WORLD CLIMATE RESEARCH PROGRAMME

WORLD OCEAN CIRCULATION EXPERIMENT

CLIMATE VARIABILITY AND PREDICTABILITY

Report of the WOCE/CLIVAR Workshop on Ocean Modelling for Climate Studies

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WOCE International Project Office
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH
UK
Tel: +44-(0)2380-596789
Fax: +44-(0)2380-596204
e-mail: woceipo@soc.soton.ac.uk

International CLIVAR Project Office
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH
UK
Tel: +44-(0)2380-596777
Fax: +44-(0)2380-596204
e-mail: icpo@soc.soton.ac.uk

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1. INTRODUCTION

The ocean is a key component in the climate system, having a role both in moderating and in generating climate anomalies. For these reasons the ocean component is always an important part of the coupled models used for climate change prediction. This is why the WCRP has encouraged the development, improvement and testing of ocean models for many years through the WOCE and TOGA programmes. The WOCE programme in particular has been responsible for the development of ocean models suitable for the mid- and high-latitude oceans and for long climate runs.

However WOCE has now entered its final analysis stage, the WOCE NEG is no longer in existence and many of its responsibilities are being transferred to CLIVAR and the WGCM. As part of this process, WOCE and the WGCM jointly proposed and supported a workshop on Ocean Modelling for Climate Studies. As well as continuing to encourage the improvement of ocean models and the transfer of knowledge to the climate modelling community, it was hoped that this would also help to clarify how future support for ocean modelling should best be organised within the WCRP.

The joint WOCE/CLIVAR workshop was held at NCAR, Boulder, USA between 10th and 13th August 1998. It was organised by an ad-hoc committee (see Appendix C) chaired by Dr C. Böning of the Alfred-Wegener-Institute in Bremerhaven, Germany, with the local NCAR support of Dr P. Gent and Dr W. Large.

The workshop brought together sixty four invited experts representing the climate modelling, ocean modelling, and observational communities. The workshop focused on the problem of realistically representing the ocean's role in climate variability, particularly at decadal time scales. It tried to understand how well different aspects of ocean dynamics need to be represented. It tried to identify the key modelling factors that limit a realistic representation of critical processes, and it tried to see how current and future observational datasets could be used to guide the development of improved models.

A cross-cutting theme throughout the workshop was the strategy for future programs that would help to clarify unresolved questions and aid in developing improved ocean components for the next generation of coupled models. The discussions included coordinated programs of experimentation directed at resolving the impact of factors such as resolution, parameterisation schemes and numerical algorithms. A question in this regard was the usefulness of, and necessary resources for, an organised ocean model intercomparison project (OMIP).

Discussions were divided (about equally) between plenary sessions with invited speakers asked to address a number of specific questions, and six working groups centred around classes of key processes and phenomena. Most WG discussions were based on pre-defined sets of questions, assigned to attendees in advance of the meeting. Some groups had a continued discussion during preparation of their final reports, aiming, where possible, at specific recommendations concerning definition of coordinated modelling programs, including model diagnostics and datasets for model sensitivity and intercomparison studies.

In the planning for the workshop it was recognised that it would not be possible to cover all relevant issues in the simulation of ocean dynamics in coupled climate models. Two particularly important issues have been left out, mainly because it was felt that these are being considered already in other WCRP group activities: sea ice modelling, and the question of initialising the ocean component in coupled simulations. It was strongly suggested though that these needed more attention and should be included in future workshops.

The outline of the present report is as follows. Instead of a chronological rapport of the meeting's deliberations, it attempts to give a summary of the workshop's main conclusions concerning important issues that need to be considered in future strategies for model development and testing (sections 2 and 3). This is followed by more detailed recommendations from the six working groups concerning the representation of key ocean processes and phenomena. A collection of abstracts of selected contributions to particular discussion items is included in Appendix B.

2. MAJOR ISSUES IN OCEAN MODELLING ON DECADAL TIME SCALES

2.1 Importance of Small-Scale Processes

Perhaps the most important aspect that distinguishes model studies on decadal and longer time scales from those on intraseasonal, seasonal, and (to some extent) interannual, is the impact of small-scale interior processes on large-scale ocean currents. Away from the deep water formation regions in the high-latitudes, ocean response to atmospheric forcing at seasonal time scales can be understood primarily in terms of linear dynamics, involving wind-driven (Ekman-) transport anomalies, and deep current variations governed by barotropic and (in low latitudes) baroclinic Rossby waves. Model intercomparisons such as in DYNAMO (Dynamo Group, 1997) have revealed relatively little sensitivity of simulated transport variations to choices of numerical model (e.g., geopotential, isopycnic, or sigma coordinates), or the parameterisation of mixing in the surface boundary layer and in the interior.

This rather favourable situation, i.e., the insensitivity to a number of conspicuous choices of numerical algorithms and parameters, is in sharp contrast to the behaviour at longer time scales which begin to involve the ocean's dynamical response to changes in buoyancy forcing. As has consistently been shown by a host of ocean model sensitivity and intercomparison studies, the response of the large-scale circulation to surface flux variations becomes extremely dependent on the representation of a host of interior, often very small-scale processes. A particular problem is the strong dependence of large-scale circulation patterns in the Atlantic Ocean, including its meridional heat transport, on small-scale details of the topography in the overflow regime, the dynamics of flows through sills and narrow passages, the entrainment in downslope flows, the representation of boundary currents and their interaction with topographic features.

CONCLUSION: Any program aiming at improving ocean models for climate studies must take into account these sensitivities and their (sometimes hidden) manifestation in different numerical model concepts, or choices of horizontal and vertical resolution.

While the dependence on the representation of small-scale physics can be considered as a basic characteristic of thermohaline circulation variability, there are some important, qualitative differences concerning the role of certain processes at decadal and at longer time scales. For decadal-scale simulations, particular attention has to be paid to all factors governing the evolution of deep boundary currents. In contrast to the behaviour at secular scales or of equilibrium solutions, representation of interior diapycnic mixing (apart from localised areas with strong mixing rates such as in deep convection, entrainment in downslope flows, or enhanced mixing above rough topography) probably plays a secondary role, compared to the representation of adiabatic, wave mechanisms and their interaction with topography and boundary currents.

CONCLUSION: Assessing the ability of ocean models for decadal-scale studies cannot be based on equilibrium solutions (e.g., testing of watermass properties by comparison with WOCE hydrography) alone; it must include an assessment of those factors that govern the transient behaviour of the thermohaline circulation, i.e., its dynamic response to flux anomalies.

2.2 Critical Processes

The Working Groups considered a host of oceanic processes and phenomena whose representation in ocean climate models have been found or are thought to be critical. For a more detailed account of conclusions and recommended actions we refer to the WG reports on page 8 et seq. However, a brief summary appears in order here.

Processes of particular importance to the large-scale circulation and its response to atmospheric forcing anomalies, include the following:

- Flows over sills and through narrow passages. There are two particular questions that need to be addressed: How best to define the topography of ridges and gaps in models of less than very high resolution? What is the optimal approach for simulating the dynamics of through-flows? The suite of recommended actions includes (WG C): research on high resolution modelling, nesting of high-resolution models, and parameterisation as parallel activities, with the aim of finding an approach which can be successfully applied in climate models.

- Downslope flow of dense water masses and the associated near-bottom mixing. Recommended actions (WG II) include coordinated studies on the representation of down-slope flows in basin-scale ocean models, first of all in the North Atlantic (especially Denmark Strait outflow and the Gulf of Cadiz) where the data coverage is best. Model intercomparisons need to be complemented by exploration of sensitivities to bottom friction, newly developed submodels for the bottom boundary layer, and mixing schemes.

- Convection. An outstanding problem is the representation of lateral exchange processes, i.e., the horizontal restratification via small-scale eddies that is crucial for an accurate description of the water mass renewal (WG I). Questions to be addressed, through sensitivity studies and verification, include the parameterisation of this process, and what horizontal resolution is required.

- Parameterisation of eddies. The best way forward to test and improve parameterisations is to analyse very high resolution model runs, rather than to analyse the rather sparse observations. Among the questions to be addressed (WG III): the dependency of the isopycnal thickness diffusivity on geographical location and mean flow properties.

A number of potentially critical processes were identified for which it was recommended to first test their impact (e.g., through crude parameterisation) by sensitivity runs, and then to devise strategies for improved representation, either by explicitly resolving them or through parameterisation. These include

- Tidal mixing. Enhanced mixing around topographic features gives rise to elevated and inhomogeneous diffusivities that may have a profound effect in ocean models on aspects such as meridional overturning and spin-up behaviour (WG I). A first step should be sensitivity runs with enhanced, inhomogeneous interior mixing to assess its potential impact. This should be followed up by high resolution tidal model runs from which a 3-D diffusivity map could be derived and used in ocean climate models.

- Western boundary currents. It is still an open question whether ocean climate models can get the correct mean climate AND climate variability with realistic transport, but unrealistic speeds and dynamics in their WBCs (WG III). The only way forward may be through analysis of higher resolution, possibly coupled, runs.

- Residual mean circulation. Two rectification effects have been discussed which may both lead to a mean cyclonic circulation around ocean basins, of possible significance for climate studies. While the rectified flow from tidal forcing can be taken into account on the basis of estimates from global tidal models (WG II), the magnitude of the rectified circulation due to unresolved eddy form stress (called 'Neptune' effect) is still under debate (WGs II and III).

2.3 Model Resolution

The large computational requirements of coupled models put serious constraints on the resolution of the ocean sub-model that may be used in coupled models during the next years. The horizontal resolution anticipated for the ocean component in the next-generation of climate models is of the order of 1 degree. While further decrease in grid size may be possible, this has to be balanced against needs for long coupled runs, ensembles of experiments, and sensitivity runs, and must also take into account more complexity in the atmospheric part (chemistry, land surfaces etc.). (For further discussion: P. Gent; Appendix B.)

It is clear that a 1-degree, or even a 1/2- or 1/3-degree resolution is not sufficient to accurately represent many oceanic processes that may be relevant for the dynamics of the large-scale circulation. Hence two aspects appear important in the development of ocean models for climate studies: to improve on, or develop, parameterisations for phenomena that necessarily remain of subgrid scale at this level of model resolution; and to quantitatively assess the effects of higher resolution in the ocean component on the behaviour of coupled models.

An issue requiring special attention is the representation of bottom topography. Irrespective of the need for improving the numerical treatment of topographic interactions and of near-bottom processes, it will geometrically be impossible to resolve in models of O(1-degree) the ridges and gaps that are extremely critical for the thermohaline circulation. There is a danger here that model performance will remain dependent on a fortuitous choice of bathymetric details at single grid cells. To build confidence in the behaviour of such models under climate-change scenarios, it is clearly necessary to examine the impact of alternatives in the adaptation of the real topography, and to build final choices of model topographies on a firm basis of sensitivity studies and testing.

For some phenomena such as western boundary currents and recirculation regimes, property transport by Agulhas rings, or the narrow regimes with deep winter mixing along the margin of the north-eastern North Atlantic, parameterisations may not be envisioned at all. The effect of not resolving these and other potentially important phenomena needs to be quantitatively assessed in the context of climate dynamics. The most promising approach here would be a rigorous comparison of climate models not resolving these phenomena, with both high-resolution, eddy-resolving ocean-only models and eddy-permitting coupled models. A discussion of issues related to this approach was given by D. Webb (Appendix B).

RECOMMENDATION: Some carefully-planned, eddy-permitting coupled experiments could contribute significantly to an understanding of the importance of ocean-model resolution in climate studies. It is extremely important, however, that ocean models used in such studies are built on the best possible parameterisations of critical physics, to avoid masking the effects of resolution by other factors. The model analysis should focus not only on the relevance of resolving western boundary currents and eddies, but should cover other potentially important phenomena, including those mentioned above.

A particular issue that could also be addressed in this context is the transient response behaviour of the large-scale circulation, especially meridional overturning and heat fluxes in the Atlantic: e.g., what is the effect of resolution on the representation of oceanic processes such as boundary waves that govern the ocean's adjustment to changes in high-latitude thermohaline forcing? Is there an impact on the time scales, amplitudes, and geographical patterns of the response?

2.4 Numerical Algorithms

During the last decade, the diversity of numerical formulations for ocean circulation models has increased considerably. Models based on different vertical coordinate schemes in both vertical (z, sigma, isopycnal, or generalised) and horizontal (curvilinear co-ordinates, adaptive grids, finite elements) direction have been developed and applied to basin-scale or global domains. There is a choice now of alternative schemes dealing with the polar problem, of various advection schemes, isopycnal diffusion schemes, free surface instead of rigid lid formulations, etc.

Two different, and to some extent, complementary approaches have been advocated to quantitatively assess the strengths and weaknesses of alternate ocean models and model algorithms. One involves tightly organised intercomparison studies with basin-scale ocean models under realistic (and, as far as possible, identical) boundary conditions, permitting an assessment of results in relation to ocean data sets. The alternative is to apply ocean models to simplified process-oriented test problems with known analytical solutions.

A discussion of various aspects of these approaches may be found in the abstracts of J. Willebrand, D. Haidvogel, and C. Covey (Appendix B). Conclusions from previous efforts include the following:

- Both test problems and basin-scale model intercomparisons indicate considerable inter-model differences particularly with respect to phenomena which involve interaction with solid boundaries: e.g., western boundary currents, buoyancy-driven downslope flows; the latter with strong implications for basin-scale flow patterns in different model solutions.

- Differences between different ocean models run under identical conditions are usually of the same order as differences within one model when run under slightly different conditions, e.g., with alternative parameterisation choices. This leads to the following, general

CONCLUSION: In order to assess effects of numerics in inter-model differences, these have to be isolated from a host of other factors. Model intercomparisons should therefore not be based on single realisations; they need to be accompanied by carefully planned sensitivity experiments.

3. STRATEGY FOR MODEL DEVELOPMENT: RECOMMENDATIONS

A strategy for the development of improved ocean models for climate prediction was put forward in the report of the WOCE Synthesis and Modelling Working Group (SMWG) (WOCE Report No. 153/97). The SMWG recommended that work on the development of ocean models for climate studies proceeds on three parallel tracks. First, by working on high resolution ocean-only models (order of 1/10-degree) that provide as realistic a simulation of the oceans as is presently possible. Second, by developing process models that may eventually be used as parameterisations in climate models. Finally, by developing medium resolution, possibly eddy-permitting models that are of higher resolution than is used today in coupled models, yet that are not forbiddingly expensive computationally. It was envisaged that these medium resolution models will serve as the next generation ocean models within coupled climate models.

Some of the recommendations proposed by the SMWG have been addressed to some extent (e.g., use of surface and bottom boundary layer models, improved surface forcing schemes, eddy parameterisations), other items have not been addressed, yet are still very relevant. Instead of re-iterating the specific recommendations of the SMWG, the following summary focuses on aspects of an implementation of that strategy, namely, on elements of coordinated programs of experimentation.

Simulations of large-scale ocean circulation and its response to flux variations on decadal and longer time scales depend on a multitude of factors: resolution, parameterisation schemes, numerical model choices. The role of any individual factor, for example, effects of WBC resolution on meridional heat transport, is very difficult to isolate. Understanding their relative impacts on model performance and assessment of alternative choices is, however, a prerequisite for the development of improved models. Advances in this regard would benefit greatly from more coordination, transparency and feedback between different modelling teams.

RECOMMENDATION: Coordinated programs of experimentation are strongly encouraged, in order to achieve a more comprehensive and systematic exploration of model parameter space and numerics.

3.1 Ocean Model Intercomparisons

Ocean model intercomparisons should be one possible aspect in coordinated programs of experimentation, however, they are meaningful only if embedded in studies investigating sensitivity to the representation of critical physical processes.

A meaningful program for ocean model intercomparisons and sensitivity studies necessarily has to be of a level that requires participating groups to run models in strictly defined configurations in terms of model domain and forcing. It is clear therefore that any program requires participating groups to set up models specifically for the given purpose. This implies that a considerable fraction of the resources available to ocean modelling groups have to be involved. It means that such programs will only have a realistic chance to be realised if they are primarily science-driven, requiring that each individual model run has to be of scientific interest, the intercomparison part representing a significant value-adding aspect.

Two possibilities were discussed. The first was to encourage self-organising ocean model intercomparison projects, following previous examples such as the WOCE Community Modelling Effort (CME), the European DYNAMO project, the US DAMEE, and others. The second was to set up a fixed framework with specified model extent, surface forcing and timescale, and which provides resources for storage and analysis of results. The considerations above led to the conclusion that it cannot be recommended at this stage of ocean model development, to set up a centralised Ocean Model Intercomparison Project (OMIP). Instead:

RECOMMENDATION: Ocean modelling groups should be strongly encouraged to strive for a closer coordination of experimentation by defining and joining in self-organising model intercomparison projects.

Since any such effort requires close coordination: of model configuration, initial, forcing and boundary conditions, model diagnostics and data sets for evaluation, there will necessarily be limitations on the possible number of partners. (This, however, does not exclude, as previous examples of multi-institutional modelling programs (e.g., CME, DYNAMO) have shown, the possibility of establishing 'baselines' that may provide useful test-beds for new parameterisation schemes or alternate models.)

3.2 Model Configurations

Model domains for ocean model intercomparisons could either be global or concentrate on an individual basin. An attractive scenario is to encourage tests of global models using re-analysed surface forcing data sets. Such runs would be limited to periods of a few decades, allowing high and coarse resolution models to be intercompared and also emphasising validation against recent oceanographic measurements.

RECOMMENDATION: It is recommended that coordinated modelling efforts include both high resolution models and models with resolutions comparable to those adopted in present (and next-generation) climate models.

Experience shows that basin-scale models are strongly controlled by the specification of the lateral boundary conditions. However, in some cases this may actually be an advantage, by allowing the avoidance of unwarranted dependence on delicate physics (e.g., interaction with sea ice or ice shelves in polar regions) outside of the domain of interest. In the working group discussions, two regions emerged for which coordinated programs of model sensitivity and intercomparison studies could contribute significantly to both an understanding of the critical processes and the model factors affecting their representation: the Southern Ocean for which several groups already expressed interest and have initiated a collaborative effort (see also WG B report); and the North Atlantic (WG II, WG A). Modelling studies for the North Atlantic can build on a rich experience from previous efforts; recently, several modelling projects, involving models of different resolution, different numerics, and with different parameterisations of mixing processes, have been built on the domain used in the DYNAMO intercomparison, i.e., a northern boundary near 70°N which allows an explicit simulation of the overflows, but mimics Arctic processes by specifying their effect through the conditions imposed at the open northern boundary.

3.3 Equilibrium vs. Non-Equilibrium Runs

An issue requiring special attention is integration time, i.e., the question of (thermohaline) equilibrium vs. non-equilibrium simulations. While ocean models ultimately, i.e. for being useful in coupled climate studies, need to demonstrate sufficient realism in equilibrium solutions, there are a number of arguments for putting the focus of intercomparison efforts on the transient behaviour, in particular, if aiming at improved model capabilities for decadal climate studies. An important one is that equilibrium behaviour tends to be controlled by model factors disjunct from those governing transient behaviour on decadal time scales, exemplified especially in the different impact of adiabatic and diabatic processes.

RECOMMENDATION: It is recommended that ocean model intercomparison and sensitivity studies encompass an analysis of the transient behaviour to prescribed forcing anomalies, including the question of the relative merit of high-resolution vs. coarse-resolution runs.

3.4 Model-Data Comparisons

The definition of common standards/metrics by which ocean models could be meaningfully judged against observations and against each other is a necessary precursor to an ocean model intercomparison. There is agreement that this step is a valuable task in itself even without a follow up OMIP; it would provide a baseline for the testing of individual model studies, and could lead to more transparency, comparability and feedback between different development efforts.

Recommendations for model data comparison and model validation were formulated by the SMWG. Many of these will be valid for any coordinated modelling effort, however, there is the need to become much more detailed in individual programs. A number of recommendations have been worked out in different working groups and may be found in the respective reports. A discussion of data issues is also provided in contributions (P. Saunders, S. Rintoul) compiled in Appendix B. It is apparent that further work, e.g. by a focused group is necessary to move forward.

RECOMMENDATION: The definition of common standards for model diagnostics and data products should be considered a task of high priority.

3.5 Infrastructure

While a centralised big OMIP was considered less useful, there was agreement that some centralised infrastructure supporting individual model development and intercomparison efforts would be necessary, in particular, to avoid wasting resources by duplication of efforts concerning construction of data sets for model forcing, initialisation, and testing. Establishment of high-quality, standard forcing fields and protocols, analysis tools, and evaluation data sets was described as an important legacy of any ambitious modelling program; but mechanisms for facilitating better communication and coordination between different efforts need to be considered.

ACKNOWLEDGEMENTS

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REPORT FROM WORKING GROUP I: THREE-DIMENSIONAL TURBULENT MIXING
Chair: W. Large

PREMISE

The entire spatial and temporal spectrum of 3-D turbulent mixing must be parameterised in Ocean Climate Models (OCMs). This mixing is the net result of numerous ocean processes, and may be in any direction. Since it directly determines surface layer properties, including temperature, 3-D turbulent mixing is especially important in coupled OCMs. However, the charge to the working group was limited to the Ocean Surface Boundary Layer (OSBL) and to diapycnal mixing of the ocean interior. Nonetheless, other instances when a process might be important were noted. The ultimate product of the working group should be an overall assessment of what parameterisations are needed for OCMs, of the adequacy of the observational database, of how well present parameterisations represent the process, and of how to improve those parameterisations that are found to be lacking or non-existent.

REPORT

A. INTERIOR MIXING PROCESSES

A.1 Internal Waves (Breaking)

Thought to be the major contributor to diapycnal mixing throughout the interior. Always parameterised as downgradient diffusion, but there are different forms for the eddy coefficients. Often the diffusivity is constant with the viscosity somewhat larger i.e., turbulent Prandtl number greater than 1, and perhaps of order 10. However, the physical value of the Prandtl number is not known. A competing form has the eddy coefficients varying inversely with the buoyancy frequency, N, but this is not supported by measurements which suggest that the coefficients are independent of N. The most relevant observations are microstructure measurements and deep tracer release experiments. In the seasonal thermocline these support the downgradient diffusion parameterisation with a diffusivity of .1–.2 cm^2/s. The observations are showing that these coefficients are much larger, by a factor of 10 or more, throughout much of the deep water column above rough topography in the South Atlantic. This enhanced mixing can be related to the generation of internal waves by tidal interaction with the topography, and the subsequent vertical propagation of these waves. Further discussions of this process is reported in Section A.4, below.

A.2 Shear Instability (Kelvin-Helmholtz)

Parameterisation of vertical mixing as a function of the Richardson number, R_i, has been proposed to take into account the role of shear instability in the ocean interior. Some studies with models using a relatively high vertical resolution has shown that this kind of parameterisation could significantly improve the result. However, this might not be the case in ocean models used in climate studies, since the resolution in the ocean interior is generally not sufficient to have a good estimate of R_i. The question is is it possible to modify the parameterisation in order to make it useful at a coarse resolution by, for example, making it dependent on the vertical resolution, or is it impossible to account for this process unless the vertical resolution is increased. In this case, what is the minimum vertical resolution needed? It is noted that this is an issue only at the equator where there is sufficient vertical shear generated by the westward wind shear and eastward undercurrent to produce small enough values of R_i.

A.3 Double Diffusion

A true physical process that appears to occur in several ocean regions. Parameterisations in term of the density ratio, or Turner angle are available, but these have not been rigorously tested. The main reason for this state of affairs is that salt fluxes, unlike temperature fluxes, cannot be inferred from microstructure measurements. Also, most of the ocean measurements have gone into the parameterisations and that only a few values of density ratio are found in the ocean. The sensitivity of

Ocean Climate Models to these parameterisations needs to be assessed. If high sensitivity is found, there is a problem, because the parameterisations are based only on indirectly inferred fluxes of heat and salt.

A.4 Tidal Mixing

Tides are not included in most ocean models at present including stand-alone and coupled ocean climate models. Therefore, tidal mixing and its effects on properties, such as SST are not accounted for, either implicitly or explicitly.

Tidal mixing is of primarily three types: (a) mixing in shallow water – continental shelves – barotropic tides, (b) interior mixing – thermocline and below – internal tides, and (c) benthic mixing – flanks of ridges, seamounts – currents.

Barotropic tides are well known. Barotropic tidal currents in shallow and deep water are also well known and modelled well. Mixing due to barotropic tides in shallow regions is easily parameterised.

Internal tides, long regarded as unimportant, are now being regarded as consequential and in some regions indispensable to ocean models. Not as well known as barotropic tides, but progress is being made. Approximately 20% of tidal power input by the moon and the sun may go into internal tides generated at mid-ocean ridges, island chains, etc. This is far in excess of the power required to produce abyssal mixing levels of $10^{-5}m^2s^{-1}$ and significant fraction of $10^{-4}m^2s^{-1}$ needed for thermocline maintenance. Interior tidal mixing is thought to be important for SST maintenance in regions such as the Bay of Bengal, and the western tropical Pacific.

Enhanced mixing around topographic features (due to topographic gradients and benthic roughness) gives rise to elevated AND inhomogeneous diffusivities (in both horizontal and vertical) that may have a profound effect in ocean models on aspects such as meridional overturning and spin-up. Ocean models use at present a constant value for diffusivity (or one based on N) and do not account for the enhancement or inhomogeneity.

Tidal mixing in shallow water is also important to SST maintenance and other aspects in many regions.

CONCLUSION: Tidal mixing must be included in ocean models, including ocean climate models. The question is one of strategy.

Tides can be included explicitly in ocean models. However, resolution requirements (20 km for barotropic and 10 km for internal tides) are prohibitive for climate type ocean models.

The best strategy is to parameterise tidal mixing via a 3-D map of diffusivities prescribed *a priori.* Determination of these diffusivities, however requires a high resolution ocean model with explicit astronomical tidal potential included in its forcing, sufficient vertical resolution provided to resolve mid-ocean ridges, etc. and run for a period to encompass spring-neap tidal cycle.

Sensitivity runs with current ocean climate models should be run, with enhanced, inhomogeneous interior mixing (crudely parameterised if need by) to assess its potential impact. This is the first step. This should be followed up by high resolution tidal model runs from which a 3-D diffusivity map could be derived and used in ocean climate models. Tidal mixing effects can no longer be ignored.

B. OCEAN SURFACE BOUNDARY LAYER PROCESSES

There are numerous processes at work within the Ocean Surface Boundary Layer (OSBL). Those discussed include wind mixing, boundary layer convection, surface wave breaking, Langmuir circulation and deep convection. None of these is believed to be adequately treated by a constant depth layer that is perfectly well mixed. Bulk mixed layer models produce variable depths of the perfectly well mixed layer, and are based largely on energy arguments. As such they are better representations of wind and buoyant mixing, but may not extend the small-scale fluxes of heat, salt and momentum below the mixed layer as well as some turbulent closure models.

B.1 Surface Wave Breaking

Mainly concentrated in the upper few meters, and so is not resolved at the vertical resolution of climate models. The implicit assumption with such models is that the uppermost grid is well mixed, because of processes like surface wave breaking. However, any attempt to refine this assumption to allow for diurnal cycling, and surface skin layers, must include surface wave effects.

B.2 Langmuir Circulation

An apparent discrepancy between observations and high resolution turbulence modelling, namely *large eddy simulations* (LES), was noted. The former appear to show Langmuir activity confined to the upper 2/3 or so of the mixed layer, although the data base is insufficient to be definitive. In contrast, the latter show it penetrating into the stratification at the mixed-layer base. The implications regarding the OSBL are very different, with the model penetration of Langmuir circulation having a profound effect. Before any attempt to parameterise Langmuir circulation in Ocean Climate Models, this discrepancy must be resolved, and it is recommended that the two communities involved get together to do so.

B.3 Ocean Deep Convection

The parameterisations that are presently used are simple mixing of unstable layers in an iterative process that may leave residual static instability, complete mixing of unstable stratification, and mixing that allows also for the turbulent energy due to convection resulting in further mixing below the unstable stratification.

Tests have been performed comparing physically fuller models to non-hydrostatic models. The conclusion is that simple parameterisations reproduce the initial convection reasonably well. Nordic and Labrador Sea observations of convection are available to perhaps test fuller models.

The outstanding problems are as follows: (a) artificial multiple equilibria of convective patterns in the absence of stochastic forcing, (b) representation of capping of convection, and (c) a determination of what horizontal resolution is required.

The overall evaluation is that deep convection parameterisations themselves do not seem a critical area needing further improvement, but the capping process and other lateral transport processes need parameterisation and verification.

These processes determine the final water mass properties and result in convective water masses not being uniformly mixed. convective adjustment might be fine if the models had a 1 km resolution. At lower resolutions, parameterisation of the interplay of vertical convection and horizontal restratification, via mesoscale eddies, is crucial for accurate description of the water mass creation process. Accurate sea ice models are also crucial.

B.4 Lateral Mixing in the OSBL

Clearly OSBL turbulence acts to mix in all directions, but the numerical horizontal diffusion implicit in Ocean Climate Models would seem to much larger than the explicit turbulent mixing, so the latter can be safely neglected, as is usually the case.

C. OTHER RELATED ISSUES

C.1 Surface Boundary Conditions

Although outside the purview of the working group, surface boundary condition were frequently discussed, because the performance of OSBL models depends so critically on them. This fact makes evaluation and intercomparison of OSBL models complicated and often ambiguous. It was noted that boundary conditions with both the atmosphere and overlying sea-ice are important issues.

C.2 Diurnal Cycle

The diurnal cycle of solar heating can cause the daytime turbulent layer to be considerably shallower than at night, especially where winds are light. The SST may also cycle diurnally, typically by

0.1–0.2°C (e.g., Brainerd and Gregg, 1993) though in very light winds, it may range by 0.5° or so (Price et al., 1986).

The daytime trapping of the wind-stress near the surface strengthens the time-mean Ekman velocities there (Price et al., 1986; Price et al., 1987), and creates shear in the time-mean velocity throughout the (apparently mixed) night-time mixed layer. This has implications for the advection speeds of surface trapped (buoyant) particles, and ice.

Resolution of the diurnal cycle requires different tuning of mixed-layer models, especially Kraus-Turner energy budget models, as overnight convection destroys potential energy.

SUMMARY OF MAJOR RECOMMENDATIONS

- That the effects of tidal mixing in shallow shelf regions, where the main thermocline intersects mid-ocean ridges and over rough topography be incorporated (although perhaps simply at first) into Ocean Models for Climate. The high resolution WOCE hydrographic lines display features which may be signatures of these effects, and so could be a valuable evaluation data set.
- That Ocean Climate Models test their ability to represent ocean deep convection in conditions similar enough to those observed recently in the Labrador and Greenland Seas to allow the observational data sets to be used for evaluation purposes. An important feature will be the ability of the models to restratify as observed.
- That the sensitivity of Ocean Climate Models to double diffusion parameterisations be assessed.
- That the overall effects of vertical mixing be assessed by comparing the strengths of the seasonal and permanent pycnoclines to the high resolution WOCE hydrographic sections.

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REPORT FROM WORKING GROUP II: BOTTOM BOUNDARY LAYER PROCESSES
Chair: A. Beckmann

1. SUMMARY AND RECOMMENDATIONS

Bottom boundary layer (BBL) and near bottom processes in the ocean have not received much attention in large scale and climate modelling until recently. It is, however, quite clear from modelling efforts like DYNAMO (DYNAMO Group, 1997) that the large scale circulation and water mass distribution depends critically on BBL processes, like

- the downslope flow of dense water,
- near bottom mixing,
- rectified along slope flows,
- boundary wave propagation, and, to a lesser degree,
- upslope flows.

The working group discussed our current knowledge of these processes and their importance, their representation in today's ocean circulation models, and the availability of data sets suitable for model validation.

A theoretical understanding of the above processes is more or less developed. While there is a theoretical basis for both rectified flows and boundary wave propagation, the entrainment and detrainment rate in dense water plumes (and their dynamical behaviour) is only known roughly from observations.

With respect to model representation of near bottom processes, it was agreed, that geopotential models of currently used resolutions do need a separate BBL submodel. It is not clear, whether isopycnal and terrain-following models can get away without such a submodel, and only a moderate increase in vertical resolution. It is also unclear how to deal with the large sensitivity to small changes in topography for geopotential coordinate models and how smoothing of the topography (as needed for coarse resolution terrain-following models) degrades the representation of BBL processes.

Data sets (climatological and synoptic) are available but with a few exceptions have not been systematically edited for near-bottom/BBL phenomena.

As a result of the presentations and discussions, the following recommendations are made:

- Further work is necessary with respect to all five different areas of near-bottom/BBL dynamics and their representation in climate ocean models, with clear emphasis on downslope flow of dense water masses and the associated near-bottom mixing (entrainment, detrainment).
- A variety of idealised process studies is necessary to increase our understanding of the dynamics of near bottom flows, and their representation in numerical ocean models; this includes models of all three vertical concepts (geopotential, terrain-following and isopycnic), as well as new developments in BBL submodels. These studies need to be accompanied by laboratory studies and high resolution measurements in areas of down-slope flows (especially the Irminger Sea and the Gulf of Cadiz). An additional reference solution, especially with respect to the rates of entrainment in dense bottom water plumes, can be obtained by *large eddy simulations* (LES).
- Independent of these studies, coordinated modelling studies need to be conducted on the representation of downslope flows in coarse resolution basinwide models, first of all in the North Atlantic, where the data coverage is best. Sensitivities to bottom friction, newly developed BBL submodels, and mixing schemes need to be explored. Additional experiments should focus on high latitude oceans.

- A systematic investigation should be initiated to focus on the dependence of adjustment time scales on model factors (resolution, vertical coordinate, effect of BBL submodels on boundary wave propagation). This should be combined with a study of the impact of inclusion of rectified flows in ocean climate models.

- Existing data sets (both climatological and synoptic, with special emphasis on recent WOCE data) need to be scanned for high quality near-bottom data. Data products focusing on BBL measurements would be helpful for model validation. Global maps of bottom roughness, near-bottom mixing, tidal energy and rectified flows need to be compiled.

2. WORKING GROUP AGENDA

The purpose of this working group was to identify the climate relevant near-bottom/BBL processes, to report on recent improvements in the modelling of these processes and to point out necessary further research. The main questions for this working group were:

1. Which BBL and near-bottom processes are relevant for climate and climatic variability?

2. How are BBL processes represented in today's climate ocean models? Which model configurations exist to test the representation of BBL processes?

3. Which existing observational BBL data sets are suitable for quantitative model evaluation? Which diagnostic quantities can be used to assess the performance of climate models with respect to relevant BBL processes?

The working group was very well attended (~25 participants), equally well representing the areas of observations, theory/process studies, and large-scale and climate modelling.

3. WORKING GROUP FINDINGS AND CONCLUSIONS

The working group discussed near-bottom processes that are directly or indirectly influenced by the lower boundary of the ocean, i.e., by bottom stress, bottom roughness, and sloping topography. This includes phenomena like the deep western boundary currents, rectified flows along the shelf break, and boundary waves.

This rather wide definition of BBL processes reflects the fact that the relative coarseness of the near-bottom vertical resolution in today's ocean models does not resolve the frictional boundary layer, thereby increasing the upward influence of the lower boundary.

Most issues were discussed without controversy, partly because all participants agreed that a lot of more work needs to be done in this area.

3.1 Identification of climate relevant processes

The most obvious climate-relevant near-bottom process is the **downslope flow of dense water,** as it occurs after overflowing sills between ocean basins (e.g., south of the Denmark Strait, south of the Faeroe-Bank Channel, west of the Strait of Gibraltar) or in form of drainage of shelf water masses (e.g., from the Barents Sea and Western Weddell Sea shelves). This process and the associated entrainment and detrainment due to **near-bottom mixing** determines to a large degree the characteristics of deep water masses, their circulation, and, in cases of quasi-continuous downslope flow, the depth and strength of deep boundary currents. At the same time, there are fundamental deficits in the representation of these processes in most climate ocean models, which are mostly of the GFDL model type with geopotential coordinates (see also Section 3.2). Bottom plumes exhibit a rich phenomenology. Strong density contrasts between these plumes and the ambient water masses, and steep topographic slopes cause instabilities (meandering) of the downslope flow; complex topography and bottom roughness will influence the path of the bottom water masses. The parameter dependence of the plume dynamics is still incompletely understood.

Another important near bottom process is the **rectified flow,** arising either from tidal forcing or eddy form stress. Global tidal model results show that rectified flows are typically cm s^{-1} to tens of cm s^{-1} (C. LeProvost), and will have an effect on the water mass structure and overturning in long-term integrations. It is now possible to generate global maps of mean flows from barotropic tides (as well as tidal energy, which could be used for parameterisation of tidal mixing). The generation of rectified flow by eddy form stress (Holloway, 1992; Alvarez and Tintore, 1998) has to be considered an equally important process; locally, however, the relative importance of the two mechanisms is unknown. Neither of these effects, which in general produce cyclonic circulation around ocean basins, is implemented in today's climate models, and there was an agreement among the working group participants that this leads to systematic errors, especially for integrations of decadal and longer time scales.

The adjustment process following a perturbation in an area with sloping topography occurs in two phases; a relatively fast wave response and a slower advective response (Gerdes, 1995). Then, **boundary waves** are responsible for propagating the information in a prograde direction. By this process, a climate signal can be transmitted from high to low latitudes within months. Both barotropic and (bottom-intensified) baroclinic coastally trapped waves depend on the topographic factors (bottom slope, bottom roughness), which influence phase and group velocities, and damping. And while there are reports that the initial wave signal can sometimes be observed, it is unclear whether or not there is a strong net effect on climate and climate variability.

Finally, **upslope flows,** either directly wind-induced or due to the secondary circulation of along-boundary flows, were identified as potentially important for climate modelling; however, there was no direct evidence presented for it.

In conclusion, the highest priority was given to down-slope flows and related near-bottom mixing. This process is extremely important for climate and climate variability studies, because the strength and structure of the large-scale thermohaline circulation and deep water mass distributions depend on this rather small-scale process, and the sensitivity of the ocean climate to, changes in downslope transports is large. An coordinated effort seems necessary, because this process is not very well represented in today's climate ocean models of the GFDL type and the entrainment/detrainment is still poorly understood. Studies in this area have to rely on high resolution model experiments in combination with laboratory studies and small-scale field studies (e.g., Krauss and Käse, 1998), for comparison and validation.

3.2 Representation in today's climate models

It can be asserted that BBL processes are not very well represented in today's climate ocean models. Most of the vertical resolution is usually placed near the surface, such that the bottom boundary layer is not well resolved (see, e.g., Beckmann, 1998). In addition, the currently employed parameterisations (linear or quadratic bottom friction) are rather simple; e.g., they do not consider bottom slope or roughness.

It has been demonstrated (DYNAMO group, 1997) that standard models (independent of the vertical coordinate) have enormous difficulties to get **downslope flow** right, even in eddy-permitting 1/3° experiments. It is important to know the right amount of entrainment and detrainment in such plumes, and then to make sure that the model is actually able to reduce the implicit mixing to or below that value. This places different constraints on different model types: It was agreed, that geopotential models of currently used resolutions need a separate BBL submodel (although a case was presented where the solution of a z-coordinate model seems acceptable). It is not clear, if isopycnal and terrain-following models can get away without such a submodel, and only moderate increase in vertical resolution. It is also unclear how smoothing of the topography (as needed for coarse resolution terrain-following models) degrades the representation of BBL processes.

With respect to geopotential coordinate models, several recent approaches exist which specifically try to improve the representation of dense water plumes. Beckmann and Döscher (1997), Killworth and Edwards (submitted) and Gnanadesikan (submitted) have independently developed BBL submodels, which improve this aspect of the BBL dynamics. So far, they have been applied to idealised configurations, and are currently being tested in coarse resolution basin-wide models (Döscher and Beckmann, submitted; FLAME group, in preparation). A systematic intercomparison, however, has not been performed.

Several idealised test cases exist to investigate aspects of the downslope flow of dense water. There is the widely used "dam-break" plume configuration of Jungclaus and Backhaus (1994), which has been adopted by Jiang and Garwood (1995) and Beckmann and Döscher (1997). Here the short term evolution of a dense water plume over sloping topography is investigated. Another test configuration considers the steady state solution (Winton et al., 1998). All these test problems yield more or less plausible solutions, which cannot be quantified. This is in part due to our ignorance of small scale near-bottom mixing and the corresponding entrainment/detrainment in such plumes. We therefore need high resolution studies in areas, where high resolution measurements are available. Such studies exist in the Gulf of Cadiz (Jungclaus and Mellor, 1998).

The parallel utilisation of alternative vertical coordinate systems (terrain-following, isopycnic) is highly recommended, because much can be learned from comparing and combining different approaches.

At the same time, the representation in climate models with much less resolution needs to be investigated systematically. The best testing ground for numerical representation of BBL processes in ocean models is certainly the North Atlantic, where our knowledge on all aspects of the ocean circulation is best and the modelling is most advanced. In such a realistic configuration, the BBL process can be studied in connection with other competing processes, like surface forcing, advection of other water masses, etc.

Rectified flows are not considered in today's climate models, and it is unclear how to best implement their effects. Methods exist (which all amount to some form of restoring to precomputed data sets), but are not generally accepted.

The representation of **boundary waves** in coarse resolution models needs to be explored systematically, as they set the fast time scales for transmitting changes in the thermohaline circulation. It has been demonstrated (Gerdes, 1993) that these waves depend on the representation of topography in ocean models. Differences have also been shown to exist in different resolution models of the North Atlantic (Döscher et al., 1994). The relative importance might be highly dependent on resolution, mixing, representation of topography, etc. Here again, the vertical coordinate of the ocean model is important, as well as the prescribed near bottom mixing.

3.3 Existing BBL data sets

Detailed data sets have been collected in the Irminger Sea (Dickson and Brown, 1994), the Gulf of Cadiz (Zenk), and the high latitude areas of the Barents Sea (Schauer, in preparation) and Western Weddell shelves (Gordon, 1998). We can therefore list a few representative numbers that can be used as constraints for numerical models.

For both the Denmark Strait and the Mediterranean Outflow we have estimates of the sinking and entrainment: in the Irminger Basin, sinking occurs at a rate of 5–10 m km^{-1} for the first 200 km and 1 m km^{-1} thereafter (Dickson and Brown, 1994). The value in the Gulf of Cadiz is about 5 m km^{-1}. The entrainment rate is roughly 20–25% per 100 km.

With respect to near bottom mixing we can now discriminate typical values in different areas of the world's ocean: (a) central basins with $0.1–0.2 \cdot 10^{-4}$ m^2s^{-1} (b) very localised (e.g., steep flanks of seamounts) with $2 \cdot 10^{-4}$ m^2s^{-1}, and (c) even $10 \cdot 10^{-4}$ m^2s^{-1} at the upper flanks of a particular seamount (Fieberling Guyot). The vertical scale is several 100 m (Toole, 1998).

Data from CFC measurements and the deep ocean tracer release study can be used to compare and validate the mixing and spreading of water masses in ocean models in the deep basins. However, the general question is how well climatologies represent the existence of bottom plumes, their paths, entrainment etc. For example, the climatologies of Levitus (1982) and Reynaud differ quite drastically in their near bottom temperature and salinity distributions.

Diagnostic quantities which determine the quality of climate models with respect to BBL and near-bottom processes are the large-scale overturning streamfunction in density space, the corresponding meridional heat transport, and volumetric TS-diagrams.

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REPORT FROM WORKING GROUP III:
MESOSCALE PROCESSES
Chair: P. Gent

There was unanimous agreement on the following issues:

1. An eddy parameterisation must ensure a domain average positive definite sink of total energy. It is not necessary to have a domain average sink in the PE and KE budgets separately, as in the GM forms. However, see point 11 below.

2. Schemes where the eddy-induced velocity is proportional to the gradient of PV should not be used at the equator. Perhaps the value of κ should be reduced near the equator in climate models with enhanced meridional resolution.

3. Evidence from eddy permitting and resolving model solutions indicates that the isopycnal kappa should depend on the mean flow, and maybe other variables. Visbeck et al. and Killworth have proposed schemes. Work with the Visbeck et al. scheme shows that this may be more important at 1 deg., than 2 or 3 degs.

4. For diabatic runs, everyone was happy with imposing diapycnal or vertical diffusion, which is the small slope approximation to diapycnal diffusion.

5. The best way forward to test parameterisations is to analyse very high resolution model runs, rather than to analyse the rather sparse observations. However, see point 12 below.

There was less of a consensus on, but a majority in favour of, the following issues:

6. The momentum equation should be for the mean velocity, not for the effective transport velocity. Thus, the KE is half the square of the mean velocity, and the eddy-induced velocity in the tracer equations has to be parameterised. Smith justifies this choice because the resulting correlations are easier to parameterise. Greatbatch disagrees with this choice, and advocates that, at midlatitudes, the momentum equation should be for the effective transport velocity.

7. The form of the PV equation need not be the same as the T and S equations. One reason is friction in the interior due to breaking waves, for example.

8. The need for horizontal mixing in the surface mixed layer, and possibly the bottom boundary layer, as proposed by Treguier et al. Again, this may be more important at 1 deg, than at 2 or 3 degs.

There was no consensus or agreement on the following issues:

9. About the relevance of Fofonoff gyres, which occur in the inviscid, barotropic limit. Must an eddy parameterisation allow solutions of this type?

10. About whether the correct boundary conditions are $w^* = 0$ at top and bottom. Killworth showed that this isn't true for the Eady problem, and argues that it should not be used in climate models. However, McDougall and McIntosh argue this is the correct boundary condition for an eddyless model, where one has to interpret the model's density variable in a very specific fashion (the distinction being whether one averages density at fixed height or height at fixed density). Several climate modelling groups seem happy tapering κ to zero near the surface in the mixed layer.

11. About the need for a parameterisation of the Neptune type. Holloway states that a model that allows a resting steady state is wrong. The reason is that there is subgrid energy, not resolved in climate models, that locally forces a mean flow, but the relation between the two is not yet understood. Holloway and Killworth argue for additional eddy sources of both mean KE and PE, from unresolved motions, but the correct way to do this is not clear. Greatbatch has proposed an implementation of a Neptune-like effect as a bottom boundary condition, rather than relaxation to a barotropic streamfunction. This has not been thoroughly tested, but it

seems more physically plausible to me to implement something at the topography, and let the effect propagate upwards in the water column, rather than to impose a barotropic relaxation term. Holloway disagrees with this opinion from "an entropy perspective".

12. About precisely what quantities should be analysed from high resolution runs. McDougall and McIntosh's work uses an averaging operator which is a pure time average. They advocate that the quantities to be analysed are:

    (a) the thickness weighted tracers at constant density, including potential temperature and salt, and

    (b) the eddy-induced velocity, which is the difference between the thickness-weighted velocity at constant density and the Eulerian mean velocity at a fixed depth.

    Smith, and others, I believe, advocate that the eddy-induced velocity should be the difference between the thickness-weighted velocity and the Eulerian mean velocity, both evaluated at a constant density.

13. About the need to get much stronger western boundary currents in climate ocean models. Do stronger WBCs just locally recirculate water at the same temperature, and so not contribute to poleward heat transport? The question here is can ocean climate models get the correct mean climate and climate variability with realistic transport, but unrealistic speeds, in their WBCs? This question has not yet been answered well. Is the only way forward to do somewhat higher resolution, possibly coupled, runs?

The working group spent less time discussing how to proceed in improving eddy parameterisations and their implementations, but my impressions are:

If higher resolution runs are to be analysed, then the higher the resolution the better. There are two very high resolution runs of the N. Atlantic Ocean, using the POP and MICOM codes, but not yet of the global ocean at 1/10 deg. Willebrand suggests doing a run with one of these codes for a few years with only fluctuating atmospheric forcing, starting from a state of rest. This would enable the magnitude of the rectified circulation to be estimated.

Several of the different parameterisation choices could be tried in ocean models used for climate. I think the best resolution to do these runs would be a global 1 degree model, as I believe this will be the standard resolution for climate models in 3 years time, even if some climate runs use higher resolution. Then the question is what WOCE data can be used to verify these climate resolution runs over and above the comparisons with Levitus data that we tend to rely on at present? There are numerous high resolution WOCE hydrographic and tracer sections, with some in the southern oceans. There will also be the tracer inventories that should be used to verify the models.

REPORT FROM WORKING GROUP A: MERIDIONAL OVERTURNING IN THE ATLANTIC

Co-Chairs: R. Wood and C. Böning

1. SESSION OVERVIEW

The meridional overturning circulation (MOC) plays a key role in the northward transport of heat in the North Atlantic, and hence in the climate of Western Europe. The MOC has been extensively studied using a variety of models, and it has become clear that the large scale circulation is dependent on a number of modelling details, for example parameterisation of diapycnal mixing (Bryan, 1987) and representation of sill overflows (Roberts and Wood, 1997) and downslope flow (Roberts et al., 1996; Döscher and Redler, 1997; DYNAMO Group, 1997). The working group attempted to identify key questions and areas for coordinated modelling studies on the MOC, rather than making a comprehensive review of the field.

The group discussions were split into two sections: the circulation of the subpolar region and the meridional circulation in the subtropical North Atlantic (together with wider issues). For each of the two sections the group considered three questions, essentially aiming to identify what is known observationally, which features of the circulation are important for modelling climate on decadal timescales, and what modelling developments are required. The main features of the discussion are presented below in sections 2 and 3, and recommendations are summarised in section 4.

2. SUBPOLAR REGION

2a. What is known about the development of the southward transport of NADW in the subpolar North Atlantic? Which datasets could provide a baseline for model testing and intercomparison?

A quantitative picture of the circulation of water denser than $\sigma_\theta = 27.8$, from the overflows in the Greenland-Iceland-Scotland Ridge to Cape Farewell, based on current meter observations, is available and contains some robust features. This picture is summarised in Fig. 1 (courtesy P. Saunders; see also Dickson and Brown, 1994). There is little increase in the transport of Iceland-Scotland overflow water (ISOW) downstream from Section B, south of Iceland. The bulk of this water mass is believed to cross the Mid-Atlantic Ridge through the Charlie Gibbs Fracture Zone; however, recent CFC data suggests there may be some penetration of this water mass south of the Charlie Gibbs Fracture Zone in the Eastern basin (M. Rhein, pers. comm.).

The estimates of the downstream increase in transport of Denmark Straits Overflow Water (DSOW) are based on current meter sections which, although unique, are still 'snapshots' on decadal timescales. There is a suggestion that the Cape Farewell section may have been observed during a year of untypically strong flow there (Bacon, 1998); this remains controversial. The Greenland-Iceland-Scotland outflow and entrainment rates are prime targets for model testing, and because of their importance in driving the large scale circulation should be a priority for observational programmes (see also the notes from WG II, Bottom Boundary Layer Processes).

There is as yet little quantitative knowledge of the annual-mean transport of the deep boundary current in the Labrador Sea; a valuable target for models is expected soon from a multi-year Canadian-German current meter array near 53°N. A most important constraint for models would be the net export of North Atlantic Deep Water (NADW) from the subpolar region, around 43°N. Information is expected from direct current meter measurements at this latitude (Clarke et al., 1999) which coincide with the western end of a transatlantic section (WOCE A2) which has been repeated several times (Sy et al., 1997a). The western boundary current here includes a large recirculation component, but combining the two data types promises to give a constraint on the southward transport of dense water as it leaves the subpolar gyre.

Transport measurements for the East Greenland Current (EOC) at 75°N vary between 4 and 8 Sv (McCartney and Talley, 1984; Woodgate et al., 1999). The latter estimate is based on current meter measurements. Surface freshwater flux for the Labrador Sea is also uncertain (see 2b below).

Figure 1

Labrador Sea Water was more abundant in the 1990's than in the 1970's. Variability in the surface fluxes and export of freshwater from the Arctic, associated with the North Atlantic Oscillation and reflected, e.g., in the Great Salinity Anomaly, is thought to be implicated in this (Dickson et al., 1996; Clarke and Yashaeyev, 1999). It is unknown as yet to what extent changes in the underlying stratification of the Labrador Sea could also be important. The importance of high-frequency forcing variability is not known. The depth of winter mixing in the central Labrador Sea increased from 500 m in the 1960's to 2300 m in the 1990's (Rhines et al., 1998). Mixing in the Irminger Sea is thought to reach 600 m (McCartney and Talley, 1982; Bacon et al., 1998).

An additional test of models can be provided by tracer data. Tracer, e.g., CFC distributions in the deep water, reflect the ventilation of this water mass, i.e. the intensity of the contact with the surface layer. Specifically, the onset of deep convection in the Labrador Sea tagged the newly formed LSW with a unique tracer signal which was used to estimate the spreading paths and time scales of spreading, i.e. 5–6 years into the eastern North Atlantic (Sy et al., 1997b) and 8–10 years in the DWBC to 26.5°N (Molinari et al., 1998). Both estimates implied mean spreading velocities of 2–2.5 cm/s (not to be confused with the probably much higher spreading rate of dynamic signatures by boundary waves). CFC measurements show two cores in the deep western boundary current, corresponding to Labrador Sea Water (LSW) and Overflow Water. These cores are less obvious in geostrophic velocity estimates, because the flow has a strong barotropic component with no level of no motion (Sy et al., 1997a). About 1–2 Sv of LSW passes through the Flemish Channel (M. Rhein, pers. comm.).

2b. What features of the circulation are important for climate models?

The East Greenland Current and its extension into the Labrador Sea are believed to be important for the Labrador Sea freshwater budget.

The sensitivity of the mean MOC to changes in the Labrador Sea surface buoyancy flux depends on the strength of the Nordic Sea overflows (Döscher and Redler, 1997; Lohmann, 1998). In a coupled model, Labrador Sea convection and circulation may be more sensitive to anthropogenic climate change than the Nordic Sea overflow (Wood et al., 1999). Hence correct modelling of the distribution of deep water formation between these two sources is important (also the underlying water mass structure of the Labrador Sea – see 2a above). Further, the distribution of overflow water between the Denmark Straits and the Faroe Bank Channel has been shown to affect the path of the North Atlantic Current in a GCM (Redler and Böning, 1997).

A number of ocean and climate models have poor representations of the path of the North Atlantic Current in the Newfoundland Basin. There have been suggestions that the properties of the Nordic Sea outflows are involved, but it is also possible that deficits in the local representation of the WBC dynamics and the topographic interaction along the Grand Banks are to be blamed. The differences, e.g., between realisations of level and isopycnal models (e.g., Roberts et al., 1996; DYNAMO Group, 1997) appear greatly reduced at very high resolution (Bryan and Smith, 1998; E. Chassignet, pers. comm.); the critical model factors governing the behaviour of coarser models have not been identified yet. This is an important area for improvements of ocean climate models, since a shift in the position of the subarctic front in the Newfoundland Basin can lead to large local surface heat flux anomalies; the consequences for simulations of climate variability are not known.

The dynamics of the response of the deep flow to perturbations in the deep water formation regions appear important for variability on the decadal timescale; hence testing and comparing the adjustment to specified forcing anomalies of models differing in resolution, representation of topography, or parameterisation of small-scale physics (passage throughflows, downslope flows, lateral mixing, deep convection) should be included in model development efforts.

2c. What are the key modelling factors that limit a realistic representation of the features identified in 2b? How well do present models perform, and what developments are required and feasible?

A number of important features of the circulation are poorly represented at current (order 1 degree) climate model resolution. These include:

- Sill overflows. Dense overflows from the Nordic Seas take place largely through channels with width of order 10 km, which are not resolved by climate models. See reports of WG II and WG C for further discussion.

- Boundary currents. Examples are the East Greenland Current and the North Atlantic Current, discussed in 2b above. In the case of the North Atlantic Current, resolution is an important factor but not necessarily the only one.

- Convection. Simulated convection patterns in the Greenland, Irminger and Labrador Seas vary widely between models, and between model realisations with different resolutions and eddy mixing parameterisations, e.g. Gent and McWilliams. The sensitivity to the various modelling factors, particularly to lateral mixing schemes, has not been explored.

3. SUBTROPICAL MOC AND WIDER ISSUES

3a. What are the important elements of the large-scale structure of the MOC that models need to reproduce?

The most commonly used model diagnostic of the MOC is the meridional streamfunction in z-space. This does *not* just show the thermohaline circulation, since flow along sloping isopycnals (e.g. in the subtropical gyre), and barotropic circulations over sloping topography also give a signal. The overturning streamfunction in density space focuses attention on flows where water mass transformations are taking place, but can give a misleading picture if the model is in an unsteady state. A 'water mass transformation streamfunction' has been proposed in this case (Nurser and Marsh, 1998).

The currently best estimates of the MOC are those obtained from hydrographic sections. Basically two approaches have been applied to solve the underdetermined problem: one method needs mean transports from Western Boundary Current measurements (Hall and Bryden, 1981); the alternative is to impose additional constraints on the mass balance to derive a solution and error bounds to the inverse problem (Roemmich and Wunsch, 1985). Recent computations for a host of transoceanic sections are due to Macdonald and Wunsch (1996) and Macdonald (1998).

All estimates (using above methods) give a fairly robust result for the net southward NADW flow at 24°N and 36°N, approximately 18 ± 4 Sv. The overall depth structure of the flow at 24°N also appears robust, with southward flow between about 1200 m and 5000 m. Upper and lower lobes can be identified with Labrador Sea and Nordic Seas sources; there is some decadal variation in these, due possibly to variations in the production rate of northern source waters (Lavin et al., 1998).

The six repeats of the 48°N section (Koltermann et al., 1998, submitted) indicate a much higher temporal variability, with NADW transports varying between 12 and 20 Sv, whereas Macdonald (1998) estimates 26 Sv. This may be better constrained when western boundary current data are included (see 2a above).

A qualitative, though potentially useful (for model testing) aspect of the latitudinal structure of the MOC is that there is no evidence of NADW production south of 48°N, with the possible exception of some effect due to the Mediterranean Outflow water around 40°N.

A useful, additional constraint on the structure of the southward flow is provided by tracer distributions. In particular, in contrast to the mean Eulerian velocities (e.g., as seen in long-term measurements near 26°N), CFCs exhibits two deep maxima in the Deep Western Boundary Current. The shallower core characterises the water renewed by deep winter convection in the Labrador Sea, the deeper one reflects the intense ventilation of the Denmark Strait Overflow north of the sills. In the tropical Atlantic, the lower CFC core coincides with the Eulerian velocity core, but this is not the case for the upper NADW, for which there is less topographic constraint of the flow (Rhein et al., 1995; Rhein at al., 1998).

3b. What features of the MOC are important for climate models?

The strength of the MOC seems to be driven largely by the difference between the deep densities of the subpolar North Atlantic and the *south* (rather than equatorial) Atlantic. This in turn is influenced by the surface forcing of the deep water production regions (see 2a, 2b), and by interior mixing (Bryan, 1987; Polzin et al., 1997). Ekman divergence in the Southern Ocean, which drives upwelling of NADW there, may also be a factor.

The stability of the present day MOC is determined by a number of feedbacks. The relative importance of these feedbacks is not clear, but early models using mixed boundary conditions may underestimate the stability of the present circulation. The strength of the atmospheric hydrological cycle appears to be a particularly important factor (Rahmstorf and Ganopolski, 1999).

3c. What are the key modelling factors that limit a realistic representation of the features identified in 3b? How well do present models perform, and what developments are required and feasible?

It is not known how well current ocean models handle the wave dynamics which control the decadal transient response of the MOC to surface forcing changes (Kawase, 1987; Suginohara and Fukasawa, 1988; Döscher et al., 1994). A focused model comparison (perhaps with real forcing), including the relevance of resolution of the western boundary layer, would be useful here (see also recommendations of WG II).

The importance of the Neptune effect for the MOC is not yet clear (see also WGs II and III). It may play a role in, e.g. Gulf Stream separation. Tuning of model parameterisations is a difficulty, because the quantitative effect is not known observationally. It could perhaps be tackled through fine resolution models and limited observational evidence (e.g. Zapiola anticyclone, Dewar, 1998). A particular suggestion put forward at the workshop was to study the relevance of rectification effects, including Neptune, using very high resolution experiments under fluctuating (no mean) forcing.

Coupled GCMs provide the most complete tool for studying the stability and variability of the MOC (because of the many atmospheric feedbacks mentioned in 4b above), but flux adjustments are a source of uncertainty in many coupled models. However some coupled GCMs can now be run without flux adjustments to study this problem (Bryan, 1998; Wood et al., 1999). Modelled MOC stability appears to be dependent on the details of the convection scheme, and on vertical resolution (Marotzke, 1991; Vellinga, 1998), as well as on the other factors above which influence the mean state.

4. RECOMMENDATIONS

The group discussion was lively and wide-ranging. The recommendations below reflect specific points that were discussed, but they should not be considered as an exhaustive list of issues in this area.

4a. Coordinated modelling programmes

Two specific areas emerged during the discussions which should provide important foci for model sensitivity and intercomparison studies. Both are areas where small-scale processes are thought to be important and hence where coarse resolution models (with appropriate subgrid parameterisations) should be tested against fine resolution models:

- Transient dynamical response of the MOC to changes in thermohaline forcing (timescales associated with boundary and possibly equatorial waves, bottom boundary layer flows – also recommended as a focus by Working Group II).

- Subpolar gyre circulation, especially in the Labrador Sea (freshwater budget, especially P-E, East Greenland Current and shelf currents. Convection, and its dependence on surface forcing, underlying water mass structure and interaction with the eddy field).

4b. Baseline datasets for model testing

The group focused on parameters of the circulation which are considered to be robustly known from the current observational dataset, and against which models can be tested. The following parameters were identified:

Subpolar flow of dense water

The flow scheme shown in Fig. 1 for water denser than σ_θ = 27.8 between the Greenland-Iceland-Scotland ridge and the Grand Banks is based on current meter observations and includes some robust elements. There is a suggestion that the flow downstream of the Denmark Strait is subject to considerable interdecadal variability and that the transport shown may be towards the high end of this. The Grand Banks array data are still being worked up. Tracer data can provide valuable additional constraints on the flow (see section 2b).

Meridional Overturning

We concentrate on the overturning in z-space, but note that this may contain contributions which are not thermohaline driven (barotropic circulations over sloping bottom, gyre circulations on sloping isopycnal surfaces).

At 24°N and 36°N, the magnitude of the NADW cell is 18 ± 4 Sv.

There is little unambiguous information at present about the structure of the MOC between 36°N and 60°N. However the following statements can be made:

- There is little evidence for any NADW production south of 48°N, except for possible effects due to mixing of Mediterranean outflow water around 40°N.
- The section at 48°N has been repeated six times. To obtain the meridional overturning the section data must be combined with the Grand Banks current meter array (see above), which covers its western end. This work is planned for the future, and may lead to a very important constraint on the net water mass renewal rate and export of NADW from the subpolar North Atlantic.

5. PARTICIPANTS

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REPORT FROM WORKING GROUP B: SOUTHERN OCEAN DYNAMICS
Chair: M. England

INTRODUCTION

Modelling the (mean and transient) circulation in the Southern Ocean (SO) lags the North Atlantic (NA) by perhaps 10 years. There are probably a number of reasons for this; including sparse density of ocean and air-sea flux data, geographic remoteness of the SO (with respect to countries that fund ocean modelling), and perceptions of the relative roles of each in determining global/regional climate. In addition, the task of modelling the SO on a regional scale is more daunting than the NA – it has a much greater ocean area, wider open boundaries, sparse surface forcing data, important sea-ice interaction, and so on. Whilst NA models have already undergone formal inter-comparison at eddy-permitting resolution (e.g., DYNAMO), been widely used to understand variability processes, and analysed in wide-ranging sensitivity studies (e.g., CME), modelling of the SO has been relatively limited. To date, much of what we know has been derived from global domain experiments and limited to a steady circulation state (notable exceptions include the Fine Resolution Antarctic Model and several process-oriented quasi-geostrophic studies).

WORKING GROUP OBJECTIVES

The objectives of the Southern Ocean (SO) working group included the following:

to identify the key SO processes that need to be captured in ocean climate models

to quantify the best means of testing model performance with regard to these processes

to describe the status of present-day modelling in the SO context

to detail the fundamental limiting factors in contemporary models of the SO

to identify necessary model developments that might alleviate these limiting factors

to define observational programmes that would extend the library of model benchmarks

to identify modelling programmes that will lead to an improved ability to model the SO

WORKING GROUP OVERVIEW

Modelling in the SO spans many model types, including eddy-permitting and coarse resolution, primitive equation, quasi-geostrophic, and regional (with open boundaries) or within a global domain. Present-day coarse resolution models do a reasonable job at capturing key SO water-mass formation processes so long as the GM parameterisation is adopted and some attention is paid to the details of surface forcing near Antarctica. However, recent radiocarbon simulations show that SO ventilation rates can be too slow under GM. Also, in some instances southward surface eddy-induced transports can result if the thickness diffusion coefficient is large (order 1000 m^2/sec or greater), interfering with water-mass transformation processes. Problems remain, in addition, with the representation of bottom boundary flows in z-level models unless a parameterisation for downslope flow is adopted.

The strength and structure of the Antarctic Circumpolar Current turns out to be critical in ocean and climate models, as small errors in its pathway or intensity can result in significant errors in model SST (and therefore air-sea fluxes). This results from poorly resolved topography in coarse models. Eddy-permitting models successfully reproduce eddy kinetic energy density in the circumpolar ocean, although they do not generally resolve deep water renewal processes due to short integration times. Some rely on high latitude interior T-S forcing to capture reasonable Antarctic water-mass properties. In addition, they are computationally expensive and at this stage generally impractical for climate model studies.

Coarse resolution models are likely to improve further as modellers develop schemes to represent subgrid-scale bottom boundary flows and stratification-dependent GM mixing. Further modelling studies are recommended to detail, among other things,

the stability and variability of water-mass formation and circulation in the SO,

an appropriate parameterisation for the GM thickness diffusion parameter κ, and

the role of sub-ice shelf circulation on bottom water production.

Certain observational data products were noted to be of particular importance for models in the SO, both for forcing and validation purposes. Further to those well recognised by the WOCE community, such as poleward heat transport and hydrographic sections, we can list the following to be of high priority in the SO context:

Climatologies of air-sea flux data, regional mean buoyancy fluxes (e.g., in enclosed seas);

Late winter surface/near-surface salinity climatology, especially over the Antarctic continental shelves and over the intermediate water and some mode water formation regions;

Large-scale fields of mixed layer depth, convection depth (especially in late winter);

Climatologies of transient tracer fields (normalised products), including CFCs, tritium/helium, ^{14}C

Eddy fluxes; Heat/freshwater transport *components*.

Water-mass formation rates. Bottom water flow rates through deep SO bathymetry. Bottom boundary layer properties.

Sea-ice thickness.

The possibility of a loosely formatted Southern Ocean Modelling Intercomparison Project (SOMIP) was discussed. Several groups showed an interest in such a project although there was concern over it being overly prescriptive.

WHAT SOUTHERN OCEAN CIRCULATION PROCESSES ARE IMPORTANT FOR CLIMATE (MODELS)?

There was general agreement within the WG that the following processes are critical to capture in ocean models used for climate studies:

ACC (strength, including structure/variability), eddies (or parameterisations thereof), frontal structure. It was noted that there still exists a degree of uncertainty in the mean strength and variability of the ACC, even though a standard value of 120 Sv was often sought by modellers. For model benchmarking, eddy-permitting models continue to rely on satellite products for validating ACC spatial structure (e.g., mean/seasonal sea surface height (SSH), rms SSH variability and eddy KE, wavenumber spectra, and so on), although too often these models simulate rather strong barotropic transports (order 200 Sv). Coarse models do not capture much ACC structure, apart from first-order topographic steering effects, and modellers tend to rely on a standard benchmark check on barotropic transport rates. WOCE pressure measurements will provide better model constraints in the future. More attention needs to be paid to the baroclinic structure simulated by models in the ACC region.

Poleward heat/freshwater transports, (regionally-averaged) air-sea fluxes, sea-ice interaction. Uncertainty remains in the estimates of poleward and zonal heat/freshwater transports. Modellers also noted the need to have full flux component data (Ekman, geostrophic, eddy, etc.). There is a dramatic need for improved climatologies of air-sea heat and freshwater fluxes over the SO. High latitude sea-ice coverage and general remoteness of the SO has left this region with extremely sparse data in this regard. Regional mean buoyancy flux estimations based on horizontal heat/FW transports should be a high priority (e.g., regional seas near Antarctica or oceanic areas enclosed by WOCE sections). The influence of ice processes on the fluxes at the ocean surface is also poorly known and it is thus difficult to assess precisely the importance of these fluxes for the oceanic circulation at regional or global scale.

Water-masses, formation rates, mechanisms, transformation processes. The conventional approach has been to benchmark models against regional mean T-S distributions; often models are poor enough in this context that there is little need to go further than profile comparisons. However, more recently the large-scale mean hydrographic properties of the SO are being reasonably well reproduced by models, so some attention is being made to other more sophisticated tests of model performance, including tracers (CFCs, ^{14}C, tritium, helium, and so on), MLD, convection depth, and formation mechanisms. Unlike the North Atlantic, there is a tendency to overlook actual formation rates, as this is reasonably poorly known for AABW and SAMW/AAIW. Models also efficiently form water-masses via a hydrostatic convection scheme, so actual meridional overturning rates remain ambiguous. More sophisticated water-mass analyses, such as formation mechanisms, tracer budgets, transformation rates and potential vorticity diagnostics, can be recommended for SO modelling studies. Critical water masses include SAMW (which links atmospheric anomalies to thermocline anomalies), AAIW (a decadal time-scale water mass), AABW (key sea-ice and climate interactions), and CDW (which includes a substantial contribution from NADW and whose density controls upper ocean ventilation depths).

Interocean exchange and teleconnections (e.g., Antarctic Circumpolar Wave, Agulhas leakage, Drake Passage throughflow, gyre structures, and so on). These are critical for climate models. Preliminary model experiments have identified an ACW in certain climate simulations, although speed of propagation, zonal wavenumber, and intensity of anomaly are often at odds with the sparse observational record that does exist. The Agulhas leakage of saline Indian Ocean water into the Atlantic is generally missing in coarse resolution models. As mentioned above, exact heat/salt transport rates need to be well measured at such choke-points in the SO. For example, it remains unclear to what degree Agulhas rings leak salt into the Atlantic Ocean, as much of this may be returned in a retroflection into the ACC.

Variability and stability of the above (e.g., thermohaline circulation, water-mass formation, air-sea interaction, ACC, trends in water mass characteristics, variability in AABW outflow rates from the Weddell and Ross Seas, variability of gyre transports, and so on).

PRESENT-DAY STATUS OF MODELLING THE SOUTHERN OCEAN CIRCULATION

How well do present-day ocean models capture the circulation in the SO with respect to the processes detailed above? Rather than focusing on the successes of contemporary ocean models in this regard, it is more useful to concentrate on their weaknesses. These include the following:

In coarse resolution models, the ACC is broad, diffuse, lacking in frontal structure and with no intrinsic eddy variability. Transport rates do, however, normally agree to a reasonable extent with observations. Under GM the ACC slows due to a tendency for isopycnal surfaces to flatten under that scheme. The exact role of thermohaline and wind forcing of the ACC remains unclear, although model studies find a large sensitivity of ACC transport rates to AABW properties. In fine resolution models much of the ACC structure and variability is captured, although barotropic transport rates are generally too high. Benchmarking of coarse resolution models in this regard is mostly superficial: analyses of baroclinicity and zonal fluxes of water-mass properties should also be checked. Eddy fluxes have the right sign under GM in the ACC region, although exact magnitudes remain poorly known, so assessing this quantity remains ambiguous in models.

Deep poleward-flowing eastern boundary currents are generally absent in coarse and fine resolution ocean models; for example, in the eastern Pacific Ocean. This can be rectified by adopting a parameterisation for subgrid-scale topographic stress. Other spurious ocean flow patterns include a tendency for models to put a substantial component of ACC flow north of the Kerguelen Plateau and a near absence of a westward tendency along the Antarctic margin (e.g. underdeveloped cyclonic rim flows around the Weddell and Ross Seas). These erroneous circulation patterns affect the simulated air-sea interaction and bottom water formation in the region.

Water masses, thermohaline circulation. Present-day coarse resolution models do a reasonable job at capturing key SO water-mass formation processes so long as the GM parameterisation is adopted and some attention is paid to the details of surface forcing near Antarctica. However, recent radiocarbon simulations show that SO ventilation rates can be too slow under GM. Also, in some instances southward surface eddy-induced transports can result if the thickness diffusion coefficient is large (order 1000 m^2/sec or greater), interfering with water-mass transformation processes. In terms of model evaluation, detailed T-S analyses are rarely performed (e.g., volumetric census, T-S on isopcynal surfaces, etc.). Generally AABW is too warm and too fresh. A possible reason for this is a too simple representation of sea-ice processes. Sea-ice interaction remains largely unexplored and modelling studies are strongly recommended in this direction. Problems remain, in addition, with the representation of bottom boundary flows in z-level models unless a parameterisation for downslope flow is adopted. CDW is generally too buoyant, even under GM. A substantial component of CDW comes from recirculated NADW, which is generally overturned too slowly or suffers from excessive mixing in coarse models. Stratification and density structure are not well resolved in models, although these properties are often overlooked in diagnostic analyses. Simulated density layering is critical for determining the model ventilation rates. A key limiting factor here is the poorly known air-sea heat and freshwater fluxes, which after all determine interior water-mass properties. Related to this, there is a temptation to adjust (poorly known) surface fluxes in order to capture realistic interior T-S, particularly in ice-covered regions. To this end we strongly advocate "passive" tracers such as CFCs and ^{14}C to determine model performance.

High resolution models, while capturing a richer ACC structure and intrinsic eddy-scale variability, do not necessarily resolve the large-scale distribution of water-mass formation. Short integration times means these models are generally very close to their initial conditions in the ocean interior, with realistically high deep and bottom water densities, and therefore quite weak surface ocean overturn and ventilation. It would be wise for these models to be analysed in terms of their simulated overturn and ventilation rates (with chemical tracers, for example) prior to their incorporation into coupled climate studies. Key achievements of high resolution models (in comparison with their coarser cousins) include the following: they capture intrinsic eddy-scale variability, they resolve western boundary current spatial scales, they simulate Agulhas leakage of saline Indian Ocean water, they resolve eddy fluxes to some degree, and they include a better resolution of critical topographic features.

LIMITING FACTORS

In view of the above we can list a number of key limiting factors in ocean modelling for climate studies in the SO context. The more important processes affected by these limitations are cited in parentheses. They include:

Surface boundary conditions (poor climatologies of air-sea heat/freshwater fluxes, upper ocean salinity, and wind stress),

Horizontal resolution (ACC structure, eddy fluxes, boundary currents, topographic features, convection spatial scales, Agulhas salt leakage),

Vertical resolution (Ekman layer resolution, mixed layer resolution, vertical momentum transfer),

Eddy-parameterisations (including how best to characterise the GM thickness diffusion coefficient. Schemes for subgrid-scale viscosity and the "horizontal residual mean" circulation),

Sea-ice processes and ice-ocean interactions needs to be represented in SO models, as do ocean/ice shelf interactions,

Downslope plume flows: bottom boundary layers are poorly resolved in z-level models unless parameterised,

Convection (spatial scale exaggerated in coarse models, integral effects, parameterisation).

FUTURE WORK AND RECOMMENDATIONS:

It is clear from this report that interactions between the modelling/observational oceanographic and sea-ice communities need to be fostered, but what model and observational developments do we need in the coming years to progress in SO modelling in the most effective way? Summarising the key recommendations of the WG we have listed a number of items that should be developed into active research programmes where possible:

1. A diverse range of ocean models should be configured for studying the SO circulation, either as a piecemeal approach, or eventually within the framework of a Southern Ocean Modelling Intercomparison Project (SOMIP). Several groups showed an interest in participating in collaborative research in this context, although research initiatives are in their infancy, so formalising a SOMIP would be premature at this stage. There is certainly a need to diversify the library of models used to study the SO circulation. SO modelling efforts across different research groups would ideally cover three different vertical discretisations (z, isopycnal, and sigma level; as in DYNAMO), a variety of surface T-S forcings, and a range of horizontal resolutions. In addition, more efforts need to be fostered in the coupling of sea-ice models to SO models: certainly sea-ice processes need to be included but to what extent appears to be a function of the various project goals.

   A central result of WG B has been the realisation by a number of research groups of the importance of investigating the SO dynamics using a hierarchy of numerical models. Some groups are currently establishing the necessary groundwork for realising ensembles of simulations over the next few years in which mesoscale eddies are active if not vigorous. Initial work will focus on the basic dynamical balances present in these models as rendered by a range of forcing fields. A long term goal of these investigations is to further our understanding of the physics, chemistry, and biology of the SO, and ultimately how they interact with the global climate.

2. Coarse resolution models require the further development of a number of parameterisations to represent subgrid-scale circulation features. In some cases high resolution eddy-resolving models can provide some guidance, for example, with eddy statistics and calculations of the GM thickness diffusion term, which can be understood as a parameterisation of the temporal-residual-mean. The parameterisations required include:

   an appropriate parameterisation for the GM thickness diffusion parameter,

   bottom boundary layers, particularly in the context of bottom water formation around Antarctica,

   convective overturn of gravitational instabilities – possibilities to include subgrid-scale structure?,

   an appropriate implementation and testing of the “horizontal residual mean” circulation.

3. Further modelling studies are recommended to detail, among other things,

   the stability and variability of water-mass formation and circulation in the SO,

   the role of sub-ice shelf circulation on bottom water production,

   the quantitative importance of the above-listed parameterisations in the context of climate properties (for example, just how important is κ for surface air-sea interaction?)

4. Observational data products need to be developed for models in the SO. Further to those well recognised by the WOCE community, such as poleward heat transport and hydrographic sections, the following are of high priority:

   Climatologies of air-sea flux data, regional mean buoyancy fluxes.

   Large-scale fields of mixed layer depth, convection depth, particularly during winter.

Climatologies of transient tracer fields (normalised products), including CFCs, tritium/^{3}He, ^{14}C.

Eddy fluxes; Heat/freshwater transport rates and their components.

SO bathymetry in poorly measured regions, particularly along bottom water spreading pathways.

Water-mass formation and spreading rates, bottom water transports in deep SO bathymetry.

Sea-ice thickness distribution, ice shelf melting rates.

REPORT FROM WORKING GROUP C: FLOW THROUGH SILLS AND STRAITS
Chair: Peter Killworth

SUMMARY

Sills, straits, and narrows dominate the control of water mass structure in the ocean. It is impossible for climate models to successfully reproduce water masses in a basin if incorrect fluxes and water types enter that basin through its boundaries with other oceans, no matter how well mixing is parameterised.

The group discussed our knowledge of processes occurring in sills and straits, briefly examined observational evidence, and spent most time on techniques for representing sill flow in climate models. We found that changes of sill topography in coarse climate models by as little as a single grid cell could grossly change the throughflow and water properties, so that extant climate models are essentially tuned by the choice of topography. Three modelling approaches were discussed:

- high resolution modelling. We found that sufficiently resolved numerical models, at least for the Romanche Fracture Zone (where rotation is unimportant) could accurately reproduce the observed flow, mixing, and water properties.

- nesting. We noted that although a fine resolution nested model around a sill can be successfully forced by a coarser climate model around it, the latter does not respond well to the fine jets produced at the sill without application of excessive mixing near the sill.

- parameterisation. There are two approaches, due to Killworth (1994) and Pratt and Chechelnitsky (1997). Both are only available for simple reduced-gravity models, and their extension to stratified fluids is unclear. The first bounds the flow; attempts to use these bounds in models produce solutions dominated by gridpoint noise. The second has not been tested in models to our knowledge.

Accordingly, we *recommend parallel research on all high resolution modelling, nesting, and parameterisation, with the aim of finding an approach which can be successfully applied in climate models*.

RECOMMENDATIONS

- continuation and extension of analytical studies of sill flow, with extensions to time variation and continuous stratification

- laboratory experiments of sill flow, with associated numerical modelling

- examination of how best to define topography in sensitive areas within climate models

- encourage observational programmes on upstream water mass structure near sills

- examination of resolution near sills in numerical models to locate how much resolution is 'adequate'

- research on high resolution modelling, nesting, and parameterisation as parallel activities, aimed at finding the optimal approach to representation of sills in coarse resolution models.

ISSUES ADDRESSED AND GROUP AGENDA

The issues addressed were:

- What are the key processes occurring in sill/strait flow that need to be represented in ocean climate models?

- What limits existing models in their reproduction of volume fluxes and water mass transitions at sills?

- What is the best way to parameterise throughflows in climate models?

- What are the key observations which will validate and select between differing approaches?

- What form would a future modelling effort to attack this problem take?

The initial agenda, modified by which participants could attend, covered the following:

1. Key processes

    (a) to what extent is sill flow controlled hydraulically?

    (b) to what extent are dynamical quantities (potential vorticity, energy, etc.) conserved?

    (c) for climate purposes, can the flow be considered steady?

    (d) what is the role of lateral eddy mixing in straits/sills?

    (e) what is the role of turbulent bottom/side layers in straits/sills?

    (f) to what extent can sill flow be considered in isolation from the rest of the fluid? In particular, how does the JEBAR effect on the barotropic flow affect the throughflow?

    (g) what is the role of upstream and downstream influence, e.g. hydraulic jumps?

2. Representation of processes in ocean models

    (a) Behaviour of existing models: climate models and eddy-permitting models at marginal and fine resolution

    (b) Numerics of existing models

    (c) Effects of resolution: does high resolution 'solve' the problem? nesting issues

    (d) Parameterisation: Is parameterisation the best route forward? If so, what form should it take?

    - bounding flow properties

    - dynamical response models

    - other

3. Validation issues

    - Observations: Gibraltar Denmark Strait Iceland-Faeroes Romanche Fracture Zone Other Deep Basin sills Other areas

    - Data sets – where and what? Can these be usefully combined with bottom boundary layer data sets?

4. Future efforts

- What is the best way to improve handling of sill/strait flows in climate models'?

WORKING GROUP FINDINGS

Observations

There are surprisingly many observations of flow and water mass structure in important sills. Table 1, prepared by Saunders, lists known sills and references. Only sills for which transport estimates have been derived from moored current meter arrays are listed.

Analytical theory of flows through sills

The problem of hydraulic control has been studied for over a century. Despite this, understanding of the problem in an oceanic context, where stratification and rotation may both be important, is lacking. Stratified flows have almost exclusively been treated in a layered context, examples being Armi and Farmer (1986) and, more recently, Odulo et al. (1997). Continuous stratification has been treated mainly as a similarity problem, including Wood's classic (1968) paper, and more recently Williams and Armi (1991). Killworth (1992) and Armi and Williams (1993) are two of the few studies of the behaviour of a fully stratified fluid, although multiple layer approaches can yield similar answers (Engqvist, 1996).

These papers all related to non-rotating fluids. The problem becomes considerably more difficult when rotation is added, since cross-sill variability appears. Pratt and Lundberg (1991) give a review, and Whitehead (1998) gives a partial review of more recent work as well as a summary of flows through nine sills. Almost all work in situations other than single layer channel flow has needed gross simplifications, the most popular being a restriction of the potential vorticity to a uniform value, either zero or some arbitrary constant. Neither of these choices are physically realistic, since they necessarily imply changes in along-sill velocity across the sill whose values are much higher than observed. Killworth and McDonald (1993), Killworth (1994, 1995) address maximum principles in a single rotating layer with arbitrary potential vorticity distribution, and show that the Whitehead et al. (1974) laboratory results form an achievable upper bound to the sill throughflow for such configurations. Almost no work addresses the effects of friction, with Johnson and Ohlsen (1994) being an important exception. Effects familiar from non-rotating studies such as shock fronts, etc., remain far from understood (Nof, 1986; Pratt, 1987). Exclusively, no attempt has been made to include the barotropic flow component, which will react with the topography and stratification on length scales which differ from either those of the topography itself or the internal deformation radii; Wadley and Bigg (1996) show how difficult it is to create a meaningful numerical problem in this vein. Few papers even extend consideration to two active layers, exceptions being, e.g., Hogg (1983).

Another fundamental difference between rotating and non-rotating flows is the manner in which the upstream (and downstream) flow approaches the sill. In non-rotating fluids this occurs as a wide slowly varying, usually subcritical, flow. In a rotating fluid, for most extant solutions, the upstream flow is confined to a boundary layer, so that upstream flow, and geometry, details are not only important, but can dominate the solution.

A major omission in theories is that of time dependence, despite early work by Wang (1987, 1989). Flows through sills are unsteady for two reasons: first, they are naturally unsteady because of internal dynamics such as instabilities; and second, they are unsteady because of externally varying forcing such as tides, seasonal variability, etc. In natural situations in which rotation plays only a minor role (such as the Gibraltar throughflow) tides often induce major variability (Bryden et al., 1994). In particular, the interface between in- and outflow rises and falls at the sill during the tidal cycle. Helfrich (1995) showed that the effects of such forcing were important in a two-layer non-rotating model when particle excursion or signal propagation during a period of the forcing was of the order of the along-sill length scale, and unimportant either in the limit of little or very large excursion. In other words, rapidly varying forcing 'averaged out', while slowly varying forcing had a response that resembled the local steady state at that part of the cycle. Helfrich also found that, unlike most theories of hydraulic control, geometric details of the entire sill area affected the throughflow. Recent unpublished work by Kuo, Helfrich and Pratt is beginning a thorough examination of time-dependence in dam-break one-layer flow in a channel using advanced numerical methods.

A separate approach is that of Pratt and Chechelnitsky (1997), who seek dynamical formulae relating inflow and layer depth upstream of some unresolved sill, with the fluid restricted to uniform potential vorticity. This approach seems promising, although it is not tested in models to our knowledge.

The theories above possess fundamental limitations:

- the sills are assumed to be 'slowly varying' along the sill, in the sense that across-sill variations are much more rapid than along-sill
- flows are assumed laminar, despite observations of baroclinic and barotropic instability in sills
- the dynamics are largely assumed to be those of a perfect fluid, with little extant work on effects of mixing of water masses and of momentum, despite clear observations that mixing is important in most sills.

To date, we have a variety of formulae representing flow over sills:

- Non-rotating, one-layer, reduced gravity flow of fluid whose surface upstream is a height h above the height of the 'col' of the sill has a hydraulically controlled flux of $(g'(2h/3)^3)^{1/2}$, where g' is a reduced gravity for the layer
- Non-rotating two-layer exchange flow (e.g. Gibraltar in- and out-flow) has a maximum controlled flux of $0.25WH(g'H)^{1/2}$ where W and H are the width and depth of the sill, assumed rectangular
- Rotating, one-layer, reduced gravity flow in the same configuration has a maximum controlled flux of $g'h^2/2f$, where f is the Coriolis parameter
- There are no extant formulae for rotating, stratified fluid flow at sills.

Application of such formulae in coarse resolution models has not been productive to date. The Pratt and Chechelnitsky (1997) approach, as noted, has not apparently been tested. Attempts to use maximum bound formulae has yielded severe numerical noise, essentially because the coarse model is attempting to handle fine-resolution results and cannot easily do so without heavy frictional damping.

<u>We recommend</u>:

- analytical studies of rotating hydraulic flow, especially with continuous stratification
- laboratory experiments with concomitant numerical simulations

Sills in numerical models

To date, even the finest resolution global models cannot resolve the sill flows adequately; for example, the DYNAMO (1997) intercomparison of three eddy-permitting N. Atlantic models (the DAMAE intercomparison was similar) showed large differences between the three model responses in the Denmark Strait, despite – formally, at least – the models possessing the same forcing and topography. The Denmark Strait, furthermore, is wide and so apparently resolved by these models. For the foreseeable future, even eddy-permitting models, to function adequately, will need parameterisations of some kind to represent sill flow correctly; the problem is far more urgent for the ocean component of coarse resolution climate models, which usually have to undertake major excisions of ocean floor even to possess a sill between basins at all.

Coarse resolution models

Climate models possess the coarsest resolutions, and so are the most sensitive to details near sills. Roberts and Wood (1997) give an enlightening example (Fig. 1). It shows the topography of the Greenland-Iceland-Scotland (GIS) ridge in the Met. Office coarse resolution z-coordinate model climate model. The top diagram shows the original topography used. This resulted in no net flow across the ridge. Changes in topography by as little as one grid box, indicated in the lower three diagrams, resulted in gross changes not only to cross-ridge flux (12 Sv being achieved in the bottom diagram) but also to the location of this flux, and to the composition of the water mass actually crossing the sill. Put another way, a 50% change in heat flux at the GIS ridge latitude can be achieved by the addition or subtraction of a single grid box. It is unclear whether the most realistic results are given by excavating to the deepest, widest, or deepest and widest, points. Certainly current practice of taking median or (worse) mean depth over the grid point using a source of fine resolution depth data is flawed if used in coarse models.

Medium-resolution process models

We found that medium-resolution models gave valuable input as to why these models were so sensitive. Process models of flows over simple ridges demonstrated how easily flow patterns became complex near the ridge, with mixing slightly upstream of the sill. This, in a coarse resolution model, would not occur easily. Yet columns are squeezed as they pass over the sill and so generate relative vorticity in such process models. Coarse resolution models cannot easily generate relative vorticity and so require large amounts of mixing, which may be erroneous. The dependence on upstream conditions and mixing means that observations within and downstream of sills may not give sufficient information to determine the physics within the sill.

We also examined results which parameterised outflow as a relaxation towards observations (designed to simulate, but not explain, sill flow). Simple relaxation to observations needs careful tuning: too weak a relaxation has no effect, while too strong a relaxation forces flow around, rather than through, the relaxed area. Numerical experiments by Gerdes and Beckmann show that inflow must be explicitly included to reach the correct amount of water in a given class.

Nesting

Gerdes and Beckmann discussed results (extending Fox and Maskell's, 1996 work) to see if nesting can be used as a general method to improve the representation of passage throughflows. Two-way nesting experiments were performed with a 1° geopotential coordinate model of the Northern North Atlantic, between 50°N to 75°N. A nest was placed in the Denmark Strait and around Iceland, twenty by ten degrees wide. The resolution inside the nest was increased by a factor of 3, both horizontally and vertically. As a reference, experiments without the nest and with increased resolution throughout the domain were conducted. (Note that at the time of the experiments there was no BBL sub-model available.)

The focus of this study was on the effects of the nest on the coarse grid solution. The expected effects of the nesting approach were twofold: (a) a less diffusive (more advectively dominated) solution, with less wide/thick currents; (b) widening of passages.

The results can be summarised as follows:

1. Technical aspects: some restrictions to topography in the nest need to be considered: volume conservation; isobaths should intersect the nest boundaries at right angle. There is a rather strong sensitivity of the results on the placement of the nest boundaries.

2. While one way nesting works fine and in the expected way (i.e., the solution inside the nest looks much better), two-way nesting failed to improve the solution outside the nest significantly: apparently, the necessary averaging at the nest boundaries reduces the impact of the nest too much.

3. Even a moderate nesting factor (3 in this case) can cause partial reflection at the nest boundaries, both inside and outside the nest. This can be reduced by additional smoothing, averaging in time, or restoring zones at the nest boundaries; however, these measures further reduce the net effects of the higher resolution in the nest on the outside domain.

4. Nesting is expensive; for a nest area of, say, 2% of the horizontal domain at a three-fold increase in resolution leads to an additional CPU requirement of 2% x 3^4 = 162% of the original model, even without the coupling overhead.

5. With respect to the opening of passages, the overall impression was that (without a BBL model) the improvement was small.

It was felt that stronger nesting ratios would prove even more problematic with respect to partial refection of waves and increase costs dramatically; nesting in sigma or isopycnic models might perform better, because the topography is assumed to vary smoothly between grid points; and a combination of nesting and a BBL sub-model may improve matters (this is untested).

In conclusion, nesting alone does not solve the problem of throughflows in coarse resolution z-coordinate models. However, despite these difficulties, it is clear that nesting remains an approach which must be further investigated, as it is a natural approach at least for sills which are generally accepted to be important to climate.

We recommend:

- continuing studies of nesting, with emphasis on the effects on the coarse resolution outer model.

Fine-resolution models

The group examined two fine-resolution studies, simulating the Vema Channel and Romanche Fracture Zones. We found that in both cases, it was possible to obtain an accurate simulation with sufficient resolution. In the Vema Channel simulation by Jungclaus and Vanicek (1998), the float behaviour observed by Hogg was reproduced, with the flow switching sides within the channel (as predicted in theory by Straub, 1998). Again, there was strong mixing and recirculation present. Ferron's Romanche Fracture Zone used high vertical resolution (and free slip on the vertical walls to lessen frictional retardation) and a realistic mixing scheme (Mellor-Yamada). The fit with data is shown in Fig. 2. High vertical mixing rates (0.1 m^2 s^{-1}) are found downstream of the sills.

Thus *we found examples when numerical modelling with 'adequate' resolution has been capable of reproducing reality.* However, (a) this resolution is far beyond the ability of any climate model in the foreseeable future, and (b) without either data or large resources, it is impossible to determine what constitutes 'adequate' resolution.

The question of identification of sills which are hydraulically controlled was also raised. Process studies at high resolution demonstrated that Ekman sidewall effects, combined with MacCready and Rhines shutdown, yield a similar cross-stream structure to hydraulic control. Accordingly, accurate determination of the physics is necessary to distinguish these two cases.

We recommend:

- a study of how best to define topography for coarse resolution climate models
- observational programmes should include analysis of upstream water mass structure and velocity structure
- process/numerical studies to determine what resolution is needed for extant numerical models to reproduce data to some required degree of accuracy.

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TABLE – SILLS AND STRAITS
Prepared by Peter Saunders

Simon Thompson wrote a manuscript entitled "Sills of the Global Ocean: a compilation". This was (un)published in Ocean Modelling issue 109, Oct. 1995, but the material is also on the Web at the OCCAM site: www.soc.soton.ac.uk/JRD/OCCAM/sills/furthersills.html. Thompson describes the location, sill depth and width of 100 sills.

Below I list sills and straits for which transport estimates have been made, in all cases employing moored current meter arrays. Many of these measurements were not made in the WOCE period. Transport determinations have been made at other locations using hydrography alone. I know of no way of estimating the reliability of these latter estimates and so have not included them.

Atlantic Ocean

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Indian Ocean

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Pacific Ocean

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VITIAZ STRAIT: S.Murray, E.Lindstrom, J.Kindle and E.Weeks 1995; US WOCE Notes 7(1), 21–23.

Figure 1, adapted from Roberts and Wood (1997). The variation in net throughflow at the GIS ridge as the topography is varied in a coarse resolution model. Grid point depths are shown by dashed lines, and grid point widths are as indicated.

Figure 2, from Ferron, 1998. Simulation and data from the Romanche Fracture Zone.

WOCE/CLIVAR Workshop on Ocean Modelling for Climate Studies
NCAR, Boulder, 10-13 August 1998

The aim of the workshop is to bring together climate modellers, observationalists and ocean modellers, in order to understand how current and future observational datasets can be used to guide the development of ocean models, particularly those used to study climate. In particular:

- to develop an understanding and consensus on how well different aspects of ocean dynamics need to be represented in order to achieve realistic simulations of the ocean's role in climate variability on decadal time scales.
- to develop a consensus of benchmark data sets for quantitative model tests that could lead to more coordination, transparency and feedback between individual model development efforts. The aim would be to establish a sort of 'baseline' for sensitivity studies with existing models, model intercomparisons and new model developments.

AGENDA

Monday, 0900 – Opening (Claus Böning)

Local organisation (Bill Large/Peter Gent)

Plenary session (1) John Church, Claus Böning

WORKSHOP OBJECTIVES AND STRUCTURE

- What should be the outcome of the workshop?

0945 – Plenary session (2) Lead: Peter Gent

DEVELOPMENTS IN OCEAN MODELS USED FOR CLIMATE STUDIES

- Impact on climate simulations of improvements in the ocean component?
- Deficits as perceived in the climate modelling community?
- Model resolution foreseen for the next generation of coupled models?

1100 – Plenary session (3) Lead: Jürgen Willebrand

LESSONS FROM OCEAN MODEL INTERCOMPARISONS

- Which processes and model factors have been identified as potentially critical for decadal-scale simulations?
- Role of model intercomparison vs. sensitivity studies?
- Organisation of intercomparison projects?

1145 – Plenary session (4) Lead: Dale Haidvogel

IMPACT OF NUMERICAL METHODS ON SIMULATION OF PROCESSES RELEVANT TO CLIMATE

1330 – Working Groups

WG I (Bill Large)	3-D Turbulent Mixing
WG II (Aike Beckmann)	Bottom Boundary Layer
WG III (Peter Gent)	Mesoscale Processes

APPENDIX A

Tuesday, 0830 – Working Groups, continued

1100 – Plenary: Working Group Reports

- What are the key processes that need to be captured in ocean models used to study (decadal-scale) climate variability/change?
- Can we define quantitative data-oriented tests of the model's ability to capture these critical processes?
- Are there fundamental limiting factors in the ability of models to capture critical processes? e.g., resolution, numerics? How well do present climate models capture the effect of these processes?
- What should be done in terms of future modelling efforts to clarify the questions brought up in the WG sessions? In particular, would an "ocean model intercomparison project" (OMIP), or a set of coordinated modelling studies be useful?

1330 – Plenary session (5) Lead: Jim McWilliams

HOW TO USE (WOCE) DATA TO TEST OCEAN CIRCULATION MODELS?

- What are the critical aspects of testing models used for decadal-climate studies?
- What should be calculated from the data?
- How can the data be used to test models?
- How can the data be used to improve models?

1500 – Working Groups

WG A (Richard Wood/C. Böning)	Meridional Overturning in the Atlantic Ocean
WG B (Matthew England)	Southern Ocean Dynamics
WG C (Peter Killworth)	Passage Throughflows

Wednesday, 0830 – Working Groups, continued

1100 – Plenary: Working Group Reports

- Same questions as above •

1400 – Plenary session (6)

OBJECTIVES, ORGANISATION, AND RESULTS FROM INTERNATIONAL MODEL INTERCOMPARISON PROJECTS

Coupled Model Intercomparison Project (CMIP)	Curtis Covey
Ocean Carbon-Cycle Model Intercomparison Project (OCMIP)	James Orr

- Are there lessons for future ocean model development?

1600 – Free Discussion

Possible meetings of reorganised groups and/or continuation of previous groups to address questions left open or raised during the workshop

Thursday, 0830 - Plenary sessions

(7) DISCUSSION OF FUTURE PROGRAMS, IN PARTICULAR DEFINITION OF ELEMENTS OF COORDINATED MODEL DEVELOPMENT EFFORTS

(7a) SPATIAL RESOLUTION IN COUPLED MODELS — David Webb

- Do we need (an) eddy-permitting coupled experiment(s) to clarify the role of resolution for climate studies?
- Can we suggest a model configuration?

0930 (7b) COORDINATION OF MODEL INTERCOMPARISONS AND PARAMETER SENSITIVITY STUDIES

- What are the questions an (several?) 'OMIP(s)' could help to answer? — Matthew England
- What should be the key elements of OMIP configurations, i.e. basin vs. global-scale domain, resolution, integration period? — Dirk Olbers
- What are the organisational requirements, which resources are needed? — Eric Chassignet
- Can model consortia built around standardised 'community' models (e.g., following the examples of MICOM, SPEM etc.) be an effective means to promote and coordinate improvements in parameterisation, numerical aspects etc.?

1100 (7c) ATMOSPHERIC FORCING FIELDS FOR OCEAN MODELLING — Serge Gulev, Bernard Barnier

- Assessment of existing flux fields: temporal and spatial coverage, errors
- Can we agree on a 'standard' forcing set for coordinated model development and intercomparison purposes?

1145 (7d) OCEAN DATA SETS/MODEL DIAGNOSTICS — Rainer Bleck

- Can we, based on the WG recommendations, agree on standard model diagnostics and data sets to provide a 'baseline' for model testing?

1215 (8) ORGANISATIONAL MATTERS — John Church

- Do we need a (WOCE/CLIVAR) committee for ocean modelling oversight?

1230 – End of the workshop

1400 – Meeting of the Workshop Committee

ABSTRACTS OF INVITED CONTRIBUTIONS

1.1 RESOLUTION OF FUTURE OCEAN MODELS – Peter R. Gent, NCAR

I address the question of what should the resolution be of ocean models used for climate studies in 3 to 5 years time?

The first point to make is that a recent study at Los Alamos and NCAR by Rick Smith and Frank Bryan has shown that to "resolve" the ocean mesoscale field requires a horizontal resolution of 10 km or smaller. The study consists of a series of North Atlantic simulations using progressively finer resolution, that were run out for a decade or two. Thus, the possibility of running "eddy-resolving" resolution for climate models is out of the question for the foreseeable future.

Thus, the question to be addressed is should non-eddy-permitting (1° or coarser) or eddy permitting resolution (finer than 1°) be used? I think our current eddy parameterisations have been much more thoroughly tested in the non-eddy-permitting regime. However, there is no doubt that finer horizontal resolution allows faster western boundary currents, for example, and can resolve narrow straits and topographic features much better. The difficult question is then "How important are these more realistic features in improving the ability of the ocean model to realistically capture climate variability compared to the rather large increase in computational cost"? Also, in terms of computational cost, how does one balance the relative merits of fewer coupled runs with higher resolution components against lower resolution components that allow more sensitivity experiments and ensembles of climate runs to be performed?

These are difficult questions to answer, but my opinion is that we will learn more about the climate system by running more coupled simulations rather than running fewer with eddy-permitting ocean resolution. I believe it may be more important to resolve narrow straits better and have faster western boundary currents than to have global eddy-permitting resolution. This could be achieved by using irregular, or adaptive, horizontal grids that allow finer resolution in predetermined locations. This would result in a much more modest increase in computational cost than using a globally uniform finer grid. I think that the standard ocean model resolution used for climate work in 3 to 5 years will be 1°, with finer resolution at some specific locations. I believe that this is the resolution that WOCE/CLIVAR development work should be aimed at.

APPENDIX B

1.2 THE NEED FOR HIGH RESOLUTION MODELS – David Webb, Southampton Oceanography Centre

The talk was concerned with the questions (a) why may a Rossby radius resolving ocean model be required for climate change research? (b) what physical processes affecting climate require high resolution? (c) can any or all of these processes be parameterised in a low resolution ocean model? and (d) what should be included in a anthropogenic climate change run using a Rossby radius resolving ocean model?

The eddy field

Research with high resolution ocean models has indicated that over most of the ocean the mesoscale eddy field has a relatively small effect on the large scale heat transport of the ocean. However they may still be important at smaller scales. As an example the UK Meteorological Office climate model which uses a 1.25° ocean shows systematic (2°C) errors in sea surface temperature in a number of regions where the eddy field is known to be well developed.

The situation is different in the Southern Ocean where the mesoscale eddy field appears to be important for transporting heat and fresh water across the Antarctic Circumpolar Current and for transporting warm, high salinity water between the Indian and Atlantic Oceans.

Boundary currents

Rossby radius resolving ocean models can also generate the high temperature cores of the major western boundary currents. The extra heat transport due to such core is again small, but the effect could again be significant in areas like the Gulf Stream extension region.

High resolution can also help reduce errors due to the Veronis effect in level ocean models. This effect can produce significant long term errors in climate models. (Isopycnal mixing schemes can also reduce the error and for this reason they are recommended for all level models used for climate studies).

Topographic effects

It is arguable that in a high resolution model the improvements coming from the improved representation of topography are as important as the ability to resolve the Rossby radius. In the case of climate models the most important effect is likely to be in the improved representation of overflows and the resulting effect on the thermohaline circulation in the model. Good vertical resolution is also needed to represent the sill depths well.

Other processes

The mixed layer

Heat storage in the surface layers of the ocean is known to redden the climate spectrum – i.e. increase the long period variability. This appears to be primarily a local effect, not influenced much by advection, but requires a good mixed layer model (i.e. Large, McWilliams and Doney). A good mixed layer model is also required before the atmospheric model will produce a realistic distribution of stratus clouds over the ocean (an important source of climate error in many coupled models).

Ventilation

It has been suggested that oceanic ventilation provides potential for feedback to the atmosphere on decadal timescales. This may be achieved by storing heat for release back to the atmosphere at a later time. It may also be achieved by producing changes in the stratification, affecting equatorial Kelvin and Rossby waves associated with the El Niño.

Isopycnal models should represent such processes well. Level models will probably need good resolution in both the vertical and horizontal to represent such processes well.

Strong non-linear response

In climate change research the ocean model needs to represent the mean state well and to respond correctly to small perturbations in external forcing. However it should be remembered that there are also areas where strongly non-linear effects are important.

An example is in the West Pacific Warm Pool where the latent heat loss increases exponentially with temperature. Another example is in the Arctic and Antarctic where salinity changes can have a strongly non-linear effect on deep convection and the position of the ice edge.

Resources required

The talk concluded with a short discussion of the resources required to carry out climate change runs using a high resolution ocean model. Although the computer requirement is large it seems to be achievable with the present generation of high performance computers.

2.1 LESSONS LEARNT FROM OCEAN MODEL INTERCOMPARISONS – J. Willebrand, IfM Kiel

In several fields of climate research, projects for systematic intercomparisons between different models have been or are being organised on an international level (e.g. AMIP, CMIP, OCMIP and others). So far, the idea of an OMIP has not had much support in the ocean modelling community. There are several reasons for this abstinence which ultimately result from the different dynamical regimes in the ocean as compared to the atmosphere:

- Forcing dependence/sensitivity

  The oceanic state depends to a much larger extent than the atmospheric state on surface fluxes which are notoriously poorly known. Small differences in surface forcing can lead to very different oceanic response because there is only a very weak diabatic forcing in the ocean interior, and can mask differences between different models unless specific care is taken.

- Scale difference ocean-atmosphere

  While all atmospheric models resolve the synoptic scale, some ocean models do while others don't. An intercomparison between both types is however difficult. Furthermore, the time scale for thermohaline equilibrium is of order 1,000 years, whereas observations and climatological averages extend roughly over the last 50 years. The concept of (statistical) equilibrium which has been useful for several intercomparison projects is hence not applicable with regard to any model-data comparison.

- Localised processes

  As discussed elsewhere at this meeting, many large-scale aspects of the ocean circulation are controlled by localised small-scale processes (e.g. convection and watermass transformation, flow through straits and over sills) which are not resolved in nearly all present ocean models. Therefore, different numerical concepts have a much

- Data coverage for validation

  Global data sets as e.g. hydrographic atlases are felt to be too smooth to show important features of the ocean circulation. Satellite altimetry has been very useful for determining synoptic and seasonal variability but less so for longer-term means. It is however expected that with the AIMS-phase of WOCE this situation will greatly improve, and that analysed data sets of higher accuracy will become available.

- Size of modelling community

  Global ocean models are mainly run in the context of coupled climate models, and also for a few other purposes. Most ocean modelling groups are involved in regional/basin scale models, with relatively few groups working in for each basin. It is therefore more difficult to interest a sizeable community of modellers for one single intercomparison effort.

Despite these difficulties, there have been some individual successful intercomparison studies, most recently DAMEE in the US and the DYNAMO project in Europe. A few specific examples from these projects which focus on the North Atlantic will be discussed which demonstrate the important role of the numerical representation of certain physical processes for the large-scale circulation.

This workshop will address the issue how to formulate an international program of organised ocean model experimentation. Tightly organised intercomparison studies should be one important element of such program. Perhaps the principal results of such studies will be a better and more quantitative appreciation of shortcomings of different model concepts. The open information on model performance associated with an intercomparison project is not only very useful for model development/improvement but also for potential users of models in other communities, and will ultimate lead to an overall gain in model credibility.

As differences between different models run under identical conditions are usually of the same order as differences within one model when run under slightly different conditions, any model intercomparison should always be accompanied by carefully planned sensitivity experiments. A specific issue should be an assessment of the relative virtues of coarse-resolution models as used in climate computations vs. state-of-the-art high resolution models.

2.2 THE COUPLED MODEL INTERCOMPARISON PROJECT
– Curt Covey, Lawrence Livermore National Laboratory

CMIP, the Coupled ocean-atmosphere Model Intercomparison Project, began under auspices of the WCRP Working Group on Coupled Models in 1995. The purpose of CMIP is to examine fully global coupled ocean-atmosphere GCMs (including interactive sea ice) in both "control" simulations of the pre-industrial climate and human-perturbed scenarios such as anthropogenic global warming. In that sense CMIP is more ambitious than its cousin AMIP (the Atmospheric Model Intercomparison Project), which is restricted to atmospheric GCMs, but CMIP so far has collected a more restricted data set than AMIP, focusing on seasonal and annual means of selected variables. A more ambitious phase of CMIP may be announced at the October 1998 meeting of the WGCM.

CMIP has now collected several gigabytes of output from 19 coupled GCMs. Documentation of participating models, a detailed list of available data and application procedures for obtaining data are all available on the CMIP Web site http://www-pcmdi.llnl.gov/cmip. Oceanographers should note that ocean heat transports as well as heat penetration into the ocean under global warming scenarios are included in the CMIP database.

The CMIP and AMIP experiences offer lessons for organisers of future model intercom-parisons such as a possible OMIP. Beyond a threshold of a half-dozen or so models and a dozen or so output fields, a project needs to have one or more people working full-time on database construction and management. Even with such a team receiving the data, it is necessary to impose standards on the format and structure of the submissions. (The new phase of AMIP has even required that all data be pre-processed by a "transmission standards" software library before submission.) In short, comprehensive model intercomparison requires a transition from "small science" to "big science."

2.3 LESSONS FROM OCEAN MODEL INTERCOMPARISONS ON SIMPLE TEST PROBLEMS
– Dale Haidvogel, Rutgers University

Recent ocean model intercomparison studies in the North Atlantic Ocean (e.g., CME DYNAMO, DAMEE) have yielded important insights into the strengths and limitations of alternate ocean models and model algorithms. Though essential, such studies are difficult to formulate cleanly and are often costly to conduct. An alternative, and complementary, approach is to devise a set of simplified process-oriented test problems to which ocean models may be applied easily and inexpensively, and whose quantification and interpretation are more straightforward.

We (Haidvogel and Beckmann, 1998a,b) have begun to assemble such a suite of test problems, and to apply them systematically across a representative range of available ocean models. The ocean models we are using include the z-coordinate Modular Ocean Model (MOM), the terrain-following S-Coordinate Rutgers University Model (SCRUM), the Miami Isopycnic Coordinate Model (MICOM), and the finite-element-based Spectral Element Ocean Model (SEOM). The first three of these models use lower-order numerical methods, and are primarily distinguished by their alternate choices of vertical coordinate; the latter model differs by use of a higher-order approximation technique, and an unstructured quadrilateral finite element mesh.

The test problem suite includes processes which span the range from purely two-dimensional to fully three-dimensional flow. Of these, the test problems which tend to exaggerate inter-model differences are those which involve substantial interaction with solid boundaries – either sidewalls and/or bottom topography. Examples of such boundary-influenced oceanic processes which show considerable inter-model sensitivity include wind-driven western boundary currents along an inclined western boundary, wind-driven residual circulation over a steep coastal canyon, and buoyancy-driven downslope flow.

These simplified model intercomparisons emphasise several general conclusions. First, it is best to avoid stepwise (i.e., "staircase") representations of either lateral boundaries or bottom topography. Systematic errors and/or slow convergence to the known solution are invariably obtained with such discontinuous boundary treatments. Second, sensitivity to subgridscale closure is large, particularly in the combined limit of strong stratification and steep topography. Further understanding leading to new parameterisations for mixing in (e.g.) the bottom boundary layer are needed. Lastly, these simplified test problems underscore the utility of non-traditional numerical algorithms, in particular high-order methods, novel advection schemes, and adaptive and/or variable mesh techniques.

References

Haidvogel, D.B. and A. Beckmann, 1998a: Numerical Modelling of the Coastal Ocean. The Sea, 10, 457–82.

Haidvogel, D.B. and A. Beckmann, 1998b: Numerical Ocean Circulation Modelling, Imperial College Press, 300 pp. Forthcoming.

3.1 TESTING MODELS WITH WOCE DATA: LARGE-SCALE FLUXES – S. Rintoul, CSIRO, Hobart

Estimates of large-scale transports provide perhaps the most obvious and commonly used benchmarks against which to assess ocean circulation models. Examples include the volume transport through Drake Passage and meridional heat flux in the North Atlantic. More fundamentally, it is largely through the transport of mass, heat, and freshwater that the ocean influences the Earth's climate: if our ocean climate models are to adequately simulate the present climate, and predict the response to changes in forcing, they need to reproduce the large-scale fluxes in the ocean.

Testing models with estimates of transports based on ocean observations needs to go beyond a simple comparison of net fluxes. The mechanism by which the ocean carries properties also must be captured by the model. We know from ocean observations that the meridional heat flux in the Atlantic is dominated by the overturning circulation, while the North Pacific heat flux at mid-latitudes is dominated by the circulation of the subtropical gyre. If a model gets the right heat transport for the wrong reason, it is unlikely to respond to changes in forcing in a realistic manner.

Ocean property (e.g. heat) transports can be estimated using a variety of techniques. These include integration of air-sea fluxes derived from bulk formulae, subtraction of atmospheric heat transport (derived from observations or models) from satellite measurements of the energy balance at the top of the atmosphere to give ocean heat flux as a residual, and direct estimates from ocean observations. The first two methods suffer from biases which are difficult to assess and may lead to large uncertainties when integrated over large areas. The uncertainty in direct estimates of ocean fluxes are also often difficult to evaluate, but is arguably lower than the indirect techniques.

To what extent will the WOCE data set improve our understanding of the magnitude and mechanisms of ocean fluxes, and so provide more useful benchmarks for testing ocean models? To answer this question we need to consider what new information is provided by the WOCE data set, advances in our ability to exploit this information, and the challenges that must be met to estimate transports from ocean observations.

The WOCE hydrographic program provides a global data set of unprecedented coverage, data quality, and spatial resolution. Tracer measurements provide information about ventilation and time-scales which is independent of the distribution of temperature and salinity. Direct velocity measurements from drifters, floats, lowered and shipboard acoustic Doppler current profilers (ADCP), and western boundary current arrays have been made throughout the world ocean.

Leaving aside the very real issue of asynoptic observations of a time-varying ocean circulation, the problem of determining transports across a WOCE section primarily comes down to determining the reference level velocity. While the direct velocity measurements, in particular, provide useful information on the distribution of the reference level velocity, to exploit this information it is essential to take into account the sampling characteristics and uncertainties of each measurement type. For example, ALACE float trajectories can be averaged in space and time to provide an estimate of the mean absolute velocity at the depth of the floats. Wijffels and colleagues (personal communication) have shown that the ALACE-derived absolute velocity provides useful constraints on spatially-averaged reference level velocities in the interior of the South Pacific subtropical gyre, where the signal in other properties is weak. Beal and Bryden (1997) and Donohue (personal communication) have used lowered ADCP measurements to show a persistent equatorward under-current exists inshore of the strong poleward flow of the Agulhas Current. The under-current returns some Red Sea Water toward its source; a reference level chosen to make all water originating in the Red Sea flow away from its source would misrepresent the absolute flow there and lead to significant changes in the transport estimates.

Rapid progress is being made in determining how best to exploit the WOCE observations. The main conclusion is that none of the measurements by themselves is sufficient to pin down the reference level velocity, hence the transports, by themselves. For example, ALACE float estimates of the mean flow may prove to be most useful in the interior of the ocean gyres rather than the high velocity boundary currents. ADCP measurements, either shipboard or lowered, provide valuable constraints in regions of strong flow, but small biases may lead to large transport errors if used to reference geostrophic flow across long sections. Tracer budgets provide integral constraints on net fluxes across ocean sections. To bring these diverse measurements together, some sort of model is required. Many WOCE flux estimates will be based on box inverse models which combine the WOCE measurements with simple dynamics and conservation constraints. Progress with more sophisticated data assimilation schemes is also rapid, although substantial challenges remain, particularly with regard to assimilating the WHP data.

The task of estimating ocean transports is made more challenging by what WOCE did not do: sample the variability of the ocean circulation. Some repeat sections were occupied during WOCE, most using XBTs, and satellite altimeters provide global coverage of sea surface height variability, but for the most part WOCE did not measure the variability of the oceans, particularly in the ocean interior. Models suggest the seasonal variability of ocean heat transport can be large, particularly at low latitudes; we know less about the interannual variability of ocean fluxes. We have more to learn about how best to combine a data set collected in different years and seasons to make consistent estimates of ocean fluxes.

Another challenge is assessing the uncertainty in the flux estimates. Inverse models and other data assimilation techniques provide formal estimates of the uncertainty in the solution. However, the formal error estimates may underestimate the true uncertainty if the data do not resolve important oceanographic structure or variability, or the model physics are deficient. Sources of error in ocean transport calculations are many, ranging from "technical" issues (e.g. how best to account for transport in the "bottom wedge" beneath the deepest common depth at a station pair?) to more "physical" questions (e.g. what wind stress should be used to estimate the Ekman transport – observed during the cruise, monthly mean, annual mean? how serious is aliasing by internal waves?). It is straightforward to determine the projection of a physical quantity of interest (e.g. heat content) onto the "null-space" not resolved by the observations, but determining the heat flux carried by the null-space requires ad hoc assumptions about the strength of the flow with this spatial structure. Often the most useful statements about the uncertainty of ocean transport estimates are obtained by varying the assumptions (e.g. initial reference level) through a reasonable range and exploring the sensitivity of the resulting transport estimates. We have more to learn about evaluating the uncertainty of direct ocean flux estimates.

In summary, the prospect for a significant improvement in our understanding of the magnitude and mechanisms of ocean property fluxes from synthesis of the WOCE data set is excellent. The WOCE flux estimates will provide benchmarks of climatically-relevant oceanographic processes against which model performance can be assessed. Nevertheless, a number of challenges remain. The two most difficult problems are those of (1) combining non-synoptic observations while avoiding both aliasing of short-term variability and excessive spatial smoothing, and (2) assessing the accuracy of the flux estimates.

3.2 DATA-OUTPUT COMPARISONS IN HIGH RESOLUTION OCEAN MODELS – Peter Saunders, WOCE International Project Office

High resolution (1/2 degree or less) ocean models are generally initialised using a T-S climatology and because of short integration times and surface relaxation do not move far from their initial state. Consequently it is preferable not to employ such data for validation purposes: instead the use of quantities such as sea-level and direct current observations is to be much preferred.

Sea surface height (SSH) variance and the eddy kinetic energy derived from SSH gradients are well known to underestimate the observations of satellite altimeters both in frequency and wavenumber space. Underestimates are factors of between 2 and 4. Increasing resolution reduces the gap in energetic regions, such as western boundary currents, but does little in the open ocean. Changing model wind-forcing from a smooth (say monthly) climatology to daily fields including synoptic disturbances generates energetic inertial motions which for most data-output comparisons must be filtered during run time to prevent aliasing into the model output. Hence the discrepancy of unknown cause persists.

Lagrangian observations of currents made with drifters (at 15 m depth) and with ALACE floats (at 900 m depth) provide gridded fields in well measured regions. The analyses of both data types are in disagreement with those model results so far examined, but the comparison is not straightforward.

During WOCE numerous moored current meter arrays were deployed and transports from these measurements will become increasingly employed in data-output comparisons. Preliminary results suggest that there is better agreement for mean transports than for transport variance. Finally observationalists must be spurred on to combine WOCE transport arrays with WOCE hydrographic sections and generate robust estimates of heat and freshwater fluxes along with the overturning circulation, all elements currently missing in WOCE data model output comparisons.

A list ofWOCE current meter arrays at which transport estimates have or will be made is reproduced in an annex to the report of WG C (Flow through sills and straits). Where data is public it can be found at the WOCE current meter DAC or on the WOCE CD-ROM; where it is not yet available the PI can be approached. References attached to the list generally identify transport values. Arrays not described in this list were designed for other purposes such as measuring EKE. A compilation of EKE measurements (R. Dickson and K. Medler, MAFF, UK) can be found on the Web at kepler.oce.orst.edu/dickson/top.html

4. ATMOSPHERIC FORCING – S. Gulev, P. Shirshov Institute of Oceanology

Atmospheric forcing fields for driving ocean GCMs include individual meteorological variables such as wind, SST, surface salinity, air temperature and humidity, cloudiness, and fluxes of momentum, heat and fresh water, which can be estimated on the basis of individual measurements or measured directly.

APPENDIX B

Although bulk parameterisations widely used to estimate fluxes are considered to be well developed, there are some issues which are still poorly understood. These are: the effect of the ocean skin layer, parameterisations for the calm conditions (free convection), non-turbulent mechanisms of the moisture exchange under the storm conditions, aerosols impact on radiative fluxes, and dependence of wind stress on the sea state. Each of these processes can result in the uncertainty of several percent to several tens percent of different flux components.

Global and basin scale estimates of the sea-air fluxes and flux related parameters are available at present from VOS, satellites measurements, and numerical weather prediction systems (re-analyses and operational analyses). Each source has its strengths and weaknesses. Crucial issues for forcing ocean models are space resolution, time resolution, continuity of data available, and space-time homogeneity of errors inherent in the flux fields. At present, there is no source of flux fields which fits all these requirements simultaneously.

(a) Data from Voluntary Observing Ships (VOS)

Voluntary observing ship (VOS) measurements provide at present global-scale coverage of the World Ocean for the period from the mid 19th century. Comprehensive Ocean-Atmosphere Data Set (COADS) (Woodruff et al., 1998) contains marine reports available from GTS and those contributed from different data archaeology activities. The most advanced COADS update known as COADS Release 2 for 1860–1996 is expected preliminary in 1999 (Woodruff et al., 1998). For most ocean regions sufficient data coverage appears only for the post World War II period. Thus, estimates of the variability of fluxes can be done only for a 50-year period from 1946 to 1996. There is also remarkable inhomogeneity of the data coverage in space. Large areas in the Southern Hemisphere do not have enough data for the description of both mean climatology and interannual variability of fluxes. Alternative sources of the VOS measurements are UK Meteorological Office Main Marine Data Bank (MDB) which has, of course, considerable overlap with COADS, Bunker (1976) data set for 1941–1972 which was updated for the North Atlantic Ocean by Isemer and Hasse (1985, 1987) at IfM (Kiel).

Although data accuracy is a high priority issue for the producers of the VOS data collections, detailed studies undertaken over the last years indicate that there are still significant random and systematic errors and uncertainties in sea-air interface climatologies based on VOS. Significant biases can result from the choice of equivalent Beaufort scale, day/night time differences and historical changes in the observational techniques. Reliable estimates of these uncertainties requires validation of the VOS observations against instrumental measurements available from field experiments, Ocean Weather Stations (OWS), and meteorological buoys. During the last years there were a number of activities to correct different biases in the COADS collection. As a result, several COADS-based climatologies of the gridded directly observed quantities and sea-air fluxes were produced (Oberhuber, 1988; da Silva et al., 1994; Josey et al., 1996; Lindau, 1996).

VOS based sea-air flux climatologies extend over the longest period (50 yr) in comparison to the other sources. At present they provide 1° spatial resolution for climatological fields and 2° resolution for individual months. VOS gives temporal resolution of 1 month, although for some basins (North Atlantic) 10-days resolution could be achieved for some individual years. Inhomogeneity of sampling results in sampling errors which are the same order of magnitude as measurements errors and uncertainties of bulk-parameterisations. In particular, VOS based flux fields are of a very poor quality in important ocean regions, e.g. the Labrador Sea and Southern Ocean.

(b) Satellite global scale observations of sea-air interface

Forcing fields available from satellites have a present global scale coverage in space and a duration of several years. Moreover, remotely sensed data provide a number of directly observed quantities, which are only available from satellites (radiative fluxes, precipitation, waves, and others). The GEOSAT project with the TOPEX/POSEIDON, the ERS-1/ERS-2 program and the Special Sensor Microwave Imager (SSM/I) on the US Air Force Defense Meteorological Satellite Program (DMSP) together now constitute a rather long continuous data time series. ERS-scatterometer winds derived at IFREMER (Brest) (Katsaros, 1995; Bentamy et al., 1995) are available on CD-ROM for the period 1991–1996. NASA scatterometer winds available from the ADEOS crafts can compete successfully with ERS when the longer series appear. Altimeter wind and waves fields are already available from GEOSAT, ERS, and TOPEX for 15 years. An intercalibrated wind and wave climatology merged from different satellites was constructed at SOC (Southampton) (Cotton and Carter, 1994) and gives one of the first examples of a climatologically valuable satellite product which can successfully serve many purposes. SSM/I gridded wind data are available for a ten-year period from 1987 to 1996.

Precipitation measurements are available from microwave passive instruments (SSM/I) (Schulz et al., 1997) and from the altimeter of TOPEX/POSEIDON (Turnade and Morland, 1995; Katsaros, 1995). The Earth Radiation Balance Experiment (ERE) and the International Satellite Cloud Climatology Project (ISCCP) provide remotely sensed ocean surface radiation fluxes. Products for short-wave radiation obtained from different algorithms exist for periods from several years to a decade from the early 1980s to present (Charlock, 1995). Long-wave net radiation fields are also developed at MPI (Hamburg) and now at DLR (Köln) on the basis of combination of SSM/I and AVHHR data (Schulz et al., 1995; Schluessel et al., 1995). The advantage of the remotely sensed forcing fields is their complete coverage of the globe and relative homogeneity of data. In other words, even if these data are erroneous (and they are), they are at least homogeneously erroneous and should depict the interannual changes even better than the climate means. At the same time, these data need to be inter-compared and compared to in-situ measurements. Some of this work has already been carried out in the calibration/validation periods of each satellite instrument, but a comprehensive analysis of their consistency still needs to be performed. At present only the SSM/I mission provides all the forcing fields with a daily resolution in time and 1° resolution in space for a period of 10 years.

There was a hope that microwave instruments would quite soon give surface salinity, but unfortunately, it will take another 5 to 10 years to achieve an accuracy which can satisfy the ocean modelling community.

(c) Forcing fields from numerical weather prediction systems

During the last several decades re-analysis projects at ECMWF, NASA and NCEP created model climatologies of fluxes with 6 hourly resolution in time and 1 to 2° resolution in space. ECMWF T106 model outputs are available for the period 1979–1998 and will be scaled back to late 1940 by the end of this year. NASA re-analysis has somewhat shorter continuity of about 13 years from 1980 to 1993. These products are of considerable importance for ocean modelling, because they provide very complete coverage as well as synoptic scale resolution in space and in time. At the same time, variability patterns seen in these products are influenced by the impacts of the models, interpolation algorithms, and data processing, and comprehensive validation is desirable in order to study the reliability of both mean climatologies and interannual changes. Despite the fact that re-analyses flux products best satisfy all ocean modelling needs, operational fluxes will have their own value for some years, particularly for case studies.

WORKSHOP ORGANISING COMMITTEE

Organising Committee:

Dr Claus Böning (chair)
Institute fur Meereskunde an der Universtät Kiel
Düsternbrooker Weg 20
D-24105 Kiel
Germany
Tel: 49-431 597 3979
Fax: 49-471-4831-425
e-mail: cboening@ifm.uni-kiel.de

Dr Matthew H. England
Centre for Environmental Modelling & Prediction
School of Mathematics
University of New South Wales
Sydney, NSW 2052
Australia
Tel: 61-2-9385-7065
Fax: 61-2-9385-7123
e-mail: m.england@unsw.edu.au

Dr Dale B. Haidvogel
Department of Marine & Coastal Sciences
Rutgers University
PO Box 231
Cook Campus
New Brunswick, NJ 08903-0231
USA
Tel: 1-908-932-6555
Fax: 1-908-932-8578/6520
e-mail: dale@ahab.rutgers.edu

Dr Lynne Talley
Scripps Institution of Oceanography
University of California San Diego, M/C 0230
9500 Gilman Drive
La Jolla, CA 92093-0230
USA
Tel: 1-619-534-6610
Fax: 1-619-534-9820
e-mail: lynne@sam.ucsd.edu

Dr Eli Tziperman
Department of Environmental Sciences
Weizmann Institute of Science
Rehovot 76100
Israel
Tel: 972-8-9342544
Fax: 972-8-9344124
e-mail: eli@beach.weizmann.ac.il

Dr David J. Webb
James Rennell Division
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH
UK
Tel: 44-2380-596199
Fax: 44-2380-596204
e-mail: david.webb@soc.soton.ac.uk

Prof. Jürgen Willebrand
Abteilung Theoretische Ozeanographie
Institut für Meereskunde
Universität Kiel
Düsternbrooker Weg 20
24105 Kiel
Germany
Tel: 49-431-597-3979
Fax: 49-431-565-876
e-mail: jwillebrand@ifm.uni-kiel.de

Dr Richard A. Wood
Ocean Applications Branch
Hadley Centre for Climate Prediction and Research
Meteorological Office
London Road
Bracknell, Berks. RG12 2SY
UK
Tel: 44-1344-856641
Fax: 44-1344-854898
e-mail: rwood@meto.gov.uk

Dr Carl Wunsch
Dept. of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology
77 Massachusetts Avenue, 54-1522
Cambridge, MA 02139-4307
USA
Tel: 1-617-253-5937
Fax: 1-617-253-4464
e-mail: carl@pond.mit.edu

APPENDIX C

Local Organisation:

Dr Peter Gent
Climate and Global Dynamics Division
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80307
USA
Tel: 1-303-497-1355
Fax: 1-303-497-1137
e-mail: gent@ncar.ucar.edu

Dr William G. Large
National Center for Atmospheric Research
PO Box 3000
Boulder, CO 80307
USA
Tel: 1-303-497-1364
Fax: 1-303-497-1700
e-mail: wily@ncar.ucar.edu

PARTICIPANTS

Peter Baines
Commonwealth Scientific and Industrial Research Organisation
pgb@dar.csiro.au

Aike Beckmann
Alfred Wegener Institute for Polar and Marine Research
beckmann@awi-bremerhaven.de

Rainer Bleck
Rosenstiel School of Marine and Atmospheric Science
University of Miami
bleck@rsmas.miami.edu

Claus Böning
Alfred Wegener Institute for Polar and Marine Research
cboening@awi-bremerhaven.de

Frank Bryan
National Center for Atmospheric Research
bryan@ncar.edu

Kirk Bryan
Geophysical Fluid Dynamics Laboratory
kbryan@splash.princeton.edu

Eric Chassignet
Rosenstiel School of Marine and Atmospheric Science
University of Miami
eric@akee.rsmas.miami.edu

John Church
CSIRO Marine Research
john.church@marine.csiro.au

Allyn Clarke
Bedford Institute of Oceanography
a_clarke@bionet.bio.dfo.ca

Curt Covey
Lawrence Livermore National Laboratory
covey@pcmdi.llnl.gov

Eric D'Asaro
Applied Physics Laboratory
University of Washington
dasaro@faraday.apl.washington.edu

Gokhan Danabasoglu
National Center for Atmospheric Research
gokhan@ucar.edu

Sybren Drijfhout
Koninklijk Nederlands Meteorologisch Instituut
drijfhou@knmi.nl

John Dukowicz
Los Alamos National Laboratory
duk@lanl.gov

Matthew England
University of New South Wales
m.england@unsw.edu.au

Bruno Ferron
Massachusetts Institute of Technology
bferron@sea.mit.edu

Peter Gent
National Center for Atmospheric Research
gent@ucar.edu

Rüdiger Gerdes
Alfred Wegener Institute for Polar and Marine Research
rgerdes@awi-bremerhaven.de

Anand Gnandesikan
Princeton University
gnana@phoenix.princeton.edu

Hugues Goosse
Université Catholique de Louvain
hgs@astr.ucl.ac.be

Richard Greatbatch
Dalhousie University
richard.greatbatch@dal.ca

Steve Griffies
Geophysical Fluid Dynamics Laboratory
smg@gfdl.gov

Sergey Gulev
P.P. Shirshov Institute of Oceanology
gul@gulev.sio.rssi.ru

Dale Haidvogel
Rutgers University
dale@ahab.rutgers.edu

Robert Hallberg
Geophysical Fluid Dynamics Laboratory
rwh@gfdl.gov

APPENDIX D

Hiroyasu Hasumi
Center for Climate System Research
University of Tokyo
hasumi@ccsr.u-tokyo.ac.jp

Anthony Hirst
Commonwealth Scientific and Industrial Research Organisation
ach@atmos.dar.csiro.au

Bill Holland
National Center for Atmospheric Research
holland@ucar.edu

Greg Holloway
Institute of Ocean Sciences
zounds@ios.bc.ca

Nelson Hogg
Woods Hole Oceanographic Institution
nhogg@whoi.edu

Johann Jungclaus
Institut für Meereskunde an der Universität Kiel
jjungclaus@ifm.uni-kiel.de

Lakshmi Kantha
University of Colorado, Boulder
lakshmi.kantha@colorado.edu

Peter Killworth
Southampton Oceanography Centre
peter.d.killworth@soc.soton.ac.uk

Eric Kunze
University of Washington
kunze@ocean.washington.edu

William Large
National Center for Atmospheric Research
wily@ucar.edu

Christian Le Provost
Centre National d'Etudes Spatiales
christian.le-provost@cnes.fr

Gurvan Madec
Laboratoire d'Océanographie Dynamique et de Climatologie
madec@lodyc.jussieu.fr

Ernst Maier-Reimer
Max-Planck-Institut für Meteorologie
maier-reimer@dkrz.de

Jochem Marotzke
Massachusetts Institute of Technology
jochem@sound.mit.edu

Trevor McDougall
CSIRO Marine Research
trevor.mcdougall@marine.csiro.au

Jim McWilliams
National Center for Atmospheric Research
jcm@ucar.edu

Norikazu Nakasiki
Central Research Institute of Electric Power Industry
nakasiki@criepi.denken.or.jp

George Nurser
Southampton Oceanography Cent re
g.nurser@soc.soton.ac.uk

Dirk Olbers
Alfred Wegener Institute for Polar and Marine Research
dolbers@awi-bremerhaven.de

James Orr
Commissariat à l'énergie atomique/Saclay
orr@cea.fr

Scott Power
Bureau of Meteorology Research Centre
sbp@bom.gov.au

Monika Rhein
Institut für Meereskunde an der Universität Kiel
mrhein@ifm.uni-kiel.de

Steve Rintoul
Commonwealth Scientific and Industrial Research Organisation
steve.rintoul@marine.csiro.au

Malcolm Roberts
Hadley Centre for Climate Prediction and Research
mjroberts@meto.gov.uk

Peter Saunders
Southampton Oceanography Centre
peter.saunders@soc.soton.ac.uk

Bert Semtner
Naval Postgraduate School
sbert@ucar.edu

Rick Smith
Los Alamos National Laboratory
rdsmith@lanl.gov

Ron Stouffer
Geophysical Fluid Dynamics Laboratory
ris@gfdl.gov

Nobuo Suginohara
Center for Climate System Research
University of Tokyo
nobuo@ccsr.u-tokyo.jp

Lynn Talley
Scripps Institution of Oceanography
lynne@sam.ucsd.edu

Anne-Marie Treguier
Institut Français de Recherche pour l'Exploitation de la Mer
treguier@ifremer.fr

Eli Tziperman
Weizmann Institute of Science
eli@beach.weizmann.ac.il

Mark Warner
University of Washington
mwarner@ocean.washington.edu

David Webb
Southampton Oceanography Centre
david.webb@soc.soton.ac.uk

Jack Whitehead
Woods Hole Oceanographic Institution
jwhitehead@whoi.edu

Jürgen Willebrand
Institute für Meereskunde an der Universität Kiel
jwillebrand@ifm.uni-kiel.de

Jörg Wolff
University of Tasmania
j.wolff@utas.edu.au

Richard Wood
Hadley Centre for Climate Prediction and Research
rwood@meto.gov.uk

Jiayan Yang
Woods Hole Oceanographic Institution
jyang@whoi.edu