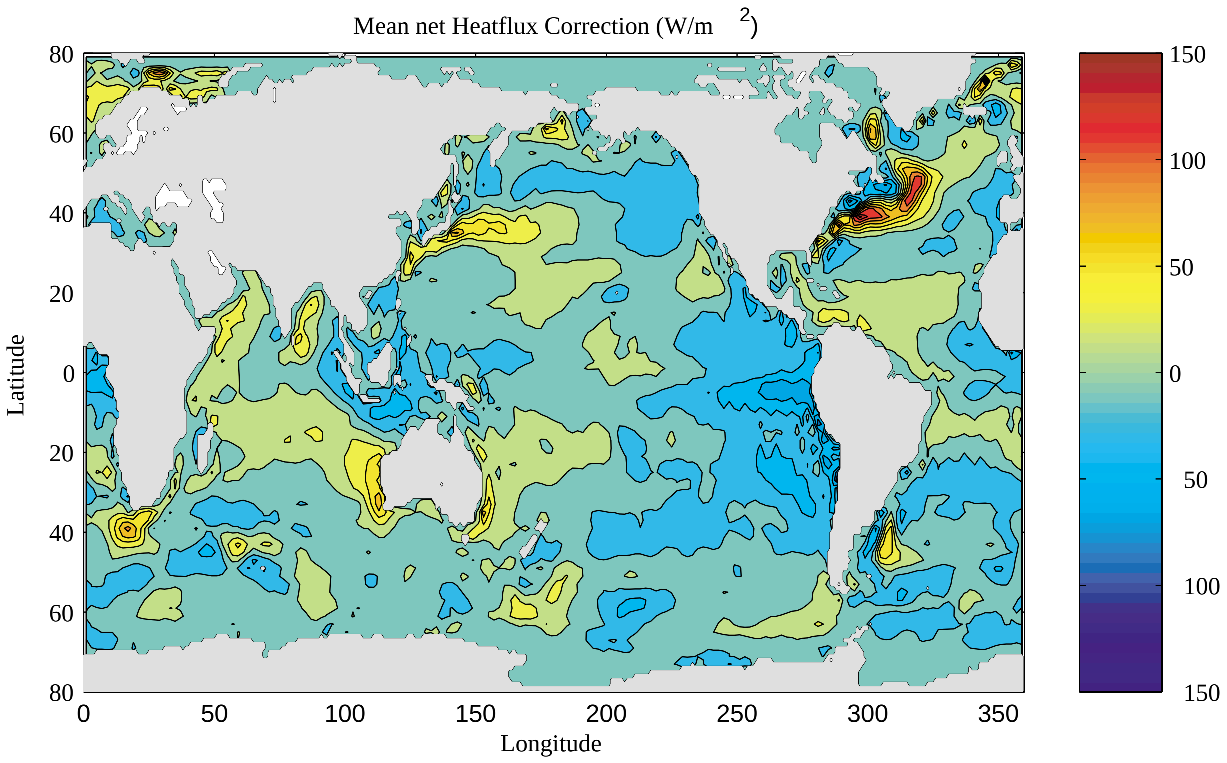

Figure 1: The mean net surface heat field as it results from the optimization is displayed in the upper panel. Its mean change relative to the prior NCEP fields is provided in the lower panel. All resulting modifications of the net NCEP heat fluxes, which are of the order of ±20 W m^{-2} over large parts of the interior oceans and reach ±80 W m^{-2} along the boundary currents, are consistent with our prior understanding of NCEP heat flux errors.

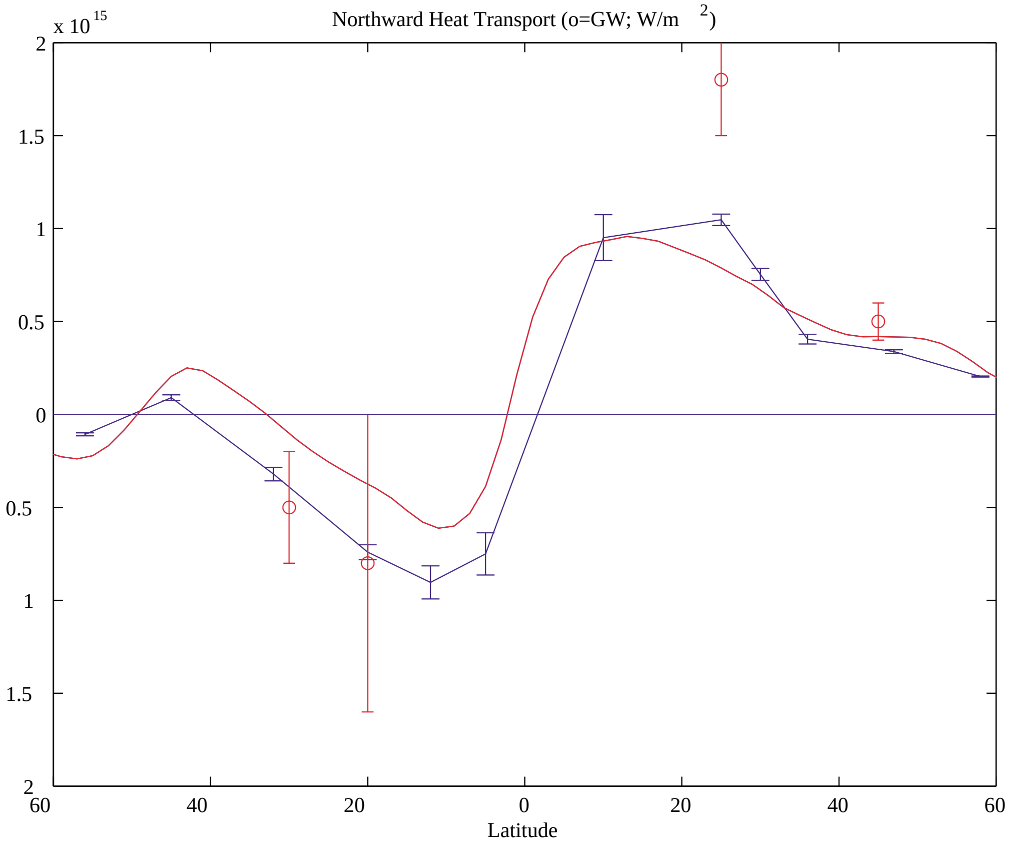

Figure 2: Integrated time-mean meridional heat transports for the global ocean estimated for various zonal sections in the model (blue curve). The blue error bars are estimated as $\sigma/\sqrt{N}$ where s is the standard deviation in time of those fluxes, evaluated over the 5 year period every 5 days and $N = 435$, assuming individual estimates are independent. The red error bars mark the standard deviation obtained from individual annual mean estimates. The red curve represents the ocean heat transport inferred from estimated surface heat fluxes.

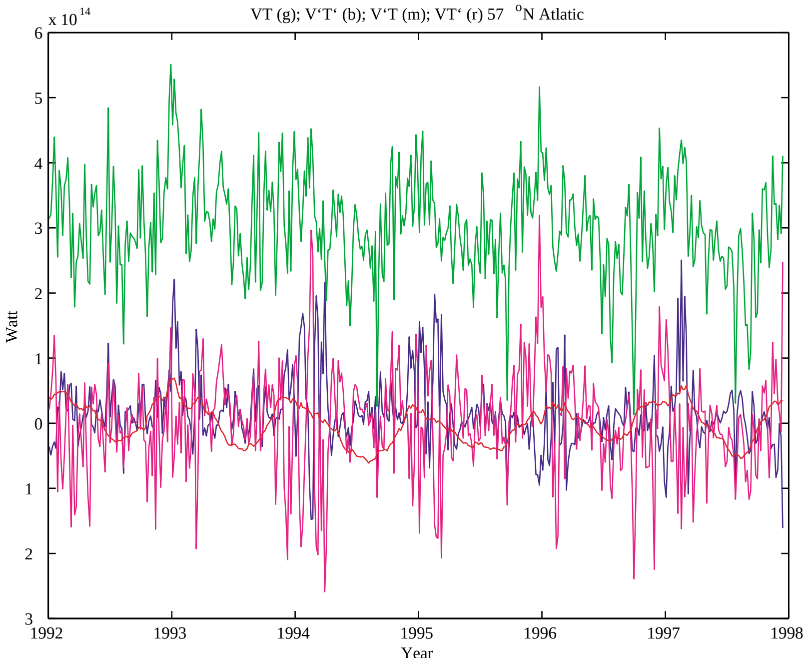

Figure 3: Timeseries $H_Q(t) = \iint v\theta dzdx$ (green curve) across a zonal section at 25∞N in the North Atlantic. Also shown are $\iint v'\theta' dzdx, \iint \bar{\theta} v' dzdx$ and $\iint \bar{v}\theta' dzdx$ as blue, magenta and red lines, respectively.

observations appears to be due primarily to the Veronis effect. In the N Atlantic, the effect of fluctuations (i.e. the meso-scale eddy field) is again small but in the Southern Ocean they dominate near 40 S. In the Southern Ocean the effect of the northwards surface Ekman transport is also important, the stronger winds of the OCCAM run giving a net northward transport at 40 S whereas the in the FRAM model, where the winds were weaker, the net heat transport is southwards.

The OCCAM model also allows study of the other major choke points of the ocean circulation. In the Bering Strait, the model shows a large amount of variability in transport due to the local winds acting on the extensive shallow continental shelf. However the mean transport is northwards, apparently because of the sea level drop from the Pacific to the Atlantic. This possibly reflects the increased salinity of the Atlantic. Transports through the other Arctic straits are discussed by Aksenov and Coward (2001).

Between year 8 and 12 of the OCCAM run, the annually averaged Indonesian Throughflow has a value which is roughly 0.8 of that given by Godfrey's Island Rule (Godfrey 1989). At 1 cycle per year the amplitude is similar but the maximum is delayed by approximately 1 month. The relationship needs to investigated further but in both cases the discrepancy may be due to the time it takes Rossby waves to cross the Pacific. At higher frequencies there appears to be no connection between variations in the throughflow and Godfrey's Rule.

Although OCCAM was driven by an annually repeating monthly wind field, the transport variations of the Antarctic Circumpolar Current are irregular. The variations, which often occur over periods of a month or less, are strongly correlated with sea level changes on the Antarctic Continental shelf.

Concluding Remarks

The high resolution primitive equation models are good at generating velocity fields which are dynamically correct and which are consistent with both the density field and topography. The modelling community has most confidence in the horizontal fluxes obtained from the models. Detailed error estimates are not available but at 0.1 degree resolution the differences with observations are usually less than 20%.

References

Aksenov, Y., Coward, A.C., 2001: The Arctic Ocean Circulation as simulated in a very high resolution Global Ocean Model (OCCAM). Annals of Glaciology, 33 (in press).

de Cuevas, B.A., Webb, D.J., Coward, A.C., Richmond, C.S., Rourke, E., 1999: The UK Circulation and Advanced Modelling Project (OCCAM). Pp 325-335 in High Performance Computing, Ed Allan, R.J., Kluwer Academic/ Plenum Publishers, New York, 584pp.

Godfrey, J.S., 1989: A Sverdrup model of the depth-integrated flow for the world ocean allowing for island circulation. Geophysical and Astrophysical Fluid Dynamics, 45, 89-112.

Smith, L.T., Chassignet, E.P., Bleck, R., 2000a: The impact of lateral boundary conditions and horizontal resolution on North Atlantic water mass transformations and pathways in an isopycnic coordinate ocean model. Journal of Physical Oceanography, 30(1), 137-159

Smith, R.D., Maltrud, M.E., Bryan, F.O., Hecht, M.W., 2000b: Numerical simulation of the North Atlantic at 1/10°, Journal of Physical oceanography, 30 (7), 1532-1561.

Thompson, S.R., Stevens, D.P., Doos, K., 1997: The importance of interocean exchange south of Africa in a numerical model. Journal of Geophysical Research, 102 (C2), 3303-3315.

SENSITIVITY OF MERIDIONAL TRANSPORTS IN GLOBAL OCEAN MODELS

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In numerical modelling, the question often arises how a central element of the model solution, such as the strength of the meridional overturning circulation (MOC) or maximum meridional heat transport, depends on the various independent parameters that enter the simulation, such as surface forcing, initial conditions, or diffusion parameters. Typical sensitivity calculations vary one parameter or one group of parameters at a time, which is not very efficient as the number of input parameters grows large. In contrast, the “adjoint” of a model calculates the sensitivity of one output variable, simultaneously to all input variables. Marotzke et al. (1999) have used R. Giering’s “Tangent-Linear and Adjoint Model Compiler” (TAMC; Giering and Kaminski 1998) to create the adjoint to the ocean general circulation model (GCM) of Marshall et al. (1997a,b). A particular application, based on the global data assimilation solution of Stammer et al. (1997) for year 1993, is presented, analysing the sensitivity of mean 1993 Atlantic heat transport across 29°N.

The “kinematic sensitivity” to initial temperature variations is isolated, showing how the latter would influence heat transport if they did not affect the density and hence the flow. Over 1 year the heat transport at 29°N is influenced kinematically from regions up to 20° upstream in the western boundary current and up to 5° upstream in the interior.

In contrast, the dynamical influences of initial temperature (and salinity) perturbations spread much faster. Shown is the sensitivity to temperature and salinity at 1160 m, on 1 January 1993. Most notable is the influence of density anomalies arising from as distant as the Labrador Sea, and its concentration on the zonal boundaries. This latter property is consistent with the concept that the MOC is in thermal-wind balance with the zonal density drop, and suggests that monitoring of the MOC by way of density observations near the boundaries should be a feasible strategy.

Finally, results are shown from bugnion (2001) who performed century-timescale adjoint sensitivity calculations with a lower-resolution global gcm. The sensitivity of the Atlantic MOC depends very strongly on whether the ocean model is uncoupled or coupled to a simple parameterisation of atmospheric transports.

References

Bugnion, V., 2001: Driving the ocean’s overturning: An adjoint sensitivity study*. Ph.D. thesis*, MIT.

Giering, R., and T. Kaminski, Recipes for adjoint code construction*, Association for Computing Machinery Transactions on Mathematical Software*, Volume 24, Number **4**, 437-474, 1998.

Marotzke, J., R. Giering, K. Q. Zhang , D. Stammer, C. Hill, and T. Lee, 1999: Construction of the adjoint MIT ocean general circulation model and application to Atlantic heat transport sensitivity. *J. Geophys. Res.*, **104,** 29 529 - 29 547.

Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey, A finite volume, incompressible Navier Stokes model for studies of the ocean on parallel computers, *J. Geophys. Res*., **102**, 5753-5766, 1997a.

Marshall, J., C. Hill, L. Perelman, and A. Adcroft, Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling, *J. Geophys. Res*., **102**, 5733-5752, 1997b.

Stammer, D., C. Wunsch, R. Giering, Q. Zhang, J. Marotzke, J. Marshall, and C. Hill, The global ocean circulation estimated from TOPEX/POSEIDON altimetry and a general circulation model, *Center for Global Change Science Repor*t No. **49**, 40pp, MIT, 1997.

RELATIONSHIP OF SHIP BASED AIR-SEA FLUXES TO CONSTRAINED GCM FLUX ADJUSTMENTS, NWP MODEL REANALYSES AND ATMOSPHERIC RESIDUAL METHODS

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1) Overview of Surface Flux Datasets.

Various sources of information regarding the surface heat flux forcing of the ocean were briefly reviewed with regard to the advantages and disadvantages of each. These may be categorised as follows: NWP Model Reanalyses, Ship Based Estimates, Satellite Retrievals, Residual Method, Hybrid and Constrained GCM. Atmospheric model reanalyses e.g. NCEP/NCAR and ECMWF have the advantage of high temporal resolution (6 hourly) and full spatial coverage but still suffer from significant spatial biases resulting from a.) problems with the representation of stratiform clouds and b.) overestimation of turbulent heat losses due to the choice of transfer coefficients used in bulk formula estimates of the fluxes. Ship based estimates e.g. SOC and UWM/COADS have the disadvantage of significant sampling problems and failure to close the global ocean heat budget but tend to be in better agreement than the reanalyses with independent high quality research buoy and ship flux measurements (Josey, 2001). Satellite estimates are currently limited by their inability to obtain accurate retrievals of key surface fields, in particular the air temperature which is necessary to obtain useful estimates of the net heat exchange. Residual Method and Constrained GCM estimates are discussed further below. Hybrid refers to combinations of flux estimates from different sources e.g. reanalyses and satellites, which have been developed for use as model forcing fields (e.g. Large and Nurser, 2001). However, the method employed for such combinations remains somewhat subjective at present and the fields described in Large and Nurser (2001) are at present not intended to provide an alternative to the flux datasets discussed above (W. Large, personal comm.).

2) Evaluation of the ECCO Model Surface Fluxes.

Surface fluxes output from ocean models which assimilate observations, e.g. the ECCO model developed by Stammer et al. (2001), are now being advanced as an improvement on the original fields used to force such models. For the purposes of this review talk, output from iteration 103 of the ECCO model run was compared by the author with a subset of the independent SOC dataset for the same period, 1992-1997, averaged to the same grid scale, $2^o \times 2^o$. Note that the model was originally forced with NCEP/NCAR fluxes for the same period. The difference in the annual mean net heat flux field between SOC and ECCO is shown in Fig.1. The model is seen to underestimate the heat loss over the Gulf Stream and Kuroshio by of order 50 Wm^{-2} relative to SOC. As the SOC heat flux estimates in these regions are themselves thought to be underestimates (Josey et al., 1999), the model bias with respect to the true heat loss is likely to be somewhat larger than 50 Wm^{-2} in the annual mean. Further analysis reveals that the model biases are seasonal in nature with the largest differences occurring from late summer through autumn. Similar seasonal variations in the accuracy of the model fluxes are found for the Southern Ocean.

The model evaluation was extended to include comparisons with regionally averaged heat fluxes obtained from hydrographic section pair estimates of the heat transport and local measurements of the fluxes from high quality WHOI research buoys (see Josey et al., 1999, for details of this approach as applied to the SOC climatology). The model fluxes are found to be in good agreement with the independent regional estimates from hydrography in the Tropics but to underestimate the heat loss at higher at higher latitudes. Specifically, in the Atlantic Ocean, for the region bounded by sections at 11^oS and 24^oN, the area averaged surface net heat flux derived from hydrographic transport estimates is 25 Wm^{-2}, which compares well with the model value of 18 Wm^{-2}. In contrast, between 24^oN and the CONVEX section at approximately 57^oN, the model heat loss of -9 Wm^{-2} is significantly weaker than the hydrographic value of -51 Wm^{-2}. It is possible that the latter bias will be reduced in subsequent higher resolution versions of the model which will allow a better representation of the boundary currents and hence the transport of heat to the mid-latitudes. The model heat transport implied by integrating the surface annual mean net heat flux southwards from a reference value of 0.1 PW at 65^o N in the Atlantic Ocean is shown in Fig.2 together with that obtained from the NCEP fluxes used to force the model at iteration 1. The model adjustment to the NCEP fluxes appears to have caused the implied heat transport to move away from the reference hydrographic values. However, it should be noted that a significant amount of heat storage occurs in the model and that when the heat transport is calculated directly by integrating the product of sub-surface temperature with the corresponding meridional velocity better agreement with hydrography is obtained (Stammer, results presented at this meeting). The global freshwater budget of the model was also briefly considered, here there appear to be significant problems as the model global mean E-P = -0.50 Sv, indicating a net gain of freshwater by the oceans rather than the net loss which is necessary to balance the freshwater input from river runoff. By comparison the global mean E-P from SOC = 0.71 Sv and from Baumgartner and Reichel (1975) = 1.3 Sv. The research buoy comparisons are limited by the small number of surface flux reference sites for which high quality data covering a full annual cycle is available at the present time. The best of the reference sites in terms of accuracy and length of deployment is the NE buoy (located in the North Atlantic at 33° N, 22° W) of the Subduction Array (Moyer and Weller, 1997) and we summarise results from a comparison of the model with this buoy as an example of the improvement possible with data assimilation. The model run overlapped the buoy deployment between January 1992 and June 1993. For this period the model net heat flux was 15.3 Wm^{-2}, which is in good agreement with the buoy measured value of 24.4 Wm^{-2}. The corresponding value from the NCEP fluxes used for the first model iteration was 3.2 Wm^{-2}. Thus, at this particular reference site, which is representative of regions in which water is subducted from the mixed layer into the thermocline, the data assimilation process has enabled the original NCEP flux bias of greater than 20 Wm^{-2} to be brought within the 10 Wm^{-2} accuracy range required by major research programs such as CLIVAR.

3) Constraining the SOC Climatology.

Preliminary results from a project to constrain the SOC climatology using the increasing number of hydrographic estimates of the heat transport available as a result of WOCE were presented. The global SOC fluxes have been adjusted via a linear inverse analysis following Isemer et al. (1989) using 8 section estimates of the heat transport in the Atlantic Ocean together with the requirement of global heat budget closure. A solution was found which satisfied all of the constraints except that for the region between 24° - 60° N in the Atlantic Ocean. This result indicates that an inverse analysis with regionally dependent adjustments to the flux formulae parameters is necessary in order to satisfy all of the constraints and this is the subject of ongoing research at SOC. The heat transports from the original version of the SOC climatology together with that from the version which has been adjusted as described above are also shown on Fig.2.

4) Residual Estimates of the Ocean Heat Transport.

New residual estimates of the ocean heat transport determined by Trenberth and Caron (2001) from satellite TOA radiative fluxes and atmospheric flux divergences from the NCEP reanalyses were discussed. The new estimates indicate that atmospheric heat transport is more important than previously thought. Specifically, the atmosphere carries 78 / 92% of the total heat transport at 35° N in the Northern / Southern Hemisphere and the ocean is dominant only between 0-17° N. It was noted that problems remain in the analysis associated with difficulties in closing the budget over land and the requirement of corrections to fluxes in Southern Ocean. At mid-latitudes the ocean heat transport determined from the new residual estimates is very low, e.g. 0.5 PW globally at 40° N and it was suggested that the WOCE community should address whether these new estimates are consistent with hydrographic estimates of the transport. The residual heat transport estimate for the Atlantic is shown as line NCEP-R on Fig. 2.

Acknowledgements

The author would like to thank Detlef Stammer, Peter Taylor and Carl Wunsch for useful comments on the SOC-ECCO comparison. The ongoing project to constrain the SOC climatology is being funded by the UK Natural Environment Research Council as part of it's COAPEC thematic programme and the preliminary results noted here were obtained by Jeremy Grist in collaboration with Simon Josey.

References

Baumgartner, A. and E. Reichel, 1975: *The World Water Balance: Mean Annual Global, Continental and Maritime Precipitation.* Elsevier, 179 pp.

Isemer, H.-J., J. Willebrand, and L. Hasse, 1989: Fine adjustment of large scale air-sea energy flux parameterizations by direct estimates of ocean heat transport. *J. Clim.*, **2,** 1173 - 1184.

Josey, S. A., 2001: A comparison of ECMWF, NCEP/NCAR and SOC surface heat fluxes with moored buoy measurements in the subduction region of the North-East Atlantic. *J. Climate*, **14,** 1780 -1789.

Josey, S. A., E. C. Kent, and P. K. Taylor, 1999: New insights into the ocean heat budget closure problem from analysis of the SOC air-sea flux climatology. *J. Climate*, **12,** 2856 - 2880.

Large, W. G. and A. J. G. Nurser, 2001: Ocean Surface Water Mass Transformation. *Ocean Circulation and Climate*, G. Siedler, J. Church and J. Gould, Ed., Academic Press, 317-336.

Moyer, K. A. and R. A. Weller, 1997: Observations of surface forcing from the subduction experiment : a comparison with global model products and climatological data sets. *J. Clim.*, **10,** 2725 - 2742.

Stammer, D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. N. Hill, and J. Marshall, 2001: The global ocean circulation during 1992-1997, estimated from ocean observations and a general circulation model. *J. Geophys. Res.,* submitted.

Trenberth, K. E. and J. M. Caron, 2001: Estimates of meridional atmosphere and ocean heat transports. *J. Climate,* in press.

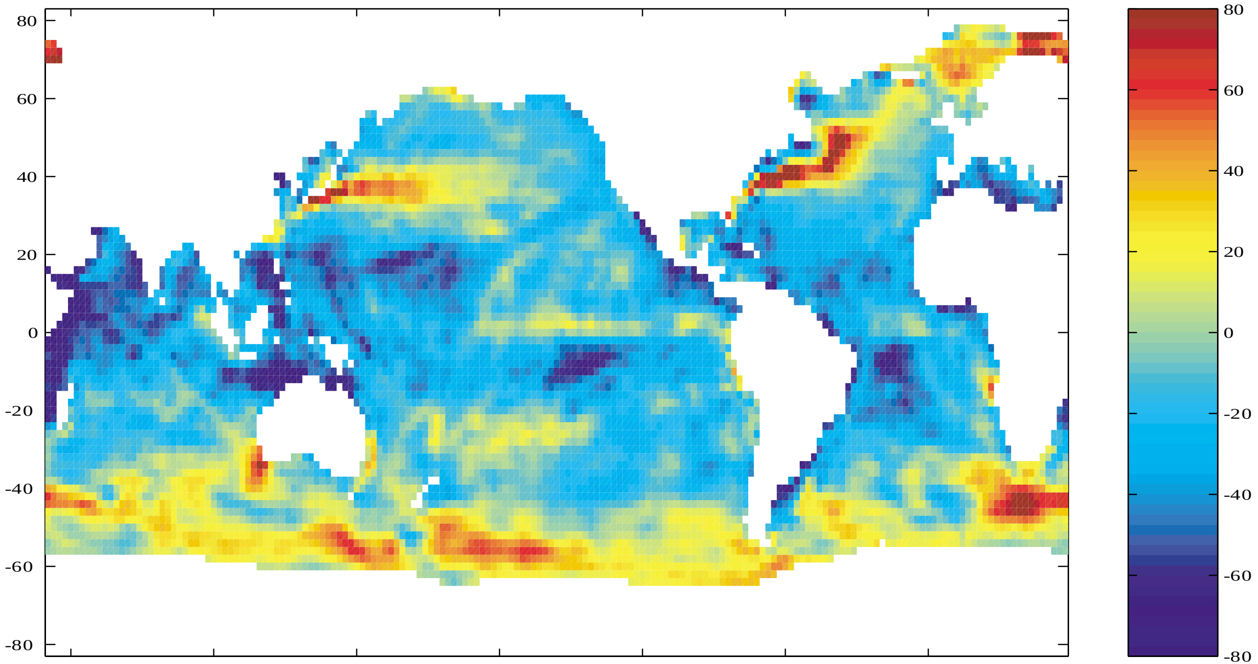

Figure 1: Difference (ECCO-SOC) of the ECCO and SOC Annual Mean Net Heat Flux, unit Wm^{-2}. Heat loss from the ocean to the atmosphere is defined to be negative, hence red colours indicate the ECCO under estimates the heat loss to the atmosphere relative to SOC.

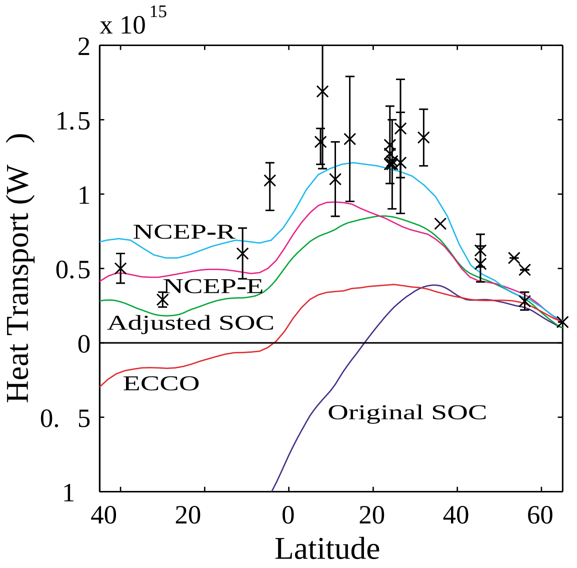

Figure 2: Atlantic Ocean heat transport determined by integrating the zonal total heat exchange from ECCO (Iteration 103), NCEP-E (fields used to force ECCO Iteration 1), SOC (original and adjusted) and NCEP-R (residual fields determined by Trenberth and Caron) southwards from a reference value of 0.1 PW at 65°N. Black crosses with error bars are heat transport estimates determined from hydrographic sections.

PROSPECTS FOR REGIONAL ESTIMATES OF HEAT AND FRESHWATER FLUX FROM WOCE

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Estimates of heat and freshwater fluxes for particular regions or basins are beginning to be made using WOCE data, as reviewed recently by Bryden and Imawaki (2001) and Wijffels (2001). Three techniques have been used to estimate ocean heat flux: direct calculations using oceanographic observations, integration of surface fluxes determined using bulk formulae, and the residual method, where ocean fluxes are inferred from the difference between top-of-atmosphere energy fluxes and atmospheric transport estimates (see Bryden and Imawaki (2001) for a discussion). Until recently, estimates using different techniques have varied widely. Even “direct” estimates using the same data and different assumptions have produced results which differ significantly (e.g., at 30S in the Indian Ocean). In recent years, the various estimates have begun to converge and provide a more consistent view of the global ocean heat and freshwater budgets. Given that the reviews mentioned above present a more or less up-to-date account of regional heat and freshwater fluxes, the focus here is on the overall prospects for the WOCE flux measuring effort.

The WOCE heat flux strategy was to a large extent based on the Hall and Bryden (1982) calculation at 24N in Atlantic. They realized that if the mean transport of the western boundary current was known from moorings, and the baroclinic transport in the interior of the ocean was known from hydrographic sections, the net barotropic transport in the interior could be determined by conserving mass. Because the vertical average temperature was nearly constant along their section, they could infer the heat flux without facing the difficult problem of determining the spatial distribution of the barotropic transport. Following this model, a number of “heat flux lines” were established in each basin during WOCE. Each line included moored arrays to determine the boundary current transports and a hydrographic section across the basin to get the baroclinic flow in the ocean interior.

The 24N section in the Atlantic is probably the “ultimate” heat flux line: the western boundary current is confined and well-measured, and the basin is nearly rectangular in shape with little gyre topography, so the vertically-averaged temperature is nearly constant along the section. The situation is not so agreeable elsewhere: western boundary currents are typically not well-confined, so they are more difficult to monitor with a modest current meter mooring array (e.g., Mata et al., 2000), and the vertically-averaged temperature usually varies across the section reflecting changes in water depth or the shape of the gyre. In this case, the *distribution* of the barotropic flow, not just the net transport, must be determined to estimate the heat flux. Similar arguments hold for the transport of freshwater and other properties.

The tool most commonly used to determine the distribution of the barotropic flow is some form of inverse method. Inverse methods provide a simple machinery to combine a variety of information to constrain estimates of the unmeasured part of the circulation, such as reference level velocities. Most direct estimates of large-scale fluxes of heat and freshwater have been derived using an inverse calculation of some type.

Diapycnal fluxes are a key part of the circulation responsible for large-scale property transports. They have sometimes been ignored in the past, in part because the uncertainty in the lateral divergence was thought to be so large that the diapycnal fluxes could not be inferred from property conservation constraints in layers. In addition, air-sea fluxes were believed to be too poorly known to estimate water mass transformations. On the other hand, it is clear that on basin-scales there can be little heat transport without diapycnal fluxes, unless large temperature differences exist along isopycnals. We need to resolve diapycnal fluxes such as those involved in the overturning circulation if we are to determine the large-scale transports of heat and other properties.

Recent studies have used output from numerical models to develop and test new approaches to parameterizing diapycnal fluxes in inverse models. They suggest that the diapycnal fluxes can be determined provided the parameterization takes into account the co-variation of diapycnal velocity and property concentrations along the surfaces bounding each layer (McIntosh and Rintoul, 1997; Sloyan and Rintoul, 2000). Inverse models have also begun to include the diapycnal fluxes driven by air-sea buoyancy exchange.

OCEAN HEAT TRANSPORT IN THE CMIP MODELS

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CMIP, the Coupled Model Intercomparison Project, began in 1995 under the auspices of the JSC/CLIVAR Working Group on Coupled Modelling. Its purpose is to examine climate variability and predictability as simulated by the models, and to compare the model results with available observations (Covey and Meehl 1997). These models have been used in the assessment of the current understanding of the climate system, and especially in the projection of the future evolution of the climate by the Intergovernmental Panel on Climate Change. In the first phase (CMIP1), the performance of the coupled models in producing the mean climate is examined using model output from
“control experiments”, in which the external forcing terms such as atmospheric CO_2 concentration and solar luminosity are held constant. For the second phase of the project (CMIP2), model responses to an idealised scenario of anthropogenic climate forcing (1% per year increase in atmospheric carbon dioxide) are examined. Parallel “control experiments” are also available. The ocean heat transport and its relationship to the ocean circulation in these coupled models are presented here making use of the output from the”“control experiments” of both CMIP1 and CMIP2.

In the Atlantic, the meridional overturning circulation that consists of the southward transport of the North Atlantic Deep Water (NADW) at depth and the northward transport of upper layer water masses is captured by all the models. The details of the circulation (e.g. the strength of the overturning and the depth range of the NADW), however, differ greatly between the models. The dominance of this overturning circulation in transporting heat northward is evident in all the models as shown in Fig. 1. With a few exceptions (amongst the CMIP1 models), the total heat transport is northward across all the latitudes of the Atlantic basin. Compared with estimates from hydrographic measurements, most of the models produce low heat transport in the subtropical regions of the North Atlantic although several recent coupled models do show significant improvements (NCAR CSM, UKMO3 and PCM). In most cases, the low heat transport results from primarily two factors (Jia 2000): a weak overturning circulation and a small temperature difference between the upper and lower branches of the overturning cell. Models differ in these factors and from observations. One problem that all the models share is that the lower branch (the NADW) is too warm compared with observations, a reflection that the production and transport of the NADW is not adequately represented by these models.

In the Pacific, most of the models have reproduced the wind-driven subtropical cells in both the hemispheres in the ocean upper layer, and the poleward heat transport by these cells. Models differ greatly in the deep meridional circulation and its contribution to the total heat transport. None of the models exhibit a deep circulation pattern close to that deduced from hydrographic measurements (e.g. Bryden et al. (1991) for 25°N and Wunsch et al. (1983) for 30°S). Some of the models have very weak deep flows that make insignificant contribution to the heat transport. In a few models, there is a large northward transport of bottom water with strong upwelling to the ocean upper layer. As a result, the poleward heat transport in these models is reduced in the Northern Hemisphere, and is much enhanced in the Southern Hemisphere.

In the Indian Ocean, most of the models show a net southward mass transport in the surface layer and weak deep flows. A few models have large northward transport of bottom water that upwells to the surface before returning south. Thus the heat transport (flux) from the mean meridional circulation is southward in all the models although the magnitude varies over a large range due to the differences in the deep circulation.

Globally, most of the models achieved the maximum poleward heat transports in the subtropical regions of both the hemispheres (Fig. 2). Such a pattern is in agreement with the recent indirect estimates of Trenberth and Caron (2001). In the Northern Hemisphere, the majority of the models underestimate the maximum northward heat transport. Trenberth and Caron (2001) derived a maximum in excess of 2 PW near 18°N. Such a magnitude is only matched by a small number of models. In the Southern Hemisphere, the maximum southward heat transport for the majority of the models coincides with the maximum strength of the subtropical cell in the mean meridional circulation (near 15°S). There are a small number of models that show excessive southward heat transport in the Southern Hemisphere as a result of a large northward transport of bottom water and strong upwelling to the ocean upper layer in the South Pacific and Indian Oceans.

References

Bryden, H. L., D. H. Roemmich, and J. A. Church, 1991: Ocean heat transport across 24°N in the Pacific. *Deep-Sea Res.*, **38**, 297-324.

Covey, C., and J. Meehl, 1997: The Coupled Model Intercomparison Project (CMIP). *CLIVAR Exchanges*, No. 3/4, 5-6.

Jia, Y., 2000: The ocean heat transport and meridional overturning near 25°N in the Atlantic in the CMIP models. *CLIVAR Exchanges*, No. 17, 23-26.

Trenberth, K. E., and J. M. Caron, 2001: Estimates of meridional atmosphere and ocean heat transports. *J. Climate*, in press.

Wunsch, C., D. Hu, and B. Grant, 1983: Mass, heat, salt and nutrient fluxes in the South Pacific Ocean. . *J. Phys. Oceanogr.*, **13**, 725-753.

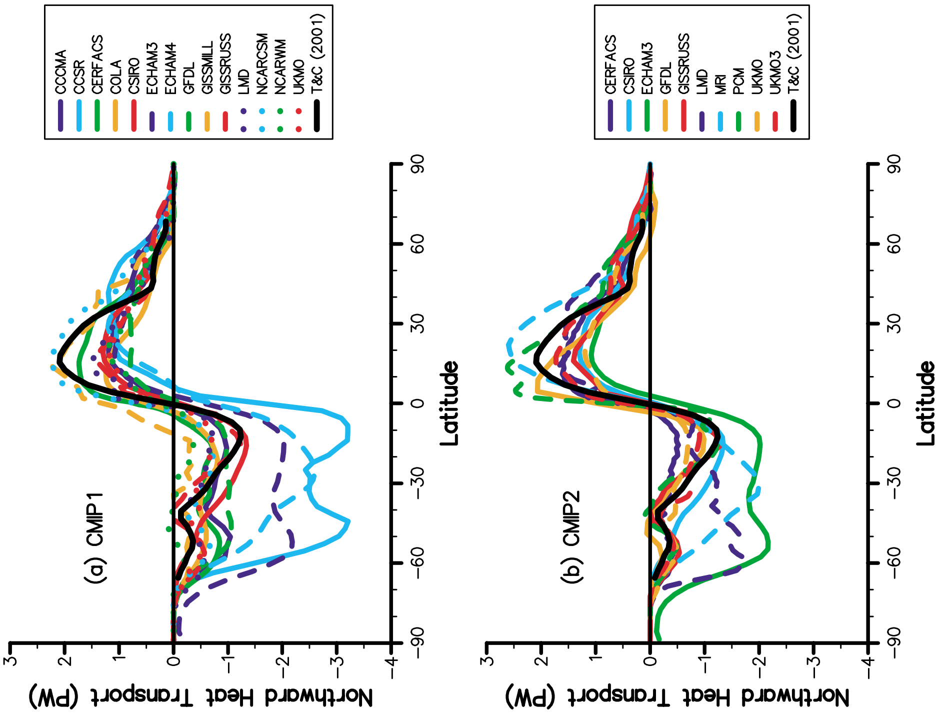

Fig 2. Global

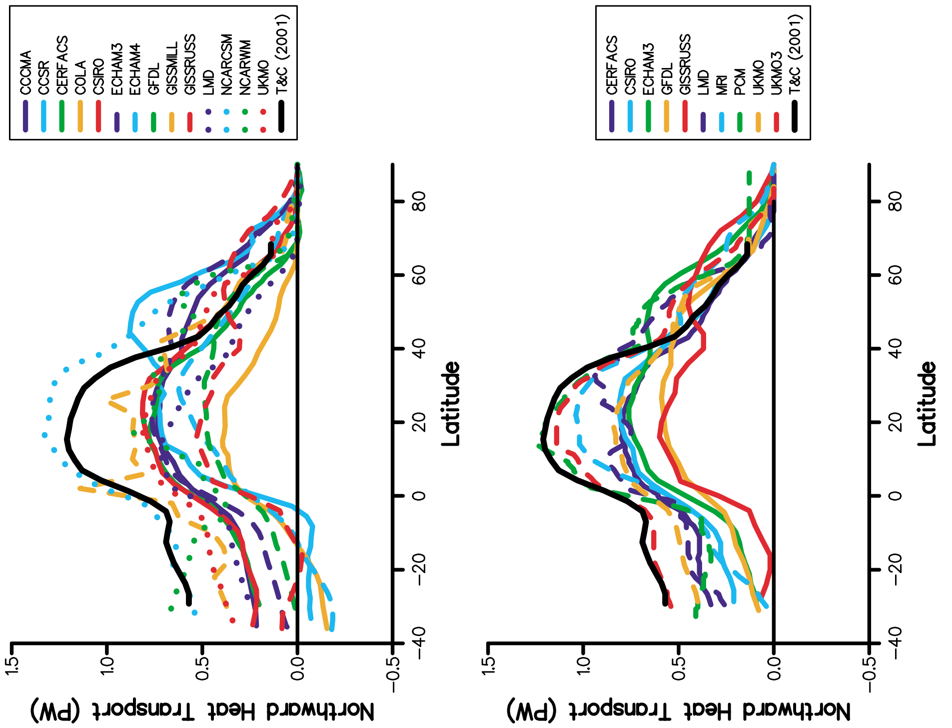

Fig 1. Atlantic

Fig. 1. The Atlantic northward ocean heat transport (PW) in the CMIP models. As a reference, the estimates of Trenberth and Caron (2001) are included (black curve).

Fig. 2. As Fig. 1 but for the global northward ocean heat transport.

THE ROLE OF OCEAN CARBON TRANSPORT IN THE GLOBAL CARBON CYCLE

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The presentation is intended as an introduction to the workshop on carbon transports. It reviews the major concepts, issues and justifications underlying attempts to estimate ocean carbon transport and reviews the observational approaches to carbon transport estimation. There are several “big issues” in carbon cycle science that can be addressed by studies of ocean transport:

(1) Terrestrial and oceanic sinks of carbon: How big? Where? Why? What are the controls?

This issue addresses the present-day budget for anthropogenic CO_2, and particularly the distribution and controlling factors of net terrestrial sinks for atmospheric CO_2. The latter are of increasing political and economic importance under international CO2 mitigation agreements. Inverse modelling of meridional and zonal atmospheric, data(e.g. CO_2, O_2, ^{13}C), is one way to constrain terrestrial sources and sinks on large spatial and temporal scales. Such modelling benefits from carbon transport estimates because ocean transports create gradients in atmospheric CO_2 which must be diagnosed in order to resolve spatial gradients arising from fossil-fuel emissions and net terrestrial sinks.

CO_2 is taken up from the atmosphere in certain regions (e.g. regions of net heat loss) and returned to the atmosphere at a different location (e.g. regions of net heating). Regional differences in the biological pump also drive carbon transports. These oceanic carbon transports can create significant atmospheric pCO_2 gradients which allow for a return transport of carbon via the atmosphere. In the Atlantic, following the suggestion of Brewer et al. (1989) it has been possible to estimate carbon transports from hydrographic section data. The present-day oceanic transport of carbon is, however, comprised of both a “natural component” and an “anthropogenic component”. The latter arises because the ocean contains anthropogenic CO_2 (anthropogenic CO_2 is the “extra” concentration of total dissolved inorganic carbon in seawater that results from exposure of ocean waters to an atmosphere with $pCO_2 > \mu 280$ atm, (i.e. the preindustrial or “natural” value)).

Using so-called pre-formed CO_2 backcalculation techniques (see review by Wallace, 2001) the section-wide distribution of both anthropogenic and “natural” components of inorganic carbon can be estimated. This, in turn, allows for estimation of the carbon transport in the preindustrial ocean (assuming circulation has not changed) as well as estimation of the anthropogenic carbon transport. In the Atlantic, this type of analysis indicates that the natural transport of carbon was southwards at all latitudes because predominantly southward-flowing deeper water contains higher TCO_2 levels than the upper-ocean return flow. This “natural” southwards transport is now, however, partially offset by northwards transport of anthropogenic CO_2 (anthropogenic CO_2 concentrations being highest in “younger” near-surface waters).

Estimation of the “natural” southwards transport across the equator allows the ocean-driven interhemispheric gradients of atmospheric CO_2 to be estimated. To-date, direct estimates have only been made for the South Atlantic (10-30°S, Holfort et al., 1988) and for 24°N (Rosón et al., 2001). No direct carbon transport estimates have been attempted for the Pacific or Indian Oceans. Hence it is presently impossible to assess the global oceanic interhemispheric transport. A recent global assessment of carbon transport in GCMs has been published by Sarmiento et al. (2000).

(2) Locations of anthropogenic CO_2 uptake by the oceans: where does anthropogenic CO_2 cross the air-sea interface? And why?

This issue relates to the physics (and chemistry) underlying anthropogenic CO_2 uptake, which must be resolved if we are to predict future uptake under a possibly altered circulation. Anthropogenic CO_2 uptake can be thought of as the anthropogenic perturbation of the natural air-sea CO_2 flux. The thermodynamic uptake capacity for anthropogenic CO_2 at the sea-surface is a function of the temperature, alkalinity and pCO_2 of the surface seawater. Due to the dissociation of CO_2 in seawater, the uptake capacity for anthropogenic CO_2 actually increases with increasing temperature and decreases with increasing pCO_2

(Revelle factor changes). The uptake is greatest where this thermodynamic uptake capacity is large and where "old'', sub-surface waters, which have not seen the atmosphere for decades or centuries, are re-exposed to the (altered) atmosphere. The uptake cannot be measured directly: the present-day air-sea CO_2 flux which can be estimated from pCO_2 measurements in surface-water and air, is a mixture of "natural'' and anthropogenic components. The distribution of this air-sea flux perturbation can be modelled using carbon-cycle GCMs. However, it is likely that the distribution of uptake in models is critically dependant on the representation of vertical/diapycnal motions, including mixing, which are themselves notoriously difficult to represent.

Holfort et al. (1998) noted that hydrographic section-based carbon transport estimates applied to the problem of anthropogenic CO_2 flux divergence and storage represents perhaps the only way, independent of GCMs, to assess the geographical distribution of anthropogenic CO_2 uptake. In this approach, the transport of anthropogenic CO_2 across different sections is estimated, and when combined with estimates of between-section anthropogenic carbon storage allows coarse estimation of the air-sea flux of anthropogenic CO_2 from mass-balance.

Based on the anthropogenic carbon transport estimates from Holfort et al. (1998) and Roson et al. (2001), such a balance can be attempted for the latitude bands 30°S-10°S, 10°S-24°N and 24°N to Bering Strait. The mass-balance can be represented in several ways. For example the calculated transports and storage terms for the period of measurements can be estimated, and by assuming (for a latitude band bounded by two sections) that:

$$\text{Storage} = (T_s - T_n) + F_{\text{air-sea.}}$$

Where T_S and T_N refer to net transport across sections defining the southern and northern boundaries of the ocean volume respectively, $(T_S\text{-}T_N)$ is therefore the horizontal transport convergence and $F_{\text{air-sea}}$ is the net air-to-sea flux within this region. The air-sea flux for the 1990's can be estimated if the storage term can be measured (by repeat surveys) or otherwise estimated. Alternatively, the transports across each section can be assumed to have increased over time in approximate proportion to the surface water anthropogenic CO_2 increase (which can be estimated). The resulting cumulative convergence or divergence can be estimated and compared with the measured anthropogenic CO_2 inventory between the sections to estimate cumulative uptake from the atmosphere. Taking the latter approach and applying it to these three latitude bands in the Atlantic results in the following pattern:

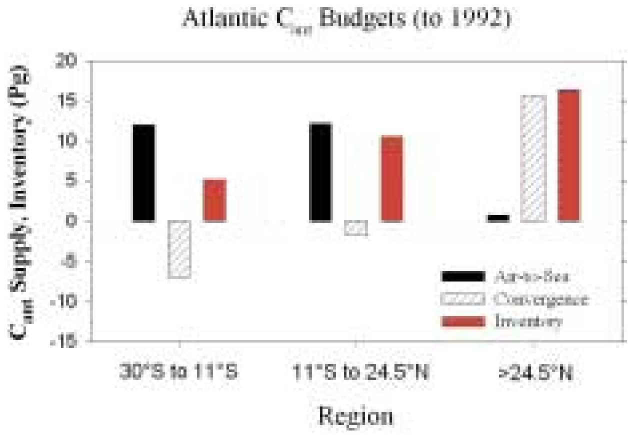

Figure 1. Bar graph depicting the cumulative anthropogenic CO_2 (C_{ant}) budget (1750-1992) of three different regions of the Atlantic Ocean (30°S-11°S, 11°S-24.5°N, and >24.5°N including the Arctic Ocean). For each region, the three bars represent the cumulative magnitude of the transport convergence, air-to-sea flux and storage terms of equation. (From Wallace et al., In prep., 2001)

This figure suggests that horizontal transport is insufficient to supply all the observed inventory of anthropogenic carbon for the mid-latitude South Atlantic and the Tropical Atlantic regions. A net atmosphere-to-ocean flux of anthropogenic carbon is required. The picture for the North Atlantic north of 24°N looks different. It appears from these estimates that the horizontal convergence of anthropogenic carbon is sufficient to explain all of the anthropogenic carbon contained in the Arctic and northern North Atlantic Ocean. This implies negligible air-sea uptake of anthropogenic CO_2 in this region. This is a surprising result which contradicts almost all GCM model results.

What is the reason for this apparent discrepancy?

1. The transport estimates are wrong. According to Rosón et al. (2001), the transport of anthropogenic carbon through the Florida Straits dominates the section budget for 24°N. Inaccurate estimation of the anthropogenic CO_2 concentration in the Florida Straits might therefore alter the overall transport estimate. In addition, there remain difficulties in estimating anthropogenic CO_2 concentrations in deeper water, especially in depth ranges where transient tracers such as CFCs are undetectable. Southward flow of anthropogenic CO_2 in the North Atlantic Deep Water may therefore have been underestimated.
2. The models are wrong. Some current ocean carbon cycle models may not accurately depict the balance between advective supply and air-sea flux due to their having too weak Atlantic overturning combined, possibly, with overly strong vertical mixing. Too weak overturning would cause underestimation of both the northwards heat transport (a common characteristic of many coarse-resolution GCMs) as well underestimate the northwards advective supply of anthropogenic CO_2. On the other hand, unrealistically strong convective activity or “artificial upwelling'' (e.g. in the vicinity of the north wall of the Gulf Stream) would tend to overexpose “older'' deeper water masses to the atmosphere in the model thereby overestimating the local uptake of anthropogenic CO_2 there.

The direct transport calculations, if they are correct, suggest that the warm upper-layer waters which flow into the North Atlantic from the South Atlantic, as the upper limb of the ocean’s meridional overturning circulation, have had time to pre-equilibrate with the contemporary atmospheric pCO_2 before entering the northern North Atlantic. In such a case there is little potential for additional anthropogenic CO_2 uptake within the North Atlantic prior to this water sinking and entering the ocean interior on its return flow to the south. At present, it is too early to say which (if any) scenario is closer to reality. It could well be that the transport estimates are in error and that the model-based estimates are more reliable. On the other hand, most GCMs have difficulties representing water mass properties, thermocline structure, heat transport, convection, etc. in the Atlantic: all of these factors have potential significance for anthropogenic CO_2 budgets. At present it is fair to say that the apparent discrepancy is interesting and illustrates one way in which transport-based estimates and model-estimates can be compared in order to test the representation of anthropogenic CO_2 uptake in models. In order to move forward, continued improvements in the methods by which anthropogenic CO2 can be estimated from hydrographic data are required as well as critical analyses of the errors and uncertainties involved in estimating carbon transports.

References

Brewer, P.G., C. Goyet and D. Dyrssen, 1989: Carbon dioxide transport by ocean currents at 25°N latitude in the Atlantic Ocean. Science, 246, 477-479.

Wallace, D.W.R., Storage and Transport of Excess CO_2 in the Oceans: the JGOFS/WOCE Global CO_2 Survey, in “Ocean Circulation and Climate”, Church, J. Siedler, G. and Gould, J. (eds.), Academic Press, San Diego. 2001

Holfort, J., K.M. Johnson, B. Schneider, G. Siedler, and D.W.R. Wallace, 1998: Meridional transport of dissolved inorganic carbon in the South Atlantic Ocean. Global Biogeochemical Cycles, 12, 479-499

Rosón, G., A.F. Rios, A. Lavin, F.F. Perez and H.L. Bryden, 2000: Carbon distribution, fluxes and budgets in the subtropical North Atlantic Ocean (24.5° N), J. Geophys. Res. (Oceans), In press.

Sarmiento, J.L., P. Monfray, E. Maier-Reimer, O. Aumont, R.J. Murnane, and J.C. Orr, Sea-air CO_2 fluxes and carbon transport: a comparison of three ocean general circulation models, Global Biogeochem. Cycles, Dec. 2000.

Wallace, D.W.R. J. Holfort, G. Roson, F. Perez, and A. Rios, Negligible uptake of anthropogenic CO_2 from the atmosphere within the northern North Atlantic, In prep. For Nature.

AIR-SEA FLUXES OF CO_2 DETERMINED BY INVERSE MODELING OF DIC OBSERVATIONS

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Direct estimates of the net exchange rates of CO_2 across the air-sea interface are associated with large uncertainties caused by the high spatial and temporal variability of the air-sea partial pressure difference and uncertainties in the parameterization of air-sea gas exchange. We have developed an inverse modeling technique that avoids these problems by estimating the net pre-industrial air-sea flux based on the observed oceanic *DIC* distribution corrected for biological cycling and the anthropogenic transient. We do this using an ocean general circulation model to establish the relationship between interior concentrations and surface fluxes. The primary assumption made is that the ocean transport is known sufficiently well from an ocean general circulation model. We invert ocean temperature data to check the inversion scheme and to identify regions where model deficiencies limit our ability to estimate the fluxes reliably.

The large number of dissolved inorganic carbon (DIC) observations obtained by JGOFS on the WOCE hydrographic survey provide us with an outstanding snapshot of the ocean carbon distribution. A technique has been developed in order to separate the anthropogenic carbon component from the pre-industrial component of the DIC (Gruber et al. [1996]) and this has been applied to data from the Atlantic, Indian, and Pacific Oceans (Gruber [1998]; Sabine [1999]; Sabine et al., personal communication). We make use of these results to estimate the pre-industrial and anthropogenic air-sea fluxes of carbon dioxide. The pre-industrial component shows the expected pattern of loss in the tropics balanced by uptake in high latitudes. The anthropogenic component is into the ocean everywhere with a total uptake of 1.8 Pg C yr^{-1}. We compare the resulting air-sea fluxes with those of Takahashi et al. [1999]. There is generally good agreement, particularly in regions where both techniques have good data coverage. However, our results show a shift of uptake from the high to the mid-latitudes, with far less uptake in the Southern Ocean. The inversion results do not show as large a cross-equatorial southward carbon transport in the Atlantic as has been proposed by Keeling et al. [1989] and Broecker and Peng [1992]. Neither does it show a large efflux of carbon dioxide from the Southern Ocean, such as would be required by Keeling et al. [1989]. The interhemispheric transport obtained by the inversion is 0.37 Pg C/yr, which is closer to that proposed by Keeling and Peng [1995].

The technique is also applied to oxygen data corrected for biological cycling to estimate the annual net air-sea fluxes of oxygen. We find that the equatorial regions emit about 330 Tmol O_2 yr^{-1}, which is compensated by uptake in the high latitudes of both hemispheres. The inversion result indicates a small interhemispheric transport of oxygen in the Atlantic of about 50 Tmol O_2 yr^{-1} directed toward the south. This transport is, however, compensated by northward transport in the Pacific and Indian Oceans, resulting in a near zero global interhemispheric oxygen transport.

References:

Broecker, W. S. and T.-H. Peng, Interhemispheric transport of carbon dioxide by ocean circulation, *Nature*, *356*, 587-589, 1992.

Gruber, N., Anthropogenic CO_2 in the Atlantic Ocean, *Global Biogeochemical Cycles*, *12*, 165-192, 1998.

Gruber, N., J. L. Sarmiento and T. F. Stocker, An improved method for detecting anthropogenic CO_2 in the oceans, *Global Biogeochemical Cycles*, *10*, 809-837, 1996.

Keeling, C. D., S. C. Piper and M. Heimann, A three-dimensional model of atmospheric CO_2 transport based on observed winds:4 Mean annual gradients and interannual variations, in *Aspects of Climate Variability in the Pacific and the Western Americas AGU Monograph 55*, vol. edited by D. H. Peterson, 305-363, AGU, Washington D.C., 1989.

Keeling, R. F. and T.-H. Peng, Transport of heat, CO_2 and O_2 by the Atlantic's thermohaline circulation, *Philosophical Transactions of the Royal Society*, *348*, 133-142, 1995.

Sabine, C. L., R. M. Key, K. M. Johnson, F. J. Millero, A. Poisson, J. L. Sarmiento, D. W. R. Wallace, and C. D. Winn, Anthropogenic CO2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, *13*, 179-198, 1999.

Takahashi, T., R. H. Wanninkhof, R. A. Feely, R. F. Weiss, D. W. Chipman, N. Bates, J. Olafsson, C. Sabine and S. C. Sutherland, Net sea-air CO_2 flux over the global oceans: An improved estimate based on the sea-air p CO_2 difference, Proceedings of the 2nd CO_2 in Oceans Symposium,1999.

UNCONSTRAINED OCEAN CARBON CYCLE MODELS

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Global ocean carbon cycle models have emerged over the last decade as powerful tools for studying marine biogeochemistry and remain one of the few viable approaches for projecting the response and feedbacks to future climate change. With respect to ocean carbon transport, prognostic or unconstrained models can be useful in linking the observed distributions and flux estimates (air-sea and horizontal) with the underlying physical and biogeochemical dynamics. Conversely, these models should be continuously confronted with the observational data as part of the ongoing cycle of model evaluation and development. Finally, data assimilation schemes are built around prognostic models and the skill of the assimilation is dependent on a good forward simulation particular, as is presently the case for carbon, for relatively data poor situations. Here we will discuss the current state of global, coarse resolution ocean carbon cycle models drawing on examples from the NCAR ocean model using the OCMIP-2 biotic routines (Doney et al., 2001).

The oceanic uptake of anthropogenic carbon, currently estimated to be about 2PgCyr^{-1} occurs on top of a large natural background inventory (~40,000 PgC) and carbon cycle. For comparison, the estimated export flux of particulate and dissolved organic carbon from the surface layer is about 10 PgC yr^{-1}. This export flux together with physical solubility effects on dissolved inorganic carbon (DIC) drives the vertical partitioning and large-scale patterns of nutrients, oxygen, DIC and alkalinity in the ocean. A number of models of varying complexity and sophistication have been developed to estimate export flux. A simple example is the OCMIP-2 biotic model which neglects the ecological details of the upper ocean and predicts the production of organic matter based on restoring of the surface nutrient concentrations to an observed climatology. The production is partitioned into sinking particles, which are remineralized over the water column with a simple empirical vertical profile, and a dissolved organic matter (DOM) pool, which is advected and mixed with the water decaying as a first order process with a 6 month half-life. Most of the dissolved organic pool is remaineralized over the upper 250m of the water column and the particles by 1000m. Observational estimates of export production range widely, but the model tends to capture the broad patterns-high in regions of upwelling and convection (Equatorial band, mid- to high latitudes) and low in the subtropical gyres (Figure 1). The subtropical gyres are regions of net horizontal convergence of DOM. Some caution should be taken with the predicted export fluxes from this class of coarse-resolution models because the production is sensitive to explicit and implicit vertical mixing and may depend upon issues such as numerical advection schemes.

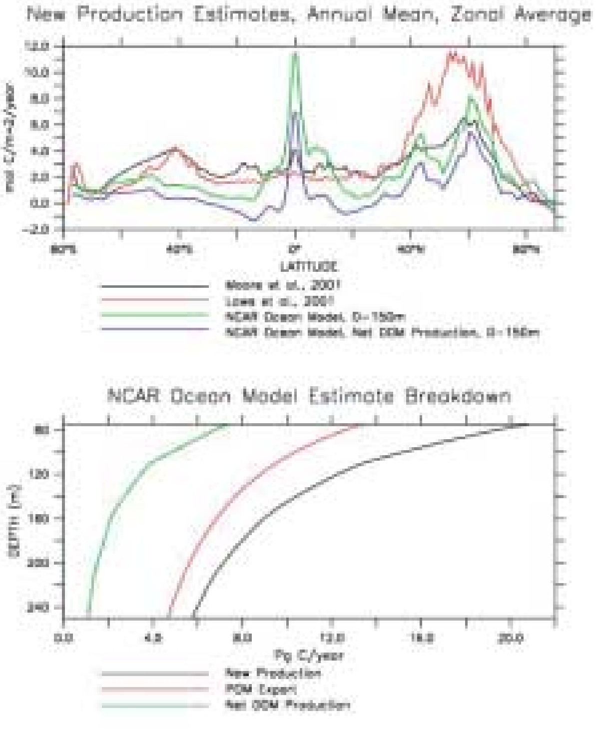
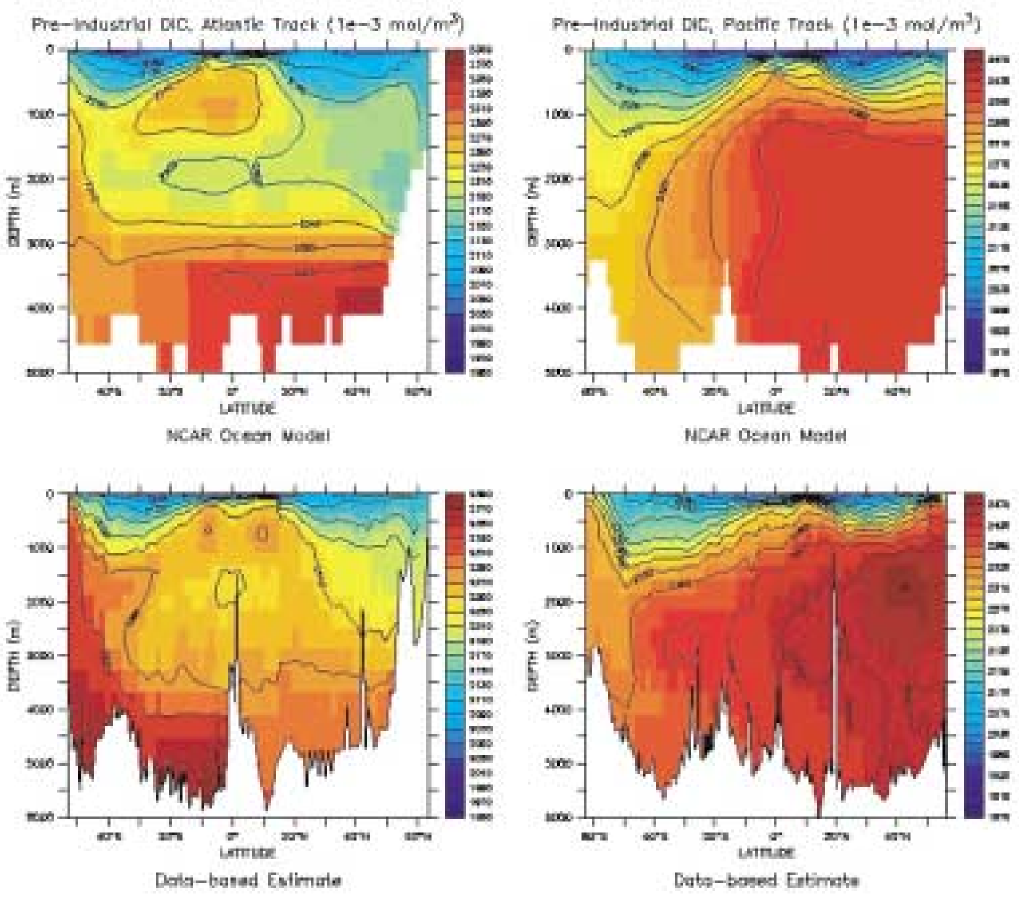


Figure 1

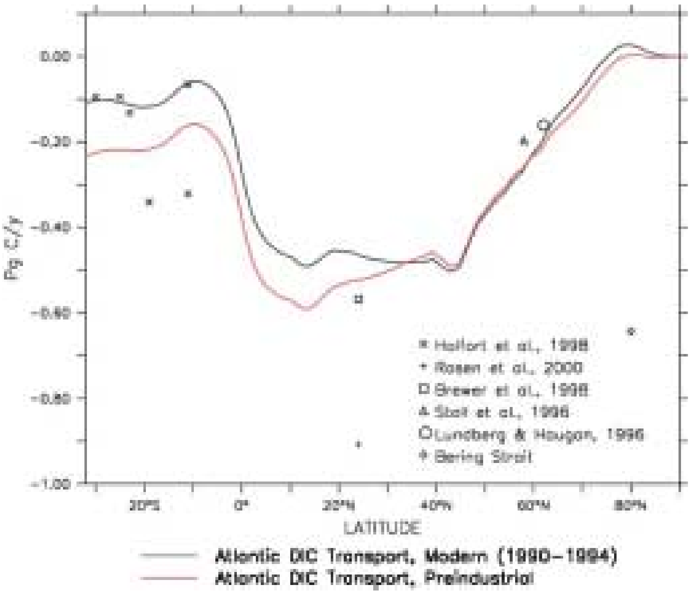
The WOCE/JGOFS global CO_2 survey data set provides an excellent and unique metric for assessing the model predicted large-scale DIC and alkalinity fields. Additional measures of model skill include the more extensive nutrient and oxygen data bases, the Takahashi et al. surface air-sea CO_2 climatology, and transient tracers (CFCs, ^{14}C) and empirical estimates of anthropogenic carbon. The NCAR model preforms reasonably well in capturing the large-scale patterns in these different field as shown for example in Figure 2 for an Atlantic and Pacific meridional section of the pre-industrial, subsurface DIC concentration. But clear regional deficiencies can be noted, and many of these problems can be traced back to a poor physical circulation field. In particular, as is common with z-coordinate models the simulated North Atlantic Deep Water outflows at too shallow a depth leading to a dipole error pattern in the Atlantic meridional section. As a rule the skill of the biogeochemical solution depends critically upon the physical circulation.

Figure 2



Global numerical models capture the key processes relevant for transport calculations namely the horizontal transport (and divergence) itself, air-sea fluxes, and internal storage (e.g. anthropogenic carbon build-up). Depending on their formulation they may or may not include aspects such as river runoff and an open Bering strait (the NCAR model has neither), important for computing absolute mass and carbon transport (which in many ways behaves more like freshwater than heat transport). Figure 3 shows the model predicted pre-industrial and modern meridional carbon transport for the Atlantic compared with observations corrected for the Bering Straits carbon inflow of roughly 0.6 PgC yr^{-1}. The model and data predict comporable net southward preindustrial DIC transport (maximum of 0.6 PgC yr^{-1}) associated with the thermohaline overturning and net northward anthropogenic DIC transport (0.1-0.12 PgC yr^{-1}) in the surface layer. One issue to be aware of is that many models do not include a full natural boundary condition for freshwater and thus resort to “virtual” surface fluxes for salt and carbon. The resulting “virtual” carbon transports are similar in size to actual fluxes and can be corrected for to first order.

Figure 3



One advantage of models is that they allow us to look in detail at the processes generating integrated properties such as the zonally average flux. As one example, the model suggests that the net transport of DOM varies regionally and could be as large as ±0.15 PgC yr^{-1}. Dynamically, most of the carbon transport is occuring via the mean Eulerian flow but a significant diffusive flux is found in the model tropics and eddy-induced advection (based on the Gent-McWilliams meoscale mixing parameterization is found along the Gulf Stream-North Atlantic Current. The model circulation/transport patterns can also be explored at the level of an individual section, though some care is warrented as coarse-resolution model exhibit known deficencies in currents (e.g. too broad Gulf Stream with limited recirculation; slow core velocities; poor representation of vertical structure in the Deep Western Boundary Current).

Several atmospheric and oceanic studies have suggested that the pre-industrial ocean had a net southward interhemispheric transport of carbon of up to 1.0 PgC yr^{-1}. This would have important ramifications for the hemispheric atmospheric gradient, which has been used extensively to infer that the main location for ocean/ land anthropogenic carbon sinks must be in the northern hemisphere. More recent 3-D ocean simulations suggest the number is more like a few tenths of a PgC yr^{-1} at most. The addition of riverine carbon input, which occurs primarily in the Northern Hemisphere but which is outgassed in both hemispheres, could add about another 0.25 PgC yr^{-1} to those values. While smaller than orginally thought, this transport has a non-negligible impact on atmospheric CO_2 fields.

Future work is required in a number of areas to improve on exisiting ocean carbon cycle models. Key areas for advancement focusing on ocean carbon transport include (Doney, 1999):

- mechanistic ecosystem biogeochemical components (e.g. plankton functional groups, particle flux & remineralization)
- physical model developments (e.g. diapycnal mixing, deep-water formation & overflows, isopycnal coordinates)
- interannual variability & eddy resolving biogeochemical simulations - net mass transport (e.g.~Bering Straits, natural boundary conditions, rivers)
- reconciliation of atmosphere & ocean flux estimates

References

Doney, S.C., 1999: Major challenges confronting marine biogeochemical modeling, Global Biogeochem. Cycles, 13, 705-714.

Doney, S.C., K. Lindsay, J.K. Moore, 2001: Global ocean carbon cycle modeling, International JGOFS Synthesis Volume, ed. M. Fasham, in press.

ATMOSPHERIC INVERSIONS: CARBON ISOTOPES

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Issues

In presenting a review of inversions of atmospheric CO_2 at a WOCE/JGOFS meeting it seems appropriate to focus on two questions:
What can the atmospheric CO_2 *and its isotopic composition tell us about the ocean carbon cycle?*
What can the ocean tell us about the atmospheric carbon budget?

In order to answer these questions we need to be able to quantify the extent to which different types of observations contribute to improved understanding.

The first step is to clarify some definitions [14]. In atmospheric studies we have learnt the importance of

carbon dioxide flux ≠ carbon flux ≠ carbon storage

The first inequality reflects release from terrestrial biomass to the atmosphere in forms other than CO_2 - generally CO and its precursors. The second reflects the transfer of carbon from terrestrial systems to the oceans via rivers [20]. These differences help explain apparent anomalies such as the very low estimates [12] of oceanic uptake of CO_2.

Atmospheric inversion with isotopes is presented in terms of (a) atmospheric CO_2 inversions, (b) global ^{13}C-^{12}C budgeting and then (c) combining these in joint CO_2-$^{13}CO_2$ inversions.

Inversions

The principle that underlies trace gas inversions is that the spatial and temporal distributions of trace gas concentrations reflect the spatial and temporal distributions of their sources and sinks, modified by the effects of atmospheric transport. Therefore, using a model to calculate the atmospheric transport, it should be possible to identify the sources and sinks. There are a range of techniques [4.5]. The two main types are:
Mass balance inversions. These are based on taking the transport equation expressing changes in concentration, $c(\mathbf{r},t)$, as the combination of transport, $T[.]$ and the net source/sink, $s(\mathbf{r},t)$:

$$\frac{d}{dt}c(\mathbf{r},t) = T[c(\mathbf{r},t)] + s(\mathbf{r},t)$$

and rewriting it as

$$s(\mathbf{r},t) = \frac{d}{dt}c(\mathbf{r},t) - T[c(\mathbf{r},t)]$$

where the second form is used at those locations (generally the earth's surface) where the concentration is known and the source is unknown. The first form is used (generally in the free atmosphere) at those locations where the source is known (often zero) and the concentrations are unknown.

Synthesis inversions. These are based on the integral form

$$c(\mathbf{r},t) = \int G(\mathbf{r},t,\mathbf{r}',t')s(\mathbf{r}',t')d^3r'dt'$$

The sources are discretised in terms of prescribed basis functions, $\sigma_j(\mathbf{r},t)$, as

$$s(\mathbf{r},t) = \sum_j a_j\sigma_j(\mathbf{r},t)$$

and the coefficients, a_j, estimated by

$$c(\mathbf{r},t) \approx \sum_j a_j G_j(\mathbf{r},t)$$

with

$$G_j(\mathbf{r},\mathbf{t}) = \int G(\mathbf{r},t,\mathbf{r}',t')\sigma_j(\mathbf{r}',t')d^3r'dt'$$

The integral form depends on the boundary conditions. Two main cases are (a) for annually-periodic sources (so that the concentrations are periodic plus a globally uniform trend) and (b) prescribed initial conditions so that the inversions follow the full time-dependence. In each case, the fitting of concentrations can be expressed as a linear regression analysis, allowing uncertainties in the observations to be propagated through the calculations, thus giving uncertainties for the estimated sources. Generalising this to a Bayesian form allows the inversions to incorporate additional information to produce combined estimates based on multiple types of data. The Bayesian form has the additional advantage of reducing the effects of the ill-conditioning in the inversion. Comparing the posterior probability distributions to the prior distributions gives a measure of how much information is contibuted by the inversion. However, because these Bayesian inversions incorporate additional information through the prior distributions, care is needed to avoid 'double counting' when comparing the results to other estimates. For example, many inversions use the air-sea flux estimates from Takahashi et al. [15] as priors, albeit with large uncertainties.

Isotopes

In atmospheric CO_2 inversions, the isotope of most interest is ^{13}C. (^{14}C is important in ocean studies and ^{18}O is important in terrestrial studies.) The atmospheric budgets for total atmospheric carbon (M_A) and atmospheric ^{13}C (written as R_A M_A where R_A is the ^{13}C:C ratio) are

$$\frac{d}{dt}M_A = \sum \Phi_X = \sum[\Phi_x^+ - \Phi_x^-] \qquad \frac{d}{dt}(R_A M_A) = \sum(R_x^+\Phi_x^+ - R_x^-\Phi_x^-)$$

where Φ_x^+ and Φ_x^- are the one-way carbon fluxes from and to reservoir x.

In the ^{13}C budget, the contributions can be written:

$$R_x^+\Phi_x^+ - R_x^-\Phi_x^- = R_x^+(\Phi_x^+ - \Phi_x^-) + \Phi_x^-(R_x^+ - R_x^-) = R_x^+\Phi_x + \Phi_x^-(R_x^+ - R_x^-)$$

The first term on the right involves the net flux. The second term has become known as an isoflux and represents a contribution to ^{13}C change that occurs even in the absence of net carbon flux.

Having two budget equations allows us to solve for 2 unknowns. Most commonly, the technique has been applied to estimating the net flxues, Φ_O and Φ_B from the oceans and terrestrial biota. This 2-component budget formalism has been used in various ways, generally using terrestrial models to estimate

$$\Phi_B^-(R_B^+ - R_B^-):$$

Quay et al.[17] used a 'carbon-storage' form with changes in ocean ^{13}C determined by observations. Tans, Berry and Keeling [13] used observed air-sea isotopic disequilibria to estimate $\Phi_O^-(R_O^+ - R_O^-)$term.

Heimann and Maier-Reimer [8] produced an estimated budget based on combining the approaches of Quay et al,, Tans et al., and a third approach based on long-term isotopic relations. Francey et al. [7] and Keeling et al. [10] applied the Tans et al. form with time dependence. Enting [3] reviewed the statistical aspects of the Francey et al. analysis. Trudinger [16] has used a response function formalism, so that rather than a slowly-varying isoflux, the isoflux varies according to the actual isotopic fluxes.

Inversions with isotopes

There have been a number of studies that combine the principles of CO_2 inversions and carbon isotope budgeting

- Keeling et al. [9] performed a CO_2 synthesis and used ^{13}C distributions as a check, rather than as part of the estimation.
- Enting et al. [6]developed the Bayesian synthesis formalism for a steady-state inversion of CO_2 and ^{13}C data.
- 2-D mass balance inversions, simultaneously inverting CO_2 and ^{13}C, have been performed by Ciais et al. [1,2] and Morimoto et al. [11].
- Rayner et al. [18] performed a 3-D time-dependent inversion of CO_2 and ^{13}C.

Summary

Some illustrative results are:

- The main information about global budgets is in the global-scale concentrations.
- Enting [5] suggests that estimates from inversions can be presented as cumulative integrals over latitude, to reduce the degree of negative spatial autocorrelation.
- Inversions studies comparing synthesis inversion with 2 forms of mass balance inversion [19] suggest that estimates of interannual variability are relatively robust.

References

1. Ciais, P. et al. (1995) *Science,* **269**, 1098-1102.
2. Ciais, P. et al. (1995) *Journal of Geophysical Research*, **100D**, 5051-5070.
3. Enting, I.G., (1999) CSIRO Atmos. Res. Tech. Paper 40. *http://www.dar/csiro.au/publications/Enting_2000a.pdf*
4. Enting, I.G. (2000) in *Inverse Methods in Global Biogeochemical Cycles*. Ed. P.Kasibhatla et al. Geophysical Monography 114. (AGU. Washington).
5. Enting, I.G. (2000) *Inverse Problems in Atmospheric Constituent Transport.* (CUP) (in press).
6. Enting, I.G., Trudinger, C.M. and Francey, R.J. (1995) *Tellus*, **47B,** 35-52.
7. Francey, R.J. et al. (1995) *Nature*, **373,** 326-330.
8. Heimmann, M. and Maier-Reimer, E. (1996) *Global Biogeochem. Cycles,* **10**, 89-100.
9. Keeling, C.D., Piper, S. and Heimann, M. (1989) pp305 of *Aspects of Climate Variability in the Pacific and Western Americas.* Ed. D.H. Peterson. Geophysical Monography 55. (AGU: Washington).
10. Keeling, C.D. et al. (1995) *Nature,* **375,** 666-670.
11. Morimoto, A. et al. (2000) *Journal of Geophysical Research* **105D,** 24315-24326.
12. Tans, P.P., Fung, I.Y. and Takahashi, T. (1990) *Science*, **247**, 1431-1438.
13. Tans, P.P., Berry, J.A. and Keeling, R.F. (1993) *Global Biogeochem. Cycles,* **7,** 353-368.
14. Tans, P.P., Fung, I.Y. and Enting, I.G. (1995) p351 of *Biotic Feedbacks in the Global Climatic System.* Ed. Woodwell and Mackenzie. (OUP).
15. Takahashi, T. et al. (1999) p9-15 of *Proceedings of the 2nd Internatioal symposium in* CO_2 *in the Oceans.* Ed. Y. Nojiri. (Center for Global Environmental Research: Tsukuba).
16. Trudinger, C.M. (2000) Ph.D. Thesis, Monash University. Available at *http://www.dar.csiro.au/publications/Trudinger_2001a0.htm.*
17. Quay, P., Tillbrook, B. and Wong, C.S. (1992) *Science,* **256**, 74-79*.*
18. Rayner, P.J., Enting, I.G., Francey, R.J. and Langenfields, R. (1999) *Tellus,* **51B,** 213-232.
19. Rayner, P.J., Law, R.M. and Dargaville, R. (1999) *Geophys. Res. Lett.,* **26,** 493-496.
20. Sarmiento, J. and Sundquist, E. (1992) *Nature,* **356,** 589-593.

Notation

α_j Coefficient of basis functions $\sigma_j(\mathbf{r},t)$ in expansion of source/sink distribution.

$c(\mathbf{r},t)$ Carbon concentration at location **r** and time *t*.

$G(\mathbf{r},t,\ \mathbf{r}',t')$ Green's function defining the concentration at **r**,*t* due to a delta-function source at **r'**,*t'*.

M_A Amount of carbon in atmosphere.

r Position vector.

R_x The ^{13}C:C ratio of flux from process/reservoir *x*.

s(**r**,*t*) Net source minus sink at location **r** and time *t*.

t time

T [.] Transport operator.

Φ_x^+, Φ_x^- Carbon fluxes to and from the atmosphere from process or reservoir *x*.

$\Phi_x = \Phi_x^+ - \Phi_x^-$ Net carbon fluxes to the atmosphere from process or reservoir *x*.

$\sigma_j(\mathbf{r},t)$ The jth basis funtion used in expanding the source/sink distribution.

CARBON TRACERS FOR OCEAN CIRCULATION

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Both carbon system measurements and derived products can be used in ocean circulation studies to infer water mass transport. In this paper we give a brief overview of the global CO_2 survey effort; then we give a few examples of how carbon data can be used to examine ocean transport. Finally, we discuss the estimates of anthropogenic CO_2 from the global survey and the relation between anthropogenic tracers and ocean circulation.

In the 1990s, several programs, including the Joint Global Ocean Flux Study (JGOFS), the World Ocean Circulation Experiment (WOCE), and NOAA's Ocean-Atmosphere Carbon Exchange Study (OACES), conducted major field campaigns that included water column measurements of at least two inorganic carbon parameters in the major ocean basins. Working with international investigators, we have been striving to synthesize these data into a unified consistent data set. The synthesis effort began with the Indian Ocean (IO). The IO survey marked the culmination of the global CO_2 survey effort. Over 20,000 water samples collected between December 1994 and July 1996 were analyzed for both total dissolved carbon dioxide (TCO_2) and total alkalinity (TA) using coulometric and potentiometric techniques as outlined in the methods handbook prepared by the CO_2 survey science team [DOE, 1994]. Based on the analysis of certified reference materials (CRMs) provided by A. Dickson of Scripps Institution of Oceanography and a post cruise analysis of the data, the accuracy of the TCO_2 and TA measurements was estimated to be ±2 and ±4 μmol kg^{-1}, respectively. These data were combined with the French INDIGO and CIVA 1 results to provide the most comprehensive data set ever assembled for the IO.

Between 1991 and 1996, 24 survey cruises in the Pacific had measurements of at least two carbon parameters. The Pacific Ocean survey involved investigators from 15 different laboratories and 4 countries. On average, carbon samples were analyzed on one third of the total water samples collected on these cruises. TCO_2 was measured on all 24 cruises, but the second carbon parameter varied depending on the carbon group responsible for the cruise. An extensive assessment of the Pacific data quality is described by Lamb *et al.* [2001]. Several approaches aimed at assessing cruise-to-cruise differences in the deep waters were used to help evaluate the data. These approaches involved a range of assumptions, but adjustments were only proposed for cruises where several lines of evidence indicated that an adjustment was necessary. TCO_2 adjustments were proposed for three cruises to give an overall estimated accuracy of 3 μmol kg^{-1}. TA adjustments were proposed for five cruises to give an overall estimated accuracy of 5 μmol kg^{-1}.

The final basin-wide synthesized data sets contain a tremendous amount of information that can be used to infer and diagnose ocean circulation and estimates of ocean transport. For example, a north-south section of potential alkalinity (PA = (TA+nitrate)/salinity*35) looks very similar to a section of $\Delta^{14}C$, a commonly used tracer for deep-water circulation. Low alkalinity values can be seen in the northward moving bottom waters, while the mid-depth flow to the south has much higher alkalinity values because of the accumulation of alkalinity from the dissolution of carbonate particles as the waters age. The potential alkalinity of Pacific bottom waters (where the bottom is deeper than 3500 m) are much lower in the western side of the basin indicating that the northward flowing bottom waters are not zonally homogeneous, but concentrated into a western boundary flow that is somewhat controlled by topography. TCO_2 can also be a useful indicator of ocean circulation. For example, Goyet et al. [1999] showed that the bottom water flowing into the Arabian

Sea through the Owen Fracture zone was easily identified as a local minimum in a zonal section of TCO_2 from the I1 WOCE cruise.

In addition to the identification of deep circulation features, carbon data can be used to identify surface phenomenon. For example, pCO_2 is a very sensitive indicator of upwelling features in the surface ocean. In the Indian Ocean, the Southwest monsoon in the summer months causes intense upwelling off the Arabian Penninsula. This upwelling can be seen as a small temperature anomaly, but if one looks at a T-S diagram from surface waters in the Arabian Sea it is not readily evident which samples are from the upwelled waters because both the upwelled waters and the non-upwelled surface waters generally show a positive correlation between temperature and salinity. pCO_2, on the other hand, exhibits a very strong upwelling signature. The thermodynamic response of CO_2 to increasing temperature is an increase in pCO_2 giving a positive correlation for non-upwelled waters. The upwelled waters, however, have a negative correlation with temperature and the signal to noise is much larger for pCO_2 than for temperature.

One of the principle products of the global CO_2 synthesis effort is an assessment of the global inventories of anthropogenic CO_2. Anthropogenic CO_2 distributions have been estimated from the survey data in the Indian and Pacific using the ΔC^* technique [Gruber et al. 1996; Sabine et al., 1999; Sabine et al., 2001]. Efforts are currently underway to synthesize a collection of 1990s data for the Atlantic. The distribution of time-dependent tracers, like anthropogenic CO_2, can provide valuable information on thermocline ventilation and circulation rates. To a first order, the distribution of anthropogenic CO_2 in the water column is controlled by uptake at the surface and ocean circulation. The deepest penetrations of anthropogenic CO_2 are observed in water mass formation regions like the subpolar North Atlantic and the subtropical convergence zones. Relatively low penetrations are observed in upwelling regions like the equatorial Pacific or much of the high latitude Southern Ocean.

A comparison of different anthropogenic tracers such as bomb C-14, anthropogenic CO_2, and pCFC-12 show very similar large scale distributions because of the strong control of ocean circulation on these tracers. When examined in detail, however, there are real differences in the regional distributions that can be attributed to differing atmospheric histories and equilibration times. These differences can be exploited to gain a better understanding of the short-term ventilation rates within the thermocline.

In conclusion, the global CO_2 synthesis effort is nearly complete. The Indian and Pacific data sets have been compiled and examined for data quality. The Atlantic synthesis is under way. When completed, the global carbon data set will encompass nearly 100,000 unique sample locations. These data can be used in a number of ways to examine transport issues with in the oceans. For more information on the synthesis program visit the Global Ocean Data Analysis Project (GLODAP) at: http://cdiac.esd.ornl.gov/oceans/glodap/

References

DOE, *Handbook of methods for the analysis of the various parameters of the carbon dioxide system in sea water; version 2*, A.G. Dickson and C. Goyet, eds. ORNL/CDIAC-74 Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1994.

Goyet, C., C. Coatanoan, G. Eischeid, T. Amaoka, K. Okuda, R. Healy and S. Tsunogai, Spatial variation of total CO_2 and total alkalinity in the northern Indian Ocean: A novel approach for the quantification of anthropogenic CO_2 in seawater, *J. Mar. Res.*, *57*, 135-163, 1999.

Lamb, M.F., C.L. Sabine, R.A. Feely, R. Wanninkhof, R.M. Key, G.C. Johnson, F.J. Millero, K. Lee, T.-H. Peng, A. Kozyr, J.L. Bullister, D. Greeley, R.H. Byrne, D.W. Chipman, A.G. Dickson, C. Goyet, P.R. Guenther, M. Ishii, K.M. Johnson, C.A. Keeling, T. Ono, K. Shitashima, B. Tilbrook, T. Takahashi, D.W.R. Wallace, Y. W. Watanabe, C. Winn, and C.S. Wong, Internal consistency and synthesis of Pacific Ocean CO_2 survey data, *Deep-Sea Res. II*, in press, 2001.

Sabine, C.L., R.M. Key, K.M. Johnson, F.J. Millero, A. Poisson, J.L. Sarmiento, D.W.R. Wallace and C.D. Winn, Anthropogenic CO_2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, 13, 179-198, 1999.

Sabine, C.L., R.A. Feely, R.M. Key, J. Bullister, F.J. Millero, K. Lee, B. Tilbrook, T. Ono, and C.S. Wong, Anthropogenic CO_2 inventory of the Indian Ocean, *Global Biogeochem. Cycles*, in prep., 2001.

OCEAN FRESHWATER TRANSPORT AND THE CARBON CYCLE

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Rainfall and evaporation require the ocean to transport mass from regions of net precipitation to regions of net evaporation. The magnitude of this freshwater transport in the ocean is of order 0.1-1 Sv. For properties with high mean concentrations relative to their dynamic range (salt, total carbon, alkalinity) transport carried by this freshwater redistribution is a crucial component of the total budget of any region.

A simple scaling argument can demonstrate this effect for nutrient and carbon transports. Suppose we imagine a simple hypothetical circulation for a bounded ocean region. The circulation consists of two components: an overturning transport of strength 20 Sv and a freshwater convergence of 1 Sv which is balanced by net evaporation. For the case of a nutrient, such as silica, the mean concentration in the ocean is about 100 μmol kg^{-1} and the dynamic range is about 200 μmol kg^{-1}. The overturning circulation will thus create a divergence of (200 μmol kg^{-1}) x (20 Sv) $\approx$ 4000 kmols^{-1}. In contrast, the freshwater transport component will only carry (100 μmol kg^{-1}) x (1 Sv) $\approx$ 100 kmols^{-1}. Thus for nutrient, transports, as with heat, the component of the net flux carried by the freshwater transport component is often safely neglected. This example can be compared with that for total carbon for which the mean oceanic value is about 2250 μmol kg^{-1} and the dynamic range is 200 μmol kg^{-1}. Since the mean value is so large, the freshwater transport component results in a convergence of 2250 kmols^{-1} while the overturning component leads to a divergence of 4000 kmols^{-1}. Therefore, unlike nutrients, the freshwater transport component is not negligible in comparison with other components of the regional budget and must be properly accounted for when estimating the net carbon or alkalinity flux.

The magnitude and geographic distribution of the freshwater transport component of the carbon flux can be estimated by examining the net freshwater transport calculated by Wijffels et al., 1992. The subtropics are a region of convergence due to the high evaporation over the subtropical gyres. The tropics and high latitude are regions of divergence as the ocean carries away the net precipitation. The net mass transport through the Bering Strait, Indonesian archipelago, and the Drake Passage complicate the interpretation and comparison of carbon transport estimates carried by the freshwater flux. Much of this confusion can be avoided by focusing on, and reporting, the flux divergence of a region rather than the total meridional flux. Additionally, the crucial scientific questions, air/sea exchange and local accumulation, must be interpreted in terms of the flux divergence rather than the net flux.

Normalization of observed concentrations of total carbon and alkalinity by observed salinity is a common technique when examining property-property relations. This salt normalization factors out the changes of total carbon due to dilution and evaporation allowing the covariation with respect to oxygen and nutrients to be more readily perceived. Some studies (Broecker and Peng, 1992; Keeling and Peng, 1995) have proposed similar salinity normalizations to factor out the effects of the freshwater transport when calculating the total carbon transport. Careful examination of the effect of these normalizations, however, reveals that they fail to accurately account for freshwater flux (Robbins, 2001). An algebraicly correct normalization can be defined but in practice it yields no advantage over the standard technique of direct calculation of the freshwater flux from the salt balance. Firstly, in order for the salinity normalization to yield accurate carbon transport estimates, the circulation must be examined to insure it results in a reasonable salt budget. Secondly, although oceanic freshwater transport often have significant uncertainty, salinity normalizations fail to reduce the impact of these uncertainties on the carbon transport. Since the salinity observed on any individual transect is a synoptic snapshot and not a long term mean, the error incurred on the carbon transport is equivalent regardless of the technique used to account for the freshwater transport component.

References:

Broecker, W.S, and T.-H. Peng, Interhemispheric transport of carbon dioxide by ocean circulation, *Nature*, **356,** 587-589. 1992.

Keeling, R.F. and T.-H. Peng, Transport of heat, CO_2 and O_2 by the Atlantic's thermohaline circulation, *Phil. Trans. R. Soc Lond. B,* **348,** 133-142, 1995.

Robbins, P.E., On the use of salinity normalizations for the calculation of the oceanic transport of carbon and other properties, *J. of Geophysical Res.,* in press.

Wijffels, S.E., R.W. Schmitt, H.L. Bryden and A. Stigebrandt, Transport of freshwater by the oceans, *J. of Physical Oceanography,* **22,** 155-162, 1992.

REGIONAL TESTBEDS:
INTERANNUAL VARIABILITY OF THE OCEANIC CARBON CYCLE AT THE U.S. JGOFS BERMUDA ATLANTIC TIME-SERIES STUDY (BATS) SITE.

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Understanding the relationship between Earth's climate and the oceanic carbon cycle requires an understanding of the time and space scales of variability of CO_2 in the ocean, it's exchange with the atmosphere and the rate of uptake of anthropogenic CO_2 by the ocean. One of the primary components of Joint Global Ocean Flux Study (JGOFS) program has been the long-term ocean observations at both the Bermuda Atlantic Time-series Study (BATS) site in the western North Atlantic and the Hawaii Ocean Time-series (HOT) site in the central North Pacific. Since 1988, hydrographic and biogeochemical data have been collected at both sites, and a large degree of variability of both physical and biogeochemical properties has been demonstrated over seasonal, interannual and decadal time scales (e.g., Michaels and Knap, 1996; Karl, 1997; Bates et al., 1998a,b; Karl et al., 2001a; Steinberg et al., 2001; Bates, 2001).

Long-term time-series studies are ideally suited to the study of slow or subtle processes, rare or irregularly spaced events and complex phenomena, all of which are fundamental to our understanding of biogeochemical cycles in the world ocean (Karl et al., 2001b). Monthly and bimonthly (during the January to April period) field expeditions to the BATS site have provided a relatively unbiased seasonal coverage, a prerequisite for unbiased data return and ecological and biogeochemical interpretations.

Both time-series have captured the time and space domain of key hydrographic, ecological and biogeochemical processes. At BATS, the relaxation of oligotrophy during winter convective mixing leads to a recurrent spring phytoplankton bloom, the magnitude and duration of which varies in relation to atmospheric forcing and entrainment of nutrients into the euphotic zone (e.g., Michaels et al., 1994a; Michaels and Knap, 1996; Steinberg et al., 2001). A major enigma is the recurrent summertime removal of inorganic carbon in the absence of nutrients (Bates et al., 1996). The apparent relaxation of chronic oligotrophy is hypothesized to result from N2 fixing microorganisms (Michaels et al., 1994b; Gruber and Sarmiento, 1997), a process potentially important for all subtropical gyre systems (Karl et al., 1997; Lee et al., 2001). The temporal variability of ocean CO_2 and the exchange of CO_2 with the atmosphere is profoundly influenced by this seasonal ecological phenomena. CO_2 variability and oceanic uptake of CO_2 is also influenced by diurnal to seasonal physical forcing (Bates et al., 1998a, 2000; Bates, 2001), with processes such as hurricanes and short-term wind variability important to the rate of oceanic uptake of CO_2 in the North Atlantic subtropical gyre (Bates et al., 1998a, Bates and Merlivat, 2001). The interpretation of key hydrographic, ecological and biogeochemical processes is also complicated by the presence of mesoscale and sub-mesocale variability. For example, the spatial variability of ocean CO_2 and air-sea CO_2 exchange in the subtropical gyre is much influenced by the presence of mesoscale eddies, and the biological response to the uplift of nutrients and carbon (e.g., McGillicuddy et al., 1999).

Secular Increase in Ocean CO_2

With over a decade of oceanographic data at BATS and HOT, the rate at which the subtropical ocean absorbs anthropogenic CO_2 can be determined. Since secular changes of CO_2 are small relative to natural seasonal and interannual variability, accurate and reproducible long-term observations of CO_2 have been required. Between 1988 and 1998, surface seawater total carbon dioxide (TCO_2) and salinity normalized TCO_2 ($nTCO_2$) increased at a rate of 2.2 ± 6.9 and 1.6 ± 5.8 μmol kg^{-1} yr^{-1}, respectively. During the same period, the partial pressure of CO_2 (pCO_2) of seawater increased at a rate of 1.4 ± 10.7 μatm yr^{-1}, similar to the rate of increase in atmospheric pCO_2 (~1.3 μatm yr^{-1}). The increase in seawater TCO_2 and pCO_2 can be attributed to a combination of uptake of anthropogenic CO_2 from the atmosphere and interannual changes in hydrographic properties of the subtropical gyre.

Interannual Variability

Some of the physical and biogeochemical variability observed at BATS over the last decade is linked to natural large-scale climate patterns such as the El Nino-Southern Oscillation (ENSO) or the North Atlantic

Oscillation (NAO). Establishing the underlying links between these large-scale climate patterns and ocean biogeochemistry will help oceanographers and climate scientists understand anthropogenic change in the context of natural variation.

Interannual trends can be examined by determining how hydrographic and biogeochemical anomalies, or deviations from a mean state, vary over time. Statistical analyses, such as cross-correlation coefficient analysis, can be used to determine whether there are significant correlations between biogeochemical anomalies at the BATS site and natural large-scale climate patterns such as ENSO or NAO. These statistical analyses reveal that upper-ocean temperatures are inversely correlated with parameters such as mixed-layer depth, rates of integrated primary production and total carbon dioxide (TCO_2). For example, during negative (cooler) temperature anomaly periods over the decade, mixed-layer depths were deeper by up to 20 meters; rates of integrated primary production were higher by up to 200 mg $Cm^{-2}d^{-1}$, and TCO_2 concentrations were higher by up to 5µmol kg^{-1}. In contrast, during periods with positive (warmer) temperature anomalies, mixed-layer depths were shallower, and rates of primary production and TCO_2 concentrations were lower.

These anomalies of temperature, salinity, mixed-layer depth, primary production and TCO_2 are correlated with variation in the NAO, a periodic shift in the strengths and positions of sub-polar high and low pressure cells in the North Atlantic and the winds associated with them. The coefficients of variability range from 0.32 to 0.52 (Table 1). The correlation between ocean temperature and salinity anomalies and the NAO in the Sargasso Sea is not a new finding. Many other research groups have found a connection between ocean temperatures and the state of the NAO in this region. During positive NAO periods, the westerlies that usually prevail in the region between Florida and Cape Hatteras west of the Azores High weaken, reducing wind stress and heat exchange and leading to warm ocean temperature anomalies. During negative NAO periods, storm tracks appear to shift southward, cooling surface waters and deepening mixed layers. Only now, with long-term time-series observations, can the connections between ocean biogeochemistry and climate phenomena be adequately demonstrated.

The anomalies of salinity and alkalinity are significantly correlated with each other (Table 1) and also correlated with variation in the Southern Oscillation Index (SOI), a periodic shift in winds and pressure areas in the Pacific that is associated with episodic El Nino and La Nina events. The periods of lower salinity and alkalinity followed El Nino events by approximately six months, while a positive (high) salinity anomaly followed the 1997 La Nina event. The correlations between normalized TCO_2, normalized alkalinity and the SOI suggest that water masses passing through the BATS area change with time. Furthermore, changes may occur in the circulation patterns of the subtropical gyre that contribute to interplay between ocean biogeochemistry and climate variability.

	SOI[2]	NAO	SST	Temp (0-100m)	Salinity	TCO_2	$NTCO_2$	TA	nTA	ML	PP
SO Index [1,2]	-	-	-	-	-	-	-	-	-	-	-
NAO Index[1]	-0.43		-	-	-	-	-	-	-	-	-
Surface Temp. (SST)[1]	0.28	0.40	-	-	-	-	-	-	-	-	-
Temp. (0-100m)[1]	0.35	0.42	-0.66	-	-	-	-	-	-	-	-
Salinity[1]	0.52	-0.48			-	-	-	-	-	-	-
TCO_2[1]		-0.46	-0.54	-0.38	0.44	-	-	-	-	-	-
$nTCO_2$[1]	-0.53		-0.65	-0.45	-0.39	0.64	-	-	-	-	-
Alkalinity (TA)[1]	0.34	-0.52			0.69	0.25		-	-	-	-
nTA[1]	-0.41				-0.37	-0.39	0.38		-	-	-
Mixed Layer (ML)[1]	0.35	-0.32	-0.56	-0.45		0.40	0.49		-	-	-
Primary Prod. (PP)[1]	-0.21	-0.33	-0.51	-0.64		0.35	0.32			0.20	-

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[1] 6 month running mean of anomaly

[2] A lag of 6 months to the SOI Index gives the best correlations between SOI, hydrographic and biogeochemical parameters.

Table 1: Correlation coefficients for hydrographic and biogeochemical anomalies at the BATS sampling site (1988-1998) and large-scale climate patterns, represented by the Southern Oscillation Index (SOI) and the North Atlantic Oscillation (NAO) Index. Coefficients of less than 0.2 were not reported. All figures represent a six-month running mean of the anomaly. A six-month lag with respect to the SOI gives the best correlation between that index and hydrographic and biochemical parameters.

This analysis indicates that NAO and ENSO play a role in modulating interannual biogeochemical variability at BATS. Long-term time-series observations thus provide valuable insight into large-scale ocean variability.

As HOT and BATS continue into a second decade of sampling, the understanding and prediction of how ocean biogeochemistry is influenced by climate variability should continue to improve.

References

Bates, N.R., 2001. Interannual changes of oceanic CO_2 and biogeochemical properties in the Western North Atlantic subtropical gyre. Deep-Sea Research II, 48(8-9), 1507-1528.

Bates, N.R., and Merlivat, L., 2001. The influence of short-term wind variability on air-sea CO_2 exchange. Geophysical Research Letters (in press).

Bates, N.R., Michaels, A.F., and Knap, A.H., 1996. Seasonal and interannual variability of the oceanic carbon dioxide system at the U.S. JGOFS Bermuda Atlantic Time-series Site. Deep-Sea Research II, 43(2-3), 347-383.

Bates, N.R., Takahashi, T., Chipman, D.W., and Knap, A.H., 1998a. Variability of pCO_2 on diel to seasonal timescales in the Sargasso Sea. Journal of Geophysical Research, 103, 15,567-15,585.

Bates, N.R., Knap, A.H., and Michaels, A.F., 1998b. The effect of hurricanes on the local to global air-sea exchange of \nco. Nature, 395, 58-61.

Bates, N.R., Merlivat, L., Beaumont, L., and Pequignet, A.C., 2000. Intercomparison of shipboard and moored buoy pCO_2 measurements: Ground-truthing of the CARIOCA sensor in the Sargasso Sea. Marine Chemistry, 72, 239-255.

Gruber, N., and Sarmiento, 1997. Global patterns of marine nitrogen fixation and denitrification. Global Biogeochemical Cycles, 11, 235-266.

Karl, D.M., 1999. A sea of change: Biogeochemical variability in the North Pacific subtropical gyre. Ecosystems, 2, 181-214.

Karl, D.M., Bidigare, R.R., and Letelier, R.M. 2001. Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: The domain shift hypothesis. Deep-Sea Research II, 48, 1449-1470.

Karl, D., Letelier, R., Tupas, L., Dore, J., Christian, J., and Hebel, D. 1997. The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean. Nature 388, 533-538.

Karl, D.M., Dore, J.E., Michaels, A.F., and Bates, N.R., 2001. The U.S. JGOFS Time-series Observation Programs. Oceanography (in press).

Lee, K., Karl, D.M., Zhang, J-Z., Wanninkhof, R., 2001. Carbon export in the nitrate-depleted tropical and subtropical oceans: Implications for marine nitrogen fixation. Geophysical Research Letters (submitted).

McGillicuddy, D.J., Johnson, R.J., Siegel, D.A., Michaels, A.F., Bates, N.R., and Knap, A.H., 1999. Mesoscale variations of biogeochemical properties in the Sargasso Sea. Journal of Geophysical Research, 104, 13,381-13,394.

Michaels, A.F., and Knap, A.H., 1996. Overview of the U.S. JGOFS Bermuda Atlantic Time-series Study and Hydrostation S program. Deep-Sea Research II, 43, 157-198.

Michaels, A.F., Knap, A.H., Dow, R.L., Gundersen, K., Johnson, R.J., Sorensen, J., Close, A., Knauer, G.A., Lohrenz, S.E., Asper, V.A., Tuel, M., and Bidigare, R.R., 1994a. Seasonal patterns of ocean biogeochemistry at the U.S. JGOFS Bermuda Atlantic Time-series Study site. Deep-sea Research, 41, 1013-1038.

Michaels, A.F., Bates, N.R., Buesseler, K.O., Carlson, C.A., and Knap, A., 1994b. Carbon system imbalances in the Sargasso Sea. Nature, 372, 537-540.

Steinberg, D.K, Carlson, C.A., Bates, N.R., Johnson, R.J., Michaels, A.F., and Knap, A.H., 2001. The U.S. JGOFS Bermuda Atlantic Time-series Study: A decade-scale look at ocean biology and biogeochemistry. Deep-Sea Research II, 48(8-9), 1405-1447.

WORKING GROUP REPORTS

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

Focus on the interation/intersection of circulation and biogeochemistry

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

Report from the Working Group on Carbon and Nutrient Transport.

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

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

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

During WOCE/JGOFS there was a wider range of participants (including both international and interdisciplinary collaborations) than has ever been achieved previously. These collaborations have meant great strides have been made in making biogeochemical transport estimates and in the application of these estimates to air/sea flux and budget studies. There have also been advances in separating biogeochemical tracers into components which represent different processes.

There has been tremendous improvement made in modeling the ocean circulation and in combining model physics with observed datasets.

II. What crucial problems remain?

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

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

There needs to be improvement still in model physics (we are thinking here particularly in terms of inverse models), the combining of data from different sources (floats, altimetry, current meters (we are not necessarily speaking of assimilation) and better use of available tracers in inverse models (C13, C14, DIC, H3, He3, SF6, CFCs and nutrients). There remains a need for collaboration between biogeochemical experts and those performing inverse studies to make this happen.

Work remains to be done in causing the advances made in understanding the Atlantic circulation system to also be made, to the same degree in the Indian, Pacific, Southern Ocean and Arctic Basins.

Although access to datasets was greatly improved during WOCE/JGOFS, the situation must continue to improve, as it is still not necessarily a simple task to obtain datasets and to obtain them in a format which is straight forward to use. These comments apply particularly to DIC, DOC, alkalinity, CFC's, C14 etc.

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

Specific topics which need further study:

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

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

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

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

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

There is now a need to resolve nutrient variability (inventory transport) which requires continued observation. There is a need for long time-series surveys (including but not exclusively long-line repeat transects) to address variability in many properties, in particular anthropogenic carbon. Regionally such surveys should resolve annual, as well as interannual variations. Fine resolution, regional model simulations could be used to improve experiment design and use of resources (in the spirit of the coarse resolution adjoint sensitivity studies presented this week by Detlef Stammer).

Throughout the last decade advances have been made in coupled ocean/atmosphere modeling. The next ten years should also address improvements in coupled atmosphere/ocean biogeochemical modeling. Along this same line, we see the need to develop more metrics for testing biogeochemical models.

Another question which was brought up and which should be answered quantitatively is how well can models predict changes in CO2 in the next ten years and can we measure that change in the ocean? The latter requires a physical and biogeochemical study of uncertainties in the carbon budget.

V. Where do we go from here?

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

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

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

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

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

Report from the Working Group on Regional Budgets and Variability.

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The working group met to discuss and list 1) the important biogeochemical advances made over the last decade as a part of the JGOFS/WOCE efforts, 2) the remaining problems, 3) future strategies, 4) opportunities for linking biogeochemical and hydrographic studies, and 5) impacts of hydrographic knowledge and uncertainties on understanding of biogeochemical processes. The working group recognized that it could not be exhaustive in its considerations, but sought instead to gain insights from some of the major successes to date. A sample list (Table 1) of the locations and types of budgets providing significant advances demonstrates the important role of data from the JGOFS process and time series stations, as well as the WOCE sections, to those budgets. The equatorial Pacific and the Southern Ocean, both of which have received particularly strong attention internationally, have perhaps the best coverage for spatially and temporally resolved budgets. Basin and global budgets are developing, and will continue to do so, with ongoing use of the WOCE section data.

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

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

Table 1:

I. Important biogeochemical advances/discoveries during WOCE/JGOFS?

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

1. The importance and role of iron in ocean biogeochemistry was identified.
2. The modulation of air/sea gas exchange in the Equatorial Pacific as controlled by ENSO was elucidated.
3. During WOCE, many transoceanic sections were occupied on which a full suite of biogeochemical measurements were collected simultaneously with high quality physical measurements such as temperature, salinity and velocity. These unique datasets are allowing the first attempts at using mass balanced circulation budgets to quantify large-scale biogeochemical flux divergences.
4. The paradigm of elemental cycles has been challenged, particularly with regard to dissolved organic matter (DOM).
5. The improved spatial and temporal resolution in the measurement of delta pCO_2 has advanced our understanding of the location and strength of the air/sea exchange of CO_2. Advances have come about largely as a result of improved air/sea gas exchange parameterizations.
6. The role of nitrogen fixation in marine elemental cycles has been re-evaluated (*e.g.* N* issues).
7. One of the most important advances to come out of WOCE/JGOFS is the estimation of anthropogenic CO_2 inventories and distributions. Geochemical rate estimates have resulted from the large scale mapping of nutrients and tracers.
8. During the intensive regional studies of JGOFS scientists have begun to observe and understand the links between variability in biogeochemical fluxes and cycles and variability in the physical system.
9. Food web variability, in response to forcing, impacts carbon dynamics (*e.g.* monsoons, stability and iron in the Southern Ocean, the nitrogen cycle at Station ALOHA).
10. Biogeochemical budgets vary in response to decadal forcing (*e.g.* ENSO)

II. Crucial Remaining Problems?

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

1. There are few measures of variability in carbon budgets beyond the equatorial Pacific region and the time-series sites. Improved carbon budgets are required in the Southern Ocean (all oceans?). Moreover, the fate of river carbon (DIC, organic matter) discharges remains largely unknown. Anthropogenic carbon algorithms need validation/improvement.

2. Very few measurements were made of dissolved organic matter (C, N, P) or trace metals on the WOCE sections. As such, we have only a superficial idea of the role of these variables in ocean biogeochemistry.
3. Bulk parameterizations of mixing, air/sea gas exchange and wind stress have improved but require further and substantial refinement.
4. Most of the WOCE sections were not suited to the study of exchanges between the coastal and open ocean. In addition, time series sites and process studies were isolated from the large-scale WOCE survey lines. Hence, there is a gap in our knowledge of the processes governing margin to open ocean interaction. Focused regional studies are needed with a coordinated suite of measurements to address the link between local and large scale processes.
5. How can we detect the changes/variability in biogeochemical processes that are due to climate change? This problem remains a central challenge.
6. Standard biogeochemical reference materials are not available (they exist for carbon, i.e. DIC & DOC, but not for others such as nutrients and metals). We need to establish standards to ensure that in the future variables are measured in a consistent way, and thereby making the measurements from various laboratories directly comparable. (Note: the U.S. National Research Council has formed a committee to address this issue. They will meet in Florida, September 10-12, 2001).
7. With the new ARGO program there is an opportunity to greatly increase the number of biogeochemical measurements. However, to take advantage of the float array, rapid technological advances are required in the development of sensors for autonomous deployments.

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

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

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

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

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

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

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

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

Conclusion of the Working Group

Every effort should be made to bring the physical and biogeochemical groups together early, before field studies are planned and conducted, to identify the questions that can be supported and answered together. The biogeochemical community should not continue the trend of asking for support from the physicists after the fact. Questions should be phrased to take advantage of the capabilities of both physicists and biogeochemists. It is beneficial to both groups, regarding rationale and achievements, to work in a coordinated way.

Report from the Working Group on Model Development and Data Assimilation

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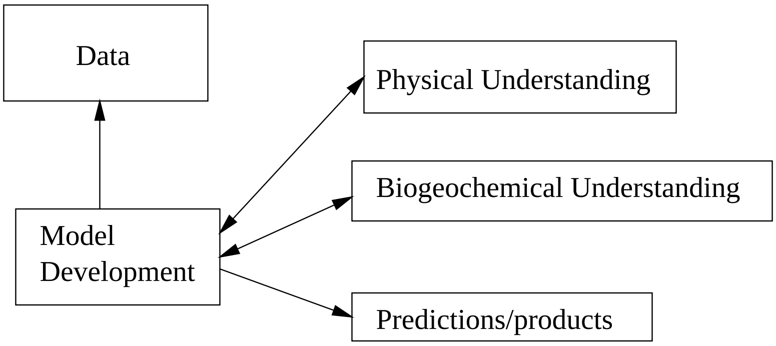
This working group was tasked with evaluating achievements during WOCE and JGOFS and opportunities for future research in the area of model development and data assimilation. The panel focussed its discussions around the schematic shown in Figure 1, indicating that model development depends on increasing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



Products

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

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

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

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

- Radiatively active gasses: **Can we monitor/predict variability of CO_2 fluxes and trace gas production on basin scales?** This will become increasingly relevant as the world moves towards a control regime for greenhouse gasses.

- Climate variability: **Can we monitor/predict coupled modes of climate variability (both physical climate and ecosystems on decadal-centennial scales?** This is also of great relevance to a number of resource management issues around the globe.

Physical understanding:

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

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

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

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

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

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

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

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

Biogeochemical understanding

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

Key opportunities, challenges: Although preliminary syntheses have been done, there is still much work to be done in extending these results to the regional scale. The coastal ocean remains a challenge as well.How the coastal and deep ocean connect biogeochemically is not well understood. A key question for future modeling is **what determines how nutrients from the surface remineralize at depth**, a question which will be at the heart of the proposed OCTET program.

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

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

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

Key opportunities, challenges: What are the fundamental processes (physical, chemical biological) that set stochiometric ratios? **How does the interplay among functional groups affect important biogeochemical budgets (Alk, N, Fe, Si)?** This question could be a key one for the proposed EDOCC program.

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

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

Data

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

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

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

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

Carbon uptake: Data-based estimates of anthropogenic carbon uptake were developed by several groups during WOCE and JGOFS using the high-quality dataset as a

Variability: The JGOFS time series stations, satellite measurements of ocean color, atmospheric measurements of oxygen and carbon isotopes all revealed that significant changes in global biogeochemical cycles occur on interannual to interdecadal time scales. The WOCE dataset shows variability in water mass formation and in heat transport on the same time scales.

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

Model development

Community models: One of the great successes during the WOCE/JGOFS period was the development of community models which enabled numerous groups around the world to begin realistic simulations of ocean circulation without having to start from scratch. Examples include the Regional Ocean Modeling System (ROMS), the Miami Isopycnic Coordinate Model (MICOM) and the Modular Ocean Model (MOM).

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

New classes and uses of models: The WOCE/JGOFS era saw a blossoming of the use of inverse models using multiple data sources and adjoint techniques for data assimilation. Global high-resolution models (POP, OCCAM) were run and analyzed in detail. Multiple groups around the world began to use general circulation models to simulate the carbon cycle. One-dimensional testbeds were developed for biogeochemical modeling, providing groups with a solid framework within which to test ideas about biogeochemical cycles.

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

Model numerics: One of the main accomplishments of the WOCE/JGOFS period was to bring to the fore the issue of model numerics as a determiner of the solutions produced by numerical models. The DYNAMO intercomparison project was particularly important in this regard. There is now a widespread recognition that the details of advection schemes, vertical coordinate system, entrainment, and lateral diffusion schemes can play a major role in model solutions- especially as regards diapycnal fluxes which are vitally important for biogeochemical applications.

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

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