World Ocean Circulation Experiment

NEWSLETTER

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Features

The Newsletter

This issue of the WOCE Newsletter focuses attention on the role of models in various aspects of WOCE and ocean research in general. This is certainly not inappropriate considering that the primary stated goal of WOCE is to develop models useful for predicting climate change (and to collect the data to test them). The many roles of models in WOCE have only been touched upon in these articles and much remains to be addressed in future issues of the Newsletter.

Most of the articles in the initial issues of the Newsletter have been solicited by the WOCE-IPO. It is however our desire that those interested in WOCE will start to volunteer articles to the Newsletter and freely put forward their ideas regarding the great variety of issues of vital importance to WOCE. These include the use of satellite data for surface-flux measurements; the role of floats; the weight to be put on various types of measurements if one wishes to measure, for example, the heat flux; the identification of those processes which truly need to be studied if one is to develop models of decadal climate change; issues of data control, management, storage and availability; etc.; etc. Several of the articles in this newsletter do indeed address issues like those just mentioned, (see, for example, the article by Joyce). All readers of the Newsletter are encouraged to make it both relevant and stimulating through their contributions.

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Editor: Denise Smythe-Wright

Eddies and the Thermohaline Circulation

How important are mesoscale eddies in the heat balance of the World Ocean? This is a question of particular relevance to WOCE. Synoptic scale motions in the atmosphere play a dominant role in poleward heat transport in the midlatitudes. Mesoscale eddies in the ocean are the dynamic equivalent of synoptic scale disturbances in the atmosphere. A priori reasoning would suggest that mesoscale eddies would be important in the poleward heat transport in those regions where they are very energetic. Model results suggest that the situation is much more complicated. Although the model results can provide new insights on ocean processes, definite answers will have to await the analysis of data sets produced by WOCE. The purpose of this note is to generate interest in the problem of heat transport by eddies in hopes that more effort will go into designing WOCE data sets that will provide the needed quantitative information.

There are two model studies that are particularly useful for examining the preliminary heat transport by mesoscale eddies. One was carried out by Semtner and Mintz (1977), with a further analysis by Mintz (1979). The other is a much more complete calculation recently carried out by Cox (1985). In both cases, mesoscale eddies are included in a model that also allows for a thermohaline circulation. Neither study is ideal for examining heat transport questions because heat and salinity are rot included explicitly. The model results only allow statements about buoyancy transport, and the contribution of mesoscale eddies to buoyancy transport. The results would apply to the real ocean in cases for which heat and buoyancy are well correlated. However, there are many interesting cases in which heat and buoyancy are not well correlated, e.g., the polar haloclines and warm core rings.

In both the Semtner and Mintz model and that of Cox, the surface buoyancy flux is proportional to the difference between surface buoyancy and a prescribed reference buoyancy which decreases linearly with latitude. The wind stress imposed at the surface is a zonally invariant idealization of the observed stress due to the easterlies and westerlies.

The Cox (1985) calculation is for a nearly rectangular ocean basin, extending from the equator poleward to 65° of longitude. An equilibrium solution corresponding to a model of 1° latitude and 1° longitude is obtained by extended integration. This solution is interpolated to a high resolution grid of 1/3° x 1/3° latitude and longitude resolution, and the integration with respect to time is resumed. The high resolution calculation is extended for the equivalent of 16 years. This is not long enough for a complete new equilibrium to be achieved, but analysis of the kinetic energy patterns in the upper ocean indicates convergence. The poleward buoyancy transport divergence agrees with the surface flux, indicating a reasonable adjustment of the density field. Buoyancy transport for the high and low resolution cases is compared in Figure 1.

The ordinate is labelled heat transport, but remember that heat and buoyancy transport are equivalent in this simple model. The low resolution model does not allow mesoscale eddies. Transport by the time-varying motions in the high resolution case is predominantly toward the equator. More detailed analysis (not shown) indicates that this equatorward flux in the subtropical gyre is due to baroclinically unstable waves in the westward flow of the type envisioned by Gill, Green and Simmons (1974). Since the thermocline tilts upward towards the equator, down-gradient flux is towards the equator rather than towards the pole.

Note that the augmentation of the transport by the time-averaged flow in the high resolution case is poleward in the same latitude range. As a final result the total poleward buoyancy flux is nearly the same in both the eddy resolving and the non-eddy resolving case! It turns out that the augmentation

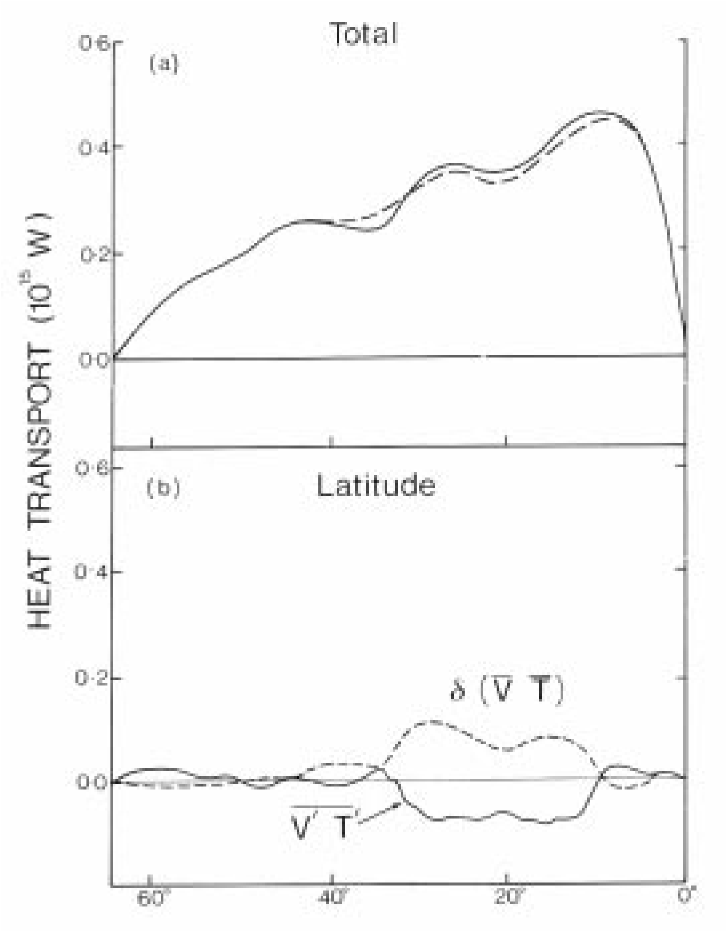

Fig. 1 (a) Total time-averaged buoyancy transport from Cox's (1985) model - the eddy resolving model (solid) and the coarse resolution, non eddy resolving model (dashed). (b) Heat flux due to transient fluctuations (solid) and the enhanced transport by time-averaged motions in the eddy resolving model.

to the poleward buoyancy (or heat) transport by time-averaged motions is also wave-induced. This transport is caused by a meridional cell which has an upper poleward moving branch and a southward return flow in the main thermocline. Taking into account that the thermocline slopes upward toward the equator, the induced circulation by the eddies is thermally indirect. In this sense it is like the Ferrel cell in the atmosphere, as suggested by Mintz (1979) . Unlike the Ferrel cell, however, the overturning can be geostrophically balanced due to the existence of meridional walls at the boundaries. This discussion has focused on the Cox (1985) model. Although it has not been possible to analyze the Semtner and Mintz model in precisely the same way, the published results appear consistent.

What is the physics behind these apparently complex buoyancy transport

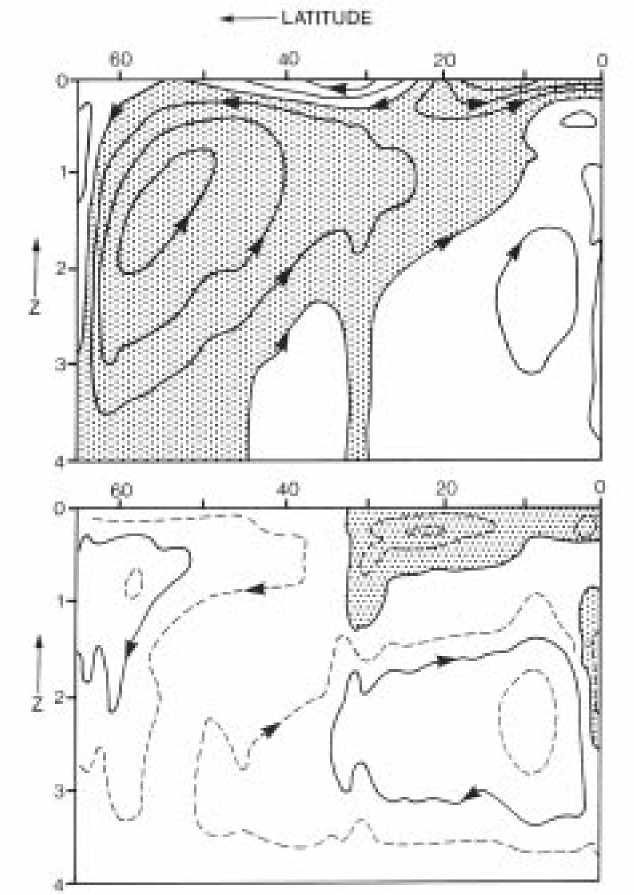

Fig. 2 (a) The total time-averaged mass transport in the meridional-depth plane in Cox's (1985) model. (b) the enhanced circulation due to high resolution and the existence of eddies. Note the shallow counterclockwise cell in the subtropical gyre.

signatures? In the model, density tends to be conserved along the trajectories associated with the mesoscale waves. Consider the linear case with a horizontally uniform buoyancy gradient in the y and z directions. The perturbation buoyancy can be expressed in terms of displacements, Y' and Z',

$$B' = -Z'\delta_z B_o - Y'\delta_y B_o \qquad (1)$$

multiplying by v′ and averaging with respect to time,

$$v'B' = -v'Z' \, \delta_z B_o \qquad (2)$$

Imagine a train of baroclinic eddies in the westward flow on the equatorward flank of the subtropical gyre. The trajectory of a particle conserving buoyancy would be a spiral around the x-axis. Looking downstream (westward) the loops would be clockwise, transporting light, buoyant surface waters poleward, and heavier deeper water toward the equator. In the ideal density conserving case this transport is exactly compensated by the v′B′ correlation.

The idealized model described above shows the conceptual difficulty of designating the transport due to time varying motions the “eddy” transport. This terminology neglects wave-induced, time-averaged flows which are also associated with mesoscale eddies. If field measurements of the transport of heat and tracers by mesoscale eddies is attempted, the experiments should be designed to measure both components of transport, that part due to time-varying motion and that part due to wave-induced time-averaged flows. Much of the complexity is artificial, in that it is caused by viewing transport in a Eulerian framework. Transport by mesoscale eddies would be measured much more easily by Lagrangian instruments that would stay within a given density range. Drifters of this type are now under development at Woods Hole.

Returning to the question posed initially concerning the role of mesoscale eddies in the global heat balance, the models suggest that an analogy with atmospheric synoptic systems is not appropriate. The store of available potential energy in the ocean’s thermocline is primarily due to wind stress, rather than due to differential heating. Thus, the large scale available potential energy field can be depleted by baroclinic instability, and subsequently regenerated by nearly adiabatic processes. If buoyancy is conserved along trajectories, no net transport takes place. The importance of mesoscale eddies in most parts of the ocean appears to be their dynamic effect or the ocean circulation, and thus an indirect effect on heat transport.

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The Main Stream of Climate Modelling Research

This article discusses WOCE from a historical perspective. It shows it lies in the main stream of climate modelling research.

The idea of mathematically modelling the planetary climate system, on the basis of the laws of physics, taking account of the geographical variation, was first worked out in detail by L.F. Richardson (1922). He pioneered numerical integration of the prognostic equations, and so started the main stream of climate modelling research. He was concerned primarily with weather prediction, but included in his book a far-sighted chapter that contemplated numerical integration of the equations of the ocean. It is worth recalling two sentences in that chapter. After outlining the main physical principles, Richardson continues:

"Presumably these five principles could be put into a scheme of prediction such as has been worked out for the atmosphere in this book. It may come to that, but lets hope that something simpler will suffice."

His hopes were justified for weather forecasting: something simpler does suffice, at least for time scales of up to a week. But when one contemplates forecasting atmospheric changes on longer time scales it soon becomes clear that more aspects of the ocean must be treated explicitly. While the time scale remains fairly short, say one month, it will still be possible to make substantial simplifications, but as it increases beyond one year some of them become invalid, and it becomes difficult (given our present knowledge of the ocean) to decide what has to be included in the model and what can safely be left out. Broadly, one expects that more and more aspects of the ocean will have to be included as the forecast extends to longer time scales, but we have no simple criterion for deciding where the boundary lies. Ultimately it will have to be discovered from sensitivity studies with comprehensive coupled ocean-atmosphere global circulation models, but that step is for the next century.

In view of this uncertainty, the Scientific Plan for WOCE is based on the assumption that no region or layer of the World Ocean can be ignored, even though some have suggested that it would be appropriate to give lower priority to the deep ocean or to polar seas or to peripheral basins such as the Mediterranean. This strategy differs from that of TOGA, which assumes a priori that much of the interannual variability of global climate can be predicted by modelling the circulations of the global atmosphere and the upper levels of the tropical ocean. That approach was judged to be inappropriate for WOCE, where the emphasis is on learning enough about the ocean circulation to incorporate it (as a whole, if necessary) in models designed to forecast climate changes up to 100 years ahead.

Given that philosophy, we can now relate WOCE to the mainstream of climate modelling research. Ever since Richardson attempted to predict the weather by numerical integration of model equations, the limiting factor has been computing power. He contemplated global model integrations by hand, using an orchestrated team of computers (in those days the word was used for people who did sums), each of whom might have been capable of, say, one floating point operation per minute. The arrival of electronic computers enormously increased the speed of calculation, and today climate models run on computers that perform millions of floating point operations per second. In 1970, Mason drew attention to the fact that computer power was increasing by an order of magnitude every 6 years (Fig. 1).

Fifteen years later, we have computers that can perform even better than predicted by Mason's extrapolation. Machines now being developed promise to maintain the trend, so we can confidently extrapolate the same curve for another fifteen years. Actually, the advance in effective computer power is going even faster, thanks to improved architecture. Even if the curve begins to flatten in the next decade or so, it seems inevitable that early in the next century

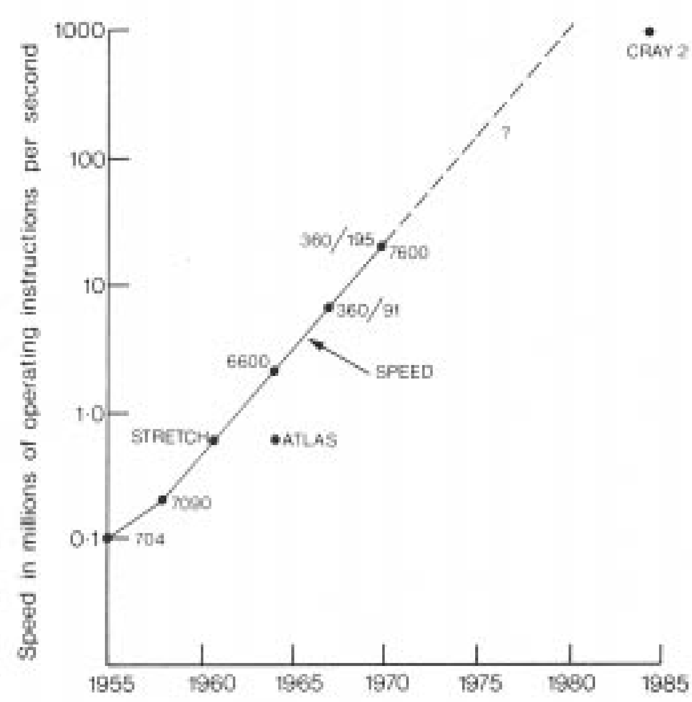

Fig. 1 Increasing computer power, 1955-1970, from B.J. Mason (1970, Quart. J. R. Met. Soc. 96, 349-368). Changes in computer architecture, since 1970 have also enhanced the precision and complexity of calculations performed in each million operating instructions per second. For the 1980s, a revised trend line expressed in Megaflops (million of floating point operations per second), would pass through the Cray-2 point and continue to increase logarithmically at a factor of about ten every six years. In terms of effective computing power, that new line is ahead of Mason’s extrapolation.

there will be supercomputers that are one thousand times more powerful than the Cray-XMP used today to make weather forecasts at the European Centre.

Climate modellers have been successful in acquiring state of the art computers, and have used them to their limits. So Mason’s trend line is the “World Line” of climate modelling. It is instructive to plot some of the major events in the history of climate modelling and observation on the World Line (Fig. 2).

Recent experience suggests that accurate climate prediction for decades ahead will depend on resolving oceanic eddies globally. That will require a computer one thousand times more powerful that the Cray-XMP, so we place it at the turn of the century. WOCE is being designed to provide the data needed to Support development of much a model. It will take at least five years to complete the fieldwork. Assuming a 1990 start for the intensive phase, that carries us to 1995, leaving just five years for data analysis before global eddy-resolving models become the norm. WOCE is

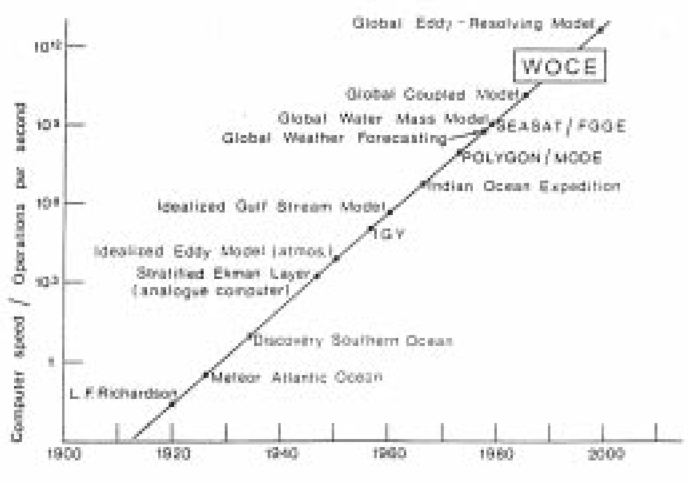

Fig. 2 Some major landmarks in the history of climate modelling plotted on Mason’s World Line. On this perspective WOCE is seen to lie in the main stream of climate prediction research. The experiment will be performed just in time to provide data to test global eddy-resolving models of the ocean, which will become possible at the end of the century.

seen to lie in the main stream of climate research. Its timing is commensurate with that of FGGE, given the imminent development of global weather forecasting models when that experiment was being planned. Indeed, we see that any delay in undertaking WOCE will mean that climatologists will be starved of data to test their new models at the start of the next century. WOCE is not only timely, but urgent.

The World Line also helps to explain one of the key ideas underlying the design of WOCE. That is to give priority to observations that will help to resolve issues confronting ocean circulation modellers in 2000 AD, when many of their present problems have been solved by increased spatial resolution. Atmospheric modelling experience in the 1970’s showed the benefits of increasing resolution, but experience in the 1980's has shown that a plateau is eventually reached; further advance then depends on improving the parameterization of unresolvable processes. Ocean modellers have not yet reached that plateau, but will be approaching it fifteen years from now.

The highest priority will be to collect a global data set that can be used to obtain an accurate and unambiguous description of the global circulation of the ocean, as a basis for testing the models and suggesting ways of remedying deficiencies so revealed. Special emphasis must be given to the global distribution of eddy energy. But that will not be sufficient. The effects of inadequate parameterization of processes that will never be resolved in global models are already beginning to be felt, and are likely to become relatively more important in the future. For example, predication of the transient climate response to CO_2 pollution is sensitive to the method of parameterizing oceanic boundary layer processes. The Scientific Plan for WOCE is designed to achieve a balance between these anticipated problems of parameterization and the perennial problem of achieving an accurate description of the global circulation of heat, fresh water and chemicals.

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An Ocean Community Model

At the recent meeting of the WOCE Numerical Modelling Group (Oct.'85), results were presented from a number of GCM'S's, forced with the same forcing fields and for the same geometry and topography of the Atlantic basin. It was apparent that the low resolution of these models (2 degrees latitude and longitude) was causing undesirable numerical features in the solutions.

Results from the high resolution model of Cox (l/3 degree) also indicated that resolution remained a problem. This latter model, which used a simplified basin configuration, required about 240 hours of CYBER 205 time to integrate 24 years. Although this latter high resolution experiment was carried out by one individual, the model output has been widely distributed for analysis by interested parties.

To increase the domain of interest of this latter model to encompass the Atlantic and to increase the resolution to better resolve the eddies would require computation and commitment beyond the resources of any one individual. This raises the question of whether such an experiment could be carried out collectively. This was the question considered by WOCE-NEG. The purpose of this note is to find out what general interest there is in the community for such an undertaking and to solicit ideas from modellers, theoreticians, and experimentalists on what the community experiments should be. In order to focus interest, we give our views on a possible experiment, as well as a suggestion as to how the community effort could be organized. The time may be right for undertaking such a project - there are a number of super computer centres coming into operation which, initially at least, may be undersubscribed. In addition, newer computers are coming on line that are considerably more powerful than the CYBER 205. With the advent of a major experiment such as WOCE, now is the time to lift bureaucracy's perception of ocean/climate modellers' needs.

To give some idea of the resources needed we outline one possible experiment. Although this was the experiment which prompted the community model idea, it is in no way sacrosanct if better ideas come forward.

A model integration could be carried cut with 1/6 degree horizontal resolution and 30 levels in the vertical, extending from, a northern latitude, possibly 68°N or 70°N, to 30°S. The geometry and topography of the Atlantic basin would be included. The model would be forced by the seasonally varying wind stress and by some yet to be determined choice of surface temperature and salinity boundary conditions. Such a calculation would require approximately 100 hours CYBER 205 time per year of simulation, so it can clearly not be run completely to equilibrium at this resolution. Therefore, initially the model would be integrated with low resolution, this being increased progressively until the 1/6 degree resolution is achieved. This approach has been widely used by Bryan and Cox and would allow some approximate equilibrium to be achieved.

Many questions and issues remain to be discussed and decisions made if such an experiment is to be carried out. For instance, how should the surface flux condition be handled and how should the southern ocean boundary be included? In what sequence should the coarse to fine integration procedure be carried out? These issues (and many others) would have to be resolved. This would be the task of a community model team that not only would contribute to the design of the experiment but would actually participate in the running and analysis of results. The method of operation, running the model, preparing output tapes and developing analysis software would require the commitment of at least two postdocs, or a postdoc and advanced programmer, more or less full time. They would be responsible for setting up the model, its day-to-day running and general supervision. The experiment would be formulated collectively by a group of interested (international) scientists. At regular intervals this group would meet to discuss progress and to examine results. Much of the preparation of analysis would be done at the host computer centre, but some subset of the model output could be taken by individuals for home analysis.

This ambitious modelling effort contributes directly to the WOCE Core Project 3 - the Gyre Dynamics Experiment. It would provide a calculation of unprecedented resolution with sufficient detail to include eddy effects as well as to accurately define the basin geometry and topography. Although such an experiment cannot hope to solve all of the numerical problems and limitations of earlier work, it will hopefully focus WOCE modelling activities upon the scientific and numerical modelling issues facing the community.

Anyone with ideas or comments should contact W. Holland at NCAR by letter or telemail. We hope to have some measure of public interest and an outline proposal for consideration by the meeting of the international WOCE SSG in April.

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Report on the WOCE/TOGA Workshop on Inverse Modelling and Data Assimilation Miami, USA, April 16-18 1985

Introduction

Both WOCE and TOGA will involve the collection and utilization of data sets of substantial (and unprecedented) size and complexity. An important issue for both experiments is how to best use these data to achieve programme objectives.

One objective of TOGA is to determine the extent to which the climate system is predictable on time scales of months to years for which the memory of the system does not lie in the atmosphere hut in the ocean (and possibly to a lesser extent in other slowly evolving surface boundary conditions). A successful climate forecast is therefore dependent on a good analysis of the ocean state. Since current data will never be plentiful enough to allow an adequate description, it must be augmented by previous data and the dynamical constraints controlling the ocean system. One way of achieving this is via data assimilation into numerical models (for TOGA, primitive equation GCM, models).

For WOCE, the objective is to assemble a global-scale data set suitable for the testing and verification of numerical models and dynamical hypotheses of the large-scale ocean circulation. Here, the techniques of inverse modelling, as well as data assimilation into oceanic general circulation models, will be important. Inverse methods can relate available observations to a specified model framework and can be used to study experimental design (for example, to optimize the individual components comprising the observing system), and to estimate and characterize error sources. Inverse models have not yet been applied to the full dynamical problem, but have been used to infer the ocean circulation (and its transport of heat, CO_2 and other tracers) from a finite number of observational and dynamical constraints. On 16-18 April, 1985, a workshop was held at the Rosenstiel School of Marine and Atmospheric Science in Miami, FL, USA to review recent activities and progress in the areas of data assimilation and inverse modelling.

Overviews were presented on inverse modelling (Wunsch) and assimilation as used in meteorology (Lorenc). Shorter lectures were contributed by scientists currently active in these areas.

Abstracts summarizing these presentations are available from WOCE-IPO.

Inverse Modelling

Wunsch introduced inverse, modelling, and related it to the substantial issue of WOCE experimental design. In general, inverse methods are systematic procedures for relating realistic observations to a model framework. In particular, according to Wunsch, a true inverse method must provide: (a) an estimate of the statistical uncertainty of the computed parameters; (b) an estimate of the resolution or the computed parameters, that is, those which are well-determined; (c) a procedure for distinguishing random error from model error; and (d) a ranking of data in order of importance to the solution. As an example, an attempt to identify optimal design criteria for the determination of meridional heat flux in the tropical ocean was described. For this WOCE observational goal, the inverse analysis suggests the importance of a better knowledge of internal tracer distributions.

Bigg described the use of the Cox and Bryan wind-driven ventilated thermocline model as a “test bed” for the beta spiral and simple box inverse methods, with the goal of checking the velocity fields provided by the inverse analysis. The beta spiral method, modified to include turbulent diffusion, was shown to work well, given adequate vertical resolution. Application of the inverse model to ocean data was less successful, presumably as a result of inadequate vertical resolution and the uncertainty in how to represent oceanic diffusion processes.

Provost described a variational inverse modelling scheme for determining the three-dimensional mean flow field in the ocean. The technique seeks the smoothest velocity field which is consistent with the data and with selected dynamical constraints within certain prescribed limits. By varying the limits, and the chosen measure of smoothness, one can assess the quality of the imposed constraints, and their impact on flow properties such as meridional heat transport. Applications to the Labrador Sea and the Central North Atlantic were presented.

Cornuelle introduced the use of an approximate Kalman filter for relating available data to a proposed dynamical model, and for estimating model likelihood. Simplifying the Kalman algorithm (by diagonalizing the associated covariarce matrix) gives a numerically efficient analysis procedure. A simple example was given which represented the ocean as a truncated set of Fourier modes in the horizontal, and the barotropic and first baroclinic quasi-geostrophic (QG) modes in the vertical; linearised QG dynamics were assumed. Model estimates using densely sampled CTD casts show the filter estimates to be in good agreement with the observed fields over three weeks.

Schroter studied the effects of uncertainties (for example, observational errors) in the forcing fields on the steady state solution of an ocean circulation model. A non-linear optimization method was described which can choose among the set of solutions which obey the dynamic model while fitting the forcing within prescribed bounds. The non-linear programming method allows for the maximization or minimization of any linear or non-linear diagnostic function that can be computed from the circulation model; thus, providing a powerful tool for exploring observational strategies. To demonstrate the method its application to two simple finite-difference models of the wind-driven ocean circulation was described.

Mercier considered inverse methods for determining the absolute velocity in the ocean while taking into account uncertainties in the density field. A formalism was described by which the resulting non-linear problem can be solved. An application of the method to the circulation in the western North Atlantic is underway.

Fiadeiro described studies of inverse procedures using multiple tracer fields, and tracers with dynamical constraints, to determine the ocean circulation. The studies used the fields predicted by a simple model as “truth” in order to distinguish inadequacies in the model and the data from errors arising from the inversion procedure itself. Using the condition number of the resulting matrix inverse problem as a measure of the quality of the inverse solution, the effects of multiple tracers and truncation errors were addressed.

Moore addressed a new generation of box models that are being used to study problems such as CO_2 uptake by the oceans, and as diagnostic tools for general circulation models of the ocean. A detailed description was given of an eighty-four box model of the Atlantic Ocean that is characterized by a total of 540 unknowns, representing advective and turbulent exchange between boxes, and formation/decomposition rates for organic and inorganic dissolved material. A constrained inverse procedure is used to solve the overdetermined system.

Data Assimilation

A review of data assimilation and objective analysis from the meteorological perspective was presented by Lorenc. Several methods of data assimilation were described including: continuous data insertion, intermittent data assimilation, and Kalman filtering. The current status of analysis procedures such as optimal interpolation and variational methods was also reviewed. The importance of quality control of observations for operational meteorological data analysis schemes was emphasized, and the question of “what is the best analysis” was considered.

Chelton detailed the key role that the TOPEX altimeter and NROSS NASA scatterometer will play in WOCE. In particular, the data from these satellite radars will be used in numerical and statistical models for initialization, assimilation and verification. Despite the likely importance of these systems, however, Chelton noted three unresolved issues that represent limitations on our present ability to use the satellite data: sampling errors, instrument noise, and other measurement errors.

Hurlburt examined the ability of a numerical ocean model to dynamically transfer simulated altimetric data into subsurface information. Specifically, given only the free surface elevation (simulated altimeter data) from the true model solution, the model was able to reconstruct the deep pressure field. This was accomplished in a variety of dynamical regimes including unstable currents and isolated eddies. However, the frequency of updating of the surface pressure was a critical parameter.

Marshall focused on the likely uses of satellite altimetry, and considered the combined problem of determining the ocean circulation and improving knowledge of the geoid. The combined problem is formulated using minimum variance estimation to form optimal estimates of both the ocean topography and the geoid. A dynamical ocean model acts as a source of a priori oceanographic information capable of discriminating between geoid errors and ocean topography. A simulation study of Gulf Stream variability was presented to illustrate the technique.

O'Brien and Smedstad suggested that strong constraints be used for data assimilation within time-dependent models of the ocean. Adopting a simplified prognostic model, they derive the relevant variational formulation, showing the role of the strong constraints. For a simple example (wind-forced inertial oscillations), the variational approach allows the accurate recovery of the ocean response, even for periods during which accurate winds are not available.

Bennett showed how the efficiency of the TOGA XBT sampling programme could be estimated in terms of the amount of data that can be assimilated into a dynamical model of the equatorial wave guide. A priori, the configuration of the TOGA XBT programme suggests that each XBT array contains 400 degrees of freedom, for frequencies of order 1 cycle/year. A linear, reduced gravity model of the equatorial - plane wave - guide was then constructed to determine the actual number of real degrees of freedom. After discussion of the details of the generalized inverse used, it was shown that the TOGA array has only about 12 real degrees of freedom. Alternate TOGA XBT sampling strategies were offered.

Using the Ship-of-Opportunity XBT data from the tropical Pacific (1979-1983), Bigg described the equatorial waves associated with El Nino and the influence of wind forcing. The data was analyzed by appeal to the baroclinic mode shallow water equations, in a form which represents the magnitudes of the various equatorially trapped waves. The XBT data indicates that the second baroclinic mode is a very important part of the 1982-1983 El Nino signal.

Bryan discussed the use of robust diagnostic constraints within models of the large-scale ocean circulation. In such "diagnostic models," internal constraints are specified, typically in the form of a requirement that the density field conform to observations. Since diagnostic models attempt to directly incorporate available density measurements into the model, other types of data must be used for verification. In their original form, diagnostic models simply fixed the density fields at their "known" values. A new version of the robust diagnostic model dampens the curvature of the vertical profile of temperature and salinity to the observed curvature. In this formulation, no subsurface sources or sinks of density arise. A simulation of meridional overturning in the Atlantic Ocean was shown to illustrate the differences associated with the new diagnostic approach.

Numerical studies of the assimilation of density data in models of the large-scale ocean circulation were described by Malanotte-Rizzoli and Holland. The data chosen for assimilation was suggested by acoustic tomography, one of the few methods capable of providing internal, synoptic data over long oceanic sections. A multi-layer, quasi-geostrophic model of the wind-driven ocean circulation was used to represent the ocean. By driving the model with and without data insertion, several questions were addressed: (a) what is the influence of data insertion in different regions of the model subtropical gyre; (b) how is the field of influence affected by the explicit model dynamics; and (c) can we infer inadequacies in model physics from the effects of data insertion?

Robinson reviewed recent progress in real-time data assimilation in dynamical ocean models. It was shown that optimal estimation of oceanic fields involved the interaction of three system elements: an observation system, a statistical model, and a dynamical model. The synthesis of model-generated and observed data sets can be used for study of local dynamical processes and for regional model verification. Real-time experiments using a regional eddy-resolving model (a baroclinic, quasi-geostrophic, finite-element model) have been conducted in the California Current System. An example of a successful two-week real-time forecast in which two eddies merged to form a zonal jet was shown.

Miller and Ghil described the Kalman filter, and its application to oceanographic data assimilation. As in optimal interpolation, the Kalman filter obtains the assimilated field by forming a linear combination of the forecast field and the observed data, using weighting coefficients that are derived from the forecast and observed error covariances. However, using the Kalman filter, the forecast error covariance is calculated directly from the model dynamics and the covariance matrix must in principle be calculated each time step. The computational requirement can therefore be considerable. Applications of the Kalman filter technique to the case of a linear dynamical system, and to a one-dimensional analogue of a regional open-ocean model, were shown to demonstrate feasibility and stability in idealized practical situations.

Holloway discussed the concept of predictability as it relates to oceanic data assimilation. Two features of strongly non-linear flows were noted: the tendency for large error growth rates and for the transfer of error to ever larger scales. Thus, even with a perfect model and boundary conditions, initial error will grow in both amplitude and scale. A simple conclusion is that, for a forecast to retain useful skill, updating by data assimilation must occur on a time scale short compared to the predictability time. For a complicated non-linear systems like the ocean, the propagation of error amplitude and scale can only be estimated by numerical means. An alternative is the use of the statistical dynamical theory of error propagation. Despite recent success in such predictability studies, however, Holloway noted the general problem of ”conditional predictability” (for example, involving regime transitions) for which current data assimilation schemes were not designed.

Lastly, Thacker addressed the problem of reconstructing a synoptic state of a dynamical system from highly asynoptic data by using dynamics to project the data on to a single time-level. Two approaches were described, both of which involve the minimization of observational errors. The two differ, however, in their treatment of the dynamics; the first incorporates dynamics as a “soft” constraint, the second as a “hard” constraint. Both methods were shown to require the solution of algebraic equations on a space-time mesh. Estimates of the resulting computational burden, and some results for simple models, were given.

Acknowledgements

Financial support for the Workshop was provided by U.S. WOCE and CCCO. D. Haidvogel and D. Anderson the chairmen of the respective modeling groups organised the meeting.

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Indigo: Etude des Gaz dans l'Ocean Indien

Indigo is a French programme, with the participation of scientists from US and Canadian institutions, devoted to the study of the redistribution of anthropogenic CO_2 and its storage by the ocean. As yet, there have been few high precision chemical tracer studies in the southern Indian Ocean. To use the full potential of transient tracers for estimating the rate of spreading of water masses, it will be necessary to revisit some reference areas every 10 years or so. Finally, for chemical tracers, the existing data bases, such as that of GEOSECS, do not provide a description of some of the areas where large fluxes are encountered, such as the boundary currents.

Indigo is thus a multi-year programme (once a year for a minimum of 4 years). The research vessel, MARION DUFRESNE, that is being used is operated by TAAF (Terres Australes et Antarctiques Francaises). The first five weeks of the Indigo mission were carried out in February-March 1985 in the south-west Indian Ocean. The original project involved a north-south section between Reunion Island and Antarctica. However, due to very poor weather conditions, the ship was forced to turn back near 54 degrees south. 24 deep stations were occupied, including 7 for large volume sampling and four GEOSECS stations. The track formed an approximate loop from Reunion to Madagascar, Crozet, Kerguelen and Amsterdam Island. Among the preliminary results is that Freon-12 was found to be at low concentration in the Antarctic Intermediate waters (about 0.5 pmol/kg).

Indigo 2 will cover the central and north-western Indian Ocean in April 86. It is a Joint mission with the hydrographic sections of the SINODE project across the Somali current area, in the framework of TOGA. Indigo 3, in 1987, is intended to finish the Reunion-Antarctica section and to run another one west of it towards South Africa. Indigo 4, in 1988, will probably sample the north-western Indian Ocean.

Indigo is related to a sister programme, named INDIVAT, which samples the near-surface ocean two or three times a year, during the quarterly transit of the MARION DUFRESNE from Reunion to Crozet to Kerguelen and Amsterdam. INDIVAT provides an excellent opportunity to investigate the seasonal variations of the carbonate chemistry system and gas exchange with the atmosphere on both sides of the Subtropical and Antarctic fronts. A similar seasonal surface programme is being set up for the tropical area.

The scientists involved in these programmes are: R. H. Byrne, University of South Florida; (Aragonite dissolution); C. T. Chen, Oregon State University (PH, Alkalinity, Total CO_2, Nitrate); J. Lebel, University of Quebec at Rimouski (Calcium, Magnesium, Boron); M. Lecorre, University de Bretagne Occidentale (Nutrients) ; L. Merlivat, Cen. Saclay (CTD, Deuteruium, Tritium, Krypton-85, Helium-3, Carbon-14); H. and M. M. Minas, Universite Daix Marseille (Nutrients, Chlorophyll) ; J. F. Minster, Groupe de Recherche de Geodesie Spatiale, Toulouse; (CTD, Nutrients, Trace metals); G. Ostlund, University of Miami; (Carbon-14); T. Packard, Bigelow Laboratory (ETS); A. Poisson, Universite de Paris 6 (Alkalinity, Total CO_2, PCO_2, Oxygen, Freons, Calcium, Magnesium).

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Report of an ad hoc Meeting on Density Profiling

on 12 December 1985 a small group met informally during the San Francisco AGU meeting to discuss density profiling. The group which included T. Joyce, L. Armi, M. Gregg, and R. Williams, met to review progress in defining the needs for ocean density profiling in the future with particular emphasis on WOCE. Three previous, larger U.S. meetings have been held resulting, for example, in a set of specifications for ‘WOCE’ CTD’s, and discussion of various new initiatives such as the fast, untethered profiler and the expendable CTD. Since much of the emphasis in the earlier meetings was on what could be achieved now or in the near future without clear cut scientific justification, two of the concerns of the group discussion were to define what needed to be done to inject scientific requirements into the planning process and to define what wasn’t being done but should be.

Scientific Requirements

Requirements for deep (to the bottom) CTD casts are quite different than those for upper ocean work. With some exceptions, the former concern the examination of the water mass structure of the general circulation irrespective of the time of year, while the latter are usually concerned with questions of heat storage and advection on seasonal time scales. Both sets of requirements need to take into consideration the eddy field in that it can alias the general circulation and induce large errors in estimation of derived quantities such as geostrophic currents and heat content.

a) Upper Ocean

It was recognized that earlier meetings had failed primarily to define requirements for the upper ocean. One major problem with defining hardware requirements for the upper ocean is the absence of a scientific plan for measurements. Planning for WOCE has been quite valuable as an aid for measurement needs in the deep ocean. To date there has been no such parallel effort for the upper ocean. One question which needs to be addressed is how well do temperature, salinity and pressure (or depth) need to be measured in order to estimate, in the absence of horizontal advection, changes in heat content (xx watts per square meter) and E-P (yy millimeters per year). Given that acoustic Doppler logs as well as satellite altimetry can be used to estimate surface currents to some accuracy and therefore surface dynamic topography, how well must T,S, and P be measured to permit a downward integration of currents from the surface to some depth below the thermocline (for example, 1000 m) with a comparable error in dynamic height of zz cm? The numeric values of xx, yy and zz need to be defined in a way consistent with the scientific objectives of WOCE. This has not been done. Is it sufficient to measure only T,S, and P? Where and how often must these measurements be made? Do in situ samples have to be collected for calibration purposes? Other alternate means of upper ocean measurement need to be considered such as SEASOAR (a CTD package towed behind a ship) or moored systems which can collect time series at strategic points for extended periods of time.

The above constraints on salt and heat budgets, and on dynamic height, are integral in nature and are offered as a first pass framework on requirements for upper ocean work. Other constraints such as resolving water mass differences may imply more restrictions. Before much progress can be made on density profiling instrumentation for the upper ocean, there is need for a fuller discussion of the scientific requirements for WOCE.

b) Deep Ocean

Different problems plague high quality deep-ocean hydrography. Present CTD capability for salinity calibration is limited by our ability to calibrate conductivity cells. Stable, redundant (platinum?) temperature sensors should replace reversing thermometers. A pressure sensor is required with less than 5 db temperature sensitivity and a comparable pressure hysteresis (0.5% linearity requirement). The present pressure sensor on the Brown CTD has a hysteresis exceeding 5 db. Data calibration requires attention to laboratory calibrations which vary depending upon the range of pressure encountered on each cast (one calibration for deep casts and a second for shallow casts as a minimum). Differences in IOS standard water salinity of as much as ±.003 ppt have been documented between labelled and measured salinities. Furthermore, standard water salinity can be a function of time. Shouldn't a different, perhaps non-fluid, conductivity standard be used; maybe precision resistors? This would permit changes in "standard water" to be monitored. In the longer term, we should consider whether or not standard water should be used at all. The Beckman polarographic oxygen cell can, with much effort, be used together with water sample titrations, to produce a continuous oxygen profile. The sensor is troubled by a short lifetime, a long time constant, a lack of station-to-station stability (fouling?) and a sensitivity to motion, or lack thereof, of the sensor through the water. Our CTD's of the future require a better sensor capable of producing a continuous trace which can be calibrated to within the accuracy of the water sample titrations (0.5% again). Higher resolution and lower noise in temperature and conductivity measurements will improve our ability to detect relative salinity changes in the deep water and will also extend the capability of CTD's for fine structure measurement. For many applications time is also an important variable to measure. This is especially critical in repeated profiling in a diagonal profiling mode and for intercomparisons with other 'dropped' profilers.

With the advent of inexpensive computers, there is no longer a requirement that sensor response be linear. Efforts should be directed towards repeatability and sensitivity, not linearity.

Some attention should be given to reducing the physical size of CTD's. This would not only make shipping and handling easier, but would also reduce the thermal mass and associated temperature lags. The present pressure transducer setup in the Brown CTD, for example, provides for a thermally isolated transducer supported by an ineffective attempt at temperature compensation. It is fine in a steady-state bath, but not under transient conditions encountered in profiling.

A related problem for deep CTD usage is the water sampler. More (36) bottles of differing size need to be tripped without stopping the package in the water. The water sampler should be a low drag package capable of tripping any bottle on command from the surface. Most chemists and some physical oceanographers reed to examine, in real time, the vertical structure in the watercolumn on the down cast before selecting sample depths on the up cast. The package should be designed so that the CTD measurements can be made on the up cast (reducing up/down differences, reducing hysteresis error, reporting final data when the water samples are actually acquired). Most of these deficiencies have been noted and specifications for a new water sampler have been put together by Nowlin and Heinmiller, though the emphasis has been on a self-contained package requiring no conducting wire.

Discussion

With the exception of the water sampler, none of the above requirements appears in any previous report made by the U.S. WOCE density profiling group. Rather emphasis has been on internal recording, use of non-conducting wire, etc. which may meet some of the requirements for CTD sampling from tow capability ships. Let's not set our sights too low! Finally, there is a real need for a high speed, level-winding conducting wire winch with an accumulator which will permit casts to be made in rough weather from oceanographic research vessels.

The group was of the opinion that a 1-1.5 day meeting between an expanded committee representing academic oceanographers and representatives from oceanographic instrumentation firms should be held somewhere in the middle of the US (Chicago or Denver) separate from other meetings (for example, AGU, MTS, etc.). Contacts with some industry representatives who were at the San Francisco AGU indicated that a separate meeting on density profiling would be more productive than a gathering which piggy-backs on some other national meeting. This was also a recommendation from one of the earlier US WOCE-sponsored density profiler meetings. The purpose of such a meeting would be to:

1) review progress (or lack thereof) of ongoing development of autonomous CTD's and XCTD's
2) air and discuss some of the above instrumentation issues
3) develop specifications for the next generation of CTD's - both deep and upper ocean
4) discuss needs for new types of water sampling devices along the lines of the Nowlin/Heinmiller rosette specifications
5) discuss a timetable for development and sea testing.

There are other issues of instrument calibration, data processing, and data dissemination which need to be considered for WOCE. The central theme of the meeting proposed above concerns sensors, underwater and on-deck support instrumentation, although sensor stability cannot be divorced from absolute calibration.

Considering cruise and other commitments for key participants, the earliest possible time for a density profiling meeting are in the summer or early autumn of 1986. Possible attendees will be polled to see when a meeting can be scheduled. Before a productive meeting can be held, there is a need to more fully discuss the scientific needs for density profiling instruments. What is likely to emerge for WOCE is what the oceanographic community will probably be 'stuck with' for the next decade.

In the context of the large-scale programmes of the next 5 to 10 years, as well as for smaller-scale operations of the next decade, we feel that the focus should be on technology that is available today. That is, we do not envisage in this time frame the widespread utilization of completely new techniques (for example, direct measurement of density) or devices. Rather the need is for stimulation, funding, and coordination of engineering development and integration in this area. Techniques end elements must be integrated into routine working systems, and those systems must be made widely available, probably on a commercial basis.

Some of the above issues must be pursued at an international level. Questions about standard water and a new conductivity standard need to be considered by the Joint Panel on Oceanographic Tables and Standards (JPOTS). On the books, there is an international SCOR working group on CTD's (WG 51). It has met twice since formation and never issued a report. If it still exists, some of the issues raised are clearly in the purview of this committee. It is hoped that this report will evoke a fuller discussion of density profiling so that a productive instrumentation meeting can be organized in the near future. The WOCE newsletter seems to be a good forum for this topic and it is in this spirit that this report is submitted to the newsletter for dissemination.

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WOCE Planning

Entering 1986, the planning of WOCE is going forward on many fronts and major advances are to be expected. Several nations have now formed national WOCE committees and are developing national WOCE objectives and making plans for assembling and co-ordinating national resources for use within the international WOCE framework.

Internationally, the WOCE Scientific Plan now provides the rational and strategy for an international programme concerned with decadal climate change in the ocean. During 1986, major steps will be taken to develop detailed scientific plans for the implementation of this strategy. Much of this planning will focus on the three Core Projects which form the heart of the international field programme to be carried cut during the Intensive Observational Period, tentatively set for 1990-1995. An international planning meeting is to be held in 1986 for each of the Core Projects at which time the international scientific community will have an opportunity to help design the experiment necessary to meet WOCE goals. The first of these meetings will be held under the chairmanship of Jim Crease in Bremerhaven in May and address Core Project 2, The Southern Ocean. Later in early September a meeting in London chaired by Francis Bretherton will address Core Project 3, The Gyre Dynamics Experiment. Core Project 1, The Global Description, will be tackled at a meeting chaired by Carl Wunsch in Washington in November. The WOCE-IPO is, of course, involved in the preparation of all these meetings and information may be received from that source on request.

Also during 1986, the first WOCE Implementation Plan will be prepared, drawing heavily on the results of the planning for the Core Projects. This will form the basis of discussion of an intergovernmental meeting on WOCE to be held in late 1987 at which time nations will be approached to make commitments to carrying out of the field phase of WOCE. For WOCE this will be a continuation of a process which will start this spring with the consideration of the Implementation Plan for the complete WCRP at an IOC/WMO Informal Planning Meeting.

In addition to the Core projects, planning is addressing or starting to address such questions as data management, ship support (the R.V. WOCE proposal), the role of CO_2 research in WOCE, the best way to obtain surface stress information from the assimilation of satellite data in numerical weather prediction models, the role of sea-ice, etc. The WOCE Numerical Experimentation Group (NEG) is also advancing the general use of numerical models in WOCE and modellers will be actively involved in most planning activities.

The success of the international activities mentioned above depends on the strong input from individual scientists and national scientific bodies and organizations. Attempts are being made to increase contacts between all identifiable WOCE participants. This is expected to be aided in the future by additional secondment of personnel to the WOCE-IPO.

The previous article raises questions about the accuracy needed of CTDs, especially in the upper ocean, if certain quantities such as heat content and current shear are to be estimated with an accuracy sufficient to meet WOCE goals. While the article addresses planning needs from a national perspective, it is equally relevant to international WOCE planning, especially concerning Core Project 1. Answers to some of the questions raised must be answered internationally before or during the Core Project 1 meeting in November of this year.

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National Update

United States

As a next step in U.S. plannirg for WOCE, the U. S. WOCE Science Steering Committee is sponsoring a series of meetings to address common elements which have been identified after careful study of the ocean sector meeting reports. The topics for consideration, chairmen of the meetings and meeting dates/locations follow:

Interbasin Exchanges and Marginal Sea Outflows; John Toole, 2-4 April 1986, Massachusetts Inst. of Technology.
Gyre Interactions, including boundary current effects; W.R. Young, 7-9 April 1986, Woods Hole Oceanographic Institution.
Deep Circulation and Topography; Nelson Hogg, 17-19 June 1986, Woods Hole Oceanographic Institution.
Oceanic Heat Flux; Dean Roemmich/Mindy Hall, 14-16 July 1986, Scripps Institution of Oceanography.
Cross Equatorial Exchange; Ed Harrison, time and location yet to be determined.

The following reports are now available from the U.S. Planning Office for WOCE:

1. U.S. WOCE Planning Report 1: Document on Ocean Sampling Strategy and Technology; Background for Ocean Sector Meetings.
2. U.S. WOCE Planning Report 2: Ocean Sector Meetings: South Pacific, North Pacific, South Atlantic and Indian Oceans.
3. U.S. WOCE Planning Report 3: Status Report on U.S. WOCE Planning.
4. U.S. Technical Report 1: WOCE Global Air-Sea Interaction Fields.

United Kingdom

A national WOCE committee has been established under the auspices of the Natural Environment Research Council and chaired by Professor H. Charnock (Southampton University) with membership: A.E. Gill (Meteorological Office/Hooke Institute), J. Woods, (Natural Environment Research Council), D.E. Cartwright, J. Crease, R.T. Pollard (Institute of Oceanographic Sciences), R. Dickson (Ministry of Agriculture, Fisheries and Food), A. Watson (Marine Biological Association), D. Ellett (Scottish Marine Biological Association), B.J. Hoskins (Reading University), M. J. Rycroft (British Antarctic Survey), P. Wadhams (Scott Polar Research Institute), D. Llewellyn-Jones (Rutherford Appleton Laboratory), D. Pugh (NERC/Secretariat).

Japan

The planning group for Japanese WOCE was established in January 1985. A preliminary report of the group was presented and discussed in a symposium of the autumn assembly of the Oceanographical Society of Japan in October. The activity of the group was reported to and endorsed by the Japanese Committees for IAPSO and for SCOR of the Science Council for Japan, in October and in November, respectively. The group is also keeping contact with the Japanese Planning Committee for the WCRP and its related groups.

The chairman of the group is Y. Nagata, Geophysical Institute, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan, and the co-chairman is K. Taira, Ocean Research Institute, University of Tokyo (instrumentation and observation). The other members are Y. Toba, Tohoku University (surface mixed layer, OMLET); J.-H. Yoon, University of Tokyo (modeling); J. Yoshida, Tokyo University of Fisheries (descriptive); Y. Nozaki, University of Tokyo (chemical); and Y. Sugimori, Tokai University (satellite). The group is reinforced by investigators belonging to the organizations responsible for operational services and their research institutions; K. Nagaska, Japan Meteorological Agency; H. Nishida, Hydrographic Department, MSA; M. Endo, Meteorological Research Institute, JMA (modeling) and A. Tomosada, Tokai

Regional Fisheries Research Laboratory, JFA. The group is keeping close contact with investigators of about 30 organizations in Japan by means of a newsletter, symposia and so or.

Japanese WCRP programme (the first phase, 1987-1990) is still under discussion by the Geodesic Council. The oceanographic community of Japan is planning an additional special research, programme, “Dynamics of the deep ocean circulation”, in the pre-WOCE period (1987-1989). The latter plan is focused on deep water circulation in the Shikoku Basin, south of Japan. It is not yet practical to make a detailed plan for the Japanese programme during WOCE. Thus, the approach of the planning group is to make a feasibility study and to propose rather conceptual plans of the Japanese activities in the WOCE period in order to organize the physical and chemical oceanographers in Japan for WOCE. As a first step, we are planning a US-Japan WOCE Workshop at the Ocean Research Institute, University of Tokyo from 20-24 March, 1986.

South Africa

An interim committee has been formed in South Africa to initiate and co-ordinate activities which could contribute to or benefit from WOCE. Its members are: Frank Anderson (Chairman) and Johann Lutjeharms, National Research Institute for Oceanology; Roy Siegfried and Geoff Brundrit, University of Cape Town; Piers Chapman, Sea Fisheries Research Institute; Gert Groenewald, Director, Research, South African Weather Bureau.

Timetable of WOCE Activities

April 21-24	WOCE-6 SSG Meeting, IOS, Wormley, UK.
May 12-16	IOC/WMO Informal Planning Meeting on the WCRP, Geneva.
May 19-23	Core Project 2 Planning Meeting, Bremerhaven, FRG.
July 22-23	Process Dynamics in Large-Scale Models (Sponsored by the USA and International WOCE numerical modelling Groups), IOS, Pat Bay, B.C., Canada.
Sept 2-5	Core Project 1 Planning Meeting, London, UK.
Nov 10-14	Core Project 3 Planning Meeting, Washington, USA.
Dec 2-5	WOCE-7 Scientific Steering Group Meeting, Cambridge, Mass., U.S.A.

The WOCE Newsletter is edited at the WOCE-IPO at IOS, Wormley, Godalming, Surrey, U.K. by Denise Smythe-Wright.

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Contributions should not be cited without the agreement of the author.

We hope that colleagues will see this Newsletter as a means of reporting work in progress related to the Goals of WOCE as described in the Scientific Plan. The SSG will use it also to report progress of working groups and of experiment design and of models.

The editor will be pleased to send copies of the Newsletter to Institutes and Research Scientists with an interest in WOCE or related research.