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INTRODUCTION

The CLIVAR Working Group on Ocean Model Development (WGOMD) organized a workshop at NOAA's Geophysical Fluid Dynamics Lab (GFDL) in Princeton USA on June 16-18, 2004. The event saw about 100 experts in ocean modelling (see Appendix I) gathering together thanks to the sponsorship of the World Climate Research Programme and NOAA Office of Global Programs. Special thanks goes also to Steve Griffies, for organizing the meeting and to GFDL for hosting it. The purpose of this report is to summarize some of the main topics discussed at the workshop and to highlight recommendations.

MOTIVATION

The main goal of the workshop was to facilitate a dialogue between modellers, theorists, and observationalists on the physical integrity of a new class of high-end global ocean models, with the particular aim to articulate how best to move forward over the next decade to improve simulation realism. These new models have been developed over the past few years largely in response to the requirements of the 4th IPCC Assessment Report (AR4) due for publication in 2006. For many climate laboratories, the recent model development efforts were unprecedented in their intensity and scope.

DESCRIPTION

The participants brought their expertise to the workshop to discuss four main topics, each comprising a separate session (see Appendix II):
(A) State of the Art in Ocean Climate Models (facilitated by Peter Gent of the National Center for Atmospheric Research, USA)
(B) Status of the Ocean Model Intercomparison Project (facilitated by Anne Marie Treguier of Laboratoire de Physique des Oceans, France),
(C) Key Physical Processes (facilitated by Raffaele Ferrari of Massachusetts Institute of Technology, USA and Sonya Legg of Woods Hole Oceanographic Institute, USA)
(D) Future Directions (facilitated by Alistair Adcroft of Massachusetts Institute of Technology, USA)
Each session consisted of a number of invited speakers who gave 30-60 minute presentations. Equal time was also allotted for general discussion and debate, with all participants invited to present material that added to the content of a session.

RECOMMENDATIONS

- To encourage future development of alternative vertical coordinates, such as isopycnal, sigma (yet to be widely used for global climate studies), and hybrid, in order to improve understanding of the ocean's role in climate, and to determine the robustness of climate change simulations.
- Further research is needed on the parameterization of the momentum equation for diffusion, eddy advection and vertical mixing
- To encourage the global modellers community to run a Coordinated Ocean Reference Experiment (CORE) to facilitate the comparison of their model solutions.
- To use as forcing dataset the Large and Yeager (2004) in both normal year and interannual form. This dataset is based on NCEP reanalysis and observational data products, corrected to ensure better global balance. The data are available at: http://data1.gfdl.noaa.gov/nomads/forms/mom4/CORE.html
- Explore alternative frameworks for the parameterization of mesoscale processes in the ocean: residual mean based models and PV-based closure schemes.
- Develop parameterizations for the restratification processes in the surface boundary layer of the ocean. Present model demonstrate skill in predicting the deepening phase of the planetary boundary layer, but not in reproducing the shallowing phase. Progress could be made by including the lateral processes that lead to restratification, missing in extant parameterization schemes. The restratification phase of the boundary layer plays an important role in the heat and salt budgets of the upper ocean, and it is important in modulating air-sea fluxes.

SESSION A: STATE OF THE ART IN OCEAN CLIMATE MODELS

Summary of Session A

Representatives from climate centres detailed aspects of their models used for IPCC assessments, with focus placed on the ocean component from fully coupled ocean-atmosphere-land-ice models, as well as coupled ice-ocean simulations. Speakers highlighted some details of their ocean component related to the key processes discussed in Session C, and they presented analyses of key metrics. They also presented analyses of the natural variability found in the model such as ENSO. Presenters were encouraged to expose the "underside" of their models so that workshop participants can learn what are the key biases and problems requiring improvements.

Details of Session A

Peter Gent opened this session with an overview of the new generation of IPCC-class ocean climate models from a dozen international climate centres. All but one model uses geopotential or z-coordinates in the vertical, with the Nansen Centre in Norway the exception that uses the Miami Isopycnal Model. The vertical coordinate represents perhaps the most important aspect of an ocean climate model. The z-models have long been the dominant choice, largely due to their simplicity and relatively clean representation of the surface mixed layer where critical air-sea and ice-sea interactions occur. However, as discussed by Rainer Bleck of Los Alamos, isopycnal models, and their derivatives, hold some promise due to their intrinsic ability to respect the quasi-adiabatic nature of the ocean interior. When used in the context of a hybrid vertical coordinate model, using pressure near the surface and potential density in the interior, such quasi-Lagrangian models will likely see much more use in the near future for ocean climate simulations (see also Bob Hallberg's presentation in Session D). Additionally, it was noted that in the 3rd IPCC assessment of 2001, only one model, an isopycnal model, maintained a stable meridional overturning the North Atlantic under increasing CO_2forcing. Correspondingly, a key recommendation of the workshop is to encourage future development of alternative vertical coordinates, such as isopycnal, sigma (yet to be widely used for global climate studies), and hybrid, in order to improve understanding of the ocean's role in climate, and to determine the robustness of climate change simulations.

Most ocean models in AR4 have horizontal resolution in the range of one to two degrees, with meridional enhancement commonly used in the tropics. Vertical resolution is also refined in the upper ocean to facilitate representations of mixed layer and pycnocline dynamics. As highlighted by Tony Rosati of GFDL, many of the ocean models participating in AR4 possess respectable equatorial dynamics critical for simulating ENSO. This situation represents an important milestone for IPCC ocean models due to the huge impact that ENSO has on global climate. Indeed, some centres, such as GFDL, now use the same model for research into seasonal-interannual (SI) predictability as for climate change projections. This merger of previously disparate modelling efforts provides climate change modellers with critical new tools to help evaluate the integrity of their simulations.

Although progress is impressive with the seasonal to interannual aspects of the climate change models relative to past IPCC reports, the models still show noticeable differences from observations and analyses. In particular, sea surface temperatures (SSTs) are too cold in the central tropical Pacific and too warm in the east, and the maximum ENSO related variability is too far west. It was speculated that reduction of these biases may require further refinement in the model grid resolution, or new parameterizations, in order to better account for heat transport provided by breaking equatorial waves.

No ocean model in AR4 uses horizontally oriented tracer diffusion. This characteristic is in strong contrast to earlier IPCC reports, where many z-models continued to use pre-1990 tracer closures. Today, all AR4 models employ some form of rotated neutral diffusion for the z-models, and isopycnal diffusion for the isopycnal model. Additionally, the models utilize the Gent and McWilliams (1990) (GM90) parameterization for eddy advection as implemented within the tracer equations in the z-models, and the thickness equation in the isopycnal models. (Some Arctic z-modellers; e.g., Greg Holloway, employ an alternative implementation of GM90 via enhanced vertical viscosity. Further research was recommended to determine the utility of this approach). Some models employ lateral tracer diffusivities that are space-time constants, and some allow them to be functions of the vertically averaged flow fields. However, none use closures based on the theoretically popular idea that potential vorticity should be diffused downgradient.

All models employ frictional dissipation in the momentum equations via a Laplacian operator, with some finding great improvements in the tropical currents when allowing for anisotropy in the viscosity as proposed by Large et al (2001). In general, momentum friction is used for numerical purposes, and so the smaller the lateral frictional dissipation, generally the more realistic the simulation, although sufficient dissipation is certainly needed to satisfy numerical constraints (e.g., grid Reynolds number must be less than unity and western boundary currents must be resolved). There is presently no general agreement about a physically based closure for the momentum equations.
There is a wide variety of vertical/diapycnal mixing schemes, with many opting for a physically based first or second order turbulent closure scheme (see Large et al. 1994 for a review) and a wide suite of included processes (e.g., breaking internal gravity waves, double diffusion, deep convection, shear instability, etc.). Vertical mixing parameterizations remain the most diverse aspect of the ocean model subgrid scales used for AR4.

Malcolm Roberts of the Hadley Centre presented a comparison of the meridional overturning circulation (MOC) in nine of the coupled models participating in AR4. In general, the simulations showed significant differences. It is not clear whether differences are due more to details of the ocean model components or the diverse forcing from the atmospheric models. One possibility is that the MOC is a function of the horizontal resolution, with the 1/3 degree Hadley ocean model showing enhanced overturning in the North Atlantic and deep Antarctic Bottom Water, relative to their 1,25 degree simulation using the same atmospheric component. Diagnosing the causes for model differences is an important yet highly nontrivial task required to understand variability and stability properties of the meridional overturning circulation.
One of the most important milestones for coupled models contributing to AR4 is the removal of flux adjustments in many of the climate simulations. It has been speculated that a combination of ocean model upgrades, from refined resolution to improved physical parameterizations, combine to allow for a stable MOC without flux adjustments. For many labs, the realization of stable MOC without flux adjustments represents the most significant advance in the AR4 models over previous incarnations.

SESSION B: COORDINATED OCEAN REFERENCE EXPERIMENTS (CORE)

Summary of Session B

This session focused on questions related to systematically comparing coupled ice-ocean model simulations. What sorts of comparisons are relevant and interesting? The ocean climate modelling community continues to struggle with these questions:

- Can the community coalesce around protocols, and associated datasets, for running the models, such as within the context of an Ocean Model Intercomparison Project (OMIP)?
- How valuable will an OMIP be for evaluating the ocean and sea ice components of coupled climate models?
- Does OMIP provide a useful venue for comparing model sensitivities to parameterizations arising from the process studies?
- Is it possible to define an OMIP protocol that is sufficient for running repeating seasonal climatological runs, interannaually varying integrations, and/or experiments with strong perturbations such as fresh water pulses added to the North Atlantic?
- What sorts of datasets are useful to assess the physical integrity and relevance of these simulations?

Overall, this part of the workshop allowed for discussions/debates of proposed protocols for model comparisons, including forcing datasets, bulk formulae, and key metrics to be used for evaluating the ice-ocean simulation. It also contained presentations from those running pilot-OMIP simulations. The main conclusion from this session is that the ocean modelling community is not interested in a formal OMIP. Instead, there was full agreement that WGOMD should encourage global modellers to run a Coordinated Ocean Reference Experiment (CORE) to facilitate the comparison of their model solution to others. CORE would consist of a protocol analogous to that developed for the Pilot OMIP, using the Large and Yeager (2004) forcing dataset in both a normal year and interannual form. A discussion of CORE will be provided in the January 2005 forthcoming issue of CLIVAR Exchanges.

If CORE concept is well received by the ocean modelling community, then a formal OMIP will follow naturally, whereby datasets are housed in a centralized location and comparison projects are performed. The WGOMD believes that CORE, and its successful reception by the international modelling community, is a necessary step towards OMIP.

Details of Session B

It is often useful for purposes of understanding as well as model development to simulate the global ocean climate without an interactive atmospheric model. Hence, it has become quite common to employ coupled ocean and sea ice models forced with atmospheric data products. The simplest atmospheric forcing for temperature and salinity can be realized by damping the surface properties to a given climatology. However, such a forcing leads in many cases to overly dissipative boundary conditions and unphysical fluxes, which are far from that seen in a coupled climate model or Nature.

Within the past few years, modellers have aimed to improve on the older "restoring" experiments by using one of the atmospheric products from the reanalysis projects. Unfortunately, deriving a useful and self-consistent set of atmospheric forcing fields constitutes a highly nontrivial and tedious task. Notably, the use of fields directly from a reanalysis project is impractical due to large imbalances that cause unacceptable model drift over the decadal to century time scales of ocean climate simulations. Hence, it is necessary to adjust the reanalysis products to maintain global balance. Even with a balanced reanalysis forcing, there remain many difficulties due to limitations of the atmospheric models and assimilation tools used to create the reanalysis fields. In particular, the reanalysis products deviate in critical and nontrivial manners from observations.

The extreme difficulty associated with deriving an atmospheric forcing dataset suitable for ocean climate modelling is the key reason that no Ocean Model Intercomparison Project (OMIP) presently exists. The potential utility that could arise from the general use of a common set of forcing fields and protocol make the aim of developing "Coordinated Ocean Reference Experiments" (COREs) a central goal of the WGOMD. The second session of the workshop focused on the needs for establishing such benchmark experiments.

As described by Frank Bryan of NCAR, an unfunded pilot OMIP (P-OMIP) was coordinated by the WGOMD in 2001-2004 using a modified version of forcing from the 15-year ECMWF reanalysis developed by Frank Roeske at the Max Planck Institute (MPI) in Hamburg. The goal of this project was to determine the feasibility of initiating a more broadly organized and sanctioned OMIP, and to see what interest the international ocean climate modelling community has in this project. Unfortunately, P-OMIP had weak participation. Two reasons explain the difficultly:

- Many of the global modellers were overwhelmed with IPCC related tasks during the past five years, thus precluding them from focusing on the development of an OMIP and the serious analysis of simulations
- Disagreements arose over the appropriateness of the atmospheric forcing based on reanalysis products, especially the radiation fields.

The bottom line is that pursuing P-OMIP, and the possibility for a more formal OMIP, was not seen to be of scientific interest to the participants. Consequently, the workshop participants encouraged WGOMD to reconsider the appropriateness of OMIP at this time, and to instead consider an alterative that has more scientific appeal.

To possibly help develop a more attractive alternative, presentations were solicited from those participating in other comparisons using ocean and sea ice models. In particular, regional ocean and sea ice comparison projects have been conducted, with some success. Two examples were discussed at the workshop: the Arctic Ocean Model Intercomparison Project (AOMIP) was summarized by Andrey Proshutinsky of Woods Hole, and the PREDICATE project focusing on Atlantic climate predictions was presented by Helge Drange of the Nansen Centre. Both projects have received external funds to provide infrastructure for systematic comparisons and workshops. Unfortunately, neither has resolved problems arising when developing a dataset and protocol for global century scale ocean and sea ice modelling. However, it became clear from discussions that should the global modelling community sanction a global forcing dataset and protocol, the regional climate communities would be quite interested in using these data for their research. Although placing the burden back onto the global modelling community, it was nonetheless considered encouraging by the WGOMD to know that if a consensus can be reached, interest from the regional communities is strong.

There are two main problems with the dataset produced by MPI for P-OMIP:

- radiation fields from reanalysis products are generally considered to be significantly inferior to satellite products,
- only a single repeating year is supported, whereas most scientific interest from researchers is with interannually varying data.

Bill Large of NCAR presented the Large and Yeager (2004) dataset, which aims to address these criticisms. Their dataset is an amalgam of NCEP reanalysis and observational data products, as well as "corrections" based on decades of experience and ocean model behaviour. Both a repeating year and 43 years of interannual forcing are provided, and both are corrected via the same algorithm. This dataset has been used for about a year by researchers at NCAR and GFDL, and it is supported by both institutions for the international modelling community. The following web site provides details:
http://nomads.gfdl.noaa.gov/nomads/forms/mom4/CORE.html

In general, workshop participants welcomed the release of this dataset for their research and development purposes. The overall recommendation from participants is that the community focus on using this dataset for purposes of establishing COREs.

In a related discussion, Mike Winton of GFDL exposed many of critical technical details about the surface boundary conditions that arise when running coupled ocean and sea ice models forced by a data product. In particular, he noted the following points that are perhaps well known to many coupled modellers, but less well appreciated by ocean modellers:

- Models participating in a comparison project should use same turbulent transfer, or bulk, formula. A comparison of fluxes resulting from GFDL and NCAR bulk formulae showed significant differences when both are run using the same SST climatology and atmospheric state from the Large and Yeager (2004) repeating year meteorology. In particular, the wind stresses were larger with the GFDL formulation (which follows ECMWF) and the latent heat fluxes were larger with the NCAR formulation. The differences were traced to differences in the neutral transfer coefficients (roughness lengths). Given these sometimes nontrivial differences, the NCAR bulk formulae scheme was adopted by GFDL for the purposes of comparison in NCAR and GFDL integrations conducted during the past year.
- Models participating in a comparison project should use properly referenced meteorological data consistent with what the bulk formulae expect. Reanalysis meteorological data is commonly distributed at 2m while oceanic turbulent transfer schemes often require 10m data. For accuracy, it is essential that the data be re-referenced to 10m. The re-referencing algorithm and the flux calculation algorithm are closely related. So, ideally, one should re-reference using a scheme that is compatible with the flux scheme. This re-referencing issue was overlooked in the P-OMIP data and bulk formulae.
- Models should use the same treatment of saltwater vapour pressure. The vapour pressure over seawater is about 2% less than that over fresh water. This difference is not negligible compared to the 20% subsaturation of marine air that drives evaporation. Consequently, the effect should be included in all models participating in a comparison.
- It is desirable to use high frequency meteorological data. A one-month run of an AMIP model was used to explore the flux errors associated with averaged meteorological inputs. With daily (rather than six hourly) wind, temperature, and humidity, latent heat fluxes are underestimated broadly over the winter storm track band by some 10's ofW/m2. There was also a smaller underestimate located in the summer storm track band. Experiments that refined the temporal resolution of the flux inputs individually showed that high frequency winds are most important for reducing the error, but temperature and humidity frequency also contribute. When all inputs are given at 6 hourly frequencies, the global RMS error is about 1 W/m2 versus near 8 W/m for daily inputs.

An issue for comparisons is the strength of the salinity restoring. Although relatively strong salinity restoring will reduce drift, it has no physical basis and so it is desirable to use the weakest possible restoring. A weak restoring also has the benefit of allowing increased variability in the surface salinity and deep circulation. However, when the salinity restoring and effective temperature restoring timescales are very different, the experiment becomes analogous to a mixed boundary condition experiment. The ability of mixed boundary conditions to represent the adjustment of the ocean in the coupled system has been called into question. In particular, mixed boundary condition experiments with strong temperature restoring have been shown to be excessively susceptible to the polar halocline catastrophe, in which a fresh cap develops in high latitudes and shuts down overturning (Zhang et al, 1993).

The effective temperature restoring determined by numerically linearizing the CORE thermal boundary condition is quite strong, yielding piston velocities around 1-2 m/day. The salinity restoring strength chosen for a comparison between NCAR and GFDL simulations with the normal year forcing was much smaller (50m/4years). Under these boundary conditions the GFDL model Atlantic overturning greatly weakened to about 4Sv in 50 years and remained so for the full 100-year simulation. In contrast, the NCAR model's MOC, while weaker than that in the NCAR climate model, remains at about 10 Sv until the end of the 100-year experiment, and slightly increases when running longer.

Contributing to the very weak MOC in the GFDL model was an effect not present in traditional mixed-boundary condition experiments: as the overturning weakened, the North Atlantic sinking regions cooled leading to a reduction in evaporation of about 0.1 Sv. The GFDL ocean-ice model's weak MOC is in contrast to the behaviour of the same ice and ocean components in the GFDL climate model runs with an interactive atmospheric model. Here, the overturning is stably maintained in multi-century runs at about 15Sv. To explore the possible role of ice dynamics in the collapse, a companion run with immobile sea ice was conducted. The overturning in this experiment was likewise very weak. Ongoing experiments with varying ocean horizontal viscosity indicate that a less viscous flow exhibits stronger MOC. Such remains a focus of research at GFDL.

In addition to forcing based on repeating annual cycle and interannually varying conditions, it is interesting to compare the response of different models to prescribed perturbations. Ruediger Gerdes of the Alfred-Wegener Institute in Germany presented an experiment where he prescribed a perturbation due to enhanced fresh water melt localized around the Greenland coast. This forcing was added to that from the MPI P-OMIP forcing (the Large and Yeager data was not available when the perturbation experiments were begun). The experimental design was largely motivated by one used by the Climate Model Intercomparison Project (CMIP), but here without the presence of an interactive atmosphere. The workshop participants largely agreed on the merits of the Greenland melt experiment for the purpose of understanding and quantifying potential changes in Arctic and North Atlantic climate (e.g., sea level) due to global warming. Full documentation of the experimental protocol will be given in the peer review literature.

SESSION C: KEY PHYSICAL PROCESSES

Summary of Session C

Ocean climate models are far too coarse to explicitly represent many of the key physical processes that set the large-scale properties of the ocean. The purpose of the Key Physical Processes session of the workshop was to facilitate discussion and debate about some of the processes deemed critical for the ocean climate system. Six topics were discussed by invited presenters, with substantial contributions from other participants.

Details of Session C

Sonya Legg from Woods Hole and Princeton opened the session with a discussion of overflows and gravity current entrainment processes. NOAA and NSF in the USA have funded two Climate Process Teams (CPT) to improve the physical integrity of ocean climate models. One of the teams focuses on gravity current entrainment processes, since they are critical for determining properties of ocean deepwater masses as well as the overturning circulation. The second CPT involves the interactions of mesoscale eddies with the planetary boundary layer. This is yet another example of where details of how the models represent/parameterize processes can have important effects on the large-scale simulation integrity. Hopefully, with the combined efforts of global modellers, process modellers, theorists, and observationalists, the next two to three years will see a nontrivial improvement in our understanding of how to include these processes in the climate models.

Sonya Legg focused on the physical processes related to overflows and gravity current entrainment, and the ability of different models to represent or parameterize them. Eric Chassignet of the University of Miami presented an example of assessments of different mixing schemes in overflow simulations using the Hybrid Coordinate Ocean Model (HYCOM). The ensuing discussion raised several key points:

- There is little understanding of how improved overflow simulation fidelity will affect climate simulations.
- While a parameterization which represents all the processes involved in overflows may still be out of reach, particularly for z-models, there is a need for either global "ugly" schemes (e.g. Beckman and Doescher, 1997) or more sophisticated approaches (e.g. Price and Baringer, 1994) used at specified locations. Both approaches are currently being implemented in global models
- Overflows are affected, in ways that are not fully understood, by many aspects of the model, such as resolved and subgrid scale transport schemes, spurious numerical diffusion and physically parameterized diffusion, vertical viscosity, representation of topography, and the vertical coordinate.
- Antarctic bottom water formation, where gravity currents are influenced by tides and thermobaricity, is an especially difficult case for models to represent, especially isopycnal models, and would benefit from regional process study simulations.

The second topic during Session C was presented by Raffaele Ferrari of MIT: interactions between mesoscale eddies and mixed layer processes. He analyzed the feedbacks between surface buoyancy fluxes, turbulent mixing at the ocean surface, and mesoscale eddy transports. Suggestions were made on specific parameterizations for these effects. John Marshall of MIT showed results from an adjoin calculation where eddy stresses were assimilated by fitting the MIT GCM to temperature and salinity observations. The following discussion focused on a number of points:

- Tapering of mesoscale eddy mixing schemes at the ocean surface is not based on physical arguments. However the details of the tapering can greatly affect surface tracer properties.
- Mesoscale eddy fluxes drive strong horizontal flows in the ocean mixed layer. The role of these circulations in the ventilation of the upper ocean is not well understood.
- Inertial oscillations in the surface ocean are modulated by mesoscale eddies and as a result shear-driven mixing is quite intermittent. There is no parameterization of these effects in ocean models.

The next presentation was from Claus Boening of Kiel. He focused on deep convection in the Labrador Sea. High resolution numerical simulations were used to confirm recent speculations that heat loss in the marginal sea interior is offset by lateral eddy fluxes originating in the boundary currents. Surprisingly, downwelling is concentrated near the boundaries and depends on vertical mixing parameterizations. Coarse resolution models fail to capture these dynamics and do not reproduce accurately the Labrador Sea stratification and circulation. Despite these shortcomings, coarse resolution models produce overturning circulation and heat transport in remarkable agreement with eddy rich models.

The ensuing discussion focused on the representation of lateral eddy transport and convection in numerical models. John Marshall mentioned that numerical studies of Labrador Sea convection suggest that convective adjustment is "perfectly adequate" for simulating buoyancy mixing, but questions remain on how to represent momentum transport by convecting plumes. Peter Gent pointed out that models are more sensitive to lateral transport processes by rim eddies than to convective parameterizations. David Marshall from the University of Reading suggested that convective schemes might be more important than generally thought, because they can affect the gradient of pressure between the interior and boundary, thus affecting boundary circulations.

Lou St. Laurent from Florida State University summarized recent progress in observing and understanding the processes involved in abyssal mixing, particularly by the tides. The chain of events from the generation of baroclinic tides, radiation, cascade to smaller scales and mixing and dissipation has been represented by a global vertical diffusivity parameterization by Simmons et. al (2004).

Discussion by participants focused on whether different parameterizations of abyssal mixing will have a significant influence on the climate. Bill Merryfield from the Canadian Climate Centre described an implementation of the Simmons et al (2004) parameterization in which tidal parameterizations show much improved simulations in the deep ocean relative to a constant vertical diffusivity. Notably, simulations with tidal parameterisations give very similar results to those with the time independent and depth dependent diffusivity of Bryan and Lewis (1979). Giulio Boccaletti of MIT showed that while mass transport is sensitive to changes in abyssal mixing, the ``heat function'' is unaffected, being dominated by the upper ocean gyres. This result suggests that climate is not sensitive to details of abyssal mixing.

Martin Visbeck of Lamont-Doherty and Kiel reviewed the processes that drive ventilation of the ocean thermoclines. These processes include:

- surface buoyancy fluxes,
- Ekman convergence,
- boundary layer entrainment,
- lateral eddy mixing.

He then showed some inverse calculations that infer lateral eddy mixing in the Antarctic Circumpolar Current (ACC) from observations of surface fluxes, mixed-layer depth, and temperature and salinity distributions.

Discussions amongst participants focused on results from the inverse calculations, which suggest a strong dependence of mesoscale eddy diffusivities with depth and latitude. Anne Marie Treguier suggested that the drop in eddy diffusivity at the ocean surface might be related to the surface-intensified potential vorticity barrier generated by the ACC. Trevor McDougall from CSIRO in Hobart emphasized that climate models are very sensitive to spatial variations in eddy diffusivities and the issue is of central importance to improve climate models skill. Greg Holloway from the Canadian Institute of Ocean Sciences argued that there is too much emphasis on eddy mixing of tracers and too little on eddy mixing of momentum. Raffaele Ferrari and John Marshall suggested that a way forward is to frame the problem in terms of residual mean theory where eddy mixing of tracers and momentum are combined into an eddy stress.

Paul Schopf introduced the topic of mixing in the upper tropical ocean by showing the importance of tropical mixing to ENSO predictions, and the sensitivity of simulations to different diffusivity and viscosity parameterizations. He also provided an overview of the planned Pacific Upwelling and Mixing Program (PUMP). Discussion focused on the Tropical Instability Waves (TIW), which are represented in the one-degree class of models with enhanced meridional resolution in the tropics. However, their representation is largely linear, with wave breaking and the associated mixing effects largely absent until more refined resolutions are employed. The coupled atmospheric wave features seen in the high resolution wind observations are less well resolved in present day atmospheric models, but these are potentially important processes for equatorial dynamics. A possible way forward is to embed a high horizontal resolution atmospheric boundary layer model into a climate model. A contribution from Debasis Sengupta from Bangalore, India described the importance of simulating intra-seasonal atmospheric variability correctly to obtain good representation of equatorial ocean properties.

SESSION D: FUTURE DIRECTIONS

Summary of Session D

Six invited lectures rounded out the workshop in the Future Directions session. This session focused on issues, which are likely to form a key part of ocean climate science during the next decade.

Details of Session D

Steve Rintoul from CSIRO in Hobart started the session with a discussion of observations that potentially will be useful to help constrain models. While the amount of data available for constraining models increases with time, we still do not have enough observations of key oceanographic features. For example, we do not have good measurements of absolute velocity and transports, and we only have indirect and sparse measurements of mixing rates, eddy fluxes, formation rates, sea-ice volume and forcing. Rintoul gave a list of what observations will probably be available for constraining models in five years time. This list includes the following:

- global upper ocean stratification, albeit with poor sampling in time,
- estimates of meridional overturning and water mass formation rates with some indication of associated variability,
- a few non-aliased records of decadal variability,
- a more global but still sparse map of mixing rates,
- more accurate measurements of absolute velocity from floats,
- altimeters and gravity missions,
- tracer inventories and improved estimates of air-sea fluxes of heat,
- fresh-water and carbon.

Notably missing from the list are significantly better measurements of sea-ice volume.

During discussions, questions were raised about how well the Argo floats resolve jets in the Southern Ocean and the difficulty in observing eddies and spatial correlations. There is still a major lead-time between the observational programs and usable data for constraining models. Observational results are often delayed due to a need for interpretation and analysis. Are the observations planned with a view to the use of resulting data in modelling and re-analysis?

Eric Chassignet from the University of Miami presented results from an operational perspective. Operational oceanography, as presently practiced, focuses on short-term prediction of the ocean state, and it is normally carried out at relatively refined resolution in a regional context. Predictions are limited by forecasts of the atmospheric state used for forcing the ocean models. There are some examples of coupled forecasting systems including seasonal-interannual prediction of ENSO and hurricane forecasts. The GODAE (Global Ocean Data-Assimilation Experiment) project aims to demonstrate a global operational capability. Objectives include the following:

- routine short-range open-ocean forecasts,
- best estimates of boundary conditions for coastal and regional models,
- initial conditions for climate forecasts.

The challenges of operational oceanography include bringing together real-time streams of diverse data and assimilating them into refined-resolution models. The connection between operational oceanography and climate modelling is through both the potential for initial conditions for ocean components of coupled models and for the creation of long reanalysis data sets of the ocean for evaluation of coupled ocean model behaviour.

One question that confronts operational oceanography is how to best use the limited computational resources. The trade-off is often made between the use of a comprehensive data assimilation methodology, which involves very expensive techniques, and refined spatial resolution needed to accurately represent many oceanic features. It was emphasized that operational products focus on dynamical features rather than climate trends. Consequently, the methods used in operational oceanography can often afford to ignore biases that may be critical for climate modelling. The issue of valid forcing data for reanalysis is similar to the problem of forcing climate ocean models. An open question is whether ocean observational satellites will still be up when operational oceanography reaches a production phase?

Eli Tziperman from Harvard University presented a discussion of adjoin methods and their use in oceanography. A significant experience has accumulated over the past decade in the use of adjoin methods for ocean data-assimilation and state estimation. But adjoin-based tools have many other applications, as emphasized in this talk. In particular, adjoin methods have been used to study the sensitivity of the North Atlantic heat transport (Marotzke et al 1999, Sirkes and Tziperman 2001) and of ENSO (Van Oldenborgh et al 1999; Galanti and Tziperman 2003; Galanti et al 2002), and there is clearly a potential for many additional ocean model sensitivity issues that may be explored this way.

Stable linear systems in which small perturbations eventually decay may exhibit significant initial (transient) amplification prior to this decay (Farrell 1988). The optimal initial conditions leading to such a transient amplification are calculated by solving a large-scale eigenproblem, which is done most efficiently using an adjoin model. This has been applied to intermediate ENSO models (e.g., Kleeman and Moore 1997), to the wind driven circulation in idealized models (Moore 1999) as well as to highly idealized models of the thermohaline circulation (Tziperman and Ioannou 2002, Zanna and Tziperman 2004). These are just a few examples of the many possible applications of adjoin based tools to the understanding of ocean models and ocean dynamics.

Bob Hallberg from GFDL discussed ocean model frameworks. Ocean model development has a long history of being primarily the fruit of individual efforts, rather than a cohesive community effort. While this may have been appropriate for an era when ocean modelling was a small enterprise and computer architectures were very heterogeneous, the limitations of this approach are increasingly apparent. This traditional mode of development has led to great difficulty in evolving ocean models to more proficiently capture the fundamental aspects of the ocean dynamics. Comparisons between simulations with different models have been largely restricted to whole models, and interchange of specific capabilities has been slow and limited to those instances where the benefits are abundantly obvious. Shockingly, potentially valuable ocean modelling capabilities have been lost when primary developers left the field or in the transition between computer architectures.
This mode of development is no longer viable in an era when increasingly diverse demands are being placed upon ocean models. For climate uses, these demands include shifts to:

- eddy-permitting models,
- generalized vertical coordinates,
- increasingly sophisticated parameterizations of unresolved processes,
- new applications of ocean models like biogeochemistry and regional impacts studies.

In the face of these increasing obligations, the shortage of human resources to continue with the traditional mode of ocean model development is increasingly acute. The time has come for the development of ocean modelling capabilities to become a coherent community effort.

This community effort will likely be channelled through Ocean Modelling Environments rather than individual models. An "Ocean Modelling Environment" is a uniform code comprising a diverse collection of interchangeable algorithms and supporting software from which a model can be selected. This is in contrast to the traditional definition of an ocean model, either as a specific collection of algorithms or a specific model configuration (including parameter settings, model grid, forcing fields, etc.). There are several nascent examples of constellations of prominent ocean model developers coming together to unify their efforts behind Ocean Modelling Environments, including the "Hybrid Ocean Modelling Environment" (HOME) (among isopycnic- and other large-scale American modellers), the "Terrain-following Ocean Modelling System" (TOMS) (among sigma-coordinate regional modellers), and potentially the European project "Nucleus for European Modelling of the Ocean" (NEMO).

There are a number of advantages to be accrued from the modelling environment paradigm. Community cohesion should be dramatically enhanced as the existing software barriers to collaboration are eradicated. Ocean modelling should exhibit much greater ingenuity, as better ocean models are "bred" from the larger "gene pool" of algorithms encompassed by the environments, and as new capabilities are evaluated and transitioned to widespread routine use much more rapidly. This can and must be done without inhibiting the ability of an individual ocean modeller to select the algorithms and capabilities that are best suited to addressing a specific question about the ocean. The impact on the value of model comparisons will be dramatic, as the interchange of algorithms enabled by the environments facilitates the exploration of why models differ. To successfully meet climate-modelling needs, the common code-base of the shared Ocean Modelling Environments must run efficiently on the diverse computer platforms in use and must couple readily with a variety of other Earth System Model components. The technology to meet this requirement is rapidly maturing through such projects as the "Earth System Modelling Framework" (ESMF) in the USA or PRISM in Europe. These software frameworks will insulate the ocean modelling code from the hardware specific details of such tasks as I/O and parallelization, while also providing a standardized and extensible interface to other components such as atmospheric models. Other facets of hardware independence will be engendered in the careful design of the common coding standards of the Environment. The availability of these frameworks will make the widespread use of Ocean Model Environments viable.

Climate studies are placing increasingly diverse demands upon ocean models. The capabilities required to meet these demands, in many cases, exist. However, the available options are not now being systematically evaluated for use in diverse applications, and the interchange of ideas is being artificially retarded by our ocean modelling software. It is likely that the ocean modelling community will respond to these demands and limitations by adopting and evolving toward the vision of community Ocean Modelling Environments, comprising a common codebase, diverse models, and the flexibility to skilfully address the wide range of ocean-climate applications.

David Marshall from the University of Reading presented a provocative talk on unstructured finite element methods. He highlighted the significant advances made during the past few years at both Reading and the Alfred Wegener Institute. Although earlier results were discouraging, recent developments indicate that these methods offer many potential advantages for ocean modelling, in particular when combined with dynamically adaptive meshing. Many of the previous problems encountered in applying these methods to rotating, stratified flows have been overcome. These methods already offer exciting possibilities for specific GFD problems (such as boundary layer separation and dense water overflows). There remain many challenges to overcome, such as the refinement of error measures guiding remeshing, and constraining this remeshing to be sufficiently adiabatic. Nevertheless we believe there is a distinct possibility that the next generation of ocean models, say ten years from now, may be based on these exciting new methods.

Hans von Storch from the Institute for Coastal Research GKSS in Germany presented the final talk of the workshop. He focused on some philosophical issues related to defining a "model". He encouraged scientists to carefully consider some of these points, especially when communicating their work to non-scientists. More practical matters for coastal ocean forecasting were also discussed, with examples drawn from the regions surrounding Germany.

ABSTRACTS OF THE TALKS

Overview of IPCC ocean models

Peter Gent National Center for Atmospheric Research Boulder USA

This talk compares the ocean components of twelve different climate models, whose results will be submitted to the fourth assessment report of the IPCC. The features compared were the different grids, horizontal viscosity, tracer equation closure and vertical mixing schemes. Ten models used a z-coordinate, one a density coordinate, and the last used a hybrid z-density coordinate. The horizontal grids and resolutions are also quite different. The models used fairly similar horizontal viscosity schemes and closures in the tracer equations. No model used horizontal diffusion in the tracer equation. There is a very wide range of vertical mixing schemes, and this is the most diverse parameterization in these twelve ocean components.

How well do ocean models simulate the tropics?

Tony Rosati, NOAA Geophysical Fluid Dynamics Laboratory, Princeton USA

This talk presents a comparison of the simulation in the upper tropical Pacific Ocean in the GFDL and NCAR ocean components. These solutions are much improved over the last ten years, but there are still significant differences compared to observations from the TOGA-TAO array and assimilation runs using the GFDL model. The sea surface temperature is too cold in the central Pacific and too warm in the east, and the maximum variability is too far west. The thermocline is a little more diffuse in the NCAR component, and the GFDL model compares better with observations. Both components have similar errors, but they are somewhat smaller in the GFDL component. The errors seen in these ocean alone runs, forced by the best forcing climatology, are substantially larger in fully coupled integrations.

Sensitivity of ENSO variability in the CCCma coupled model to ocean model parameters and improved simulation of tropical currents with anisotropic viscosity

William Merryfield, Canadian Centre for Climate Modelling and Analysis (CCCma), Victoria, BC Canada

The CCCma coupled global climate model has historically exhibited unrealistically weak ENSO-like variability (e.g., AchutaRao and Sperber 2002). This has motivated a survey of the sensitivity of modelled ENSO to the configuration of the ocean sub model. The tests were undertaken using a development version of CGCM3 that has lower resolution (T47 atmosphere, 1.87 x 1.87 degree ocean) than the T63 version (0.94 lat x 1.41 lon ocean) that is being used for the IPCC Fourth Assessment. All runs were at least 50 years long, and did not employ flux adjustments except where noted. Main results are as follows:

1. Because equatorial currents in the model were unrealistically weak, the anisotropic viscosity parameterization of Large et al. (2001) was implemented. This resulted in dramatic improvements in the modelled currents even at this coarse resolution, e.g. an increase in the peak speed of the Equatorial Undercurrent from just over 10 cm/s to 1.0 m/s. However, perhaps surprisingly, these changes had little impact on either the amplitude or pattern of ENSO variability.
2. To assess the possible influence of flux adjustment, model runs with and without flux adjustment were compared. The run with flux adjustment exhibited a slightly higher (by ~20%) ENSO amplitude.
3. Reducing vertical grid spacing in the uppermost ocean from 50 m to 15 m resulted in a slightly weaker ENSO.
4. Runs with and without the KPP mixed layer parameterization at this higher vertical resolution showed little difference with respect to ENSO.
5. A run using the higher vertical resolution and KPP in which the background vertical tracer diffusivity was reduced from 0.3 to 0.1 cm**2/s exhibited a significantly (~30%) stronger ENSO.
6. Likewise, reducing background vertical viscosity from 20 to 5 cm**2/s resulted in a ~30% stronger ENSO, and a run in which the vertical viscosity and diffusivity were both reduced showed a stronger ENSO still.

Results (3) and (5) mirror similar tendencies found in a model comparison by Meehl et al. (2001). One factor not explored here is horizontal resolution; however, model intercomparisons by Latif et al. (2001) and

AchutaRao and Sperber (2002) found little if any systematic dependence of ENSO amplitude at resolutions of less than about 2 degrees.

Even under modifications (5) and (6) that resulted in significantly larger ENSO amplitudes, the amplitudes remained approximately half of what is observed. The relative insensitivity of ENSO to significant changes in ocean model configuration suggests that the major sensitivities may lie in the atmospheric component, and indeed evidence appears to be accumulating in support of this conjecture (e.g. Guilyardi et al. 2004).

Sensitivity of equatorial currents to wind stress

Debasis Sengupta, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore India

This talk shows results from an ocean model (MOM2.2) forced by different daily wind stress products. The equatorial Indian Ocean circulation is quite dependent on whether the NCAR/NCEP Reanalysis or QuikSCAT wind stresses were used. Comparison with recent observations show that the QuikSCAT stress gives a realistic simulation of intraseasonal to interannual variability of currents.

Numerical simulation using an ocean general circulation model

Raghavan Krishnan, Indian Institute of Tropical Meteorology, Pune, India

This talk shows a simulation with the Los Alamos POP model of the Indian and Pacific Oceans from a very new global ocean model. The simulation realistically captured the ENSO phenomenon in the tropical Pacific. The simulation also drew attention to an ocean-atmosphere coupled instability in the tropical Indian Ocean that is analogous to ENSO in the tropical Pacific Ocean.

How well do ocean models represent the mean thermohaline circulation?

Malcolm Roberts, Hadley Centre for Climate Prediction, Exeter, United Kingdom

This talk assembles the meridional overturning circulation in coupled integrations from nine of the climate models discussed earlier. There was quite a range in the strength of the thermohaline circulation between the models. It is not at all clear what causes this diverse set of simulations; is it differences in the ocean components or in the forcing climatology from the different atmosphere components? One possibility is that the thermohaline circulation strength depends upon the horizontal resolution used. For example, in the one-third degree resolution ocean component of HadCEM, the thermohaline circulation is much stronger than in the 1.25 degree resolution ocean of HadCM3. The deep cell of Antarctic Bottom Water entering the deep North Atlantic is also considerably stronger in the one-third degree ocean component.

Clearly there are interesting scientific questions to answer as to the reasons for the model differences. One would hope that this round of IPCC analysis would be able to extract more of this type of information rather than simply comparing specific numbers at particular latitudes/longitudes. The question remains as to whether the THC as simulated by models can be constrained by observations, be they from assimilation/inverse models or other methods. There is also the whole area of variability, spatial and temporal, which needs to be addressed, though again this may be difficult with current observations.

Reducing systematic errors in the CSIRO model

Siobhan O'Farrell, CSIRO Division of Atmospheric Research, Aspendale, Australia

This talk documents the reduced systematic errors in the latest Mk 3.5 version of the CSIRO climate model. The main changes to the ocean component were the inclusion of a Kraus-Turner mixed layer scheme, and a variable eddy diffusivity based on Visbeck et al. There were also changes made to the atmosphere and sea-ice components, and to the ocean spin-up, which now uses the atmosphere component precipitation minus evaporation flux and very weak restoring. The improvements are largest in the Southern Ocean, to the temperature and salinity distributions, the mixed layer depths and the meridional overturning stream function.

Can isopycnal ocean models be used for climate?

Rainer Bleck, Los Alamos National Laboratory, Los Alamos, USA

This talk addresses the main elements of isopycnal models and discusses their utility in coupled ocean-atmosphere climate modelling. The main design element of isopycnal models is that depth and density trade places as dependent/independent variables, with the same number of unknowns, same number of equations, but very different numerical properties. The driving force for isopycnal model development is genetic diversity, whereby the ocean climate community expands its tool chest to include more than the traditional geopotential coordinate. The main benefits of an isopycnal model include:

- explicit PV and potential entrophy conservation under ideal flows,
- reduction of numerically induced diapycnal mixing during advection and diffusion.

The main pitfalls include:

- degeneracy of the vertical grid in unstratified water columns,
- 2-term horizontal pressure gradient force, which is prone to errors in steeply inclined layers,
- layer outcropping or "massless" coordinate layers,
- strongly varying layer thickness requiring sophisticated advection schemes for tracers.

The grid degeneracy is the main reason for introducing a hybrid vertical coordinate, where "hybrid" means different things to different people, such as:

- linear combination of z and bottom-following coordinate, or
- ALE (Arbitrary Lagrangian-Eulerian) coordinate.

The ALE approach, which is taken in HYCOM, has the advantage of maximizing the size of the isopycnic sub domain. The use of isopycnic and hybrid-ALE models in climate include (1) Hamburg (MPI) in the 1980s, (2) Miami, late 1990s, (3) New York (NASA/GISS), early 2000s, (4) Florida State University, (5) Utrecht (KNMI), (6) Bergen (Nansen Institute), and (7) Southampton Oceanography Centre.

The pilot OMIP experiment

Frank Bryan, National Center for Atmospheric Research, Boulder USA

This talk presents an overview of the pilot-OMIP organized by the WGOMD during 2001-2004. Major conclusions include the following:

- A protocol for running coupled ocean and sea ice models that can be used by multiple centres is feasible.
- Serious shortcomings remain in the forcing data. Most objections and non-compliance to the proposed protocol center on the forcing specification.
- Some indication of robust behaviours (both positive and negative) can be seen by model comparisons.
- It is tough to motivate model developers running the experiments to undertake diagnostic analysis projects unless they are interested from a scientific motivation.

The following questions were raised during P-OMIP:

- Is there a strong enough community consensus to go forward with a major ocean model intercomparison project?
- Can a single OMIP protocol meet the needs of several constituencies (climate assessment, CLIVAR basin panels)?
- How do we motivate groups to participate (obligation or attraction)?
- How do we motivate groups to take on analysis?
- Can we secure the technical and administrative infrastructure required to expand to a large scale OMIP?
- Should we focus on repeating "normal year" or interannually varying forcing or both?
- What is the lifetime for a forcing data set?
- How specific should the protocol be (e.g., bulk formula, optics)?

Lessons learned from the Arctic Ocean Model Intercomparison Project (AOMIP)

Andrey Proshutinsky, Woods Hole, USA

The Arctic Ocean Model Intercomparison Project (AOMIP) is funded by NSF via the International Arctic Research Center in Alaska, USA. The purpose of this talk is to outline the major elements of AOMIP, details of the model experiments and protocol, and to discuss some of the initial results and challenges.

The overarching project goal is to determine major directions for Arctic Ocean model improvements based on coordinated numerical experiments and intercomparisons across an international suite of participating models. One of the most difficult tasks is to identify causes of differences among model results and causes of differences between model results and observations. A logical continuation of this work (when causes of differences are identified) is model improvement based on implementation of new physics and parameterizations. Diagnostic and specially designed studies will address model-model and model-observations differences. To ensure an accurate intercomparison experiment, and to eliminate ambiguities in interpretation of model results, it is necessary to force and validate all models in as similar a manner as possible. To this end, we have collected and created a variety of standardized model forcing and validation data sets.

The second goal is to investigate the variability of the Arctic Ocean climate at seasonal to decadal time scales based on model results and observations. A community-based modelling approach provides the unique opportunity to coordinate the investigation of different aspects of Arctic Ocean dynamics and thermodynamics because it allows for the purposeful design of a set of carefully planned numerical experiments covering the most important processes and interactions. A clear advantage is that each PI will be able to work with his or her specific research theme using simulation results from all AOMIP models, and will be able to analyze differences among all model results. This approach will allow AOMIP PIs to carry out comprehensive studies of different processes and interactions, and to investigate their temporal and spatial variability.

Major AOMIP results cover several topics and include the following:

- Atlantic Water heat inflow to the Arctic Ocean: Variability caused by (i) Nordic Seas air-sea heat flux and (ii) northward currents at the Iceland - Scotland Ridge. Variations occur as “events” rather than oscillations, possibly as various factors combine positively. Models with a more southern boundary reproduce variability better.
- Atlantic Water circulation within the Arctic Ocean: Models have a wide variety of behaviours. Many produce a cyclonic circulation in the Eurasian Basin, but differences are larger in the Canadian Basin. Fundamental questions controlling this circulation are still unanswered.
- Freshwater variability: Models generally agree that the Eurasian Basin is salty, but differ on the freshwater content and circulation on the shelves and in the Beaufort Gyre. There seems to be a salty drift in the Gyre, the cause of which is still unknown.
- Sea level variability: Fully 3D models can reproduce the general seasonal cycle and even interannual variability (and they do this better than 2D barotropic models), although they frequently miss high/low events.
- Sea ice distribution: the mean-weighted ice thickness variability among models is relatively low in much of the Arctic Ocean, but increases near the MIZ. This may be a function of ocean heat fluxes.

PREDICATE: Atlantic MOC in 5 OGCMs

Helge Drange, Nansen Center and Bjerkes Centre for Climate Research, Norway

The purpose of PREDICATE was to study the mechanisms and predictability of decadal fluctuations in the Atlantic-European climate. The project was funded by the European Union from 2000-2003, with five participating OGCM groups. Preliminary conclusions from the analysis phase include the following:

For prescribed atmospheric forcing (in this case the NCAR/NCEP re-analyses for the period 1948 to present), the simulations show that the temporal evolution of the strength of the AMOC is weakly dependent on the model initial state.

There are large model differences when actual volume and heat transports are considered.

The ensemble mean of the simulations indicates that the strength of the AMOC and the associated heat transport indicated a decreasing trend of 1-2 Sv and 0.15 PW between 1950-1960, and a 3.5-4.5 Sv and 0.2 PW increase since 1960, respectively.
The simulated decadal-scale variability in the strength of AMOC is caused by surface density anomalies in the North Atlantic sub-polar gyre, either originating in the North Atlantic or by density anomalies propagating from the Nordic Seas. The density anomalies are linked to, but are not necessarily identical to, the pattern of NAO/AO forcing.

The purpose of this talk is to present details of the protocol for running the models and to discuss preliminary analyses.

Reaction of the oceanic circulation to increased melt water flux from Greenland as a model intercomparison test case?

Ruediger Gerdes, Alfred-Wegener Institute, Germany

The purpose of this talk is to propose a protocol for running coupled ocean and sea ice models to investigate the oceanic response to an enhanced fresh water input into the northern North Atlantic. Additional fresh water input is expected over the next century as the result of global warming and could be due to several sources, namely an enhanced hydrological cycle, the reduction of the Arctic fresh water reservoirs, and increased melt water from Greenland. The oceanic response to freshwater perturbations has been tested within fully coupled climate models in the framework of the Coupled Model Intercomparison Project (CMIP). It is of interest to also develop a protocol whereby ocean and sea ice models can be investigated in isolation from an interactive atmosphere.

Preliminary results are presented from a suite of experiments in a single ocean and sea ice model with altered surface boundary conditions. It turns out that all experiments show qualitatively similar results, thus adding some confidence that a rough protocol is sufficient to garner a useful comparison experiment. General model behaviour includes the following:

- There is a weakening of convection in the Labrador Sea and of the DWBC.
- Initially, salinity and age increase in the Labrador Sea Water.
- After several decades a fresh North East Atlantic Intermediate Water (NEAIW) propagates southward along the western boundary.
- Fresh mode waters appear or intensify in the eastern subtropical gyre.
- Salinity decreases in the Arctic Ocean.
- There is a reduction of inflow of Pacific Water into the Arctic Ocean.

The strength and timing of the various responses depends on surface boundary conditions. Based on the ocean-sea ice model results, a range for the strength of the response can be estimated.

A new global forcing field for ocean and sea ice modelling

Bill Large, National Center for Atmospheric Research, Boulder USA

Available surface forcing data have been merged to form a complete set of fields needed to force global ocean and/or sea-ice models. The individual data sets were chosen on the basis of global coverage, spatial resolution, frequency duration and, to some extent, the needs and behaviour of the ocean and sea-ice components of the Community Climate System Model. Broad utility is suggested by initial results from the coupled GFDL ocean and sea-ice models. The global NCEP/NCAR reanalysis gives the atmospheric state, the recent ISCCP-FP product provides the radiation fields, the precipitation is a blend of multiple products, the continental runoff is derived from continental water budgets and climatological river discharge, the sea-ice concentration comes from the National Snow and Ice Data Center, historical SST is a reconstruction that has been made compatible with sea-ice concentration, and ocean salinity is non-standard at high latitudes. Other data sets are used to determine objective corrections to the forcing data sets, with the major factors a general increase in the wind speed, a reduction in the near surface humidity and a reduction in the solar insolation between 60S and 40N. Further adjustments to high latitude air-temperatures and downwelling longwave radiation are needed to improve water mass formation and sea-ice simulations.

The corrected/adjusted forcing is used in conjunction with observed SST to produce an observationally based air-sea flux climatology over 43 years. A necessary achievement of this exercise is to lower the global air-sea heat flux over 17 years (1984--2000) from 31 W/m2 heating to a more reasonable 1 W/m2. A freshwater imbalance of 3.4 mg/s/m2 is overcompensated by increased evaporation, so an overall increase in precipitation is used to give a nearly balance (-0.1 mg/s/m2) global mean budget. As an alternative to forcing with a full 43-year cycle and its interannual variability, a "Normal" Year Forcing (NYF) is developed. It consists of single annual cycles of all the forcing data. For a given SST it produces comparable fluxes as the full cycle, provided the same corrections are applied. NYF is constructed so that it can be repeated over and over without initiating spurious transients, while still retaining seasonal and propagating synoptic (weather) variability.

Issues of surface boundary conditions for ocean model intercomparisons

Mike Winton, NOAA Geophysical Fluid Dynamics Lab, Princeton, USA

The purpose of this talk is to highlight various technical issues, which are critical to keep in mind when running ocean and sea ice models within a comparison project. The following points will be emphasized:

- Models should use same turbulent transfer, or bulk, formula.
- Models should use properly referenced meteorological data consistent with what the bulk formulae expect.
- Models should use the same treatment of saltwater vapour pressure.
- It is desirable to use high frequency meteorological data.
- An outstanding issue concerns the treatment of salinity boundary condition, given the often extreme sensitivity seen in mixed boundary condition experiments.

Biweekly Yanai waves in the Indian Ocean

Debasis Sengupta, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore India

Recent moored current meter observations at the Indian Ocean equator show a 15-day oscillation of meridional current (v) at all depths, in addition to higher period intraseasonal variability. An ocean model forced by QuikSCAT wind stress is used to show that the biweekly oscillation is due to packets of Yanai waves with 3000-4500 km zonal wavelength, and westward and upward phase propagation. The biweekly wave in the ocean is resonantly forced by westward propagating quasi-biweekly oscillations in the tropical atmosphere.

OMIP experiments with two z-coordinate models at MPI-Hamburg and IfM-Geomar Kiel

Johann Jungclaus, MPI-Hamburg, Germany

Two z-coordinate ocean general circulation models (OGCM) using the forcing provided by Frank Roeske (http://www.omip.zmaw.de/omip/forcing365.php) were compared. At IfM-Geomar the OPA (version 9-beta) ocean model (with the Louvain Ice Model (LIM)) was run in the configurations ORCA2-LIM at 2 degree nominal resolution with 31 levels and in the configuration ORCA0.5-LIM at 0.5 degree resolution and 46 levels. The tripolar ORCA grids feature two grid poles in the Northern Hemisphere, over North America and Russia, respectively. At the Max Planck Institute for Meteorology (MPI) the MPI-OM was run in the configuration GR1.5 with 1.5 degree nominal resolution and 40 levels. The GR1.5 grid is dipolar with one pole over Greenland and the southern pole over Antarctica, close to the Weddell Sea. Both groups largely followed the P-sOMIP protocol. At MPI the model set up deviated from the P-OMIP protocol in the following way: The long wave radiation field was not used. Instead the thermal radiation was calculated in the model using the cloud coverage provided by Roeske. Salinity relaxation was reduced to 0.2m/day instead of 0.5m/day. The IfM ORCA2 and the MPI-OM models were run for 100 years and the last 10 years were analysed. In addition, at IfM a high resolution version (ORCA0.5) was run for a couple of decades. Owing to the lack of time only a quite superficial analysis could be performed.

Some of the key oceanic variables are summarized in this talk. There are some similarities, such as the meridional heat fluxes, but also some discrepancies, such as the overly high Drake Passage throughflow in MPI-OM. Interesting aspect that we want to pursue in the future are details of deep water formation and spreading (parameterization of convection, vertical mixing, and bottom boundary layer processes). At MPI also an analysis of the ocean circulation and water mass transformation in certain density classes was carried out. This appears to be a useful tool to understand the global overturning circulation in different models. A unified forcing is a valuable tool for model development and the test of new model set-ups. Comparing models that are run with the same forcing gives the opportunity to better understand model-specific behaviour and to improve deficiencies by systematically analyzing the effects of particular model features, such as parameterizations, resolution, and grid configurations. Scientifically more interesting aspects are, however, expected, from multi-model studies with time-varying interannual forcing.

Overflows and Gravity Currents

Sonya Legg, WHOI and GFDL Princeton. USA

In this talk we explore questions related to physical processes active in overflow regions and dense currents over topography. In particular, what role does hydraulic processes, shear instability, geostrophic eddies and frictional bottom boundary layers play in determining path and properties of dense water? Bulk entrainment parameterizations will be discussed, as well as more refined parameterizations such as turbulence closure theories. Results from isopycnal, sigma, and z-models will be presented at varying resolutions to see how the models perform in idealized contexts. Finally, an overview of the Gravity Current and Entrainment Climate Process Team (CPT) will be discussed, whereby a collaboration of climate modellers, process modellers, theorists, and observationalists aim to understand and parameterize overflow processes with the ultimate goal of improving methods in large-scale climate models.

Eddy-surface mixed layer interactions

Raffaelel Ferrari, Massachusetts Institute of Technology, USA

Variability in the surface boundary layer results from a combination of processes arising from three fundamental sources:

- Turbulence generated by atmospheric forcing,
- balanced mesoscale motions,
- and their interactions.

The first two are reasonably well understood. The purpose of this talk is to describe the interaction problem. In the stably stratified interior of the ocean, mesoscale eddies transport large-scale material properties through a combination of quasi-adiabatic mean advection and along-isopycnal stirring. Near the surface, however, boundary-layer turbulence overcomes the adiabatic, isopycnal constraints for the mesoscale transport: this interaction produces advective and diffusive fluxes along the surface. A residual mean formalism is shown to be quite suitable for diagnosing and representing the transition from the adiabatic interior to the diabatic boundary layer. High-resolution eddy simulations are diagnosed to study this transition. Parameterizations for models that do not resolve mesoscale eddies are proposed, and their consequence is illustrated in idealized flows. This work is carried as part of a CPT that focuses on the interactions between balanced and unbalanced motions in the surface boundary layer.

Open Ocean Deep Convection

Claus Boening, IfM-Geomar, Kiel, Germany

The talk focuses on deep convection in the Labrador Sea, a phenomenon of key importance for the replenishment of NADW. Its representation in model simulations of large-scale ocean circulation has been found highly sensitive to a host of model factors, resulting in strong model-model differences and a notorious difficulty in reproducing the salient characteristics of observed features such as the spatial extent, depth and water mass characteristics.

After an overview of the fundamental processes thought to be active in deep winter convection, recent studies with idealized process models and high resolution, basin-scale models are used to highlight the key role of lateral eddy fluxes for both the preconditioning and the restratification phases of deep convection. Of particular interest in current research is the relative importance of different sources of eddy activity in the Labrador Sea. Observational results and model studies have directed attention recently on the intense eddy field originating from a localized instability area in the boundary current off West-Greenland. Apart from being an important factor in conditioning the interior Labrador Sea by importing T/S-properties from the Greenland Current system and its different source waters of North Atlantic and Arctic origin, the "boundary eddies" may also play a significant part in the restratification phase: recent simulations using idealized configurations suggest a dominant role of these eddies compared to "rim current eddies" generated as part of the convection process, supporting the view that surface heat loss in the marginal sea interior may be offset primarily by lateral eddy fluxes originating in the boundary current. While awaiting confirmation by high resolution models in realistic geometry, these results raise some important questions: what is the impact of the interannual modulation of the boundary current and its eddies on the convection intensity, and how can this lateral mixing be realistically captured in coarse resolution models?

Abyssal and Tidal Mixing Processes

Lou St. Laurent, Florida State University USA

Turbulent mixing in the deep ocean is maintained by internal wave processes, with energy deriving from wind and tidal sources. In particular, internal tides are generated in regions where the barotropic tides flow over rough abyssal topography. This results in a spatial variation of the diffusivity quantifying the turbulent mixing rate for the oceanic deep and bottom water masses. While the ventilated waters of the upper ocean are characterized by a diffusivity of kv=0.1 cm2/s (1x10-5 m2/s), average diffusivities for these deeper water masses range from 3 to 10 cm2/s. Microstructure observations, theoretical studies, and numerical simulations have examined many aspects of the cascade processes that transfer energy from internal waves to turbulence. Simple parameterizations have been proposed to account for the spatial variation of mixing that results from the internal tide driven turbulence at rough topography sites. However, a precise understanding of cascade physics is generally lacking, and many questions remain regarding the radiative component of the internal wave energy budget. Specifically, no model exists for estimating the spatial distribution of turbulence levels associated with the dissipation of radiated wave energy.

Thermocline Ventilation

Martin Visbeck, Lamont-Doherty USA and IfM Kiel Germany

The process of thermocline ventilation is important for the exchange of properties between the atmosphere and ocean. In the modern ocean the ability of the ocean's uptake of atmospheric pollutants such as CO2 and the regulation of atmospheric oxygen are important issues. At the same time the exchange of heat and freshwater and the subsequent transport in the ocean interior are important to maintain the ocean's stratification.

The adequate simulation of the upper ocean stratification, however, is a long-standing problem for ocean models. Even today, where many vertical levels are computationally feasible, and low levels of vertical mixing can be numerically implemented, the representation of thermocline stratification remains an issue.

Thermocline ventilation as a process is regionally different. In wind driven ocean gyres a theory has been well developed and many models are capable to reproduce this process. Thermocline ventilation can also occur near fronts as found near major western boundary currents or north of the Antarctic Circumpolar Current (ACC). In these regions lateral transfer by mesoscale eddies is believed to be the major process. While a significant body of theoretical and numerical process modelling has advanced our understanding of this process, there are still issues when trying to parameterize this process in non-eddy resolving and eddy permitting models.

A skilful representation of eddy induced lateral fluxes requires information about the magnitude and vertical profiles of the eddy exchange efficiency (eddy mixing coefficient). While some progress has been made in relating this to the large-scale stratification in particular the vertical modulation is not well understood. Secondly the interaction of the adiabatic eddy and wind driven circulation in the interior of the ocean with mixed layer processes is receiving an increasing amount of attention. Those processes are most likely very crucial for a better simulation of upper ocean biogeochemical processes and had shown to influence the amount of heat and freshwater flux in the ACC region.

I conclude my presentation with a discussion of the possibly most important missing ingredients in the current IPCC class type models. While thermocline ventilation near fronts is certainly an important issue that needs attention, the poor representation of shelf water formation and the overflow/entrainment process are a possibly bigger concern.

Mixing in the Tropical Ocean

Paul Schopf, George Mason University, USA

The purpose of this talk is to describe mixing in the upper tropical and equatorial ocean, and to highlight its importance for such climate phenomena as ENSO, MJO, tropical Atlantic variability and monsoons. Ocean simulations are quite sensitive to the levels of equatorial mixing used in the models, and these uncertainties become highly magnified when coupled to atmosphere models. This prompts further explorations of the processes, their parameterizations, and observational constraints. Little is known of the spatial and temporal homogeneity of small scale mixing within the highly sheared and variable flow regimes of the tropics, or how the large scale net effects of this mixing depends on the large scale flow. We present an overview of a proposed Pacific Upwelling and Mixing Program, which is a process study designed to improve our understanding of the mechanisms that connect the thermocline to the surface in the equatorial Pacific cold tongue. Its goal is to observe and understand the interaction of upwelling and mixing with each other and the larger equatorial currents, bridging the gap between microstructure measurements and the net grid scale mixing of importance to ocean models.

Observations to help constrain the models

Steve Rintoul, CSIRO Hobart, Australia

In this talk, we explore the ability of large-scale observations planned for the next decade to provide useful constraints on global ocean climate models. While the amount of data available for constraining models increases with time, we still do not have enough observations of key oceanographic features. For example, we do not have good measurements of absolute velocity and transports and only indirect and sparse measurements of mixing rates, eddy fluxes, formation rates, sea-ice volume and forcing. We will discuss a list of what observations will probably be available for constraining models in five years time, including global upper ocean stratification albeit with poor sampling in time, estimates of meridional overturning and water mass formation rates with some indication of associated variability, a few non-aliased records of decadal variability, a more global but still sparse map of mixing rates, more accurate measurements of absolute velocity from floats, altimeters and gravity missions, tracer inventories and improved estimates of air-sea fluxes of heat, fresh-water and carbon. Notably missing from the list is significantly better measurements of sea-ice volume.

Operational Oceanography

Eric Chassignet, University of Miami, Miami, USA

In this talk, we explore some of the elements of an operational oceanographic system and discuss its potential usefulness for climate work. Operational oceanography here refers to the routine provision of oceanic information that can impact decisions made by the public, government, or the military. On one hand, short-term prediction of ocean state is normally carried out at high resolution and is limited by forecasts of the atmospheric state used to force the ocean models. The international Global Ocean Data-Assimilation Experiment (GODAE) aims to demonstrate global operational capability. Some of GODAE's objectives include making routine short-range open-ocean forecasts, provide best estimates of boundary conditions for coastal and regional models, and provide initial conditions for climate forecasts. On the other hand, coupled ocean atmosphere forecasting systems are mostly regional. Some examples are seasonal-interannual prediction of ENSO and hurricane forecasts. The challenges of operational oceanography include bringing together real-time streams of diverse data and assimilating them into high-resolution models. Among other things, operational oceanography can be useful for climate studies by:

- providing better initial conditions,
- providing a better understanding of model limitations and forecast errors,
- providing reanalyses that can be used as a benchmark.

Adjoin tools for understanding the ocean

Eli Tziperman, Harvard University, Cambridge, USA

There has been much emphasis on the use of adjoin methods in data-assimilation and state estimation. However, based-based tools have many other applications including sensitivity analysis, optimal initial conditions, and stochastic optimals. The aim of this talk is to convince the audience that adjoins can provide oceanographers with a powerful tool to understand the mechanisms of variability of the ocean circulation and the ocean role in climate variability. Examples will be drawn from the thermohaline circulation, North Atlantic heat transport and ENSO. The availability of adjoin models is anticipated to increase due to the automatic differentiation tools that are now available.

Model frameworks and environments

Robert Hallberg, NOAA Geophysical Fluid Dynamics Lab, Princeton, USA

The purpose of this talk is to discuss the emergence of a new paradigm in ocean model development: ocean model environments. Environments promise to bring together a wide array of model practices under single code bases, with closer collaborations between developers of previously distinct model codes. The advent of increased complexity in both computational architectures and model needs and capabilities make it impractical for single developers to maintain the code and do interesting science with the code. The use of common ocean modelling environments will reduce the barriers between oceanographers by allowing them to employ the same tool, increase the range of methods that can be selected among to most effectively study a particular question, and speed the transition of superior techniques to widespread use. There are nascent efforts ongoing now to realize these goals, with the next decade likely seeing a significant merger of many previously disparate efforts.

Finite element methods and adaptive meshing: towards the next generation of ocean models?

David Marshall (University of Reading UK), Sergey Danilov, Gennady Kivman, Jens Schr√∂ter (Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany), Chris Pain, Matthew Piggott, Gerard Gorman, Lucy Bricheno, Colin Cotter, Matthew Eaton, Fangxin Fang, Philip Power, Adrian Umpleby, Cassiano de Oliveira, Tony Goddard (Imperial College, London UK), Caroline Bain, Adam Candy, David Munday (University of Reading UK)

Despite tremendous advances over the past decade, numerical ocean general circulation models are based on essentially the same finite-difference methods employed in the earliest ocean models, developed in the 1960s. Finite elements and, in particular, adaptive meshing have been employed to great effect in engineering applications, and potentially offer several advantages for ocean modelling. These include: the ability to conform accurately to complex basin geometries; the ability to focus resolution where it is most needed in response to the evolving flow; the ability to incorporate various natural boundary conditions in a straightforward manner; and the ability to make rigorous statements about model errors and numerical convergence.

Despite these apparent advantages, the application of finite element methods to ocean modelling has been limited, due to issues concerning the intellectual overhead of learning the new methods, issues concerning the computational overhead of the finite-element method (unless offset through the use of adaptive meshing), and technical challenges concerning the treatment of geostrophic and hydrostatic balance. Over the past few years considerable progress has been made in overcoming these challenges. This presentation contains a brief discussion of two major initiatives: the Finite Element Ocean Model (FEOM) at Bremerhaven, a nonhydrostatic model which uses a horizontally-unstructured (but static) mesh, which has been run in a realistic North Atlantic configuration; and the Imperial College Ocean model (ICOM), a nonhydrostatic model which employs fully-unstructured (in 3 dimensions), dynamically-adaptive meshing which, to date, has been run only in idealised configurations. Both of these models have been coded to run efficiently on parallel architectures, with domain-decomposition methods employed in the case of ICOM to balance the computational load during remeshing.

FEOM (see Danilov et al, 2004, Ocean Modelling, 6, 125-150) is an important project because it demonstrates, for the first time, that unstructured, finite-element methods can be successfully applied to model the ocean circulation in a realistic basin here the North Atlantic. It employs an unstructured mesh in the horizontal with a resolution that varies between 0.2 and 1.5 degrees (with approximately 16000 surface nodes); the mesh is structured in the vertical, with 23 levels, with each full prism being divided into three tetrahedra. Finite differences are used to calculate the hydrostatic pressure (and thus overcome the difficulties with hydrostatic and geostrophic balance), but otherwise standard finite-element methods are employed. The model successfully captures several realistic features, including an inertial Florida Current and recirculation gyre, the Azores Current, and the North Atlantic Current and subpolar gyre. In a comparison with the POP model at 0.1 and 0.28 degree resolutions, the performance of the FEOM simulation lies somewhere between the two POP simulations. Certain features, such as the North Atlantic Current and subpolar gyre, both of which are strongly influenced by the bathymetry, are captured particularly well by FEOM. The overturning circulation is of the correct magnitude (12-14Sv), although there are some issues with spurious diapycnal mixing and premature upwelling in the tropics (the latter most likely due to the limited domain and the treatment of the open boundary). Further development of FEOM, and its application to idealised test problems such as the dense water overflows, is ongoing.

ICOM (see Pain et al., 2004, submitted to Ocean Modelling), in contrast to FEOM, is attempting to apply fully unstructured, dynamically adaptive meshing in all three dimensions. This is an extremely ambitious project, but very significant progress has already been made in demonstrating the utility of the approach. The model is based on an existing Navier-Stokes solver, including a suite of options for the spatial derivatives (such as high-resolution methods for accurate tracer advection). The mesh is adapted at prescribed time intervals, using an objective function, based on the curvature of the underlying flow fields and prescribed error tolerances. A new method is also employed to treat geostrophic and hydrostatic balance, which amounts to decomposing the Coriolis and gravitational accelerations in rotational and divergent components; the rotational component drives a net acceleration and is retained, whereas the divergent component balances a pressure gradient and is discarded.

Initial simulations have been performed for a variety of idealised test problems. An example is shown in this talk of a barotropic simulation of the Mediterranean basin, forced by an idealised surface wind stress. The minimum and maximum element sizes are prescribed to be 1/30 degree and 1 degree respectively. In this example, the resolution is focused in the jets and eddies shed downstream of the various peninsulas and islands, and in the lateral boundary layers. One advantage of the adaptive meshing is that one can efficiently test of statistical convergence. For example, in a series of calculations for the barotropic wind-driven circulation in a rectangular basin (at a Reynolds number of 2000 and with prescribed error tolerances), we found that decreasing the minimum element size by a factor of 4 resulted in an increase in the number of nodes (and hence in computational overhead) of just 10%. This is due to the additional resolution not being required, and hence not being taken up by the model. The equivalent calculations, without adaptive meshing, would involve a 64-fold increase in computational overhead.

Initial calculations for stratified flows are also encouraging. Preliminary results for idealised dense-water overflows using the DOME configuration are shown in this talk. Dense water is formed in a shallow sill region (through the use of a sponge layer), exits onto an idealised continental slope and turns along the slope under the influence of the Coriolis acceleration. However, the overflow current is physically unstable and quickly forms baroclinic eddies. In the figure, one can see the resolution being focused into the dense water filaments, and into the boundary layers. The enhanced resolution corresponds to regions of strong vorticity gradients in the flow. Similar calculations, using the MITgcm and the Hallberg Isopycnal Model (HIM), have recently been reported by Legg et al. (2004, submitted to Ocean Modelling). While the present calculations are at somewhat lower Reynolds numbers, they are roughly two-to-three orders of magnitude more efficient than the conventional models run at the equivalent lateral and vertical resolutions. It remains to be seen whether similar efficiency gains are possible at higher Reynolds numbers, and how this efficiency gain scales with the prescribed error tolerances. Nevertheless it is clear that dynamically-adaptive meshing has tremendous potential, in particular for resolving smaller-scale features, such as overflows, which we know play a crucial role within the larger-scale circulation.

In summary, unstructured finite elements offer many potential advantages for ocean modelling, in particular when combined with dynamically adaptive meshing. Many of the previous problems encountered in applying these methods to rotating, stratified flows have been overcome. These methods already offer exciting possibilities for specific GFD problems (such as boundary layer separation and dense water overflows). There remain many challenges to overcome, such as the refinement of error measures guiding remeshing, and constraining this remeshing to be sufficiently adiabatic. Nevertheless we believe there is a distinct possibility that the next generation of ocean models, say ten years from now, may be based on these exciting new methods.

Coastal ocean model applications that serve the needs of the coastal impacts community

Hans von Storch, Institute for Coastal Research, GKSS, Germany

Before addressing specifics of models needed for coastal applications, a brief introductory discourse about knowledge building with quasi-realistic models is offered. Such models are an incomplete replica of the real world. They are consistent with some parts of the observational evidence. They disregard a greater part of the phase space. Models cannot be verified. All models are eventually falsified. To speak about "models of XX" (e.g. XX = ocean' is not useful. Better language is to refer to "models for the purpose YY". YY could be, for instance: "understanding dynamics ZZ". "analysing state ZZ", "predicting state ZZ", "laboratory to study sensitivity of ZZ to UU". The significant issue for the workshop is that different YYs need different models.

The range of purposes (=YY) of coastal modelling is broad: Operational analysis and forecasting. Retrospective analysis for detecting and analyzing past, recent and ongoing trends. Forecasts/scenarios of effects of global change as well as of regional and local usage of catchment and coastal zone. Understanding dynamics in coastal seas.

Examples on retrospective analysis and scenarios are presented - wind, waves, currents, deposition of matter and risks in the North Sea and adjacent coasts. Based on an hourly regional re-analysis and on SRES scenarios of marine surface wind and air pressure, prepared with atmospheric LAMs on a 50km grid, dynamical models of North Sea currents, water level and surface waves were integrated for 1958-2002 and 2070-2100. These data sets are used for assessing and envisioning changing storminess, storm surge statistics, and ocean wave conditions. Other applications refer to long-range pollution (e.g., gasoline lead and benz-a-pyren), and a variety of "commercial" applications: Assessment of oil drifts in case of coastal accidents, assessment of fatigue in ships and off-shore construction, planning of harbour constructions, planning of off-shore wind energy, assessment of coastal defence measures, and wave conditions in estuaries.

Outlook: For the purposes listed above coastal sea models should be expanded to include the following:

- Introduction of more constituents - chemicals, biotic material, suspended matter, sand
- Coupling with wind waves, bathymetry (morphodynamics), ecology, chemistry
- Explicit representation of tides; time variable domain (Wadden areas); flexible nesting.
- Much higher resolution of both atmospheric forcing as well as oceanic description, allowing for decadal simulations.
- Coastal modelling needs high-resolution coastal sea operational analyses and decadal re-analyses.

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APPENDIX II. Workshop Programme

Day 1. 16th June 2004

Session A. State of the art in ocean climate models (Facilitated by Peter Gent)

- Overview of IPCC ocean models (P. Gent)
- How well do ocean models simulate the tropics? (A. Rosati)
- Anisotropic horizontal viscosity (B. Merryfield)
- Indian Ocean simulations. (D. Sengupta)
- How well do some IPCC-class represent the mean THC? (M. Roberts)
- Reducing systematic errors in the CSIRO model (S. O'Farrell)
- Ocean GCM simulation studies (R. Krishnan)
- Isopycnal ocean representation in coupled climate models (R. Bleck)

Session B. Ocean Model Intercomparison Project Facilitated by Anne-Marie Treguier)

- The Pilot Ocean Model Intercomparison Project (POMIP) (F. Bryan)
- Lessons learned in AOMIP (A. Proshutinsky)
- Atlantic MOC in 5 OGCMs (H. Drange)
- Reaction of the oceanic circulation to increased melt water flux from Greenland as an OMIP test-case? (R. Gerdes)
- The forcing fields used at NCAR for ocean/ice and ocean only model experiments (W. Large)
- Surface Boundary condition issues and preliminary comparison (M.Winton)
- OMIP experiments with two z-coordinate models (J. Jungclaus)

Day 2. 17th June 2004

Session C. Key physical processes (Facilitated by Sonya Legg and Raffaele Ferrari)

- Overflows and Gravity Currents (S. Legg)
- Eddy surface-mixed layer interactions (R. Ferrari)
- The Heatfunction (G. Boccaletti)
- Mesoscale eddies and mixed layer interactions (A-M Treguier)
- Open ocean deep convection (C. Boening)
- Tidal and abyssal mixing (L. St. Laurent)
- Ventilation processes in the thermocline (M. Visbeck)
- Tropical Mixing (P. Schopf)

Day 3. 18th June 2004

Session D. Future Directions (Facilitated by Alistair Adcroft)

- Observations to help constrain ocean climate models (S. Rintoul)
- Operational oceanography in the context of global ocean-atmosphere modelling (E. Chassignet)
- Based-based tools for understanding the ocean (E. Tziperman, J. Gebbie and P. Heinbach)
- Ocean Modelling environments and frameworks (B. Hallberg)
- Coastal ocean model applications that serve the needs of the coastal impacts community (von Storch)
- Finite Element methods and adaptive meshes (D. Marshall)

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